



Meson Physics at HERA



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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)

→ $\gamma^* p \rightarrow \text{hadrons}$

$Q^2 \approx 0$ (quasi-) photoproduction (PHP)

$Q^2 > 0$ deep inelastic scattering (DIS)

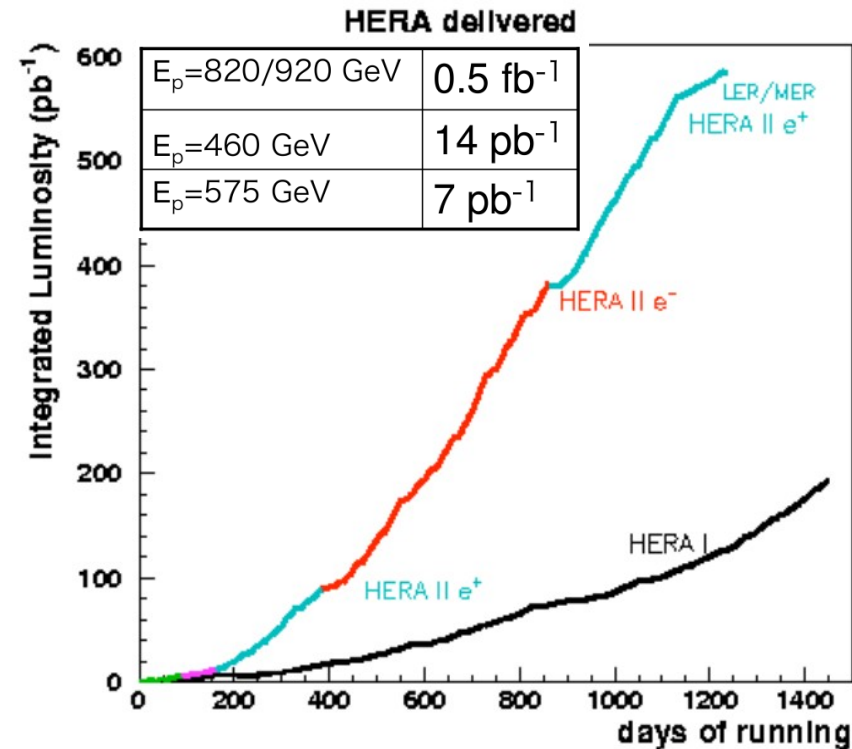
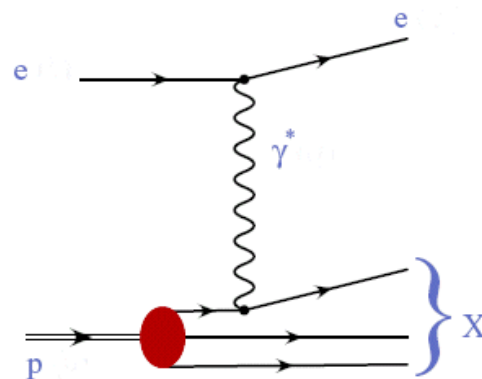
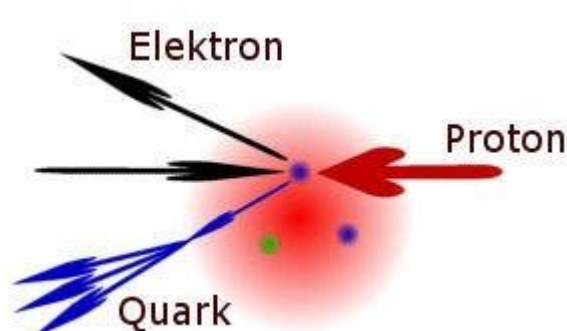
DIS (Quark/parton model, QPM):

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 GeV²)

$s \approx E_e E_p$, $\sqrt{s} \approx 300$ GeV

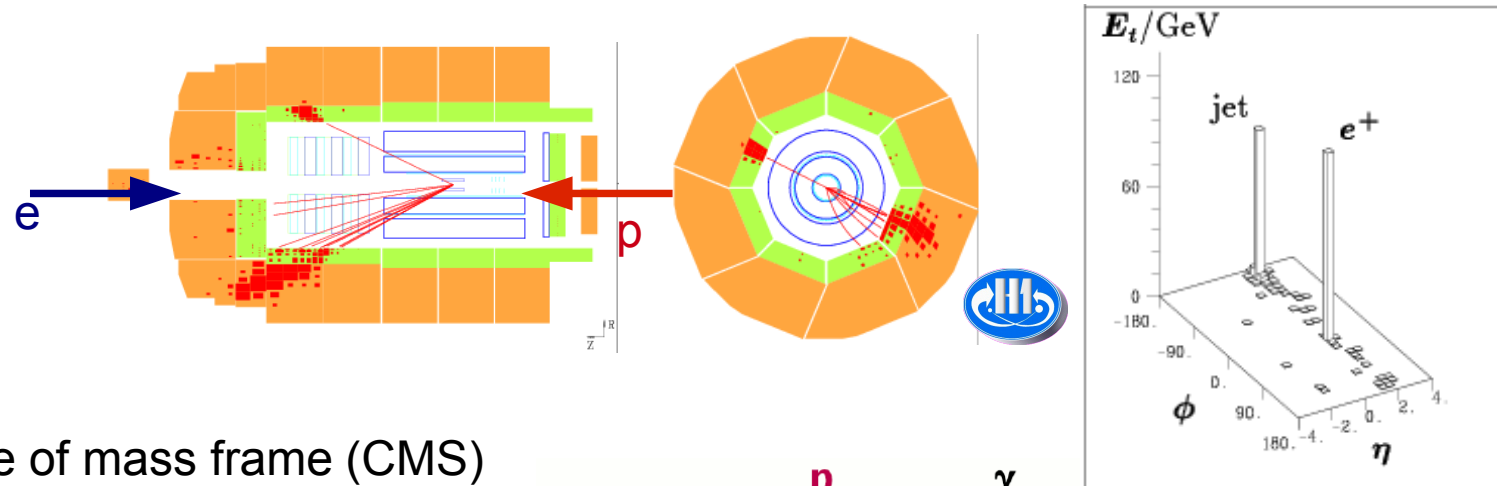
W – $\gamma^* p$ CMS energy (20 -290 GeV)

$x \approx Q^2/W^2$ – 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: $q(\gamma^*) = (0,0,0,Q)$

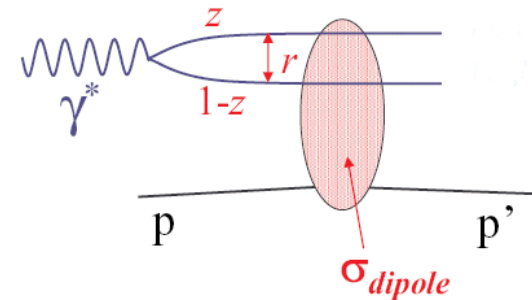
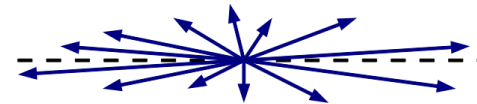
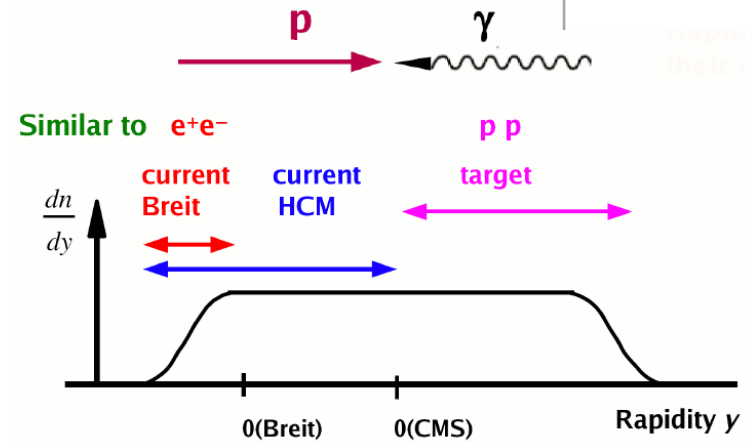
$$x_F = p_L/p_{\max}, \text{ Feynmann } x$$

$$y \approx \eta = -\ln(\tan(\theta/2)), \text{ (pseudo-)rapidity}$$

$$p_T = \text{transverse momentum}$$

- proton rest frame:

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

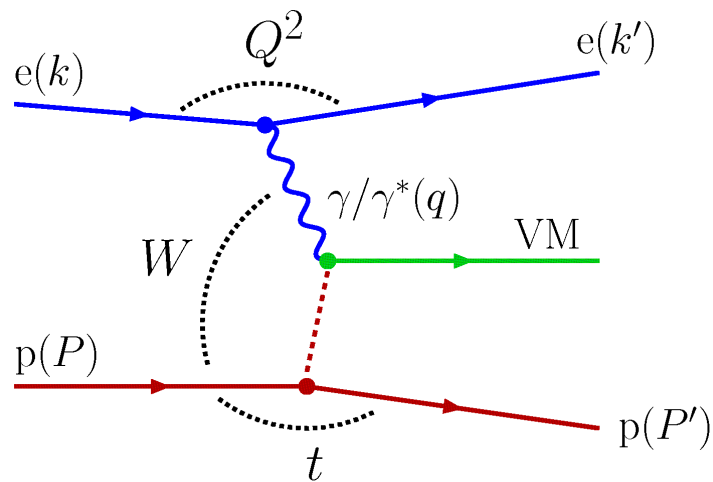


At HERA we observe **diffraction**, (also at $Q^2 \gg 0$) and it makes $\sim 10\%$ of the visible cross section !

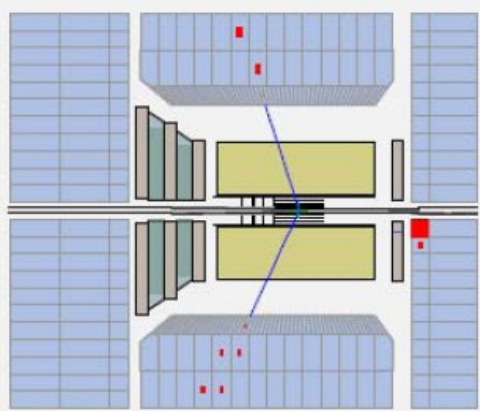
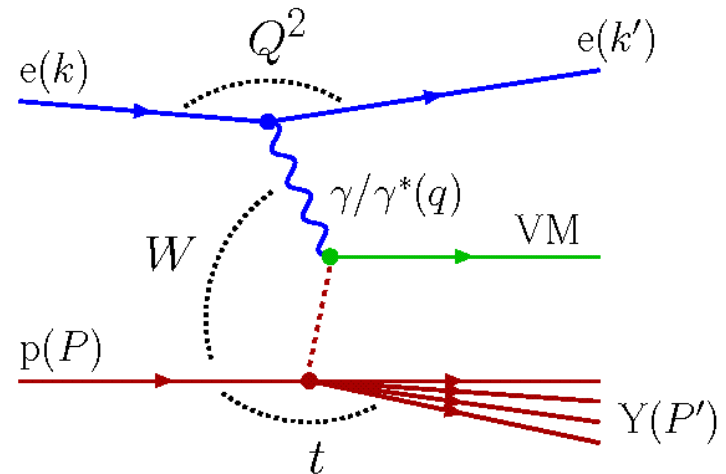
- Diffractive vector meson photo- and electro-production
- Inclusive (inelastic) meson production
- Heavy flavoured meson production
- $K^0 \bar{K}^0$ spectra - search for a glueball

Diffractive vector meson production in e-p

'elastic' (exclusive)



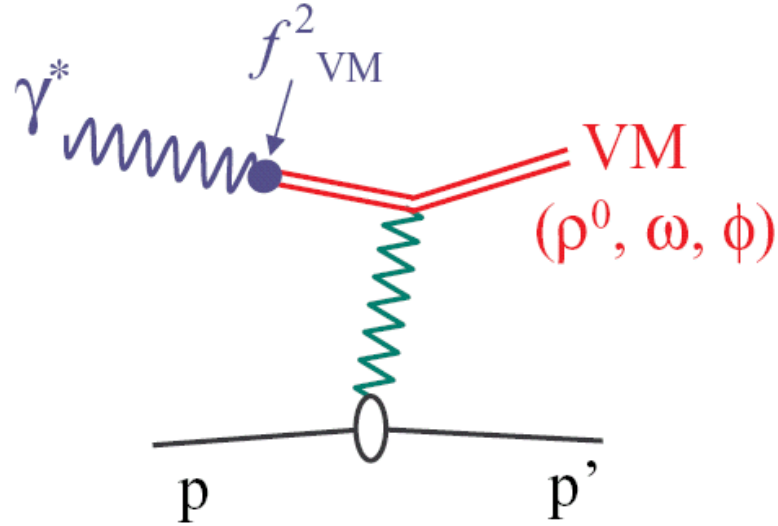
'proton-dissociative'



VM	vector meson	$\rho, \omega, \phi, J/\psi \dots$
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

$$\gamma^* p \rightarrow VM p = (\gamma^* \rightarrow VM) \otimes (VM p \rightarrow VM p)$$

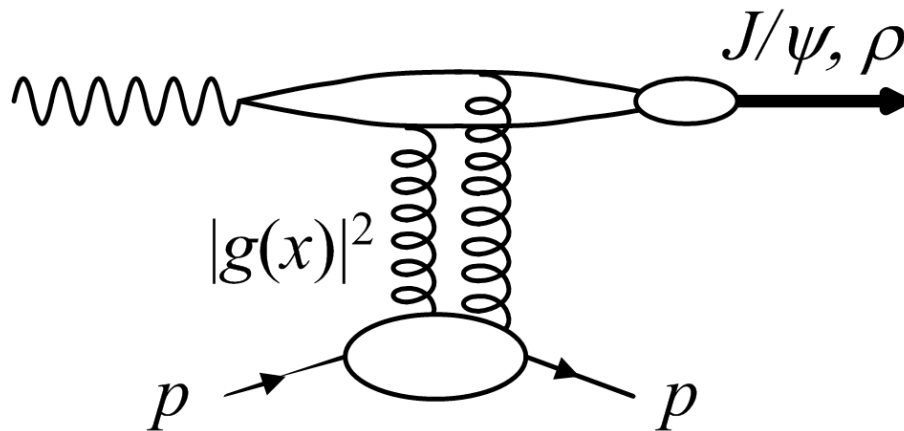
$$VM p \rightarrow VM p \Rightarrow \text{DL IPomeron exchange}$$

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

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

$$\sigma_{VMp} \sim W^{4(\alpha_0-1)}/b(W) \sim W^\delta, \quad \delta \approx 0.22$$

Perturbative QCD



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

QCD Pomeron exchange:
 ≥ 2 gluons (colour singlet)

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

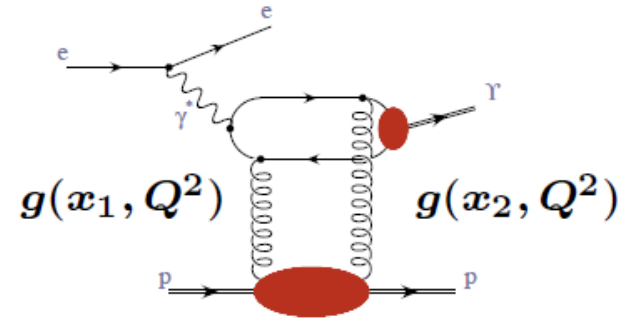
$$b \ll 10 \text{ GeV}^{-2}, \text{ weak shrinkage}$$

VM@HERA: transition "soft" \rightarrow "hard" interaction; testbed for QCD scales
 "soft" Pomeron \rightarrow QCD Pomeron

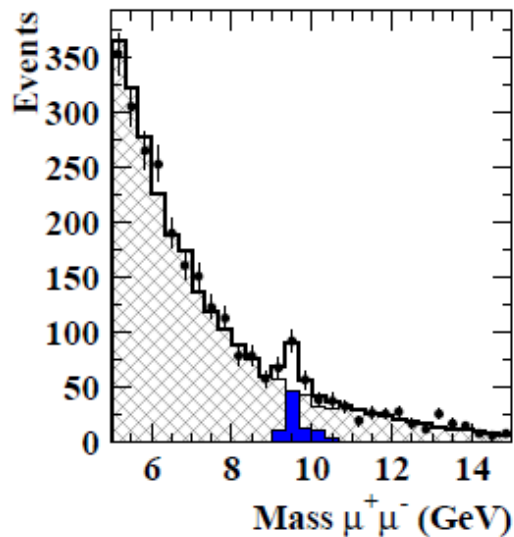
Diffractive vector meson production in e-p ("elastic") (2)

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

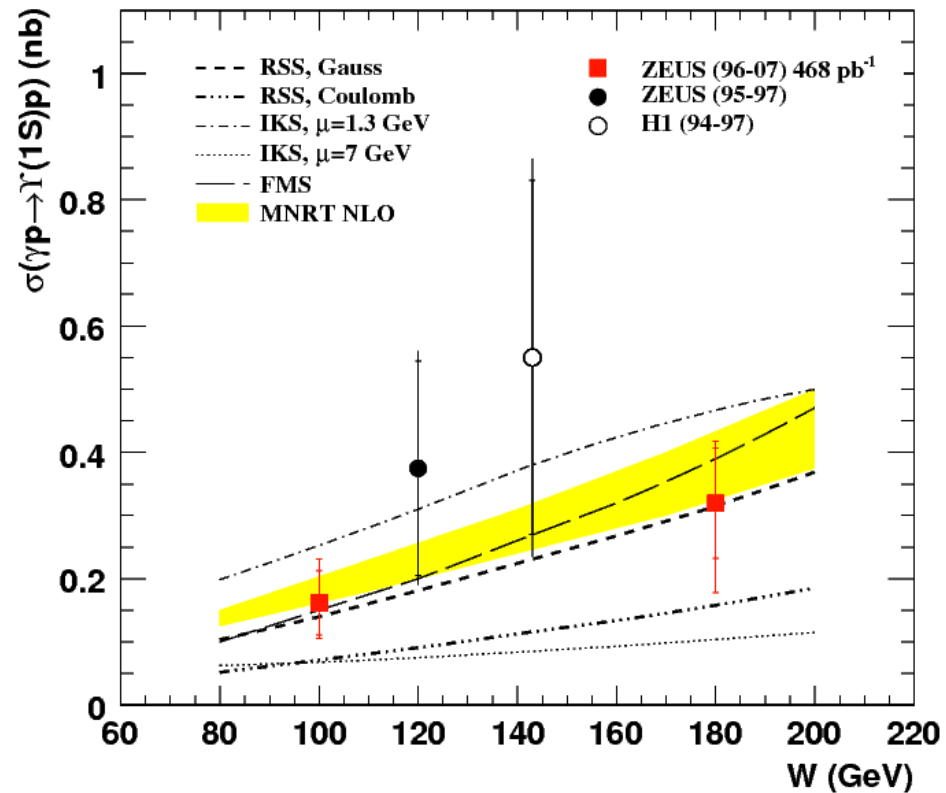
$$\gamma p \rightarrow Y p \rightarrow \mu^+ \mu^- p$$



ZEUS



- ZEUS 96/07 (468 pb⁻¹)
- ▨ GRAPE $\gamma\gamma \rightarrow \mu^+ \mu^-$ (BH)
- DIFFVM $\Upsilon \rightarrow \mu^+ \mu^-$
- BH + Υ

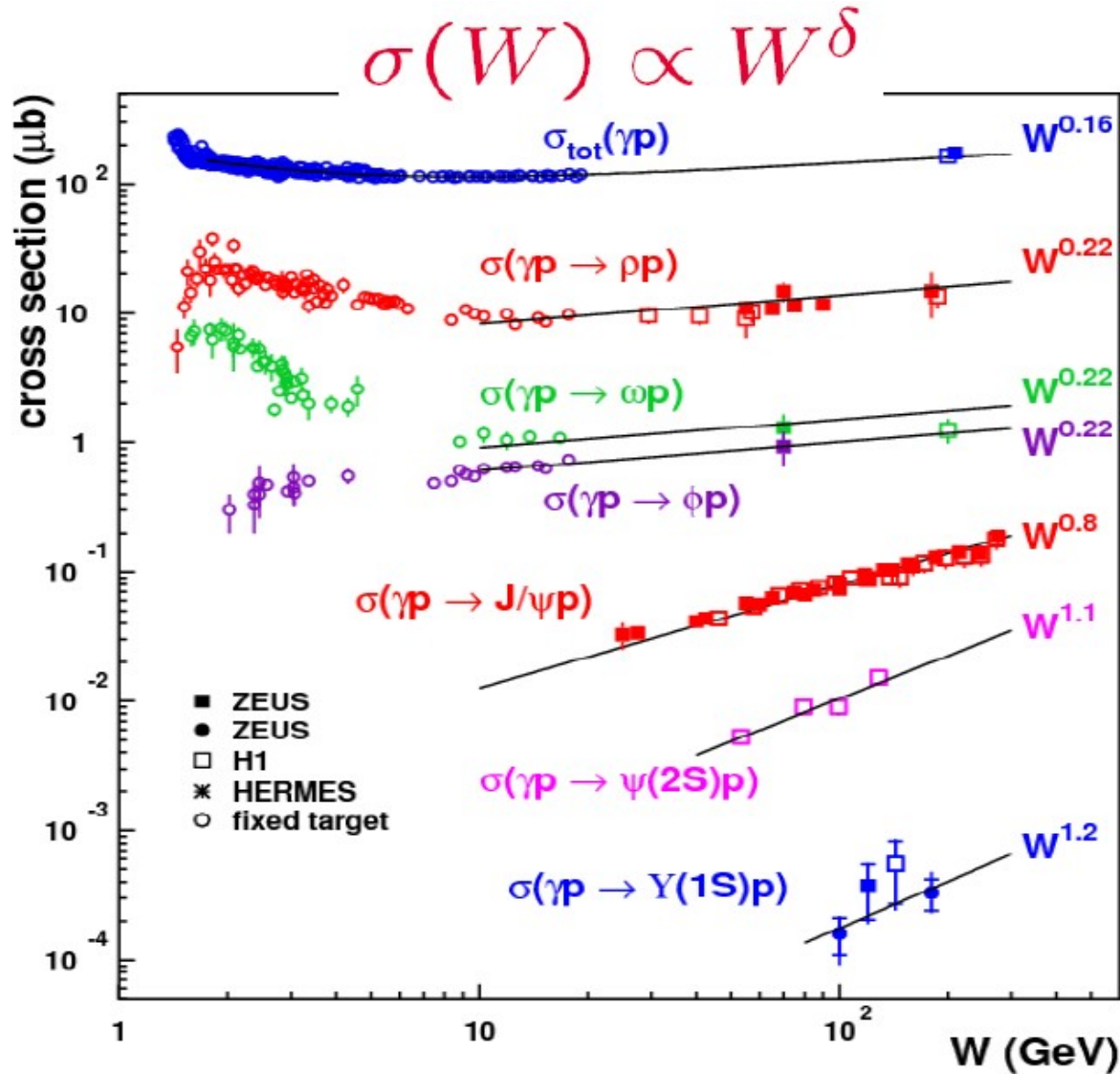


pQCD models sensitive to Υ wave function and hard scale value

$\sigma \sim W^\delta$: 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

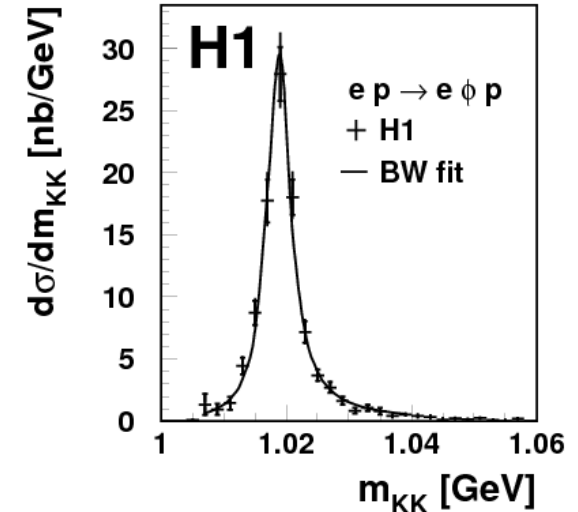
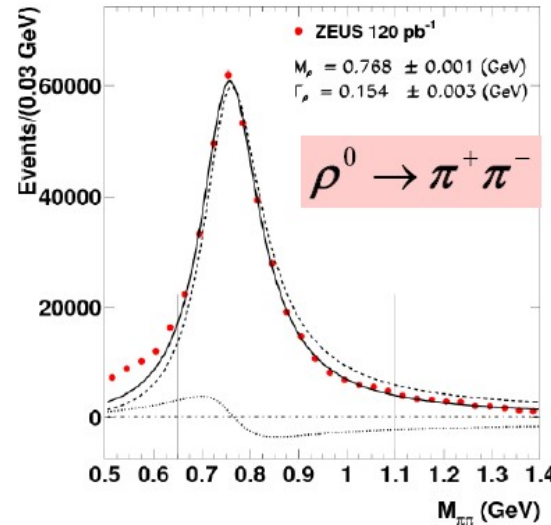
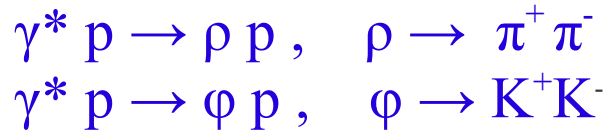
VM photoproduction: energy dependence



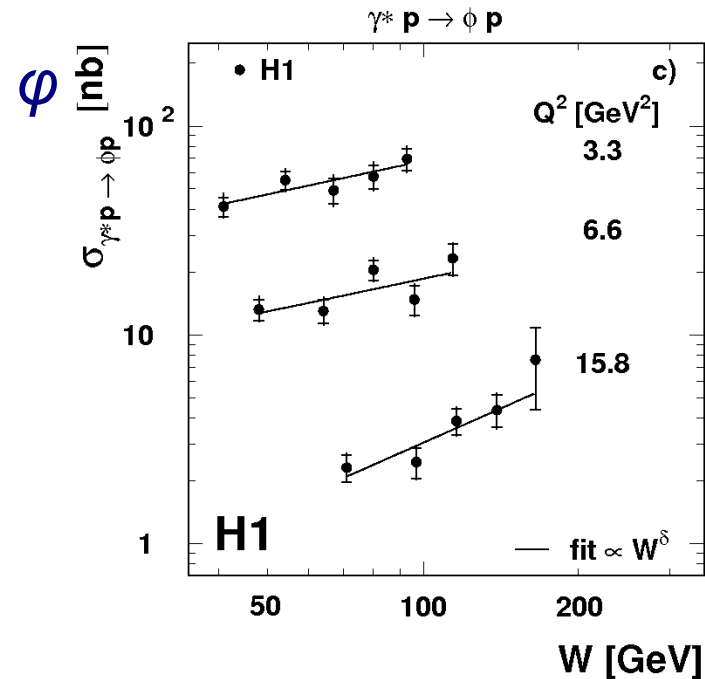
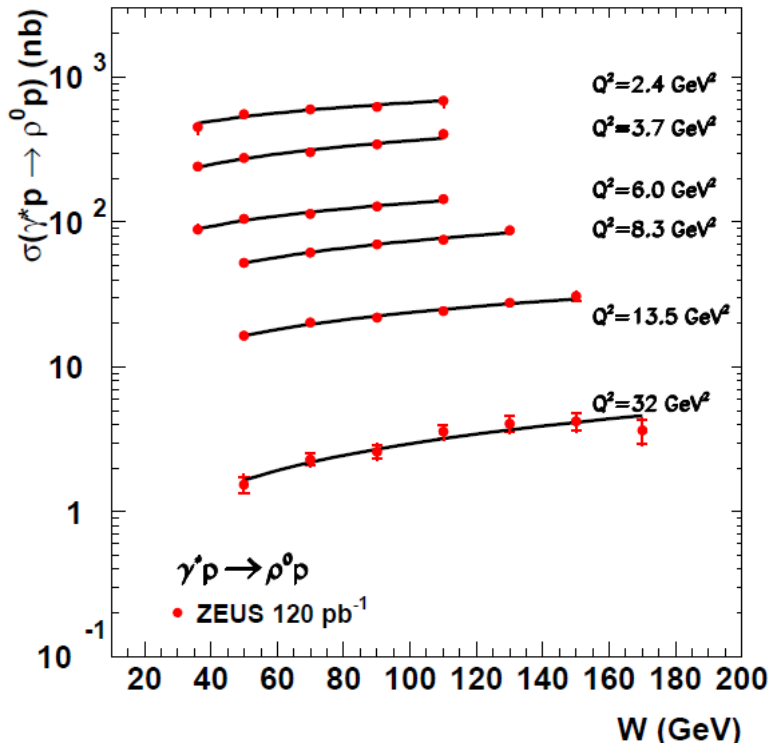
- The heavier VM –
– the stronger W-dependence,
- VM mass sets the hard scale

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

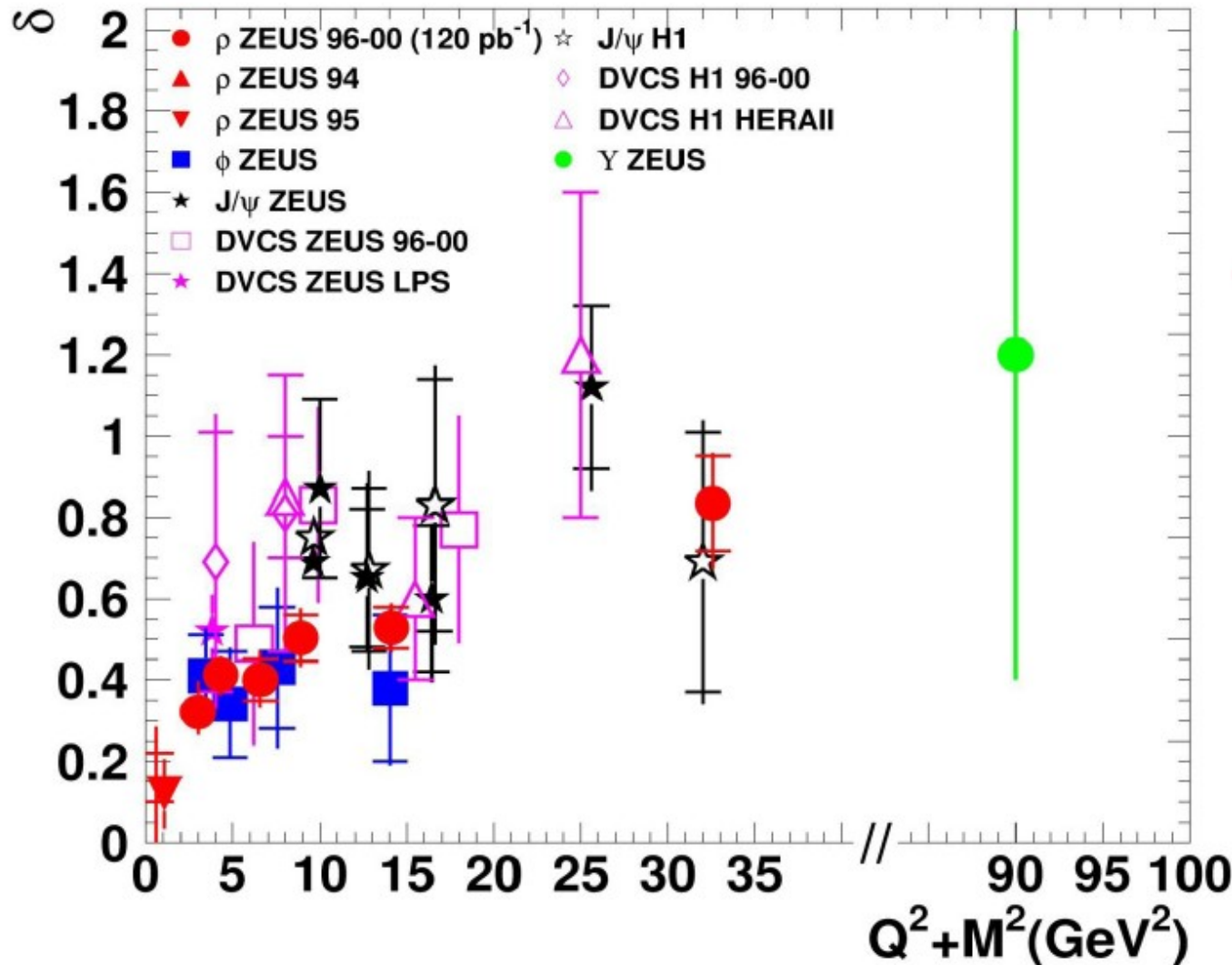
Diffractive electroproduction of ρ^0 and ϕ mesons: H1, DESY 09-093,
 Exclusive ρ^0 production in DIS at HERA: ZEUS, DESY 07-118, PMC Physics A1,6



ρ : ZEUS



VM photo- and electroproduction: energy dependence

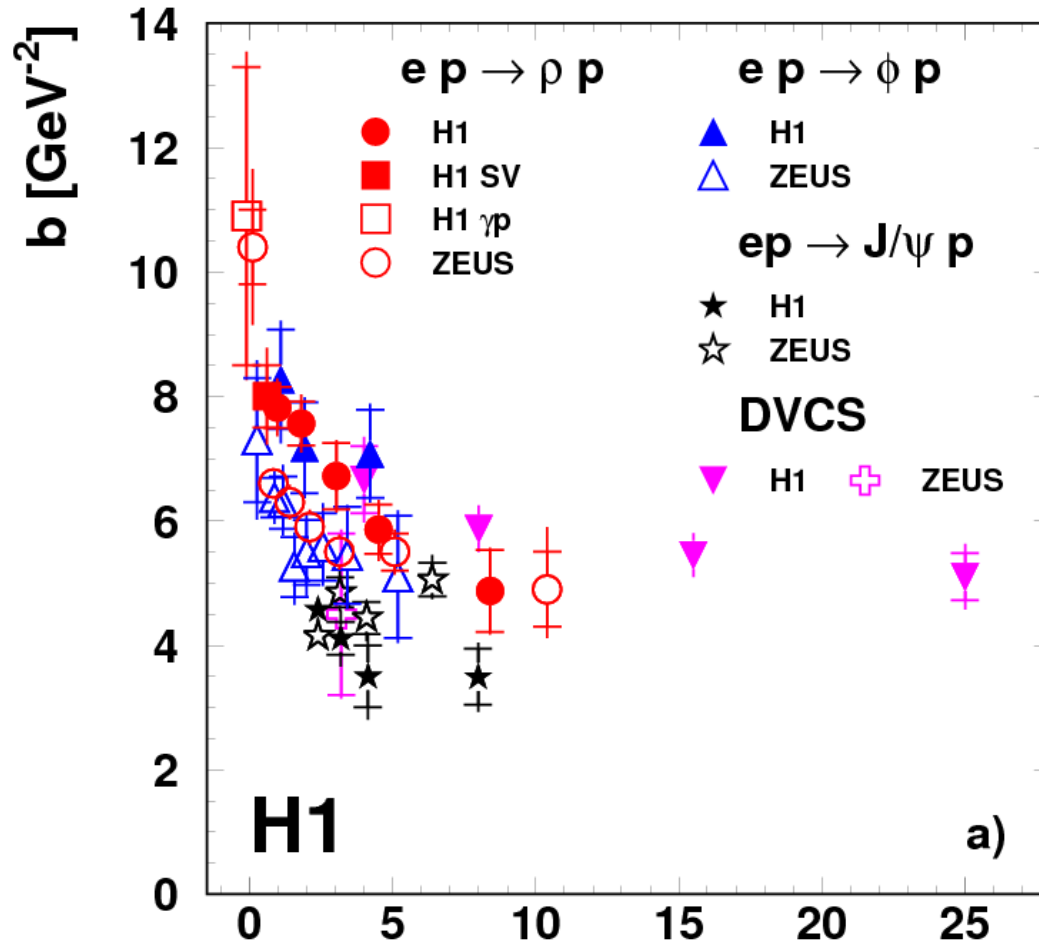
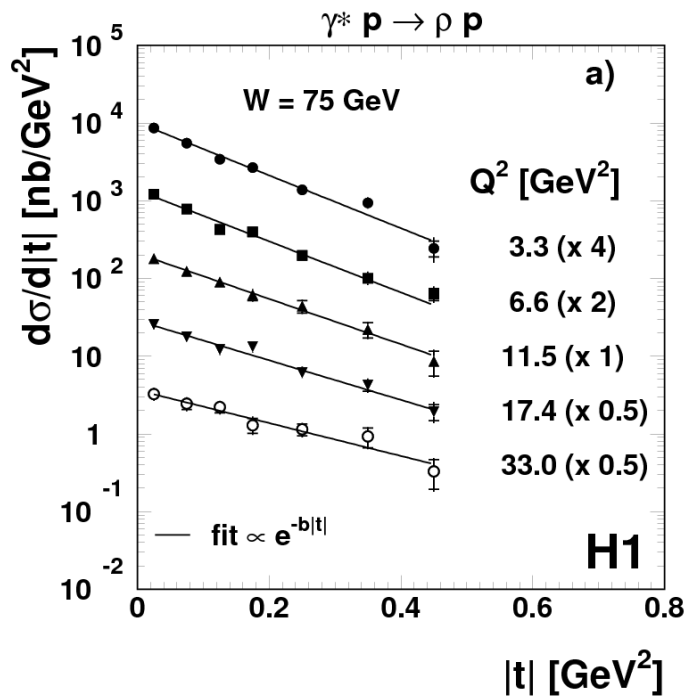


$$\sigma \sim W^\delta$$

- 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

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



$$\mu^2 [\text{GeV}^2] = (Q^2 + M^2)/4$$

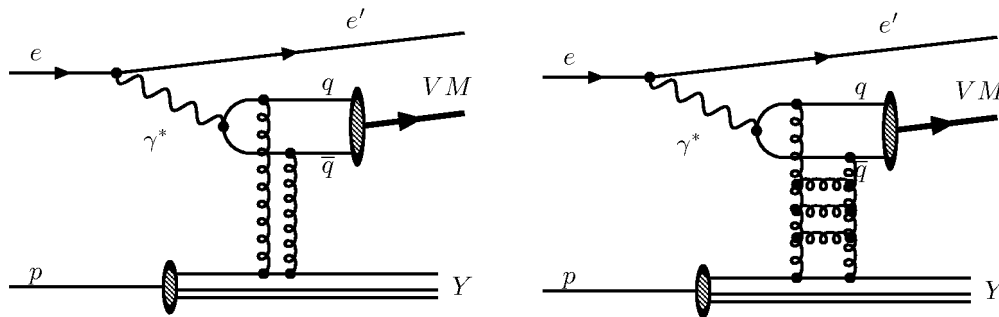
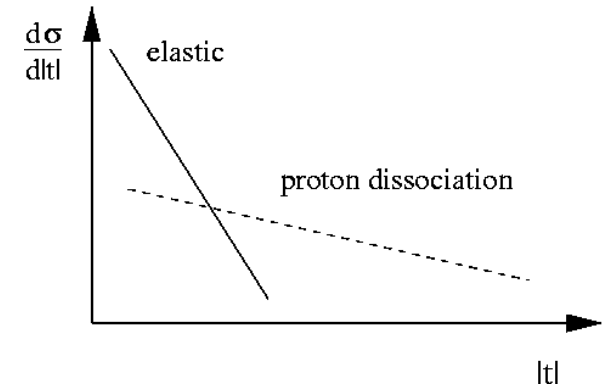
The larger Q^2 and/or M_{VM} – the smaller slope b (\sim interaction range)

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



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

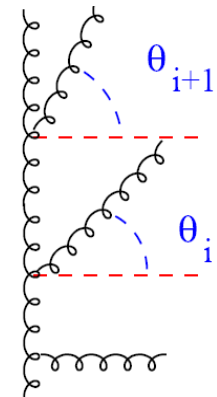
- 2-gluon exchange – $\sigma(W) = \text{const!}$
- gluon “ladder” exchange \rightarrow

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

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

Gluon cascade dynamics:

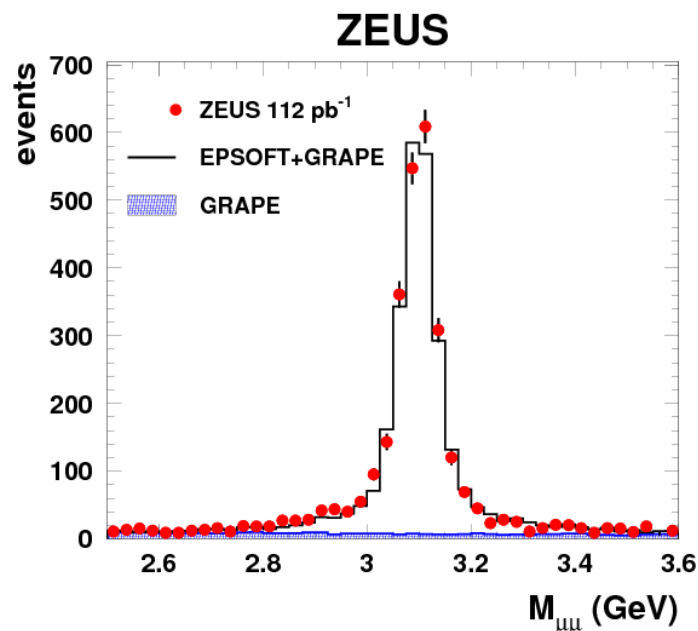
- Dokshitzer, Gribov, Lipatov, Altarelli, Parisi (DGLAP): gluon transverse momenta ordered, evolution in Q^2
- Balitsky, Fadin, Kuraev, Lipatov (BFKL): no ordering of gluon transverse momenta, evolution with x ($1/W$)



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

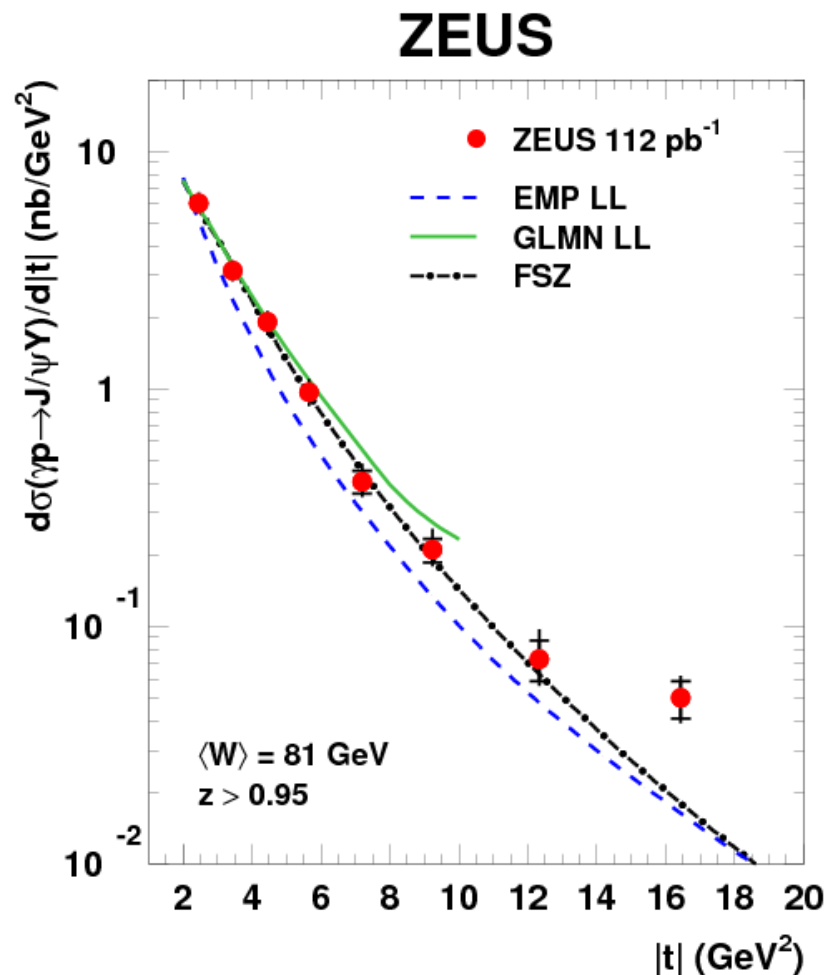
BFKL LL – EMP LL:

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) –

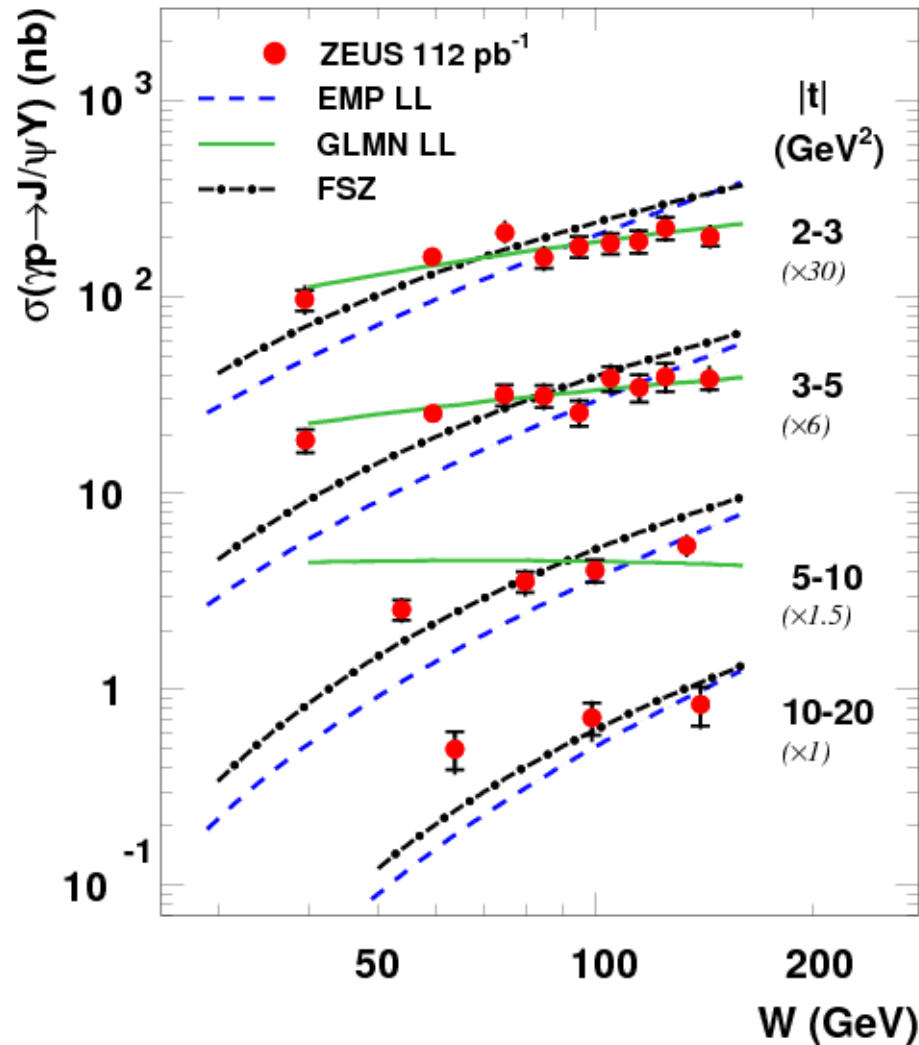
– ok up to $|t| = 5$ GeV²

BFKL (EMP LL) – too steep,

FSZ – ok up to $|t| = 12$ GeV²

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

ZEUS



DGLAP (GLMN LL) – ok up to $|t|=5 \text{ GeV}^2$,

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

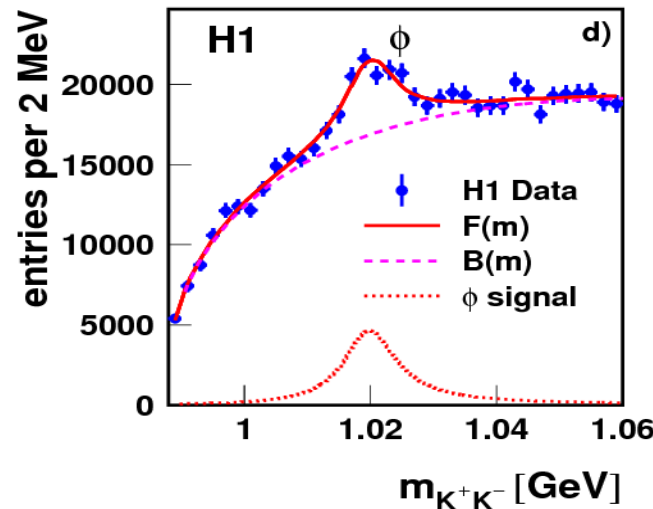
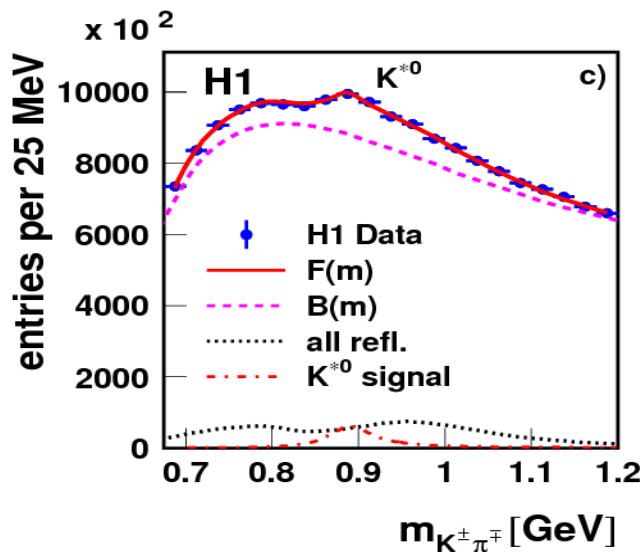
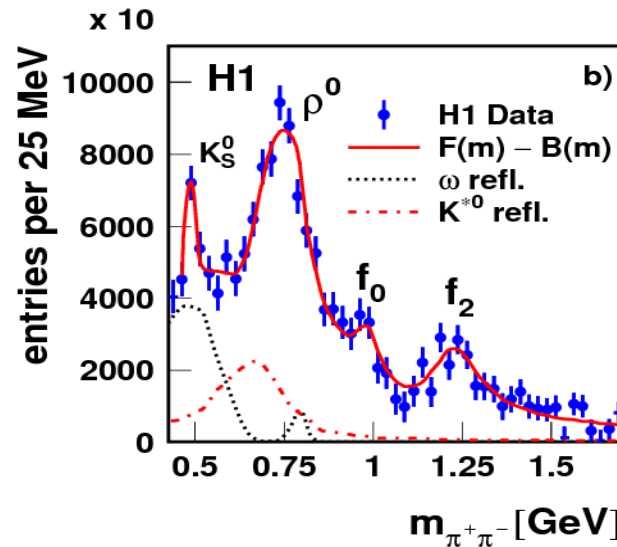
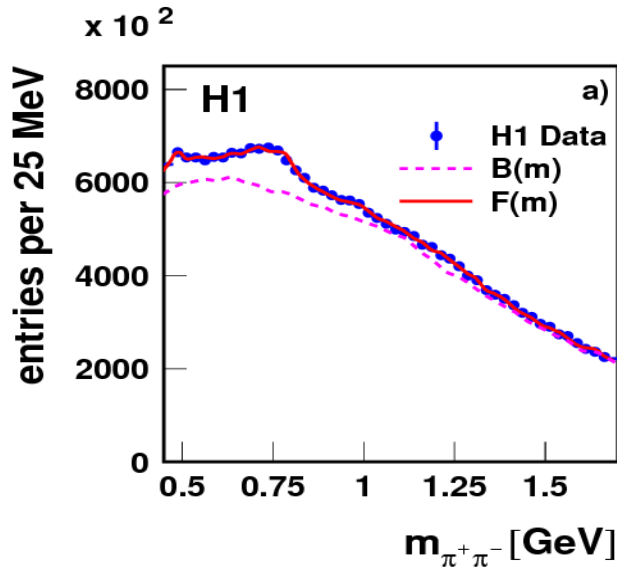
- No clear evidence for BFKL dynamics...

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

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

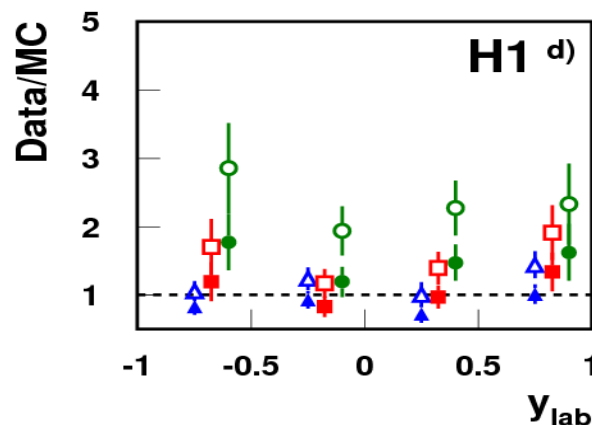
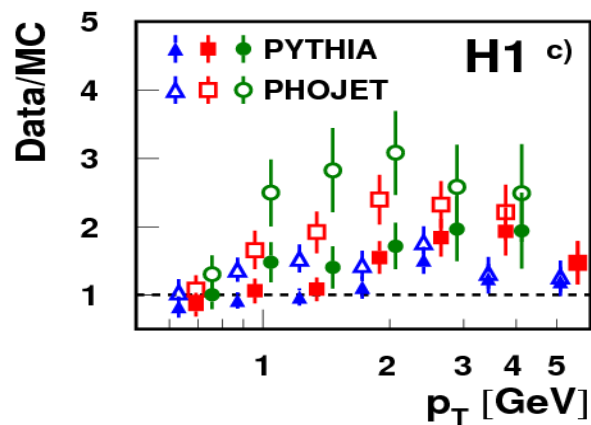
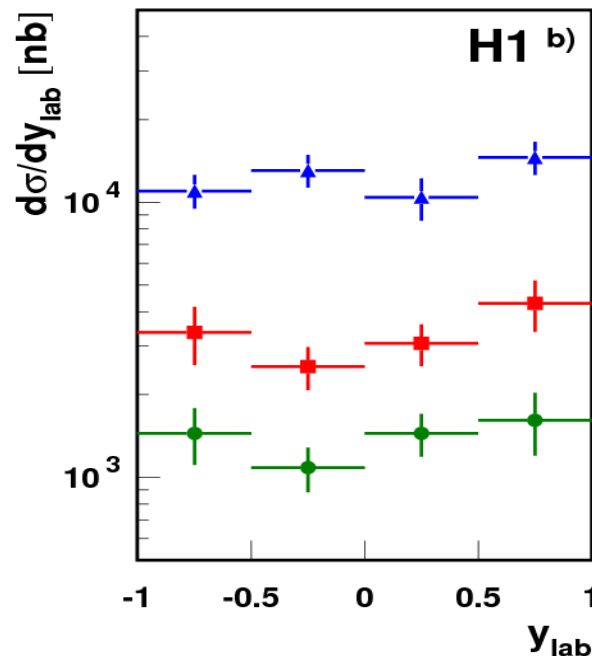
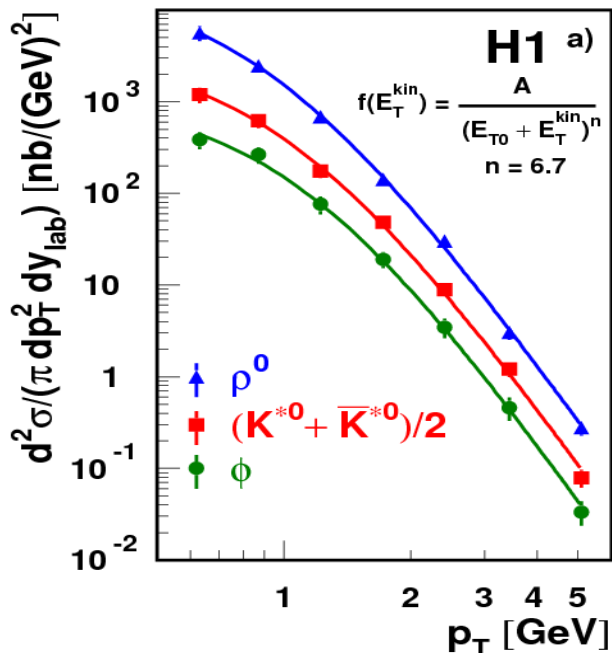
$\rho^0 \rightarrow \pi^+\pi^-$, $K^{*0} \rightarrow K\pi$, $\Phi \rightarrow K^+K^-$

$174 < W < 256$ GeV
 $\Rightarrow \langle W \rangle = 210$ GeV



$distr(m) = \text{signal} + \text{reflection} +$
 $+ \text{comb. backgr.}$

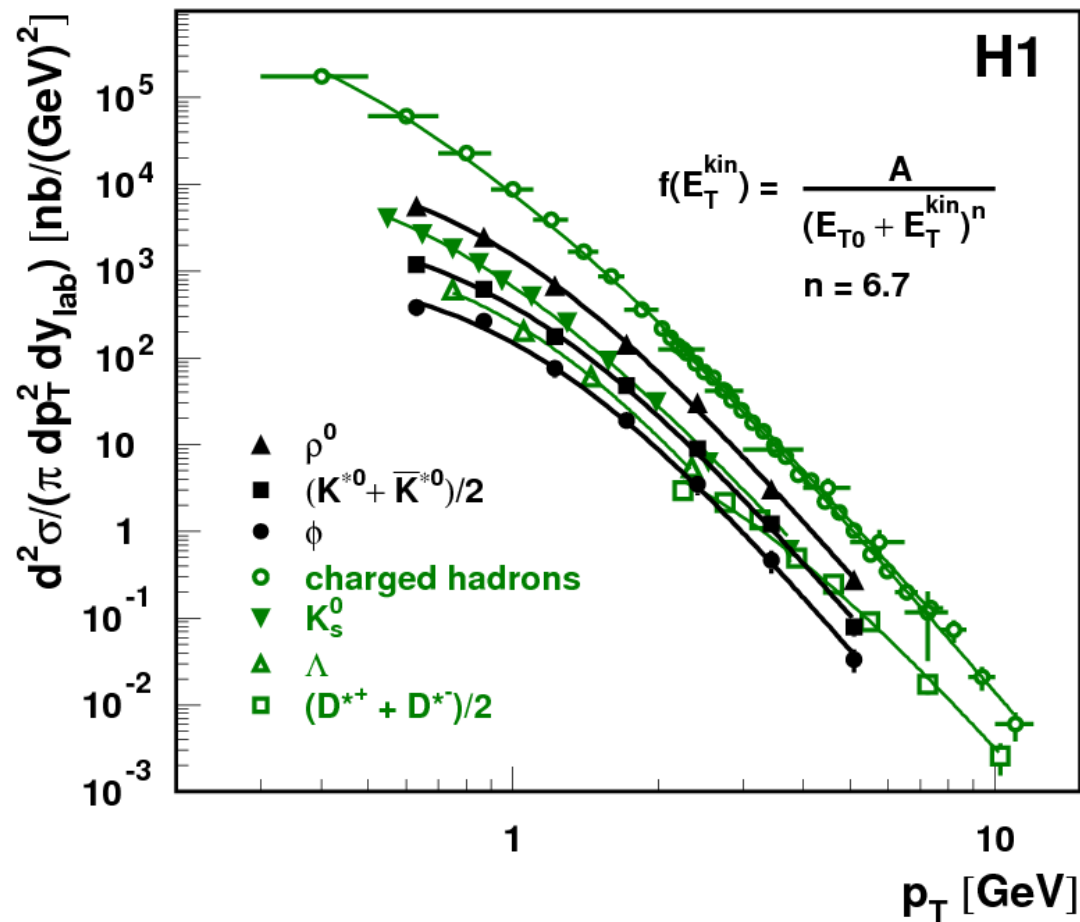
ρ^0 , K^{*0} and Φ : differential cross sections



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

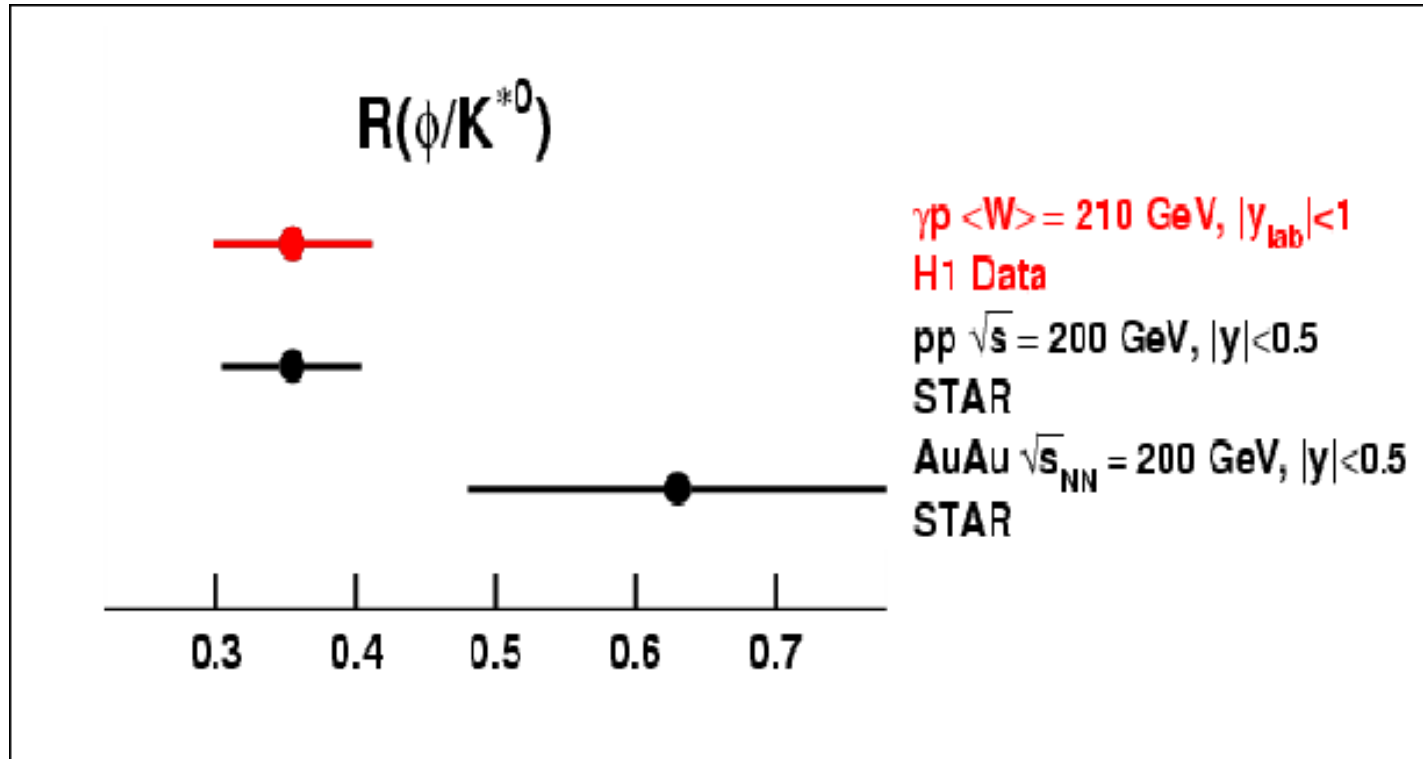
- Power law p_t spectra
- Flat rapidity distributions
- PYTHIA and PHOJET models fail to describe p_t spectra

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...

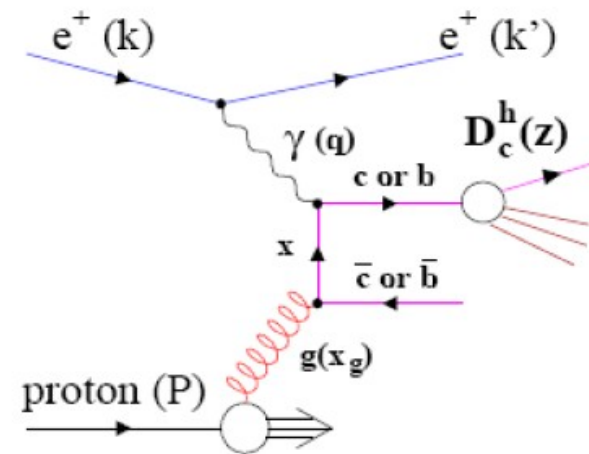
The cross section ratio $R(\Phi/K^{*0})$: comparison with RHIC



- The cross-section ratio $R(\Phi/K^{*0})$ in γp interactions is:
- similar as in pp interactions ,
 - below the result for $Au Au$ collisions.

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**

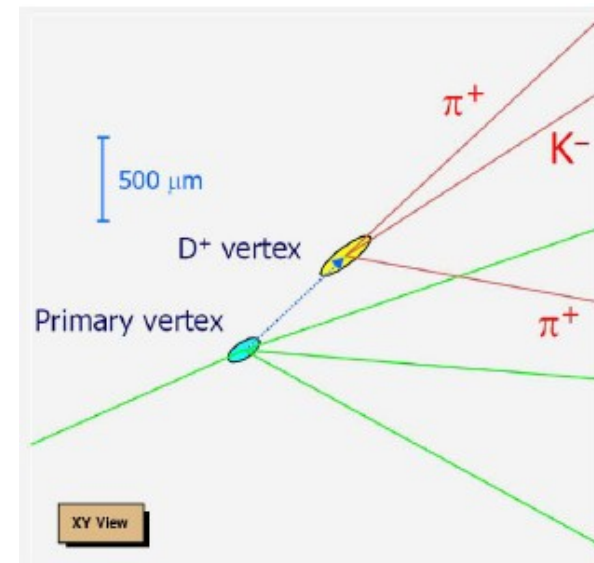
Reconstructed decay modes:

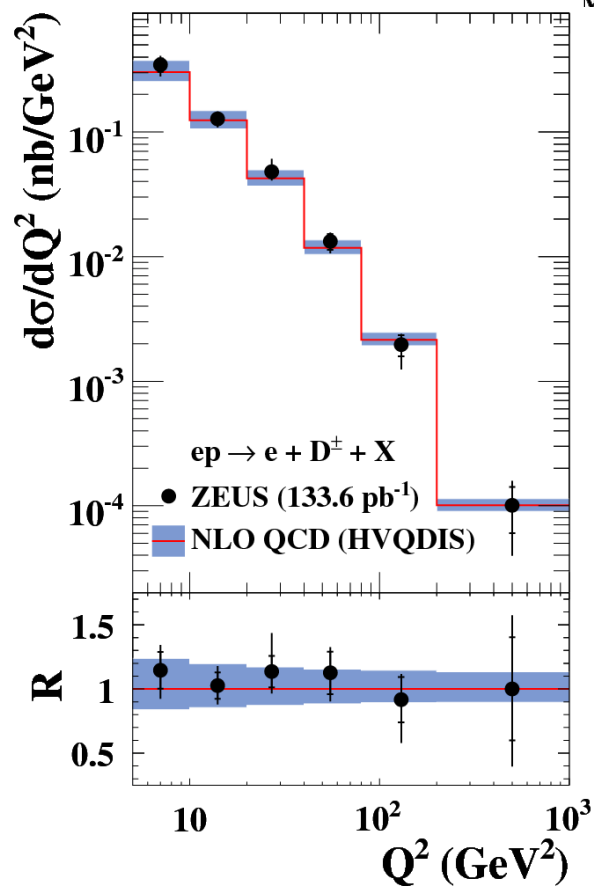
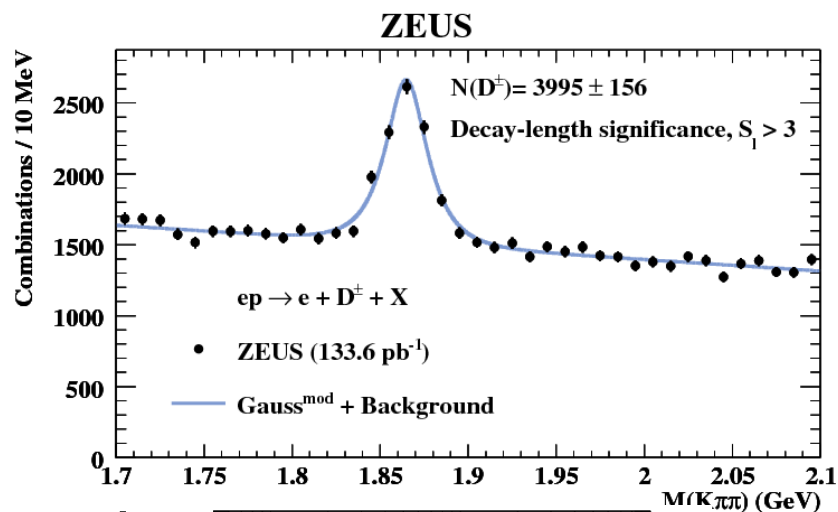
$$D^+ \rightarrow K^- \pi^+ \pi^- \quad (+ c. c.)$$

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

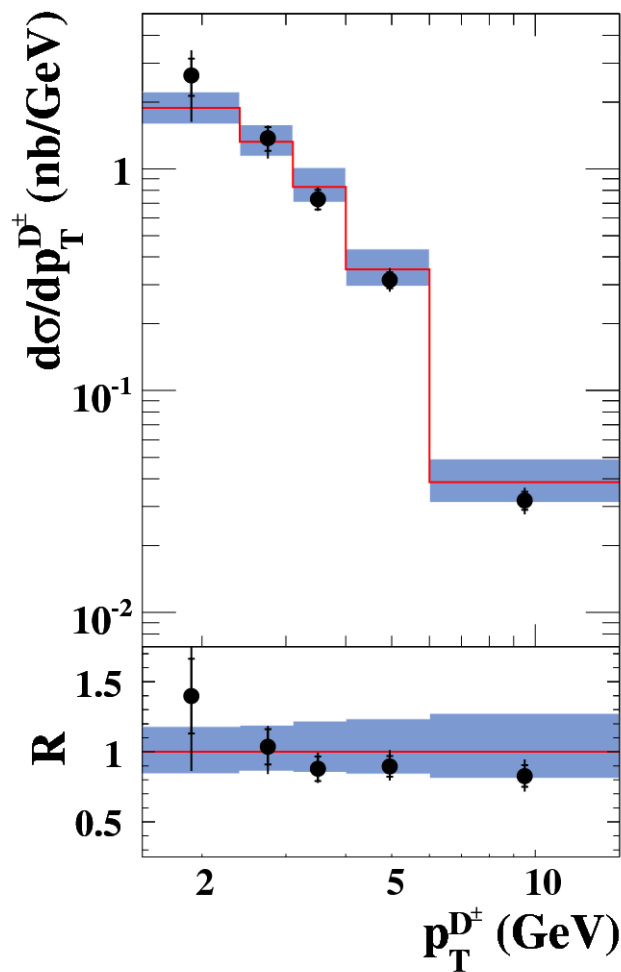
(D^0 not from $D^{*+} \rightarrow D^0 \pi^+$)

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

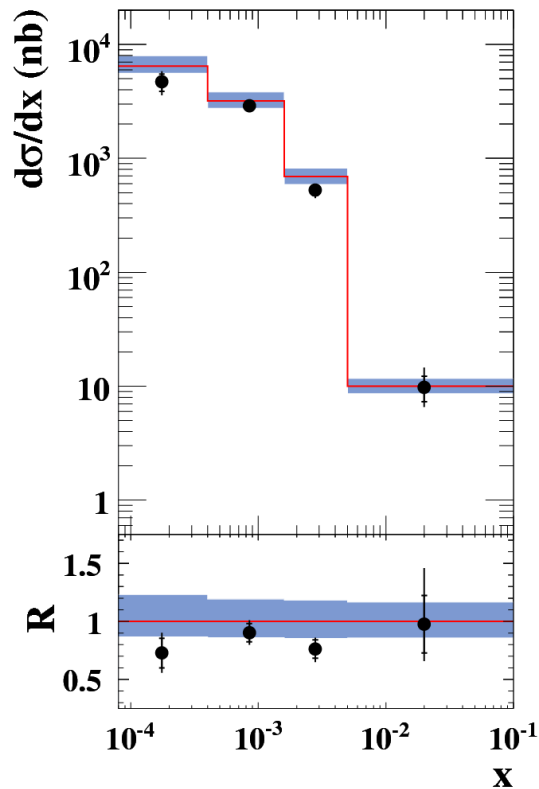
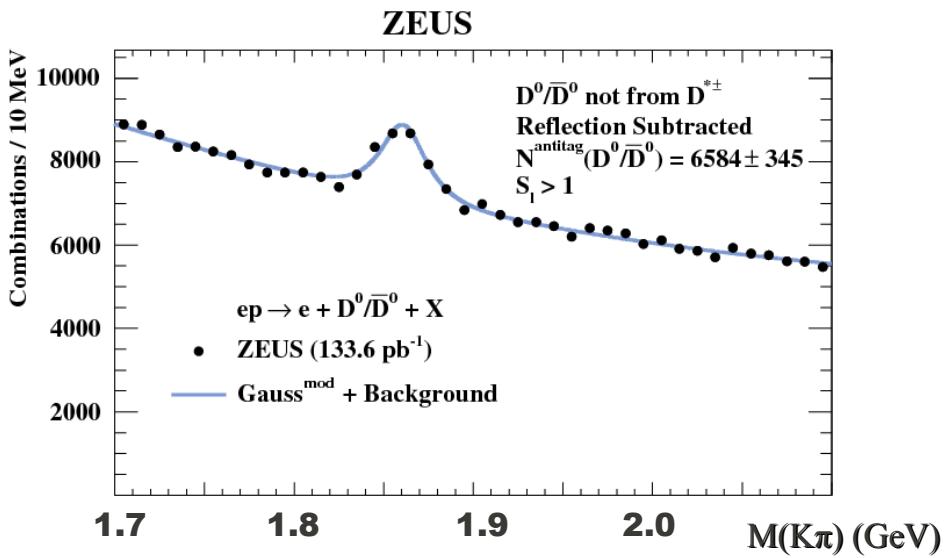




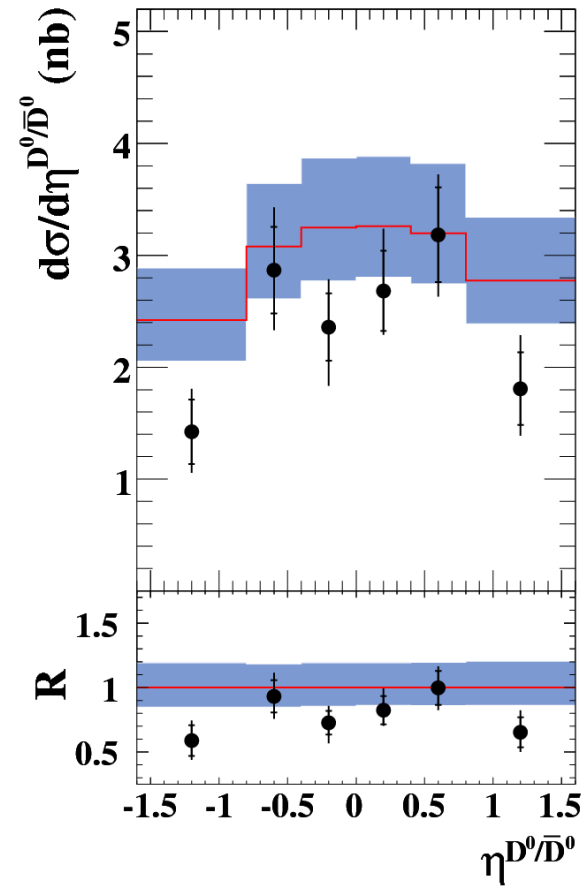
Inclusive D^\pm cross-sections



D^\pm

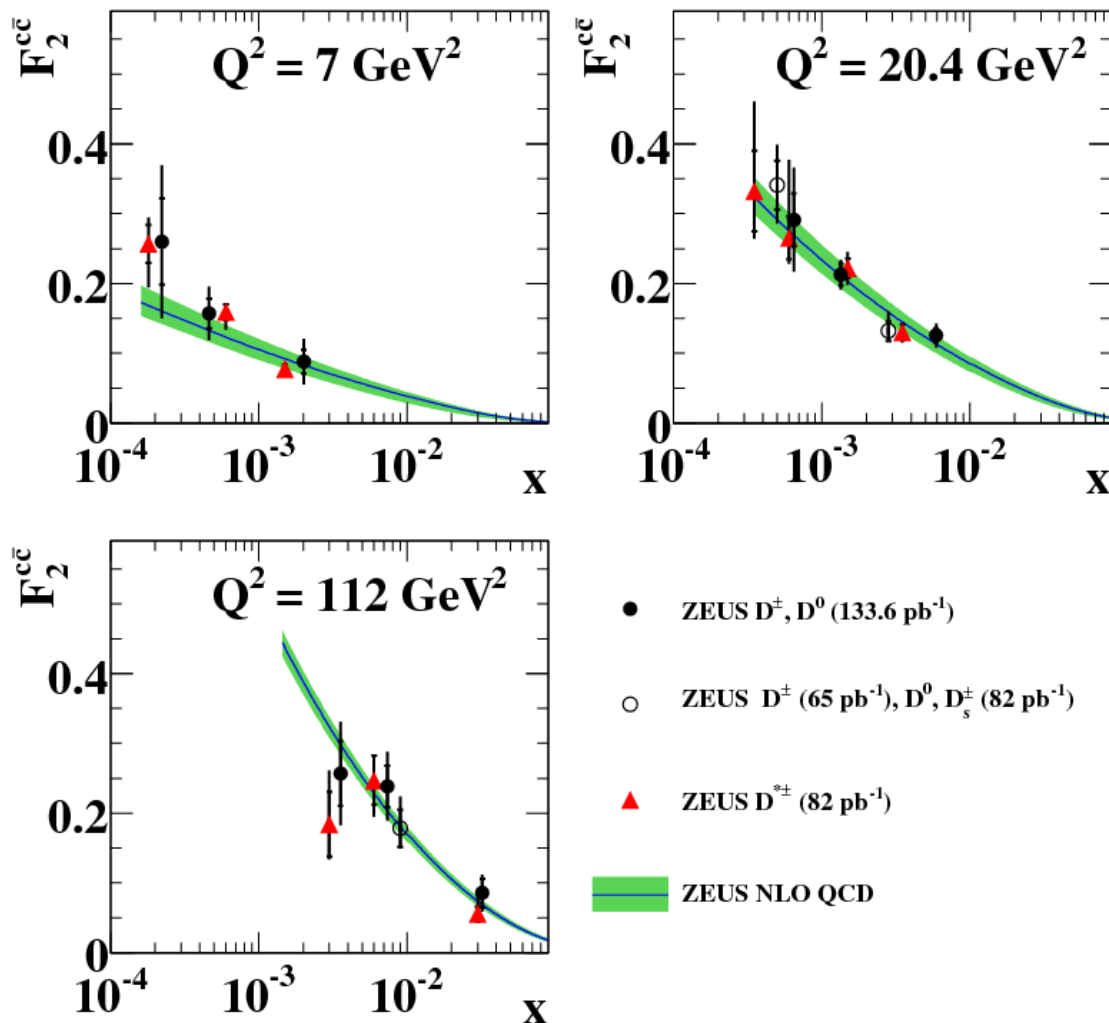


Inclusive D^0 cross-sections



Massive NLO QCD calculations HVQDIS - ok!

Charm structure function F_2^{cc} from inclusive D cross-section



Model-dependent extrapolation!

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

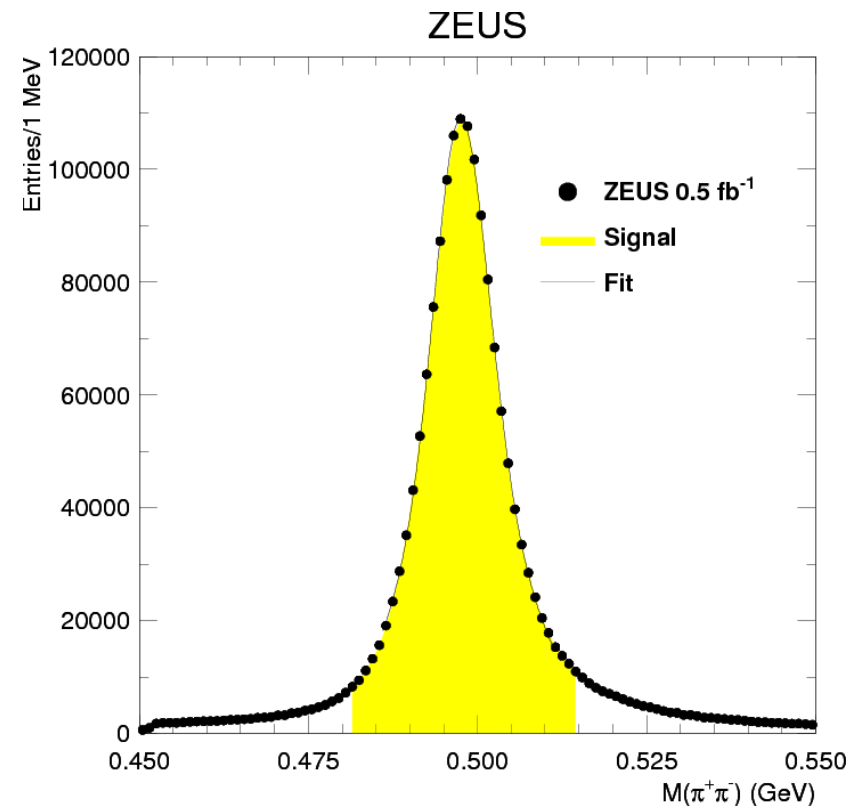
Inclusive $K_S^0 K_S^0$ resonance production in ep collisions..., ZEUS, PRL **101**, 112003 (2008)

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 $K_S^0 K_S^0$ system can couple to $J^P = 0^+, 2^+$
- $f_0(1710)$ can be a possible glueball candidate...

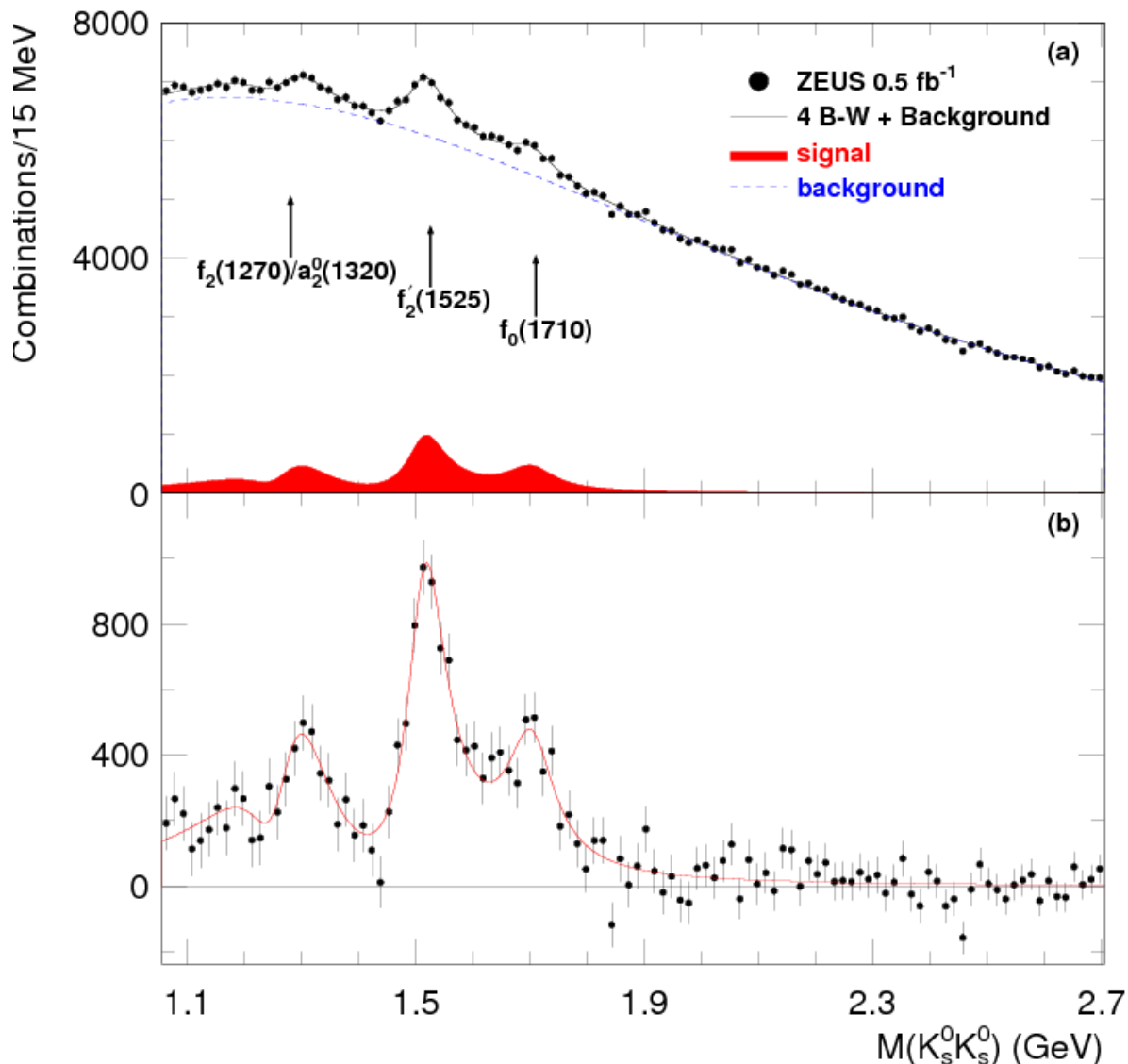
ZEUS data 1996 – 2007:

1 258 400 K^0 s candidates



$K_s^0 K_s^0$ mass spectrum:

ZEUS

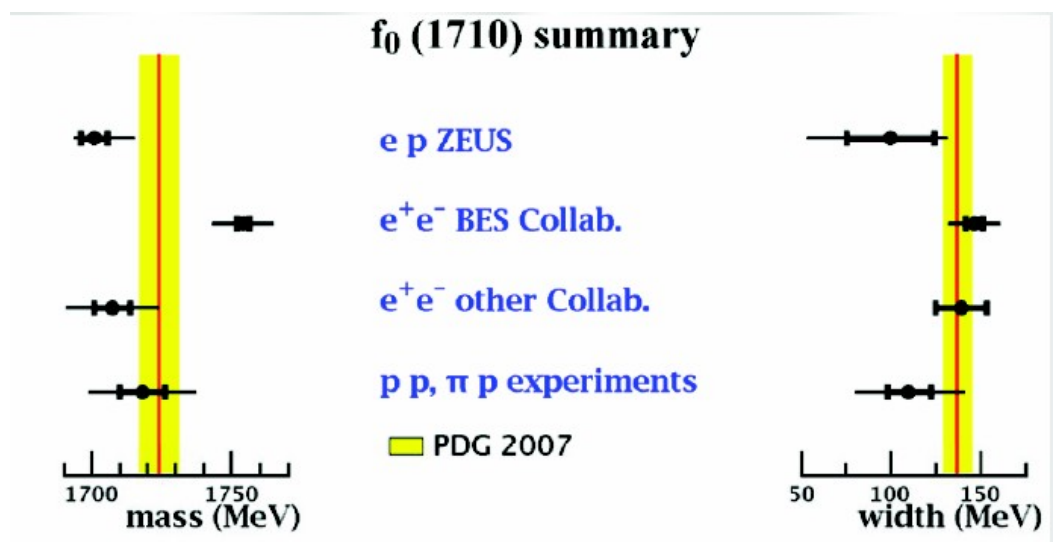
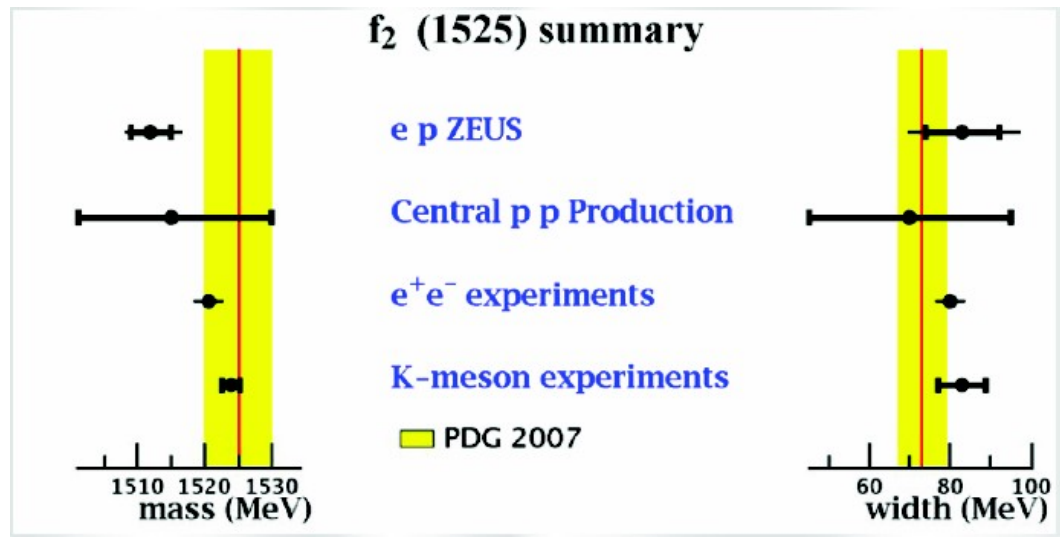


- 4 BW fit with SU(3) motivated interference (M, Γ – free parameters)
- Very good $f_0(1710)$ signal:
4058±820 events ~ 5 s. d.

Question: Is this a glueball ?!

Answer: as $f_0(1710)$ is also seen in $\gamma\gamma \rightarrow K_s^0 K_s^0$ 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 success 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

