

Confronting low x evolution with photoproduction data of *J*/Ψ and Ψ(2*s*)

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- I. Bautista, Fernandez Tellez, MH, PRD 94 (2016) 5, 054002, arXiv:1607.05203
- A. Arroyo Garcia, MH, K.Kutak, PLB 795 (2019) 569-575, arXiv:1904.04394
- MH, E. Padron Molina, arXiv:2011.02640

Snowmass EF06 meeting: Low x, BFKL, diffraction, forward physics December 2nd, 2020

based on:

A process to explore the low x gluon in the proton at the LHC: exclusive photo-production of $J/\Psi s$ and $\Psi(2s)$

- hard scale: charm **mass** (small, but perturbative)
- reach up to x≳.5・10-6
- perturbative crosscheck: ϒ (b-mass)
- measured at **LHC** (LHCb, ALICE, CMS) & **HERA** (H1, ZEUS)

vs low x

- linear low x (BFKL)
-

$$
\frac{N(x,r)}{\log N}\left[-\frac{N(x,r_1)N(x,r_2)}{\log N}\right]
$$

BK evolution for dipole examples at the section of the section of the at θ amplitude $N(x, r) \in [0, 1]$ [related to gluon distribution] the following observation can be made: Recalling the particularly solution of NLO BFKL

details: HSS gluon provides a very good description of both ⌥ and *J/* photo-production data,

$$
\frac{dN(x,r)}{d\ln\frac{1}{x}} = \int d^2r_1 K(r,r_1) \left[N(x,r_1) + N(x,r_2) - N(x,r) \right] - \left[N(x,r_1)N(x,r_2) \right]
$$

*r*² = *|r r*1*|* $linear$ BFKL evolution = subset complete BK

kernel calculated in pQCD

> non-linear term relevant for N~1 (=high density)

0.2

0.6

1.0

 F_2 (**x**, Q^2)

1.4

0.2

0.6

1.0

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1.4

0.2

0.6

1.0

 F_2 (**x**, Q^2)

1.4

0.2

0.6

1.0

 F_2 (**x**, Q^2)

linear low x evolution as benchmark \rightarrow requires precision (updated version desirable, work has started; not expected too soon)

use: HSS NLO BFKL fit

1.4

• initial kT distribution from fit to combined HERA data

0.6

1.0

 F_2 (**x**, Q^2)

1.4

• uses NLO BFKL kernel [Fadin, Lipatov; PLB 429 (1998) 127] + resummation of collinear logarithms

[MH, Salas, Sabio Vera; 1209.1353; 1301.5283]

- based on unified (leading order) DGLAP+BFKL framework [Kwiecínski, Martin, Stasto, PRD 56(1997) 3991]
- combined with leading order BK evolution [Kutak, Kwiecinski;hep-ph/0303209][Kutak, Stasto; hep-ph/0408117]
- initial conditions: fit to combined HERA data [H1 & ZEUS collab. 0911.0884]
- both non-linear and linear version available (= non-linearity switched off)

gluon with non-linear terms: KS gluon [Kutak, Sapeta; 1205.5035]

⇠ *^eBD*(*x*)*|t[|]* t of standard procedure for comparing inclusive gluon to exclusive data) normalization of the cross-section with a mild logarithmic dependence on the energy. To I Standard procedure for comparing inclusive giuon to exclusive data) *b* (sort of standard procedure for comparing inclusive gluon to exclusive data) total cross-section for vector meson production is therefore obtained as *i* + tan y inclusiv *drW*(*r*) .
י *i* + tan lusive da

a) analytic properties of scattering amplitude \rightarrow real part 0 by its imaginary part. Corrections due to the real part of the scattering amplitude can be α scattering amplitude \rightarrow real part

t = 0 (which can be expressed in terms of the inclusive gluon distribution); in a second step

correction to the *W* dependence of the complete cross-section. We therefore do not assume

b) differential Xsection at t=0:

c) from experiment: $d\sigma$ \int f_{reco} \in 0.40 σ σ is numerical values $d\sigma$ \int I_{reco} \in $B_{\text{D}}(W)$. *b* \overline{dt} ^{(γp})

 $d\sigma$

 $\sigma^{\gamma p\to V p}(W^2) = \frac{1}{B_D(W)} \frac{d\sigma}{dt} \left(\gamma\right)$ *<i>z D*_{*D*}(*W*) $\frac{a}{\sqrt{a}}$ $\overline{\gamma^{N,p}(W^2)} = \frac{1}{B_D(W)} \frac{d\sigma}{dt}$ $B_D(W)$ $d\sigma$

how to compare to experiment? *^Ap*!*V p*(*x, t* = 0) = ✓ *i* + tan (*x*)⇡ ◆ and the state of the Z *drW*(*r*) ✓ *i* + tan (*x*)⇡ *p BD*(*W*) $\overline{}$ *dt d d d i s i d i s i d i s i d i s i d i s i d i s i d i d i d i d i d i d i d i d i d i d i d i d i d i d i* description, Sec. 3 is dedicated to a discussion of the large perturbative corrections of the large perturbativ
The large perturbative corrections of the large perturbative corrections of the large perturbative corrections NLO BFKL gluon in the large *W* region while in Sec. 4 we present our conclusions. Following [21, 22], we use for the numerical values ↵⁰ = 0*.*06 GeV² where *^A*(*W*2*, t*) denotes the scattering amplitude for the reaction *^p* ! *V p* for color singlet exchange in the *t*-channel, with an overall factor *W*² already extracted. For a more detailed discussion of the kinematics we refer to [25].

 Γ ean energy dependence noming the $B_{\mathcal{D}}(W)$ $\frac{1}{2}$ = $\frac{1}{2}$ = photons. The photon photons is provided a photon of photons. The photons of photons is provided a photons. *r*2, while *f* = *c, b* denotes the flavor of the $B_D(W) = \left\lvert b_0 + 4\alpha' \ln \frac{1}{W_0} \right\rvert \text{ GeV}^{-2},$ a naramatar ϵ boranneren ϵ ⇠ *^eBD*(*x*)*|t[|]* nergy dependence from
arameter $D_D(VV) =$ $B_D(W) = \left\lfloor b_0 + 4\alpha' \right\rfloor$ $\frac{V}{T}$ \overline{a} eV ⁻ The uncertainty introduced by the modeling of the *t*-dependence mainly a↵ects the overall wear energy dependence norm $B_D(W) = \left| b_0 + 4\alpha' \ln \frac{W}{W} \right| \text{ GeV}^{-2}$ siope parametermine the state \mathfrak{c}_1 $\sqrt{ }$ $b_0 + 4\alpha' \ln \frac{W}{W}$ *W*⁰ $\overline{}$ \rm{GeV}^{-2} . weak energy dependence from slope parameter

$$
A^{\gamma p \to Vp}(x, t=0) = \left(i + \tan \frac{\lambda(x)\pi}{2} \right) \cdot \Im \mathbf{m} A^{\gamma p \to Vp}(x, t=0)
$$

with intercept

$$
\lambda(x) = \frac{d \ln \Im \mathbf{m} A(x, t)}{d \ln 1/x}.
$$

$$
\frac{d\sigma}{dt} \left(\gamma p \to Vp \right) \bigg|_{t=0} = \frac{1}{16\pi} \left| \mathcal{A}^{\gamma p \to Vp} (W^2, t=0) \right|^2
$$

$$
\frac{d\sigma}{dt}(\gamma p \to Vp) = e^{-B_D(W) \cdot |t|} \cdot \frac{d\sigma}{dt}(\gamma p \to Vp)\Big|_{t=0}
$$

$$
\sigma^{\gamma p \to V p} (W^2) = \frac{1}{B_D(W)} \frac{d\sigma}{dt} (\gamma p \to V p) \Big|_{t=0}
$$
 extracted from data

 \overline{Q}

determine the scattering amplitude, we first note that the dominant contribution is provided *drW*(*r*)*qq*¯(*x, r*)

error band: variation of renormalization scale \rightarrow in general pretty small = stability

[Bautista, MH, Fernandez-Tellez;1607.05203]

First study (BFKL only, also for Υ) NLO BFKL describes energy dependence, but …..

…but error blows up for highest energies

does it mean something?

- linear vs. nonlinear *d^p dt* $\overline{}$ \mathfrak{p} \overline{a}
- with standard scale choice *p*(*x*) = ¹ $\frac{1}{2}$ (*x, r*)= $\frac{1}{2}$ (*x, r*)= $\frac{1}{2}$ (*x, r*)= $\frac{1}{2}$

Second Study \overline{I} \overline{O} d 1 *x* $\sqrt{ }$ Z

but find:

- energies
	-
-

$$
\hat{\sigma}_{q\bar{q}}^{\rm (HSS)}(x,r)=\hat{\sigma}_{q\bar{q}}^{\rm (dom.)}(x,r)+\hat{\sigma}_{q\bar{q}}^{\rm (corr.)}(x,r),
$$

$$
M^2 = \frac{4}{r^2}
$$

• with standard scale choice, HSS gluon is unstable for largest ● with standard scale choice, HSS gluon is unstable for largest *x* d scale o

• fix this through dipole size dependent renormalization scale

$$
\frac{4}{r^2} + \mu_0^2
$$
 with $\mu_0^2 = 1.51$ GeV²

 \rightarrow stabilize perturbative expansion through resummation

stabilizes perturbative $expanion \rightarrow stable NLO$ BFKL evolution at highest *W*

BUT:

- resulting growth too strong for *J*/Ψproduction
- classical sign for onset of high density effects/transition towards saturated regime?

Shortcomings of our 2nd study

- Vector meson wave functions use (conventional) boosted Gaussian model →what about more refined descriptions?
- We do not address excited states $\Psi(2s) \rightarrow$ different *r*-shape of the transition due to nodes in the wave function
- refit of NLO BFKL gluon \rightarrow desirable, but beyond this study; project for future
- estimate uncertainties (scale variation) \rightarrow how stable is our observation

 ^V (*z, |p|*)*,* ²*m^T* (*m^T* ⁺ *^mL*) *^V* (*z, [|]p|*)*,* (8) \bullet **T**_{*V*}(\mathbb{Z} , \mathbf{P}) provided as lable by aum
of **1912,02001** 1001,026641 01 <u>[IOTZ.00001, ISOT.02004]</u>
2 2 2 2 2 4 2 *e* $\frac{1}{2}$ *y*(*z*, *p*) provided as to $\frac{1}{2}$ *m*² *i*² *m*² *i*² *m*² *i*² *m*² *i*² *n*² *i*² $e^+{}^{m_L}$ $\qquad \qquad \bullet \ \Psi_V(z,{\bf p})$ provided as table by authors \bullet $\begin{array}{ccc} \bullet & \cdots & \bullet & \bullet & \bullet \end{array}$ $\begin{matrix} 1 & 0 \\ 0 & 0 \end{matrix}$ the mass of the m $m_T^2 = m_f^2 + p^2$ $m_L^2 = 4m_f^2z(1-z),$

Transition amplitude *γ* **→ VM** 2 \blacksquare indistead determined the slope \blacksquare ⁼m*A*(*W*2*, t*) = tan \blacksquare As noted in the slope parameter \blacksquare with \blacksquare with \blacksquare and \blacksquare with \blacksquare correction to the *W* dependence of the complete cross-section. We therefore do not assume

includes relativistic spin rotation effects + (more) realistic $c\bar{c}$ potential both for J/Ψ and $\Psi(2s)$ \overline{C} includes relativistic spin rotation effects + (more) realistic $c\bar{c}$ potential $t_{\rm orb}$ for I/Ψ and $\Psi(2r)$ both for J/Ψ and $\Psi(2s)$

[Hufner, Y. Ivanov, B. Kopeliovich, A. Tarasov; hep-ph/0007111], [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001;](https://arxiv.org/abs/1812.03001) [1901.02664](https://arxiv.org/abs/1901.02664)] _thumer, t. ivanov, p. Kopenovich, A. Tarasov, <u>nep-pri/oov/ i i i j</u>,
[M. Krelina. J. Nemchik. R. Pasechnik. J. Cepila: 1812.03001: 1901.02664] [Hufner, Y. Ivanov, B. Kopeliovich, A. Tarasov; hep-ph/0007111], then in the format limit of th
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section and its derivative
iined in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; <u>1812.03001; 1901.02664</u>] through • wave functions have been obtained in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001;](https://arxiv.org/abs/1812.03001) [1901.02664](https://arxiv.org/abs/1901.02664)] through *dz* Z *d*2*p* $\mathfrak{a},$ *F R i*² *C M*_{*D*} *i*² *n i*² r *m^T* + *m^L dz* P ¿ *^eip·^r ^m*² *^T* ⁺ *^m^T ^m^L* ²*p*² *^T z*(1 *z*) 1; <u>T8T2.0300</u> *<i><u>864</u>] throug*

$$
\Im \mathbf{m} \mathcal{A}_T(W^2, t=0) = \int d^2 \boldsymbol{r} \left[\sigma_{q\bar{q}} \left(\frac{M_V^2}{W^2}, r \right) \overline{\Sigma}_T^{(1)}(r) + \right.
$$

- depends both on dip(
● *Waye* functions have apure cross-section and its derivative
Transpected in the Kallee photon Development photon • depends both on dipole cross-section and its derivative
- **V** wave functions have been opt numerical solution to corresponding Schrödinger equation ● adpends both on appute cross-section and its derivative
● wave functions have been obtained in **M** Krelina J Nemchik B Pas *victio* into a vector of the state of $\frac{1}{3}$
	- ⌃(*i*) *^T* (*r*)=ˆ*e^f i*actorizes ²⇡² *^K*0(*m^f ^r*) ⌅(*i*) ⌃(*i*) *^T* (*r*)=ˆ*e^f e.*
*i*_c *i*_c *n fact* • transition function factorizes for real photon ($Q = 0$)

$$
\text{ton } (Q = 0) \frac{\overline{\Sigma}_{T}^{(i)}(r)} = \hat{e}_f \sqrt{\frac{\alpha_{e.m.} N_c}{2\pi^2}} K_0(m_f r) \,\Xi^{(i)}(r), \qquad i = 1, 2
$$

 $\Psi_V(z,|\boldsymbol{p}|),$ $\{z, |\mathbf{p}| \}$.

$$
\Xi^{(1)}(r) = \int_{0}^{1} dz \int \frac{d^{2} \mathbf{p}}{2\pi} e^{i \mathbf{p} \cdot \mathbf{r}} \frac{m_{T}^{2} + m_{T} m_{L} - 2p_{T}^{2} z (1 - z)}{m_{T} + m_{L}} \Psi_{V}(z, |\mathbf{p}|),
$$
\n
$$
\Xi^{(2)}(r) = \int_{0}^{1} dz \int \frac{d^{2} \mathbf{p}}{2\pi} e^{i \mathbf{p} \cdot \mathbf{r}} |\mathbf{p}| \frac{m_{T}^{2} + m_{T} m_{L} - 2\mathbf{p}^{2} z (1 - z)}{2m_{T} (m_{T} + m_{L})} \Psi_{V}(z, |\mathbf{p}|),
$$
\n
$$
\Psi_{V}(z, \mathbf{p}) \text{ provided as table by authors}
$$
\n
$$
\Pi_{T}^{(1812.03001; 1901.02664]} \text{or}
$$
\n
$$
m_{T}^{2} = m_{f}^{2} + \mathbf{p}^{2}, \quad m_{L}^{2} = 4m_{f}^{2} z (1 - z),
$$

potentials for wave functions:

Buchmüller-Tye Potential: Coulomb-like behavior at small r and a string-like behavior at large *r* [Buchmüller, Tye; PRD24, 132 (1981)]

as implemented in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001;](https://arxiv.org/abs/1812.03001) [1901.02664](https://arxiv.org/abs/1901.02664)]

- plots show transition function $\gamma \rightarrow VM$, not wave function
- \bullet $\Psi(2s)$: node structure of wave function absent in transition after integration over photon momentum fraction *z*
- $\overline{\Sigma}^{(2)}(r)$ enhanced for $\Psi(2s)$, but still considerable smaller

 $\rightarrow \Psi(2s)$ gives access to a (slightly) different region in *r* than J/Ψ

 \rightarrow requires separate diffractive slopes $B_D(W)$ as obtained in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001](https://arxiv.org/abs/1812.03001); [1901.02664\]](https://arxiv.org/abs/1901.02664)

Note:

• Fix normalization with low energy data point (HERA); offset in normalization also seen in

• Uncertainty band = variation of renormalization scale $\bar{M}\in [M/\sqrt{2},M\sqrt{2}]$

- [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001;](https://arxiv.org/abs/1812.03001) [1901.02664](https://arxiv.org/abs/1901.02664)]
-
- Difference between linear & non-linear persists, but scale uncertainty too large to distinguish them clearly

- Gaussian model; most likely related to $d\sigma_{q\bar{q}}/dr$ term
- stabilized BFKL and non-linear evolution appear closer than for *J*/Ψ [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001;](https://arxiv.org/abs/1812.03001) [1901.02664](https://arxiv.org/abs/1901.02664)] Steeper (perturbative) energy node at higher energies

• Complete breakdown of the fixed scale HSS (NLO BFKL) gluon \rightarrow not seen for simple

dependence for $\Psi(2s) \rightarrow$ attributed to reduced cancellation below and above $\Psi(2s)$

More interesting: the ratio *σ*[Ψ(2*s*)]/*σ*[*J*/Ψ]

problem: no data at high energies evolution?

 $(J/\Psi$ and $\Psi(2s)$ LHCb data in different W-bins)

-
- rise of non-linear gluon also observed in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1812.03001;](https://arxiv.org/abs/1812.03001) [1901.02664\]](https://arxiv.org/abs/1901.02664) →KST dipole X-section [Kopeliovich, Schäfer, Tarasov, [hep-ph/9908245](https://arxiv.org/abs/hep-ph/9908245)]
- here: confirmed for KS (BK) gluon
	- rise is not present for HSS (NLO BFKL) gluon (stabilized version)
	- both slope & curvature differ
	- general feature of perturbative QCD

• despite of all of its challenges: VM production remains a useful observable to quantify

• probes different aspects (& suffers different uncertainties) than e.g. angular de-correlation

Conclusions:

- *J/Ψ*: theory uncertainty bands due not allow to clearly distinguish between linear (stabilized) and non-linear $evolution \rightarrow reduction of uncertainty bands is needed$
- \bullet $\Psi(2s)$: fixed scale HSS gluon breaks down; stabilized HSS and KS gluon too close to distinguish them $(\Psi(2s)$ more sensitive to small r region due to node structure?)
- ratio: find different energy dependence for BFKL and BK gluon [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; [1901.02664](https://arxiv.org/abs/1901.02664)] see decreasing ratio for Υ at the level of dipole models
	- presence of non-linear effects in low x evolution equations
	- dihadron or dijet \rightarrow complementary observables