Collinearly improved BK equations vs HERA data

POETIC VI Conference
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Continuation of AAMQS fits with N. Armesto, JG Milhano, P. Quiroga and CA Salgado

OUTLINE

Problem: Perturbative expansions in high-energy QCD are unstable

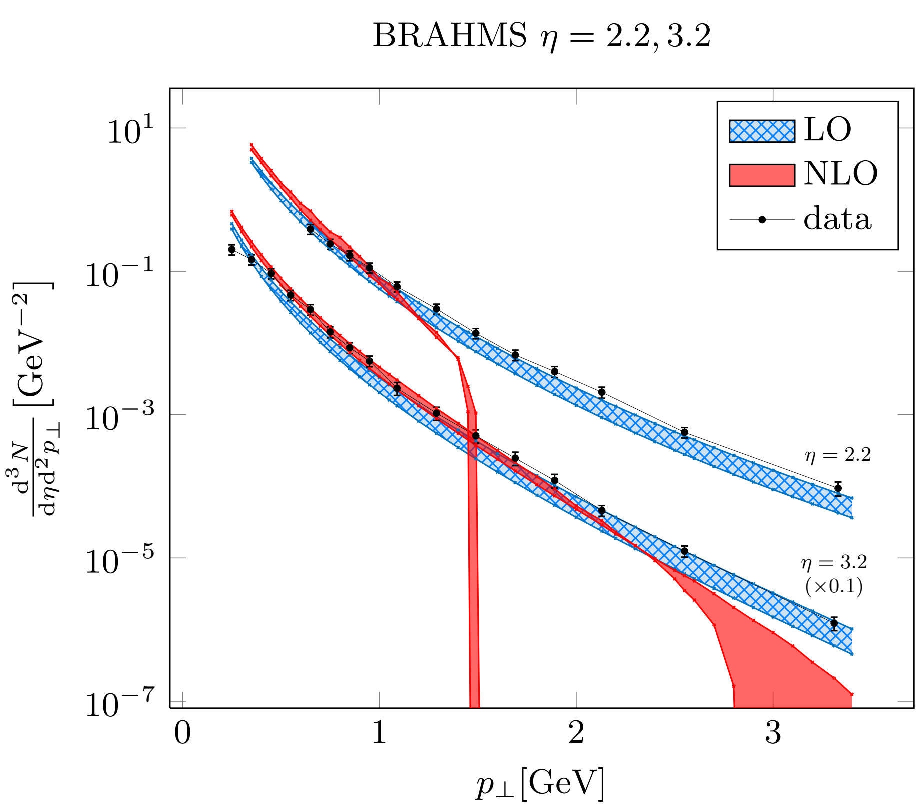
Evolution equations

- NLO BK T. Lappi, Maantysaari; Phys.Rev. D91 (2015) 7, 074016
- NLL BFKL + saturation boundary Avsar, Stasto, Triantafyllopoulos, Zaslavsky JHEP 10 (2011) 138

$$\mathcal{N},\ \sigma < 0$$

Production Processes

- Forward hadron production in p-A collisions at NLO Stasto, Xiao, Zaslavsky Phys.Rev.Lett. 112 (2014) 1, 012302



Why? **Large, negative contributions from transverse logarithms at NLL**

$$\alpha_s Y \sim \alpha_s Y \rho \sim \alpha_s \rho^2 \quad \text{with} \quad \rho \equiv \ln\left(\frac{Q^2}{Q_0^2}\right)$$

LL NLO

Solution: Resum large (double and single) collinear logs to all orders

- Already done for BFKL

  G P Salam; JHEP 07 019

  Ciafaloni, Colferai, Salam; Phys Rev D 60 114036 (1998)

  G Altarelli R D Ball, S. Forte Nucl Phys B575 (313) 2000

- BK: two recent approaches

  Double Logarithmic Accuracy BK equation, ***DLA-BK***

  Iancu et al
  Phys.Lett. B744 (2015) 293-302

  Kinematically corrected BK equation, ***KC-BK, G. Beuf***

  G. Beuf
  Phys.Rev. D89 (2014) 7, 074039

This talk: tests of the DLA improved BK equations against HERA data on the e-p reduced cross section

- Fits to H1 and ZEUS combined analysis of HERA I data.

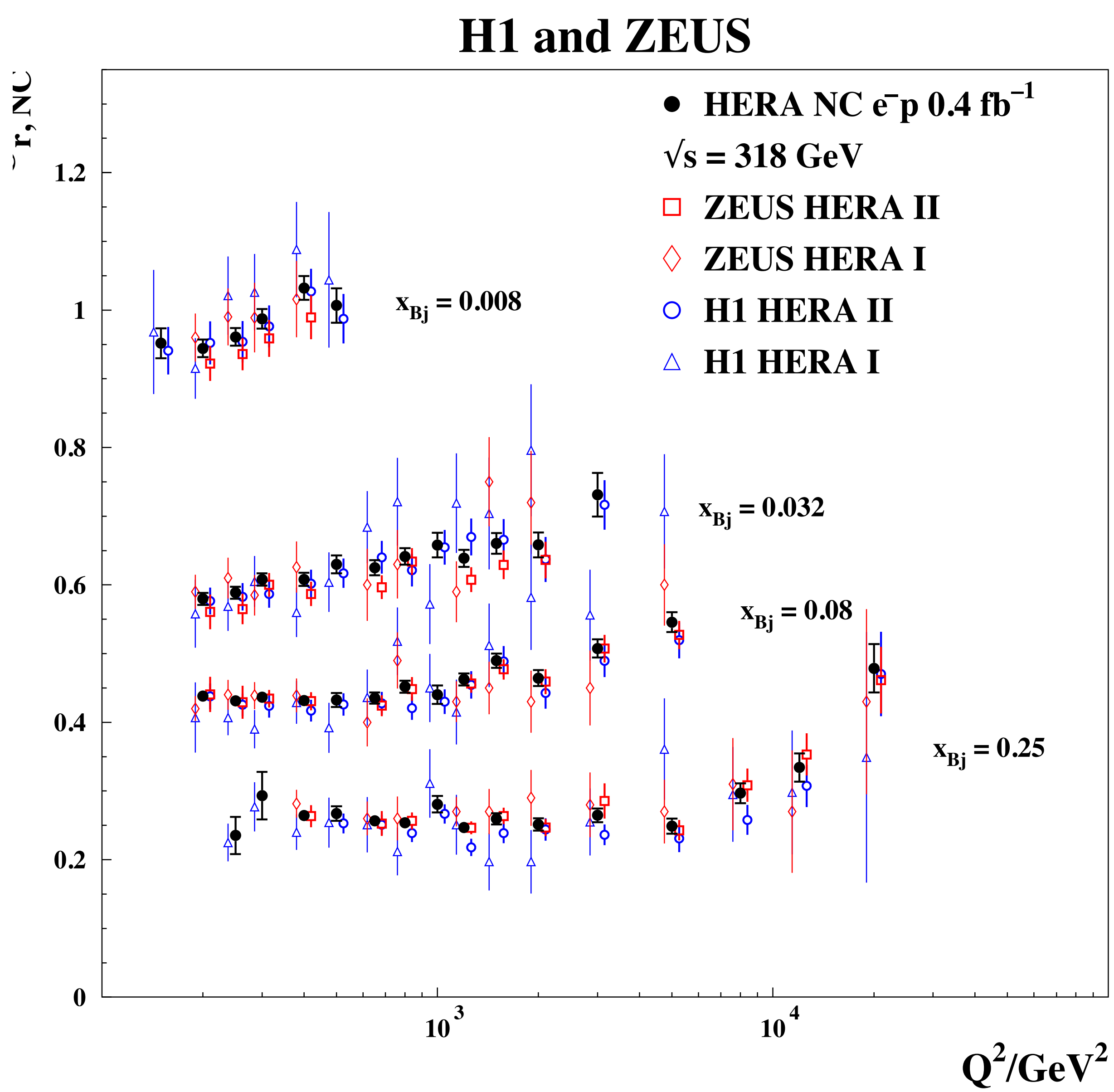
JLA arXiv:1507.0712

Iancu et al arXiv:1507.03651

Goof fits for

$$x < 0.01$$

$$Q^2 < Q^2_{\max} = 50, 500\,\mathrm{GeV}^2$$



- H1 and ZEUS combined analysis of HERA II data. Released june 2015

arXiv:1506.06042

The strong reduction of experimental errors at high-Q^2 introduces tension in the fits

$$\chi^2 \sim \frac{(theo - exp)^2}{err^2}$$

Preliminary results!

running coupling BK EVOLUTION, rcBK

$$\frac{\partial \mathcal{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\, \mathcal{M}_{\mathbf{012}} \left[\mathcal{S}_{\mathbf{02};Y}\, \mathcal{S}_{\mathbf{12};Y} - \mathcal{S}_{\mathbf{01};Y}\right]$$

Balitsky's

Phys.Rev. D75 (2007) 014001

$$\mathcal{M}^{\mathrm{Bal}}_{\mathbf{012}} = \frac{\alpha_s(r_0^2)\, N_c}{\pi} \left[\frac{r_0^2}{r_1^2 r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

Parent dipole

$$\mathcal{M}^{\mathrm{pd}}_{\mathbf{012}} = \frac{\alpha_s(r_0^2)\, N_c}{\pi} \frac{r_0^2}{r_1^2 r_2^2}$$

Proxy to Kovchegov-Weigert's

Nucl.Phys. A784 (2007) 188-226

Smallest dipole

$$\mathcal{M}^{\mathrm{pd}}_{\mathbf{012}} = \frac{\alpha_s(r_{\mathrm{min}}^2)\, N_c}{\pi} \frac{r_0^2}{r_1^2 r_2^2} \quad \text{with} \quad r_{min} \equiv \min\{r_0, r_1, r_2\}$$

$$\mathcal{S}(\mathbf{x_0}, \mathbf{x_1}; Y) = \frac{1}{N_c} \langle \mathrm{tr}\left\{U(\mathbf{x_0}) U^\dagger(\mathbf{x_1})\right\}\rangle_Y \equiv \mathcal{S}_{\mathbf{01};Y}$$

DLA-rcBK evolution

Iancu et al
Phys.Lett. B744 (2015) 293-302

$$\frac{\partial \tilde{\mathcal{S}}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\, \mathcal{M}_{\mathbf{012}}\, \mathcal{K}^{\mathrm{DLA}}_{\mathbf{012}} \left[\tilde{\mathcal{S}}_{\mathbf{01};Y}\, \tilde{\mathcal{S}}_{\mathbf{12};Y} - \tilde{\mathcal{S}}_{\mathbf{01};Y}\right]$$

DLA kernel

$$\mathcal{K}^{\mathrm{DLA}}_{\mathbf{012}} = \frac{\mathrm{J}_1(2\sqrt{\bar{\alpha}_s \rho'^2})}{\sqrt{\bar{\alpha}_s \rho'^2}} \quad \text{with} \quad \rho' = \sqrt{\ln\left(r_1^2/r_0^2\right)\, \ln\left(r_2^2/r_0^2\right)}$$

Analytic continuation

$$\tilde{\mathcal{A}}(Y,\rho) \equiv \int_0^\rho d\rho_1\, \tilde{f}(Y,\rho-\rho_1)\, \mathcal{A}(0,\rho_1) \quad \text{with} \quad \tilde{f}(Y=0,\rho) = \delta(\rho) - \sqrt{\bar{\alpha}_s}\, \mathrm{J}_1(2\sqrt{\bar{\alpha}_s \rho^2})$$

and $\left(1 - \mathcal{S}_{\mathbf{xy};Y}\right) \equiv r^2 Q_0^2 \mathcal{A}_{\mathbf{xy};Y}$

Initial conditions also affected by the resummation

KC-rcBK evolution

Beuf
Phys.Rev. D89 (2014) 7, 074039

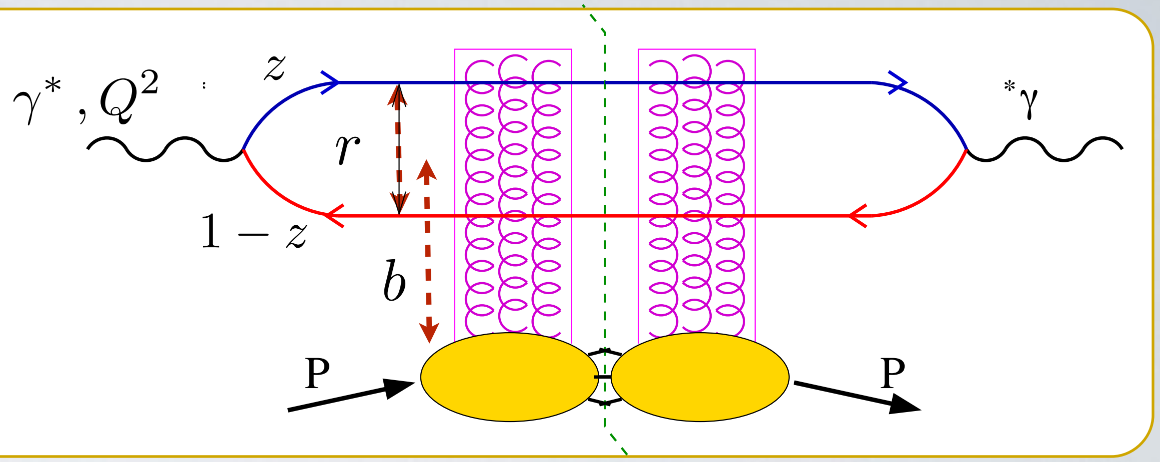
$$\frac{\partial \mathcal{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\,\mathcal{M}_{\mathbf{012}}\,\Theta(Y-\Delta_{\mathbf{012}})\left[\mathcal{S}_{\mathbf{02};Y-\Delta_{\mathbf{012}}}\,\mathcal{S}_{\mathbf{12};Y-\Delta_{\mathbf{012}}} - \mathcal{S}_{\mathbf{01};Y}\right]$$

$$\Delta_{\mathbf{012}} = \max\left\{0, \ln\left(\frac{l_{\mathbf{012}}^2}{r_0^2}\right)\right\} \quad \text{with} \quad l_{\mathbf{012}} = \min\{r_1, r_2\}$$

- ***The observable:*** reduced x-section:

$$\sigma_r(y,x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

$$F_2(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,(\sigma_T+\sigma_L) \qquad F_L(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,\sigma_L$$



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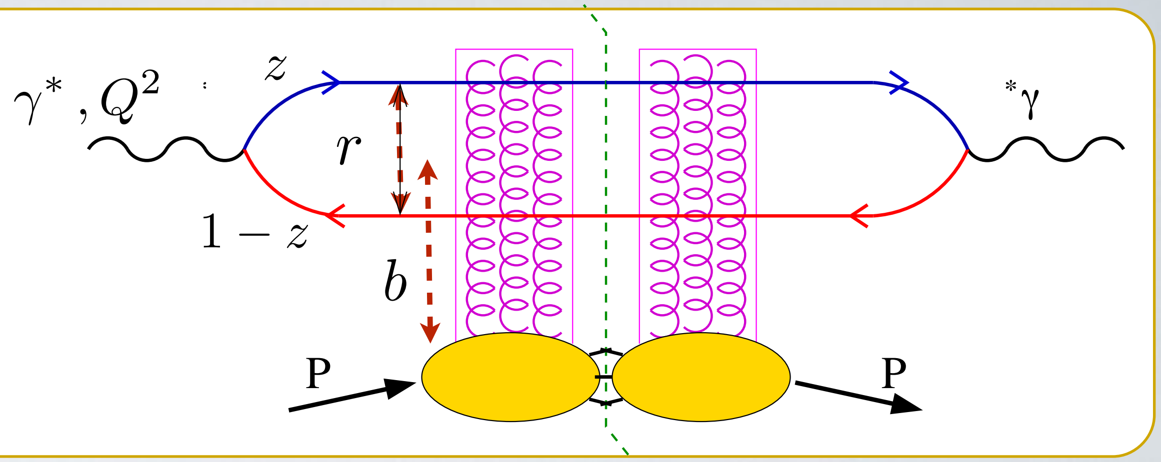


- ***The formalism:***
  dipole model of DIS at LO:

$$\sigma_{T,L}(x,Q^2) = \sum_f \int_0^1 dz \int d^2\mathbf{r}\,|\Psi^f_{T,L}(e_f,m_f,z,Q^2,\mathbf{r})|^2\,\sigma^{q\bar{q}}(\mathbf{r},x)$$

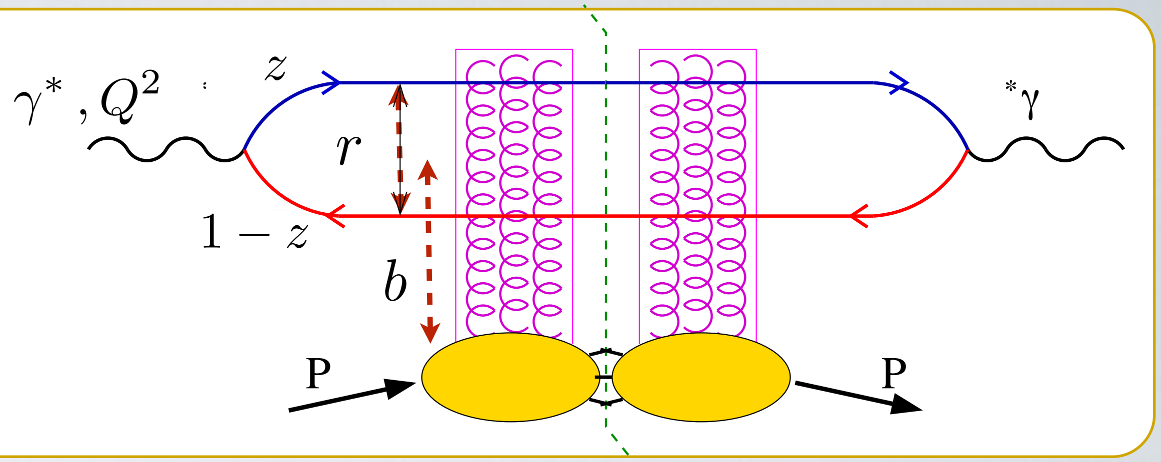
$$\sigma^{q\bar{q}}(r,x) = 2\int d^2b\,\mathcal{N}(x,r,b) = \sigma_0\,\mathcal{N}(x,r)$$

Evolved with BK-evolution

- ***The observable:*** reduced x-section:

$$\sigma_r(y,x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

$$F_2(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,(\sigma_T+\sigma_L) \qquad F_L(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,\sigma_L$$



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$$\sigma^{q\bar{q}}(r,x) = 2\int d^2b\,\mathcal{N}(x,r,b) = \sigma_0\,\mathcal{N}(x,r)$$

* Photon impact factors at NLO are known. Should be included for a consistent description

Balitsky, Chirilli; Phys.Rev. D83 (2011) 031502

Beuf; Phys.Rev. D85 (2012) 034039

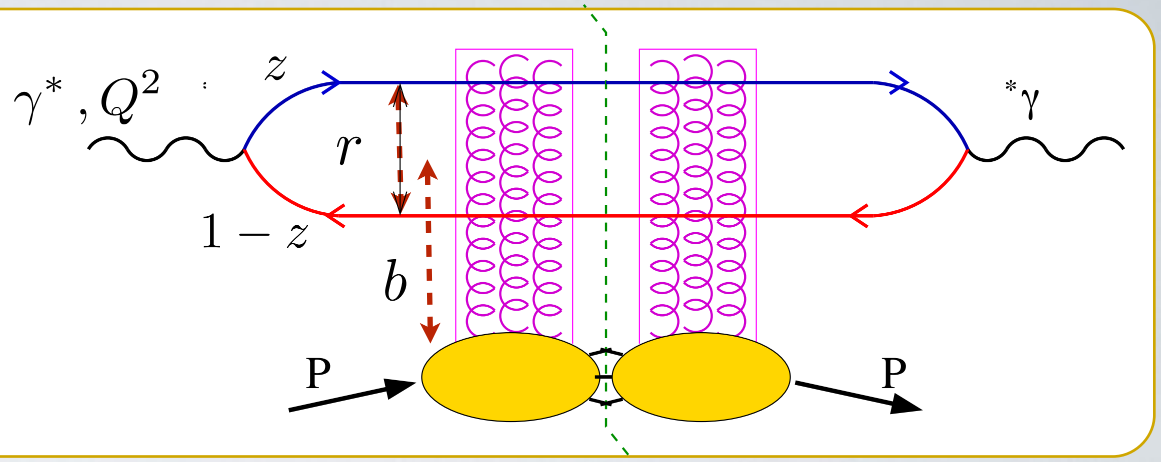
NLO corrections to the dipole model

$$+\bar{\alpha}\int_{k^+_{\min}/q^+}^{1-z_1} \frac{\mathrm{d}z_2}{z_2} \int \frac{\mathrm{d}^2\mathbf{x}_2}{2\pi}\, \mathcal{I}^{NLO}_{T,L}(\mathbf{x}_0,\mathbf{x}_1,\mathbf{x}_2,z_1,z_2,Q^2)\,\frac{2\,C_F}{N_c}\left[1-\langle\mathbf{S}_{012}\rangle_0\right]$$

- ***The observable:*** reduced x-section:

$$\sigma_r(y,x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

$$F_2(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}(\sigma_T+\sigma_L) \qquad F_L(x,Q^2) = \frac{Q^2}{4\,\pi^2\alpha_{em}}\,\sigma_L$$



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$$\sigma^{q\bar{q}}(r,x) = 2\int d^2b\,\mathcal{N}(x,r,b) = \sigma_0\,\mathcal{N}(x,r)$$

- ***Some details***

- 3 or 5 active flavours: $m_{\mathrm{u,d,s,c,b}} = 0.05, 0.05, 0.140, 1.27, 4.5\,\mathrm{GeV}$

- One-loop running coupling

$$\alpha_s(r^2) = \frac{4\pi}{\beta_{N_f}\ln\left(\frac{4C^2}{r^2\Lambda^2_{N_f}}\right)}$$

- Matched at the threshold

$$\alpha_{s,N_f-1}(r_*) = \alpha_{s,N_f}(r_*) \quad \text{with} \quad r_*^2 = 4C^2/m_f^2$$

- Frozen in the infrared

$$\alpha_{s,frozen} = 0.7 \text{ or } 1$$

- Calibrated at Mz

$$\alpha_s(M^2_{Z_0}) = 0.1176$$

Initial Conditions

MV-γ: $$\mathcal{N}(r, Y=0) = 1 - \exp\left[-\frac{(r^2\, Q_0^2)^\gamma}{4} \ln\left(\frac{1}{\Lambda_{QCD}\, r} + e\right)\right]$$

solve MV-γ

rapidity shift ΔY_0

Pre-scaling: $$\mathcal{N}(r, x_0 = 0.01) = \mathcal{N}(r, \Delta Y_0) \;\Rightarrow\; \mathcal{N}(r, x \leq x_0) = \mathcal{N}(r, \Delta Y_0 + \ln(x_0/x))$$

Fit parameters: 4 or 5

Initial condition:	$Q_0,\ \gamma,\ \Delta Y_0$
Normalisation	σ_0
Fudge factor	C

Initial Conditions

MV-γ: $$\mathcal{N}(r,Y=0) = 1 - \exp\left[-\frac{(r^2\,Q_0^2)^\gamma}{4}\,\ln\left(\frac{1}{\Lambda_{QCD}\,r}+e\right)\right]$$

solve MV-γ

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Running-MV $$\mathcal{N}(r,Y=0) = \left\{1-\exp\left[-\left(\frac{r^2Q_0^2}{4}\,\bar{\alpha}_s(C_{\rm MV}r)\left[1+\ln\left(\frac{\bar{\alpha}_{\rm sat}}{\bar{\alpha}_s(C_{\rm MV}r)}\right)\right]\right)^p\right]\right\}^{1/p}$$

Parameter constraints

- We require the FT of the dipole amplitude to be a positive definite, non-oscillatory function:

$$\phi(k,Y) \sim \int \frac{d^2r}{(2\pi)^2}\exp\left(ik\cdot r\right)\left(1-\mathcal{N}(r,Y)\right)$$

MV-γ $\Rightarrow$ $\gamma \lesssim 1.125$

Pre-scaling: Case by case

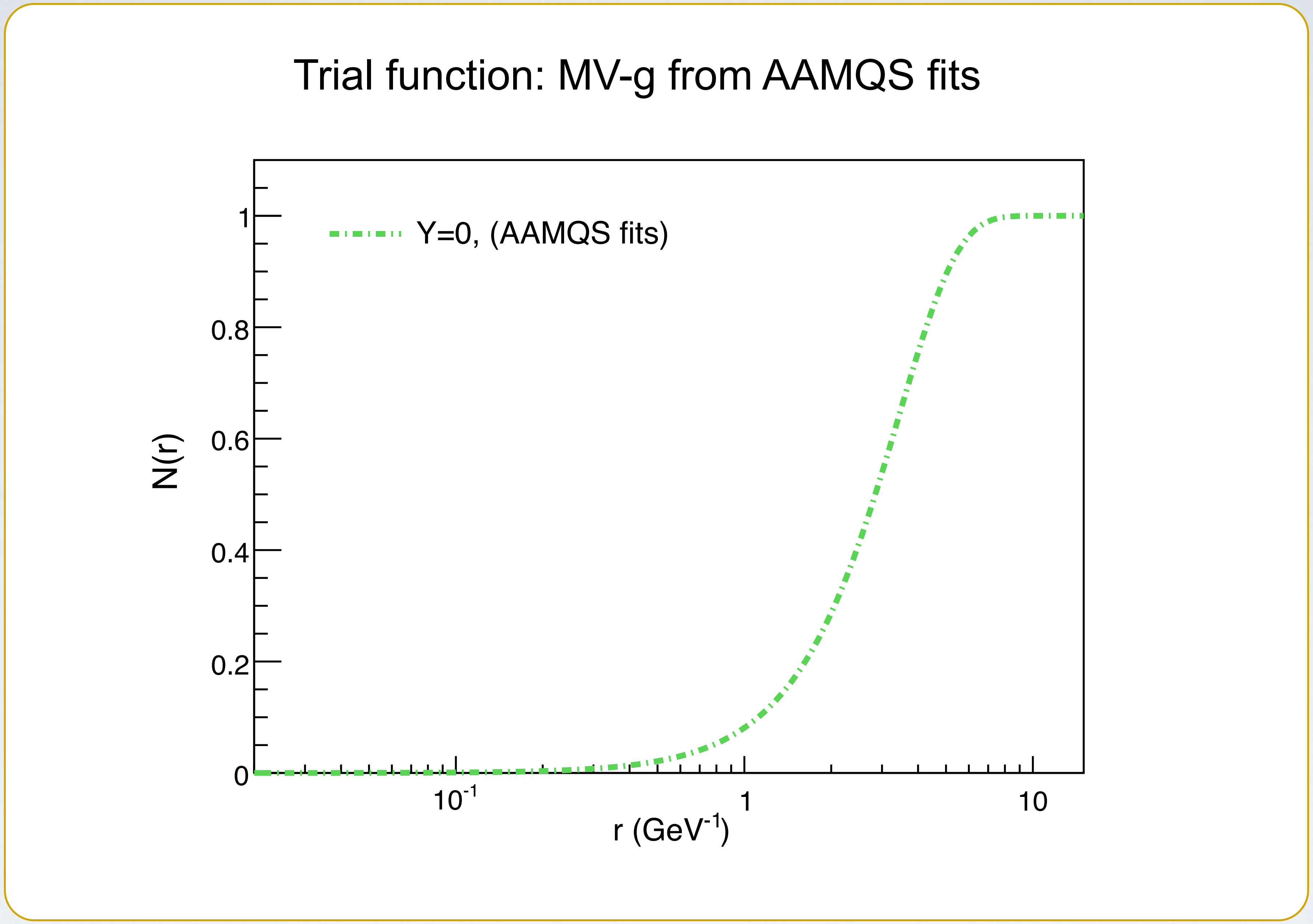
Running-MV: Strongly oscillating FT (tbc)

- Right collinear limit: $\gamma(r\to 0) = 1$

MV-γ $\gamma(r) = \gamma + \frac{1-\gamma}{1+(Q_s r)^a}$, with $a \approx 0.25$

Running-MV Ok, by construction.

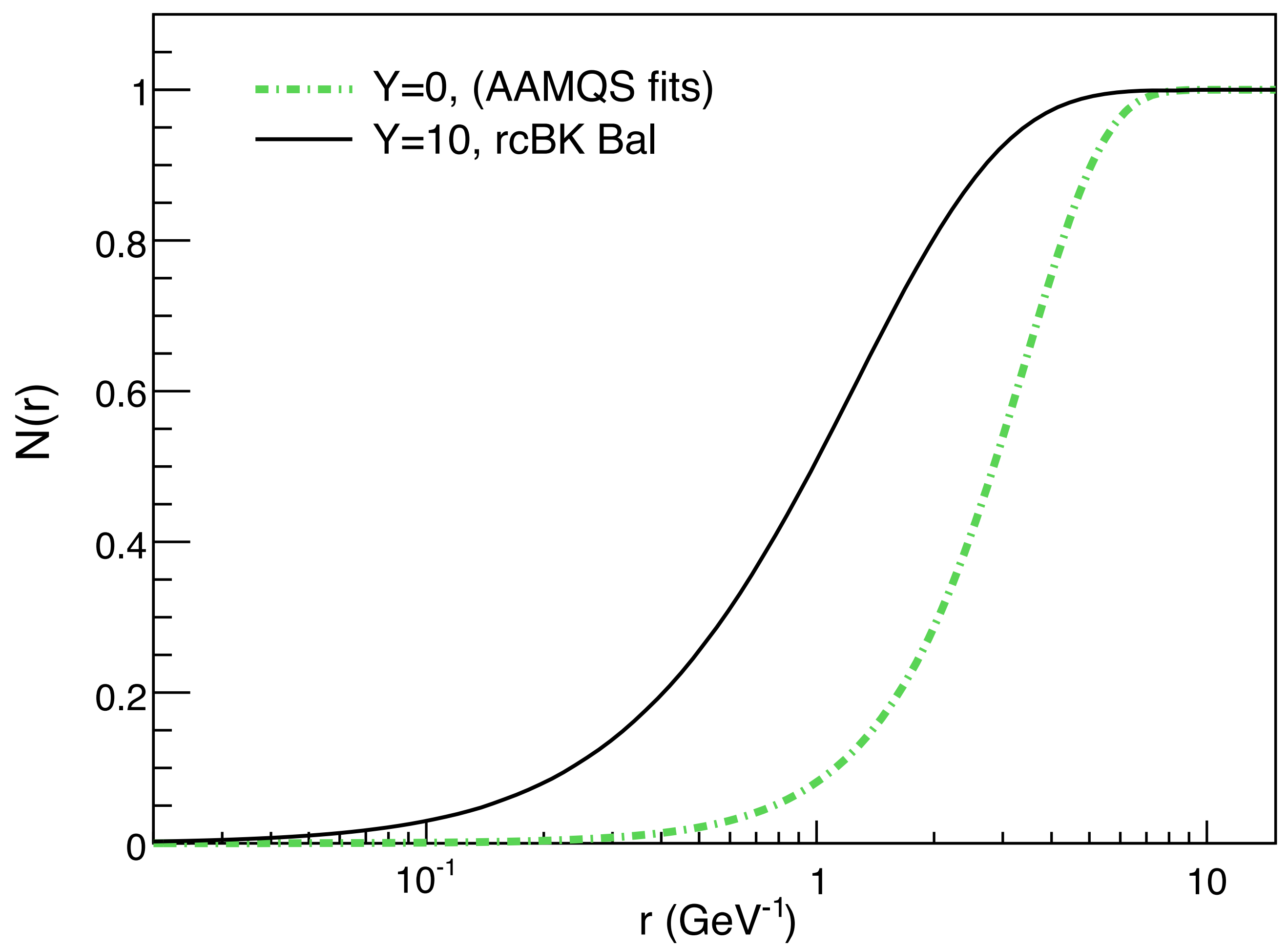
Playing before fitting…



Playing before fitting…

$$\frac{\partial \mathcal{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\, \mathcal{M}_{\mathbf{012}} \left[\mathcal{S}_{\mathbf{02};Y}\, \mathcal{S}_{\mathbf{12};Y} - \mathcal{S}_{\mathbf{01};Y}\right]$$

Evolve it with rcBK, Balitsky's kernel

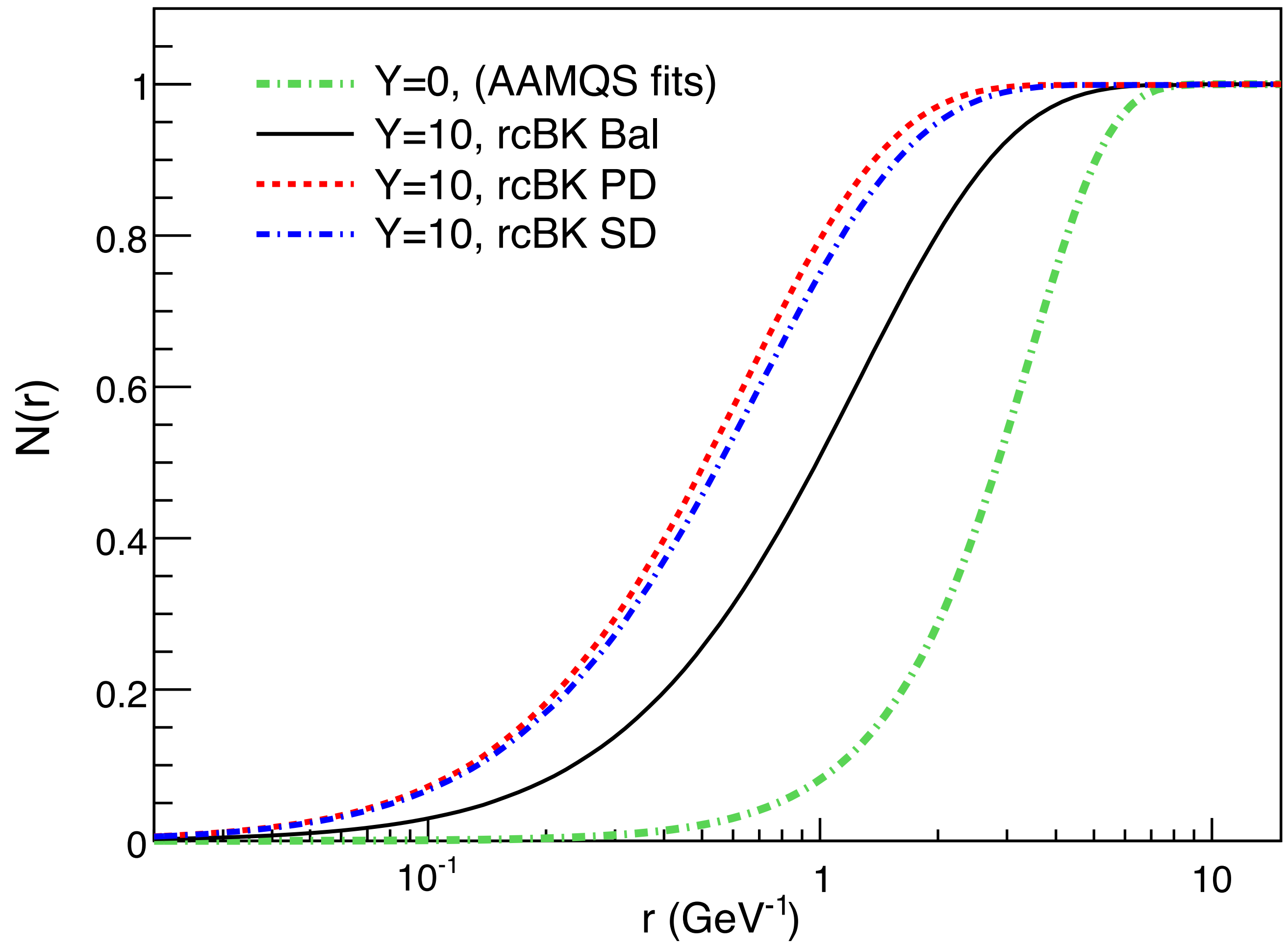


This parametrisation yields a good fit to HERA-I data

Playing before fitting…

$$\frac{\partial \mathcal{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\, \mathcal{M}_{\mathbf{012}} \left[\mathcal{S}_{\mathbf{02};Y}\, \mathcal{S}_{\mathbf{12};Y} - \mathcal{S}_{\mathbf{01};Y}\right]$$

Compare to rcBK evolution with SD and PD kernels

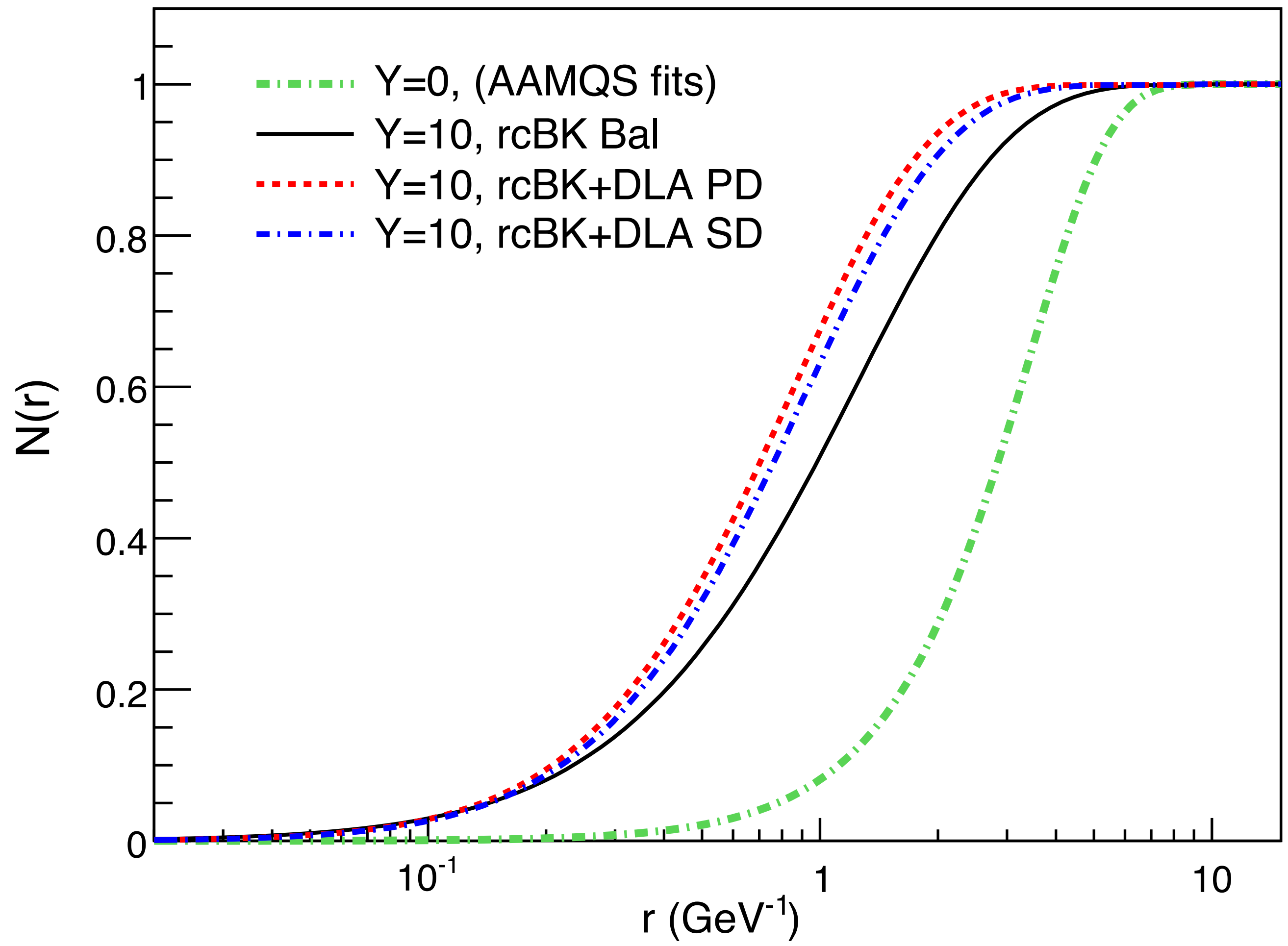


Balitsky's prescription for the kernel yields the slowest evolution

Playing before fitting…

$$\frac{\partial \tilde{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi} \mathcal{M}_{\mathbf{012}} \mathcal{K}^{\mathrm{DLA}}_{\mathbf{012}} \left[\tilde{S}_{\mathbf{01};Y} \tilde{S}_{\mathbf{12};Y} - \tilde{S}_{\mathbf{01};Y}\right]$$

Add DLA corrections to PD and SD evolution



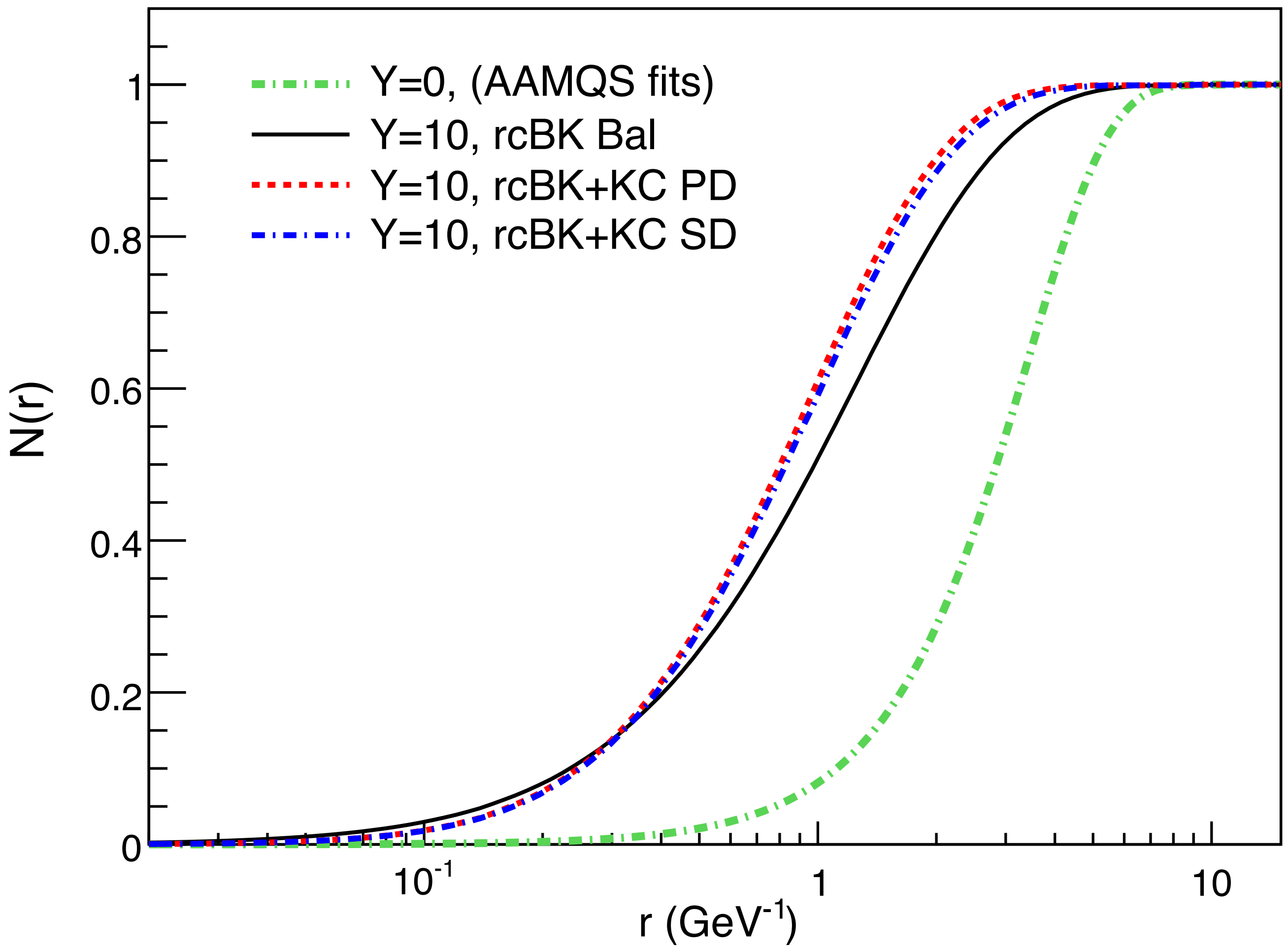
rcBK + DLA evolution is stable

Reduction of evolution speed and suppression of small dipole sizes

Playing before fitting…

$$\frac{\partial \mathcal{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\,\mathcal{M}_{\mathbf{012}}\,\Theta(Y-\Delta_{\mathbf{012}})\,[\mathcal{S}_{\mathbf{02};Y-\Delta_{\mathbf{012}}}\,\mathcal{S}_{\mathbf{12};Y-\Delta_{\mathbf{012}}} - \mathcal{S}_{\mathbf{01};Y}]$$

Add KC corrections to PD and SD evolution



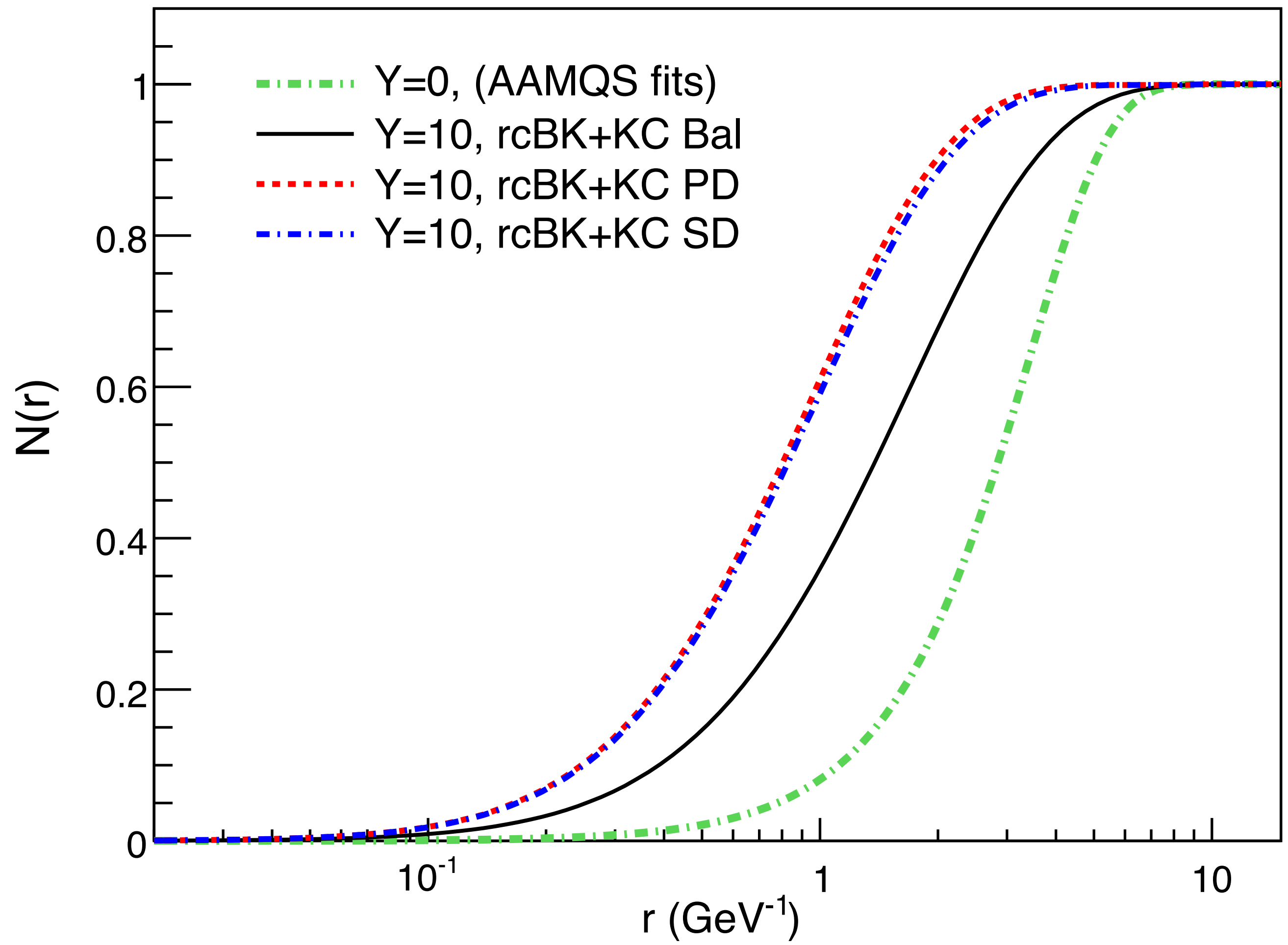
rcBK + KC evolution is stable

Reduction of evolution speed and even larger suppression of small dipole sizes

Playing before fitting…

$$\frac{\partial \mathcal{S}_{\mathbf{01};Y}}{\partial Y} = \int \frac{d^2\mathbf{x_2}}{2\pi}\,\mathcal{M}_{\mathbf{012}}\,\Theta(Y-\Delta_{\mathbf{012}})\left[\mathcal{S}_{\mathbf{02};Y-\Delta_{\mathbf{012}}}\,\mathcal{S}_{\mathbf{12};Y-\Delta_{\mathbf{012}}} - \mathcal{S}_{\mathbf{01};Y}\right]$$

and also to rcBK + Balitsky's evolution…



rcBK + KC evolution is stable

Reduction of evolution speed and even larger suppression of small dipole sizes

Fit Results

Nf =3

rcBK "only"

$N_f = 3, \ \alpha_{fr} = 0.7$

Q^2_{max} (GeV^2)	Evolution scheme	Q_0^2(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.
50	rcBK-Bal	0.192	0	26.11	1.129	1.709	1.010
650	rcBK-Bal	0.226	0	22.99	1.160	1.305	0.948
	rcBK-Bal	0.189	0	25.987	1.240	2.013	1.04

- Good, stable fits with rcBK evolution only
- Preferred, unphysical γ values at high Q^2 can be avoided in 2 ways:

Physical i.c.: $\gamma \lesssim 1.125$ $\qquad$ $\gamma(r) = \gamma + \dfrac{1-\gamma}{1+(Q_s r)^a}\,,$ with $a \approx 0.25$

Reminder: Preliminary results

Fit Results

***Nf* =3**

$N_f = 3,\ \alpha_{fr} = 0.7$

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Q^2_{max} (GeV^2)	Evolution scheme	Q^2_0(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.
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rcBK + DLA

Q^2_{max} (GeV^2)	Evolution scheme	Q^2_0(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.
50	DLA+PD	0.1974	0	23.43	1.078	3.692	1.177
	DLA+PD	$3.511{\cdot}10^{-2}$	5.12	23.39	1.117	3.67	1.21
	DLA+SD	0.1973	0	23.45	1.080	2.927	1. 202
	DLA+SD	$3.93{\cdot}10^{-2}$	4.95	23.57	1.124	3.066	1.25
650	DLA+SD	0.224	0	21.98	1.119	2.499	1.62
	DLA+PD	$2.189{\cdot}10^{-2}$	6.37	221.972	1.127	3.131	1.52

rcBK + KC

Q^2_{max} (GeV^2)	Evolution scheme	Q^2_0(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.
50	KC+SD	$5.72{\cdot}10^{-2}$	4.21	23.83	1.021	3.627	1.27
	KC+PD	$5.025{\cdot}10^{-2}$	5.27	22.997	1.067	3.876	1.23
650	KC+SD	$5.82{\cdot}10^{-2}$	3.99	24.01	1.024	3.781	1.67
	KC+PD	$4.715{\cdot}10^{-2}$	5.44	22.127	1.077	3.726	1.73

- Good fits with rcBK+DLA and rcBK + KC evolution up to Q^2 =50 GeV^2
- Pre-scaling initial conditions preferred for rcBK+ KC evolution
- Tension in the fits at high Q^2

Fit Results

Nf =5

$$N_f = 5, \quad \alpha_{fr} = 0.7$$

Q^2_{max} (GeV^2)	Evolution scheme	Q^2_0(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.

rcBK "only"

- No good fits to data using rcBK evolution only.
- Additional charm contribution cannot be compensated by changes in the i.c.
- Confirmation of previous results from AAMQS fits Eur.Phys.J. C71 (2011) 1705
- Separate treatment of heavy and light quarks?

$$\sigma_{T,L}(x,Q^2) = \sigma_0 \sum_{f=u,d,s} \int_0^1 dz\, d\mathbf{r}\, |\Psi^f_{T,L}(e_f, m_f, z, Q^2, \mathbf{r})|^2\, \mathcal{N}^{light}(\mathbf{r}, x)$$
$$+ \sigma_0^{heavy} \sum_{f=c,b} \int_0^1 dz\, d\mathbf{r}\, |\Psi^f_{T,L}(e_f, m_f, z, Q^2, \mathbf{r})|^2\, \mathcal{N}^{heavy}(\mathbf{r}, x)\,.$$

Reminder: Preliminary results

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rcBK + DLA

Q^2_{max} (GeV^2)	Evolution scheme	Q_0^2(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.
50	DLA+PD	0.192	0	23.623	1.065	3.88	1.20
	DLA+PD	$3.78 \cdot 10^{-2}$	5.12	23.66	1.155	3.89	1.31
	DLA+SD	0.188	0	24.12	1.066	3.14	1.19
650	DLA+SD	0.17	0	27.98	1.25	7.13	1.82
	DLA+PD	0.168	0	29.37	1.27	7.76	2.1

rcBK + KC

- Work in progress. So far fits yield $\chi^2/\text{d.o.f.} \sim 2$

Fit Results

Nf =5

$$N_f = 5, \quad \alpha_{fr} = 0.7$$

Q^2_{max} (GeV^2)	Evolution scheme	Q_0^2(GeV^2)	ΔY_0	σ_0 (mb)	γ	C	χ^2/d.o.f.

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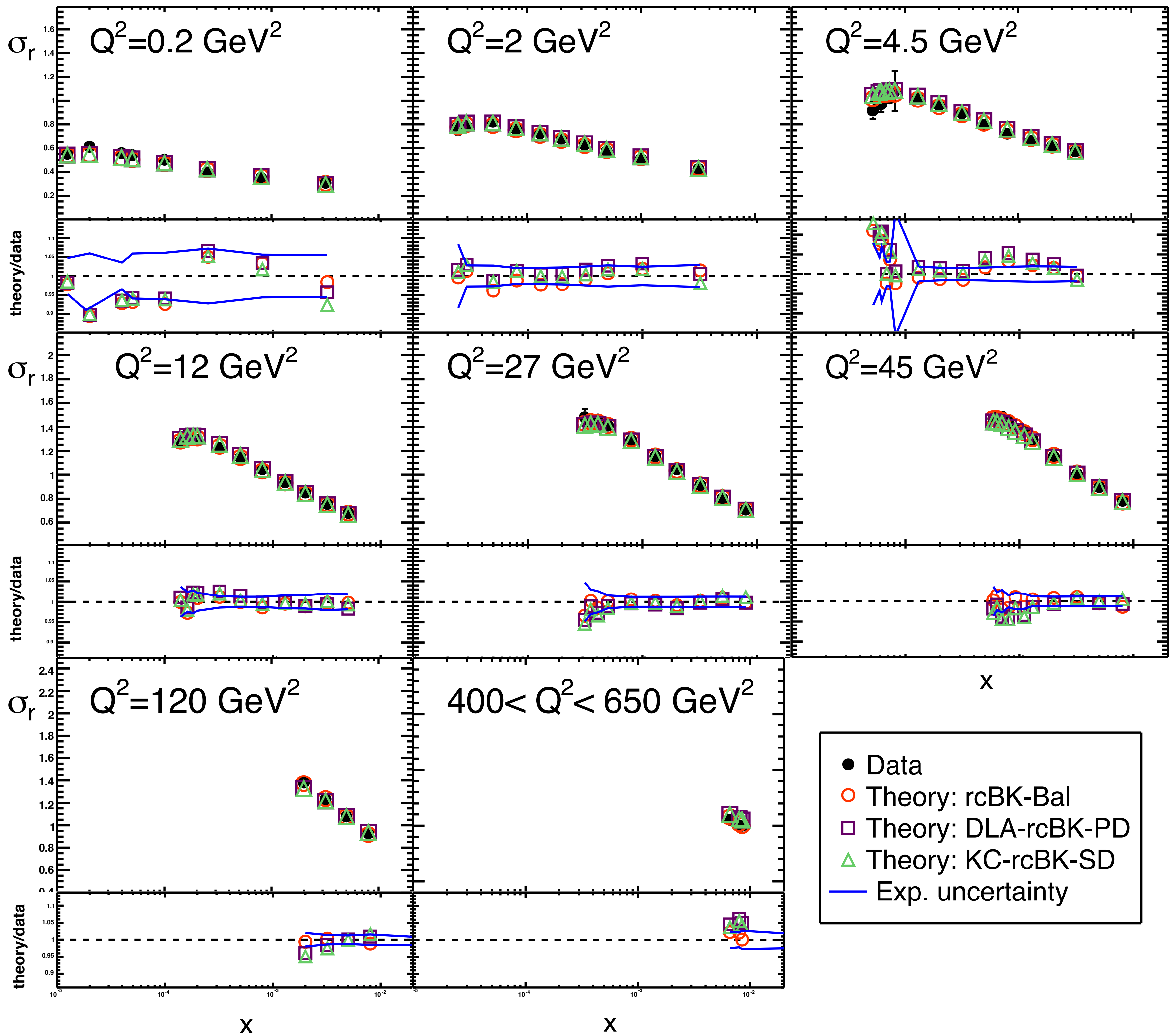
rcBK + DLA

- Very good fits using rcBK +DLA evolution up to high Q^2 reported by Iancu et al. Only concern: physicality of the initial conditions

arXiv:1507.03651

init cdt.	RC schm	sing. logs	χ^2/npts for Q^2_{max} 50	100	200	400
GBW	small	yes	1.135	1.172	1.355	1.537
GBW	fac	yes	1.262	1.360	1.654	1.899
rcMV	small	yes	1.126	1.172	1.167	1.158
rcMV	fac	yes	1.222	1.299	1.321	1.317
GBW	small	no	1.121	1.131	1.317	1.487
GBW	fac	no	1.164	1.203	1.421	1.622
rcMV	small	no	1.097	1.128	1.095	1.078
rcMV	fac	no	1.128	1.177	1.150	1.131

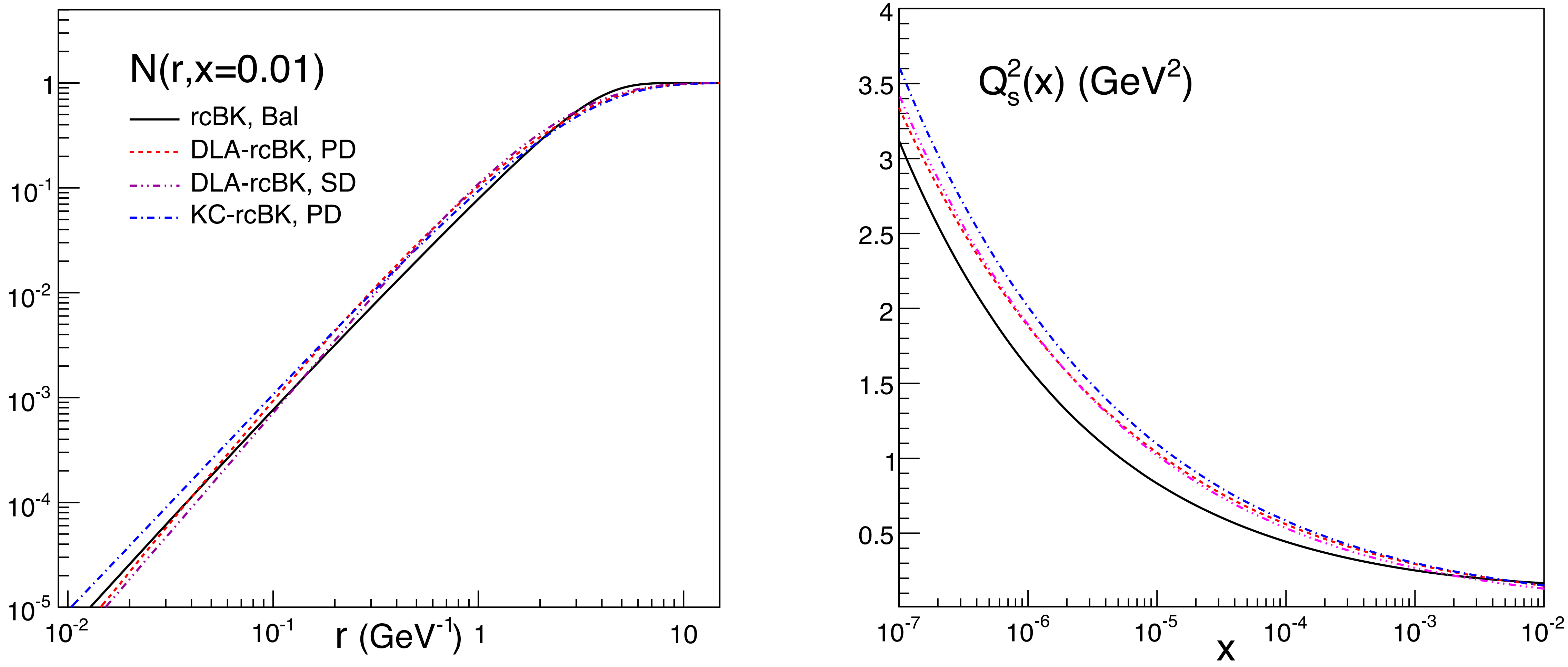
Fit Results



σ_r
Q^2=0.2 GeV^2
Q^2=2 GeV^2
Q^2=4.5 GeV^2
theory/data
Q^2=12 GeV^2
Q^2=27 GeV^2
Q^2=45 GeV^2
Q^2=120 GeV^2
400< Q^2< 650 GeV^2
x
Data
Theory: rcBK-Bal
Theory: DLA-rcBK-PD
Theory: KC-rcBK-SD
Exp. uncertainty

Fit Results

Good fits conspire to yield a very similar dipole amplitude in all kinematic space tested by the fits



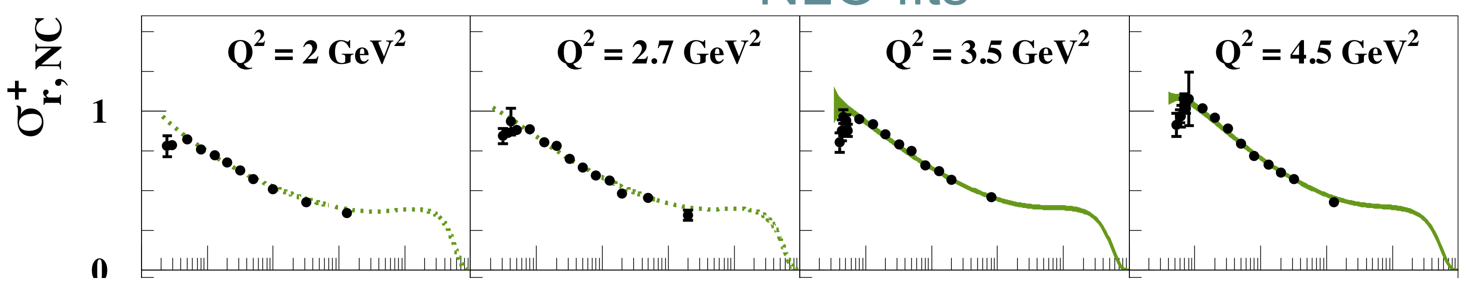
A glimpse to DGLAP fits to HERA II data

arXiv:1506.06042

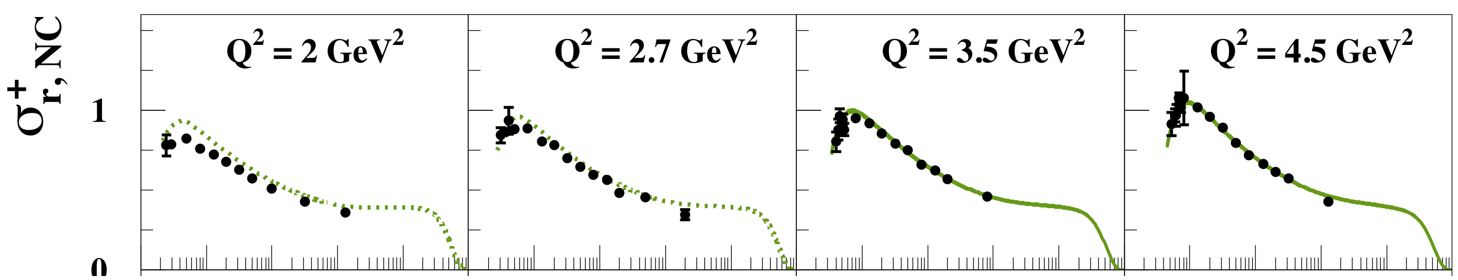
New data also cause tension in DGLAP fits

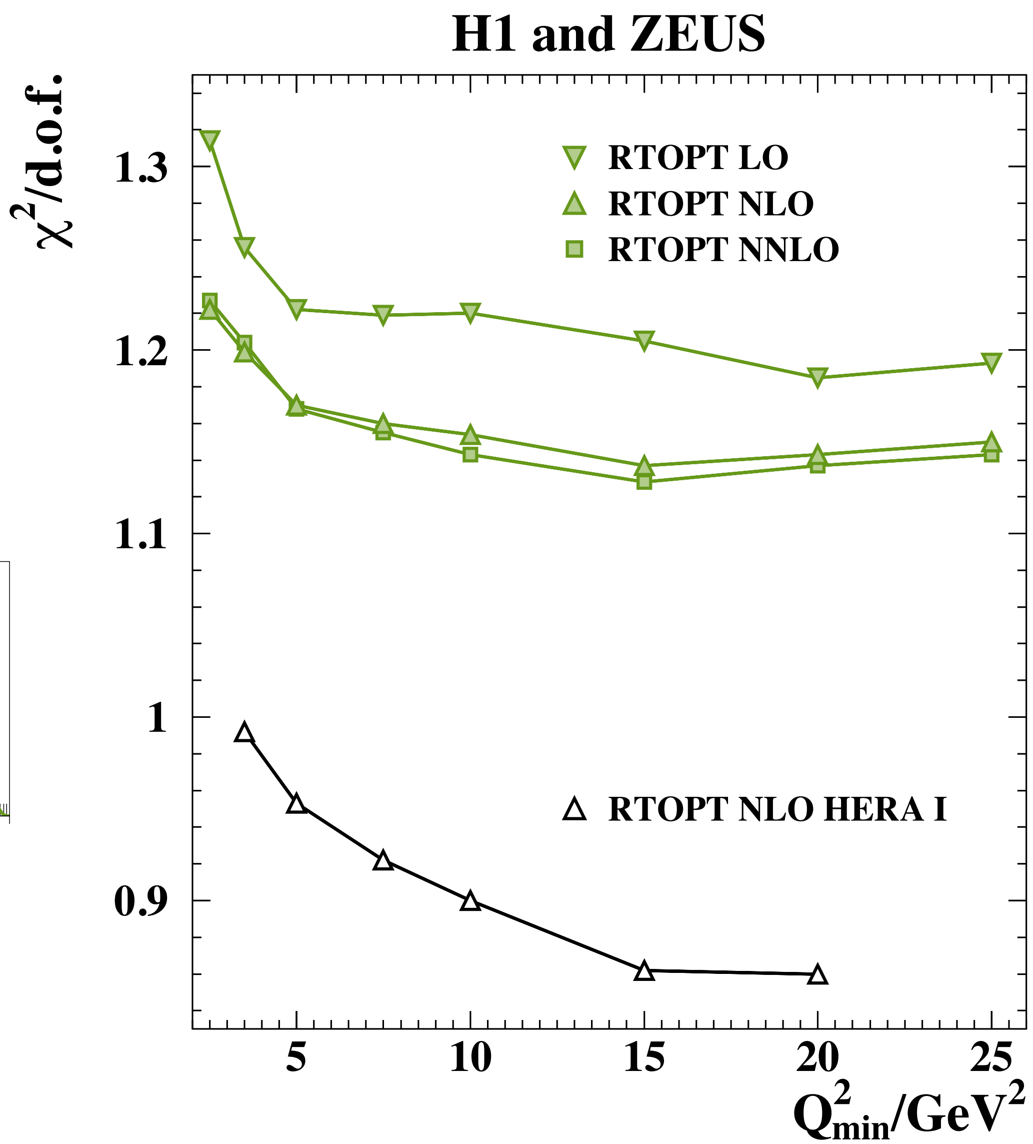
Bad extrapolation of the fits results to the unfitted kinematic region (low-Q^2)

NLO fits



LO fits





Final comments

★ Main conclusion: collinearly improved rcBK equations are compatible with HERA II data, but do not improve previous descriptions based on rcBK evolution only.

★ Reduced errors from combined HERA II analysis induce tension in the fits when extended to $Q^2 > 50$ -100 GeV^2

★ To be checked

- NLO photon impact factors
- Sensitivity to charm mass and variable flavour scheme.
- Details: resummation of the initial condition, precise definition of the rapidity variable etc
- Effect of DLA corrections in e-A scattering and expectations for the EIC
- Impact on neutrino astrophysics: talk by Alba Soto on wednesday

Merci!