QCD low x evolution & the onset of gluon saturation in exclusive photo-production of vector mesons

Martin Hentschinski
Universidad de las Americas Puebla
Ex-Hacienda Santa Catarina Martir S/N
San Andrés Cholula
72820 Puebla, Mexico
martin.hentschinski@gmail.com

in collaboration with **Krzysztof Kutak** (IPN Cracow) and **Alfredo Arroyo Garcia** (UDLAP)

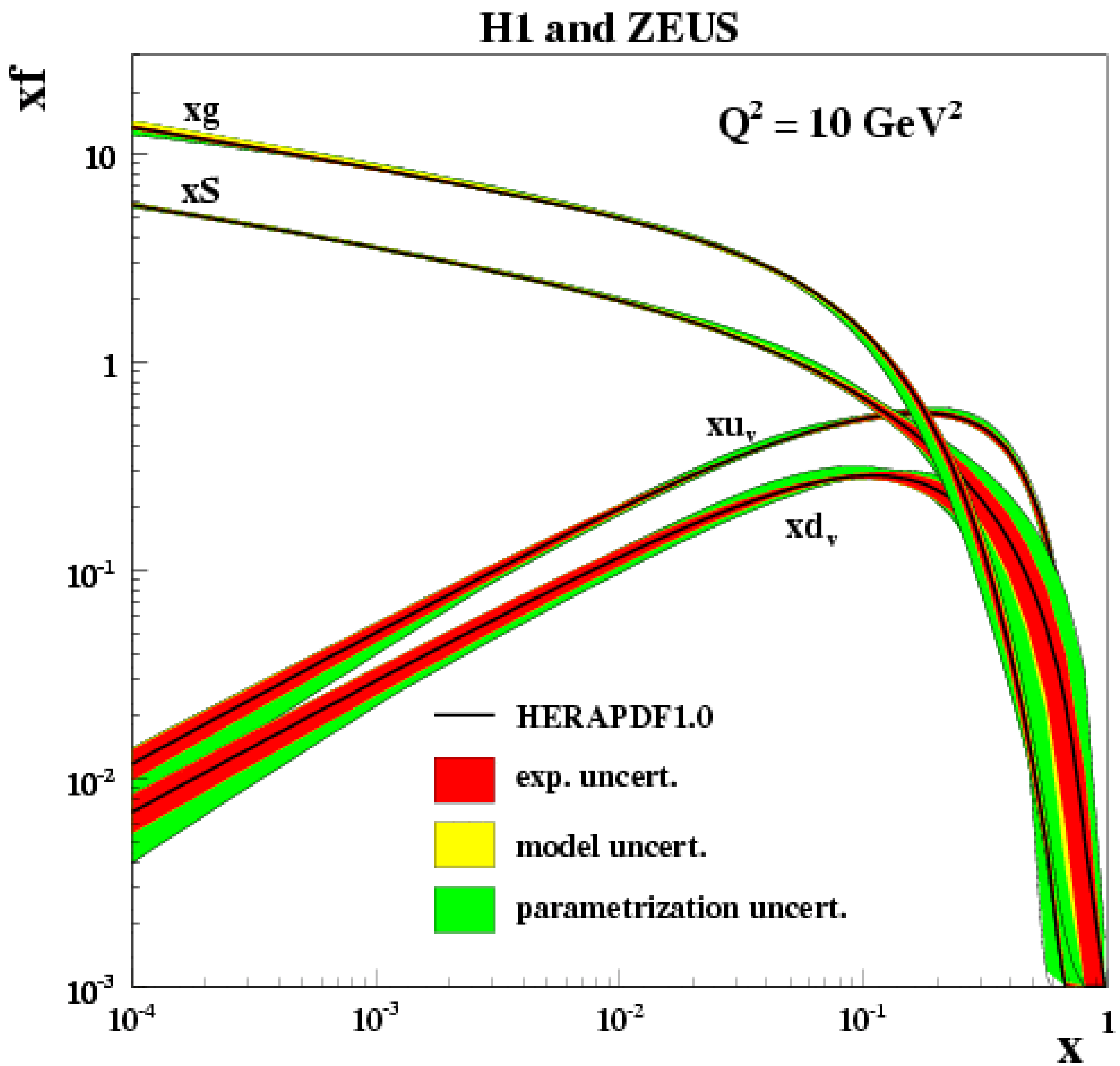
arXiv:1904.04394

LHCP 2019, May 20-25, Puebla, Mexico

UDLAP®

Experimental fact + theory prediction (BFKL):

[Fadin, Lipatov, Kuraev, PLB429 (1998) 127],
[Balitsky, Lipatov, Sov.J.Nucl.Phys. 28 (1978)]

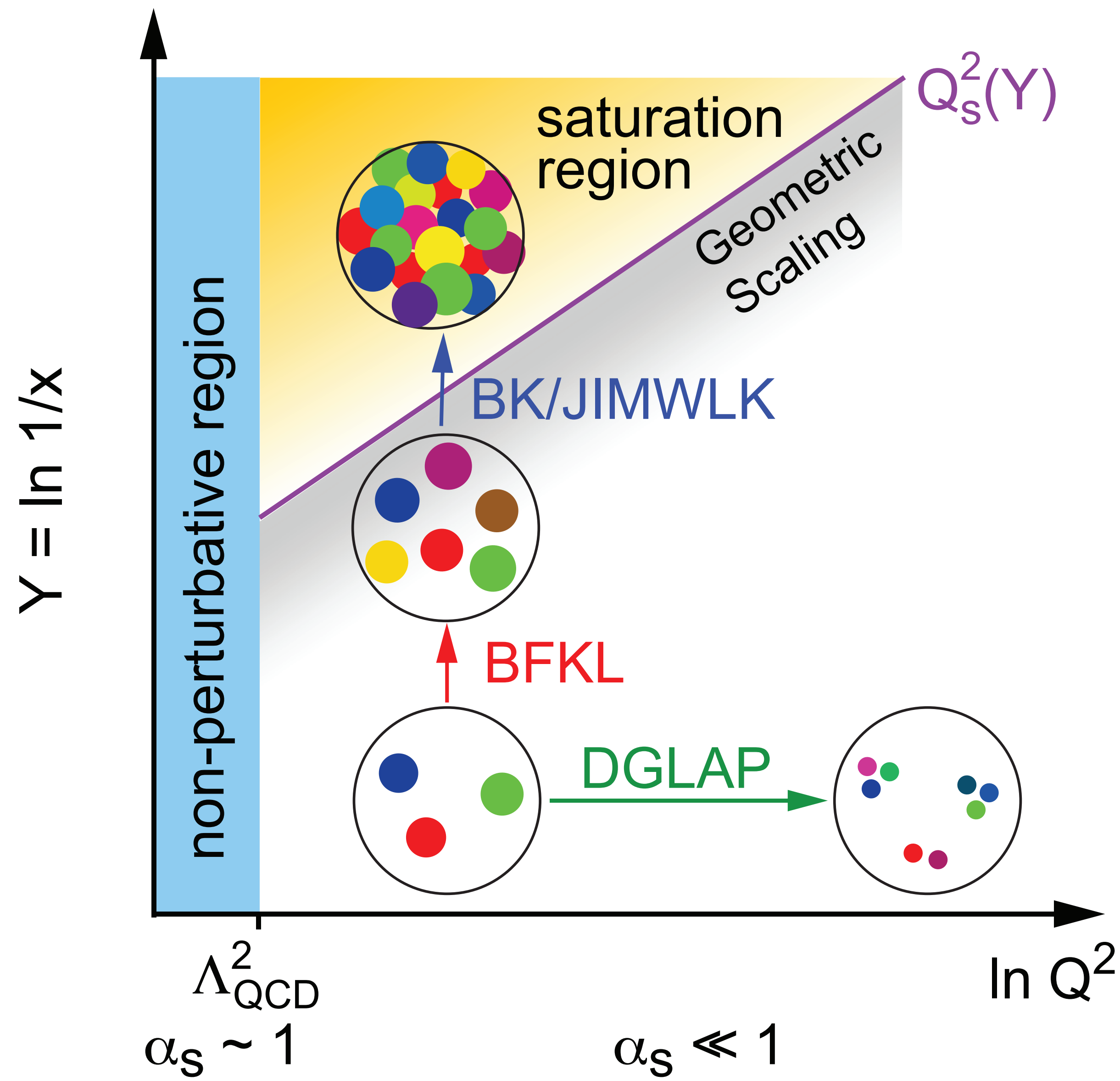


power like growth of the gluon distribution at low x

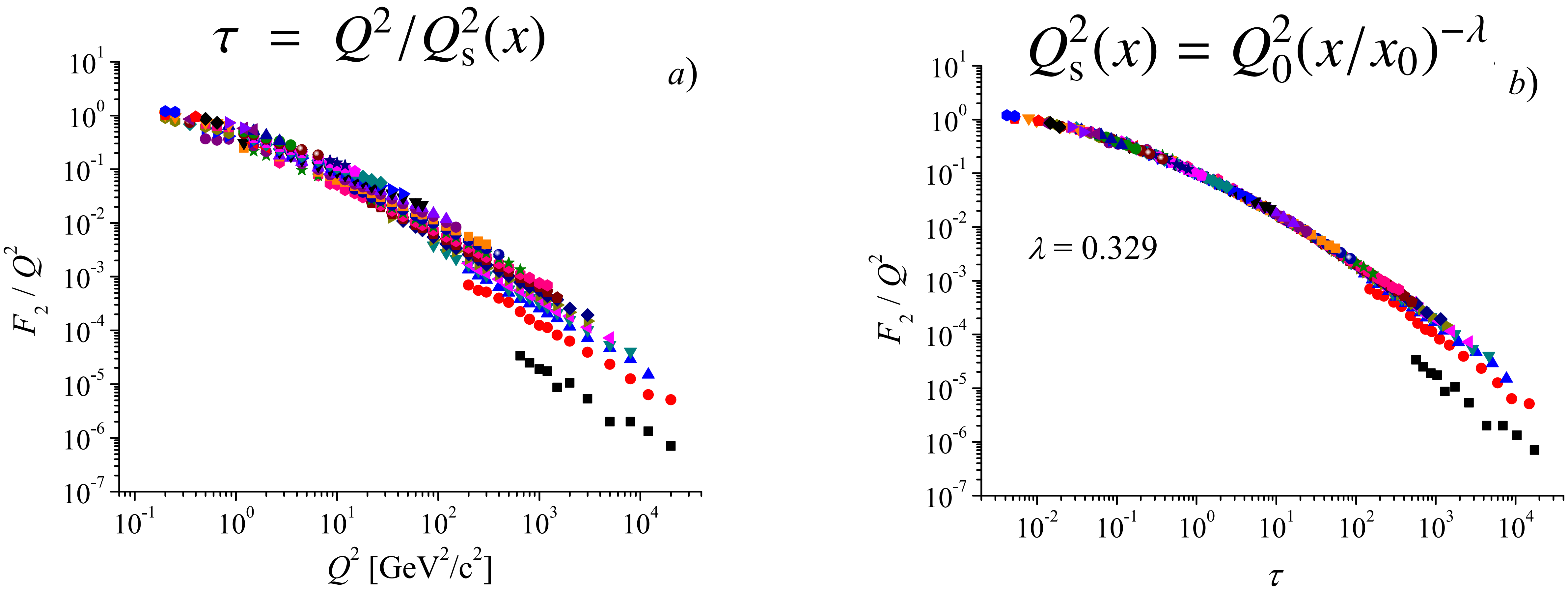
Saturation of gluon densities at low x

[Gribov, Levin & Ryskin Phys. Rept. 100 (1983)]
Color Glass Condensate effective theory: [McLerran, Venugopalan PRD 49 (1994) 3352]

- if continued forever, power like growth of violates unitarity bounds
- in the limit $x=Q^2/s \rightarrow 0$: copies production of gluons = high parton densities
- high densities slow down/stop growth of low x gluon: *saturation*



Phenomenological evidence: geometric scaling



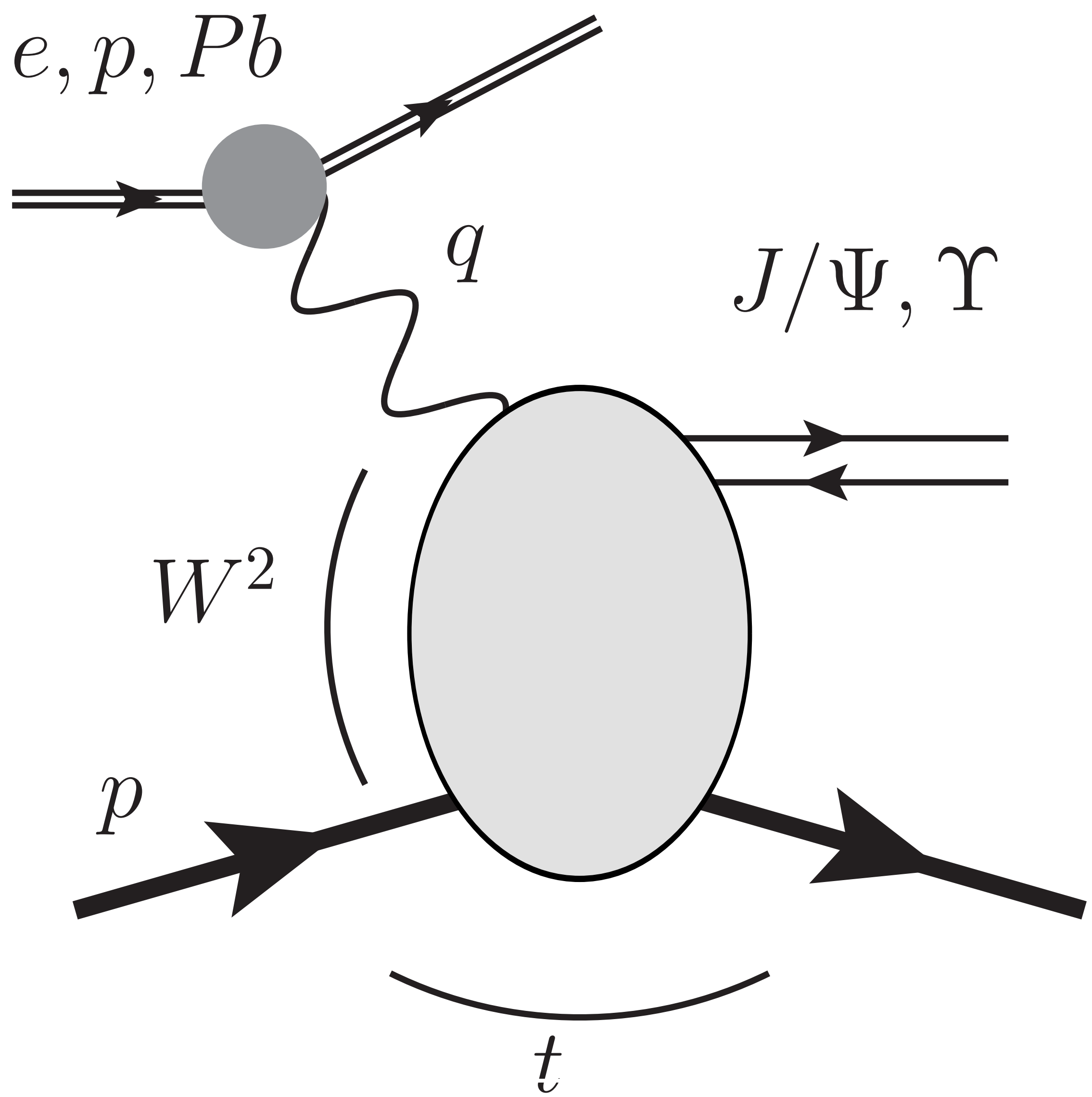
[Praszalowicz, Stebel, JHEP 1303, 090 (2013); JHEP 1304, 169 (2013)]

also:

- BK fits to low x data
- di-hadron de-correlation
- application to heavy ion collisions & high multiplicity events

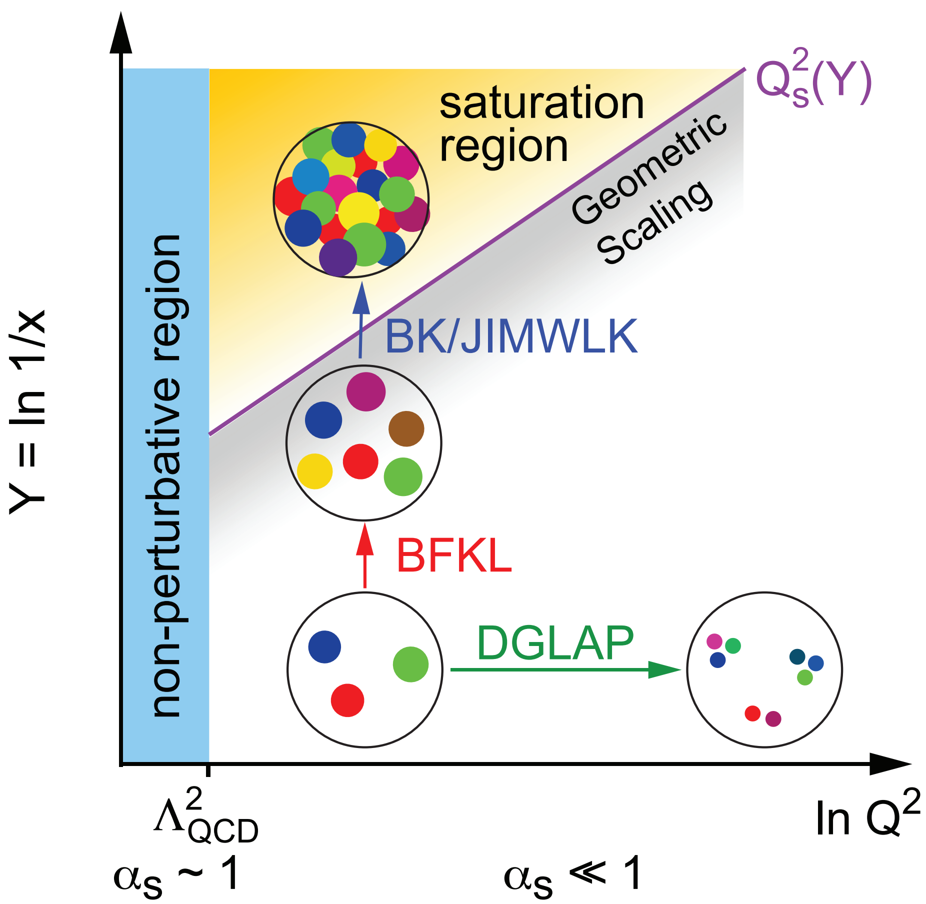
Can we see it in a more direct way? As a consequence of evolution?

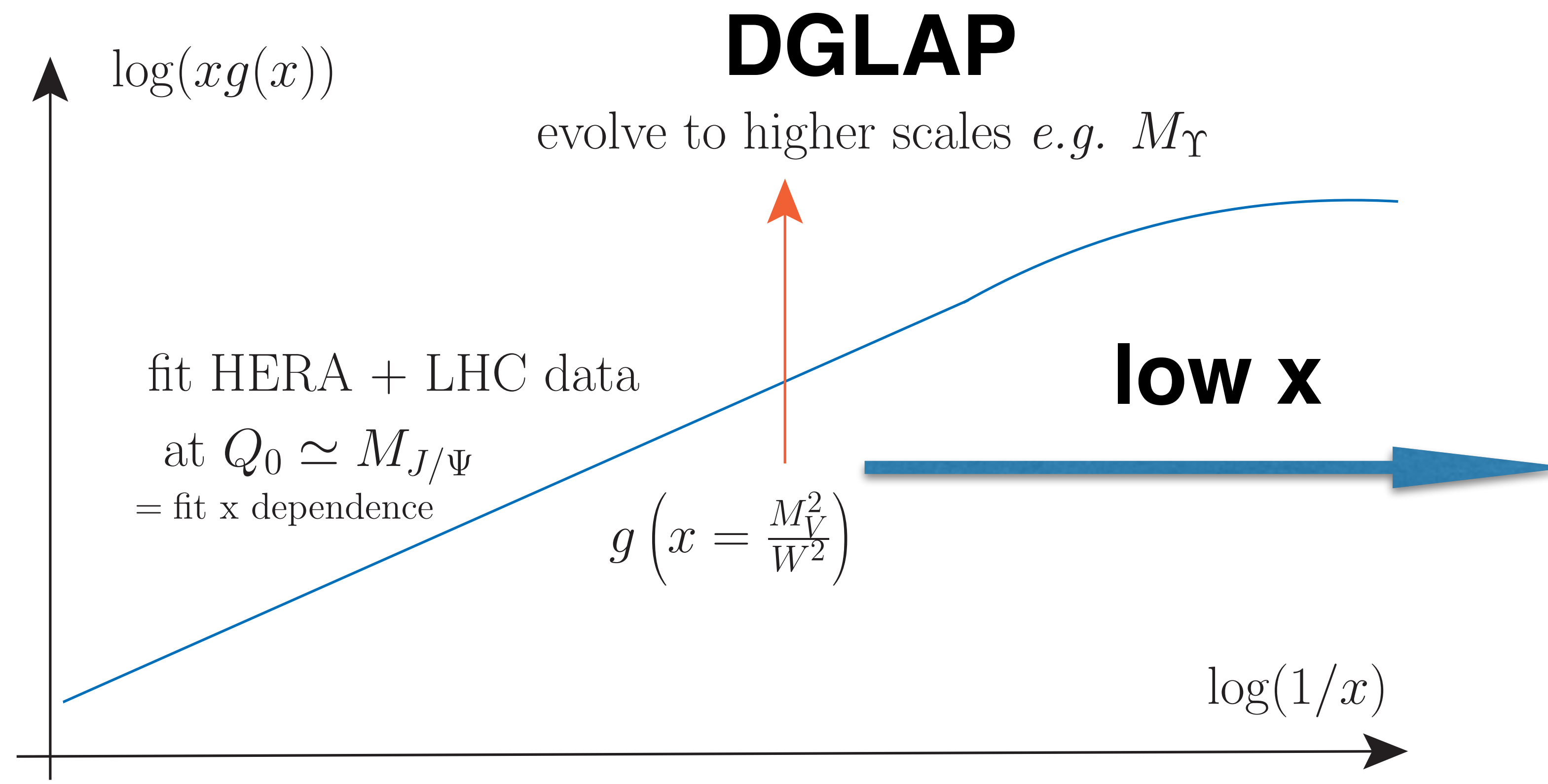
A process to explore the low x gluon at the LHC: exclusive photo-production of J/Ψs



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

schematic vs. reality

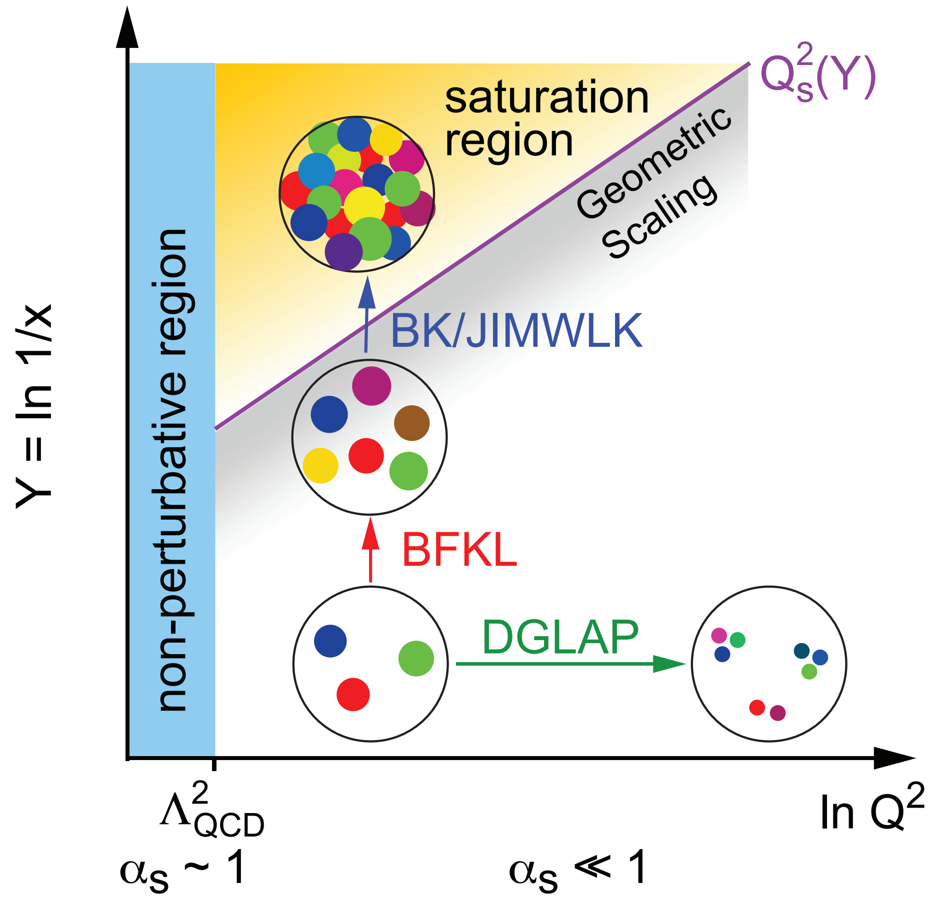




DGLAP:

- fit x-dependence + evolve from J/Ψ (2.4 GeV^2) to Υ (22.4 GeV^2)
- DGLAP shifts large x input (low scales) to low x (high scales) + higher twist dies away fast in evolution

→ constrain pdfs, but don't learn about saturation (easily overseen)



our study:

- instead of DGLAP vs low x
- linear low x (BFKL) vs. non-linear low x (BK)
- failure of BFKL = sign for BK
  → high & saturated gluon

details:

BK evolution for dipole amplitude $N(x,r) \in [0,1]$ [related to gluon distribution]

kernel calculated in pQCD

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

$$\frac{dN(x,r)}{d\ln\frac{1}{x}} = \int d^2\boldsymbol{r}_1 K(\boldsymbol{r},\boldsymbol{r}_1)\left[N(x,r_1)+N(x,r_2)-N(x,r) - N(x,r_1)N(x,r_2)\right]$$

linear BFKL evolution = subset of complete BK linear low x evolution as benchmark →requires precision

use: HSS NLO BFKL fit [MH, Salas, Sabio Vera; 1209.1353; 1301.5283]

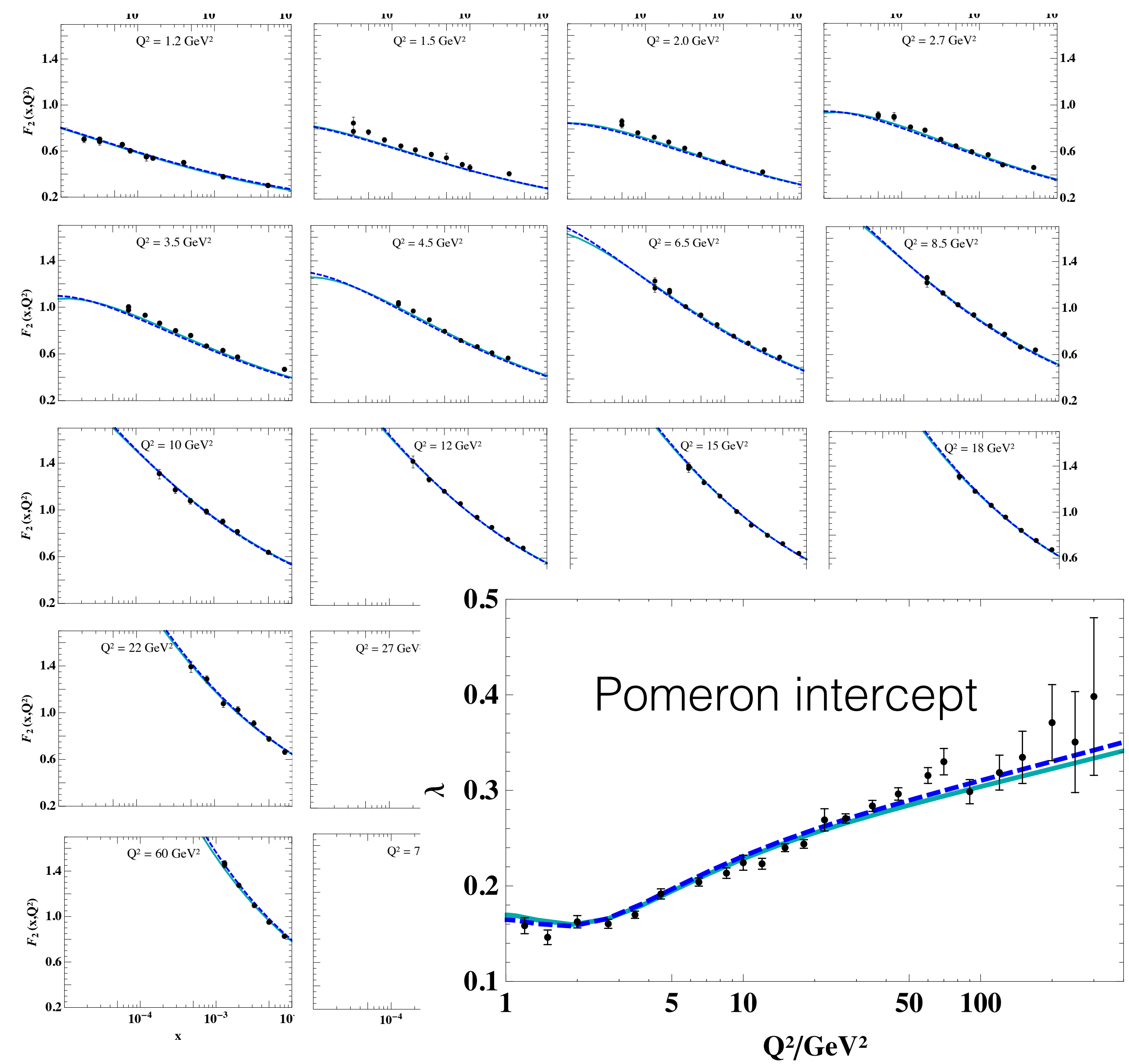
- uses NLO BFKL kernel

  [Fadin, Lipatov; PLB 429 (1998) 127]

  + resummation of collinear logarithms

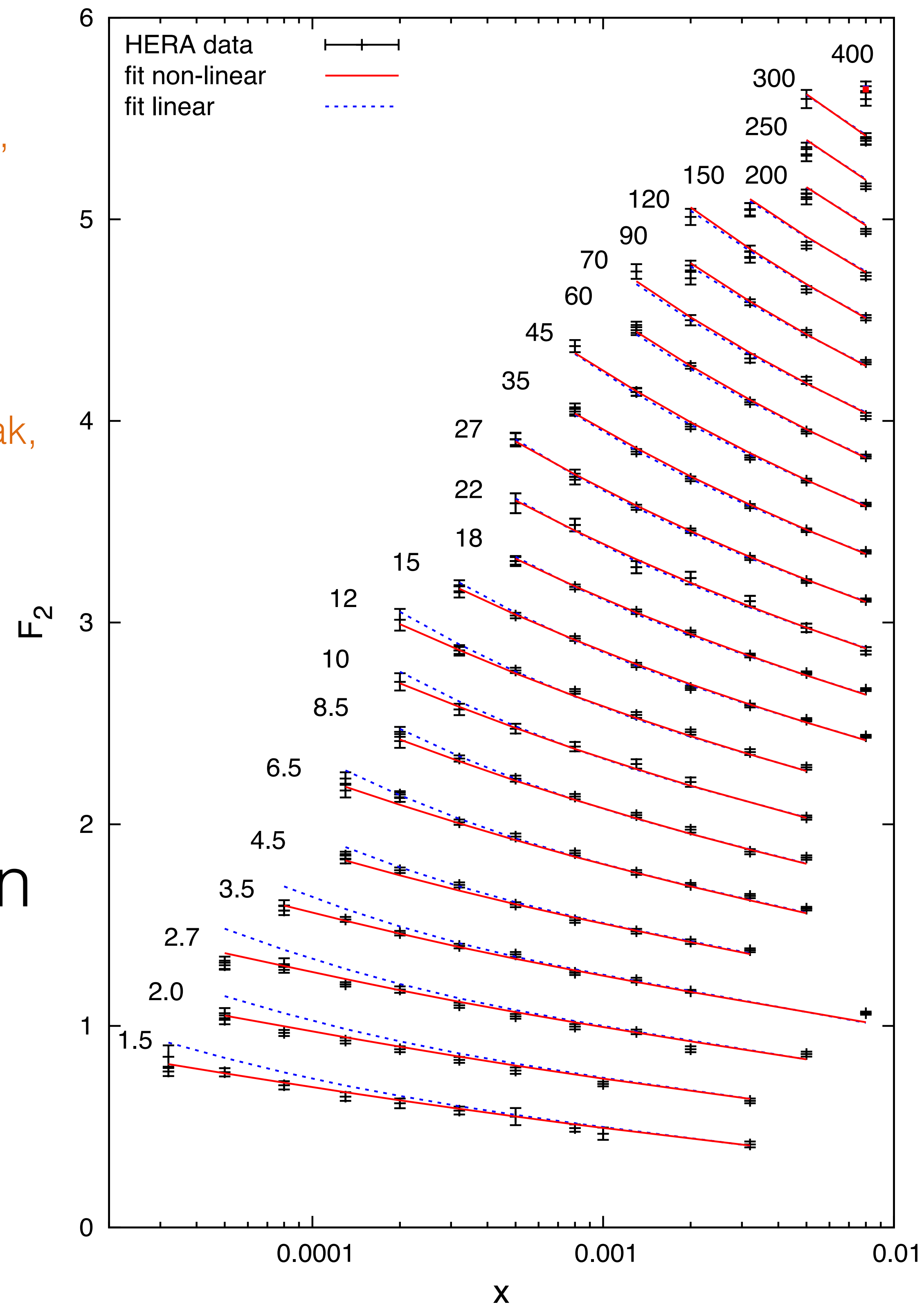
- initial kT distribution from fit to combined HERA data

  [H1 & ZEUS collab. 0911.0884]

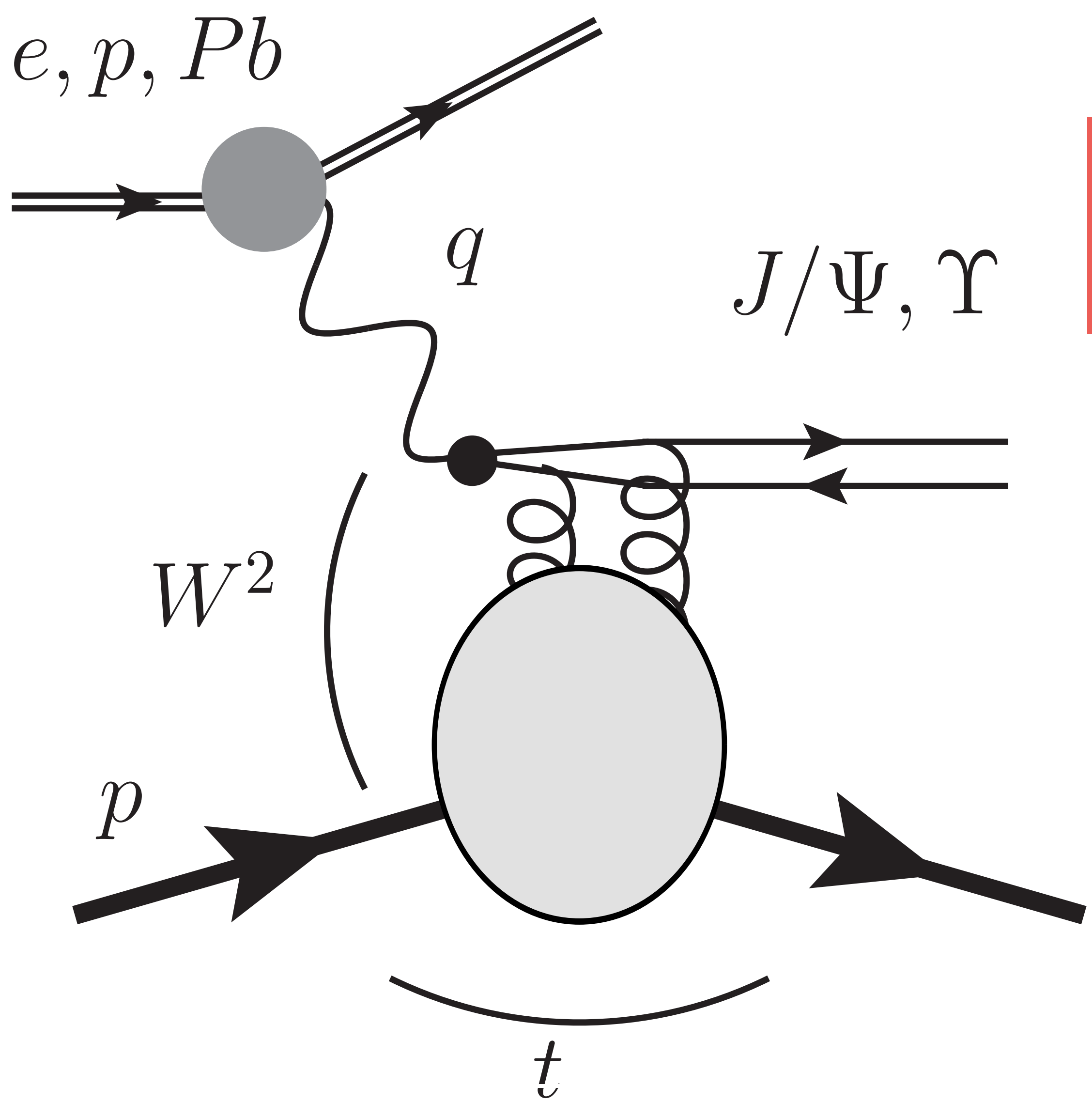


gluon with non-linear terms: KS gluon [Kutak, Sapeta; 1205.5035]

- 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)



The photo-production Xsection



= diffraction process

$$\Im\mathrm{m}\mathcal{A}^{\gamma p \to Vp}(x, t=0) = \int_0^\infty dr W(r) \sigma_{q\bar{q}}(x, r)$$

r: transverse size of quark-antiquark dipole

<u>elements:</u>

$$W(r) = 2\pi r \int_0^1 \frac{dz}{4\pi} \, (\Psi_V^* \Psi)_T(r, z)$$

integrated light-front wave function overlap = transition photon → dipole → vector meson

$$\sigma_{q\bar{q}}(x, r) = \frac{4\pi}{N_c} \int \frac{d^2\boldsymbol{k}}{\boldsymbol{k}^2} \left(1 - e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\right) \alpha_s \mathcal{F}(x, \boldsymbol{k}^2)$$

dipole cross-section from unintegrated gluon $\mathscr{F}$=**object of interest**

explore inclusive gluon → can only calculate imaginary part of scattering amplitude at t=0

how to compare to experiment?

(standard procedure for this kind of study)

a) analytic properties of scattering amplitude → real part

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

with intercept $\lambda(x) = \frac{d\ln \Im\mathrm{m}\mathcal{A}(x,t)}{d\ln 1/x}$

b) differential Xsection at t=0:

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

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

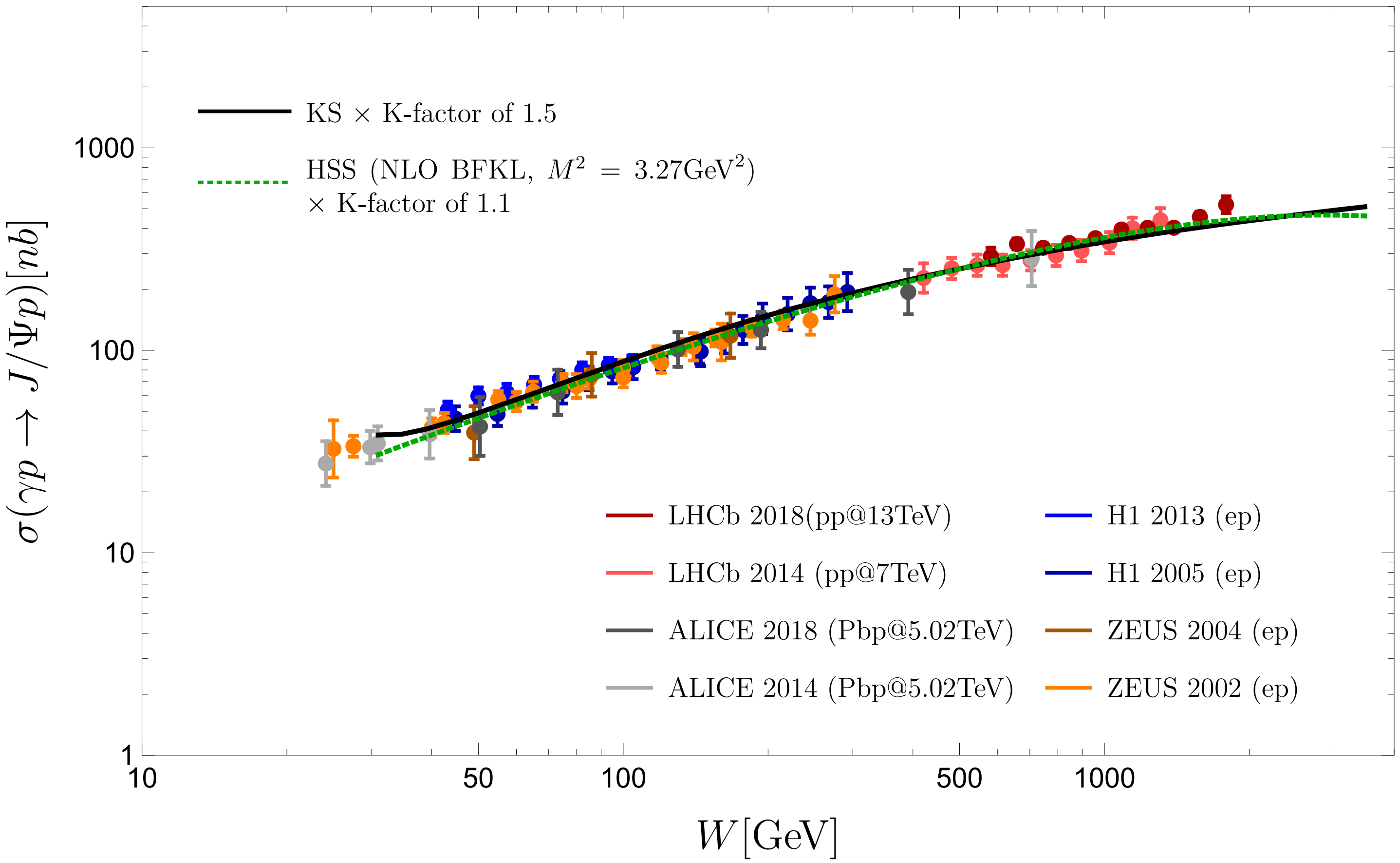
$$\sigma^{\gamma p\to Vp}(W^2) = \frac{1}{B_D(W)}\frac{d\sigma}{dt}(\gamma p\to Vp)\Big|_{t=0}$$

extracted from data

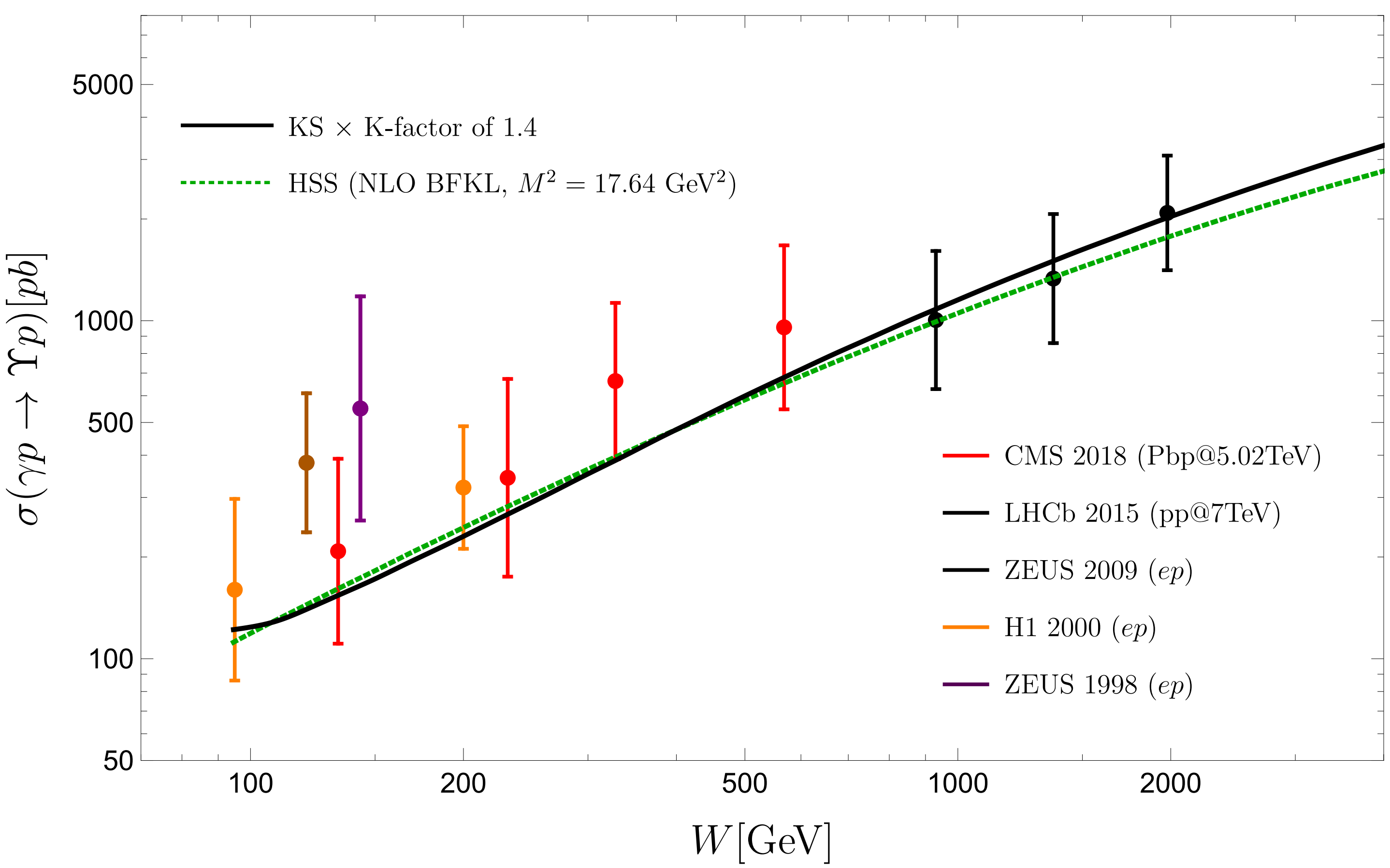
weak energy dependence from slope parameter

$$B_D(W) = \left[b_0 + 4\alpha'\ln\frac{W}{W_0}\right]\mathrm{GeV}^{-2}$$

Results I



Υ as perturbative control:



- leading order wave function → don't control normalization (scale of α_s)

$$\Im\text{m}\mathcal{A}^{\gamma p \to Vp} \sim \alpha_s(\mu^2)$$
$$\Rightarrow \sigma^{\gamma p \to Vp} \sim \alpha_s^2(\mu^2)$$

- standard scale choices for dipole cross-sections (~external scales)→ very good description of energy dependence with both HSS and KS gluon
- premature (?) conclusion: non-linear dynamics is absent

Why premature?

HSS gluon (NLO BFKL) comes with 2 terms:

$$\sigma_{q\bar{q}}^{(\mathrm{HSS})}(x,r) = \alpha_s \hat{\sigma}_{q\bar{q}}^{(\mathrm{HSS})}(x,r).$$

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

running coupling corrections which do not exponentiate = a perturbative correction

$$\hat{\sigma}_{q\bar{q}}^{(\mathrm{dom})}(x,r,M^2) = \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \left(\frac{4}{r^2 Q_0^2}\right)^{\gamma} \frac{\bar{\alpha}_s(M \cdot Q_0)}{\bar{\alpha}_s(M^2)} f(\gamma, Q_0, \delta, r) \left(\frac{1}{x}\right)^{\chi(\gamma, M^2)}$$

$$\hat{\sigma}_{q\bar{q}}^{(\mathrm{corr.})}(x,r,M^2) = \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \left(\frac{4}{r^2 Q_0^2}\right)^{\gamma} \frac{\bar{\alpha}_s(M \cdot Q_0)}{\bar{\alpha}_s(M^2)} f(\gamma, Q_0, \delta, r) \left(\frac{1}{x}\right)^{\chi(\gamma, M^2)}$$
$$\times \frac{\bar{\alpha}_s^2 \beta_0 \chi_0(\gamma)}{8N_c} \log\left(\frac{1}{x}\right) \left[-\psi(\delta-\gamma) + \log\frac{M^2 r^2}{4} - \frac{1}{1-\gamma} - \psi(2-\gamma) - \psi(\gamma) \right]$$

NLO BFKL kernel (BLM scale setting) + coll. resummation

$$\chi(\gamma, M^2) = \bar{\alpha}_s \chi_0(\gamma) + \bar{\alpha}_s^2 \tilde{\chi}_1(\gamma) - \frac{1}{2} \bar{\alpha}_s^2 \chi_0'(\gamma) \chi_0(\gamma) + \chi_{\mathrm{RG}}(\bar{\alpha}_s, \gamma, \tilde{a}, \tilde{b}).$$

Why premature?

HSS gluon (NLO BFKL) comes with 2 terms:

$$\sigma_{q\bar{q}}^{(\mathrm{HSS})}(x,r) = \alpha_s \hat{\sigma}_{q\bar{q}}^{(\mathrm{HSS})}(x,r).$$

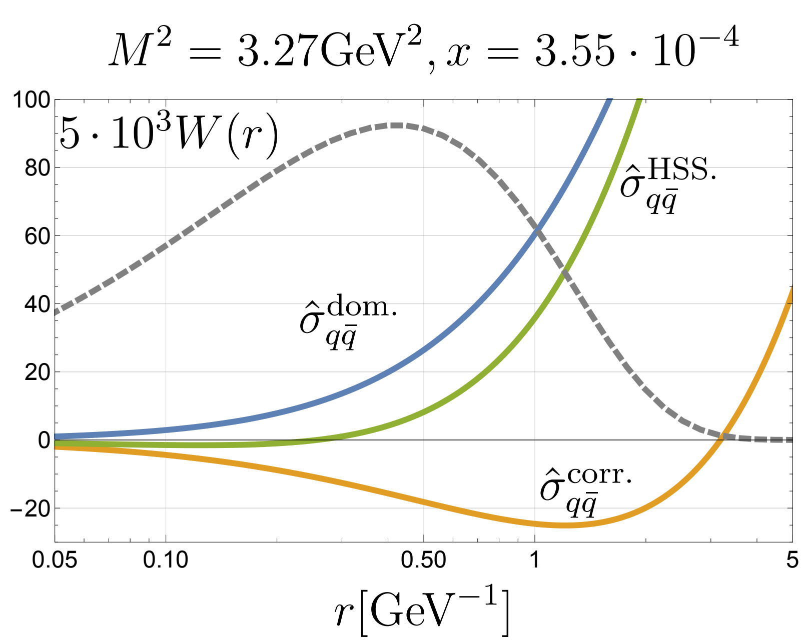
$$\hat{\sigma}_{q\bar{q}}^{(\mathrm{HSS})}(x,r) = \hat{\sigma}_{q\bar{q}}^{(\mathrm{dom.})}(x,r) + \hat{\sigma}_{q\bar{q}}^{(\mathrm{corr.})}(x,r),$$

negative + enhanced by log(1/x)

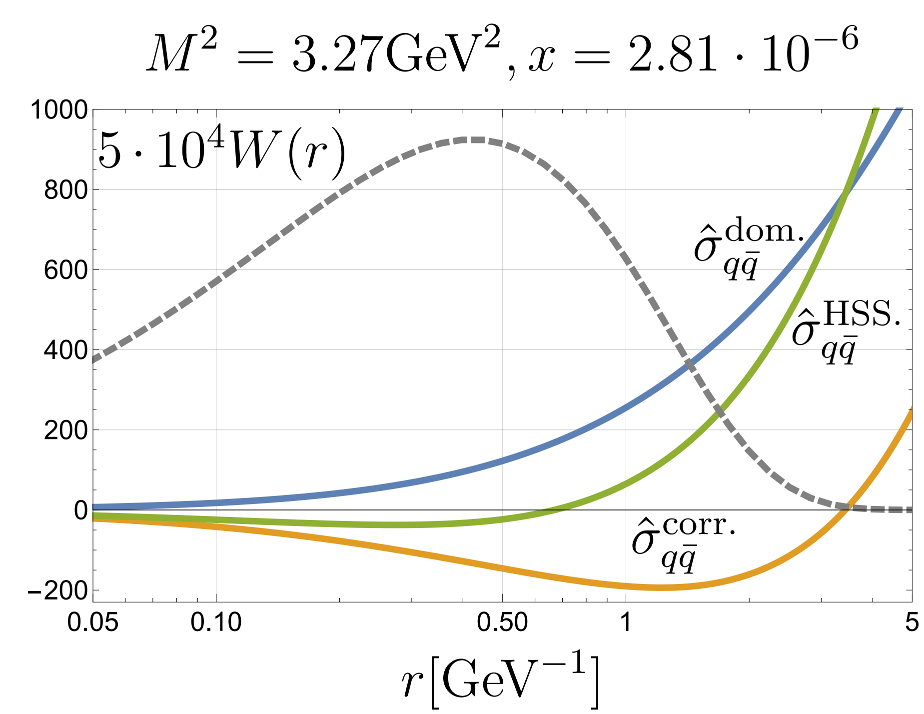
$$\hat{\sigma}_{q\bar{q}}^{(\mathrm{corr.})}(x,r) = -\alpha_s^2 \ln\left(\frac{1}{x}\right) \hat{\sigma}_{q\bar{q}}^{(1)}(x,r)$$

running coupling corrections which do not exponentiate = a perturbative correction

→ will eventually dominate the leading term!

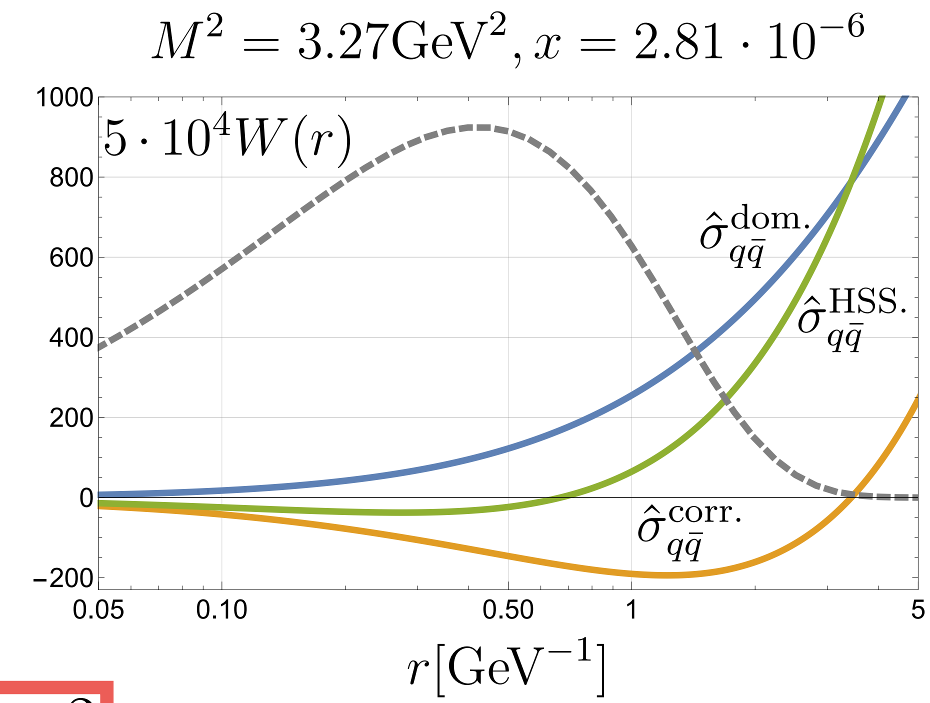


not a problem for HERA kinematics



LHC: correction dominates!

fixed external scale for running coupling
→ breakdown of perturbative expansion
at low x for certain dipole sizes *r*

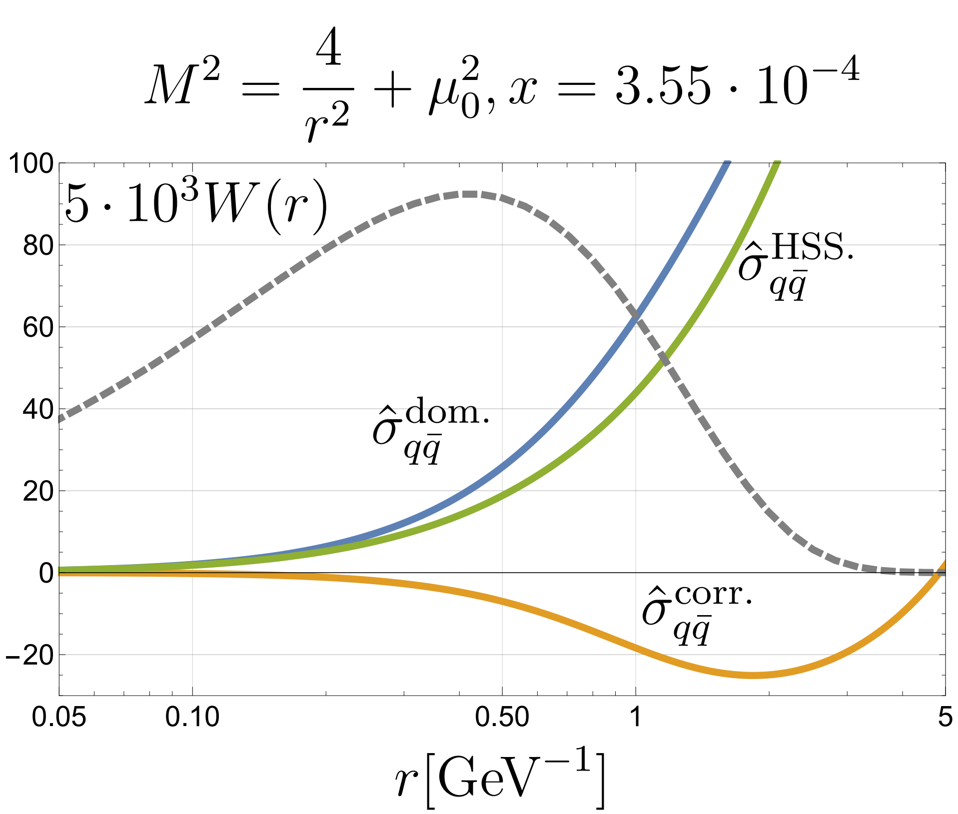


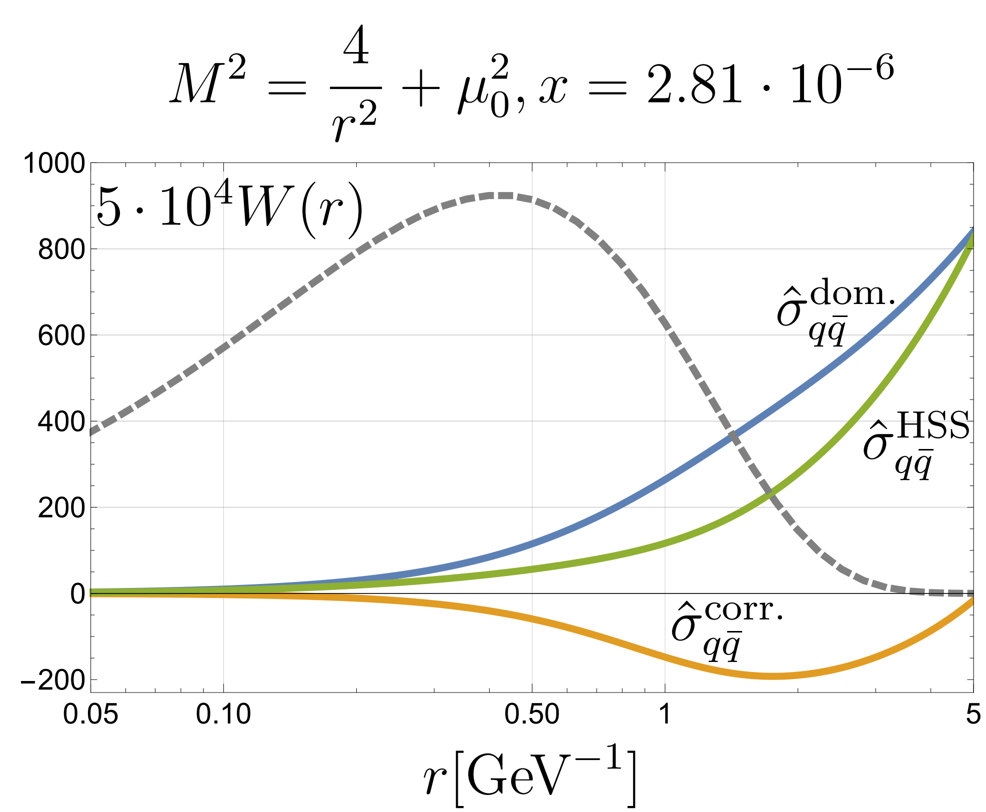
possible fix: r-dependent
running coupling scale

$$M^2 = \frac{4}{r^2} + \mu_0^2 \text{ with } \mu_0^2 = 1.51 \text{ GeV}^2$$

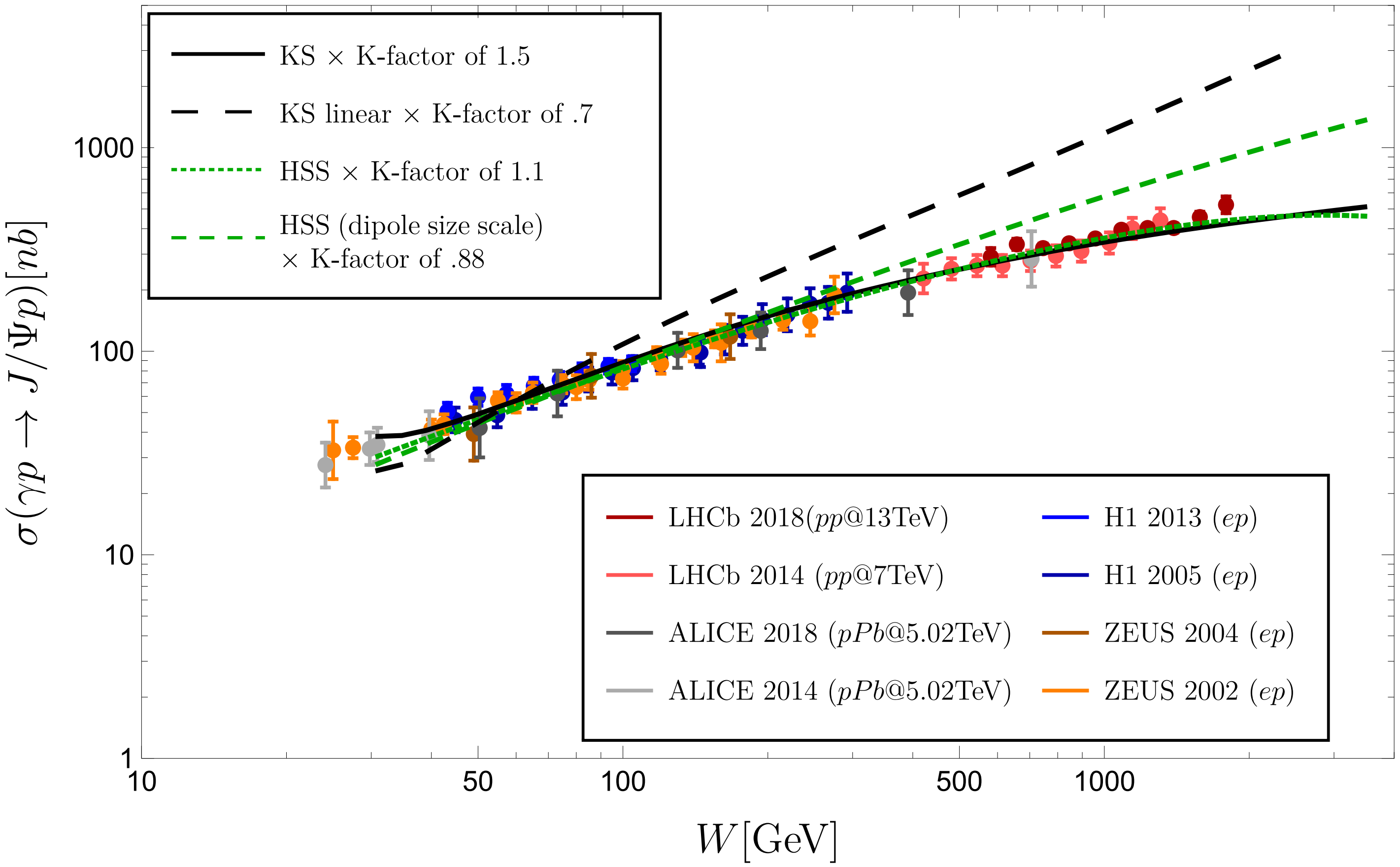
= scale choice used in IPsat dipole model [Bartels, Golec-Biernat, Kowalksi, hep-ph/0203258];
fit: [Rezaeian, Siddikov, Van de Klundert, Venugopalan; 1212.2974]

→stabilizes perturbative expansion

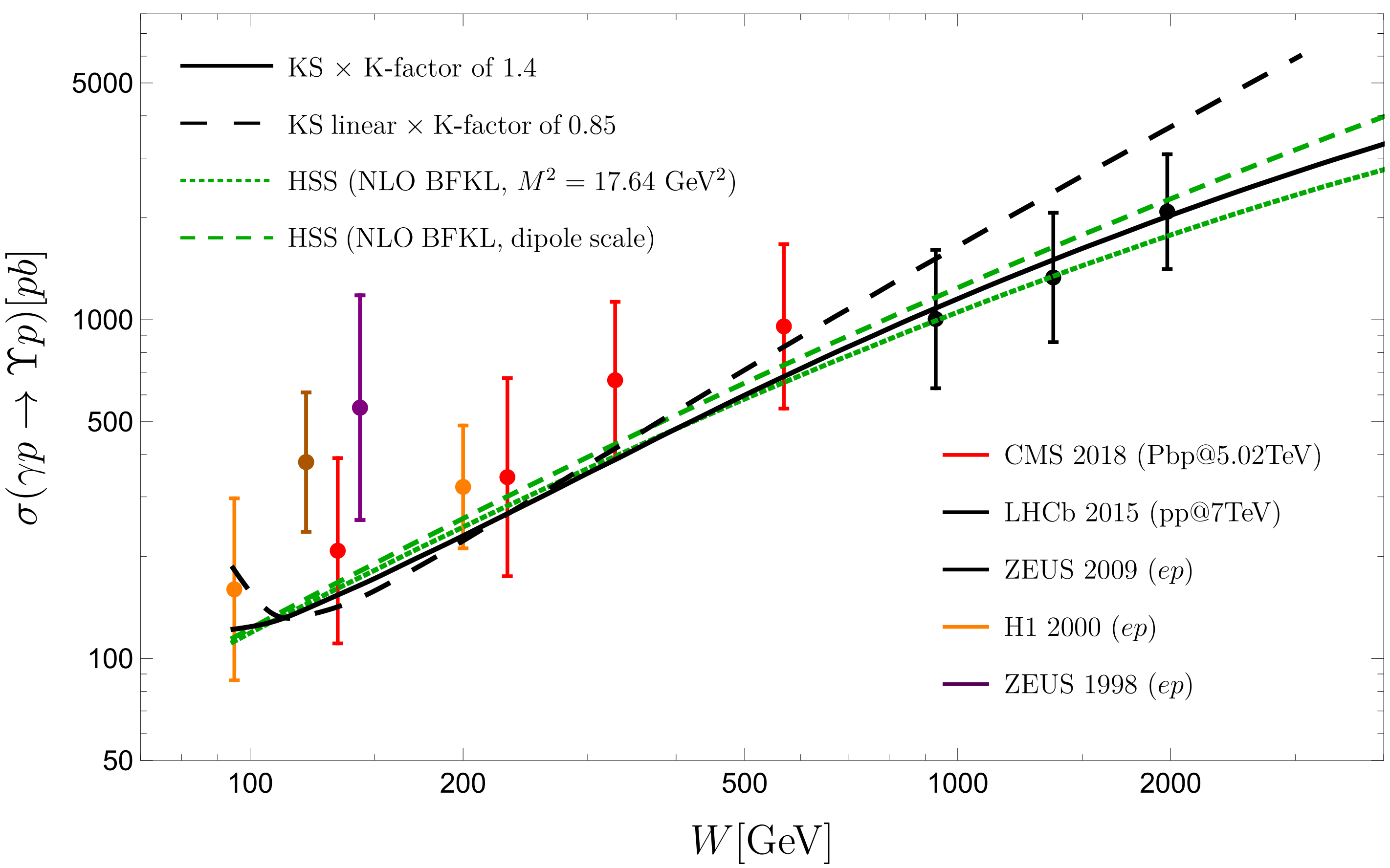




Results II



Υ as perturbative control:



- works well for Υ & J/ψ in HERA region ($W < 400$GeV)
- overshoots J/ψ data in LHC region ($W > 500$GeV) → growth is too strong
- also shown: linear KS gluon → growth too strong for both Υ & J/ψ

→ non-linear terms are essential for KS description of data

Summary and Conclusion

- NLO BFKL (linear evolution) only describes data if (negative) perturbative corrections is larger than the leading term (= breakdown of expansion)

- Tame size of correction → description of Υ and J/ψ in HERA region, growth too strong for J/ψ at LHC

- non-linear KS gluon describes data & non-linear terms essential

= a strong indication for the on-set of non-linear dynamics

Possible limitations

- NLO accuracy for both non-linear evolution, wave functions for VM production + DIS fit highly desirable
- extraction of γp an own challenge (gap survival factors etc.)→ how well do we control the errors?
- as long as the “correction term” is under control, x-dependence of NLO BFKL gluon stable
→ control theory uncertainty
[Bautista, MH, Fernandez-Tellez;1607.05203]
- for this observable = this is how the onset of gluon saturation would like

→ need to complete picture with more observable & higher theoretical accuracy;
→ so far: most direct evidence for gluon saturation

Back up

HSS gluon = 2 terms

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

$$\hat{\sigma}_{q\bar{q}}^{(\mathrm{dom})}(x,r,M^2) = \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \left(\frac{4}{r^2 Q_0^2}\right)^{\gamma} \frac{\bar{\alpha}_s(M\cdot Q_0)}{\bar{\alpha}_s(M^2)} f(\gamma, Q_0, \delta, r) \left(\frac{1}{x}\right)^{\chi(\gamma, M^2)}$$

$$\hat{\sigma}_{q\bar{q}}^{(\mathrm{corr.})}(x,r,M^2) = \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2\pi i} \left(\frac{4}{r^2 Q_0^2}\right)^{\gamma} \frac{\bar{\alpha}_s(M\cdot Q_0)}{\bar{\alpha}_s(M^2)} f(\gamma, Q_0, \delta, r) \left(\frac{1}{x}\right)^{\chi(\gamma, M^2)}$$
$$\times \frac{\bar{\alpha}_s^2 \beta_0 \chi_0(\gamma)}{8N_c} \log\left(\frac{1}{x}\right)\left[-\psi(\delta-\gamma) + \log\frac{M^2 r^2}{4} - \frac{1}{1-\gamma} - \psi(2-\gamma) - \psi(\gamma)\right]$$

<u>core element:</u>

NLO BFKL eigenvalue with collinear resummation ('RG')

$$\chi\left(\gamma, M^2\right) = \bar{\alpha}_s \chi_0(\gamma) + \bar{\alpha}_s^2 \tilde{\chi}_1(\gamma) - \frac{1}{2}\bar{\alpha}_s^2 \chi_0'(\gamma)\chi_0(\gamma) + \chi_{\mathrm{RG}}(\bar{\alpha}_s, \gamma, \tilde{a}, \tilde{b}).$$

proton & dipole impact factors

$$f(\gamma, Q_0, \delta, r) = \frac{r^2 \cdot \pi \Gamma(\gamma)\Gamma(\delta-\gamma)}{N_c(1-\gamma)\Gamma(2-\gamma)\Gamma(\delta)}$$

the transition photon → quark-antiquark dipole → vector meson

$$W(r) = 2\pi r \int_0^1 \frac{dz}{4\pi} \, (\Psi_V^* \Psi)_T(r, z)$$

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

boosted Gaussian scalar wave function using Brodsky-Huang-Lepage prescription

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

parameters fitted by [Armesto, Rezaeian; 1402.4831] (J/Ψ) and [Goncalves, Moreira,Navarra;1408.1344] (Υ)

Meson	m_f/GeV	$\mathcal{N}_T$	$\mathcal{R}^2$/GeV^{-2}	M_V/GeV
J/ψ	$m_c = 1.4$	0.596	2.45	3.097
Υ	$m_b = 4.2$	0.481	0.57	9.460