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(on behalf of the
ZEUS collaboration)

Investigation of high-mass hadrons at HERA

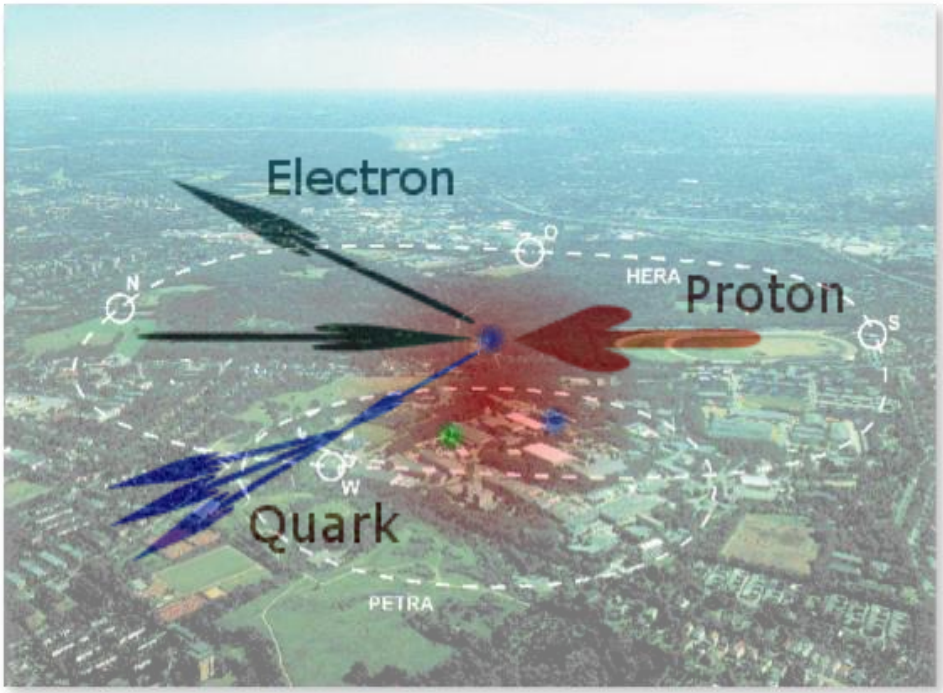
(abstract # 531)

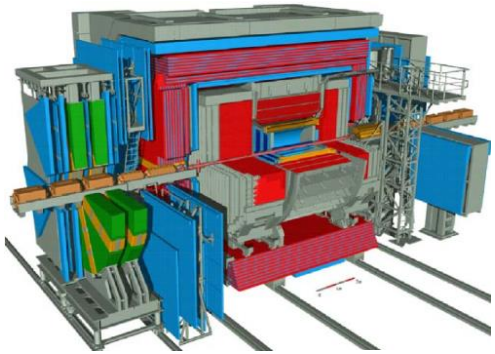
① $\sigma_{\psi(2s)}/\sigma_{J/\psi(1s)}$ in DIS

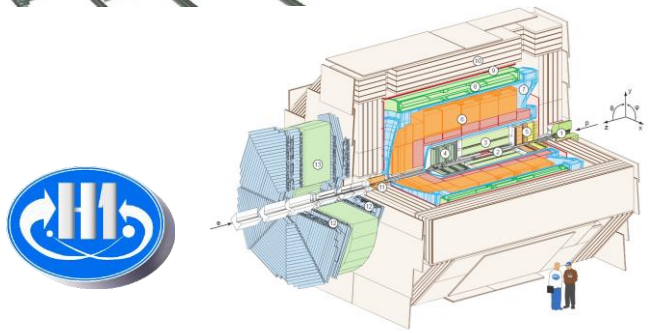
② Search for strange pentaquarks

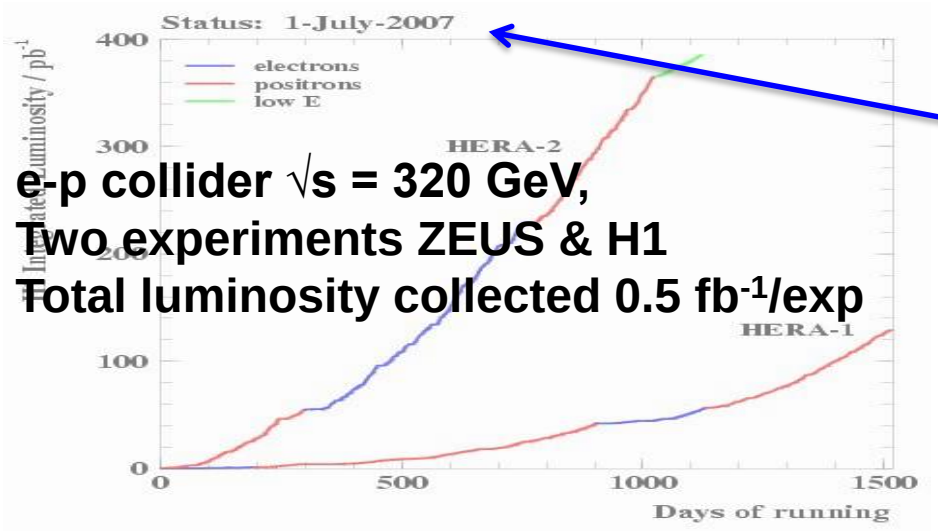
HERA

HERA-1 (1993-2000) ≃ **120** pb^{-1}
HERA-2 (2000-2007) ≃ **380** pb^{-1}









e-p collider √s = 320 GeV,
Two experiments ZEUS & H1
Total luminosity collected 0.5 fb^{-1}/exp

General-purpose 4π de

- Overconstrained s
- Electron me nc.
- Jet en
- T zation unc: 1-2 %
  .3 – 2.5%

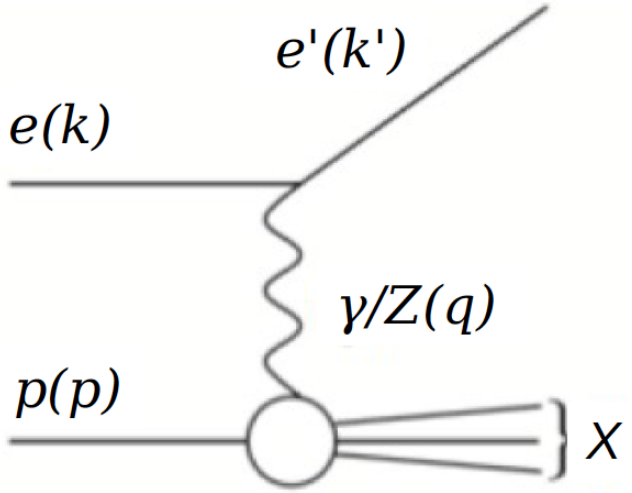
Over 10 years ago, but still valuable analyses!

Deep Inelastic Scattering

Neutral current deep-inelastic scattering

Process: $ep \to e'X$

Electron or positron



Kinematic variables

Virtuality of exchanged boson Q^2

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

Inelasticity

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

Factorisation in ep collisions

Hard scattering coefficients and parton distribution functions (PDFs)

$$\sigma_{ep \to eX} = f_{p \to i} \otimes \hat{\sigma}_{ei \to eX}$$

Predictions in perturbative QCD

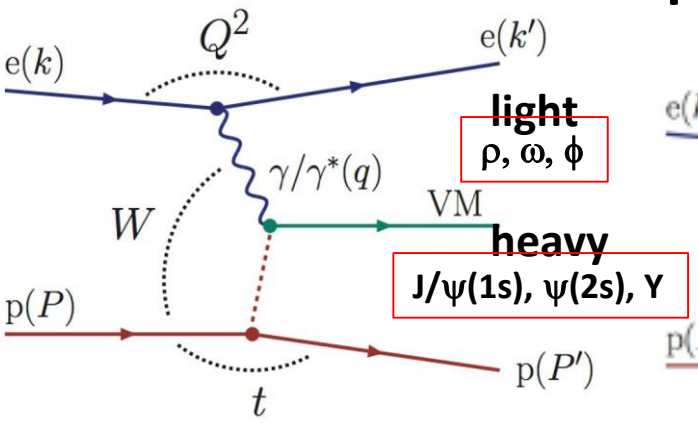
Hard scattering is calculated perturbatively

PDFs have to be determined from experimental data (usage of DGLAP)

(Dokshitzer–Gribov–Lipatov–Altarelli–Parisi)

Diffractive Vector Meson (VM) production at HERA

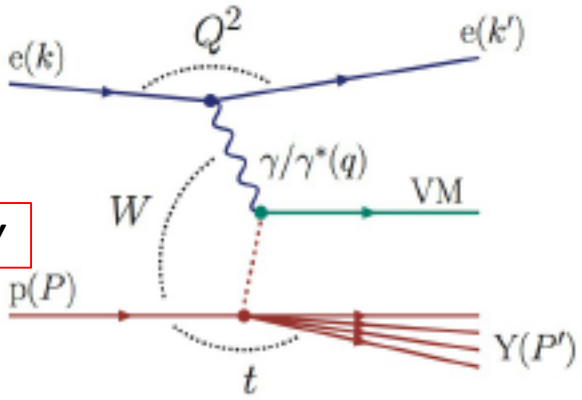
elastic

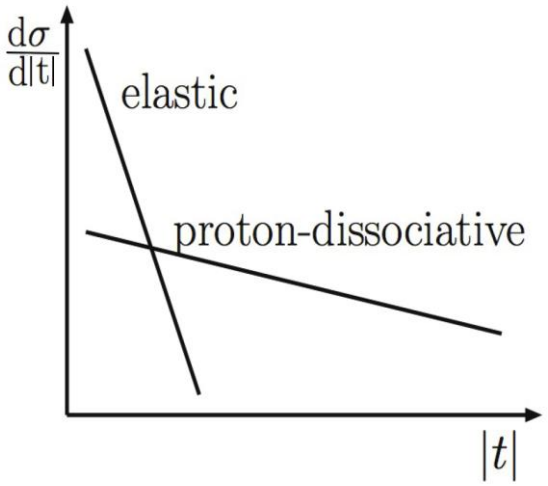


light
ρ, ω, ϕ

heavy
J/ψ(1s), ψ(2s), Υ

proton-dissociative





Kinematics of the process

Q^2: photon virtuality { $Q^2 < 1$ GeV^2: γp ; $Q^2 > 1$ GeV^2: DIS } $Q^2=-q^2=-(k-k')^2$

W: photon-proton CMS energy $W^2=(q+P)^2$

t: 4-mom transfer squared at proton vertex $t=(P-P')^2$

Cross-sections ratio of ψ(2s) over J/ψ(1s) in DIS

1

$$R = \frac{\sigma_{ep\to\psi(2s)p}}{\sigma_{ep\to J/\psi(1s)p}}$$

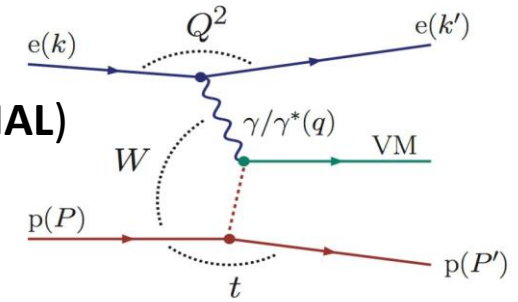
gives information about
The dynamics of hard process *(as function of Q^2, W, t)*

pQCD model calculations predicts R ~ 0.17 (γP) and rise of R with Q2 (DIS)

Investigated channels:

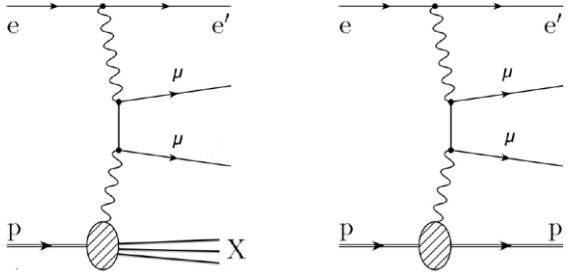
$$\psi(2s) \to J/\psi(1s)\ p^+p^-;\ J/\psi(1s)\ \mu^+\mu^-$$
$$\psi(2s) \to \mu^+\mu^-$$
$$J/\psi(1s) \to \mu^+\mu^-$$

Data samples: HERA I + HERA II data (1996 — 2007)
Integrated luminosity: 468 pb^{-1}



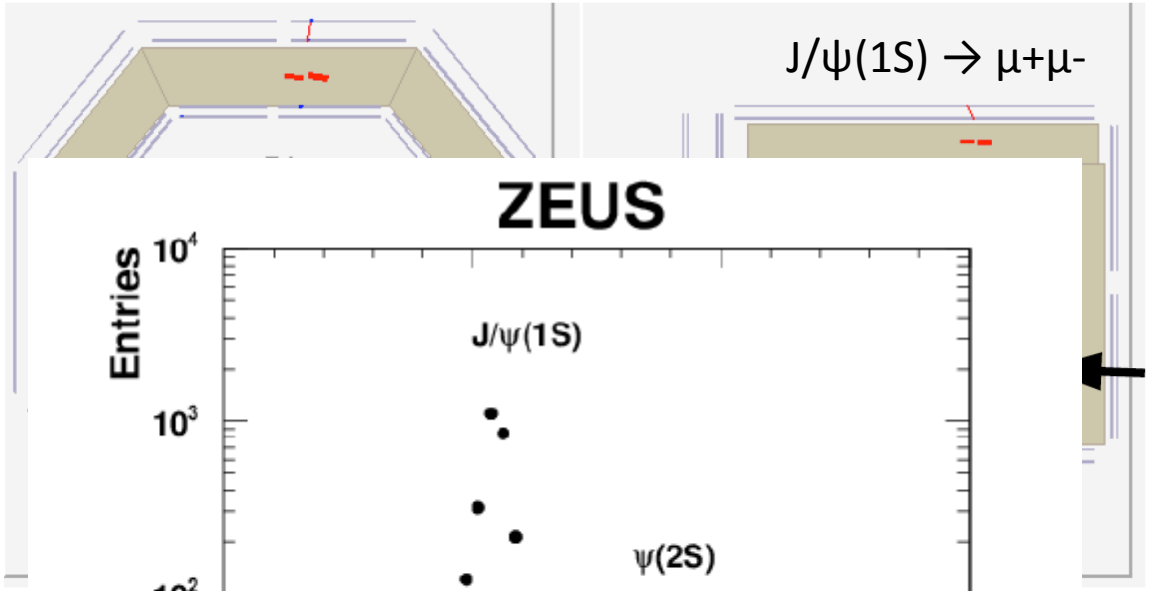
Monte Carlo samples: DIFFVM for exclusive VM production (**SIGNAL**)

GRAPE for Bethe-Heitler
mu-pair production (**BCK**)

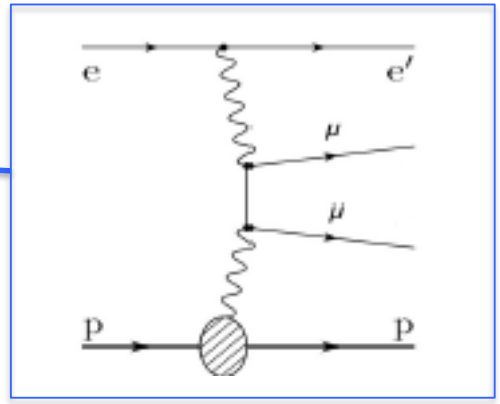


Selection criteria

$30 \leq W \leq 210$ GeV
$2 \leq Q^2 \leq 80$ GeV^2
$|t| \leq 1$ GeV^2



- Scattered e with E > 10 GeV reconstructed in CAL
- Scattered p undetected
- Two reconstructed tracks identified as muons
- for ψ(2S) → J/ψ(1S) π+π- additionally two pion tracks from μμ vertex
- Nothing else in detector (above noise)



Even lower bck for ψ(2S) → J/ψ(1S) π+π- (very clean selection)

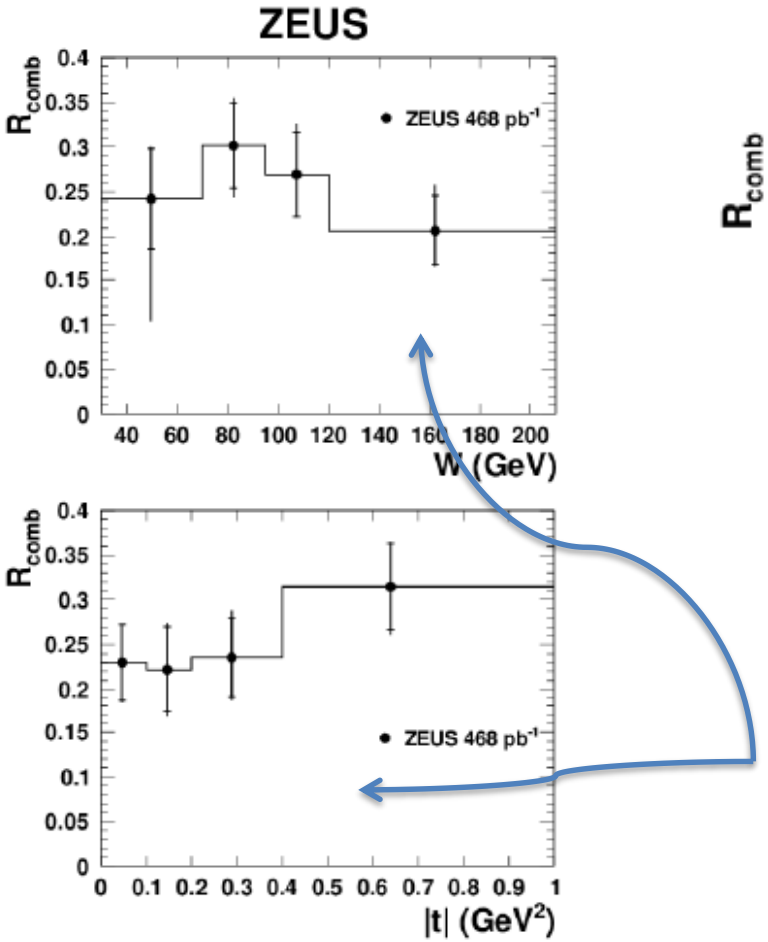
RESULTS

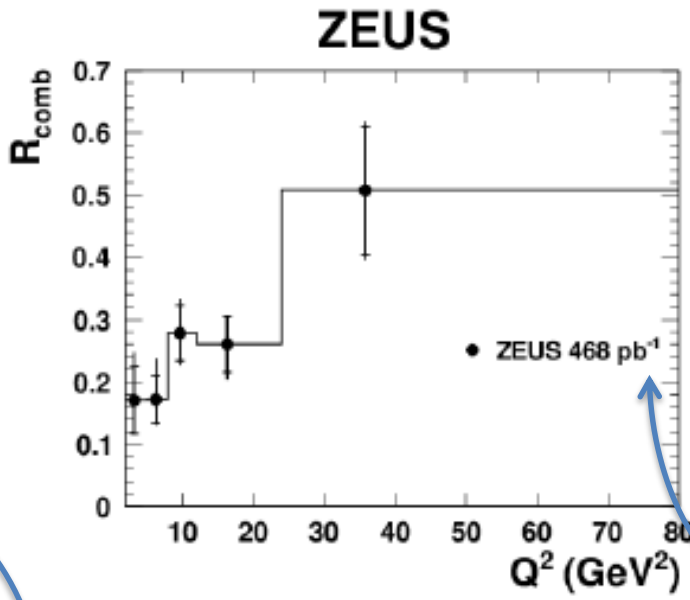
$$R_{J/\psi\pi\pi} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to J/\psi\pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S)\to J/\psi\pi^+\pi^-}}$$

$$R_{\mu\mu} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to\mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S)\to\mu^+\mu^-}}{BR_{\psi(2S)\to\mu^+\mu^-}}$$

$$R_{\psi(2S)} = R_{J/\psi\pi\pi}/R_{\mu\mu}$$

$R_{J/\psi\pi\pi}$	$0.26 \pm 0.03^{+0.01}_{-0.01}$
$R_{\mu\mu}$	$0.24 \pm 0.05^{+0.02}_{-0.03}$
$R_{\rm comb}$	$0.26 \pm 0.02^{+0.01}_{-0.01}$
$R_{\psi(2S)}$	$1.1 \pm 0.2^{+0.2}_{-0.1}$

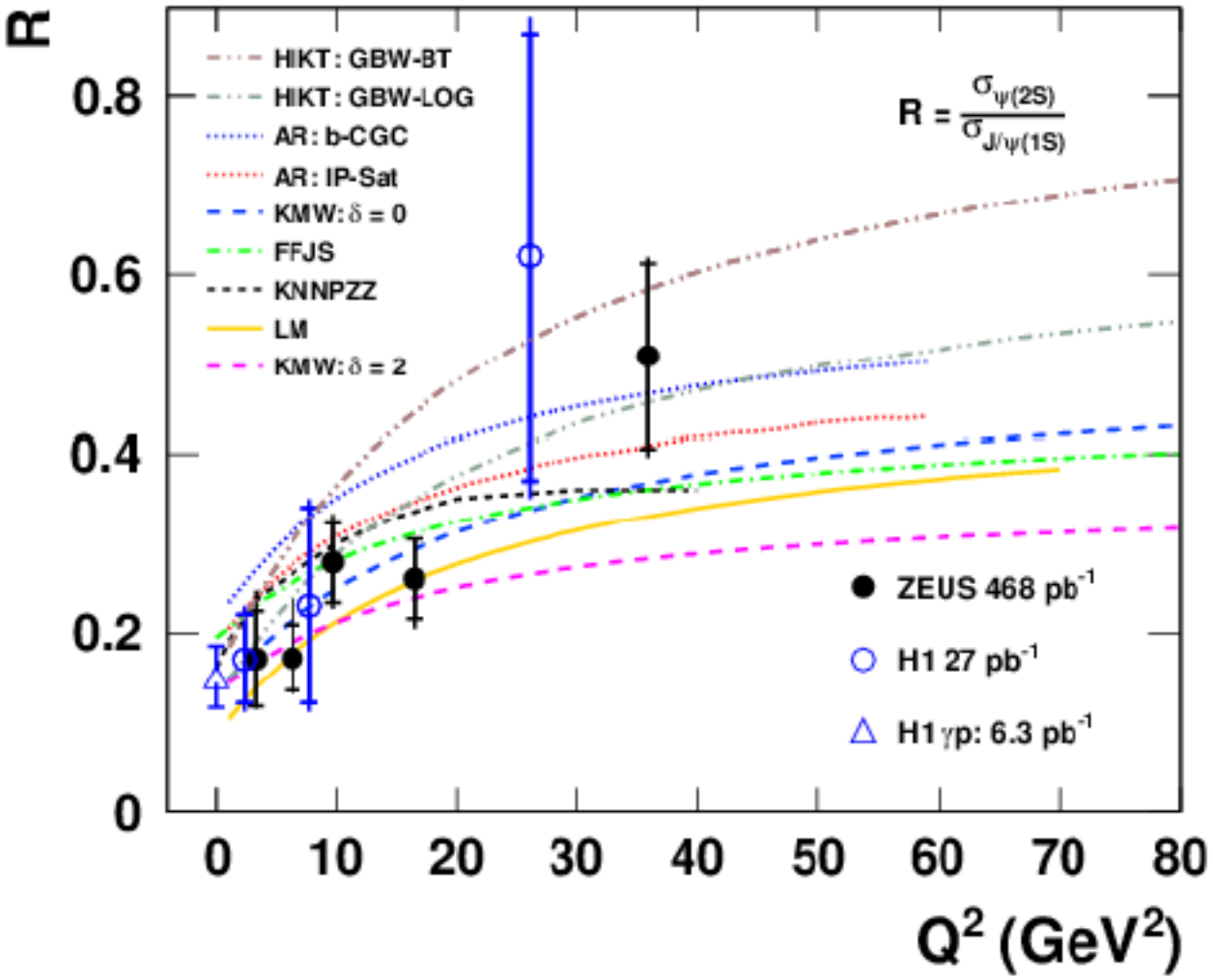




- Independent of W and |t|
- Indication of an increase with Q^2

Comparison with QCD inspired models:

discrimination of different models possible



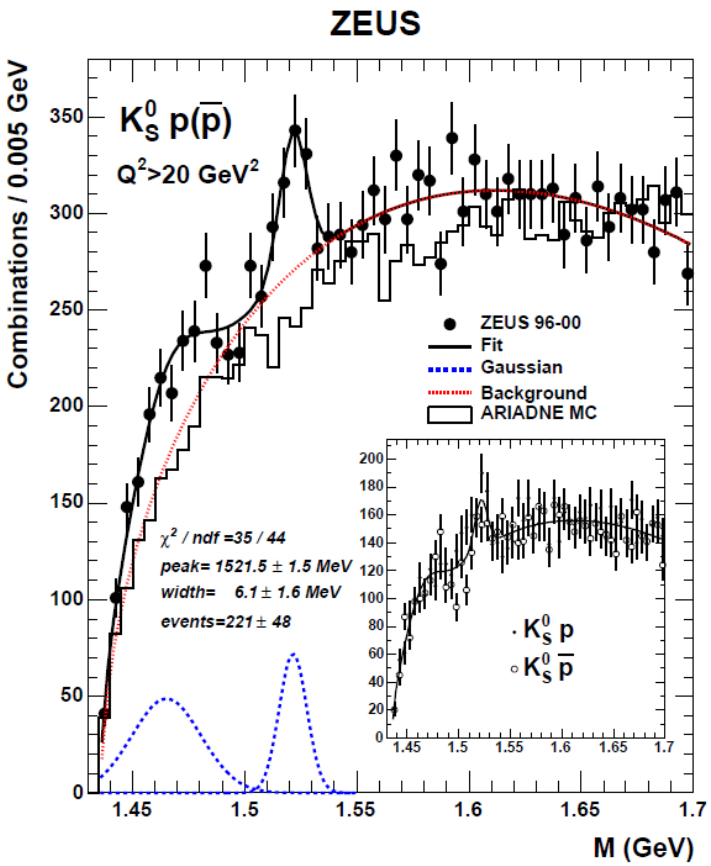
Published: Nuclear Physics B 909 (2016) 934.

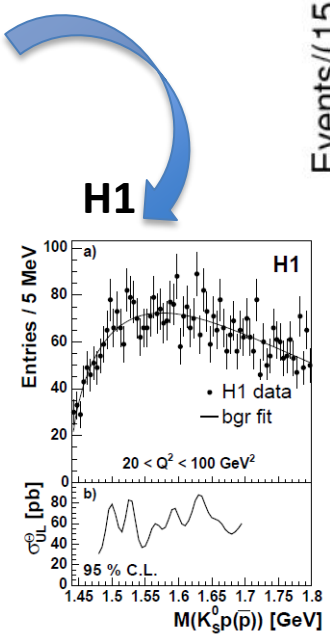
Strange penta-quarks at HERA

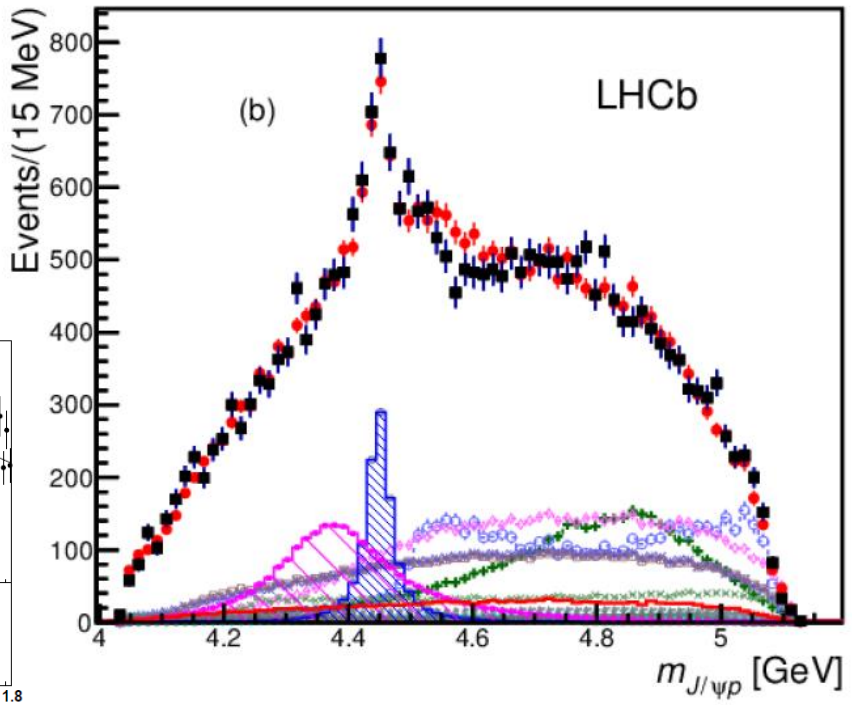
Search for a narrow baryonic state decaying to p-K^0_S and pbar-K^0_S in DIS at HERA

A candidate for a uudd-sbar state θ^+ was observed at HERA-I in M(p-K^0_S)
Phys. Lett. B 591 (2004)

The next observation of LHCb can be considered as a strong evidence of existence of 5q states,
Phys. Rev. Lett. 115 (2015) 072001 etc.



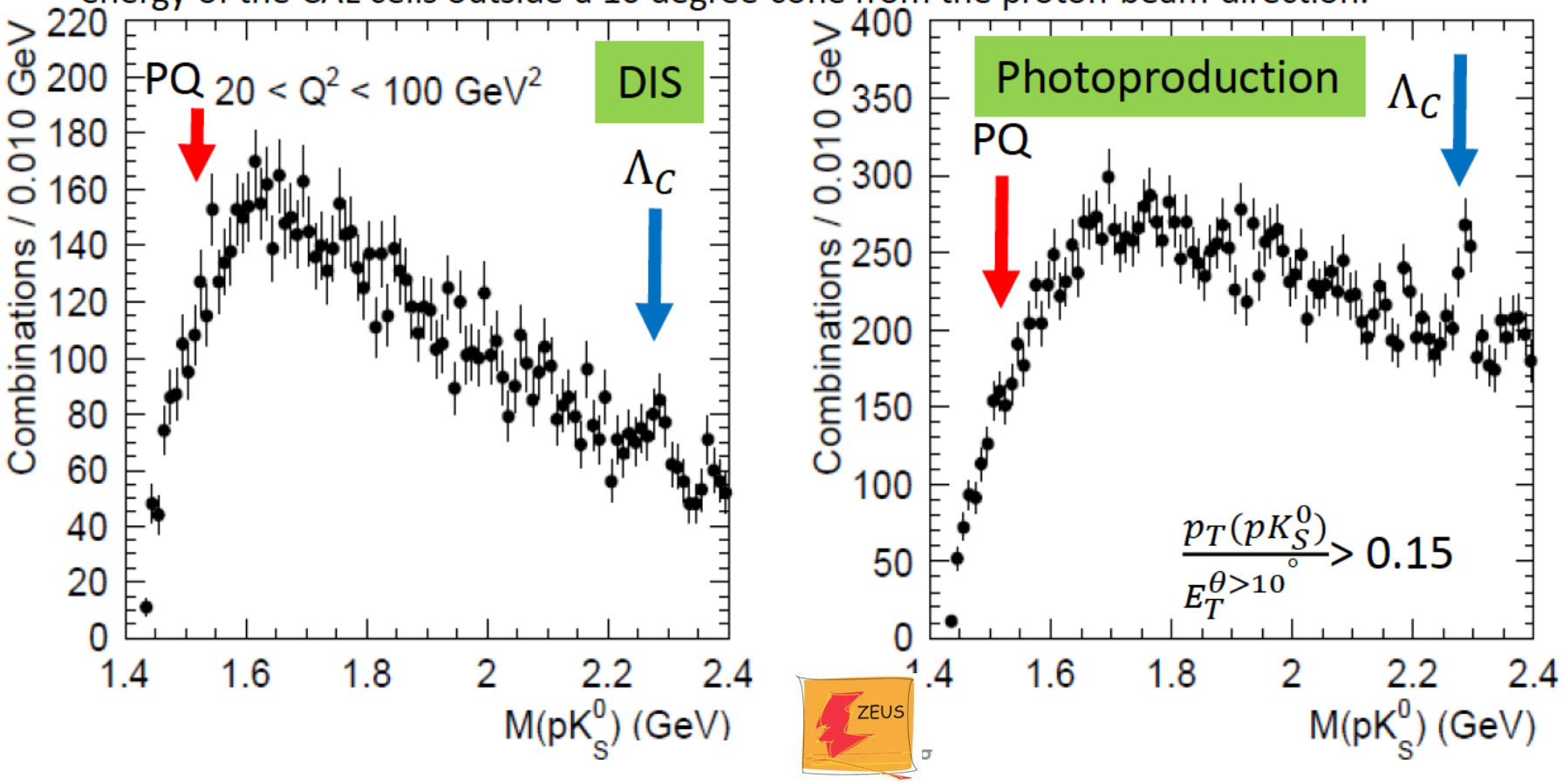




A clear motivation to look for the θ^+ signal in HERA-II data.

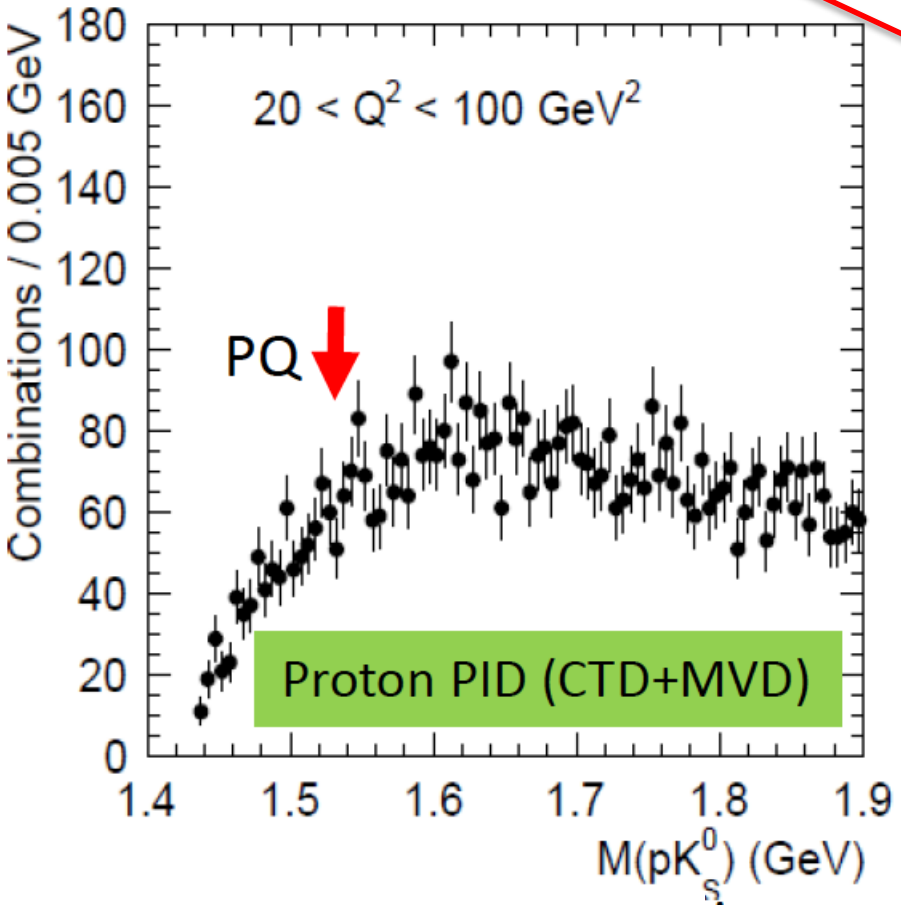
pK^0_S invariant mass distribution in DIS and photoproduction samples:

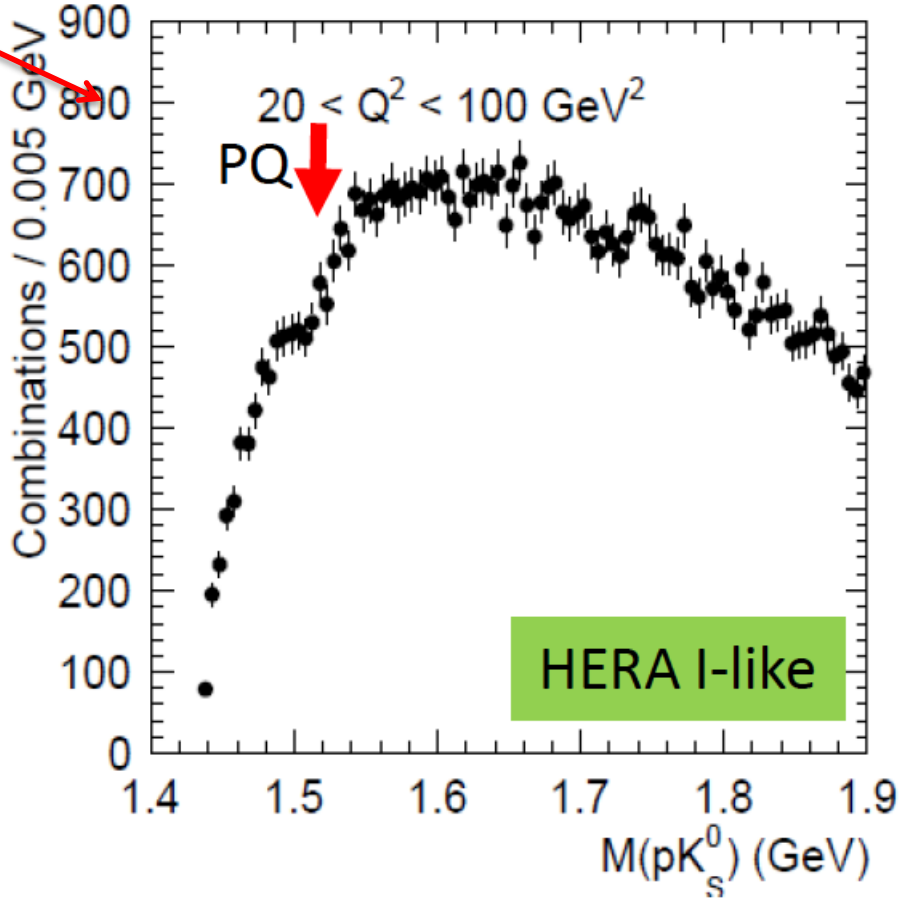
energy of the CAL cells outside a 10 degree cone from the proton-beam direction.



No PQ peak at the mass of Θ⁺(red arrow) is seen

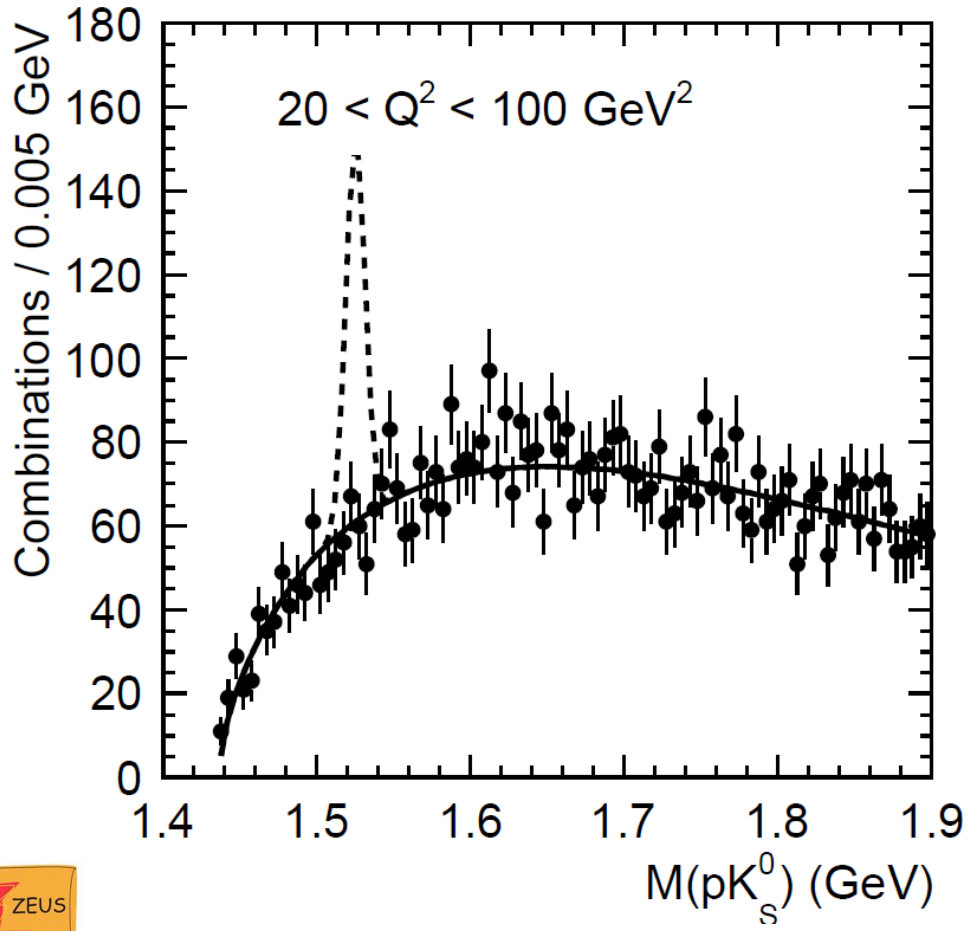
A closer look (also with similar cuts to HERA-I) in DIS sample





No PQ peak is seen, ever

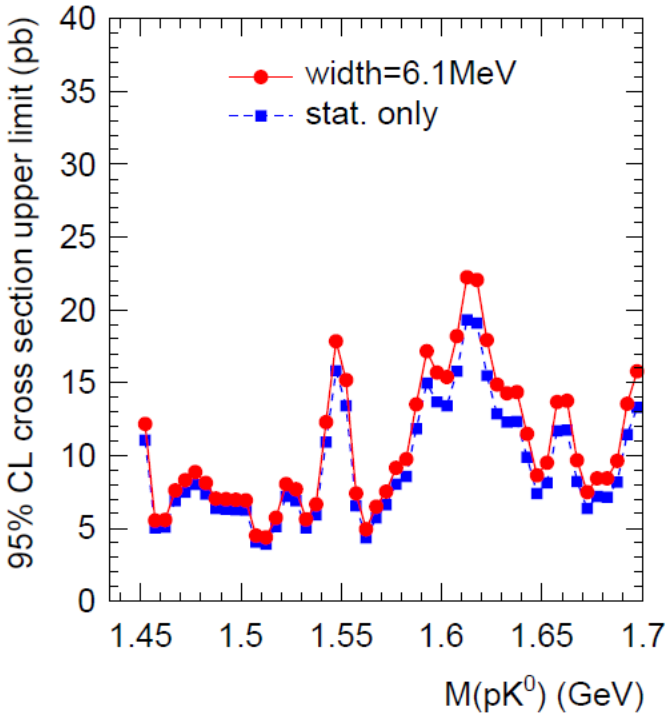
Comparison with ZEUS HERA I analysis

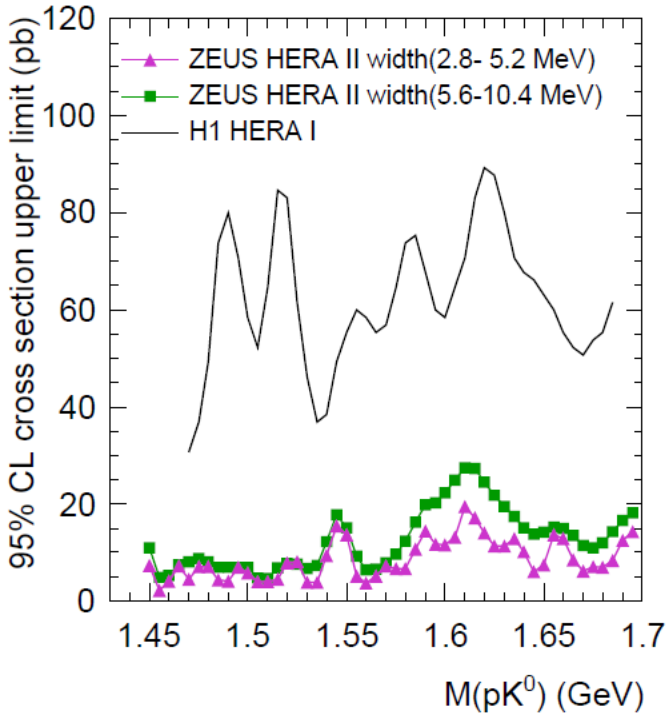


The dashed line represents the Θ+ signal as it would be observed if it had the same strength as reported in the ZEUS HERA-I analysis

(expected 286 events)

As no clear signal is seen, the limits on the production cross-section of $\Theta^{\pm}$ is set.
B ($\Theta \rightarrow p\,K\,S0$) = 1 is assumed;
different widths hypotheses are tested;
results are compared with H1.





The search contributes to the $5q$ state puzzle.
Published: Phys. Lett. B 759 (2016) 446.

Conclusions

- Ten years after the end of data taking, HERA experiments continue to deliver innovative, valuable physics results.
- Some results are unique and will remain the only source for the tests of state-of-the-art theoretical predictions for a long time.

- $\psi(2s)$ over $J/\psi(1s)$ ➔ refined increase with Q^2, model comparisons
- Strange Pentaquarks ➔ stronger exclusion than previous results

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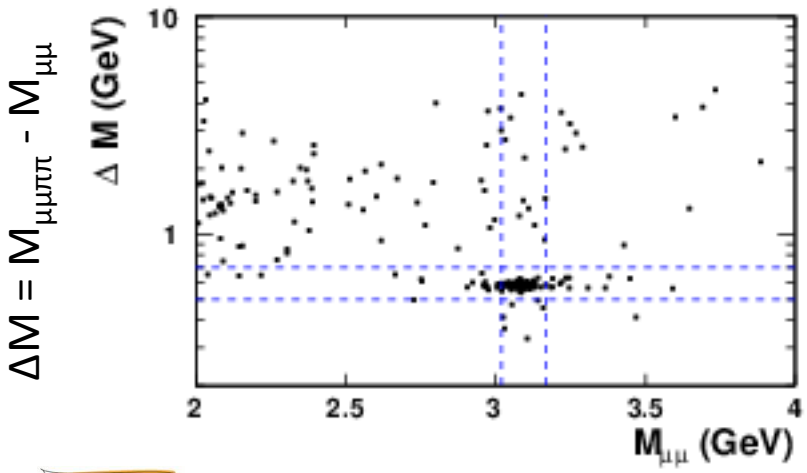
BACKUP

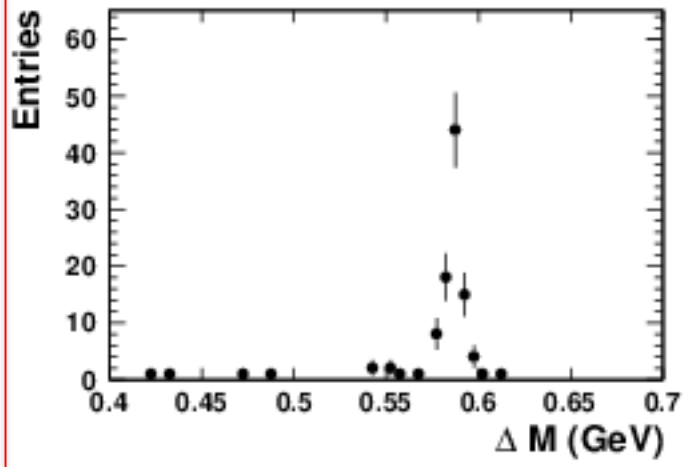
ψ(2S) → J/ψ(1S) π+ π-

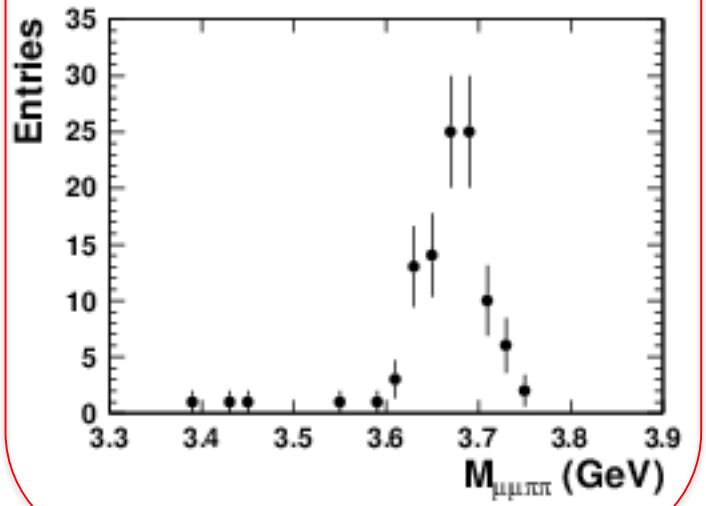


ZEUS

- ZEUS 468 pb^{-1}

3.02 < Mμμ < 3.17 GeV
0.5 < ΔM < 0.7 GeV





≤ 3 events background (after cut on $M_{\mu\mu}$)

L. Maiani' conclusions at La Thuile, March 2016:

- until now, exotics seen contain heavy quark flavours: an experimental reexamination of the lack of existence of light exotic mesons ("bad" diquarks) and positive strangeness baryons is in order.
- much remains to be done, in theory and experiments,
- we look forward to exciting times for hadron spectroscopy: maybe we can understand QCD better.

STRANGE PENTAQUARKS (Hi)STORY

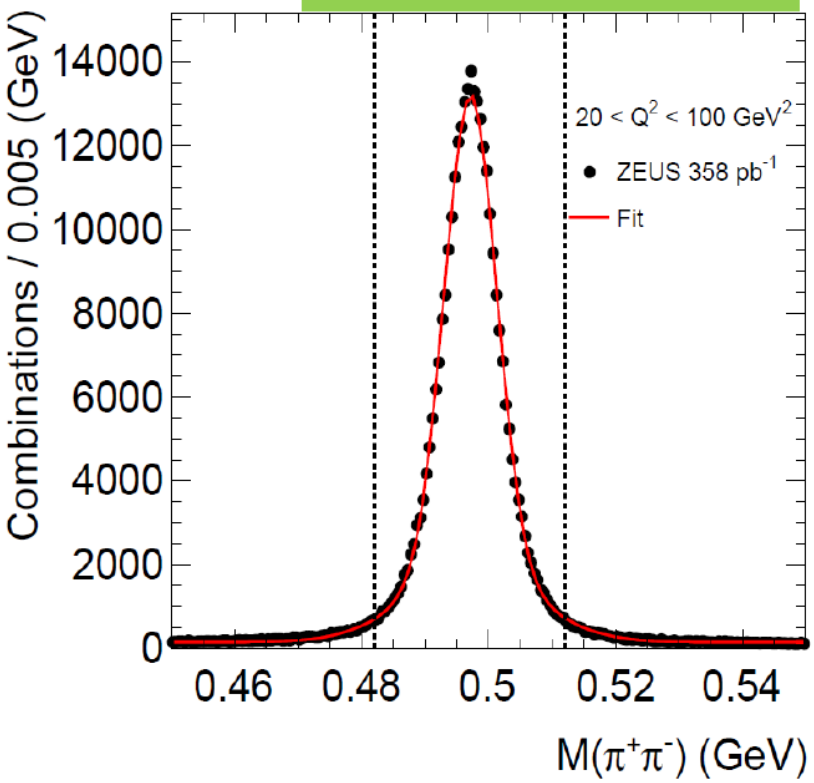
- The observation of a narrow baryon resonance with a mass of ~1.53 GeV was reported first by the LEPS experiment in 2003 in the missing-mass distribution for $\gamma A \rightarrow nK+$ reaction. Such a baryon would be manifestly exotic and impossible for a three-quark state. But could be explained as a bound state of five quark state i.e. a pentaquark, named Θ+(*uudd-sbar*). Many experimental groups have looked for this state via various production processes in decay mode $nK+$ or p-K^0_S (pbar-K^0_S).
  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-cbar* and were observed with high significance.

- The ZEUS experiment reported the evidence of a peak structure in p-K^0_S (pbar-K^0_S) mass distribution in deep inelastic scattering (DIS) data in HERA I period (1996-2000).
  The present search for a Θ+ pentaquark in the p-K^0_S (pbar-K^0_S) system is reported with the ZEUS data taken at HERA II period (2003-2007).
  The HERA II period not only provided larger statistics (358pb-1), but the ZEUS tracking system was upgraded. Looking for pentaquarks in DIS event with $20 < Q^2 < 100$ GeV^2 in order to compare with the HERA I results.

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

of K_S^0 0.31M events



- Two tracks with opposite charge
- $p_T(\pi) > 150$MeV
- $|\eta(\pi)| < 1.75$
- π track's MVD hit > 2
- $p_T(\pi\pi) > 250$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($\pi\pi$) < 0.512 GeV, dashed line).