Search for a narrow baryonic state decaying to pK_S^0 and $\bar{p}K_S^0$ in deep inelastic scattering with the HERA II data

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on behalf of ZEUS collaboration

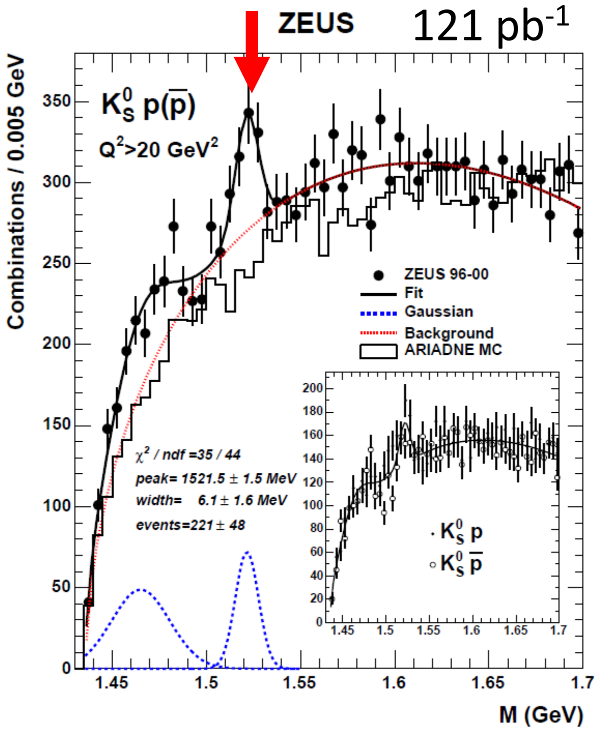
Introduction

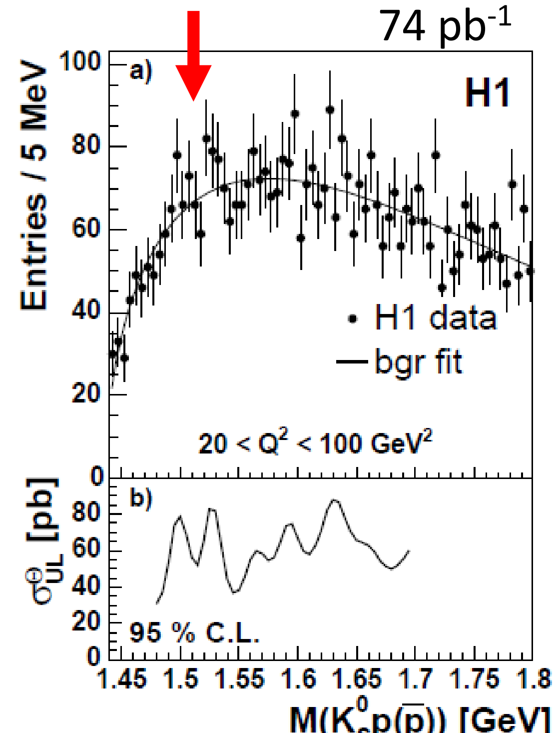
- The observation of a narrow baryon resonance with a mass of ~1.53 GeV was reported first by the LEPS experiment in 2003 in the missing-mass distribution for $\gamma A \rightarrow nK^+$ reaction. Such a baryon would be manifestly exotic and impossible for a three-quark state. But could be explained as a bound state of five quark state i.e. a pentaquark, named $\Theta^+(uudd\bar{s})$. Many experimental groups have looked for this state via various production processes in decay mode nK^+ or $pK_S^0(\bar{p}K_S^0)$. Some experiments confirmed the signal while others refuted it.
- Recently, interest in pentaquark state has arisen with the discovery of two pentaquark candidates by the LHCb experiment at 4.38 and 4.45 GeV. They have a valence quark content of $uudc\bar{c}$ and were observed with high significance.

- The ZEUS experiment reported the evidence of a peak structure in $pK_S^0(\bar{p}K_S^0)$ mass distribution in deep inelastic scattering (DIS) data in HERA I period (1996-2000).
- In this talk, a search for a Θ^+ pentaquark in the $pK_S^0(\bar{p}K_S^0)$ system is reported with the ZEUS data taken at HERA II period (2003-2007).

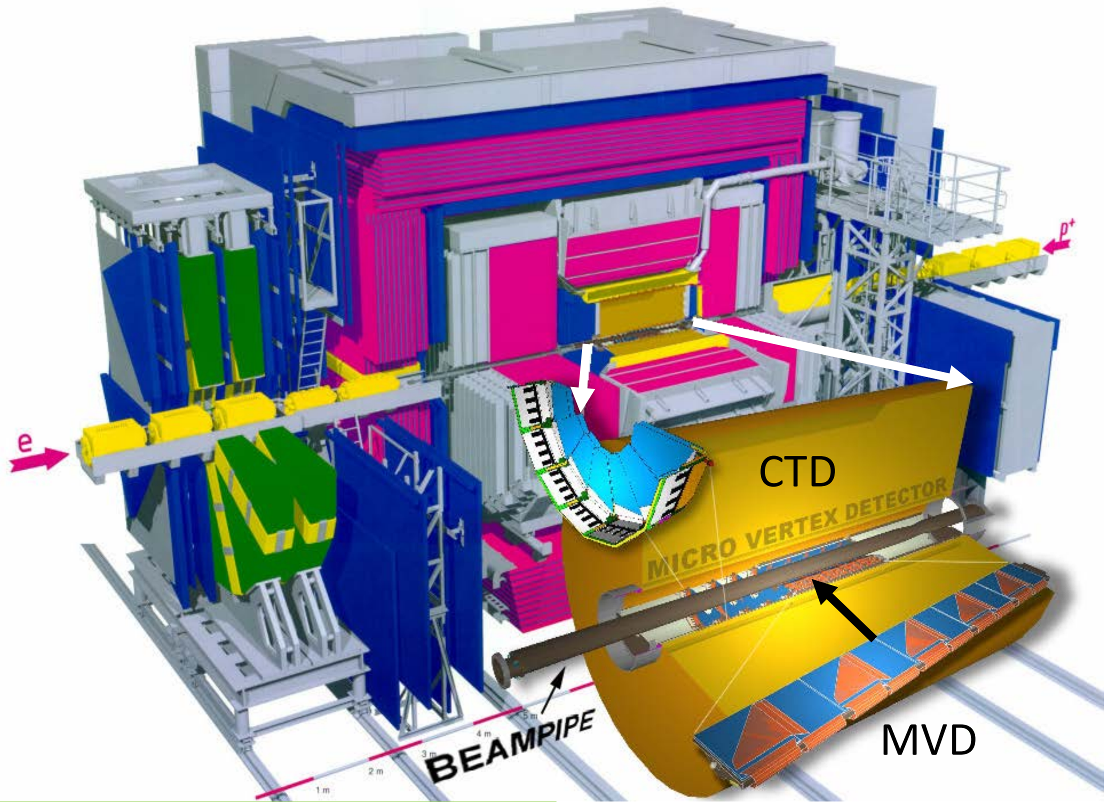
HERA I Results

- ZEUS experiment reported the evidence of a peak structure in $pK_s^0(\bar{p}K_s^0)$ mass distribution in DIS data, consistent with Θ⁺. The data were taken between 1996 and 2000 (HERA I) and correspond to an integrated luminosity of 121 pb^{-1}. (Phys. Lett. B591, 7 (2004)).
- The H1 collaboration also presented mass distributions in a similar kinematic region (Phys. Lett. B 639, 202 (2006)), but did not find any structure and presented an upper limit.
- The HERA II period not only provided larger statistics (358pb^{-1}), but the ZEUS tracking system was upgraded. We were looking for pentaquarks in DIS event with 20 < Q^2 < 100 GeV^2 in this analysis in order to compare with the HERA I results.





ZEUS detector at HERA II



- HERA accelerator at DESY, Hamburg
- HERA II Run (2003-2007)

  E_p = 920GeV

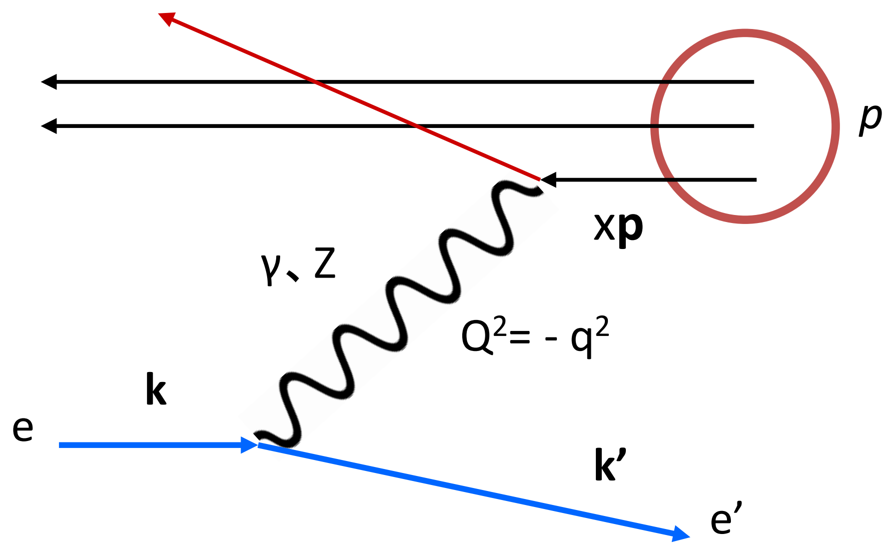
  E_e = 27.5GeV

  √s = 318 GeV

  total luminosity 358 pb^{-1}

- Silicon-strip micro vertex detector (MVD) was installed closer to the beam line than central-tracking detector (CTD). It can provide more information on the ionization energy loss per unit length, dE/dx.
- The proton selection was improved by using both of CTD and MVD dE/dx.

DIS Event selection

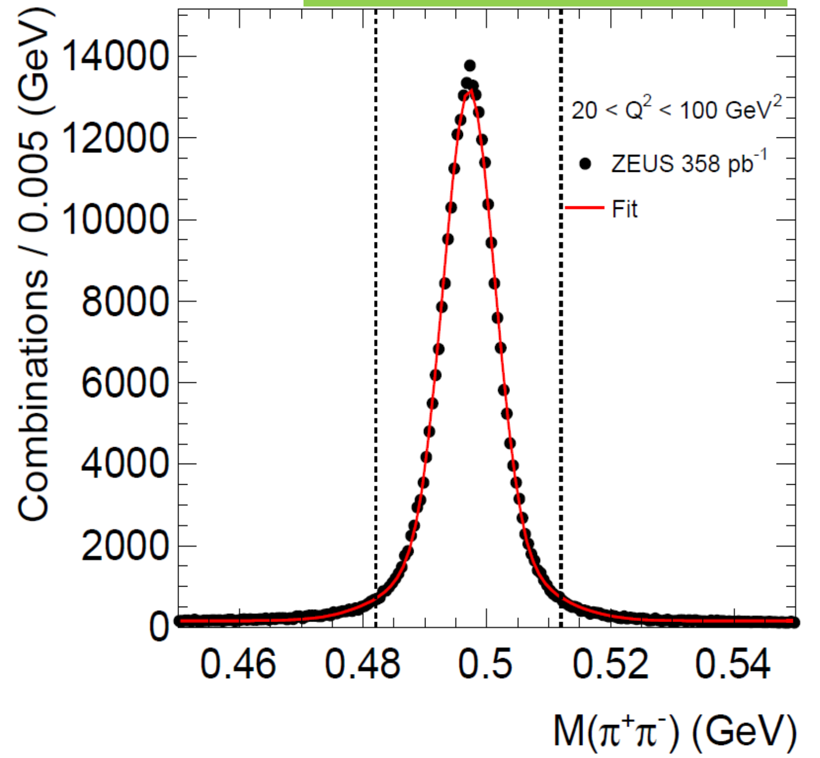


- DIS kinematical variable
  $Q^2 = -q^2$: square of 4-momentum transfer
  x: fraction of p momentum carried by quark
  y: inelasticity parameter

- DIS event selection
  - $20 < Q^2 < 100$ GeV^2
  - $E'_e > 10$ GeV
  - $38 < E\text{-}p_z < 60$ GeV
  - $y_{el} < 0.95$
  - $y_{JB} > 0.04$
  - Electron Probability > 0.90
  - Electron position |X|> 12cm |Y|> 12cm
  - $|Z_{vtx}| < 30$cm
  - Number of track > 2 & < 400
  - At least one track from the primary vertex.

$K_S^0 \to \pi^+\pi^-$ selection

of K_S^0 0.31M events



- Two tracks with opposite charge
- $p_T(\pi) > 150\text{MeV}$
- $|\eta(\pi)| < 1.75$
- π track's MVD hit > 2
- $p_T(\pi\pi) > 250\text{MeV}$
- $|\eta(\pi\pi)| < 1.6$
- Pion mass constraint fitting
  - χ^2 of fit < 5.0 (of the two tracks fit)
  - DCA between two tracks < 1.5 cm
  - DCA between beam spot and K_S^0 vertex > 0.2 cm
- 2D co-linearity < 0.06 rad
- 3D co-linearity < 0.15 rad

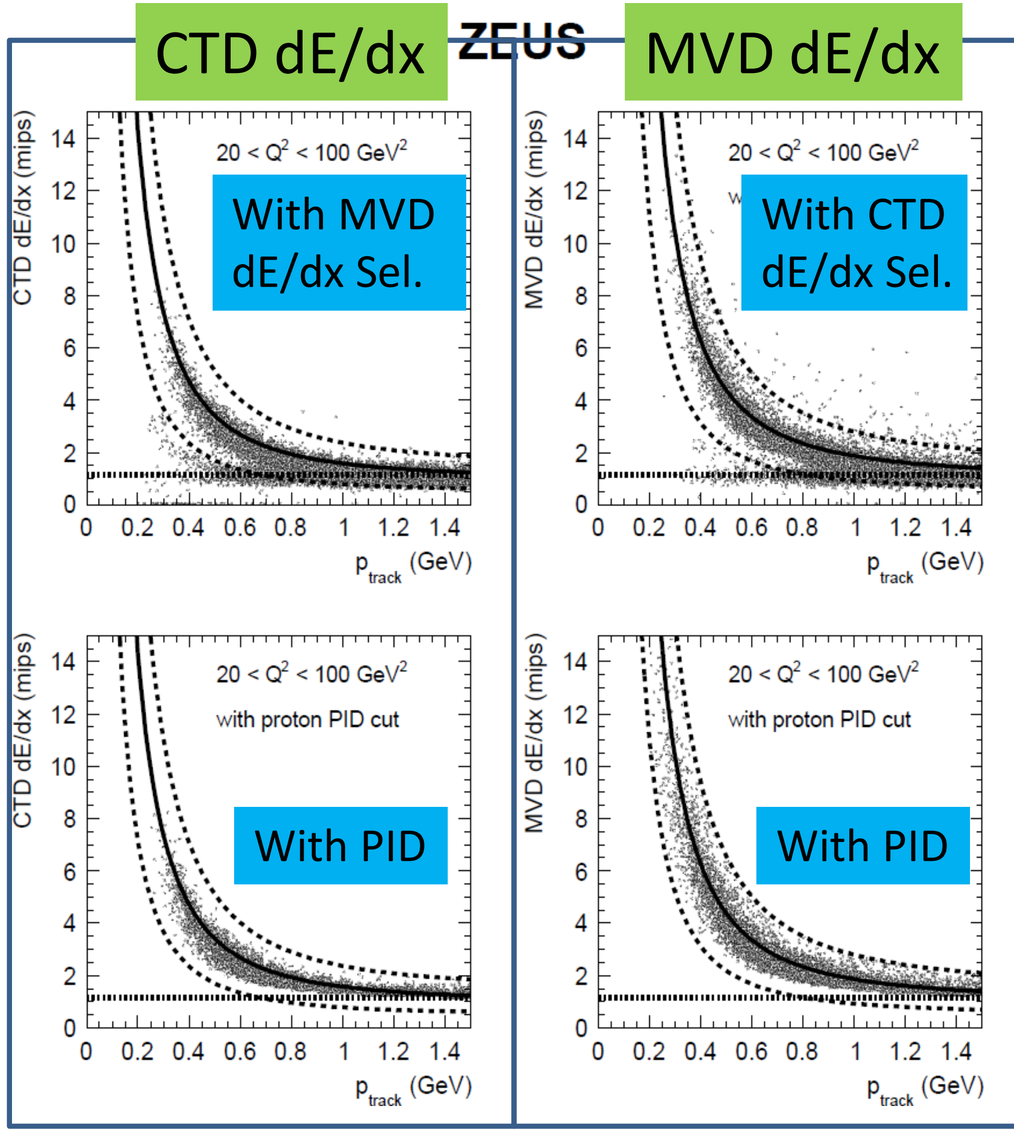
  (co-linearity; the angle between position and momentum vectors.)
- K_S^0 decay length (DL) > 0.5 cm
- When we assign the electron mass to the track, M(ee) > 0.070 GeV
- When we assign the proton mass to one of the tracks, M(pπ) > 1.121 GeV
- Finally, we set a K_S^0 mass window (0.482 < M(ππ) < 0.512 GeV, dashed line).

Proton identification (PID)

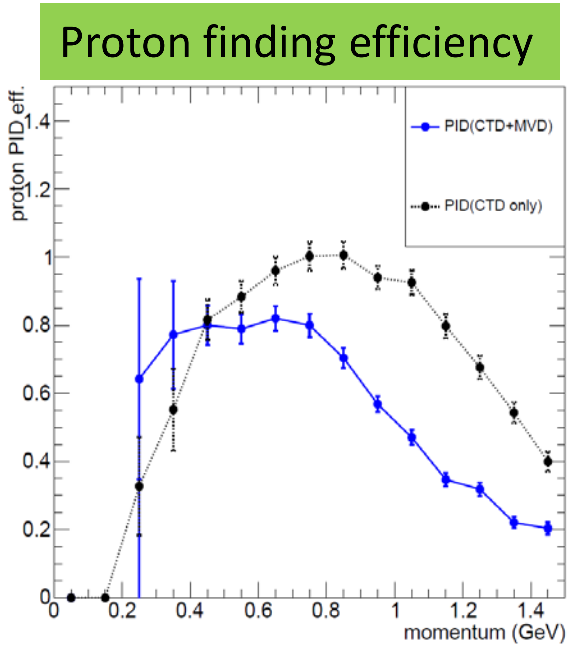
- Track selections
  - not used as π of K_S^0
  - 0.2 < p(p) < 1.5 GeV
  - CTD innermost layer = 1
  - CTD outermost layer >= 3
  - PID by both of CTD and MVD dE/dx

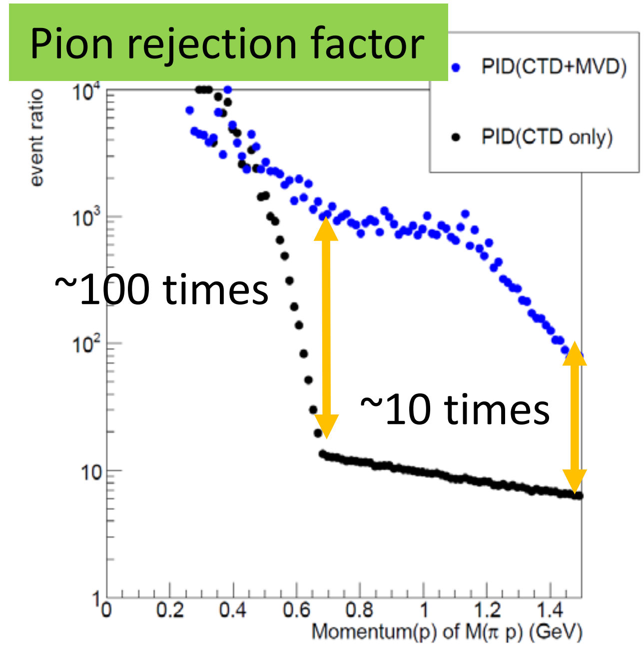
- CTD dE/dx
  - Maximum ~70 hits with full length track.
  - Truncated mean method.

    (the lowest 10% and the highest 30% hits are excluded from the mean.)
  - Resolution for protons ~9.4%.
- MVD dE/dx
  - Nominal 6 hits with full length track.
  - Calculation with probability density function of hit.
  - Resolution for protons ~11.7%.



Proton PID efficiency and pion rejection factor

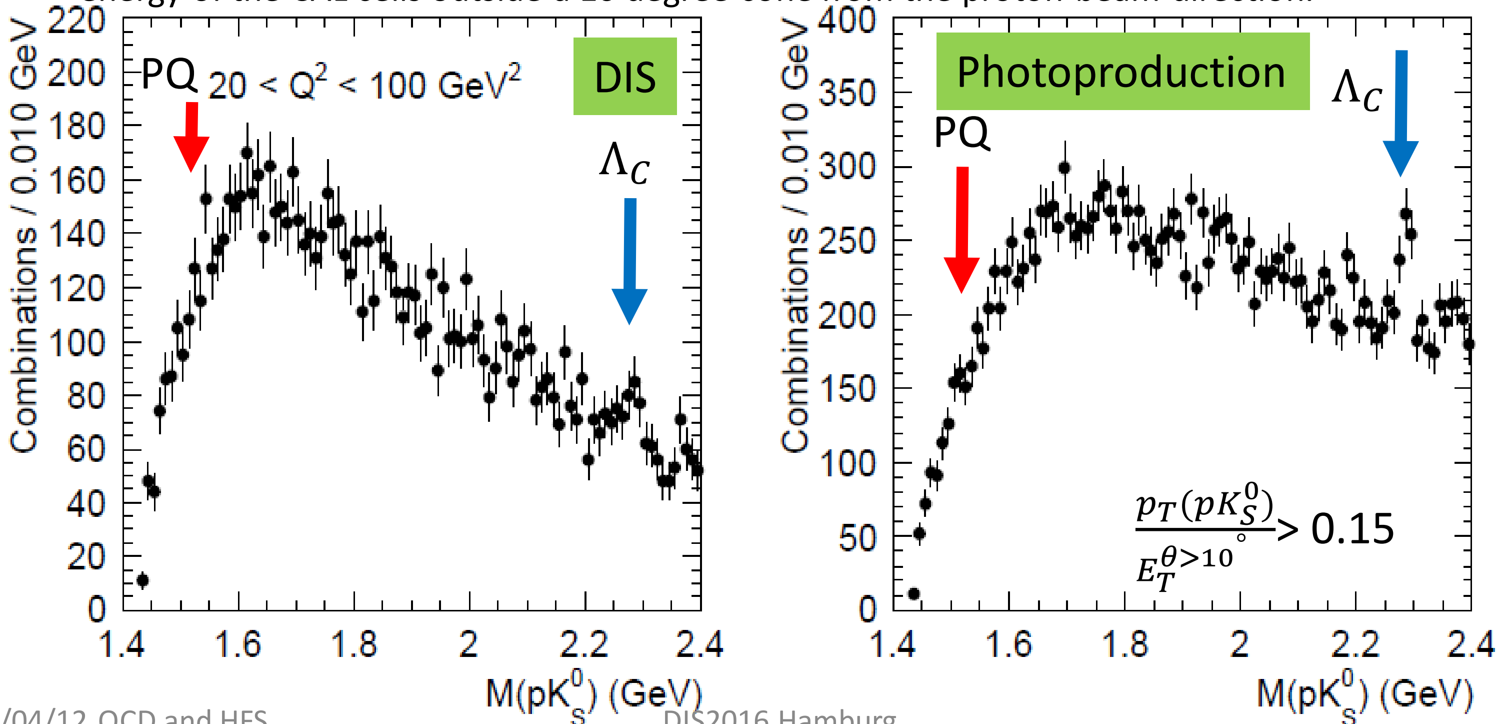




- Proton finding efficiency is estimated with a special Λ sample (Left figure) and pion Rejection factor is estimated with a special K^0s sample (Right figure).
  - Black: CTD only: only CTD dE/dx was used with a similar proton-band selection to HERA I analysis.
  - Blue: CTD+MVD: both CTD and MVD dE/dx were used with a tighter proton-band selection. (Default in this analysis)
- The proton finding efficiency of the CTD+MVD selection is lower in higher momentum.
- But, the pion rejection factor is about 100 times better for momenta below 1.2 GeV and 10 times at 1.5 GeV.

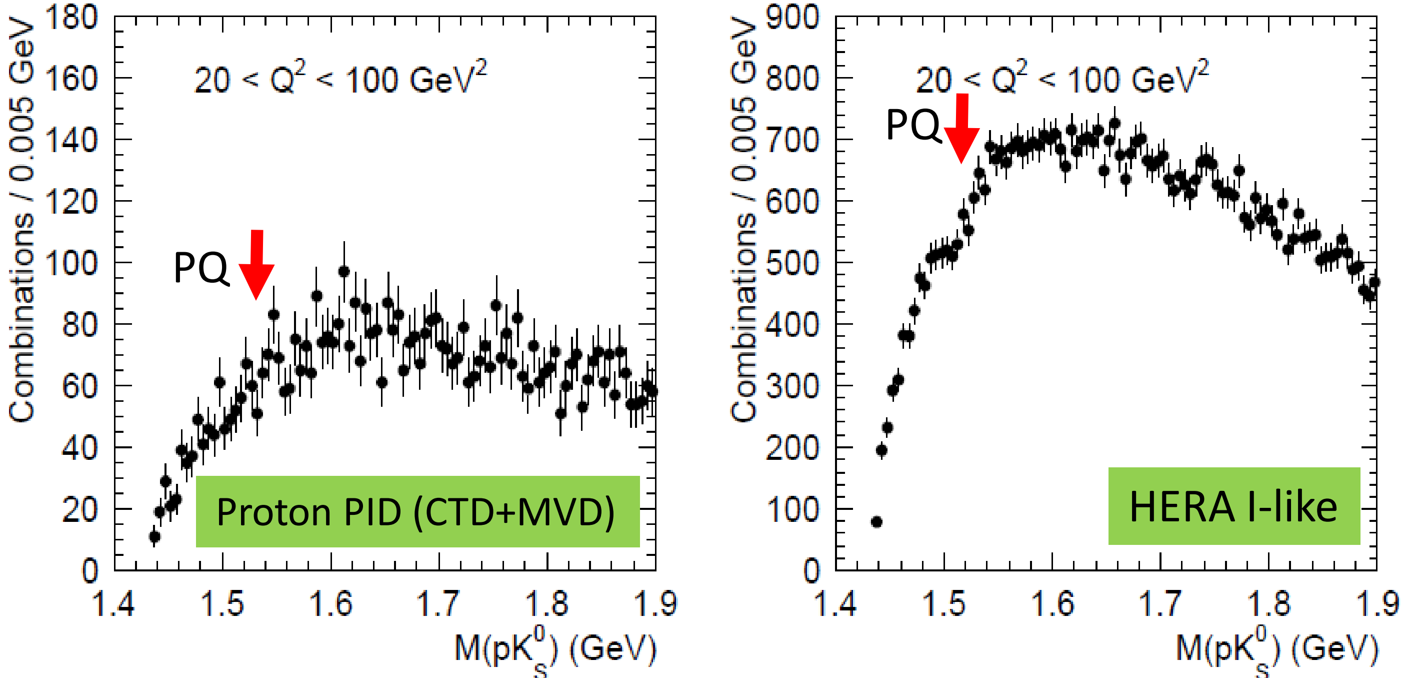
Λ_c^+ resonance

- pK_S^0 invariant mass distribution in DIS and photoproduction samples.
  - MVD+CTD dE/dx is used for the proton PID.
  - A clear Λ_C (2286) peak (blue arrow) is observed in the PHP sample. It is also seen in the DIS sample with less significance.
  - No PQ peak at the mass of Θ^+ (red arrow) is seen.
    - Photoproduction event with $\frac{p_T(pK_S^0)}{E_T^{\theta>10^\circ}}$ cut to enhance charmed event. $E_T^{\theta>10^\circ}$ is the sum of the transverse energy of the CAL cells outside a 10 degree cone from the proton-beam direction.



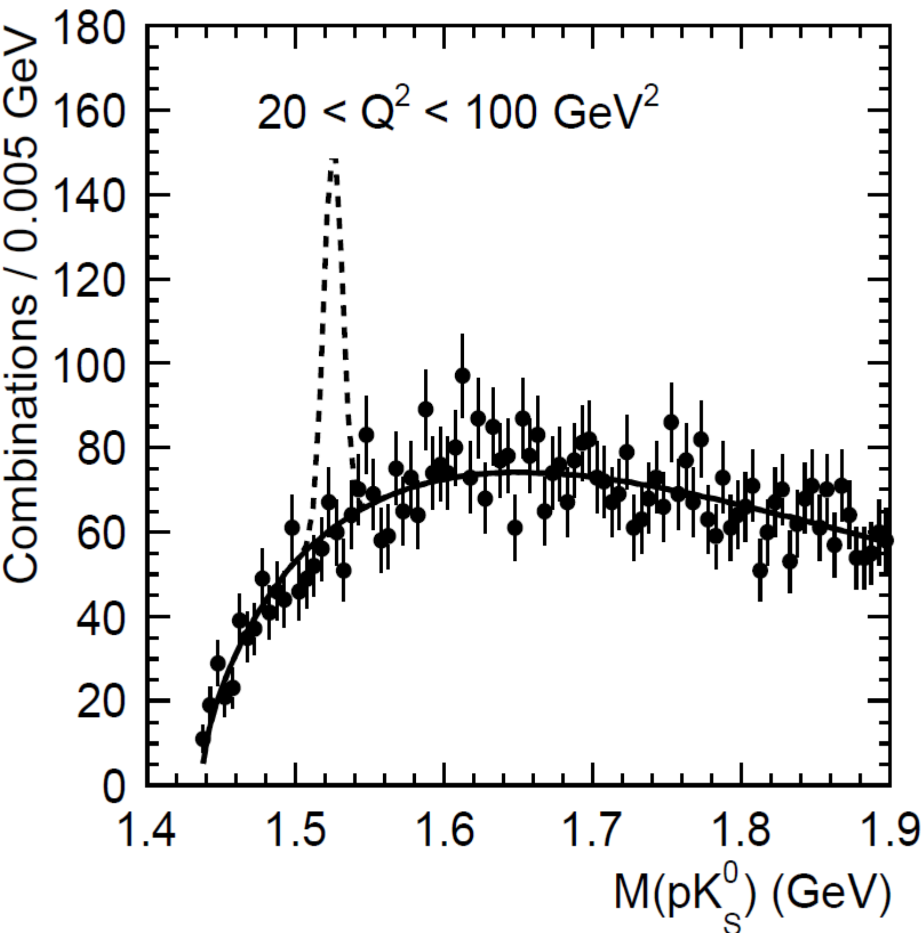
pK_S^0 invariant mass distribution in DIS sample

- Q^2 requirement
  - $20 < Q^2 < 100$ GeV²
- pK_S^0 requirements
  - $0.5 < p_T < 3.0$ GeV
  - $|\eta| < 1.5$



- The pK_S^0 invariant-mass distribution with finer bins. (Left figure)
  - No PQ peak is seen.
- For a more direct comparison to the previous ZEUS result, an analysis with CTD-only dE/dx selection and with similar cuts as in HERA I analysis was performed. (Right figure)
  - The increase of the number of events is mainly due to the looser PID selection for the proton candidates. For this looser selection, the pion contamination in the proton candidates was estimated to be more 50%. It was ~5% in the left figure.
  - No PQ peak is seen, either.

Comparison with ZEUS HERA I analysis



- The dashed line represents the Θ^+ signal as would be observed if it had the same strength as reported in the ZEUS HERA I analysis (expected 286 events).
- The HERA I signal is not confirmed in this analysis.

$\Rightarrow$ Upper limit estimation was performed.

PQ MC samples for the limit calculation

- Pentaquark MC samples were generated by RAPGAP 3.1030 in order to determine the detector acceptance to estimate the production cross section of the PQ state.
  - PQs were simulated by replacing $\Sigma^+(1189)$ in the particle table with pentaquark,
  - PQ isotropically decays to $p + K^0$,
  - PQs were generated for various mass values. (1.45,1.5,1.522,1.54,1.56,1.6,1.65 GeV),
  - Q^2>1GeV and at least one Θ event in rapidity |y| < 2.5,
  - The generated events were passed through the GEANT 3.21-based ZEUS detector and trigger simulation program.

Setting of PQ cross section limit calculation

- Kinematical limits were set with the well identified phase space.
  - (DIS, 20 < Q^2 < 100 GeV^2, 0.5 < $p_T(pK_S^0)$ < 3.0 GeV , |η(pK_S^0)| < 1.5)
  - Acceptance correction ASSUMING the p_T spectrum of pentaquark is similar to Σ^+(1189). : the systematics uncertainty according to the slope was estimated by varying it between different p_T slopes.

- The pK_S^0 mass distribution was fitted in the range from 1.435 to 1.9 GeV using a Gaussian function for the postulated signal and an empirical function with three parameters for the background. (see next page)

- The cross section of either of Θ^+ or $\overline{\Theta^+}$ is defined as

$$\sigma\,(\Theta) \;=\; (\,\sigma(ep \rightarrow\; e\,\Theta^+\,X) \;+\sigma(ep \rightarrow\; e\,\overline{\Theta^+}\,X)) \times\; BR(\Theta^+ \rightarrow\; p\,K^0).$$

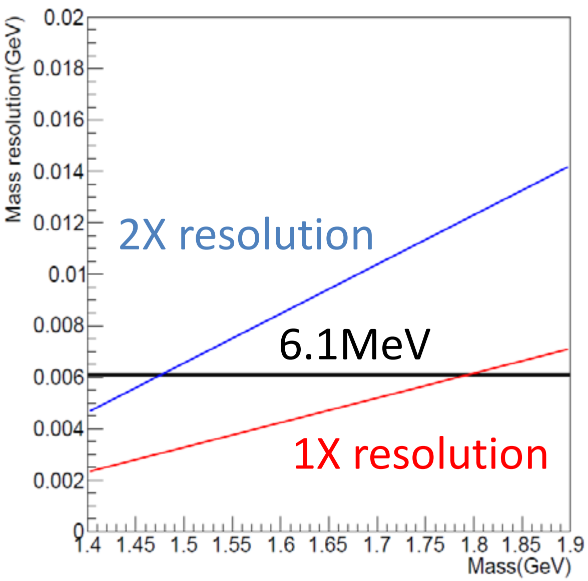
  - The branching ratios of the K^0 to K_S^0 transition and of the K_S^0 to $\pi^+\pi^-$ decay in the cross-section calculation were 0.5 and 0.6895 respectively.

Fitting method for the calculation

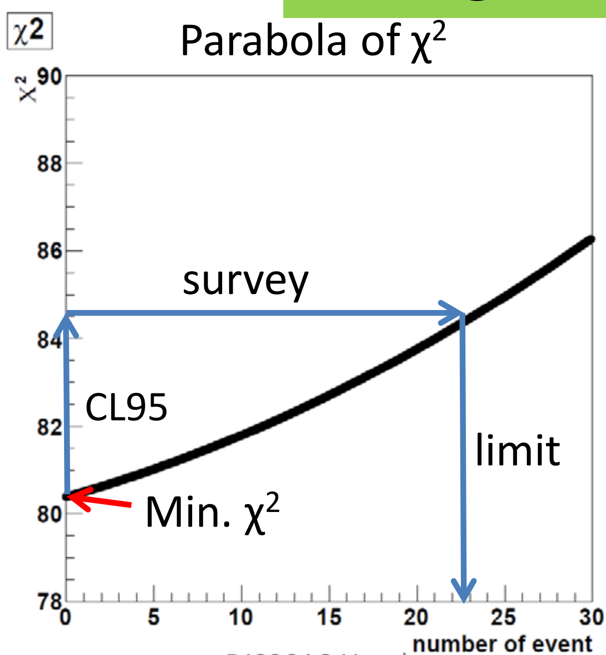
- Signal: Gauss function (3 options of Gaussian width)
  - 6.1MeV; reported in ZEUS HERA I analysis.
  - 1 times and 2 times the detector mass resolution R = 0.009591M- 0.01111 GeV
- B.G.: an empirical function $\alpha(M-M_0)^{\beta} \times \left(1+\gamma(M-M_0)\right)$, where M is pK_S^0 mass and M_0 is the sum of the nominal proton and K_S^0masses
- Calculations of χ^2_{min} and 95% CL = χ^2_{min} + 3.84 are performed with changing a number of signal.

Ex. limit@1530 MeV with σ=6.1MeV

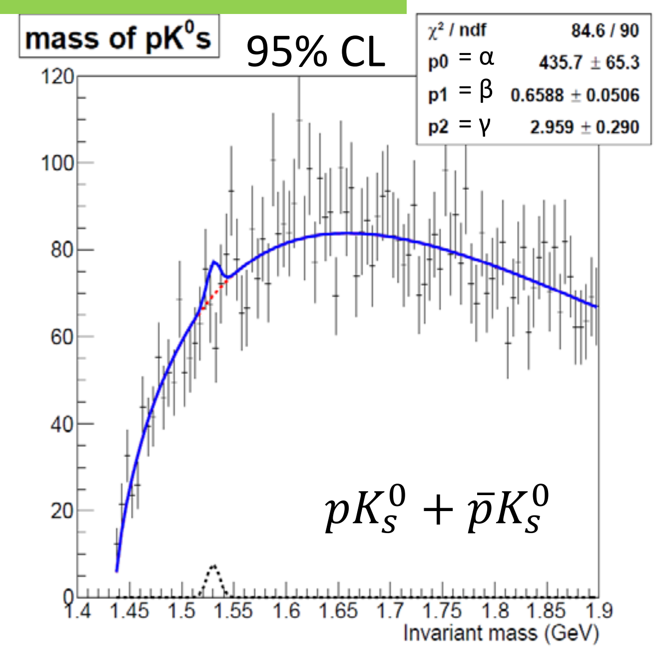
Gaussian width



Parabola of χ^2

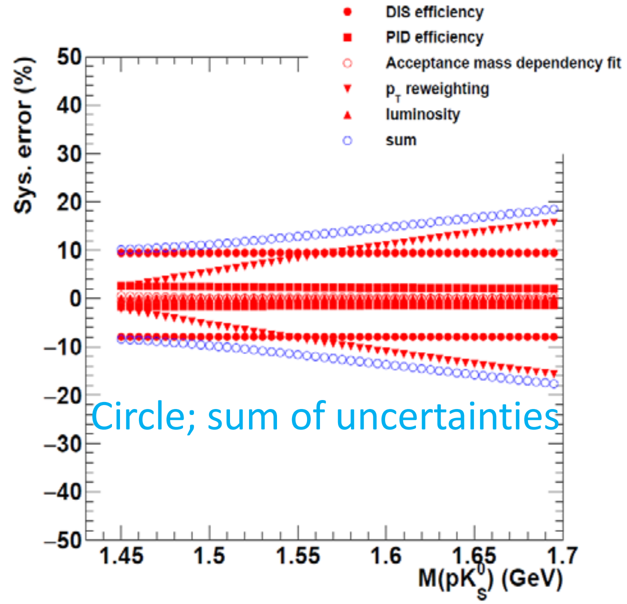


95% CL



Systematic uncertainties

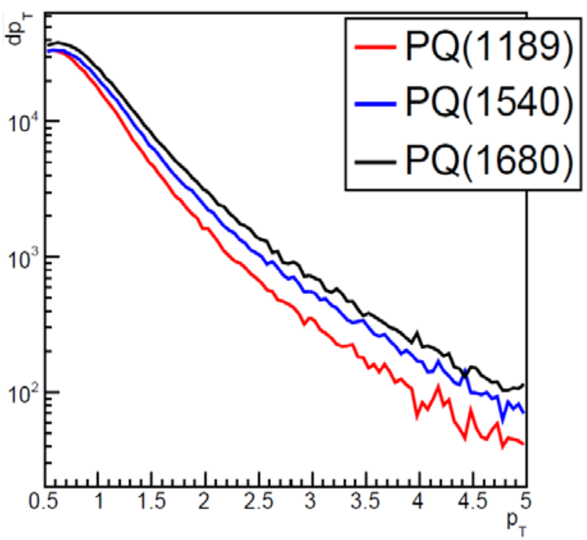
- Systematics uncertainties were estimated for 5 items.
  - DIS event selection
  - PID
  - Acceptance for pK_S^0 system
  - p_T distribution of the pK_S^0 system
  - Luminosity



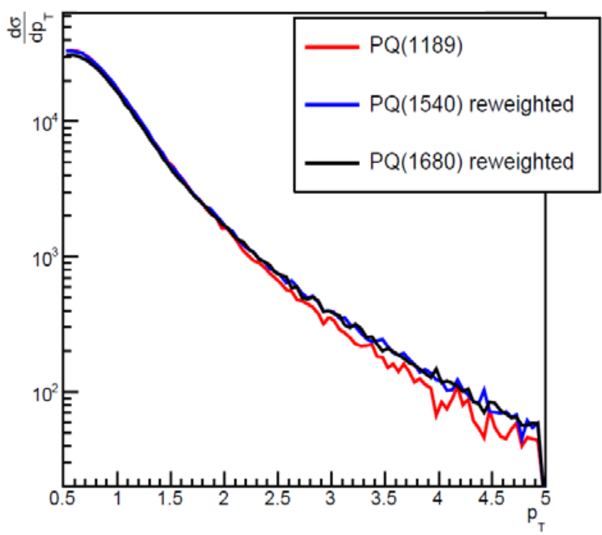
- ~10% changes on the upper limit.
- The largest is from the difference of 2 models in the p_T distribution;

1. (default) p_T slopes as modeled in the RAPGAP. (left)
2. same p_T slope, independent to the mass of pentaquark. (right)

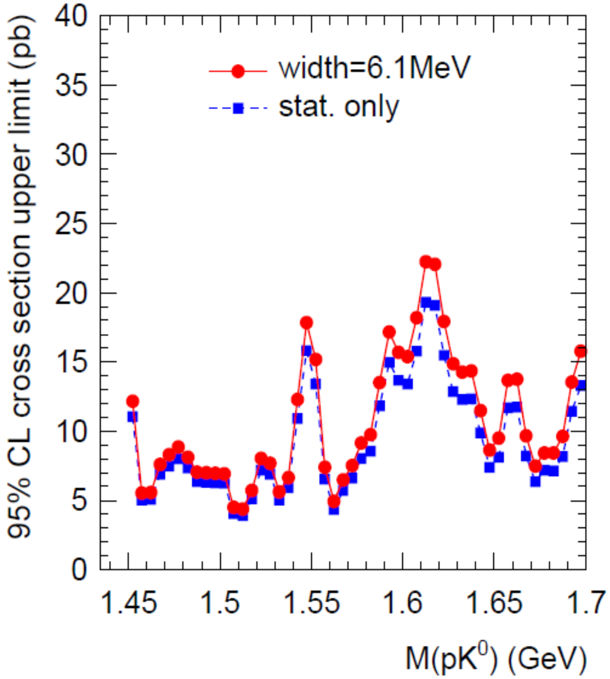
1. default

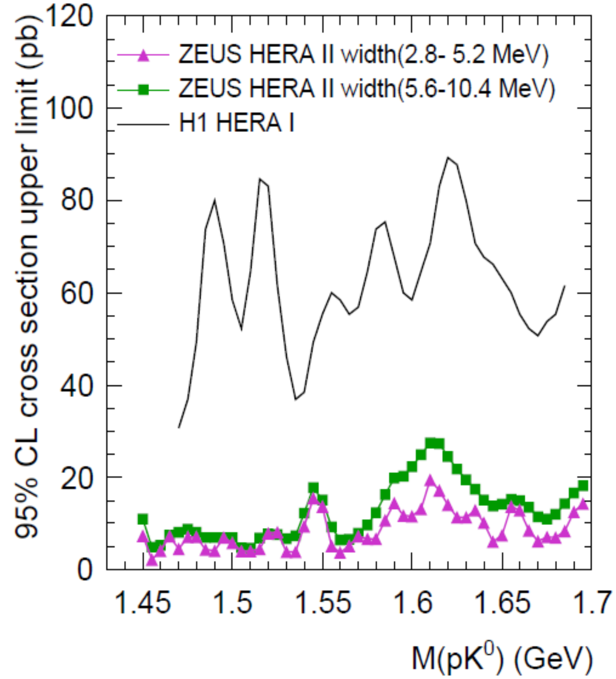


2. reweighted



Cross section upper limit: comparison with H1 result in HERA I





- The 95% CL upper limit with the 6.1MeV mass width in ZEUS HERA II data (Left).
  - Blue; with statistical error only.
  - Red; including systematic uncertainties.
- Upper limits with a width reconstructed as mass resolution and twice mass resolution (Right).
  - purple; mass resolution (2.8-5.2MeV)
  - Green; twice mass resolution (5.6-10.4MeV)
  - Black solid line; the C.S. limit reported by H1 HERA I analysis. (mass width 4.8-11.3 MeV)
  - The ZEUS limits are more stringent than those obtained by H1.

Summary

- A resonance in the $pK_s^0(\bar{p}K_s^0)$ system consistent with a Θ-like state has been searched for in the HERA II data collected with the ZEUS detector, exploiting the improved proton identification capability made possible by the use of the micro vertex detector.
- A peak at 1.52 GeV for which evidence had been observed in a previous ZEUS analysis, based on HERA I data, was not confirmed.
- Upper limits on the production cross section of such a resonance have been set as a function of the pK_S^0 mass in the kinematic region: $0.5 < p_T(pK^0) < 3.0$ GeV, $|\eta(pK^0)| < 1.5$ and $20 < Q^2 < 100$ GeV^2.