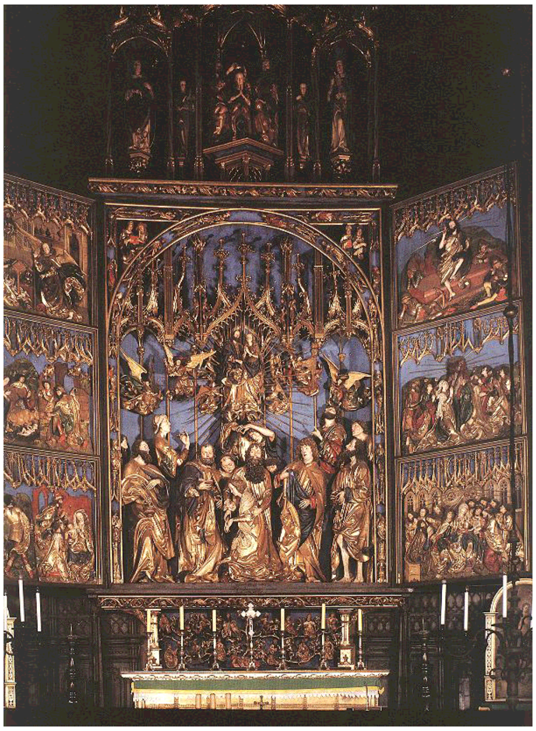


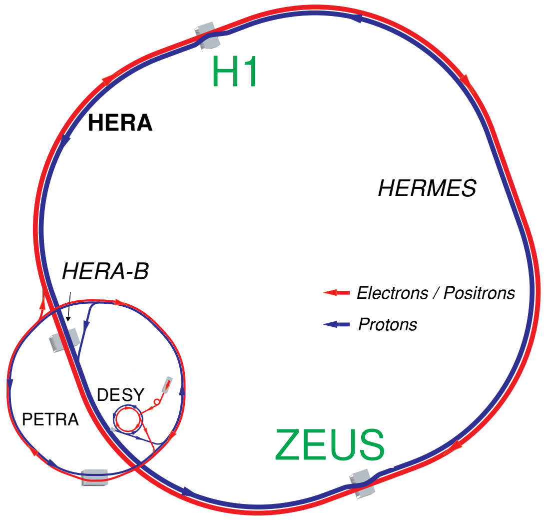
Kraków
24-28 May, 2002

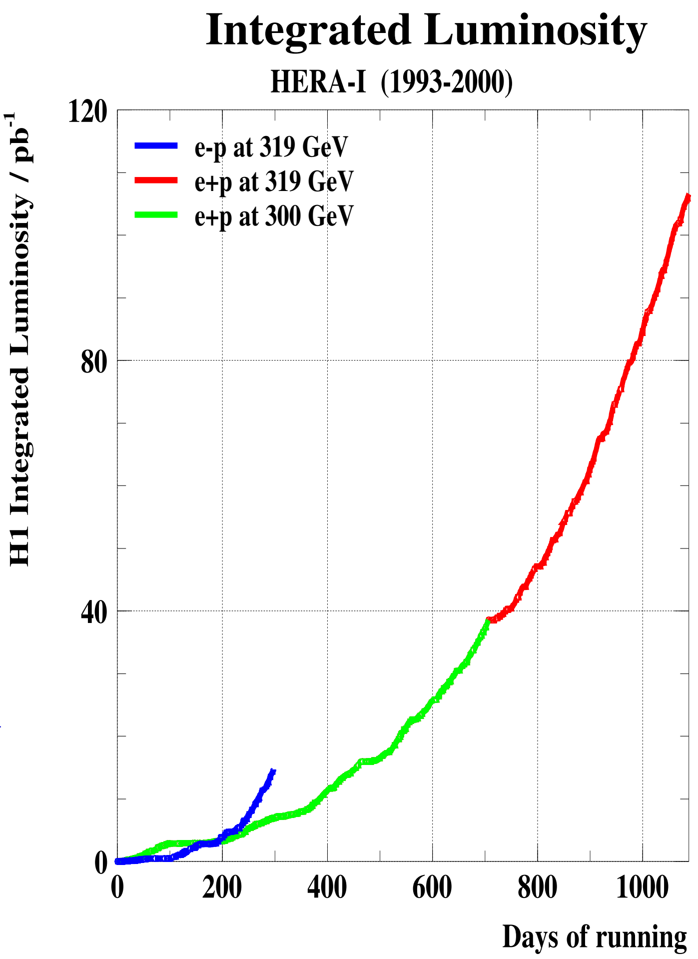
Meson Production and Spectroscopy at HERA

Jan Olsson, DESY, Hamburg
On behalf of
the H1 and ZEUS Collaborations

- Introduction
- Exclusive Production of Vector Mesons
- Search for Odderon Exchange
- Charm Spectroscopy
- Conclusions

The HERA ep collider

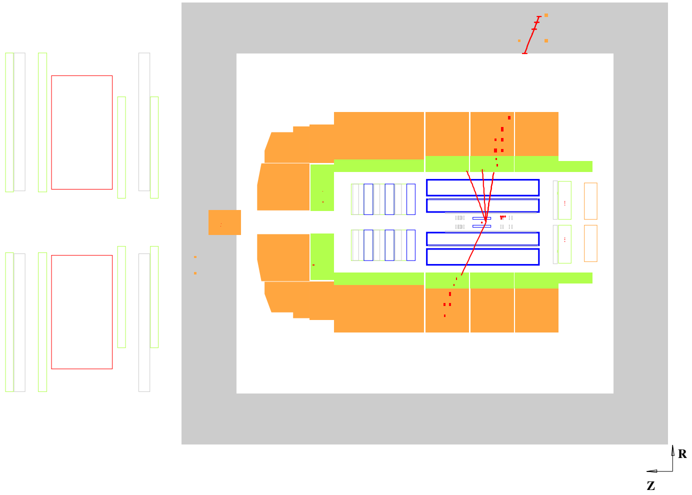


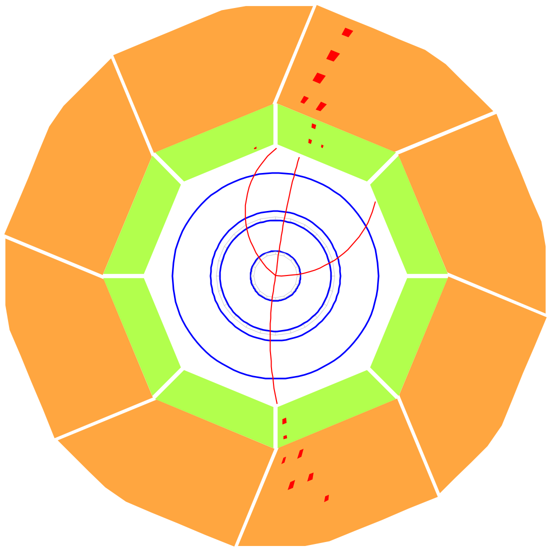


$$e^{\pm} \quad \Longrightarrow \quad \Longleftarrow \quad p$$

27.5 GeV **820 – 920 GeV**

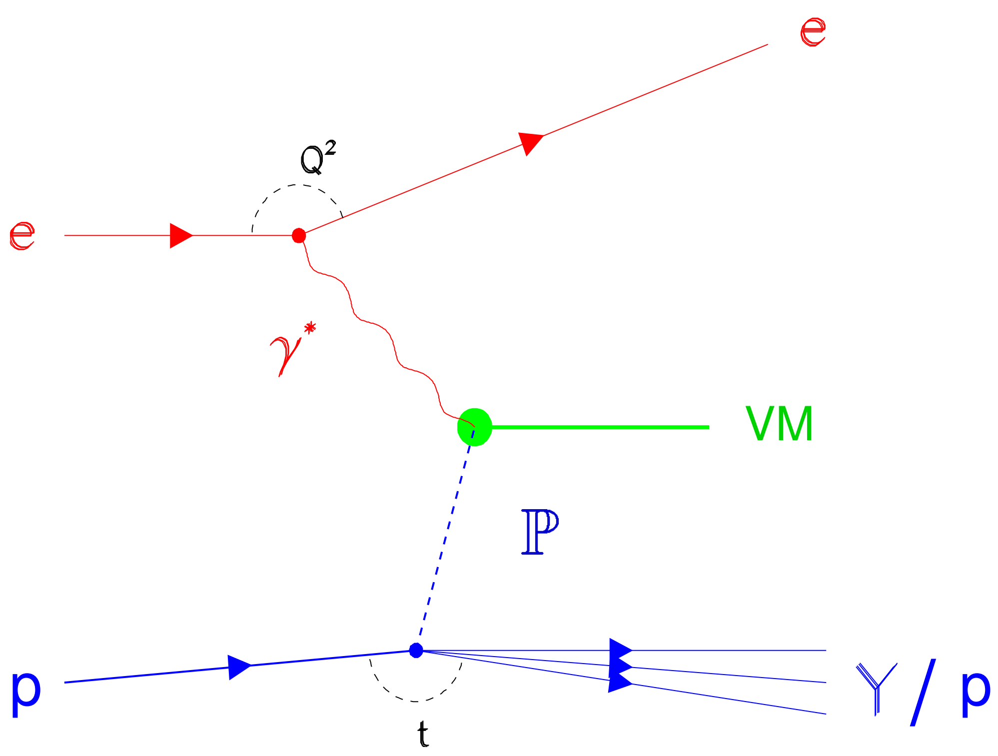
$$\sqrt{s} = 300 - 319 \text{ GeV}$$





$$e\,p \longrightarrow e\,\psi'\,p, \quad \psi' \longrightarrow J/\psi\,\pi^+\pi^-, \quad J/\psi \longrightarrow \mu^+\mu^-$$

DIFFRACTIVE VECTOR MESON PRODUCTION



γ^*	**Virtuality Q^2 :**	$0 - 100\ GeV^2$
t	**Squared 4-mom. transfer at p vertex:**	$0 - 20\ GeV^2$
$W_{\gamma p}$	**CM Energy :**	**20 – 290 GeV**

VM $\rho^\circ,\ \omega,\ \phi,\ J/\Psi,\ \Psi',\ \Upsilon$

Classical (Regge) Approach:

σ_{tot} and Light Vector Meson production described via "Soft ℙomeron" exchange

$$d\sigma/dt \ \propto\ e^{bt}\,(W/W_0)^{4(\alpha_{I\!P}(t)-1)}$$
$$\alpha_{I\!P}(t) \ = \ \alpha_{I\!P}(0) \ + \ \alpha'_{I\!P}\,t$$
$$b \ = \ b_0 \ + \ 4\,\alpha'_{I\!P}\,ln(W/W_0)$$

Expect

Slow rise of $\sigma(W)$

$$\sigma \propto W^{0.2-0.3}$$

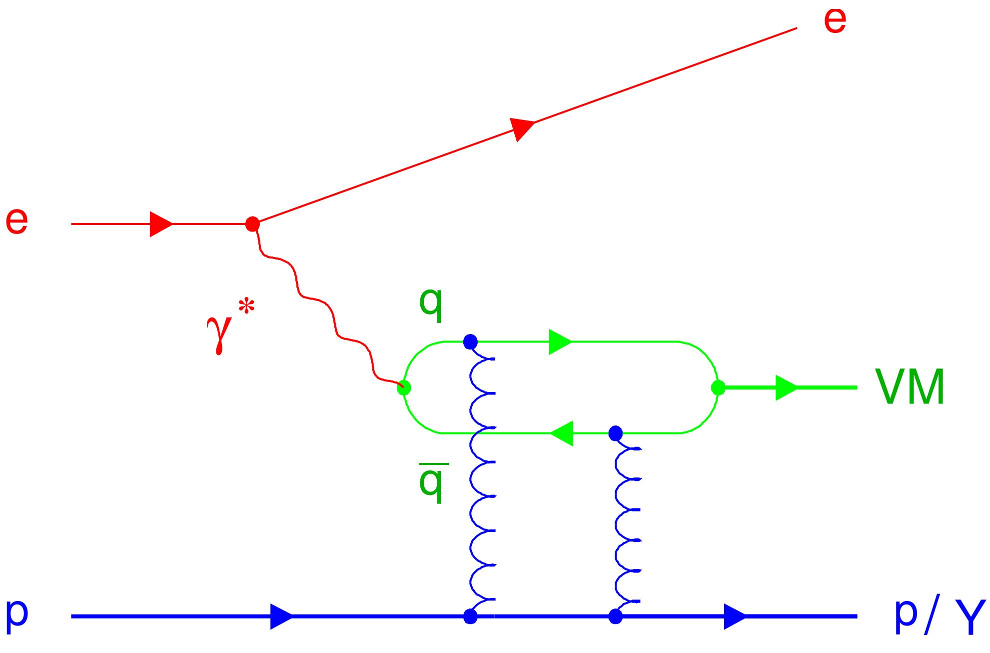
Shrinkage

SCHC

$R = \sigma_L/\sigma_T \propto Q^2/M^2_{VM}$

Is this approach valid at large values of $Q^2,\ t,\ M_{VM}$?

DIFFRACTIVE VECTOR MESON PRODUCTION



pQCD Approach:

Factorization (timescales !)

1. **Photon fluctuates into $q\bar{q}$ (colour dipole)**
2. **$q\bar{q}$ scatters off proton**
   under exchange of ≥ 2 gluons
3. **$q\bar{q}$ forms a bound state**

Expect: $\sigma \propto [x\, g(x, Q^2)]^2$

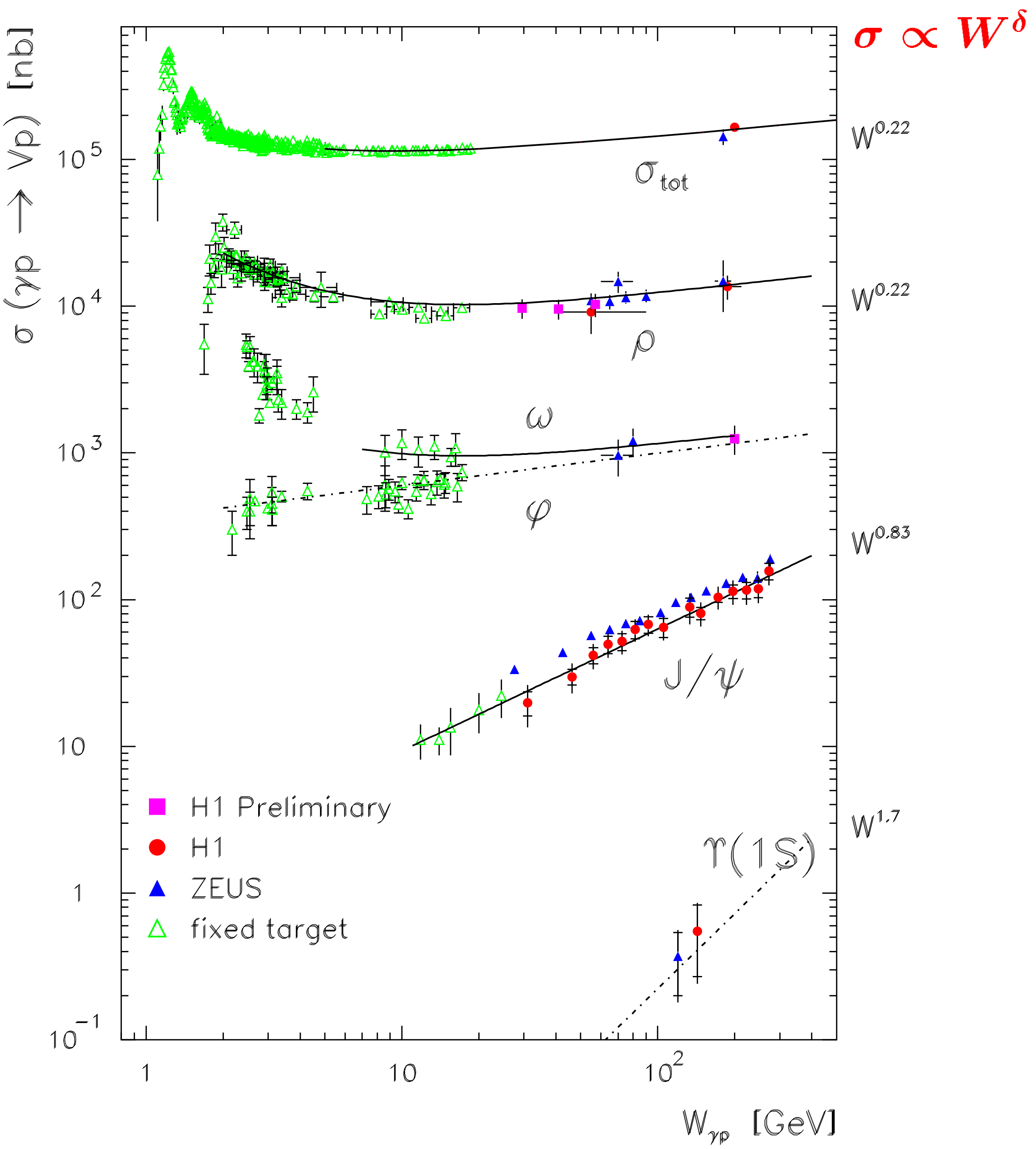
Steep rise of the cross section with W,
due to increasing gluon density in the proton

No (or little) shrinkage of the diffractive peak,
and at large $|t|$, $d\sigma/dt \propto -t^n$

SCHC violation

pQCD needs a hard scale !

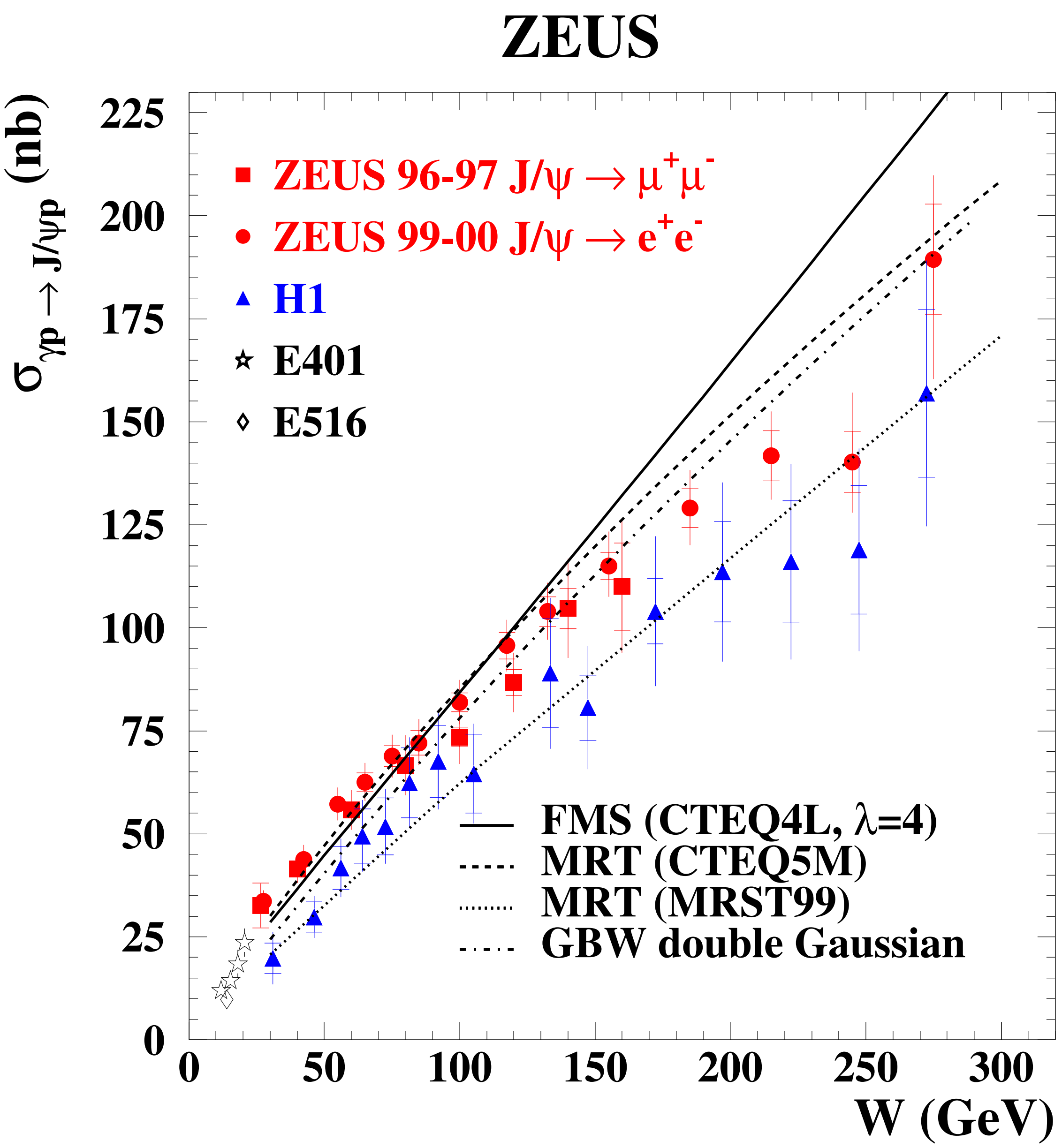
W DEPENDENCE IN VM PHOTOPRODUCTION



Steeper W dependence for heavy Vector Mesons

M_{VM} hard scale for pQCD calculations ?

J/Ψ PHOTOPRODUCTION



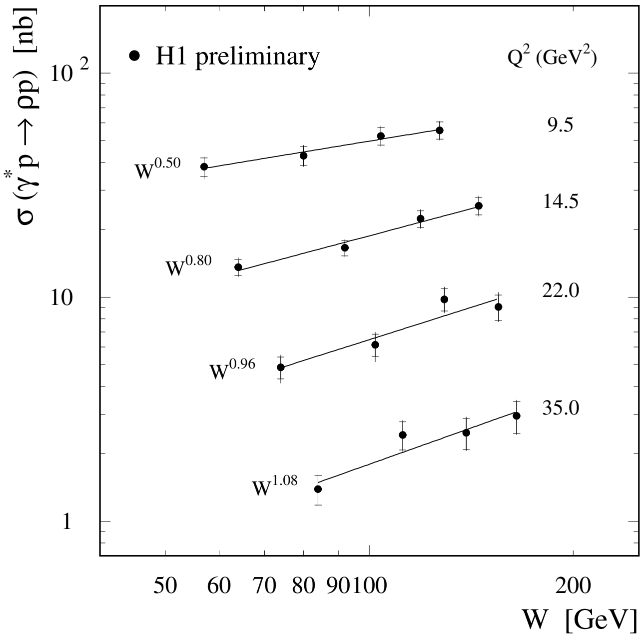
pQCD describes steep rise of Cross Section

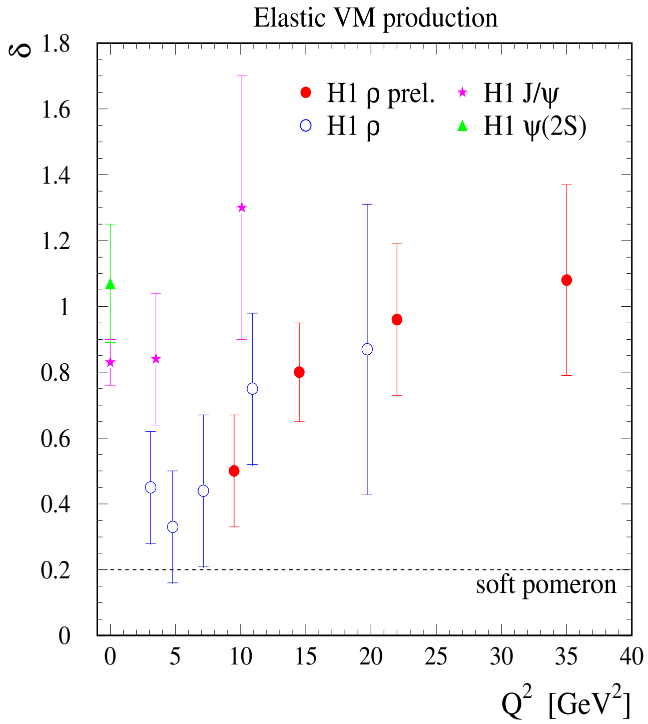
$M_{J/\Psi}$ hard scale

Precise data sensitive to the proton parton density, in particular to the Gluon Density

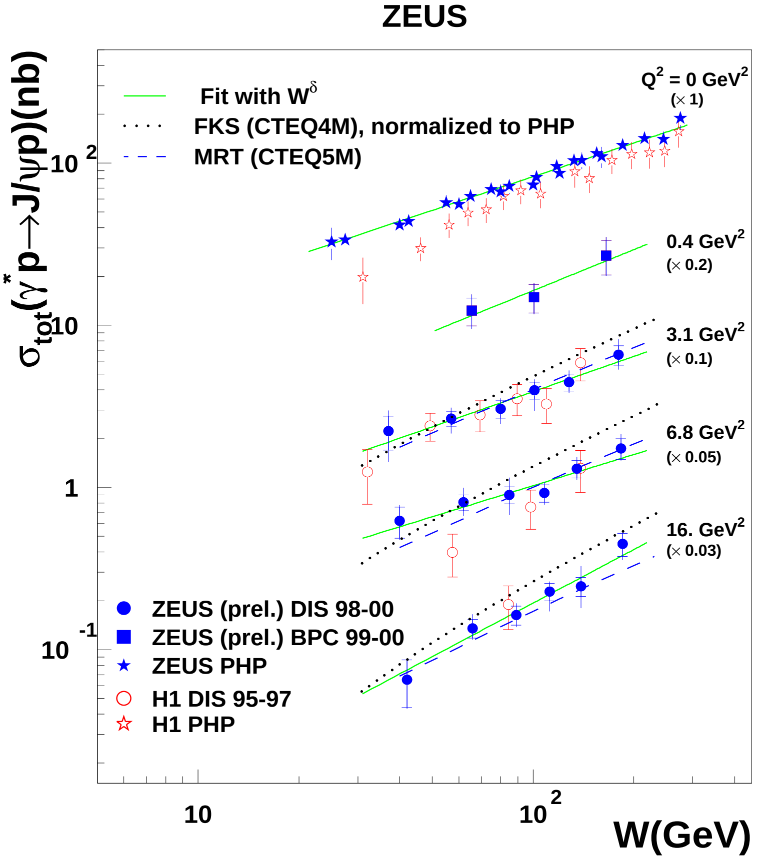
W DEPENDENCE IN DIS PRODUCTION OF VM

$\gamma^* p \to \rho^\circ\, p$





$\gamma^* p \to J/\Psi\, p$



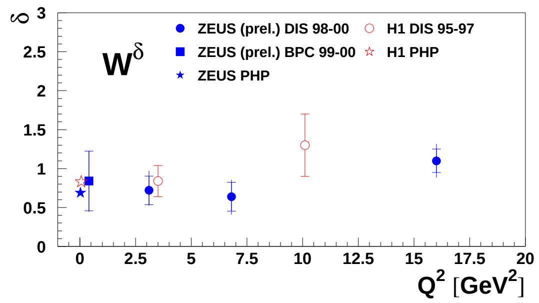
ρ°

W dependence steeper with increasing Q^2

Transition from "soft" to "hard" scattering

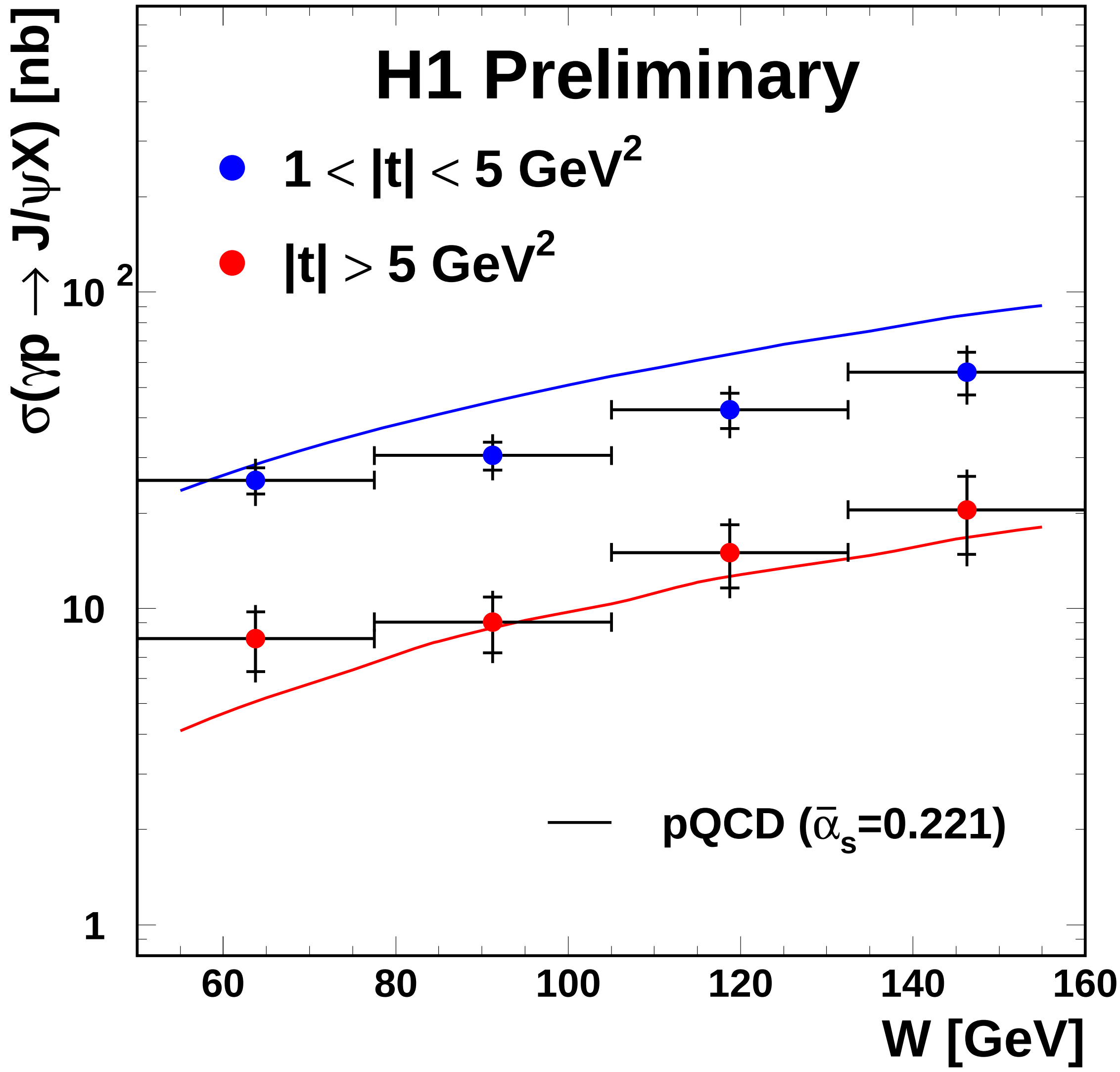
J/Ψ

W dependence steep already at $Q^2 \sim 0$



W DEPENDENCE IN J/Ψ PHOTOPRODUCTION AT HIGH $|t|$

$50 < W < 160\,\mathrm{GeV}$ $\quad Q^2 < 1\mathrm{GeV}^2$ $\quad 1 < |t| < 21\mathrm{GeV}^2$



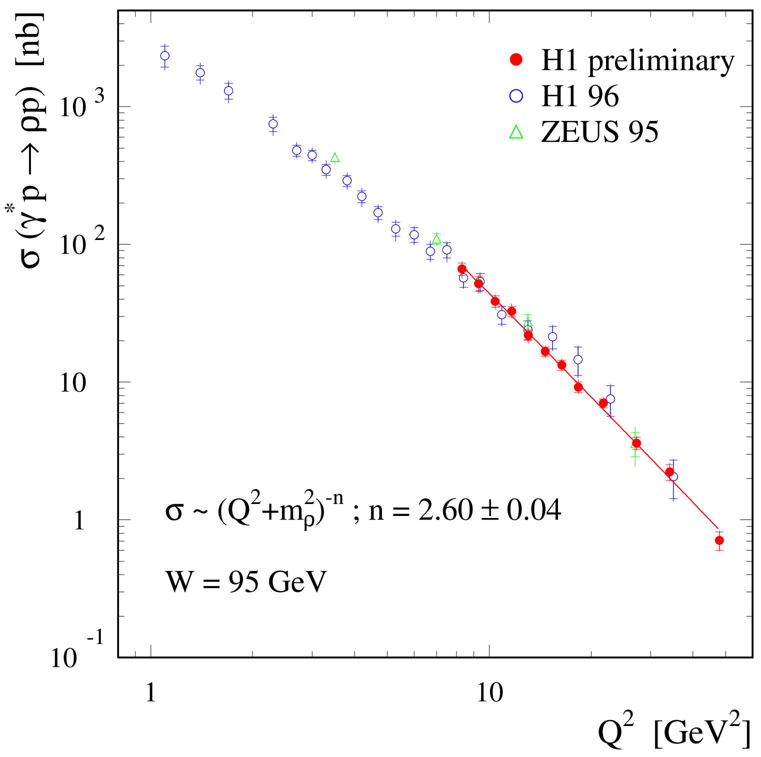
$$\sigma \propto W^{\delta} \longrightarrow \delta_{J/\Psi} \sim 1$$

Similar rise in W at low and high $|t|$

Predicted in pQCD models

Q^2 DEPENDENCE IN VM DIS PRODUCTION

$$\gamma^* p \rightarrow \rho^\circ p$$



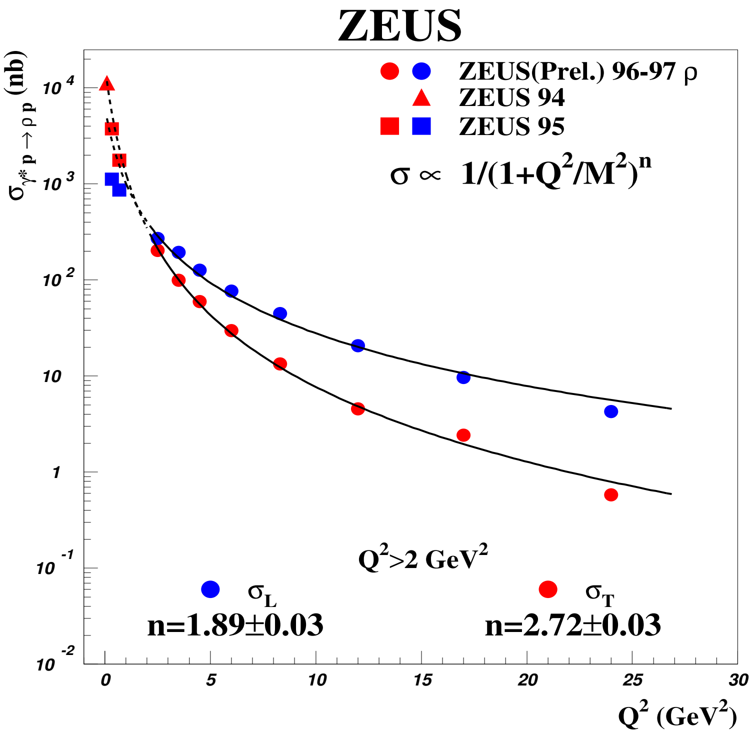
pQCD:

$$\sigma \propto \alpha_s^2(Q^2)/Q^6 \; [xg(x,Q^2)]^2$$

The Q^{-6} dependence of the cross section is weakened by the Q^2 dependence of the gluon density and of α_s,

$$\Longrightarrow \quad \sigma \propto 1/Q^{4-5}$$

Data bear this out

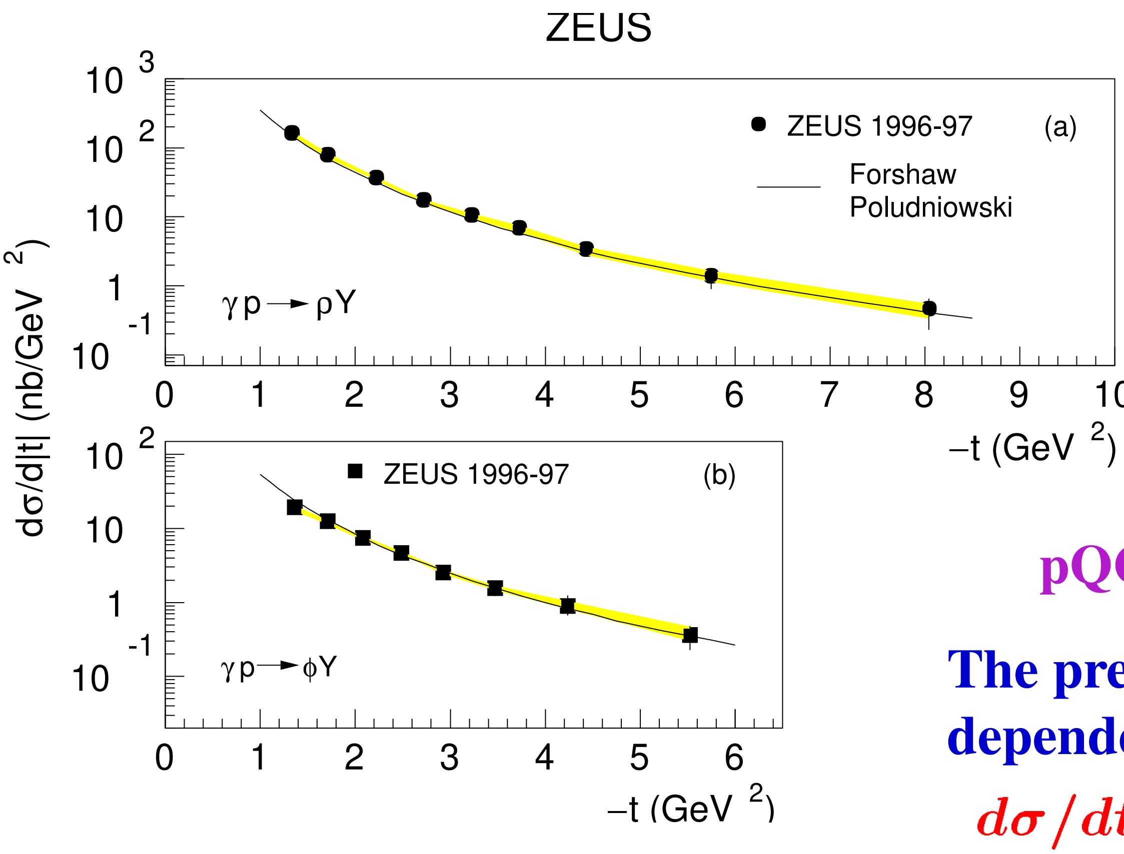


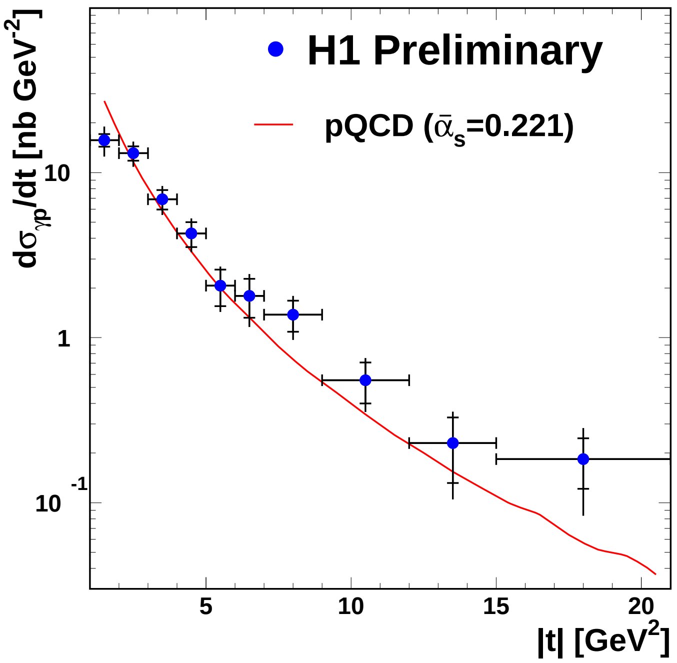
At large Q^2 values,

σ_L dominates (pQCD prediction)

σ_T still significant

t DEPENDENCE IN VM PHOTOPRODUCTION





pQCD:

The predicted dependence

$$d\sigma/dt \propto -t^n$$

is clearly seen

$$n \sim -3$$

for both ρ° and ϕ

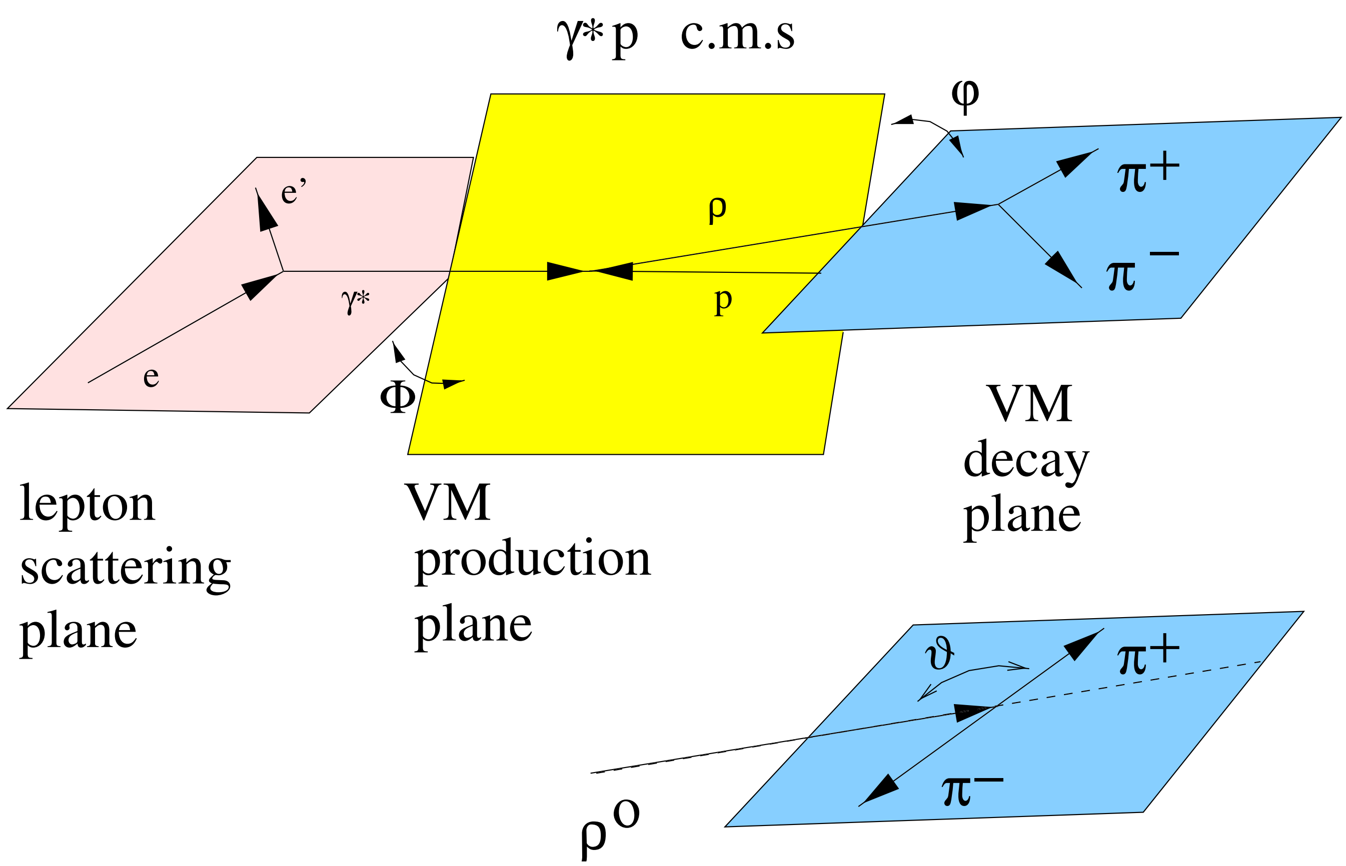
J/Ψ

flatter t dependence,

$$n \sim -1.7$$

t dependence well described in pQCD, both for light and heavy vector mesons

HELICITY STUDIES



Use Helicity Frame

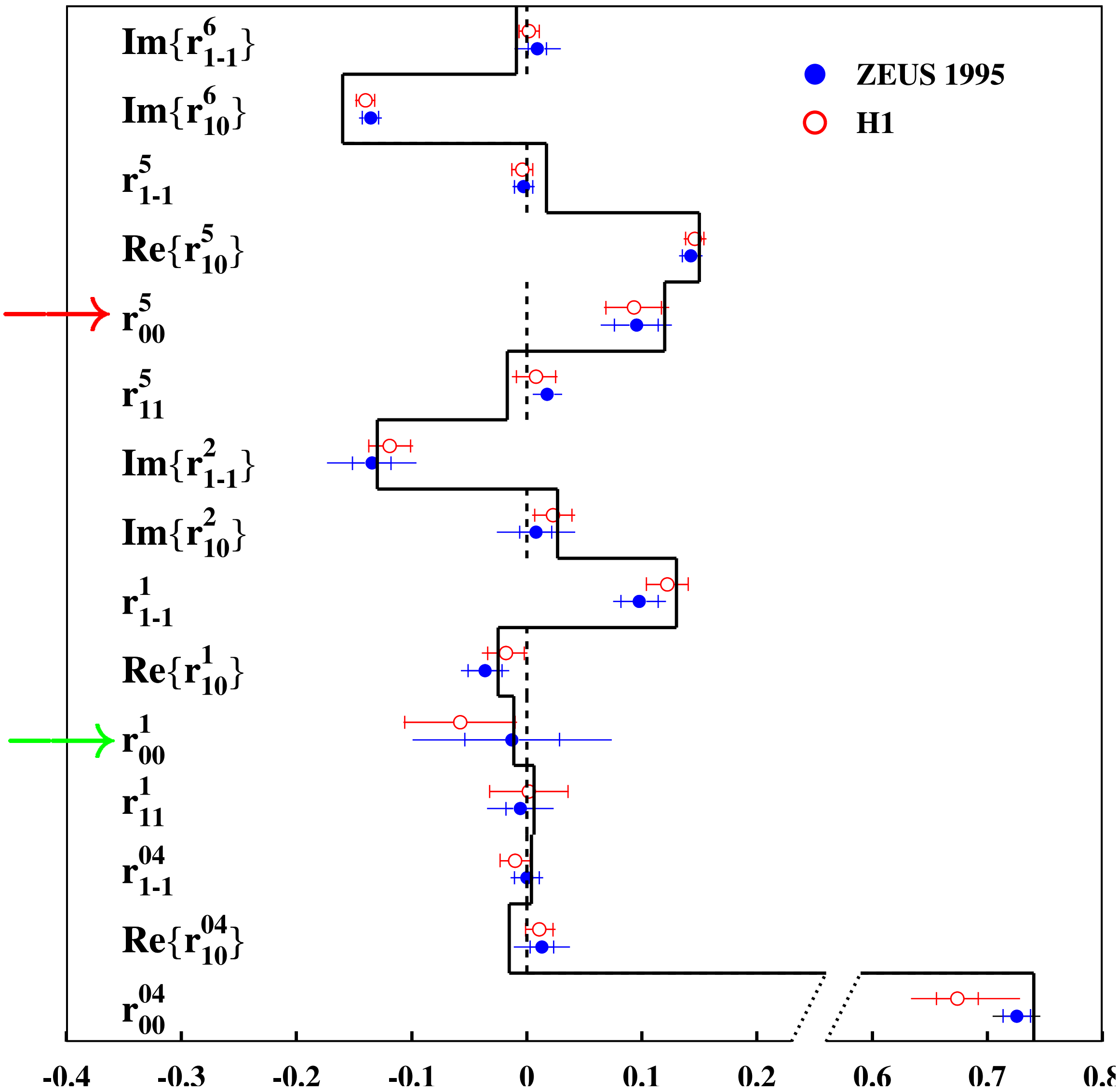
Decay angular distribution $W(\cos\vartheta, \varphi, \Phi)$**,**
15 indep. combinations of spin-density matrix elements

SCHC, NPE: Only 5 combinations $\neq 0$
$\Longrightarrow$ **only** $\gamma_T \to \rho_T$ **and** $\gamma_L \to \rho_L$

pQCD: quantitative prediction of SCHC violation

SCHC VIOLATION IN PQCD

$\gamma^* p \to \rho^\circ\, p$ **Low Q^2, low $|t|$**



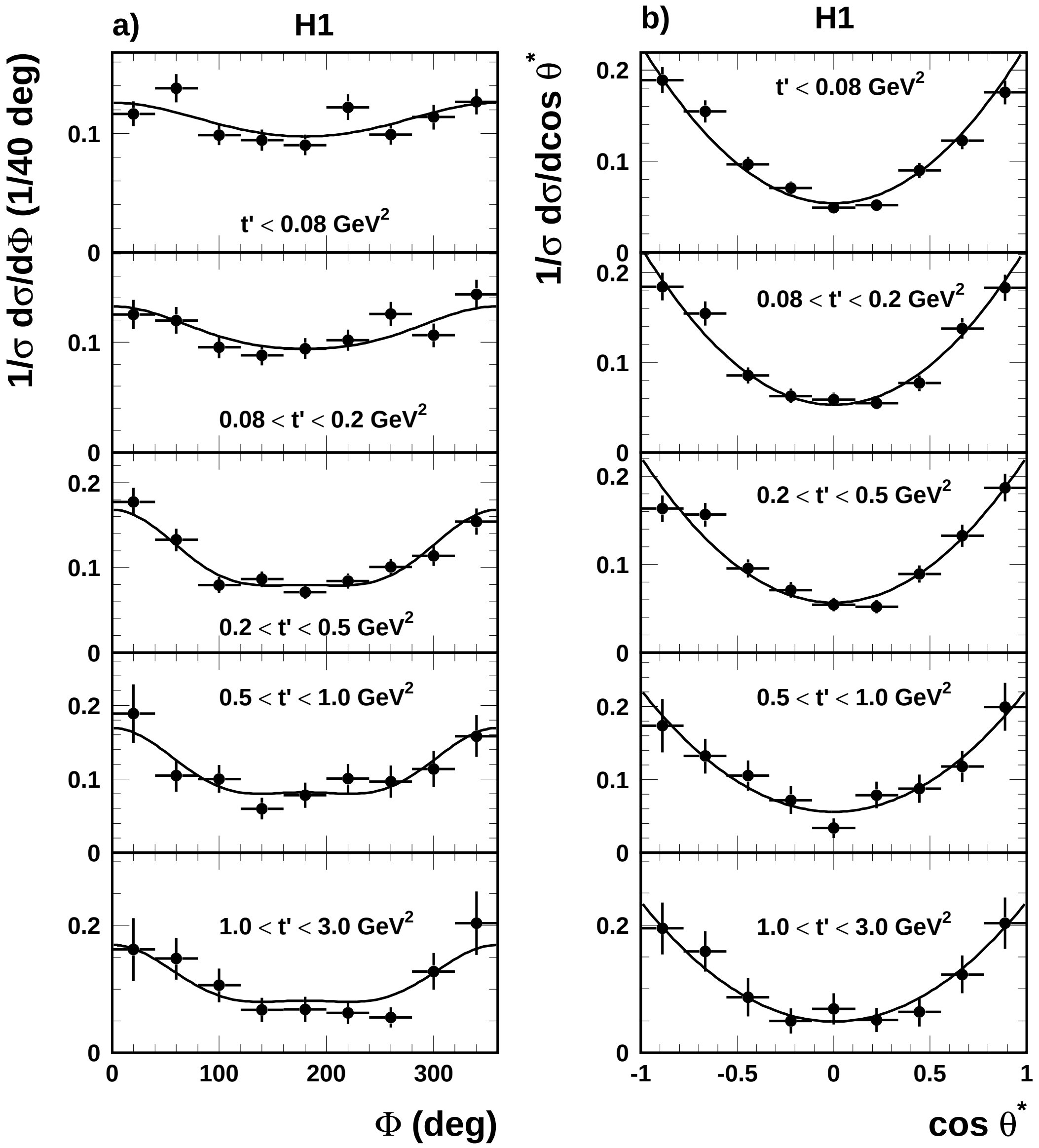
$$r^5_{00} \propto T_{00}T^*_{01} + T_{01}T^*_{00}$$

SCHC Violation: $\gamma_T \to \rho_L$

Success for pQCD !

t DEPENDENCE OF ANGULAR DISTRIBUTIONS

$\gamma^* p \to \rho^\circ\, p/Y$ **high $|t|$**



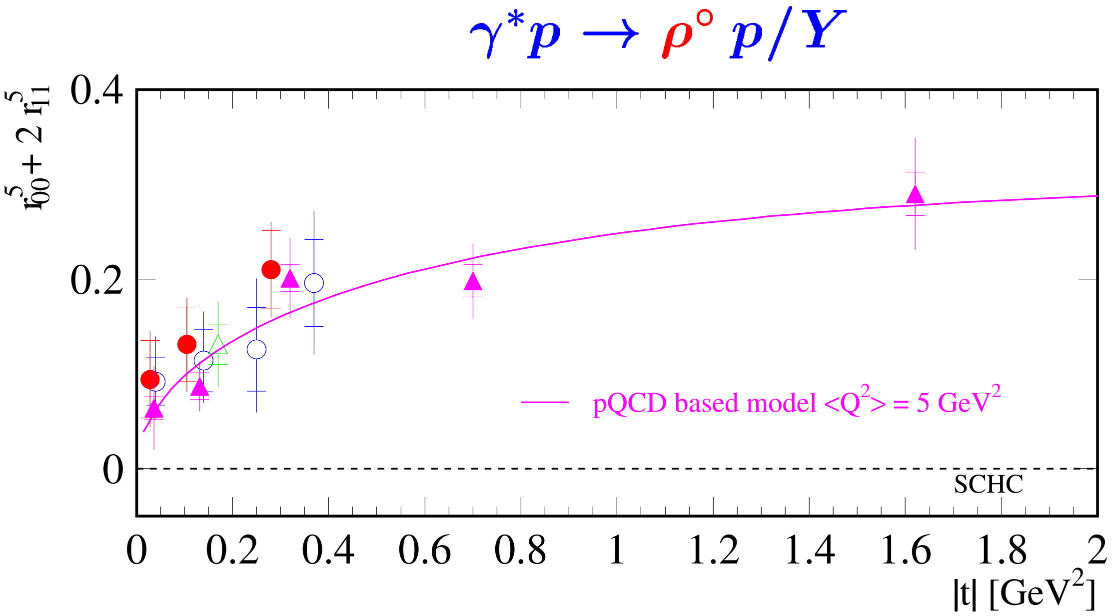
$$W(\Phi) \propto 1 - \epsilon \cos 2\Phi (2r^1_{11} + r^1_{00}) + \sqrt{2\epsilon(1+\epsilon)} \cos \Phi (2r^5_{11} + r^5_{00})$$

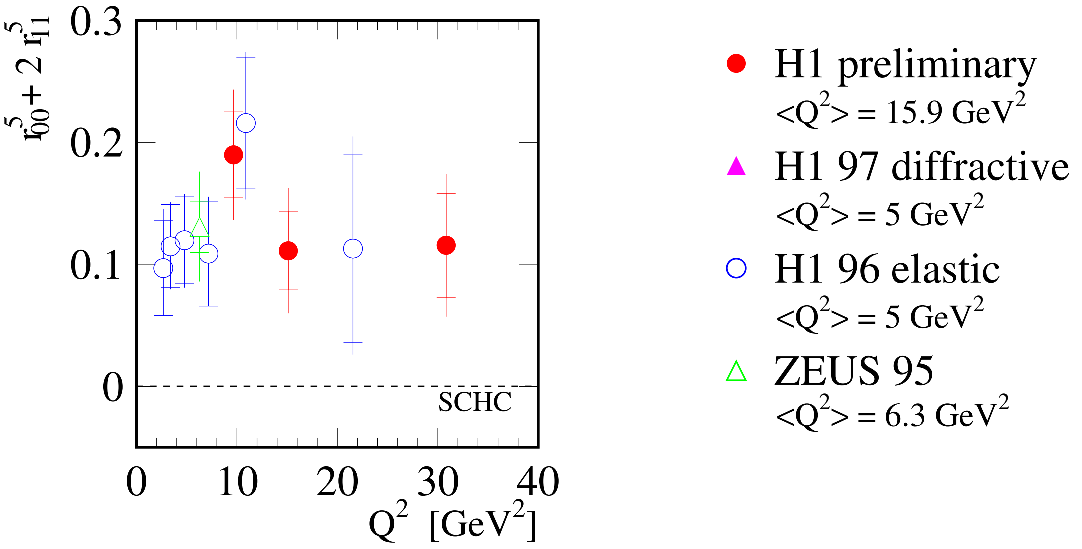
(integrate over $\cos\theta^*, \varphi$)

$$W(\cos\theta^*) \sim 1 - r^{04}_{00} + (3\, r^{04}_{00} - 1) \cos^2\theta^*$$

(integrate over Φ, φ)

t AND Q^2 DEPENDENCE OF $r^5_{00} + 2r^5_{11}$



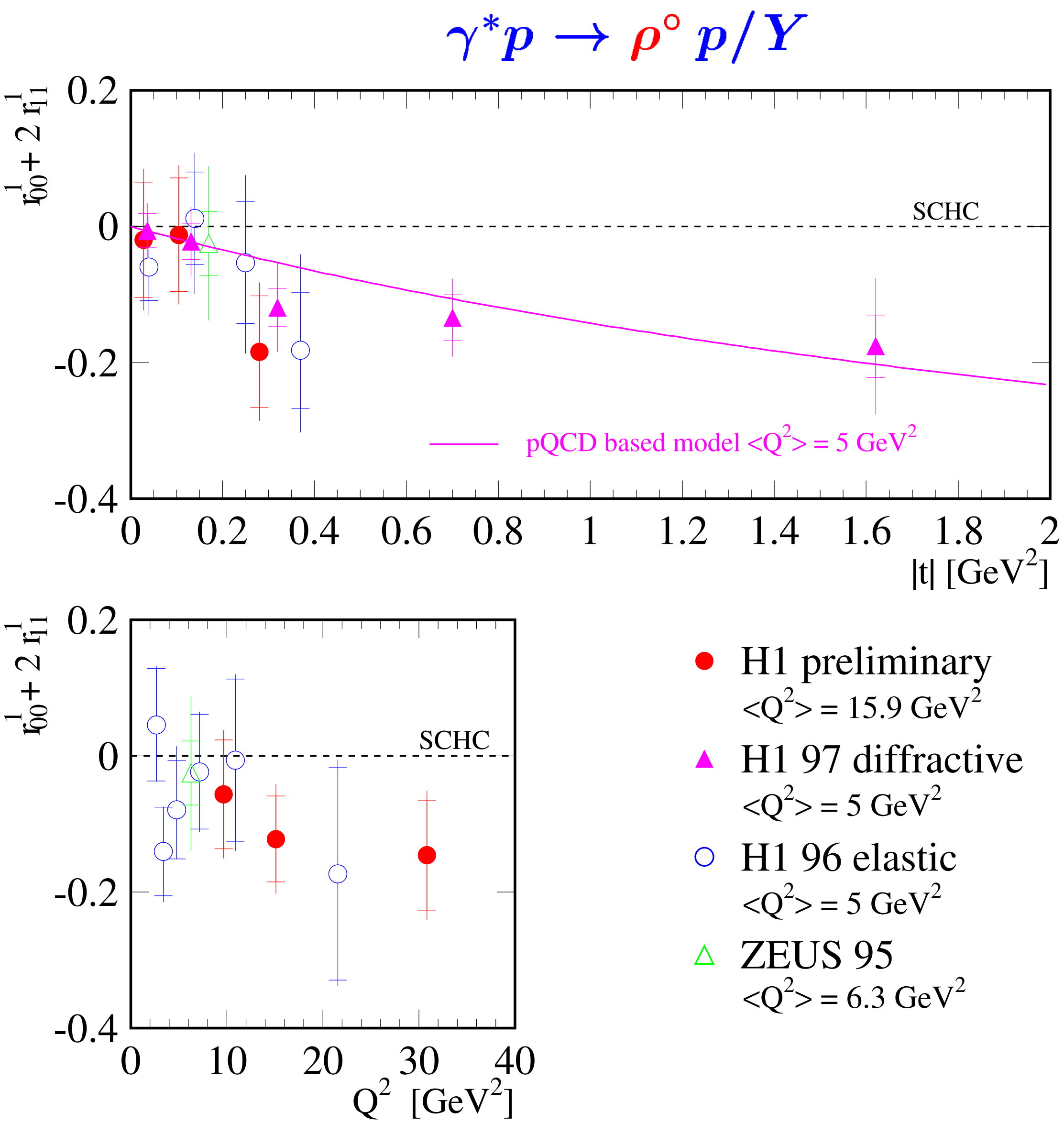


r^5_{00} dominates: Significant SCHC violation,
increasing with $|t|$

pQCD: predicts $\sim \sqrt{|t|}$ dependence
for both r^5_{00} and r^5_{11}

describes the data very well !

t AND Q^2 DEPENDENCE OF $r^1_{00} + 2r^1_{11}$



r^1_{00} dominates: Significant SCHC violation, increasing with $|t|$ and with Q^2

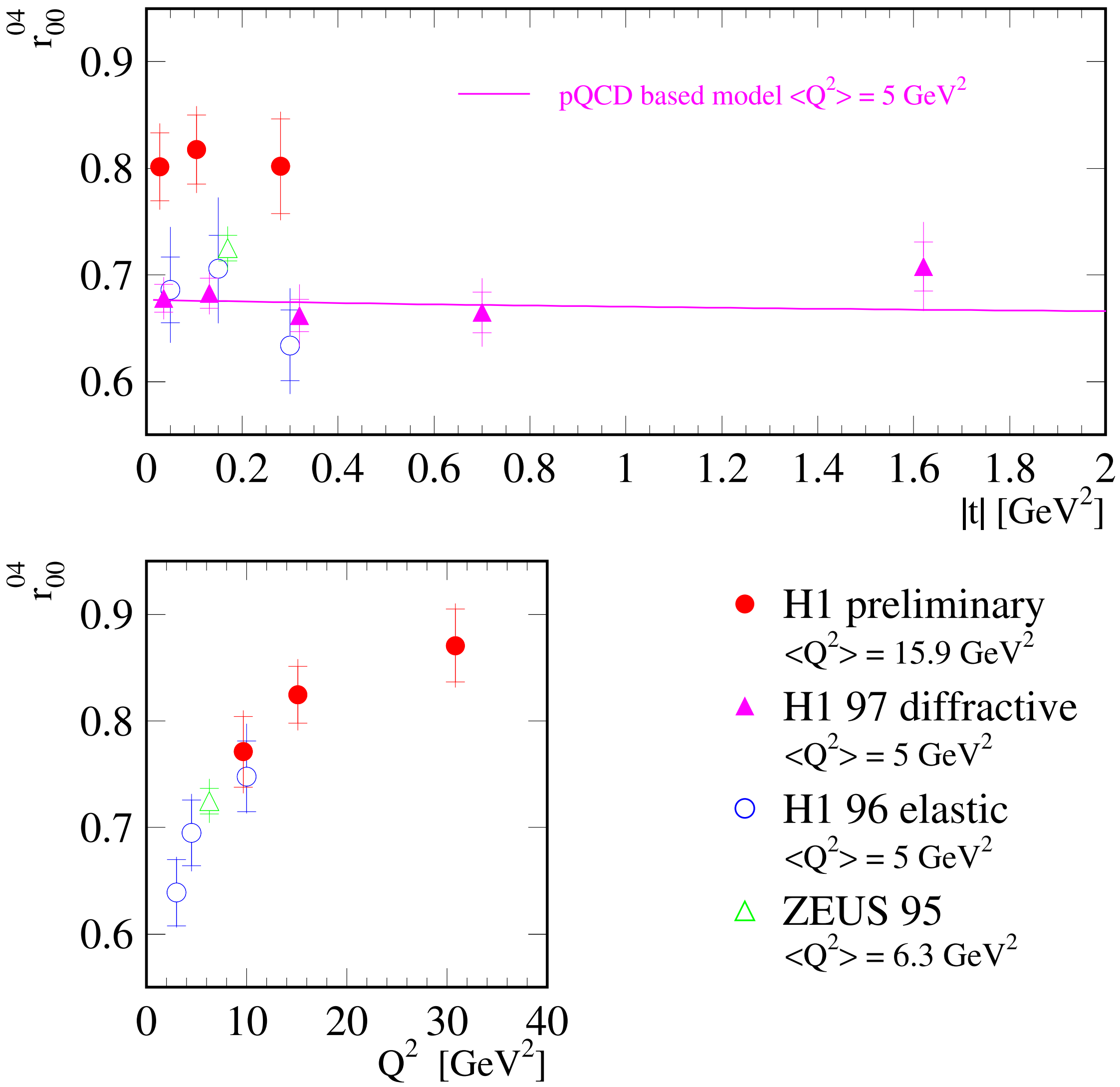
$r^1_{00} \propto |T_{01}|^2 \qquad \gamma_T \to \rho_L$

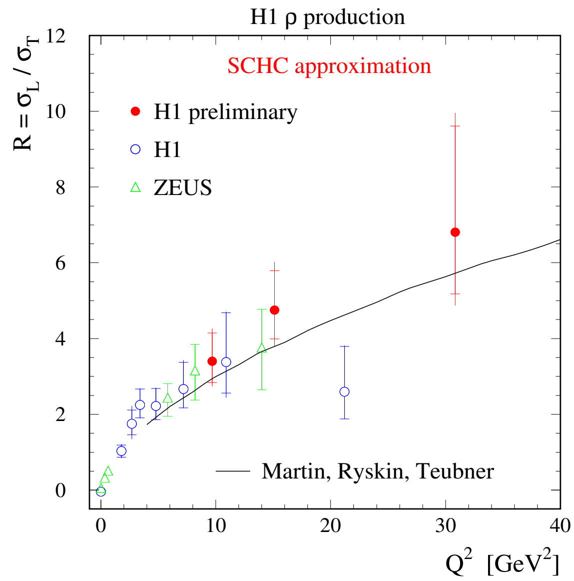
pQCD: predicts $\sim$ linear $|t|$ dependence

Data consistent with this

t AND Q^2 DEPENDENCE OF r_{00}^{04}

$\gamma^* p \to \rho^\circ \; p/Y$





***Influence on R: few %**

Assuming* SCHC,

$$R = \sigma_L/\sigma_T = \frac{1}{\epsilon}\frac{r_{00}^{04}}{(1-r_{00}^{04})}$$

r_{00}^{04} **: probability to produce longitudinal ρ°, from either transverse or longitudinal γ^***

pQCD describes the data

SUMMARY

EXCLUSIVE PRODUCTION OF VECTOR MESONS

- **The last years of High Luminosity running at HERA provide High Precision Data Samples**
- **Data span the Transition from Soft to Hard Diffractive Scattering**
- **Good Evidence that M_{VM}, Q^2 and t all serve as Hard Scales in the pQCD Approach to Hard Diffraction**
- **pQCD gives a Successful Description of the Features of Vector Meson Production at Large Values of these Scales**
- **Examples were given:**
  - $\triangleright$ **Cross Section Dependences on W, Q^2 and t**
  - $\triangleright$ **t - dependence of SDMEs $\longrightarrow$ Violation of SCHC**

The perturbative Odderon

QCD developments 1980's, 1990's

- **Pomeron interpreted as exchange of 2 gluons**
  Odderon interpreted as exchange of 3 gluons
- **Meanwhile the Odderon is recognized as**
  important and basic prediction of QCD
- **Predictions, based on perturbative calculations,**
  using hard scales Q^2, m_c, etc., e.g. (J. Bartels et al. 2001):

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} \eta_c p) = 50 \text{ pb at } Q^2 = 0$$
$$= 1.3\text{pb at } Q^2 = 25 \text{ GeV}^2$$

The non–perturbative Odderon

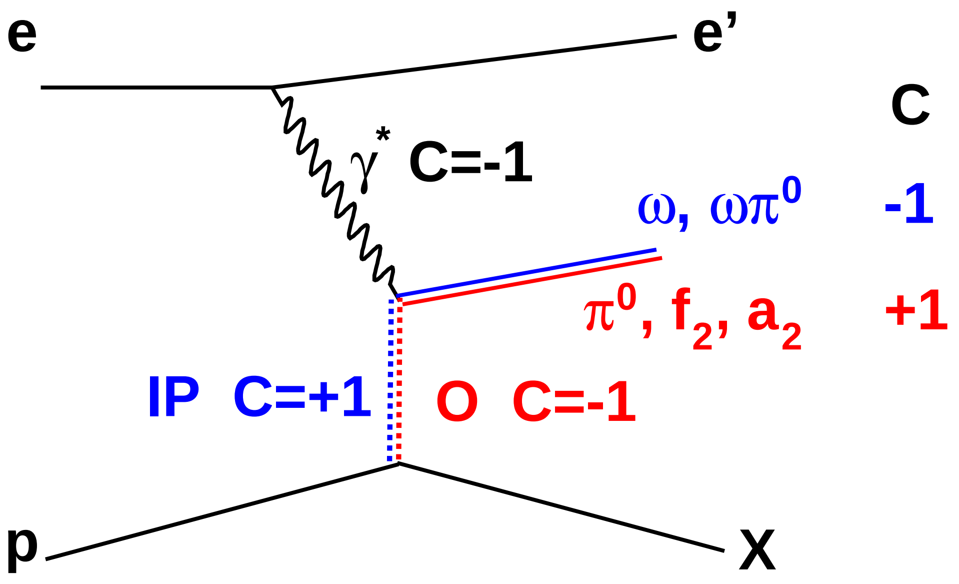
Predictions for the processes (E.R. Berger et al. 1999-2000)

$$\gamma\, p \xrightarrow{\mathbb{O}} \pi^\circ\, N^*$$
$$\gamma\, p \xrightarrow{\mathbb{O}} f_2(1270)\, N^*$$
$$\gamma\, p \xrightarrow{\mathbb{O}} a_2(1320)\, N^*$$

"Stochastic Vacuum Model"

- **Non-perturbative QCD, using Functional Integral techniques**
- **Diquark model of the proton**
- **Tuned to $\mathbb{P}$ Exchange reactions, Extended to $\mathbb{O}$ Exchange**
- **Large visible Cross Sections predicted: 20 - 200 nb !!**

SEARCH FOR ODDERON EXCHANGE
MULTI-PHOTON FINAL STATES



$\mathbb{O}$dderon exchange

Final States with $C = +1$ **Even number of photons**

$$
\begin{array}{rcccl}
 & & \pi^\circ & \longrightarrow & 2\gamma \\
f_2(1270) & \longrightarrow & \pi^\circ\pi^\circ & \longrightarrow & 4\gamma \\
a_2(1320) & \longrightarrow & \pi^\circ\eta & \longrightarrow & 4\gamma
\end{array}
$$

$\mathbb{P}$omeron exchange

Final States with $C = -1$ **Odd number of photons**

$$
\begin{array}{rcccl}
\omega & \longrightarrow & \gamma\pi^\circ & \longrightarrow & 3\gamma \\
b_1(1235) & \longrightarrow & \omega\pi^\circ & \longrightarrow & 5\gamma
\end{array}
$$

Tagged Photoproduction

$$ep \longrightarrow e\,\pi^{o} N^{*}$$

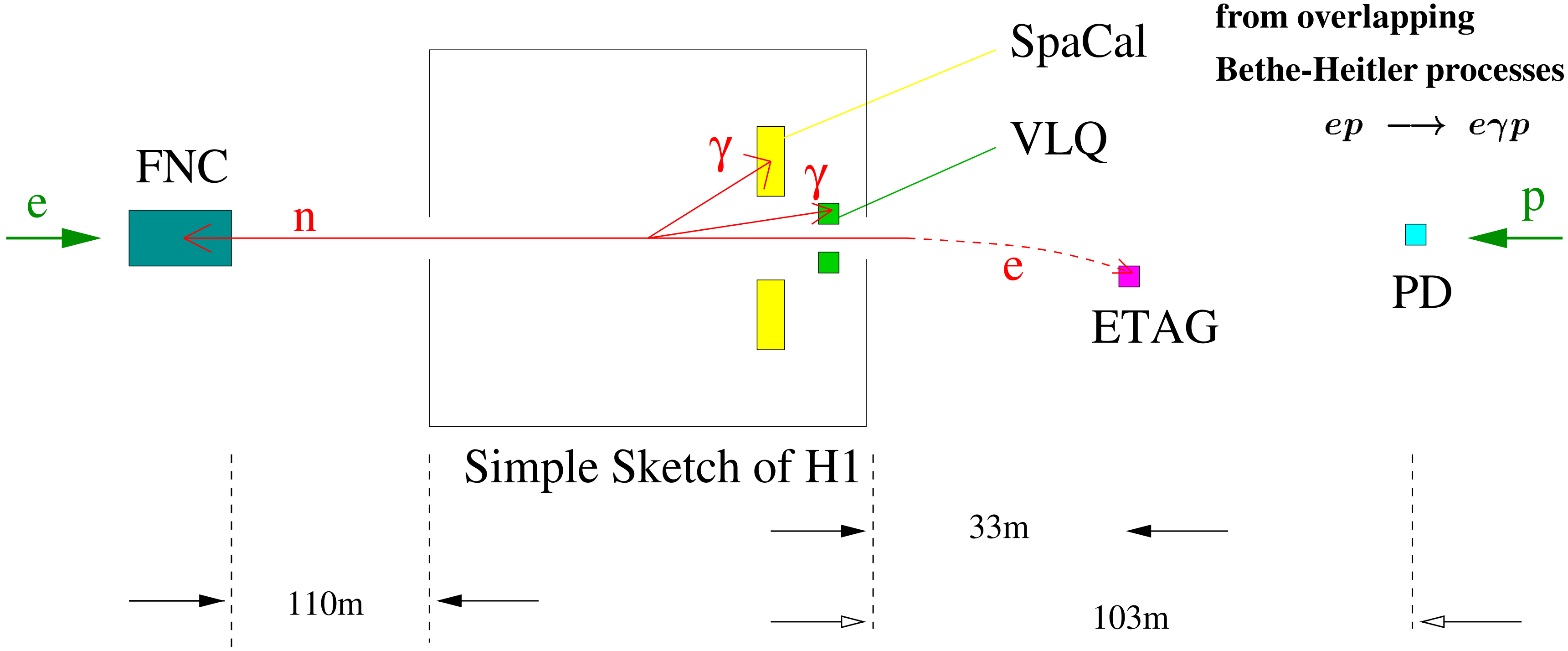
$$N^{*} \longrightarrow n\,X \qquad \pi^{o} \longrightarrow \gamma\gamma$$

TRIGGER:

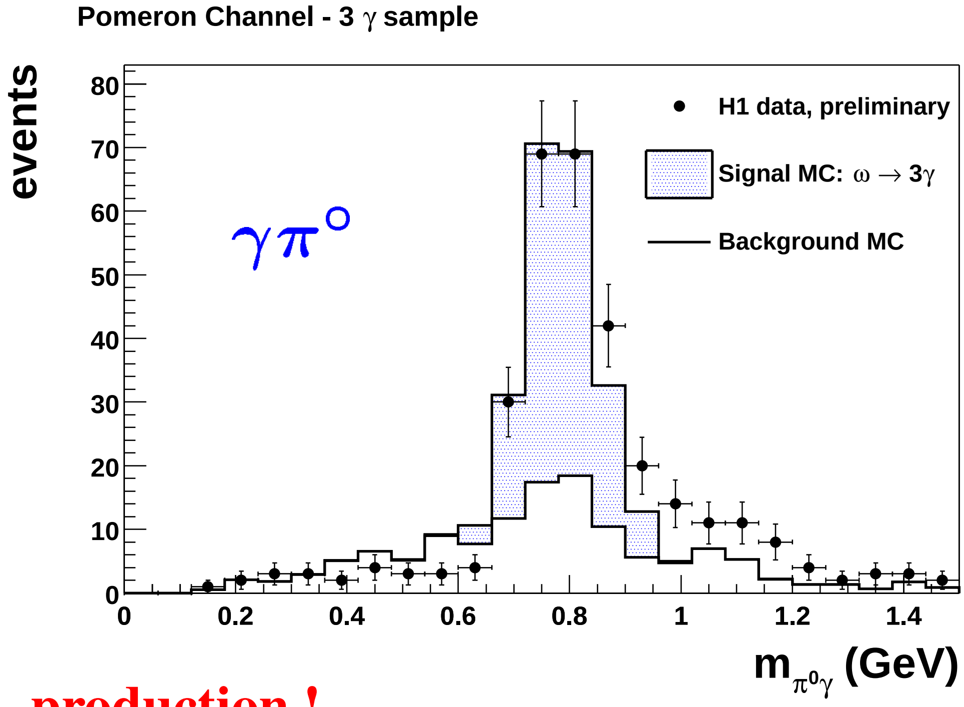
Neutron Energy $>$ 200 GeV
VLQ Energy $>$ 6 GeV
Electron Energy $>$ 6 GeV
PD Energy $<$ 2 GeV

Rejection of background from overlapping Bethe-Heitler processes

$$ep \longrightarrow e\gamma p$$



Select π° band, plot 3γ mass

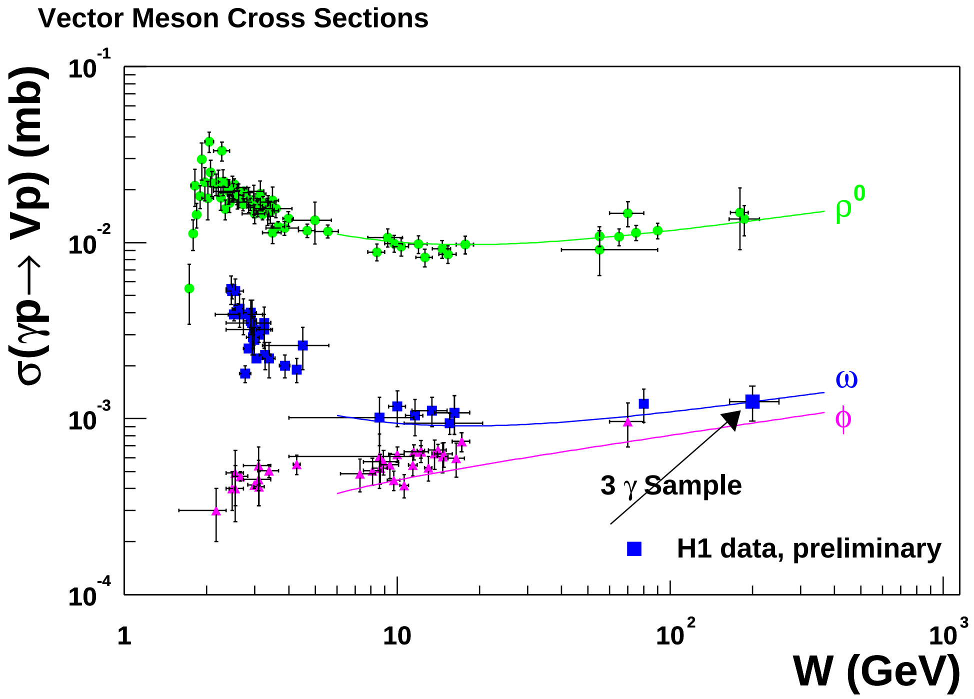


Clear ω production !

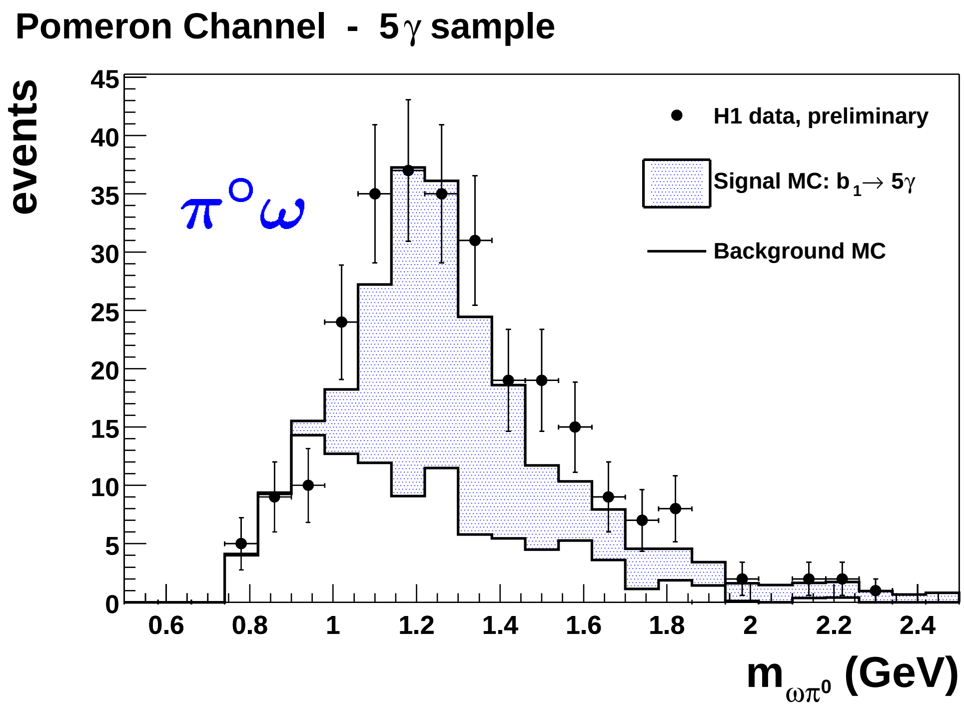
$$\sigma(\gamma p \longrightarrow \omega p) = (1.25 \pm 0.17 \pm 0.22)\ \mu\mathrm{b}$$

H1 Preliminary

W dependence of the cross section



Select $\pi^\circ, \pi^\circ, \omega$ bands, plot 5γ mass



$$\sigma(\gamma p \longrightarrow \omega\pi^\circ X) = (980 \pm 200 \pm 200) \text{ nb}$$

H1 Preliminary

PYTHIA (background) expectation 190 nb

$\omega\pi^\circ$ excess due to $b_1(1235)$???

$b_1(1235)$ ($J^{PC} = 1^{+-}$) photoproduction previously observed at CERN*

Extrapolate Cross Section to HERA energies $\Longrightarrow$

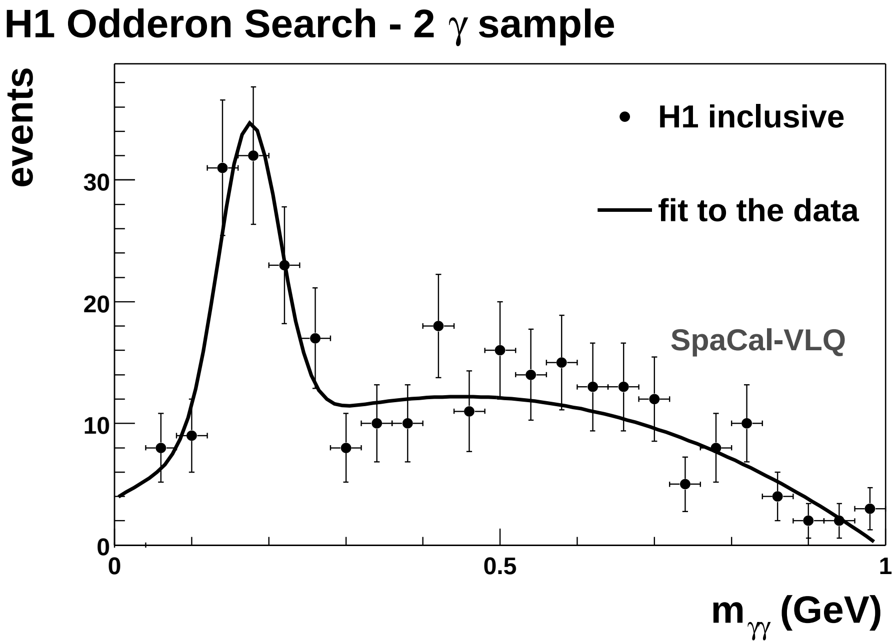
$$\sigma(\gamma p \longrightarrow \omega\pi^\circ X) = 660 \pm 250 \text{ nb}$$

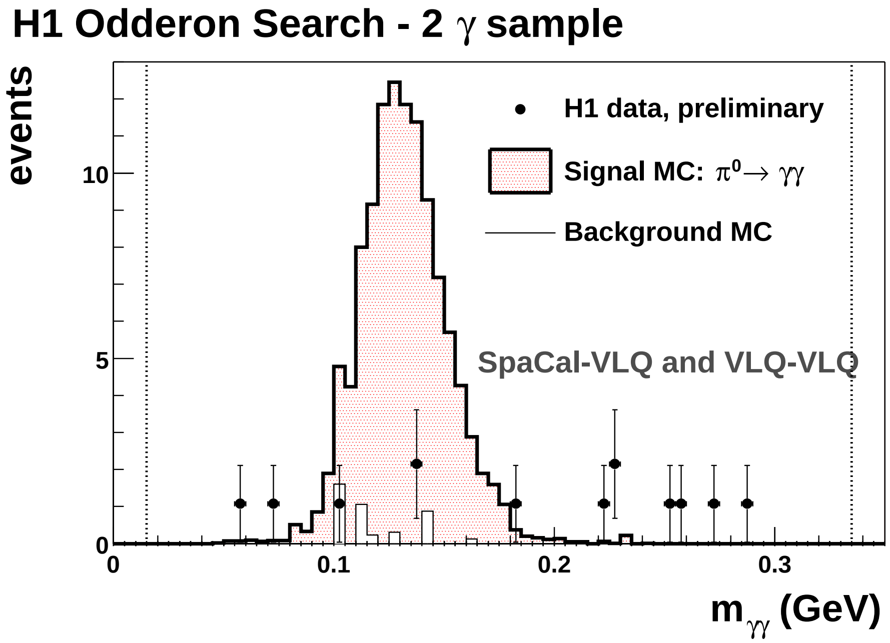
Nice Agreement !

but needs further study to confirm resonance

* **M. Atkinson et al., Omega Photon Coll., Nucl.Phys. B243 (1984) 1**

Two Photon Final State





Inclusive Sample:

Shows π° Detection Sensitivity

H1 Preliminary 95% C.L.

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} \pi^\circ N^*) < 39\ \text{nb}$$

For $\langle W_{\gamma p} \rangle = 210$ **GeV,** $0.02 < |t| < 0.3$ **GeV**^{2}

Exclusive Sample: No Signal !

Few events only

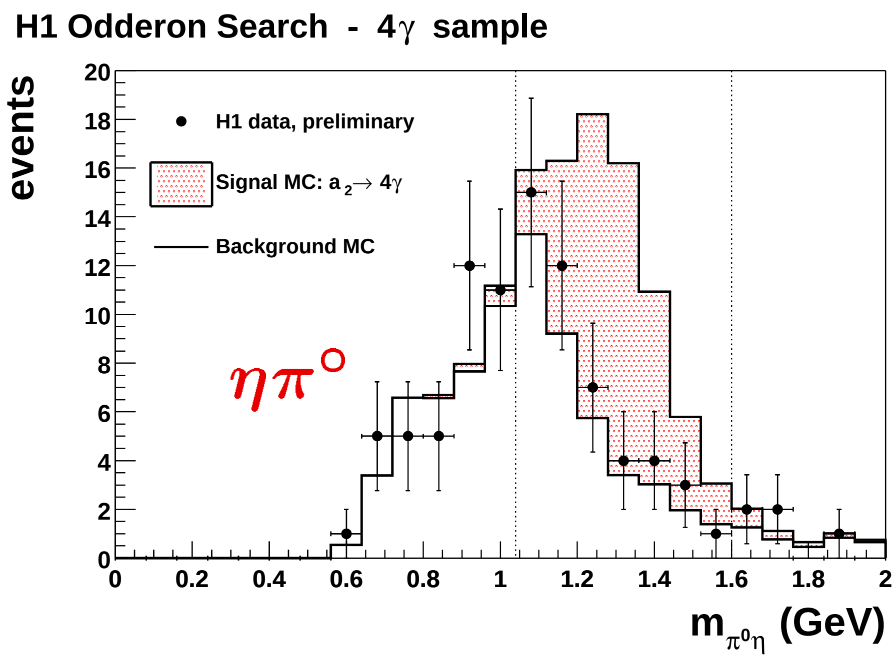
Consistent with Background

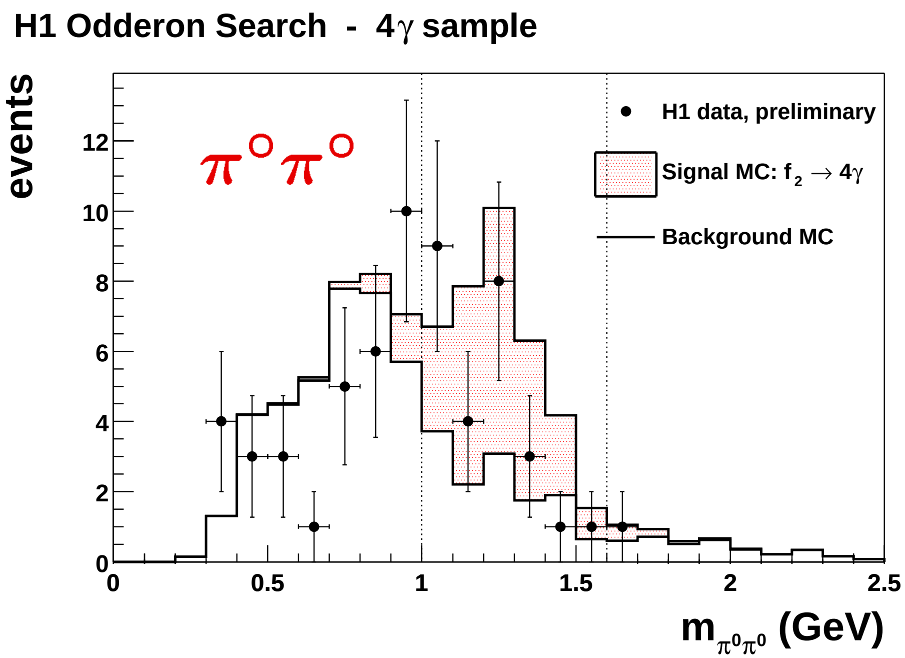
Theory expects >100 events !

prediction

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} \pi^\circ N^*) = 200\ \text{nb}$$

Four Photon Final State





No a_2 or f_2 signals above background

H1 Preliminary 95% C.L.

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} f_2(1270)X) < 16 \text{ nb}$$

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} a_2(1320)X) < 96 \text{ nb}$$

For $\langle W_{\gamma p}\rangle = 200$ GeV

Theory predictions

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} f_2(1270)N^*) = 21 \text{ nb}$$

$$\sigma(\gamma p \xrightarrow{\mathbb{O}} a_2(1320)N^*) = 190 \text{ nb}$$

SUMMARY

SEARCH FOR ODDERON EXCHANGE

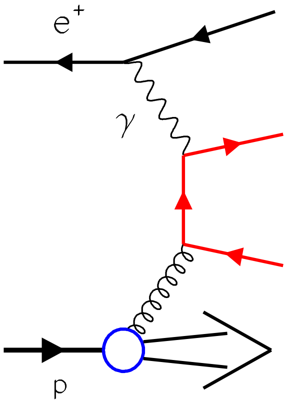
- **A Search for Odderon exchange was performed, using Exclusive Meson Photoproduction reactions with Multi-Photon Decay modes**

- **No Odderon Signal found above trivial background in 2γ and 4γ final states. Upper Limits of Cross Sections below Predictions of E.R. Berger et al.**

  (Non-perturbative QCD, Stochastic Vacuum Model)

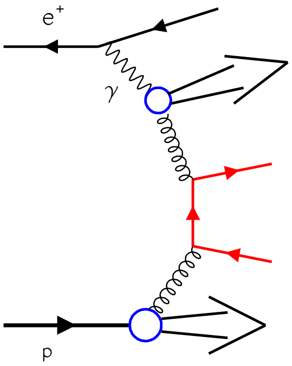
- **Exclusive ω and $\omega\pi^\circ$ photoproduction observed in 3γ and 5γ final states, consistent with expectations from $\mathbb{P}$omeron exchange and consistent with other observations of Exclusive Vector Meson photoproduction**

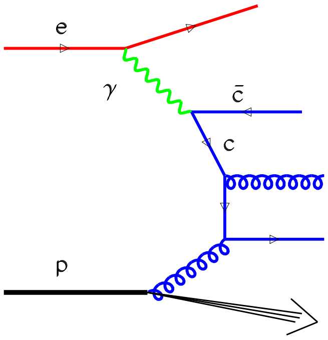
Contributions to Charm production in LO QCD



Boson-Gluon-Fusion

Pointlike interaction of γ





Resolved Photon,
Charm Excitation

Interaction of partons from Proton and Photon

m_c **and** Q^2 **two hard scales**

$\Longrightarrow$ **pQCD calculations available**

Main Field of Interest at HERA:

Charm Structure of the Proton (and of the Photon)

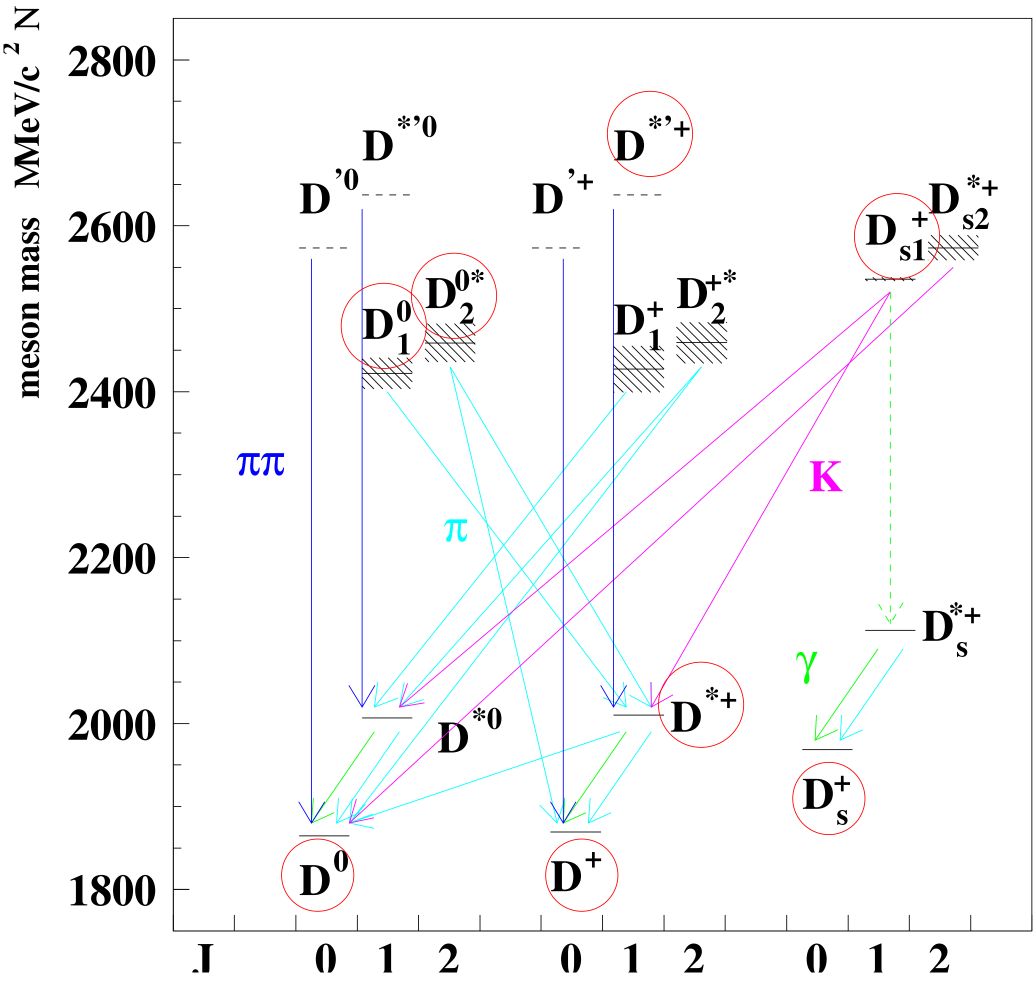
Gluon Density in the Proton via BGF

Here: Open Charm Spectroscopy

$\Longrightarrow$ **Compare to Results from e^+e^-**

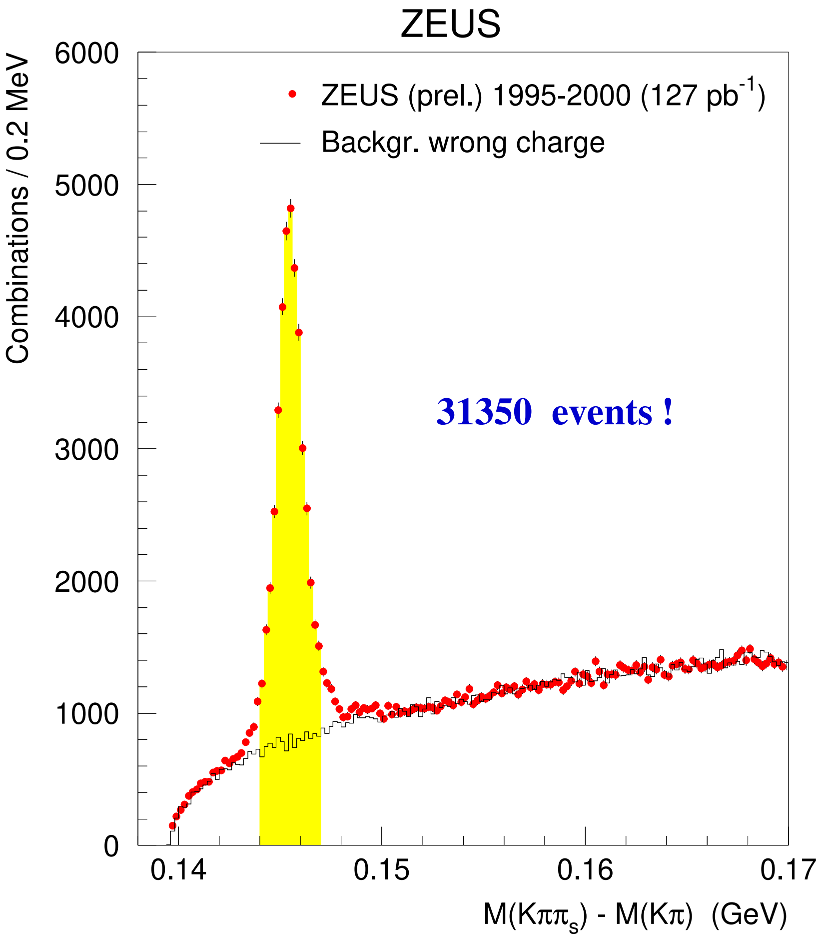
$\Longrightarrow$ **Test Universality of the Quark-Hadron Fragmentation**

D MESON SPECTROSCOPY



- **Only final states which can be accessed via decays into charged particles**
- **Large track multiplicities in HERA events $\Longrightarrow$ low S/B ratio**
- **Use Tagging methods**
  - ▷ **Δm tagging**
  - ▷ **Lifetime tagging – Vertex Detector**
  - ▷ **S-L Decay tagging**

ΔM TAGGING



Used in almost all analyses

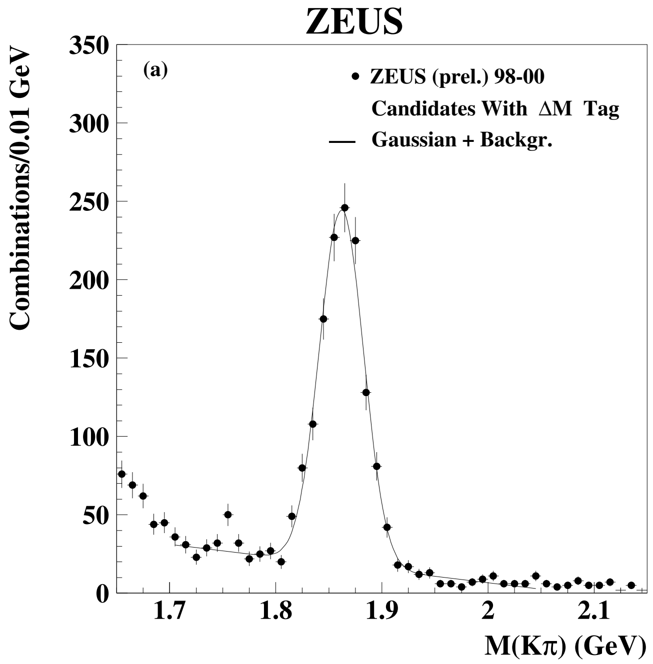
$\Delta M = M(D^{*\pm}) - M(D^{\circ})$

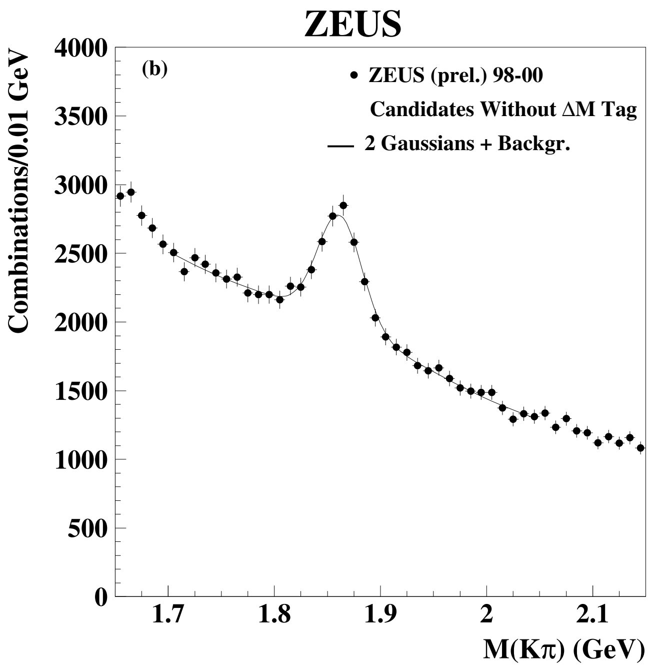
only $\sim$ 6 MeV above $m_{\pi^\pm}$

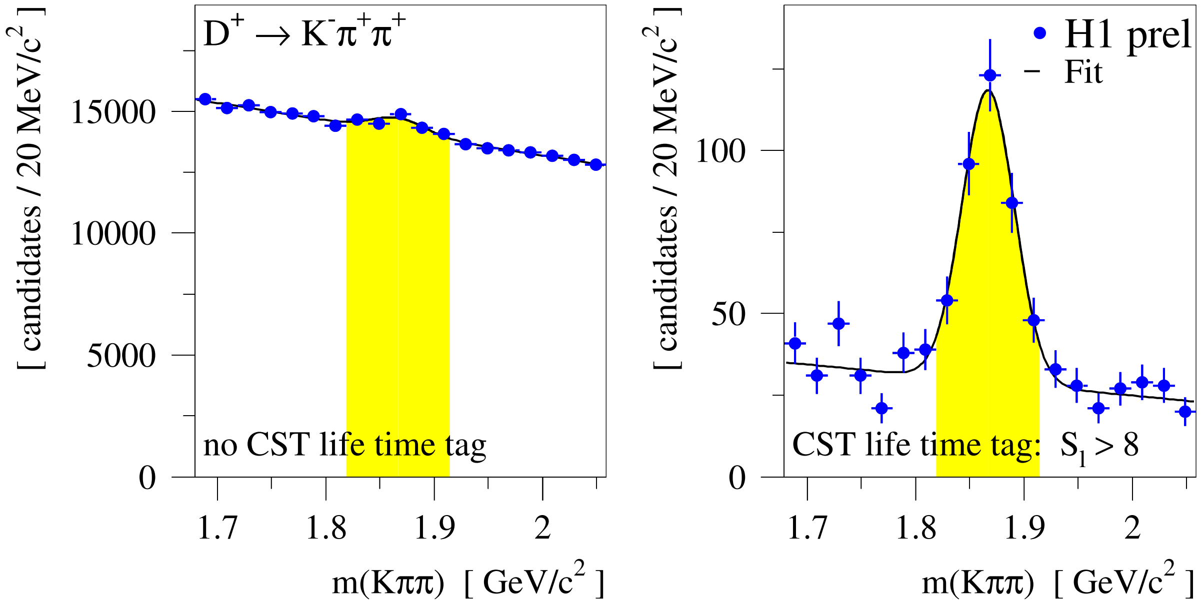
Typical kin. range

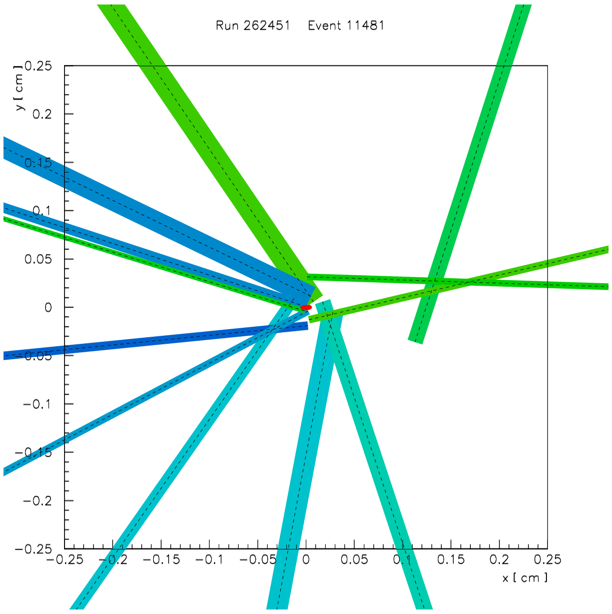
$p_\perp(D^*) \;>\; 1.5 - 2.5$ GeV

$|\eta(D^*)| \;<\; 1.5$





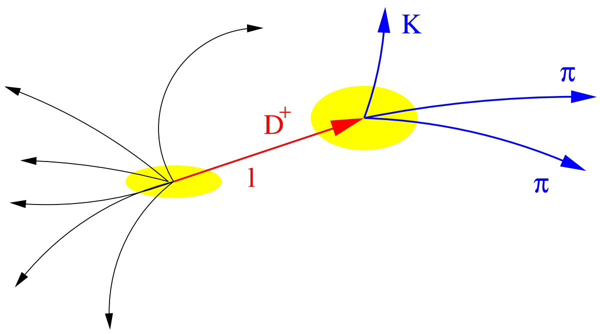




To fight Combinatorics
Vertex Information
is essential !!

Bkgr. Suppression $\mathcal{O}$ (300)

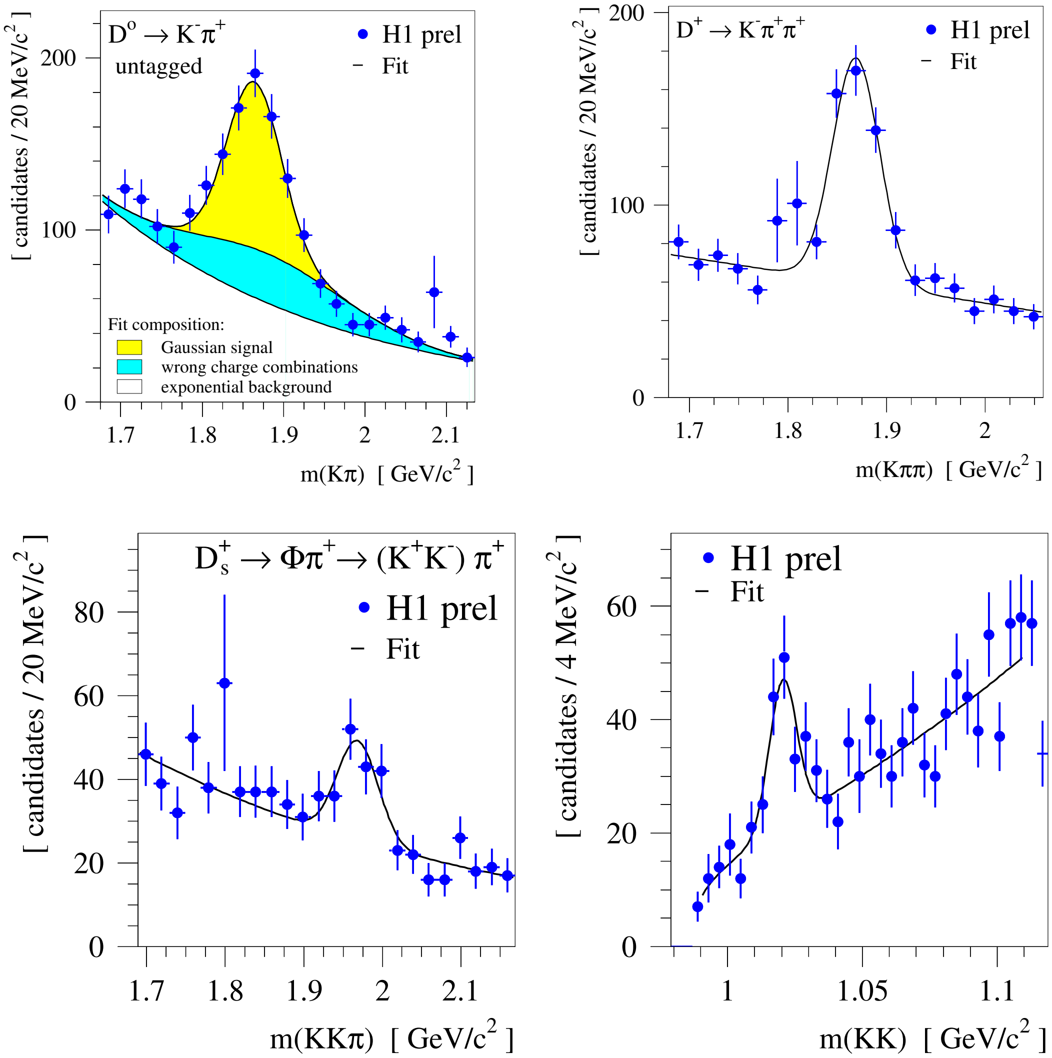
S/B Improvement $\mathcal{O}$ (50)



$$S_L = l/\sigma_l$$

Decay length significance

D-meson Production Cross Sections



using

H1 CST

Vertex Detector

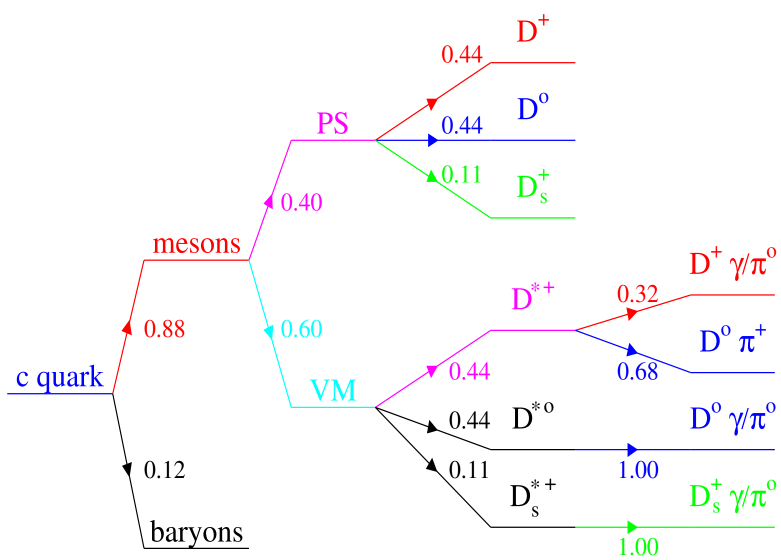
H1 Preliminary **47.8 pb^{-1}, 1999-2000**

Visible Cross Section *	D^+	D°	D_s^+	D^{*+}
$\sigma_{vis}(ep \to eDX)$ (nb)	2.16	6.53	1.67	2.90
stat. error on σ_{vis}	± 0.19	± 0.49	± 0.41	± 0.20
syst. error on σ_{vis}	$^{+0.46}_{-0.35}$	$^{+1.06}_{-1.30}$	$^{+0.54}_{-0.54}$	$^{+0.58}_{-0.44}$
AROMA LO prediction σ_{vis}	2.45	5.54	1.15	2.61
error on prediction	± 0.30	± 0.69	± 0.30	± 0.31

*
$2 < Q^2 < 100$ GeV^2
$0.05 < y < 0.7$
$p_\perp(D) > 2.5$ GeV
$|\eta(D)| < 1.5$

Good Agreement between Data and LO Prediction

CHARM FRAGMENTATION



D^+	D^o	D_s^+
0.156		
	0.156	
		0.040
0.076		
	0.159	
	0.234	
		0.061
0.232	0.549	0.101

$$f(c \to D) = \frac{\sigma_{vis}^{meas} - \sigma_{vis}^{MC}(ep \to b\bar{b} \to eDX)}{\sigma_{vis}^{MC}(ep \to c\bar{c} \to eDX)} \cdot f^{MC}(c \to D)$$

Fragmentation Factors	D^+	D°	D_s^+	D^{*+}
$f(c \to D)$	**0.202**	**0.658**	**0.156**	**0.263**
stat. error	± 0.020	± 0.054	± 0.043	± 0.019
syst. error	$^{+0.045}_{-0.033}$	$^{+0.115}_{-0.148}$	$^{+0.036}_{-0.035}$	$^{+0.056}_{-0.042}$
theo. error	$^{+0.029}_{-0.021}$	$^{+0.086}_{-0.048}$	$^{+0.050}_{-0.046}$	$^{+0.031}_{-0.022}$
world average	**0.232**	**0.549**	**0.101**	**0.235**
error	± 0.018	± 0.026	± 0.027	± 0.010

Good agreement between Measurements and World Averages

Charm Fragmentation: P_V, $R_{u/d}$, γ_s

$$P_V = \frac{VM}{PS+VM}$$
$$= \frac{f(c\to D^{*+})}{f(c\to D^+) + f(c\to D^{*+})\,BR(D^{*+}\to D^\circ\pi^+)}$$

$$P'_V = \frac{2\,f(c\to D^{*+})}{f(c\to D^+) + f(c\to D^\circ)}$$
$$= (\sigma_{tot}(D^\circ)/\sigma_{tot}(D^{*+}) - BR(D^{*+}\to D^\circ\pi^+))^{-1}$$

(Assuming Isospin Invariance, i.e. $f(c\to D^{*+}) = f(c\to D^{*\circ})$**).**

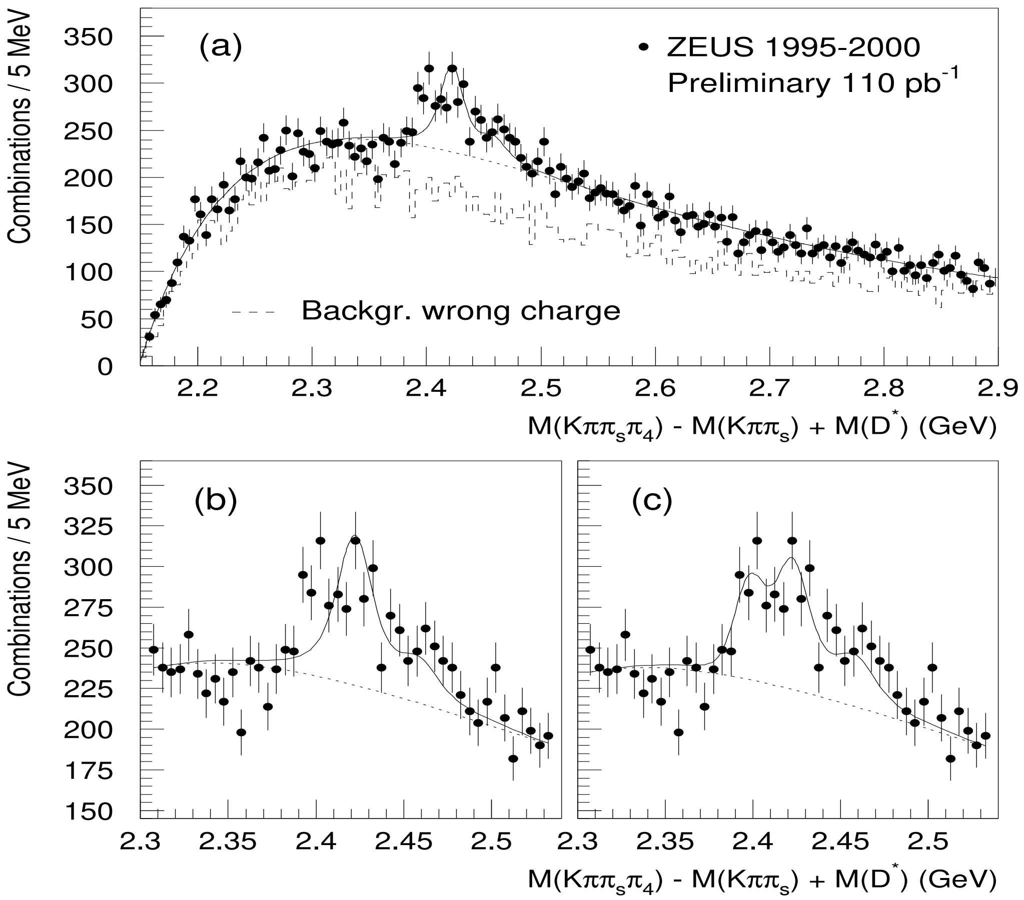
$$R_{u/d} = \frac{f(c\to D^\circ) - f(c\to D^{*+})\,BR(D^{*+}\to D^\circ\pi^+)}{f(c\to D^+) + f(c\to D^{*+})\,BR(D^{*+}\to D^\circ\pi^+)}$$

$$\gamma_s = \frac{2\,f(c\to D_s^+)}{f(c\to D^+) + f(c\to D^o)}$$

	H1 prel.	**W. A.**	**ZEUS**
P_V	$0.693 \pm 0.045 \pm 0.004 \pm 0.009$	0.601 ± 0.032	
P'_V	$0.613 \pm 0.061 \pm 0.033 \pm 0.008$		$0.546 \pm 0.045 \pm 0.028$ **(prel.)**
$R_{u/d}$	$1.26 \pm 0.20 \pm 0.13 \pm 0.04$	1.00 ± 0.09	
γ_s	$0.36 \pm 0.10 \pm 0.01 \pm 0.08$	0.26 ± 0.07	$0.27 \pm 0.05 \pm 0.07$

Charm Fragmentation Universal !

Neutral P-wave Charm states



Search for the narrow $L = 1$ states $D_1^\circ(2420)$ and $D_2^{*\circ}(2460)$:

"Extended" $\Delta M^{**} = M(K\pi\pi_s\pi_4) - M(K\pi\pi_s) + M(D^{*\pm}(2010)$

Fit with BW shapes, Gaussian resolution and background term

Fit includes the expected helicity spectra ($J^P = 1^+$ and 2^+)

$\Longrightarrow$ $N(D_1^\circ) = 526 \pm 65$, $N(D_2^{*\circ}) = 203 \pm 60$

Good fit, but for the excess of events at $M = 2.4$ GeV

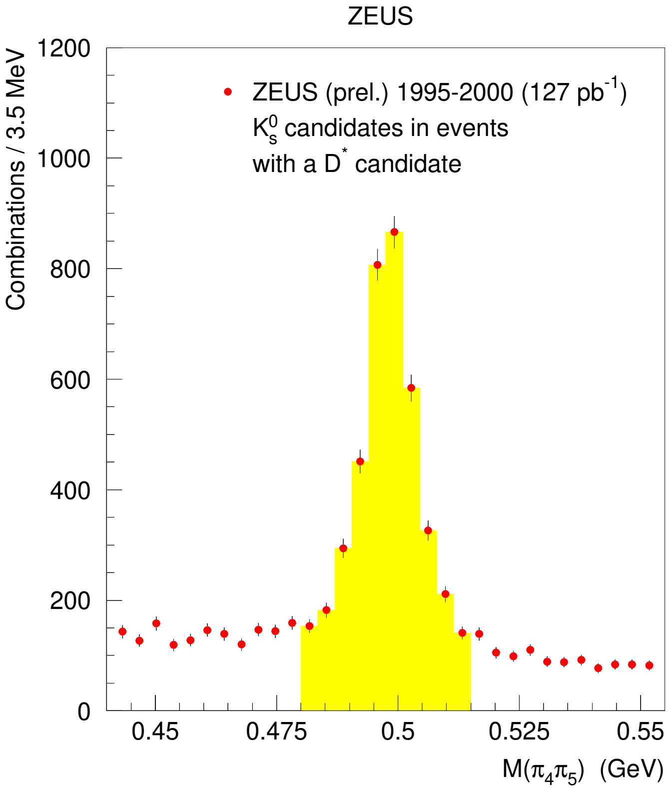
New State ? Interference effect ?

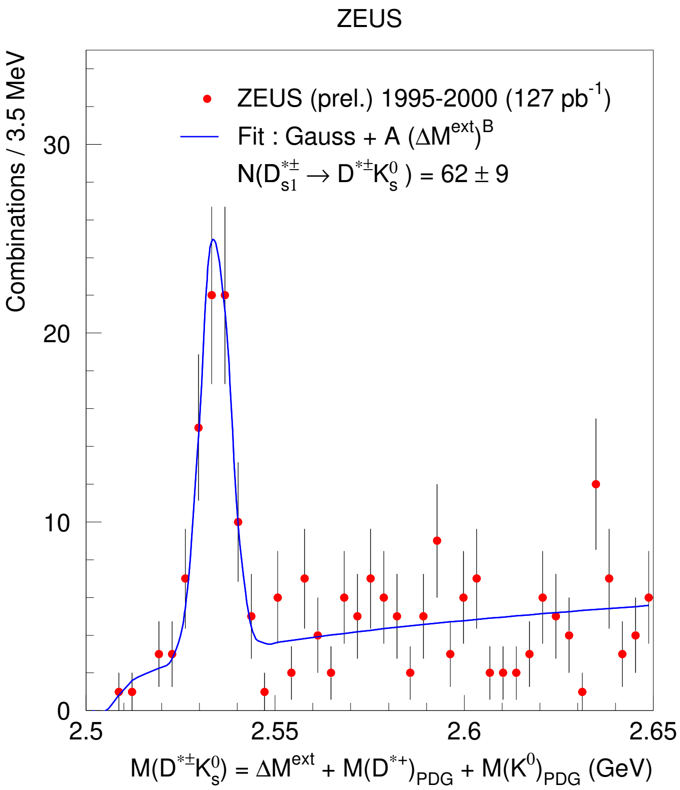
$$f(c \longrightarrow D_1^\circ) = 1.46 \pm 0.18\,^{+0.33}_{-0.27} \pm 0.06\%$$
$$f(c \longrightarrow D_2^{*\circ}) = 2.00 \pm 0.58\,^{+1.40}_{-0.48} \pm 0.41\%$$

ZEUS Prel.

In good agreement with previous measurements (e^+e^-)

OBSERVATION OF $D_{s1}^{\pm}(2536)$





Add K_S° to $D^{*\pm}$ candidates

"Extended" $\Delta M^{ext} = M(K\pi\pi_s\,\pi_3\pi_4) - M(K\pi\pi_s) - M(\pi_3\pi_4)$

62 ± 9 events $D_{s1}^{\pm}$ **$M = 2534.2 \pm 0.6 \pm 0.5$ GeV**

Statistics not enough to establish $J^P = 1^+$

(helicity distribution consistent both with $1^+, 1^-$ and 2^+)

$$\boxed{f(c \longrightarrow D_{s1}^{\pm}) = 1.24 \pm 0.18\,^{+0.08}_{-0.06} \pm 0.14(\mathrm{br.})\,\%}$$

ZEUS Prel.

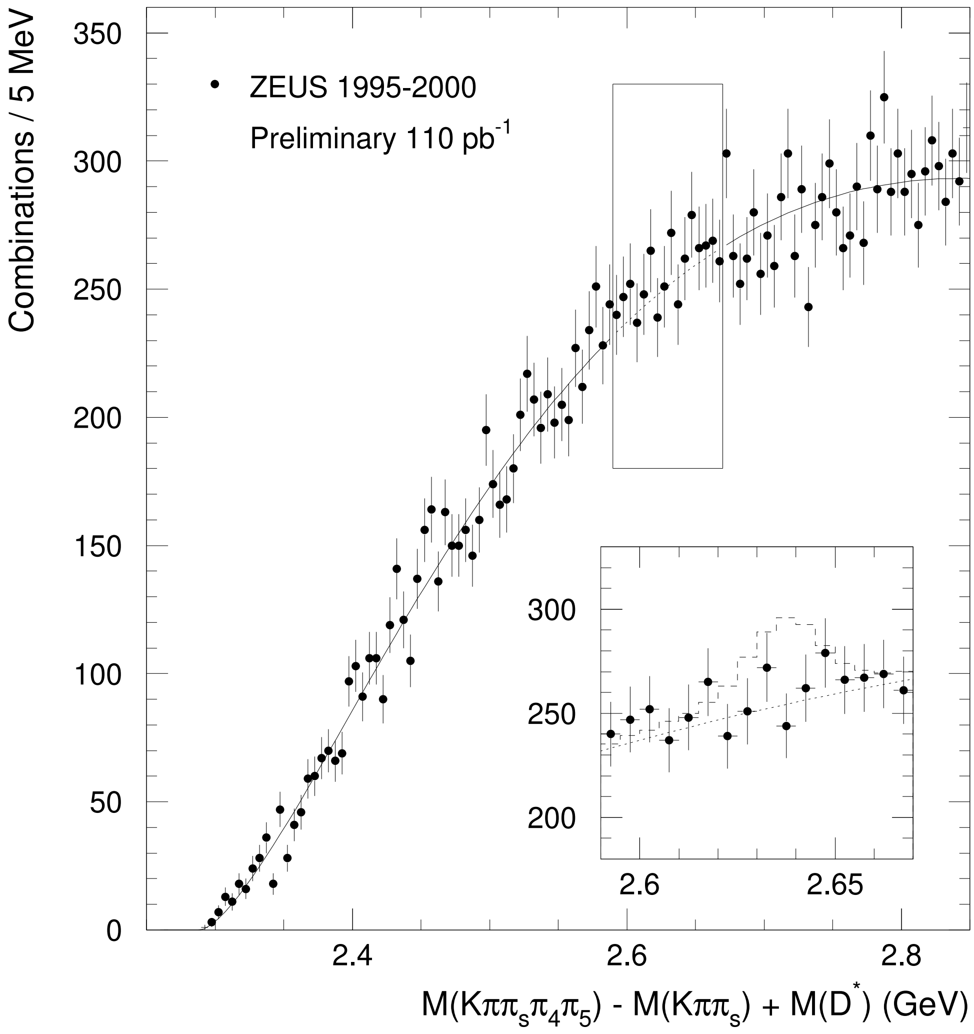
In good agreement with the previous measurements (e^+e^-)

Note:

$$f(c \longrightarrow D_{s1}^{\pm}) \; > \; \gamma_s\, f(c \longrightarrow D_1^{\circ})$$

$1.5 - 2\,\%$

Strangeness Suppression ?



DELPHI:
Narrow state seen at 2637 MeV decaying to $D^{*\pm}\pi^+\pi^-$

Search in ZEUS data: Add $\pi^+\pi^-$ to $D^{*\pm}$ candidates

"Extended" $\Delta M^{*\prime} = M(K\pi\pi_s\,\pi_4\pi_5) - M(K\pi\pi_s) + M(D^{*\pm})$

No signal $\Longrightarrow$ set upper limit

ZEUS Prel.

$$R_{D^{*\prime\pm}\to D^{*\pm}\pi^+\pi^-/D^{*\pm}} < 2.3\% \text{ (95\% C.L.)}$$

$$f(c \to D^{*\prime\pm}) \cdot BR(D^{*\prime+} \to D^{*+}\pi^+\pi^-) < 0.7\,\% \text{ (95\% C.L.)}$$

cf. Limit of 0.9 % set by OPAL

SUMMARY

CHARM SPECTROSCOPY

- **Very active field in HERA Physics !**
- **Visible Production Cross Sections measured**
  for the pseudoscalars D°, D^{+}, D_S^{+}
  and for the vector D^{*+}
- **Charm Fragmentation is Universal**
- **The P-wave states**
  $D_1^{\circ}(2420)$, $D_2^{*\circ}(2460)$ **and** $D_{s1}^{\pm}(2536)$
  are observed, with fragmentation factors
  in agreement with previous measurements
- **Radial Excitations: Not yet seen at HERA**
- **Charm Spectroscopy at HERA will greatly profit**
  from the HERA II Luminosity Upgrade,
  from the H1 and ZEUS Detector Upgrades:
  Triggering
  Tracking
  Vertex Detection