# $J/\Psi$ and $\Psi(2s)$ production as a probe of low x evolution


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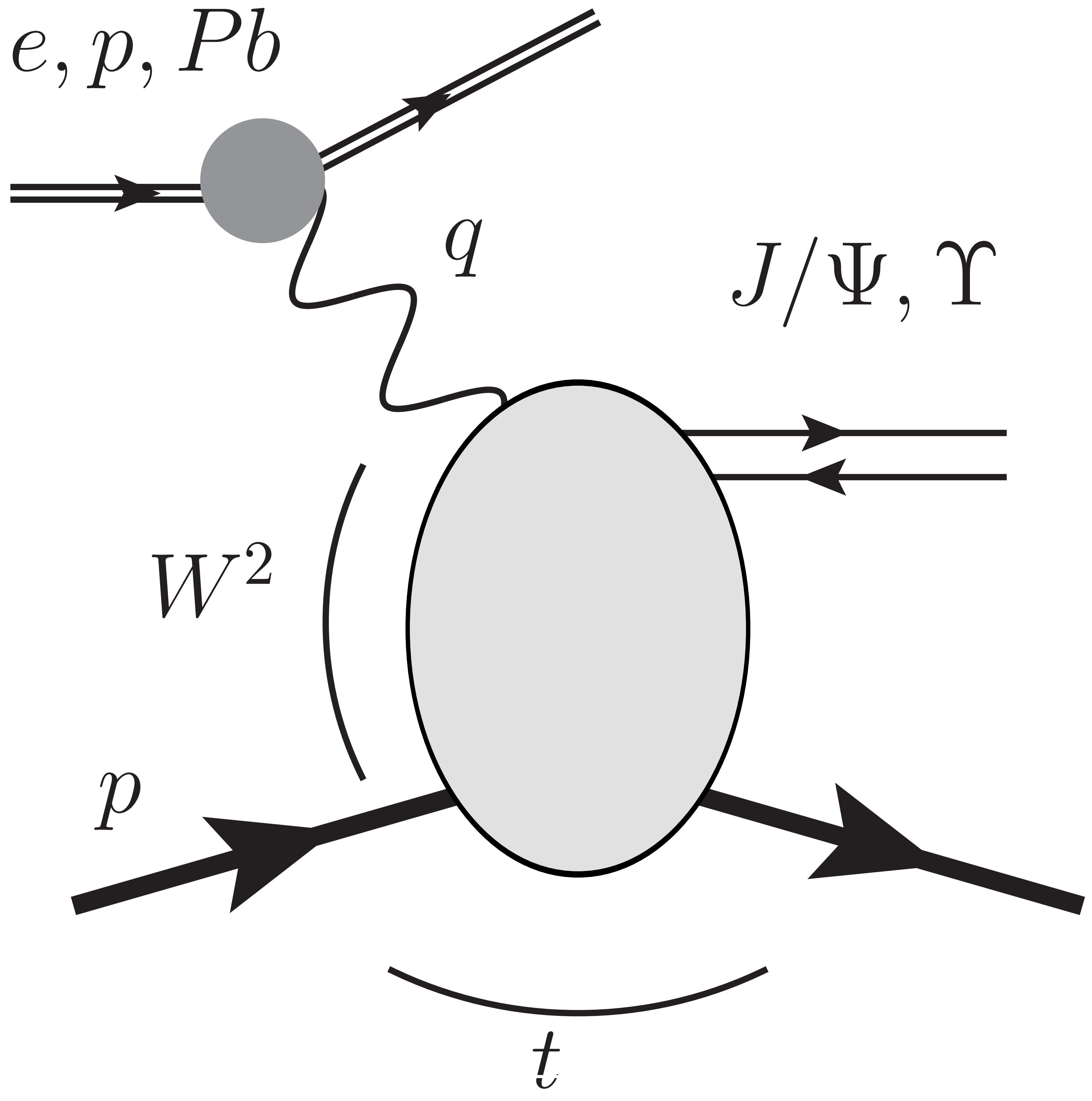
based on:

- 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

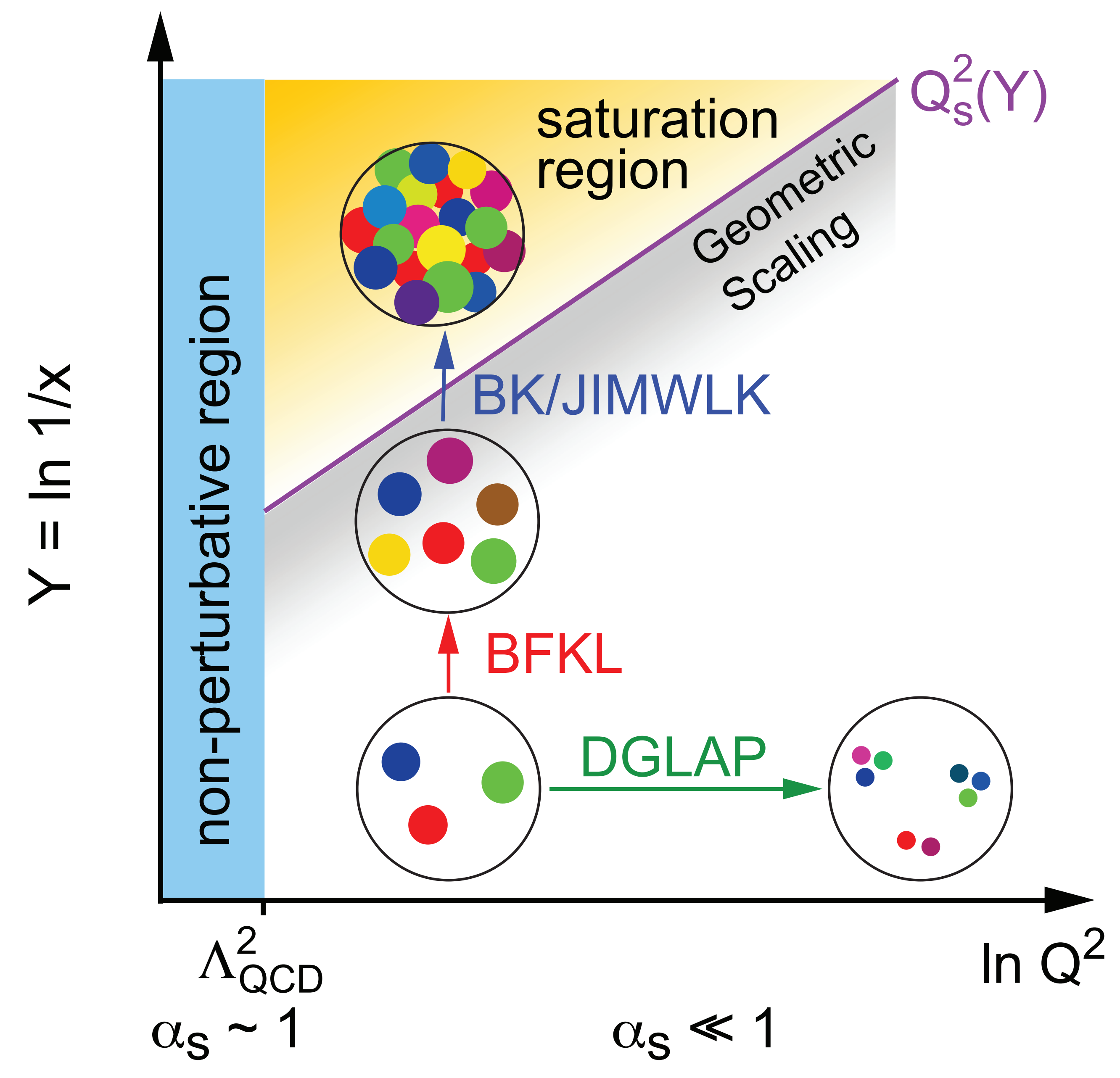
EIC opportunities for Snowmass, Januar 25-29, 2021, Online

This talk: photo induced processes at the LHC → prospects for EIC:
Process: exclusive photo-production of J/$\Psi$s and $\Psi(2s)$



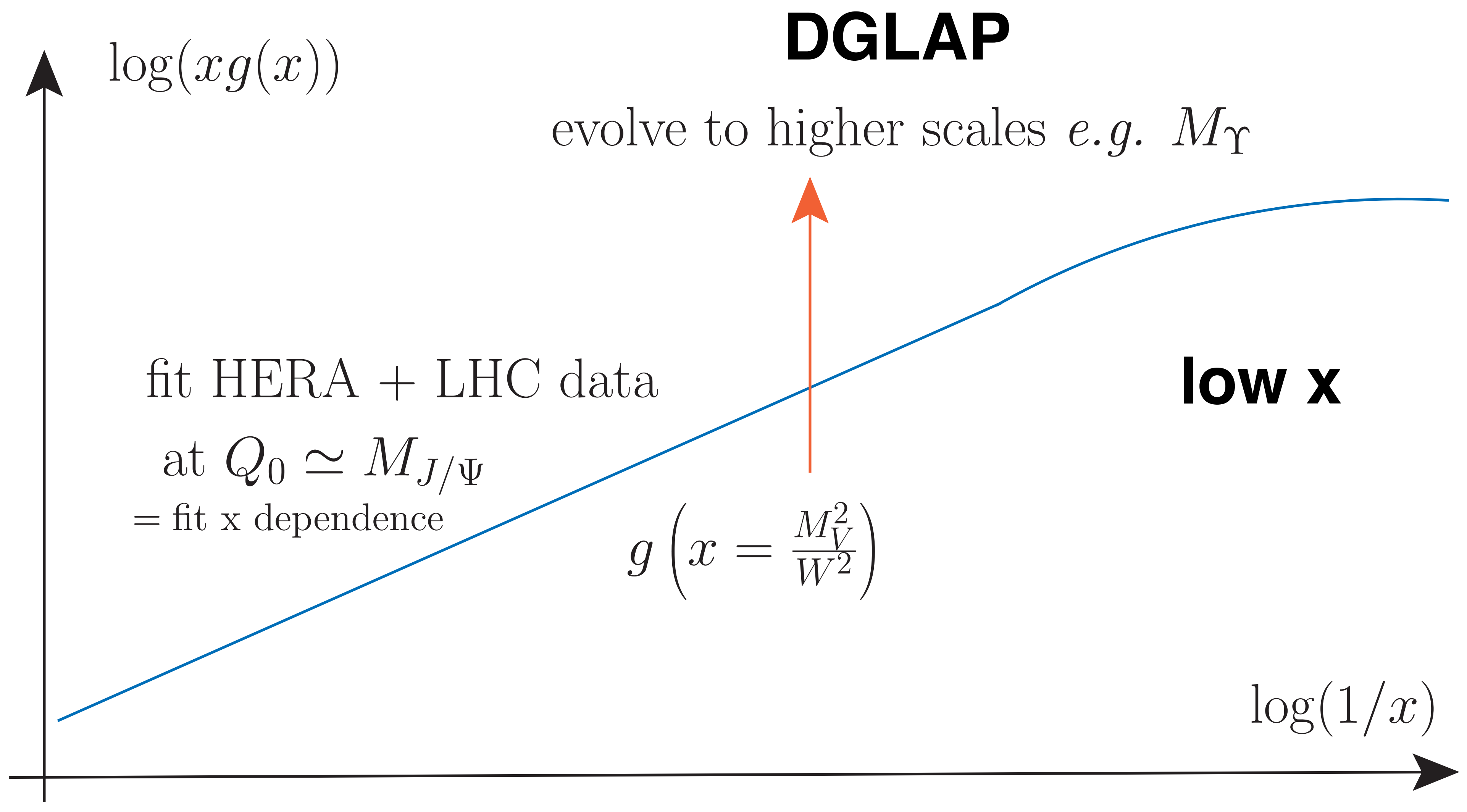

technical details: see appendix

- 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)




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

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

linear BFKL evolution = subset of complete BK

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

# linear low x evolution as benchmark →requires precision

(updated version desirable, work has started; not expected too soon)

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

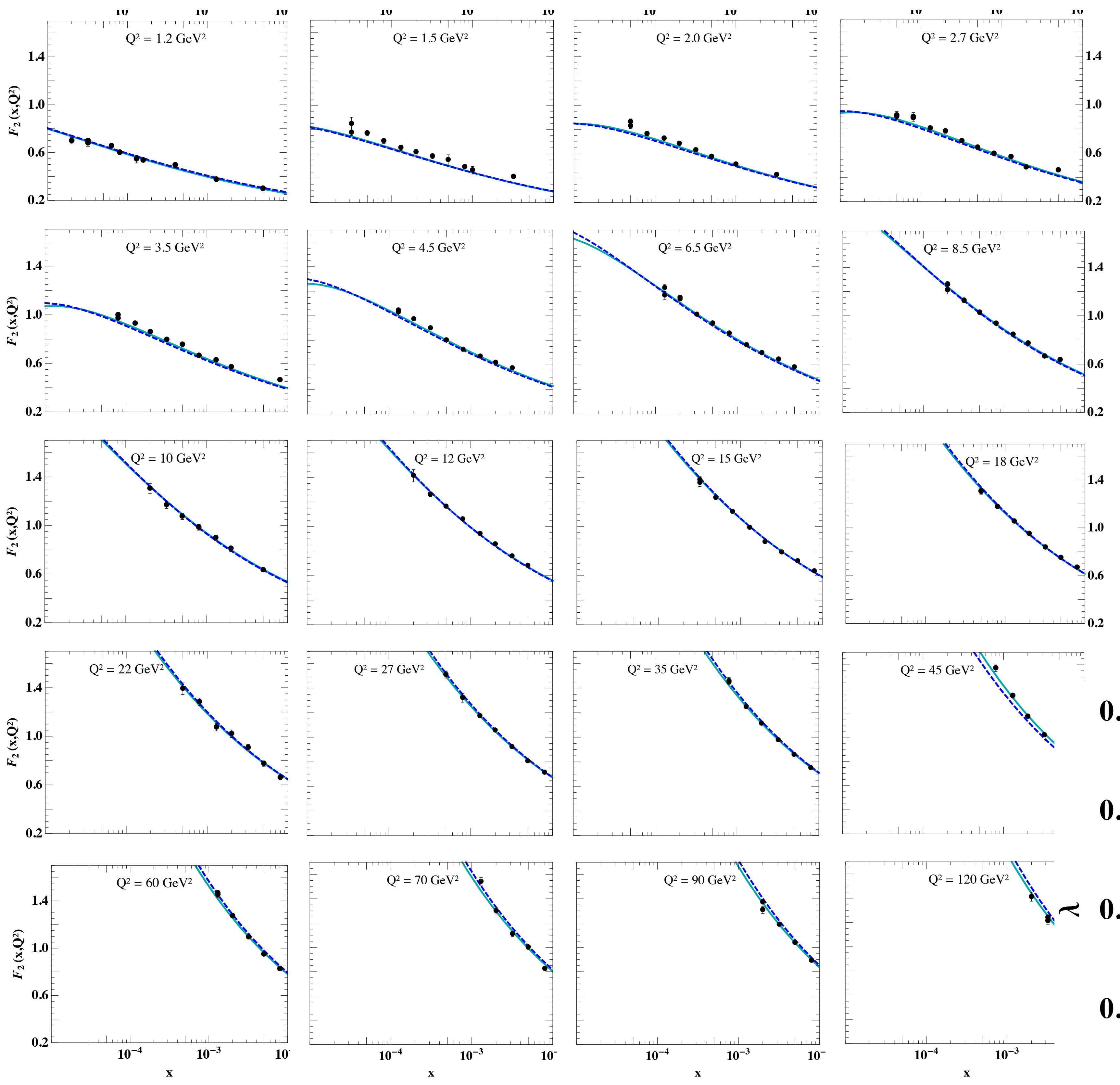
- uses NLO BFKL kernel

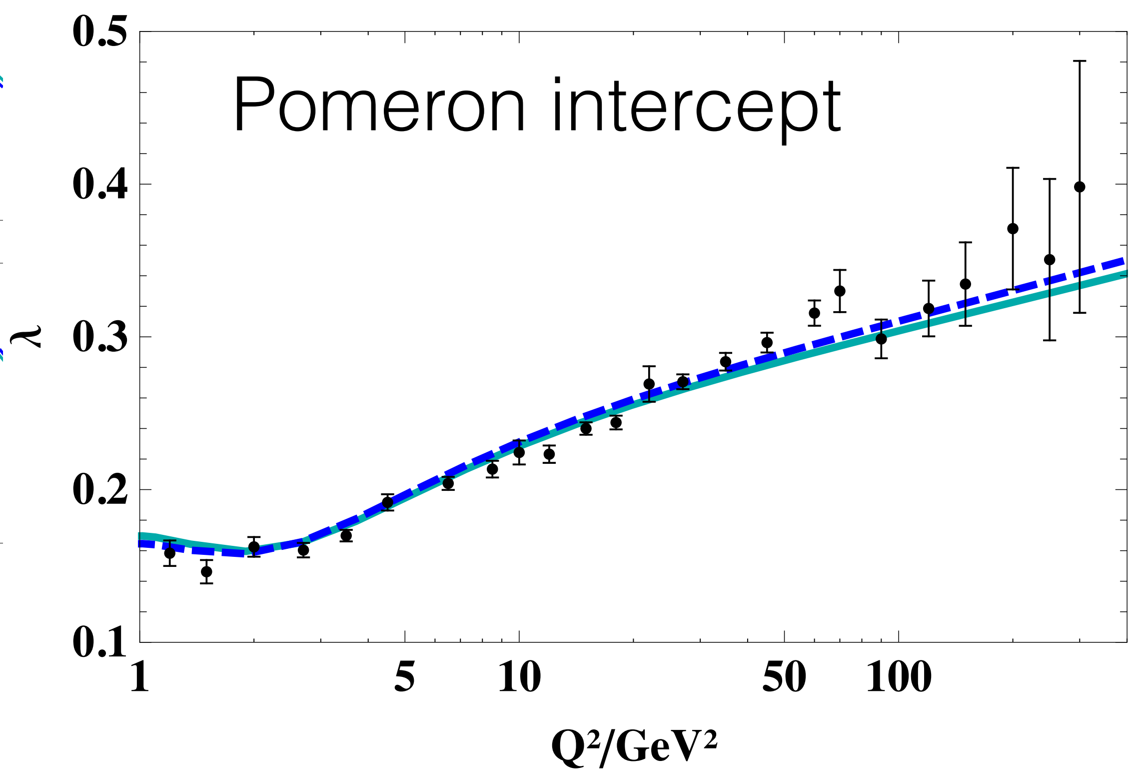
  [Fadin, Lipatov; PLB 429 (1998) 127]

  + resummation of collinear logarithms

- initial kT distribution from fit to combined HERA data

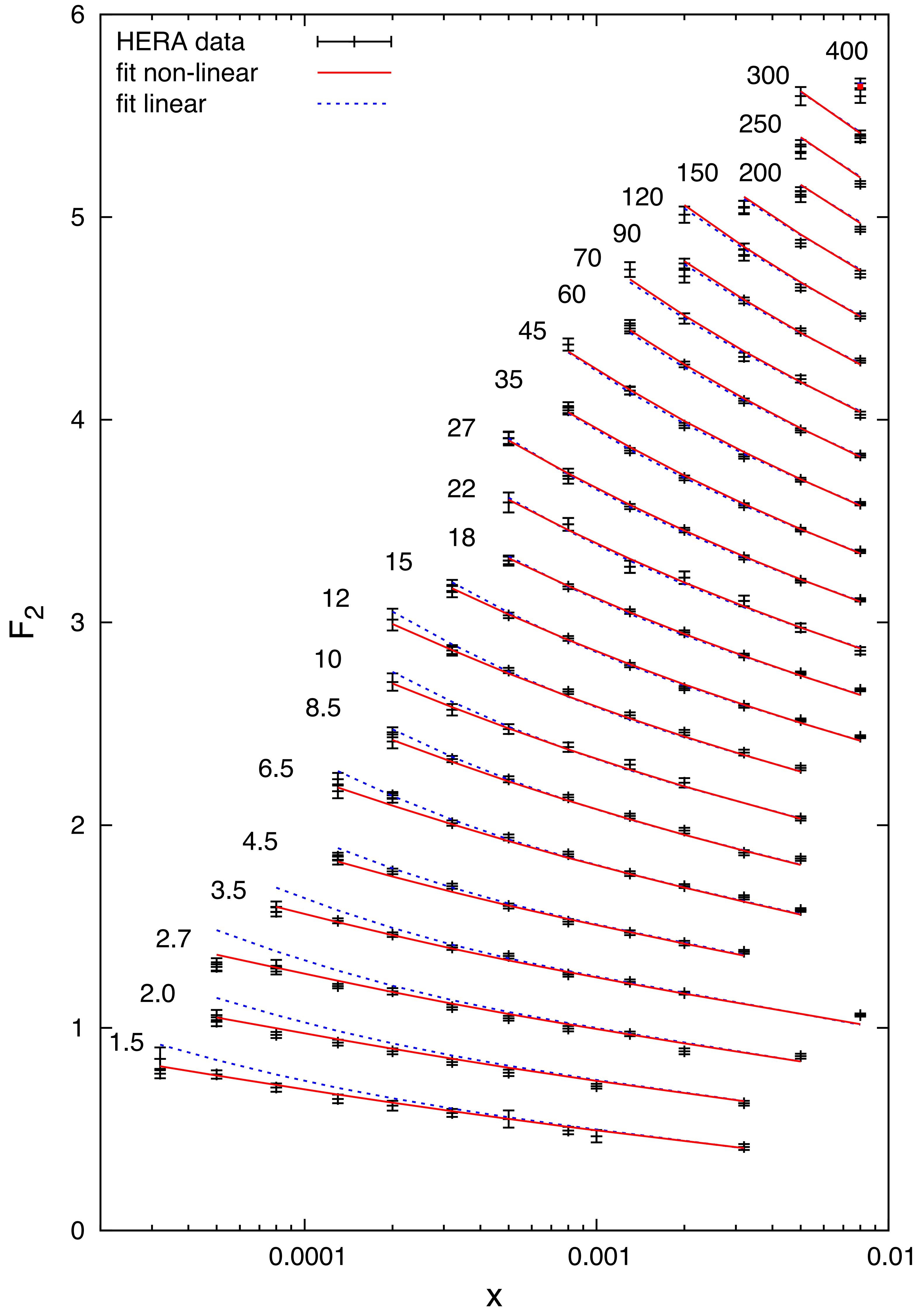
  [H1 & ZEUS collab. 0911.0884]



# 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)



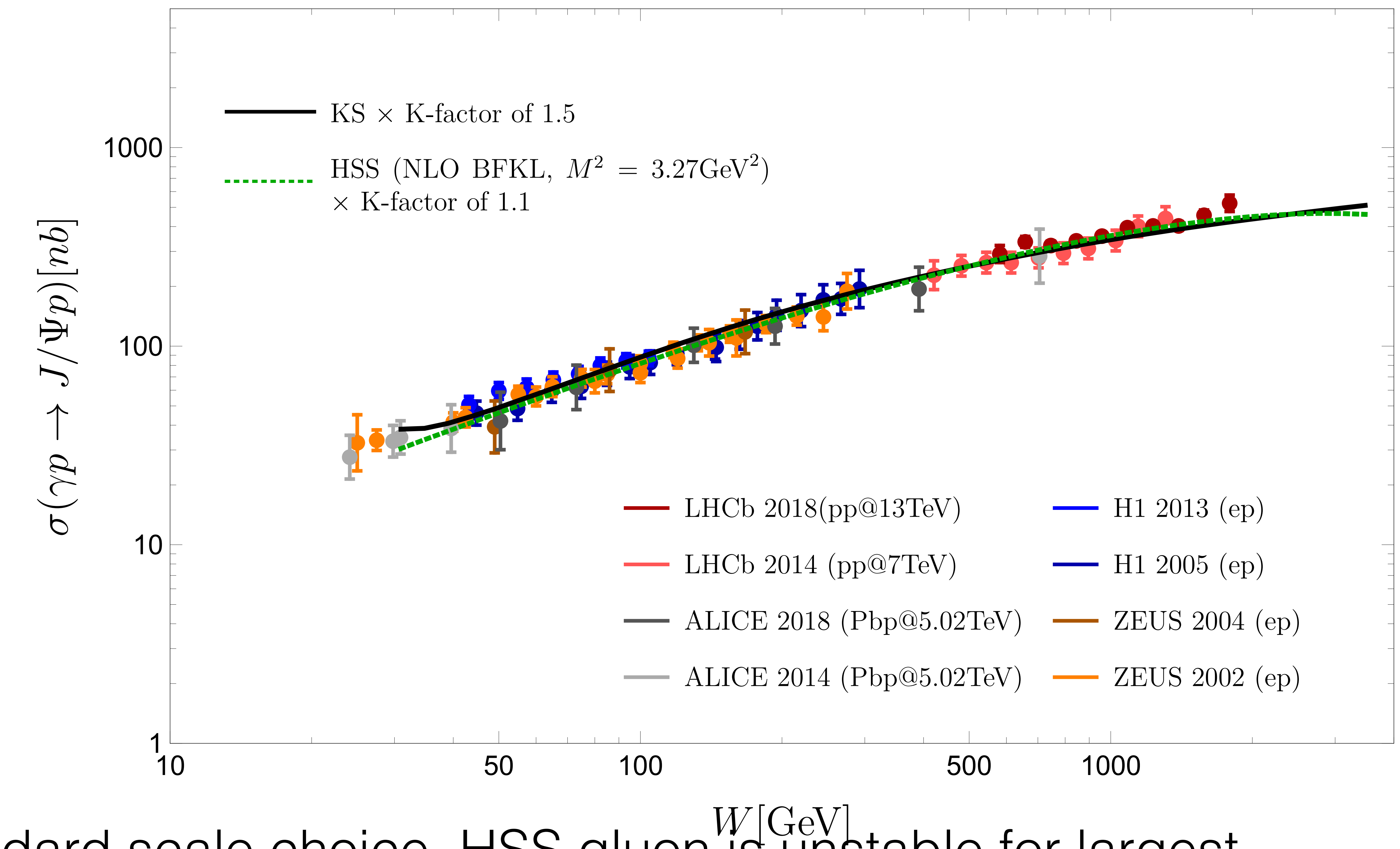
uses conventional Gaussian VM wave function & LC $\gamma \to$ VM transition + dipole cross-sections calculated from gluon distribution

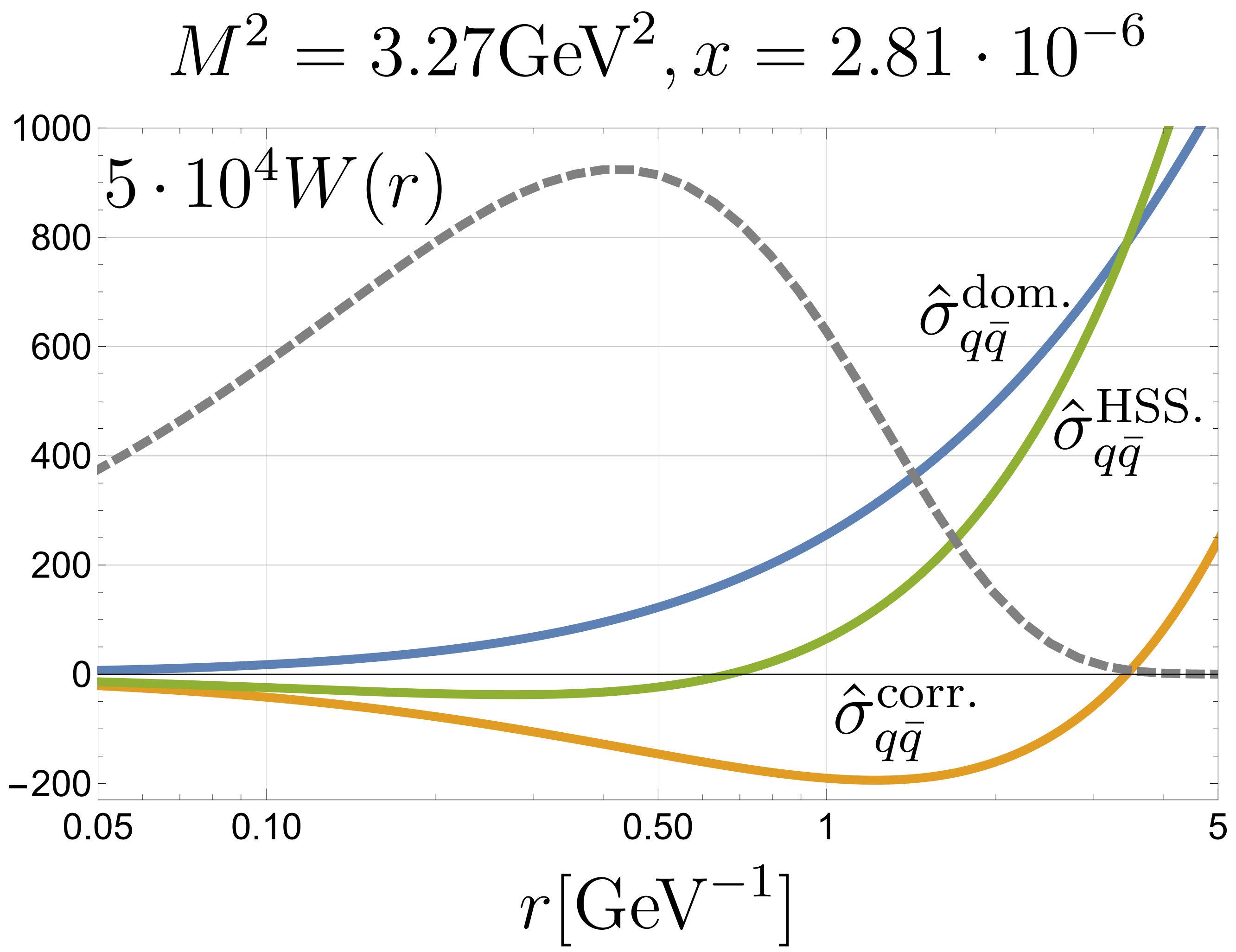
$$\Im\mathrm{m}\mathcal{A}_T^{\gamma p \to V p}(W, t=0) = \int d^2\boldsymbol{r} \int_0^1 \frac{dz}{4\pi} \, (\Psi_V^* \Psi)_T \, \sigma_{q\bar{q}}(x, r)$$

# At first sight …

[Arroyo, MH, Kutak;1904.04394]

- with standard scale choice for NLO BFKL gluon, both distribution describe energy dependence with **equal** quality




but find:

- with standard scale choice, HSS gluon is unstable for largest energies

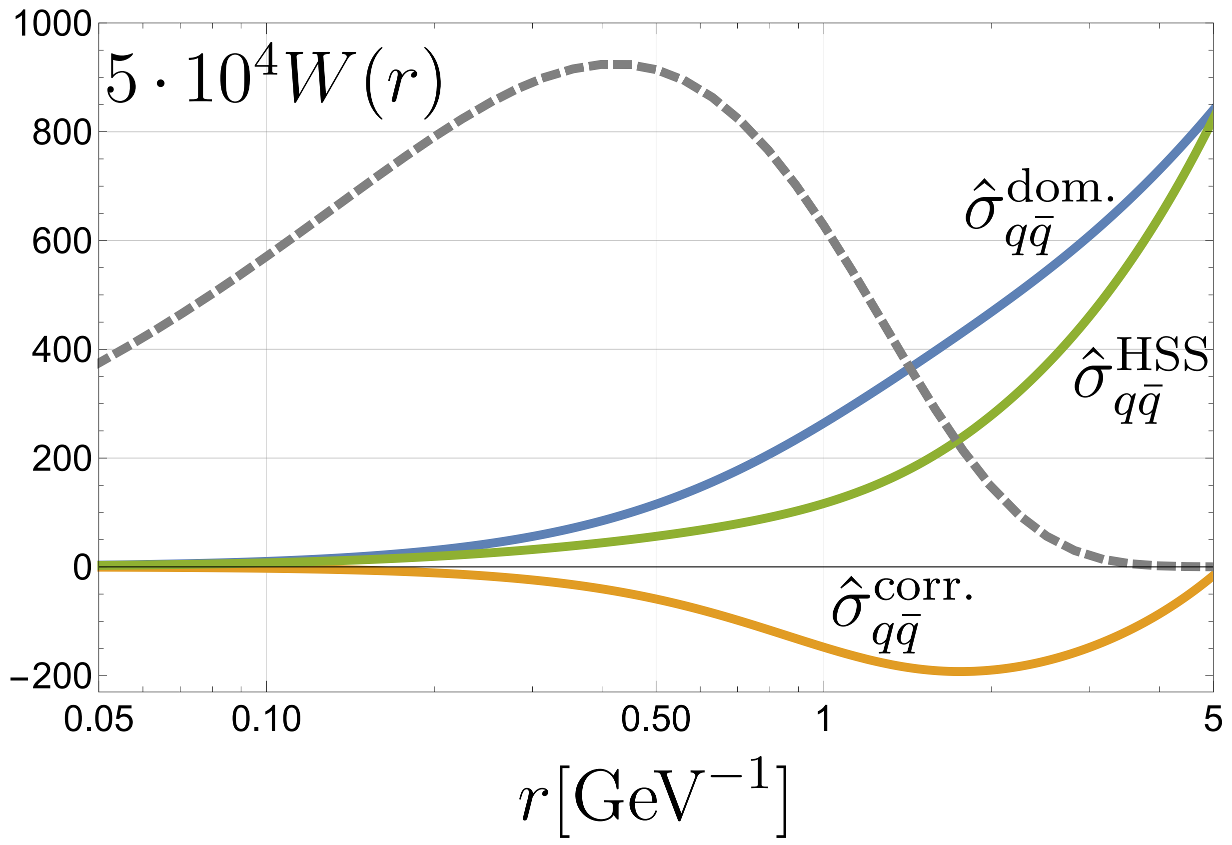
$$\hat{\sigma}_{q\bar{q}}^{(\text{HSS})}(x, r) = \hat{\sigma}_{q\bar{q}}^{(\text{dom.})}(x, r) + \hat{\sigma}_{q\bar{q}}^{(\text{corr.})}(x, r),$$

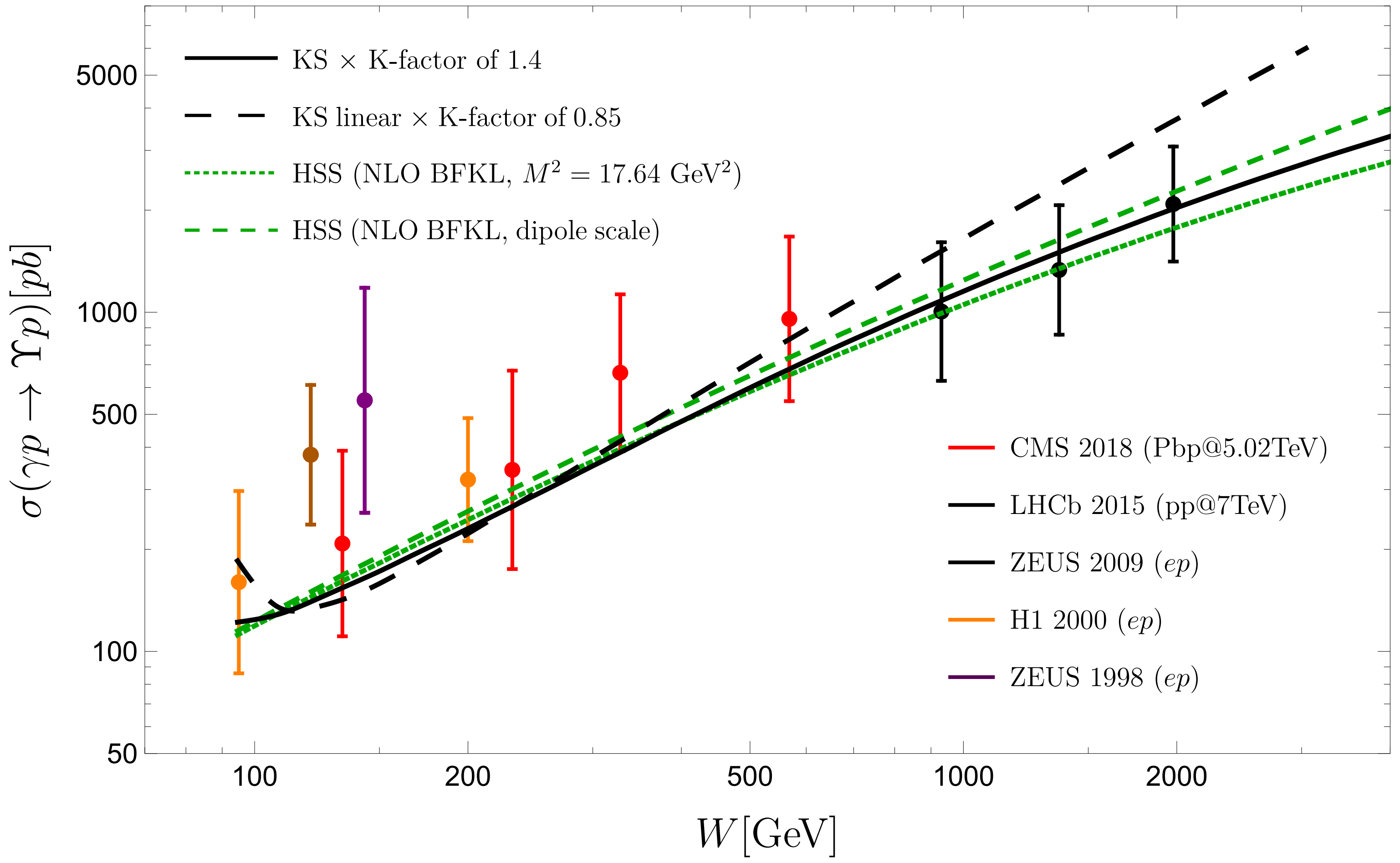
- fix this through dipole size dependent renormalization scale

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

→ stabilize perturbative expansion through resummation

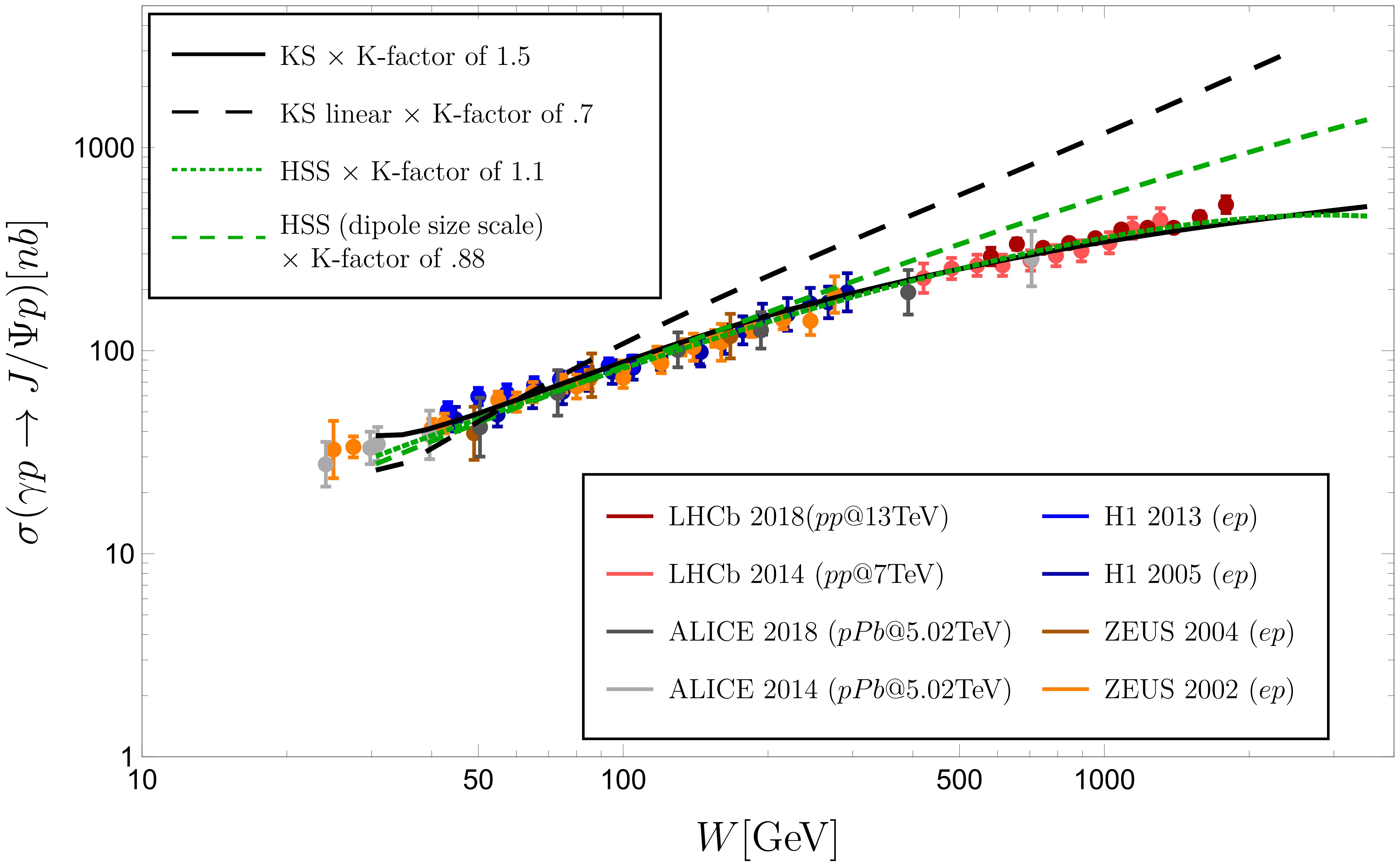
$$M^2 = \frac{4}{r^2} + \mu_0^2, x = 2.81 \cdot 10^{-6}$$




- still describe $\Upsilon$ production
  → perturbative cross-check
- not true for high precision HERA data

**stabilizes** perturbative expansion → stable NLO BFKL evolution at highest $W$



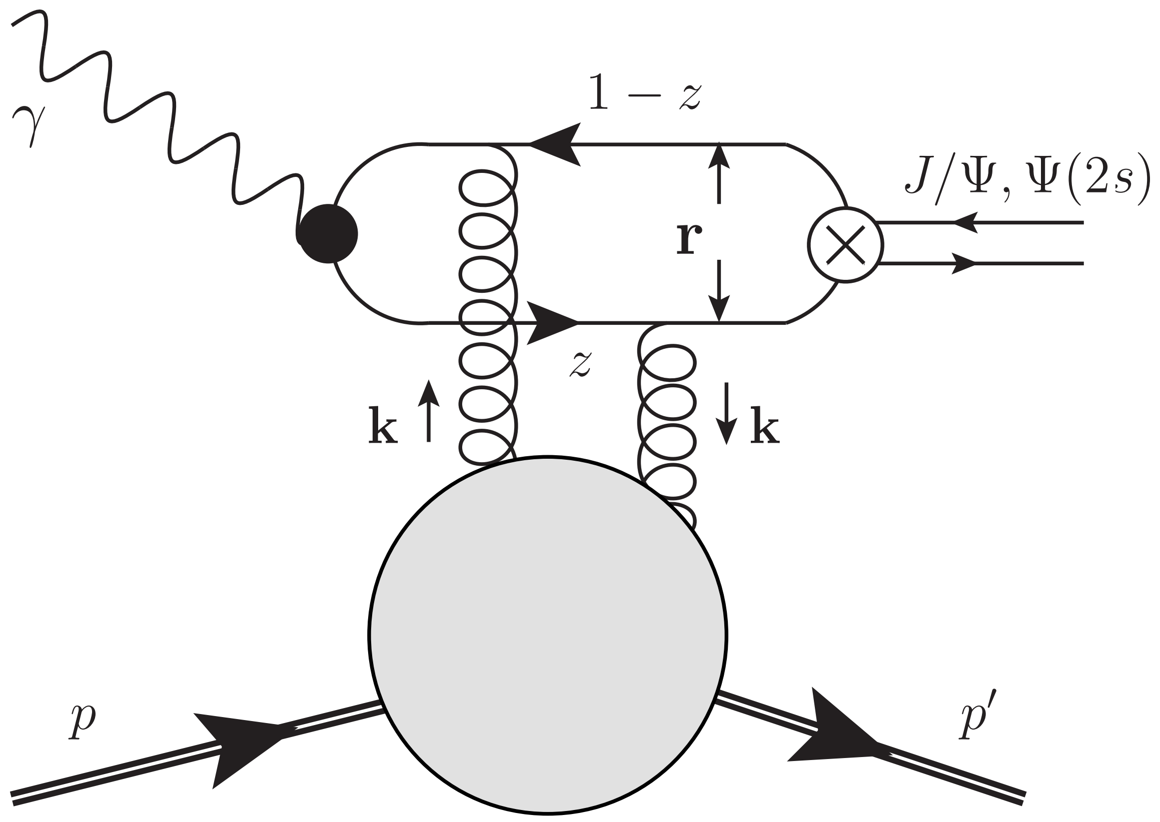

BUT:

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

# Next study: improved transition amplitude $\gamma \to$ VM + include $\Psi(2s)$

includes relativistic spin rotation effects + (more) realistic $c\bar{c}$ potential
both for $J/\Psi$ and $\Psi(2s)$

[Hufner, Y. Ivanov, B. Kopeliovich, A. Tarasov; hep-ph/0007111],
[M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; 1812.03001; 1901.02664]




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

- depends both on dipole cross-section and its derivative
- wave functions have been obtained in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; 1812.03001; 1901.02664] through numerical solution to corresponding Schrödinger equation
- transition function factorizes for real photon ($Q = 0$)

$$\Sigma_T^{(i)}(r) = \hat{e}_f \sqrt{\frac{\alpha_{e.m.} N_c}{2\pi^2}} K_0(m_f r)\, \Xi^{(i)}(r), \qquad i = 1, 2$$

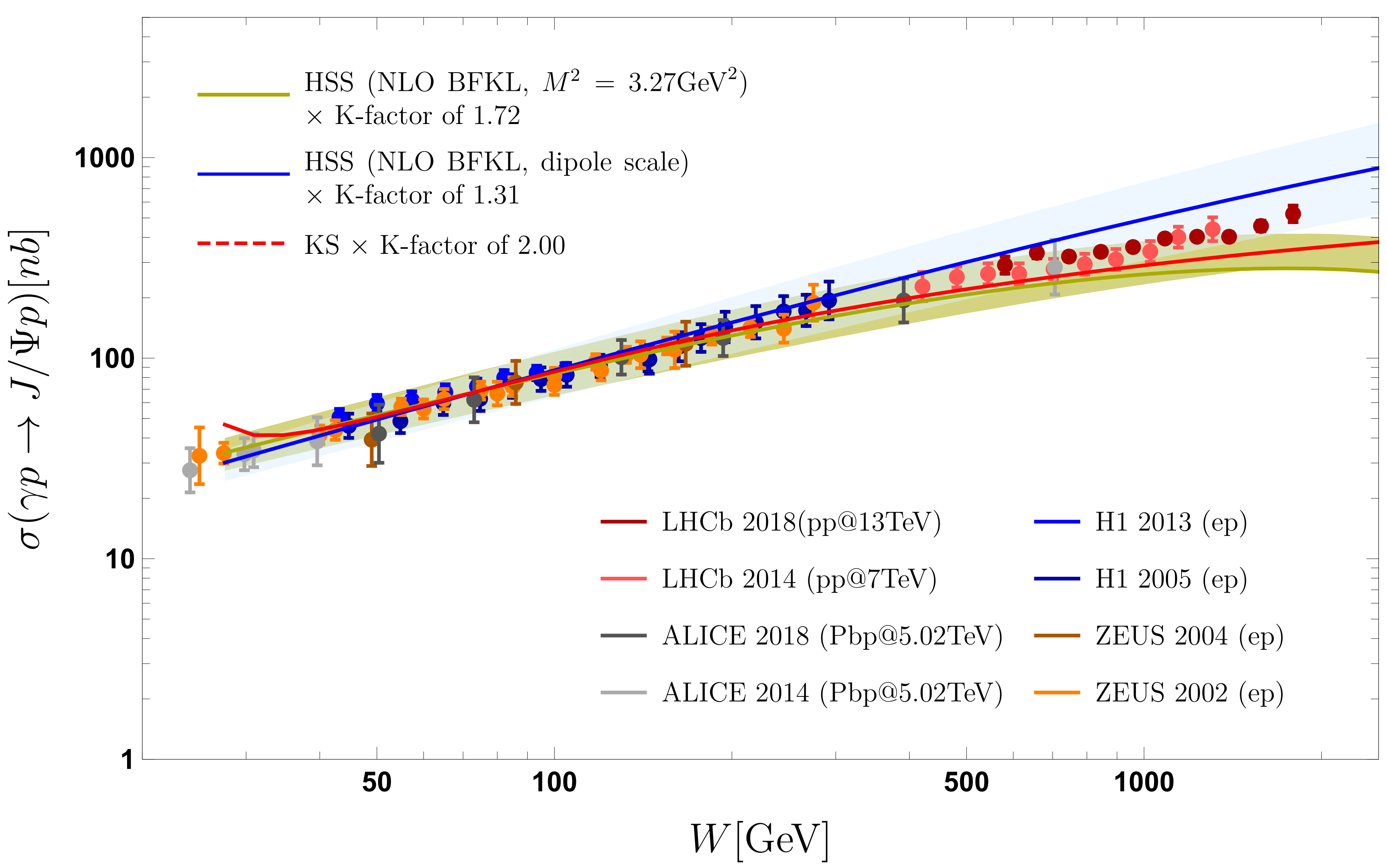
$$\Xi^{(1)}(r) = \int_0^1 dz \int \frac{d^2\boldsymbol{p}}{2\pi} e^{i\boldsymbol{p}\cdot\boldsymbol{r}} \frac{m_T^2 + m_T m_L - 2p_T^2 z(1-z)}{m_T + m_L} \Psi_V(z, |\boldsymbol{p}|),$$

$$\Xi^{(2)}(r) = \int_0^1 dz \int \frac{d^2\boldsymbol{p}}{2\pi} e^{i\boldsymbol{p}\cdot\boldsymbol{r}} |\boldsymbol{p}| \frac{m_T^2 + m_T m_L - 2\boldsymbol{p}^2 z(1-z)}{2m_T(m_T + m_L)} \Psi_V(z, |\boldsymbol{p}|),$$

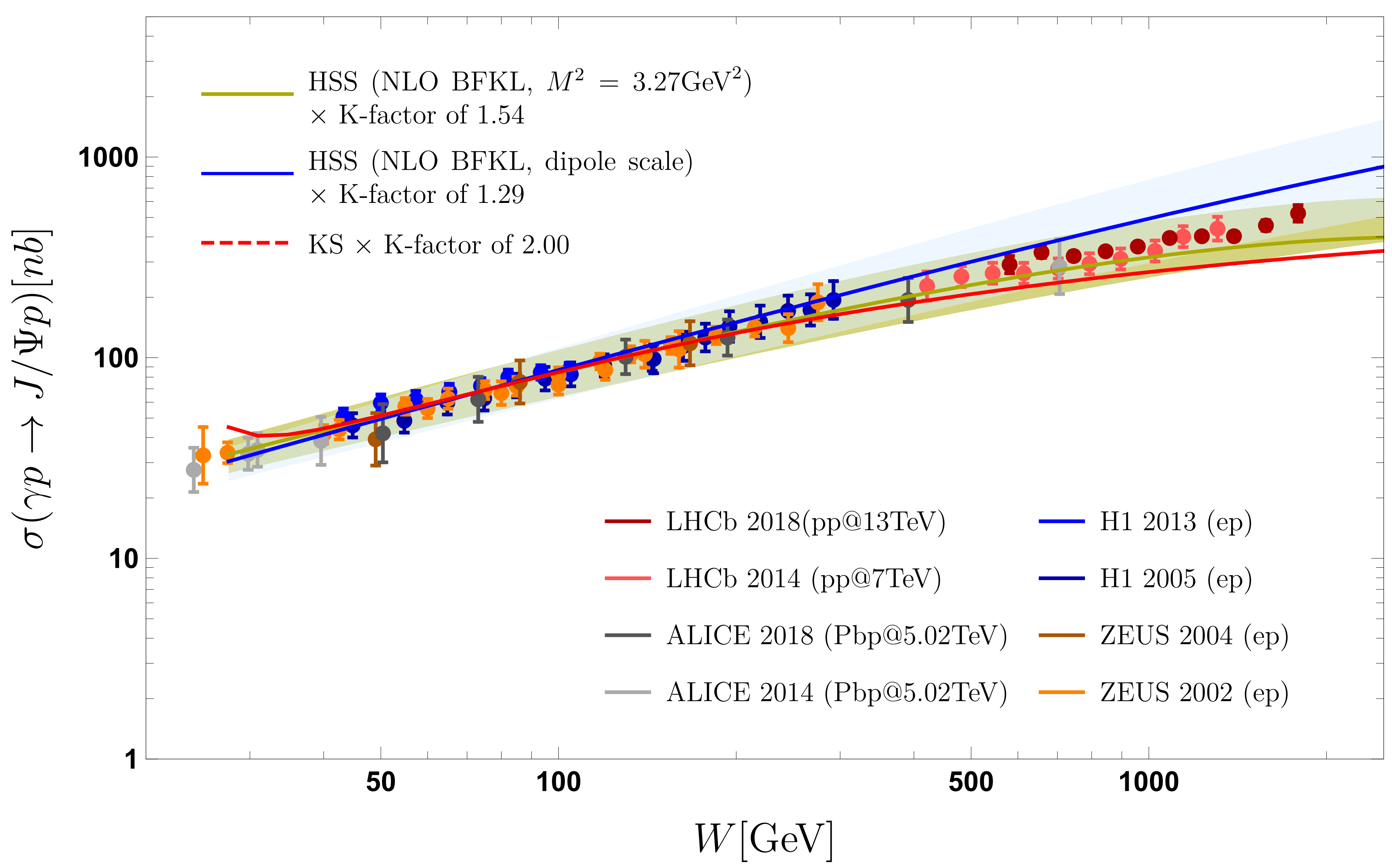
- $\Psi_V(z, \mathbf{p})$ provided as table by authors of [1812.03001; 1901.02664]
- $m_T^2 = m_f^2 + \boldsymbol{p}^2$ , $m_L^2 = 4m_f^2 z(1-z)$,

# $J/\Psi$

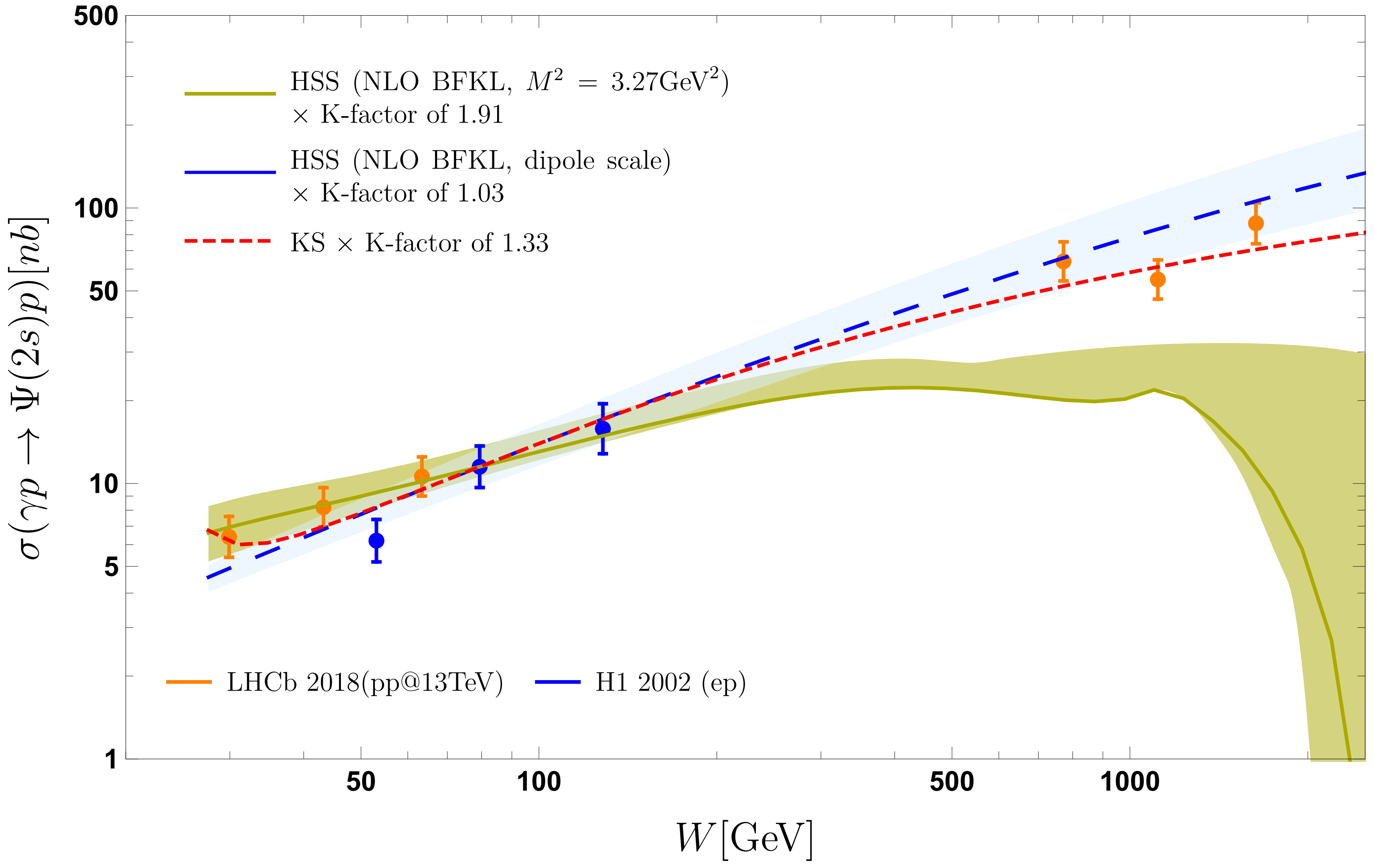
Buchmüller-Tye potential

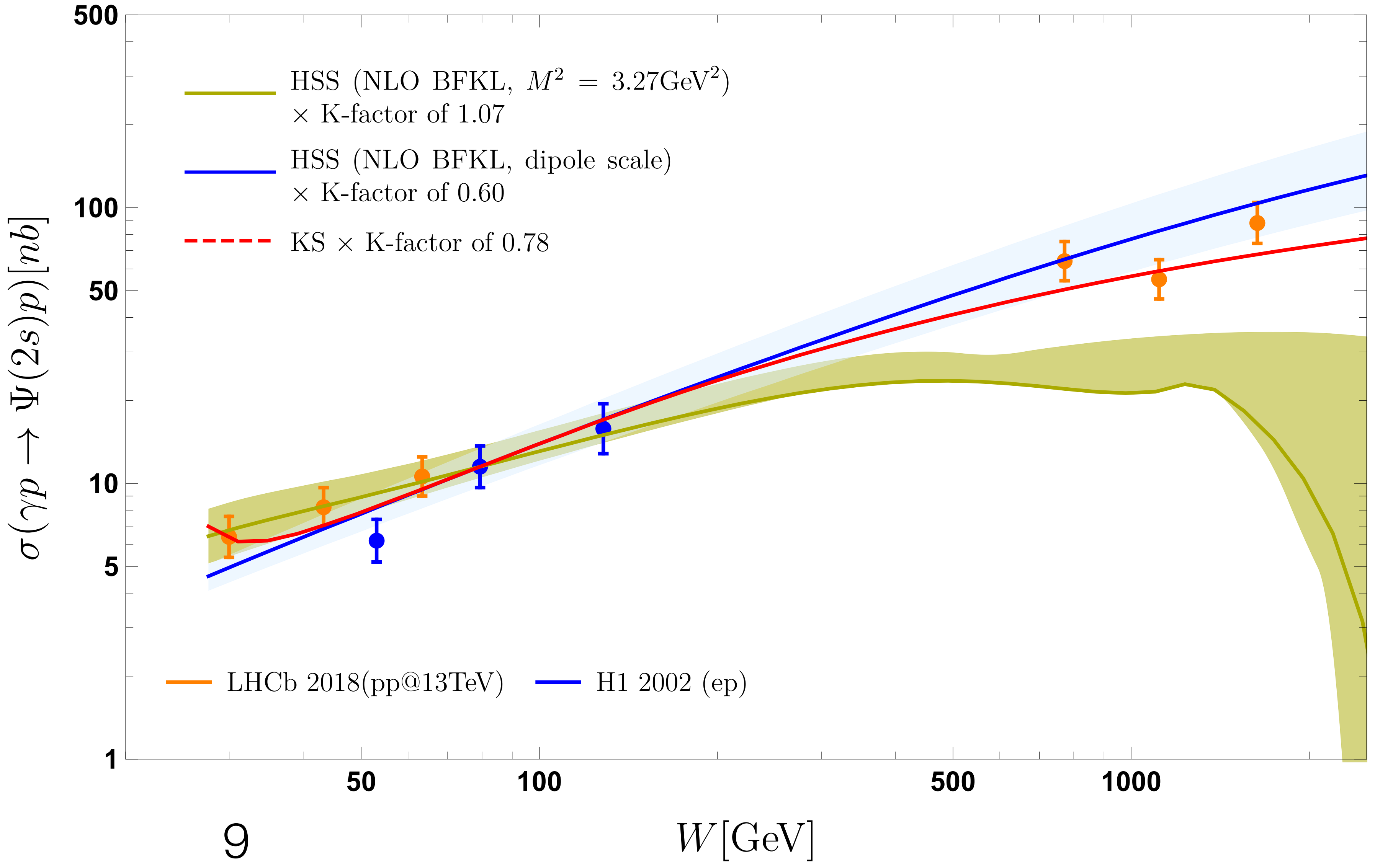



Harmonic Oscillator potential

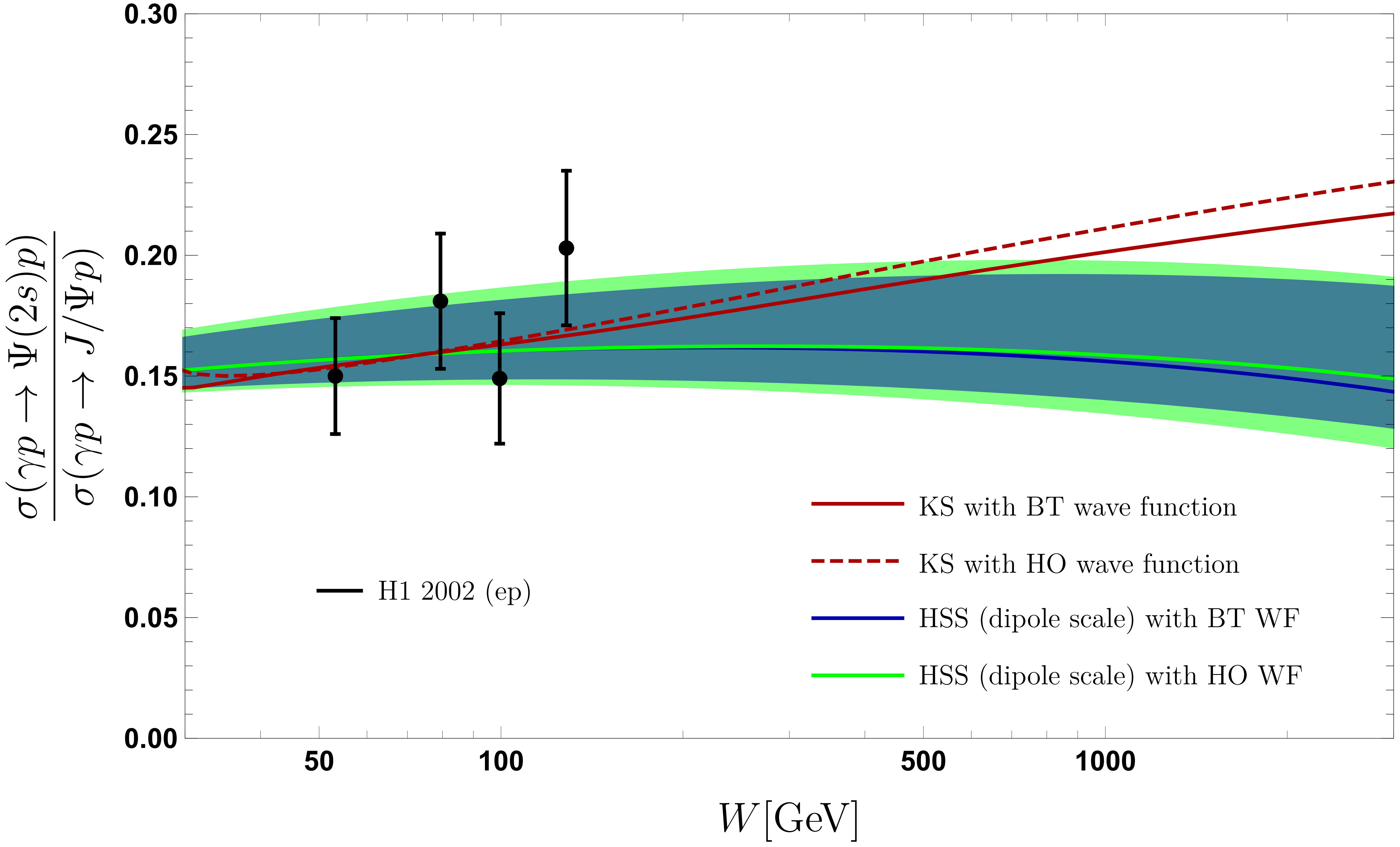



# $\Psi(2s)$



# More interesting: the ratio $\sigma[\Psi(2s)]/\sigma[J/\Psi]$




problem: no data at high energies

($J/\Psi$ 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; 1901.02664] →KST dipole X-section [Kopeliovich, Schäfer, Tarasov, 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 evolution?

# The ratio within the GBW model

work in progress

general feeling: it would be good to understand the observed behavior a bit better
how? use a simple model & see what it tells us

GBW model: [Golec-Biernat, Wusthoff, hep-ph/9807513]

$$\sigma_{q\bar{q}}(x,r) = \sigma_0 \left( 1 - \exp(-\frac{r^2 Q_s^2(x)}{4} \right) \text{ with saturation scale } Q_s^2(x) = Q_0^2 \left( \frac{x}{x_0} \right)^\lambda$$

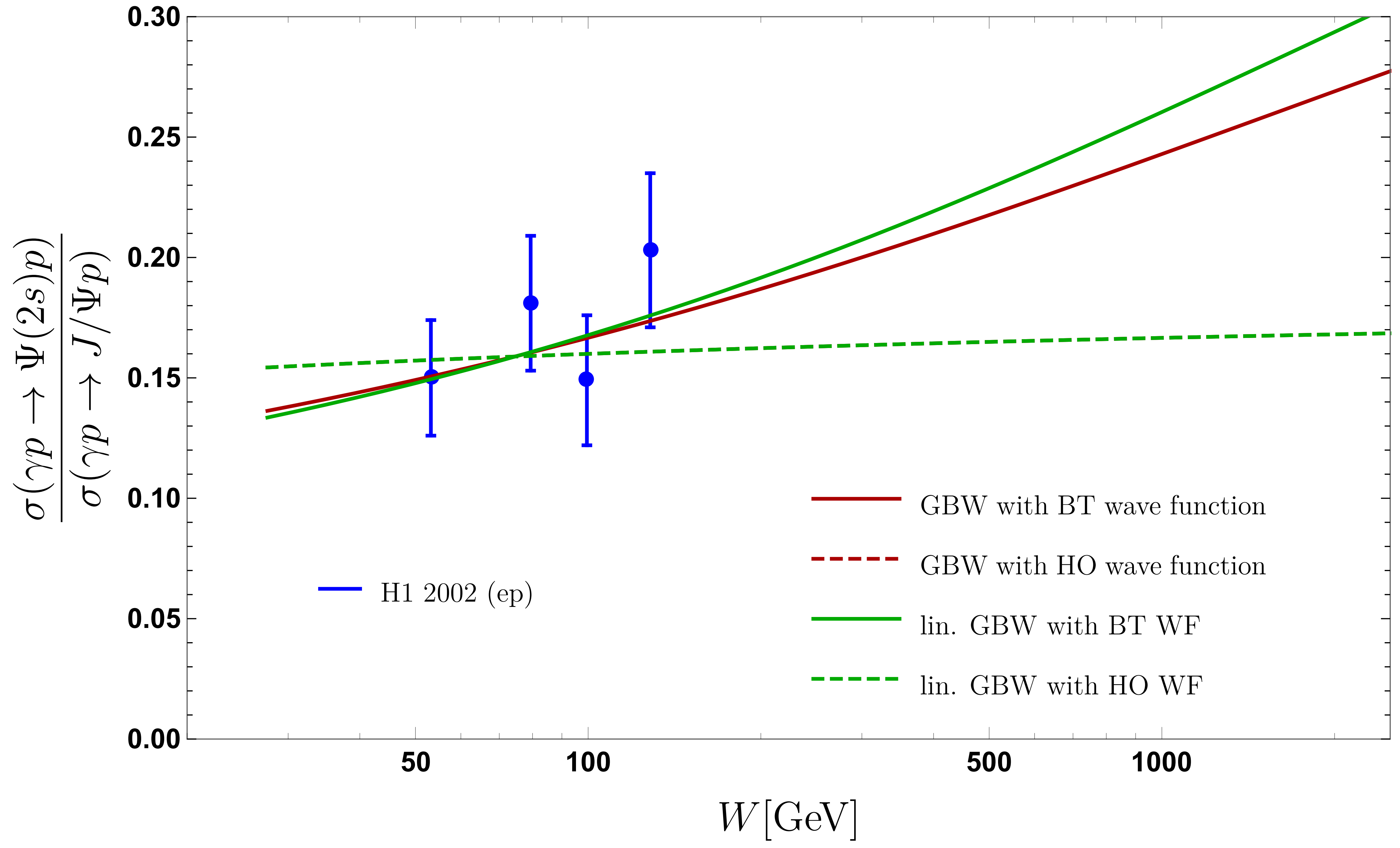
linearized version: $$\sigma_{q\bar{q}}^{lin.}(x,r) = \sigma_0 \frac{r^2 Q_s^2(x)}{4}$$

use most recent fit [Golec-Biernat, Sapeta, 1711.11360] to combined HERA data with $Q^2 \leq 10\text{GeV}^2$ and $\chi^2/N_{dof} = 352/219 = 1.61$

| $\sigma_0[mb]$ | $\lambda$ | $x_0/10^{-4}$ |
|---|---|---|
| 27.43±0.35 | 0.248±0.002 | 0.40±0.04 |

# The ratio for the GBW model

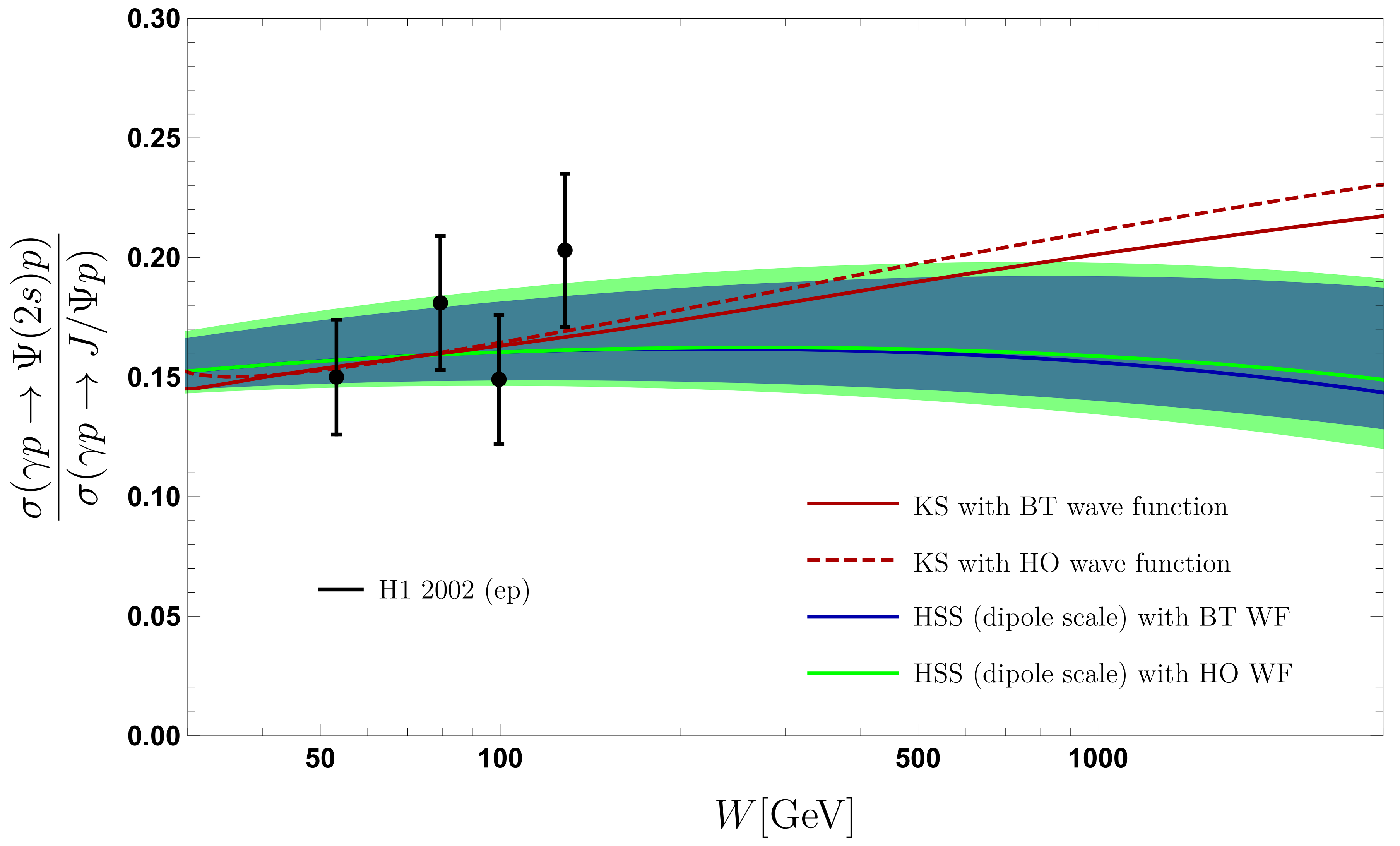
work in progress




- similar behavior as in HSS vs KS study
- complete non-linear GBW is growing
- linearized GBW is constant (no energy dependence → easy explanation)

$$\Im\mathrm{m}\mathscr{A}^{lin.}(x) \sim Q_s^2(x) \cdot \int dr\ldots$$

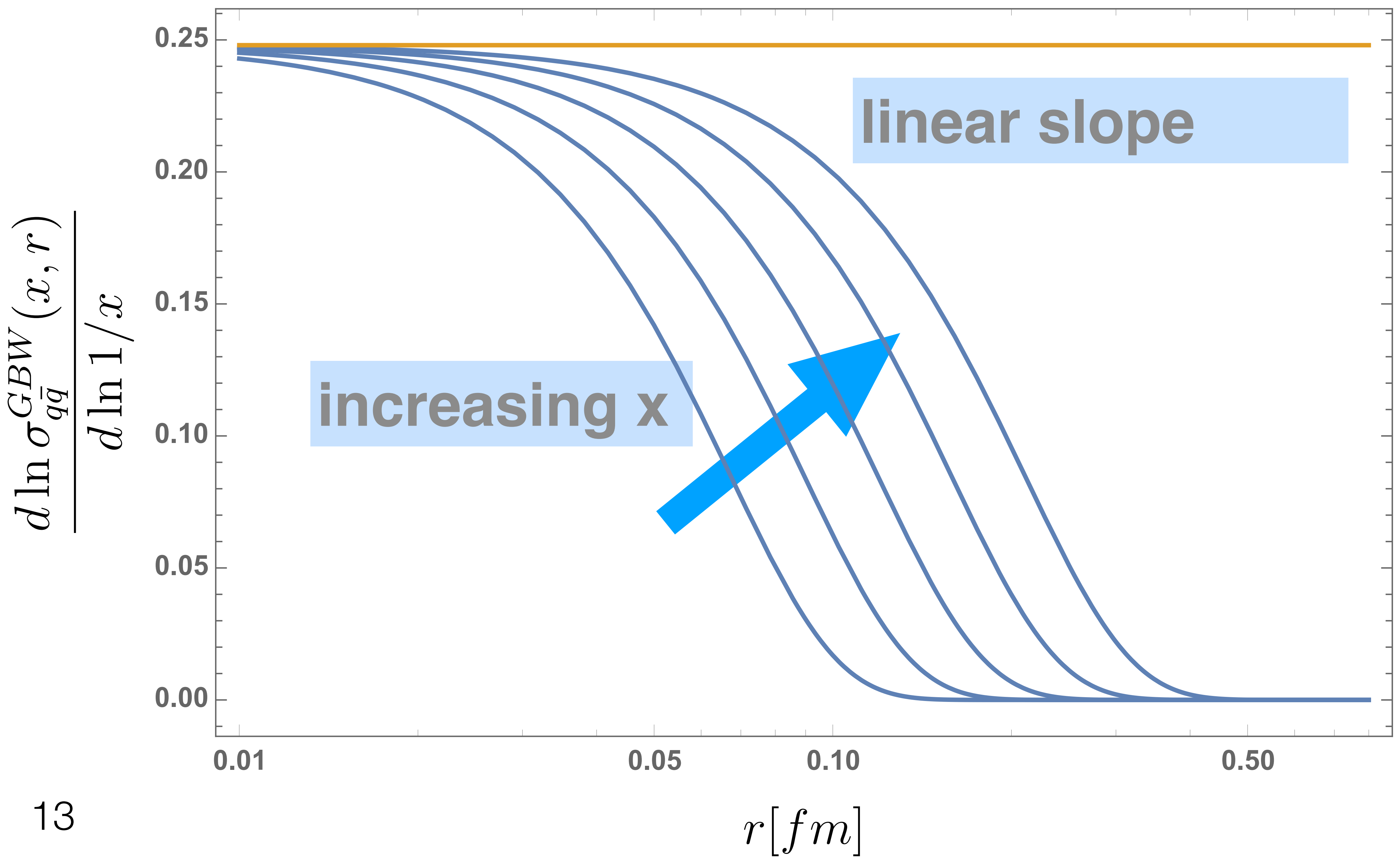
- saturation scale/$x$-dependence does not depend on the size of the vector meson → cancels in the ratio
- BFKL/realistic HERA fit: $x^{-\lambda(Q^2)}$, but ratio is still almost constant
- $Q_{x,p}^2(x) \to Q_{s,A}^2 = A^{\frac{1}{3}} Q_{s,p}^2(x)$: expect similar effect at the EIC



# Conclusion (short)

- despite of all of its challenges: VM production remains a useful observable to quantify presence of non-linear effects in low x evolution equations
- probes different aspects (& suffers different uncertainties) than e.g. angular de-correlation dihadron or dijet → complementary observables
- BFKL vs. BK at LHC:
- Nuclear enhancement within GBW model: a similar effect should be expected for photon-nucleus at *e.g.* the EIC

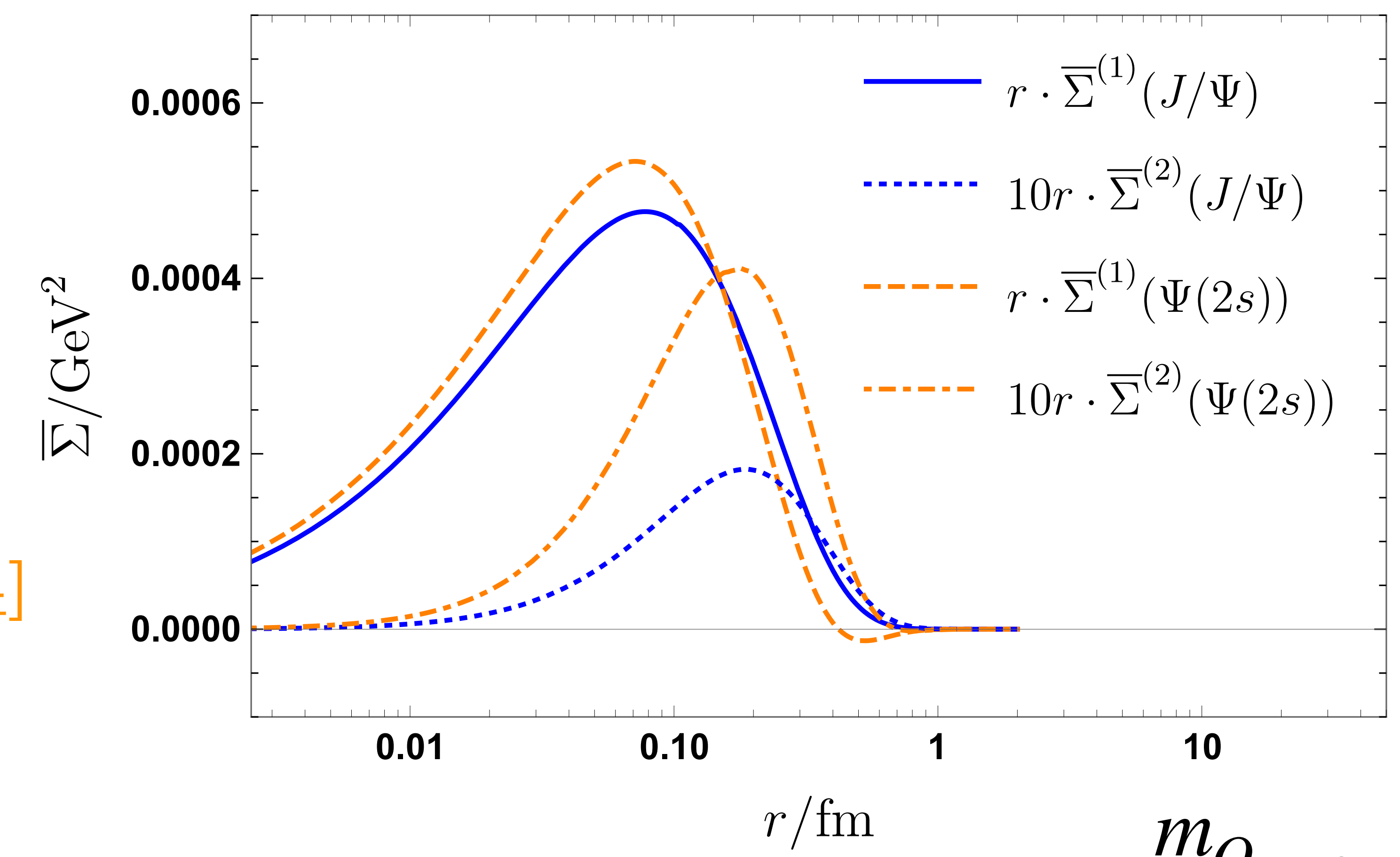
- central point: if $\Im\mathrm{m}\mathscr{A}_{lin.} \sim x^{-\lambda}$ with → energy dependence cancels → approximately constant ratio
- non-linear $\lambda^{J/\Psi} \simeq \lambda^{\Psi(2s)}$r model/evolution: with $\sigma_{q\bar{q}}(x, r) \sim x^{-\lambda(x,r)}$, slope $\lambda$-very sensitive to dipole size
- more complete study in progress



# Appendix

# potentials for wave functions:

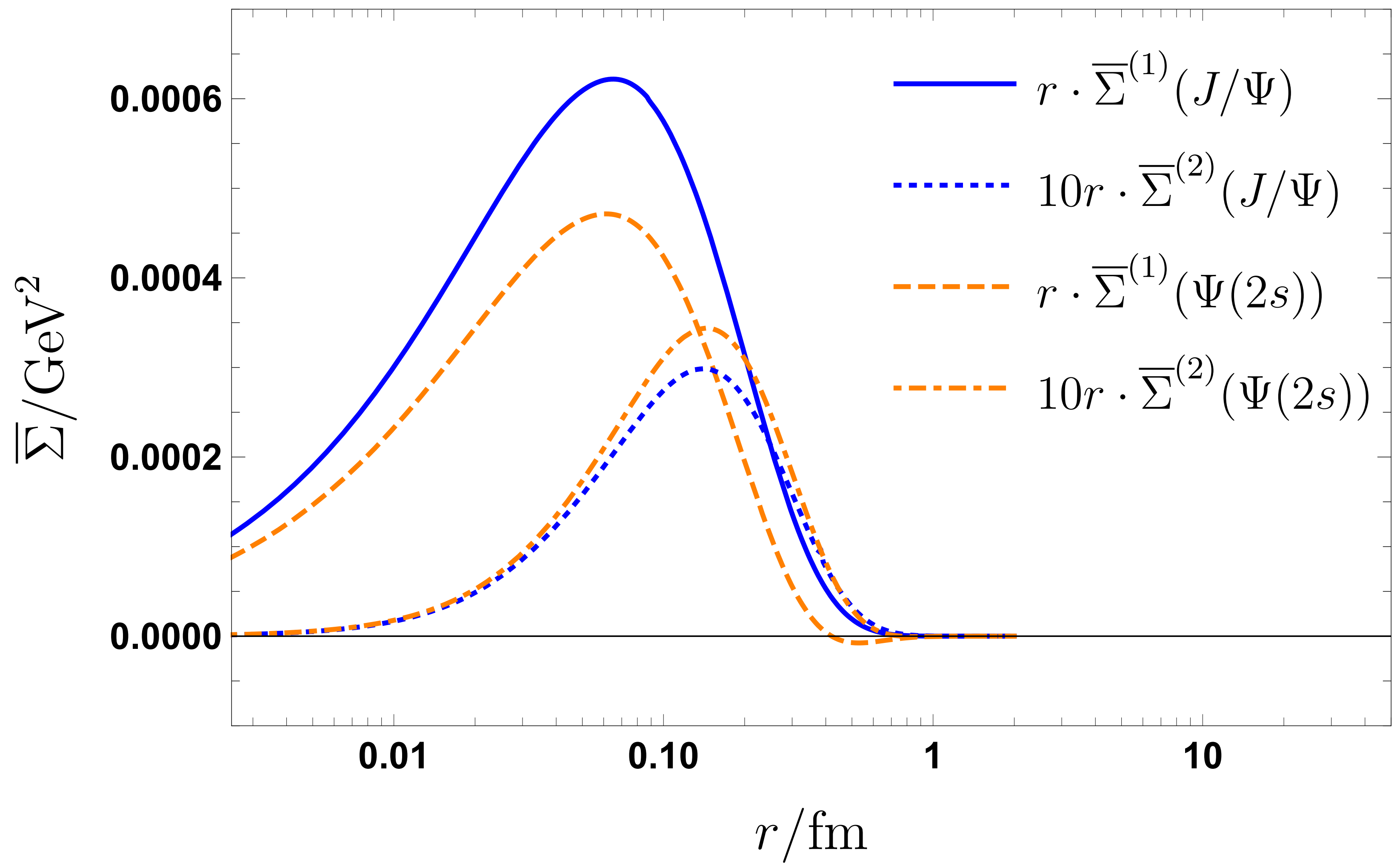
as implemented in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; 1812.03001; 1901.02664]




harmonic oscillator (HO): $U(r) = \dfrac{m_Q}{2}\omega^2 r^2$

$\omega = 0.3$GeV→ Gaussian shape

Note:
- plots show transition function $\gamma \to VM$, not wave function
- $\Psi(2s)$: 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




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

→ requires separate diffractive slopes $B_D(W)$ as obtained in [M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; 1812.03001; 1901.02664]

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

# how to compare to experiment?

(sort of standard procedure for comparing inclusive gluon to exclusive data)

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:

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

c) from experiment:

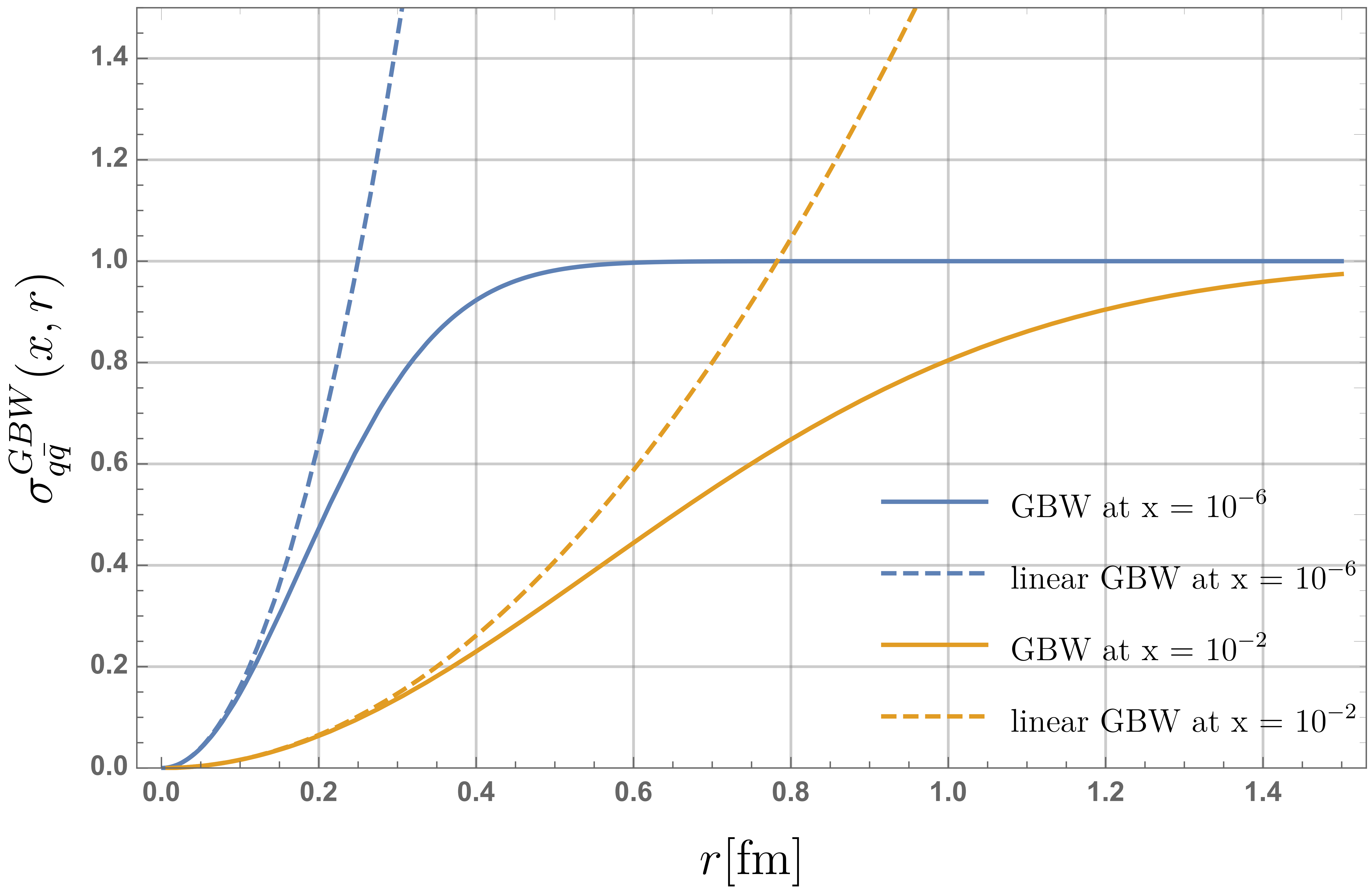
$$\frac{d\sigma}{dt}(\gamma p \to Vp) = e^{-B_D(W)\cdot|t|} \cdot \frac{d\sigma}{dt}(\gamma p \to Vp)\bigg|_{t=0}$$

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

extracted from data

weak energy dependence from slope parameter

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



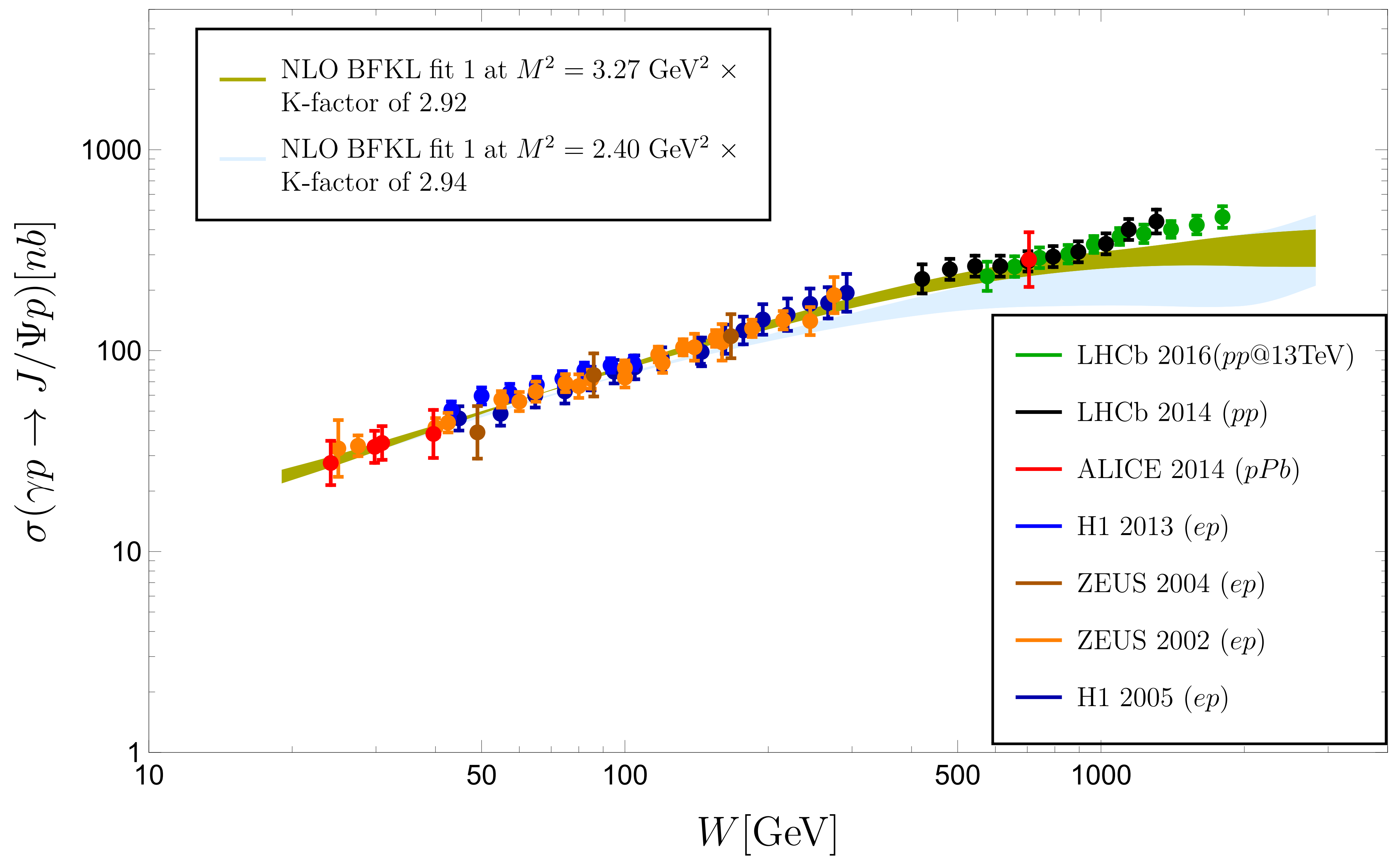

work in progress

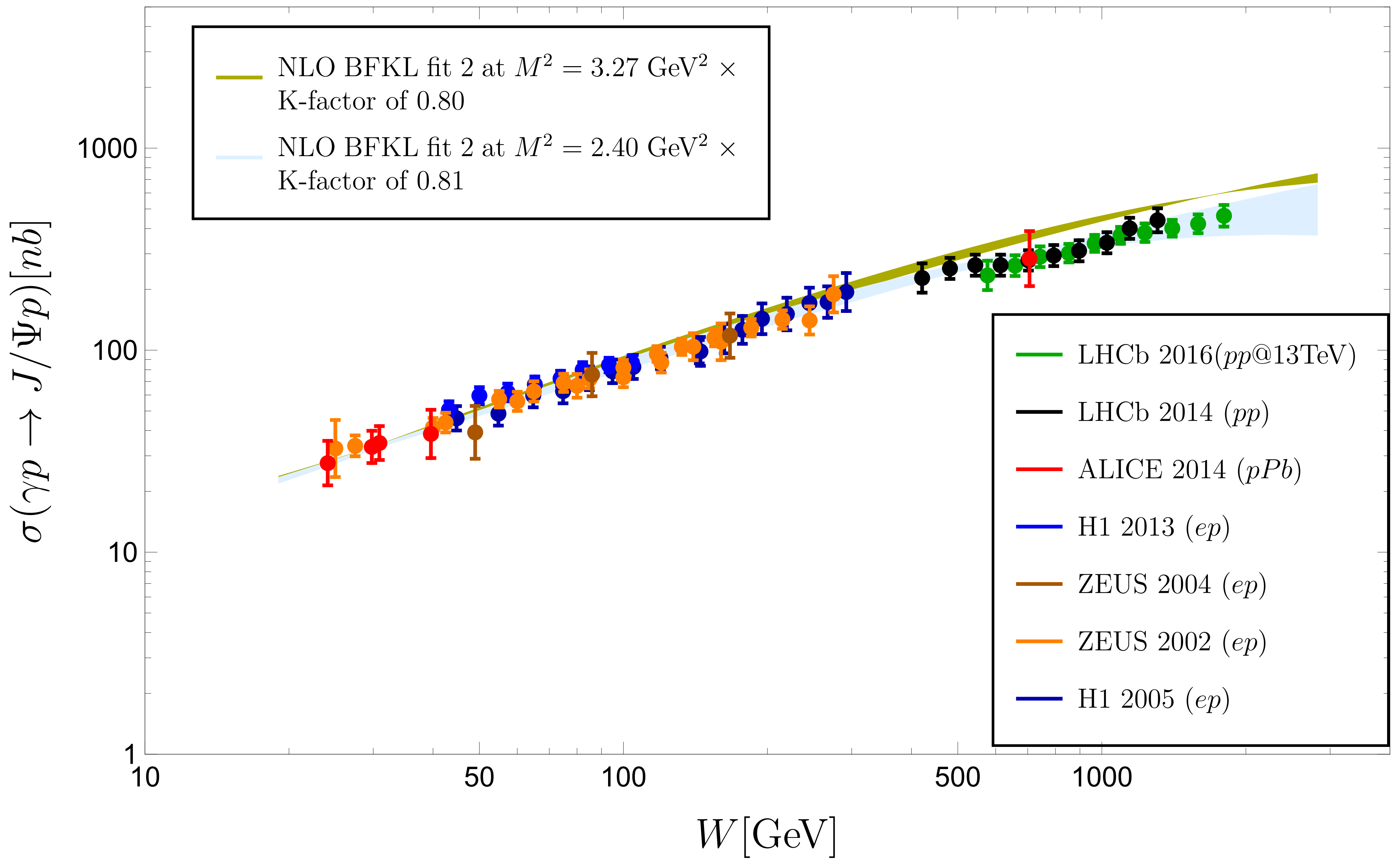
- as expected linear and complete GBW model agree for small dipole sizes
- for large dipole sizes linearized version breaks overshoots complete saturation model

# First study (BFKL only, also for $\Upsilon$)

[Bautista, MH, Fernandez-Tellez;1607.05203]

NLO BFKL describes energy dependence, but .....




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

…but error blows up for highest energies

does it mean something?