Proton structure functions at NLO in the dipole picture with massive quarks

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Based on arXiv:2211.03504 with Hänninen, Paatelainen, Penttala

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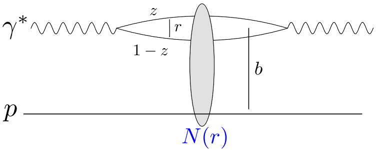
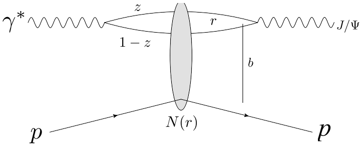
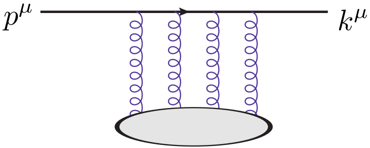
Probing high density gluonic matter: CGC and dipole picture (LO)







Total cross section

$\sigma^{\gamma^* p} \sim \Psi^* \otimes \Psi \otimes N$

Diffractive processes

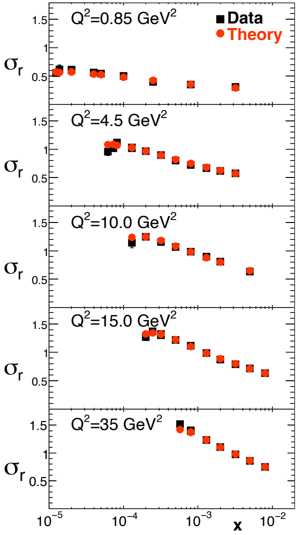
$\sigma \sim |\int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta} \Psi^* \otimes \Psi_V \otimes N|^2$

$p + A$ collisions

$\sigma \sim xf(x) \times |\int \mathrm{d}^2\mathbf{r} e^{-i\mathbf{r}\cdot\mathbf{k}} N|^2$

- Dipole picture at high energy: $\gamma^* \to q\bar{q}$ fluctuation has a long lifetime $\Rightarrow$ factorization
- Dipole amplitude N: eikonal propagation in the color field, resumming multiple scattering
  - Convenient degree of freedom at small-x
  - Center-of-mass energy dependence perturbative: BK/JIMWLK
  - Necessary input for all CGC calculations: non-perturbative initial condition

State-of-the-art at LO



Albacete et al (AAMQS), 1012.4408

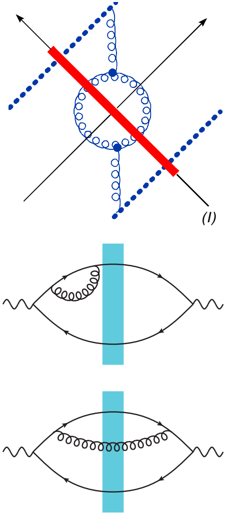
Many works at LO
(note power counting: $\alpha_s \ln 1/x \sim 1$, so actually LL)

- Parametrization for the dipole amplitude at $x = 0.01$ + BK evolution with running α_s
- AAMS 0902.1112: F_2 from H1&ZEUS
- AAMQS 1012.4408: combined precise σ_r data
  - Charm data requires an additional normalization factor
- H.M, Lappi, 1309.6963: different parametrizations, applications to p+A

Status at LO

- $\chi^2/N \sim 1$
- Can not simultaneously describe total and charm data

Progress towards NLO



Full NLO accuracy ($\sim \alpha_s^2 \ln 1/x$) requires

- Evolution equation
  - NLO BK: Balitsky, Chirilli, 0710.4330
  - Resummation of transverse logs: Iancu, et al, 1502.05642, 1507.03651
  - Numerical solution: Lappi, H.M, 1601.06598
- Impact factor (γ^* wave function at NLO)
  - $m_q = 0$: Hänninen, Lappi, Paatelainen, 1711.08207; Beuf 1708.06557
  - With heavy quarks (mass renormalization in LCPT): Beuf, Lappi, Paatelainen 2103.14549 2112.03158, 2204.02486
  - Numerical implementation: Hänninen, H.M, Paatelainen, Penttala, 2211.03504
- Also many other processes, talks by Dumitru, Tawabutr, Mulian, Penttala, Salazar, Hänninen, . . .

Resumming higher order contributions in the evolution equation

NLO BK numerically heavy, here different resummation schemes, drop α_s^2 w/o transverse logs
Resummation needed to render NLO BK stable Lappi, H.M, 1601.06598

ResumBK

- Single and double transverse logs
- Resummation tuned to approximate NLO BK

  Lappi, H.M, 1601.06598
- Iancu et al, 1502.05642, 1507.03651

KCBK

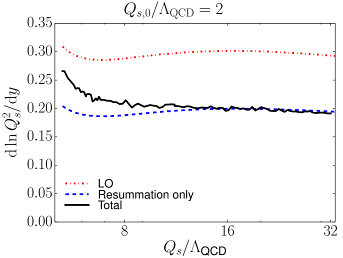
- Kinematical constraint (life time ordering for emitted gluons)
- Same physics as double log resummation
- Beuf, 1401.0313

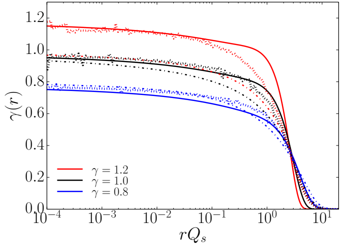
TBK

- Evolution in target (not projectile!) rapidity
- Impact factor in projectile rapidity, need to shift
- Ducloue et al, 1902.06637

- Differences quantify the resummation scheme dependence
- Dropped α_s^2 terms have only a small effect in fits Hänninen, 2112.08818

What happens at NLO: evolution





Solid: IC, dashed: evolved

Lappi, H.M, 1601.06598

BK evolution at NLO (ResumBK, KCBK)

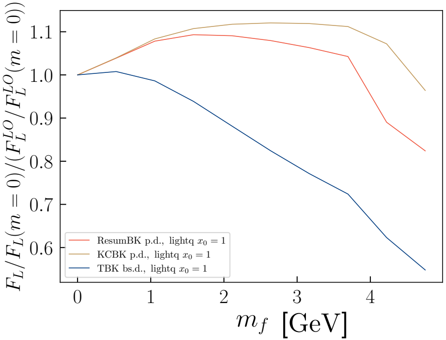
- Slower evolution speed
- Anomalous dimension γ ($N \sim (r^2 Q_s^2)^\gamma$) approx. constant
  Compare to LO: $\gamma \to 0.6 \ldots 0.8$

- Slower evolution speed good: LO fits need smallish α_s
- Anom. dimension affects virtuality and mass dependence: suppresses high Q^2 and m_q^2:
  $\sigma^{\gamma^* p} \sim |\Psi_\gamma|^2 N(r^2 = 1/\mu^2) \sim |\Psi_\gamma|^2 \mu^{-2\gamma}$, $\mu^2 = \mu^2(Q^2, m_q^2)$
- Ducloue et al, 1912.09196: (approximative) NLO evolution + LO impact factor not enough to describe total + charm data

TBK more complicated:

develops $\gamma < 1$ (enhances heavy quark production), but also need a shift to projectile rapidity

What happens at NLO: impact factor



NLO vs LO impact factor

> 1: enhances heavy q production

< 1: suppresses heavy q production (TBK-evolved dipole)

NLO photon wave function

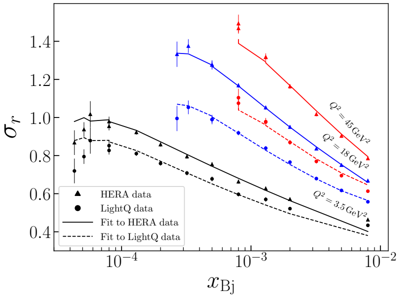
- NLO impact factor enhances heavy quark production compared to LO
- Opposite effect than from the evolution

With TBK evolved dipole different:

- Impact factor suppresses heavy quarks,
- Again opposite effect than from evolution

Quantitative question if m_q and x, Q^2 dependence is compatible with HERA at full NLO?

Fit initial condition to HERA data



Beuf, Hänninen, Lappi, H.M, 2007.01645

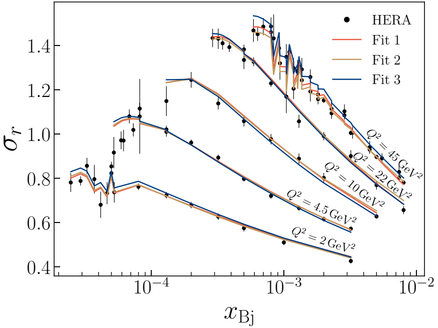
Goal

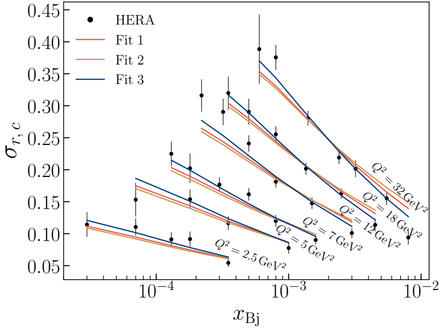
- Global analysis, fit simultaneously total and charm&bottom data

Here

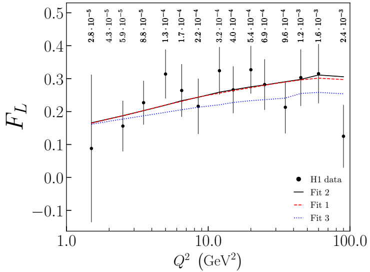
- Use $m_q = 0$ fits from Beuf et al, 2007.01645
  - Fitted light quark pseudodata: interpolated c and b subtracted form total σ_r
  - In total 12 different fits (different running coupling prescription, resummation scheme, . . .)
- Compute predictions for c and b production

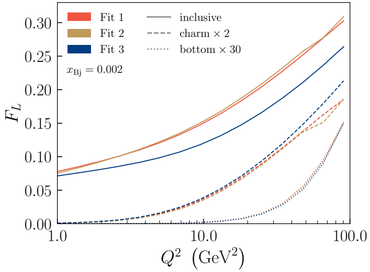
Comparison to world data





- 3/12 fits: successful predictions, $\chi^2_c/N < 2.5$ using optimal $1.1\,\mathrm{GeV} < m_c < 1.6\,\mathrm{GeV}$
- Also b data well described with these 3 fits
- Obtain $\chi^2/N = 1\ldots2$: excellent description of *all* small-x DIS data
- Additional constraints as charm probes dipole amplitude at much shorter length scales





- No F_L data included in fits
- All 3 determined fits compatible with the F_L data
- More precise data from the EIC can provide further constraints
- F_L is different from $F_2 \approx \sigma_r$, as no aligned jet contribution from large dipoles

Conclusions

- First CGC description of all (total+charm) HERA small-x structure function data
- Successfully predict heavy quark production data at full NLO accuracy
- Charm provides strong additional constraints for the initial condition of the BK evolution
- Having both (approximative) NLO evolution and NLO impact factor is crucial
- Demonstrated feasibility of global analyses
- The determined 3 fits should be used in all NLO CGC phenomenology
  - Deviations rough estimate for initial condition uncertainty
- Outlook/in progress: Bayesian inference including total and heavy quark data

Best fits

#	Resum. scheme	α_s	$Y_{0,BK}$	m_c [GeV]	χ^2_c/N	m_b [GeV]	χ^2_b/N	χ^2_{tot}/N
1	ResumBK	PD	0	1.42	1.86	4.83	1.37	1.25
2	KCBK	PD	0	1.49	2.55	4.96	1.58	1.23
3	TBK	BSD	0	1.29	1.02	5.04	1.12	1.83