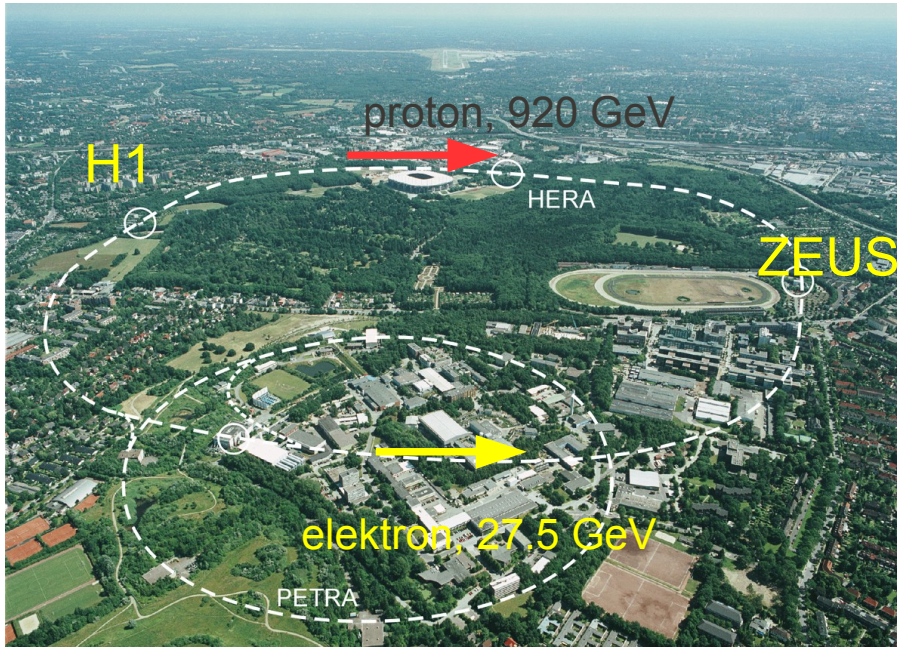
Meson Physics at HERA

Jan Figiel

Institute of Nuclear Physics, Kraków
on behalf of the H1 and ZEUS collaborations



... we investigate the **fundamental forces** and **particles** in e p collisions at highest energies – quark and gluon interactions, we verify the Standard Model and seek „new physics" ...
... among the other - studying **meson** production ...

Hadron production in e-p interactions: (1)

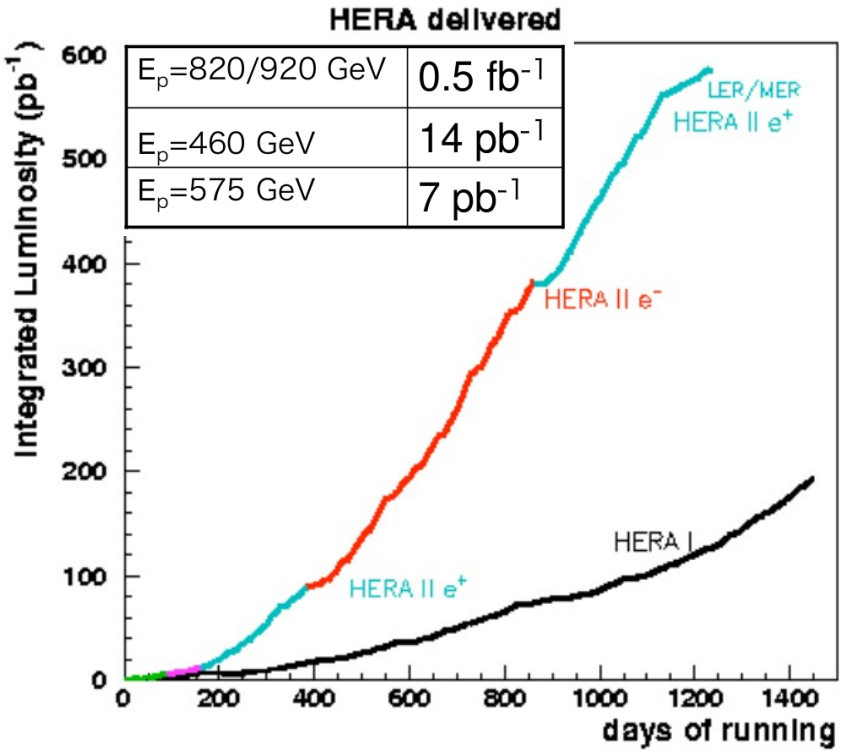
HERA: $e^{\pm}$ (27.5 GeV) – p (820/920/575/460 GeV)

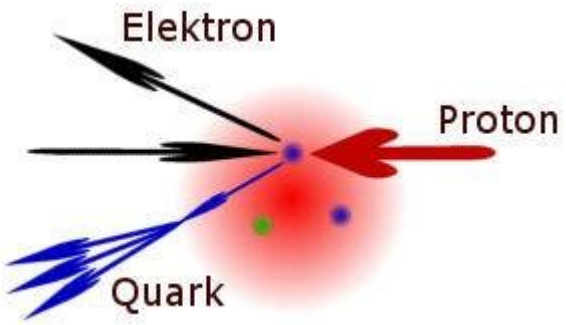
→ $\gamma^* p \rightarrow$ hadrons

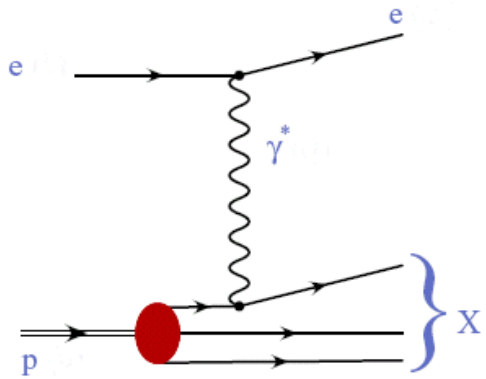
$Q^2 \approx 0$ (quasi-) photoproduction (PHP)
$Q^2 > 0$ deep inelastic scattering (DIS)

DIS (Quark/parton model, QPM):
γ^* proton = sum of inter. γ^* quark/parton
parton fragmentation → hadrons ≈ mesons (!)
= factorisation of the „hard" and „soft" interaction

- Proton structure, quarks, gluons...
- Quantum Chromodynamics (QCD)
  – theory of quarks and gluons interactions



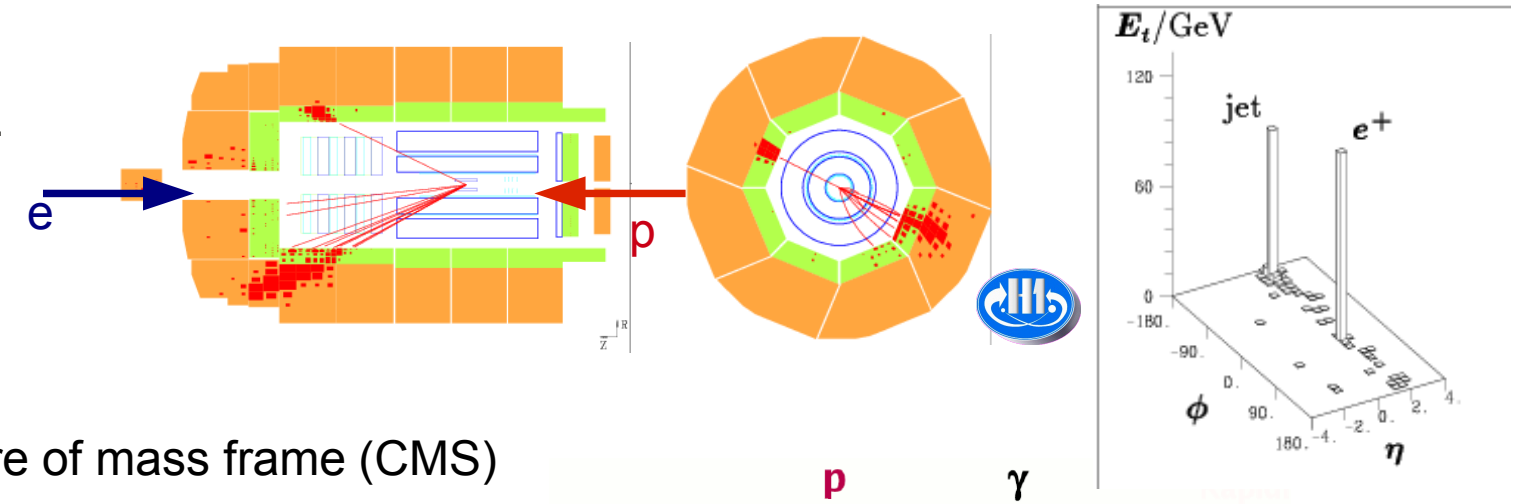




Q^2 – γ^* virtuality $(0 - 10^5\ \mathrm{GeV}^2)$
$s \approx E_e E_p$, $\sqrt{s} \approx 300$ GeV
W – $\gamma^* p$ CMS energy (20 -290 GeV)
$x \approx Q^2/W^2$ – Bjorken x = fractional parton momentum in proton Breit frame
$y \approx Q^2/(sx)$ – fractional energy transfer to p

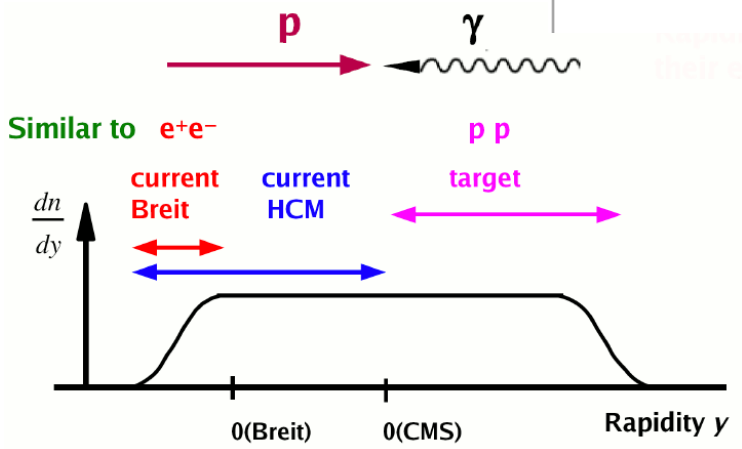
Hadron production in e-p interactions: (2)

- LABoratory frame...



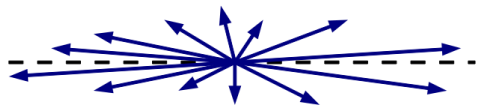
- $\gamma^* p$ (hadronic) centre of mass frame (CMS)
- Breit frame: $q(\gamma^*) = (0,0,0,Q)$

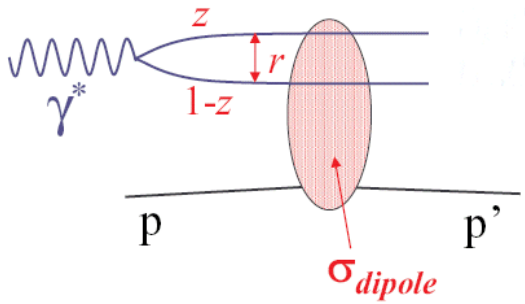
$x_F = p_L/p_{max}$, Feynmann x
$y \approx \eta = -\ln(\tan(\theta/2))$, (pseudo-)rapidity
p_T = transverse momentum



- proton rest frame:

diffraction (coherence) condition:
fluctuation "length" ($\gamma^* \rightarrow$ dipol qq) =
$= 2E_\gamma/(m_{qq}^2 + Q^2) > 1$ fm
$\rightarrow$ x < 0.01





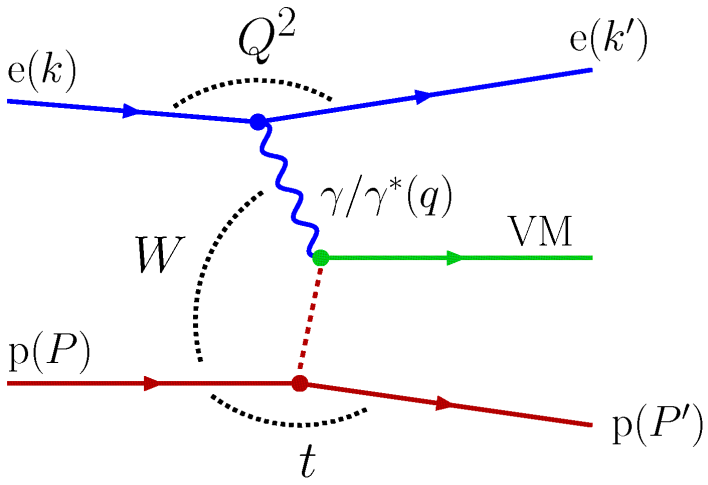
At HERA we observe **diffraction**, (also at $Q^2 >> 0$) and it makes ~10% of the visible cross section !

Meson physics at HERA

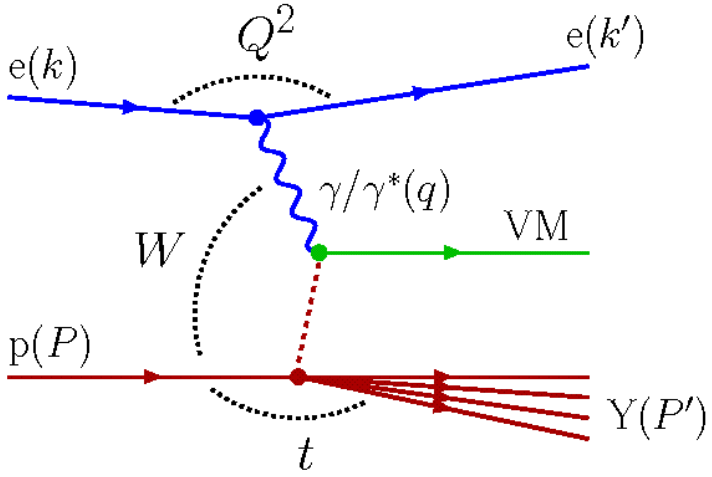
- Diffractive vector meson photo- and electro-production
- Inclusive (inelastic) meson production
- Heavy flavoured meson production
- K^0 K^0 spectra - search for a glueball

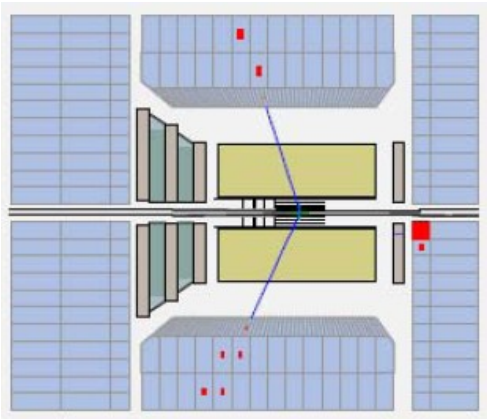
Diffractive vector meson production in e-p

'elastic' (exclusive)



'proton-dissociative'

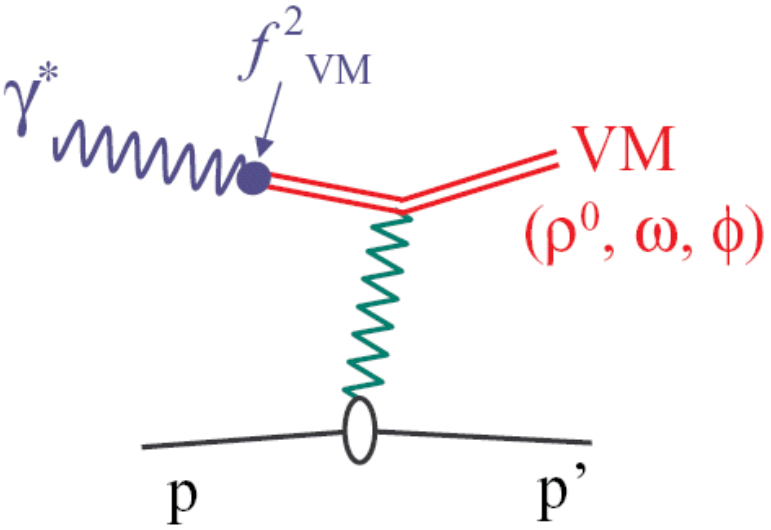




VM	vector meson	$\rho, \omega, \varphi, J/\psi...$
Q^2	photon virtuality	$Q^2 = -q^2 = -(k - k')^2$
W	γp CMS energy	$W = (q + p)^2$
t	(4-mom. transfer)^2	$t = (p - p')^2$

→ simultaneous control of different scales: Q^2 , $|t|$, M_{VM}

Diffractive vector meson production in e-p ("elastic") (1)



Vector Dominance Model + Regge

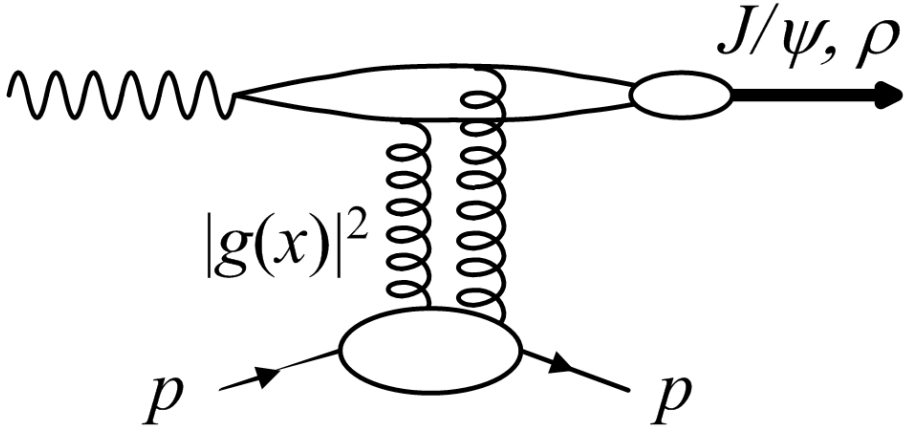
$$\gamma^* p \to VM\, p = (\gamma^* \to VM) \otimes (VM\, p \to VM\, p)$$

$VM\, p \to VM\, p \Rightarrow$ DL IPomeron exchange

$d\sigma/dt \sim \exp(-b(W)t), \quad b \sim R_{int}^{\,2} \approx 10\ \mathrm{GeV}^{-2}$

$b(W) = (b_{VM} + b_p + \alpha' \ln(W^2))$ ("shrinkage")

$\sigma_{VMp} \sim W^{4(\alpha 0-1)}/b(W) \sim W^{\delta}, \ \delta \approx 0.22$



Perturbative QCD

Large Q^2, M_{VM} or $|t| \to$ small qq dipol

QCD Pomeron exchange:

$\geq$ 2 gluons (colour singlet)

$\sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7}$!!!

$b \ll 10\ \mathrm{GeV}^{-2}$, weak shrinkage

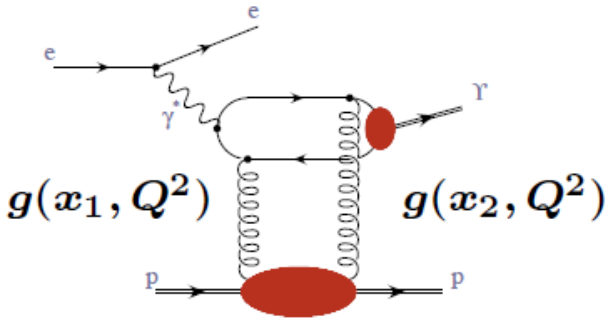
VM@HERA: transition "soft" → "hard" interaction; testbed for QCD scales

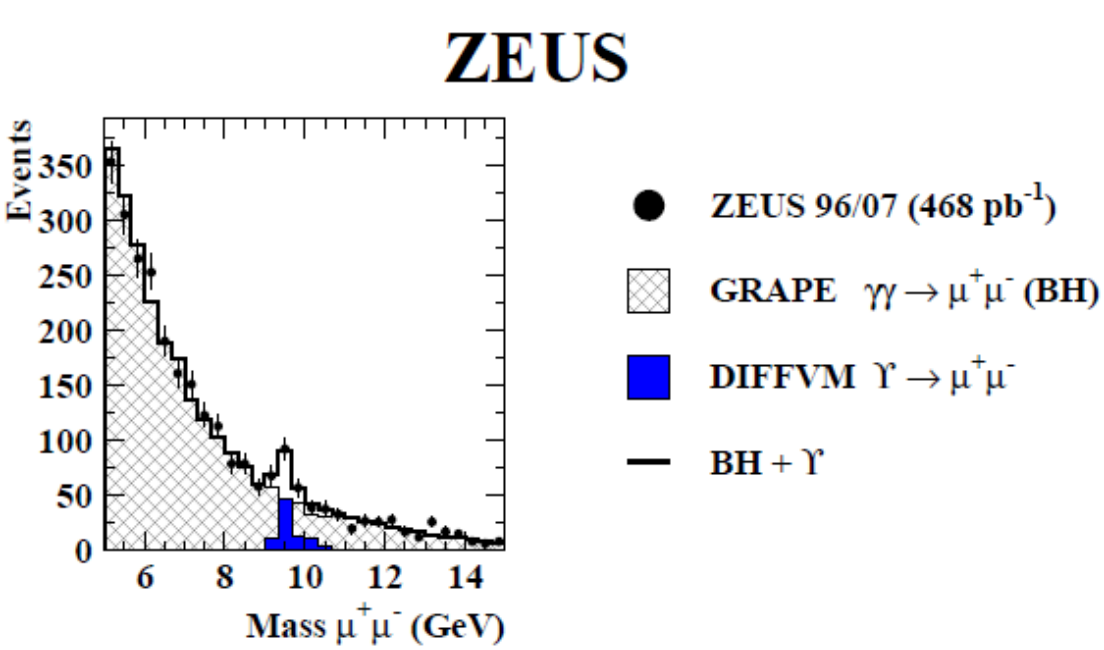
"soft" Pomeron → QCD Pomeron

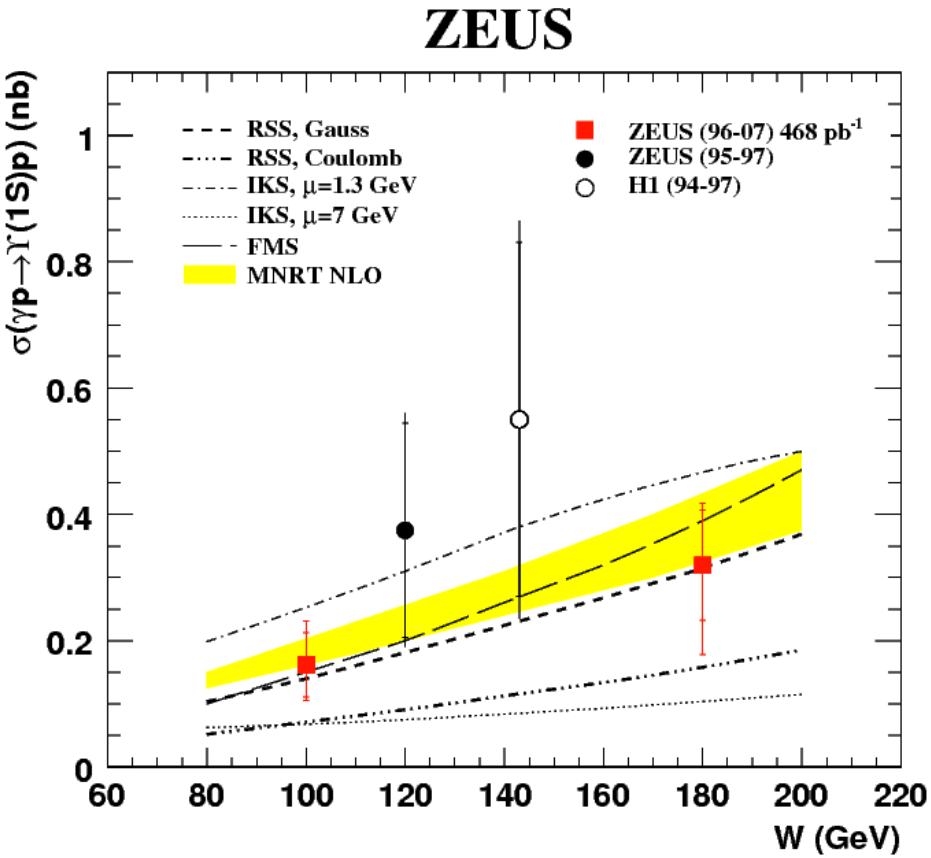
Diffractive vector meson production in e-p ("elastic") (2)

Upsilon photoproduction: ZEUS, Phys. Lett. **B680** (2009) 4

$$\gamma\, p \rightarrow \Upsilon\, p \rightarrow \mu^+\mu^-\, p$$





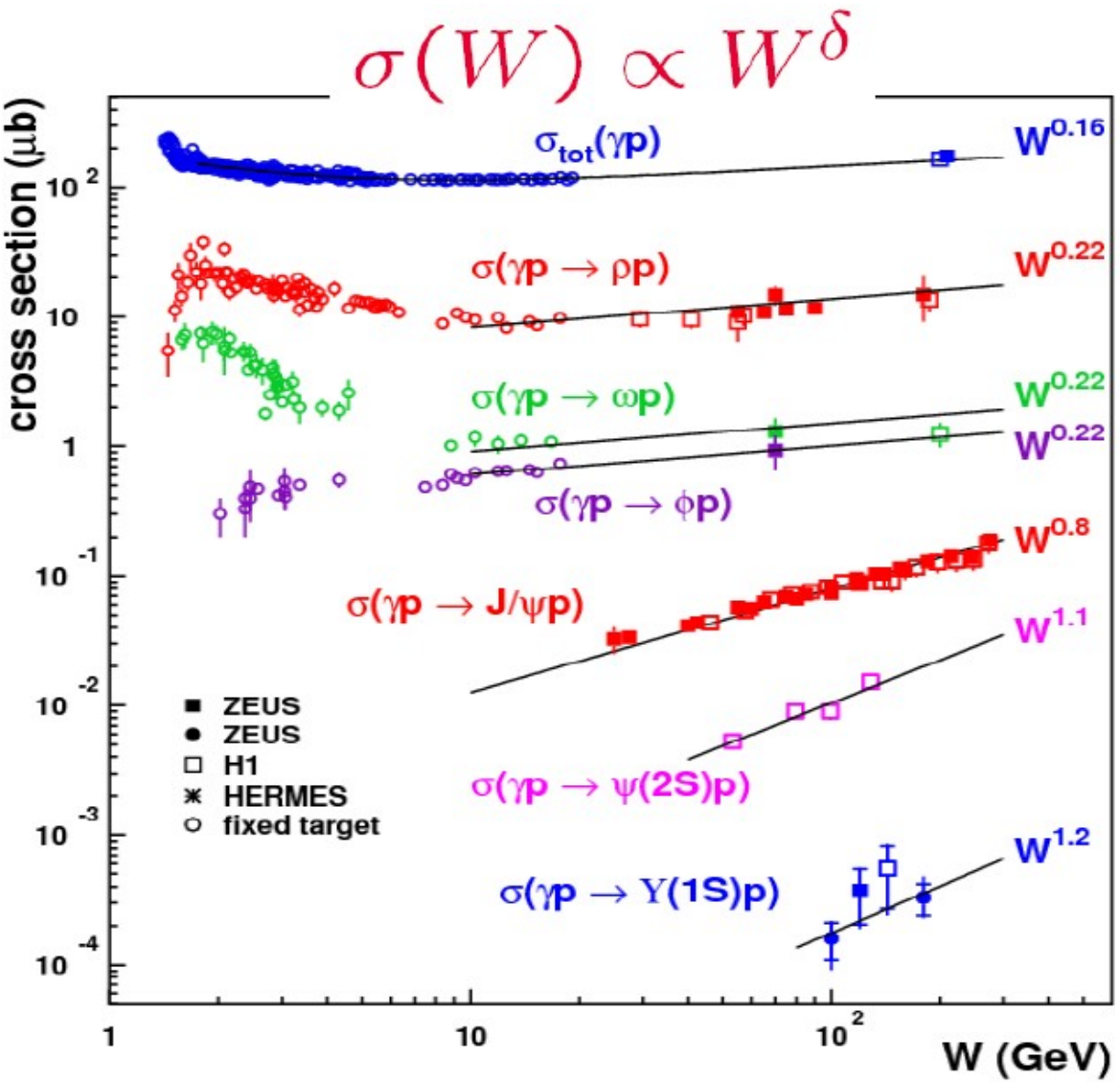


pQCD models sensitive to Y wave function and hard scale value

$\sigma \sim W^{\delta}$: data: $\delta = 1.2 \pm 0.8$,
MNRT NLO: $\delta \approx 1.2$

FMS – Frankfurt, McDermott, Strikman (CTEQ4L)
MNRT NLO – Martin, Nockles, Ryskin, Teubner
IKS – Ivanov, Krasnikov, Szymanowski
RSS –Rybarska, Schaefer, Szczurek

VM photoproduction: energy dependence

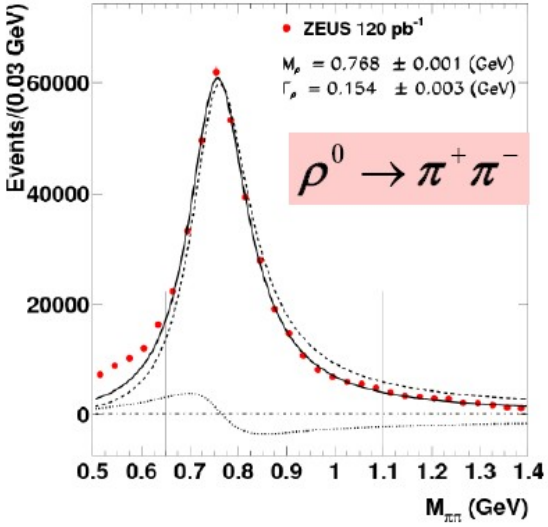


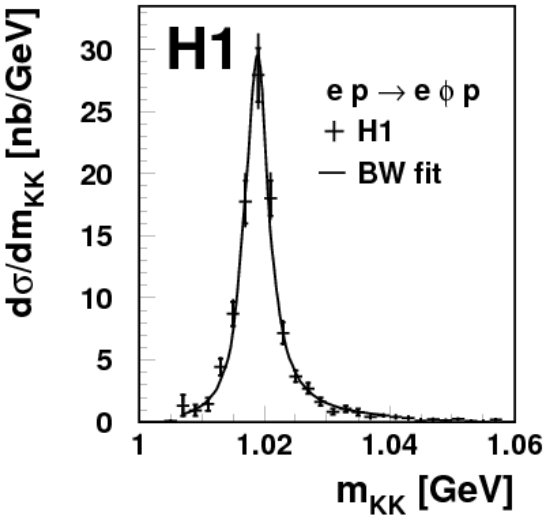
- The heavier VM –
  – the stronger W-dependence,
- VM mass sets the hard scale

Diffractive vector meson production in e-p ("elastic") (4)

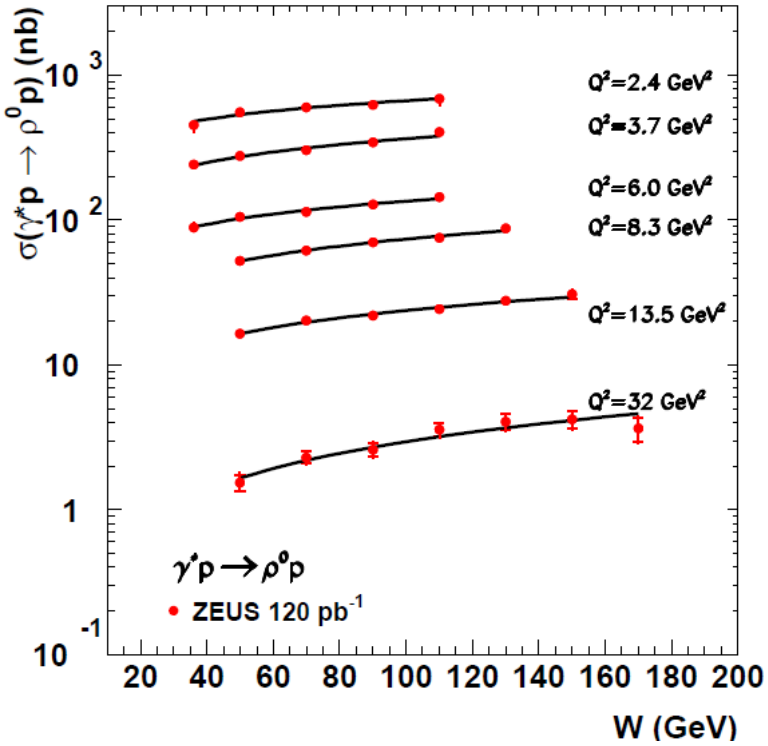
Diffractive electroproduction of ρ^0 and φ mesons: H1, DESY 09-093,
Exclusive ρ^0 production in DIS at HERA: ZEUS, DESY 07-118, PMC Physics A1,6

$\gamma^* p \to \rho p$, $\rho \to \pi^+\pi^-$
$\gamma^* p \to \varphi p$, $\varphi \to K^+K^-$

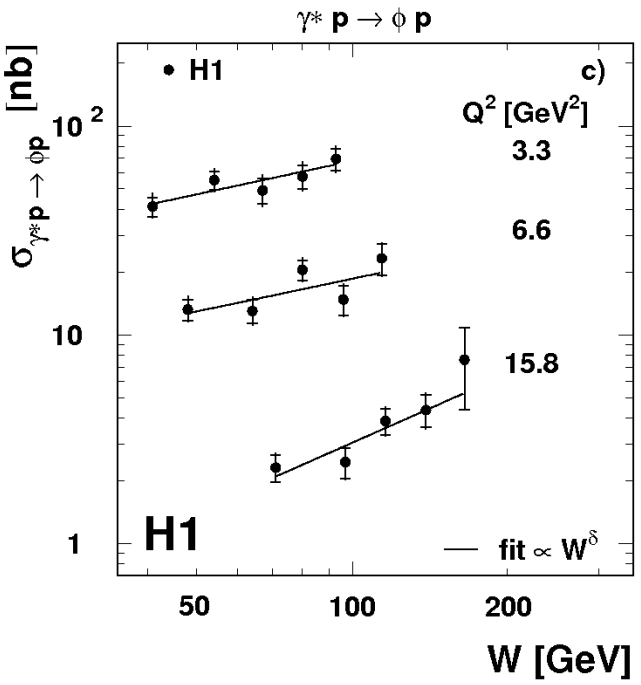




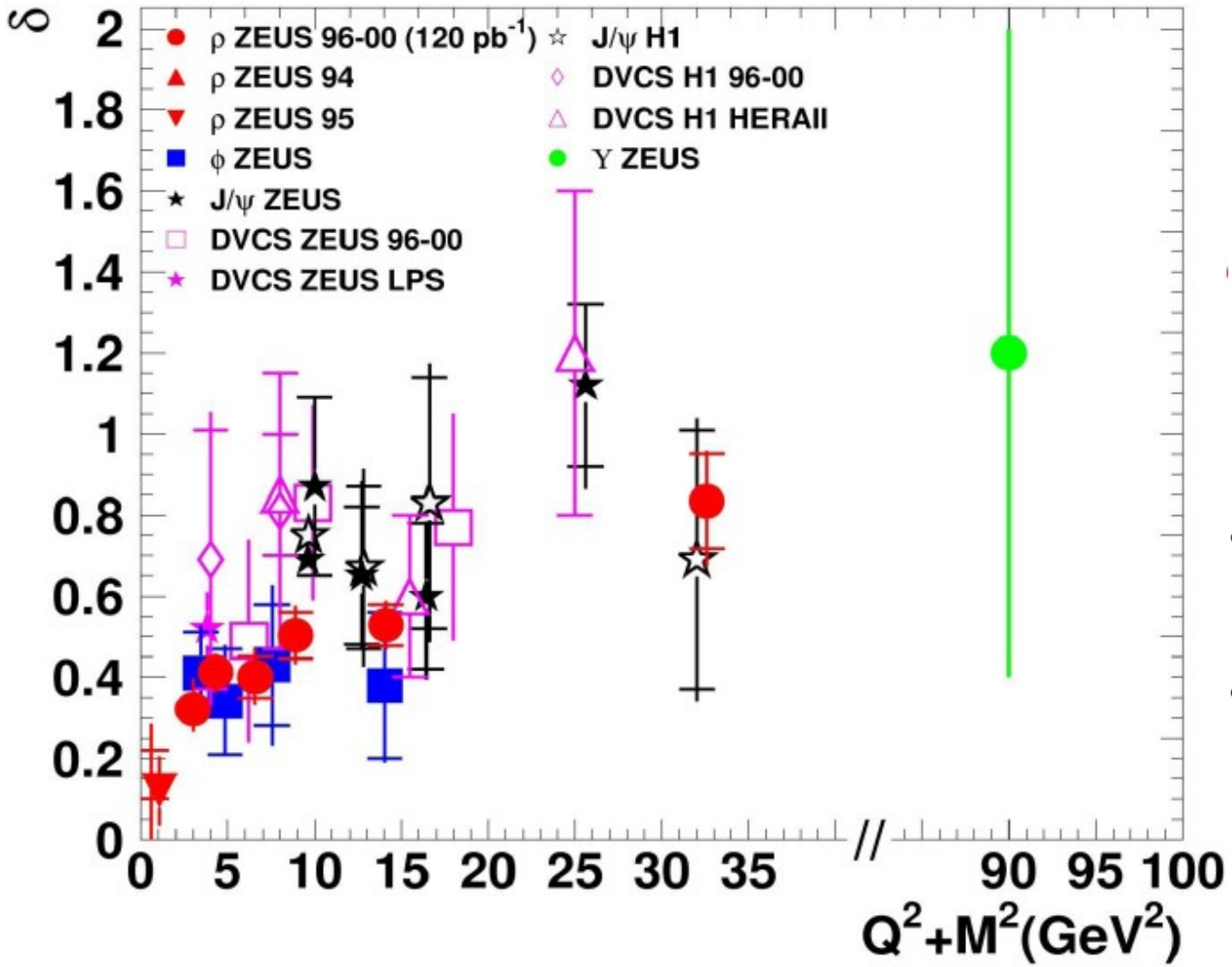
ρ: ZEUS



φ



VM photo- and electroproduction: energy dependence

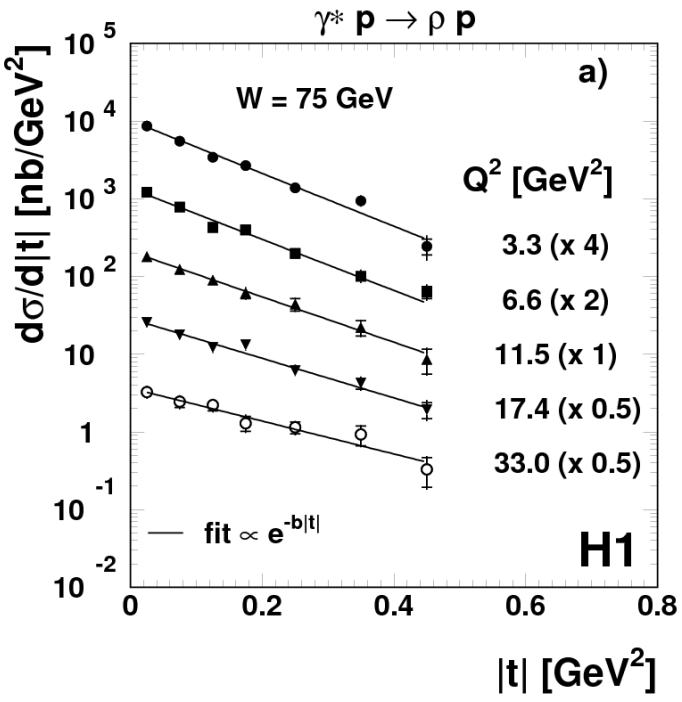


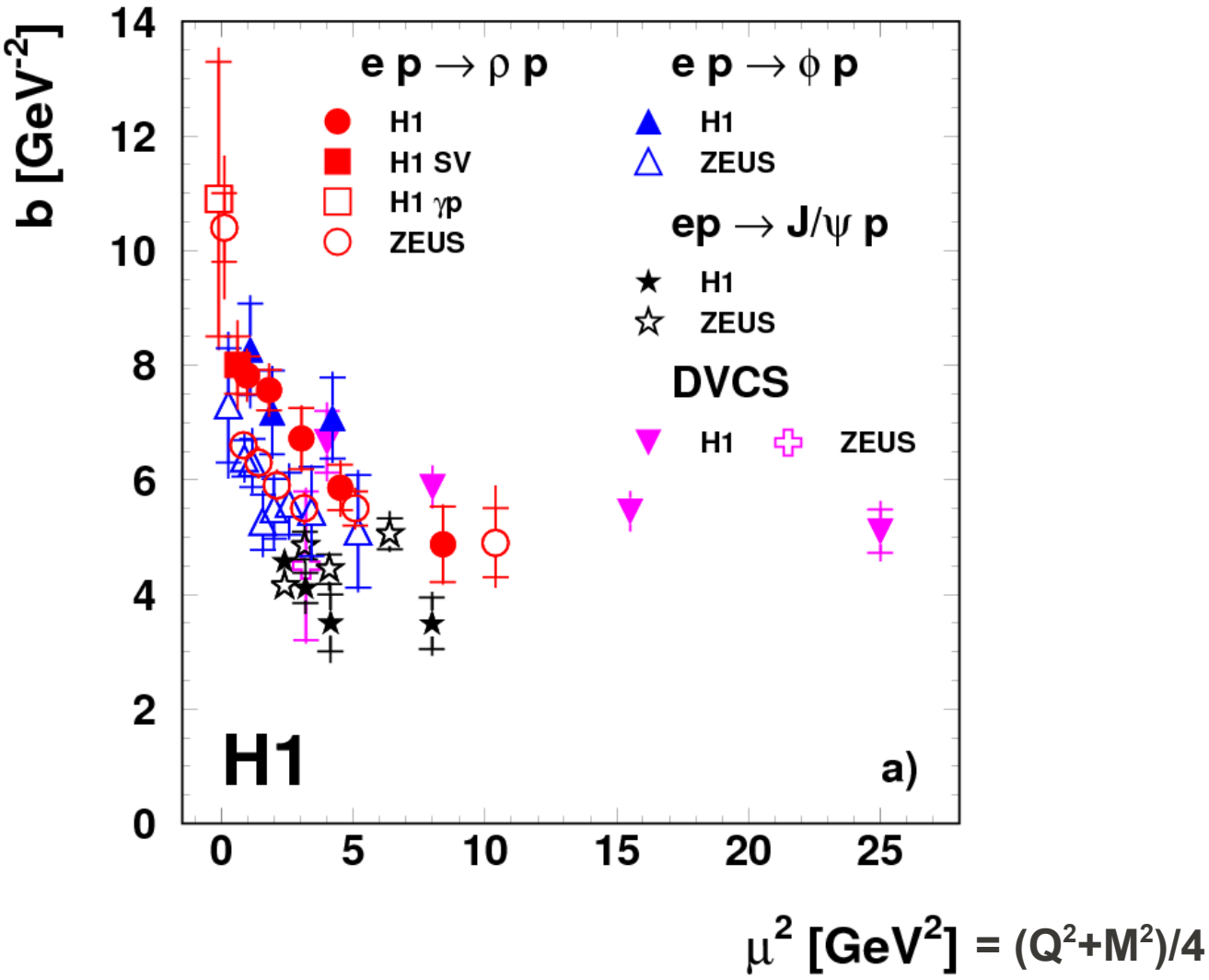
$$\sigma \sim W^{\delta}$$

- The larger Q^2 and/or M_{VM} – – the stronger W-dependence,
- Q^2+M^2 scale controls "soft" - "hard" regime transition

VM photo- and electroproduction: differential cross-section

$$d\sigma/dt \sim e^{-b|t|}$$





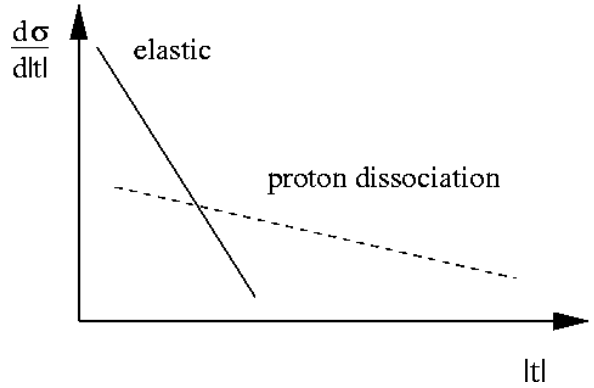
The larger Q^2 and/or M_{VM} – the smaller slope b (~ interaction range)

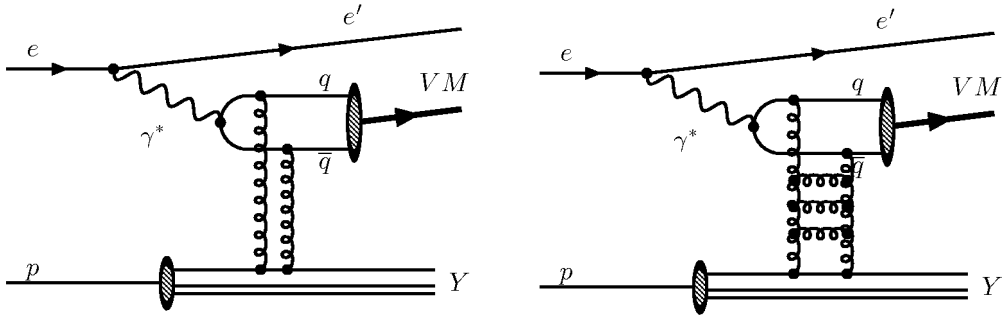
Diffractive VM photoproduction (p-dissociative) (1)

Colourless exchange (Pomeron) in QCD = ?...

$\gamma\, p \rightarrow J/\psi\, Y \rightarrow \mu^+ \mu^-\, Y$, proton dissociates...

Large $M_{J/\psi}$, $|t| \rightarrow$ perturbative QCD





$d\sigma/dt \sim |t|^{-n}$

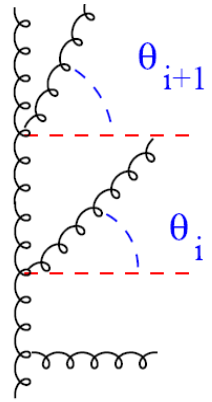
- 2-gluon exchange – $\sigma(W) = \text{const}$!
- gluon "ladder" exchange →

  DGLAP – $\sigma(W) \approx \text{const}(W)$

  BFKL – $\sigma(W) \uparrow$, $W \uparrow$...!

Gluon cascade dynamics:

- Dokshitzer, Gribov, Lipatov, Altarelli, Parisi (DGLAP): gluon transverse momenta ordered, ewolution in Q^2
- Balitsky, Fadin, Kuraev, Lipatov (BFKL): no ordering of gluon transverse momenta, ewolution with x (1/W)

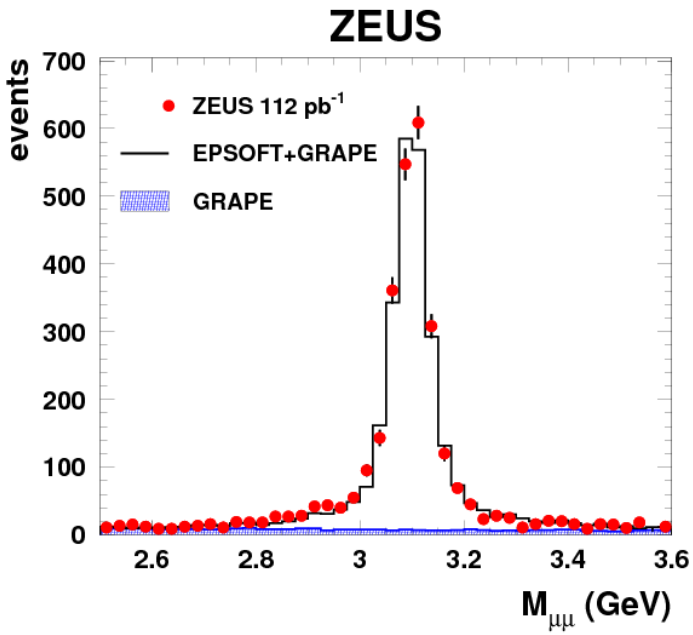


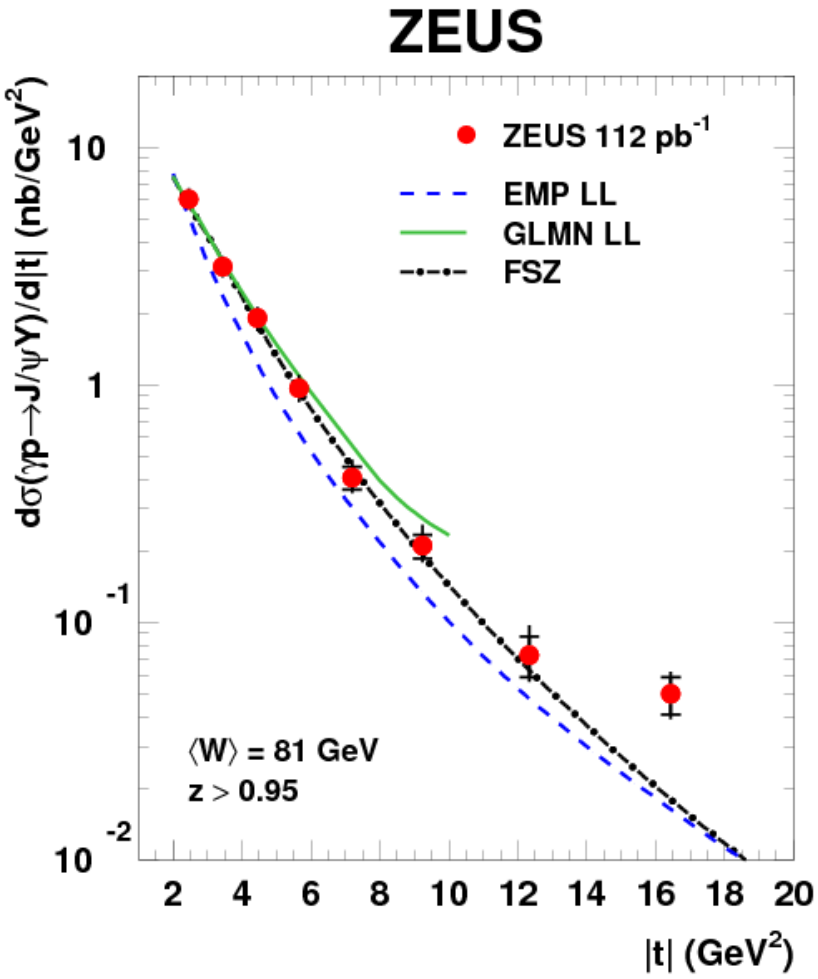
Diffractive VM photoproduction (p-dissociative) (2)

Measurement of J/Ψ Photoproduction at large t...

ZEUS, DESY 09-137, accepted in JHEP

$$\gamma\, p \rightarrow J/\psi\, Y \rightarrow \mu^+ \mu^-\, Y$$





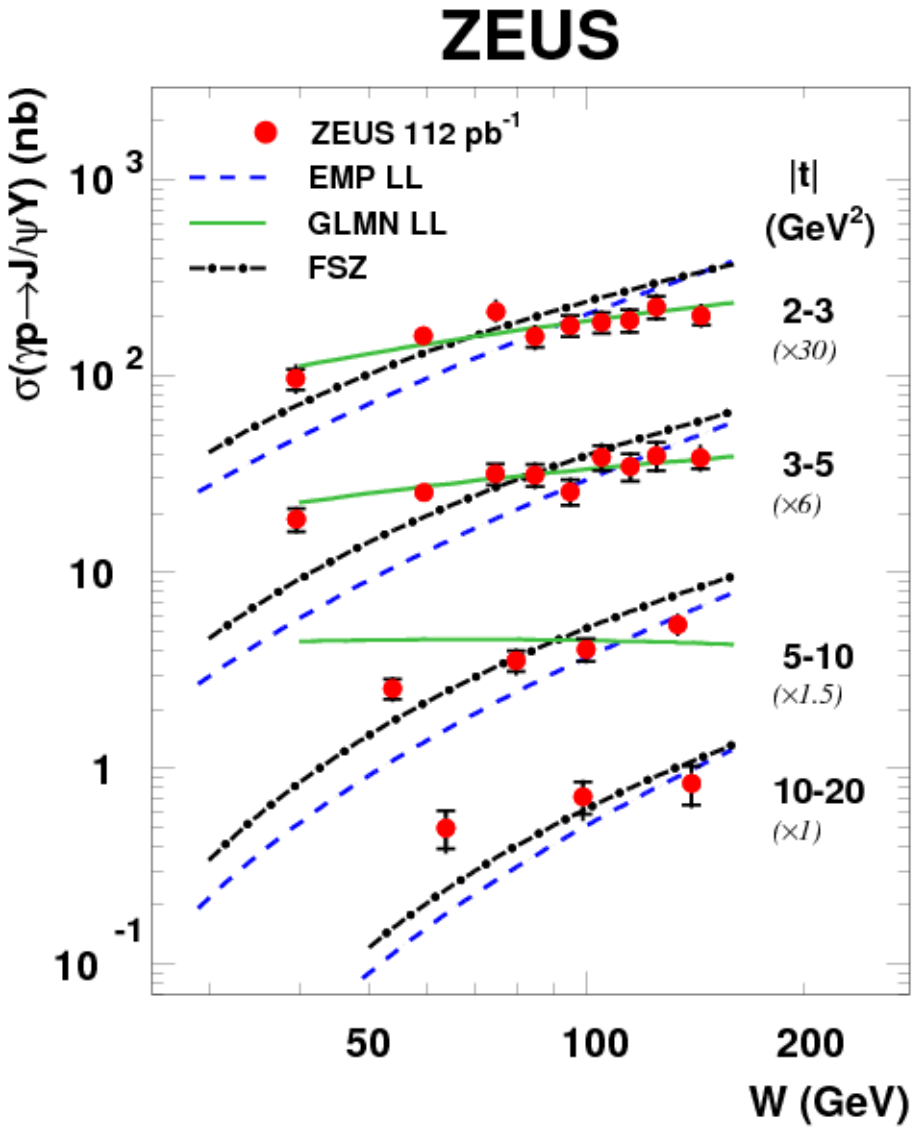
DGLAP–GLMN LL:
E.Gotsman, E.Levin, U. Maor, E. Naftali Phys. Lett. B532 (2002) 37

BFKL LL – EMP LL:
R.Enberg, L. Motyka, G. Poludniowski, Eur. Phys. J. C26, (2003) 219

FSZ:
L. Frankfurt, M.Strikman, M. Zhalov, Phys. Lett. B670, (2008) 32
L. Frankfurt, M.Strikman, Phys. Rev. Lett. 63 (1989) 1914

DGLAP (GLMN LL) –
– ok up to $|t| = 5$ GeV^2
BFKL (EMP LL) – too steep,
FSZ – ok up to $|t| = 12$ GeV^2

$\gamma p \rightarrow J/\psi Y, \quad 50 < W < 150$ GeV



DGLAP (GLMN LL) – ok up to |t|=5 GeV2,

BFKL (EMP LL, =0.16) and **FSZ** –
– too strong W-dependence

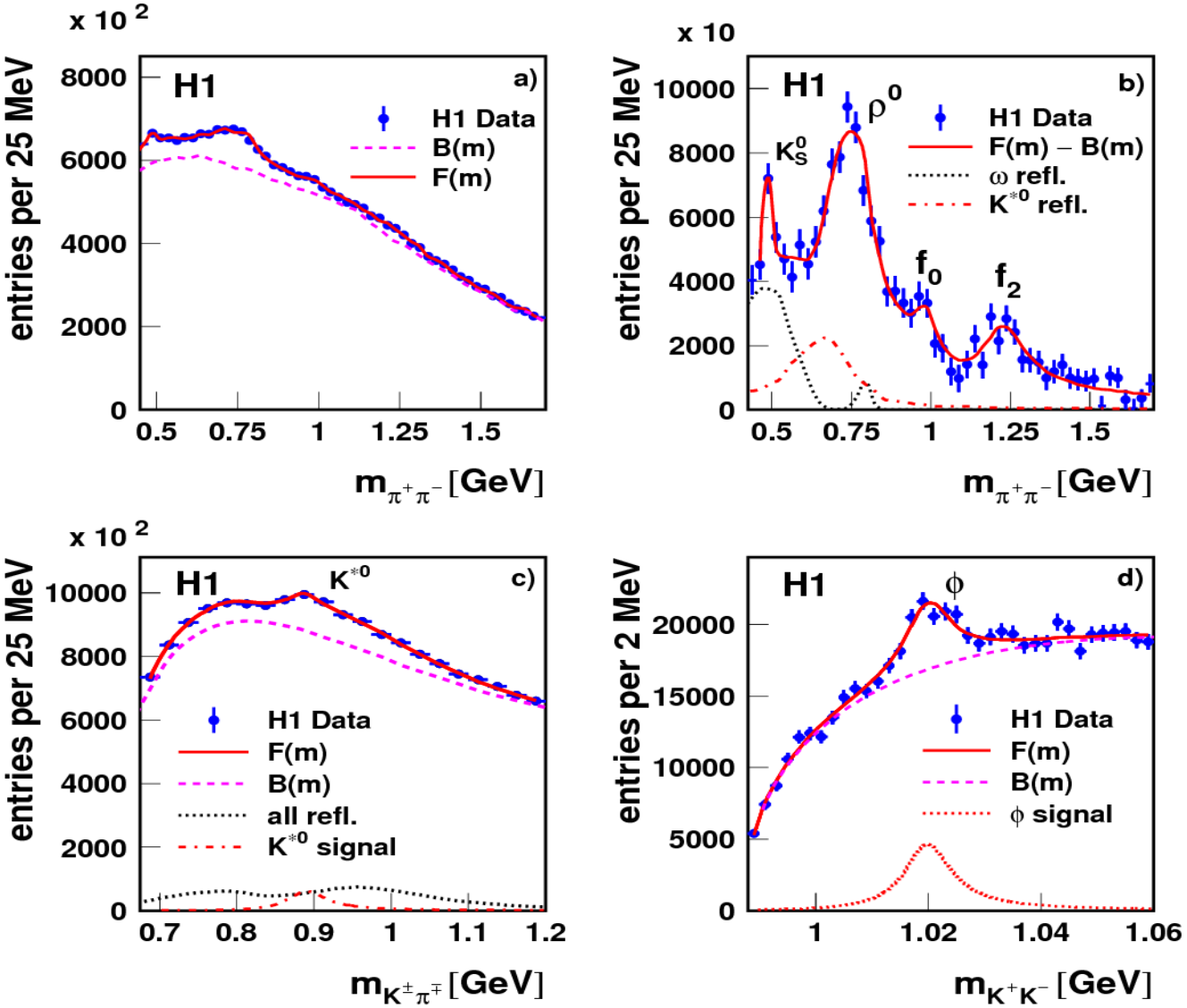
- No clear evidence for BFKL dynamics...

Inclusive meson production at HERA (1)

Inclusive photoproduction of ρ^0, K^{*0}, Φ mesons at HERA,

H1: Phys. Lett. B **673** (2009) 119

$\rho^0 \to \pi^+\pi^-$, $K^{*0} \to K\pi$, $\Phi \to K^+K^-$

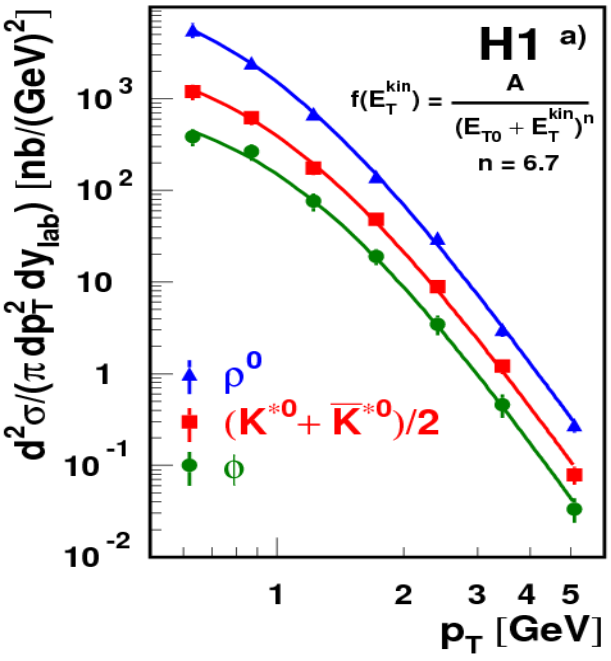


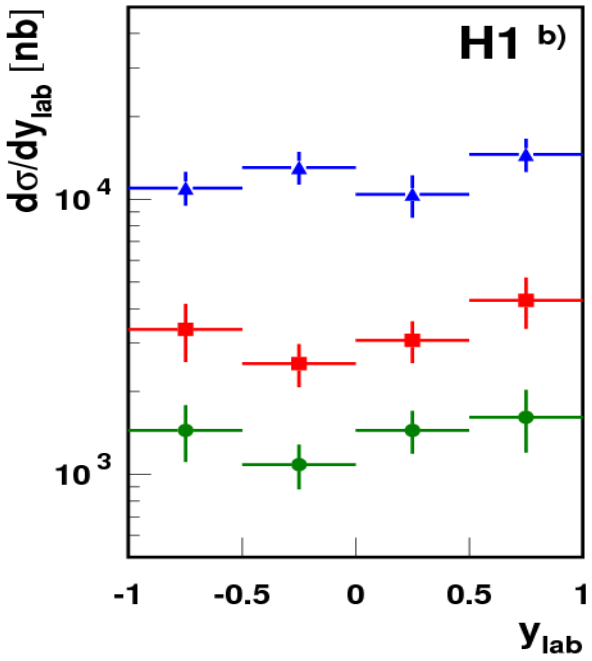
174 < W < 256 GeV

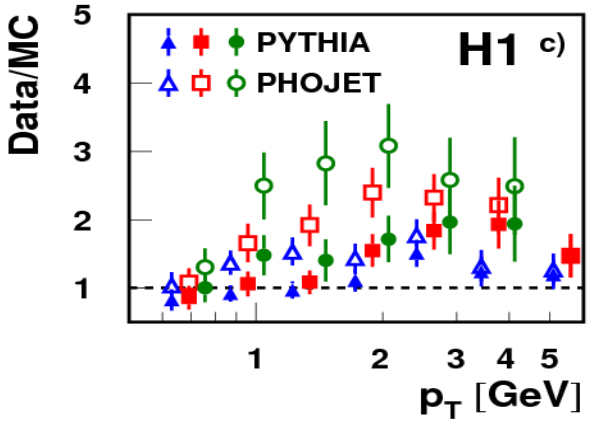
$\Rightarrow$ <W> = 210 GeV

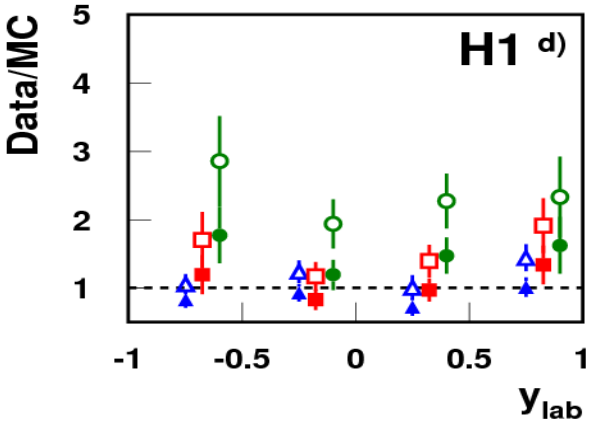
distr(m) = signal + reflection + + comb. backgr.

ρ^0, K^{*0} and Φ: differential cross sections





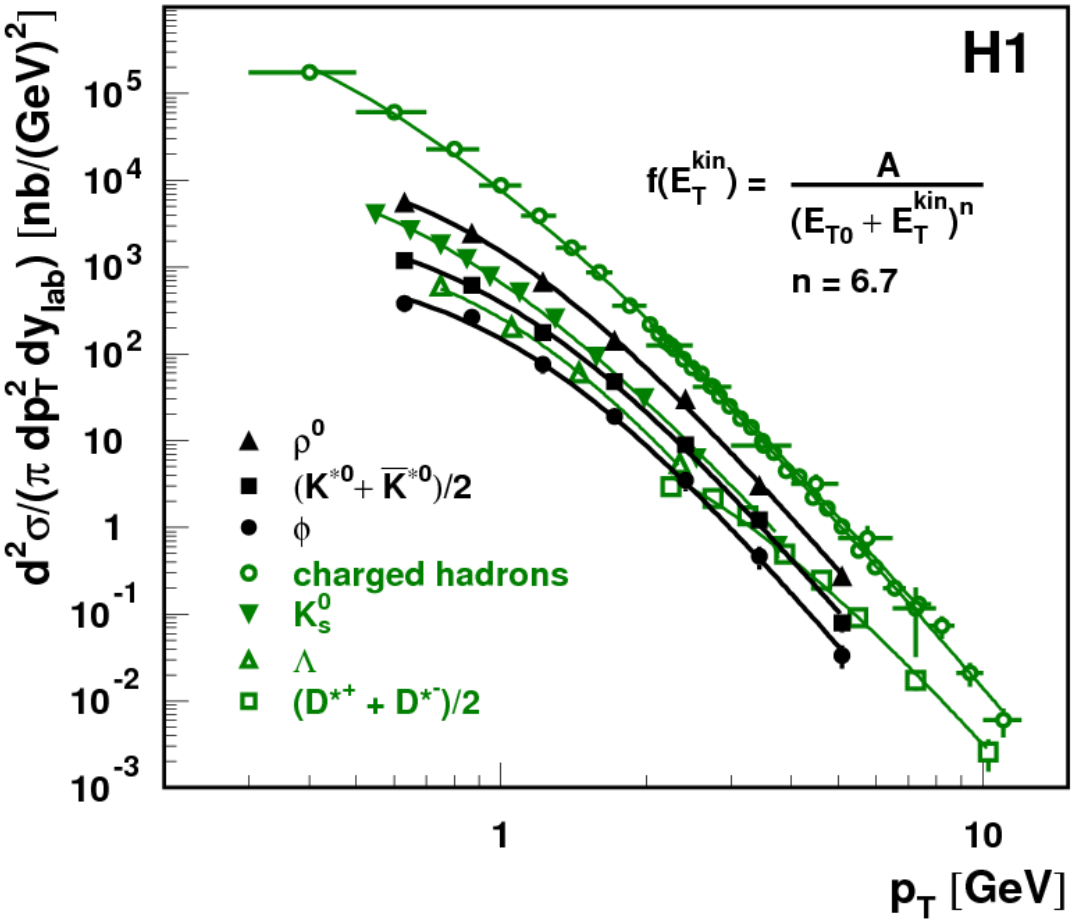




PHOJET10: DPM
PYTHIA6.2: LO QCD ME
with PS and Lund string model
for hadronisation

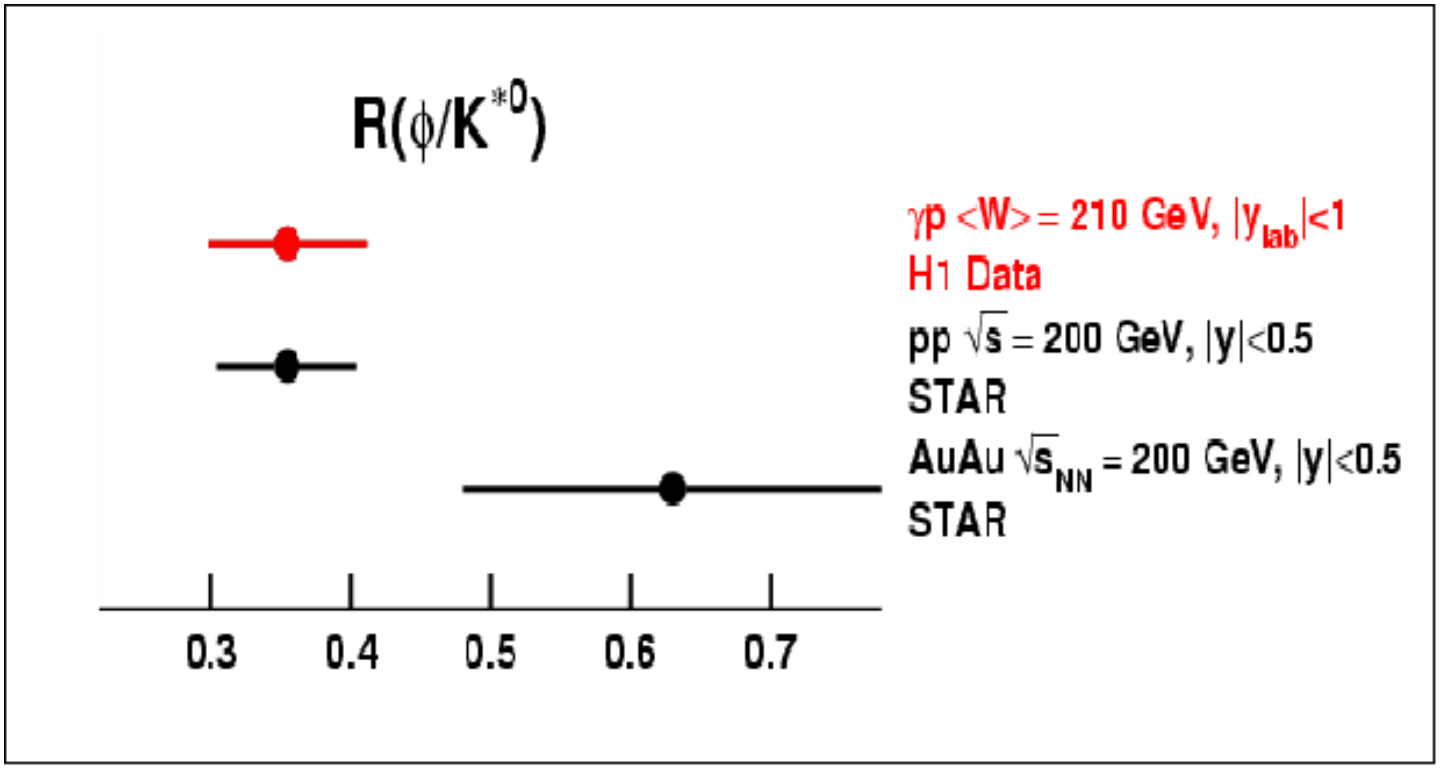
- Power law p_t spectra
- Flat rapidity distributions
- PYTHIA and PHOJET models fail to describe p_t spectra

ρ^0, K^{*0} and Φ: differential cross sections



- All cross sections are described by power law distribution with the same power n = 6.7 (→ the same average transverse kinetic energy)
- The same average transverse kinetic energy of various mesons → → thermodynamic picture of hadron production...

The cross section ratio R(Φ/K*⁰) : comparison with RHIC



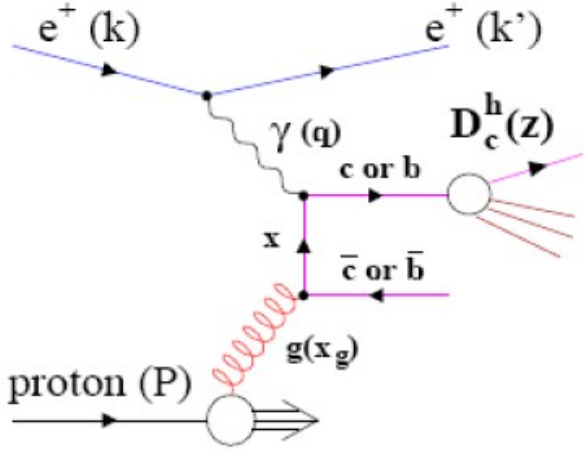
The cross-section ratio R(Φ/K*⁰) in γ p interations is:

- similar as in pp interactions ,
- below the result for Au Au collisions.

Heavy flavoured meson production at HERA (1)

Measurement of **D+-** and **D0** production in DIS using a lifetime tag at HERA
ZEUS, DESY 08-201, EPJ **C63** (2009) 171

- Predominantly boson-gluon fusion
- Test of pQCD
- Multi-scale problem: Q^2, M_c^2, p_T^2
- sensitive to gluon density in the proton (PDFs)



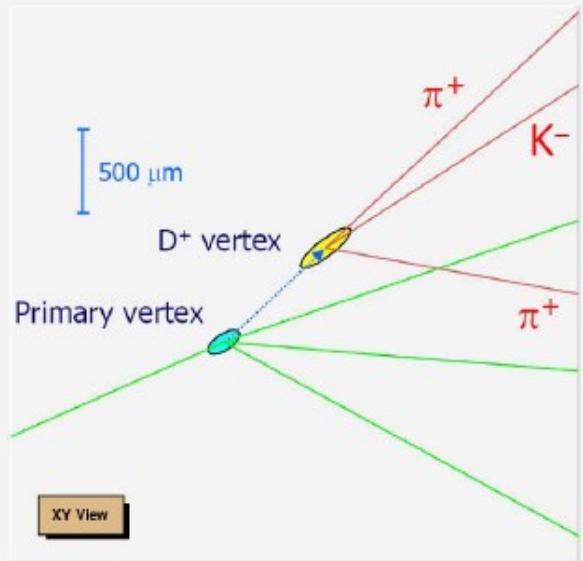
NLO QCD model for charm and inclusive charm meson production in DIS: HVQDIS

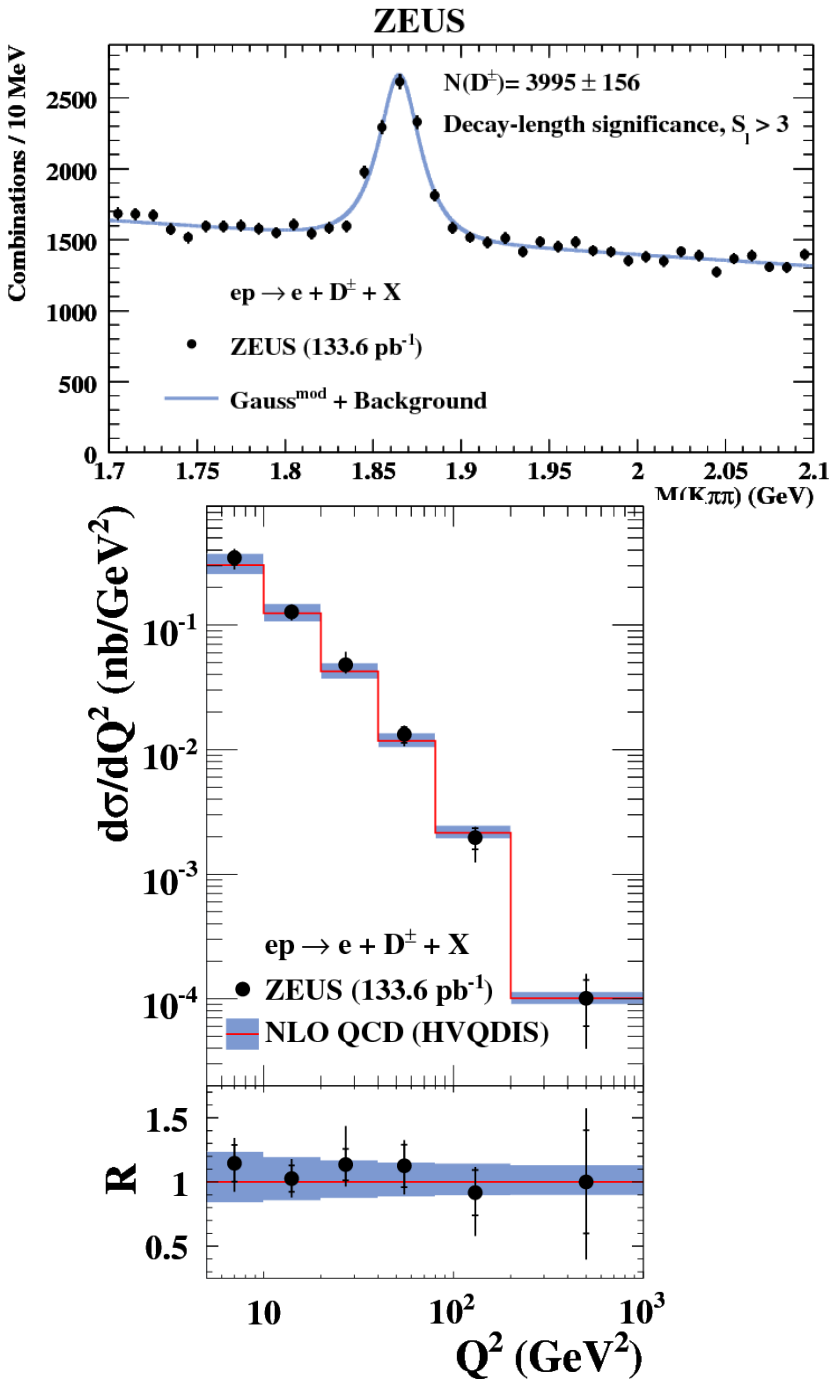
Reconstructed decay modes:

$$D^+ \rightarrow K^- \pi^+ \pi^- \quad (+ \text{c. c.})$$
$$D^0 \rightarrow K^- \pi^+ \quad (+ \text{c. c.})$$

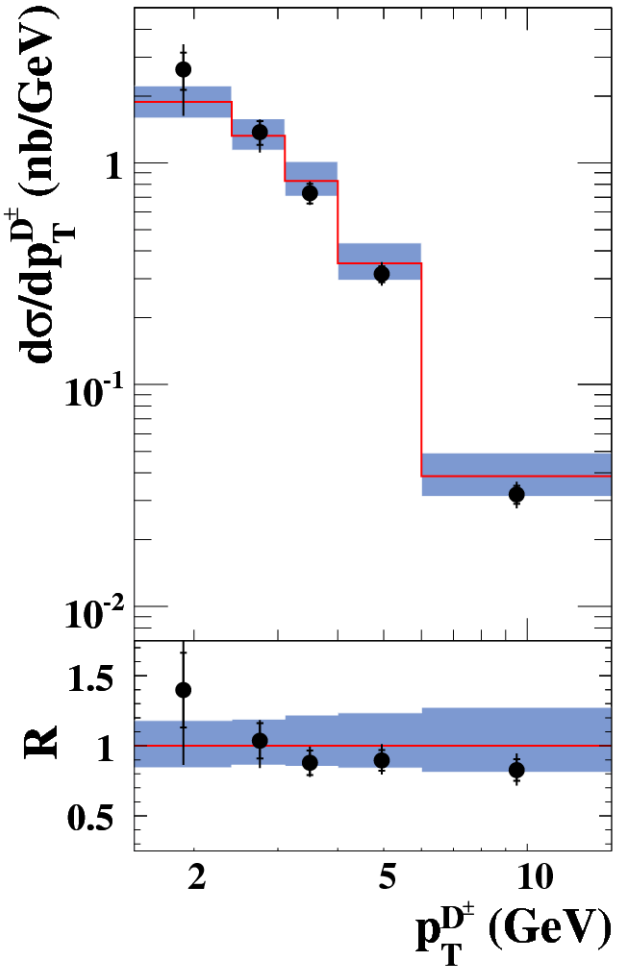
(D^0 not from $D^{*+} \rightarrow D^0 \pi^+$)

Deacy products from reconstructed secondary vertex -
- (ZEUS microvertex detector)



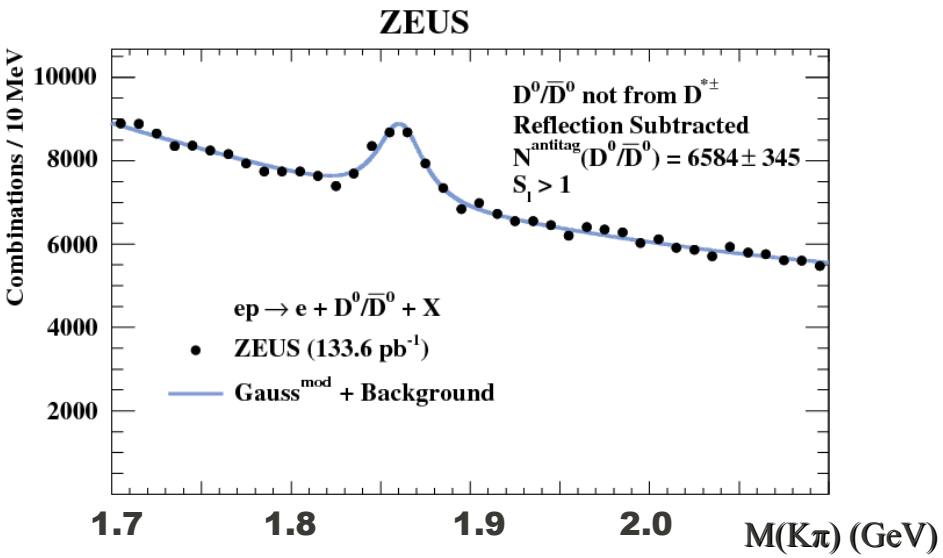


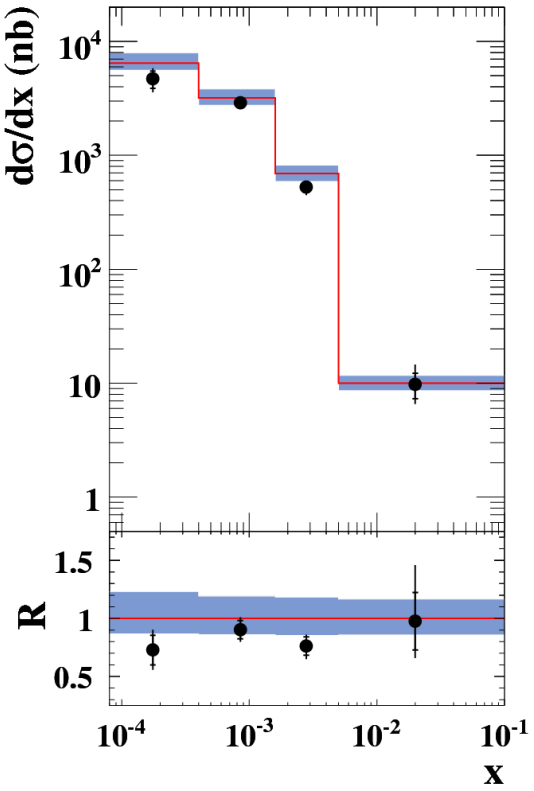
Inclusive $D^{\pm}$ cross-sections



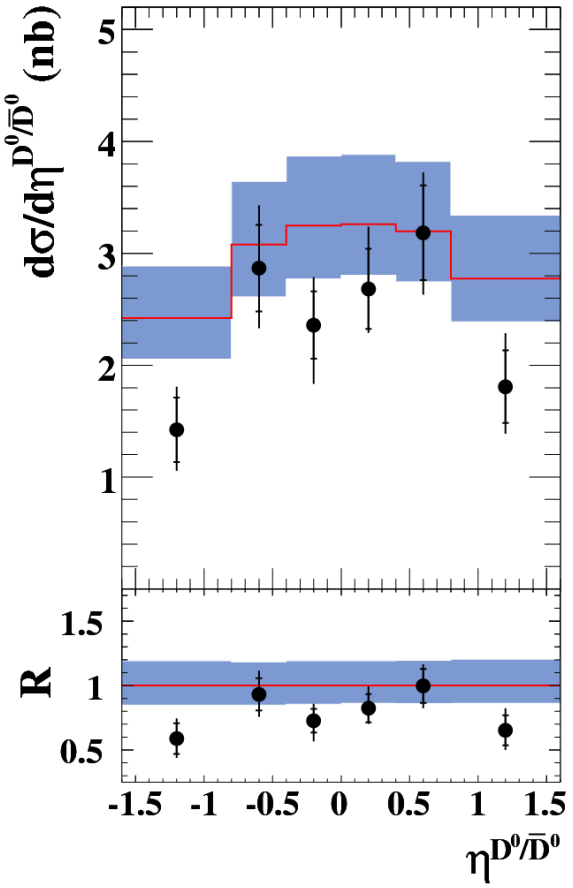
$D^{\pm}$

Data/model
HVQDIS





Inclusive D^0 cross-sections

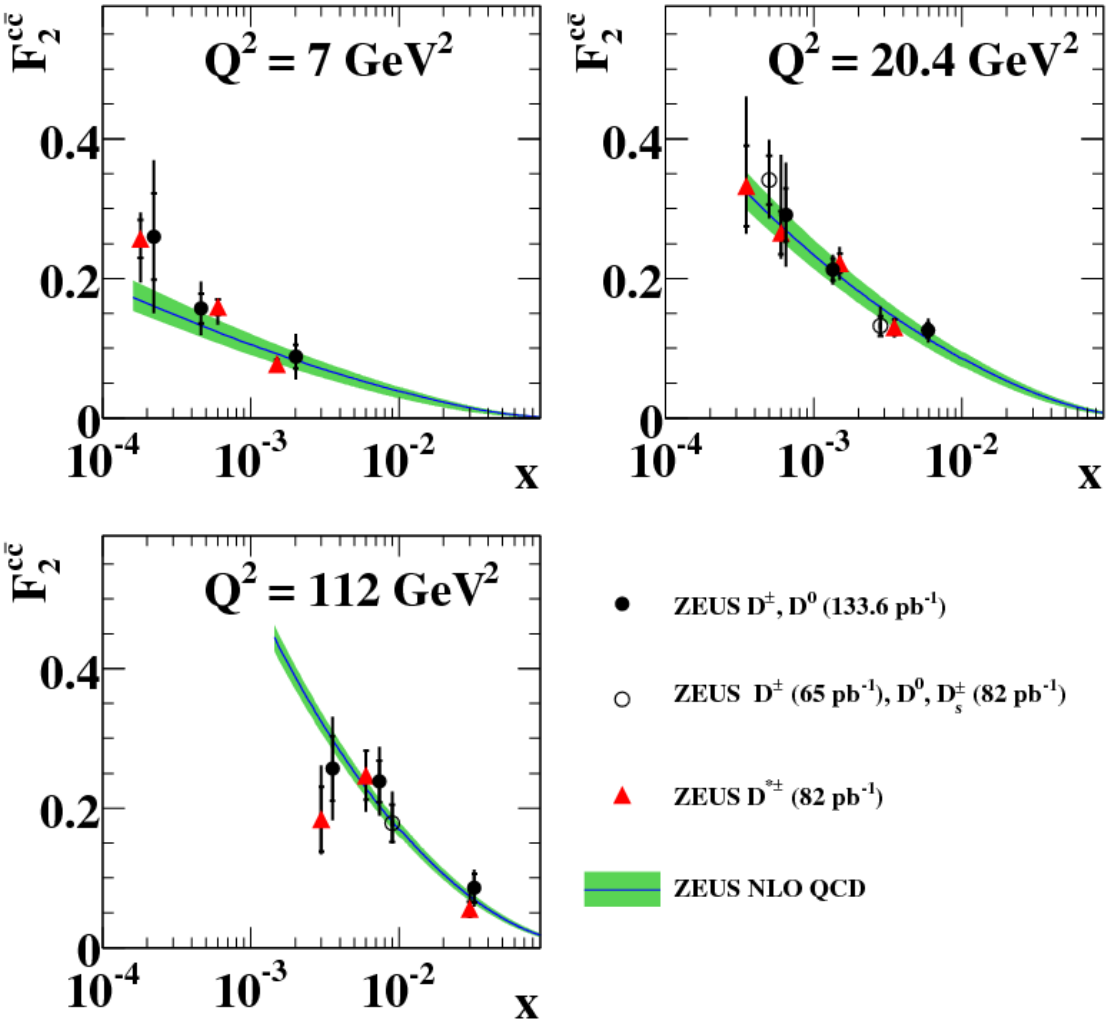


D^0

Data/model HVQDIS

Massive NLO QCD calculations HVQDIS - ok!

Charm structure function $F_2^{c\bar{c}}$ from inclusive D cross-section



Model-dependent extrapolation!

NLO QCD calculations with global PDFs (from inclusive F_2) - ok!

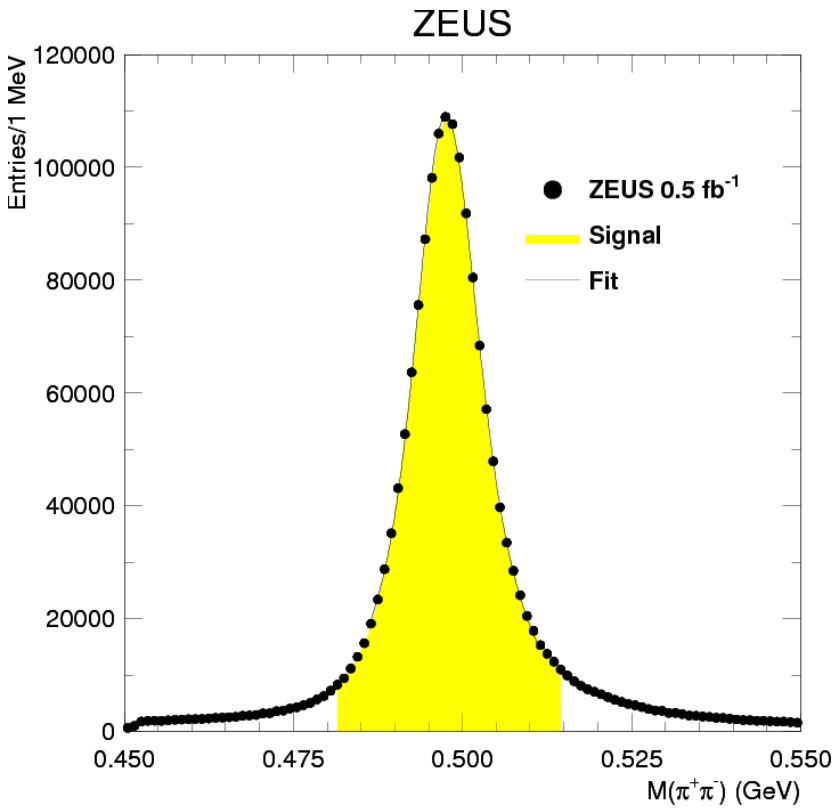
$K^0_S K^0_S$ "spectroscopy" (1)

Inclusive $K^0_S K^0_S$ resonance production in ep collisions..., ZEUS , PRL **101**, 112003 (2008)

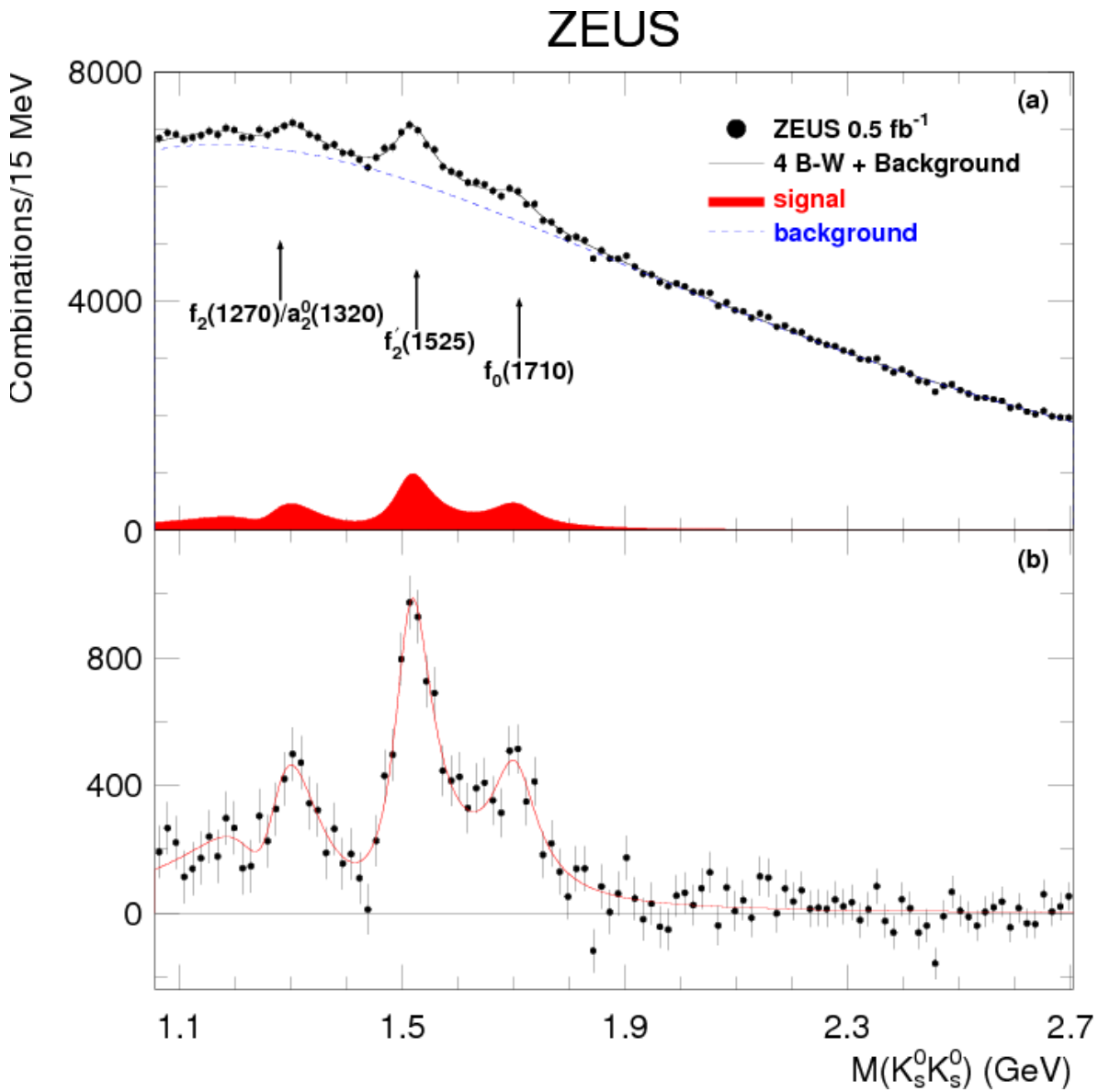
Hunt for a glueball (gg)...

- Too many scalar mesons ($J^P=0^+$) with I = 0 : $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$; only two fit into qq nonet
- QCD lattice calculations predict the lightest glueball $J^{PC} = 0^{++}$ with mass 1550 – 1750 MeV
- It can mix with qq states close in mass
- The $K^0_S K^0_S$ system can couple to $J^P = 0^+,\ 2^+$
- $f_0(1710)$ can be a possible glueball candidate...

ZEUS data 1996 – 2007:
1 258 400 K^0s candidates



$K^0_S K^0_S$ mass spectrum:

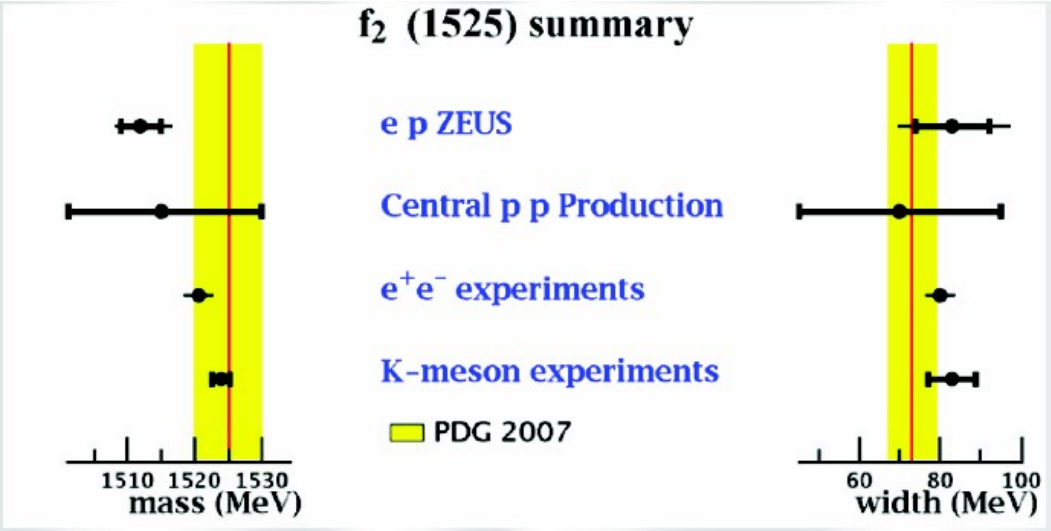


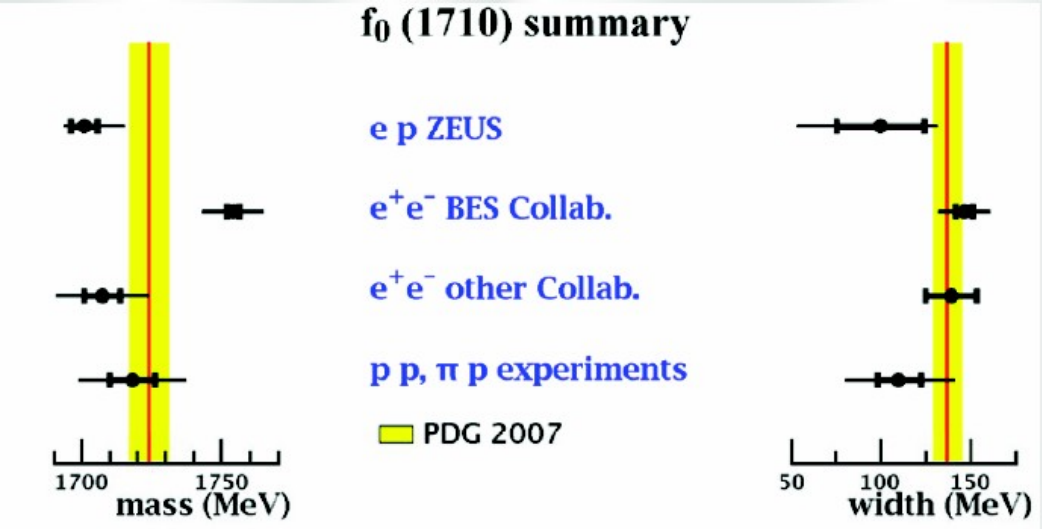
- 4 BW fit with SU(3) motivated interference (M, Γ – free parameters)
- Very good $f_0(1710)$ signal:
  4058±820 events ~ 5 s. d.

Question: Is this a glueball ?!

Answer: as $f_0(1710)$ is also seen in $\gamma\gamma \rightarrow K^0_S K^0_S$ it cannot be pure glueball state...

$f'_2(1525)$ and $f_0(1710)$: mass and width





Summary

- HERA was meson factory: only selected, recent results were presented

- Diffractive vector meson production: observation of transition between ”soft” and ”hard” hadronic interactions - semi-quantitative succes of perturbative QCD

- Inclusive, light meson production – challenge for soft fragmentation phenomenology (MC models)

- Heavy flavour mesons – perturbative QCD at work

- Quality and amount of HERA data enable investigations of rare and ”difficult” mesons