Exclusive processes at HERA and EIC

Predictions of color dipole model

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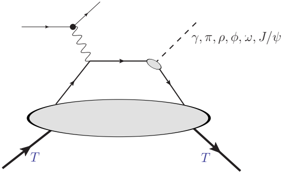
Exclusive processes

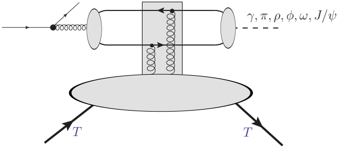
- Include DVCS, DVMP ($\rho, \phi, \omega, J/\psi, ...$), diffractive DIS, hard dijet production, pion dissociation to jets etc.
  - Closely related are ultraperipheral collisions ($pp \to ppV$, $AA \to AAV$), cross-section just differs by extra photon flux.
  - We'll speak mostly about DVCS and DVMP, in Bjorken kinematics (Q^2 large)
- For HERA (& EIC), there are two major competing approaches, based on collinear factorization and on the dipole model

Collinear approach



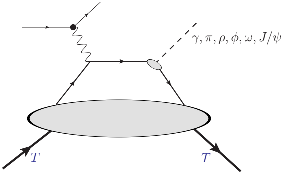
- Probes 2-parton distributions (q & g)

Dipole model



- Probes gluons in the target

Collinear approach

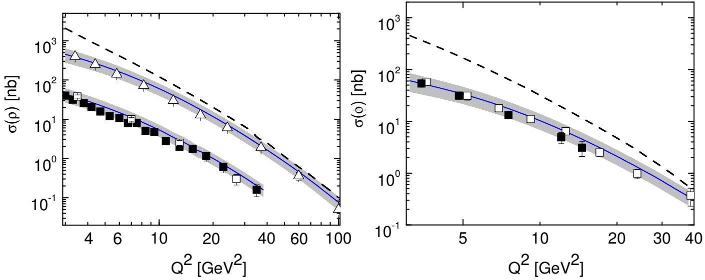


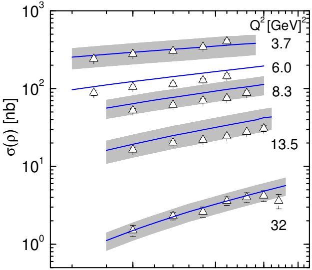
- Applicable in a wide kinematic range, from JLAB & COMPAS up to HERA and LHeC.
- Has a solid theoretical base (X. Ji *et.al.* PRD 58 (1998) 094018, J. Collins *et.al.*, PRD 56(1997) 2982, PRD 59 (1999) 074009, S. Brodsy *et.al.* PRD 50(1994) 3134)

- The cleanest is DVCS, allows to rule out some GPD models
  - Several competing parametrizations of GPDs on the market (Kroll *et.al.*, EPJC 59, 809; Diehl *et.al.* EPJC 39, 1; Guidal *et.al.* PRD 72, 054013; Kumericki *et.al.*, NPB 841, 1, ...)
    - ★ Knowledge of GPDs = distribution of partons in transverse plain ("tomography"), orbital angular momenta of partons etc.
- DVMP is more challenging
  - in DVMP DAs are not known,
  - contribution of higher-twist DA components might be important (Ahmad *et. al.*, PRD 79 (2009) 054014; Goldstein *et. al.*, PRD 84 (2011) 034007; CLAS, PRL 109 (2012) 112001)

Collinear approach (contd.)

Kroll-Goloskokov model, (Eur.Phys.J.C53:367-384,2008)

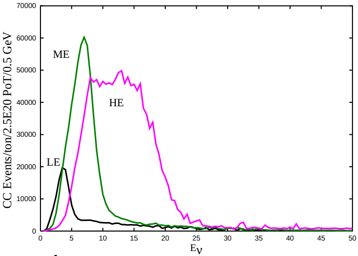




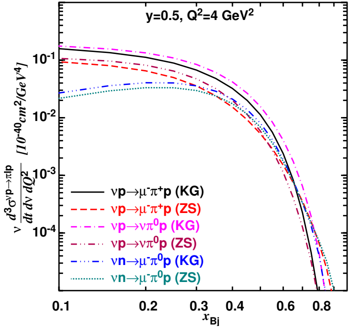
- Give reasonable description for various quantities from JLAB up to HERA kinematics

Collinear approach (contd.)

Minerva@Fermilab will start in summer measurements with 6 GeV high-intensity $\nu/\bar{\nu}$-beam [potentially up to 20 GeV possible (Minerva proposal, hep-ex/0405002)]

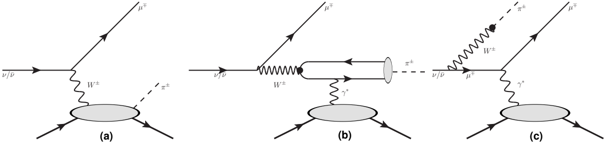


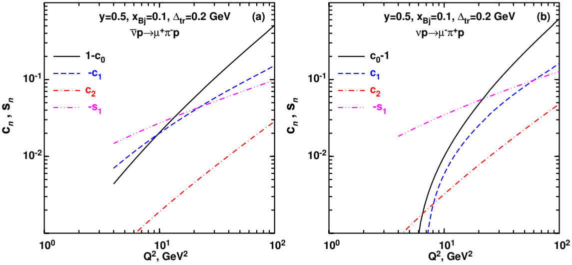
- Challenge for analysis: $\nu/\bar{\nu}$ not monochromatic
  - Test GPDs from *ep*, especially flavour structure, just from π & K production.
    - Can probe NC and CC processes
    - Use $SU(3)$ for $H_{p\to Y}$, (B. Kopeliovich, I. Schmidt, MS, PRD 86 (2012) 113018, PRD 87 (2013), 033008)



Collinear approach (contd.)

- (PRD 87 (2013), 033008)
  - Interference with $\mathcal{O}(\alpha_{em})$ EM corrections–access to real and imaginary parts, similar to DVCS





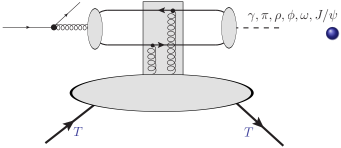
$$\frac{d^4\sigma^{(tot)}}{dt\,dQ^2\,d\ln\nu\,d\phi} = \frac{1}{2\pi}\frac{d^3\sigma^{(DVMP)}}{dt\,dQ^2\,d\ln\nu} \times \sum_n \left(c_n \cos n\phi + s_n \sin n\phi\right)$$

Small @Minerva, dominate in asymptotic Bjorken regime.

Collinear approach vs. small-x

- For all processes there are large BFKL-type logs $\sim \alpha_s \ln x$ @small-x (D. Y. Ivanov *et. al.*, EPJC 34 (2004) 297; JETP Lett. 80 (2004) 226; M. Diehl *et. al.*, EPJC 52 (2007) 933)
  - Need systematic resummation, take into account gluon recombination ($gg \to g$)

Color dipole approach



- Probes dipole cross-section in a gluon field, assume $\bar{q}q$ dominates ($\bar{q}qg$ sometimes included).

$$\sigma|\mathscr{A} = \Psi^{\dagger}_{fin} \otimes \sigma_d \otimes \Psi_{in}$$

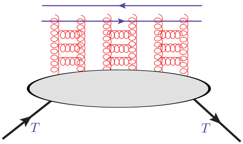
- Assume target unpolarized, σ_d respects CT and match DGLAP @small-r, built-in saturation @large-r, unitarity. GS ($\sigma = \sigma(\tau)$, $\tau = Q^2/Q_s^2(x)$ (Stasto *et.al.*, PRL 86 596)).
- Small-x evolution given by BK equation (mixing with higher Fock states: JIMWLK)
- b-dependence is nontrivial (Golec-Biernat *et.al*, NPB 668 (2003) 345), b-dependent BK: large dipoles⇒power tail, violates unitarity.

Dipole parametrizations

- Huge variety of parametrizations (GBW, KST, CGC, b-CGC, IP-Sat, AAQMS, Berger-Staśto model, ...).
- We plan to discuss IP-Sat
  - Corresponds to eikonalization of a simple Muller dipole

    (Kowalski *et. al.*, PRD 74 (2006), 074016)

    (A. Rezaeian, MS, M. V. Klundert, R. Venugopalan, PRD 87 (2013) 034002, New H1+ZEUS combined data)

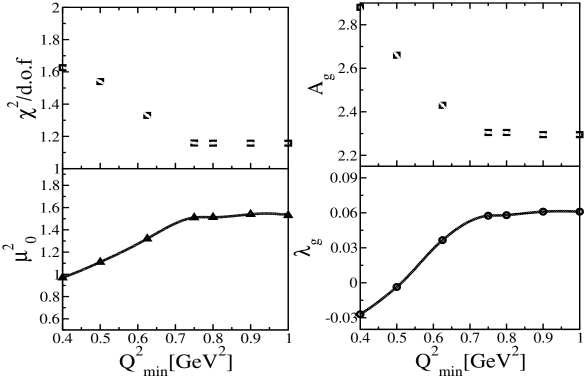


$$\frac{d^2\sigma}{d^2b} = 2\left(1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_s\left(r^{-1}\right) xg\left(x, r^{-1}\right) T_A(b)\right)\right)$$

$$xg\left(x, \mu_0^2\right) \sim A_g x^{-\lambda_g} (1-x)^{5.6}$$

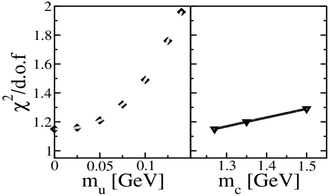
  - $g(x, r)$ is a gluon distribution, evolved according to DGLAP
  - Twist-expansion and small-α_s expansions coincide
  - b-dependence is not factorizable, however there is no dependence on relative orientation of $\vec{b}$ and $\vec{r}$.

IP-Sat parametrization

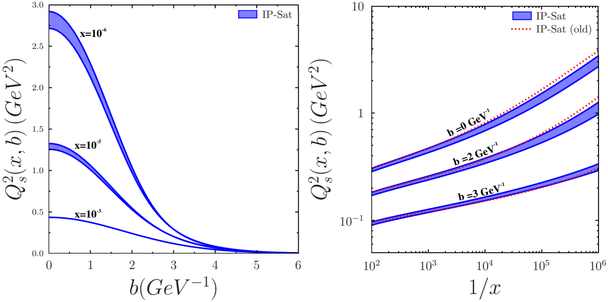


- Due to pQCD WFs of γ^*, cannot describe data with $Q^2 \lesssim 0.75 \mathrm{GeV}^2$
  - Consider $Q^2 \in (0.75, 650) \mathrm{GeV}^2$
  - $x \lesssim 10^{-2}$
  - 263 points for σ_r

- Data prefer small mass $m_q \approx 0$. Earlier fits with data down to $Q^2 \approx 0.25 \,\mathrm{GeV}^2$: $m_q \lesssim 0.14 \,\mathrm{GeV}$

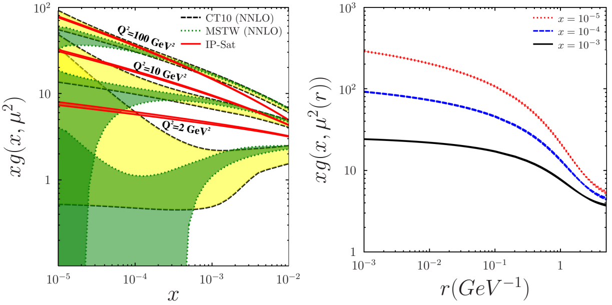


Saturation scale



- The nonlinear effects depend on impact parameter b, stronger in the center of the proton than on the periphery. This result is in contrast with b-independent models (GBW, AAMQS, ...).
  - $Q_s^2 \sim x^{-0.3}$ in the center and $Q_s^2 \sim x^{-0.1}$ on the periphery
- Blue band shows a typical uncertainty in the saturation scale

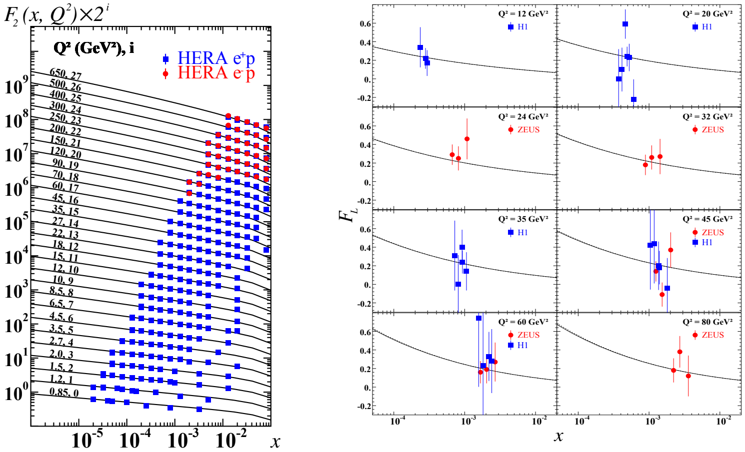
Gluon PDFs: dipole vs. DGLAP



- At large Q^2 the color dipole gluon PDF $g(x,\mu^2)$ coincides with NNLO DGLAP PDFs, at small Q^2 differs due to higher twist effects
- As a function of r, the gluon PDF homogeniously decreases, but saturates for large dipoles

Results for F_2 & F_L

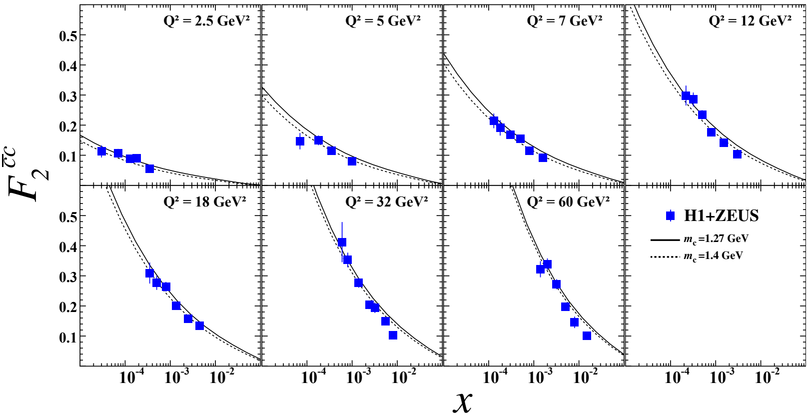
- (Remember $\sigma_r = F_2 + f(y)\,F_L$, and σ_r is used for fits) (JHEP 1001 (2010), 109 , PLB 665 (2008), 139; PLB 682 (2009), 8)



- F_2 has extremely small errorbars, described perfectly
- F_L sensitive to gluons; has large errors since extracted with Rosenbluth separation (keep x, Q^2 fixed and vary $\sqrt{s}$ (y)).

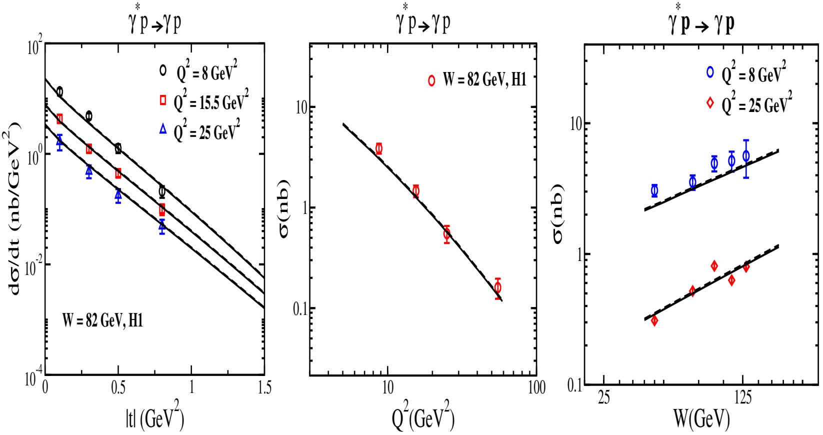
Results for $F_2^{\bar{c}c}$

(H1+ZEUS combined data, arXiv:1211.1182)



- $F_2^{\bar{c}c}$ data are not icluded in the fit, results describe data very well, so flavour structure of the model is correct.
- Sensitivity to charm mass for small-Q^2

Results for DVCS



- DVCS is the cleanest exclusive process, t-dependence is described by $\sim \exp(Bt)$
  - @fixed W: $\sigma \sim Q^{-2.6}$
  - @fixed Q^2: $\sigma \sim W^{0.7}$

$\Rightarrow$geometric scaling,
$\tau \sim Q^2/Q_0^2(x) \sim Q^2 x^{0.3}$

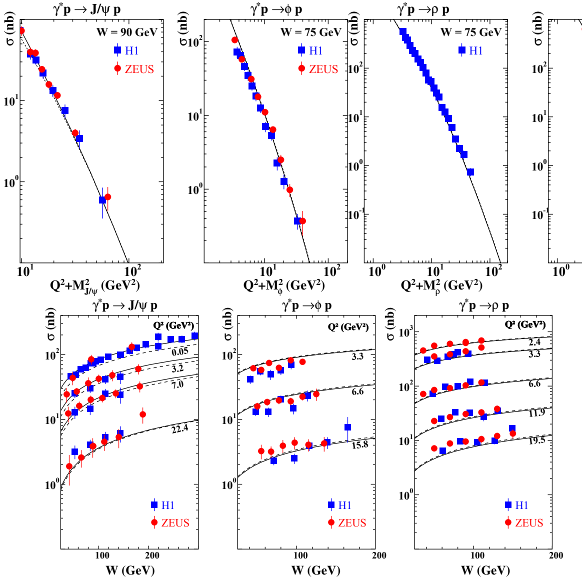
Meson production

- Description of the DVMP is challenging: vector meson wave function is needed
  - controlled by confinement
  - depend on the model
  - never measured directly in the experiment
- There are several models, we rely on boosted Gaussian WF (Nemchik *et. al.*, PLB 341(1994), 228; ZPC 75(1997), 71)

$$\phi(r,z) = N\,z(1-z)\exp\left(-\frac{m_q^2\mathscr{R}^2}{z\,(1-z)} - \frac{2z(1-z)r^2}{\mathscr{R}^2} + \frac{m_q^2\mathscr{R}^2}{2}\right)$$

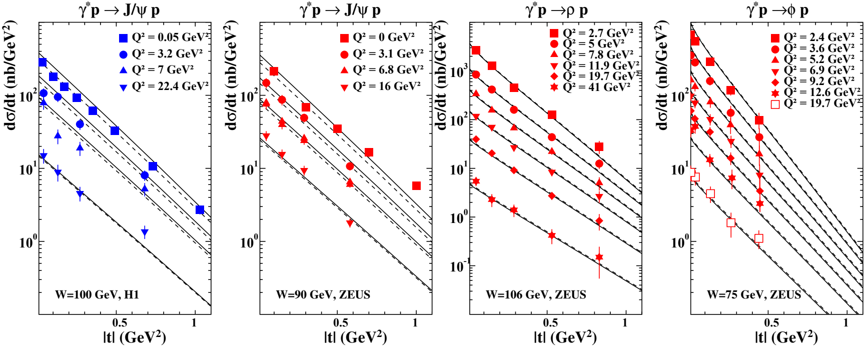
  - other options are ADS/CFT(Forshaw *et.al.*, PRL 109 (2012) 081601); for J/ψ-potential models (Cornell, Buchmueller)(Hufner *et.al.* PRD 62 (2000) 094022, Yu. Ivanov *et.al.*, PRC 66 (2002) 024903)
  - Data precision insufficient to rule out the WF (hopefully EIC will let to select the right model)

Q^2- and W-dependence of DVMP cross-section



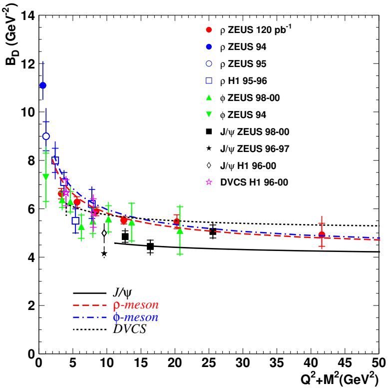
- Q^2-dependence: $\sigma \sim Q^{-n}$, $n \approx 2.4$
- W-dependence: $\sigma \sim W^{\delta(Q^2)}$.
- Sensitivity to charm mass at small-Q^2 for J/ψ

t-dependence of the cross-section



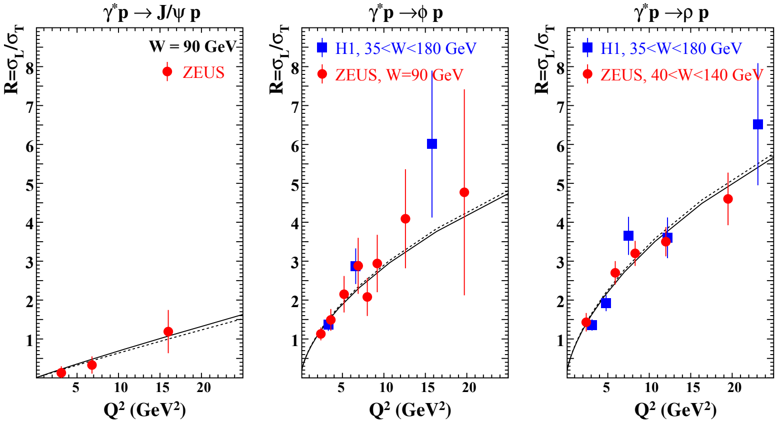
- The t-dependence is well approximated by $\sim \exp(Bt)$, but the slope B depends on Q^2 and meson.
- Sensitivity to charm mass at small-Q^2 for J/ψ

Diffractive slope



- Diffractive slope, defined under assumption $\frac{d\sigma}{dt} \sim e^{Bt}$, $|t| \in (0, 1)\mathrm{GeV}^2$.
- Reasonable description for all processes, approximate universality as a function of $Q^2 + M^2$
- $B_\infty^{J/\psi} \approx 4\,\mathrm{GeV}^2$, corresponds to effective radius $\langle b^2 \rangle < R_{em}$

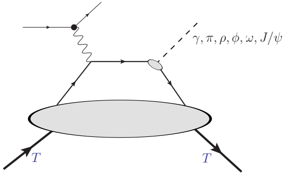
Results for the ratio $R = \sigma_L/\sigma_T$



- Grows as $\sigma_L/\sigma_T \sim Q^2$ modulo log corrections due to DGLAP.
- At large Q^2, $\sigma \approx \sigma_L$. Agrees with factorization theorem (and known from models since (Sakurai *et. al.*, PLB 40(1972), 121)).

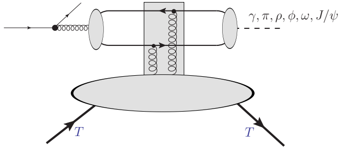
HERA data described by various approaches

Collinear approach



- Probes 2-parton GPDs (quarks & gluons)

Dipole model



- Probes gluons in the target

- Other approaches to HERA data – NLO BFKL with running α_s (J. Ellis *et. al.*, PLB 668 (2008), 51.), collinearly improved NLO BFKL (M. Hentschinski *et. al.*, PRL 110 (2013) 041601; arxiv:1301.5283), phenomenological reggistics.
- In HERA kinematics range in x is limited, so models with saturation and without it describe the data equally well. Hopefully, future accelerators (EIC, LHeC) will help to single out the correct one.

Summary

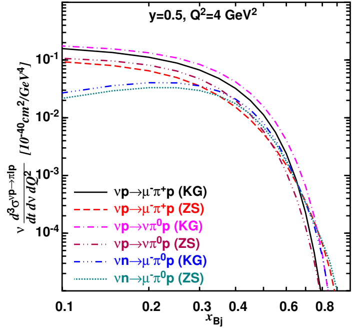
1. We revised the color dipole model (IP-Sat parametrization) using the most recent data from HERA (inclusive σ_r). Good $\chi^2/dof \approx 1.16$, with just 4 free parameters and > 260 points
2. We checked that this model gives reasonable results for all the DVCS and DVMP observables from HERA
3. For EIC and LHeC we provide the code for evaluation of exclusive cross-sections (available on demand)

Thank You for your attention

Collinear approach (contd.)

Advantages of the neutrino beam:

- For pions and kaons H, E dominate⇒Expect smaller contamination by tw-3
  - $\phi_{2;\pi}$ from $F_{\pi\gamma\gamma}(Q^2)$@CLOE, CLEO, BABAR, BELLE compatible with ϕ_{as}.
  - For kaons chiral corrections are controlled by $\mathcal{O}\left(m_s/1\,\mathrm{GeV}\right)$.



- Can probe NC and CC processes, using $SU(3)$ for $H_{p\to Y}$, one may get the full flavour structure