Dipole models beyond HERA data

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SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

IPhT cea saclay

Motivation

- HERA data offer compelling evidence for the presence of saturation effects at low (x, Q^2):

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$$Q_s^2(x = 10^{-4}) \approx 1\,\mathrm{GeV}^2$$

- DGLAP works fine for $Q^2 > 10$ GeV^2.
  Valence-like or negative gluons, tension in the fits when pushed down to $Q^2 \sim 1$ GeV^2

- Saturation-based approaches describe well high Q^2 data (for $x < 10^{-2}$) for F2 and FL

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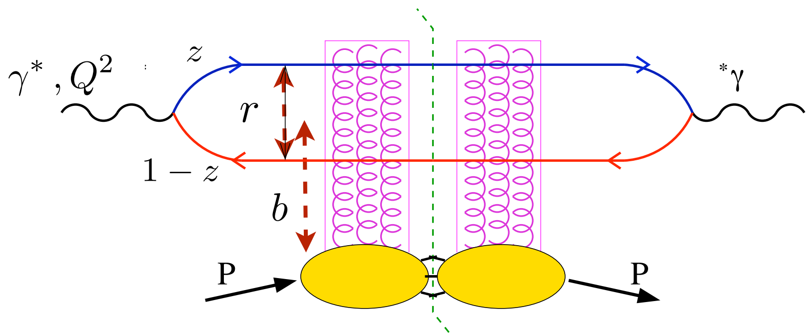
⇓

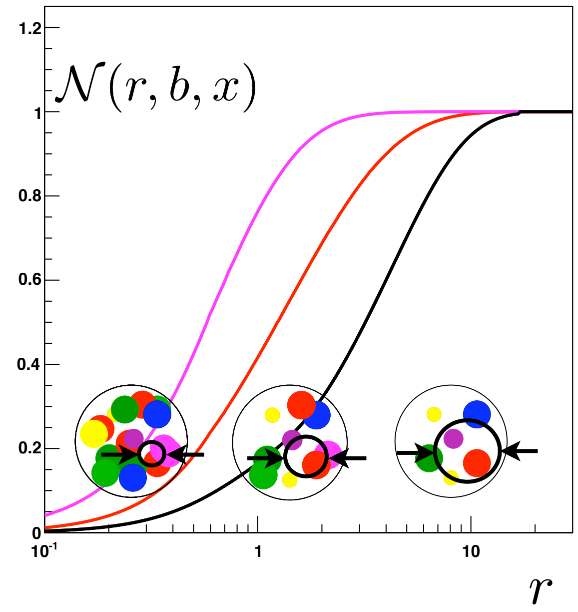
- Can we see DGLAP (or any other linear approach) fail in a region where it is supposed to work?

How low in x does one need to go? What are the best suited observables?
This question is not purely academic: LHeC Working group.

I'll assess this question just for inclusive observables: FL and F2

Saturation in the dipole model of DIS





$$\sigma^{\gamma^* P}_{T,L}(x,Q^2) = \int_0^1 dz \int d^2\mathbf{r} \left| \Psi^{\gamma^* \to q\bar{q}}_{T,L}(z,Q,r) \right|^2 \sigma^{dip}(x,r)$$

$$\sigma^{dip}(x,r) = 2 \int d^2 b \, \mathcal{N}(x,b,r)$$

(My) Classification of dipole models in the market

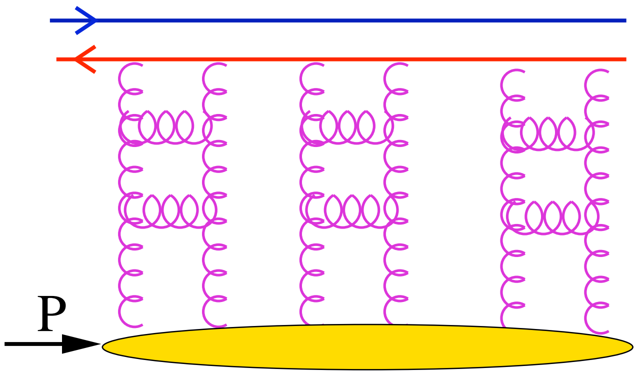
⇒ According to the physical mechanism driving saturation, i.e (x,Q^2,r)-dynamics:

- Eikonalization of leading twist result + DGLAP
- BK or BFKL+saturation
- Phenomenological models: Regge Theory; non-perturbative input.

⇒ According to phenomenological details:

- Impact parameter dependence
- quark masses, inclusion of charm or beauty contributions

⇒ **DGLAP-based models:** Saturation results from eikonalization of two-gluon exchange:



$$\frac{d\sigma^{dip}}{d^2b} = 1 - \exp\left[-\frac{\pi^2}{2\,N_c}\,r^2\,xg(x,Q^2)T_p(b)\right]$$

initial gluon d.f. fitted to data

$$xg(x, Q_0^2 = 1\,GeV^2) = A_g\,x^{-\lambda_g}\,(1-x)^{5.6}$$

Leading $\ln Q^2$ terms in each cascade resummed through DGLAP

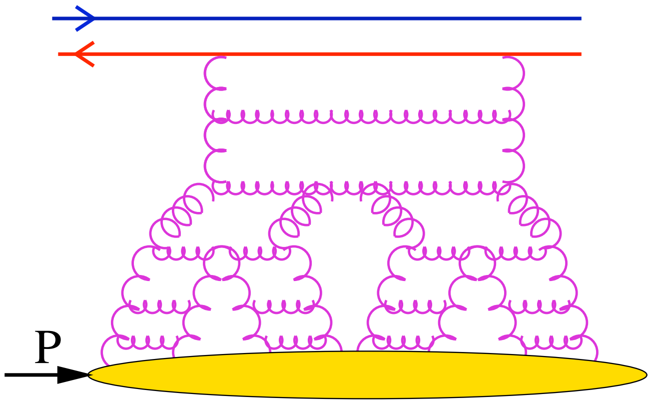
- BGBK (Bartels-Golec-Biernat-Kowalski): Trivial impact parameter dependence
- IPSat (Kowalski-Teaney): Gaussian profile $T_p(b) \sim \exp\left(-b^2/2\,B\right)/(2\pi\,B)$

- Good description of HERA data (F2, F2charm, diffractive J/Ψ)
- Admits a trivial extension to nuclear targets. Good description of shadowing

- No dynamical input for extrapolation to small-x
- Fits to data allow for growing or "valence like" initial gluon d.f:

$$-0.41 < \lambda_{glue} < 0.3$$

Models based on the Balitsky-Kovchegov equation or Color-Glass-Condensate:



$$\frac{\partial \mathcal{N}(r,x)}{\partial \ln(x_0/x)} = \int d^2r_1\, K(r,r_1,r_2)\, [\mathcal{N}(r_1,x) + \mathcal{N}(r_2,x) - \mathcal{N}(r,x) - \mathcal{N}(r_1,x)\mathcal{N}(r_2,x)]$$

A) Calculations based on numerical solutions of BK eqn with running coupling
JLA-Armesto-Milhano-Salgado (AAMS), Kuokkanan-Rummukainen-Weigert (KRW).

- Trivial impact parameter dependence. Overall normalization fitted to data
- Input: Initial conditions for the evolution, $\mathcal{N}(x_0, r)$ (GBW, G-M, scaling)
- KRW: Energy conservation (i.e., large-x) effects considered.

B) Models based on analytical solutions of BFKL+ absorptive barrier
Iancu-Itakura-Munier-Soyez (CGC), Kowalski-Motyka-Watt (b-CGC)

- Evolution speed λ fitted to data
- b-CGC: Impact parameter dependence.

χ/d.o.f ~ 1.6. Lowest evolution speed of all models: λ ~ 0.16

⇒ "Phenomenological" models

A) Golec-Biernat-Wusthoff
$$\begin{cases} \mathcal{N}^{GBW}(x,r) = \theta(R_p - b)\left(1 - \exp\left[-\frac{r^2\, Q_s^2(x)}{4}\right]\right) \\ Q_s^2(x) = Q_0^2\left(\frac{x_0}{x}\right)^{\lambda} \end{cases}$$

B) Models based on Regge Theory.
Forshaw-Shaw (FS04).

FS04: $$\sigma^{dip}(r,x) = \begin{cases} A^{soft}\, x^{-\lambda_{soft}}\,, & \text{for } r > r_1 \quad (\lambda_{soft} \sim 0.66) \\ A^{hard}\, r^2\, x^{-\lambda_{hard}}\,, & \text{for } r < r_0 \quad (\lambda_{hard}\ 0.34) \end{cases}$$

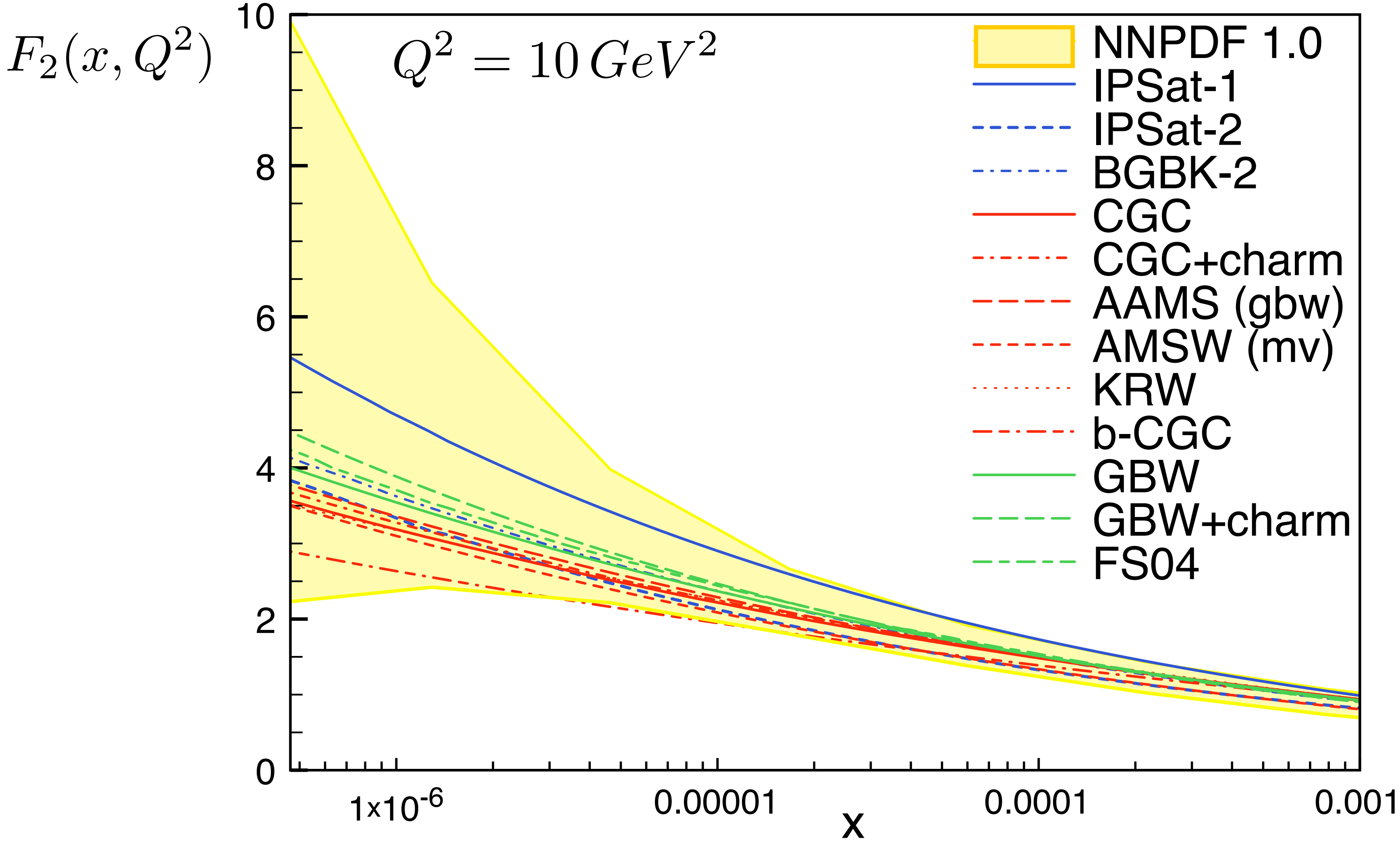
C) Strong coupling dipole from AdS/CFT. Kovchegov-Lu-Rezaeian

- Valid in the photo productiion region: $Q^2 < 2\ \mathrm{GeV}^2$
- Main feature: "Saturation of saturation": $Q_s^2(x) \longrightarrow \text{constant}\,, \quad \text{for} \quad x \longrightarrow 0$

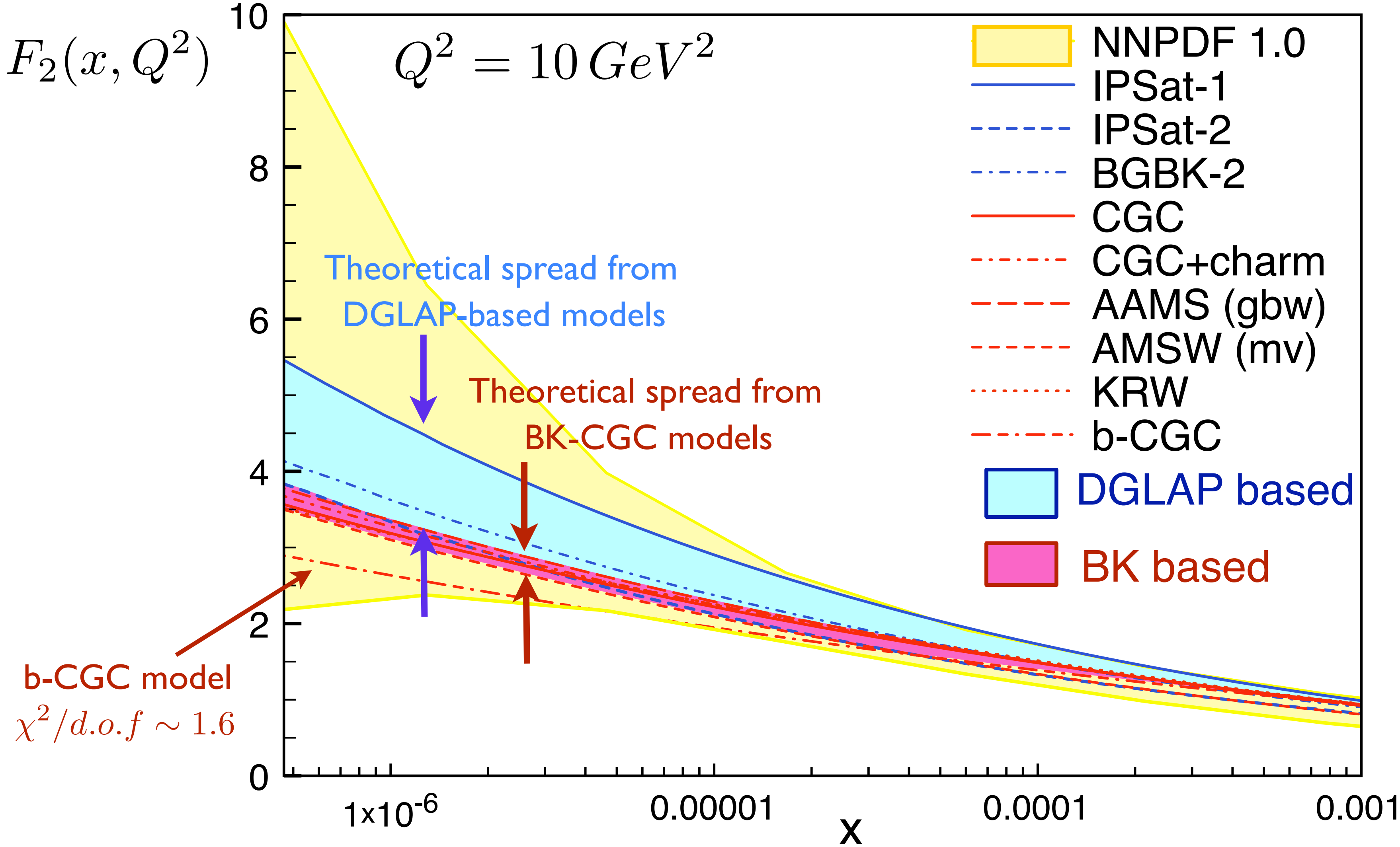
D) Models tuned to fit also RHIC data.

E) Others (my apologies).

Extrapolation for F2 beyond HERA kinematic regime (LHeC?)

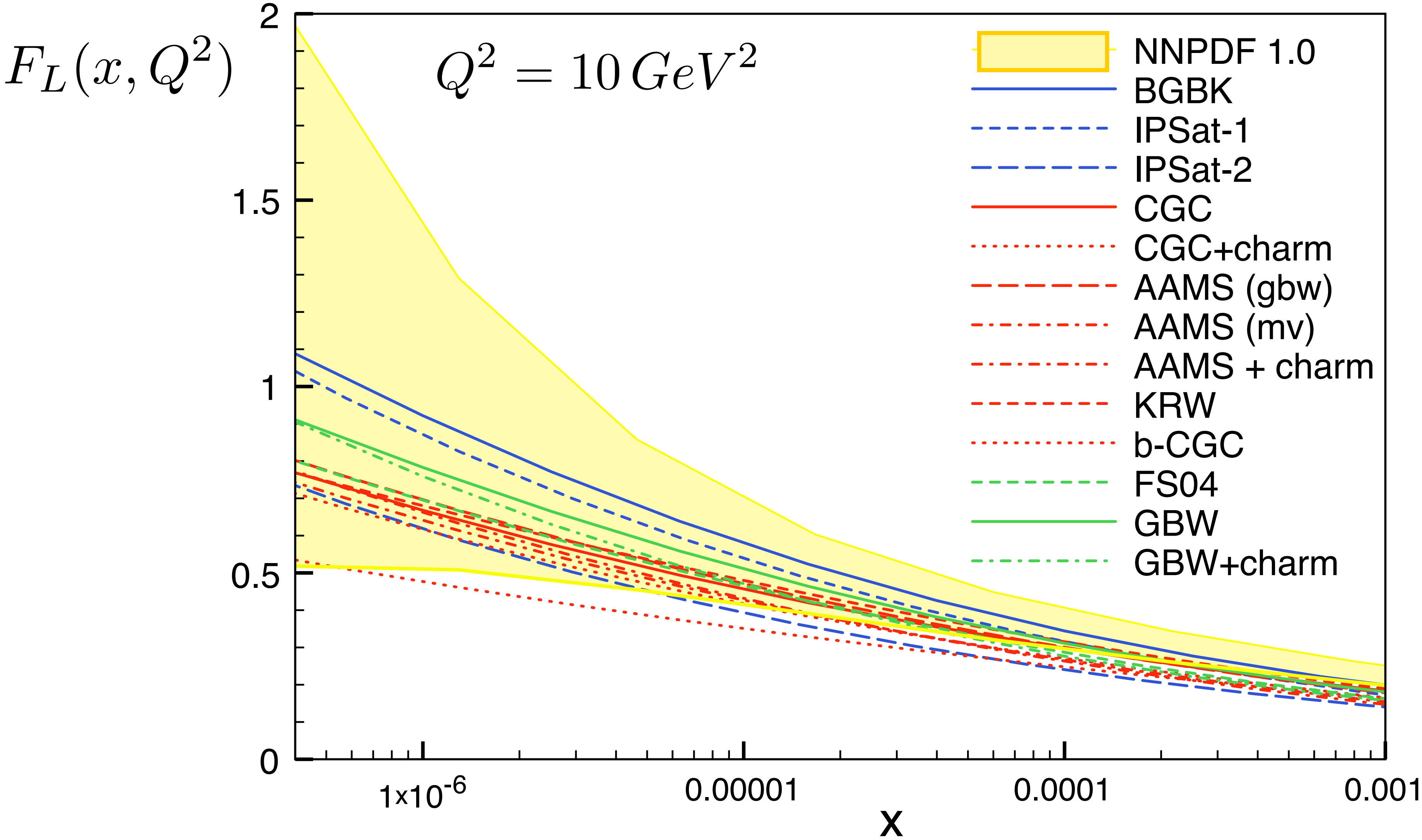


Extrapolation of the models for F2 : Only BK vs DGLAP-based models



- A democratic treatment of all models results in very large uncertainties (~100% at $x=10^{-7}$)
- BK-CGC models closer to each other (b-CGC diverges a bit, χ/ d.o.f ~ 1.6)
- The largest error band is spanned by DGLAP-based models

Extrapolation for FL beyond HERA kinematic regime (LHeC?)



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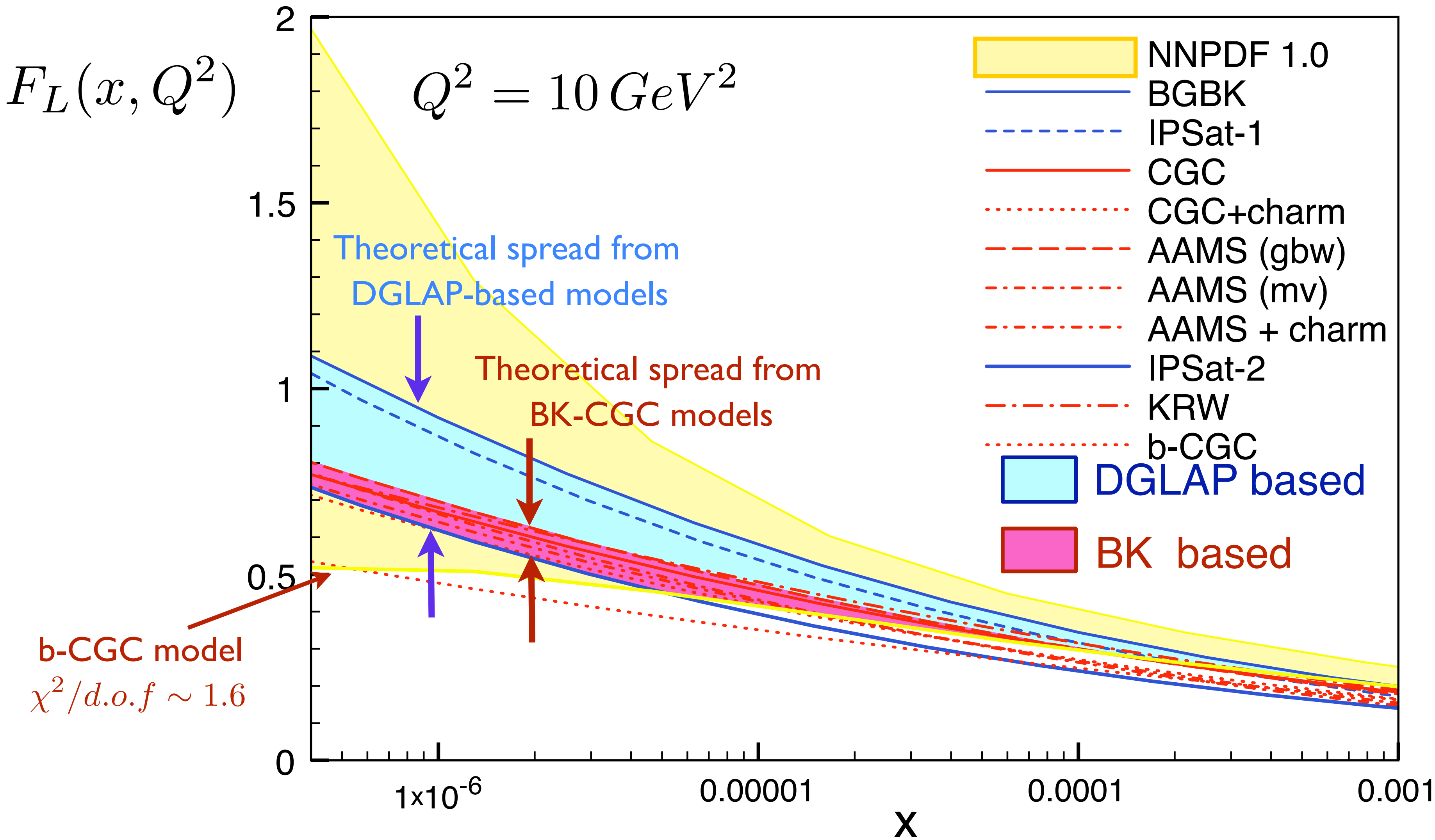

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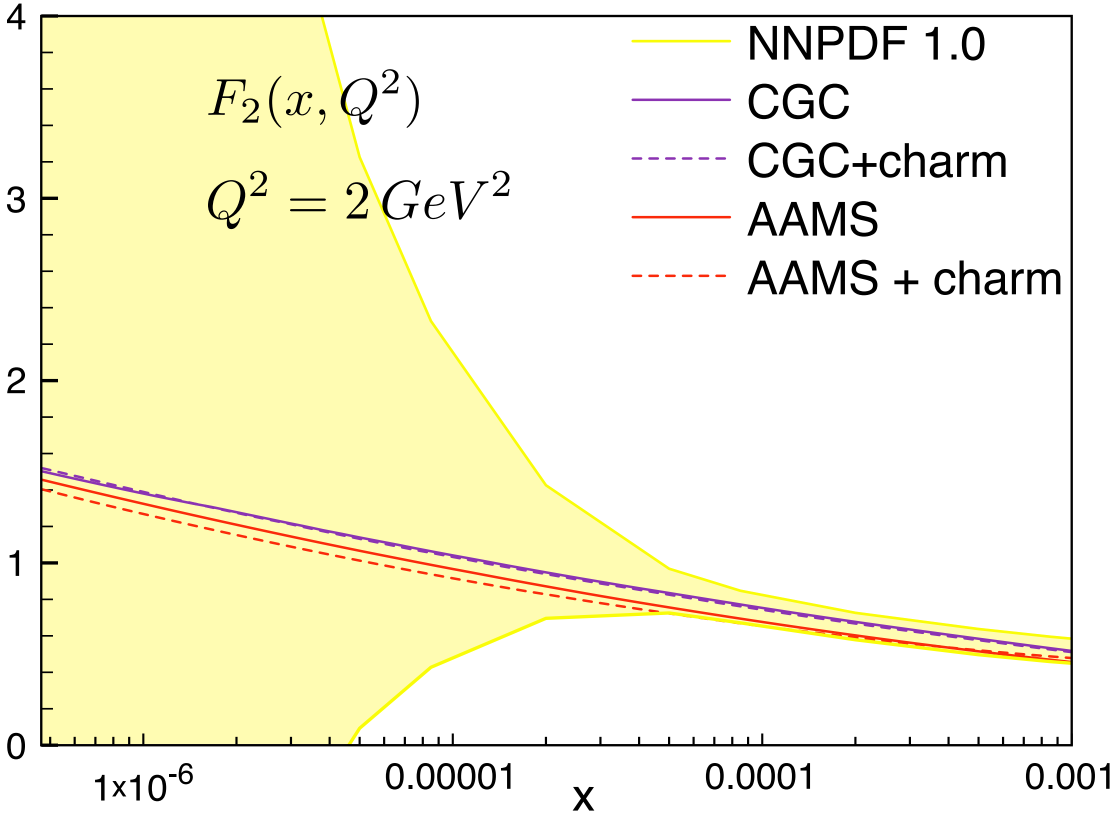
Quark masses

$$\sigma_{T,L}^{\gamma^* P}(x,Q^2) = \sum_{flavors} \int_0^1 dz \int d^2\mathbf{r} \left| \Psi_{T,L}^{\gamma^* \to q\bar{q}}(z,Q,r,m_f) \right|^2 \sigma^{dip}(\tilde{x},r)$$

$$\tilde{x} = x \left(1 + \frac{4\, m_f^2}{Q^2} \right)$$

- Light flavors (u,d,s): $0 < m_{u,d,s} < 140\ \mathrm{MeV}$. Fits in the photoproduction region demand a large (pion) mass.
- Charm (& beauty): Needed in order to reproduced measured F_2^{charm}
- Extrapolations are stable after switching on the charm. Value of the saturation scale change.



$$Q_s^2(x) = \left(\frac{x_0}{x} \right)^{\lambda}\ \mathrm{GeV}^2$$

x_0 /10^{-4}	charm	no charm
GBW	0.41	3
CGC	0.1	0.27

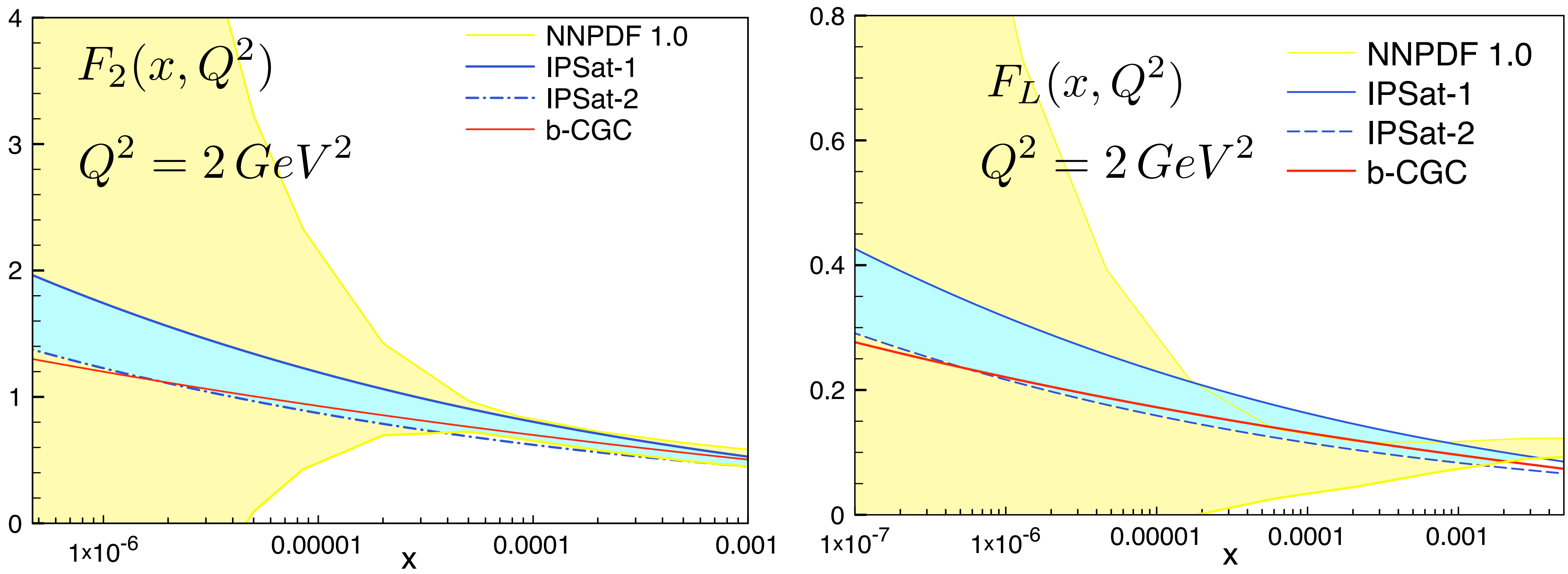
Impact parameter dependence

- Only two of the models shown include impact parameter dependence (crucial physical ingredient for exclusive measurements, diffraction ...)

•IPSat: Good description of exclusive observables (VM, Diffraction) at HERA

Poor extrapolation to small-x

- b-CGC: Not so good description of HERA data. χ /d.o.f ~ 1.6. Lowest evolution speed of all models: λ ~ 0.16

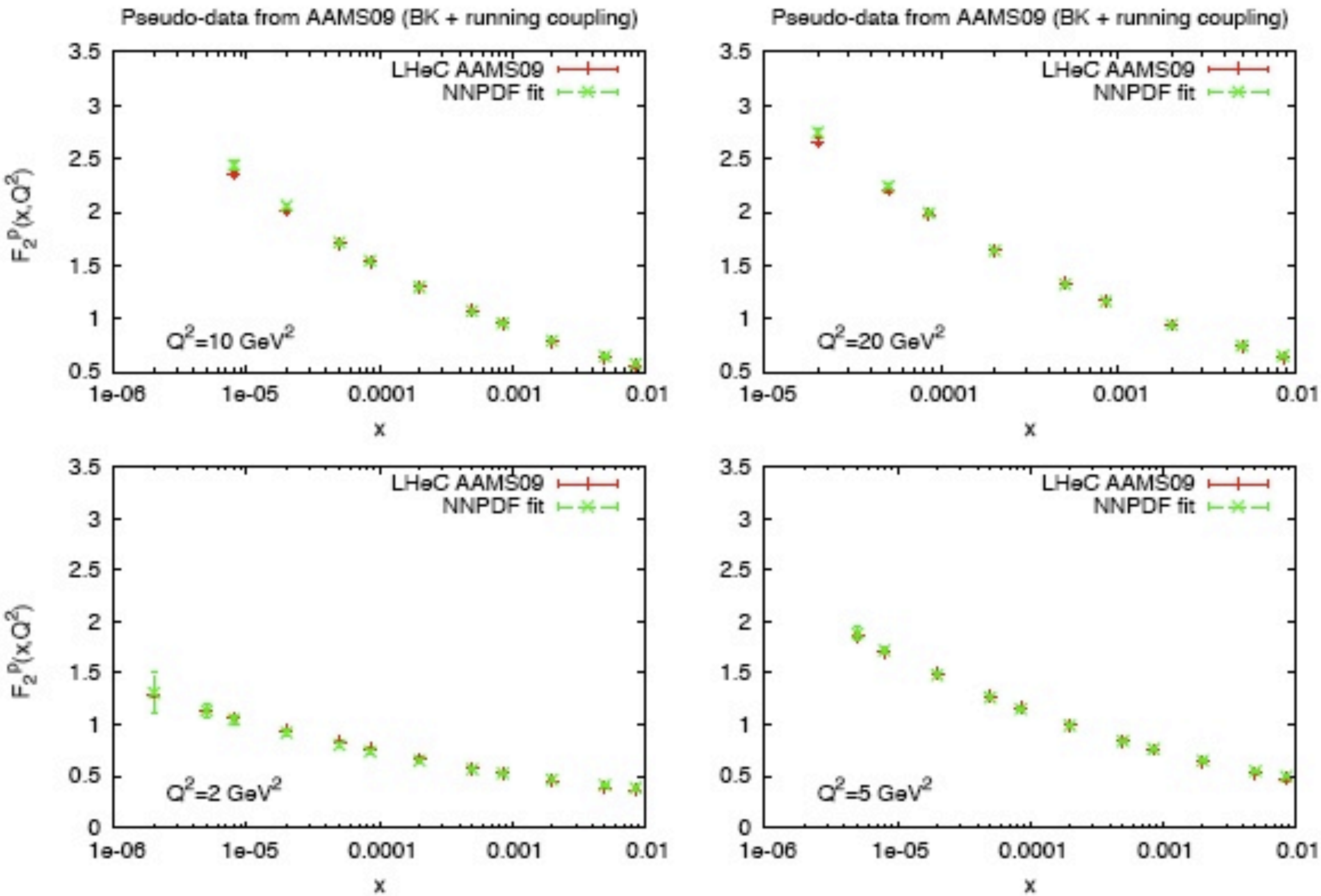


⇒ Could DGLAP account for data compatible with the previous predictions?

1- Generate pseudo-data for F2 & FL using AAMS input (BK with running coupling)

2- Include it in the DGLAP data set, and run the fits

DGLAP NNPDF (fits and figure by Juan Rojo) can fit the pseudo-data for F2



DGLAP can adjust its initial condition to account for a “fully saturated” F2

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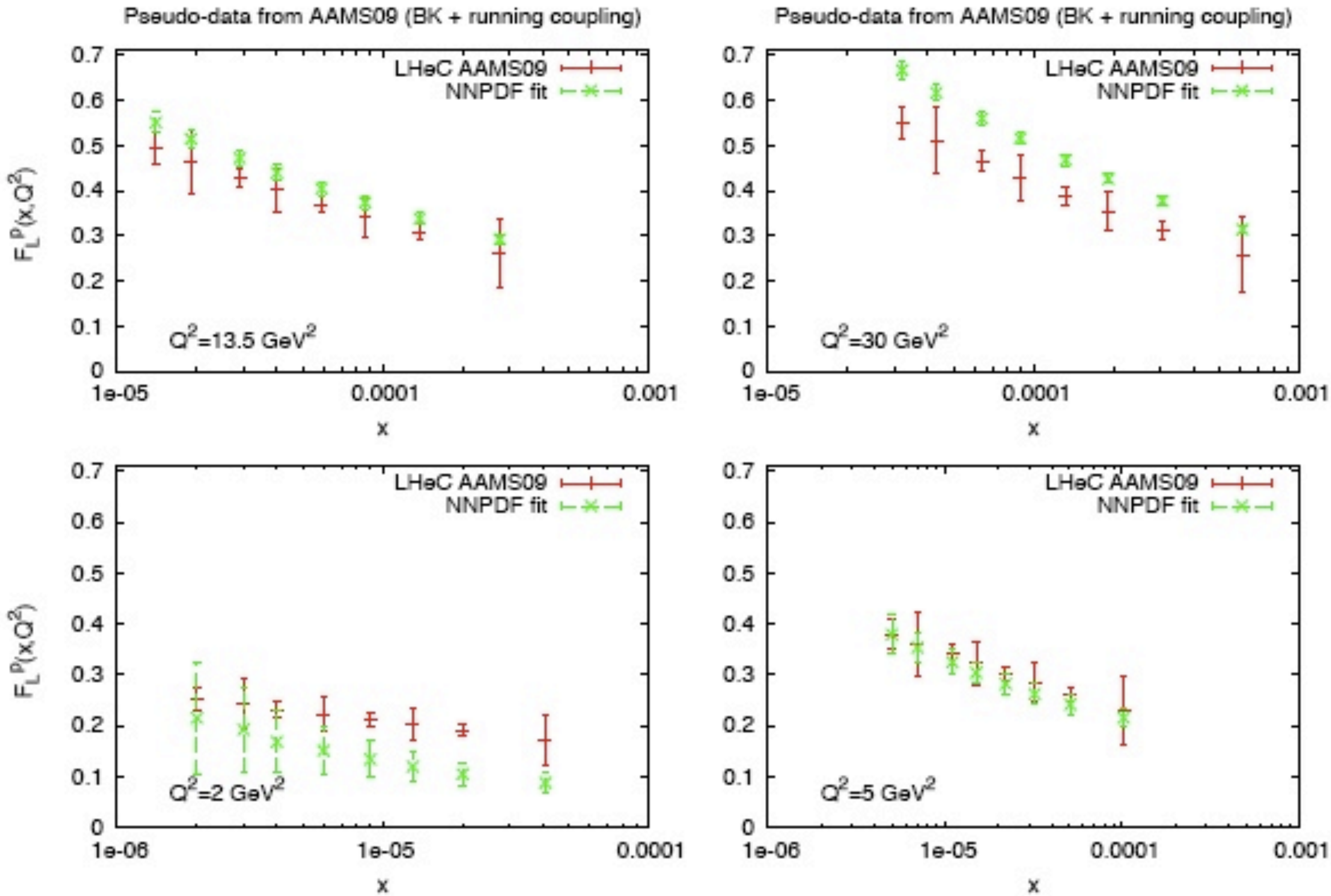

The divergence between linear DGLAP analyses and non-linear small-x dynamics is visible in FL already for x~10^{-4}. Around the corner!!

SUMMARY

- Little spread in extrapolations towards small-x for FL and F2 from BK-CGC dipole models
- F2 is not well suited to tell DGLAP from non-linear QCD dynamics
- A measurement of FL at x~ $10^{-4} \div 10^{-5}$ could suffice to pin down the onset of non-linear effects (provided a large lever arm in Q^2)

SUMMARY

- Little spread in extrapolations towards small-x for FL and F2 from BK-CGC dipole models
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OUTLOOK

- Not all linear approaches are DGLAP. The checks should be extended to other approaches: small-x resumed DGLAP, kt-factorization...)
- This studies should be extended to other observables: diffraction, vector mesons...
- In order to do so, a more satisfactory inclusion of charm and impact parameter dependence in BK-based models is needed