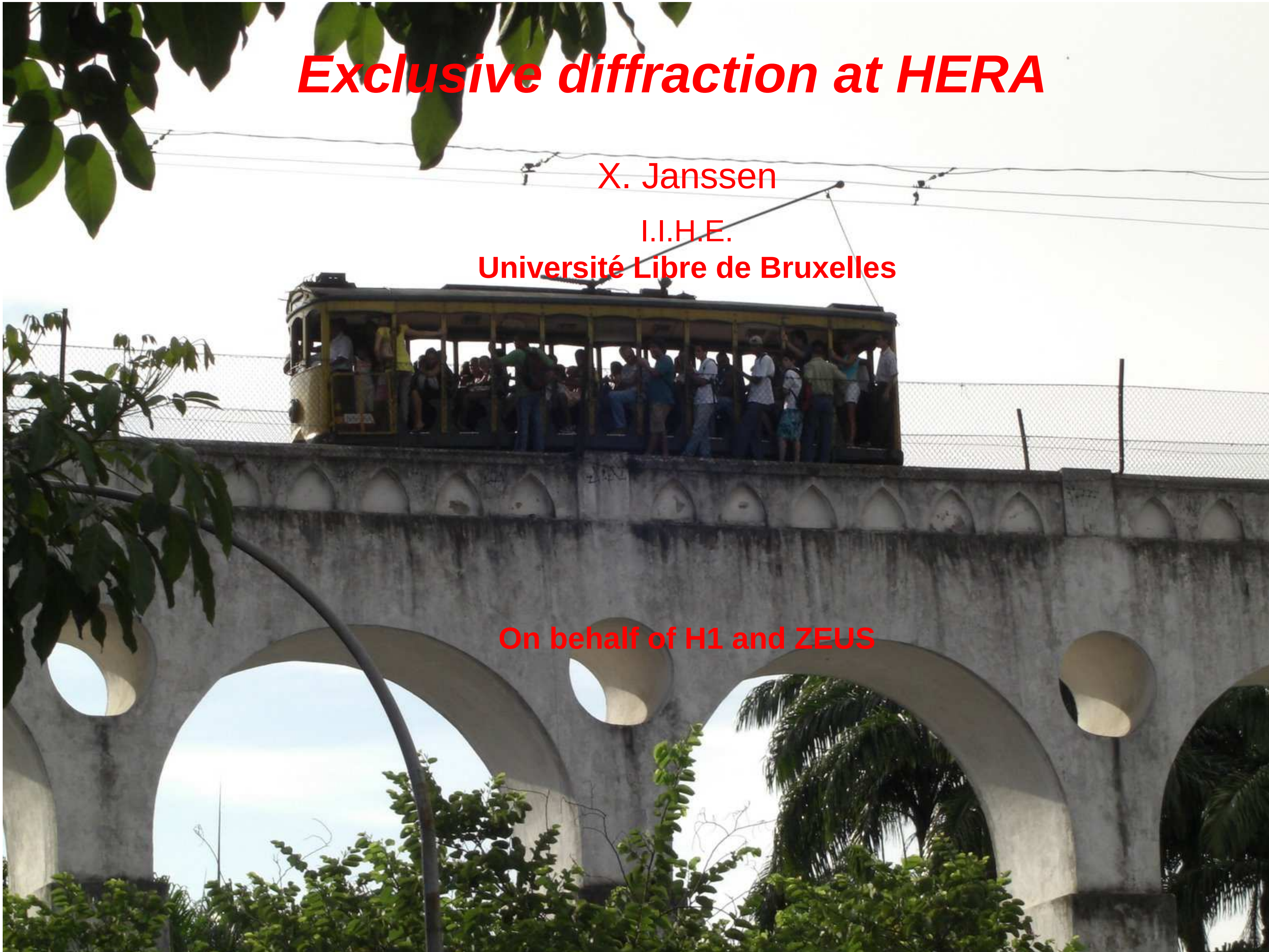


Exclusive diffraction at HERA

X. Janssen

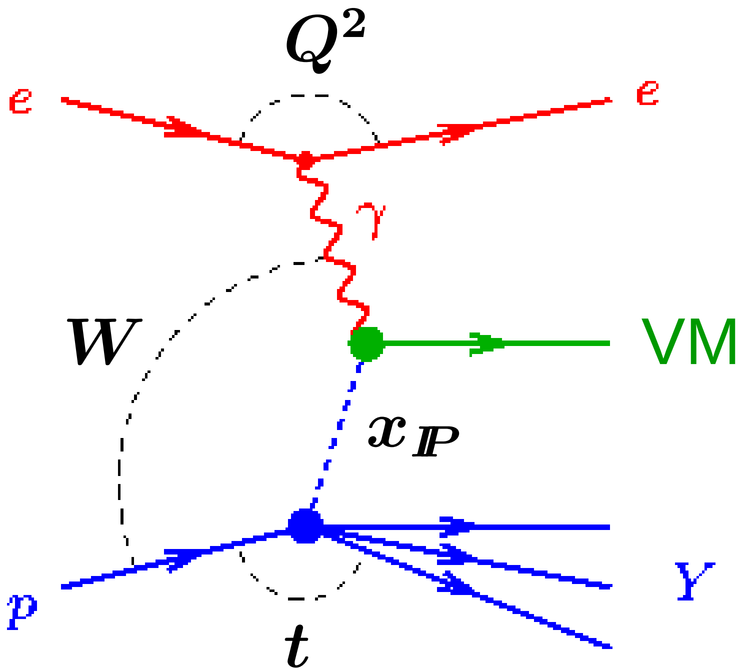
I.I.H.E.

Université Libre de Bruxelles

On behalf of H1 and ZEUS

Diffractive Vector Meson Production and DVCS

$$e + p \rightarrow e + VM\,(= \rho, \phi, J/\psi, ..., or\ \gamma) + Y\,(or\ p)$$



Q^2	Photon Virtuality Photoproduction: $Q^2 \sim 0$
W	γp CMS energy
t	4-momentum transfer squared
$x_{I\!P}$	Momentum fraction of the colour singlet exchange

Regge Theory

= Soft $I\!P$omeron exchange

$$\sigma \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{I\!P}(t)-1)}$$

$$\alpha_{I\!P}(t) = 1.08 + 0.25\,t \text{ (DL)}$$

Light VM at low Q^2 and low $|t|$

pQCD Models

Exchange of $\geq$ 2 gluons

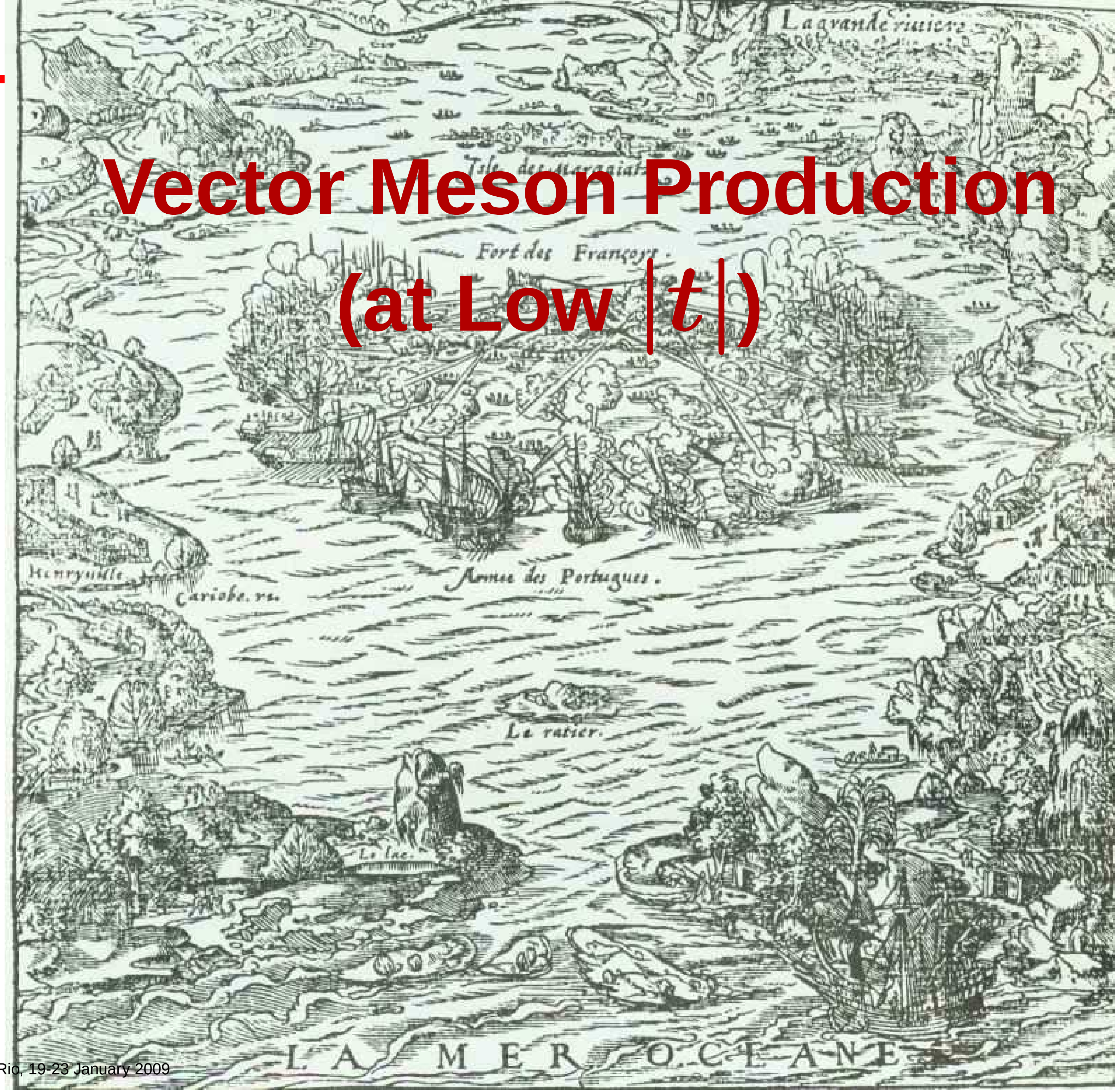
$$\sigma \propto (xG(x, Q^2))^2$$

Steep rise of $xG(x, Q^2)$

Requires hard scale: Q^2, t or m_q

$\Longrightarrow$ Investigate transition between soft and hard regimes

Vector Meson Production
(at Low $|t|$)



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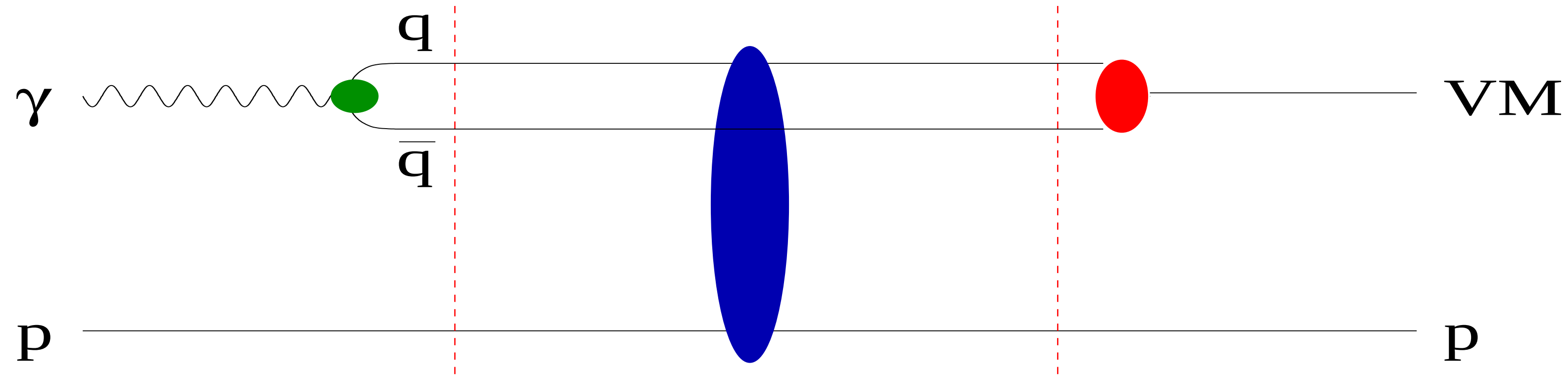
VM theory: Dipole approach and k_T factorisation

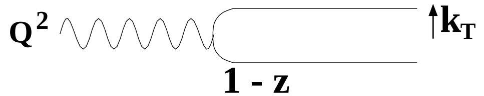
In proton rest frame at large energy, for $\mathcal{A}_L$ (large μ^2 = Q^2 or m_q^2):



$$t_c \sim \frac{1}{2m_p x} \quad \gg \quad t_I \sim \frac{1}{\Delta E_I} \quad \ll \quad t_f \sim 1\ \text{fm}\ \frac{E}{m}$$

$$\mathcal{A}_{\gamma^{(*)}p\to Vp} = \Psi^{\gamma}_{q\bar{q}} \otimes \sigma_{q\bar{q}-p} \otimes \Psi^{VM}_{q\bar{q}}$$

- Scaning radius is expected to decreases with increasing Q^2_z or M_V
  $\Rightarrow$ "universal scale": $\mu^2 = z(1-z)(Q^2 + M_V^2)$



- For $\mathcal{A}_L$ (large Q^2 or m_q): $z \simeq 1/2 \Rightarrow \mu^2 \simeq (Q^2 + M_V^2)/4$
- For light quarks, $\mathcal{A}_T$: contrib. from end points $z = 0, 1$
  $\Rightarrow \mu^2$ can be small even for large $Q^2 \Rightarrow$ soft contributions

VM theory: Dipole approach and k_T factorisation

Dipole approach - Saturation :

Shown here: C.Marquet, R.Peschanski, G.Soyez [hep-ph/0702171]

- $\sigma_{q\bar{q}-p}$ extracted from fits to inclusive data (F_2) with geometric scaling.
- Fits may include VM data as well (see later) and QCD evolution at high Q^2.

k_T factorisation - BFKL pomeron:

Shown here: I.Ivanov, N.Nikolaev, A.Savin [hep-ph/0501034]

- Conjugate approach to dipole one in "k_T space".
- $\sigma_{q\bar{q}-p}$ computed from k_T-unintegrated gluon pdf $\mathcal{F}(x,\vec{\kappa})$:

$$\sigma_{q\bar{q}-p} = 4\pi/3 \int d^2\vec{\kappa}/\kappa^4 \, \mathcal{F}(x,\vec{\kappa}) \, \alpha_s(\mu^2) \, [1 - \exp(i\vec{\kappa}\vec{r})]$$

N.B: for small dipole,

$\sigma_{q\bar{q}-p} \simeq \pi^2/3 \, r^2 \, \alpha_s(\mu^2) \, G(x,\mu^2)$ with $\mu^2 = A/(z(1-z)Q^2 + m_q^2)$; $A = 9 - 10$

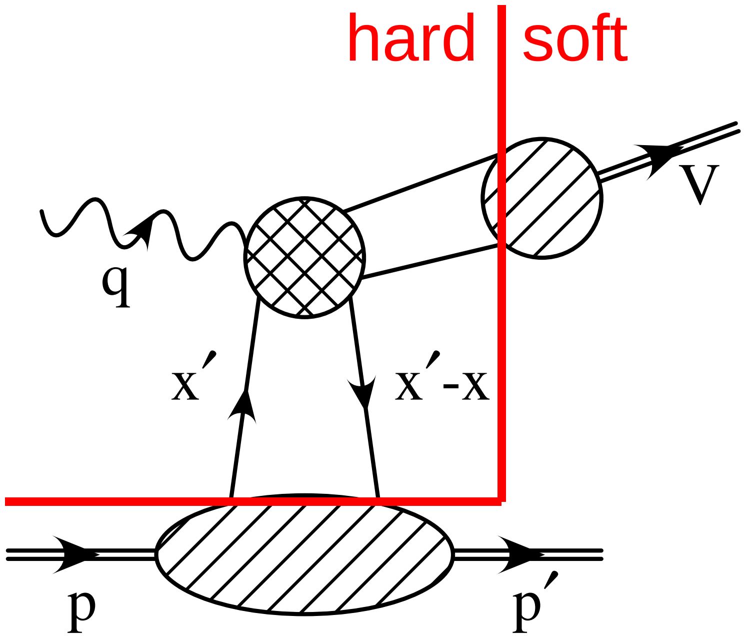
$$\longrightarrow \sigma_T \propto (Q^2 + M_V^2)^{-4} \, [\alpha_s(\mu^2) \, G(x,\mu^2)]^2$$

$$\longrightarrow \sigma_L \propto Q^2/M_V^2 \, (Q^2 + M_V^2)^{-4} \, [\alpha_s(\mu^2) \, G(x,\mu^2)]^2$$

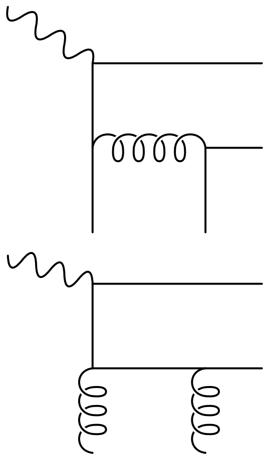
VM theory: *Collinear factorisation*

QCD factorisation theorem valid for leading power of Q in DIS:

Collins, Frankfurt and Strikman [hep-ph/9611433]



Typical LO diagrams for H_{ij}:



$$\mathcal{A}_{\gamma^{(*)}p\to Vp} = \sum_{i,j} \int_0^1 dz \int dx' \; f_{i/p}(x', x'-x, t, \mu) \; H_{ij}(Q^2 x'/x, Q^2, z, \mu) \; \Psi_j^V(z, \mu)$$

where $f_{i/p}$: non-forward PDF ($x' \neq x' - x$, t dependant) $\longrightarrow$ GPD's

H_{ij}: hard scattering m.a. ; Ψ_j^V: VM wave fct

Theorem is proven for γ_L ; extended/assumed for γ_T in many models

Shown here: S.Goloskokov and P.Kroll [hep-ph/07083569]

VM theory: Main features / expectations

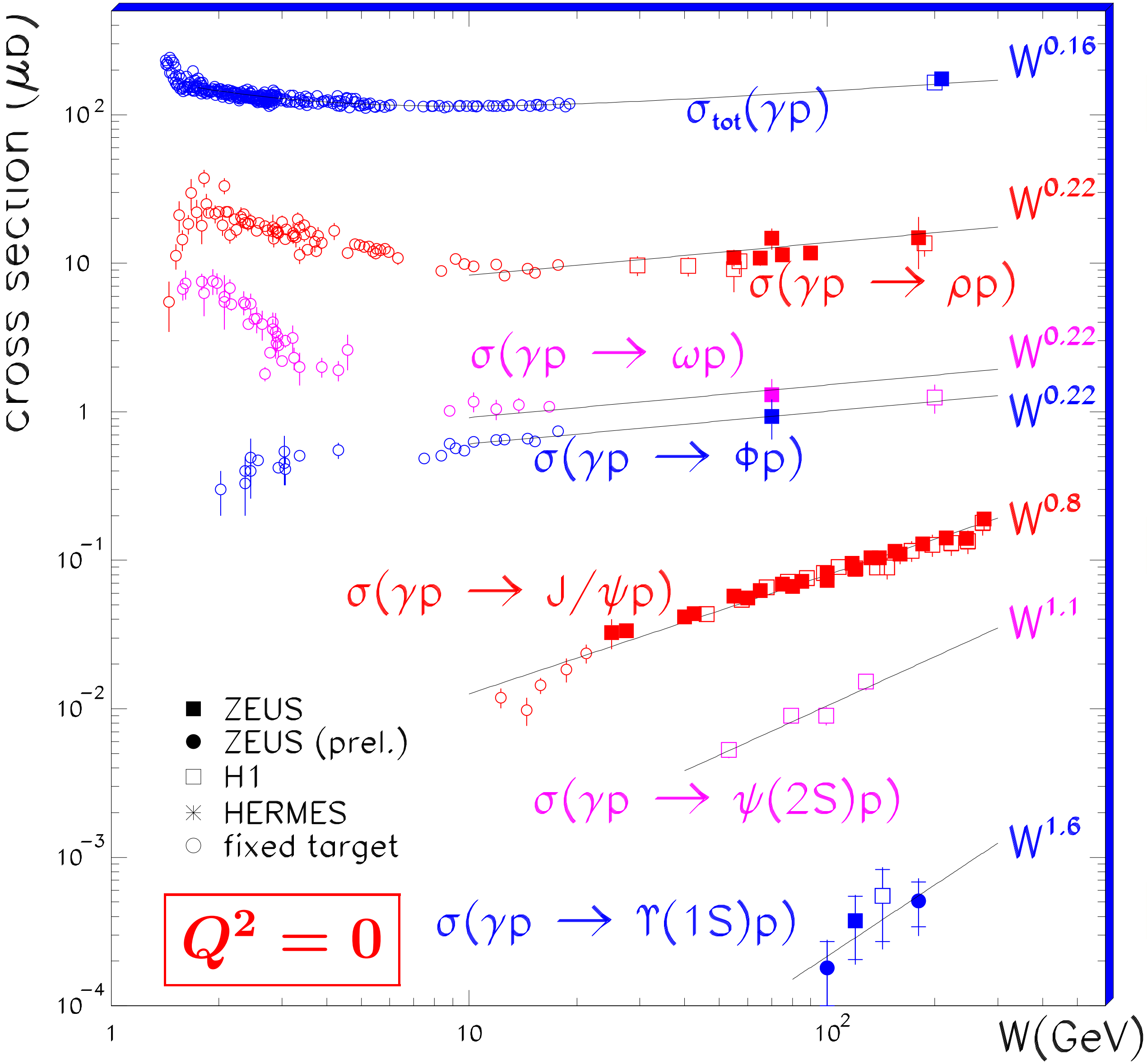
$\sigma(Q^2)$: $\sigma_L \propto Q^{-6}$; $\sigma_T \propto Q^{-8}$ but modified by gluon pdf Q^2 depend., quark Fermi motion and virtuality, $\alpha_s(Q^2)$, higher order.
$\longrightarrow$ Naive $R = \sigma_L/\sigma_T \propto Q^2/M_V^2$ also modified.

$\sigma(W)$:
- For σ_L at high Q^2 and heavy VM, hard (universal) W depend. expected from $1/x$ hard gluon pdf evolution.
- For light VM, delayed approach to hard pQCD regime (σ_T).

dσ/dt: $\propto \exp(-b|t|)$ for low $|t|$, where $b = b_{q\bar{q}} \otimes b_{I\!P} \otimes b_p$
- Expect common b for σ_L at high Q^2 and heavy VM.
  $\longrightarrow$ Naive universality of b vs. $\mu^2 = 1/4(Q^2 + M_V^2)$
- Larger dipole in σ_T than in σ_L $\rightarrow$ expect $b_T > b_L$
  $\longrightarrow$ Delayed universality of b vs. μ^2

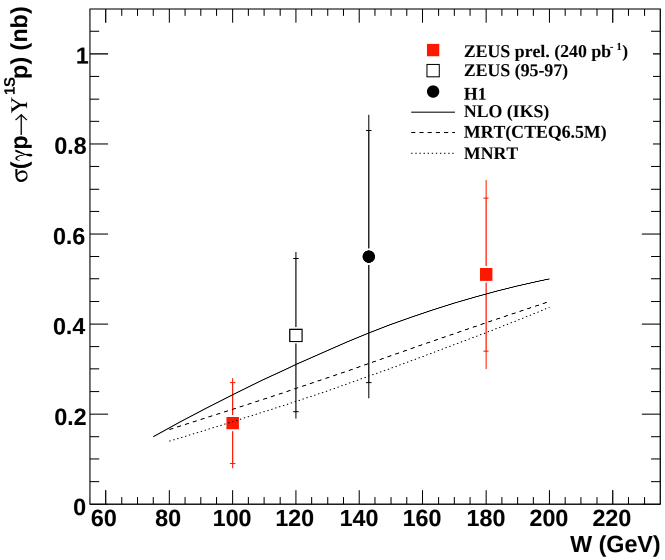
Helicity amplitudes: see later

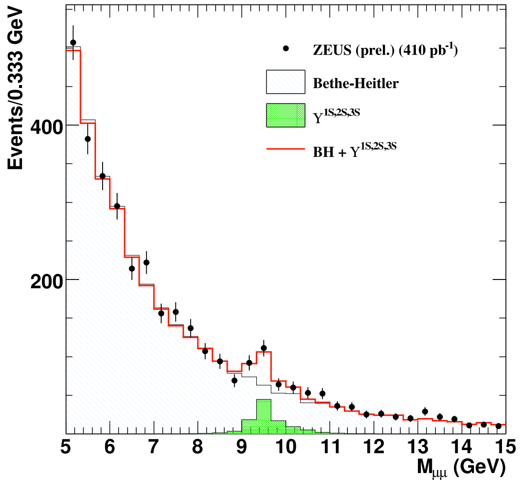
Soft to hard transition: mass



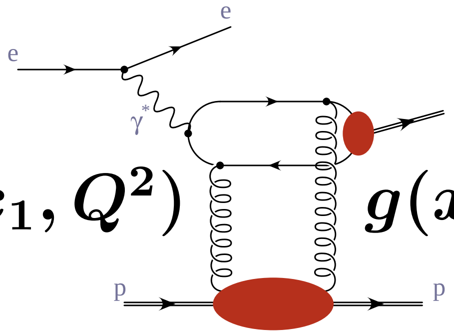
- Low mass (ρ, ϕ, ω; $M_V^2 \simeq 1$ GeV²): no pert. scale → weak energy dep. (soft regime)
- High mass (J/ψ, υ): pert. scale → strong energy dep. (hard regime)
- Large mass (Υ) important skewing effect

Upsilon Photoproduction : ***New ZEUS result***



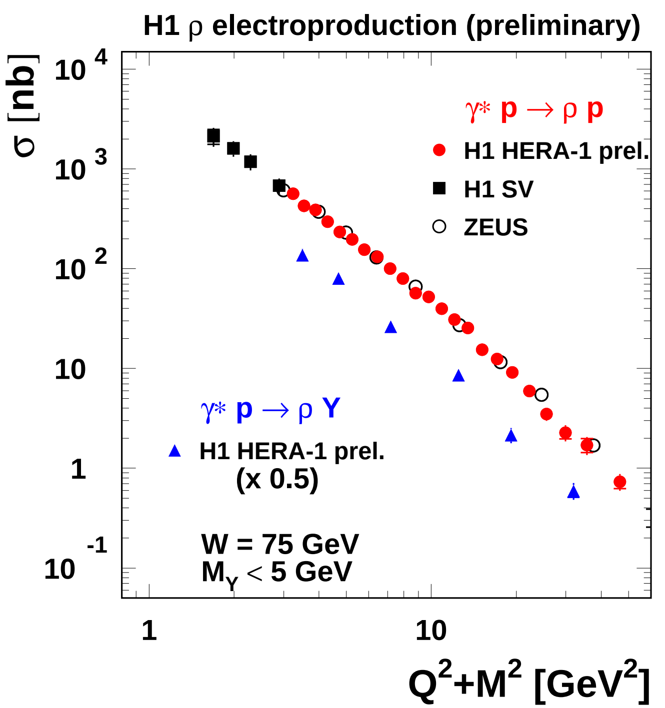


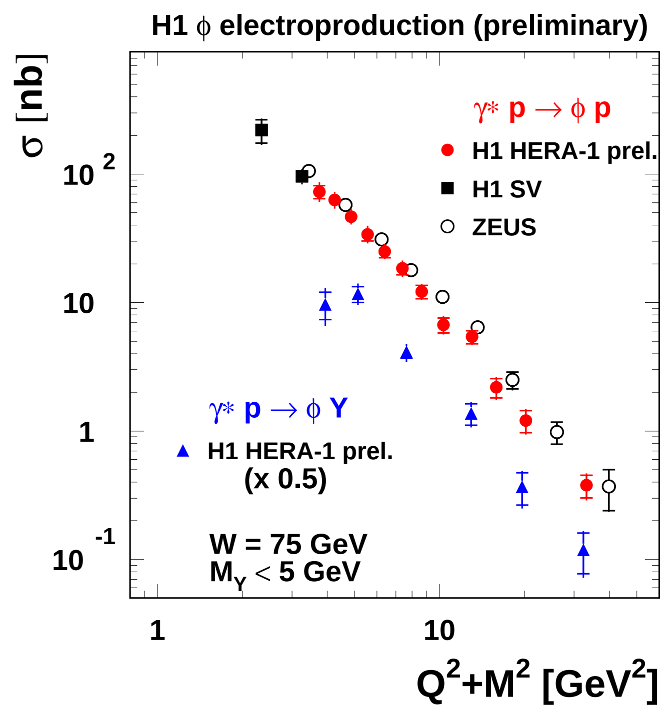
ZEUS (HERA I+II): 104 ± 21 events candidates
In agreement with NLO predictions including skewing and real part of the amplitude



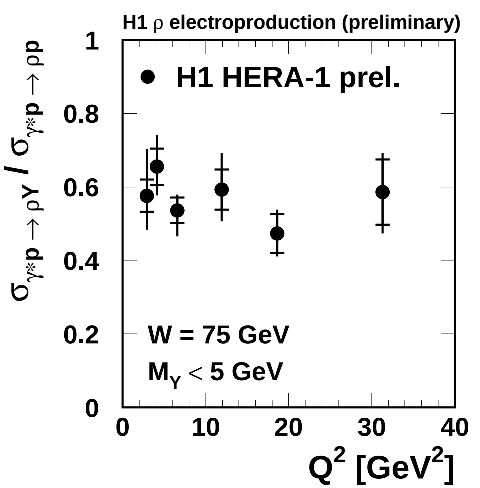
$$g(x_1, Q^2) \qquad g(x_2, Q^2) \qquad x_1 \neq x_2$$

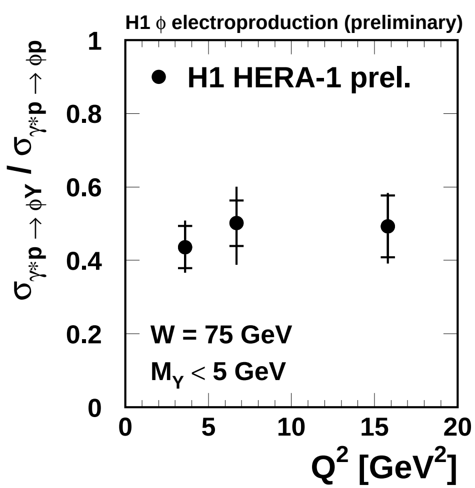
Light VM Cross-sections : Q^2 dependence





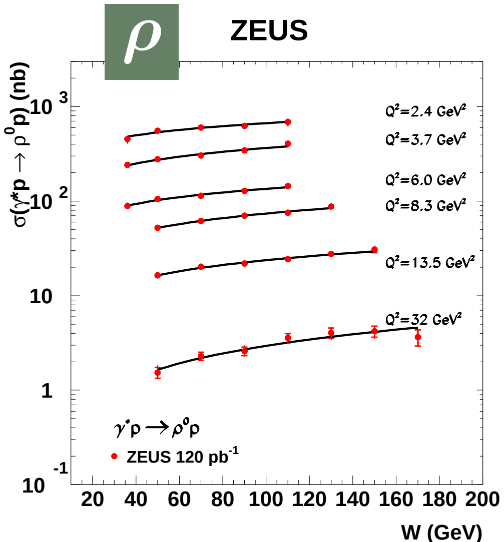
- High precision for elastic cross-sections

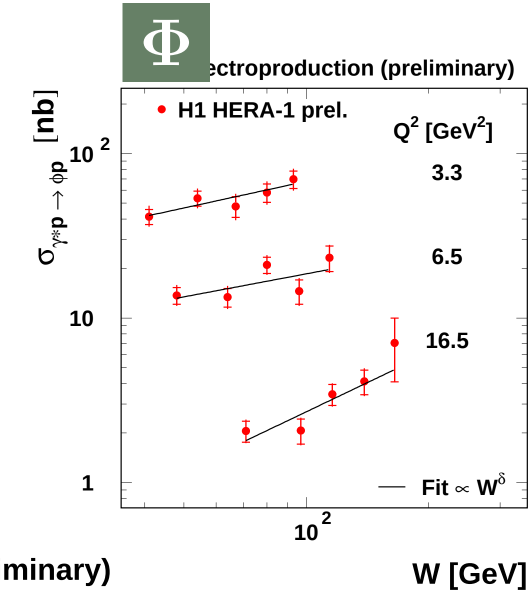


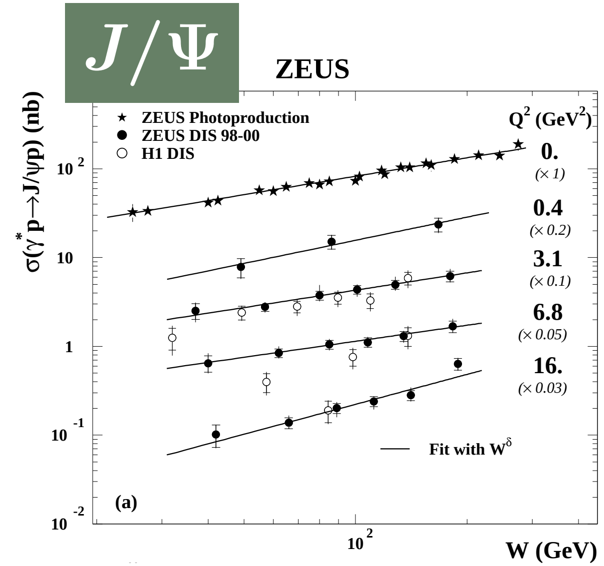


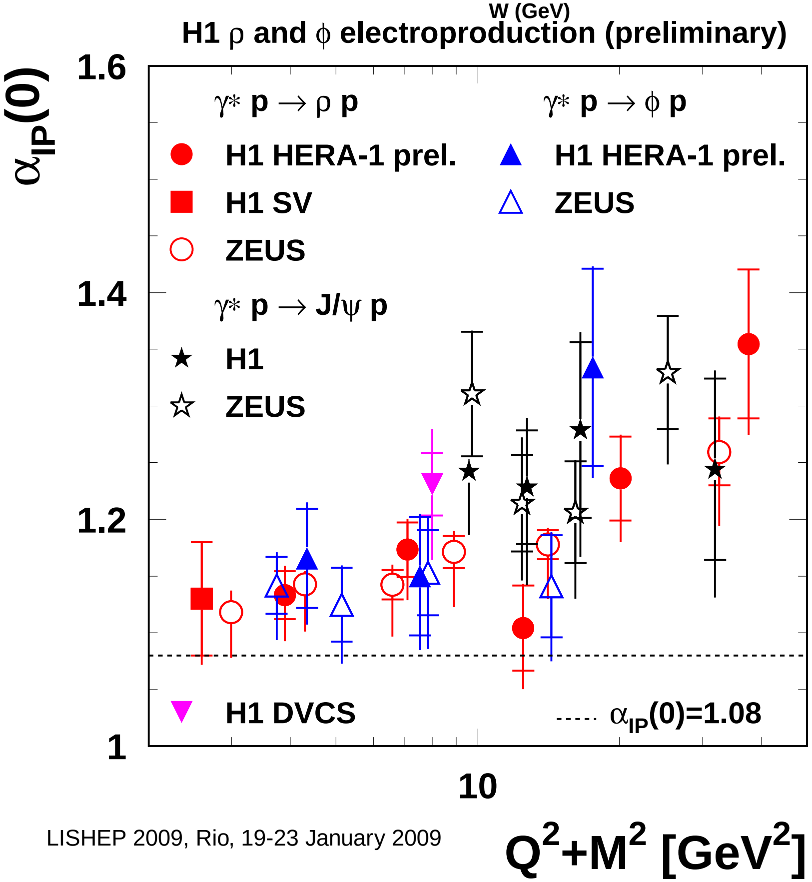
- First ϕ p-diss. cross-section
- p.diss/el: no Q^2 dep.
  i.e. vertex factorisation

Soft to hard transition: Q^2









$$\alpha_{\mathbb{P}}(0) = 1 + \delta/4 + \alpha'_{\mathbb{P}}/\langle|t|\rangle$$

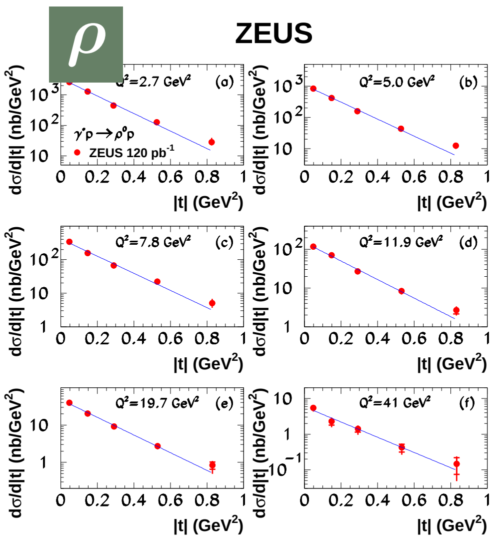
$$\alpha'_{\mathbb{P}} = 0 - 0.25\ \text{GeV}^{-2}$$

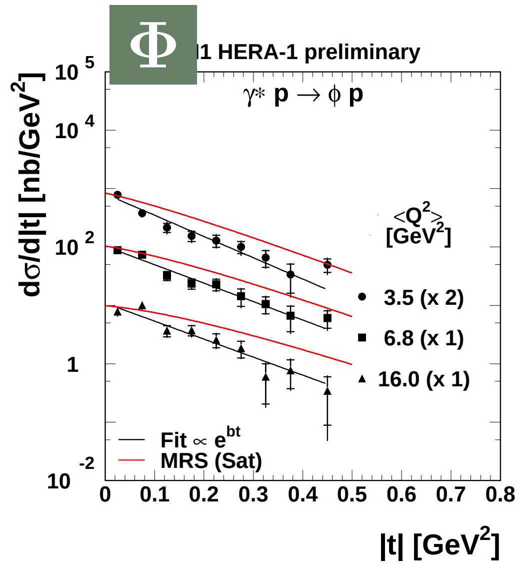
- Common hardening of $\alpha_{\mathbb{P}}(0)$ with $Q^2 + M^2$ for all VM and DVCS

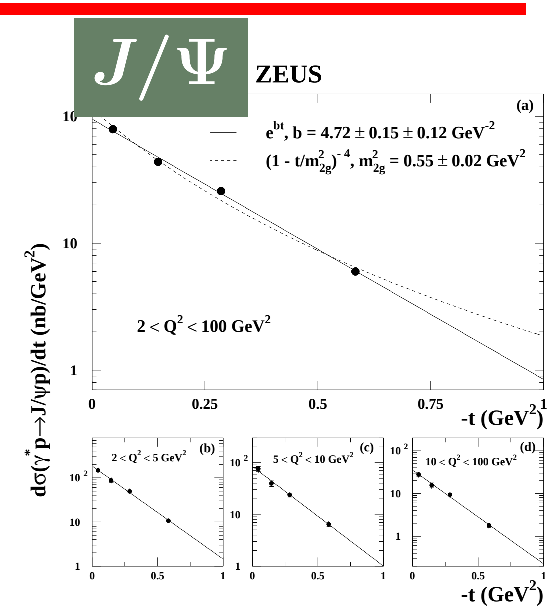
  $\Rightarrow$ Transition from soft to hard regime with $Q^2 + M^2$

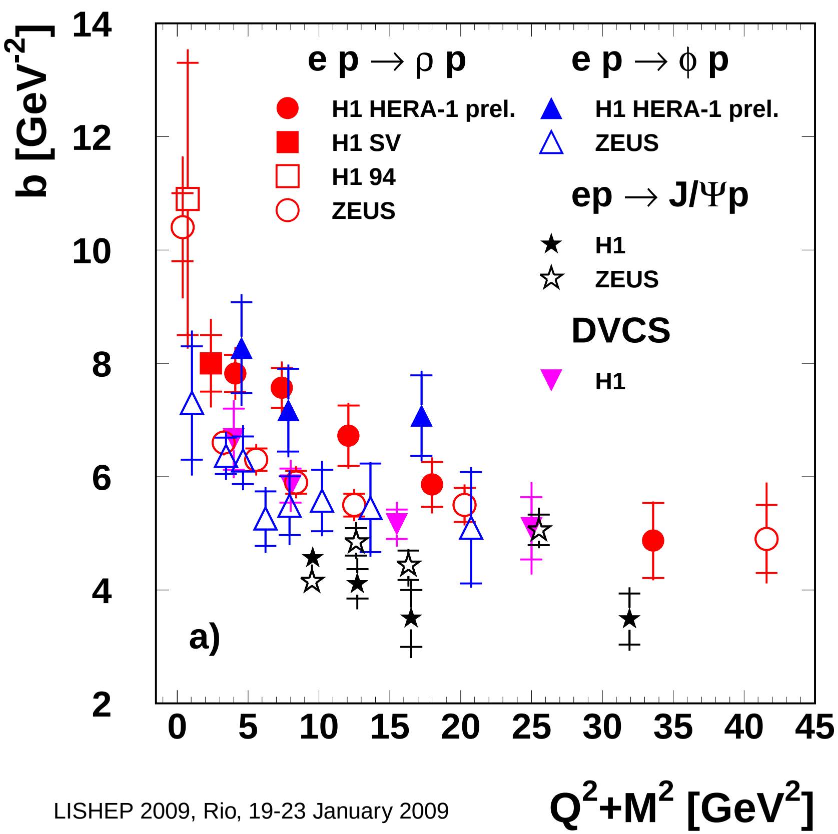
- Soft contributions (in σ_L ?) up to $Q^2 \sim 20$ GeV^2 for ρ and ϕ

t dependences: Universality and hard diffraction









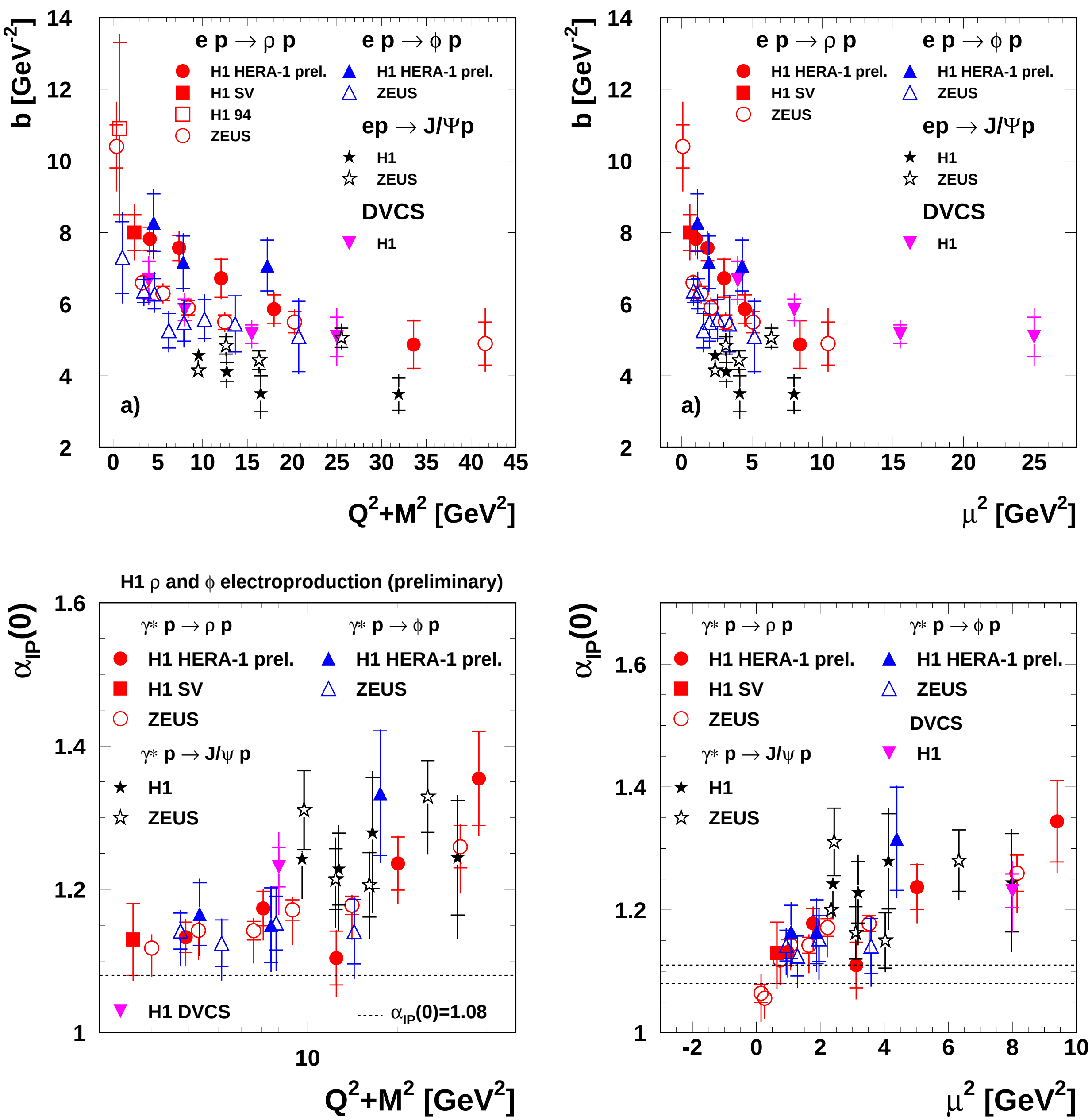
fit $e^{-b|t|}$: $b = b_p \otimes b_{q\bar{q}} \otimes b_{I\!P}$

$\longrightarrow$ $b \propto q\bar{q}$ dipole size

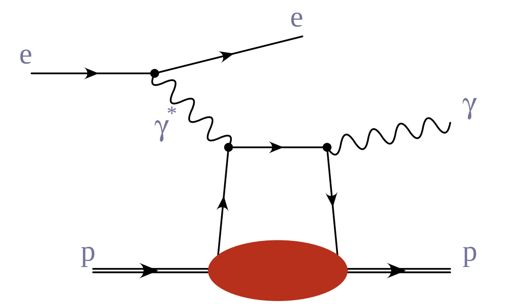
- b_ρ and b_ϕ decrease $Q^2 + M^2$
- Common value with J/ψ for $Q^2 + M^2 > 20$ GeV²
- Large dipole for light VM at low Q^2

$\Rightarrow$ Transition from soft to hard regime with $Q^2 + M^2$

Note on the scale and universality



DVCS is like DIS (at LO):



Photon interacts directly with a resolved quark

→ Hard scales are:

for DVCS: $\mu^2 = Q^2$

for VM: $\mu^2 = \frac{Q^2+M^2}{4}$

→ Universalality vs μ^2:

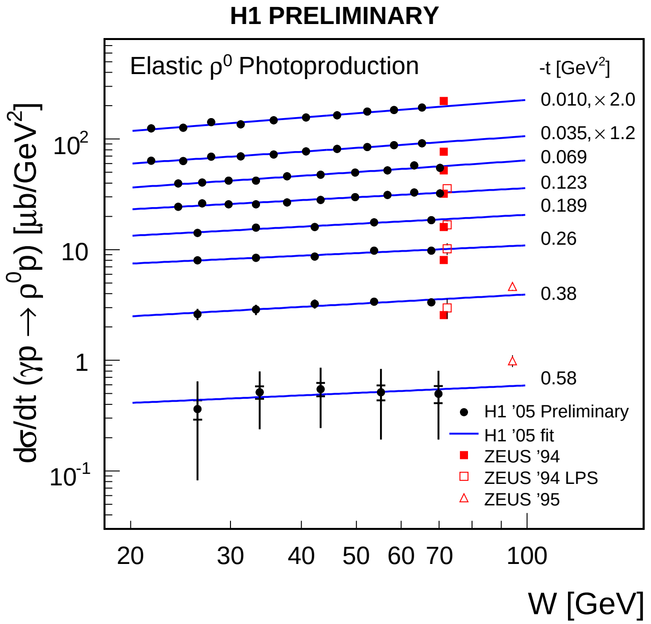
Soft/hard transition around $\mu^2 \sim 5\ \mathrm{GeV}^2$

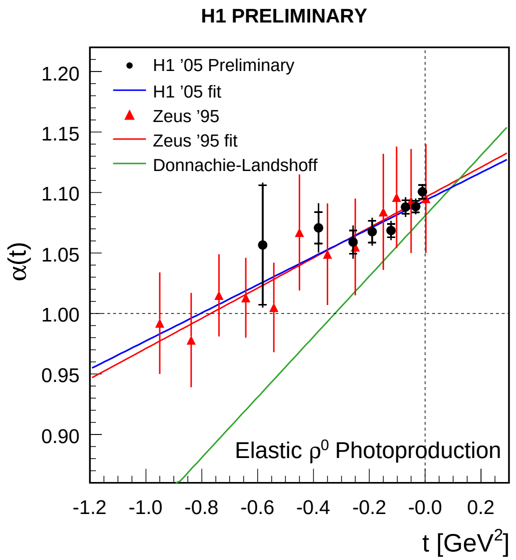
Shrinkage : $\alpha'_{I\!P}$ measurements

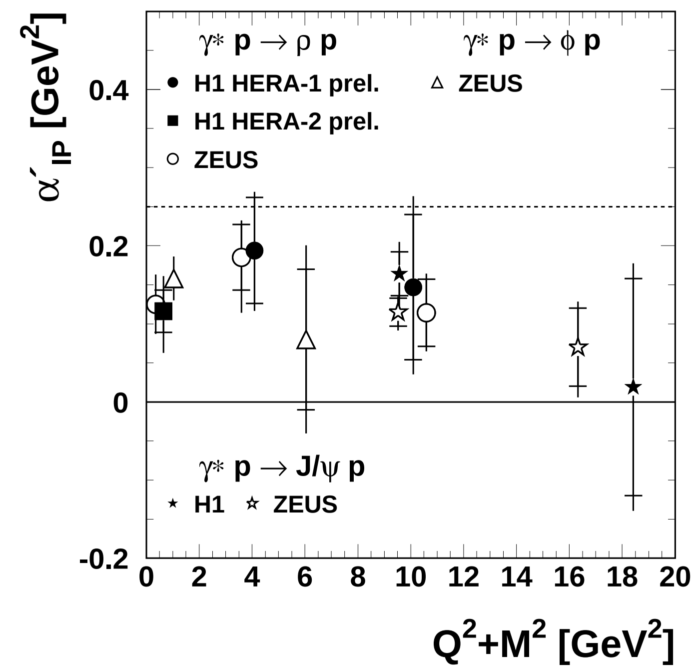
H1 ρ photoproduction measurements:

$$\frac{d\sigma}{dt}(W) \propto e^{b_0 t}\, W^{4(\alpha_{I\!P}(t)-1)}$$

1. Study W depend. in bins of t:
   $\rightarrow$ Fit: $W^{\delta} \rightarrow \alpha_{I\!P}(t) = 1 + \delta/4$
2. Study $\alpha_{I\!P}(t)$ trajectories:
   $\rightarrow$ Fit: $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} t$





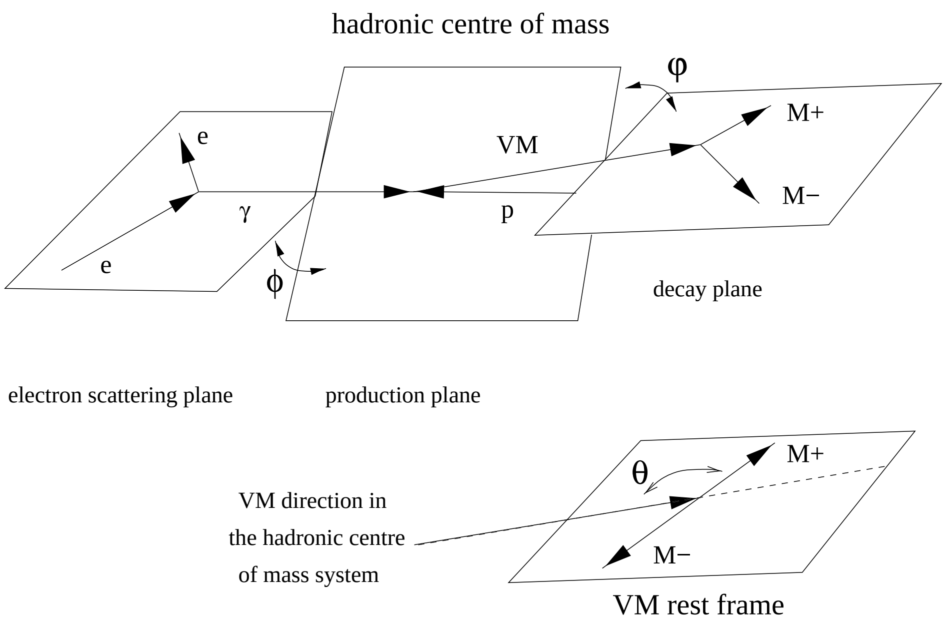


$\Rightarrow$ For all VM, $\alpha'_{I\!P}$ smaller than 0.25 (DL, $p\bar{p}$)
(cf BFKL, multiple $I\!P$ exchange)

SPIN DENSITY MATRIX ELEMENTS

θ^* , Φ , φ $\Longleftrightarrow$ 15 SDMEs : $r^{ij}_{kl} \propto T_{\lambda'_\rho \lambda'_\gamma} T_{\lambda_\rho \lambda_\gamma}$

$T_{\lambda_\rho \lambda_\gamma}$: helicity amplitudes



No helicity flip: $T_{00} : \gamma_L \longrightarrow \rho_L$

$T_{11} : \gamma_T \longrightarrow \rho_T$

Single flip: $T_{01} : \gamma_T \longrightarrow \rho_L$

$T_{10} : \gamma_L \longrightarrow \rho_T$

Double flip: $T_{1-1} : \gamma_T \longrightarrow \rho_T$

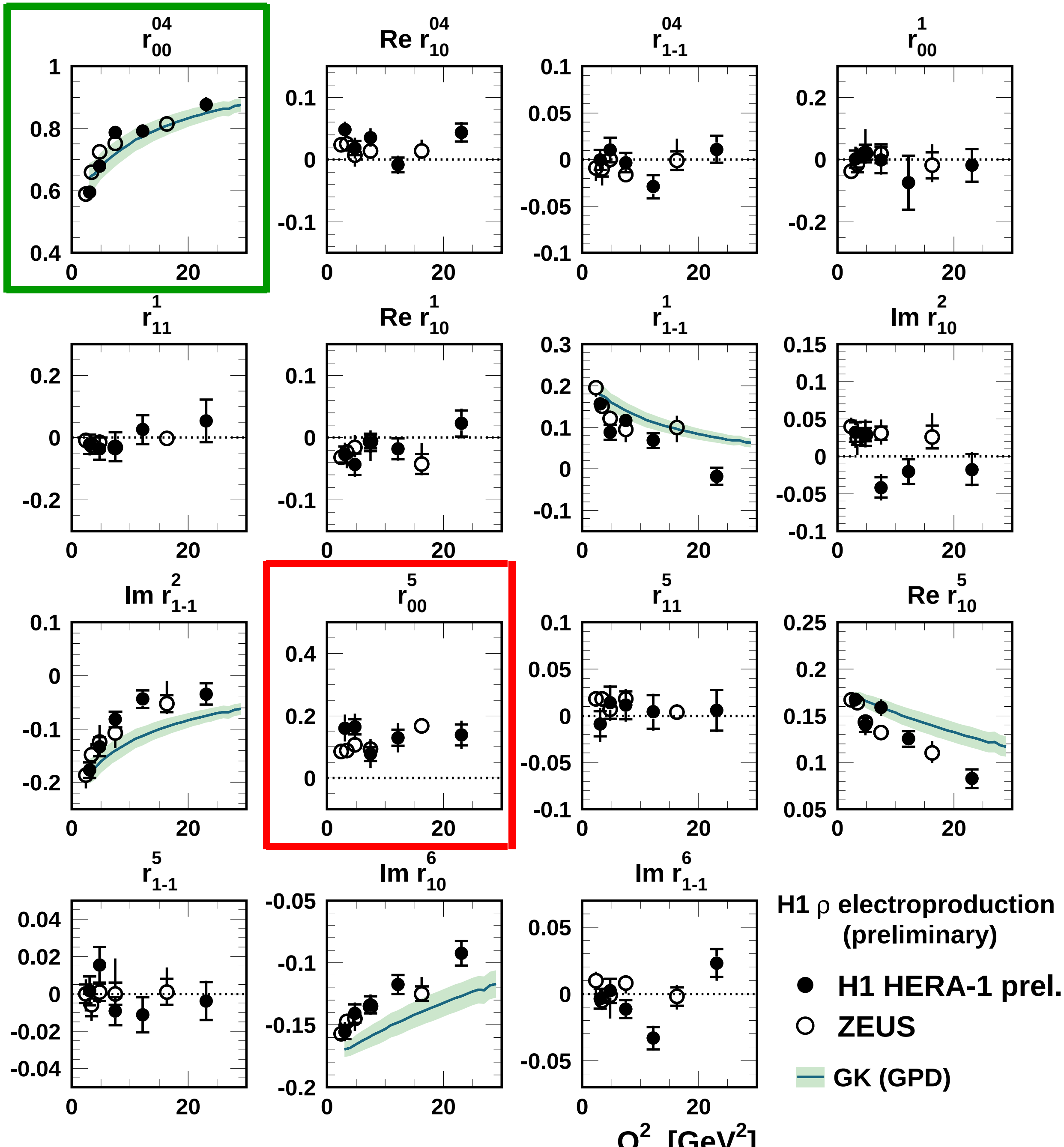
s-Channel Helicity Conservation (SCHC): $T_{01} = T_{10} = T_{1-1} = 0$

pQCD models:

D. Yu Ivanov and R. Kirschner [hep-ph/9807324]

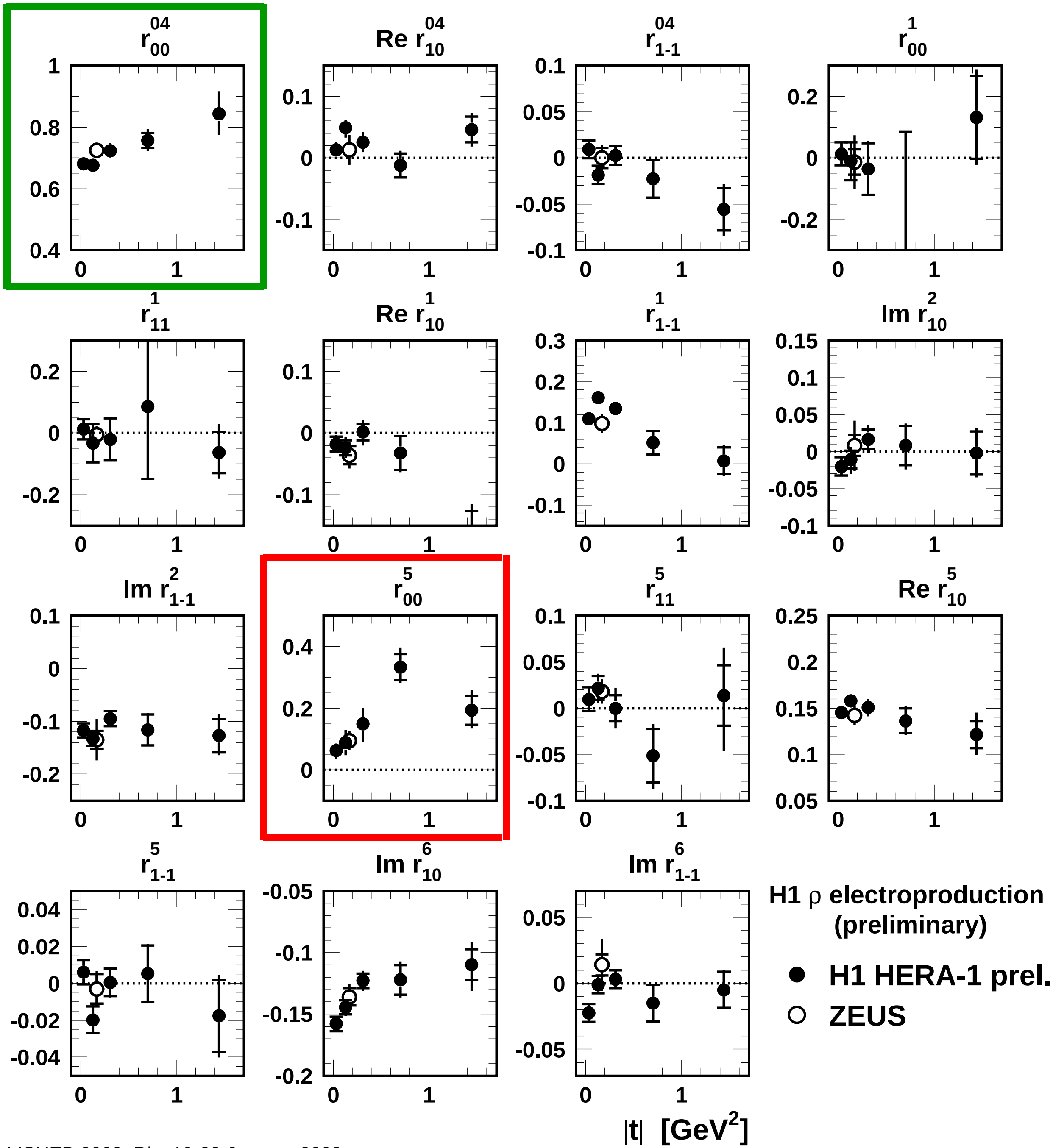
- SCHC violation (single flip $\propto \sqrt{|t|}$, double $\propto |t|$)
- Hierarchy: $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

ρ Polarisation - SDMEs vs. Q^2



- r^{04}_{00} increases with Q^2
  $\leftrightarrow$ similar effects for r^1_{1-1}, Im r^2_{1-1}, Re r^5_{10} and Im r^6_{10} (in SCHC)
  $\leftrightarrow$ Fair description by GK (GPD) model
- r^5_{00} violates SCHC
- Other SDME $\simeq 0$

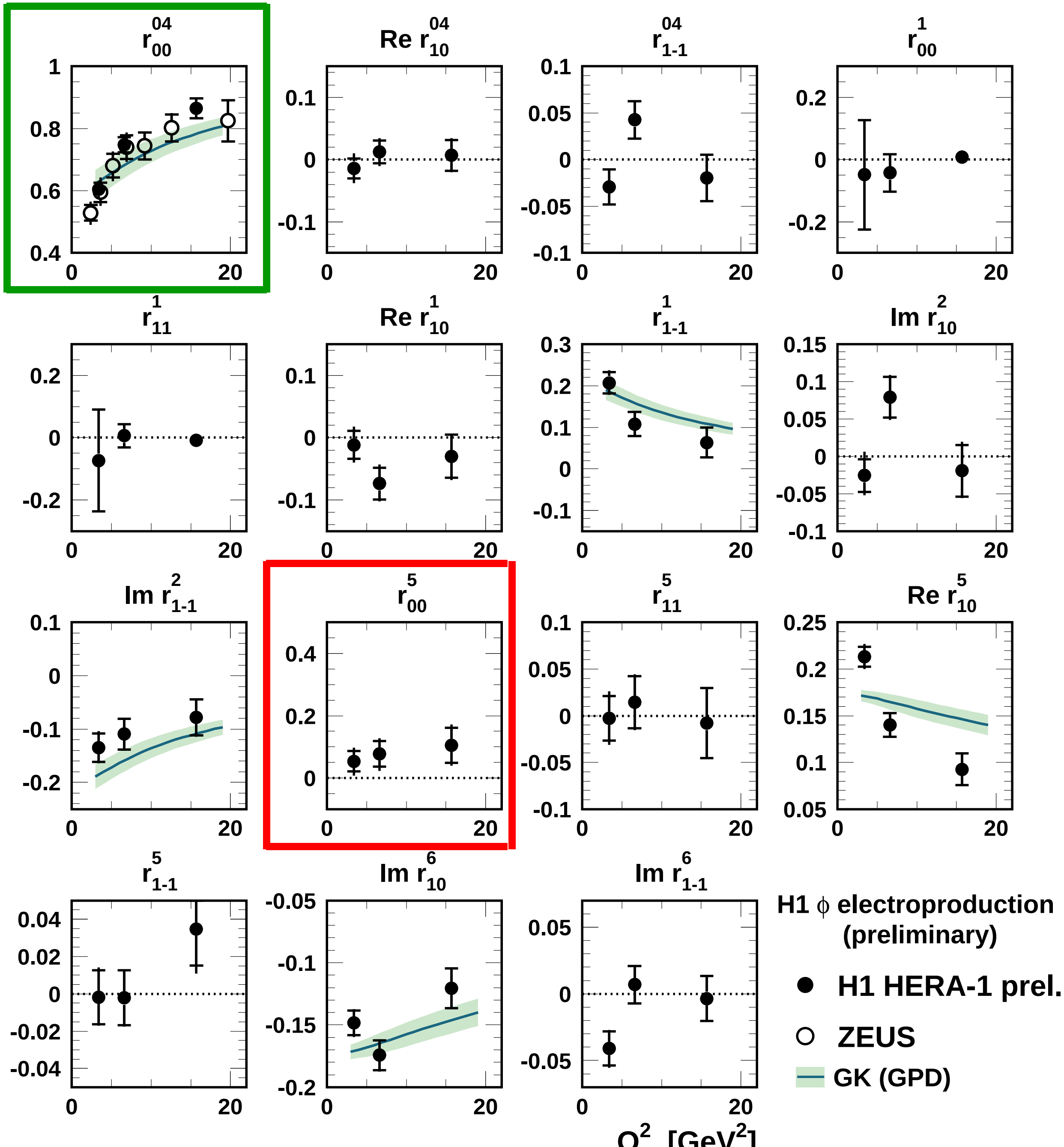
ρ Polarisation - SDMEs vs. $|t|$



- r^5_{00} increases with $|t|$
  $\leftrightarrow$ SCHC violation increases with $|t|$

- r^{04}_{00} increases with $|t|$
  $\leftrightarrow$ similar effects for r^1_{1-1}, Im r^2_{1-1}, Re r^5_{10} and Im r^6_{10} (in SCHC)

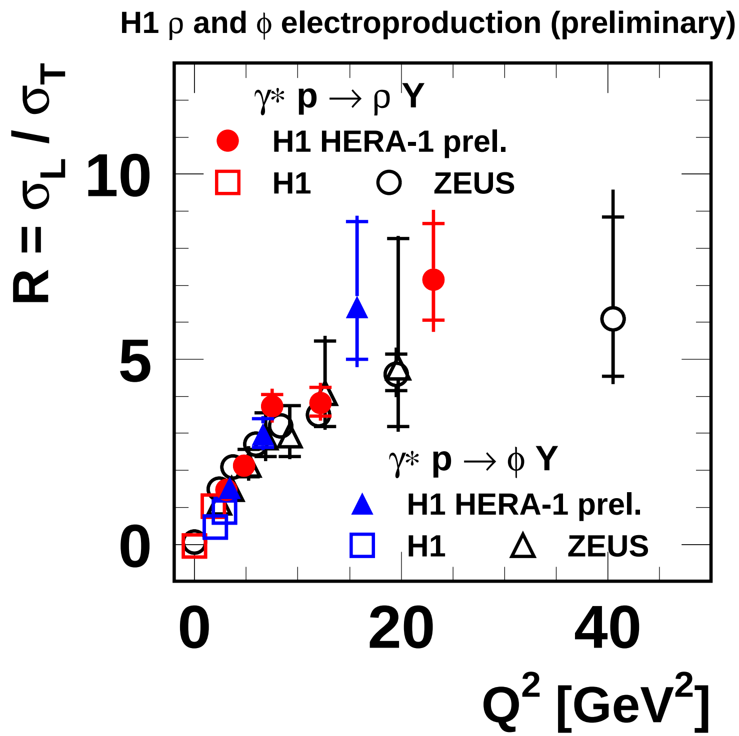
ϕ Polarisation - SDMEs vs. Q^2

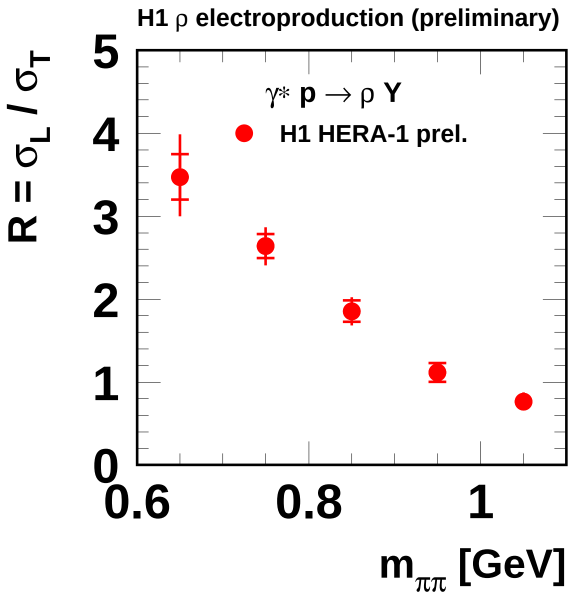


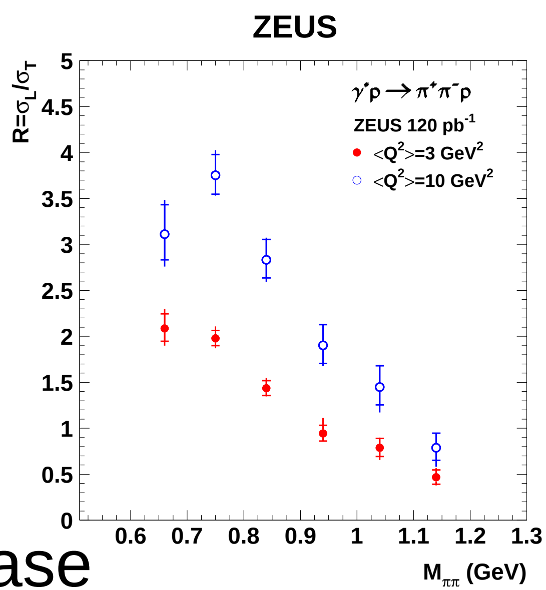
- r^{04}_{00} increases with Q^2
  $\leftrightarrow$ Fair description by GK (GPD) model
- r^{5}_{00} violates SCHC
  But larger error than for ρ
- Other SDME $\simeq 0$

ρ and ϕ Polarisation - $R = \sigma_L/\sigma_T$

$$R_{SCHC} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-\epsilon r^{04}_{00}} = \frac{|T_{00}|^2}{|T_{11}|^2}$$

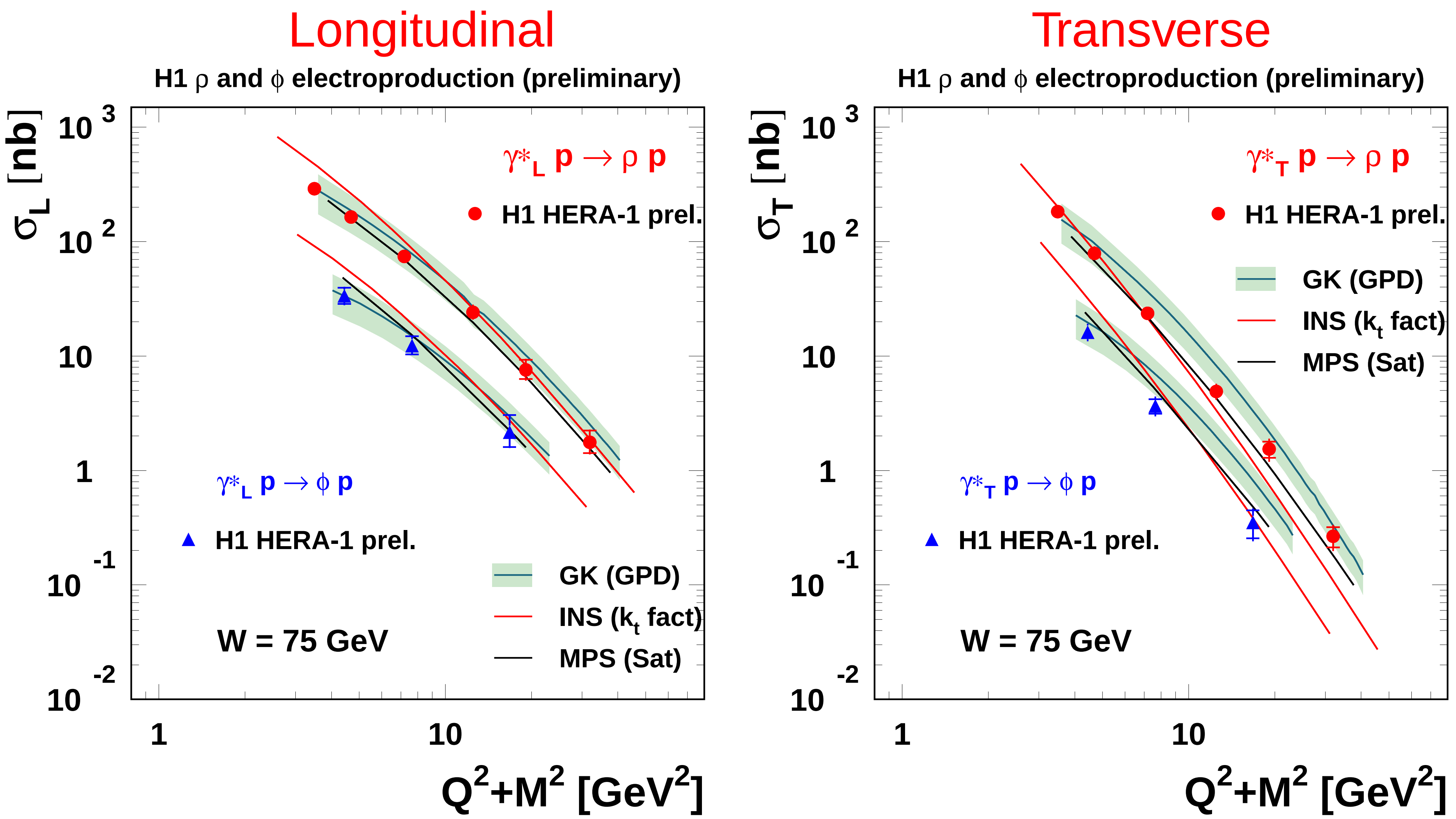






- Naive $R \propto Q^2/M^2$ - modified at high Q^2
- Similar R for ϕ and ρ
- Strong invariant mass dependence in ρ case

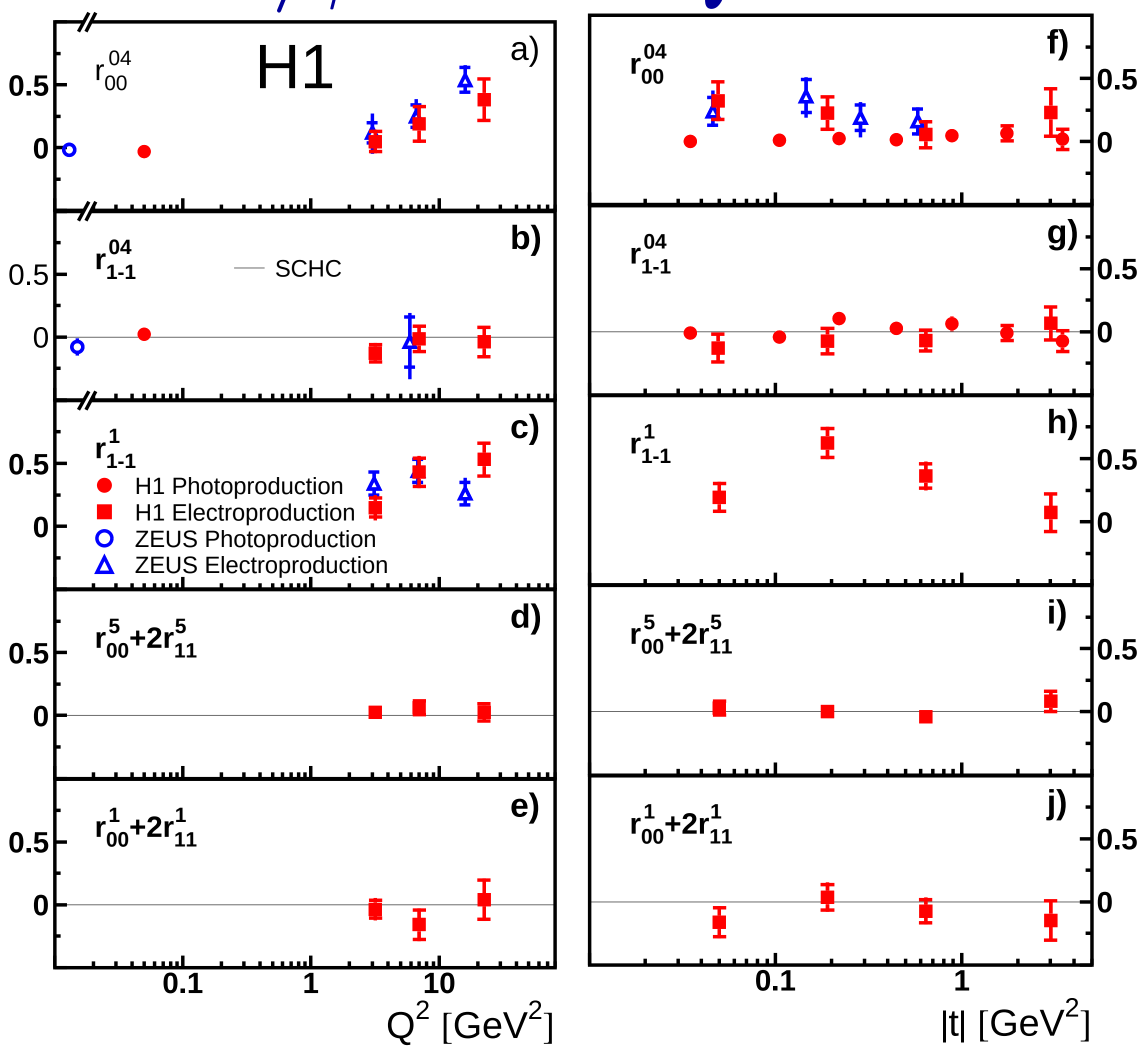
ρ and ϕ Polarisation - Cross-sections

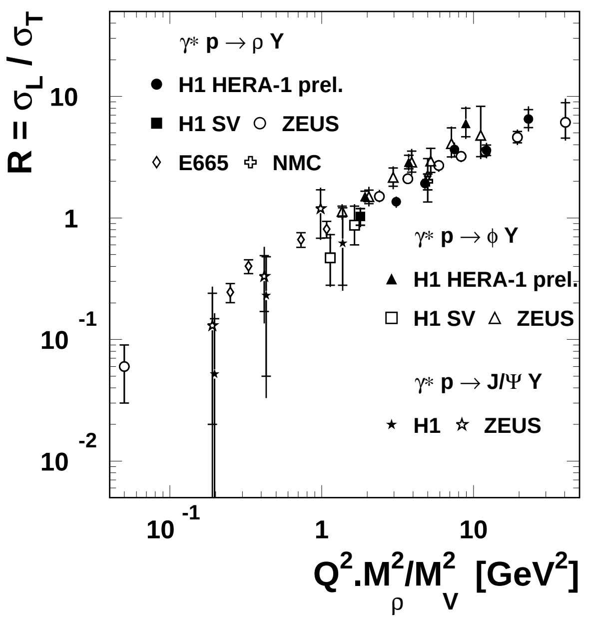


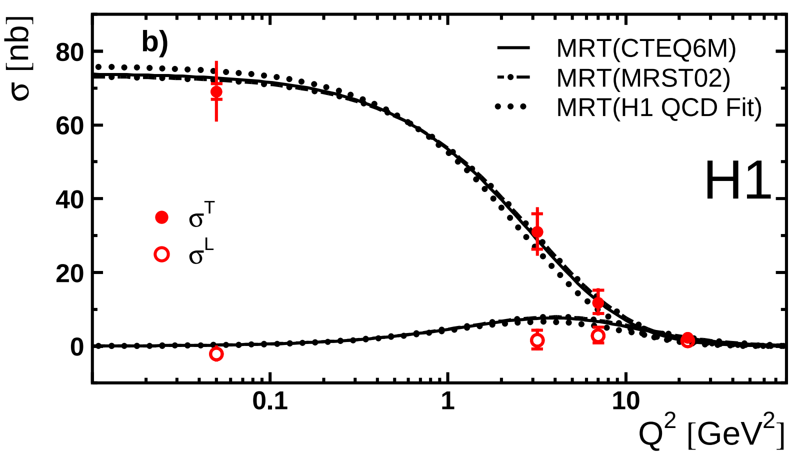
- Different $Q^2 + M^2$ dependences of σ_L and σ_T ($\sigma_L = 0$ at Q^2= 0)
- Best description of σ_L by GK (GPD) model; σ_T not described

J/ψ Polarisation

J/ψ SDME vs Q^2 and t:







- J/ψ SDME compatible with SCHC: non-relativistic WF
- Common behaviour of R for all VM vs. $Q^2 M_\rho^2 / M_{VM}^2$
- J/ψ mostly transverse

Polarisation - Retrieving Amplitude ratios

Assume purely imaginary amplitudes $\longrightarrow$ phase = $\pm$ 1 !

$\longrightarrow$ Extract $|T_{11}|/|T_{00}|$, $|T_{01}|/|T_{00}|$, $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ from fit to the 15 SDMEs:

$$
\begin{aligned}
r^{04}_{00} &= B\,(\varepsilon + \beta^2) \\
\mathrm{Re}\, r^{04}_{10} &= B/2\,(2\varepsilon\delta + \beta\alpha - \beta\eta) \\
r^{04}_{1-1} &= B\,(\alpha\eta - \varepsilon\delta^2) \\
r^{1}_{00} &= -B\,\beta^2 \\
r^{1}_{11} &= B\,\alpha\eta \\
\mathrm{Re}\, r^{1}_{10} &= B/2\,\beta(\eta - \alpha) \\
r^{1}_{1-1} &= B/2\,(\alpha^2 + \eta^2) \\
\mathrm{Im}\, r^{2}_{10} &= B/2\,\beta(\alpha + \eta) \\
\mathrm{Im}\, r^{2}_{1-1} &= B/2\,(\eta^2 - \alpha^2) \\
r^{5}_{00} &= \sqrt{2}B\,\beta \\
r^{5}_{11} &= B/\sqrt{2}\,\delta(\alpha - \eta) \\
\mathrm{Re}\, r^{5}_{10} &= B/(2\sqrt{2})\,(2\beta\delta + \alpha - \eta) \\
r^{5}_{1-1} &= B/\sqrt{2}\,\delta(\eta - \alpha) \\
\mathrm{Im}\, r^{6}_{10} &= -B/(2\sqrt{2})\,(\alpha + \eta) \\
\mathrm{Im}\, r^{6}_{1-1} &= B/\sqrt{2}\,\delta(\alpha + \eta)
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= |T_{11}|/|T_{00}| \\
\beta &= |T_{01}|/|T_{00}| \\
\delta &= |T_{10}|/|T_{00}| \\
\eta &= |T_{-11}|/|T_{00}|
\end{aligned}
$$

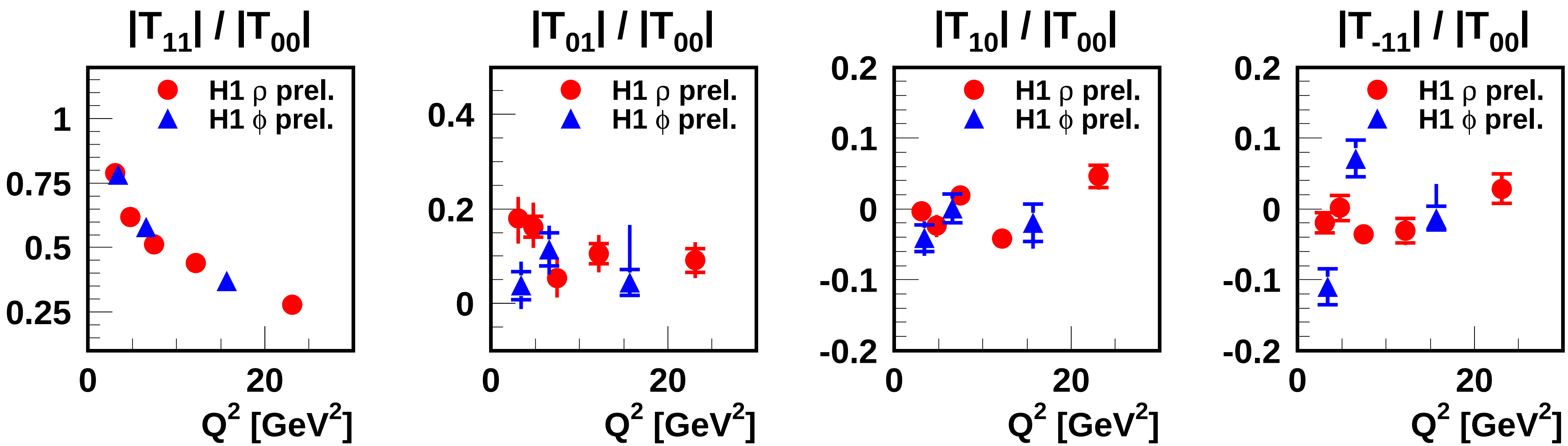
$$
\begin{aligned}
B &= \frac{1}{N_T + \varepsilon N_L} = \frac{R}{1+\varepsilon R} \\
N_T &= \alpha^2 + \beta^2 + \eta^2 \\
N_L &= 1 + 2\delta^2
\end{aligned}
$$

Polarisation - Amplitude ratios vs. Q^2

pQCD (IK):

- $T_{11}/T_{00} \propto \frac{M}{Q} \frac{1+\gamma}{\gamma}$
- $T_{10}/T_{00} \propto -\frac{M\sqrt{|t|}}{Q^2} \frac{\sqrt{2}}{\gamma}$
- $T_{01}/T_{00} \propto \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$

γ : gluon anomalous dim.



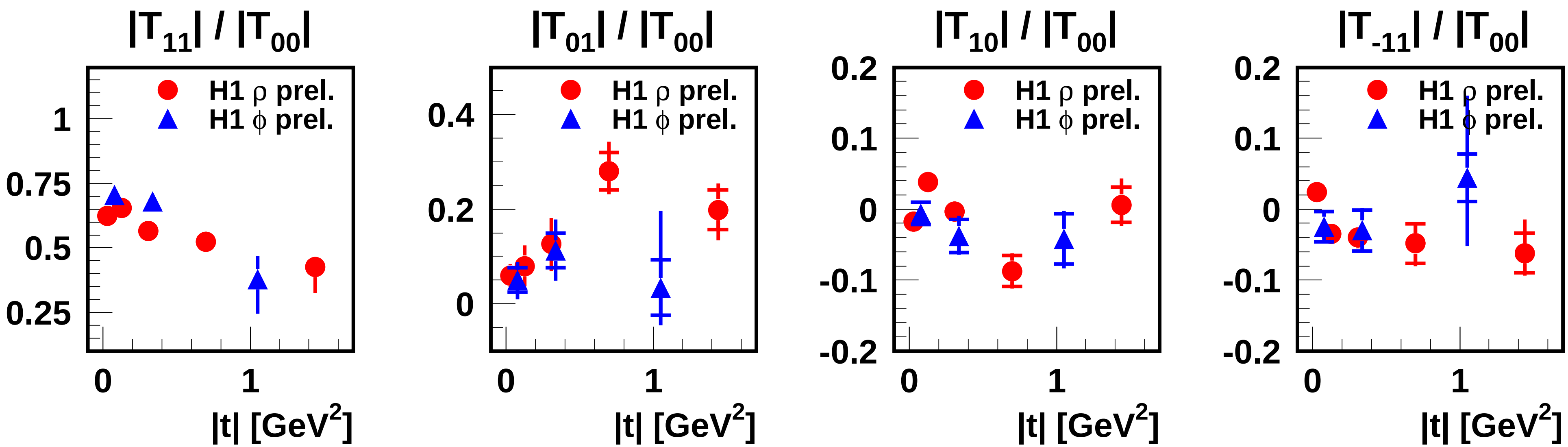
- T_{11}/T_{00} decreases with $Q^2 \leftrightarrow \sigma_L/\sigma_T$ increases with Q^2
- $T_{01}/T_{00} > 0 \leftrightarrow$ SCHC violation
- T_{10}/T_{00} and T_{-11}/T_{00} are small

$\Rightarrow |T_{00}| > |T_{11}| > |T_{01}| > |T_{10}|, |T_{-11}| \leftrightarrow$ hierarchy observed

Polarisation - *Amplitude ratios vs.* $|t|$

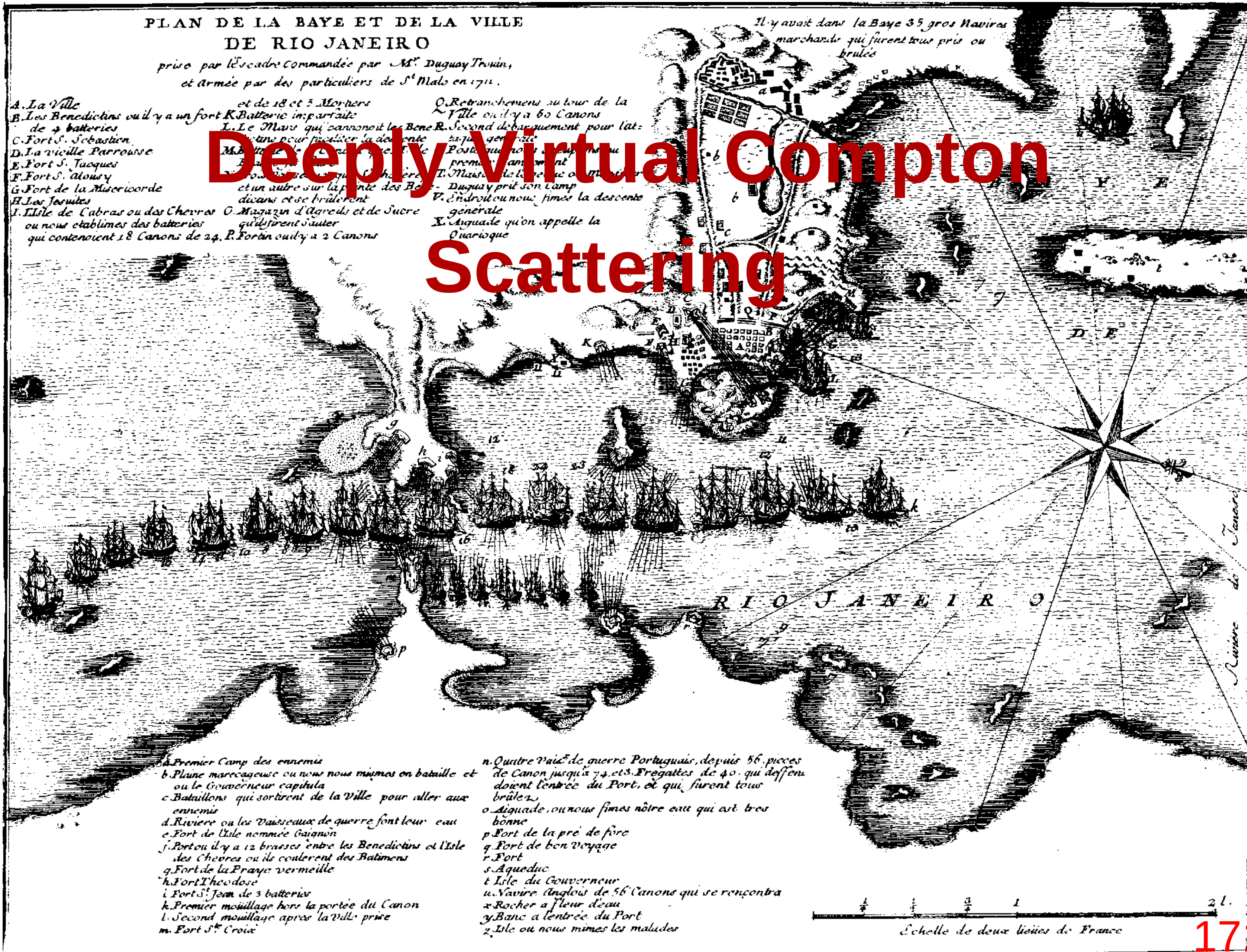
pQCD (IK): • $T_{11}/T_{00} \propto \frac{M}{Q}\,\frac{1+\gamma}{\gamma}$ • $T_{10}/T_{00} \propto -\frac{M\,\sqrt{|t|}}{Q^2}\,\frac{\sqrt{2}}{\gamma}$

• $T_{01}/T_{00} \propto \frac{\sqrt{|t|}}{Q}\,\frac{1}{\sqrt{2}\gamma}$ γ : gluon anomalous dim.



- T_{11}/T_{00} decreases with $|t|$
- T_{01}/T_{00} increases with $|t| \leftrightarrow$ SCHC violation increases with $|t|$
- T_{10}/T_{00} and T_{-11}/T_{00} are small but some $|t|$dependence
- T_{11}/T_{00} decrease compensated by T_{01}/T_{00} increase

Deeply Virtual Compton Scattering



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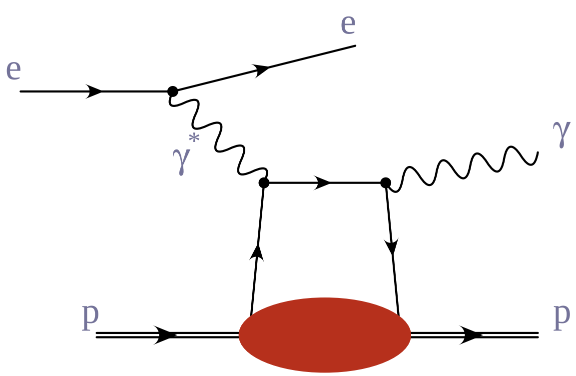
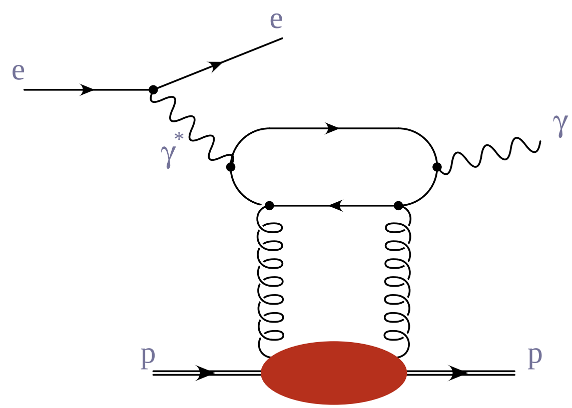
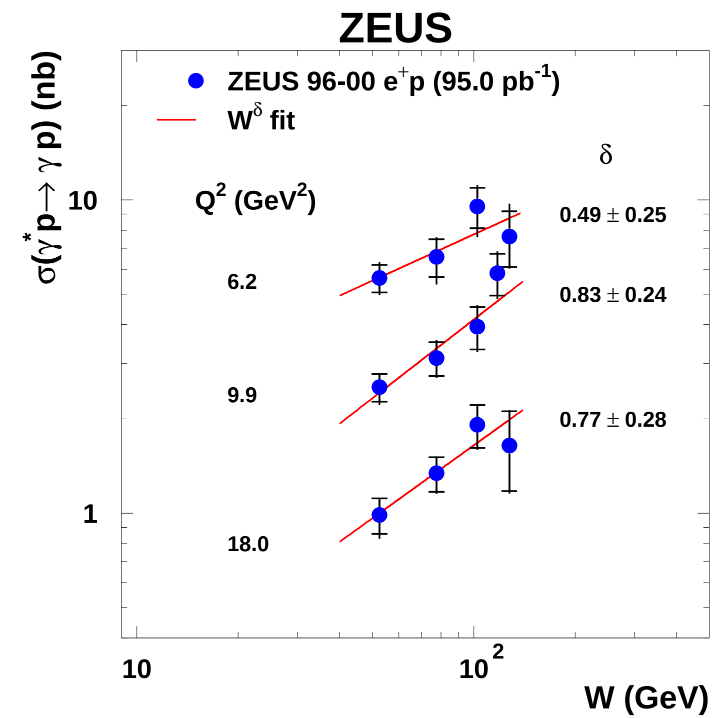
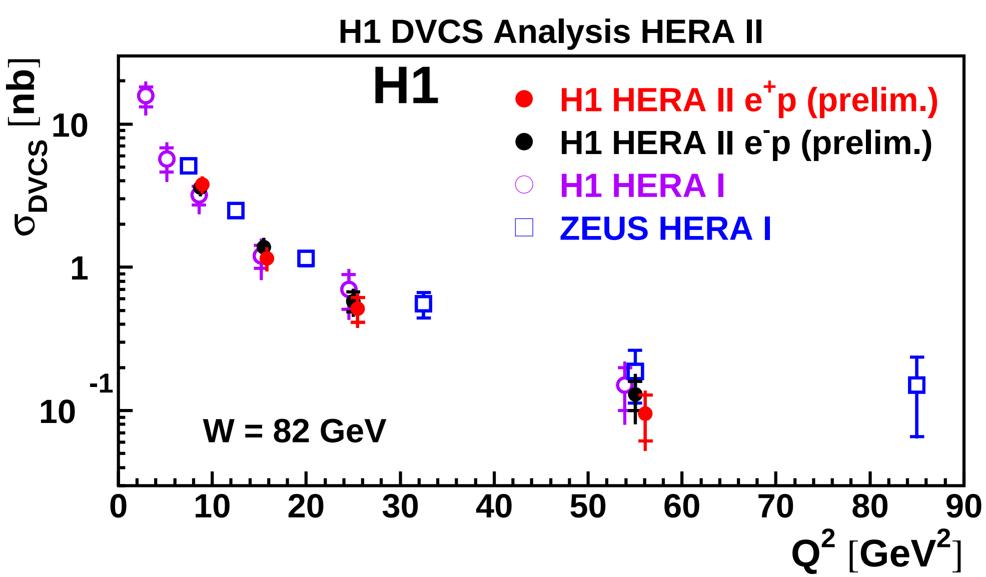
Deep Virtual Compton Scattering

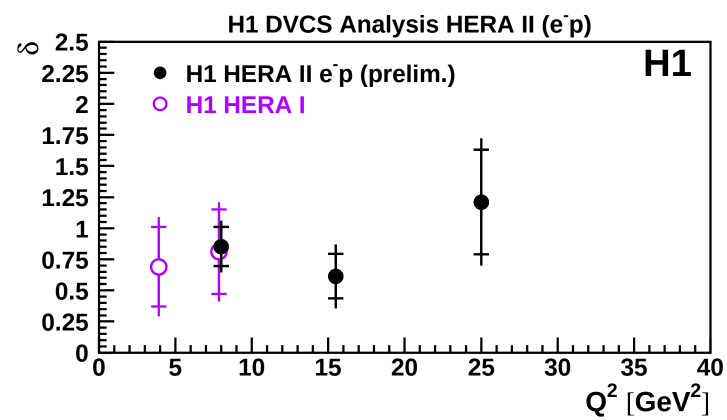






- fully calculable in pQCD
- Access to the full QCD amplitude
- Constrain gluon GPDs





W dependence indicates a hard regime (similar to J/Ψ)

DVCS: t *slope and Beam Charge Asymmetry*

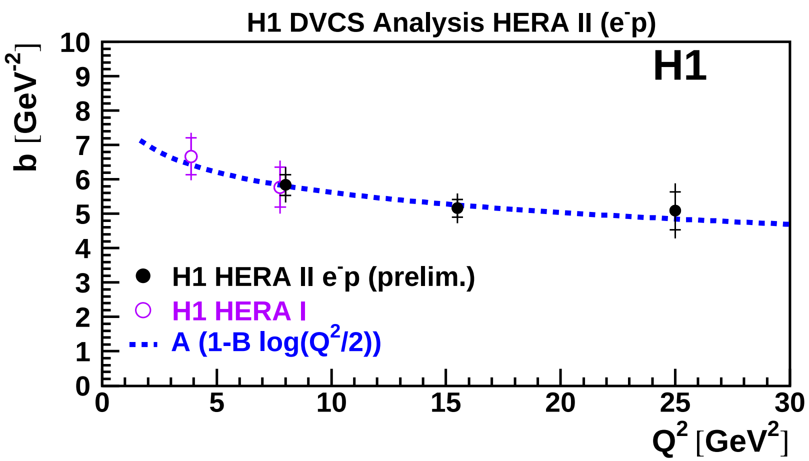
H1 measurement based on 291 pb^{-1} of HERA II data (e^+ and e^-).

• t slope as a function of Q^2

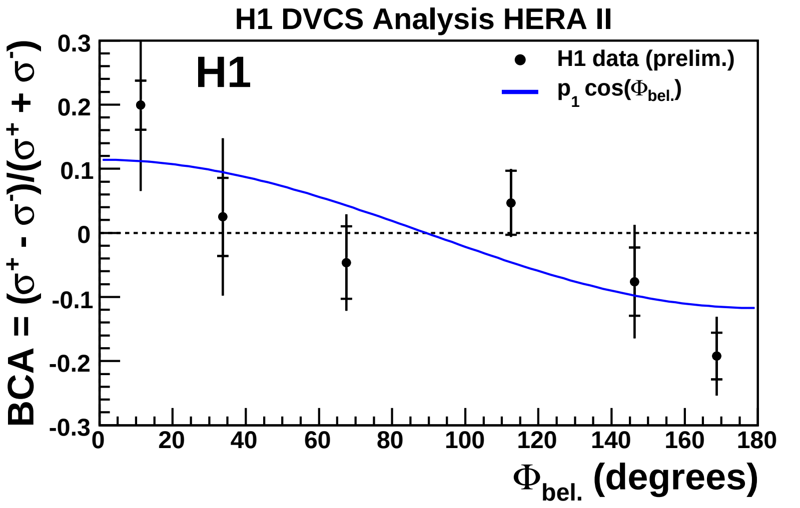
$$b(Q^2) = A\,(1 - B\log(Q^2/2))$$

A and B fitted to:
$A = 6.98 \pm 0.54$ GeV^{-2}
$B = 0.12 \pm 0.03$.

$\Rightarrow$ Similar behaviour with VM using the scale $Q^2 + M^2_{VM}$



• First DVCS BCA measured at HERA.



$$BCA \equiv \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} \sim p_1 cos(\Phi)$$

DVCS: QCD interpretation

- correct Q^2 dependence of the propagator and of b in the cross section:

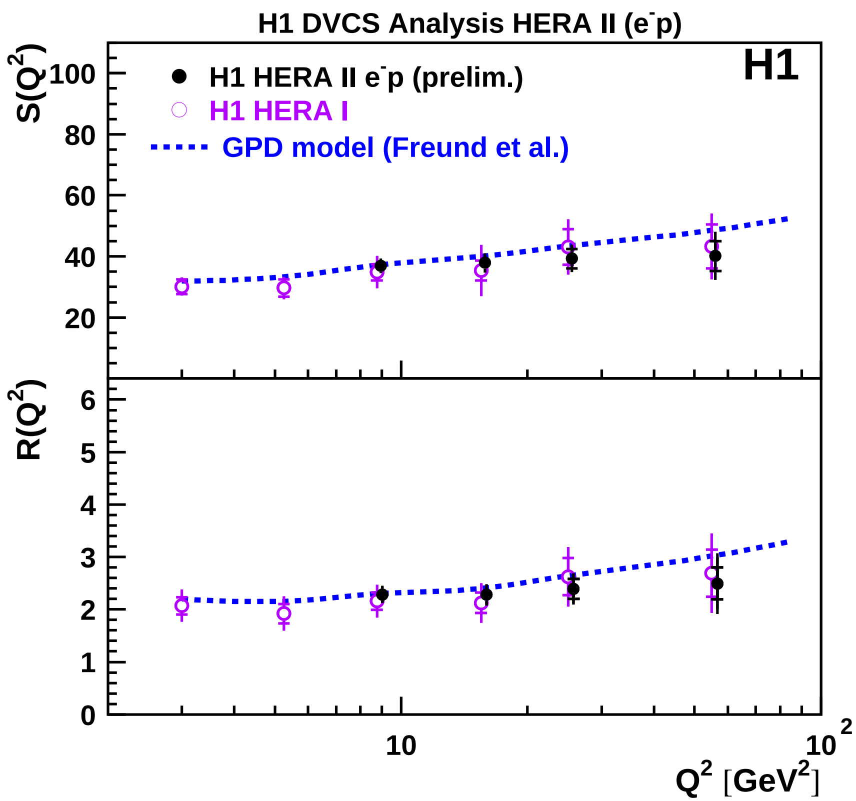
$$S = \sqrt{\frac{\sigma_{DVCS}\, Q^4\, b(Q^2)}{(1+\rho^2)}}$$

- skewing factor: around 2

$$R = \frac{\mathcal{I}m\; A(\gamma^* p \rightarrow \gamma p)}{\mathcal{I}m\; A(\gamma^* p \rightarrow \gamma^* p)}$$

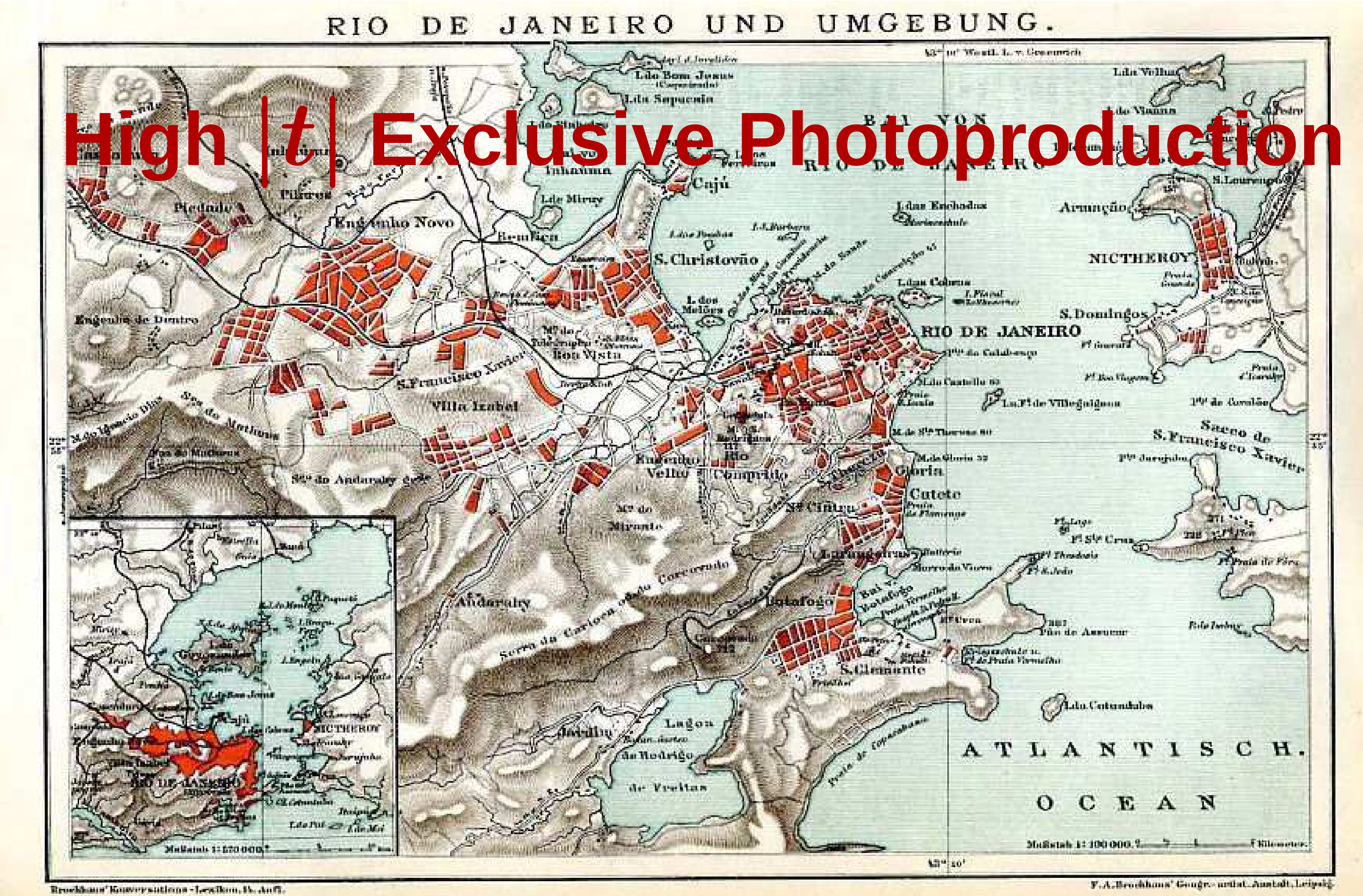
$$= \frac{4\sqrt{\pi\, \sigma_{DVCS}\, b(Q^2)}}{\sigma_T(\gamma^* p \rightarrow X)\sqrt{(1+\rho^2)}}$$

$\Rightarrow$ important skewing factor



$\Rightarrow$ Q^2 evolution close to the one of DIS (pure DGLAP)

High $|t|$ Exclusive Photoproduction



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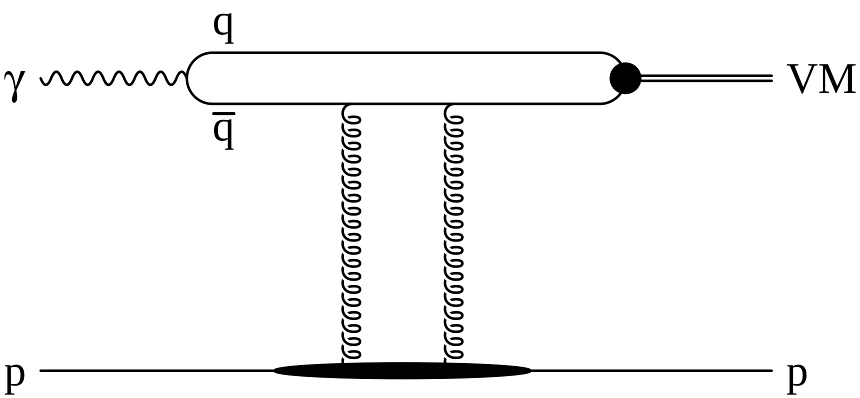
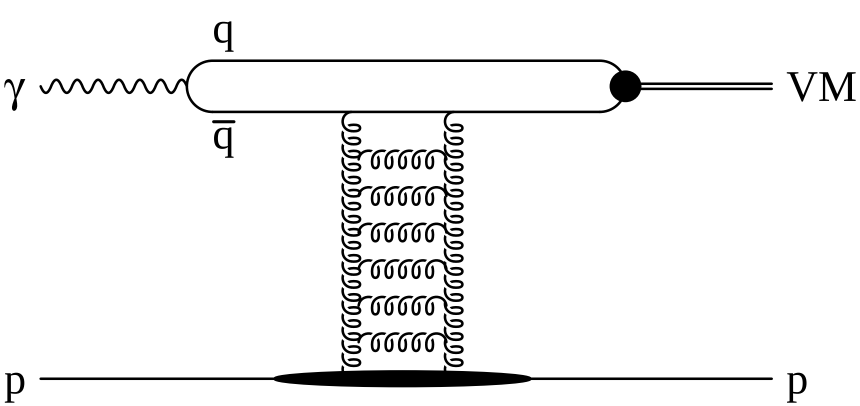
High $|t|$ Exclusive Photoproduction: ***Introduction***

LO: 2 gluon exchange



LLA: Gluon ladder



DGLAP Evolution ($|t| < M^2_{VM}$):

Strong k_T ordering along ladder

$\longrightarrow \mathrm{d}\sigma/\mathrm{dt} \sim \mathrm{e}^{\mathrm{bt}}$

$\longrightarrow$ No increase of $\mathrm{d}\sigma/\mathrm{dt}$ with W

BFKL Evolution ($|t| > M^2_{VM}$):

- p_T fully transfered from p to $q\bar{q}$
- high $W \longrightarrow$ small x_{Bj}

No k_T ordering in ladder

$\longrightarrow \mathrm{d}\sigma/\mathrm{dt} \sim |\mathrm{t}|^{-\mathrm{n}}; n = 3 - 4$

$\longrightarrow$ Increase of $\mathrm{d}\sigma/\mathrm{dt}$ with W

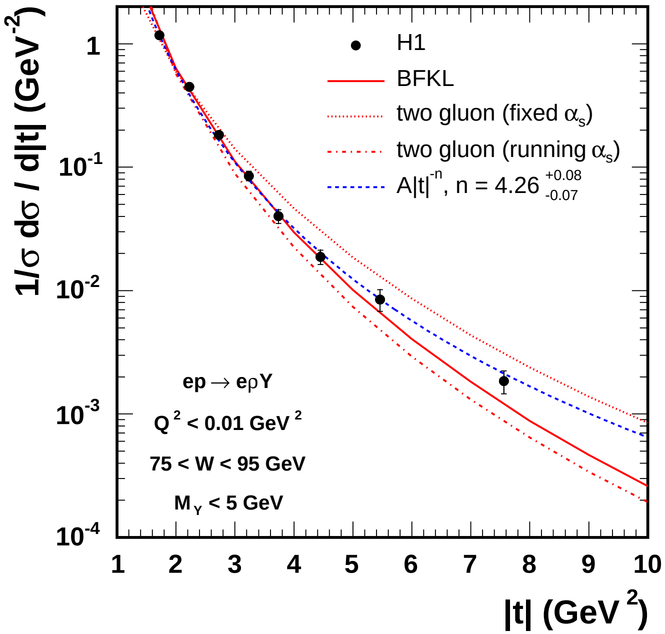
$\longrightarrow$ Little shrinkage

$\longrightarrow$ VM: SCHC expected

Models: Forshaw et al.

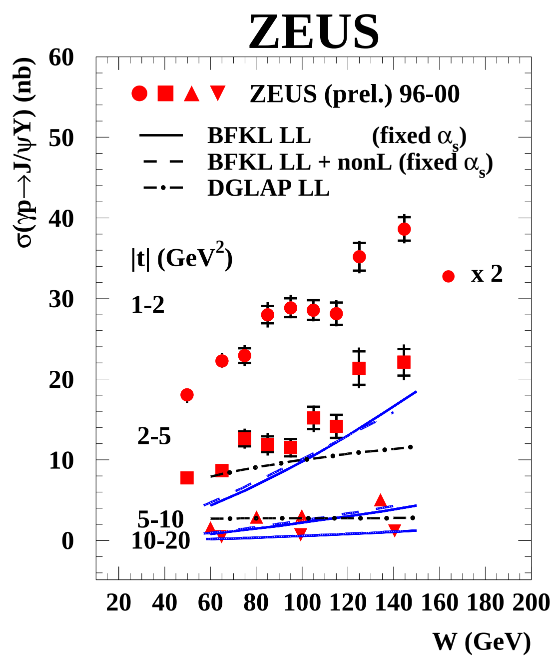
High $|t|$: Vector Meson Cross-Sections

ρ vs t



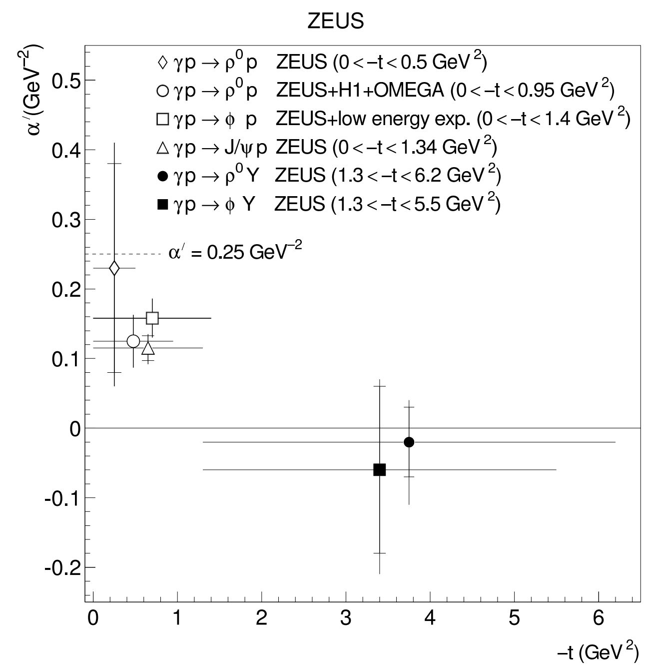
- Data follow $|t|^{-n}$
- BFKL decribes data
- 2-gluon (DGLAP-like) fails

J/ψ vs W



- Hardening of W depend. with $|t|$
- BFKL reproduces rise with W
- DGLAP fails at high $|t|$

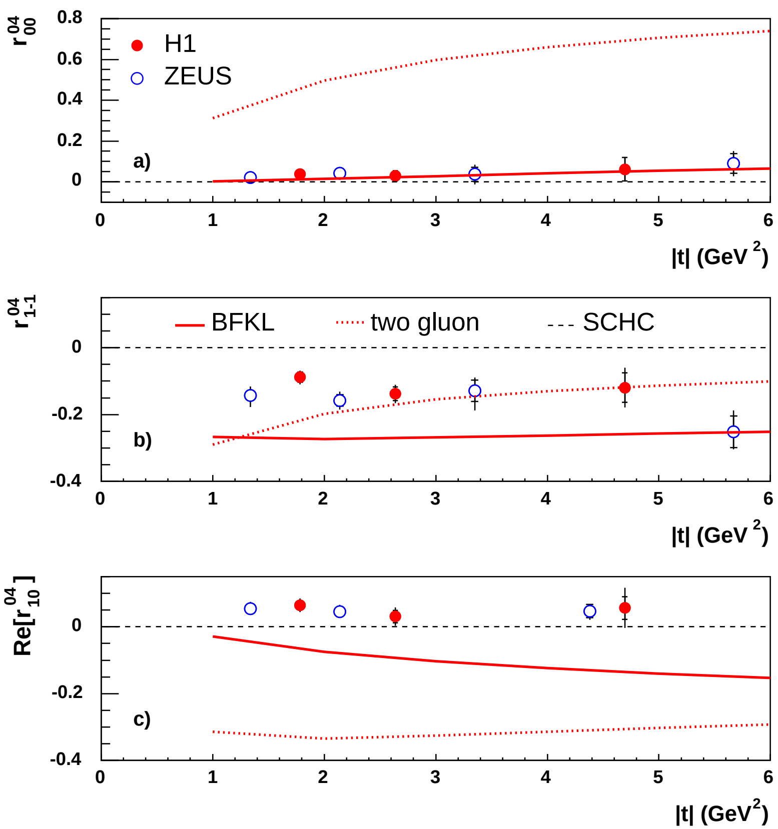
α' vs t



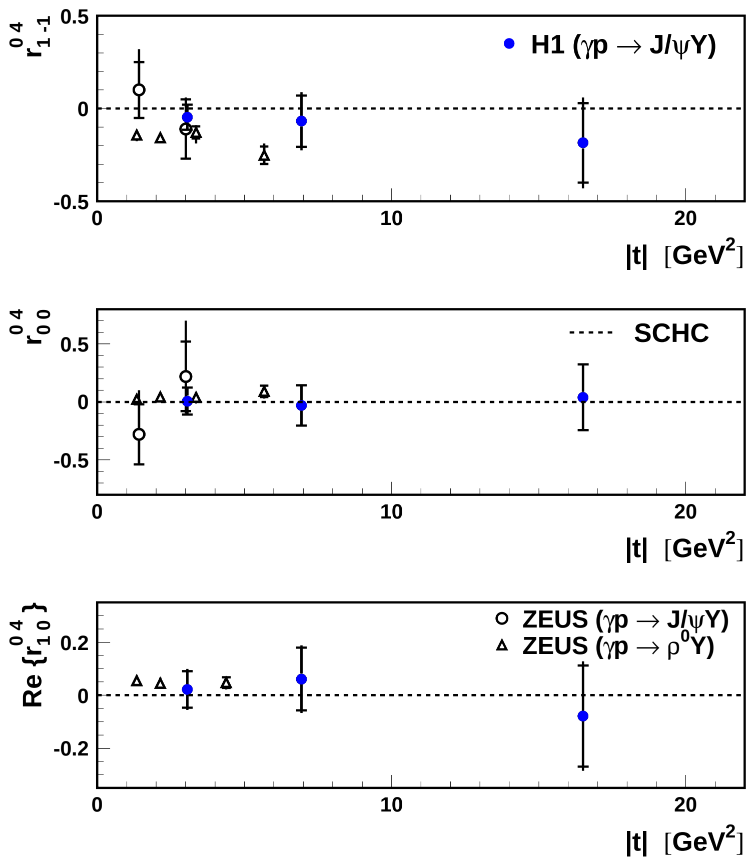
- α' decreases with $|t|$
- No shrinkage as expected for BFKL

High |t|: Vector Meson Polarisation

ρ



J/ψ



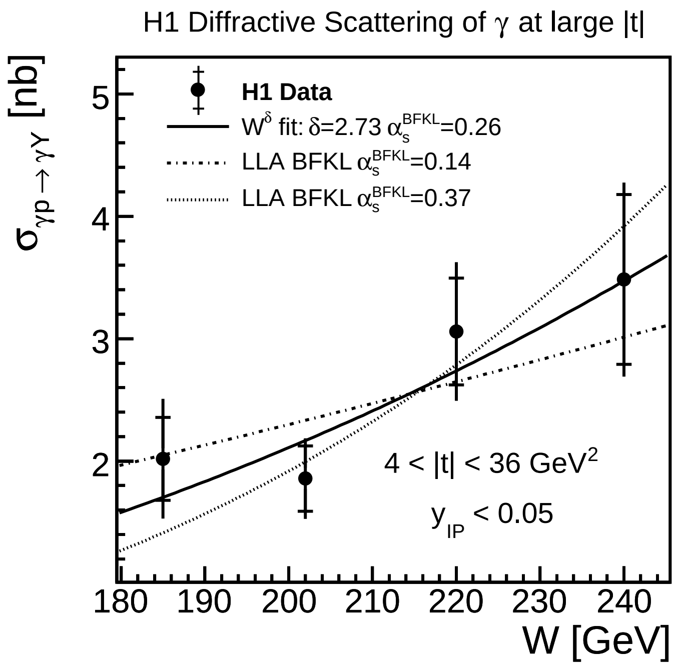
- ρ data: SCHC violation for r^{04}_{1-1} and Re$[r^{04}_{10}]$
- Two-gluon and BFKL models are unable to describes data

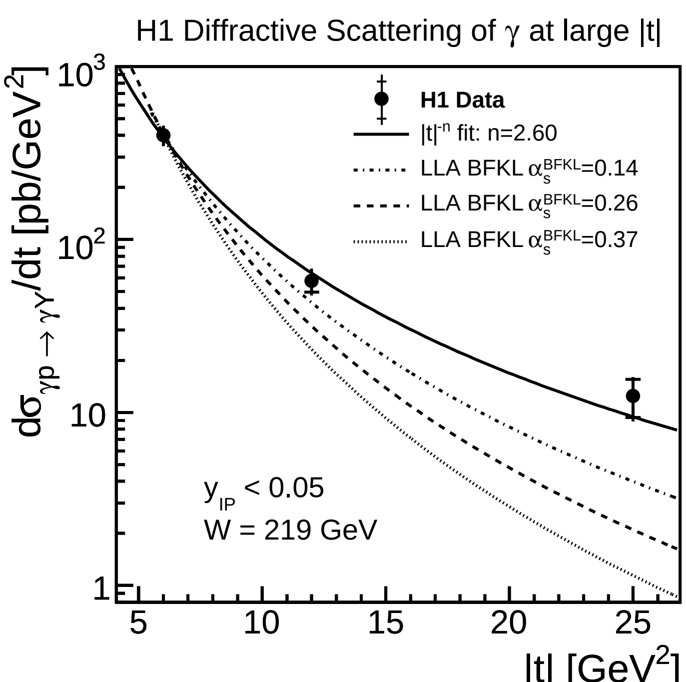
- J/ψ data: SCHC holds

$\longrightarrow$ non-relativistic WF is OK

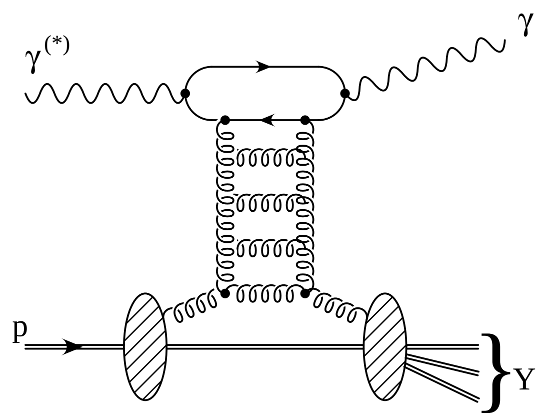
i.e. equal long. momemtum sharing between q and $\bar{q}$

High $|t|$: Diffractive High P_T Photons





First measurement of high P_T photons



H1 99-00 Data: 46 pb^{-1}

$Q^2 < 0.01\,\mathrm{GeV}^2$
$175 < W < 247\,\mathrm{GeV}$
$4 < |t| < 36\,\mathrm{GeV}^2$
$y_{I\!P} \simeq e^{-\Delta\eta} < 0.05$
$E_\gamma > 8GeV$

Strong W dependence:

- W^δ fit $\longrightarrow \delta = 2.73 \pm 1.02^{+0.56}_{-0.78}$

  $\rightarrow \alpha_s^{\mathrm{BFKL}} = 0.26 \pm 0.10^{+0.05}_{-0.07}$ <> $J/\psi : \alpha_s \sim 0.18$
- LLA BFKL (with $\alpha_s = 0.26$) prediction describe the W dependence

t dependence:

- $|t|^{-n}$ fit $\longrightarrow n = 2.60 \pm 0.19^{+0.03}_{-0.08}$
- LLA BFKL too steep for t dependence

CONCLUSIONS

Important progresses in precision of VM measurements and understanding of the underlaying dynamics for ρ, ϕ, J/ψ and Υ:

- Transition from soft to hard regime around $\mu^2 = \frac{Q^2+M^2}{4} = 5\ \mathrm{GeV}^2$.
  observed in measurements of $\alpha_{I\!P}(0)$ and b-slopes.
- Possible soft component in σ_L up to "high" Q^2 for light VM.
- Shrinkage: $\alpha'_{I\!P}$ smaller than 0.25 for all VM.
- Polarisation properties measured as a function of Q^2 and $|t|$:
  - polarised cross-section and amplitude ratios have been extracted
  - σ_L/σ_T increases with Q^2 and decreases with ρ invaraint mass
  - significant violation of SCHC for light VM, effect increasing with $|t|$

DVCS:
- W dependence indicates hard regime
- Significant skewing factor measured $\longrightarrow$ GPD
- First Beam Charge Assymetry measured

High $|t|$:
- High $|t|$ VM data are showing BFKL like behaviours
- High P_T photons measurement roughly agree with BFKL