Ultra-peripheral collisions (UPCs)

or

The growth with energy of exclusive J/Ψ and Υ photo-production cross-sections and BFKL evolution

or

some QCD theory ….

Martin Hentschinski
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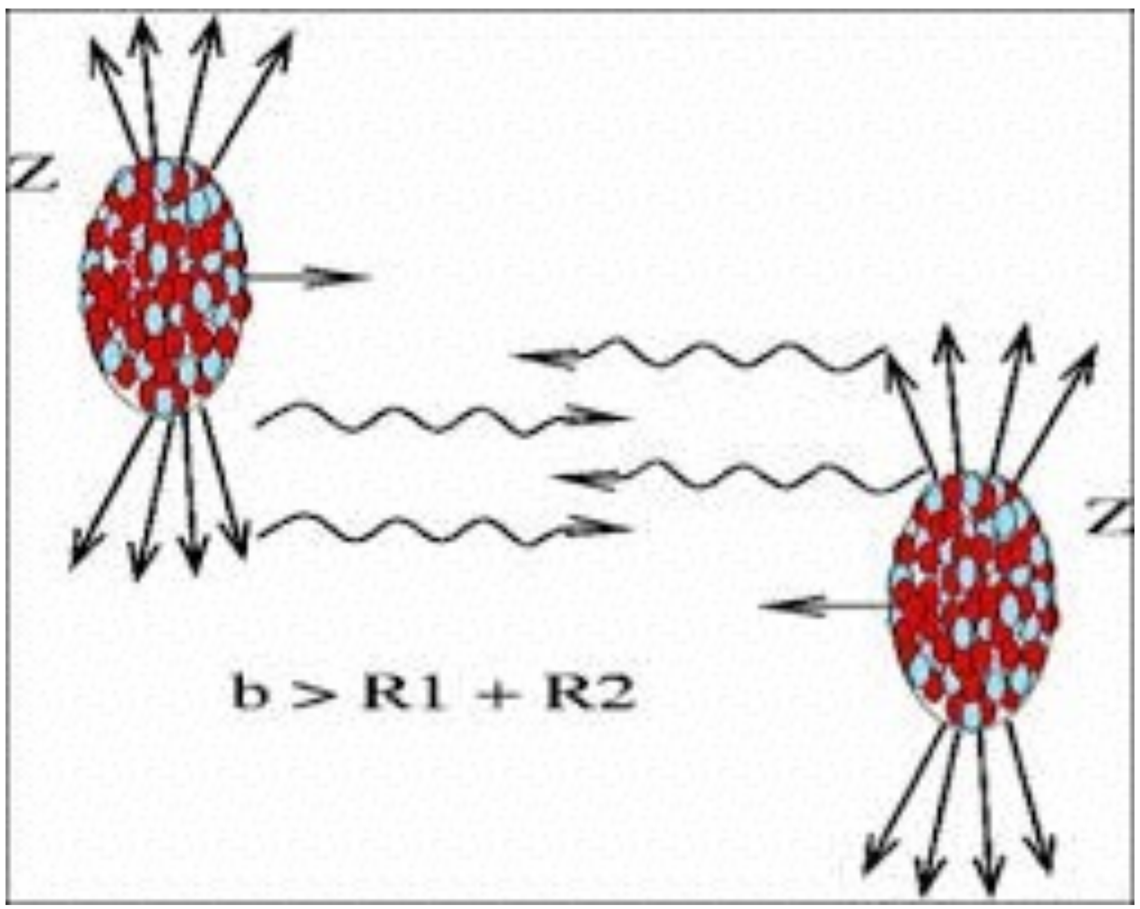
based on:
I. Bautista, A. Ferndandez Tellez, MH. [arXiv:1607.05203] (PRD 94 054002)

LHC: the most energetic photon source ever built

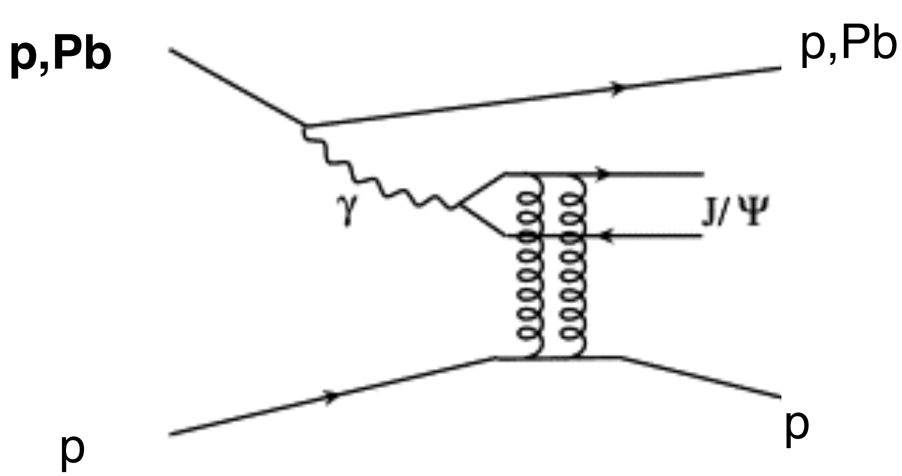


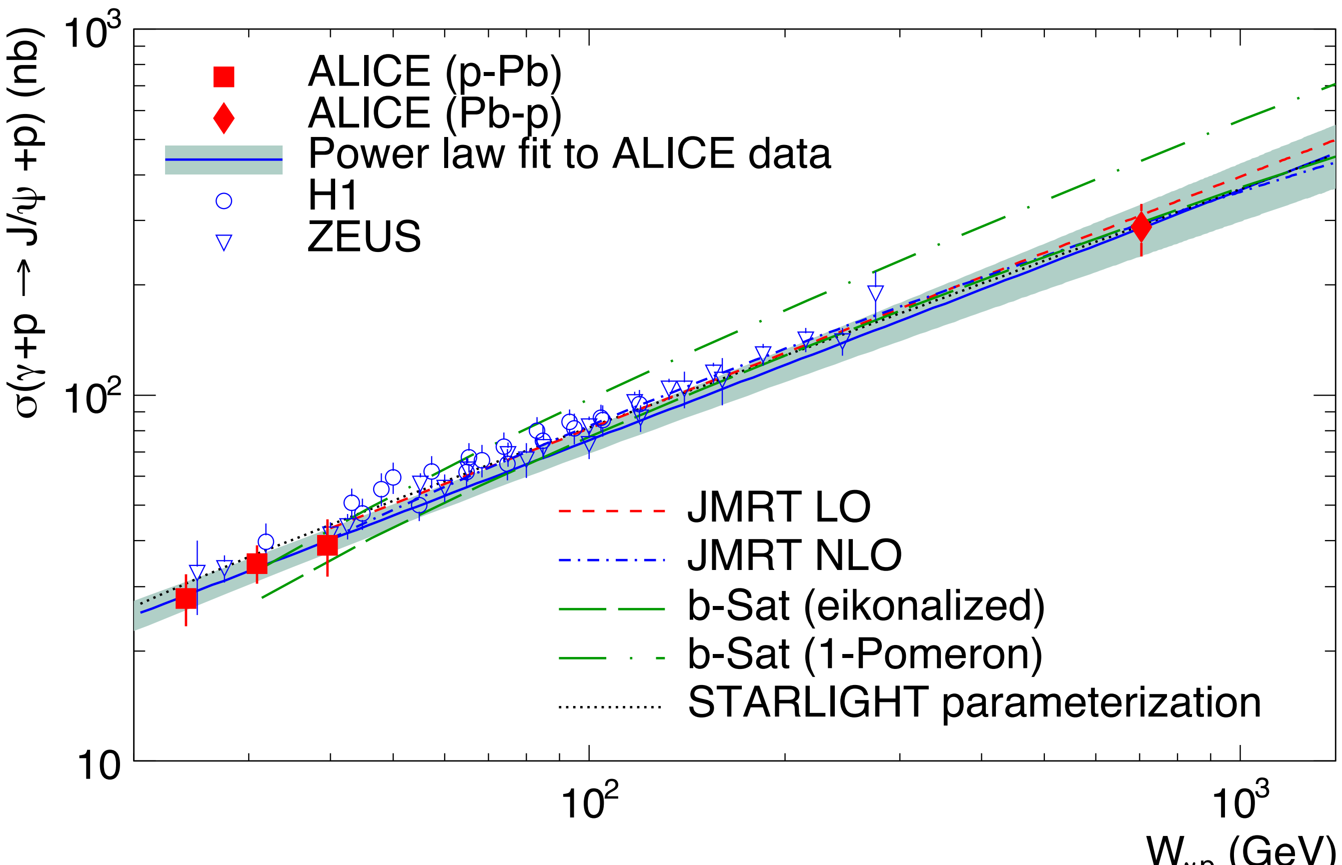
photon induced collisions
at the TeV scale

- two ions (protons) pass each other with impact parameters b > 2 R→ hadronic interactions strongly suppressed

- high photon flux ~ Z^2 well described by Weizsäcker-Williams approximation (electromagnetic field = a beam of quasi real photons)

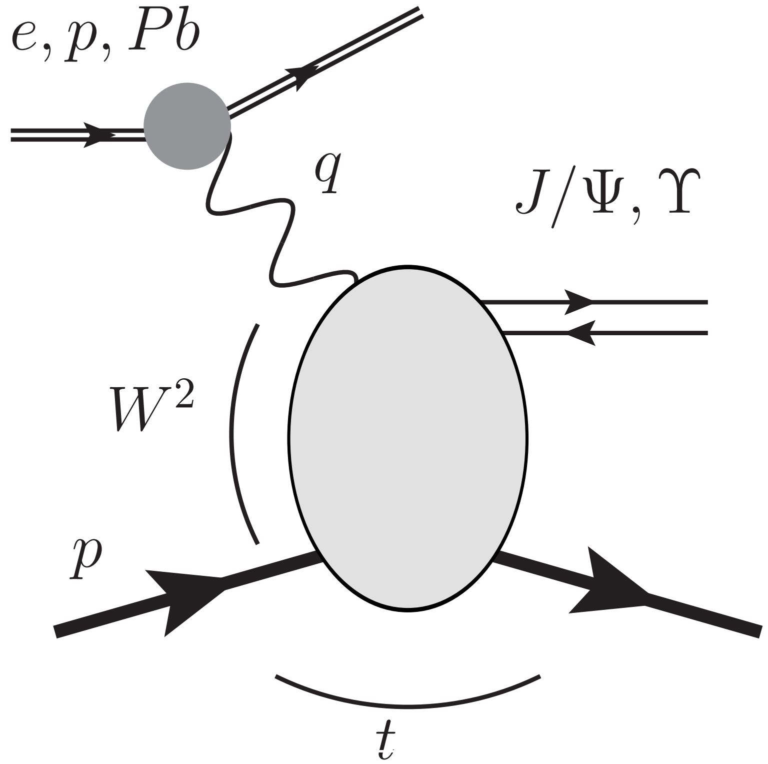
probe the proton at small x





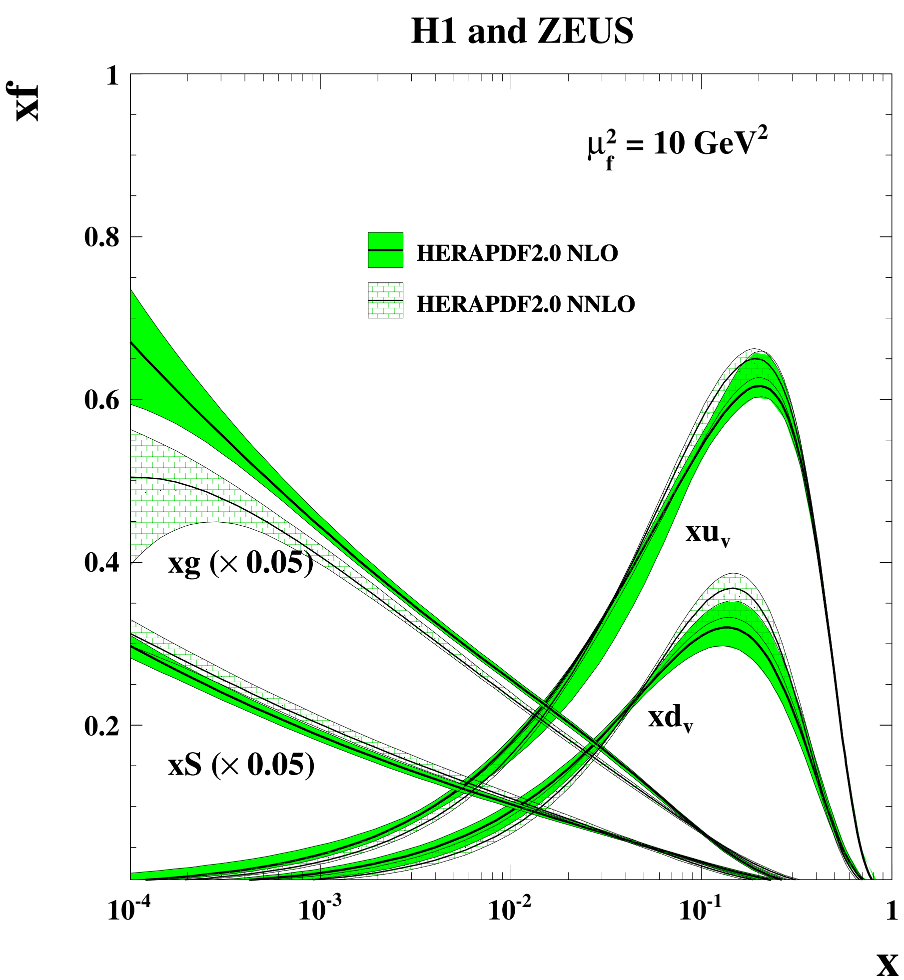
- exclusive photo production Xsec. of J/Psi ~ gluon^2
- ultra small x ~ region 10^{-2}-10^{-5} accessible at the LHC
- UPC vector meson production (VM) = a tool to access the potentially saturated proton

  shown: ALICE data (arXiv: 1406:7819) and HERA data (ep scattering)



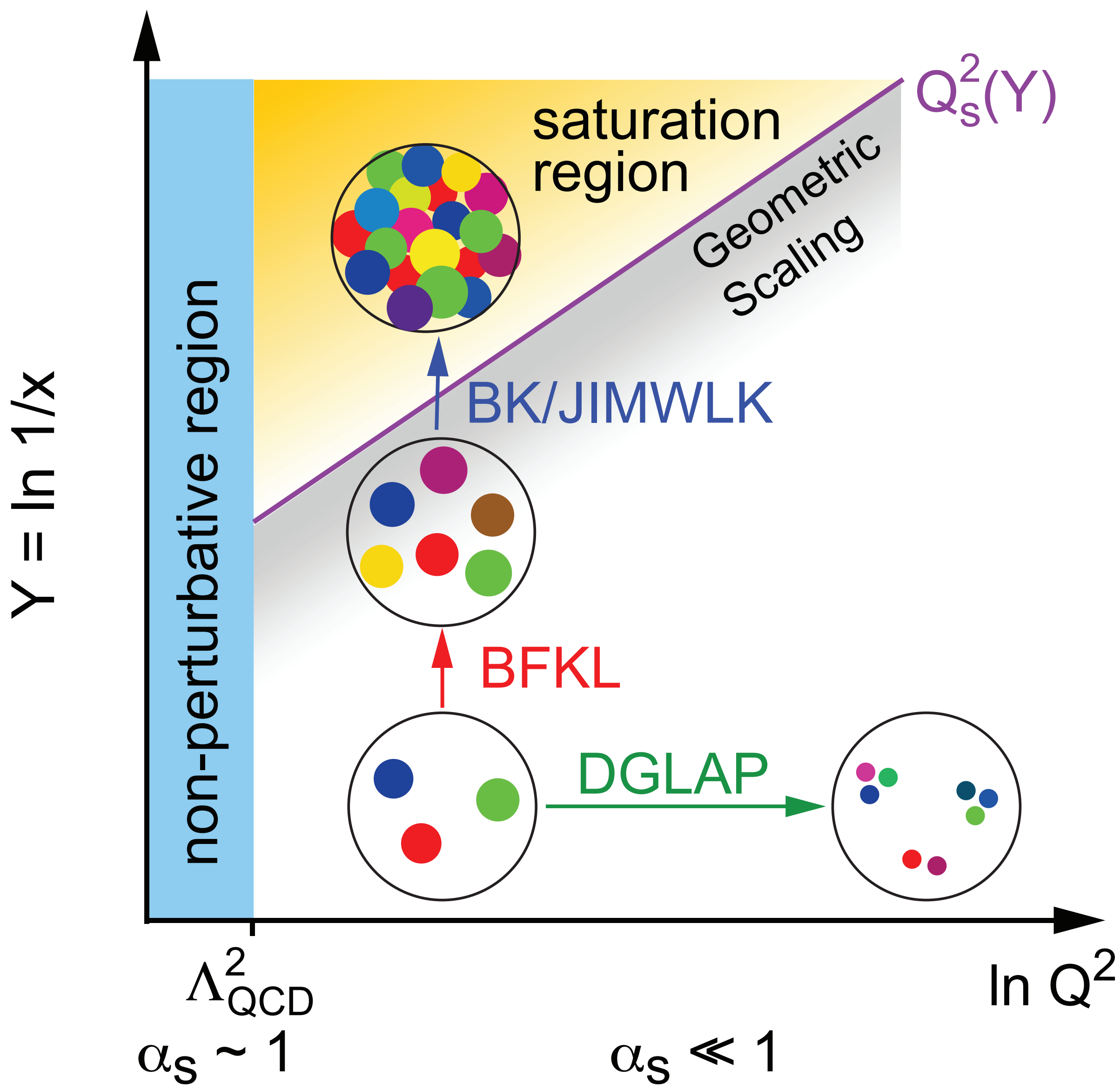
kinematics

- energy squared $W^2=(p + q)^2$
  t: momentum transfer
- probe proton and therefore gluon at $x = M_{VM}^2/(W^2 - m_p^2)$
- HERA constrains gluon down to $x=10^{-4}$,
  UPCs: gain order of magnitude
  → learn about the low x gluon



and explore (maybe?) a new regime:

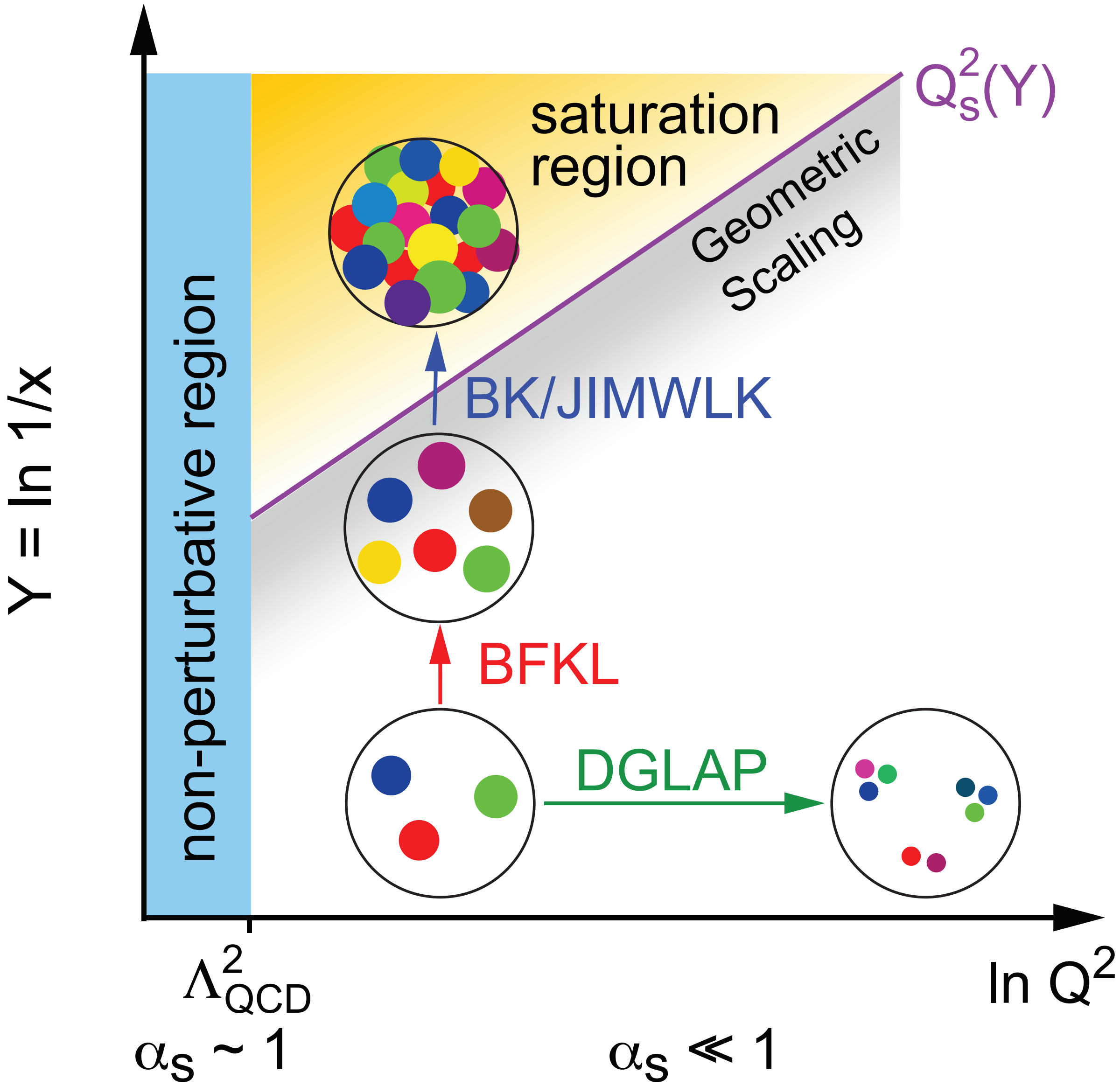
saturation?



- gluon distribution grows like a power at low x
- at some x: low density approximation invalid, patrons "overlap", recombination effects
- consequence: growth with 1/x slows down

already reached in UPCs at LHC? (saturation models describe data …)

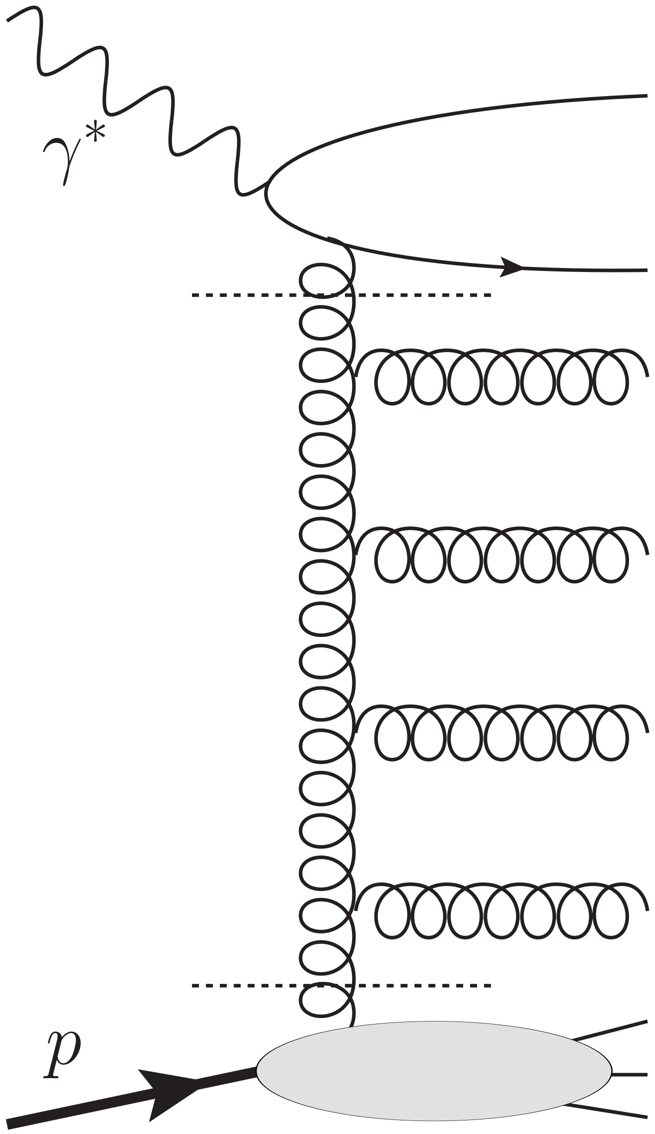
low x evolution (very schematic)



- BFKL:
  $\partial_{\ln 1/x} G(x, k) = K \otimes G$
- BK:
  $\partial_{\ln 1/x} G(x, k) = K \otimes G - G \otimes G$
- K: the BFKL kernel
  LL: [Fadin, Kuraev, Lipatov; PLB 60 (1975) 50], [Balitsky, Lipatov, SJNP (1978 822)]
  NLL: [Fadin, Lipatov; PLB 429 (1998) 127]; [Ciafaloni, Camici; PLB 430 (1998) 349]
- BFKL = low density limit of BK evolution

Question: Can BFKL evolve 'HERA gluon' to LHC values and describe UPC data on VM production or do already require non-linear effects?

The underlying NLO BFKL fit



$$F_2(x,Q^2) = \int_0^\infty d\boldsymbol{k}^2 \int_0^\infty \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2} \Phi_2\left(\frac{\boldsymbol{k}^2}{Q^2}\right) \mathcal{F}^{\text{DIS}}_{\text{BFKL}}(x,\boldsymbol{k}^2,\boldsymbol{q}^2)\Phi_p\left(\frac{\boldsymbol{q}^2}{Q_0^2}\right)$$

virtual photon: quarks mass-less, $n_f = 4$ fixed

proton impact factor: $\Phi_p\left(\frac{\boldsymbol{q}^2}{Q_0^2},\delta\right) = \frac{\mathcal{C}}{\pi\Gamma(\delta)}\left(\frac{\boldsymbol{q}^2}{Q_0^2}\right)^\delta e^{-\frac{\boldsymbol{q}^2}{Q_0^2}}$

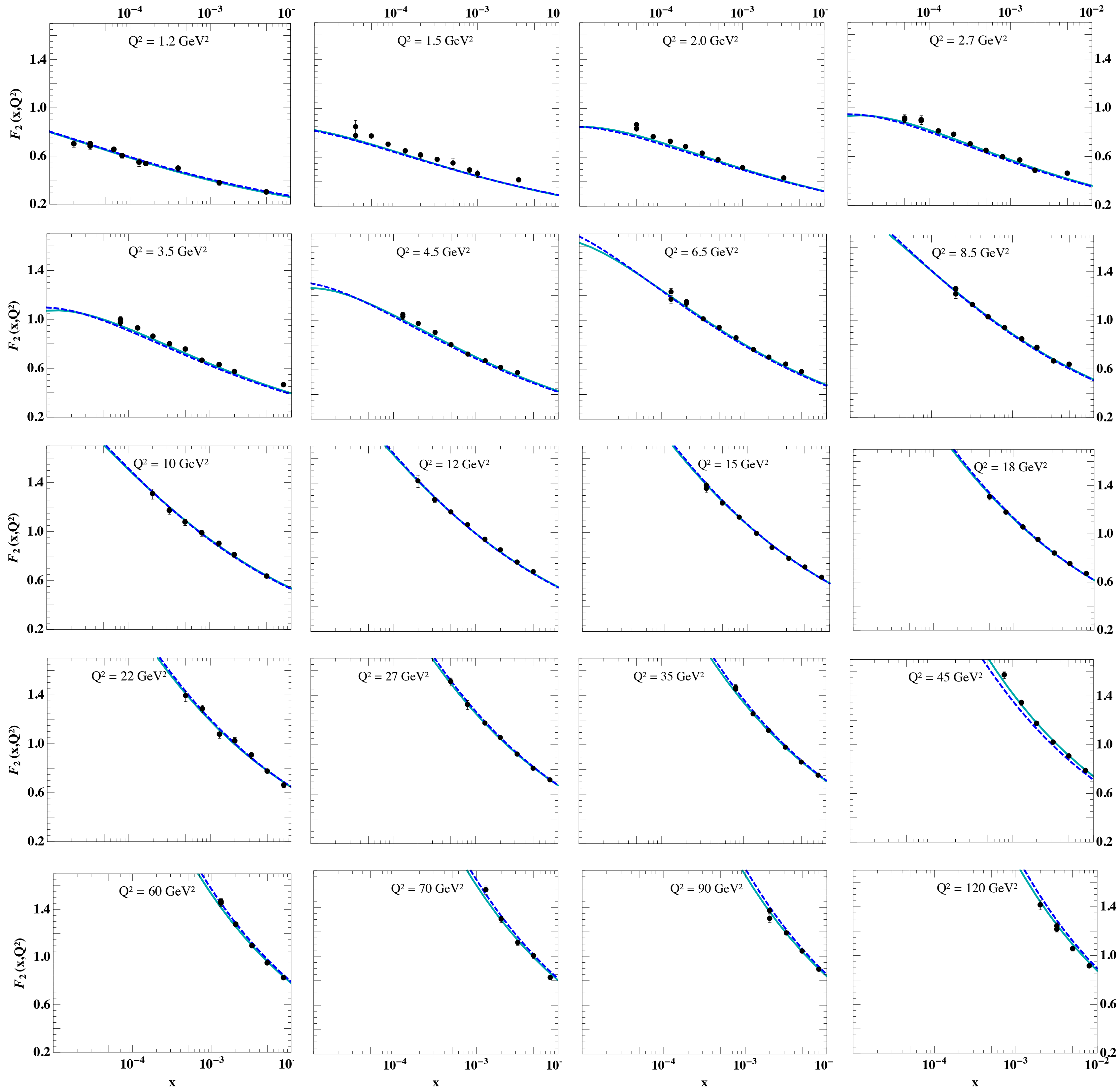
free parameters of proton impact factor from fit to combined HERA data [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]

→ allows for definition of unintegrated gluon density
[Chachamis, Deak, MH, Rodrigo, Sabio Vera; 1507.05778]

$$G(x,\boldsymbol{k}^2,Q_0^2) = \int \frac{d\boldsymbol{q}^2}{\boldsymbol{q}^2}\mathcal{F}^{\text{DIS}}_{\text{BFKL}}(x,\boldsymbol{k}^2,\boldsymbol{q}^2)\Phi_p\left(\frac{\boldsymbol{q}^2}{Q_0^2}\right)$$

	virt. photon impact factor	Q_0/GeV	δ	$\mathcal{C}$	Λ_{QCD}/ GeV
fit 1	leading order (LO)	0.28	8.4	1.50	0.21
fit 2	LO with kinematic improvements	0.28	6.5	2.35	0.21

Good description of cominbed HERA [H1 & ZEUS collab. 0911.0884]



idea:
use BFKL HERA fit & apply it to UPC data

task: relate **exclusive** photoproduction to **inclusive** gluon distribution (*use DGLAP procedure*)

The framework of this BFKL study

procedure:

a) calculate diff. Xsec. at $t = 0$

→ *exclusive* scattering amplitude can be expressed through *inclusive* gluon distribution

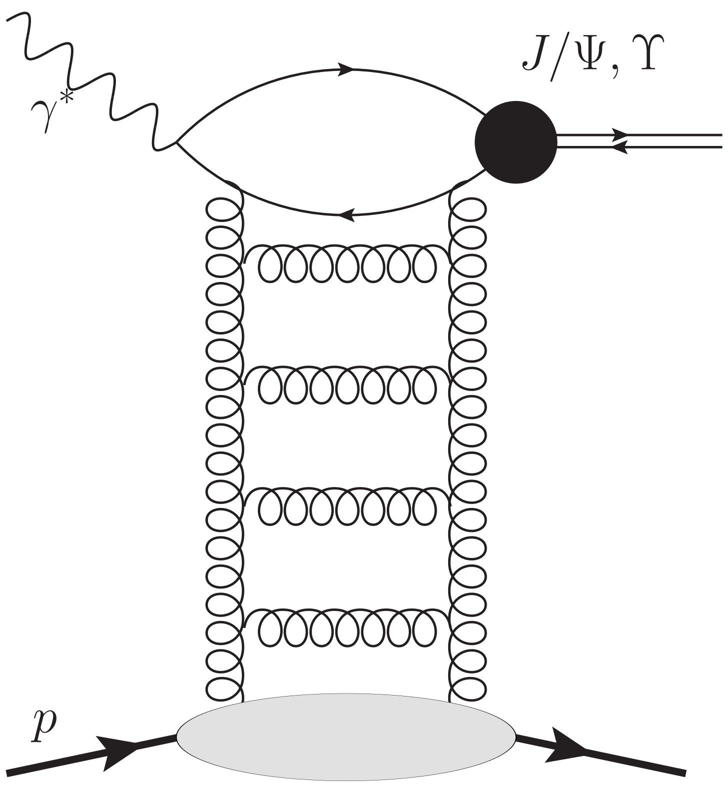
b) parametrize t dependence $\frac{d\sigma(t)}{dt} = \frac{d\sigma(t=0)}{dt} \cdot e^{-|t|B_D(W)}$,

slope $B_D(W) = b_0 + 4\alpha' \ln \frac{W}{W_0}$ + fix parameters by (HERA) data (here: values proposed by [Jones, Martin, Ryskin, Teubner; 1307.7099, 1312.6795])

→ cross-section: $\sigma^{\gamma p \to Vp}(W) = \underbrace{\frac{1}{B_D(W)}}_{\text{phenomenological}} \underbrace{\frac{d\sigma^{\gamma p \to Vp}}{dt}\Big|_{t=0}}_{\text{BFKL / theory}}$

relate 2 pictures of the BFKL Pomeron

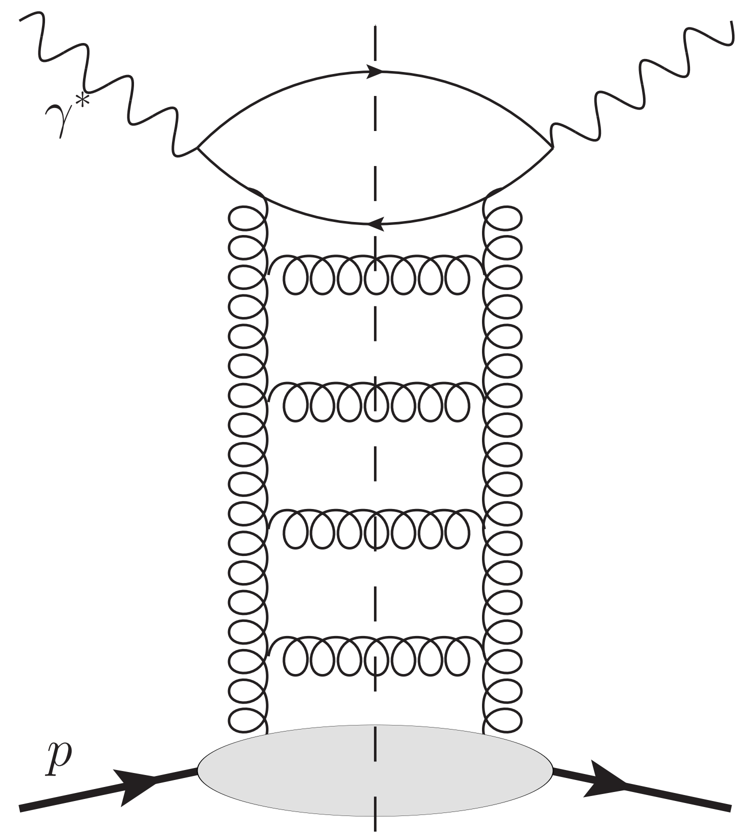
a) exclusive photo-production of vector mesons:



'uncut' Pomeron: diffractive/elastic scattering (amplitude level)

$$\mathcal{A}(s,t)$$

b) proton structure functions:



'cut' Pomeron: high multiplicity events (total X-sec.)

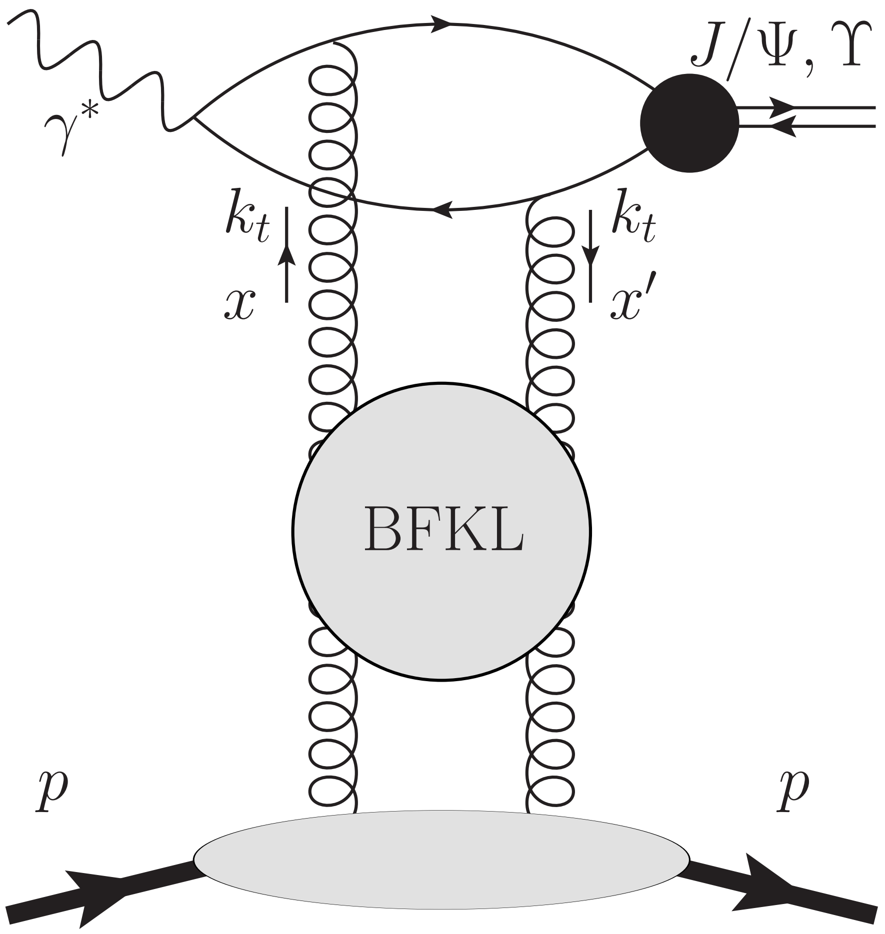
$$\sigma_{\text{tot}} = \frac{1}{s}\Im\text{m}\mathcal{A}(s, t = 0)$$

The setup: diff. Xsec. at $t = 0$

a) imaginary part of scattering amplitude:

- unintegrated gluon density from NLO BFKL fit to combined HERA data [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]
- impact factor $\gamma \to J/\Psi, \Upsilon$ from light-front wave function used in dipole model studies

  [Kowalski, Motyka, Watt; hep-ph/0606272]



b) real part:

- $\Im\mathrm{m}\mathcal{A}(W^2, t)$ dominant, real part can be numerically large

  ⟶ recover real part using dispersion relation

Vector mesons & dipole models ...

factorization into light-front wave function & dipole amplitude

e.g. [Kowalski, Motyka, Watt; hep-ph/0606272]

$$\Im\mathrm{m}\mathcal{A}_{T,L}^{\gamma^* p \to V p}(W, t=0) = 2\int d^2\boldsymbol{r}\int d^2\boldsymbol{b}\int_0^1 \frac{dz}{4\pi}\,(\Psi_V^*\Psi)_{T,L}\,\mathcal{N}(x,r,b)\,,$$

light-front wave function overlap

$$(\Psi_V^*\Psi)_T = \frac{\hat{e}_f e N_c}{\pi z(1-z)}\left\{m_f^2 K_0(m_f r)\phi_T(r,z) - \left[z^2+(1-z)^2\right] m_f K_1(m_f r)\partial_r\phi_T(r,z)\right\}$$

scalar parts of VM wave function: boosted Gaussian wave-functions with Brodsky-Huang-Lepage prescription

$$\phi_T^{1s}(r,z) = \mathcal{N}_T z(1-z)\exp\left(-\frac{m_f^2\mathcal{R}_{1s}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}_{1s}^2} + \frac{m_f^2\mathcal{R}_{1s}^2}{2}\right).$$

free parameters fixed through normalization condition & leptonic decay width $\Gamma_{e^-e^+}$:

Meson	m_f/GeV	$\mathcal{N}_T$	$\mathcal{R}^2$/GeV^{-2}	M_V/GeV	$8\mathcal{R}^{-2}$/GeV^2	$\frac{1}{4}M_V^2$/GeV^2
J/ψ	$m_c = 1.27$	0.596	2.45	3.097	3.27	2.40
Υ	$m_b = 4.2$	0.481	0.57	9.460	15.38	22.42

use parameters obtained by [Armesto, Rezaeian; 1402.4831], [Goncalves, Moreira, Navarra; 1408.1344]

From wave functions to impact factors

BFKL study requires impact factor in γ space $\Phi_{V,T}(\gamma)$:

$$\Im\mathrm{m}\mathcal{A}_T^{\gamma^* p \to V p}(W, t=0) = 2 \int d^2\boldsymbol{b} \int d^2\boldsymbol{r} \int_0^1 \frac{dz}{4\pi} \, (\Psi_V^* \Psi)_T(r) \; \cdot \sigma_0 N\,(x, r)$$

$$= \alpha_s(\overline{M} \cdot Q_0) \int\limits_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \int\limits_0^1 \frac{dz}{4\pi} \; \hat{g}\left(x, \frac{M^2}{Q_0^2}, \frac{\overline{M}^2}{M^2}, Q_0, \gamma\right) \cdot \Phi_{V,T}(\gamma, z, M) \cdot \left(\frac{M^2}{Q_0^2}\right)^\gamma$$

can be derived using relation dipole $\leftrightarrow$ unintegrated gluon *e.g.* **[Kutak, Stasto; hep-ph/040811]**

$$2 \int d^2\boldsymbol{b} \mathcal{N}(x, r, b) = \frac{4\pi}{N_c} \int \frac{d^2\boldsymbol{k}}{\boldsymbol{k}^2} \left(1 - e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\right) \alpha_s G(x, \boldsymbol{k}^2) \,.$$

yields

$$\Phi_{V,T}(\gamma, z, M) = e\hat{e}_f 8\pi^2 \mathcal{N}_T \frac{\Gamma(\gamma)\Gamma(1-\gamma)}{m_f^2} \left(\frac{m_f^2 \mathcal{R}^2}{8z(1-z)}\right)^2 e^{-\frac{m_f^2\mathcal{R}^2}{8z(1-z)}} e^{\frac{m_f \mathcal{R}^2}{2}} \left(\frac{8z(1-z)}{M^2\mathcal{R}^2}\right)^\gamma$$

$$\left[U\left(2-\gamma, 1, \frac{m_f^2\mathcal{R}^2}{8z(1-z)}\right) + [z^2 + (1-z)^2]\frac{(2-\gamma)}{2} U\left(3-\gamma, 2, \frac{m_f^2\mathcal{R}^2}{8z(1-z)}\right)\right],$$

[$U(a, b, z)$ hypergeometric function of the second kind or Kummer's function]

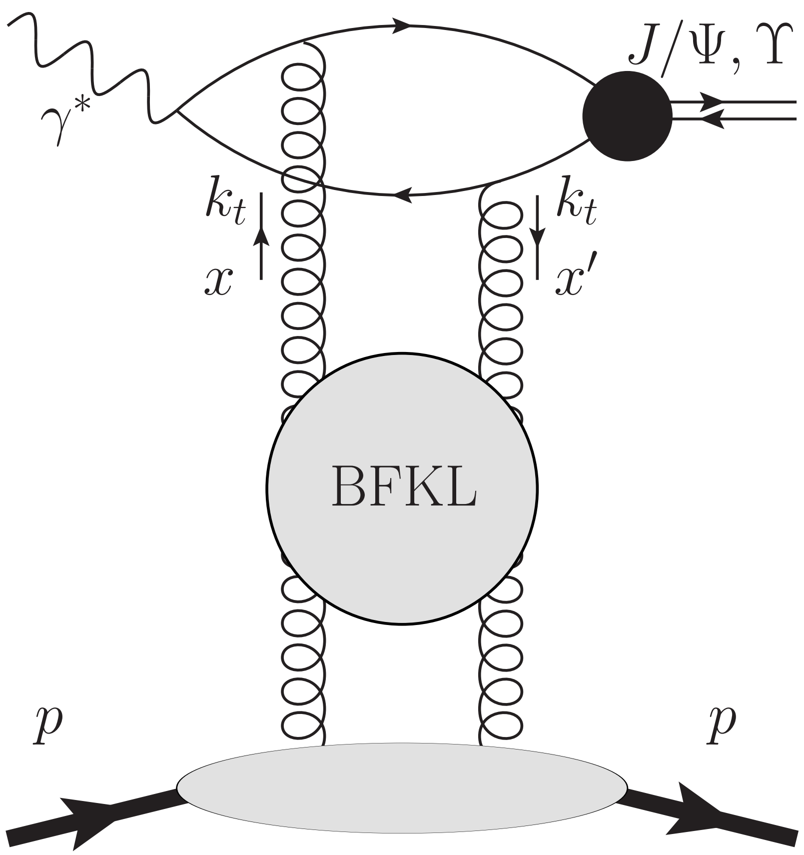
The setup: diff. Xsec. at $t = 0$

a) imaginary part of scattering amplitude:

- ✓ unintegrated gluon density from NLO BFKL fit to combined HERA data [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]
- ✓ impact factor $\gamma \to J/\Psi, \Upsilon$ from light-front wave function used in dipole model studies ....

b) real part:

- ✗ $\Im\mathrm{m}\mathcal{A}(W^2, t)$ dominant, real part can be numerically large
  ➡ recover **real part** using dispersion relation



- for $t = 0$ the (pseudo-)inclusive process fixes imaginary part of $\mathcal{A}(W^2, t = 0)$ of the exclusive process;
- Common approach: $\frac{\Re\text{e}\mathcal{A}(W^2, t)}{\Im\text{m}\mathcal{A}(W^2, t)} = \tan\frac{\lambda\pi}{2}$, with $\lambda = \frac{d\ln\mathcal{A}(W^2,t)}{d\ln W^2}$

  follows from analytic representation of scattering amplitudes of (scalar) particles in the Regge limit for positive signature
- Often: $\lambda =$ const. $\longrightarrow$ constant ratio of real & imaginary part

Real part from imaginary part

here: reconstruct real part through using representation in ω-Mellin space, conjugate to W^2:

$$\mathcal{A}(W^2, t) = \int_{\delta - i\infty}^{\delta + i\infty} \frac{d\omega}{2\pi i} \left(\frac{1}{x}\right)^{\omega} \left(i + \tan\frac{\omega\pi}{2}\right) a(\omega, t), \quad x = \frac{M_V^2}{W^2 - m_p^2}$$

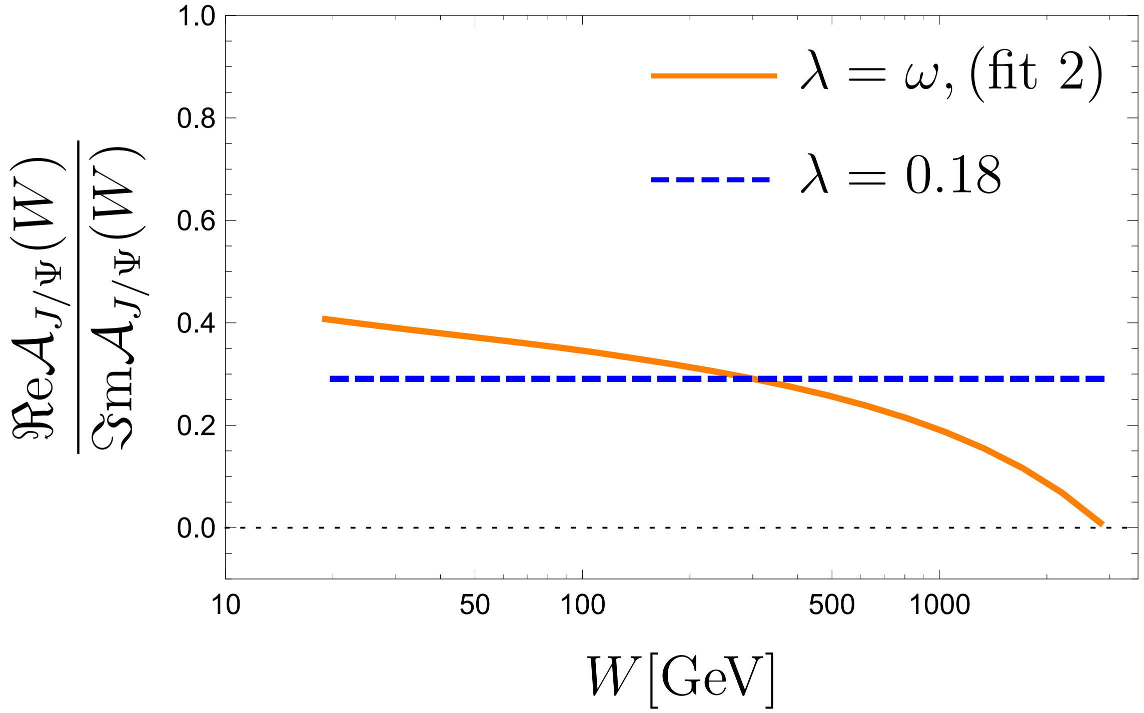
partial wave $a(\omega, t)$ can be fixed from imaginart part

$$a(\omega, 0) = \alpha_s \int_{\frac{1}{2} - i\infty}^{\frac{1}{2} + i\infty} \frac{d\gamma}{2\pi i} \left(\frac{M^2}{Q_0^2}\right)^{\gamma} \int_0^1 \frac{dz}{4\pi} \Phi_{V,T}(\gamma, z) \frac{\mathcal{C} \cdot \Gamma(\delta - \gamma)}{\pi \Gamma(\delta)} \cdot \left\{ \frac{1}{\omega - \chi\left(\gamma, \frac{\overline{M}^2}{M^2}\right)} \right.$$
$$\left. + \frac{\bar{\alpha}_s^2 \beta_0 \chi_0(\gamma)/(8N_c)}{\left[\omega - \chi\left(\gamma, \frac{\overline{M}^2}{M^2}\right)\right]^2} \left[-\psi(\delta - \gamma) - \frac{d \ln\left[\Phi_{V,T}(\gamma, z)\right]}{d\gamma} \right] \right\}$$

yields *energy dependent* ratio of real & imaginary part

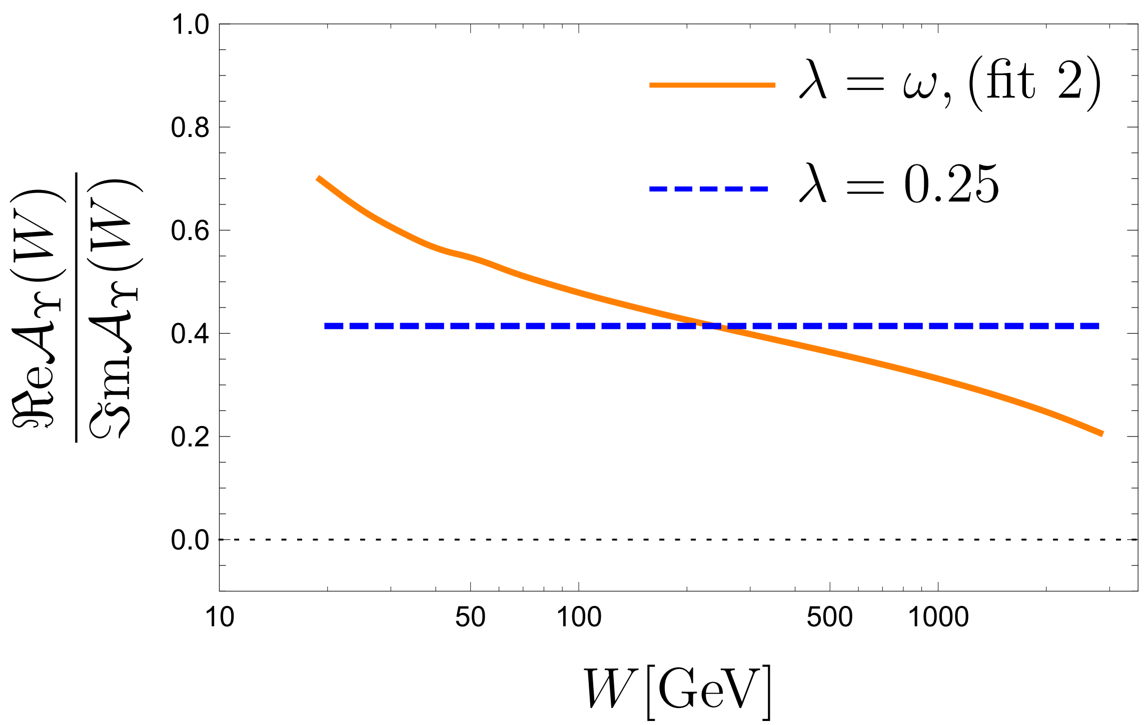
energy dependence of $r(W) = \Re\mathrm{e}\mathcal{A}/\Im\mathrm{m}\mathcal{A}$

J/Ψ:



ratio decreases with energy

Υ:



sizeable effect on overall energy dependence

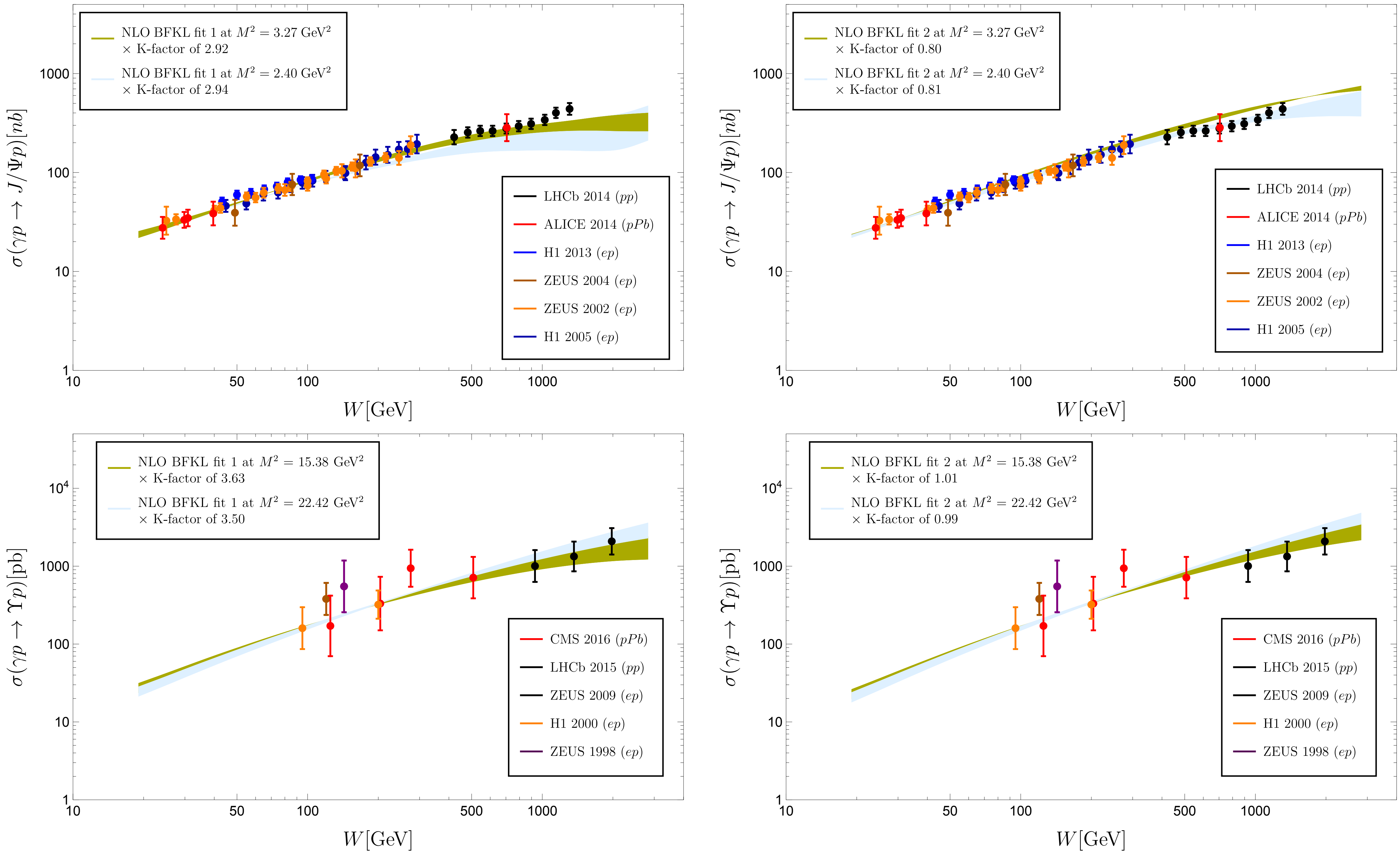
$\rightarrow$ slows down the growth

Comparison to data

- provide results for both HERA fits (standard (fit 1) & kinematic improved (fit 2) LO impact factor)
- hard scale M^2:
  - photoproduction scale $M_{\text{pp}} = M_V/2$

    $$\left(M_{\text{pp}}^2\right)_{J/\Psi} = 2.40 \text{ GeV}^2$$
    $$\left(M_{\text{pp}}^2\right)_{\Upsilon} = 22.42 \text{ GeV}^2$$
  - impact factor motivated: $M_{\text{if}}^2 = 8\mathcal{R}_V^{-2}$ – eliminates $(...)^\gamma$ factor & minimizes NLO running coupling correction related to impact factor

    $$\left(M_{\text{if}}^2\right)_{J/\Psi} = 3.27 \text{ GeV}^2$$
    $$\left(M_{\text{if}}^2\right)_{J/\Psi} = 15.38 \text{ GeV}^2$$
- (hard) running coupling scale $\overline{M} = M$, but vary in range $[M^2/2, M^2 \cdot 2]$ to check stability of result
- fix normalization by low energy ALICE (J/Ψ) and H1 (Υ) data point $\to$ K-factor


NLO BFKL fit 1 at $M^2 = 3.27$ GeV^2 × K-factor of 2.92
NLO BFKL fit 1 at $M^2 = 2.40$ GeV^2 × K-factor of 2.94
LHCb 2014 (pp)
ALICE 2014 (pPb)
H1 2013 (ep)
ZEUS 2004 (ep)
ZEUS 2002 (ep)
H1 2005 (ep)
$\sigma(\gamma p \to J/\Psi p)[nb]$
W[GeV]
NLO BFKL fit 2 at $M^2 = 3.27$ GeV^2 × K-factor of 0.80
NLO BFKL fit 2 at $M^2 = 2.40$ GeV^2 × K-factor of 0.81
NLO BFKL fit 1 at $M^2 = 15.38$ GeV^2 × K-factor of 3.63
NLO BFKL fit 1 at $M^2 = 22.42$ GeV^2 × K-factor of 3.50
CMS 2016 (pPb)
LHCb 2015 (pp)
ZEUS 2009 (ep)
H1 2000 (ep)
ZEUS 1998 (ep)
$\sigma(\gamma p \to \Upsilon p)$[pb]
NLO BFKL fit 2 at $M^2 = 15.38$ GeV^2 × K-factor of 1.01
NLO BFKL fit 2 at $M^2 = 22.42$ GeV^2 × K-factor of 0.99

Caveats ....

- both BFKL HERA fit & VM photoproduction use LO impact factor
  $\longrightarrow$ large corrections at NLO possible
- BFKL HERA fit for $n_f = 4$ mass-less quarks

both effects should affect the normalization, not so much W-dependence

- unintegrated gluon density can develop instability at ultra-small x:

$$G\left(x, \boldsymbol{k}^2, M\right) = \frac{1}{\boldsymbol{k}^2} \int\limits_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \; \hat{g}\left(x, \gamma\right) \; \left(\frac{\boldsymbol{k}^2}{Q_0^2}\right)^{\gamma}$$

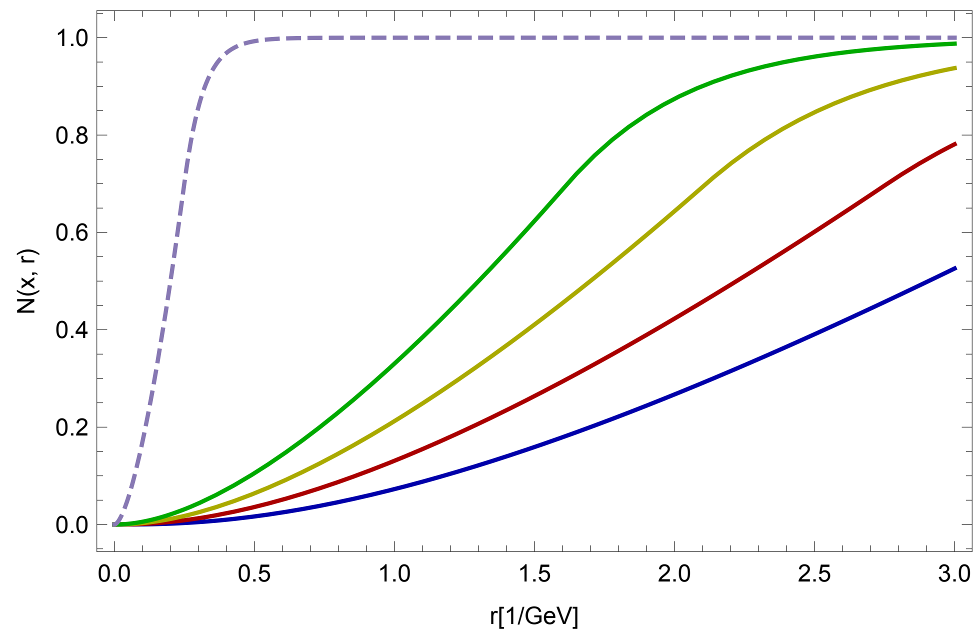
$$\hat{g}(x,\gamma) \sim \left(\frac{1}{x}\right)^{\chi\left(\gamma, \frac{\overline{M}^2}{M^2}\right)} \cdot \left\{1 + \frac{\bar{\alpha}_s^2 \beta_0 \chi_0\left(\gamma\right)}{8N_c} \log\left(\frac{1}{x}\right)\left[-\psi\left(\delta-\gamma\right) + \log\frac{M^2}{Q_0^2} - \partial_\gamma\right]\right\},$$

- will enter at some point region $\alpha_s^2 \ln(1/x) \sim 1$ $\longrightarrow$ control of such terms will become necessary

instead of conclusions: final considerations

- the given description is the most straight-forward: take HERA fit, calculate necessary impact factor/coefficient, evolve to lower x $\rightarrow$ works very good without tuning etc.
- Question: do we hide on-set of saturation in the linear NLO term? Answer: We don’t know
- Way out 1: re-fit HERA data with BFKL Green’s function which provides eternal growth (if possible) and see what happens ….
- Way out 2: Look at different observables …

inclusive DIS, exclusive photo-production: ~ to N(x,r,b) (dipole amplitude= prob. to scatter with proton gluon field)



$$\Im\mathbf{m}\mathcal{A}_{T,L}^{\gamma^* p\to Vp}(W,t=0) = 2\int d^2\boldsymbol{r}\int d^2\boldsymbol{b}\int_0^1 \frac{dz}{4\pi}\,(\Psi_V^*\Psi)_{T,L}\,\mathcal{N}(x,r,b)$$

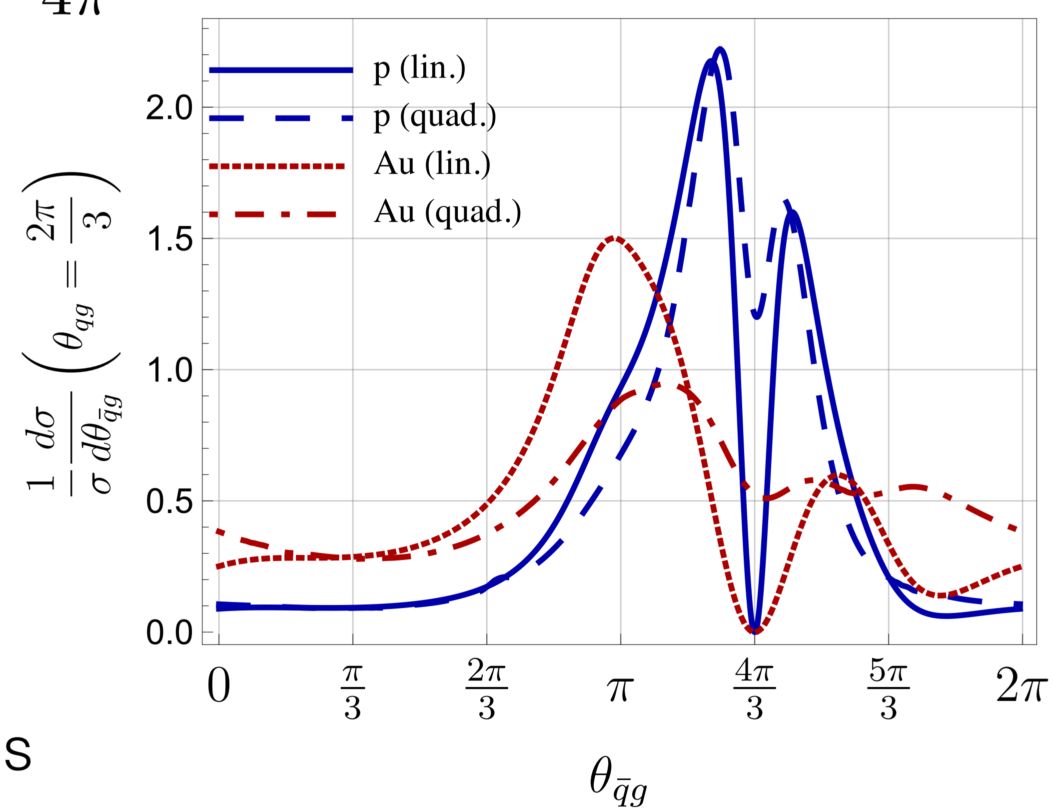
recent theory study:

[Ayala, MH, Jalilian-Marian, Tejeda-Yeomans, arXiv:1604.08526]

3 parton production in DIS

involves higher correlators
→ in Gaussian approximation as function of N(x,r) + expand $O(N^2)$

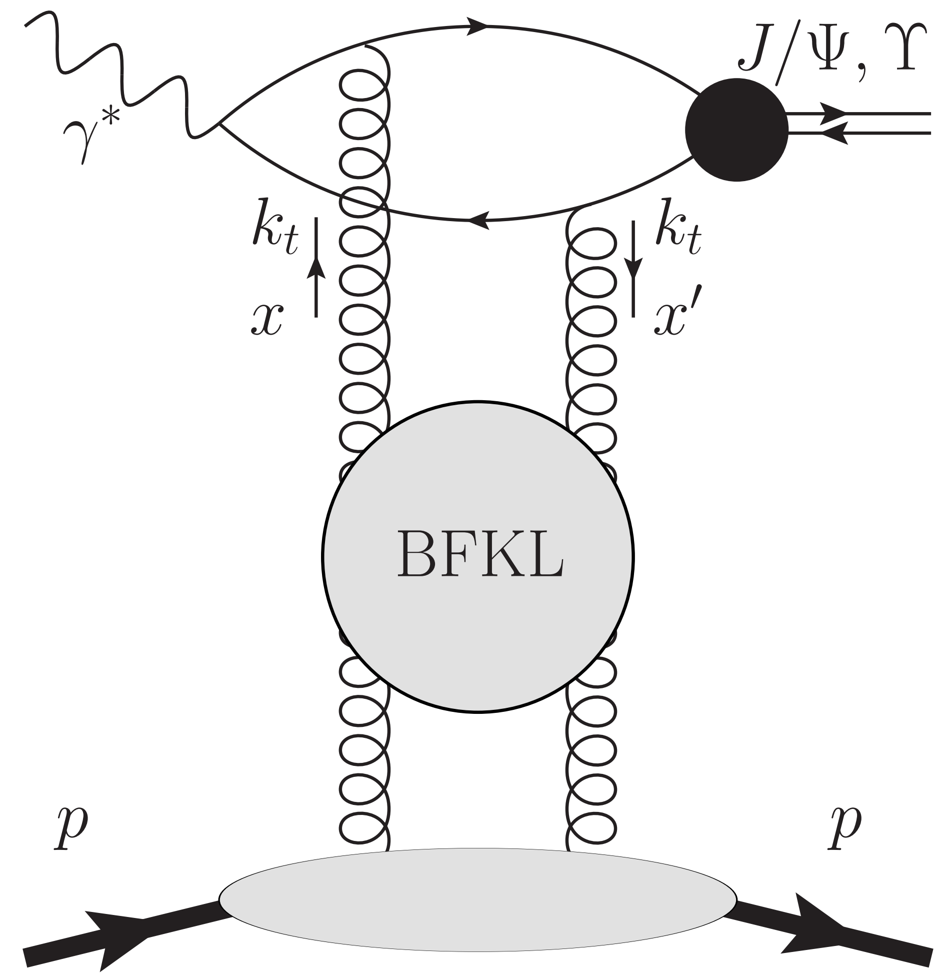
there are potential similar processes in UPCs
→ need to explore, can be measured? …



extra slides

Observations:

- K-factor: small for fit 2, sizeable for fit 1 – likely related to the impact factors in used in the HERA fit (massless, $n_f = 4$, $(\mathcal{C}_1/\mathcal{C}_2)^2 = 2.45$)
- common correction not included: GPD motivated factor to take into account $x' \neq x$; currently calculated for collinear pdf [Shuvaev, Golec-Biernat, Martin, Ryskin, hep-ph/9902410] ➞ to be calculated for k_T factorized BFKL impact factor



very good description of W-dependence

$W_{J/\Psi} > 471$ GeV & $W_\Upsilon > 669$ GeV $\equiv$ beyond region of incl. HERA fit (from $x = 4.3 \cdot 10^{-5}$ to $x = 3.5 \cdot 10^{-6}$) ➞ direct test of BFKL evolution

Existing description of data

... work pretty well

- J/Ψ: power-law fit to HERA data $\sigma \sim W^{0.67}$ [LHCb Collaboration; 1401.3288]
- collinear factorization: NLO fits [Jones, Martin, Ryskin, Teubner; 1307.7099]
- saturation models: IPsat, bCGC, rcBK

  [Armesto, Rezaeian; 1402.4831], [Goncalves, Moreira, Navarra; 1405.6977, 1408.1344]
- see also [Fiore, Jenkovszky, Libov, Machado; 1408.0530], [Cisek, Schäfer, Szczurek; 1405.2253]

BFKL special:
don't fit W -dependence, but calculate from perturbative low x evolution
don't evoke saturation ($=$ effects beyond BFKL)

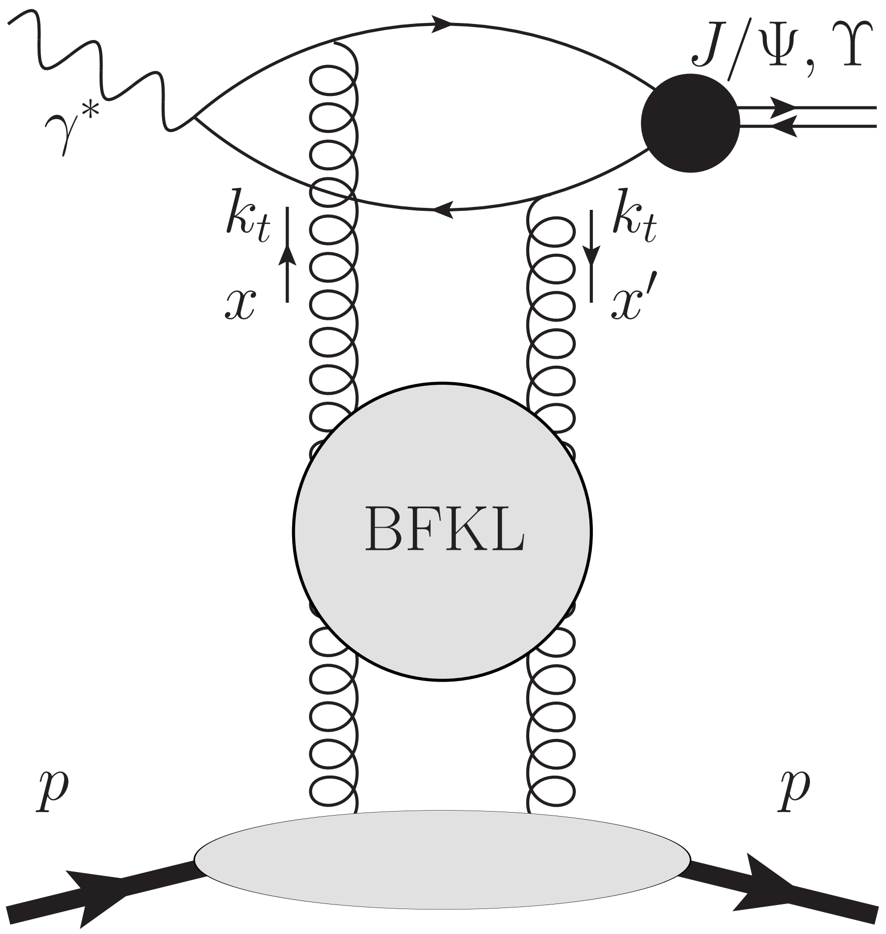
LHC: reach ultra-small x values $\simeq 4 \cdot 10^{-6}$ not constrained by HERA

The setup: diff. Xsec. at $t = 0$

a) imaginary part of scattering amplitude:

- unintegrated gluon density from NLO BFKL fit to combined HERA data [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]
- impact factor $\gamma \to J/\Psi, \Upsilon$ from light-front wave function used in dipole model studies

  [Kowalski, Motyka, Watt; hep-ph/0606272]



b) real part:

- $\Im\mathrm{m}\mathcal{A}(W^2, t)$ dominant, real part can be numerically large
  ⟶ recover real part using dispersion relation

The setup: diff. Xsec. at $t = 0$

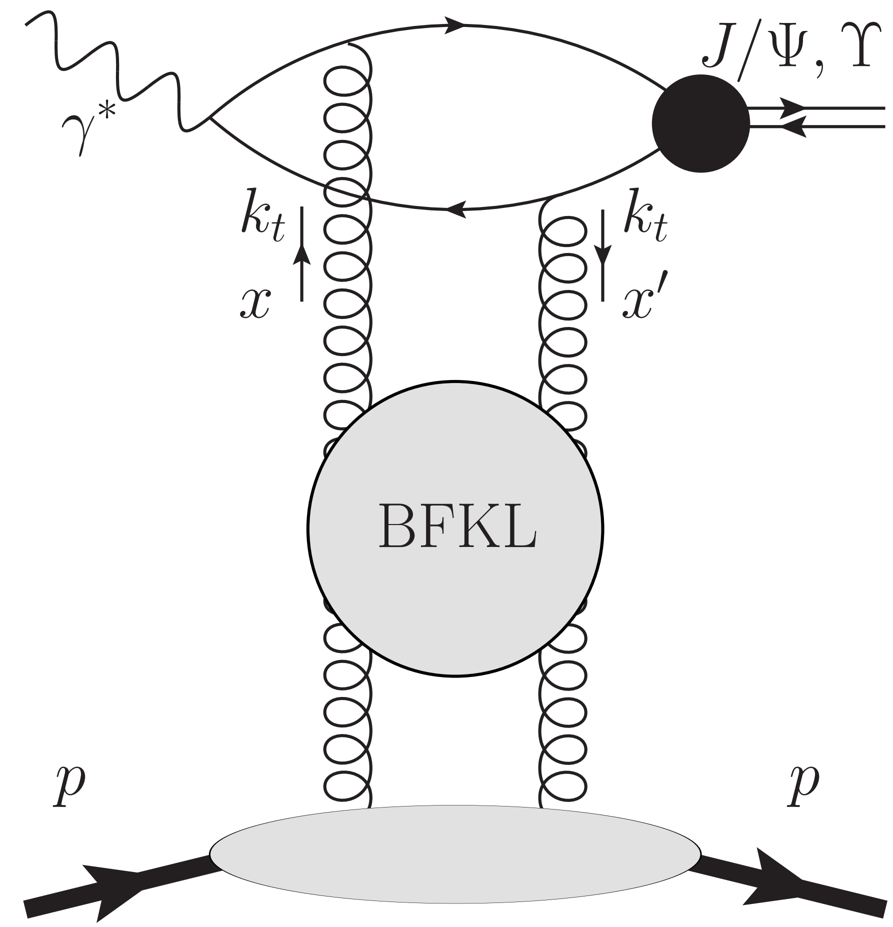
a) imaginary part of scattering amplitude:

calculate diff. Xsec. at $t = 0$

✓ unintegrated gluon density from NLO BFKL fit to combined HERA data [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]

✗ **impact factor** $\gamma \to J/\Psi, \Upsilon$ from light-front wave function used in dipole model studies ....

✗ ...



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  likely related to the impact factors used in the HERA fit
  (massless quarks, n_f=4, $(C_1/C_2)^2$=2.45)

- common “GPD” correction not included; known for collinear pdf, need to be re-calculated within high energy factorization

- very good description of W-dependence, going beyond HERA region