Photoproduction of J/ψ in ultra-peripheral collisions

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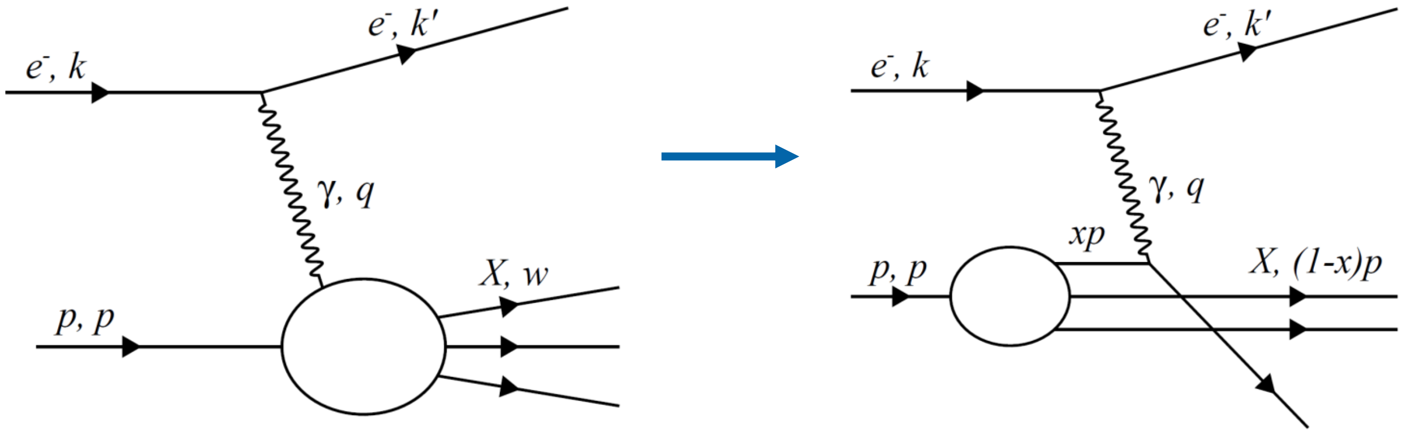
Deeply inelastic scattering

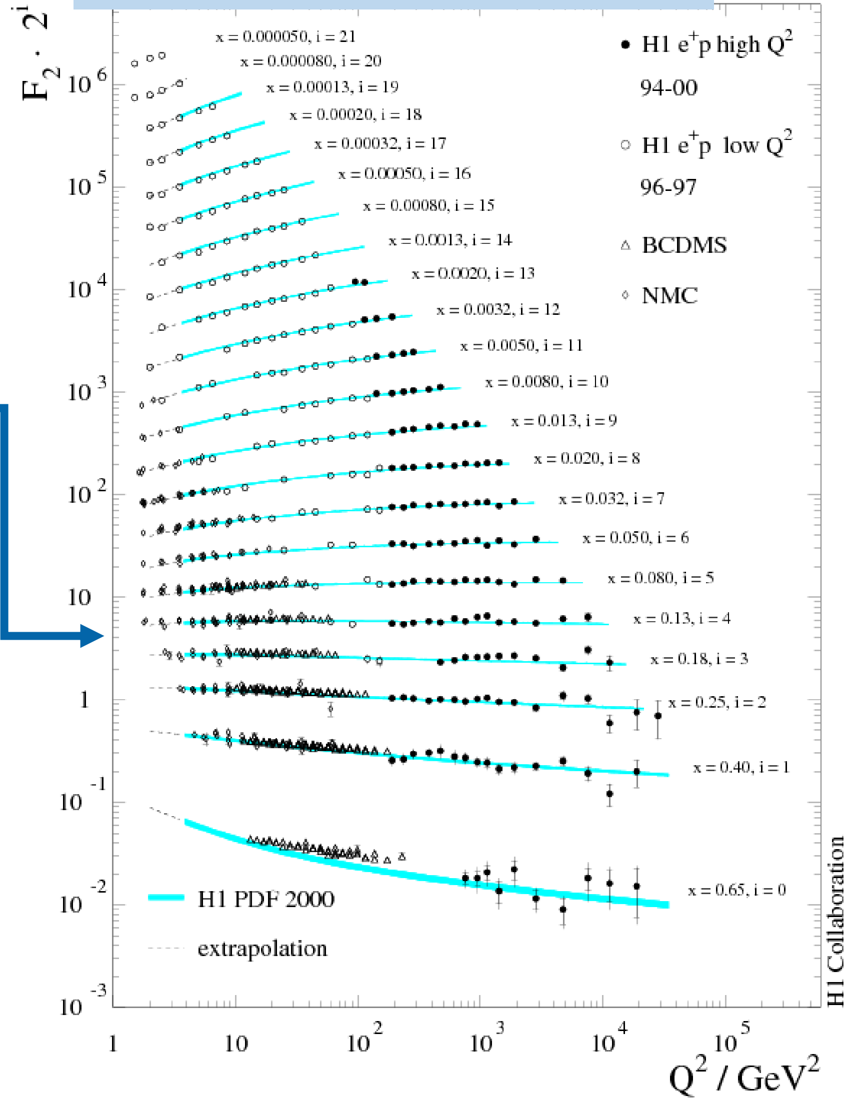
- The end of 1960s: first experiments
- From the Rosenbluth formula → the DIS cross section:

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{M_p x y}{s}\right)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

- High-x region ($x \approx 0.1$): Bjorken scaling
- 1969 (Feynman, Bjorken): **the parton model**



H1, Eur.Phys.J. C30 (2003) 1-32



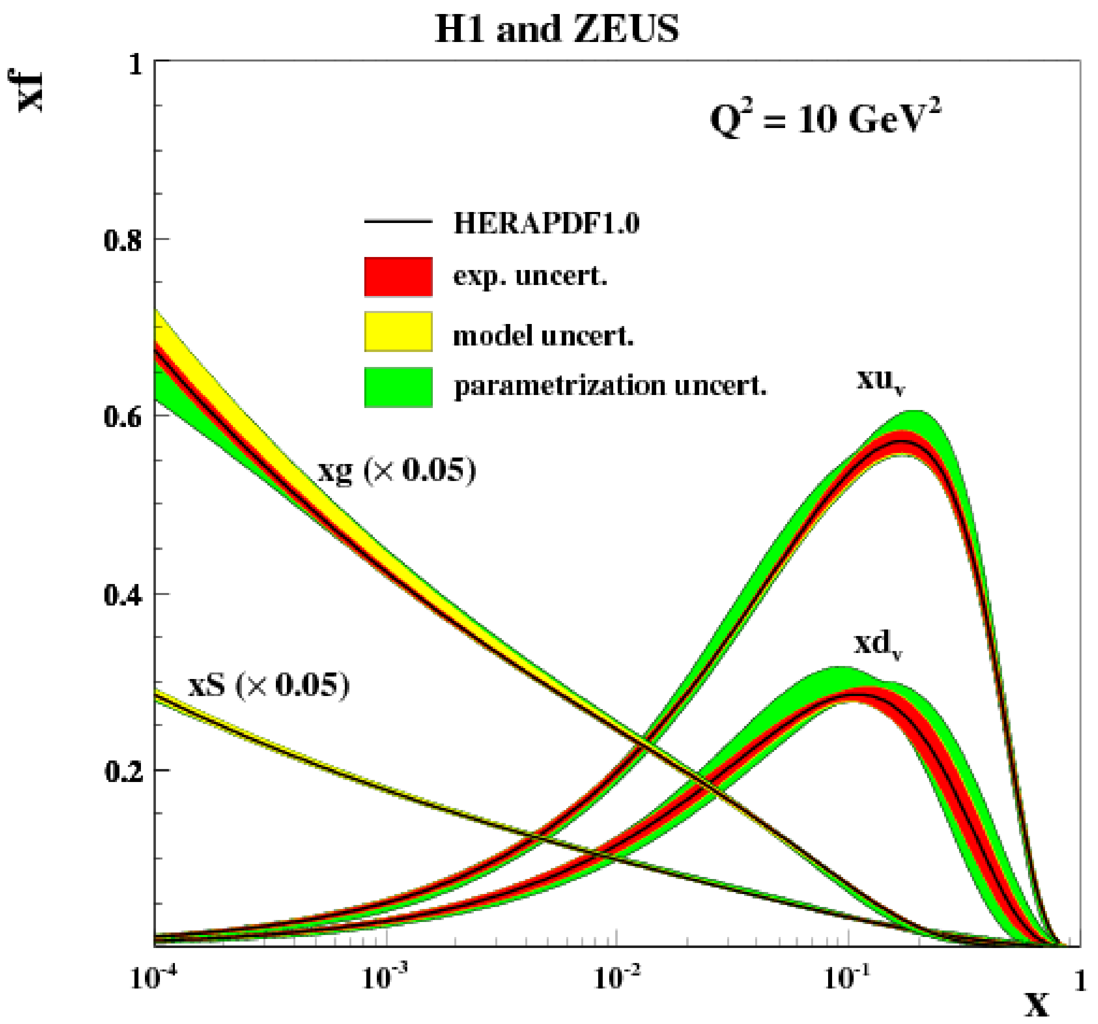
The structure function of a proton

- Calan-Gross relation: $F_2(x) = 2xF_1(x)$
- Parton-quark identification:

$$F_2(x) = x \sum_f e_f^2 \left[f(x) + \overline{f}(x) \right]$$

$(x = p_{\text{parton}} / p_{\text{hadron}})$

- Valence and sea quarks, gluons: parton distribution functions (PDFs)
- Bjorken scaling only approximate, structure becomes finer at the low-x region
- At even smaller x: **gluon saturation** expected

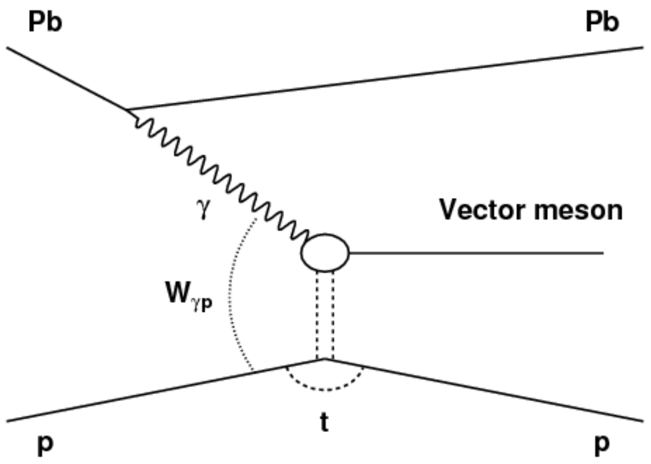


H1 and ZEUS, JHEP 1001 (2010) 109

Ultraperipheral collisions: vector mesons photoproduction

- UPCs: when $b >$ sum of nuclear/proton radii
- Interaction induced by a photon (QCD short-ranged)
- Creation of a lepton pair vs. **vector meson production:**
  - p-Pb:
    - a) Exclusive
    - b) Dissociative
  - Pb-Pb:
    - c) Coherent
    - d) Incoherent
- Other possibilities (e.g. 2-jet diffractive production) not yet studied by ALICE

a)



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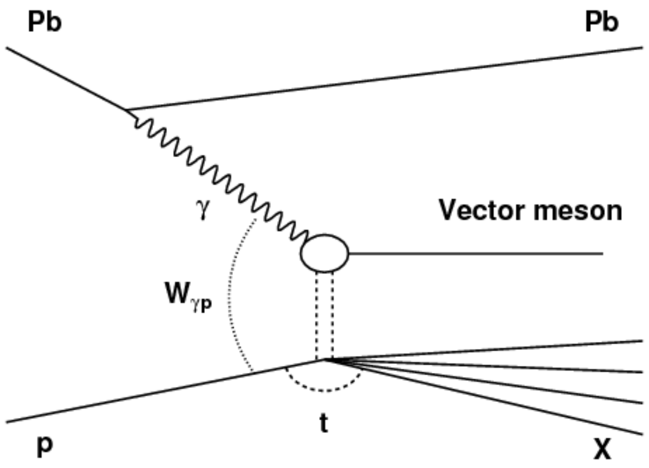

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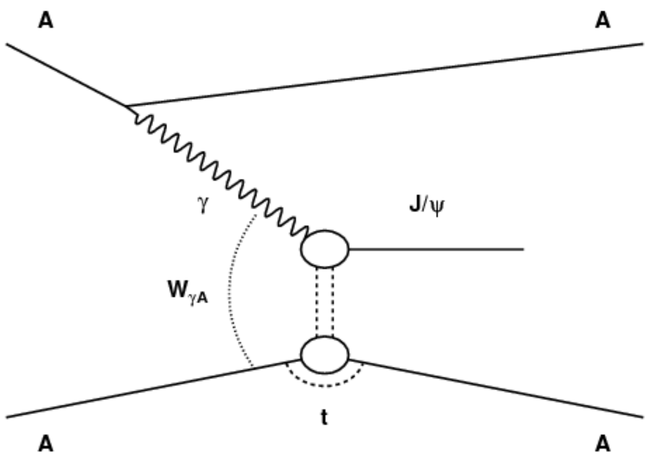
c)



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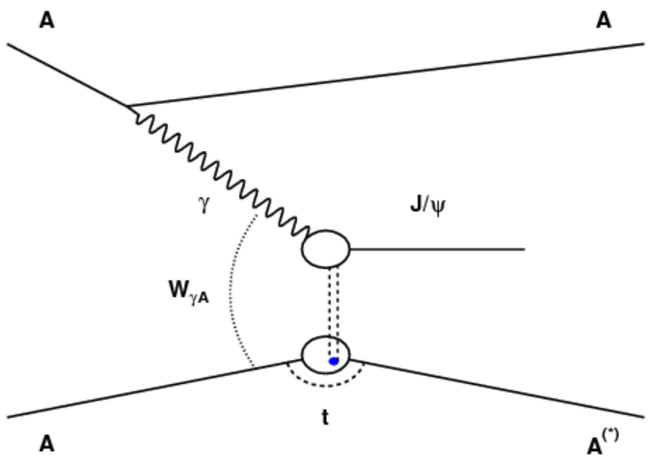

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The J/ψ photoproduction

- **Experimental observables:**
  - Rapidity of the J/ψ $\leftrightarrow$ centre-of-mass energy: $W_{\gamma A}^{2} = \sqrt{s_{NN}} M_{J/\psi} e^{-y}$
  - Transverse momentum of the J/ψ: $p_{T}^{2} = -t$
    - Coherent: $p_{T} \sim$ a few tens of MeV
    - Incoherent: $p_{T} \sim$ a few hundred of MeV

F.T.

Distribution of a target matter in the impact parameter plane (gluon distribution)

- **The cross section — factorisation:**
  - The photon emission (QED process)
  - Interaction with a target, QCD enters here (e.g. colour dipole model)

Photon flux $N_{\gamma} \propto Z^{2}$

Pb-Pb collision:

$$\frac{d\sigma_{PbPb}(y)}{dy} = N_{\gamma/Pb}(y, M)\sigma_{\gamma Pb}(y) + N_{\gamma/Pb}(-y, M)\sigma_{\gamma Pb}(-y),$$

p-Pb collision:

$$\frac{d\sigma_{pPb}(y, M)}{dy} \approx N_{\gamma/Pb}(y, M)\sigma_{\gamma p}(y).$$

The colour dipole model

- Photon fluctuates into a quark-antiquark pair
- Good-Walker formalism:

Type of a process	Sensitive to
Exclusive/ coherent	The average over target cofingurations
Dissociative/ incoherent	The variance over target configurations

γ-p and γ-A cross sections proportional to:

$$\left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2$$

$$\left(\left\langle\left|A(x,Q^2,\vec{\Delta})_{T,L}\right|^2\right\rangle - \left|\left\langle A(x,Q^2,\vec{\Delta})_{T,L}\right\rangle\right|^2\right)$$

- Amplitude: $$A(x,Q^2,\vec{\Delta})_{T,L} = i\int d\vec{r}\int_0^1 \frac{dz}{4\pi}(\Psi^*\Psi_V)_{T,L}\int d\vec{b}\, e^{-i(\vec{b}-(1-z)\vec{r})\cdot\vec{\Delta}}\frac{d\sigma_{\mathrm{dip}}}{d\vec{b}}$$

Transverse momentum of the J/ψ

Distance between the quark and the antiquark

Photon-dipole and vector meson wave functions

The dipole-proton or the dipole-nucleus cross section

Carries information about **the transverse structure of a target!** $\rightarrow T(\vec{b})$

Energy-dependent hot-spot model: γ-p collisions

- **A fluctuating proton profile** = the sum of high-gluon-density hot spots with gaussian distributions

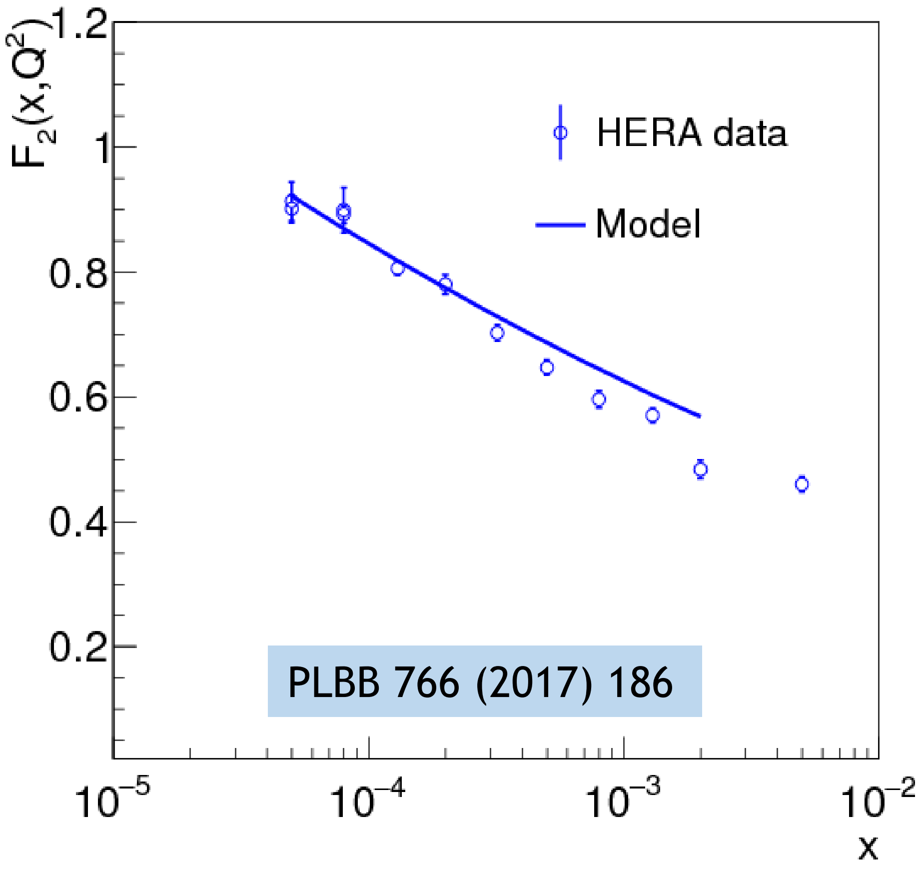
From a 2D gaussian distribution centered at $\vec{b} = (0,0)$

$$T(\vec{b}) = \frac{1}{N_{hs}} \sum_{i=1}^{N_{hs}} T_{hs}(\vec{b} - \vec{b_i}), \quad T_{hs}(\vec{b} - \vec{b_i}) = \frac{1}{2\pi B_{hs}} e^{-\frac{(\vec{b}-\vec{b_i})^2}{2B_{hs}}}$$

- Number of hot spots **grows with energy:**

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

- Data from H1 (HERA, e-p) and ALICE (p-p): energy dependence of the J/ψ cross section
- But first: the model describes also the $F_2(x, Q^2)$ data quite well!



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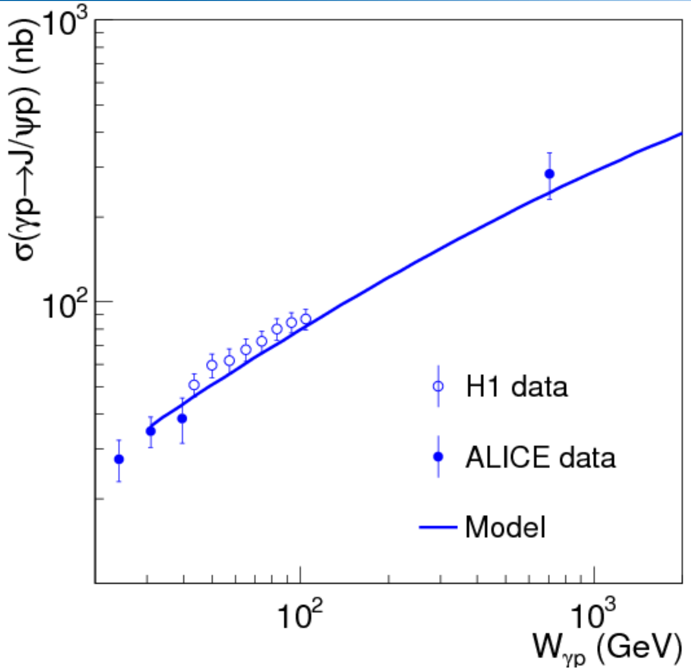
γ-p collisions: The total cross sections

a) The exclusive production

b) The dissociative production:
- *Prediction* of a maximum at $W_{\gamma p} \approx 500\ \mathrm{GeV}$
  - Ca. 10 hot spots (a sizeable overlap)
  - A decrease in variance
- A steep decrease for $W_{\gamma p} > 500\ \mathrm{GeV}$
- LHC energies
  => a way to examine the gluon saturation?

- The t-dependence (not shown): model also in a good agreement

a)



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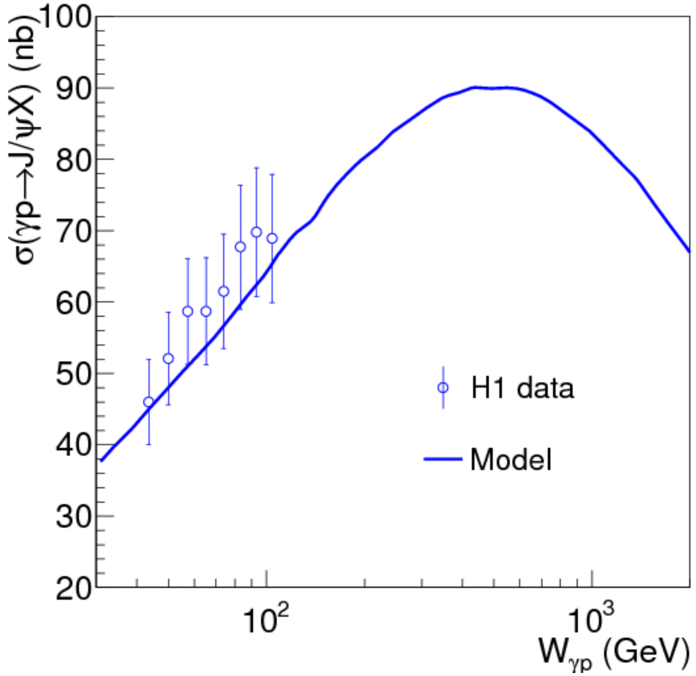

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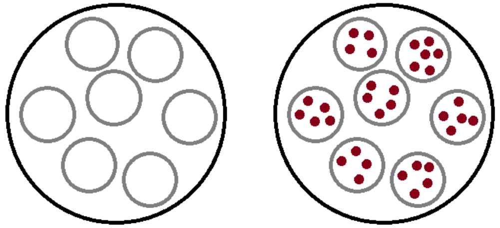
Energy-dependent hot-spot model: Pb-Pb collisions

- Extension to photonuclear interactions:
  - Glauber-Gribov formalism (GG)
  - Geometric scaling (GS)
- Models of the transverse nuclear profile:
  - Nucleons (n)
  - Nucleons made of **hot spots** (hs)
    - Inclusion of subnucleonic degrees of freedom



$$\left(\frac{d\sigma_{\mathrm{dA}}}{d\vec{b}}\right)_j = 2\left[1-\exp\left(-\frac{1}{2}\sigma_{\mathrm{dp}}(x,r)T_{\mathrm{A}}^j(\vec{b})\right)\right]$$

$$\left(\frac{d\sigma_{\mathrm{dA}}}{d\vec{b}}\right)_j = \sigma_0^{\mathrm{A}}\left[1-\exp\left(-r^2Q_{A,s}^2(x)/4\right)\right]T_{\mathrm{A}}^j(\vec{b})$$

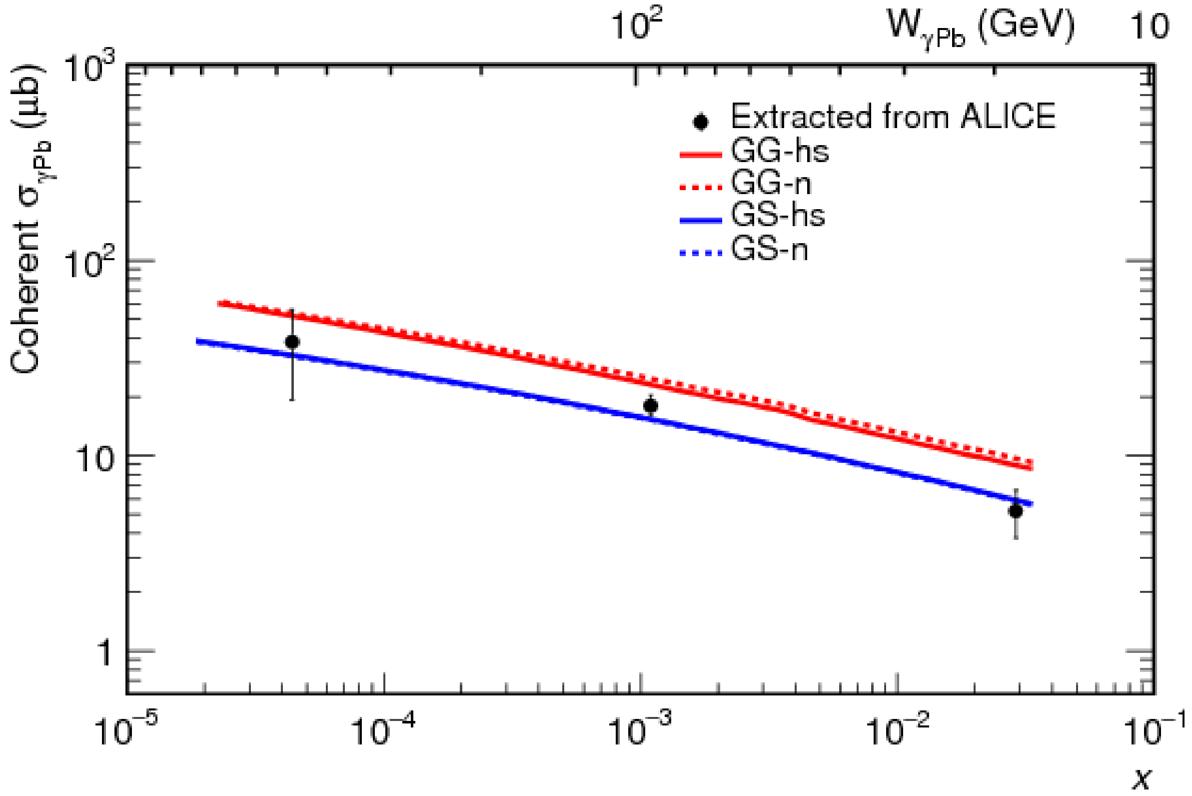
$$T_{\mathrm{A}}^j(\vec{b}) = \frac{1}{2\pi B_{\mathrm{p}}}\sum_{i=1}^{\mathrm{A}}\exp\left(-\frac{(\vec{b}-\vec{b}_i^j)^2}{2B_{\mathrm{p}}}\right)$$

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

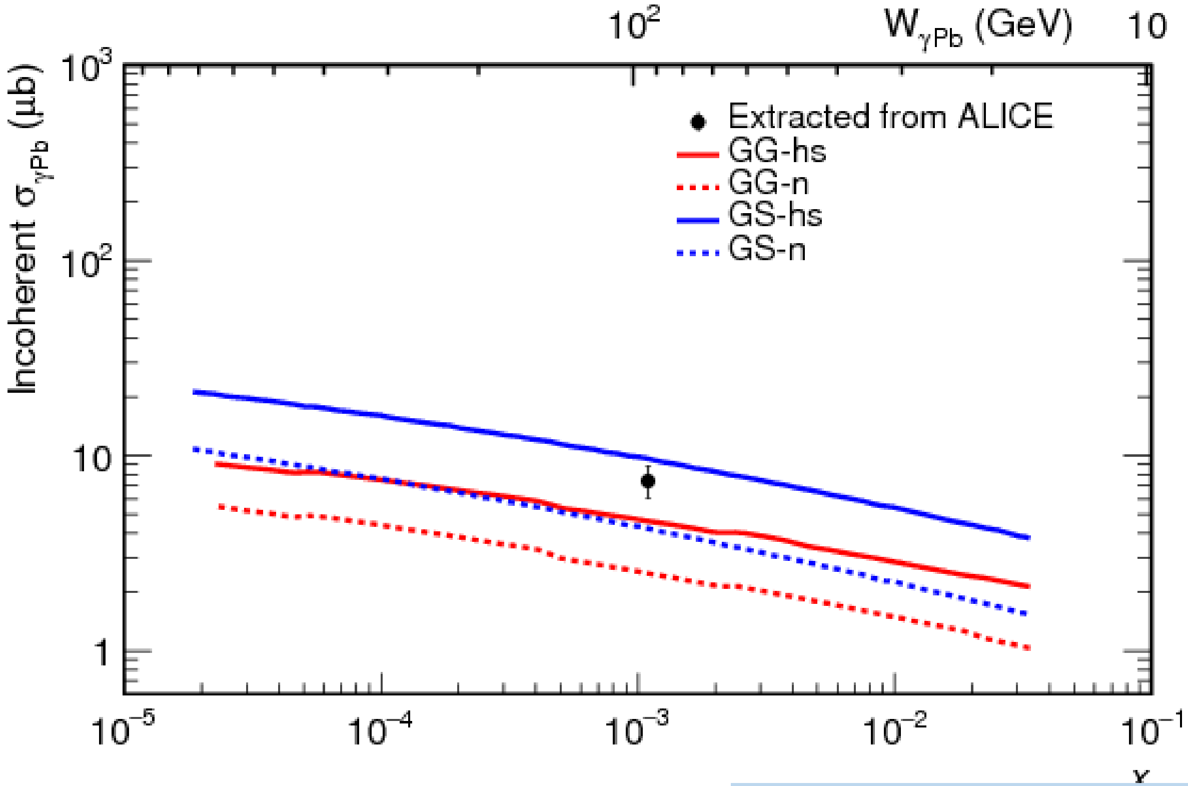
- Again $\langle N_{\mathrm{hs}}(x)\rangle = p_0x^{p_1}(1+p_2\sqrt{x})$ (mean value of the Poisson distribution)
- Comparison with data from RHIC and the LHC Run 1 (ALICE PCs and UPCs)

Pb-Pb collisions: (In)coherent cross sections

- **The coherent case:**
  - Similar predictions



- **The incoherent case:**
  - Looks like the model prefers hot-spot structure



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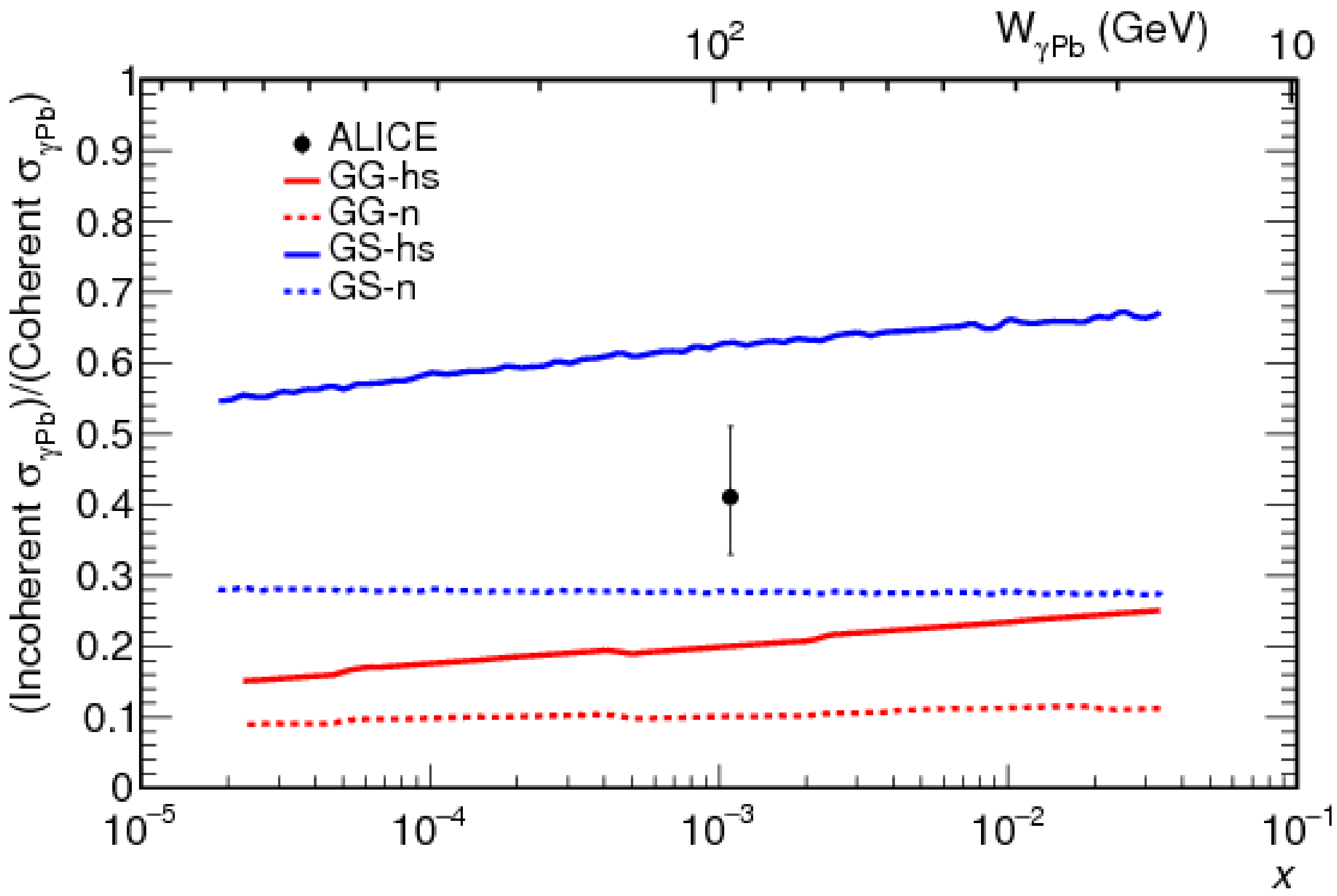
Pb-Pb collisions: Ratio of the coherent to the incoherent cross section

- Subnucleonic degrees of freedom introduce the x-dependence
  - Supported by data from PHENIX ($x \approx 0.015$)
- Motivation for new data with smaller uncertainties



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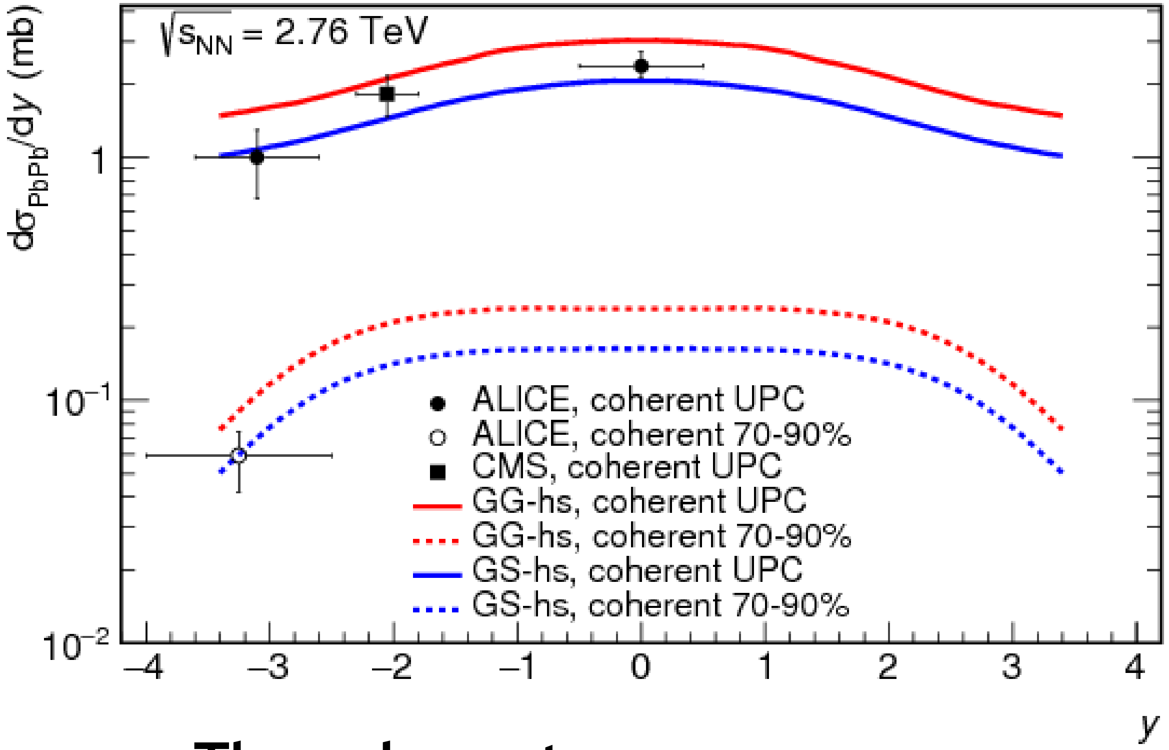
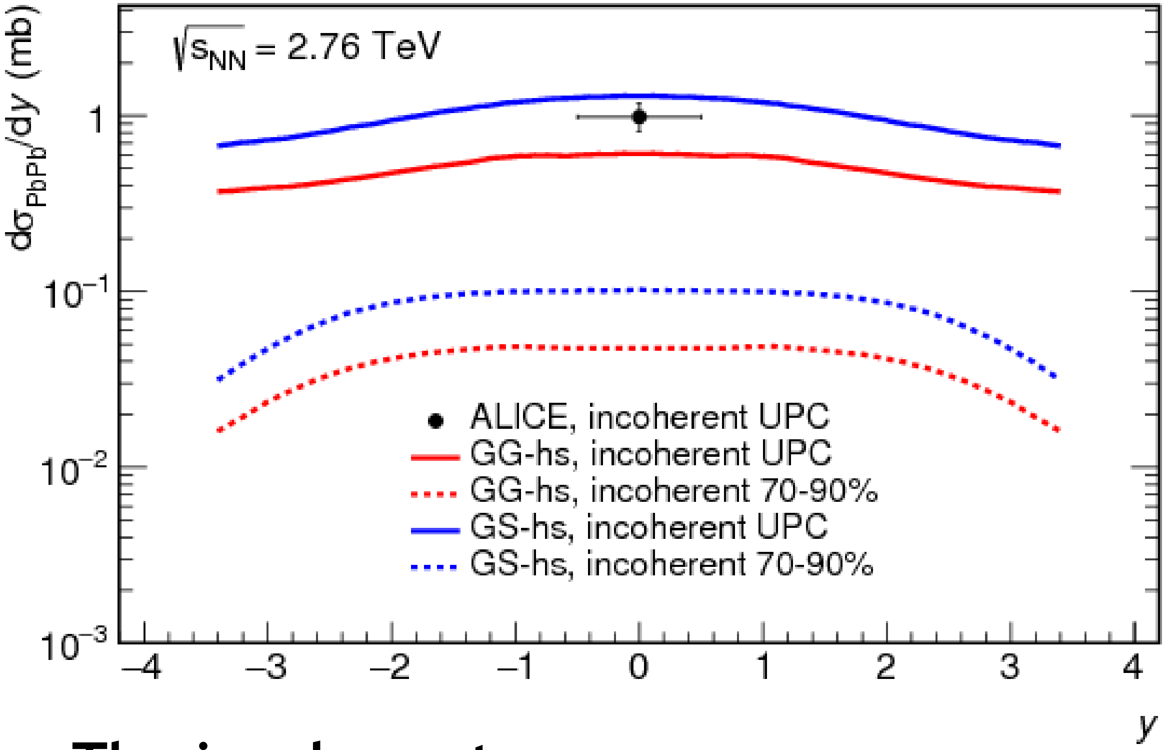
Pb-Pb collisions: The y dependence of the cross section

Note: only hot-spot transverse structure used





- **The coherent case**
  - GG model slightly overestimates the data
- **The incoherent case**
  - New data needed

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Summary

- **Ultra-peripheral collisions** = a way to examine the QCD physics in photon-induced processes
  - ALICE: measurements of PDFs in long x-range (ca. from 10^{-2} to 10^{-5})
  - Can provide evidence for gluon saturation?
- **Energy-dependent hot-spot model**
  - Fluctuating proton/nuclear transverse structure
  - Energy-dependent number of hot spots
  - Seems to be in a noteworthy agreement with the data!
  - Has a potential to predict gluon saturation

- My task is to measure the energy dependence of the incoherent cross section using ALICE data

References

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- J. Cepila, J. G. Contreras, J. D. Tapia Takaki: Energy dependence of dissociative J/Psi photoproduction as a signature of gluon saturation at the LHC, Phys. Lett. B766, 186-191 (2017).
- J. Cepila, J. G. Contreras, M. Krelina: Coherent and incoherent J/Psi photonuclear production in an energy-dependent hot-spot model, Phys. Rev. C97(2), 024901 (2018).