Deeply Virtual Compton Scattering

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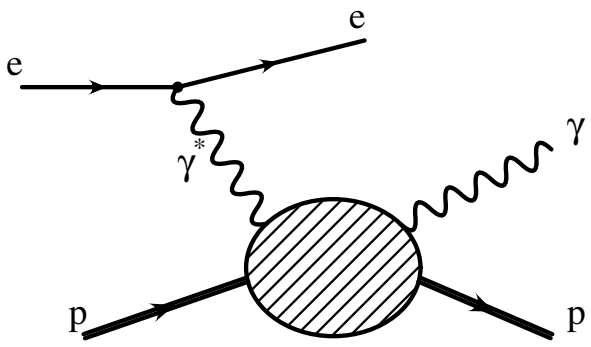
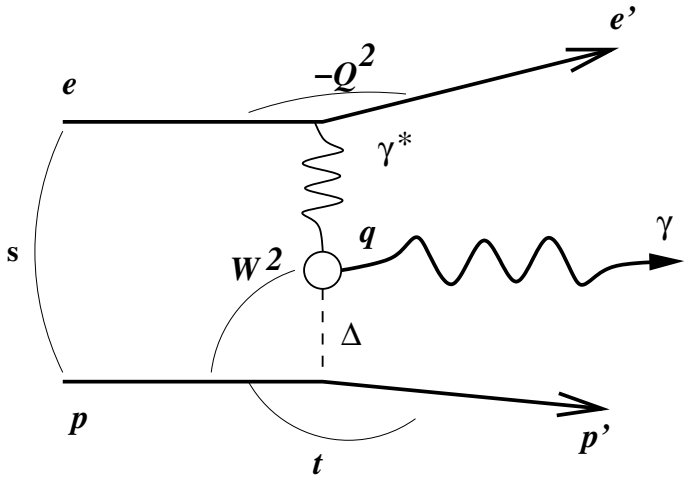


a)

- introduction
- experimental technique
- cross section measurements vs W and Q^2
- comparison with expectations:
  - GPD based models
  - colour dipole models

DVCS: QCD process → sensitivity to underlying dynamics



$s = (e+p)^2$

$Q^2 = -q^2 = -(e-e')^2$

$W^2 = (q+p)^2$

$t = \Delta^2 = (p-p')^2 \approx -p_T'^2$

HERA

$\sqrt{s} = 300, 320$ GeV

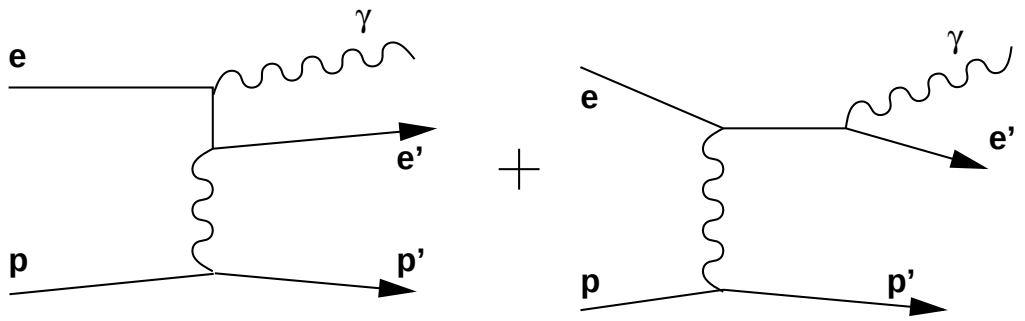
$2 < Q^2 < 100$ GeV^2

$30 < W < 140$ GeV

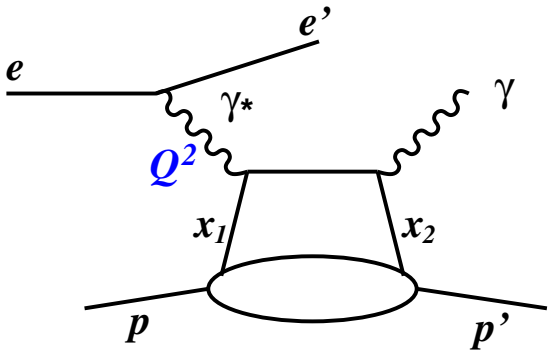
$10^{-4} < x < 10^{-2}$

Competing:

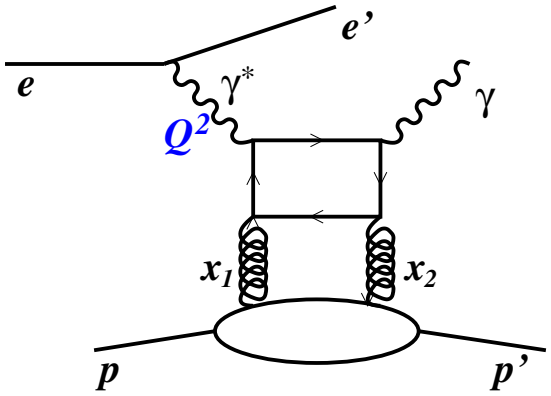
QED Bethe-Heitler process → background and interference



QCD MODELS FOR DVCS



handbag diagram



dominant contribution at low-x

at high Q, hard scattering factorization

GPD-based Model $x_1 \neq x_2$

LO calculation Frankfurt, Freund and Strikman FFS

$$\frac{d^3\sigma_{\rm DVCS}}{dxdQ^2dt} = \frac{\pi^2\alpha^3}{2xR^2Q^6}[1+(1-y)^2]e^{bt}F_2{}^2(x,Q^2)(1+\rho^2)$$

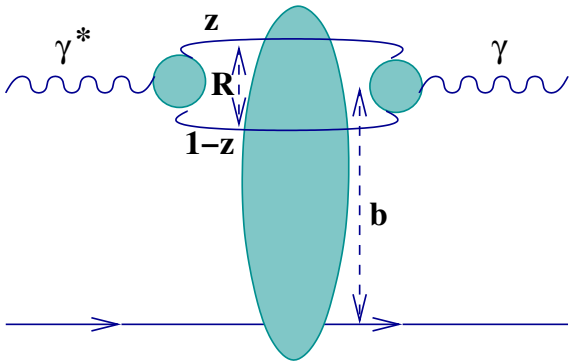
$R = \frac{Im\mathcal{A}(\gamma^\star p\to\gamma^\star p)|_{t=0}}{Im\mathcal{A}(\gamma^\star p\to\gamma p)|_{t=0}}$ from aligned jet model

$\rho = \frac{Re\mathcal{A}(\gamma^\star p\to\gamma p)|_{t=0}}{Im\mathcal{A}(\gamma^\star p\to\gamma p)|_{t=0}}$

Full NLO calculation Freund and Mc Dermott Phys.Rev. D65 (2002) 91901

MODELS FOR DVCS

Colour Dipole Model



$$\mathcal{A} \sim \int_{R,z} \psi^{\gamma^*}_{ini} \sigma_{q\bar{q}p} \psi^{\gamma}_{out}$$

Ingredients:

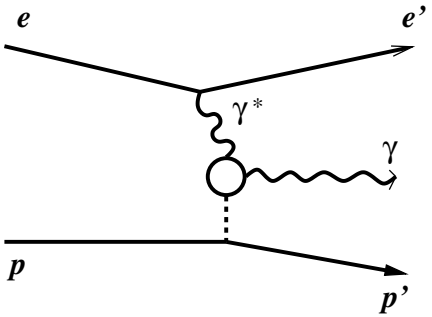
ψ^{γ^*} ligh-cone wave function

$\sigma_{q\bar{q}p}$ - dipole cross section:

- Regge approach (Forshaw Kerley Shaw)
- QCD colour transparency
  (McDermott Frankfurt Guzey Strikmann)
- perturbative + Regge (Donnachie Dosh)
- GW saturation model (Favart Machado)

At high Q and small R, $\sigma_{q\bar{q}p} \sim R^2 \bar{x} g(\bar{x}, Q)$

QCD-BASED PREDICTIONS AT LOW x, HIGH y



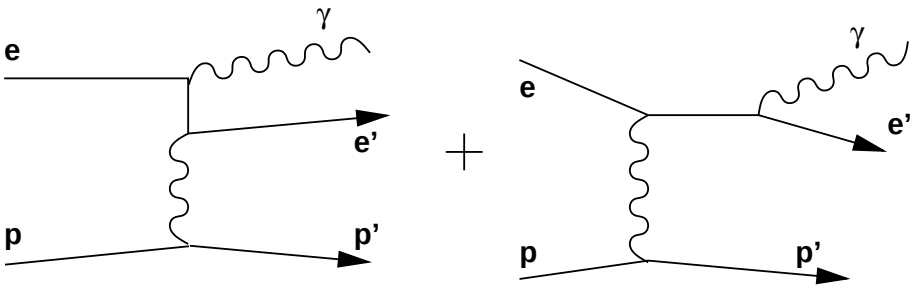
$$\frac{d^4\sigma^{DVCS}}{dxdydtd\phi} \sim \frac{1}{Q^6} e^{-b|t|}(1+\rho^2)$$

$$\rho = \frac{Re(A(\gamma^* p \to \gamma p))}{Im(A(\gamma^* p \to \gamma p))}$$

$$\frac{d^4\sigma^{INT}}{dxdydtd\phi} \sim \pm\frac{1}{Q^5}\rho\frac{e^{-b|t|/2}}{\sqrt{|t|}}\cos\phi$$

$$\phi = \phi'_e - \phi'_p$$

b-not predicted by models



$$\frac{d^4\sigma^{BH}}{dxdydtd\phi} \sim \frac{1}{Q^4}\frac{1}{|t|}$$

MC generator based on FFS → GenDVCS (Patrick Saull)

WHY IS DVCS INTERESTING?

- Simplest QCD process
- Interference between QCD with QED amplitudes $\rightarrow$ rich structure in ϕ, angle between the hadronic and leptonic planes $\rightarrow$ asymmetries (angular, charge)
- Allows to study Re and Im part of the scattering amplitude through BH-DVCS interference term $\propto Re\mathcal{A}_{\mathrm{QCD}}$
- $Re\mathcal{A}_{\mathrm{QCD}}(x,Q^2) \sim \int \frac{dx_1}{x_1} ReC_i(x/x_1,Q^2) G_i(x_1,x,Q^2)$
  $\Rightarrow$ give access to Generalized Parton Distributions GPD
- Factorization scale expected to be lower than for meson production

At low x, integrating over azimuthal angle

$$\int_0^{2\pi} \frac{d\sigma}{d\phi} \simeq \sigma_{\mathrm{DVCS}} - \sigma_{\mathrm{BH}}$$

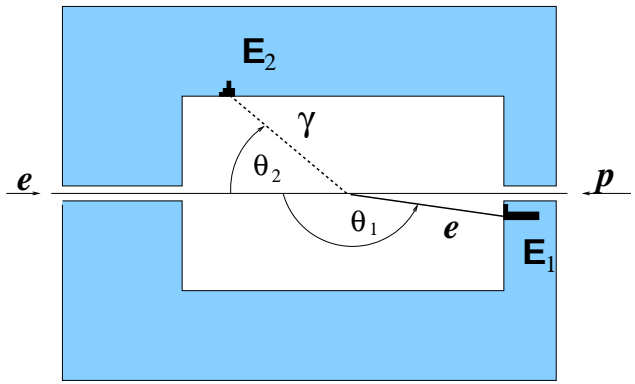
MEASUREMENT: ANALYSIS STRATEGY

H1 e^+p sample, $8\,\mathrm{pb}^{-1}$

$2 < Q^2 < 20$ GeV^2, $30 < W < 120$ GeV

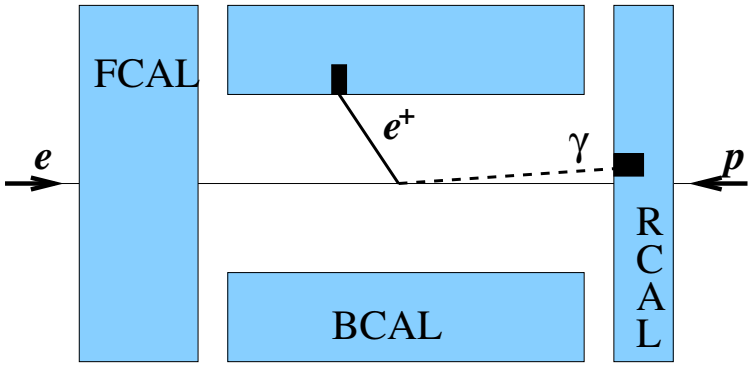
ZEUS e^+p sample, $95\,\mathrm{pb}^{-1}$, e^-p sample $17\,\mathrm{pb}^{-1}$

$5 < Q^2 < 100$ GeV^2, $40 < W < 140$ GeV



- 2 EM clusters: $E_1 > 15\,\mathrm{GeV}$, $E_2 > 2.5(3)\,\mathrm{GeV}$ and $0.6 < \theta_2 < 2.75\,\mathrm{rad} \rightarrow \theta_1 > \theta_2$
- 0 or 1 track; if 1, must be matched to EM cluster
- $40 < E - p_Z < 70\,\mathrm{GeV}$ to reject γp and hard ISR
- No other activity above noise level to reject events where the proton dissociated

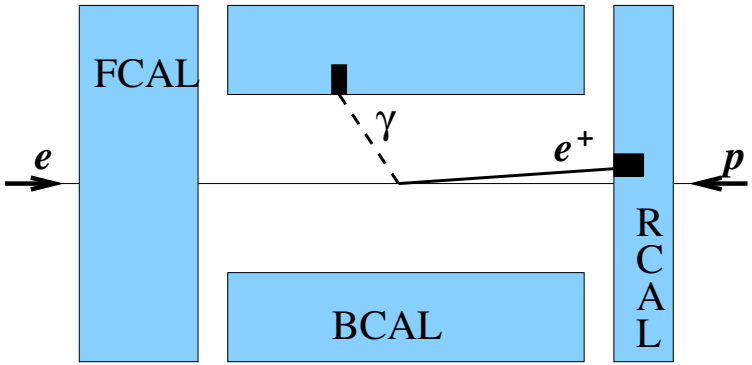
EVENT TOPOLOGY



γ from QED bremsstrahlung emitted in e-beam direction

e^+ sample CONTROL SAMPLE

only BH contributes, 7000 events



γ sample ENRICHED DVCS

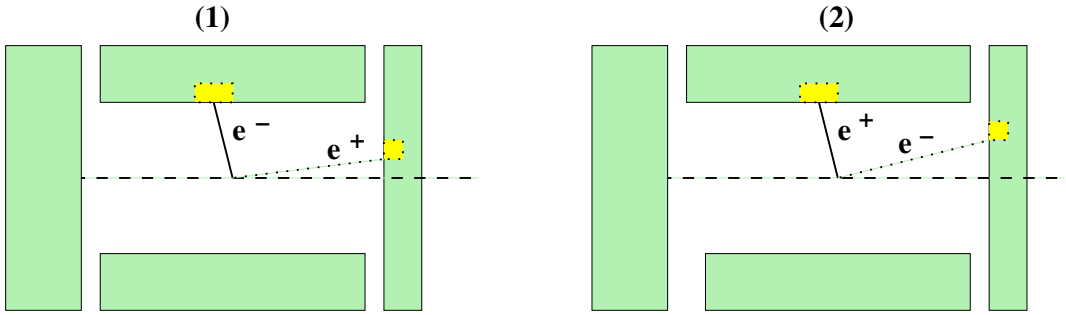
both BH and DVCS contribute, 4000 events

BH MC describes data in control sample

$\Rightarrow$ use MC to subtract BH in enriched DVCS sample

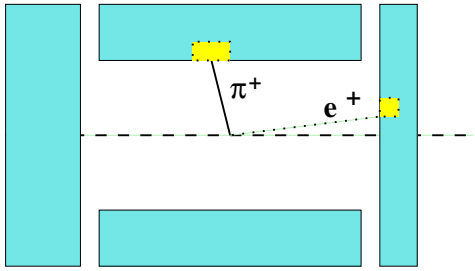
e^+ sample BACKGROUND STUDY

- Dilepton production ($e^+p \to e^+e^-e^+p$)



4% of e-sample
(75% non-resonant, $25\% J/\psi$)

- Diffractive ρ production ($ep \to e\rho p$, $\rho \to \pi^+\pi^-$)



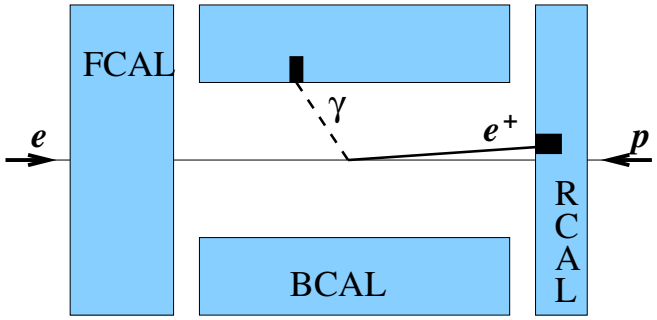
negligible for $Q^2 > 5\,\mathrm{GeV}^2$

- Proton dissociative BH ($ep \to e\gamma X$)

$(17.8 \pm 1.2)\%$ in 96-97(PRT),
$(10.5 \pm 1.0)\%$ in 98-00(FPC)

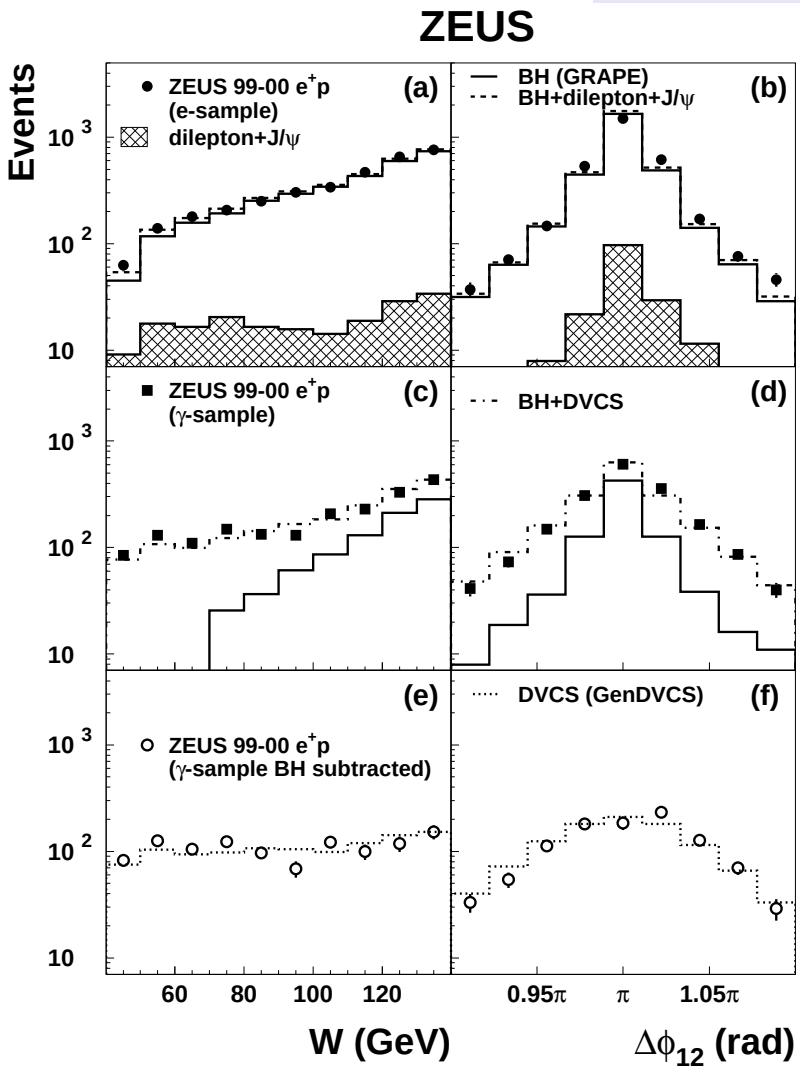
Good agreement with BH - GRAPE MC

γ sample BACKGROUND STUDY



• BH process ($ep \to e\gamma p$)	use BH MC
• Diffractive ω or ϕ production below 1%	neglected
• low-multiplicity process like	
$ep \to e\pi^0 p$, $ep \to e\pi^0\pi^0 p$, $ep \to e\pi^0\eta p$	negligible
• Proton dissociative DVCS ($ep \to e\gamma X$)	taken from J/ψ analysis:
	$22.0 \pm 3.0\%$ for 96-97 data (PRT)
	$17.5 \pm 4.0\%$ for 98-00 data (FPC)

CONTROL PLOTS

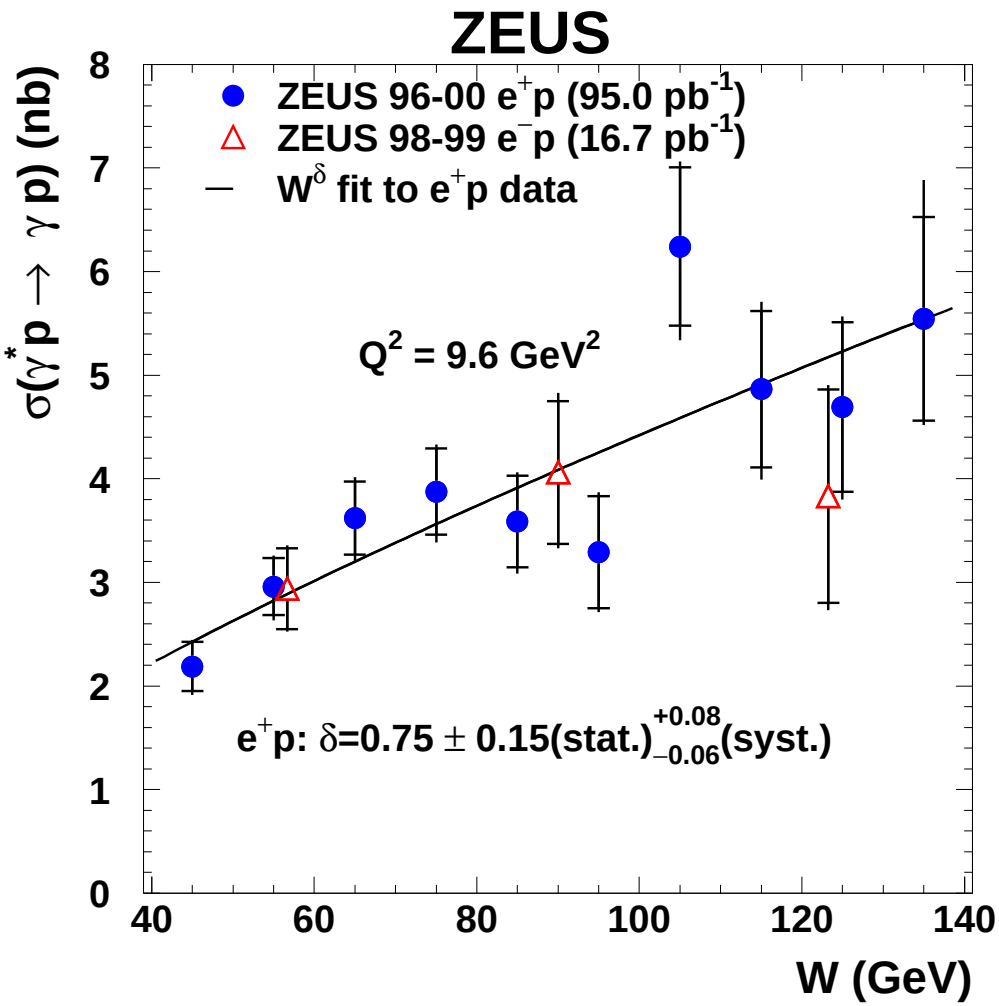


e^+ sample — BH control sample

γ sample — DVCS + BH

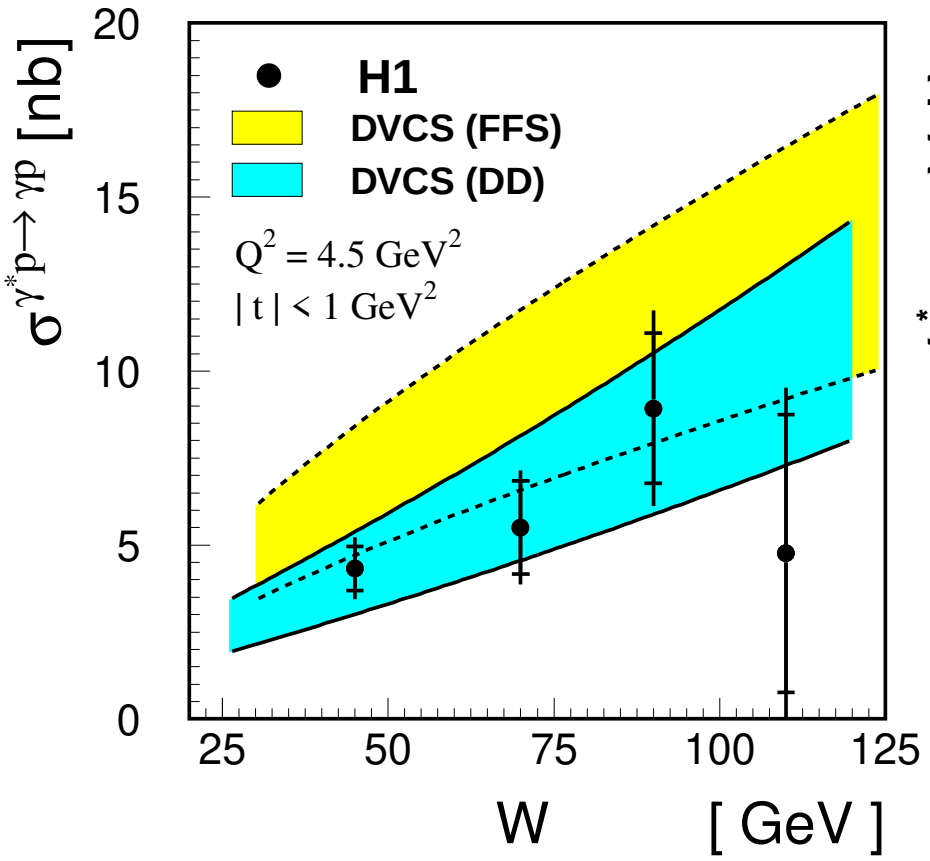
γ sample after BH subtraction — DVCS

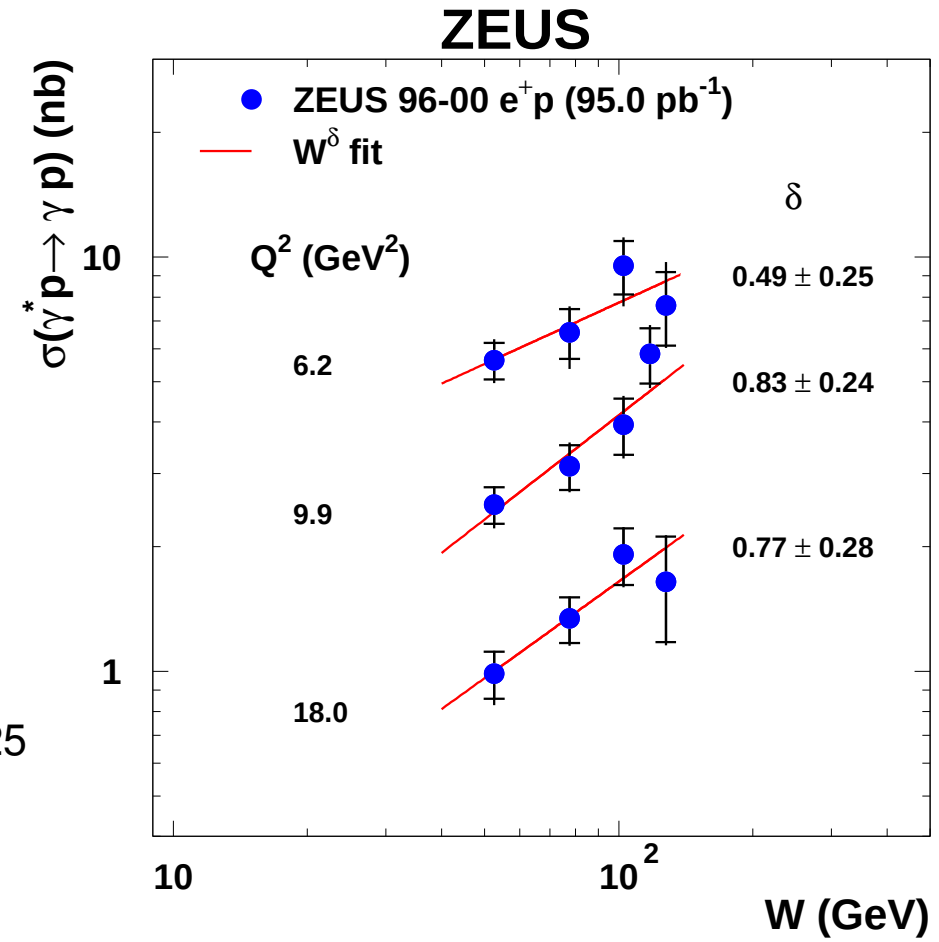
e^+p vs e^-p, $5 < Q^2 < 100\,\mathrm{GeV}^2$



- No significant differences
- $\sigma(\gamma^* p \to \gamma p) \propto W^{0.75}$

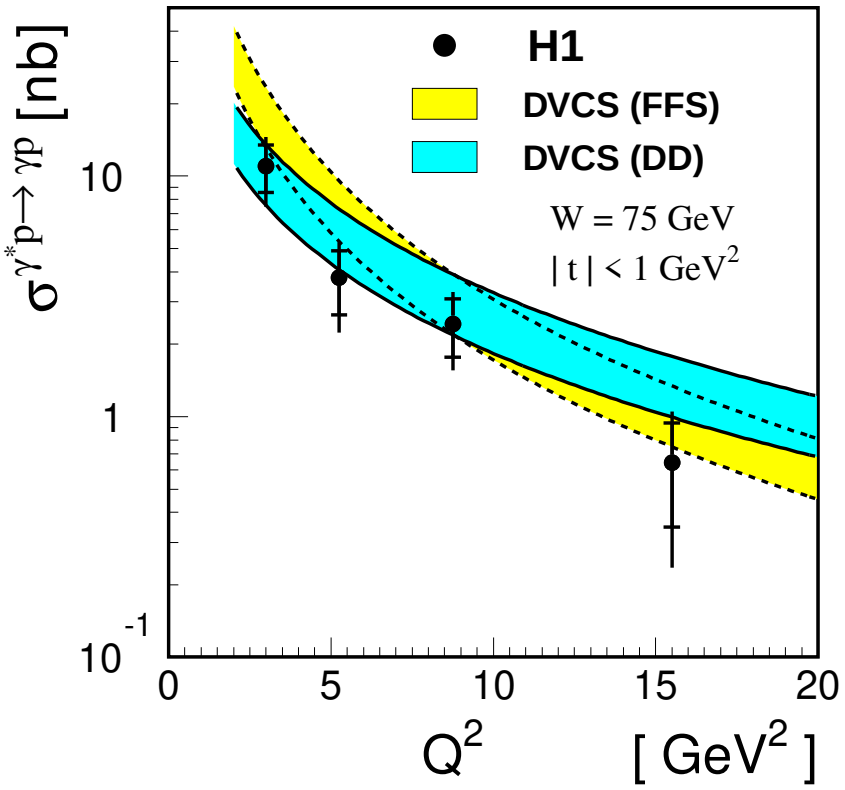
W DEPENDENCE AS A FUNCTION OF Q^2

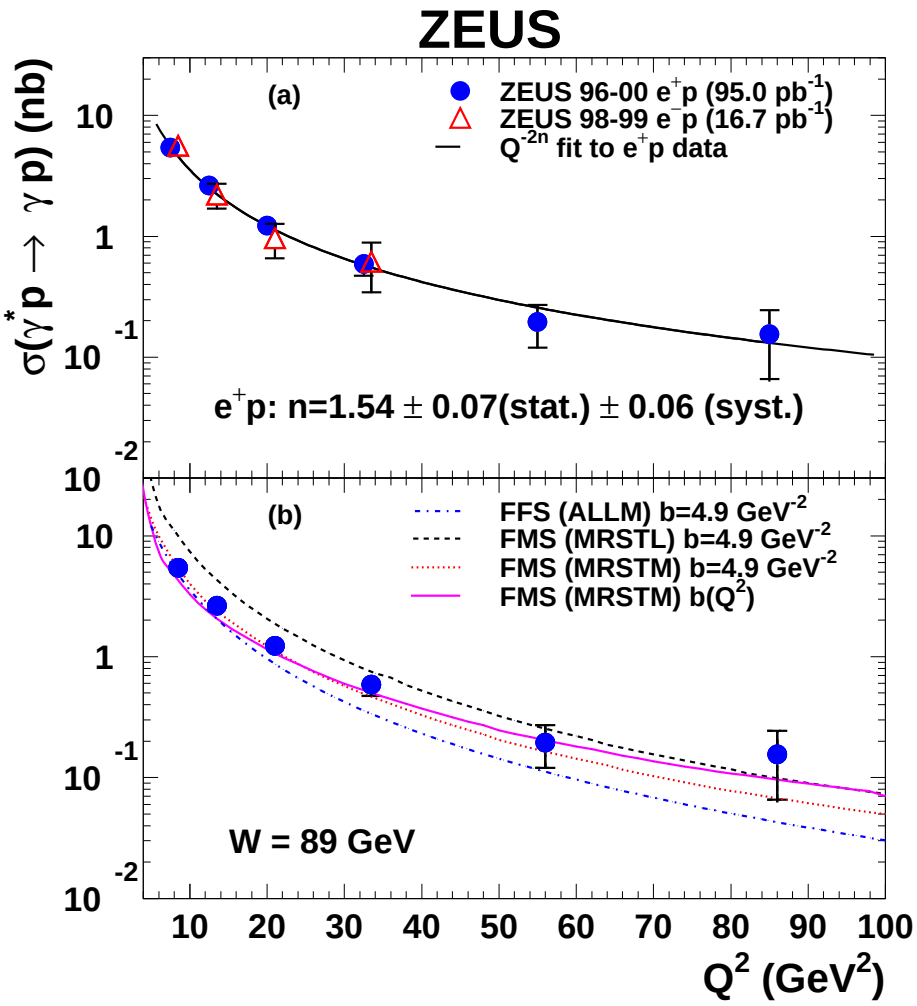




- Data compatible with δ increasing with Q^2

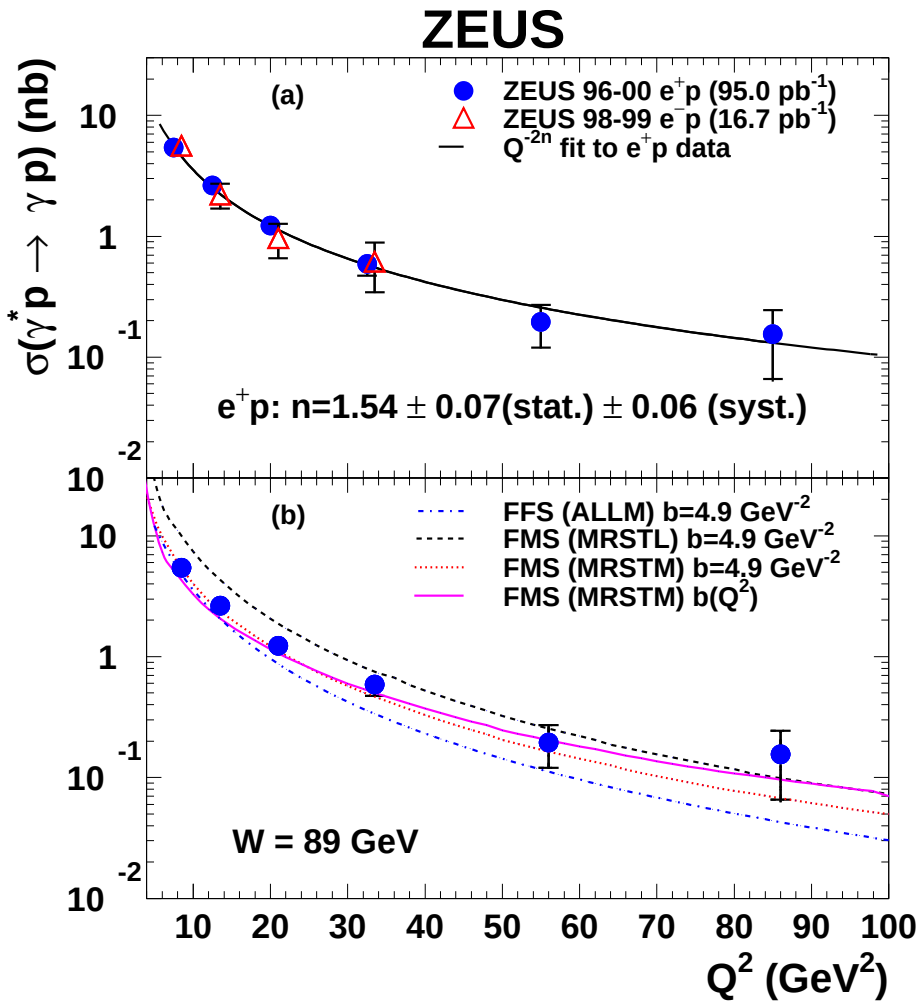
Q^2 DEPENDENCE





- $\sigma(\gamma^* p \to \gamma p) \sim Q^{-3}$

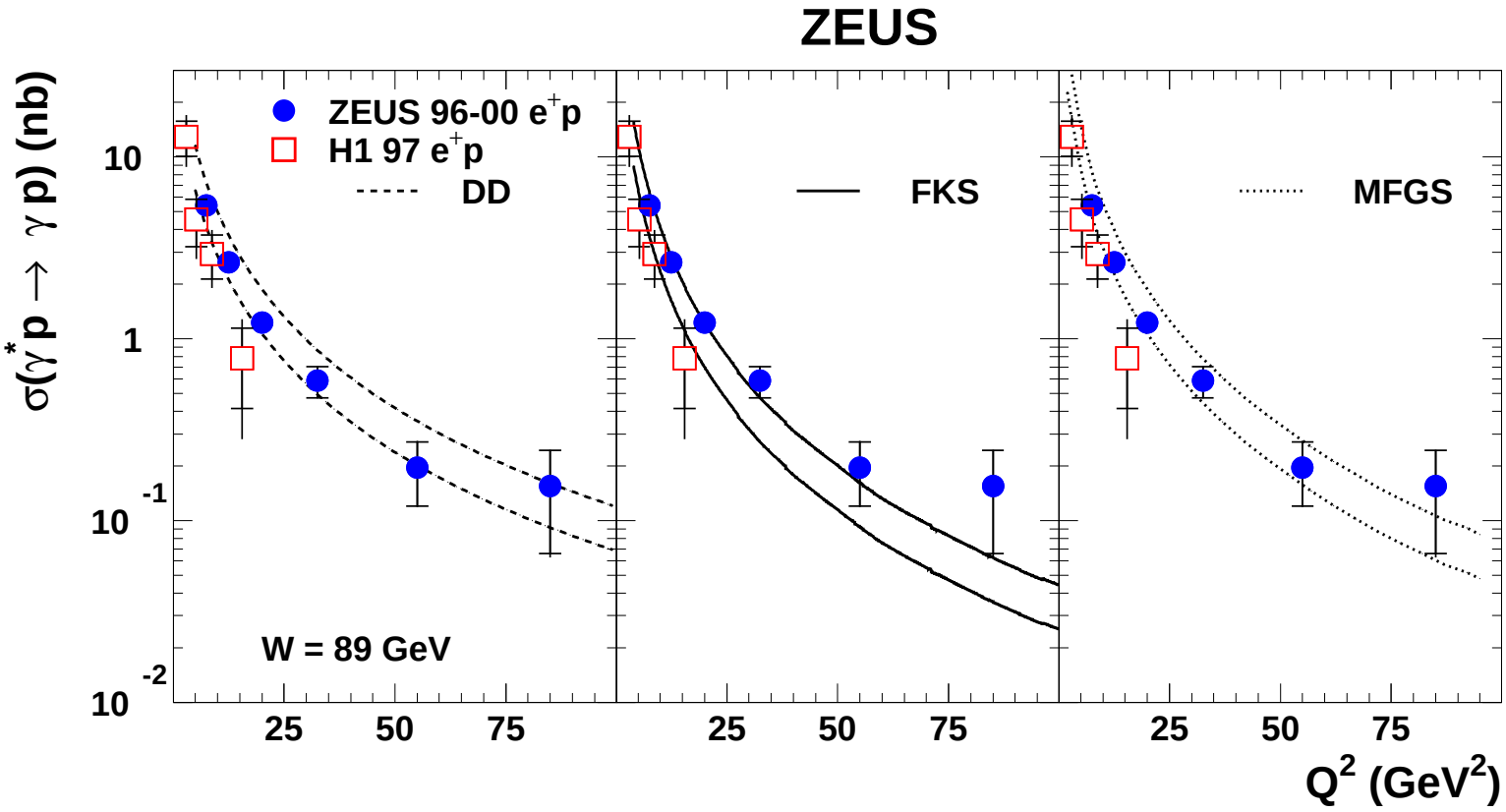
Q^2 DEPENDENCE FOR $W = 89\,\mathrm{GeV}$



Freund, McDermott and Strikman, full NLO calculation

- $b(Q^2) = 8(1 - 0.15\ln(Q^2/2))\,\mathrm{GeV}^{-2}$

Comparison with Colour Dipole Models



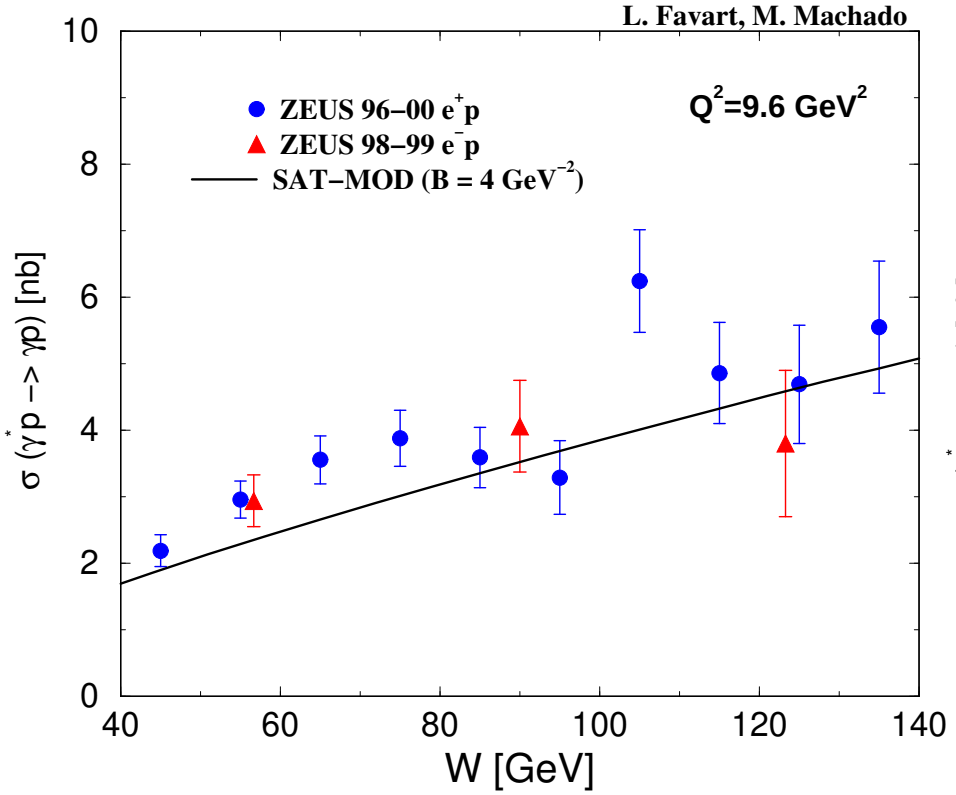
upper curves $b = 4\,\mathrm{GeV}^{-2}$ lower curves $b = 7\,\mathrm{GeV}^{-2}$

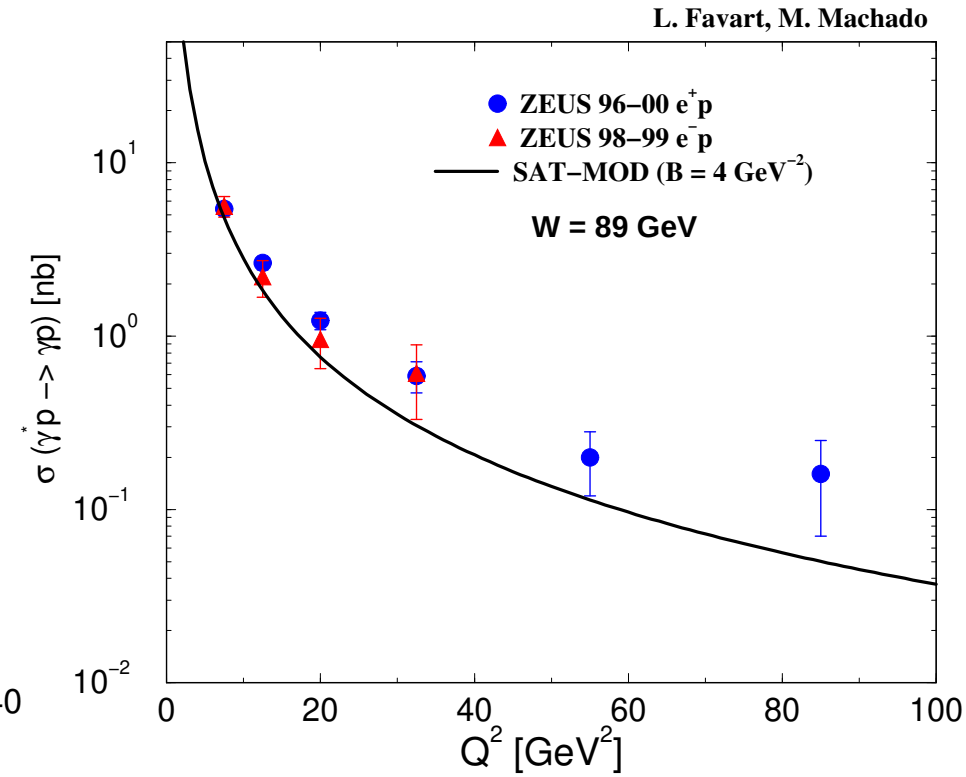
Donnachie and Dosh (DD) - perturbative + Regge

Forshaw, Kerley and Shaw (FKS) - Regge approach

McDermott, Frankfurt, Guzey and Strikman (MFGS) - QCD colour transparency

Comparison with Colour Dipole Models





GW: $\sigma_D(x, R^2) = \sigma_0[1 - e^{-Q_s^2(x)R^2/4}]$, $Q_s^2(x) = (\frac{x_0}{x})^\lambda$

$\sigma(\gamma^* p \to \gamma p) \sim \frac{1}{B}\frac{W^{4\lambda}}{Q^4}$

SUMMARY

- DVCS measured at HERA I, by H1 and ZEUS
- $\sigma(\gamma^* p \to \gamma p)$ measured in the range $2 < Q^2 < 100\,\mathrm{GeV}^2$ and $30 < W < 140\,\mathrm{GeV}$
- No significant difference between $e^+ p$ and $e^- p$
- $\sigma(\gamma^* p \to \gamma p)$ rises steeply with $W \to$ hard process
- Q^2 dependence is $\approx Q^{-3}$
- Q^2 dependence of b may be crucial in extracting GDPs, however t dependence still not measured