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Vector meson photo-production within the energy-dependent hot-spot model

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Probing QCD at the high energy frontier - ECT* Trento 21.5.2018

Contents of the presentation

- Photo-production of J/ψ on a proton target within the energy-dependent hot-spot model provides a measurable signature of saturation

  J. Cepila, J.G. Contreras, D.T. Takaki, arxiv:1608.07559

- Photo-production of ρ and Υ on a proton target within the energy-dependent hot-spot model provides a mass dependence of the saturation signal

  J. Cepila, J.G. Contreras, M. Krelina, D.T. Takaki,arxiv:1804.05508

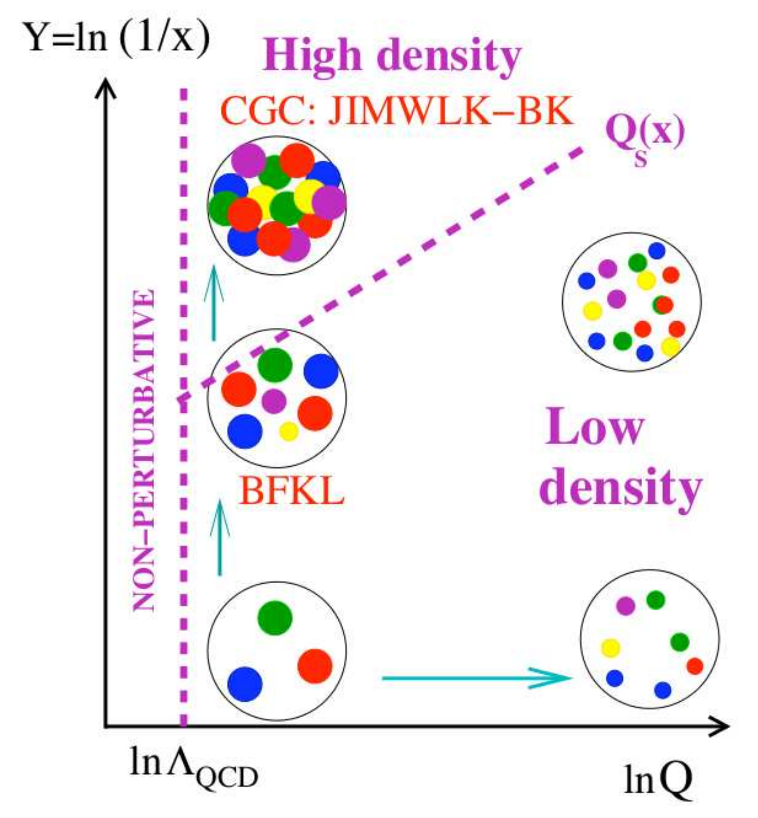
- Photo-production of J/ψ and ρ on a nuclear target within the energy-dependent hot-spot model shows clear effect of sub-nucleon fluctuations

  J. Cepila, J.G. Contreras, M. Krelina, arxiv:1711.01855
  J. Cepila, J.G. Contreras, M. Krelina, D.T. Takaki,arxiv:1804.05508

- Outlook on electro-production of J/ψ on a proton target within the energy-dependent hot-spot model

Gluon saturation

- Exclusive and dissociative vector meson production can be an excellent probe to the gluon structure of the target
- The vector meson mass fixes the position in $\ln Q^2$
- Moving to smaller x one can reach and go beyond the saturation scale $Q_s(x)$
- Linear evolution of the gluon density below the saturation scale $Q_s(x)$(dilute regime)
- Non-linear evolution above the saturation scale (dense regime) $\rightarrow$ gluon saturation

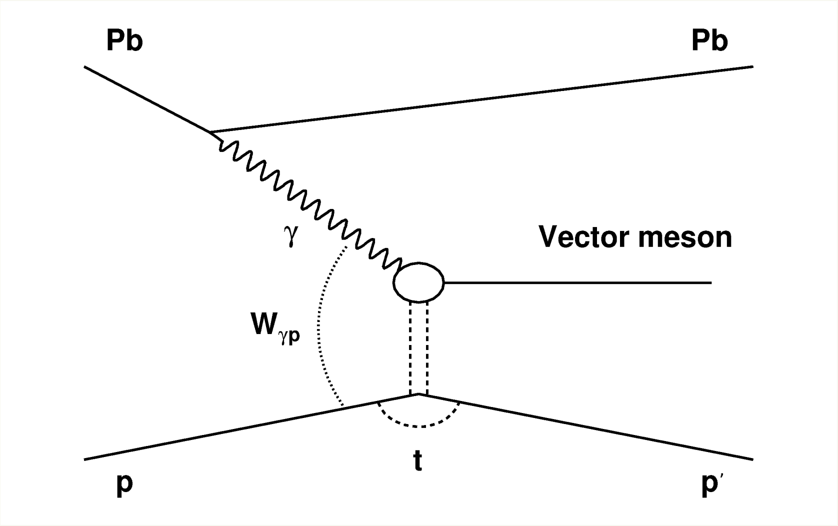


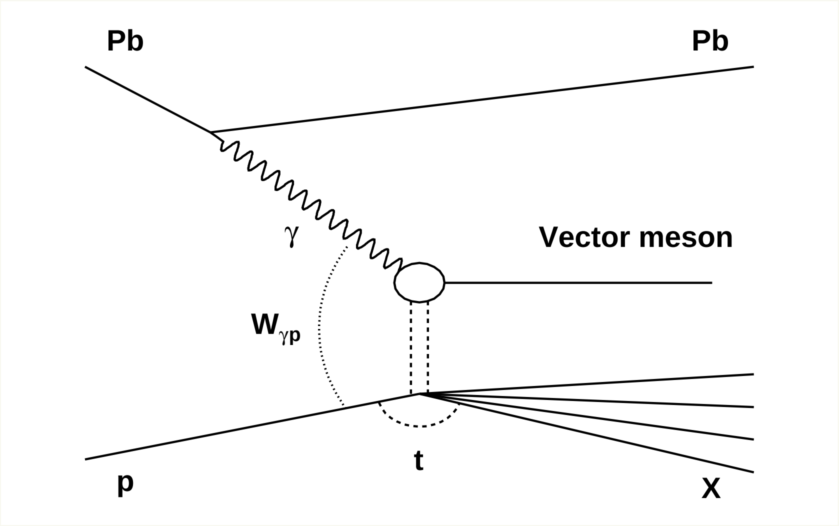
- We show that including geometrical fluctuations a signal of saturation can be seen in the energy dependence of dissociative vector meson production off protons and nuclei at LHC energies.

- The Mandelstam variable $t = (p' - p)^2$ is the square of the four-momentum transferred at the proton vertex
- $W_{\gamma p}$ is the center-of-mass energy of the photon-proton system
- Bjorken-x of the produced meson is

$$x_{Bj} = \frac{M_V^2 + Q^2}{W_{\gamma p}^2 + Q^2}$$

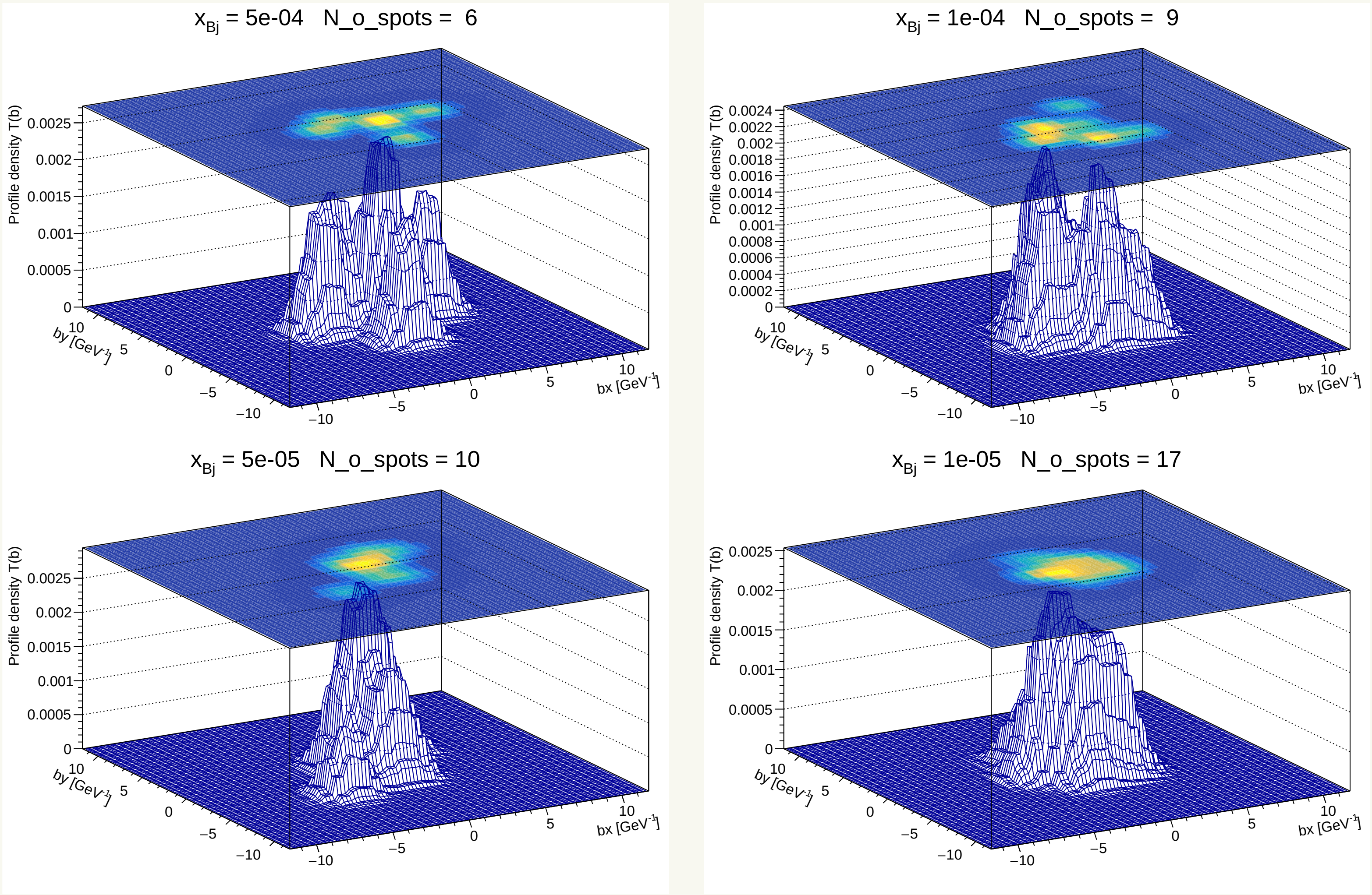
  M_V is the mass of the vector meson, Q^2 is the scale of the incoming photon
- Low-x limit (saturation regime) manifests at large $W_{\gamma p}$





Fluctuations

- Exclusive cross section = average over many geometrical configurations
- Dissociative cross section = variance over many geometrical configurations
- Configurations are represented by hot spots positions - number grows with energy



Production of vector mesons off proton in the color dipole model

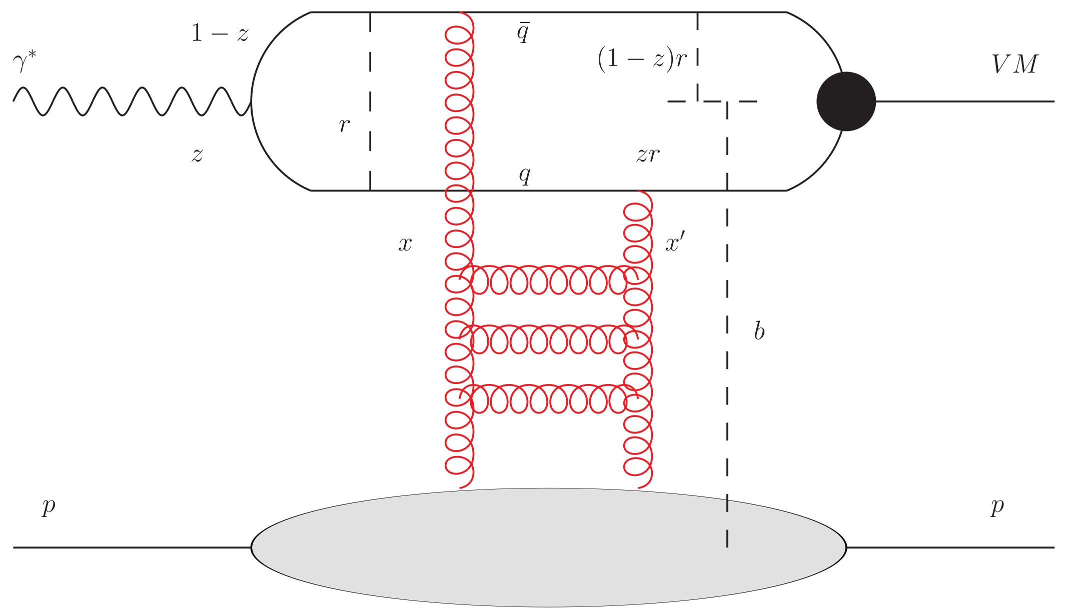
- In the rest frame of the target a photon interacts via its $q\bar{q}$ Fock component, which collapses into the vector meson

z - fraction of the photon momenta carried by the dipole quark

r - transverse width of the dipole

b - impact parameter of the γp collision

$\Delta = \sqrt{-t}$



- The scattering amplitude is given by the convolution of photon Ψ_{γ^*} and meson Ψ_M wave functions with the dipole cross section $\mathrm{d}\sigma_{q\bar{q}}/\mathrm{d}^2b$

$$\mathcal{A}_{T,L}^{\gamma^* p \to Mp}(x,Q,\Delta) = i\int \mathrm{d}^2r \int_0^1 \frac{\mathrm{d}z}{4\pi} \int \mathrm{d}^2b\, \Psi_M^* \Psi_{\gamma^*}\Big|_{T,L} e^{-i(\vec{b}-(1-z)\vec{r})\Delta} \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2b}$$

T, L denote the transverse and longitudinal degrees of freedom of the photon

Wave function

- Overlap of a virtual photon and vector meson wave function of the $|q\bar{q}\rangle$ Fock state

$$\Psi_M^*\Psi_{\gamma^*}\Big|_T = e_f\delta_{f\bar{f}}e\frac{N_c}{\pi z(1-z)}\left(m_f^2K_0(\varepsilon r)\Phi_T(r,z) - (z^2+(1-z)^2)\varepsilon K_1(\varepsilon r)\partial_r\Phi_T(r,z)\right)$$

$$\Psi_M^*\Psi_{\gamma^*}\Big|_L = e_f\delta_{f\bar{f}}e\frac{N_c}{\pi}2Qz(1-z)K_0(\varepsilon r)\left(M_V\Phi_L(r,z) + \delta\frac{m_f^2-\nabla_r^2}{M_Vz(1-z)}\Phi_L(r,z)\right)$$

$$\varepsilon^2 = z(1-z)^2Q^2 + m_f^2$$

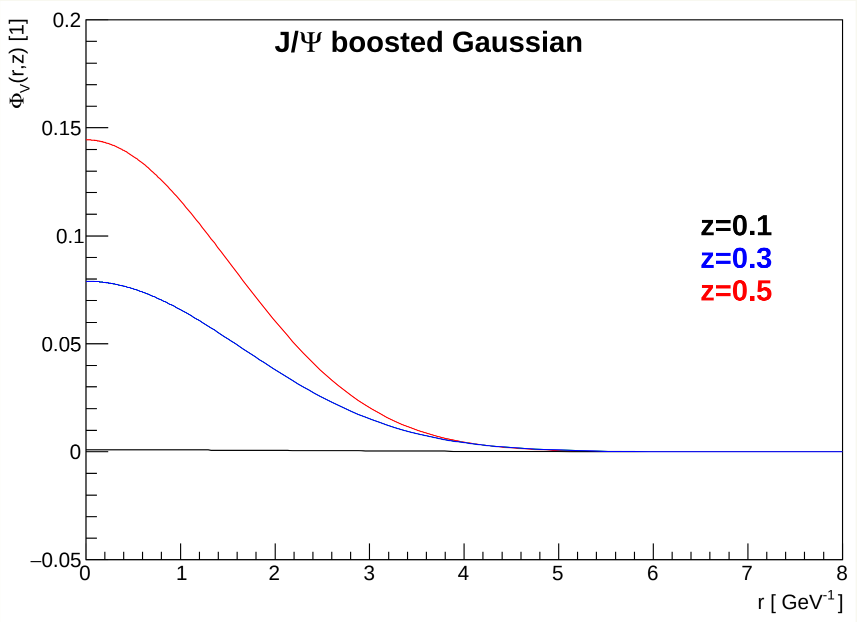
- The photon wave function can be calculated from QED
- The vector meson wave function is calculated with the presumption that the vector meson is predominantly a quark-antiquark state and the spin and polarization structure is the same as in the photon case.
- δ is a switch that enables to include the non-local part of the wave function
- $e = \sqrt{4\pi\alpha_{em}}$, $e_f\delta_{ff}$ is an effective charge of the meson, N_c is the number of color degrees of freedom

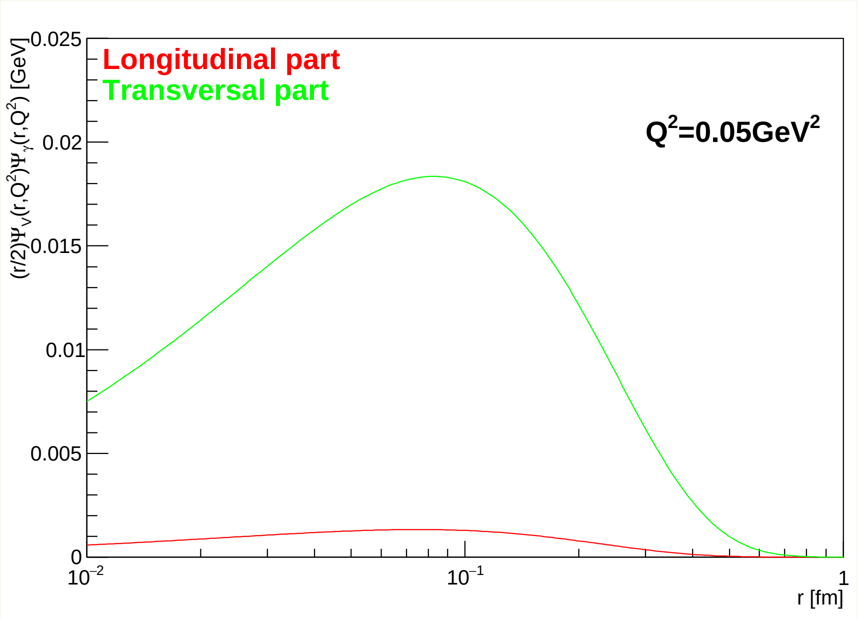
Wave function

- The scalar part $\Phi_{T,L}$ of the vector meson wave function is model dependent
- The boosted Gaussian model - assumes $\delta = 1$ and that the $q\bar{q}$ dipole wave function in the rest frame is modeled with a Gaussian shape and boosted to the proper frame

$$\Phi_{T,L}(r,z) = N_{T,L} z(1-z) e^{-\frac{m_f^2 R^2}{8z(1-z)} - \frac{2z(1-z)r^2}{R^2} + \frac{m_f^2 R^2}{2}}$$

K.Golec-Biernat and M.Wusthoff, Phys. Rev. D **59**, 014017 (1999); B. E. Cox, J. R. Forshaw, and R. Sandapen, JHEP 06, 034 (2009)





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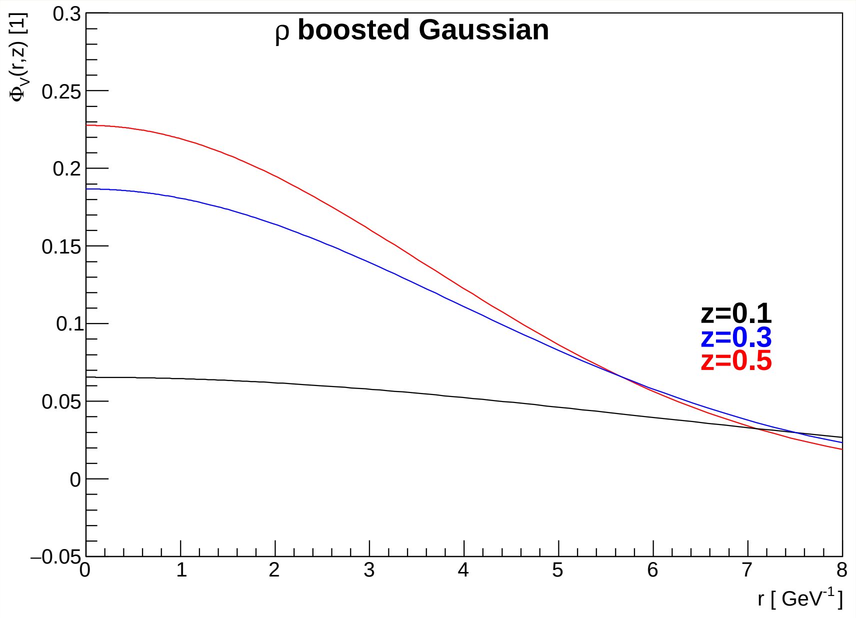

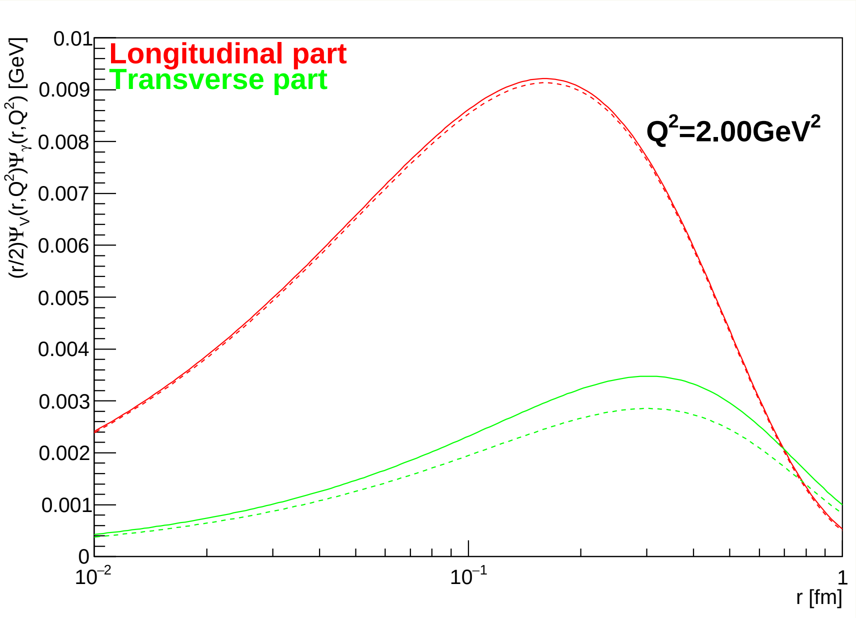

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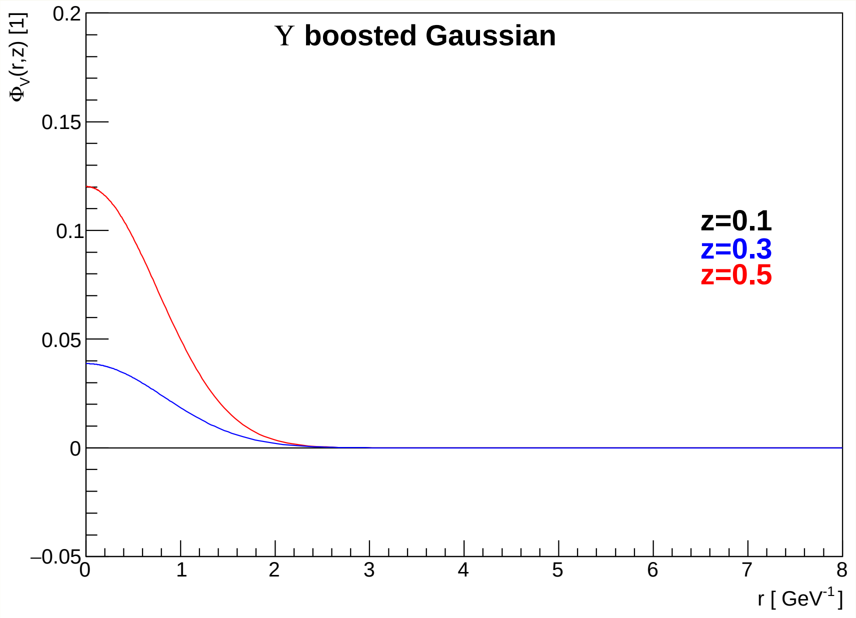
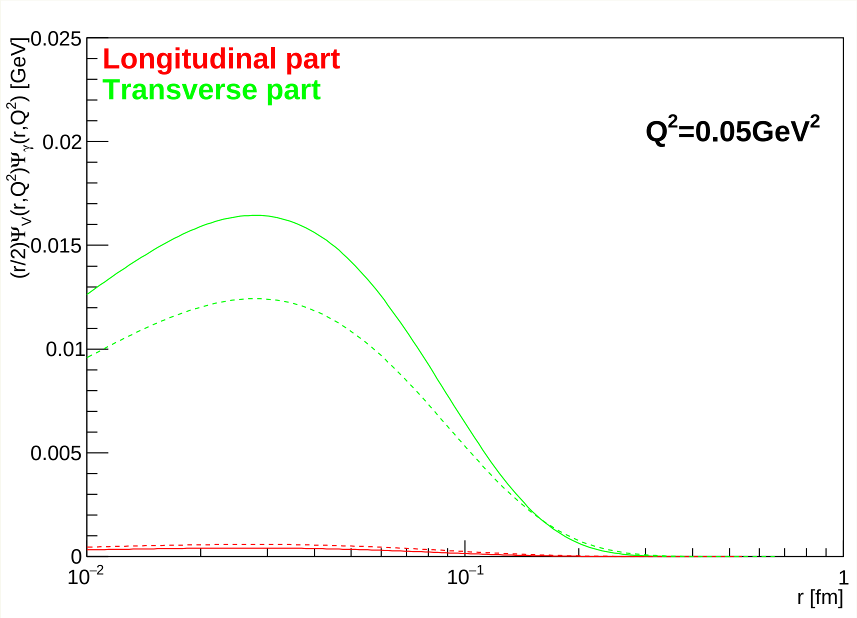




Dipole cross section

- From the optical theorem

$$\frac{d\sigma_{q\bar{q}}}{d^2b} = 2N(x,r,b)$$

- Data are integrated over impact parameter - we can access only $\sigma_{dip}(x,r)$ - impact parameter dependence has to be modeled

$$2N(x,r,b) = \sigma_0 N(x,r) T(b)$$

- $\sigma_0 = 4\pi B_p$ is a model dependent normalization
- $N(x,r)$ is the dipole scattering amplitude of a dipole with transverse size r
- $T(b)$ is the transverse profile of a proton

- Golec-Biernat and Wusthoff model

$$N(x,r) = \left(1 - e^{-r^2 Q_s^2(x)/4}\right) \qquad Q_s^2(x) = Q_0^2(x)\left(\frac{x_0}{x}\right)^{\lambda}$$

K.J. Golec-Biernat, M. Wusthoff, Phys. Rev. D 59 (1998) 014017, arXiv:hep-ph/9807513

Dipole cross section

- The transverse profile of the proton is taken as a sum of contributions from randomly sampled areas of high gluon density = hot-spots
- Each hot-spot in the proton is taken as a small Gaussian distribution with the width $B_{hs} = 0.8\text{GeV}^{-2}$ put in an arbitrary position generated from a 2-D Gaussian distribution centered at (0,0) with the width $B_p = 4.7\text{GeV}^{-2}$

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

- The number of hot spots is allowed to grow with energy - we take a value from a zero-truncated Poissonian with the mean value

$$N_{hs}(x) = p_0 x^{p_1}(1 + p_2\sqrt{x}) \quad p_0 = 0.011 \quad p_1 = -0.58 \quad p_2 = 300$$

- The final gluon profile is

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

- Similar to H. Mäntysaari and B. Schenke model, but with the number of gluon spots growing with decreasing x.

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

Vector mesons off proton in the color dipole model

- Skewedness correction - gluons attached to quarks in the $q\bar{q}$ dipole carry different light-front momenta fractions x and x' of the proton - the skewness effect

$$R_g^{T,L}(\lambda) = \frac{2^{2\lambda^{T,L}+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda^{T,L}+5/2)}{\Gamma(\lambda^{T,L}+4)} \qquad \lambda^{T,L} = \frac{\partial \ln \mathcal{A}_{T,L}^{\gamma^* p \to Mp}}{\partial \ln \frac{1}{x}}$$

A.G. Shuvaev, K.J. Golec-Biernat, A.D. Martin, M.G. Ryskin, Phys. Rev. D 60 (1999) 014015

- Final formula for exclusive production is

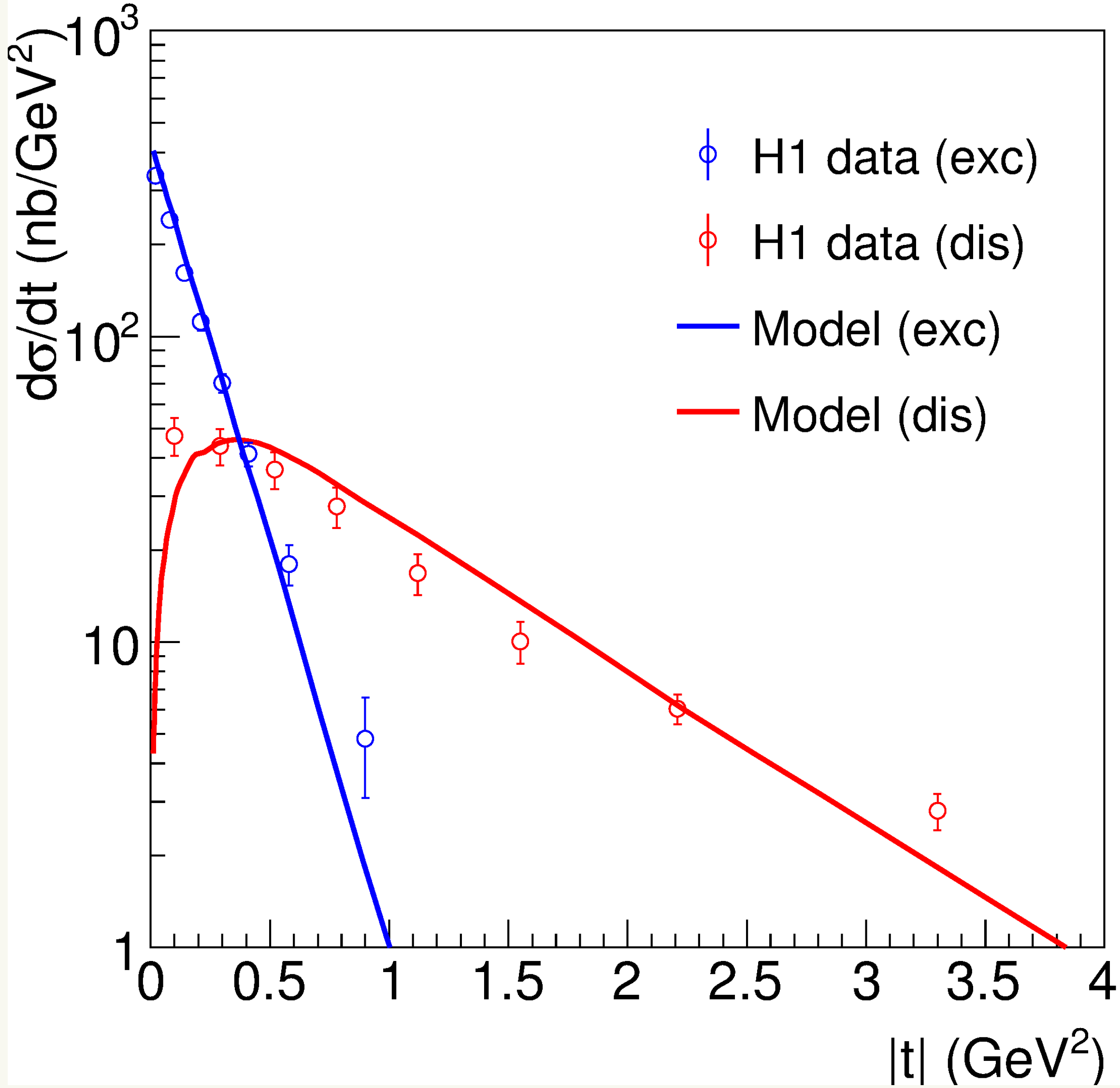
$$\frac{d\sigma_{T,L}^{\gamma^* p \to Mp}}{d|t|} = \frac{1}{16\pi} \left| \left\langle \mathcal{A}_{T,L}^{\gamma^* p \to Mp} R_g^{T,L} \right\rangle \right|^2$$

- Final formula for dissociative production is

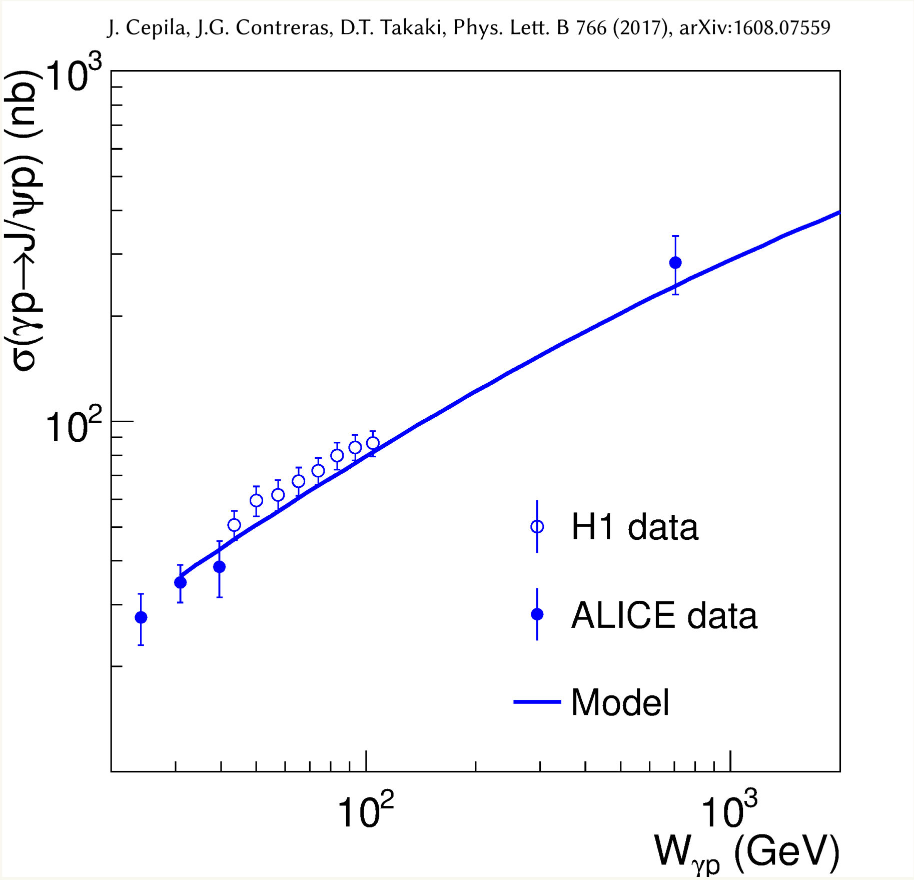
$$\frac{d\sigma_{T,L}^{\gamma^* p \to MX}}{d|t|} = \frac{1}{16\pi} \left(\left\langle \left| \mathcal{A}_{T,L}^{\gamma^* p \to Mp} R_g^{T,L} \right|^2 \right\rangle - \left| \left\langle \mathcal{A}_{T,L}^{\gamma^* p \to Mp} R_g^{T,L} \right\rangle \right|^2 \right)$$

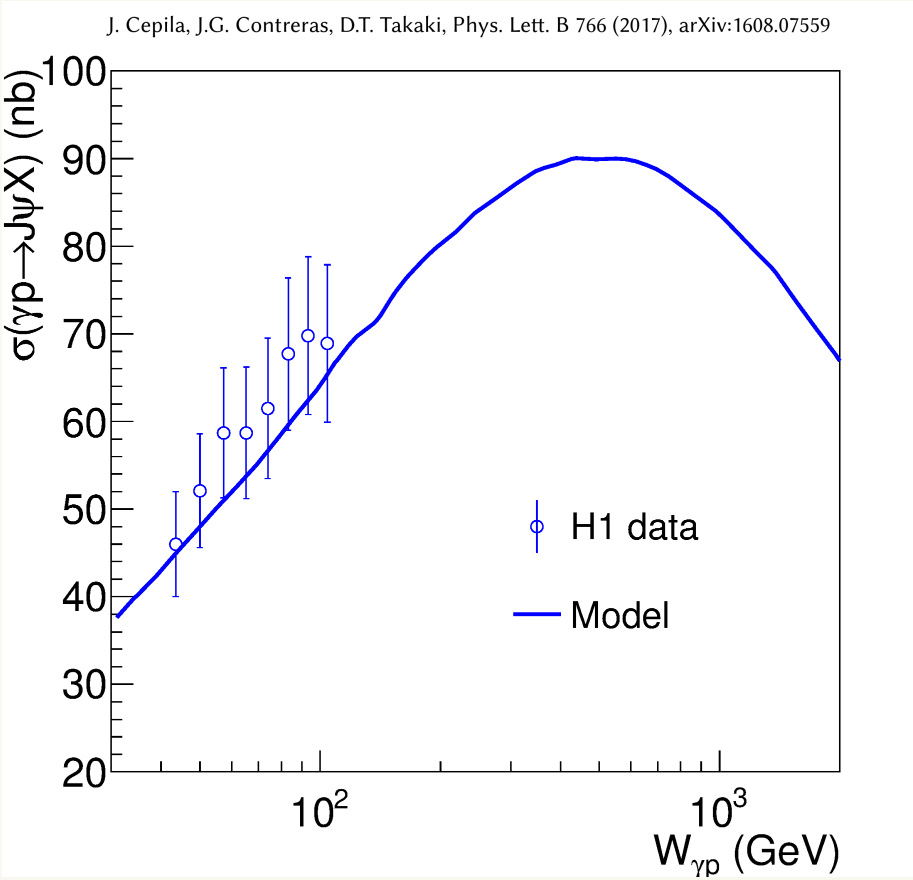
Exclusive and dissociative t-distribution of J/ψ photo-production off protons

J. Cepila, J.G. Contreras, D.T. Takaki, Phys. Lett. B 766 (2017), arXiv:1608.07559



Exclusive and dissociative total cross section of J/ψ photo-production off protons





- We did a test of the model prediction for DIS, also - see result compared to data at $Q^2 = 2.7\text{GeV}^2$

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}\left(\sigma_T^{\gamma^* p}(x,Q^2) + \sigma_L^{\gamma^* p}(x,Q^2)\right)$$

$$\sigma_{T,L}^{\gamma^* p}(x,Q^2) = \sigma_0 \int d\vec{r} \int_0^1 dz \left|\Psi_{T,L}^{\gamma^* \to q\bar{q}}(z,r,Q^2)\right|^2 N(r,\tilde{x})$$

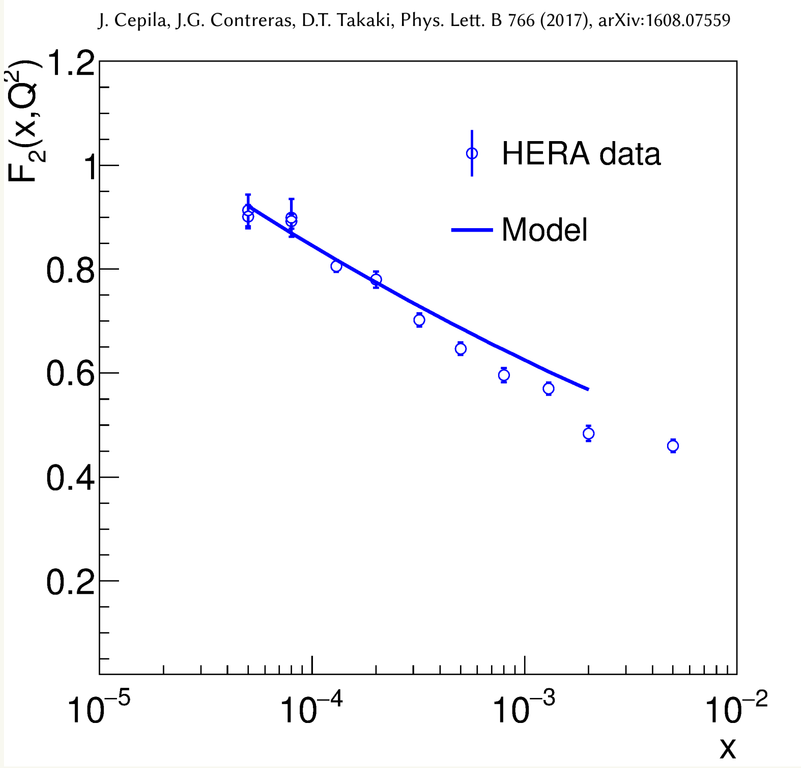
- Parameters are the same as in the vector meson case

- $\tilde{x} = x(1 + (4m_f^2)/Q^2)$

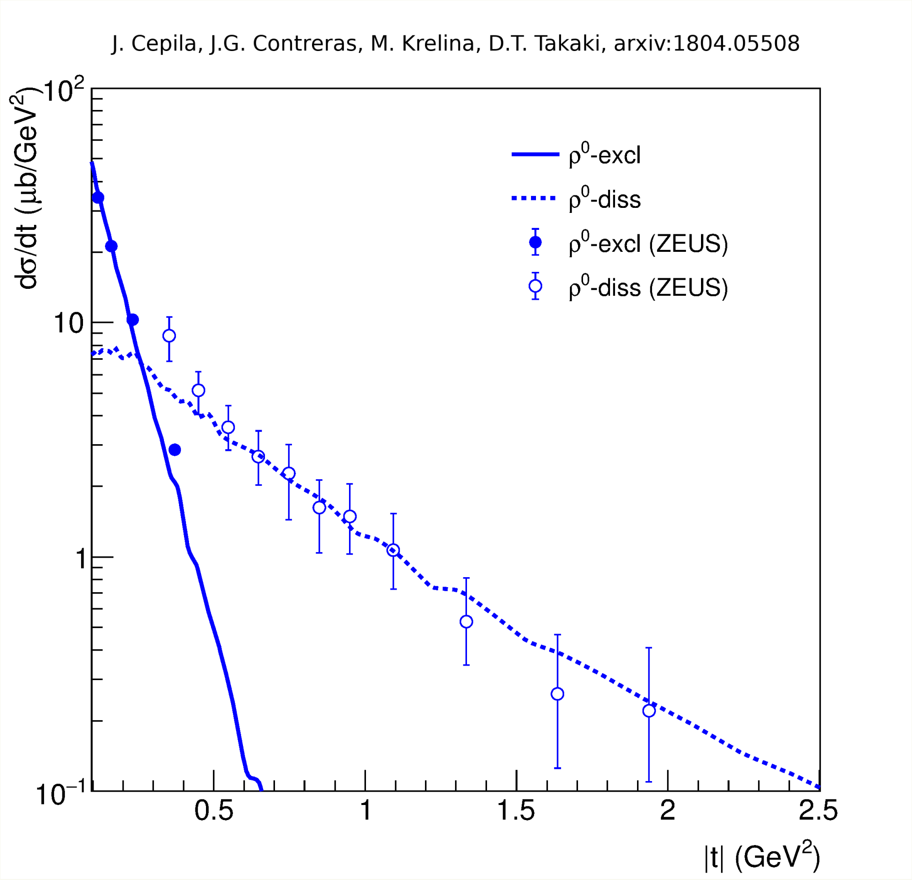
K.Golec-Biernat and M.Wusthoff, Phys. Rev. D **59**, 014017 (1999)

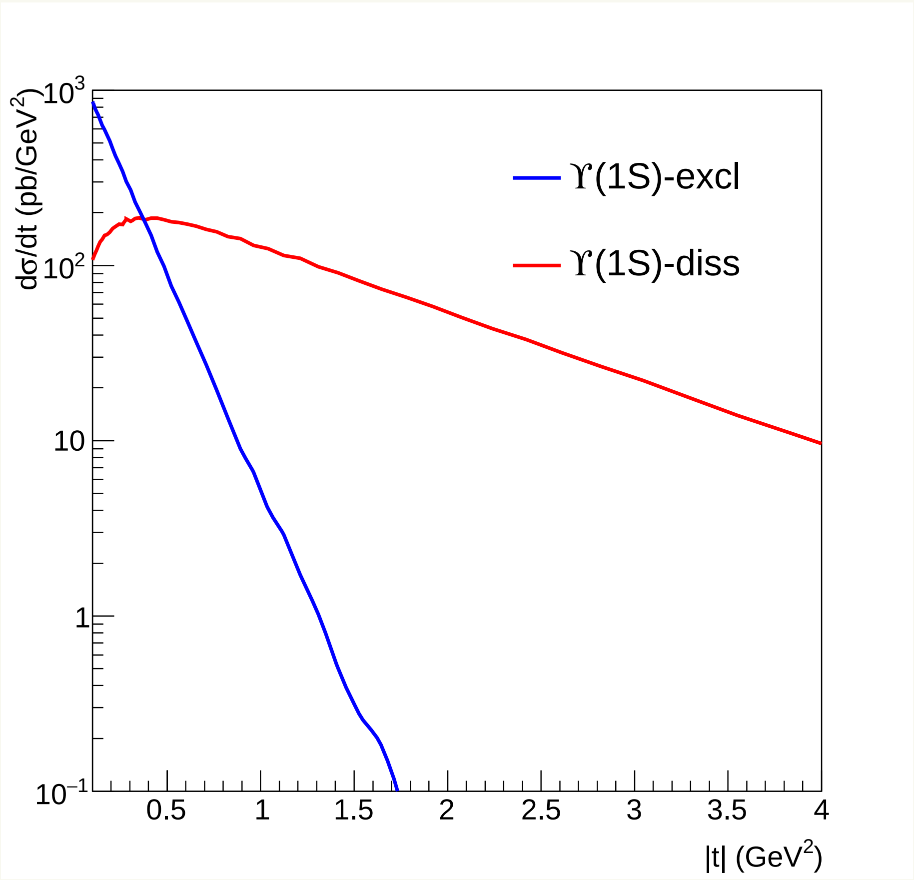
- $N(r,\tilde{x})$ taken from the GBW model

- m_f is an effective mass of a quark



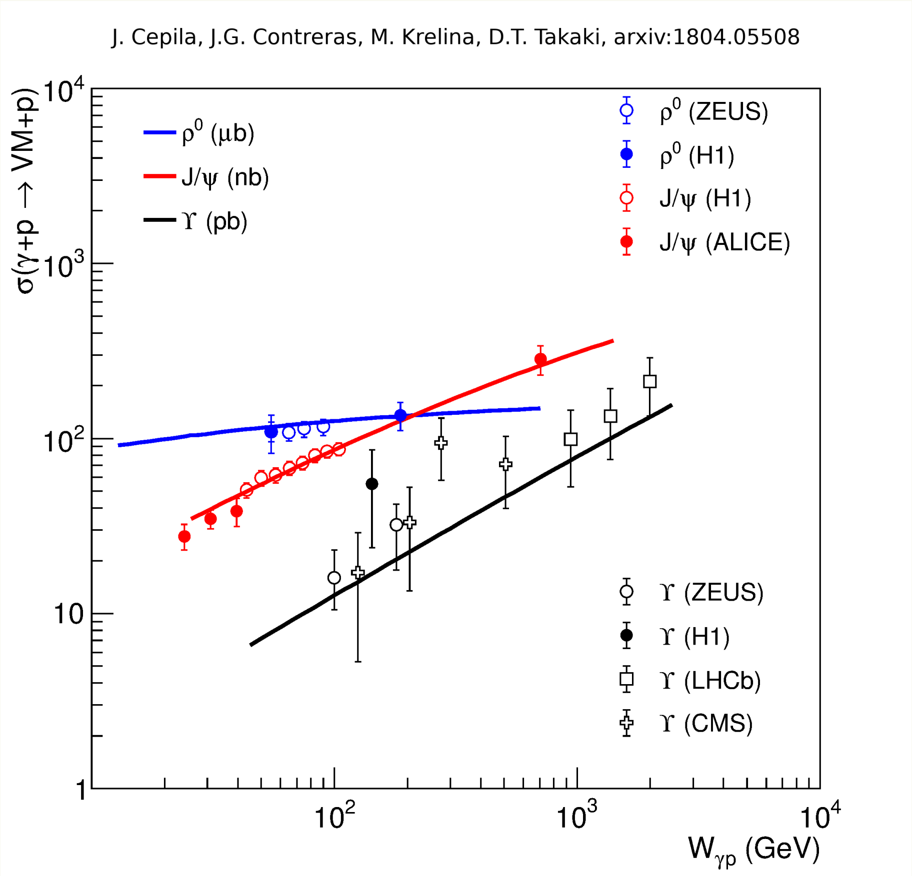
Exclusive and dissociative t-distribution of ρ and ϒ photo-production off protons

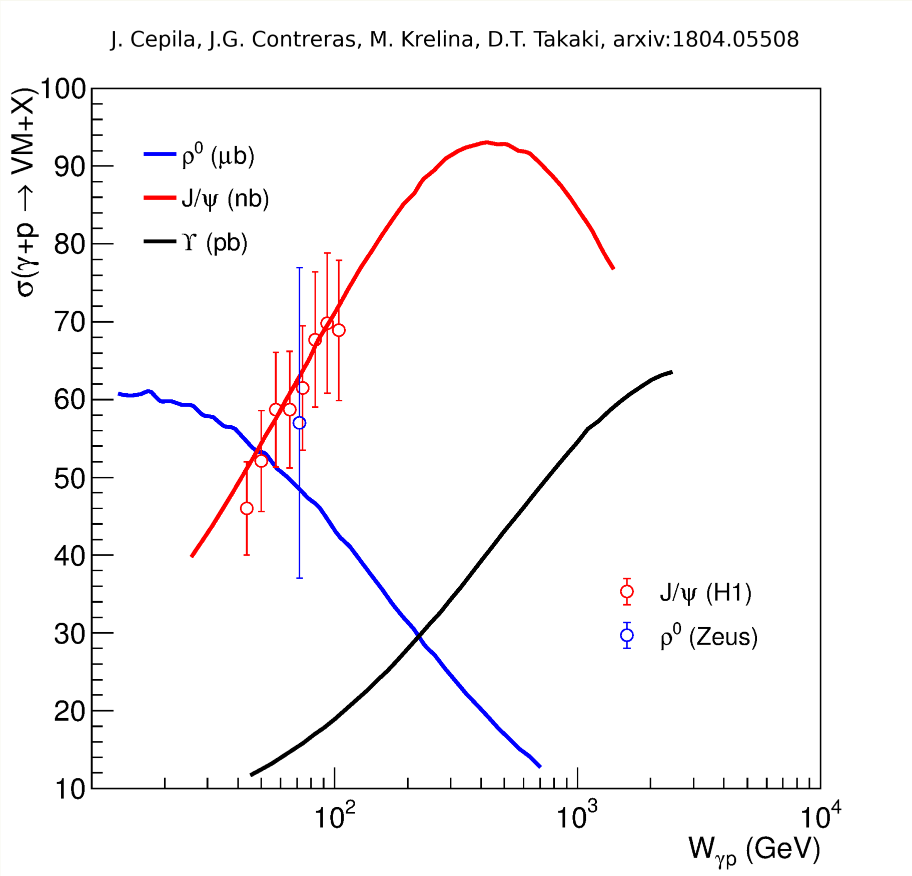




Data for t-distribution of ρ at $W = 71.7$GeV induces change of B_p to 8 GeV^{-2}.
No change in B_p for ϒ.

Total cross section of ρ and ϒ photo-production off protons





Modification of the model for nuclear targets

- Glauber-Gribov (GG) approach

$$\left(\frac{\mathrm{d}\sigma^A_{q\bar{q}}}{\mathrm{d}^2 b}\right)_j = 2\left(1 - e^{-\frac{1}{2}\sigma_{q\bar{q}}(x,r)T^j_A(\vec{b})}\right)$$

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

- Geometric scaling inspired (GS) approach

$$\left(\frac{\mathrm{d}\sigma^A_{q\bar{q}}}{\mathrm{d}^2 b}\right)_j = \sigma^A_0 N^A(x,r) T^j_A(\vec{b})$$

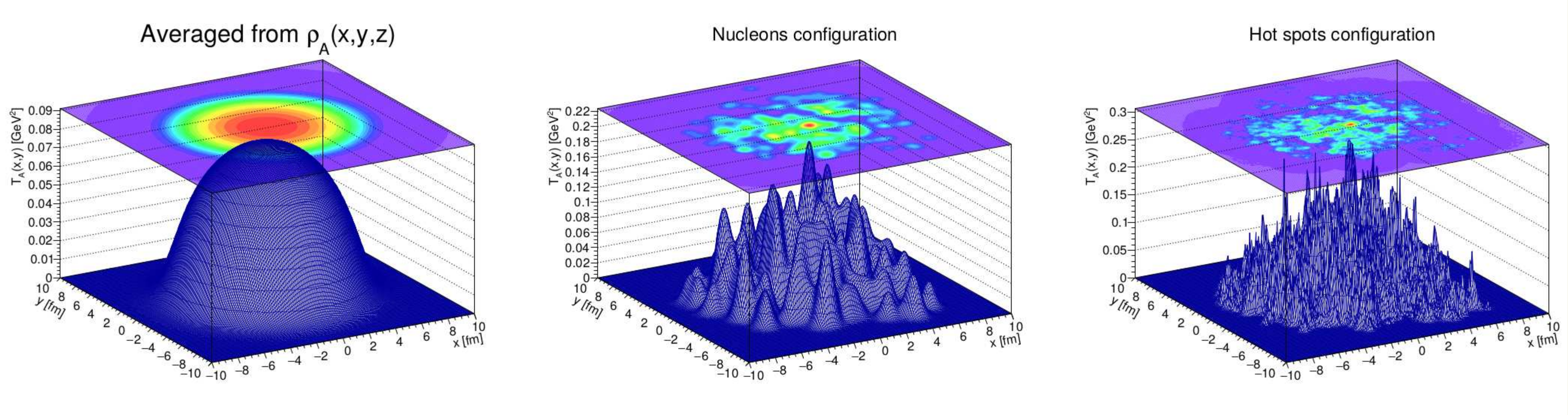
$$N^A(x,r) = \left(1 - e^{-\frac{r^2 Q^2_{sA}(x)}{4}}\right) \qquad Q^2_{sA}(x) = Q^2_s(x)\left(\frac{A\pi R^2_p}{\pi R^2_A}\right)^{\frac{1}{\delta}} \qquad \sigma^A_0 = \pi R^2_A$$

N. Armesto, C. A. Salgado, U. A. Wiedemann, Phys. Rev. Lett. 94 (2005) 022002, arXiv:hep-ph/0407018

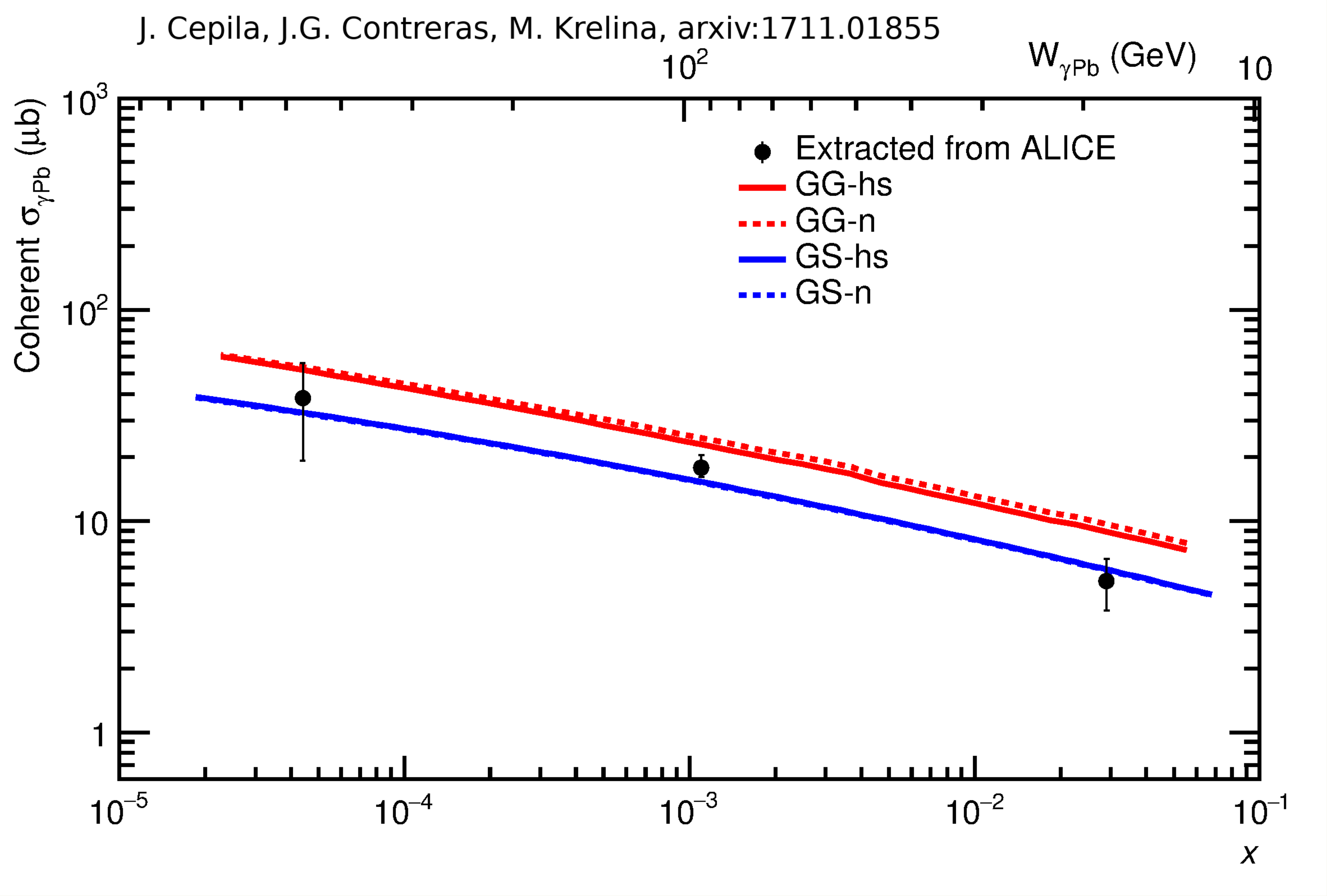
R_A is the nuclear radius from Woods-Saxon distribution, $R_p = \sqrt{2B_p}$ is the proton radius, $\delta = 0.8$

Two variants of the transverse profile

- Fluctuations in nucleon positions only (GG-n, GS-n)
- Fluctuations in nucleon positions and also at a hot-spot level (GG-hs, GS-hs)



Coherent total cross section of J/ψ photo-production off nuclei



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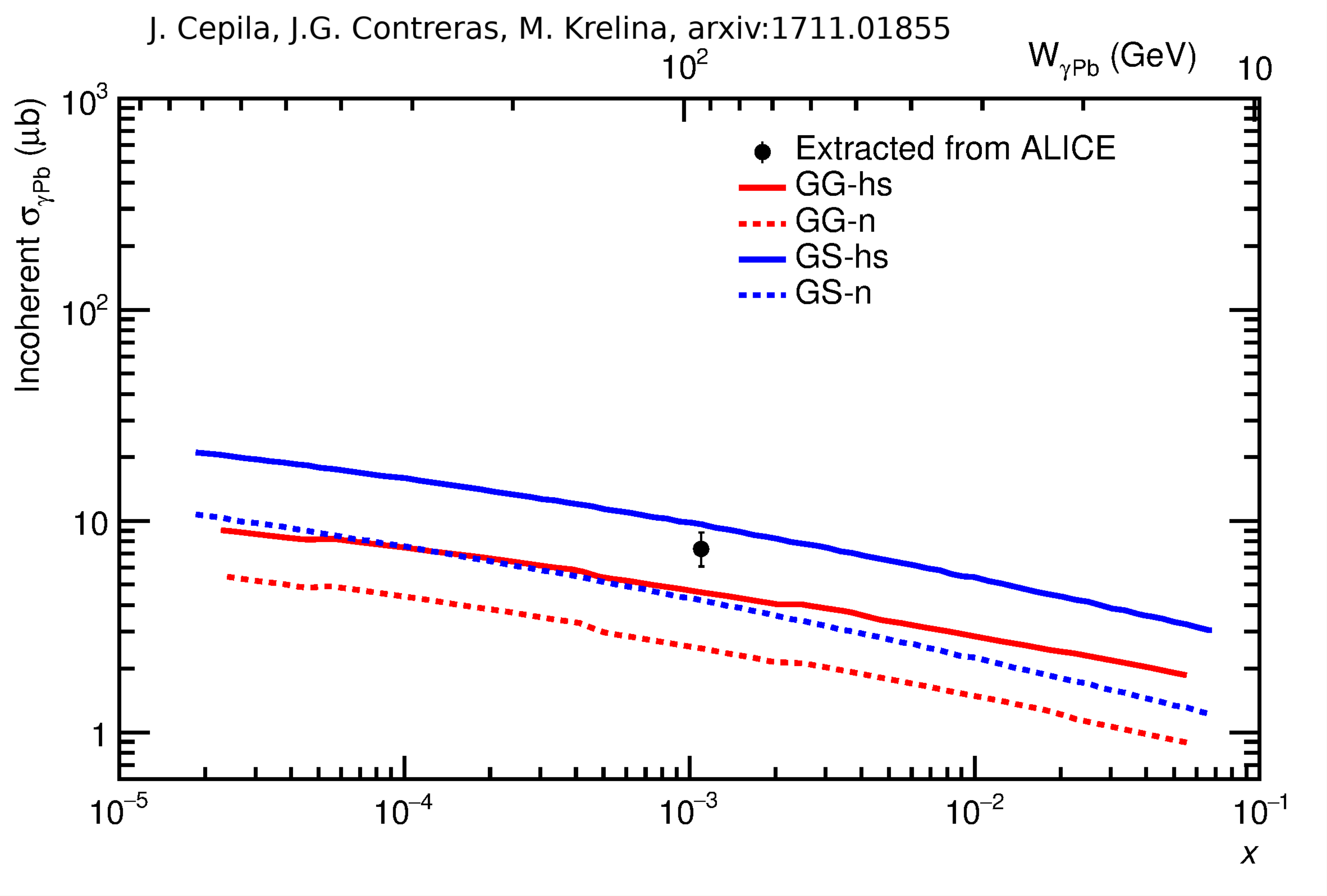
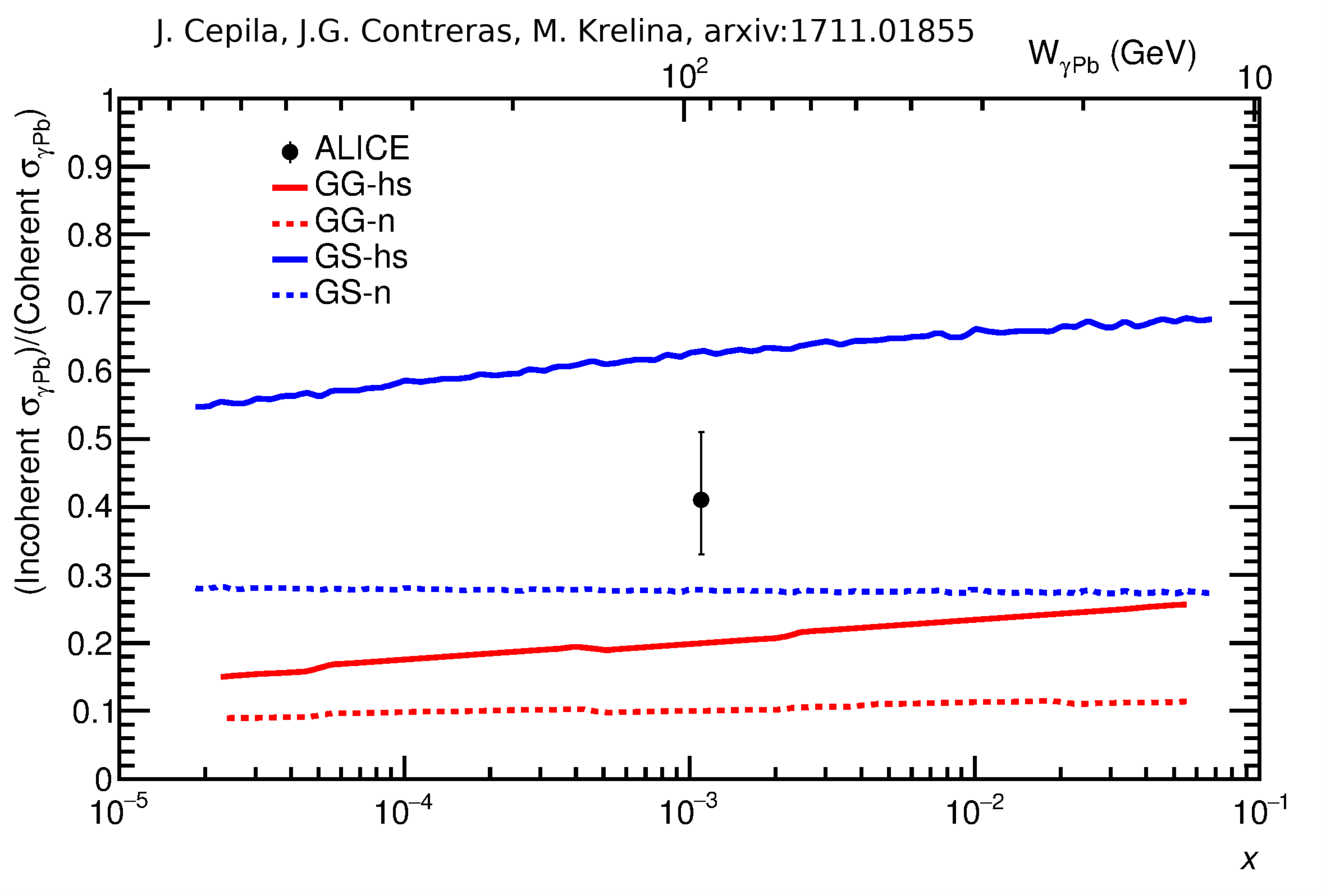
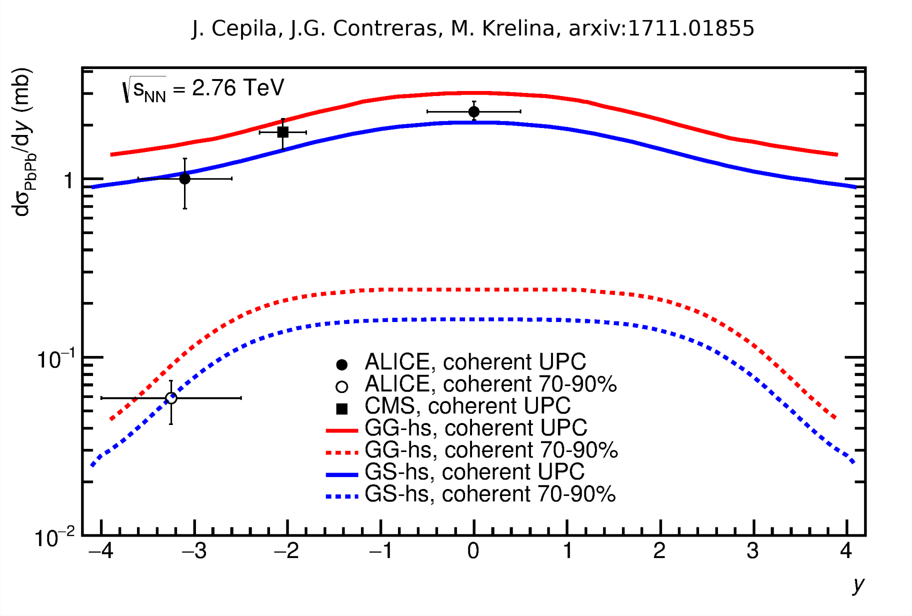
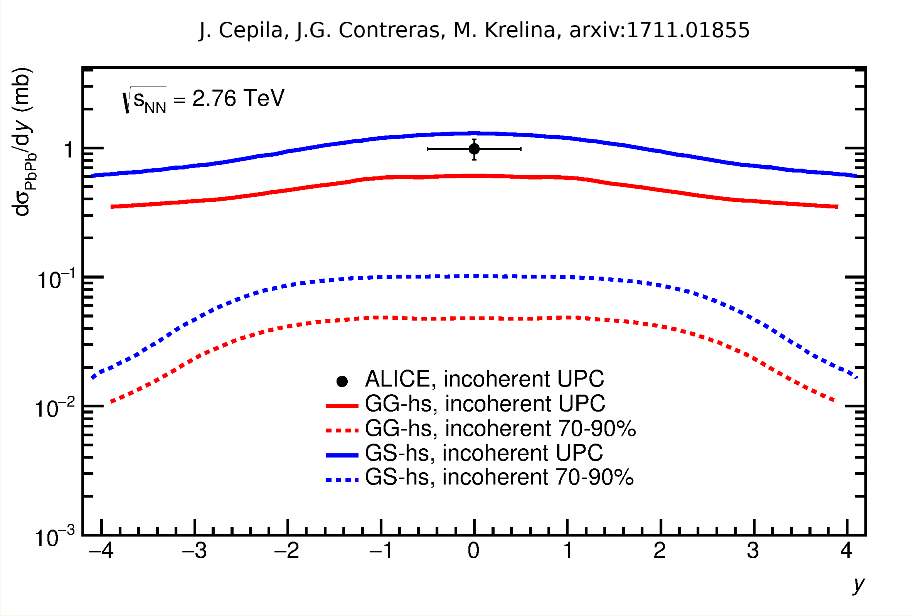


Incoherent to coherent ratio of J/ψ photo-production off nuclei

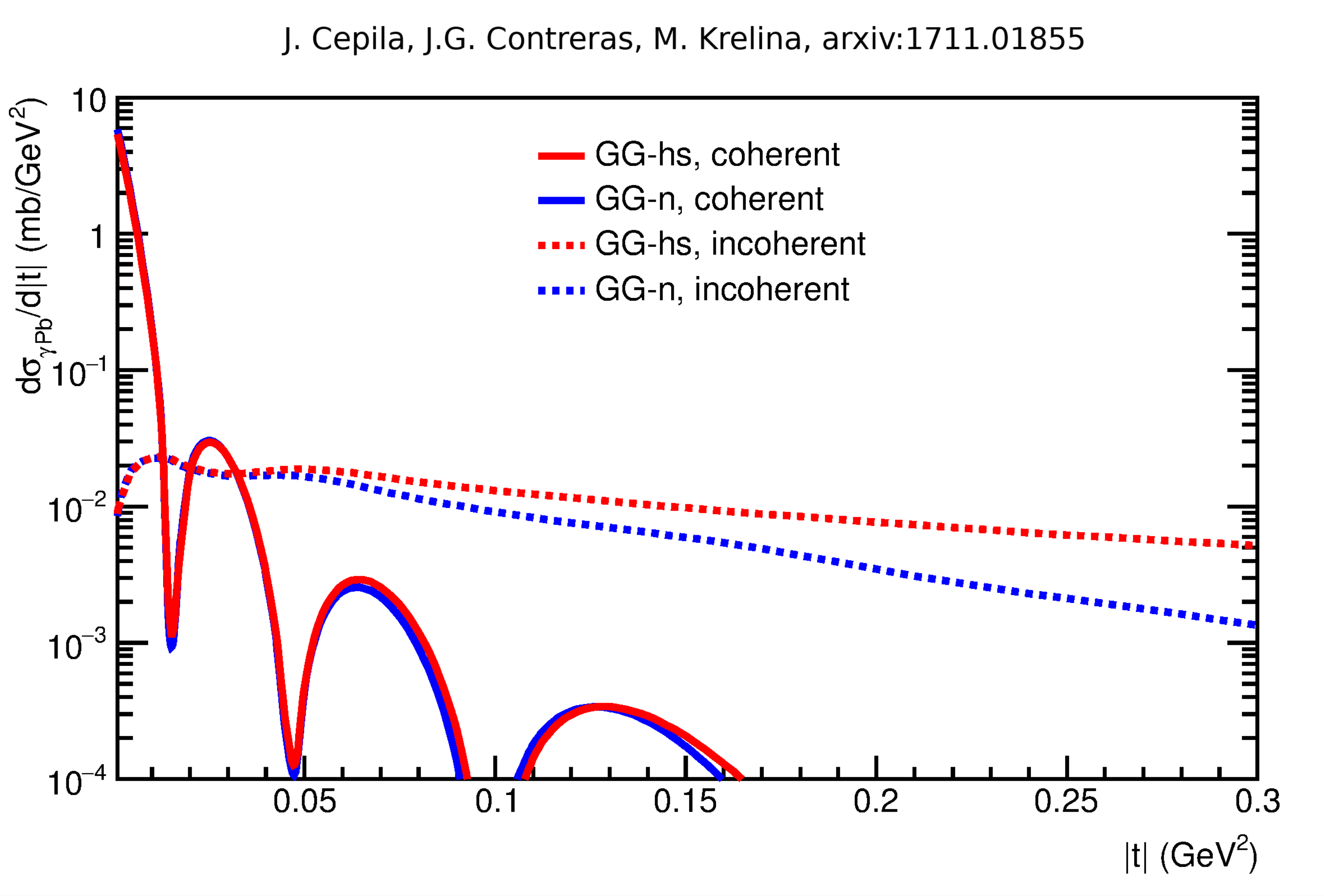


Incoherent and coherent J/ψ photo-production off nuclei



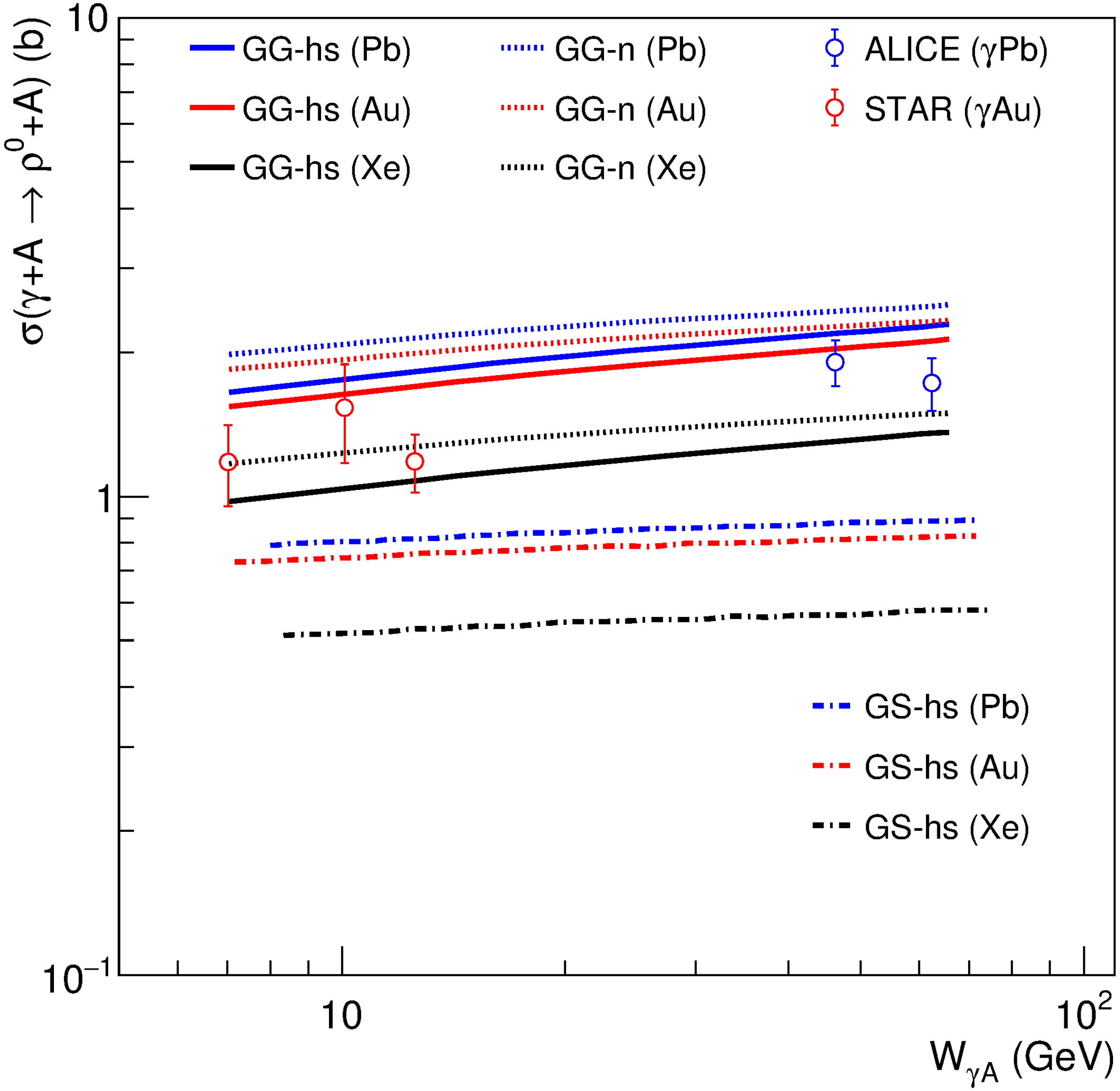


t-distribution of J/ψ photo-production off nuclei

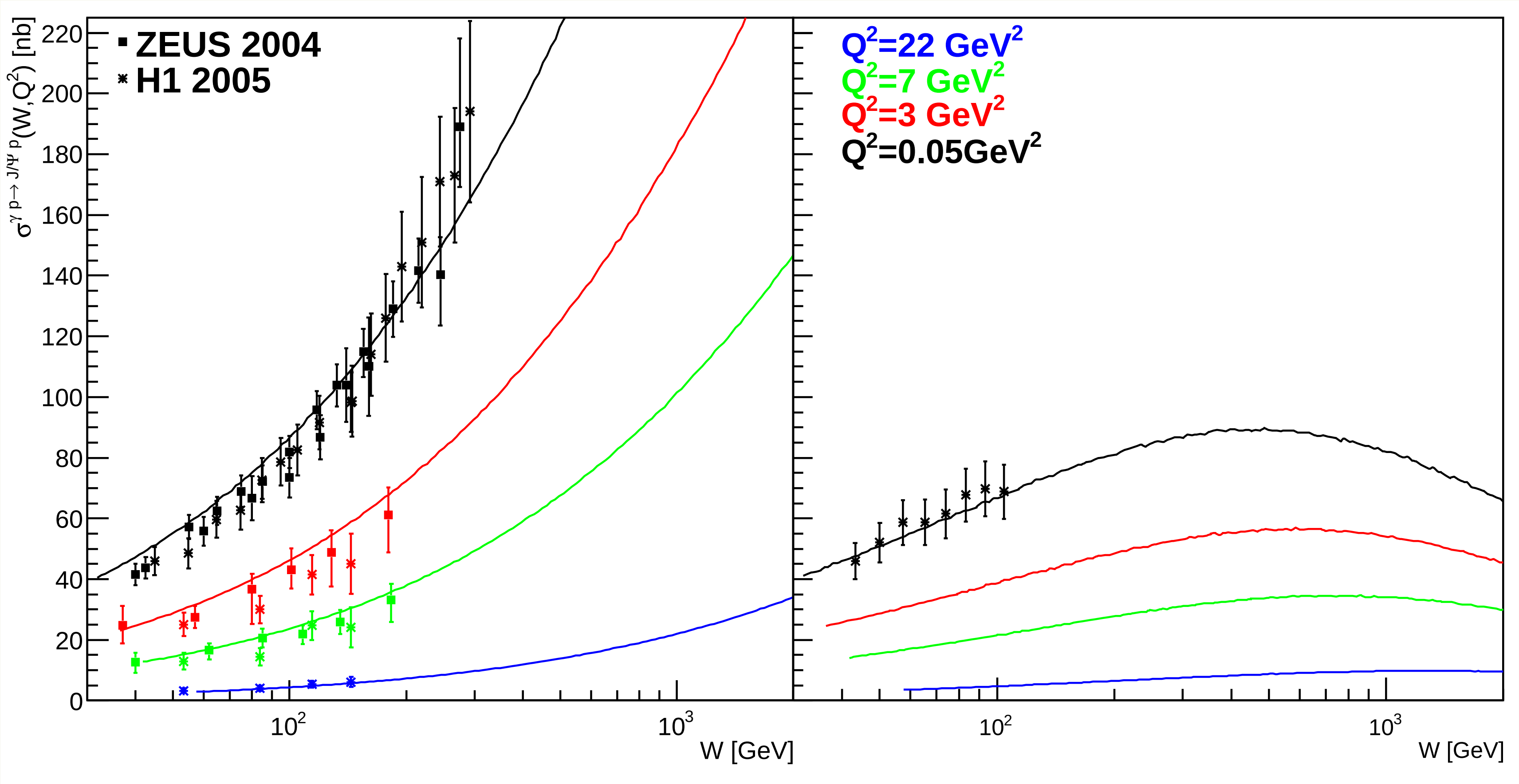


Coherent total cross section of ρ photo-production off nuclei

J. Cepila, J.G. Contreras, M. Krelina, D.T. Takaki,arxiv:1804.05508



NEW results for the hot spot model for electro-production of J/ψ - no change of parameters



Discussion

The numerical values were chosen according to the following arguments:

- The average square of the proton radius $B_p = 4.7\text{GeV}^{-2}$ is similar to that measured at HERA, rise of B_p for ρ meson is motivated by the rise of the slope parameter for small masses also seen at HERA
- The value of the average square of the hot spot radius $B_{hs} = 0.8\text{GeV}^{-2}$ corresponds to a hot spot radius of 0.35 fm, quite close to the values around 0.3 fm found in several papers on soft QCD structure
- The value of $\lambda = 0.21$ is constrained by the energy dependence of exclusive J/Ψ photo-production, similar to the value found at HERA for a scale $Q^2 \sim 2$–3GeV^2
- Due to the factorized form of the dipole cross section we can set $\sigma_0 = 4\pi B_p$.
- We related the number of hot spots with the number of gluons available for the interaction - we follow a simple functional form for the gluon distribution with coefficients varied to find best agreement with the energy dependence of H1 data of exclusive J/Ψ photo-production
- Results for nuclear targets calculated without any additional parameter.

Main results

- The model predicts that the energy dependence of the dissociative process increases from low energies up to $W_{\gamma p} \sim 500$ GeV and then decreases steeply - this energy range can be explored at LHC.
- The physics explanation according to the parton saturation phenomenon is that the growth of the number of scattering centers provides the growth of the exclusive and dissociative cross section. However, at some point the number of hot spots is so large that they overlap. When the overlap is large enough, different configurations look the same and the variance diminishes and so does the dissociative cross section.
- Fluctuations of subnuclear degrees of freedom also leave an imprint in the photo-production of J/ψ off nuclear targets. The energy dependence on the number of the subnuclear degrees of freedom produces and energy dependence on the ratio of incoherent to coherent cross section.
- The mass and scale dependence of vector meson production provides a new handle in the search for saturation effects - this can be checked experimentally by re-processing data from HERA.