Revising the Impact-Parameter dependent Saturation model with combined HERA data

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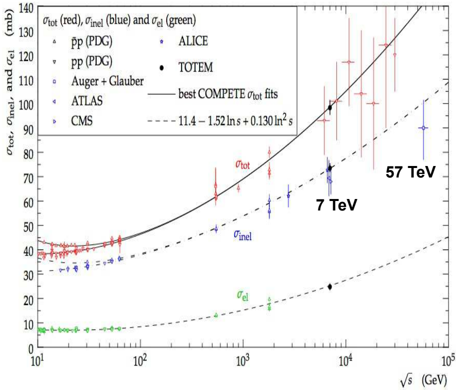
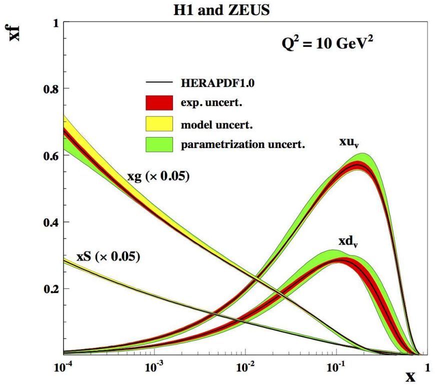
Outline

- Motivation, why color dipole approach at small-x?
- The importance of impact-parameter dependence of dipole amplitude.
- Fitting the model parameters with the recent H1+ZEUS combined data for σ_r.
- Confronting the model's results with all available data at $x < 0.01$ for F_2,F_L, $F_2^{c\bar{c}}$, and also exclusive diffractive & DVCS data.

This talk is based on:

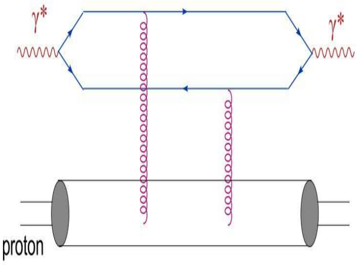
Rezaeian, Siddikov, Van de Klundert, Venugopalan, **PRD 87**, 034002 (2013) [arXiv:1212.2974].





- Unitarity or Froissart bound: $\sigma_{tot} < c \ln^2(s)$: Gluon saturation at small-x

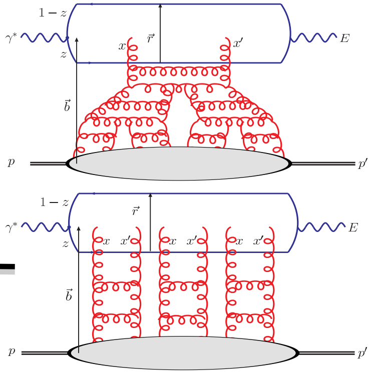
Connection between unitarization and saturation: **Kovner & Wiedemann, hep-ph/0112140**



$$T(x,r,b) \simeq \alpha_s r^2 \frac{xG(x,1/r^2)}{\pi R^2} \equiv \alpha_s n(x,Q^2 \sim 1/r^2)$$

Unitarization →

This talk ←

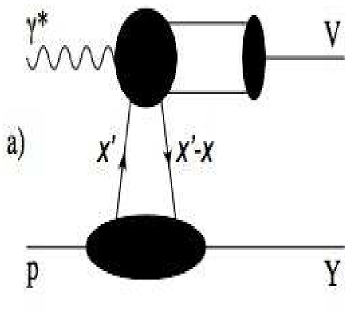


Strong scattering $T \sim 1 \Longleftrightarrow$ High gluon density $n \sim 1/\alpha_s \Longrightarrow$ gluon saturation

To preserve unitarity $\Longleftrightarrow$ Multiple scattering is important: $(\alpha_s n)^n \sim 1$

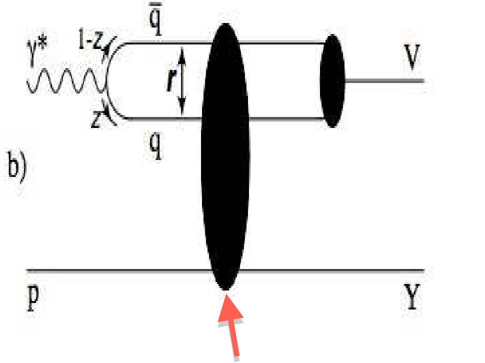
Inclusive and exclusive (**diffractive vector meson production and DVCS**) **processes :** $\gamma^* + p \to V + p$ **with** $V = J/\Psi, \rho, \phi, \gamma, \gamma^*$

Collinear factorization (GPD+DGLAP)



$$GPD_{i/p} \otimes H_{ij} \otimes \Psi_j^V$$

Color dipole factorization (dipole + small−x evolution)



$$\psi^{\gamma}_{q\bar{q}} \otimes \mathcal{N}^{q\bar{q}-p} \otimes \phi^{V}_{q\bar{q}}$$

Exclusive diffractive process: $\psi^{\gamma}_{q\bar{q}} \otimes \phi^{V}_{q\bar{q}} \otimes \mathcal{N}^{q\bar{q}-p}$

$$\mathcal{A}^{\gamma^* p\to Vp}_{T,L}(x, Q, \Delta) = 2\mathrm{i} \int \mathrm{d}^2\mathbf{r} \int_0^1 \mathrm{d}z \int \mathrm{d}^2\mathbf{b} (\Psi^*_E \Psi)_{T,L}\, \mathrm{e}^{-\mathrm{i}[\mathbf{b}-(1-z)\mathbf{r}]\cdot\mathbf{\Delta}} \mathcal{N}(x, r, b)$$

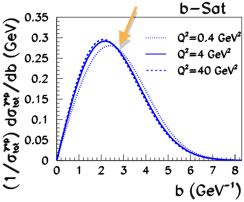
$$\frac{\mathrm{d}\sigma^{\gamma^* p\to Ep}_{T,L}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \mathcal{A}^{\gamma^* p\to Ep}_{T,L} \right|^2$$

$(r \to Q)$ and $(b \to \Delta)$ with $t = -\Delta^2$

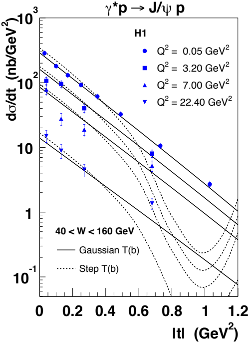
- With corrections from the real part of the amplitude and from skewedness $x \neq x'$ [Shuvaev et al., hep-ph/9902410].

Inclusive deep-inelastic scattering (DIS)

$$\begin{aligned} \sigma^{\gamma^* p}_{L,T}(Q^2, x) &= Im\, \mathcal{A}^{\gamma^* p\to\gamma^* p}_{T,L}(x, Q, \Delta = 0) \\ &= 2 \sum_f \int \int d^2b\, d^2r \int_0^1 dz\, |\Psi^{(f)}_{L,T}(r, z; Q^2)|^2\, \mathcal{N}(x, r, b) \end{aligned}$$



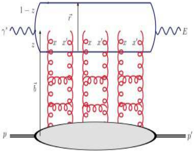
- Saturation scale strongly depends on impact-parameter.
Median values of b are between 2 and 3 GeV^2.
Kowalski, Motyka, Watt [hep-ph/0606272]
Watt, Kowalski [0712.2670].



- $\sigma_{q\bar{q}} = 2\int d^2b\,\mathcal{N}(x, r, b)$
Any factorizable step-like impact-parameter profile
$T(b) = \theta(R_p - b)$ is ruled out by diffractive data.
$\sigma_{q\bar{q}} = 2\int d^2b\,T(b)\mathcal{N}(x, r) = \sigma_0\mathcal{N}(x, r)$

- $T(b)$ can be fixed by a simultaneous description of
t-distribution of exclusive diffractive and inclusive processe

Impact-Parameter dependent Saturation (IP-Sat) model



•Kowalski, Teaney [hep-ph/0304189]
•Kowalski, Motyka, Watt [hep-ph/0606272]
•Rezaeian, Siddikov, Van de Klundert, Venugopalan [arXiv:1212.2974]

- Eikonalized DGLAP-evolved gluon density with Gaussian b dependence (Glauber-Mueller amplitude):

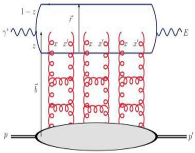
$$\mathcal{N}(x, r, b) = 1 - \exp\left(-\frac{\pi^2 r^2}{2N_c}\alpha_s\left(\mu^2\right) xg\left(x, \mu^2\right) T_G(b)\right)$$

$$T_G(b) = \frac{1}{2\pi B_G}\exp\left(-b^2/2\mathbf{B_G}\right)$$

The IP-Sat dipole amplitude gives at large Q^2 (or small r):

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p \to Ep}}{\mathrm{d}t} \approx e^{-\mathbf{B_G}|t|}$$

• Supported by data from t-distribution of exclusive vector meson & DVCS.



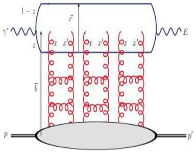
$$\mathcal{N}(x,r,b) = 1 - \exp\left(-\frac{\pi^2 r^2}{2N_c}\alpha_s\left(\mu^2\right) xg\left(x,\mu^2\right) T_G(b)\right)$$

$$T_G(b) = \frac{1}{2\pi B_G}\exp\left(-b^2/2B_G\right)$$

- with a scale related to dipole size, and initial gluon distribution:

$$\mu^2 = C/r^2 + {\mu_0}^2, \qquad\qquad xg\left(x,\mu_0^2\right) = A_g\, x^{-\lambda_g}(1-x)^{5.6}$$

- 4 free parameters: B_G is fixed from t-slope of exclusive J/Ψ production; and A_g, μ_0, λ_g are fixed by DIS **combined data for** σ_r **for** $x \leq 0.01$ and $Q^2 \in [0.75, 650]\mathrm{GeV}^2$.
- Data for F_2,F_L and $F_2^{c\bar{c}}$, exclusive diffractive (for ρ and ϕ) and DVCS are **NOT** included into the fit, but are predictions of the model.



$$\mathcal{N}(x, r, b) = 1 - \exp\left(-\frac{\pi^2 r^2}{2N_c}\alpha_s(\mu^2)\, xg(x, \mu^2)\, T_G(b)\right)$$

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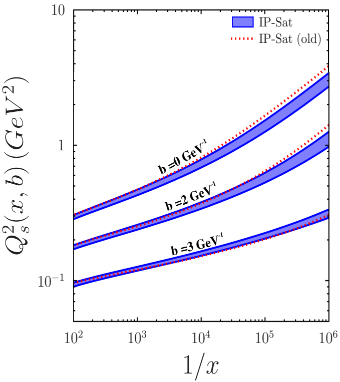
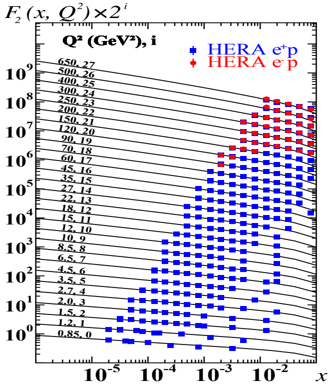
B_G/GeV^2	$m_{u,d,s}/\mathrm{GeV}$	m_c/GeV	μ_0^2/GeV^2	A_g	λ_g	$\chi^2/\mathrm{d.o.f.}$
4	≈ 0	1.27	1.51	2.308	0.058	$298.89/259 = 1.15$
4	≈ 0	1.4	1.428	2.373	0.052	$316.61/259 = 1.22$

old v. new fit obtained from combined H1+ZEUS data

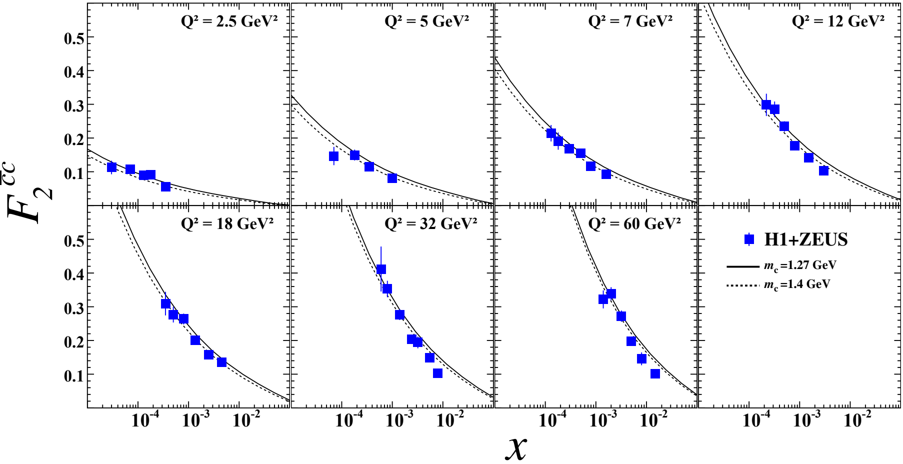
- Old IP-Sat parameters & combined σ_r data: $\chi^2/d.o.f \approx 3 \rightarrow$ parameters of new fit are different.
  - Old IP-Sat: $m_{u,d,s} = 50 - 100$ MeV, and $\lambda_{\mathbf{g}} < \mathbf{0}$.
  - New IP-Sat: $m_{u,d,s} = 0$, and $\lambda_{\mathbf{g}} > \mathbf{0} \rightarrow$ makes more sense at small-x!.



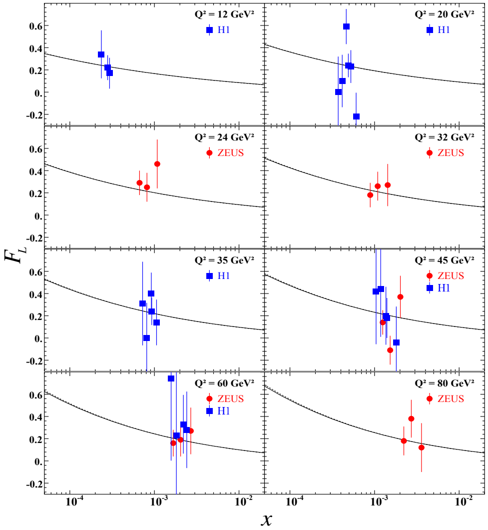


- Saturation scale extracted from old and new combined data have similar trend although parameters of the model change significantly.
- $Q_s(x, b) < 1$ GeV at HERA kinematics.
- The power-law behavior of $Q_s^2 \approx x^{-\lambda}$ changes from $\lambda \approx 0.3$ (central) to $\lambda \approx 0.1$ (peripheral).

CGC description of recent combined HERA data: Charm structure function

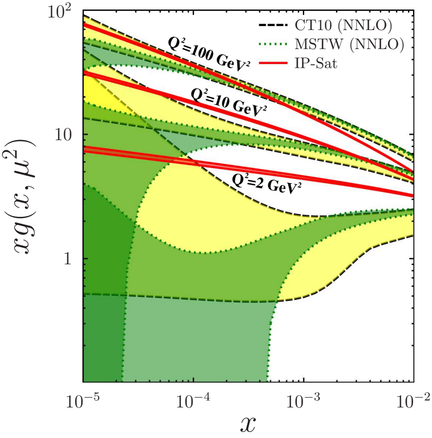


- $F_2^{c\bar{c}}$ data (combined from HERA) not included in the fit!.
- Theoretical uncertainties are due to charm mass: $1.27 \leq m_c \leq 1.4$ GeV.



- F_L data not included in the fit (Combined data are not yet available).

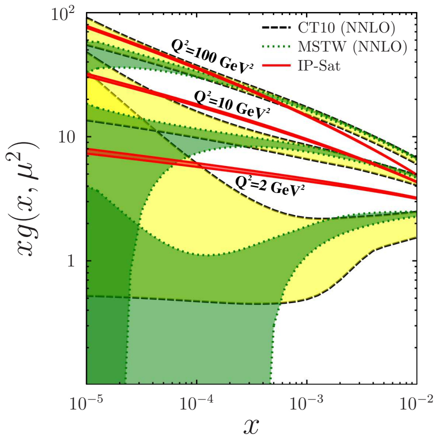
Gluon distribution: collinear factorization v. color-dipole approach



In the Color dipole (or CGC) approach:

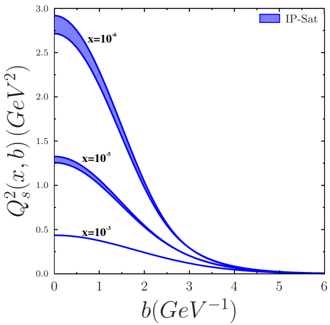
- Ground state constructed from classical color field background + Non-linear gluon saturation effect (small-x resummation) $\rightarrow$ stable results at small-x.

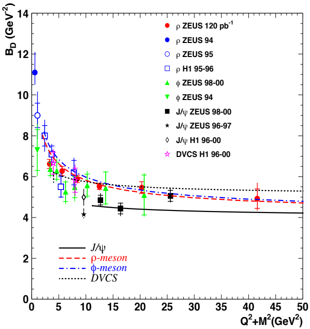
Gluon distribution: collinear factorization v. color-dipole approach



- In IP-Sat model we have **only 4 free parameters** fixed by low-x data → better constrains on parameters → smaller errors (mainly due to charm mass)
- At large Q^2 two pictures match.

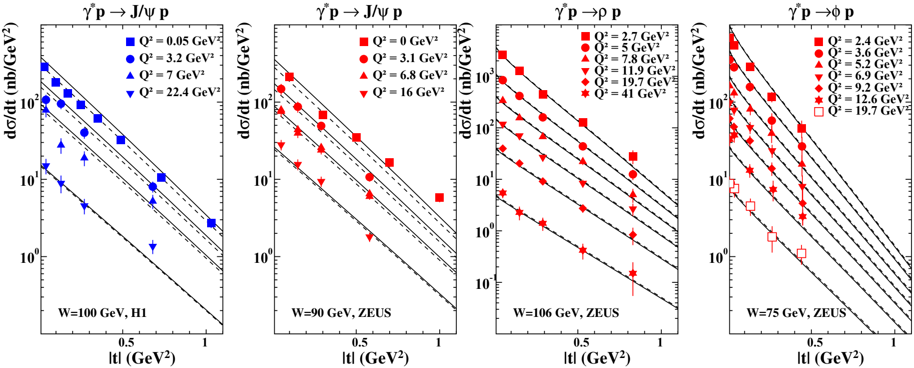
Slope of t-distribution of exclusive processes, a unified picture





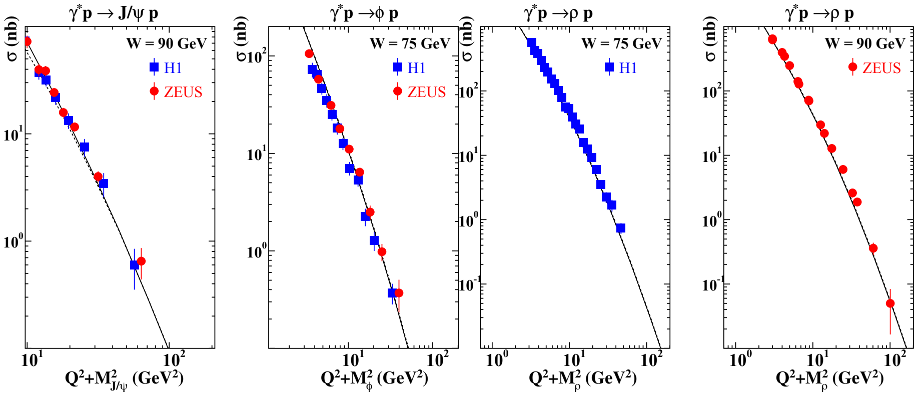
$$\frac{d\sigma_{T,L}^{\gamma^* p\to Ep}}{dt} \approx e^{-B_D|t|} \text{ (large } Q^2) \Longleftrightarrow Q_s^2(x,b) \approx Q_s^2(x) e^{-b^2/2B_D} \text{ (dilute regime)}$$

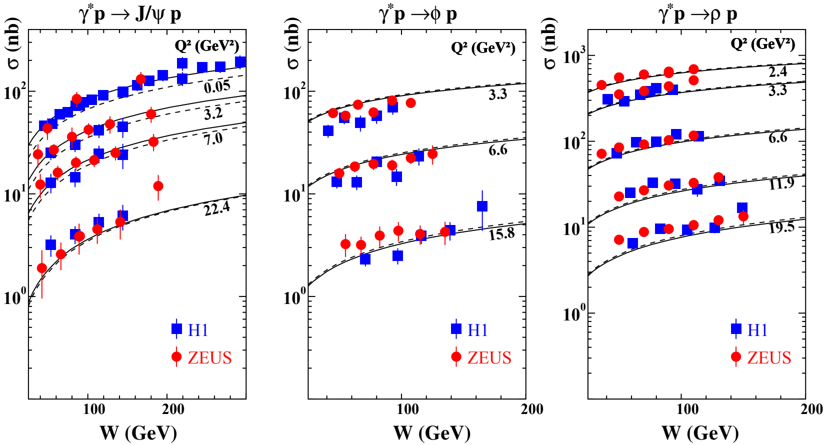
- At a fixed Q^2, the typical dipole size is bigger for lighter vector meson $\Longrightarrow$ validity of the above asymptotic expression is postponed to a higher Q^2.
- Universality of extracted impact-parameter distribution of the proton. t-slope B_D gives the width of saturation scale distribution in proton.



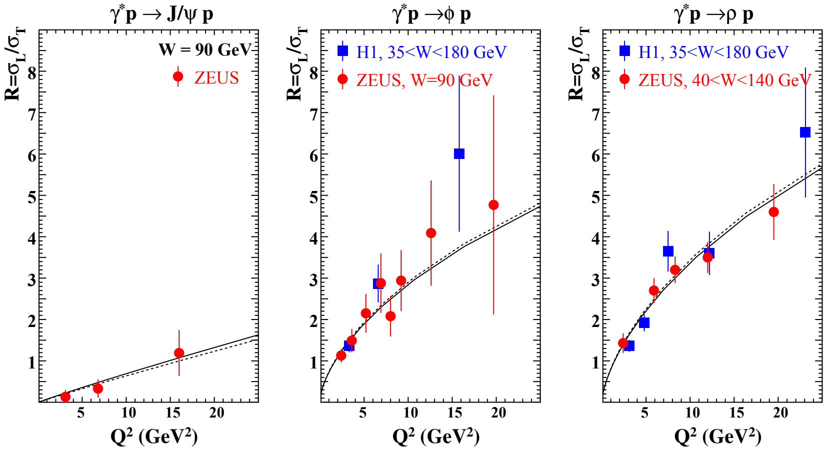
- The J/Ψ production cross-section is more sensitive to m_c at low Q^2 compared to ρ, ϕ, γ production cross-sections.
- t-dependence is described by$\sim$ $exp(-B_D t)$ at low-t, but B_D depends on Q^2 and M^2.

Q^2-dependence of exclusive processes

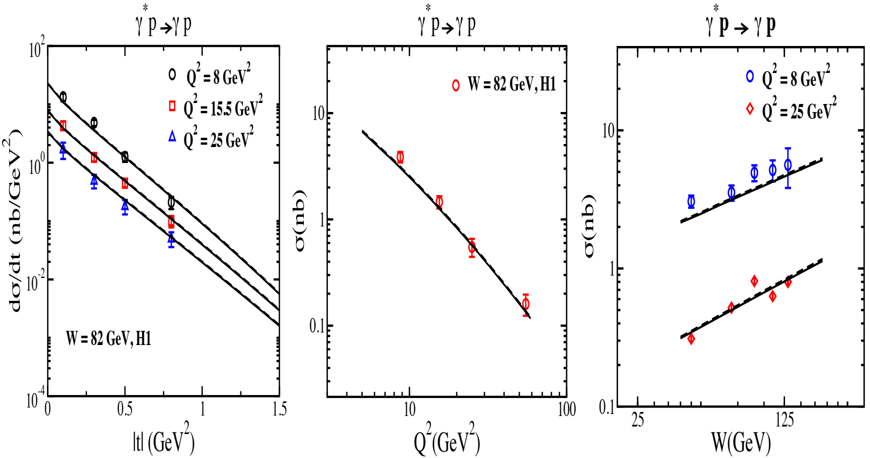




- The W-dependence of the cross-section follows a power-law behavior $\sigma \sim W^{\delta}$ $\rightarrow$ Indication of geometric scaling in diffractive data: Marquet and Schoeffel, hep-ph/0606079.



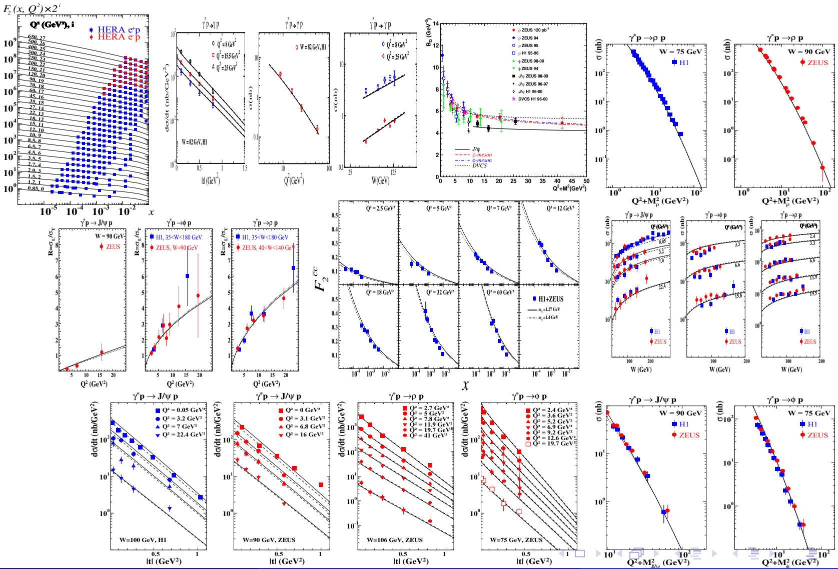
- σ_T is generally dominated by larger dipole sizes than σ_L $\rightarrow$ relative increase of t-slope of σ_T compared to longitudinal one, i.e. $B_{DT} > B_{DL}$ $\rightarrow$ $R = \sigma_L/\sigma_T$ to increase with Q^2.



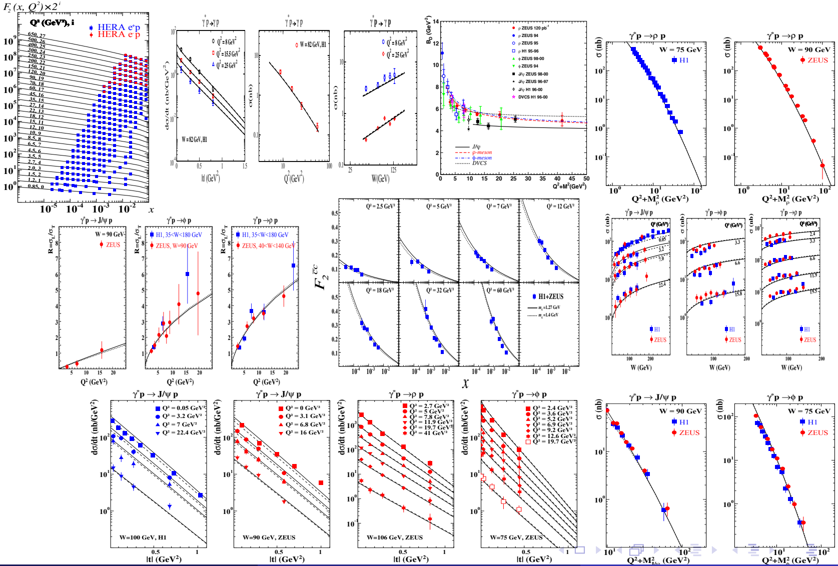
- DVCS is the cleanest exclusive process since wavefuctions is well-known, t-dependence is described by $\sim exp(-B_D t)$.

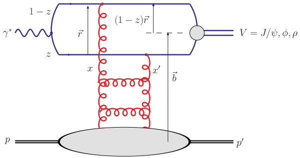
Conclusion:IP-Sat mostly gives a perfect description of all HERA data at $x \leq 0.01$.

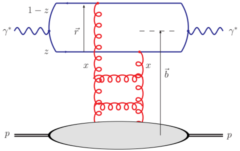
A unified description of x, Q^2, W and t dependence of data.

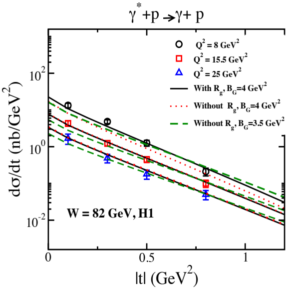


Fortran code for the IP-Sat dipole (with evolved-DGLAP) is available for public.









- At NLO level, in the limit that $x' << x << 1$, the skewedness effect can be effectively accounted for by multiplying the gluon distribution $xg(x, \mu^2)$ by a factor R_g [Shuvaev et al. hep-ph/9902410]:

$$R_g(\gamma) = \frac{2^{2\gamma+3}}{\sqrt{\pi}} \frac{\Gamma(\gamma + 5/2)}{\Gamma(\gamma + 4)}, \quad \text{with} \quad \gamma \equiv \frac{\partial \ln \left[xg(x, \mu^2)\right]}{\partial \ln(1/x)}.$$

- The inclusion of R_g improves the results, but large part of the effect can be also absorbed into the uncertainty of t-slope parameter B_D.
  • The dipole factorization needs to be proven with the inclusion of skewing effect.