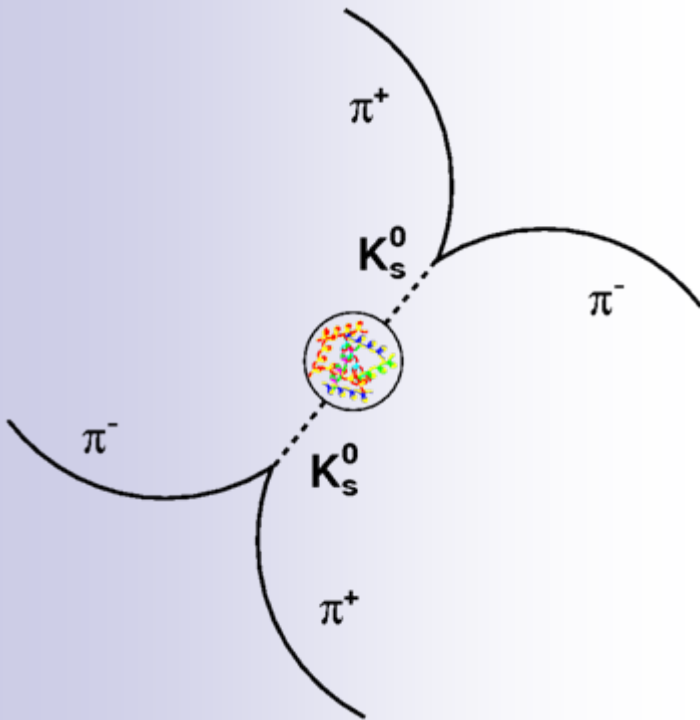




$$K_s^0 K_s^0$$

# Resonance Production at ZEUS



**Introduction**

**Previous Results**

**Experimental Details**

**$K_s^0 K_s^0$  spectra**

**Summary & Conclusion**

# Motivation

- The Standard Model (SM) describes hadrons via partons (mainly quarks)
- Mesons are usually described by spin-parity ( $J^P$ ) multiplets of  $q\bar{q}$
- The SM allows glueballs ( $gg$ ), hybrids ( $q\bar{q}g$ ) and mixed states
- The scalar meson sector ( $J^P=0^+$ ) has too many established  $I = 0$  states:

$f_0(980)$ ,  $f_0(1370)$ ,  $f_0(1500)$ ,  $f_0(1710)$

only two can fit into the  $q\bar{q}$  nonet

- Lattice calculations predict that the lightest glueball has  $J^{PC} = 0^{++}$  and mass in range 1550 – 1750 MeV
- It can mix with  $q\bar{q}$  ( $I = 0$ ) states close in mass
- $f_0(1710)$  is considered to be a possible glueball candidate
- The  $K_S^0 K_S^0$  system can couple to  $J^P = 0^+$  and  $2^+$

→  $K_S^0 K_S^0$  is a good place to search for the lightest  $0^+$  glueball



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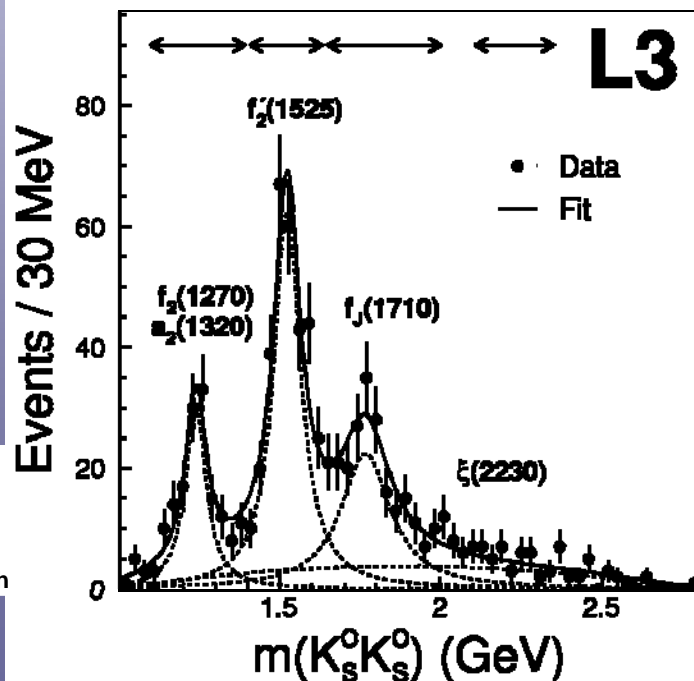
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# L3 $K_S^0 K_S^0$ Result

The L3  $e^+e^-$  LEP experiment studied in two-photon collisions the exclusive reaction  $\gamma\gamma \rightarrow K_S^0 K_S^0$

L3 Collab., M. Acciarri et al., Phys. Lett. B501, 173 (2001)

They see 3 distinct peaks over a low background and attribute them to  $f_2(1270)/a_2(1320)$ ,  $f_2'(1525)$  and  $f_0(1710)$



Spectrum dominated by the formation of the  $f_2'(1525)$  tensor meson

$f_0(1710)$  signal of  $\sim 4$  s.d. is seen

Maximum likelihood fit with 3 BW

Functions plus 2<sup>nd</sup> order polynomial

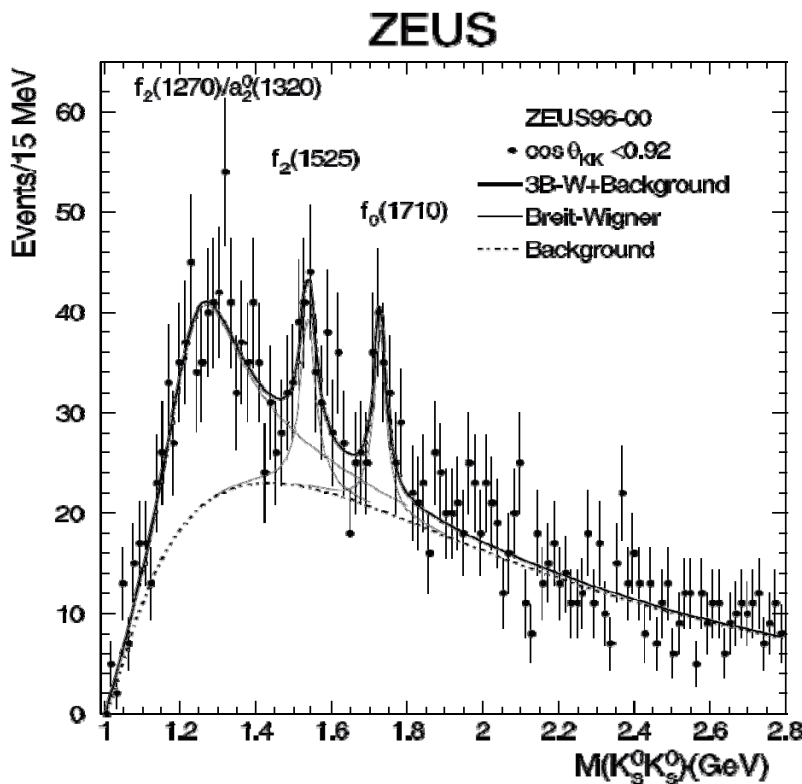
$f_2'(1525)$  parameters consistent with PDG

	$f_2(1270)/a_2(1320)$	$f_2'(1525)$	$f_0(1710)$
Mass (MeV)	$1239 \pm 6$	$1523 \pm 6$	$1767 \pm 14$
Width (MeV)	$78 \pm 19$	$100 \pm 15$	$187 \pm 60$
Events	$123 \pm 22$	$331 \pm 37$	$221 \pm 55$

# Previous ZEUS $K_S^0 K_S^0$ Result



ZEUS observed indications of  $f_2'(1525)$  and  $f_0(1710)$  decaying into  $K_S^0 K_S^0$   
 In inclusive deep inelastic scattering (DIS) HERA event sample ( $121 \text{ pb}^{-1}$ )  
 ZEUS Collab., S. Chekanov *et al.*, Phys. Lett. B578, 33 (2004)



After applying strong cuts to the data sample, the statistical significance of each resonance was  $\leq 3 \text{ s.d.}$

The  $f_0(1710)$  width ( $\sim 40 \text{ MeV}$ ) was much narrower than PDG value ( $\sim 130 \text{ MeV}$ )

The present analysis was performed on the full HERA I & HERA II sample ( $\sim 0.5 \text{ fb}^{-1}$ )

$$e^\pm p \rightarrow K_S^0 K_S^0 + X$$

The kinematic region included both photoproduction (PHP) ( $Q^2 < 1 \text{ GeV}^2$ ) and DIS ( $Q^2 > 1 \text{ GeV}^2$ )

Sample dominated by PHP events

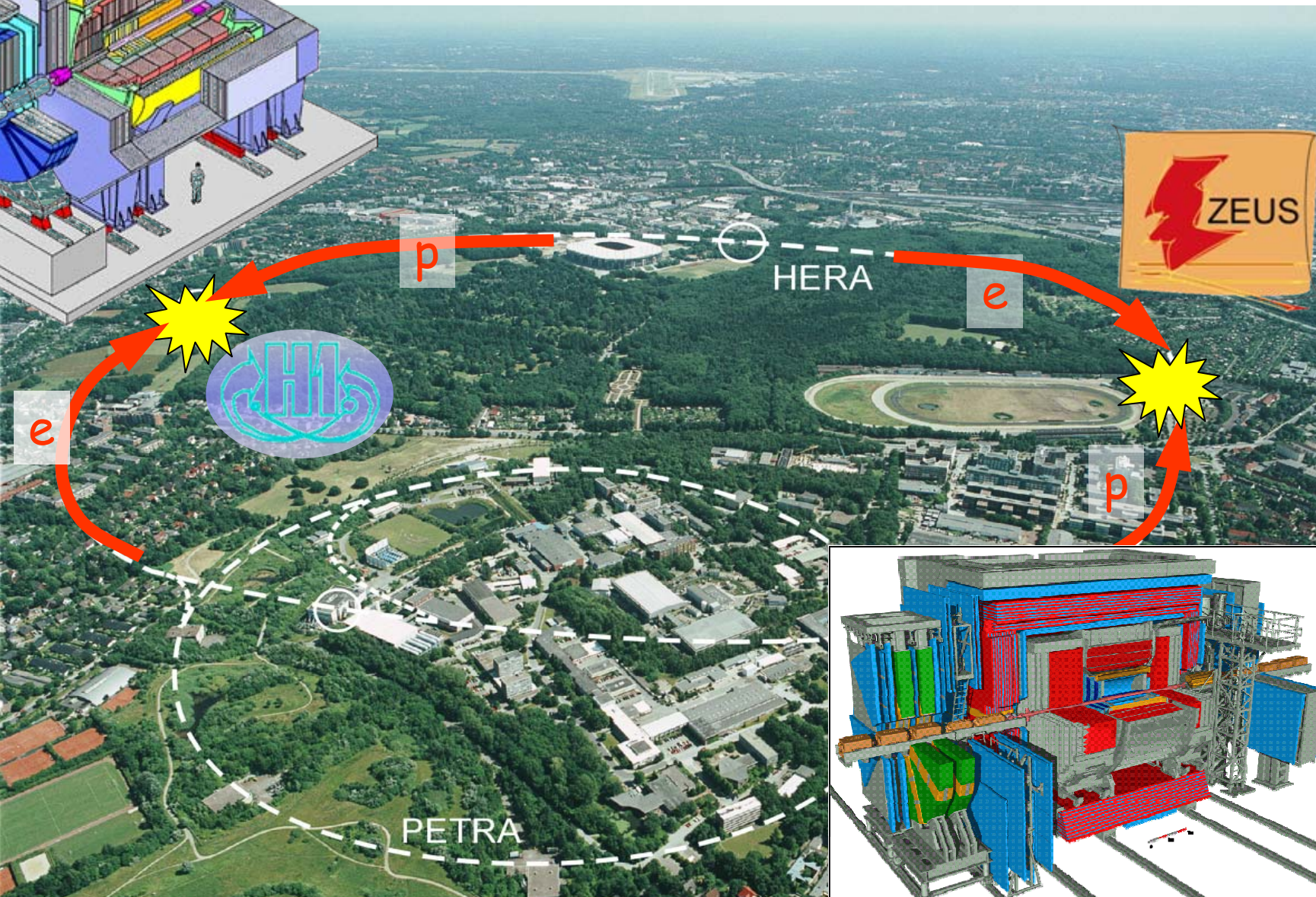
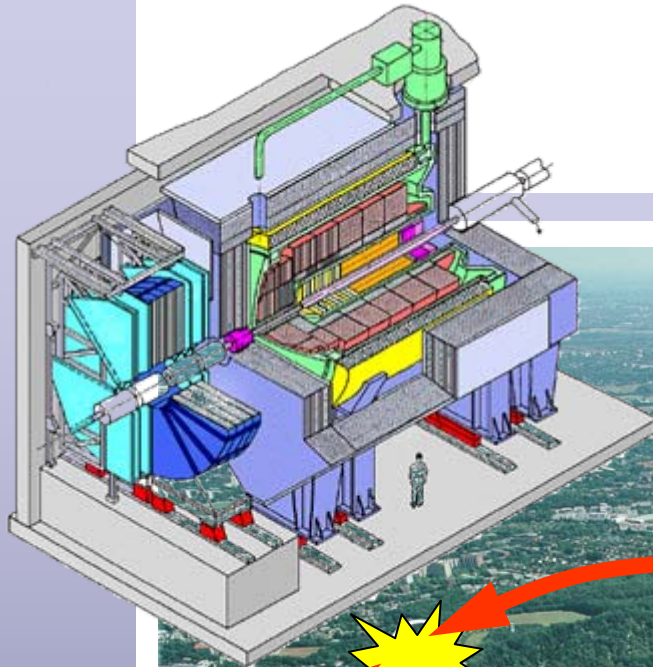


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# HERA Accelerator



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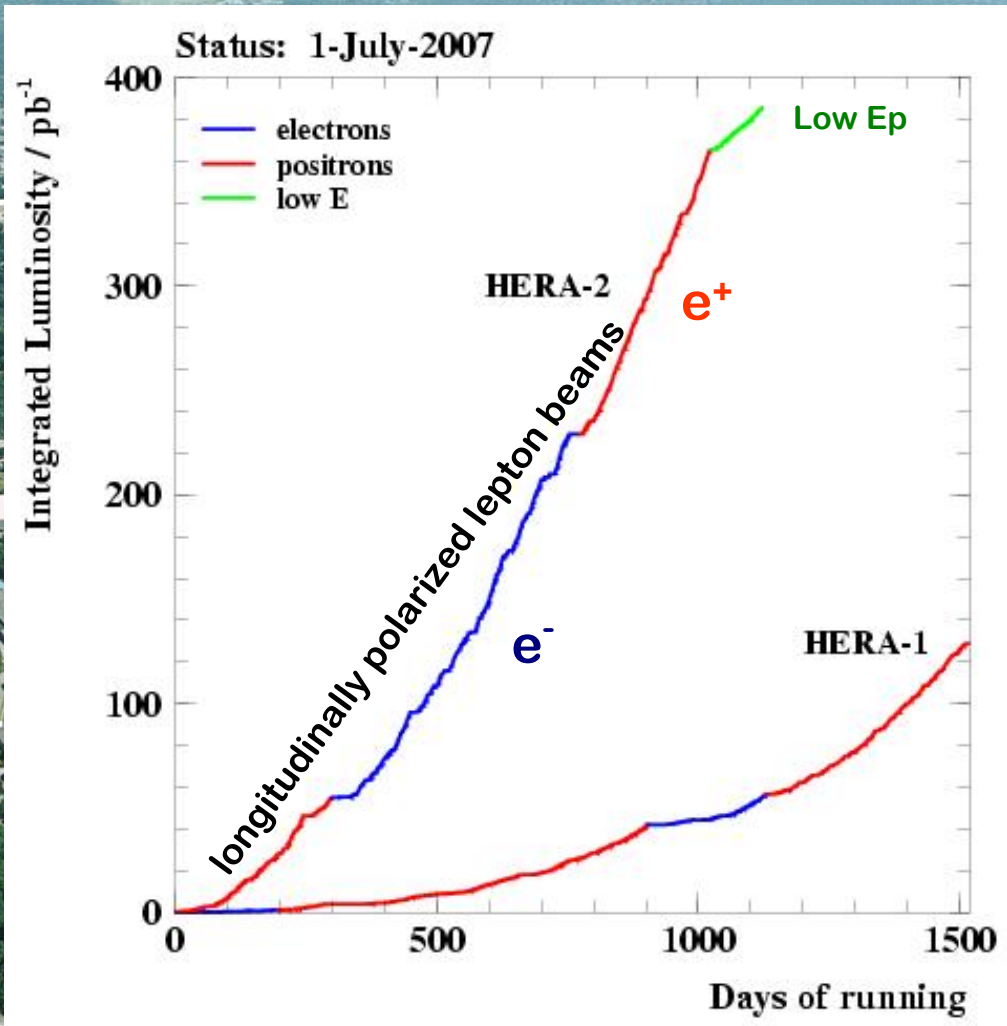
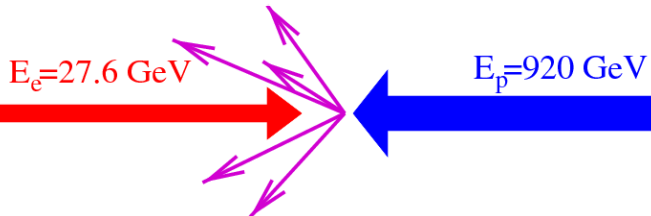
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# HERA Accelerator Performance



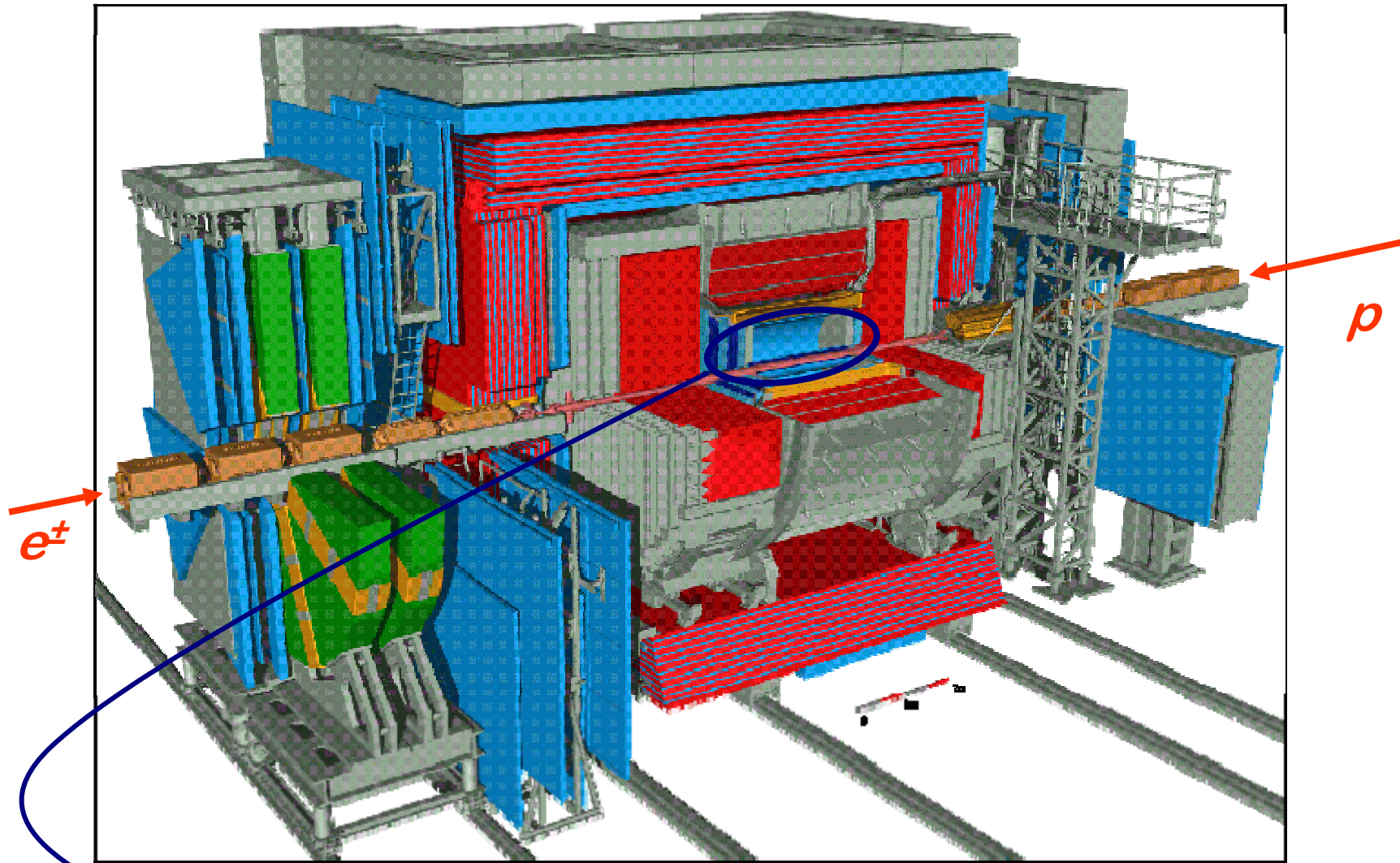
HERA-1 & HERA-2  
combined integrated  
Luminosity  $L = 0.5 \text{ fb}^{-1}$   
per experiment



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# ZEUS Detector



Tracker:  $R=80\text{cm}$ ,  $B = 1.43\text{ T}$ , 72 wire layers,



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# Experimental Details



The data were taken at the HERA e-p collider with the ZEUS detector  
 $E(e) = 27.5 \text{ GeV}$ ;  $E(p) = 920 (820) \text{ GeV}$  during 1998-2007 (1996-97)

Events with  $\geq 2 V_0$  candidates were selected

No explicit trigger requirement applied for selecting  $K_S^0 K_S^0$  events

PHP sample dominated by low- $E_T$  jet trigger ( $E_T > 6 \text{ GeV}$ )

DIS sample triggered by requiring  $e^\pm$  in the calorimeter

$K_S^0$  mesons identified via  $\pi^+\pi^-$  from secondary vertex

$K_S^0$  candidates selected from  $M(\pi^+\pi^-)$  by requiring:

- $M(e^+e^-) > 50 \text{ MeV}$  to eliminate photon conversions
- $M(p\pi) > 1121 \text{ MeV}$  to eliminate  $\Lambda/\Lambda$  contamination
- $p_T(K_S^0) > 0.25 \text{ GeV}$ ;  $|\eta(K_S^0)| < 1.6$
- $\theta_{2d} < 0.12 \text{ rad}$ ,  $\theta_{2d}$  = angle in  $xy$ -plane between  $K_S^0$  momentum vector and vector defined by interaction point and decay vertex



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# $K_S^0$ Mass Distribution

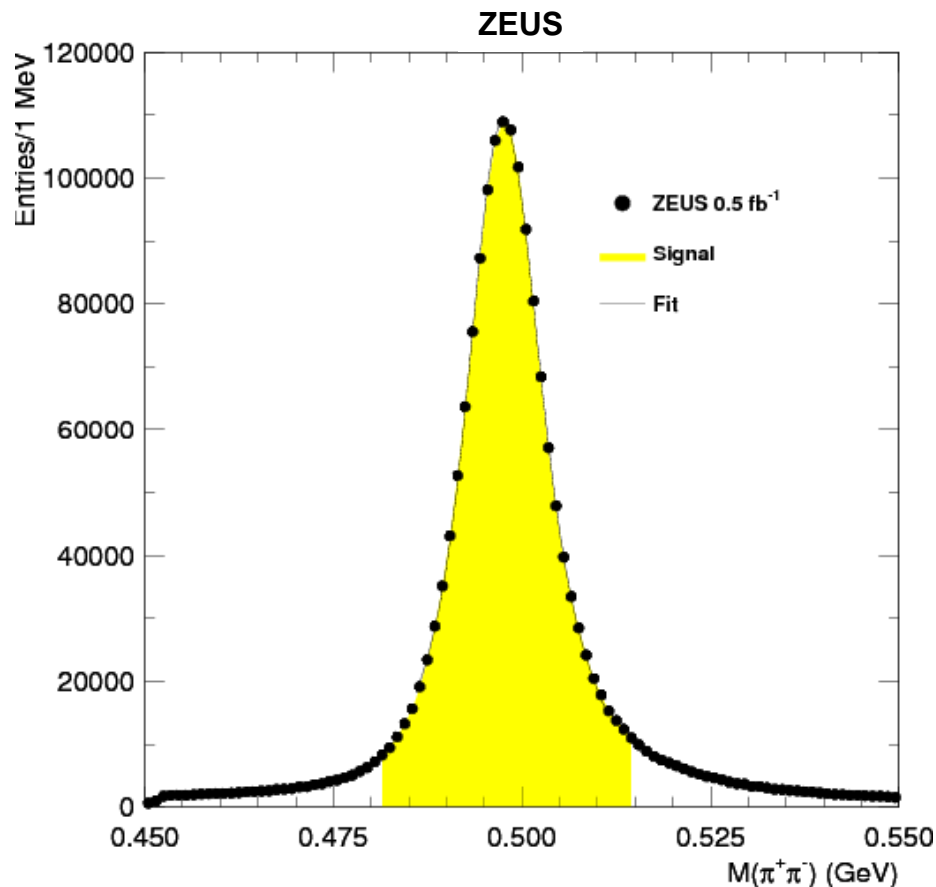


$M(\pi^+\pi^-)$  distribution for events with  $\geq 2 K_S^0$  candidates

Signal window for  $M(K_S^0 K_S^0)$  analysis:  $481 \leq M(\pi^+\pi^-) \leq 515$  MeV

No. of  $K_S^0$  candidates in signal window  $\sim 1,258,400$

Clean  $K_S^0$  signal; background  $\sim 8\%$  (estimate from 1<sup>st</sup> pol. Fit)



$K_S^0$  mass and width determined by fitting central region with double Gaussian

$M(K_S^0 K_S^0) = 497.49$  MeV  
consistent with PDG

$\sigma = 4.1$  MeV consistent with detector resolution



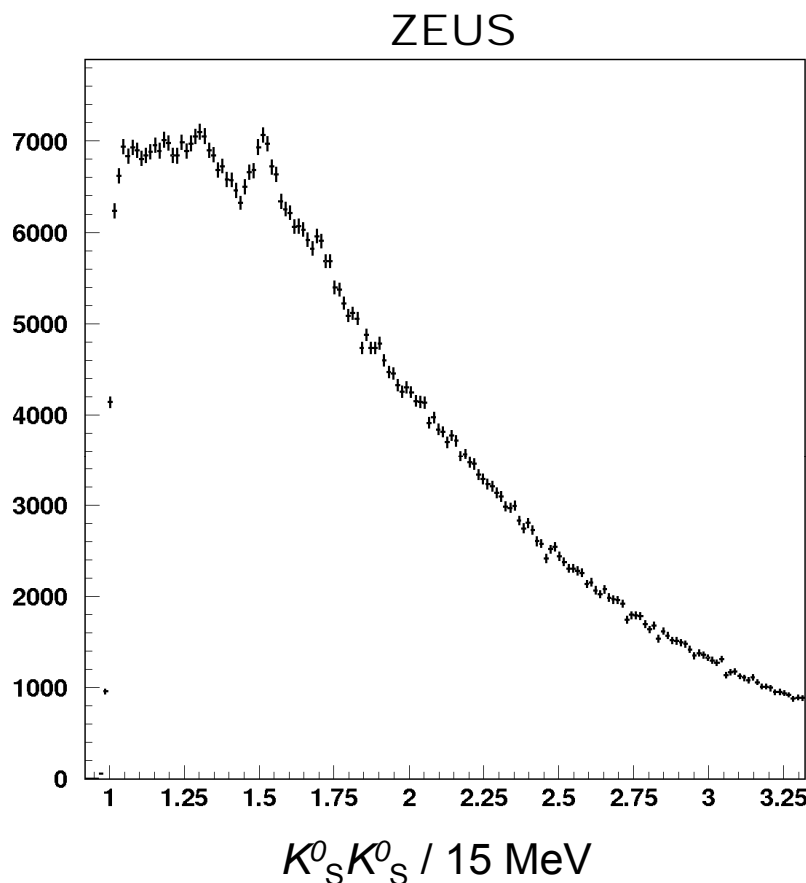
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# Fitting Procedure



Two  $K_S^0$  candidates are combined to reconstruct the  $K_S^0 K_S^0$  invariant mass distribution



3 enhancements seen around  
1.3, 1.5, 1.7 GeV

No state seen heavier than 1.7 GeV

Invariant mass distribution,  $m$ , fitted as sum of relativistic Breit-Wigner (RBW) resonances and smooth background

$$A(m - 2M_{K_S^0})^B \exp\left(-C\left(m - 2M_{K_S^0}\right)\right)$$

A,B,C are free parameters

$m(K_S^0)$  is the PDG  $K_S^0$  mass

Mass resolution below 1.8 GeV

$\sim 12 \text{ MeV} \ll$  resonance widths

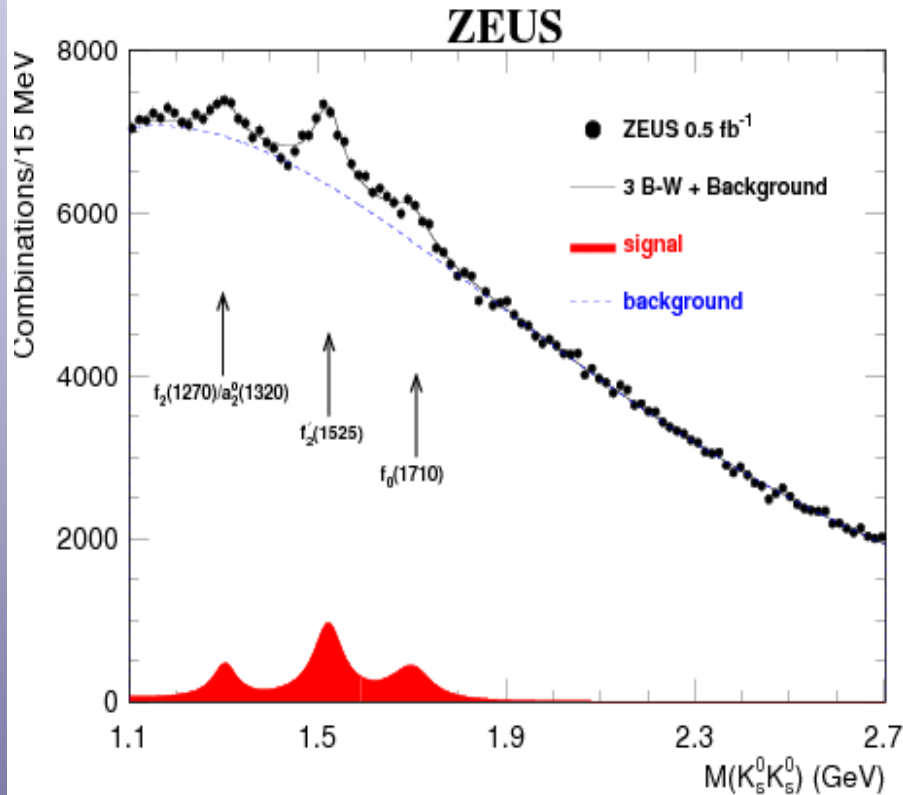
→ not included in fit



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# $K_S^0 \bar{K}_S^0$ Mass Spectrum & Incoherent Fit



Fit (as in L3) to background plus incoherent sum of 3 modified RBW resonance,  $R$ , of the form

$$F(m) = C_R \frac{M_R \Gamma_R}{\left(M_R^2 - m^2\right)^2 + M_R^2 \Gamma_R^2}$$

representing the peaks

$f_2(1270)/a_2(1320)$ ,  $f_2'(1525)$ ,  $f_0(1710)$

$C_R$  = Amplitude of resonance  $R$

$M_R$  = Mass of resonance  $R$

$\Gamma_R$  = Variable width of resonance  $R$

$m = K_S^0 \bar{K}_S^0$  invariant mass

Goodness of fit is OK  $\chi^2/\text{ndf} = 96/95$

Dip between  $f_2(1270)/a_2(1320)$  and  $f_2'(1525)$  not well reproduced

Fit without  $f_0(1710)$  is bad  $\rightarrow f_0(1710)$  is required



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# TASSO $K_S^0 K_S^0$ Result

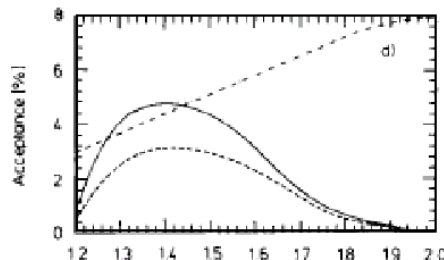
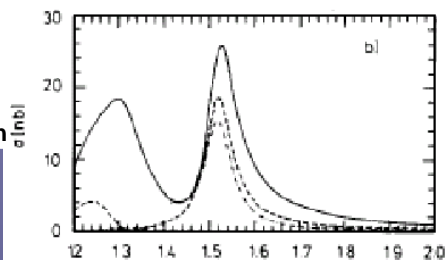
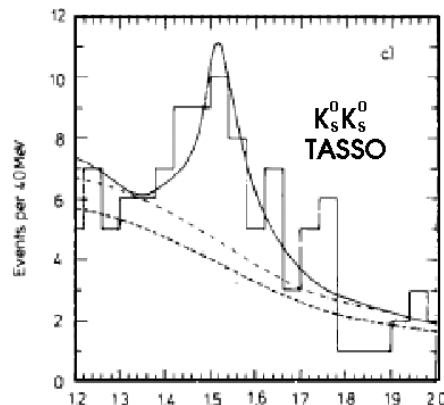
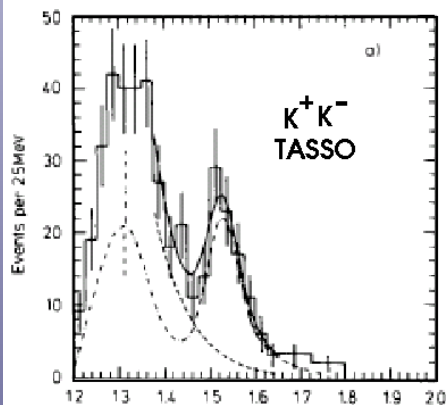
The old TASSO experiment at the PETRA  $e^+e^-$  collider studied in two-photon collisions the exclusive reactions  $\gamma\gamma \rightarrow K^+K^-$ ,  $K_S^0 K_S^0$

TASSO Collab., M. Althoff *et al.*, Phys. Lett. B121, 216 (1983)

A strong  $f_2(1270)/a_2(1320)$  enhancement is seen in  $M(K^+K^-)$

No  $f_2(1270)/a_2(1320)$  signal is seen in  $M(K_S^0 K_S^0)$

The  $f_2'(1525)$  is seen in both spectra



Results interpreted by interference effects between the 3  $J^P=2^+$  resonances  $f_2(1270)$ ,  $a_2(1320)$ ,  $f_2'(1525)$   
For the same spin-parity, production amplitude is sum of 3 coherent BW's  
 $C_1 \cdot \text{BW}(f_2(1270)) \pm C_2 \cdot \text{BW}(a_2(1320)) + C_3 \cdot \text{BW}(f_2'(1525))$

According to SU(3), sign of 2<sup>nd</sup> term is + for  $K^+K^-$ ; - for  $K_S^0 K_S^0$

Faiman *et al.*, Phys.Lett. B59, 269 (1975)



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# M( $K_S^0 K_S^0$ ) Fit of Coherent $2^+$ States

	$f_2(1270)$	$a_2(1320)$	$f_2'(1525)$
Isospin I	0	1	0
Quark content	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$(u\bar{u} - d\bar{d})/\sqrt{2}$	$s\bar{s}$
Charge factor	$(\frac{2}{3} \cdot \frac{2}{3} + \frac{1}{3} \cdot \frac{1}{3})\frac{1}{2}$	$(\frac{2}{3} \cdot \frac{2}{3} - \frac{1}{3} \cdot \frac{1}{3})\frac{1}{2}$	$\frac{1}{3} \cdot \frac{1}{3}$
Amplitude ratio	$C_1 = 5$	$C_2 = -3$	$C_3 = 2$

→ The appropriate function to fit the  $M(K_S^0 K_S^0)$  spectra for an electromagnetic production process assuming SU(3) symmetry is  
H.J. Lipkin, private communication

$$F(m) = a \left[ 5 \cdot \text{BW}(f_2(1270)) - 3 \cdot \text{BW}(a_2(1320)) + 2 \cdot \text{BW}(f_2'(1525)) \right]^2 + b \left[ \text{BW}(f_0(1710)) \right]^2 + c \cdot \text{background}$$

a, b, c are free parameters

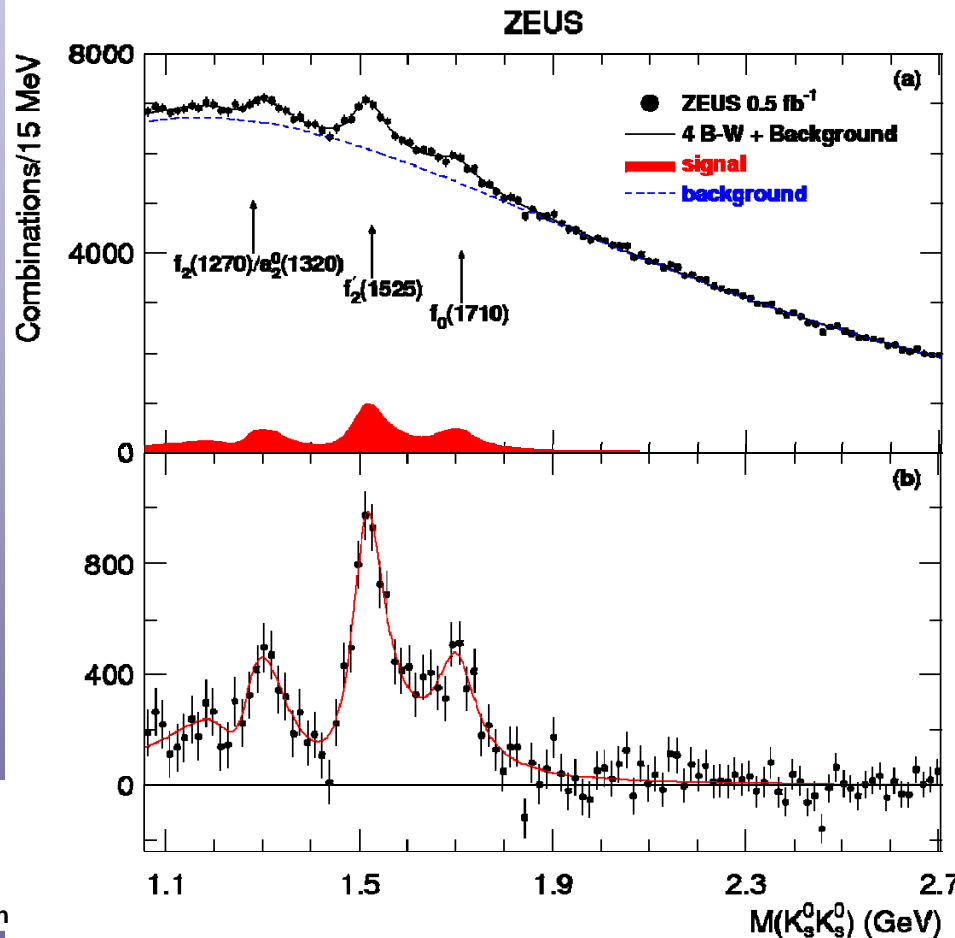
BW is a relativistic BW amplitude:  $\text{BW}(R) = \frac{M_R \sqrt{\Gamma_R}}{M_R^2 - m^2 - iM_R \Gamma_R}$



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# $K_S^0 K_S^0$ Spectrum & Interference Fit



$M, \Gamma$  of all resonances – free parameters in the fit.

Bottom plot background subtracted  $M(K_S^0 K_S^0)$  spectrum with fitted BW functions.

Good fit  $\chi^2/\text{ndf} = 86/97$ .

Peak around 1.3 GeV suppressed due to destructive interference between  $f_2(1270)$  and  $a_2(1320)$ . Dip between  $f_2(1270)/a_2(1320)$  and  $f_2'(1525)$  is well reproduced.

No. of fitted  $f_0(1710)$  events:

$4058 \pm 820 \sim 5\sigma$  significance

Fit without  $f_0(1710)$  strongly disfavoured  $\chi^2/\text{ndf} = 162/97$



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# Table of Fit Results



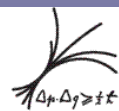
Fit	No interference		Interference		PDG 2007 Values	
$\chi^2/ndf$	96/95		86/97			
in MeV	Mass	Width	Mass	Width	Mass	Width
$f_2(1270)$	$1304 \pm 6$	$61 \pm 11$	$1268 \pm 10$	$176 \pm 17$	$1275.4 \pm 1.1$	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$			$1257 \pm 9$	$114 \pm 14$	$1318.3 \pm 0.6$	$107 \pm 5$
$f_2'(1525)$	$1523 \pm 3^{+2}_{-8}$	$71 \pm 5^{+17}_{-2}$	$1512 \pm 3^{+1.4}_{-0.5}$	$83 \pm 9^{+5}_{-4}$	$1525 \pm 5$	$73^{+6}_{-5}$
$f_0(1710)$	$1692 \pm 6^{+9}_{-3}$	$125 \pm 12^{+19}_{-32}$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+7}_{-22}$	$1724 \pm 7$	$137 \pm 8$

Incoherent fit yields narrow width for  $f_2(1270)/a_2(1320)$ :  $61 \pm 11$  MeV

Similar to the L3 incoherent fit:  $\Gamma(f_2(1270)/a_2(1320)) = 78 \pm 19$  MeV

For fit with interference:

- $a_2(1320)$  mass below PDG value. Similar shift, attributed to destructive  $f_2(1270)/a_2(1320)$  interference, seen by Faiman *et al.*
- Widths of all observed resonances close to PDG values
- $f_2'(1525)$ ,  $f_0(1710)$  masses below PDG; uncertainties compatible with PDG
- One of the best  $f_0(1710)$  reported signals:  $4058 \pm 820$  events  $\sim 5$  s.d.
- All resonances observed in DIS sample (much smaller than PHP one)

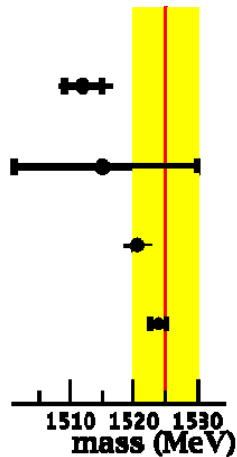


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# Mass & Width of $f'_2(1525)$ and $f_0(1710)$

## $f'_2(1525)$ summary



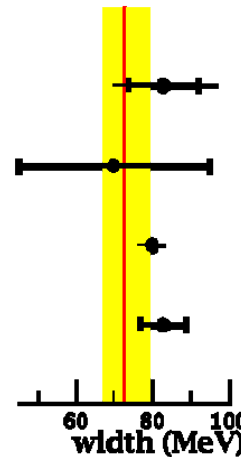
e p ZEUS

Central p p Production

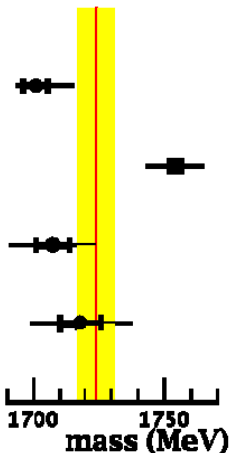
$e^+e^-$  experiments

K-meson experiments

PDG 2007



## $f_0(1710)$ summary



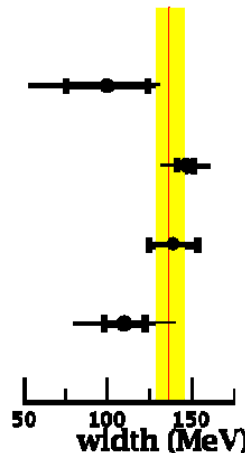
e p ZEUS

$e^+e^-$  BES Collab.

$e^+e^-$  other Collab.

p p,  $\pi$  p experiments

PDG 2007



$f_0(1710)$  mass in BES experiment  
seen in quarkonium decays:

$J/\psi$  or  $\psi(2S) \rightarrow (\gamma \text{ or } \omega) + f_0(1710)$

significantly above other  
experiments including older

$J/\psi$  radiative decays



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# Conclusions

- $K_S^0 K_S^0$  final states studied in  $ep$  collisions at HERA with ZEUS
- Observed 3 enhancements corresponding to  $f_2(1270)/a_2(1320)$ ,  $f_2'(1525)$  and  $f_0(1710)$
- No state observed heavier than  $f_0(1710)$
- States fitted taking into account interference pattern predicted by SU(3) symmetry arguments
- $M$  of  $f_2'(1525)$ ,  $f_0(1710)$  below PDG; all  $\Gamma$  consistent with PDG
- $f_0(1710)$  observed with  $5\sigma$  significance
- $f_0(1710)$  has mass consistent with  $J^P=0^+$  glueball candidate
- If  $f_0(1710)$  is same as seen in  $\gamma\gamma \rightarrow K_S^0 K_S^0$  (TASSO, L3) it is unlikely to be pure glueball since photons can couple in the partonic level only to charged quarks



# Backup Slides

- Systematic uncertainties
- Deep inelastic scattering



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# Systematic Uncertainties



Systematic uncertainties of mass and width of the resonances determined from the fit evaluated by varying selection cuts:

- Minimum track  $p_T$
- Track pseudorapidity range
- Track momenta by  $\pm 0.1\%$
- Track angles by  $\pm 0.5\%$
- Accepted  $\pi^+\pi^-$  mass range around  $K_S^0$  peak
- Collinearity cuts

Fitting procedure changed: use maximum likelihood instead of  $\chi^2$  fit

Largest systematic uncertainties:

- Fitting with fixed  $M$ ,  $\Gamma$  of  $f_2'(1525)$  from PDG affects  $f_0(1710)$  width by -19 MeV
- Variation of track momenta affects  $f_0(1710)$  width by +7 MeV

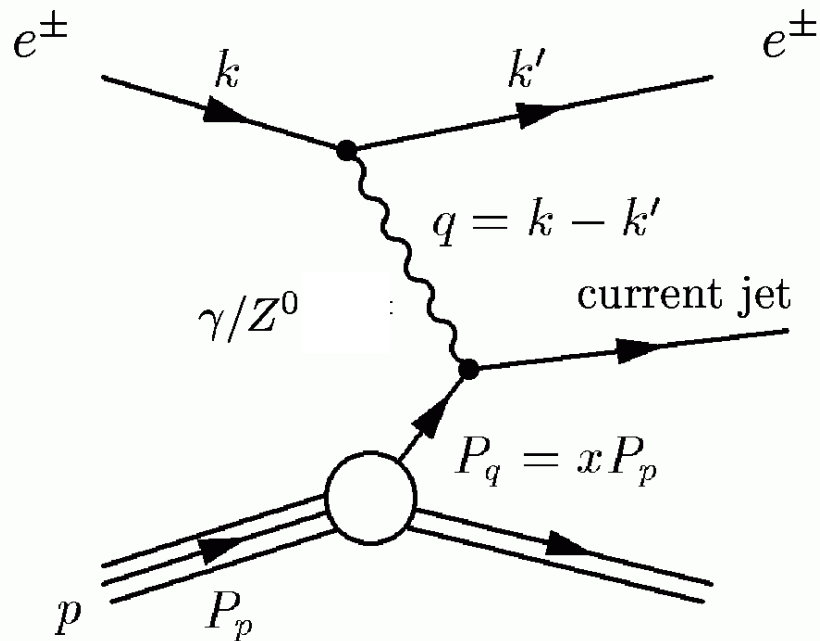
Details in: C. Zhou, Ph.D. Thesis (unpublished),  
McGill University, Montreal, Canada, 2008.



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# Deep Inelastic Scattering



## Kinematic Variables

- 4-momentum transfer resolving power  

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

- Björken scaling variable momentum fraction of struck parton  

$$x = \frac{Q^2}{2p \cdot q}$$

- Inelasticity:  

$$y = \frac{p \cdot q}{p \cdot k}$$

Center of mass energy  $\sqrt{s}$ :  $s = (k + p)^2$  relation for fixed s:  $Q^2 = sxy$

- Neutral current DIS cross section expressed by structure functions:

$$\frac{d^2\sigma^{e^\pm p \rightarrow e^\pm X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1 + (1-y)^2\right)}_{Y_\pm = 1 \pm (1-y)^2} \cdot \left( \boxed{F_2(x, Q^2)} - \frac{y^2}{Y_+} \boxed{F_L(x, Q^2)} \mp \frac{Y_-}{Y_+} \boxed{x F_3(x, Q^2)} \right)$$

valence & sea quarks

gluons

valence quarks