Exclusive photo production of charmonium as a tool to distinguish linear and non-linear QCD evolution

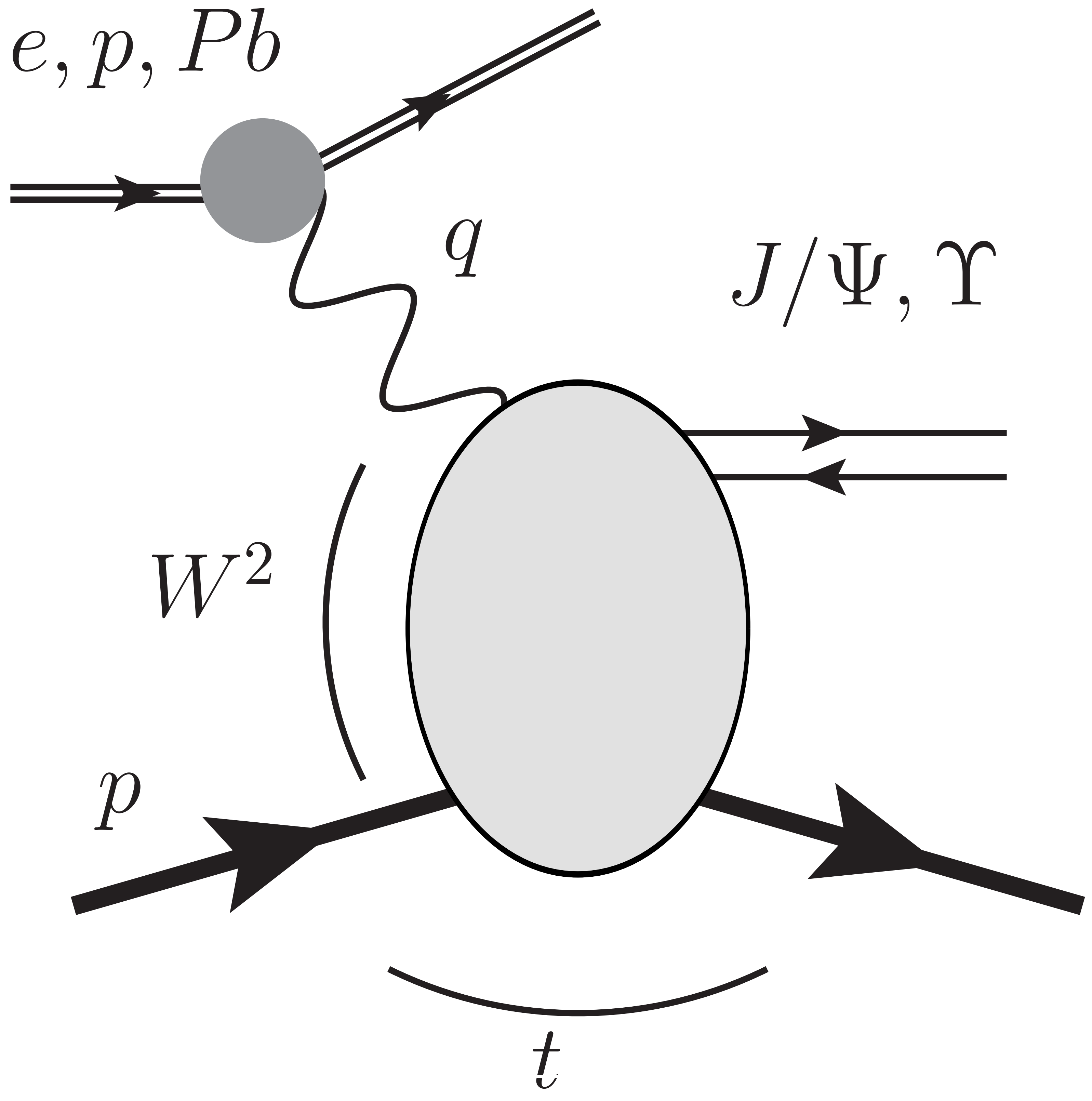
Martin Hentschinski
Universidad de las Americas Puebla
Ex-Hacienda Santa Catarina Martir S/N
San Andrés Cholula
72820 Puebla, Mexico
martin.hentschinski@gmail.com

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, *Phys.Rev.D* 103 (2021) 7, 074008 arXiv:2011.02640
- Alcazar Peredo, MH, in preparation

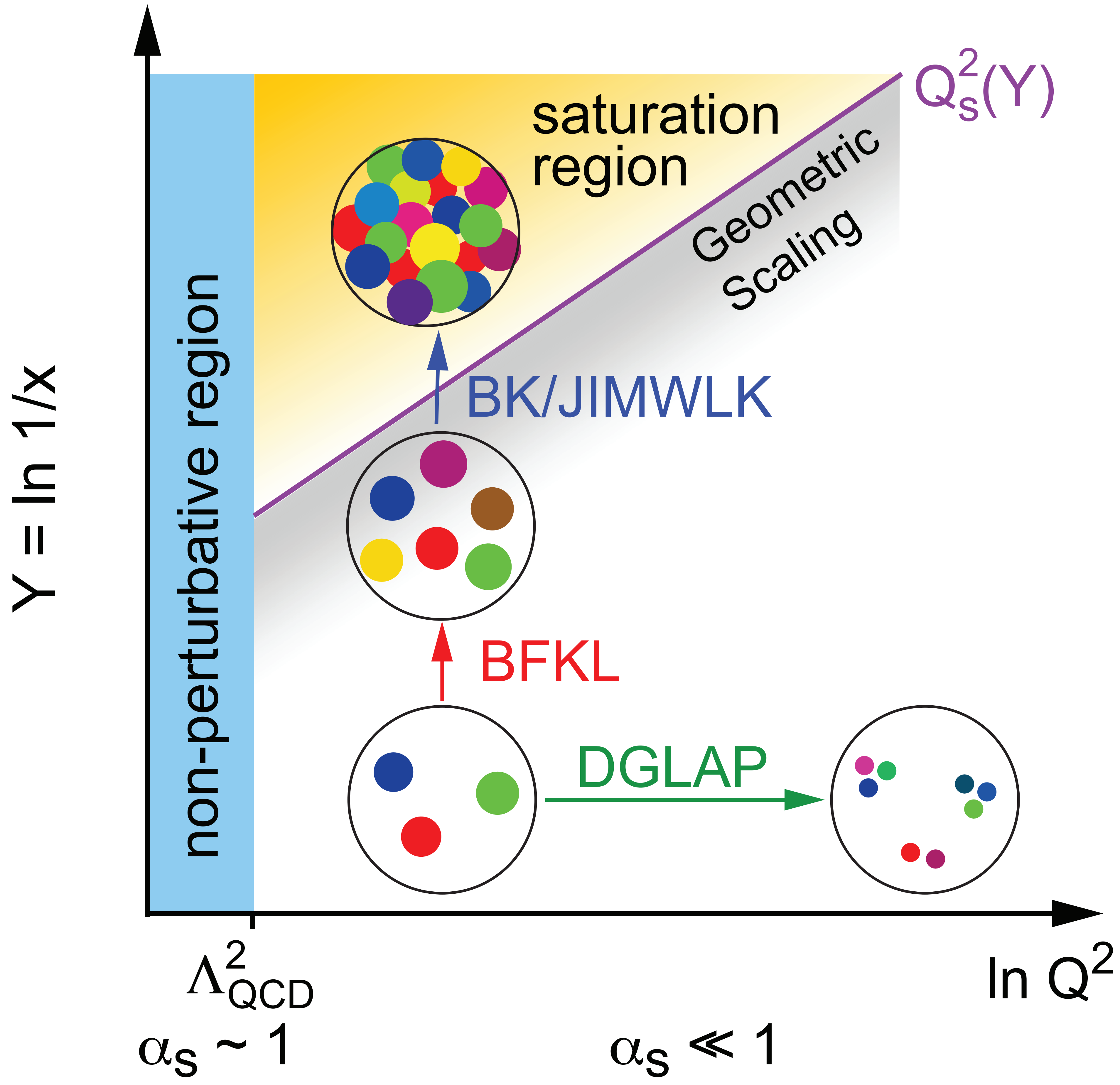
DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects,
May 2-6 2022, Santiago de Compostela, Spain

photo induced exclusive photo-production of J/Ψs and $\Psi(2s)$



- 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)

Goal: confront linear vs. non-linear QCD evolution



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

[related to gluon distribution]

kernel calculated in pQCD

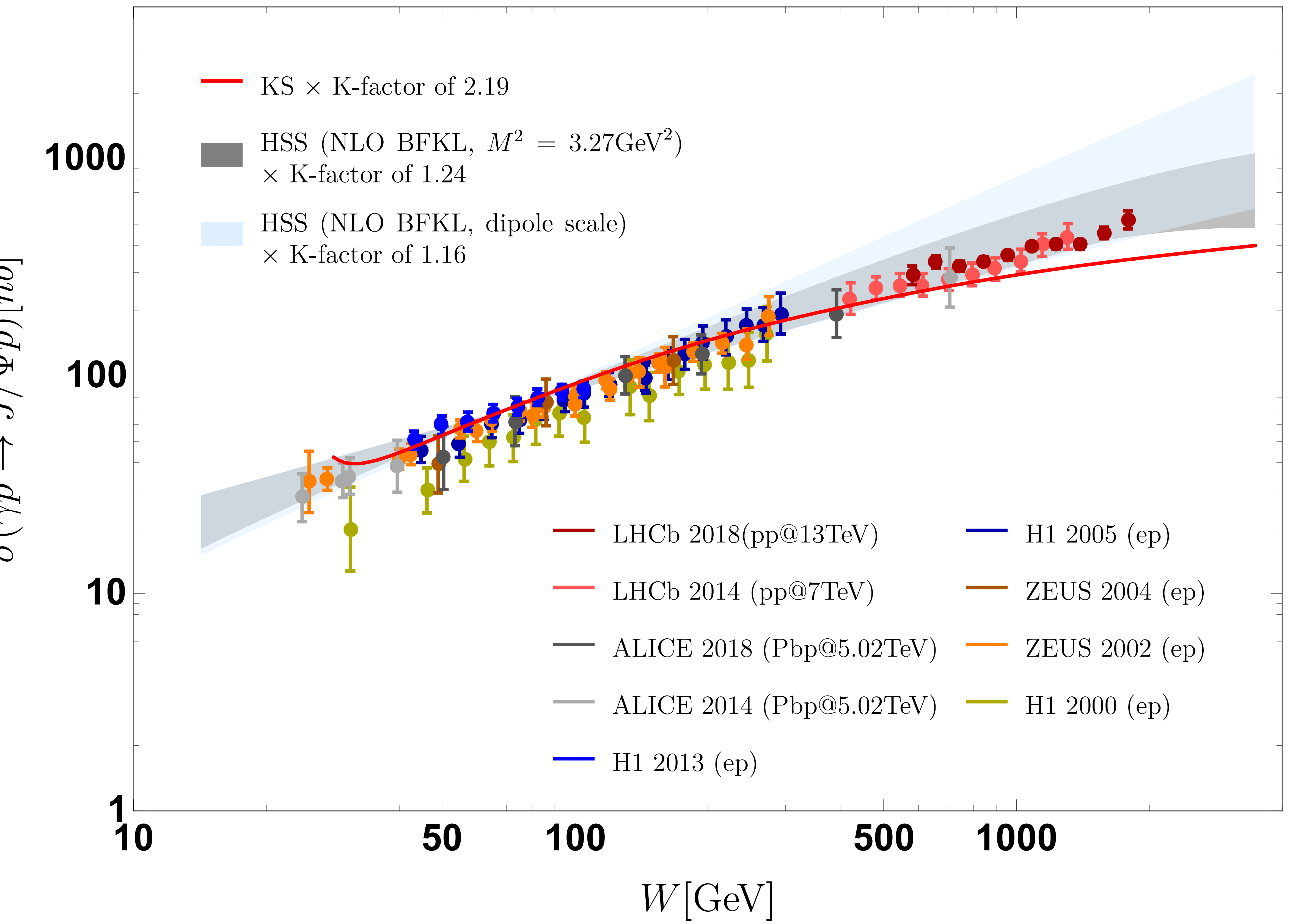
$$\frac{dN(x,r)}{d\ln\frac{1}{x}} = \int d^2\boldsymbol{r}_1 K(\boldsymbol{r},\boldsymbol{r}_1) \boxed{[N(x,r_1) + N(x,r_2) - N(x,r)} - \boxed{N(x,r_1)N(x,r_2)]}$$

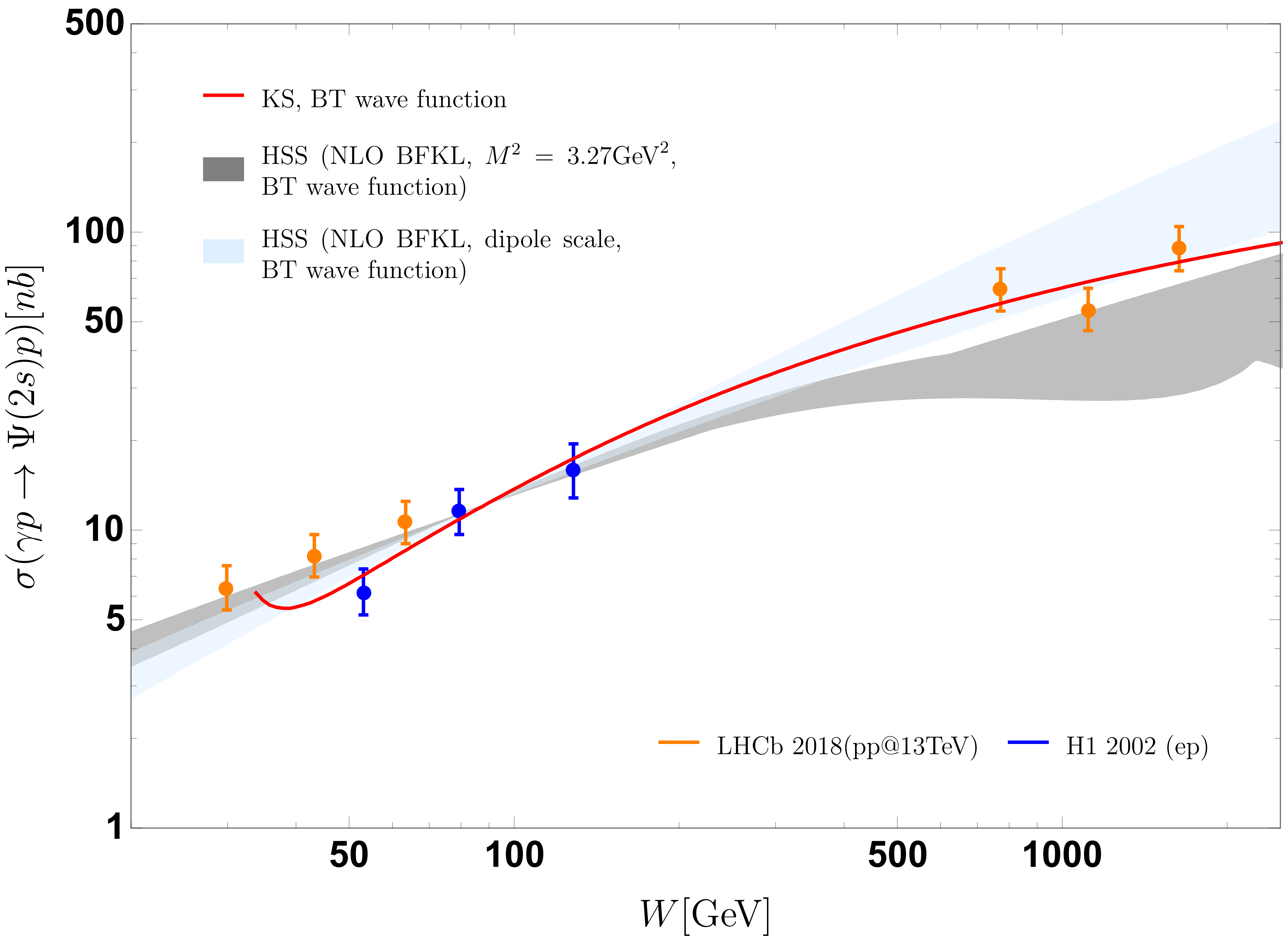
linear BFKL evolution = subset of complete BK

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

Observation:

- very similar energy dependence predicted by linear and non-linear QCD evolution for total photo-production cross-section of J/Ψ and $\Psi(2s)$
- Within uncertainties: can't distinguish

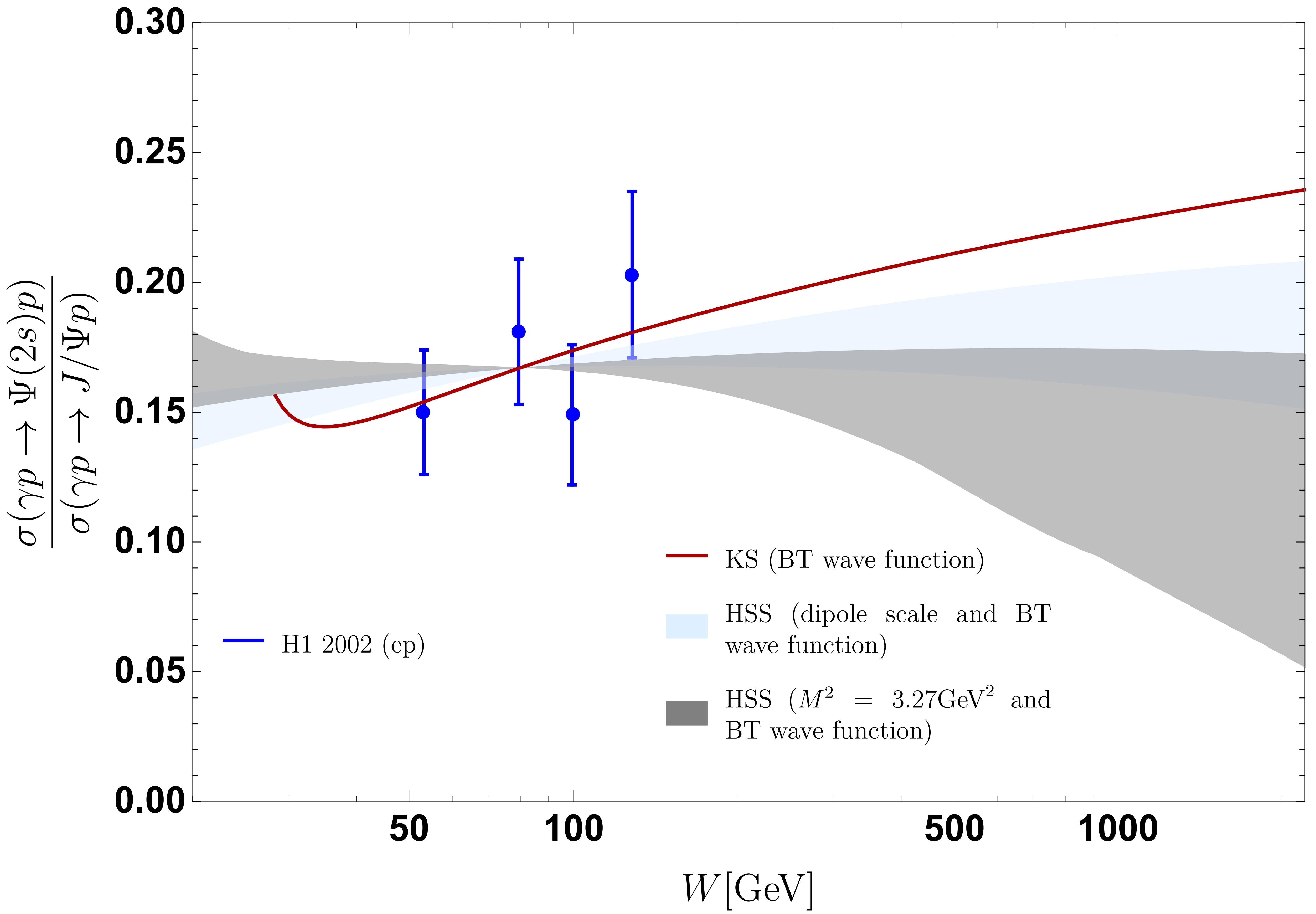




Shown: linear NLO BFKL (HSS) [MH, Salas, Sabio Vera; 1209.1353; 1301.5283] and non-linear BK (KS) [Kutak, Sapeta; 1205.5035]

Observation:

- very similar energy dependence predicted by linear and non-linear QCD evolution for total photo-production cross-section of J/Ψ and $\Psi(2s)$
- But differs for the ratio $\sigma(J/\Psi)/\sigma(\Psi(2s))$



- non-linear KS gluon (subject to BK evolution): growing ratio
- Linear HSS gluon (subject to NLO BFKL evolution): approximately constant ratio

- also: unstable fixed scale HSS gives decaying ratio: related to enhanced IR contribution for the $\Psi(2s)$

Why is this happening?

Very clear for the GBW model

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

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

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

The ratio for the GBW model

Cross-section:

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

And

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

$$\boxed{\sigma_{q\bar{q}}^{GBW}(x,r) = \sigma_0\left(1-\exp(-\frac{r^2Q_s^2(x)}{4}\right)}$$

From scattering amplitude:

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

Recall:

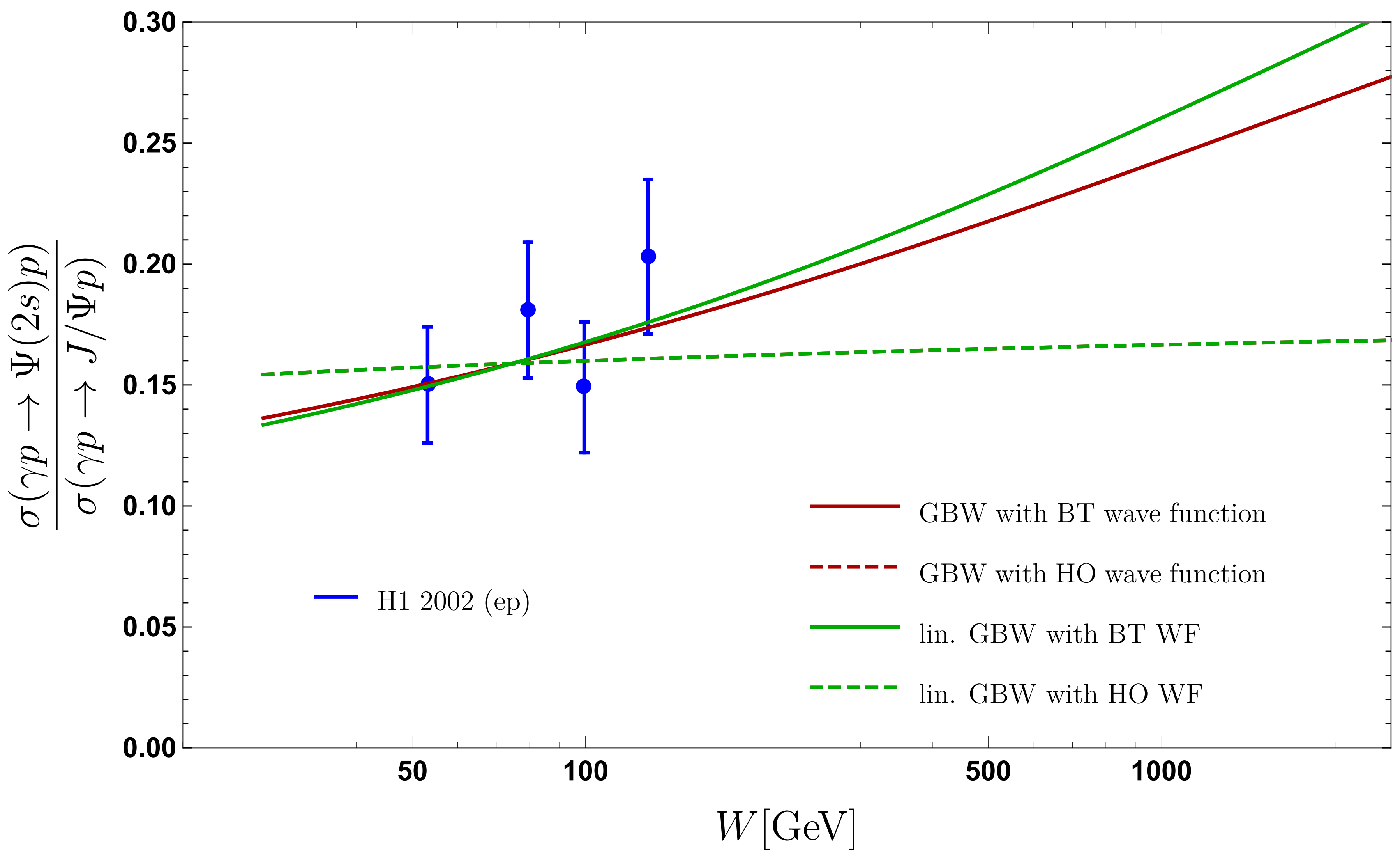
For **LINEAR** GBW

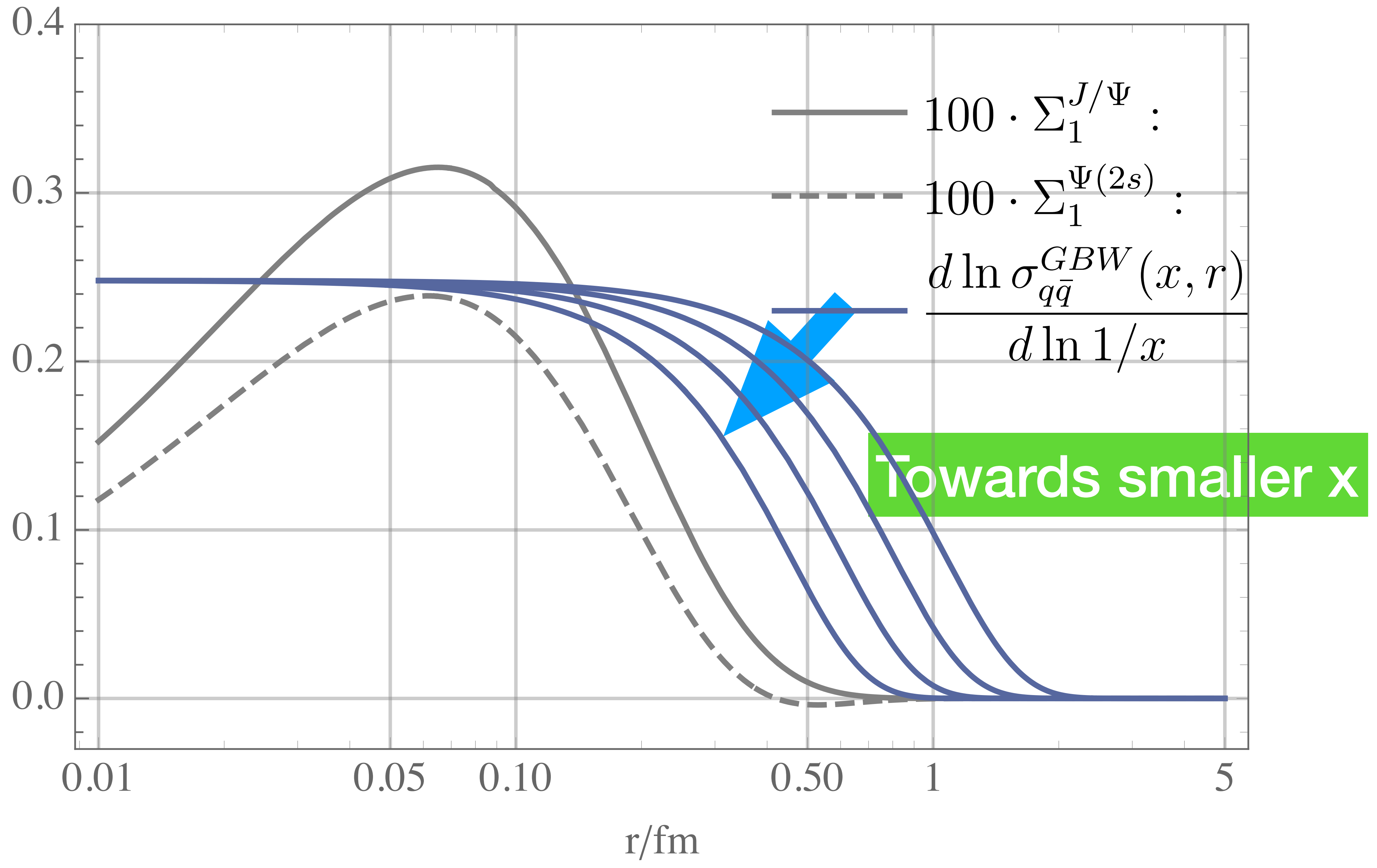
$$\Im\mathrm{m}\mathscr{A}^{lin.}(x) \sim Q_s^2(x)\cdot\int dr\ldots$$

- $Q_s(x) = Q_s(M_V^2/W^2)$ cancels for the ratio
- Ratio constant with energy for **linear GBW**

Complete GBW: non-trivial r-dependence → different energy dependence for different VM

The ratio: GBW model

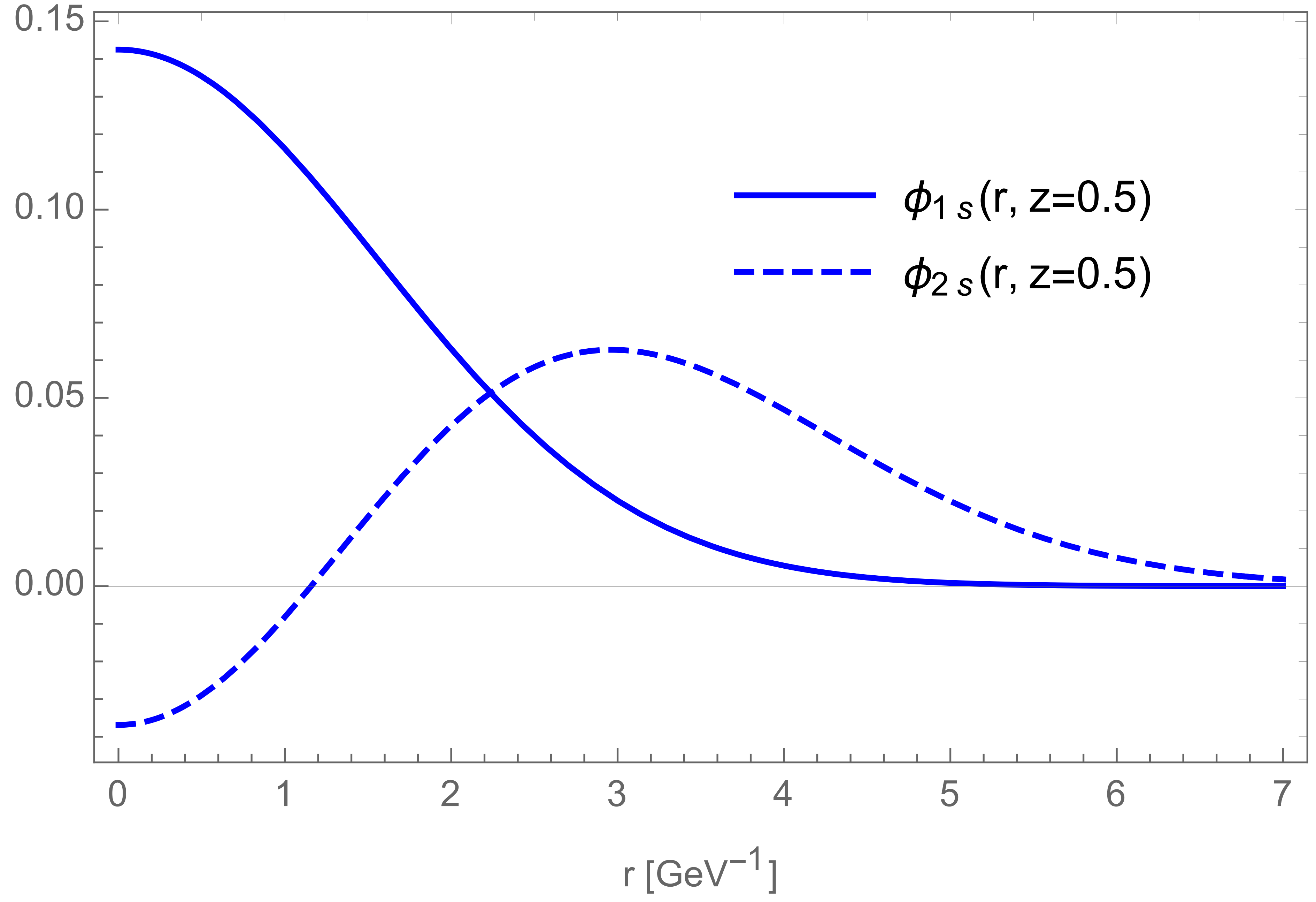




r-dependence of the "slope" $\frac{d \ln \sigma_{q\bar{q}}}{\ln 1/x}$

- for linear model x-dependence in $Q_s^2(x) = Q_0^2 \left(\frac{x}{x_0}\right)^\lambda$ we have $\frac{d \ln \sigma_{q\bar{q}}}{\ln 1/x} = \lambda$=const.
- Non-trivial r-dependence for complete GBW model → rise of the ratio

What causes the difference for $\Psi(2s)$ and J/Ψ?



- Node of the 2s state
- Makes this state (somehow counter-intuitively) more perturbative (cancellation)
- Noted before [J. Nemchik, N.N. Nikolaev, E. Predazzi, B.G. Zakharov V.R. Zoller; J. Exp. Theor. Phys. 86, 1054 (1998)] and [Cepila, Nemchik, Krelina, Pasechnik; 1901.02664]

Here:

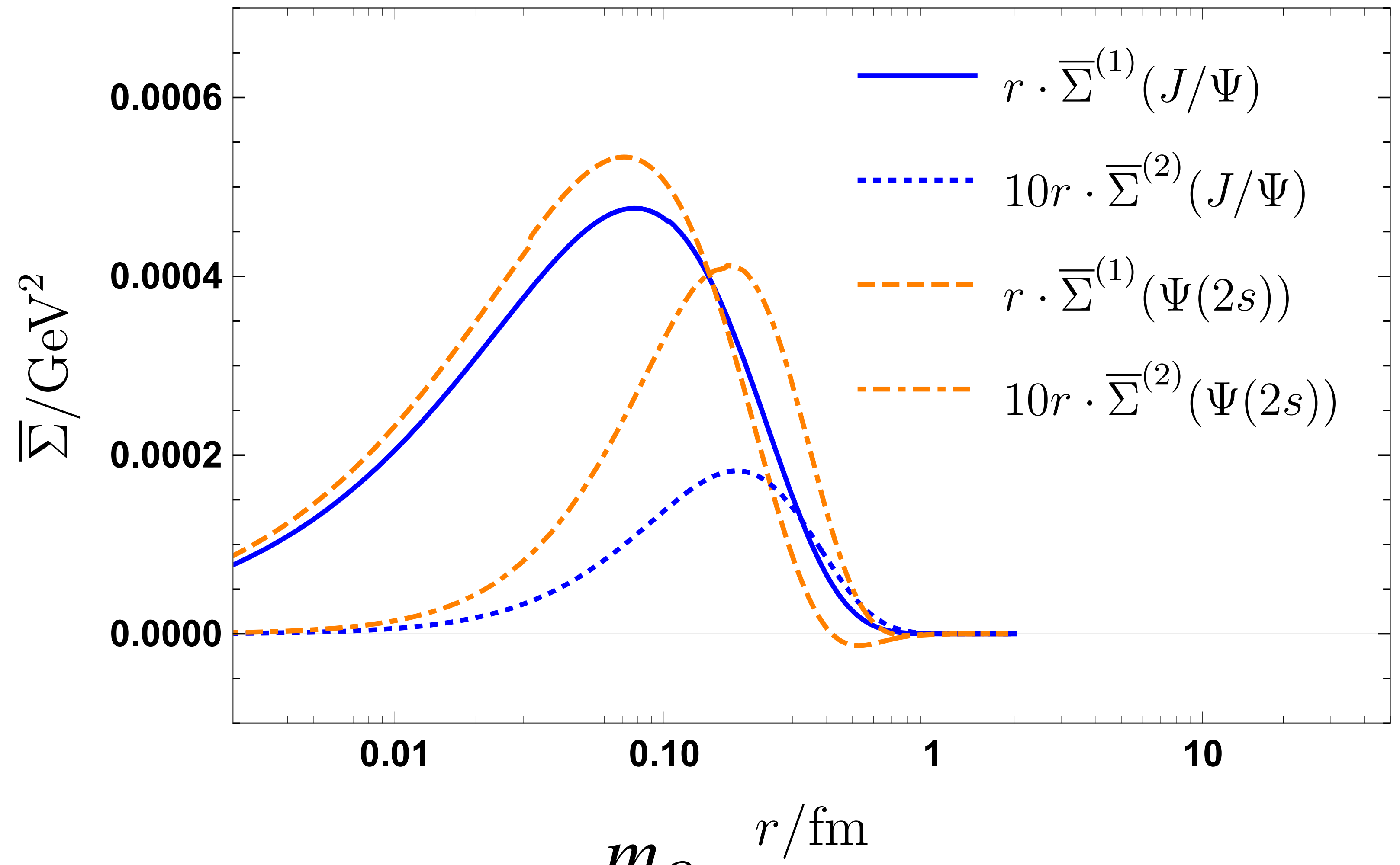
- Gaussian model, next slide: numerical solution to Schrödinger equation etc.
- In common: position of node somehow constraint through charm mass

Wave function overlap for $\Psi(2s)$ and J/Ψ?

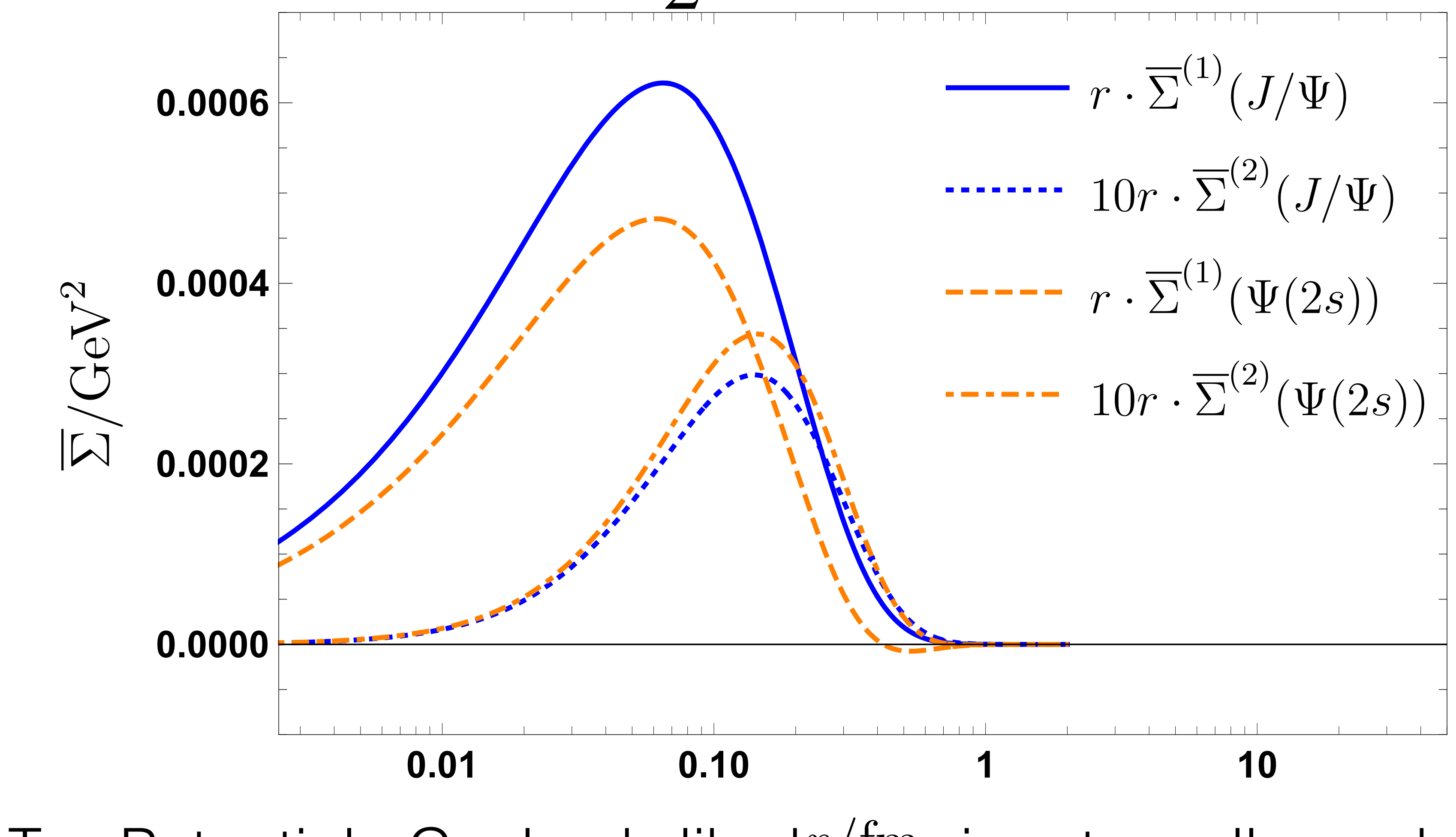
- Need to produce VM from photon
- Reduces size of node, but enhanced, once multiplied with dipole cross-section

Here: use wave function overlap as provided by
[M. Krelina, J. Nemchik, R. Pasechnik, J. Cepila; 1812.03001; 1901.02664]

- includes relativistic spin rotation effects + (more) realistic $c\bar{c}$ potential
- Obtained from numerical solution to non-relativistic Schrödinger equation & boosted
- Also seen for simple boasted Gaussian

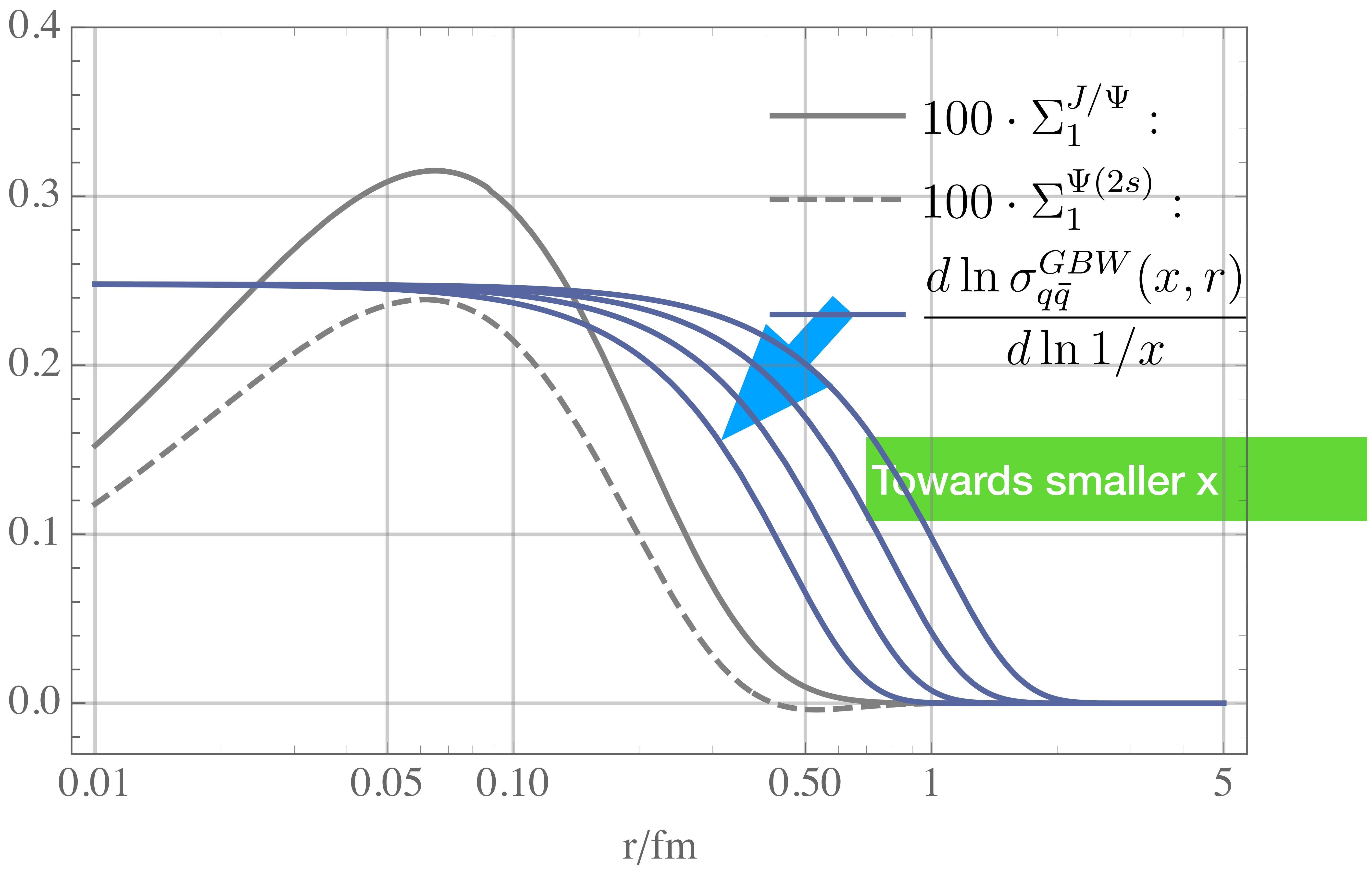


harmonic oscillator (HO): $U(r) = \dfrac{m_Q}{2}\omega^2 r^2$



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

The role of the node for slope λ where $\sigma_{q\bar{q}} \sim x^{-\lambda}$



- small, but relevant where linear and non-linear differ
- Recall: slope of linear GBW = a line at 0.248

A less trivial model: The DGLAP improved saturation model

[Bartels, Golec-Biernat, Kowalski; hep-ph/0203258]

Essentially the GBW model with DGLAP evolution

$$\sigma_{\rm dip}(r,x) = \sigma_0 \left\{ 1 - \exp\left(-\frac{\pi^2 r^2\, \alpha_s(\mu^2)\, xg(x,\mu^2)}{3\sigma_0} \right) \right\} ;$$

Factorization scale originally: $$\mu^2 = \frac{C}{r^2} + \mu_0^2 \,.$$

Recent fit: $$\mu^2 = \frac{\mu_0^2}{1 - \exp(-\mu_0^2\, r^2/C)}$$

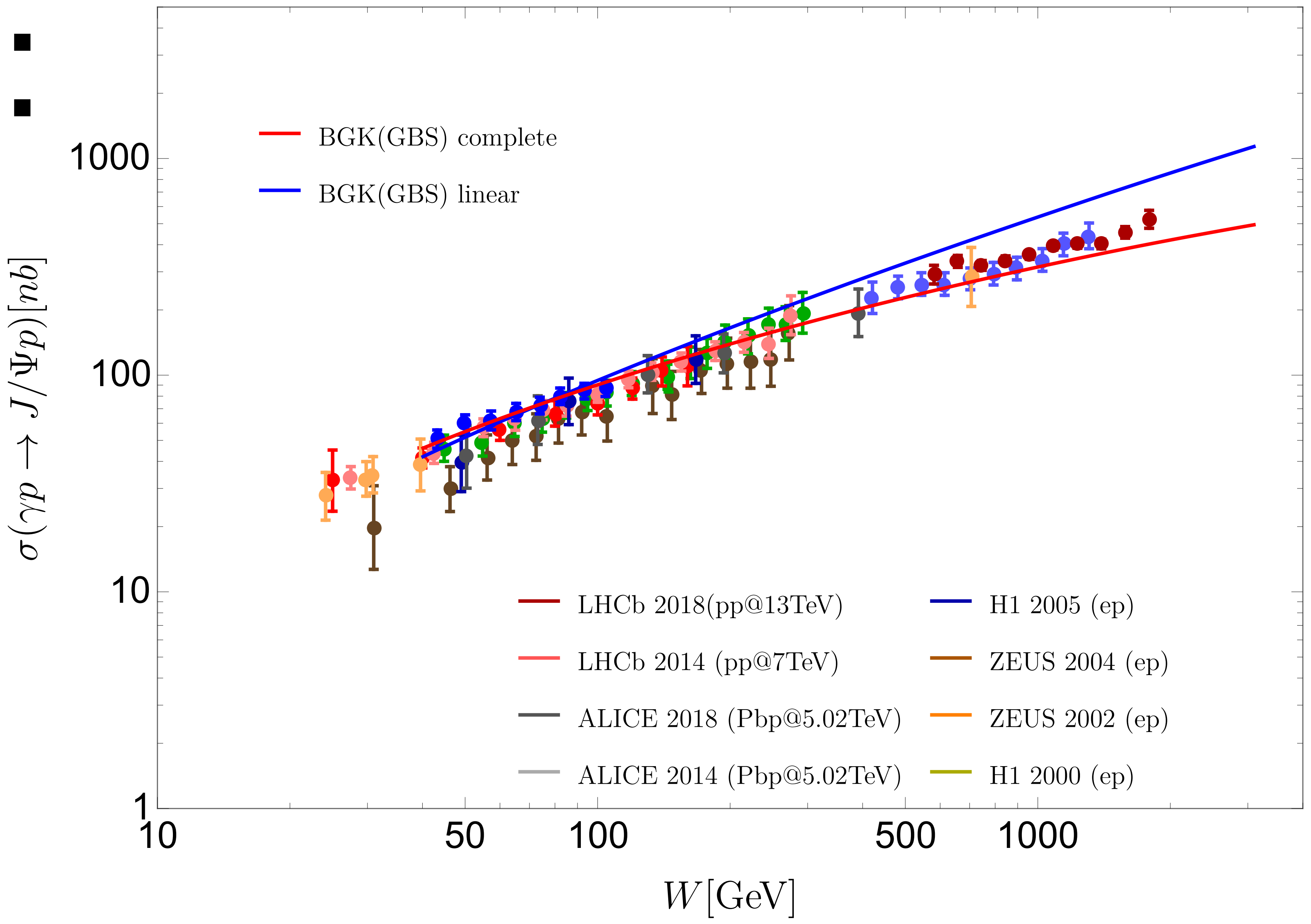
[Golec-Biernat, Sapeta; 1711.11360]

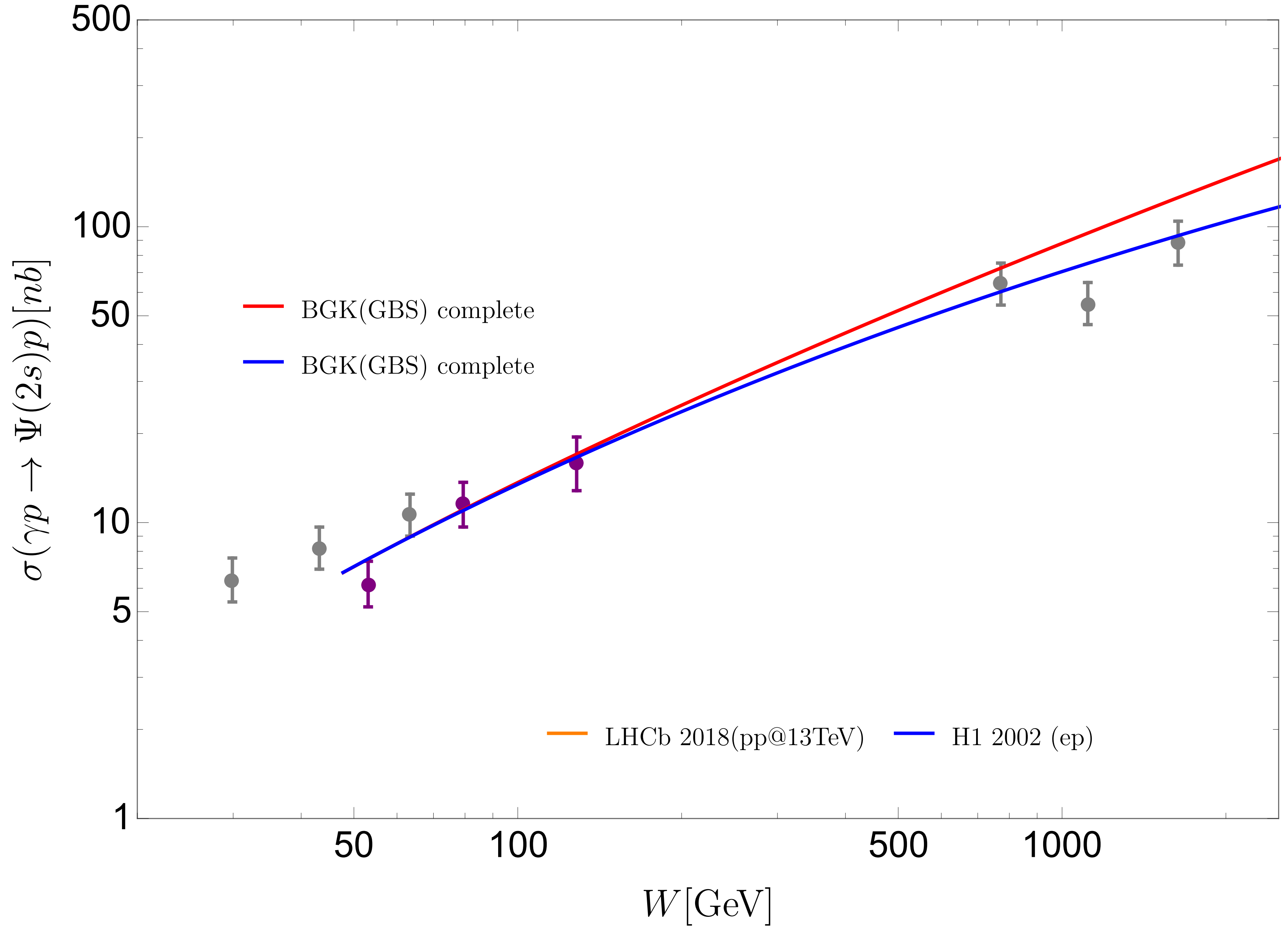
In common:
- for large dipole sizes r, $\mu \to \mu_0$
- Otherwise $\sim C/r^2$

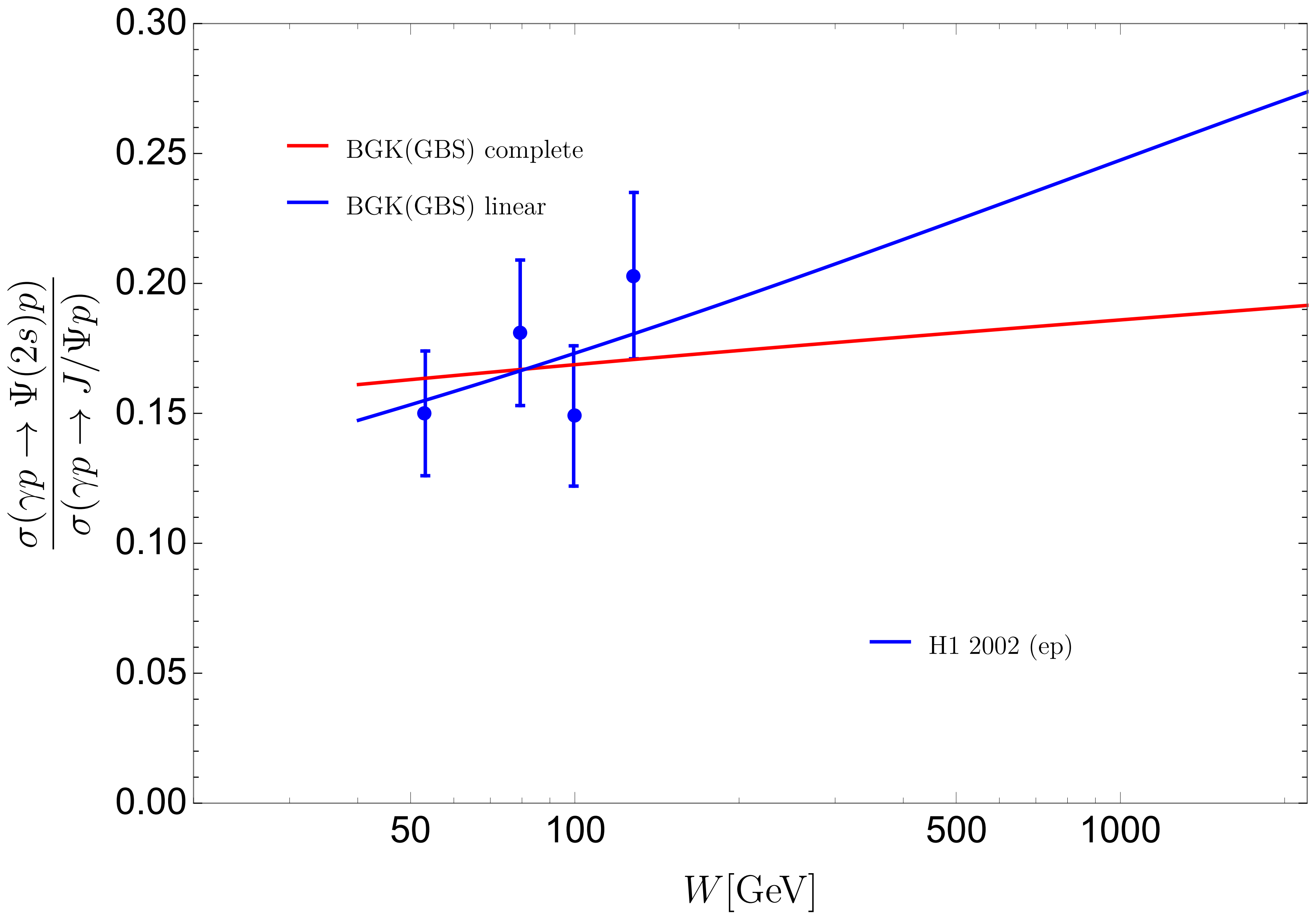
Saturation scale becomes r-dependent → includes correct DGLAP limit for small r

Complementary to BFKL/BK study

Results:

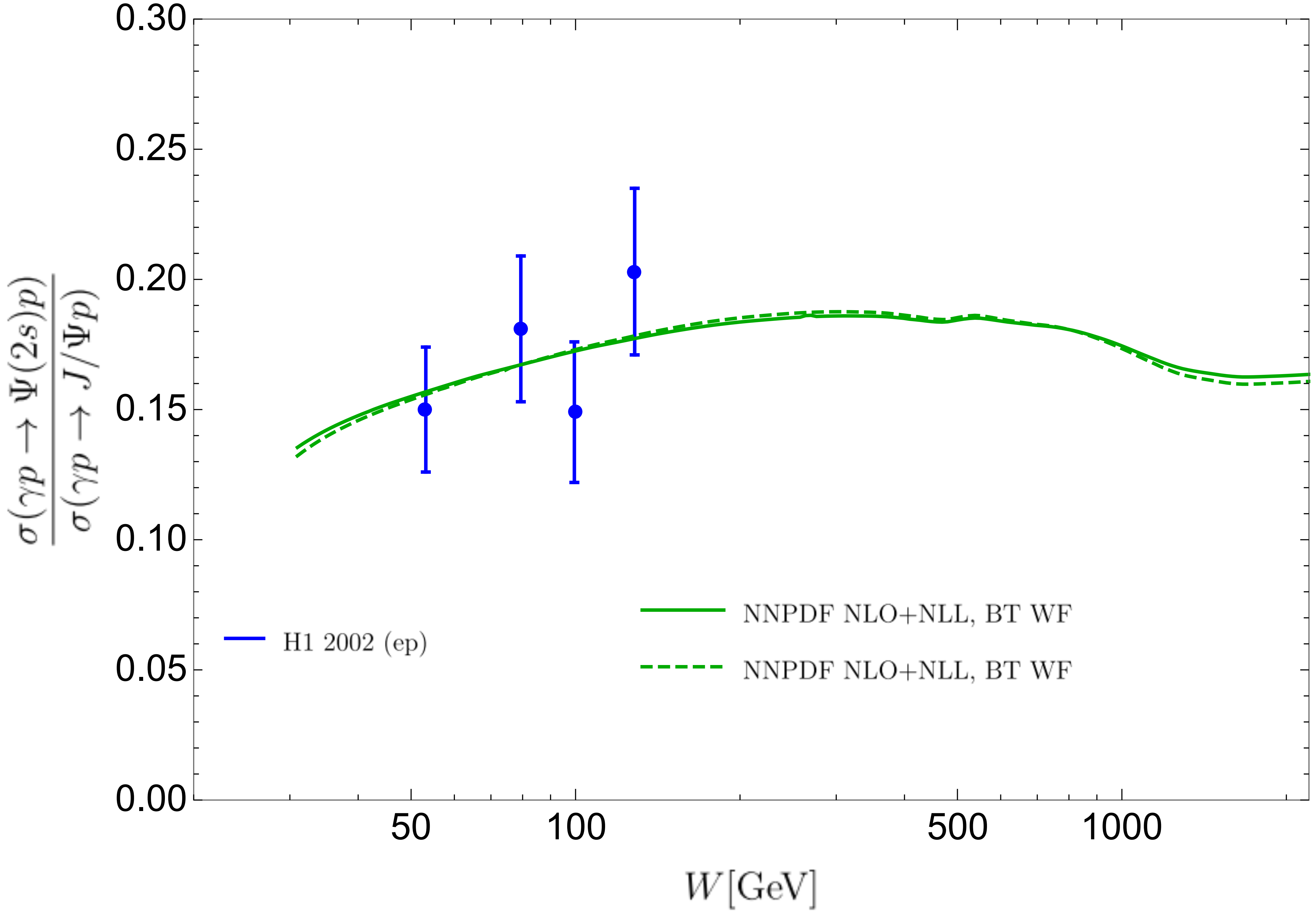






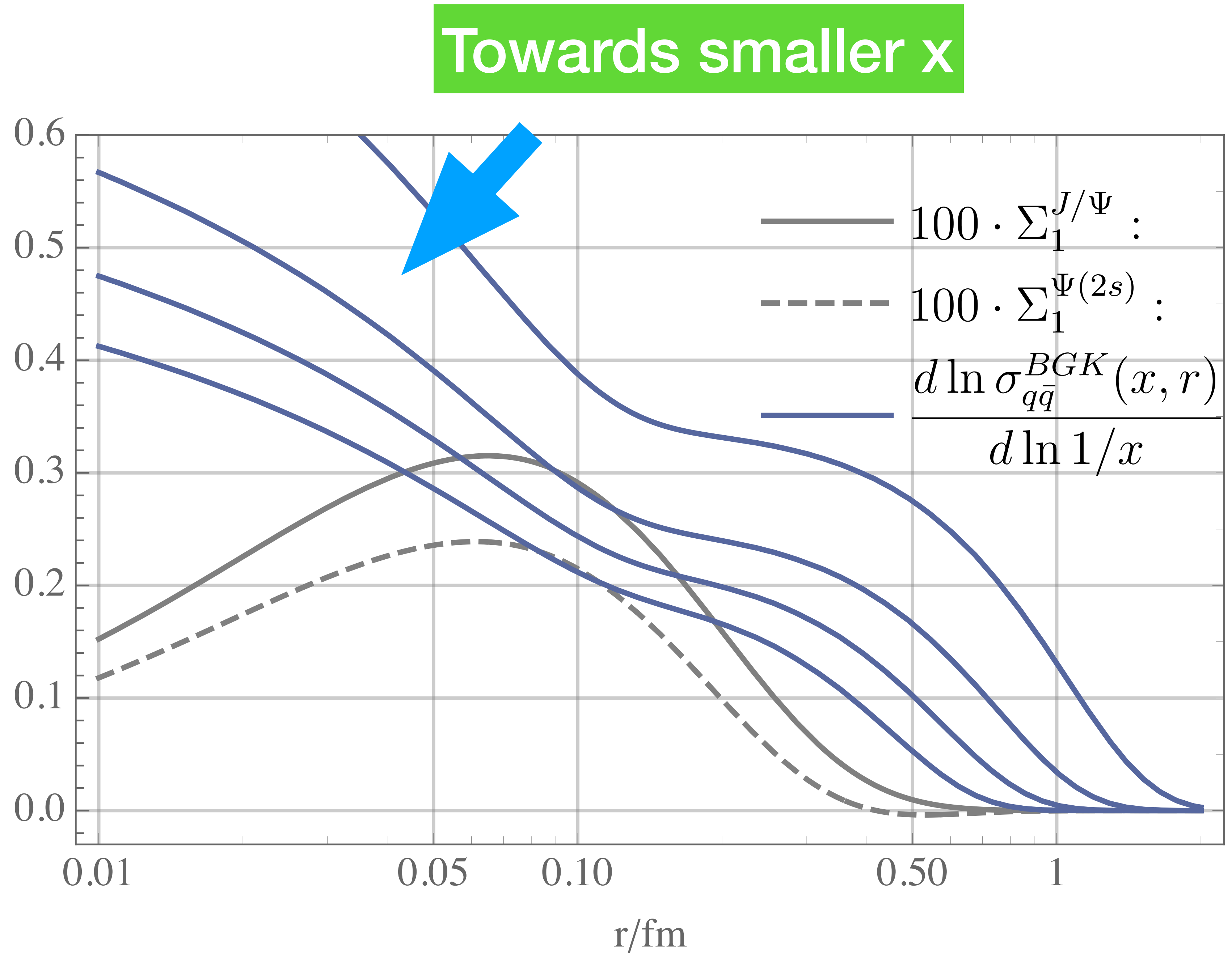
- ratio is not constant (influence of DGLAP evolution), but clear difference between linearized version and complete BGK model
- Challenge: difficult to estimate uncertainties
- Need for data (low energy to fix normalization, high energy to see which scenario is realized)

Perturbative dipole build on conventional PDF

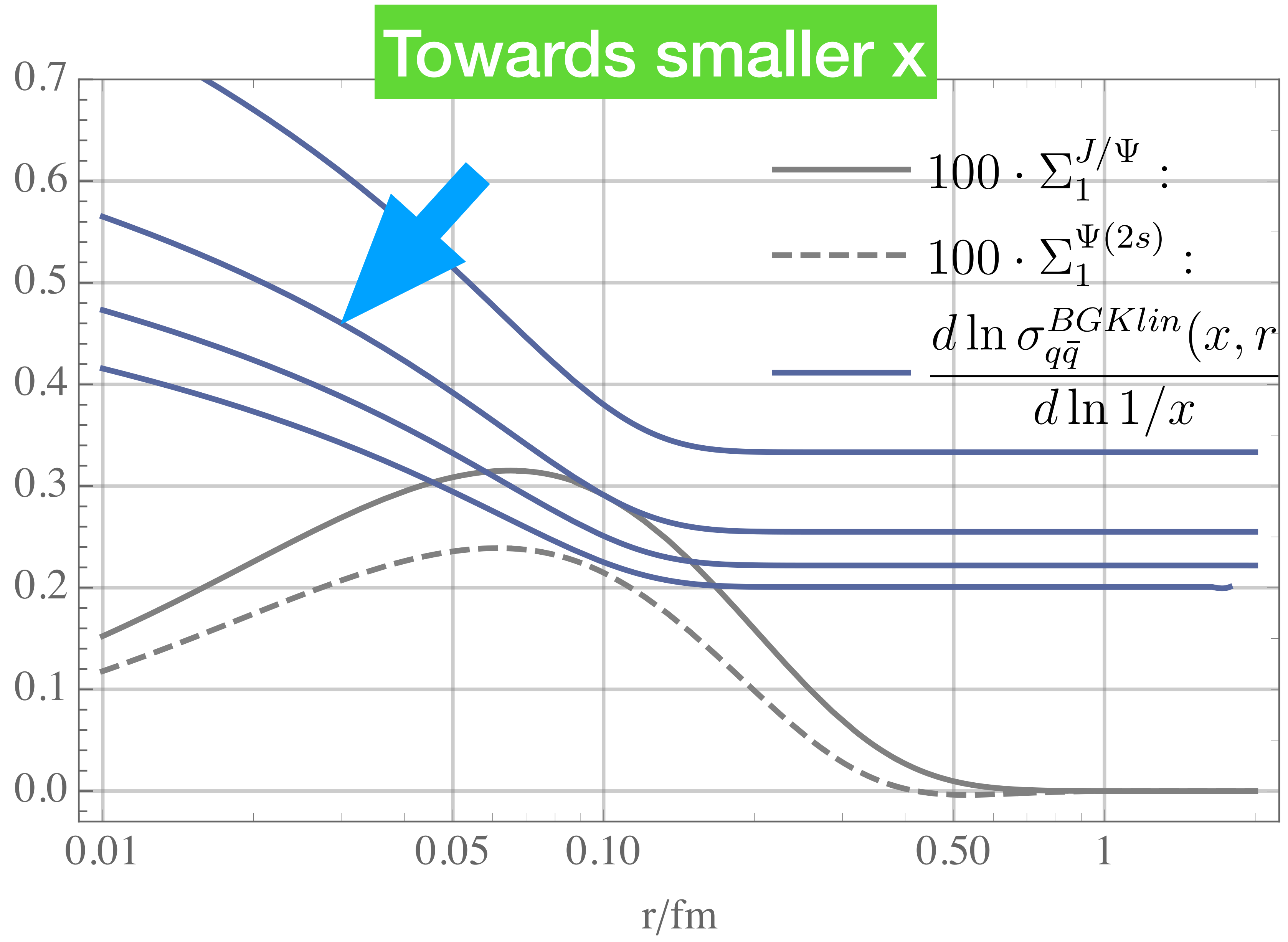


- here: $\sigma_{q\bar{q}}^{lin}(x, r) = \frac{\alpha_s(\mu(r))\pi^2}{3} r^2 xg(x, \mu(r))$
- Use NNPDF NLO fit with NLO small x resummation
- Non-trivial energy dependence + does not really describe cross-section (within our framework)
- Cross-section is approximately constant

Discussion



“Slope" for complete BGK



"Slope" for linear BGK

$$\lambda = \frac{d \ln \sigma_{q\bar{q}}}{\ln 1/x}$$

- Difference between J/Ψ and $\Psi(2s)$ at relative large dipole size r
- Full non-linear model: non-trivial x-dependence in this region
- Linear model with factorization scale frozen at large dipole size r, there is not much happening → constant ratio
- Trivial for GBW model; also seen for BFKL vs BK (QCD low x evolution)
- Prediction depends on VM wave function = the position of the node

Conclusion

- Theory predicts a difference in the energy dependence of the ratio of photo production cross-sections of $\Psi(2s)$ and J/Ψ
- Seen first for comparison gluon distributions subject to BFKL and BK evolution
- Very natural explanation within the (too simple) GBW model
- See it also for model which include DGLAP evolution

Observation depends on non-perturbative vector meson wave function

- in general model dependent
- But node of 2s state is a general feature (magnitude might differ though)
- To reproduce growth of the ratio, need non-trivial behavior of the dipole cross-section in the infra-red
- Should be a straightforward observable to see effect, if saturation scale is of the order of the charm mass at LHC (as implied by model studies and fits)

Backup

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]

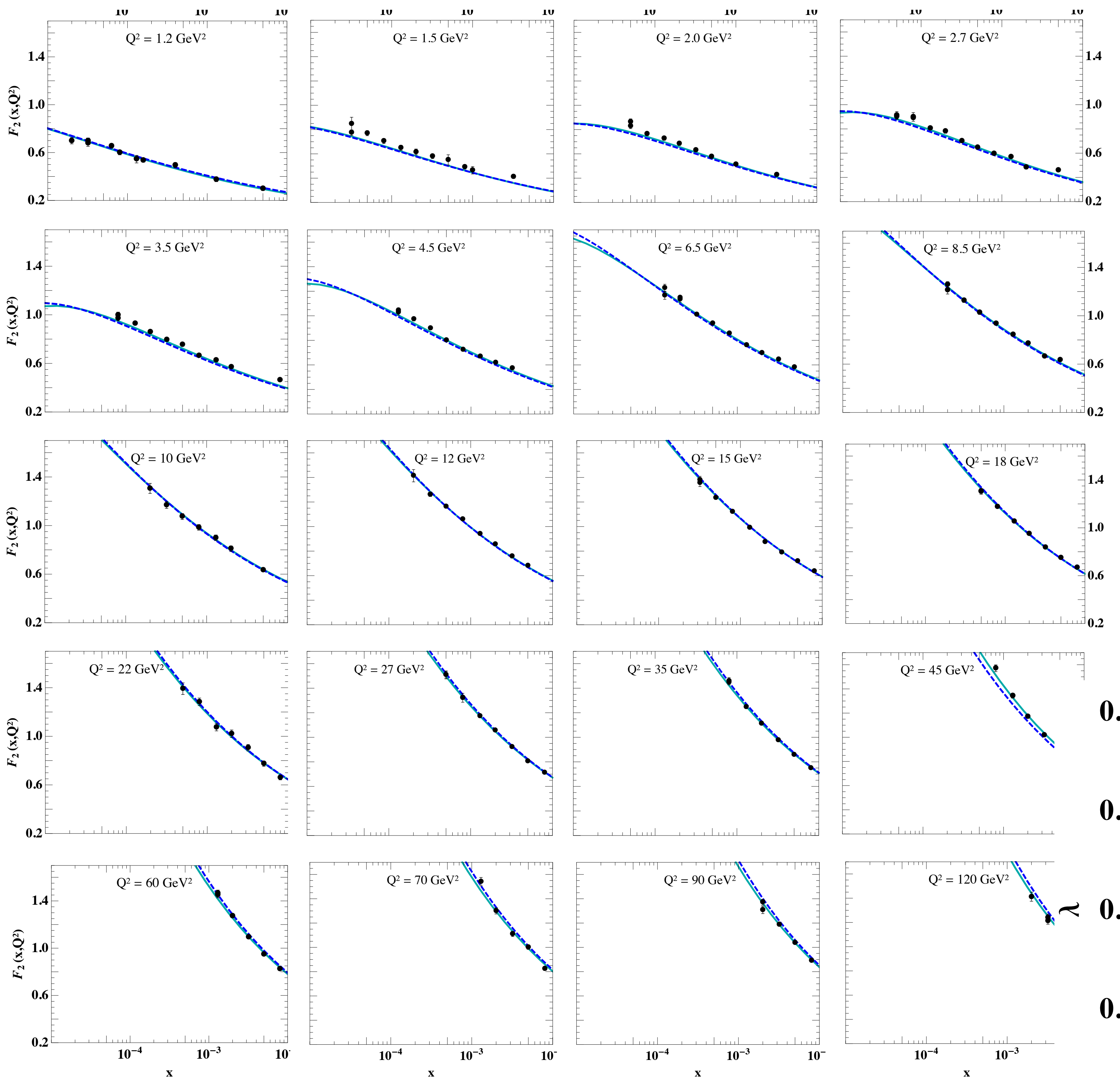
- uses NLO BFKL kernel

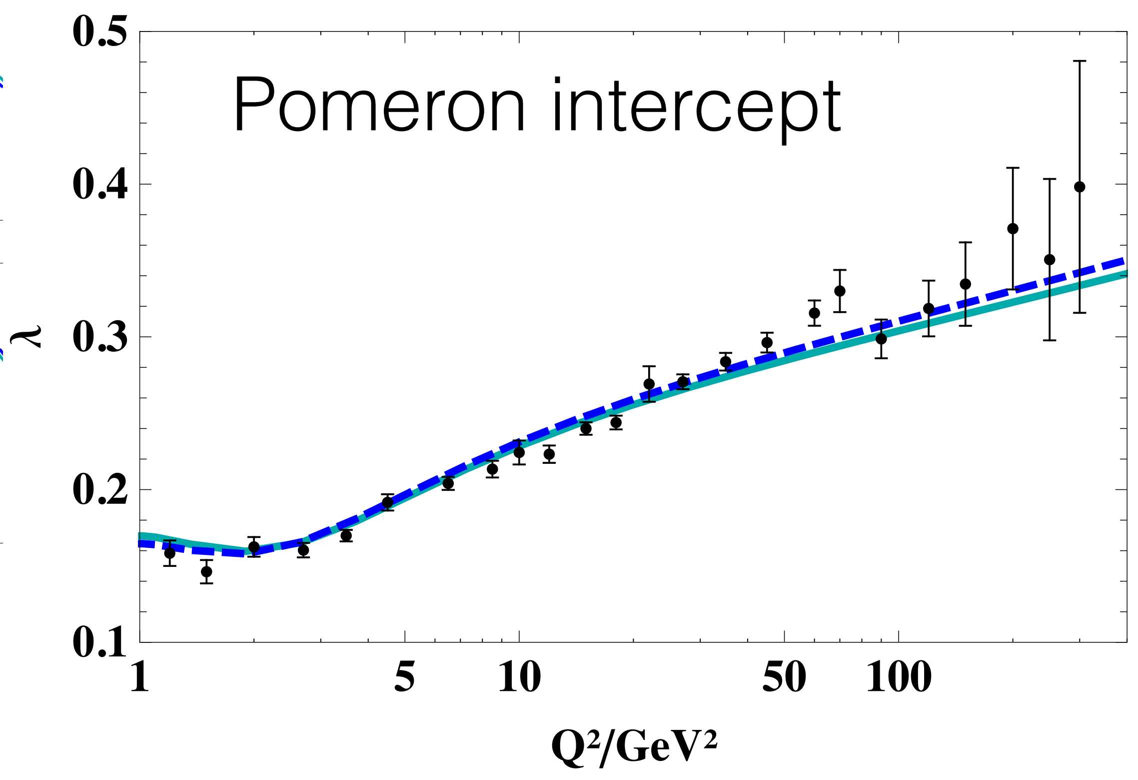
  [Fadin, Lipatov; PLB 429 (1998) 127]

  + resummation of collinear logarithms

- initial kT distribution from fit to combined HERA data

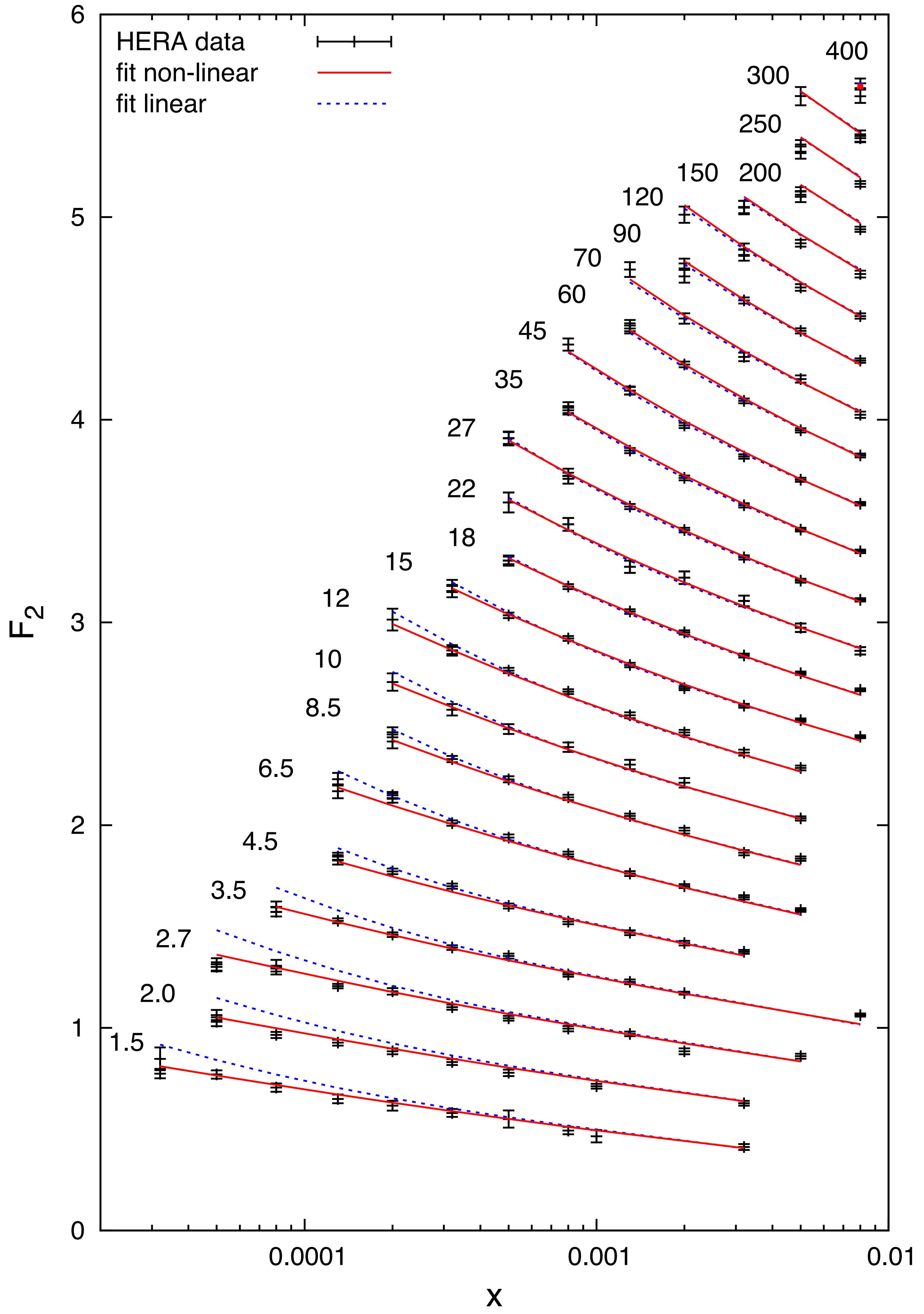
  [H1 & ZEUS collab. 0911.0884]





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)



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

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