Incoherent J/ψ production at large $|t|$ identifies the onset of saturation at the LHC

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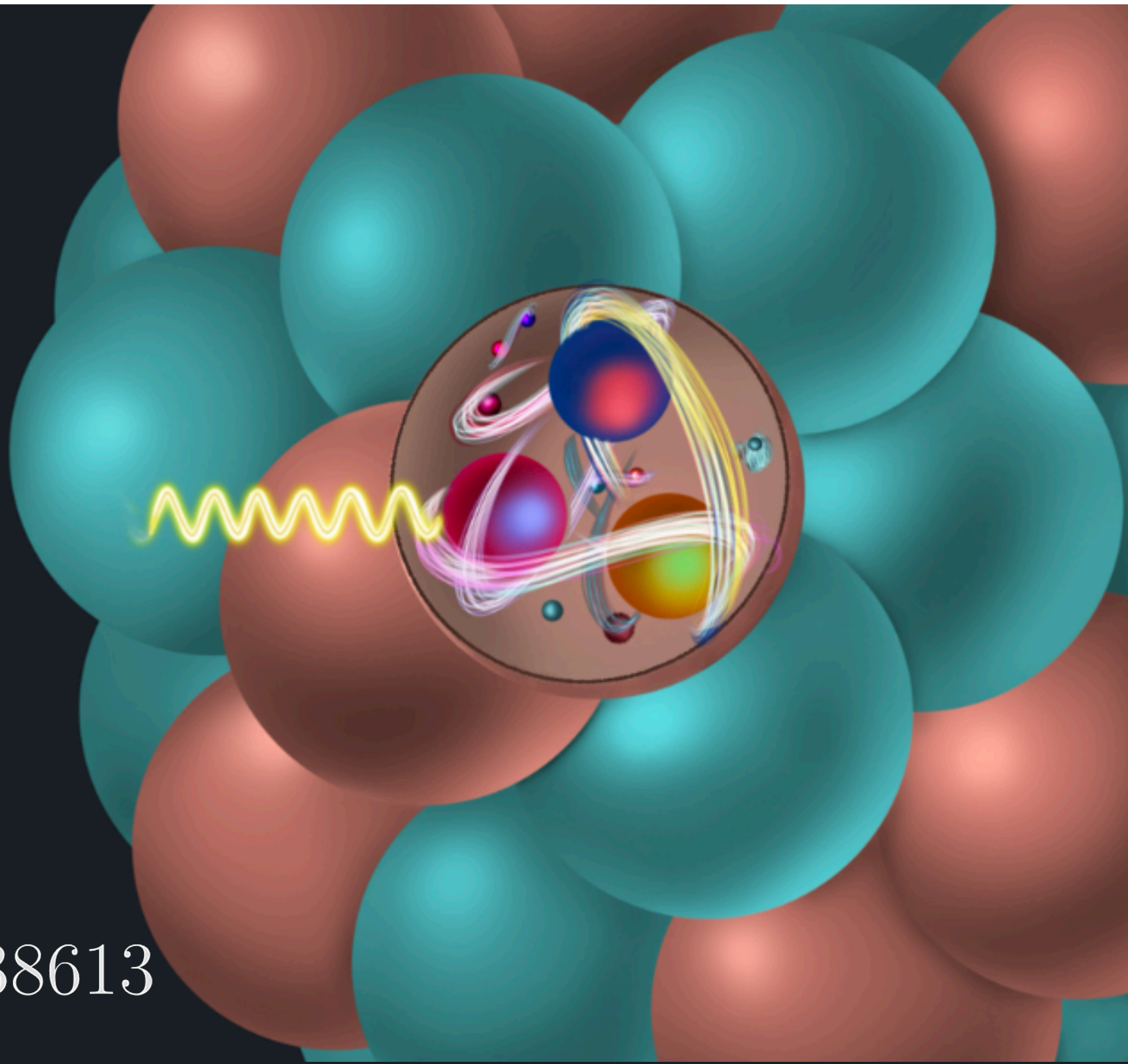
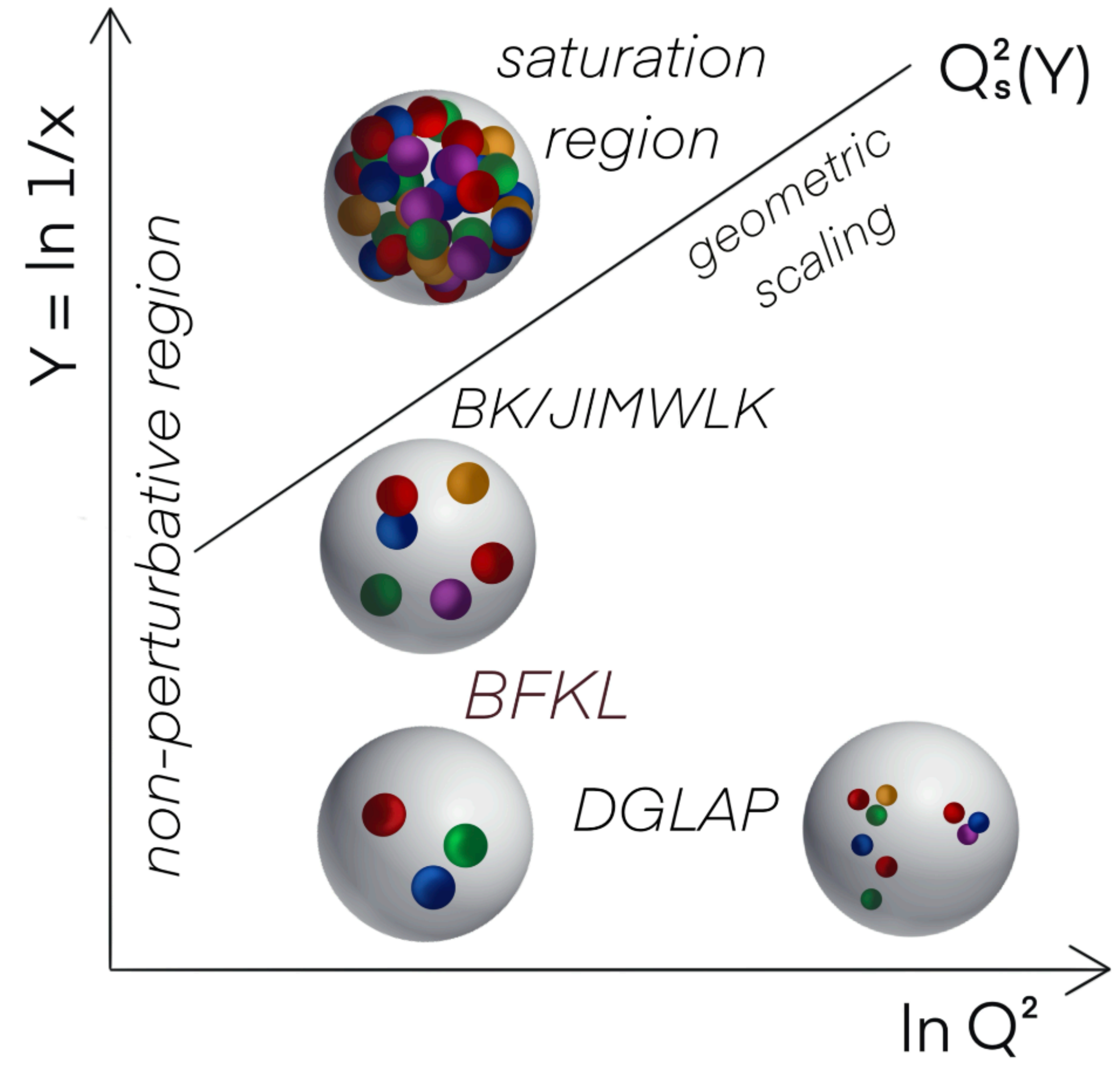
19.9.2024
Děčín

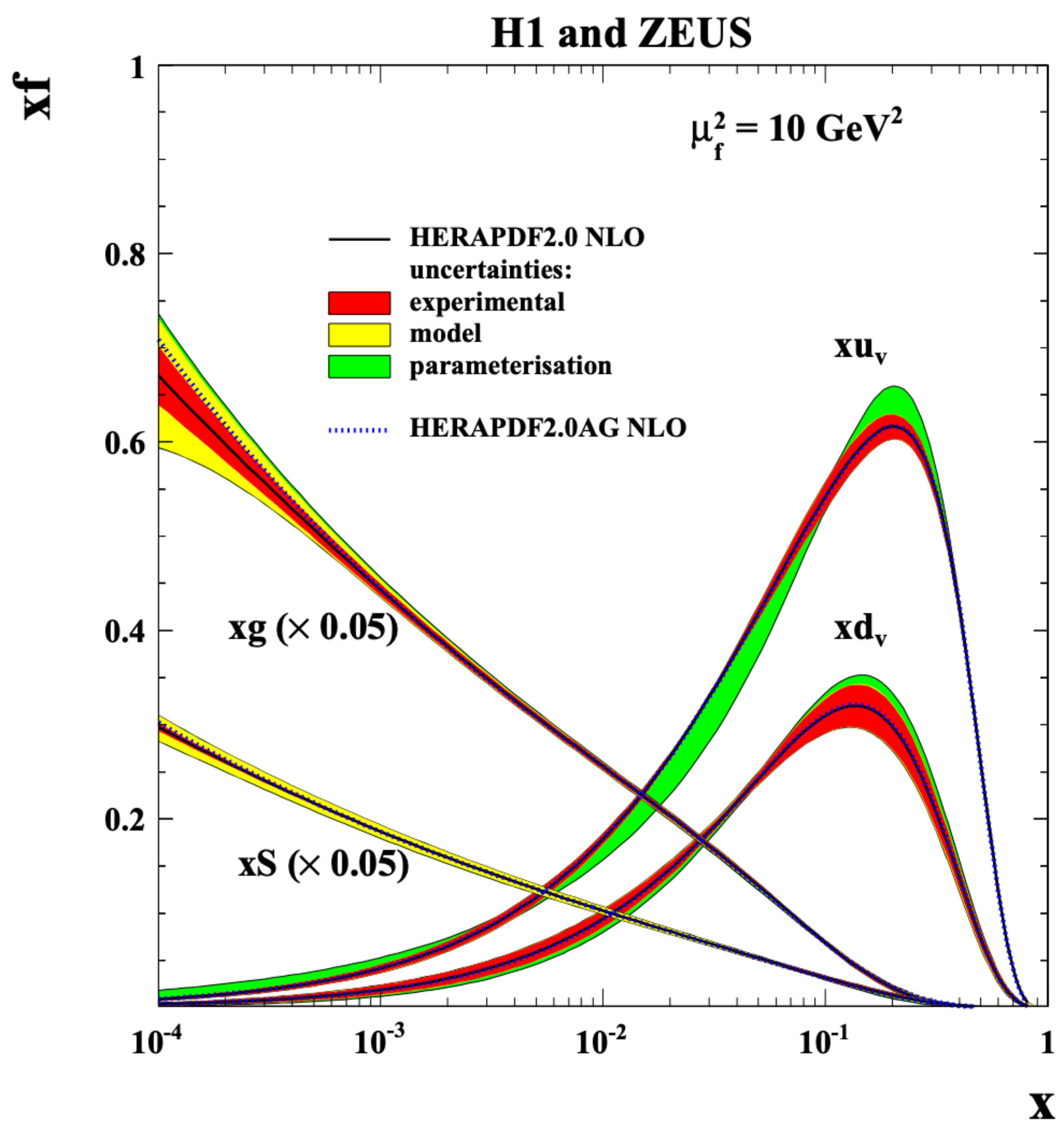


The work is based on
arXiv:2312.11320 [hep-ph] Phys. Lett. B 852 (2024) 138613

MOTIVATION

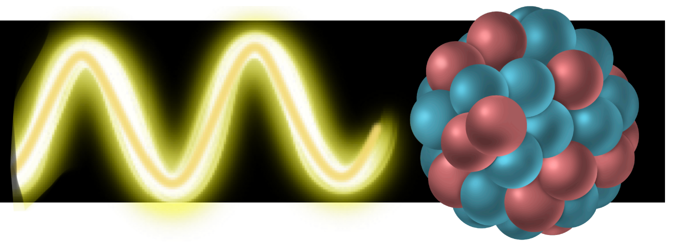
- Due to the high density in small-x region, the radiated gluons overlap each other and start interacting: ONSET OF SATURATION
  - The DIFFRACTIVE VECTOR MESON PRODUCTION serve as valuable tool for probing saturation effects due to its sensitivity to the gluon distribution within hadrons



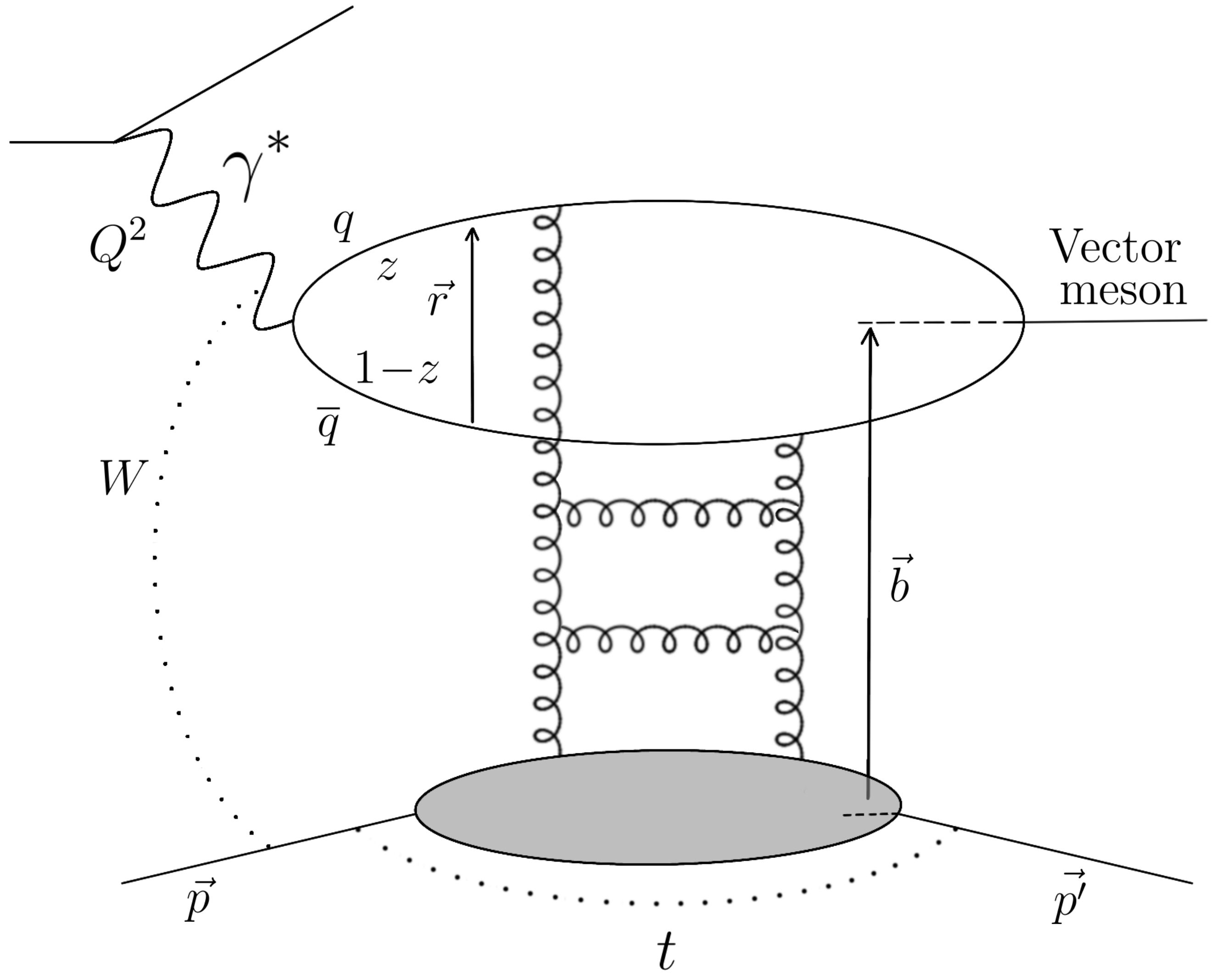


VECTOR MESON PRODUCTION

COHERENT



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



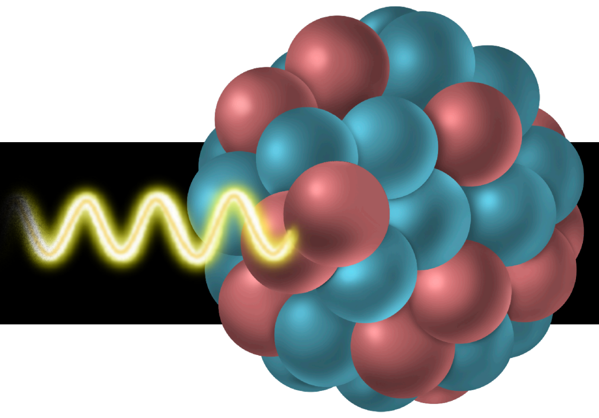
$$x = \frac{Q^2 + M^2}{Q^2 + W^2}$$

- Bjorken-x of the produced meson

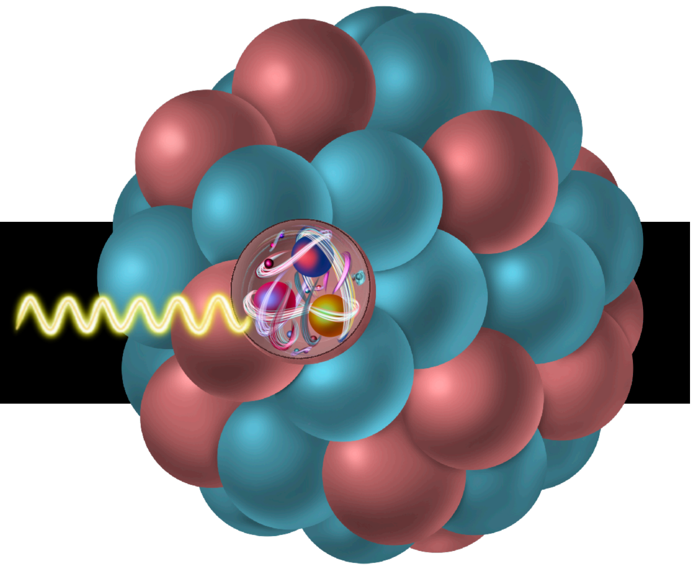
$$W$$

- the centre-of-mass energy of the photon-target system

INCOHERENT



DISSOCIATIVE



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

$$t = (p' - p)^2 = -\Delta^2$$

- the square of the momentum transferred in the interaction

- The scattering amplitude of the process is given by the convolution of photon and vector meson wave functions $|\Psi_{\mathrm{V}}^{*}\Psi_{\gamma^{*}}|_{\mathrm{T,L}}$ and the differential dipole cross section $\frac{\mathrm{d}\sigma^{\mathrm{dip}}}{\mathrm{d}\vec{b}}$

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

- The targets that we consider are proton *(p)* and lead *(Pb)*

ENERGY-DEPENDENT HOT–SPOT MODEL

PROTON

$$\frac{\mathrm{d}\sigma_{\mathrm{p}}^{\mathrm{dip}}}{\mathrm{d}\vec{b}} = \sigma_0 N(x,r) T_{\mathrm{p}}(\vec{b})$$

GBW MODEL

$$N(x,r) = \left[1-\exp\left(-\frac{r^2Q_s^2(x)}{4}\right)\right]$$

$$T_{\mathrm{p}}(\vec{b}) = \frac{1}{N_{\mathrm{hs}}}\sum_{i=1}^{N_{\mathrm{hs}}} T_{\mathrm{hs}}\left(\vec{b}-\vec{b}_i\right)$$

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

NUMBER OF HOT SPOTS

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

arXiv:1608.07559 [hep-ph]

ENERGY-DEPENDENT HOT–SPOT MODEL

PROTON

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

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

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

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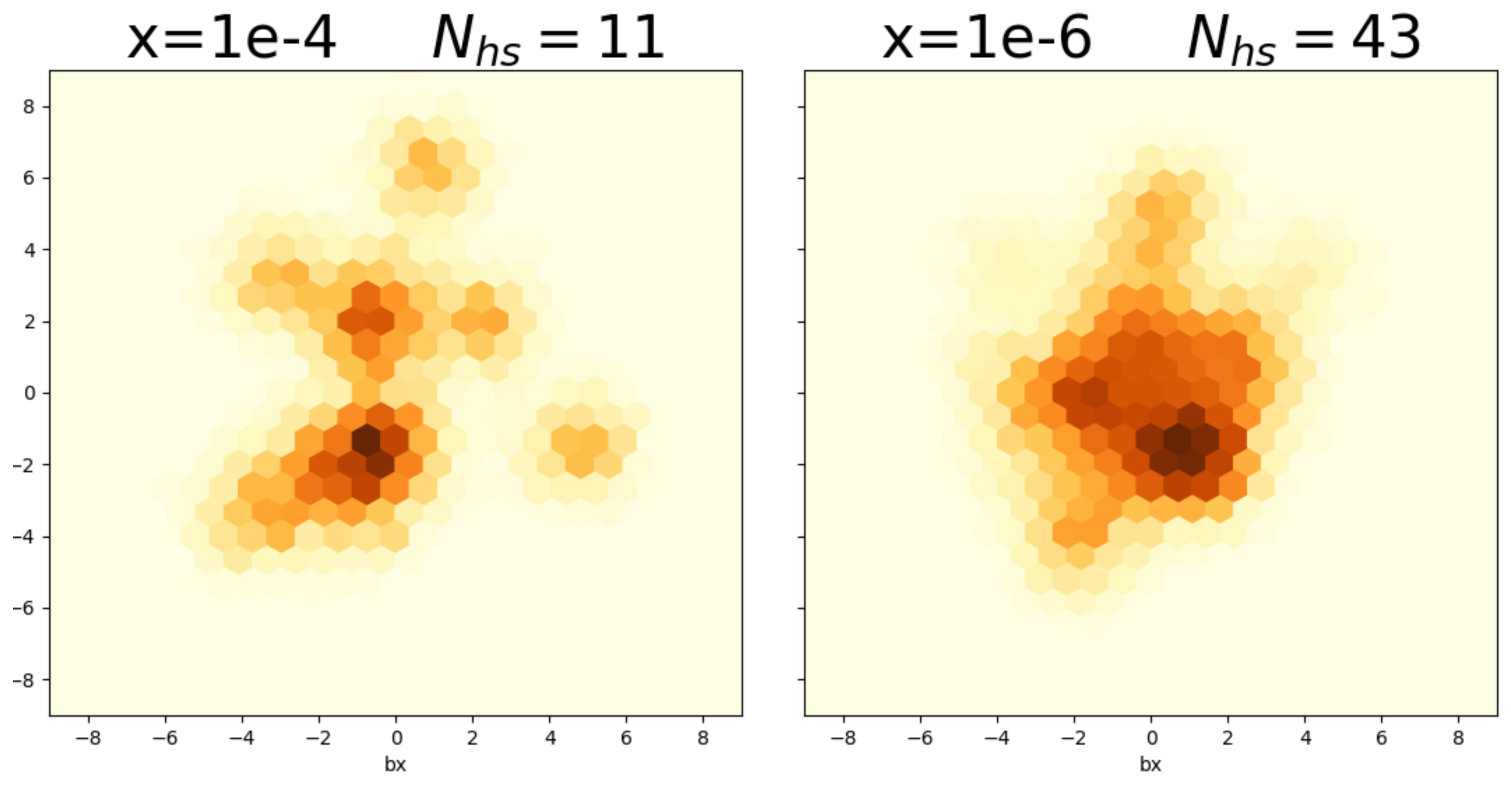
$$N(x,r) = \left[1 - \exp\left(-\frac{r^2 Q_s^2(x)}{4}\right)\right]$$

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

THE KEY FEATURE OF OUR MODEL IS THE EVOLUTION OF THE NUMBER OF HOT SPOTS WITH ENERGY IN ORDER TO REFLECT THE RAISE OF THE GLUON DISTRIBUTION, AS BJORKEN-X DECREASES

- The position of hotspot, $\vec{b}_i$ is randomly sampled from *2D* Gaussian distribution of width B_p and centred at *(0,0)*
- B_p and B_{hs} represent one-half of the averaged squared radius of the proton and of the hot spot, respectively
- $\sigma_0 = 4\pi B_p$ is twice the transverse area of the proton



ENERGY-DEPENDENT HOT–SPOT MODEL

PROTON

$$\frac{\mathrm{d}\sigma_{\mathrm{p}}^{\mathrm{dip}}}{\mathrm{d}\vec{b}} = \sigma_0 N(x,r) T_{\mathrm{p}}(\vec{b})$$

$$T_{\mathrm{p}}(\vec{b}) = \frac{1}{N_{\mathrm{hs}}} \sum_{i=1}^{N_{\mathrm{hs}}} T_{\mathrm{hs}}\left(\vec{b}-\vec{b}_i\right)$$

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

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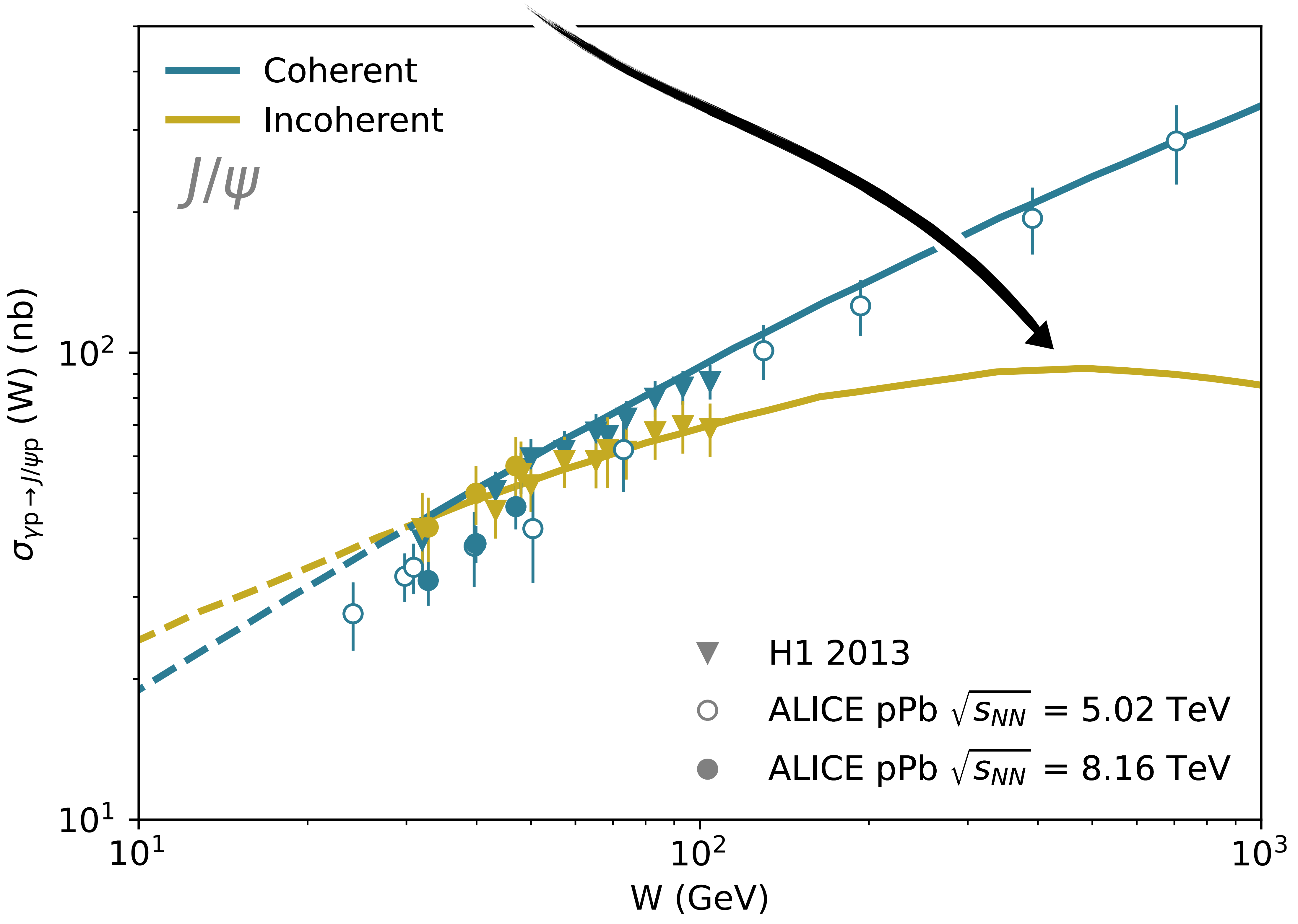
$$N(x,r) = \left[1 - \exp\left(-\frac{r^2 Q_s^2(x)}{4}\right)\right]$$

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

~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



Diffractive photo-production of J/ψ off protons for the coherent (blue) and incoherent (gold) processes.

ENERGY-DEPENDENT HOT–SPOT MODEL

LEAD

$$\frac{d\sigma_{\mathrm{Pb}}^{\mathrm{dip}}}{d\vec{b}} = 2\left[1 - \left(1 - \frac{1}{2A}\sigma_0 N(x,r) T_{\mathrm{Pb}}(\vec{b})\right)^A\right]$$

$$T_{\mathrm{hs}}(\vec{b}-\vec{b}_i) = \frac{1}{2\pi B_{\mathrm{hs}}} \sum_{i=1}^{A=208} \frac{1}{N_{\mathrm{hs}}} \sum_{j=1}^{N_{\mathrm{hs}}} \exp\left(-\frac{\left(\vec{b}-\vec{b}_i-\vec{b}_j\right)^2}{2B_{\mathrm{hs}}}\right)$$

- Position of nucleons is chosen randomly from the Woods-Saxon distribution

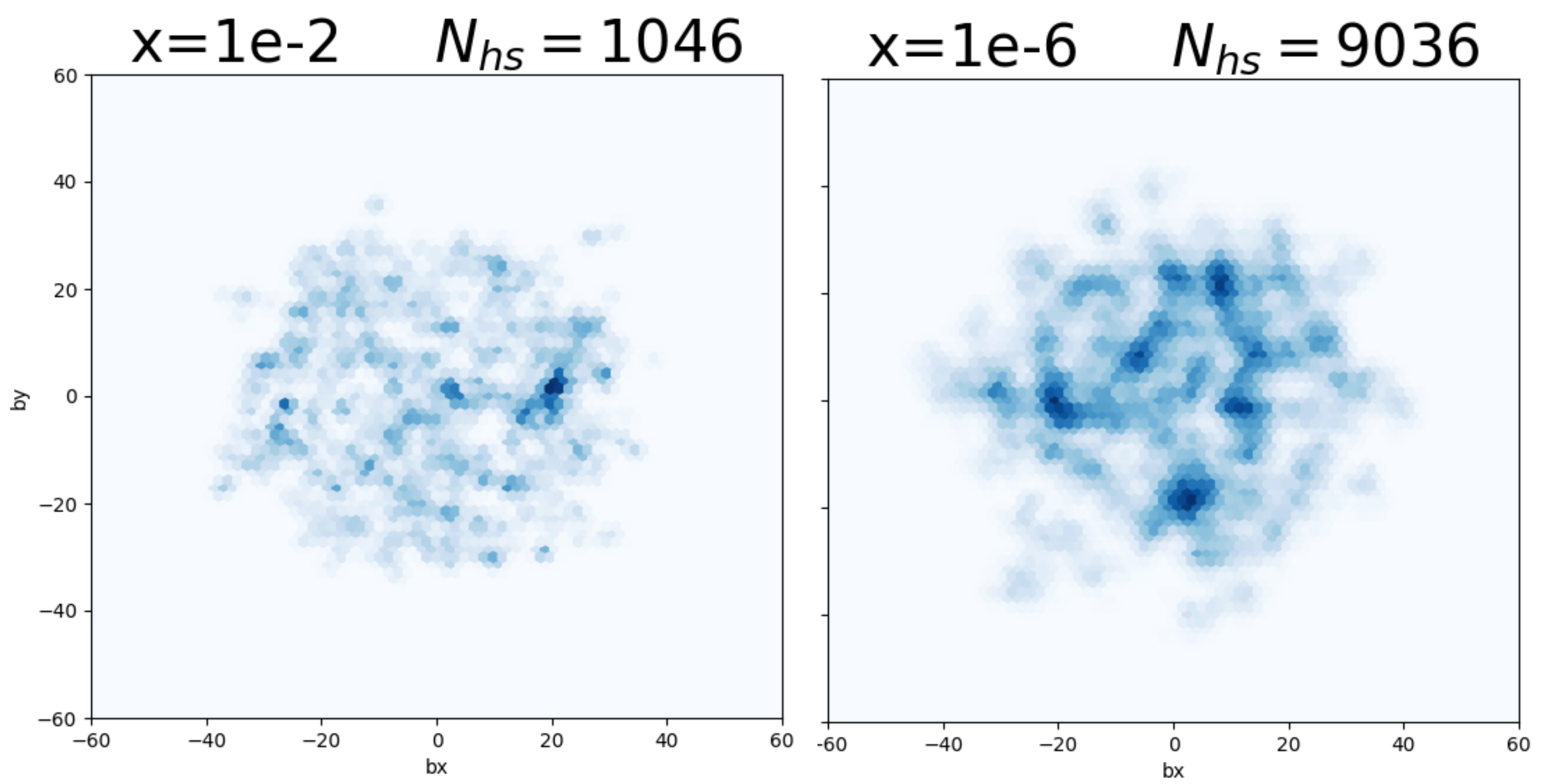
NUCLEAR PROFILE

COHERENT AND INCOHERENT DIFFRACTIVE PRODUCTION OFF NUCLEAR TARGETS OFFERS THE ADVANTAGE THAT SATURATION SETS IN AT A LOWER ENERGY THAN FOR THE CASE OF PROTON

- It is expected that saturation is mainly linked to the hot-spot degrees of freedom

$$N(x,r) = \left[1 - \exp\left(-\frac{r^2 Q_s^2(x)}{4}\right)\right]$$

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



ENERGY-DEPENDENT HOT–SPOT MODEL

LEAD

$$\frac{\mathrm{d}\sigma^{\mathrm{dip}}_{\mathrm{Pb}}}{\mathrm{d}\vec{b}} = 2\left[1 - \left(1 - \frac{1}{2A}\sigma_0 N(x,r) T_{\mathrm{Pb}}(\vec{b})\right)^{A}\right]$$

$$T_{\mathrm{hs}}(\vec{b}-\vec{b}_i) = \frac{1}{2\pi B_{\mathrm{hs}}} \sum_{i=1}^{A=208} \frac{1}{N_{\mathrm{hs}}} \sum_{j=1}^{N_{\mathrm{hs}}} \exp\left(-\frac{\left(\vec{b}-\vec{b}_i-\vec{b}_j\right)^2}{2B_{\mathrm{hs}}}\right)$$

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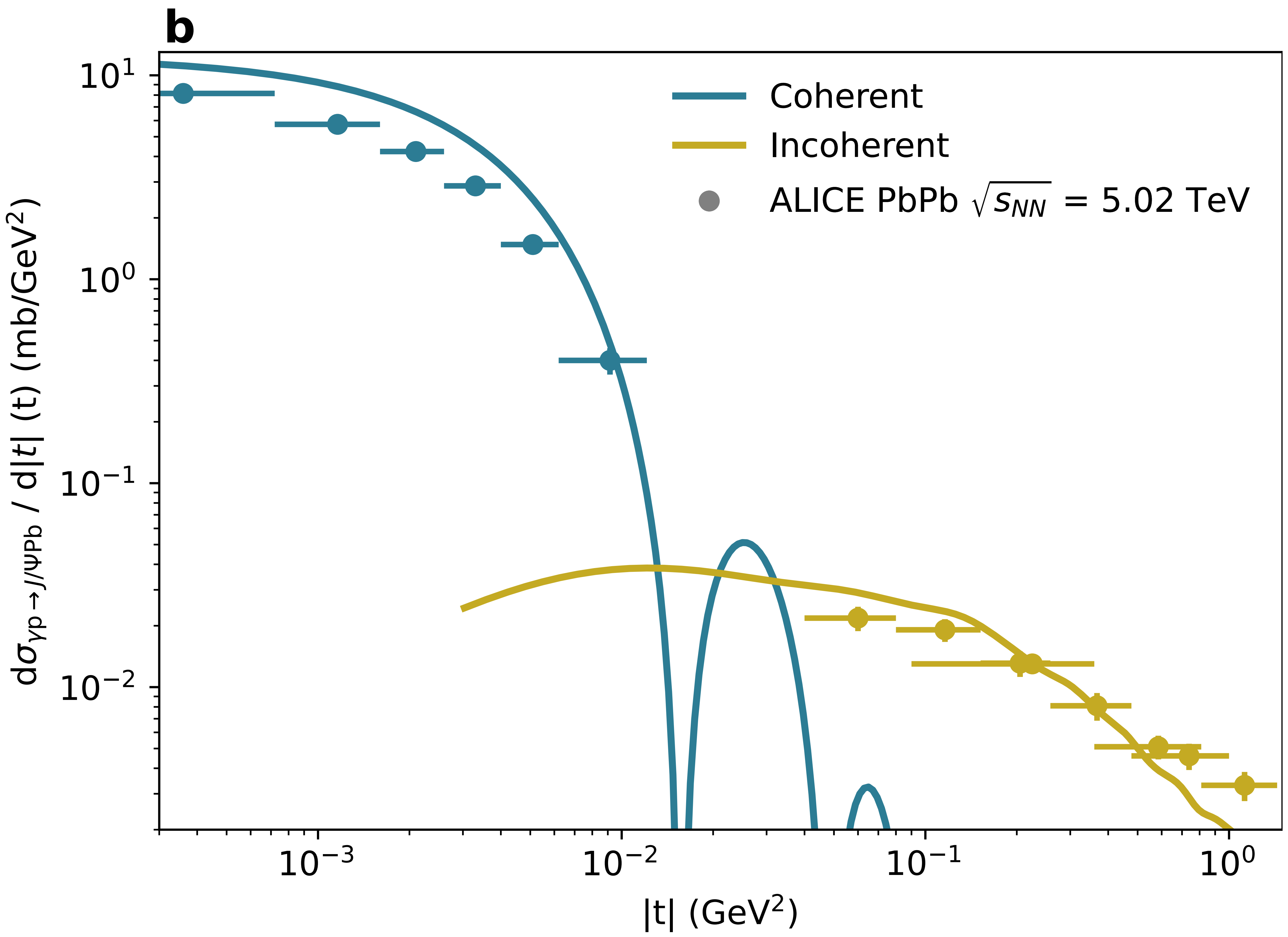

Mandelstam-t dependence of coherent (blue) and incoherent (gold) J/ψ photo-production off Pb.

ENERGY-DEPENDENT HOT–SPOT MODEL

LEAD

$$\frac{\mathrm{d}\sigma^{\mathrm{dip}}_{\mathrm{Pb}}}{\mathrm{d}\vec{b}} = 2\left[1-\left(1-\frac{1}{2A}\sigma_0 N(x,r)T_{\mathrm{Pb}}(\vec{b})\right)^A\right]$$

$$T_{\mathrm{hs}}(\vec{b}-\vec{b}_i) = \frac{1}{2\pi B_{\mathrm{hs}}}\sum_{i=1}^{A=208}\frac{1}{N_{\mathrm{hs}}}\sum_{j=1}^{N_{\mathrm{hs}}}\exp\left(-\frac{\left(\vec{b}-\vec{b}_i-\vec{b}_j\right)^2}{2B_{\mathrm{hs}}}\right)$$

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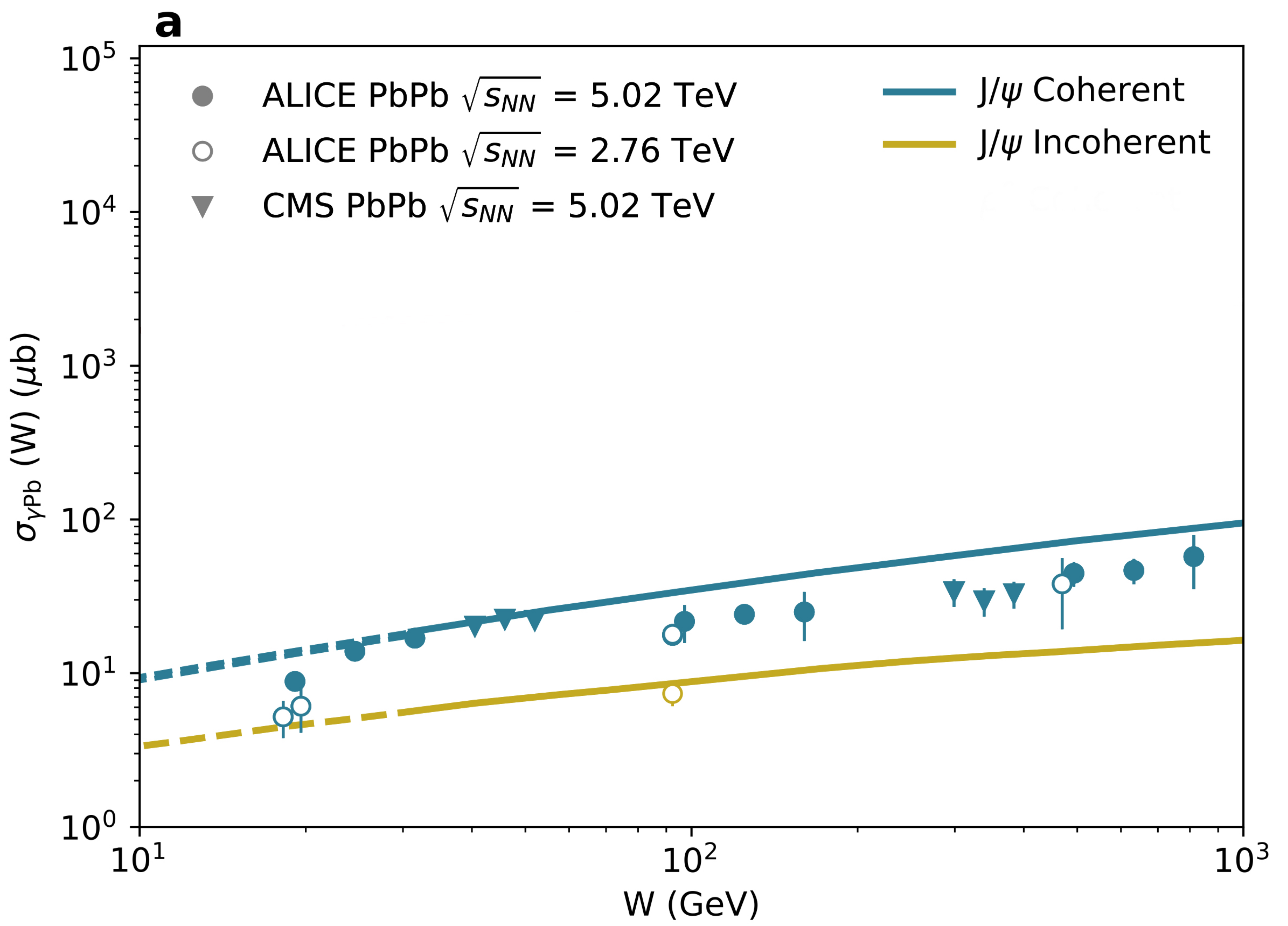
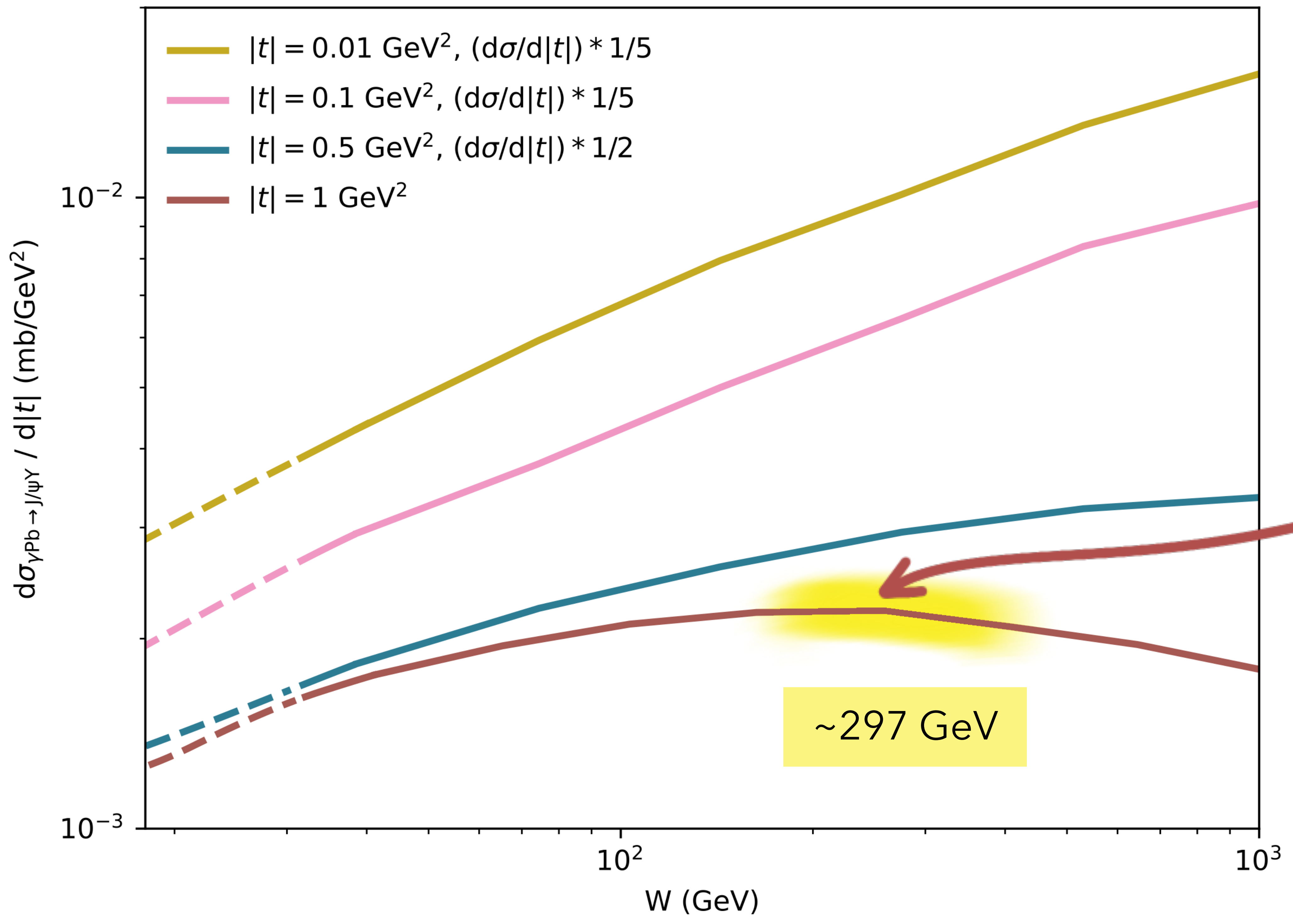


Energy dependence of coherent (blue) and incoherent (gold) J/ψ photo-production off Pb.

ONSET OF GLUON SATURATION

- Incoherent processes are sensitive to two different size scales, that of **NUCLEONS (~ 1 fm)** and that of **HOT SPOTS (~ 0.1 fm)**
- **MANDELSTAM – t** ⟵ FOURIER TRANSFORM ⟶ **MATTER DISTRIBUTION IN THE IMPACT-PARAMETER PLANE**
- scanning the energy behaviour in specific $|t|$ ranges samples fluctuations of different transverse sizes and allows for the isolation of the contribution of hot spots where one expects saturation effects to set in
- 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

ONSET OF GLUON SATURATION



Prediction of the energy-dependent hot-spot model for the incoherent photo-production of J/ψ vector mesons off Pb in diffractive interactions

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

At larger values of |t|, the rise of the cross section reaches a maximum and then decreases

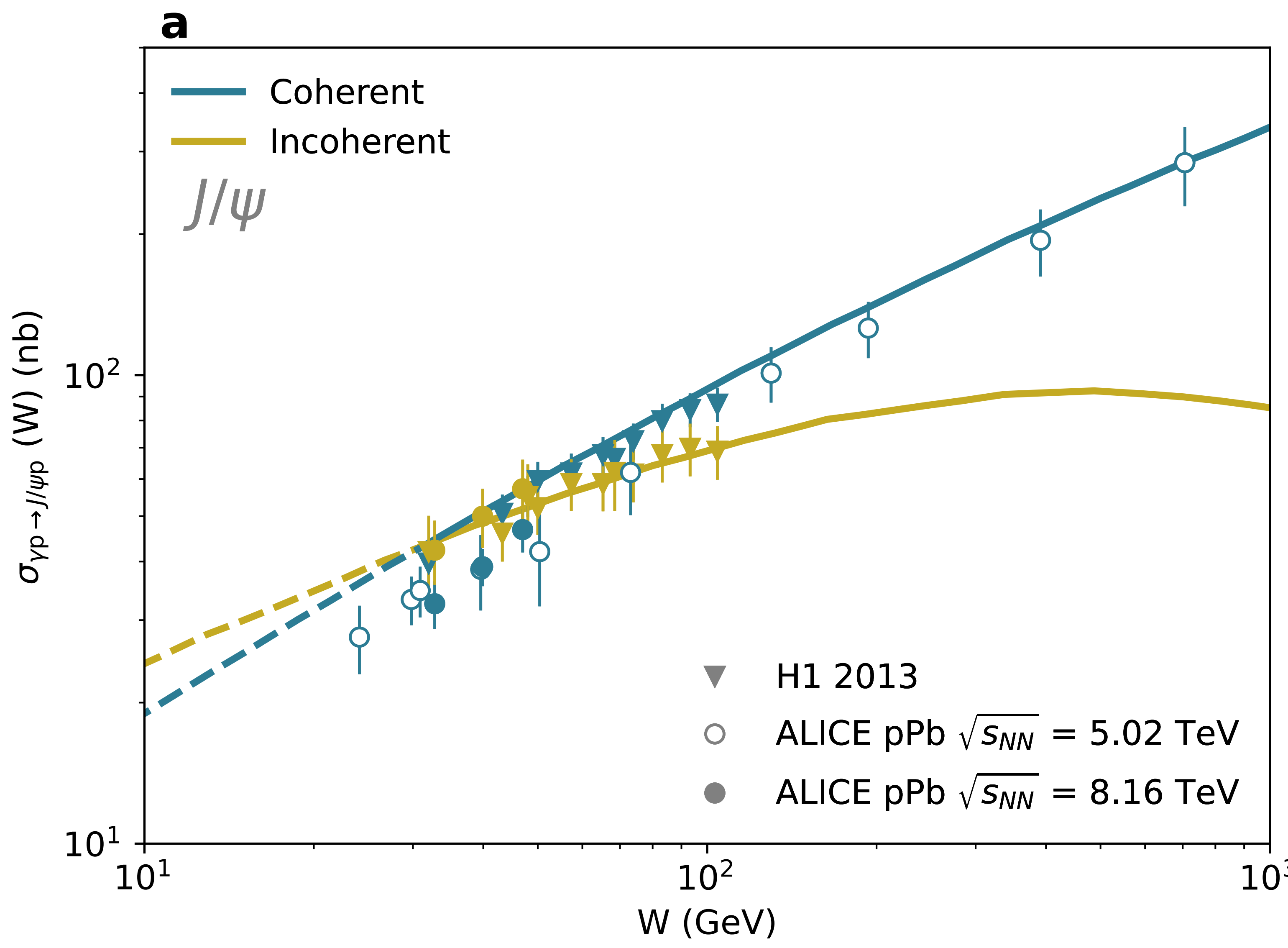
- The shape for the W dependence at a fixed value of |t| can be described by $f(W) = N\,(W/W_0)^{\delta} \exp\big(-(W/W_0)(\delta/W_{\max})\big)$
  - Fitting this function to the prediction at |t| = 1 GeV^2 we find $W_{\max}$ to be 297 ± 6 GeV.

THE MAXIMUM MARKS THE ONSET OF SATURATION EFFECTS AND IT IS WELL WITHIN THE REACH OF THE LHC

SUMMARY

PROTON

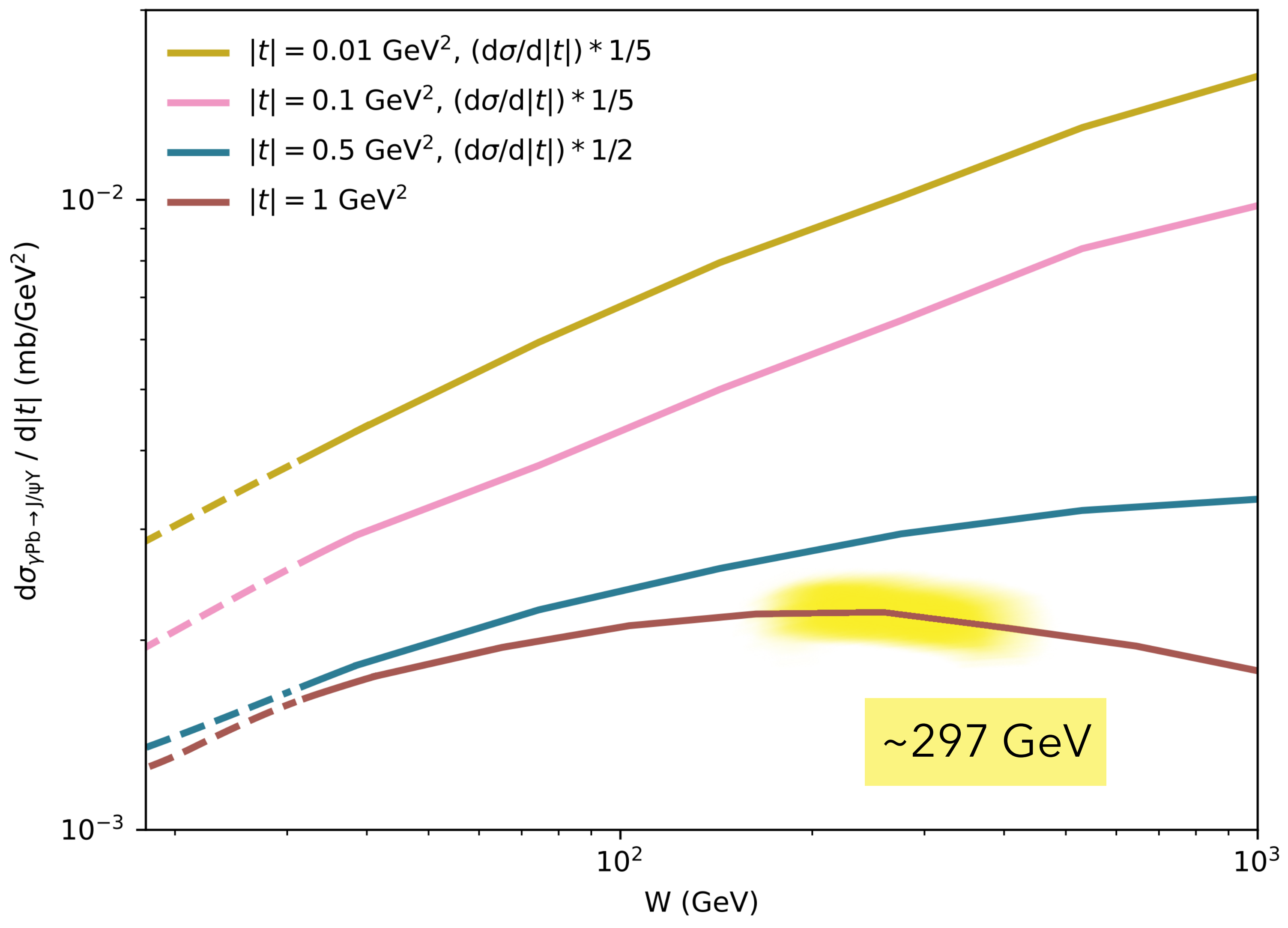
- The model predicts that the energy dependence of the dissociative process increases from low energies up to *W* ~ 500 GeV and then decreases steeply. This energy range can be explored at LHC.



arXiv:1608.07559 [hep-ph]

LEAD

- The model predicts that the onset of gluon saturation can be uniquely identified using incoherent J/ψ production in Pb–Pb collisions at currently accessible energies of the LHC.



arXiv:2312.11320 [hep-ph]