Dipole model analysis of high precision HERA data at low x

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Why low-x region is very interesting?

it is dominated by the gluon density,

precise knowledge of gluon density is very important for LHC physics

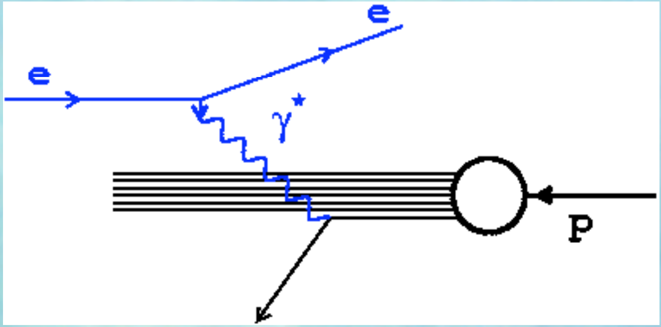
- low-x region is a multi-regge region in which it is possible to sum up QCD Feynman diagrams to infinity (BFKL resummation)
- it is the limit in which it is possible to evaluate N=4 QCD (gravitational diagrams) up to infinite order (Dixon, Bern, ...)

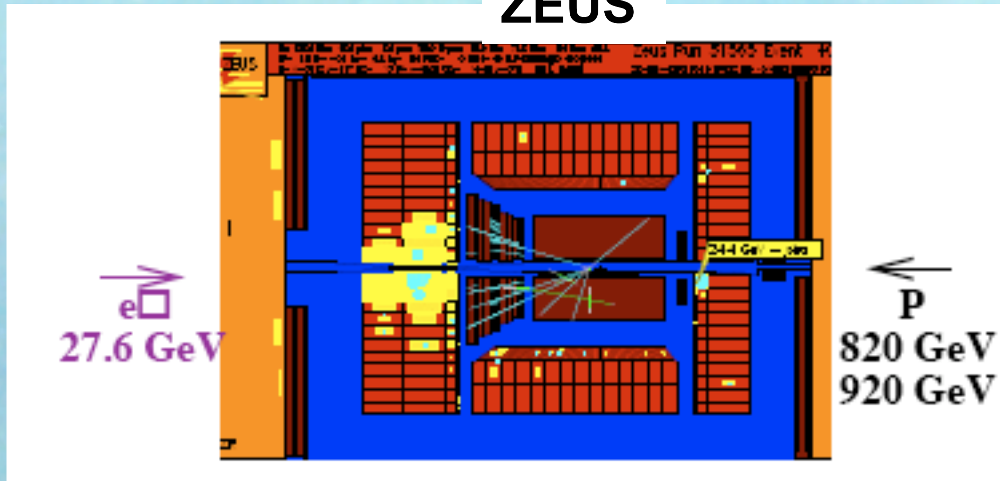
☞ could become a bridge to gravitation

It is a region with large amount of diffractive processes,
dipole picture ....
exclusive J/Psi, rho..... processes are new probes of matter

DIS at HERA at low x

Inclusive Scattering





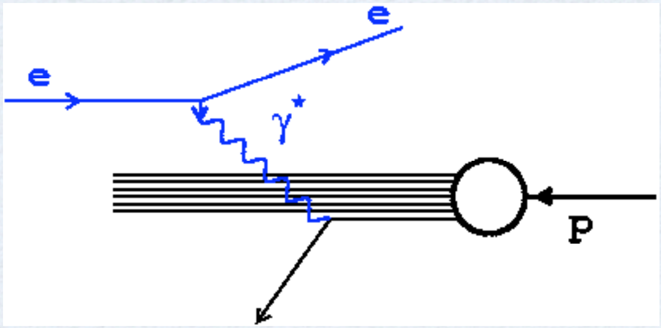
Diffractive Scattering

expectation before HERA
~ 0.01%

seen ~20% at $Q^2 = 4$ GeV^2
~10% at $Q^2 = 20$ GeV^2

Partons vs Dipoles at low-x

Infinite momentum frame: Partons



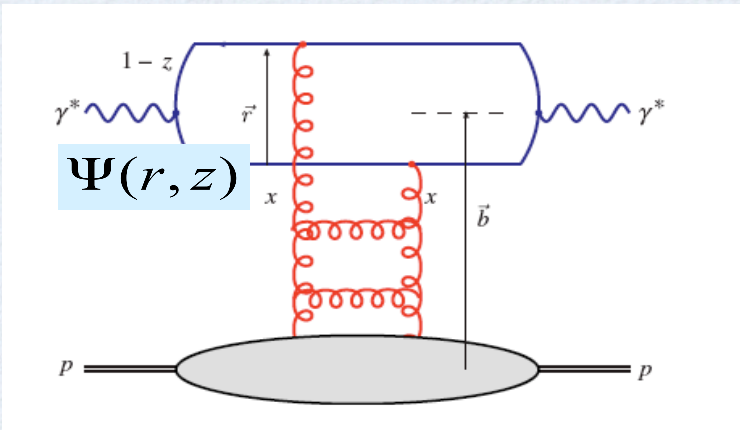
F_2 measures parton density at a scale Q^2

$$F_2 = \Sigma_f\, e_f^2\, xq(x,Q^2)$$

Proton rest frame: Dipoles - long living quark pair interacts with the gluons of the proton

dipole life time ≈ $1/(m_p\, x)$

$= 10 - 1000$ fm at $x = 10^{-2} - 10^{-4}$



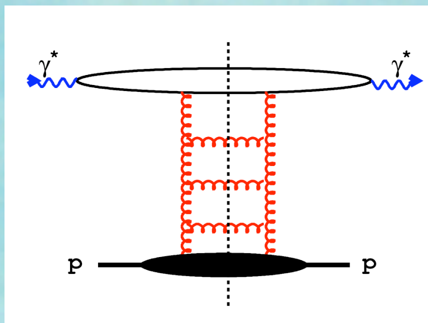
$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi \;; \qquad F_2 = \frac{Q^2}{4\pi^2 \alpha_{em}} \sigma_{tot}^{\gamma^* p}$$

for small dipoles, at low-x, dipole picture is equivalent to the QCD parton picture

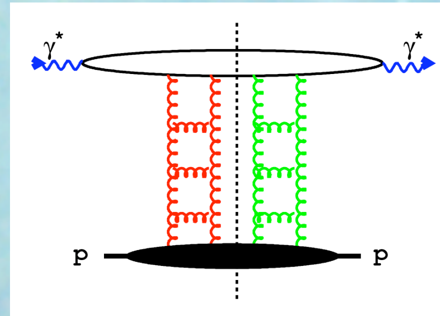
$\sigma_{qq} \sim r^2\, xg(x,Q^2)$

Low-x phenomena in DIS give access to the properties of the gluon density

- **rise of F2 with decreasing x**
- **diffractive reactions**



← Optical Theorem →



$$\sigma_{tot}^{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi$$

$$\frac{d\sigma^{\gamma^* p \to V p}}{dt} \sim \left| \int d^2 b\, \Psi_V^* \Psi e^{-i\vec{b}\cdot\vec{\Delta}} \frac{d\sigma_{q\bar{q}}}{d^2 b} \right|^2$$

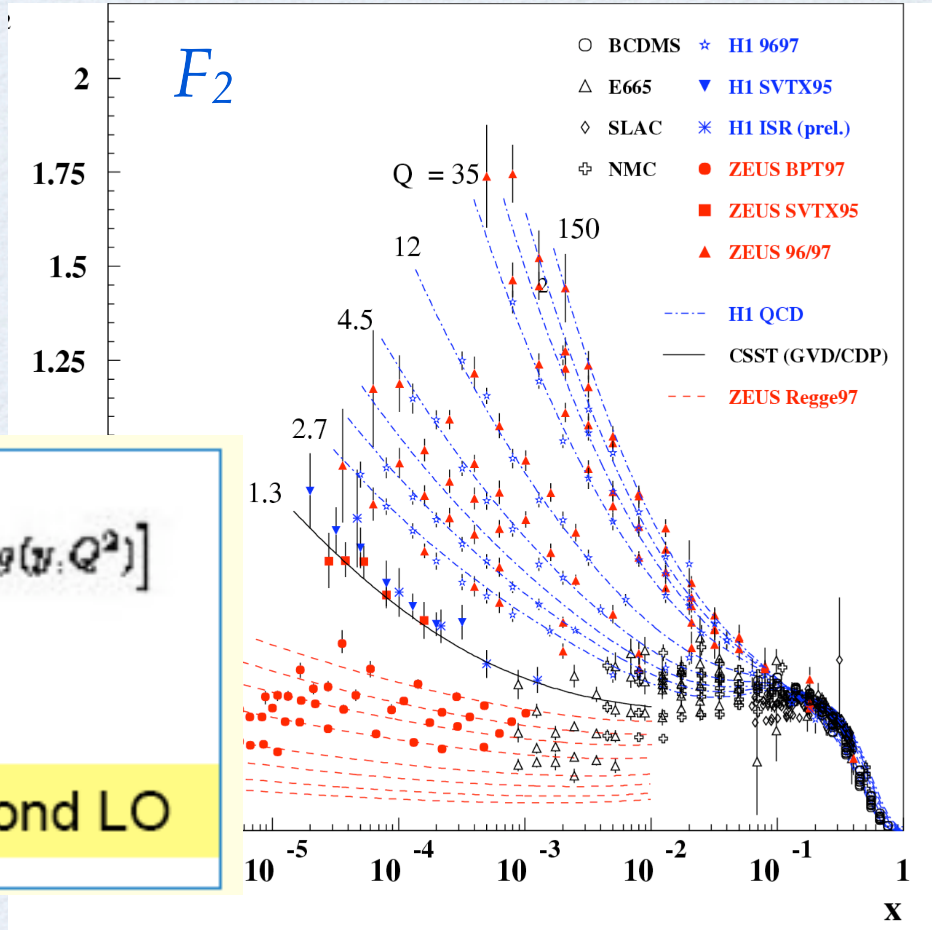
$$\frac{d\sigma_{q\bar{q}}}{d^2 b} \sim r^2 \alpha_S x g(x, \mu^2) T(b)$$ for small dipole size

The same, universal, gluon density describes the properties of many reactions: F_2, F_L, inclusive diffraction, exclusive J/Psi, Phi and Rho production, DVCS, diffractive jets

Determination of Gluon Density in pdf's

GD is determined from the increase of F_2 with x and Q^2 in low-x region

Determine pdf's densities from the χ^2 fit to the data



$$\frac{F_2(x,Q^2)}{x} = \int_0^1 \frac{dy}{y}\left[\Sigma_i C_2(z,\alpha_s)\, q_i(x,Q^2) + C_g(z,\alpha_s)\, g(y,Q^2)\right]$$

$$C_2(z,\alpha_s) = e_i^2\left[\delta(1-z) + \alpha_s f_2(z)\right]$$

$$C_g(z,\alpha_s) = \alpha_s f_g(z)$$

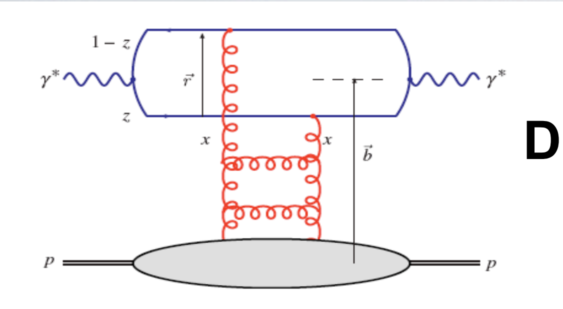
beyond LO

Who? ABM, MSTW, CT(EQ), HERAPDF, (G)JR, NNPDF

How? Start from parametrized form of $g(q)(x,Q_0^2)$ at Q_0^2 1-7 GeV^2

use N(N)LO DGLAP, MSbar factorisation, Heavy quark scheme

Dipole model analysis of high precision HERA data



A. Luszczak[1], H. Kowalski [2]

published in PRD

Data: HERA I combined inclusive DIS measurement

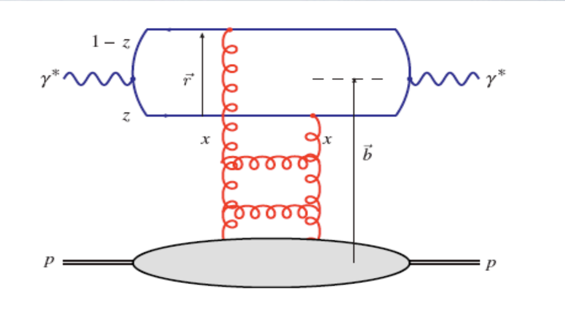
HERAFitter

Dipole model is valid in the low-x limit (x<0.01) where the valence quark contribution is small (~ 5%) and describes the sea-quark or gluon density contribution to F_2

precision of the measurements: ~ 2 % in the low-x region

For a full description one has to take the contribution of the valence quarks into account

Dipole model with valence quarks



Choice of the dipole model:
Bartels-Golec-Kowalski (BGK) model
because it uses DGLAP as a QCD evolution scheme
BGK model is the impact parameter integrated IPsat or b-Sat model

We take a heuristic approach to valence quarks:
valence quarks contribution is taken from the HERAPDF fits (or MSTW) and the fits are performed in the low-x region only

Note on a side:
although the dipole picture is valid only in the low-x region
it should be possible to overcome this limitation by analytic continuation of the amplitudes from low-x region to high-x region
(work in progress for BFKL, Kowalski, Lipatov, Ross)

$$\sigma^{\gamma p} = \frac{4\pi^2\alpha_{em}}{Q^2}F_2 = \sum_f \int d^2r \int_0^1 dz\, |\Psi^\gamma(r,z,Q^2,m_f)|^2 \;\; \hat{\sigma}(r,x)$$

Dipole cross section

- BGK (Bartels-Golec-Kowalski) parametrization

$$\hat{\sigma}(r,x) = \sigma_0 \left\{1 - \exp\left[-\pi^2 r^2 \alpha_s(\mu^2) xg(x,\mu^2)/(3\sigma_0)\right]\right\}$$

- $\mu^2 = C/r^2 + \mu_0^2$ is the scale of the gluon density
- μ_0^2 is a starting scale of the QCD evolution. $\mu_0^2 = Q_0^2$
- gluon density is evolved according to the LO or NLO DGLAP eq.
- soft gluon:

$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g}$$

- soft + hard gluon:

$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g}(1 + D_g x + E_g x^2)$$

- soft + negative gluon:

$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g} - A_g'\, x^{\lambda_g'}\, (1-x)^{C_g'}$$

BGK (NLO) + valence quarks (soft gluon)

No	Q_0^2	σ_0	A_g	λ_g	C_g	C	Np	χ^2	χ^2/Np
1	1.1	143.14	1.605	-0.056	5.884	4.0	201	198.17	0.986
3	1.3	123.18	1.589	-0.094	6.937	4.0	201	200.70	0.998
5	1.5	112.44	1.685	-0.109	8.124	4.0	201	202.26	1.006
7	1.7	97.91	1.603	-0.137	8.849	4.0	201	203.55	1.013
9	1.9	90.98	1.624	-0.149	9.696	4.0	201	202.18	1.006

$Q^2 > 3.5$ GeV
$x < 0.01$

Table 1: BGK fit with valence quarks for σ_r for H1ZEUS-NC-(e+p) and H1ZEUS-NC-(e-p) data in the range $Q^2 \geq 3.5$ and $x \leq 0.01$. NLO fit. RT HF Scheme. *Soft gluon.*

HERAPDF1.0 (NLO)

No	Q_0^2	HF Scheme	χ^2	Np	χ^2/Np
1	1.1	RT	604.64	592	1.021
3	1.3	RT	586.33	592	0.990
5	1.5	RT	579.72	592	0.979
7	1.7	RT	576.76	592	0.974
9	1.9	RT	575.08	592	0.971

$Q^2 > 3.5$ GeV^2
$x < 1.0$

Table 2: HERAPDF fit for σ_r for H1ZEUS-NC-(e+p), H1ZEUS-NC-(e-p) and H1ZEUS-CC-(e+p), H1ZEUS-CC-(e-p) data in the range $Q^2 \geq 3.5$ and $x \leq 1.0$.

BGK (NLO) + valence quarks (soft gluon)

$Q^2 > 8.5$ GeV^2
$x < 0.01$

No	Q_0^2	σ_0	A_g	λ_g	C_g	C	Np	χ^2	χ^2/Np
1	1.1	91.60	2.227	-0.022	9.322	4.0	162	131.78	0.813
3	1.3	83.393	2.047	-0.069	10.019	4.0	162	132.10	0.815
5	1.5	77.121	1.969	-0.098	10.825	4.0	162	132.23	0.816
7	1.7	71.975	1.922	-0.120	11.538	4.0	162	132.88	0.820
9	1.9	69.128	1.897	-0.135	12.175	4.0	162	132.03	0.815

HERAPDF1.0 (NLO)

$Q^2 > 8.5$ GeV^2
$x < 1.0$

No	Q_0^2	HF Scheme	χ^2	Np	χ^2/Np
1	1.1	RT	472.52	550	0.859
3	1.3	RT	469.80	550	0.854
5	1.5	RT	469.06	550	0.853
7	1.7	RT	468.67	550	0.852
9	1.9	RT	468.34	550	0.852

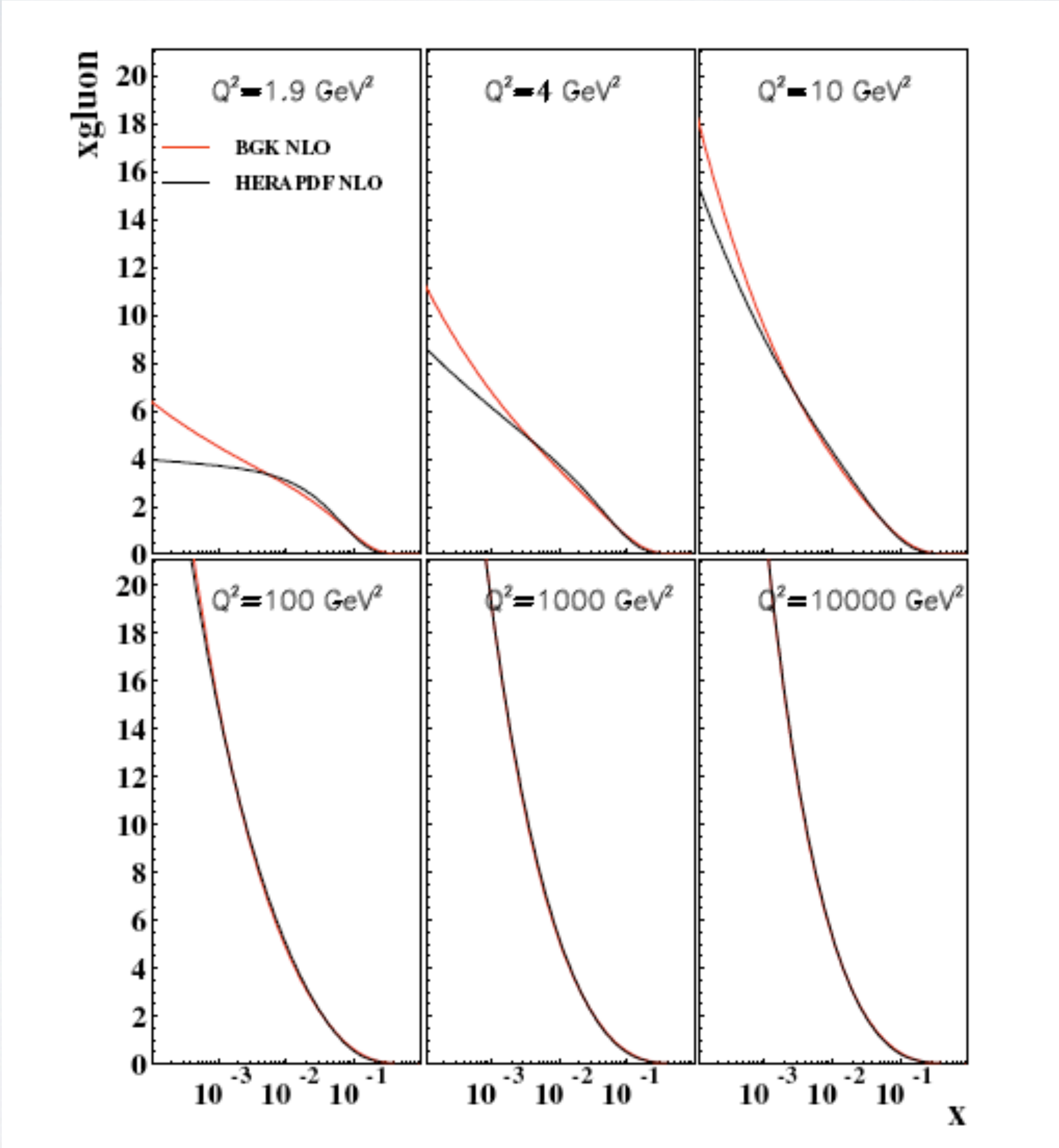
significant improvement of χ^2/N_p for $Q^2 > 8.5$

▶ *lack of NNLO effecs? (presumably not, see the talk of Voica Radescu, WG1)*

▶ *are these saturation effects?*

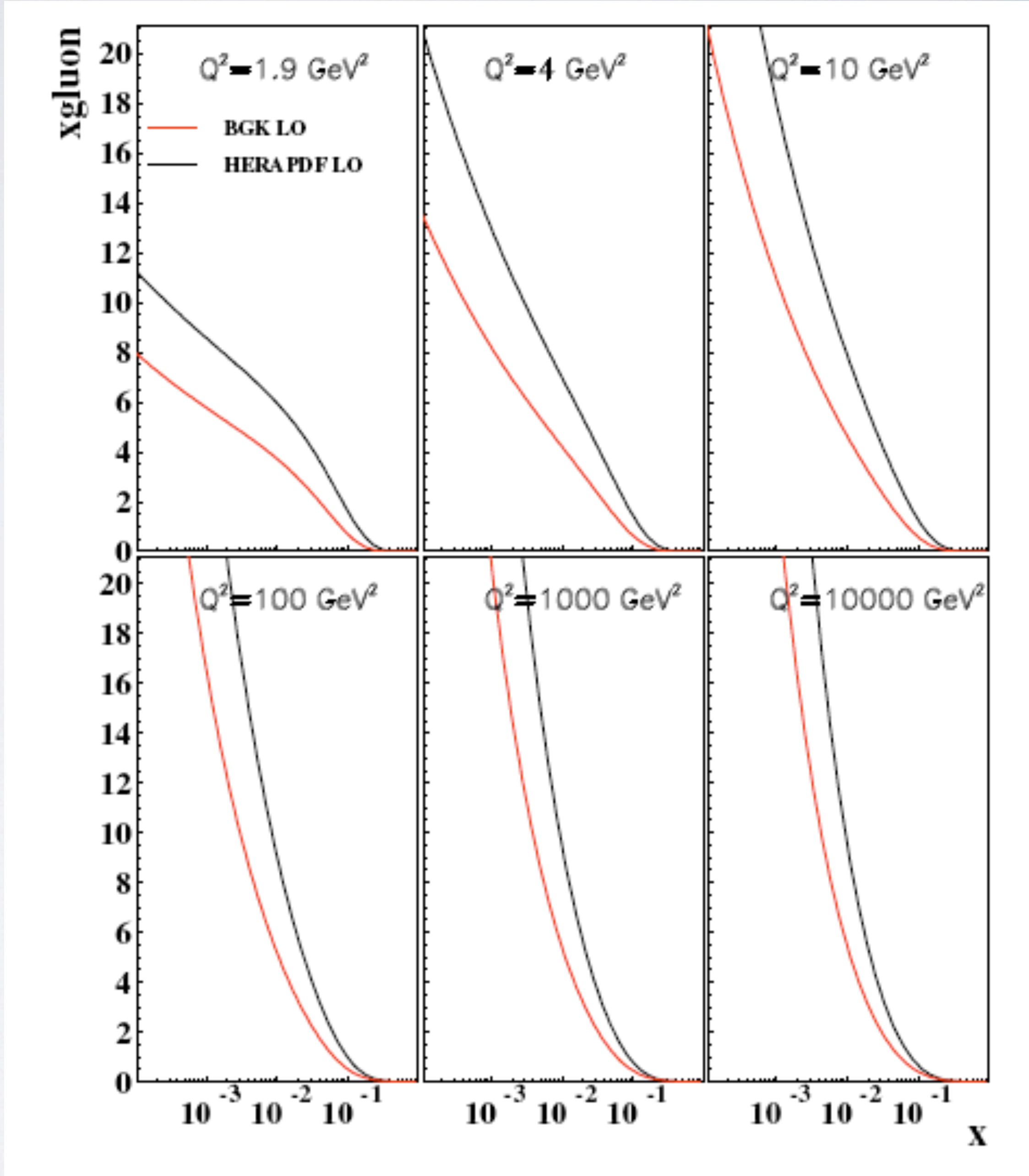
Comparison of the NLO gluon densities determined in the BGK dipole and HERAPDF

good convergence at larger scales



Comparison of the LO gluon densities determined in the BGK dipole and HERAPDF

poor convergence at larger scales



BGK + valence quarks (soft + hard gluon)
$Q^2 > 3.5$ GeV^2

No	Q_0^2	σ_0	A_g	λ_g	C_g	D_g	E_g	χ^2	χ^2/Np
1	1.1	217.09	1.976	-0.012	22.502	-35.364	1339.3	181.34	0.930
2	1.3	181.82	1.847	-0.059	21.597	-25.051	1030.3	180.80	0.927
3	1.5	165.17	1.871	-0.082	24.623	-23.630	1237.7	180.80	0.927
4	1.7	147.12	1.903	-0.099	26.720	-20.584	1310.2	181.70	0.932
5	1.9	132.26	1.948	-0.111	28.211	-18.008	1322.4	180.81	0.927

BGK + valence quarks (soft + hard gluon)
$Q^2 > 8.5$ GeV^2

No	Q_0^2	σ_0	A_g	λ_g	C_g	D_g	E_g	χ^2	χ^2/Np
1	1.1	254.97	2.524	-0.027	24.857	-46.523	1639.8	117.34	0.752
2	1.3	154.25	2.171	-0.041	13.728	-20.261	340.97	121.79	0.781
3	1.5	292.89	2.358	-0.034	31.168	-50.312	2585.8	115.51	0.740
4	1.7	221.52	2.483	-0.051	34.010	-44.156	2630.6	115.78	0.742
5	1.9	174.46	2.490	-0.070	35.347	-37.706	2499.7	116.18	0.745

BGK without valence quarks (soft gluon)

$Q^2 > 3.5$ GeV^2
$x < 0.01$

No	Q_0^2	Q^2	σ_0	A_g	λ_g	C_g	χ^2	χ^2/Np
1	1.9	3.5	115.09	2.038	-0.097	4.969	197.83	1.004

BGK with valence quarks fitted (soft gluon)

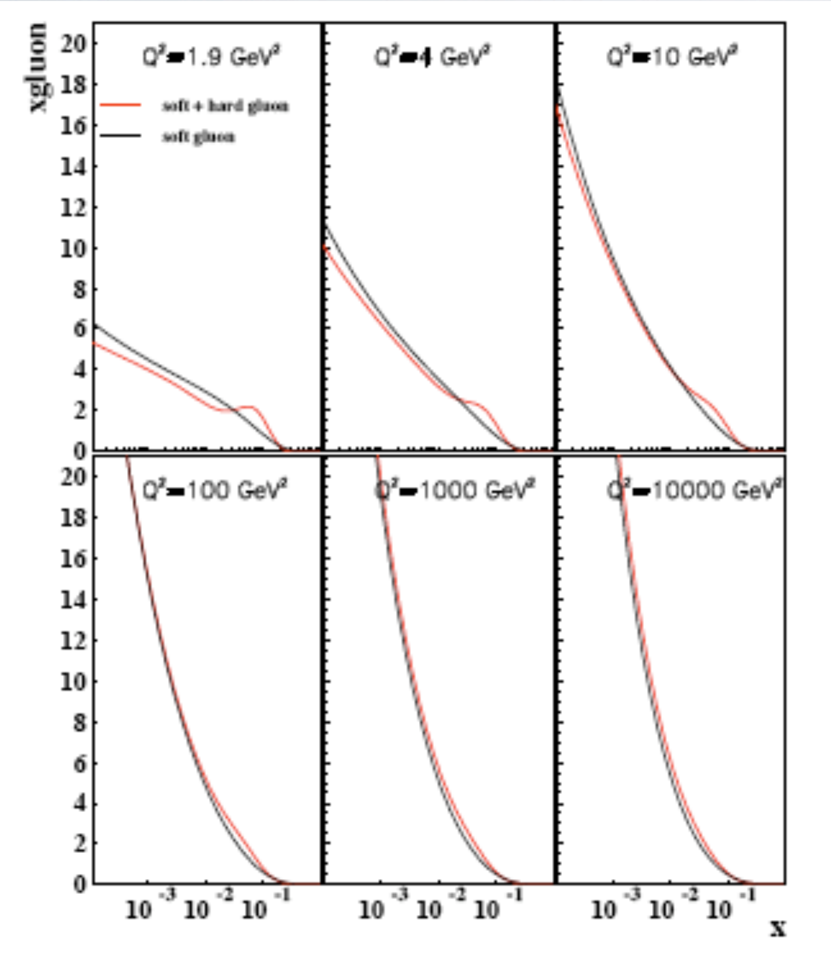
$Q^2 > 3.5$ GeV^2
$x < 0.01$

No	Q_0^2	Q^2	σ_0	A_g	λ_g	C_g	χ^2	χ^2/Np
1	1.9	3.5	88.040	1.766	-0.115	6.747	182.89	0.978

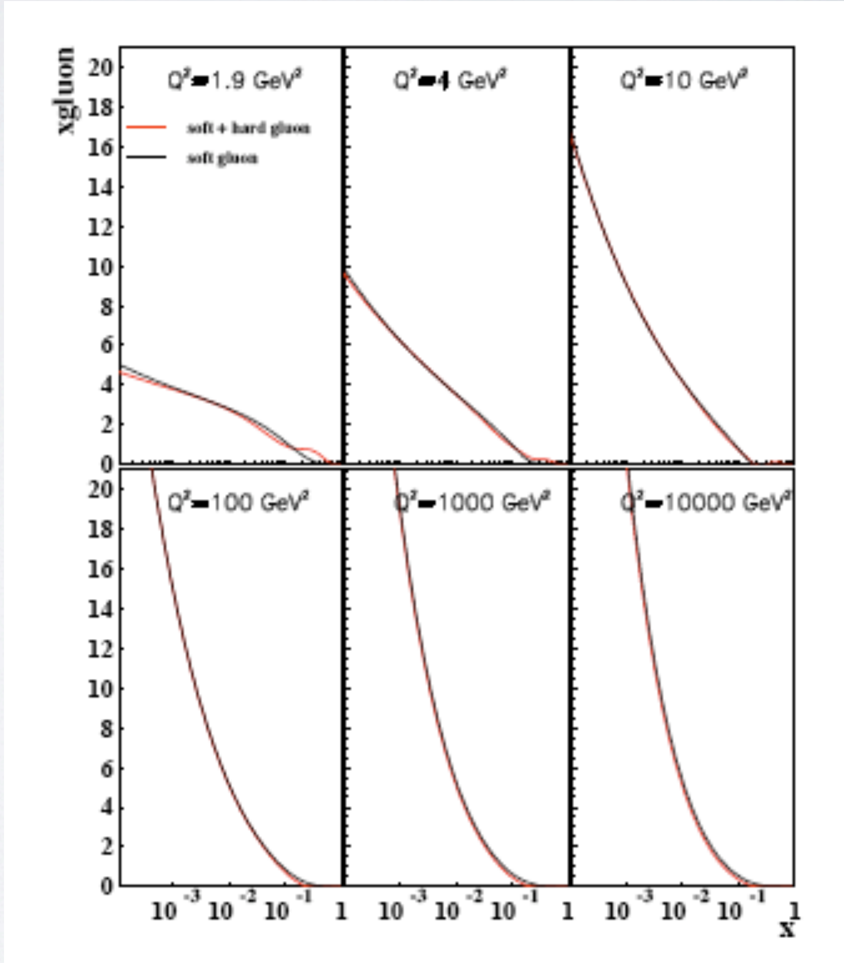
- "soft gluon": $xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\,(1-x)^{C_g}$
- "soft + hard gluon": $xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\,(1-x)^{C_g}(1+D_g x+E_g x^2)$

Comparison of the gluon density determined with the soft and soft+hard assumptions

fixed valence q.



fitted valence q.



Discussion of fits

The precise HERA data can be very well described by the kT factorized, DGLAP evolved, gluon density evaluated within the (BGK) dipole model

Valence quark contribution added to the dipol model (BGK) improve the fits significantly ($\chi^2 \searrow$) in comparison to fits with the pure dipole contribution

Large improvement of fit quality is observed when Q^2 cut is increased from 3.5 GeV^2 to 8.5 GeV^2 for both dipole and pdf fits.

- ▶ NNLO effects? (presumably not)
- ▶ saturation effects up to higher Q^2 ? (presumably not)
- ▶ some modification of the standard QCD evolution ?

CONCLUSIONS

study of the low-x region remains
experimentally (x up to 10^{-6} at LHC)
and theoretically
very interesting

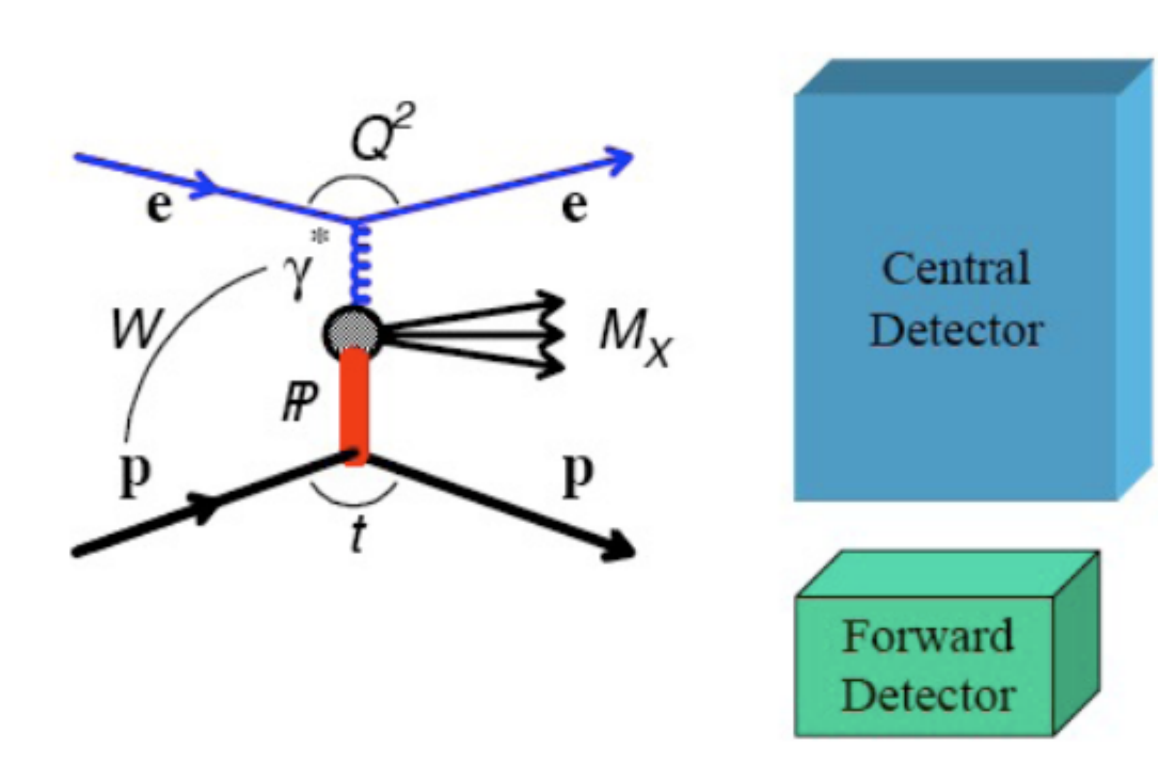
Back up

Note that:

The degree of saturation is characterized by the size of the dipole, r_S, which starts to interact multiple times (in ~60 % of cases). At HERA, $Q_S^2 = 2/r_S^2$ ~1 GeV^2 at $x = 10^{-4}$

▶ to avoid saturation effect on few % level Q^2 cut should be by an order of magnitude higher than the saturation scale

DIS Reactions



Rapidity Gaps
$\Delta Y = \ln(W^2/M_X^2) \approx \Delta\eta$

Forward protons with $x_L = 1 - x_{IP} > 95\%$
x_L ~ longitudinal fraction of proton momentum

Inclusive variables:

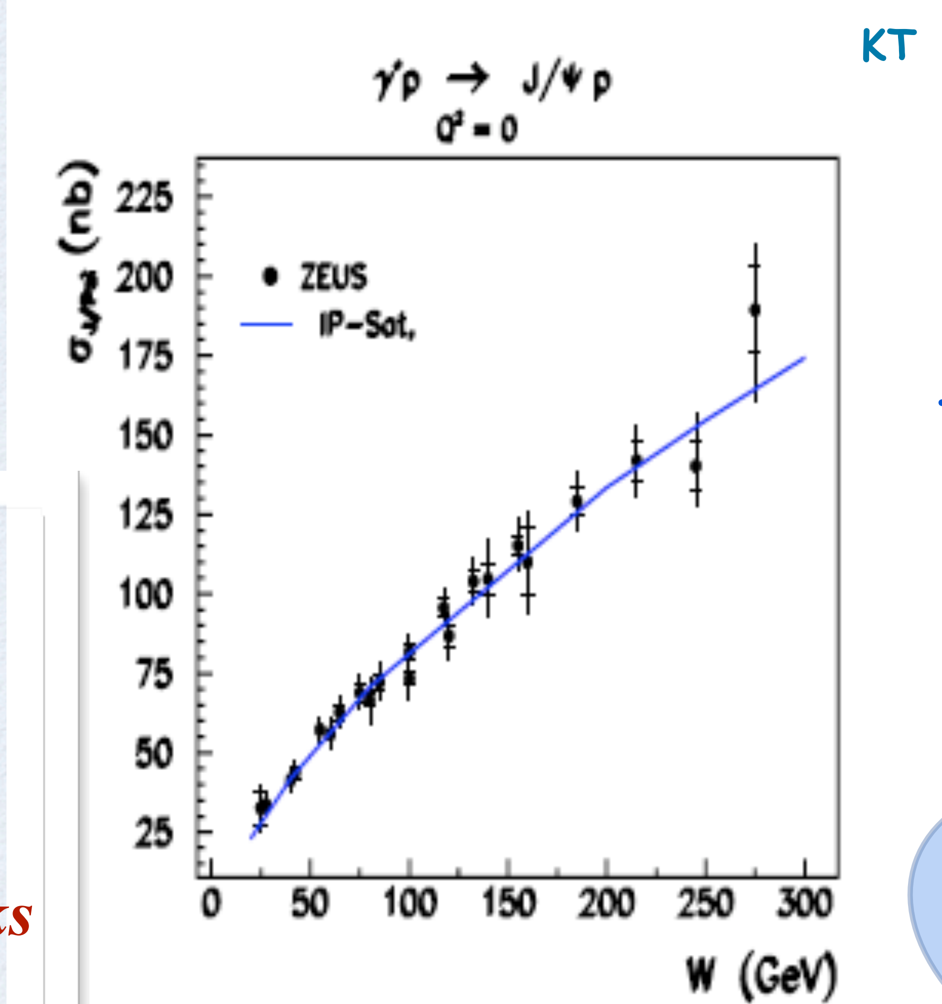
Q^2 - virtuality of the incoming photon
W - CMS energy of the incoming photon-proton system
x - $\approx Q^2/W^2$

Diffractive variables:

M_X - invariant mass of all particles seen in the detector
t - momentum transfer to the diffractively scattered proton

Exclusive J/psi production

educated guess for VM wf is working very well for J/psi and phi and DVCS



equally good description of Q2 and σ_L/σ_T dependences for J/psi and phi and DVCS

Note:
J/psi x-section grows almost like
$\sigma \propto (x\, g(x,\mu^2))^2$
no valence quarks contribution

new, precise H1 data

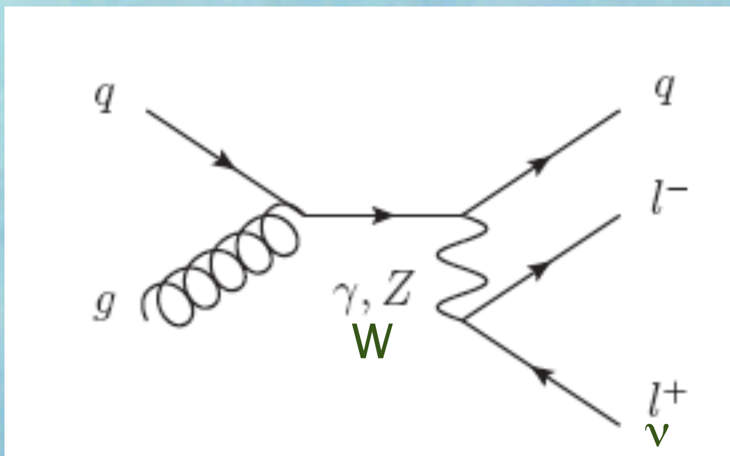
➤ **the determination of gluon density with J/psi would be more precise than by F_2 or F_L (MRT) if J/psi would have small systematic errors**

DATA

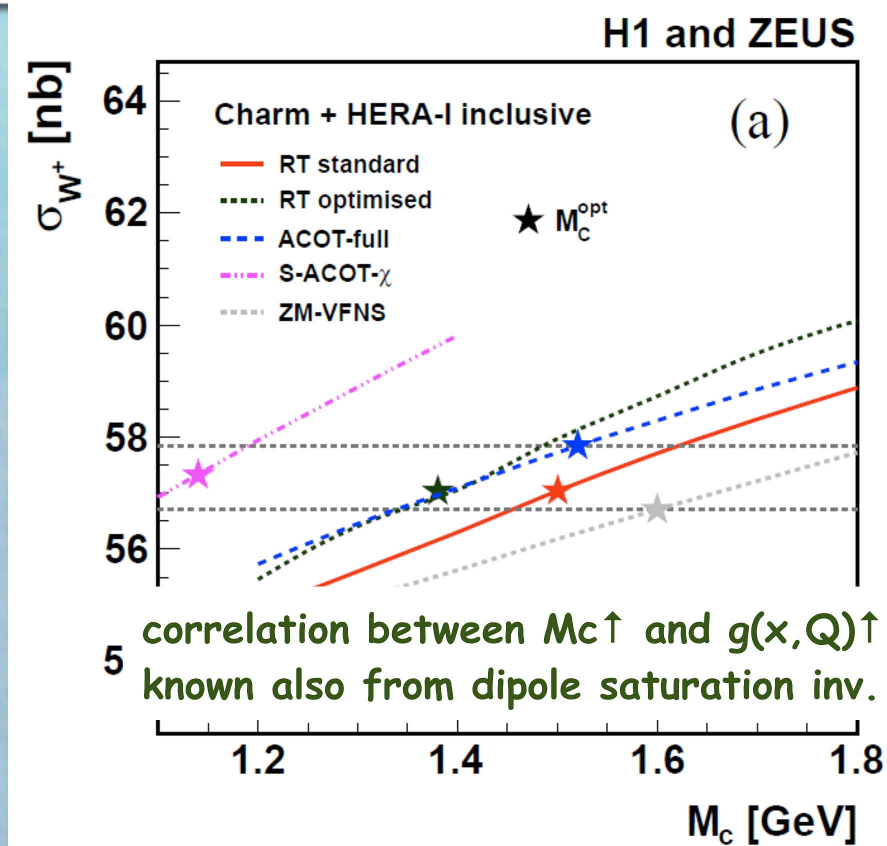
DIS (HERA and fixed target..), Drell-Yan processes (fixed target)
High E_T jets (Tevatron), W,Z rapidity (Tevatron)
νN dimuon (CCFR, NuteV)....

HERAPDF 1.0 uses combined H1 and ZEUS HERA I xs data
HERAPDF 1.5 uses, in addition, combined HERA charm data ..

Excellent test reaction
W, Z production at LHC



W, Z production at LHC is
a low-x effect



correlation between Mc↑ and g(x,Q)↑
known also from dipole saturation inv.