Particle production at HERA

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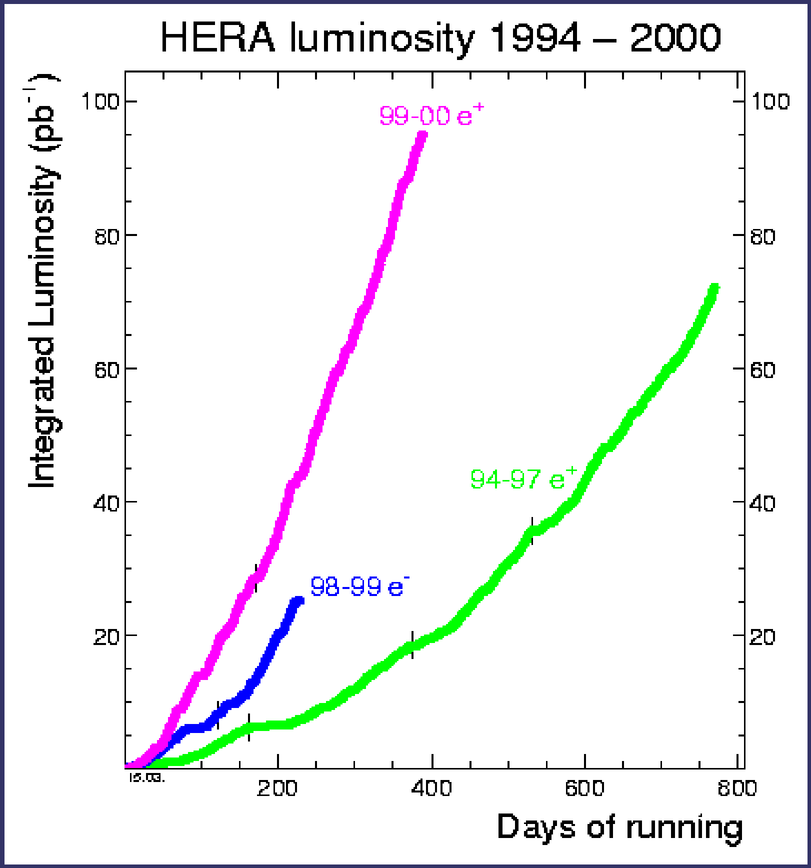
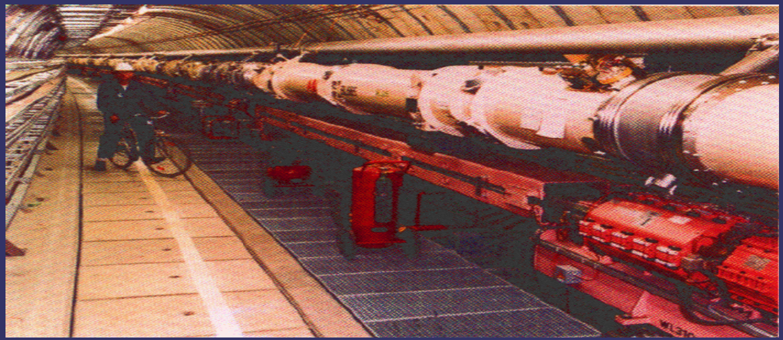
KEK seminar (Feb. 2004)



Proton 820/920 GeV → ← Electron/positron 27.6 GeV



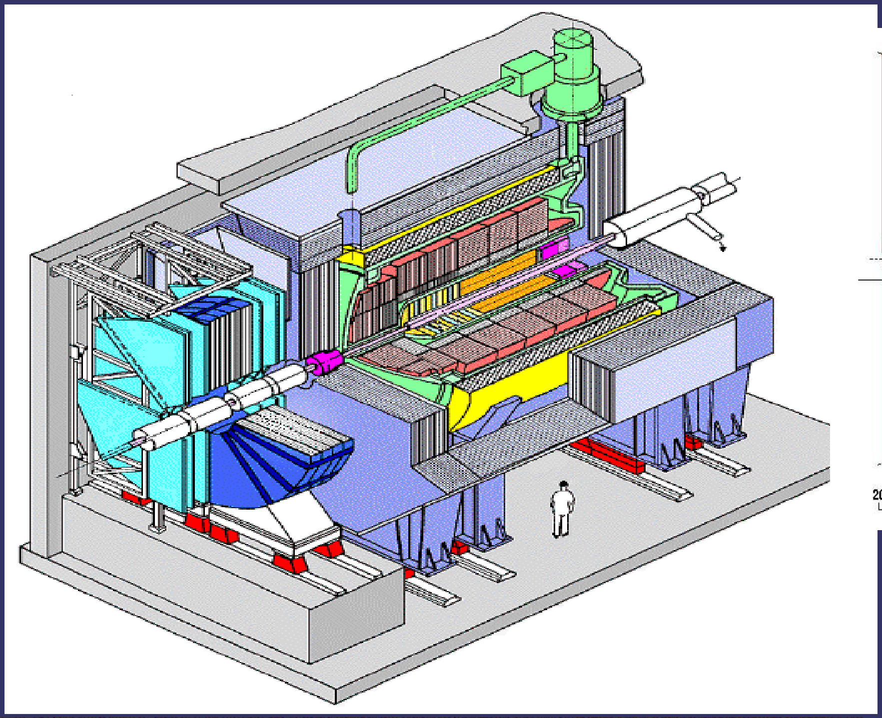
Commissioned in 1992

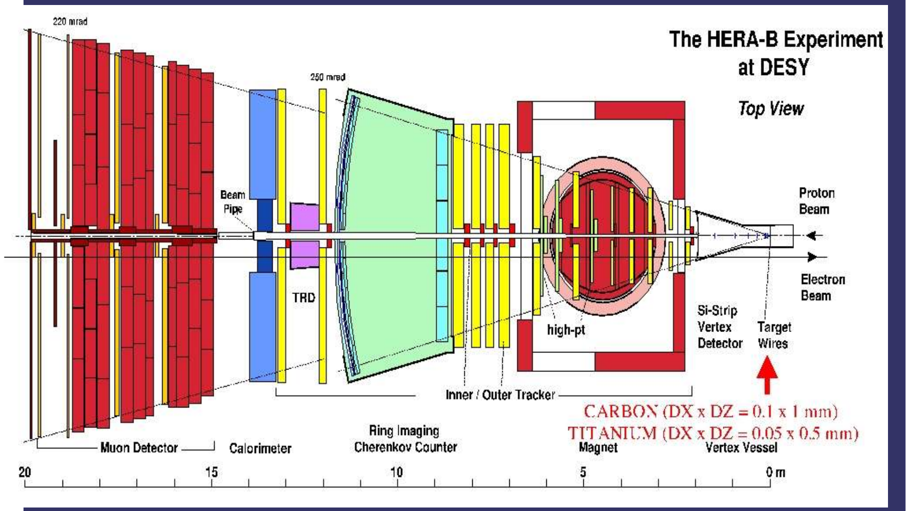
Number of produced papers ~ 200

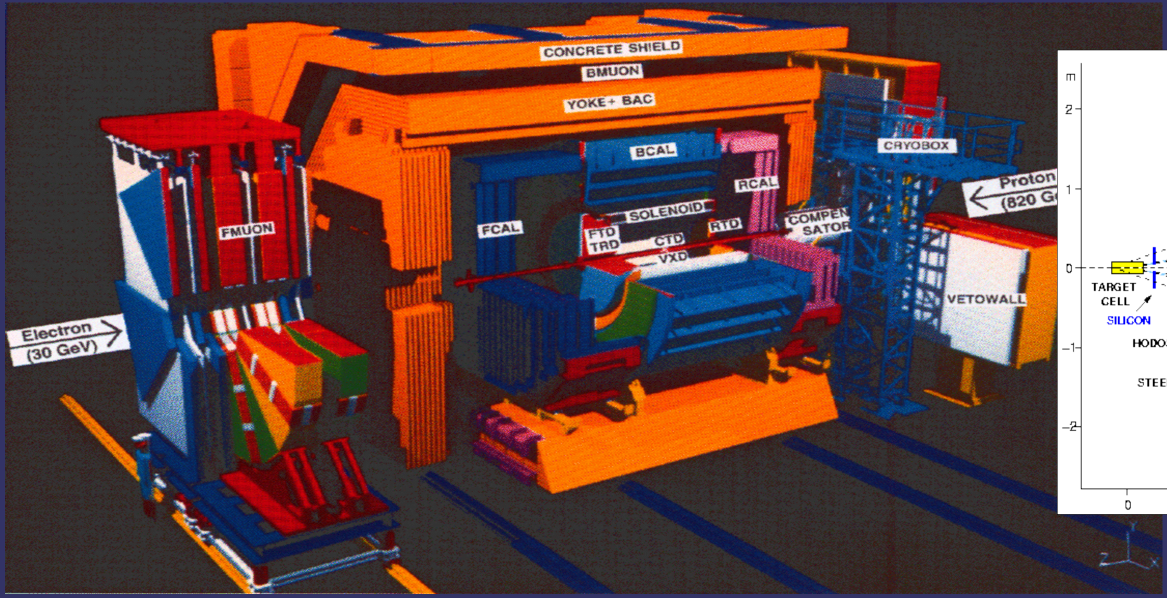
HERA II: 2001-2002 – prospects: ~ 1 fb^{-1}

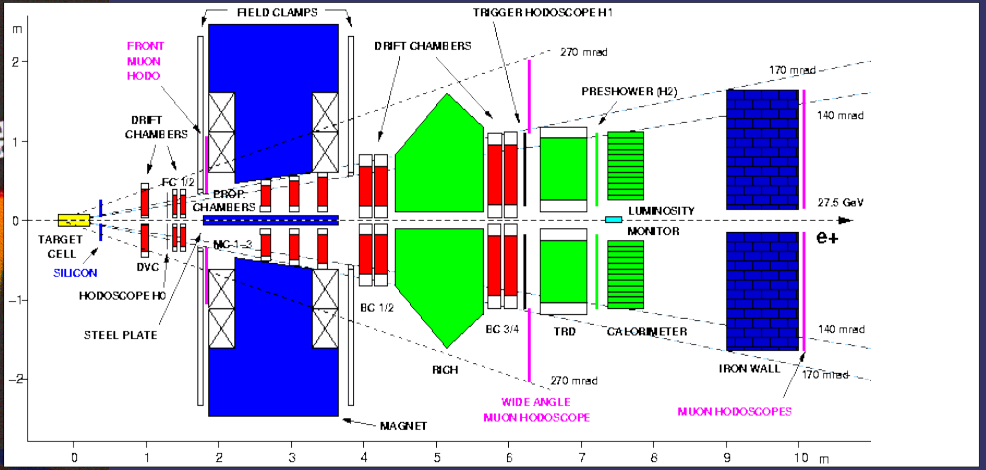
HERA experiments

- **H1**
- **ZEUS**
- **HERA-B**
- **HERMES**









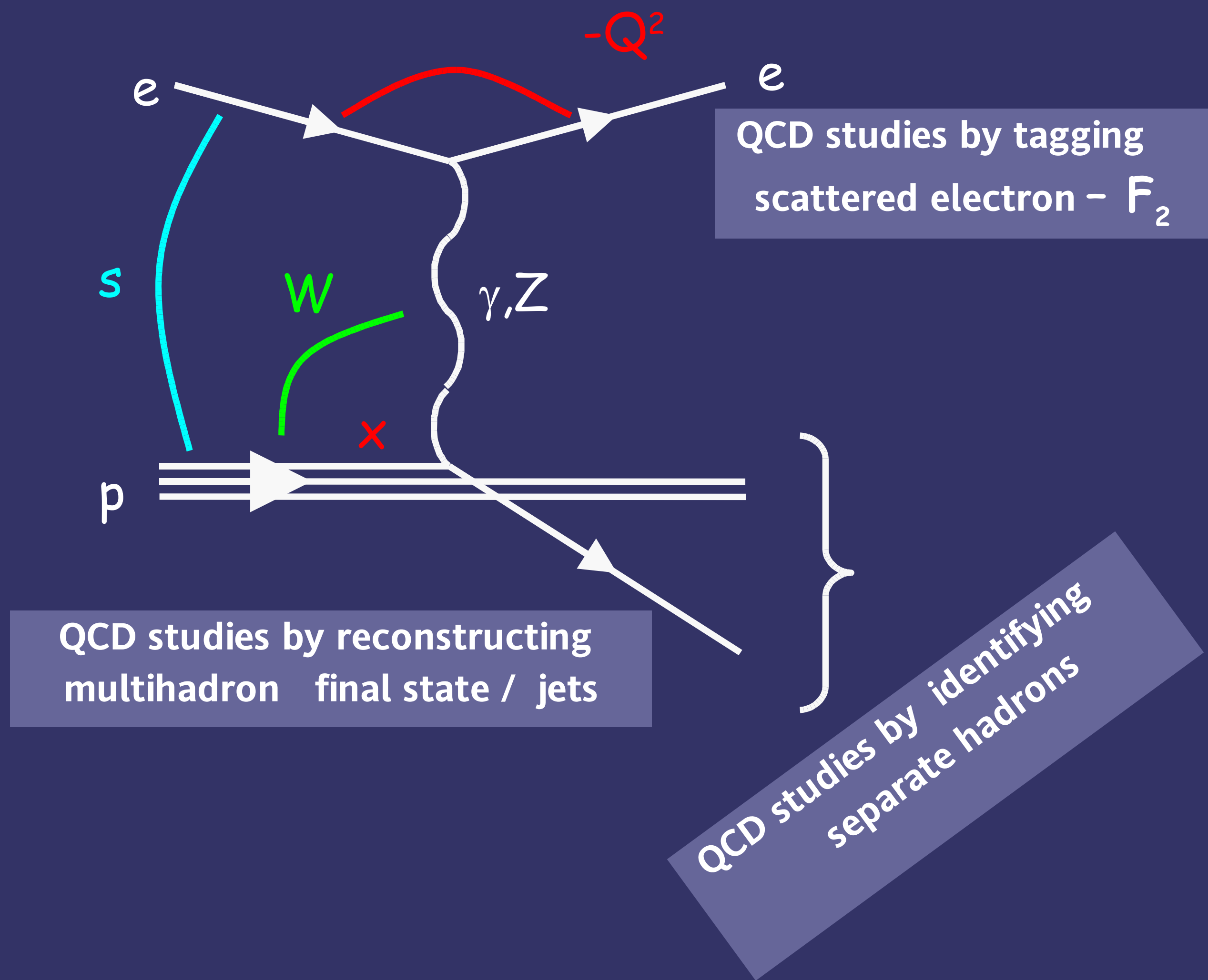
DIS variables

- s: e-p c.m. energy

  $\sqrt{s}$ = 300 – 318 GeV

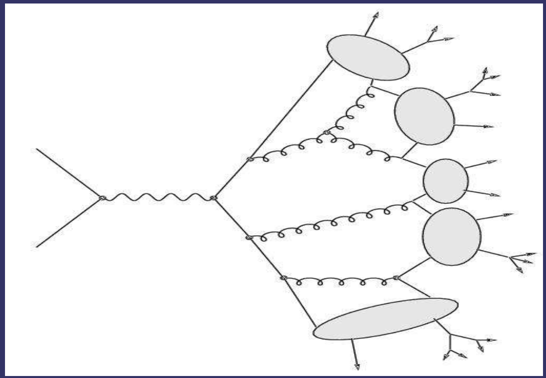
- $Q^2 = -q^2$: 4-momentum transfer squared
- x: fraction of proton momentum carried by quark
- y: scaled energy transf.
- W: γ-p c.m. energy

  $Q^2 \to 0$: photoproduction at large W(~200 GeV)



Theory

- Hadronisation – one of the central mysteries of QCD
    - Not calculable directly in pQCD
- Plenty of analytical and numerical models based on general properties of QCD are available;
- Monte Carlo models are very useful:
    - JETSET/PYTHIA: Lund string fragmentation
    - HERWIG: Cluster fragmentation
    - etc..

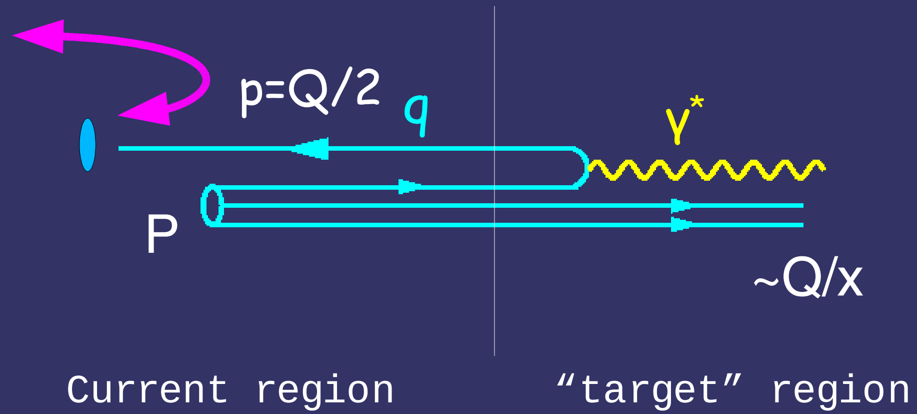


- Simulate transition regions where partons transform into hadrons;
- Solve problem of multiple hadron production (difficult to solve analytically!);
- As time goes by, more QCD is incorporated;
- But large number of tunable parameters, little predictive power, especially with respect to particle spectroscopy

Highlights of this talk

- Leading mesons as a test of the proton structure;
- Cross sections of identified mesons; Universal law ?
- Multihadron production as a test of pQCD dynamics and hadronisation;
- Bose-Einstein effect – universal final-state interaction?
- Particle spectroscopy:
  - Search for glueballs;
  - Search for pentaquarks

Leading mesons (best way to learn the Breit frame)



Leading mesons: $p_{meson} \sim p_{quark}$

$x_p = p/2Q \sim 1$

Direct access to the proton structure

Detection of mesons with strangeness may allow the reconstruction of the strange "sea" due to quantum fluctuations

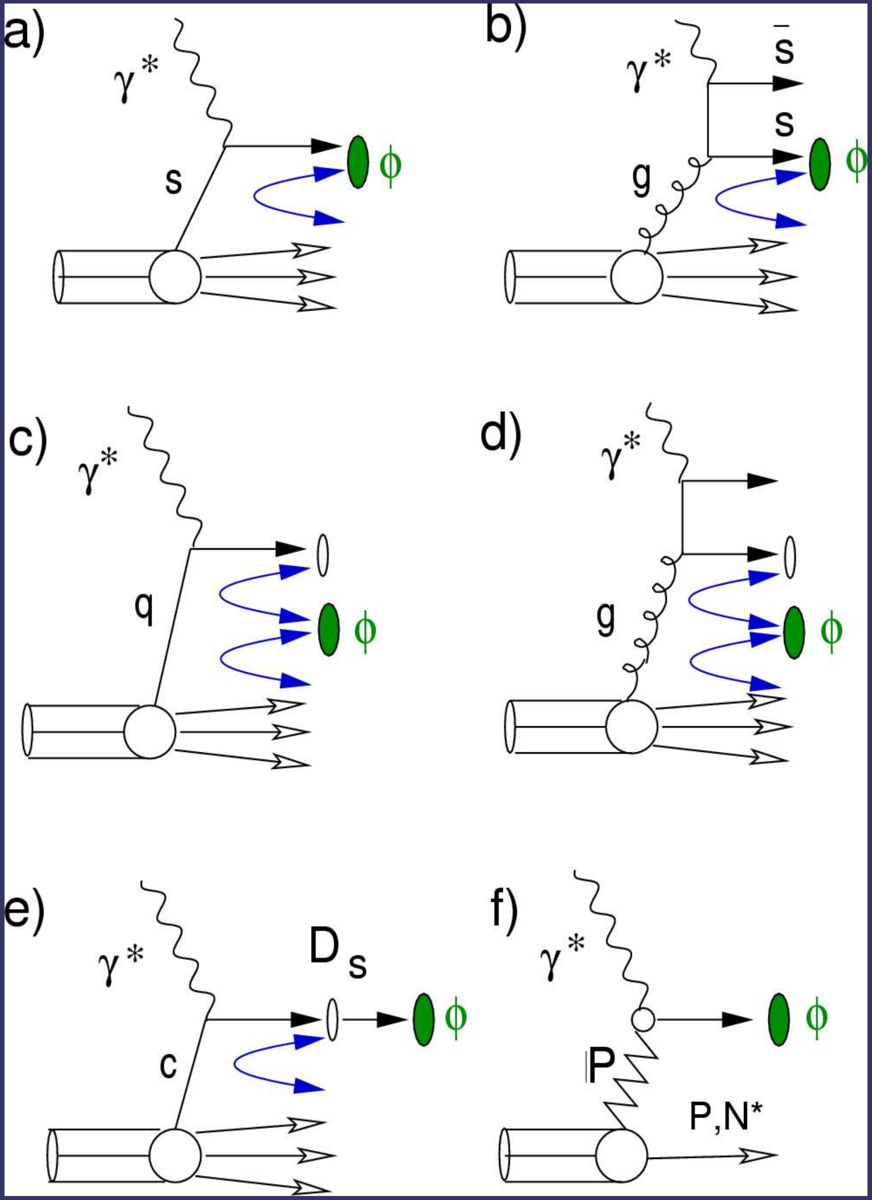
<u>Example:</u>

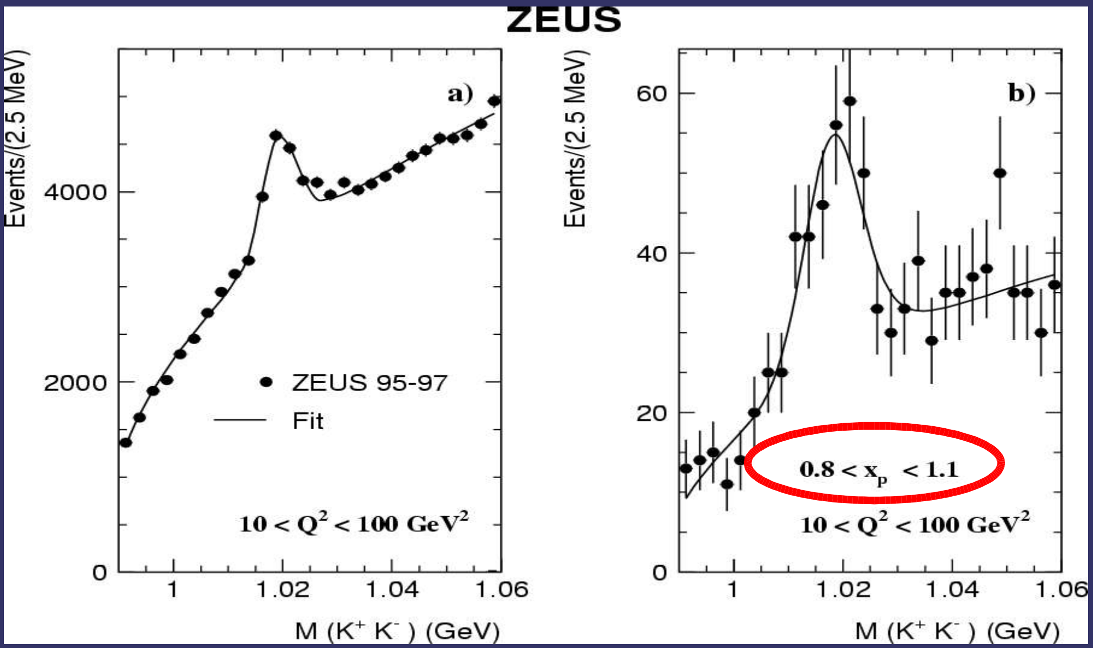
Rate of φ(1020) mesons ($\sim s\bar{s}$) should be sensitive to:

- Strange density inside proton x QED matrix element (known)
- Strangeness suppression factor (in $\lambda_s = P_s/P_{u,d}$) modeled in Lund string model

Leading Φ(1020) mesons in DIS

hep-ex/0211025





Reconstruction: φ(1020) -> K^+K^-

Clean signal for leading φ(1020) mesons:

$x_p \sim 1$

Leading Φ(1020) mesons in DIS

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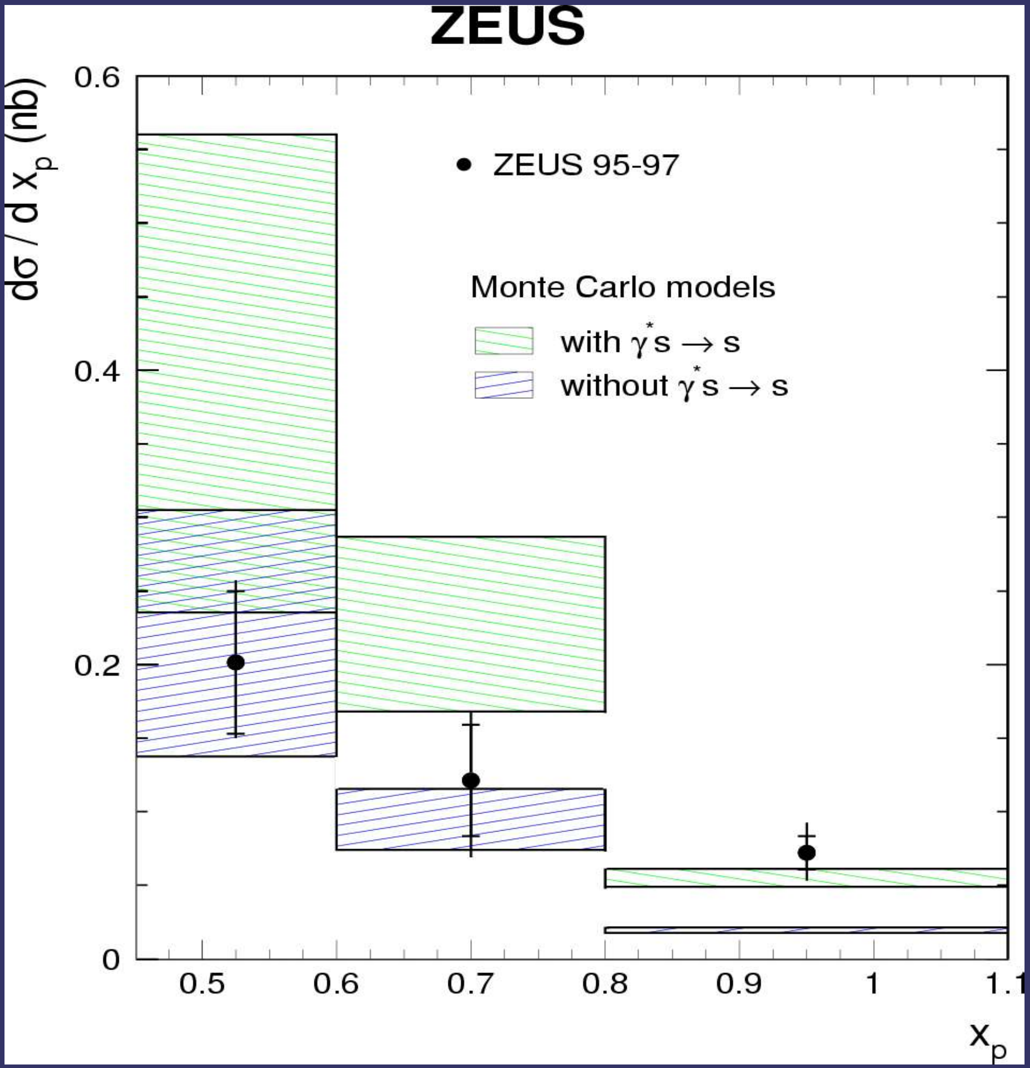


Monte Carlo models have large uncertainty at low x_p region (sensitive to QCD effects!)

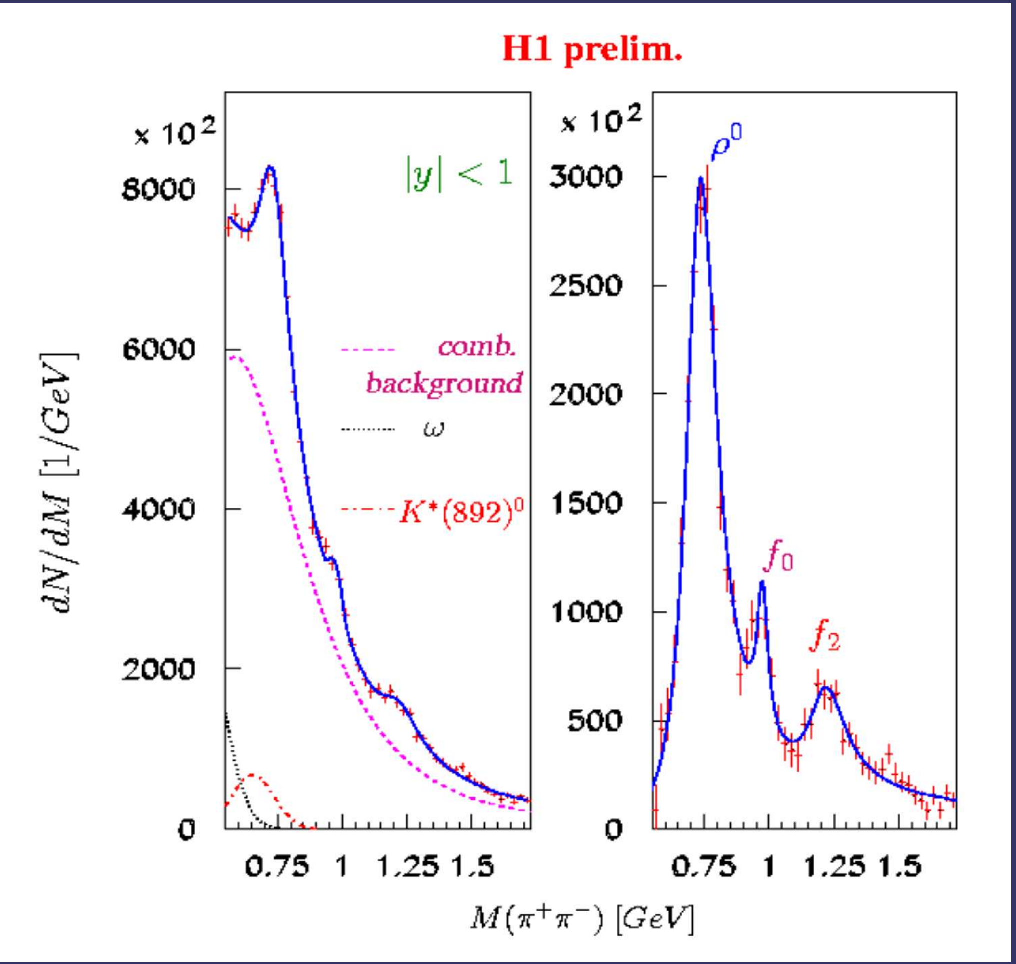
... but know very well what happens if the strange sea is OFF !

Data at large x_p are described by MC with CTEQ5L/GRV98 parameterization for strange sea

Direct evidence for strange sea via identified mesons

Spectra of identified mesons

- How to describe the production rates of identified hadrons ?
- MC simulations have many (tunable) parameters to do this...
- In hadron collisions (at central values of rapidity) particle production is governed by the fundamental properties of the QCD vacuum;
- Latest H1 studies try to understand this issue by reconstructing neutral mesons using photoproduction sample (W=210 GeV)

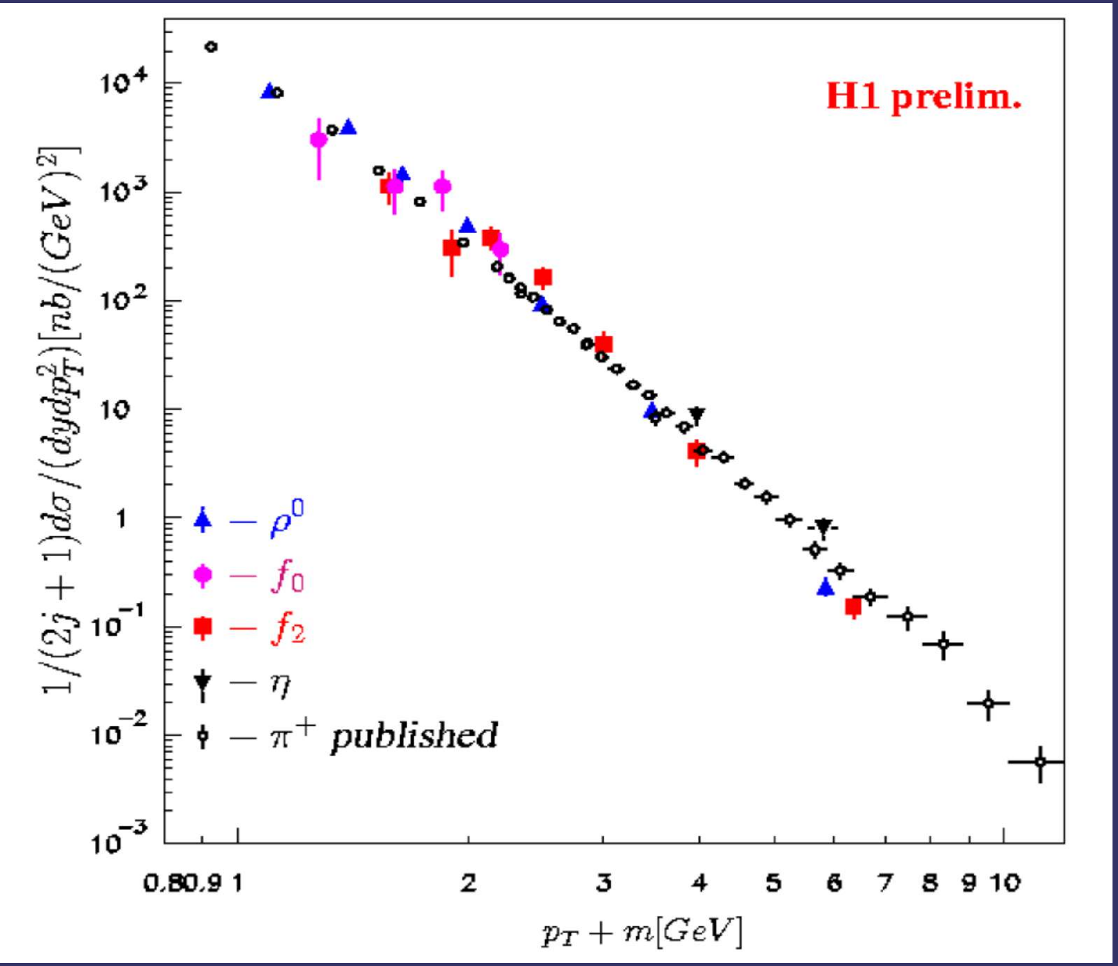


η->2γ (Lar CAL)

ρ^0, $f_0(980)$, $f_2(1270)$ (->$\pi^+ \pi^-$)

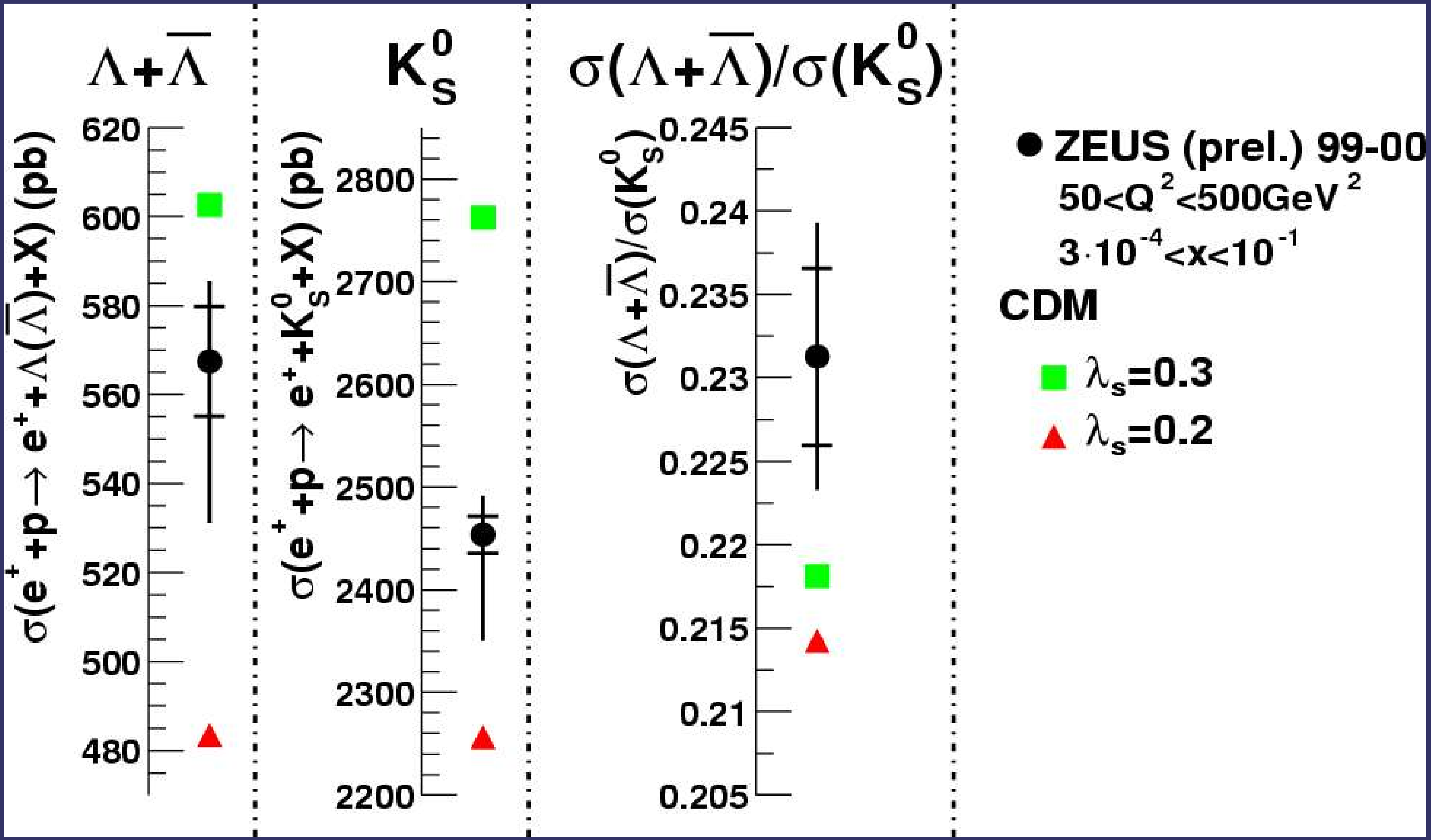
Spectra of identified mesons

- All cross sections follow the same power law as a function of $p_T + m$;
- (2j+1) spin counting factor is needed;
- Note: pions were not measured directly, but their rate was derived from charge multiplicity;
- ρ^0 mass shift? (LEP observation)



Supports a thermodynamic picture in high-energy collisions

Unresolved problem in strangeness production

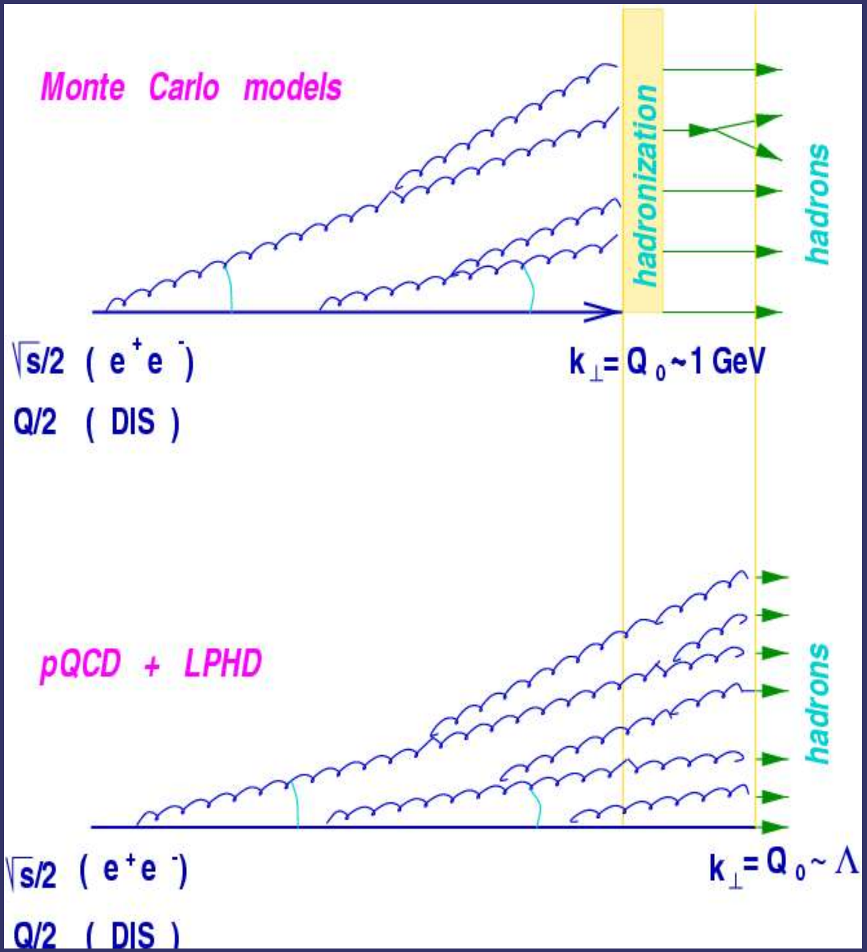


- Strangeness production in e^+e^- can be well described by the LUND model with λ_s=0.3-0.4 (LEP, SLD)
- Overwhelming evidence from HERA - λ_s=0.20-0.24 (ZEUS, H1) !

Why strangeness suppression is higher for ep ?

From single particle to multihadron system

- Multihadron production: analytical vs Monte Carlo models:
  - Most observables based on counting individual particles are infrared/collinear unsafe – sensitive to QCD cutoffs Q_0
  - In analytical QCD this cutoff is set to pion mass (LPHD hypothesis)
  - Parton showers in Monte Carlo models are terminated at $Q_0 \sim 1$ GeV
  - Hadronisation stage also depends on Q_0 (should be tuned for each Q_0 value)



Main progress of the past decade:

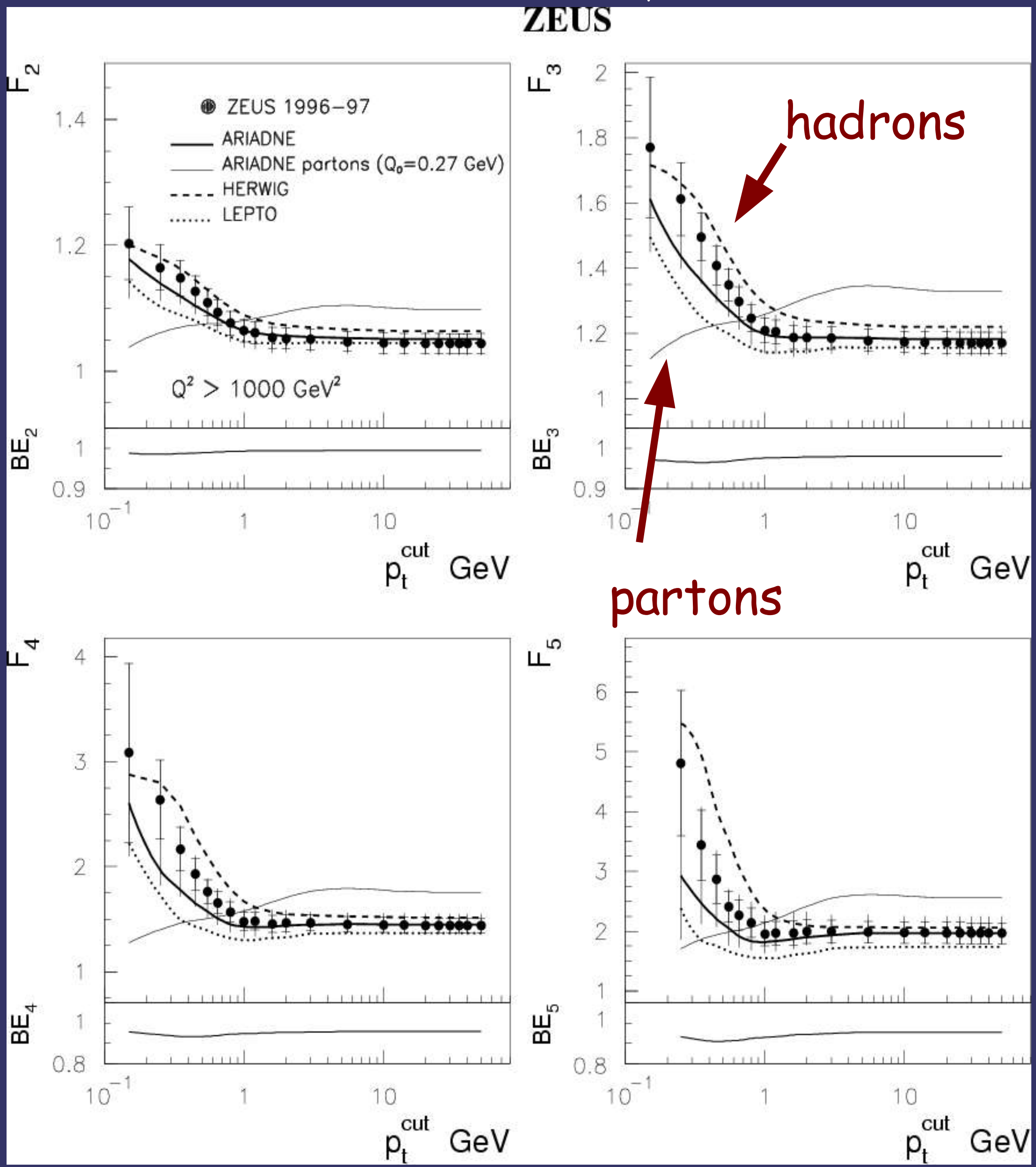
Multihadron dynamics at high energies is driven by pQCD assuming LPHD hypothesis ("soft hadronisation")

-> Multiplicities, fragmentation functions, some correlations, global event shape variables ..

Multihadron correlations: example when LPHD fails

- Restricting particle transverse momenta with respect to original parton leads to a Poisson multiplicity distribution (all factorial moments F_q are close to unity);
- derived in analytical pQCD
  S.Lupia,W.Ochs,J.Wosiek, NP B580 (1999) 405
- MC models contain this effect

Physics Letters B 510 (2001) 36-54



Data show rise with decrease of p_T !

Clear deviation from LPHD

Hadronisation effects:

1) important at low p_T;

2) reproduced by MC models !

Bose-Einstein correlations: example when MC fails

hep-ex/0311030

- Consider two π^+ with p_1 and p_2 :

  QM probability of finding a pion pair

  $<|A|^2> = 1 + <\cos[(p_1-p_2)(r_1-r_2)]>$

- For Gaussian weight function:

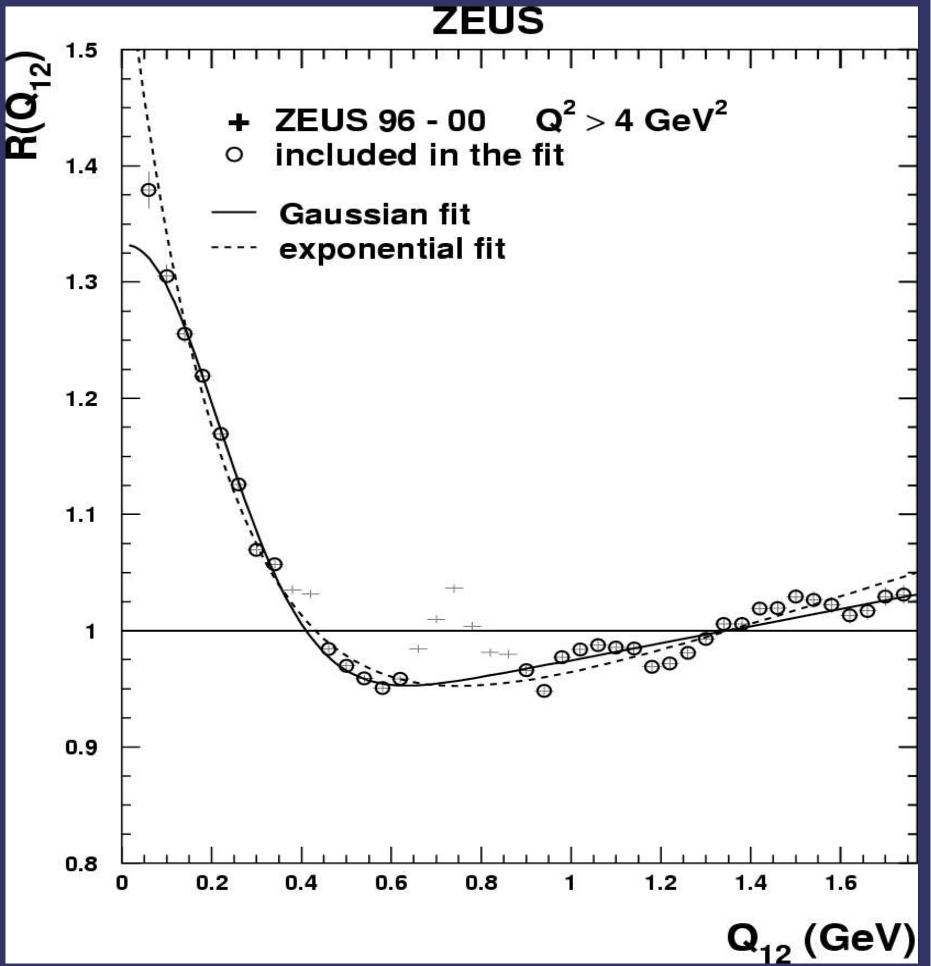
  $\rho(x_1,x_2)=(2\pi r^2)^{-3}\exp(-(x_1^2+x_2^2)/2r^2)$

  $<|A|^2> = 1 + \exp(-(p_1-p_2)r^2)$

  where r is the size of the production source

- Simple way to measure:

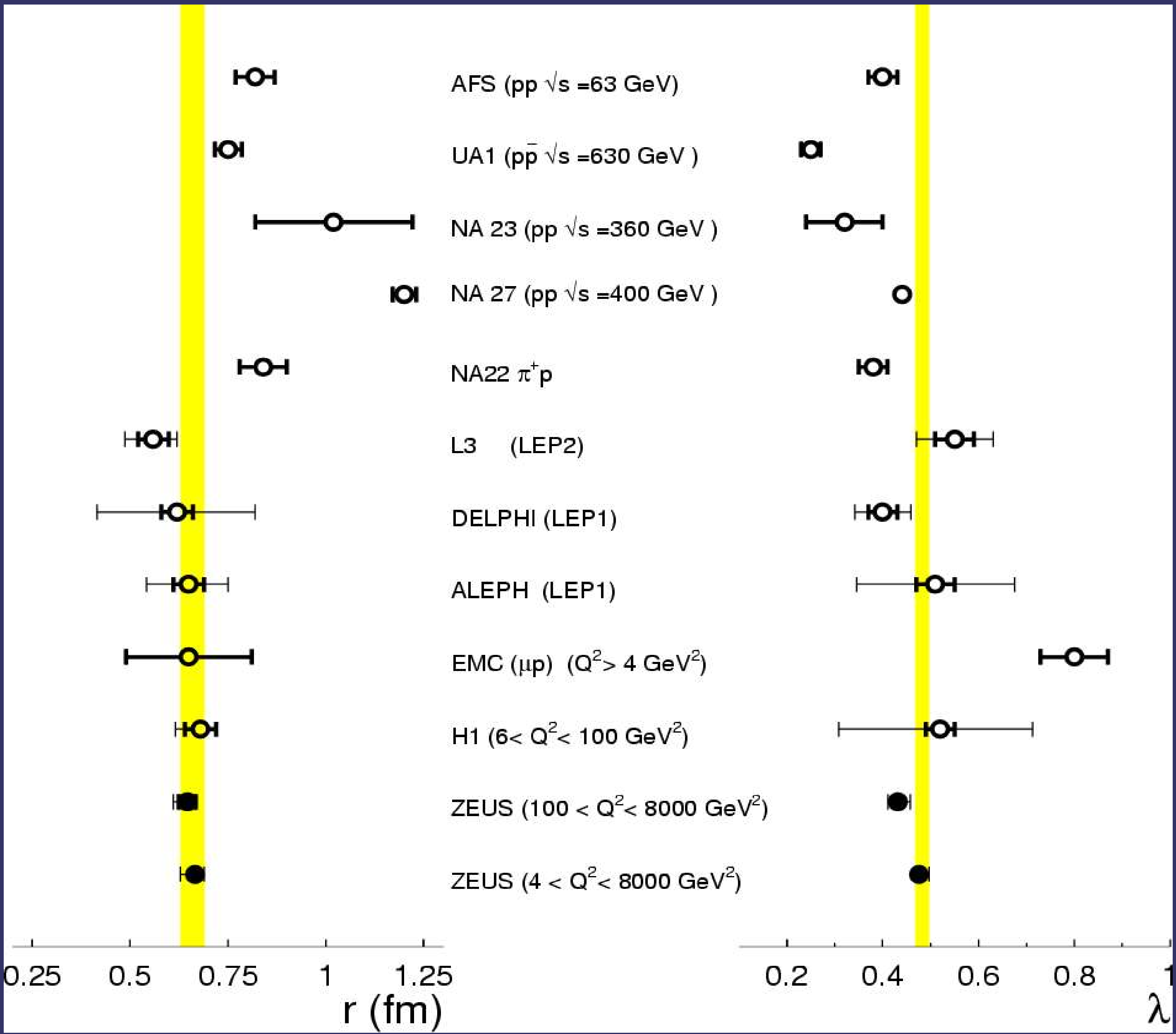
  $R(p_1,p_2)=N^{pairs}(\pm,\pm)/N^{pairs}(+,-)$



Fit using: $R=1+\lambda\exp(-r^2 Q_{12}^2)$; $Q_{12}^2= - (p_1-p_2)^2$

MC simulation does not contain the effect
(but can mimic it using a given correlation function)

Bose-Einstein correlation



DIS and e^+e^- agree

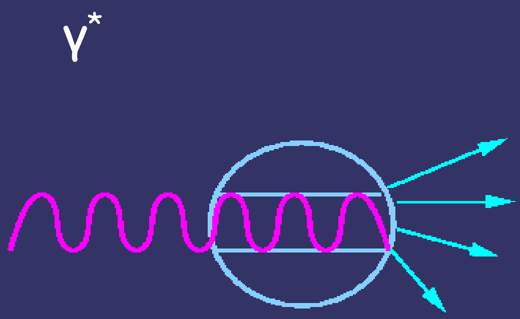
Some (small) differences between DIS and hadron-hadron productions

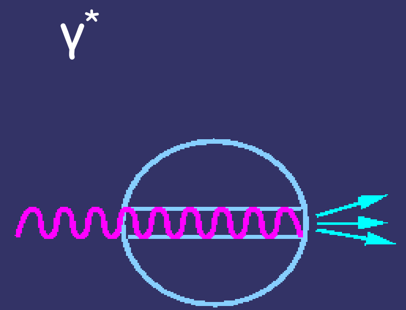
BE effect universal ?

Best way to check – use a single experiment to verify this!

Bose-Einstein correlations: two interpretations

1) BE effect reflects size of the production region:





Production region decreases with increase of Q^2

2) BE contains no information on hard subprocess:

BE effect does not depend on Q^2 as assumed by the Lund fragmentation model, but is sensitive to a "string tension"

Bose-Einstein correlations as a function of Q^2

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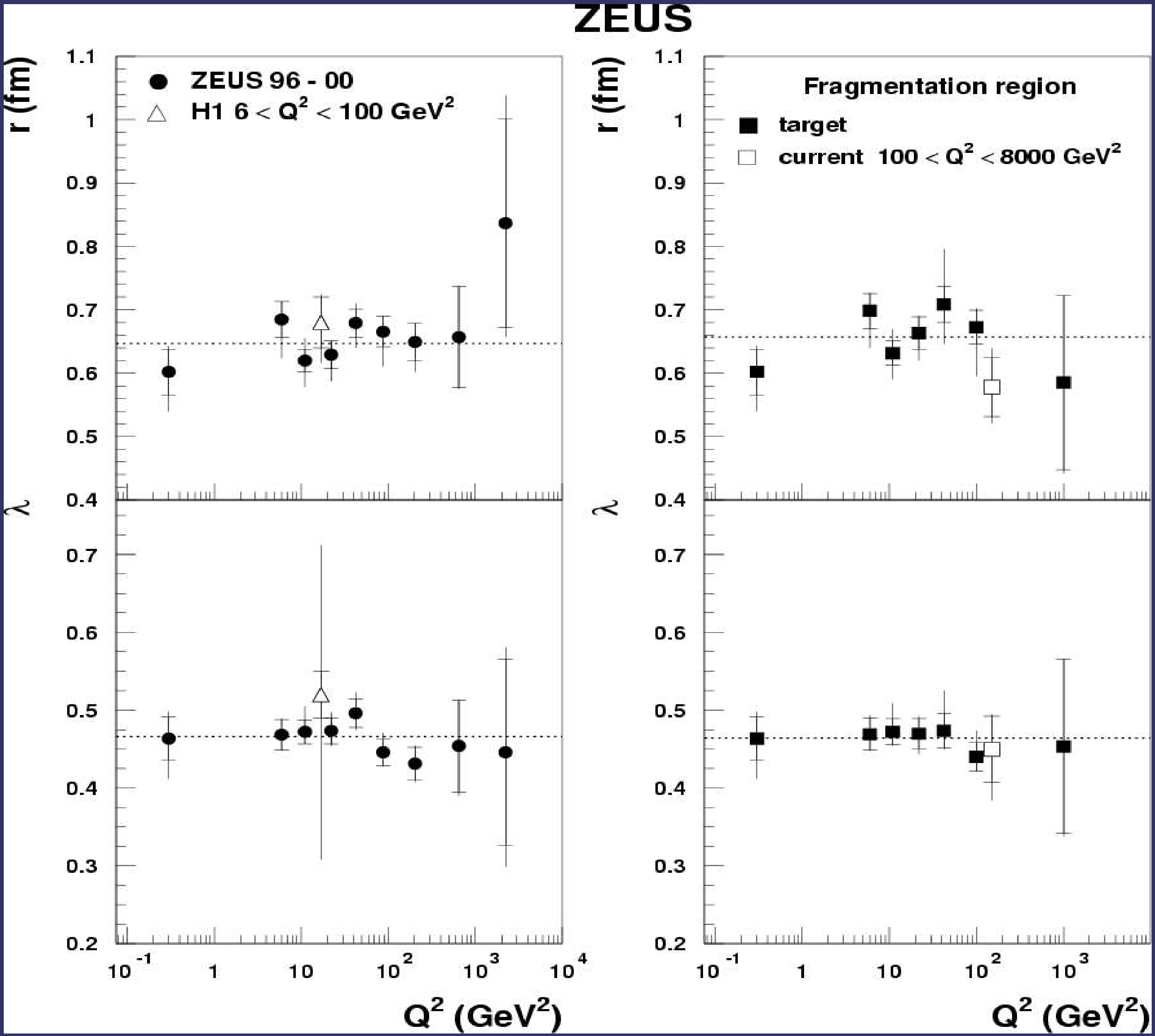


BE does not depend on Q^2

Current and target regions show the same strength of the BE effect

BE effect does not depend on hard subprocess – universal property of hadronisation stage

Particle spectroscopy

Constituent Quark Model (CQM) describes:

- Mesons as bound state of a quark and an antiquark: $q\bar{q}$ $(q=u,d,s)$
- Baryons as bound state of three quarks: qqq

+absence of baryons with strangeness S=+1

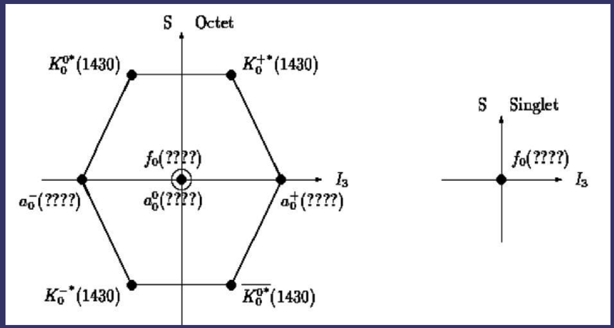
CQM does not predict more complicated states, but can accommodate them!

<u>Examples:</u>

- Excitations of QCD vacuum (glueballs): gg, etc..
- States with an excited gluon (hybrids): qqg, $qqqg$
- Multiquark states: $qq\overline{qq}$, $qqqq\bar{q}$ … (could have S=+1)

Search for glueballs

- Lattice QCD predicts:
  - Scalar glueball with mass ~ 1700 ±100 MeV
  - Tensor glueball with mass ~ 2400 ±100 MeV
- Scalar glueballs can mix with qq states with $J^{PC}=0^{++}$
  - 4 states with $J^{PC}=0^{++}$ and I=0 were established:
    $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
  - no general agreement which meson should go where



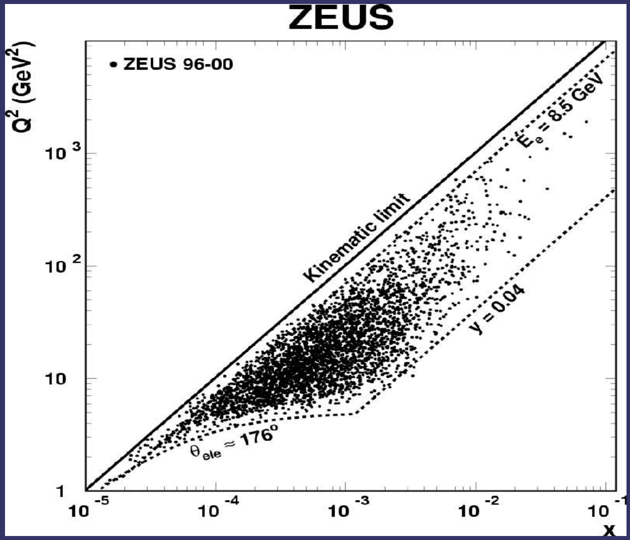
- $f_0(1710)$ – most frequently considered as a glueball candidate (WA102)
  - most recent measurement – by L3 at LEP
  - gluon content is not yet established!

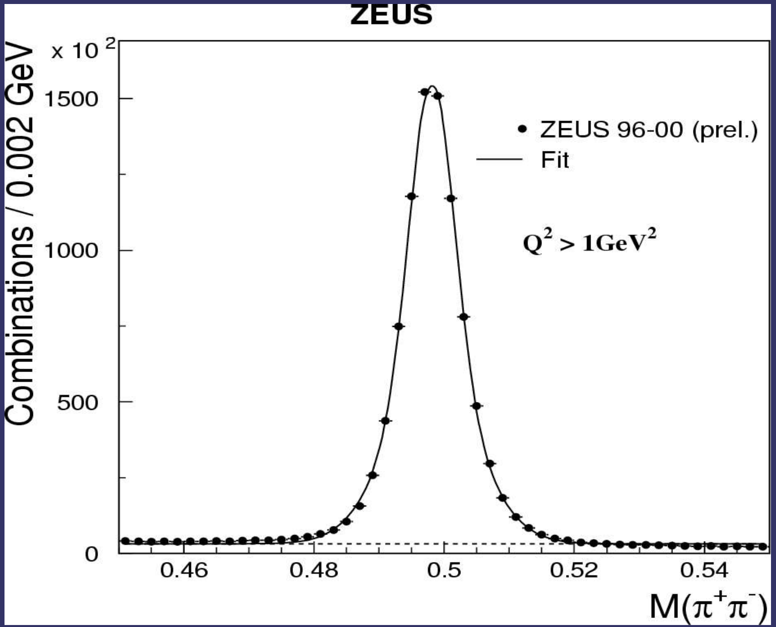
Look at production rates in gluon- and quark-reach regions!

Search for glueballs: ZEUS results

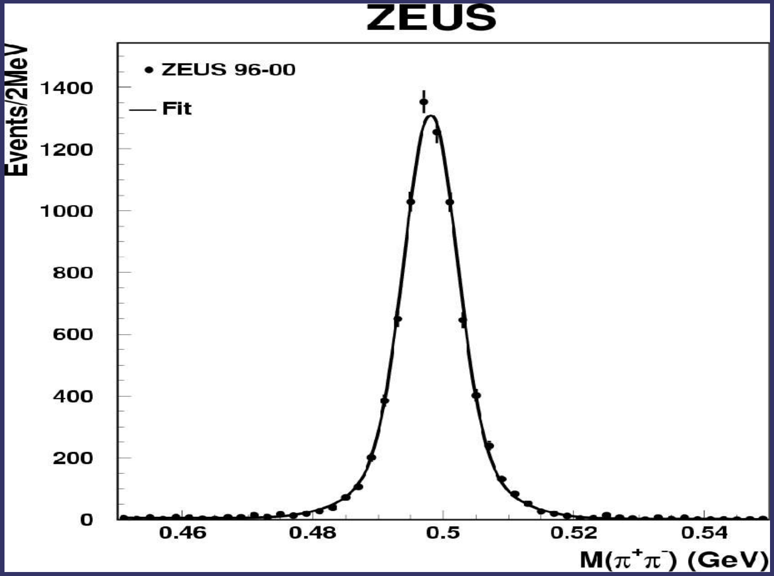
Decay channels involving detection of K_S^0 are the most promising:

$K_S^0 K_S^0$ is expected to couple to scalar and tensor glueballs





$\pi^+ \pi^-$ invariant mass for DIS events with at least one K_S^0



$\pi^+ \pi^-$ invariant mass for DIS events with two K_S^0

Search for glueballs

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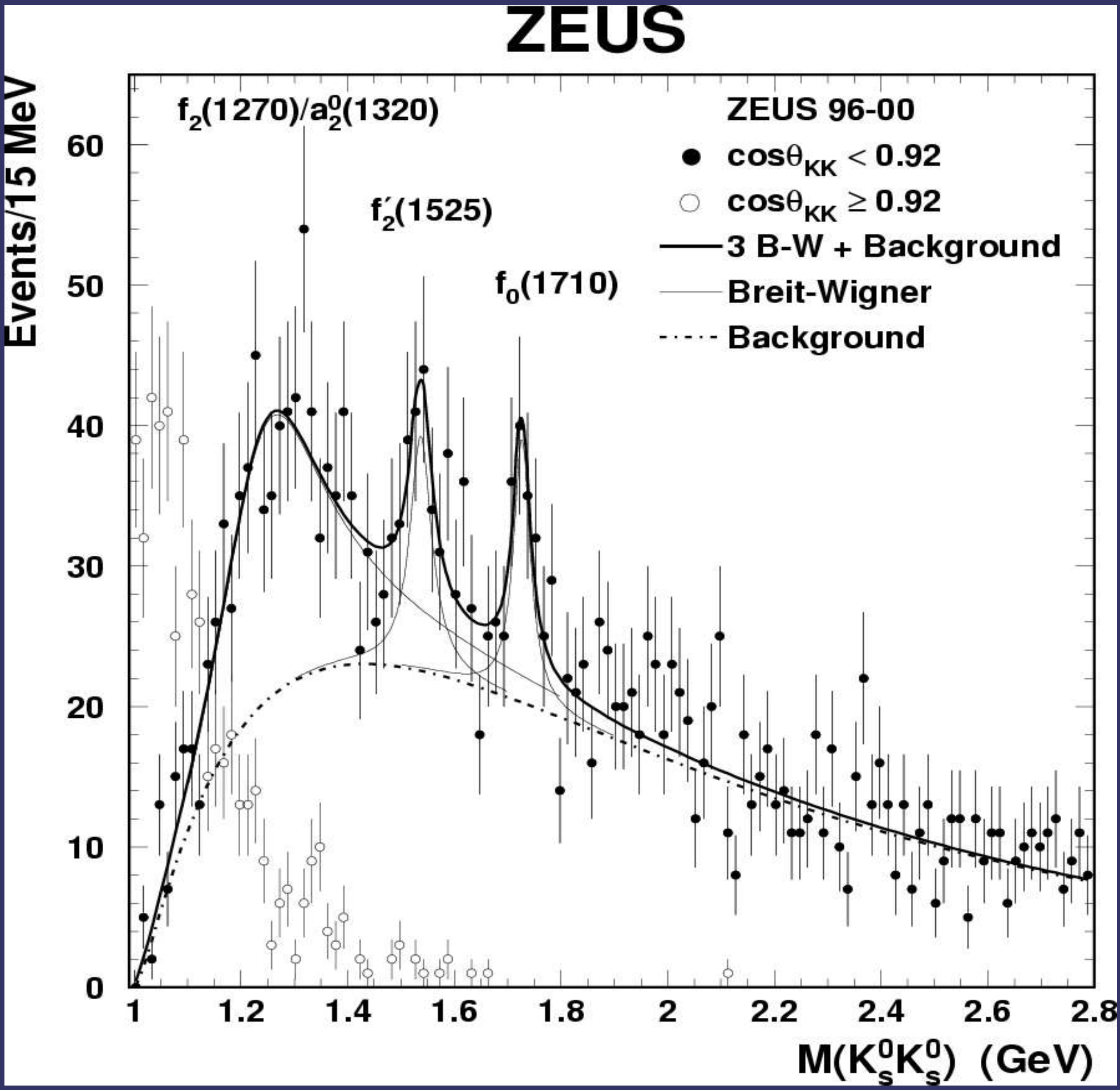


Clear signals at:

- 1726±7 MeV
  $\Gamma=38^{+20}_{-14}$ MeV
- 1537±9 MeV
  $\Gamma=50^{+34}_{-22}$ MeV
- + "enhancement" at 1270-1320 MeV

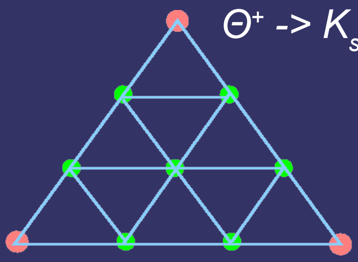
Consistent with the PDG for peak positions, but the PDG reports Γ=125±10 MeV for $f_0(1710)$!

Signal at 1710 MeV is mainly in the target fragmentation region of the Breit frame (gluon-reach region!)

Search for pentaquarks

- Significant interest in baryon spectroscopy triggered by recent observations of possible pentaquark at **1530 MeV and width <15 MeV**, predicted by D.Diakonov, V.Petrov and M. Polyakov within the Chiral Quark Soliton model;

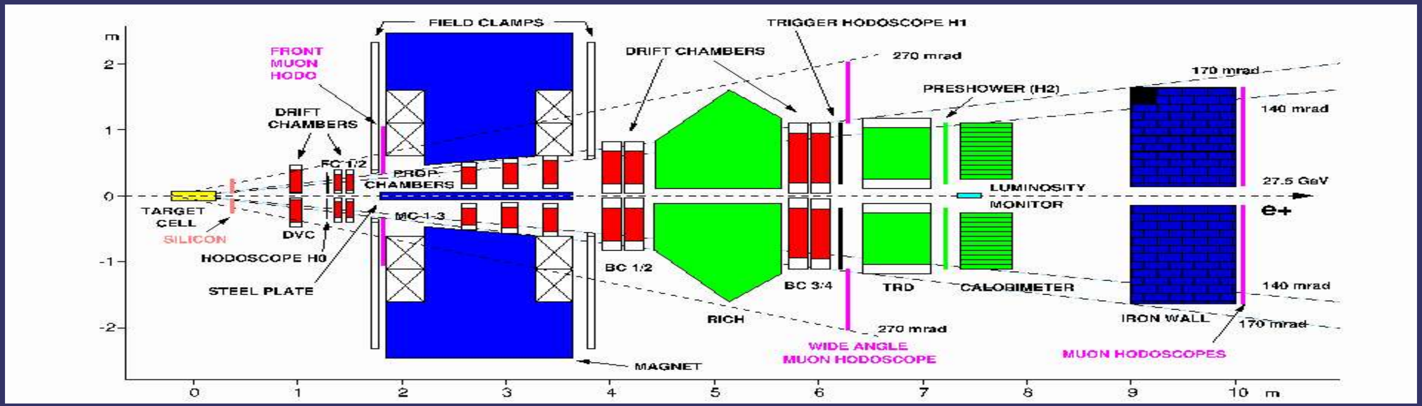
  - ✓ Baryons are rotational states of the soliton nucleon in spin and isospin space
  - ✓ Predicted spin 1/2, isospin 0, strangeness S=+1
  - ✓ lightest baryon has quark structure **$uudd\bar{s}$**, and called Θ^+
  - ✓ Very narrow – CQM cannot explain this, the soliton model can!



- A number of low-energy fixed target experiments reported a pentaquark candidate (LEPS,DIANA,SAPHIR, CLAS);

- In this talk I'll discuss recent measurements by HEPMES and ZEUS, both experiments attempted to find such a state by reconstructing K^0-(anti)proton invariant mass

Recent HERMES results (hep-ex/0312044)

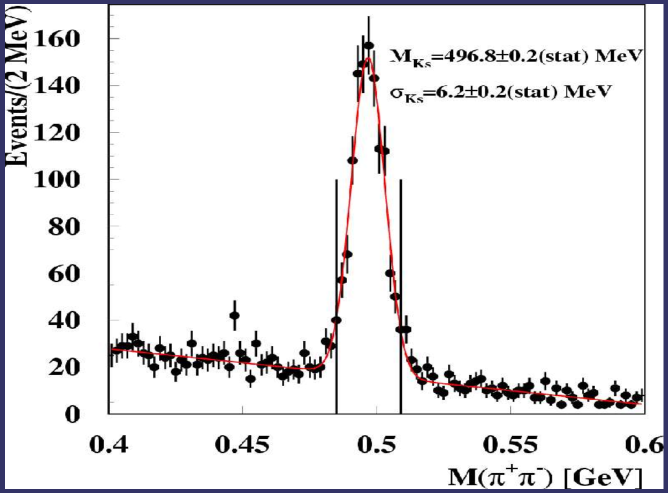


Resolution: $\delta p/p$=1.4-2.5%

Particle identification: TRD + RICH

$e^+ D \longrightarrow \Theta^+ + X \longrightarrow K_s\, p + X$

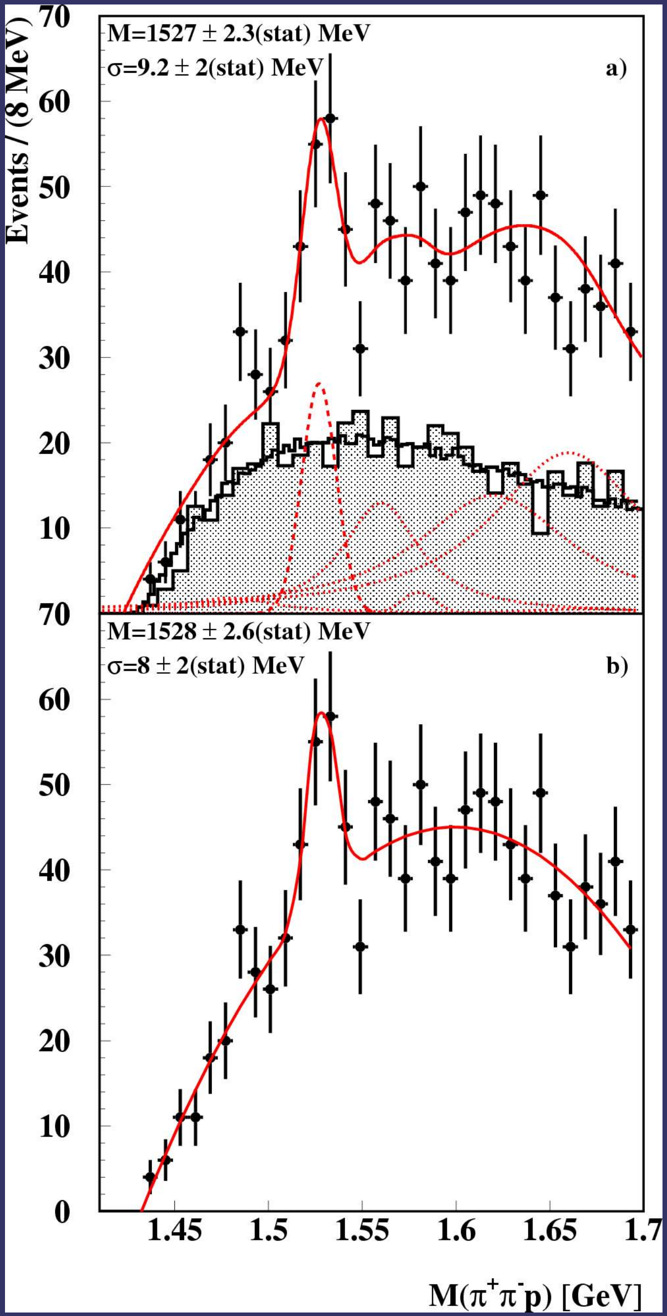
- Quasi-real photoproduction on deuterium;
- Positron beam E=27.6 GeV, 250 pb^{-1} lumi
- K_S reconstructed using decay length;
- Λ(1116) removed;
- Kinematic range: 4-9 GeV (protons), 1-15 GeV(pions)



Recent HERMES results (hep-ex/0312044)

- A few different models for background ->
- Several ways to determine the significance:

  Significance ranges from 3.4 to 6.3 σ
- Peak=1528 ± 2.6(stat.)±2.1(syst.) MeV
- Width may be larger than the experimental resolution: 4.2-6.3 σ
- No signal for pK^+ channel (not isotensor)



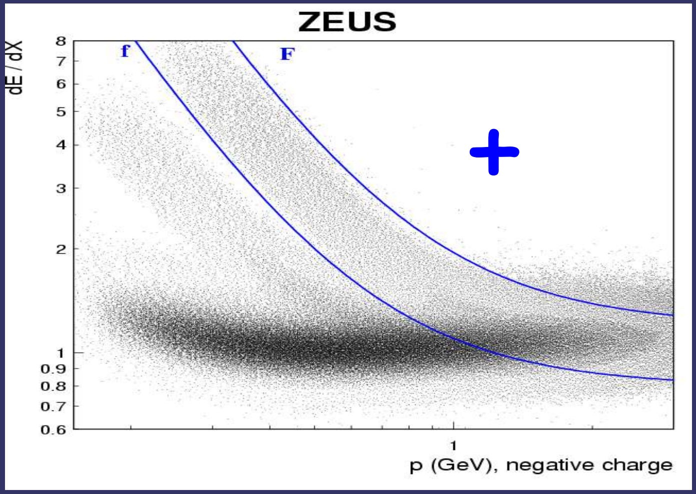
Further evidence for the existence of possible pentaquark

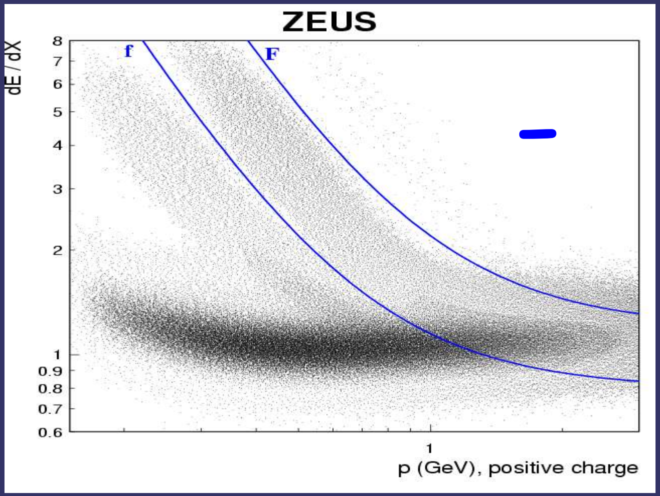
ZEUS results

- ZEUS is a colliding experiment – high energies !
- Easiest way to reconstruct Θ^+ - use the ZEUS central tracking region, where the particle production is dominated by fragmentation.

(anti)proton candidates were reconstructed using primary tracks taken f< dE/dX <F

- found from a visual examination of dE/dX;
- verified using a sample with reconstructed Λ;
- (anti)protons from ARIADNE have a similar band.



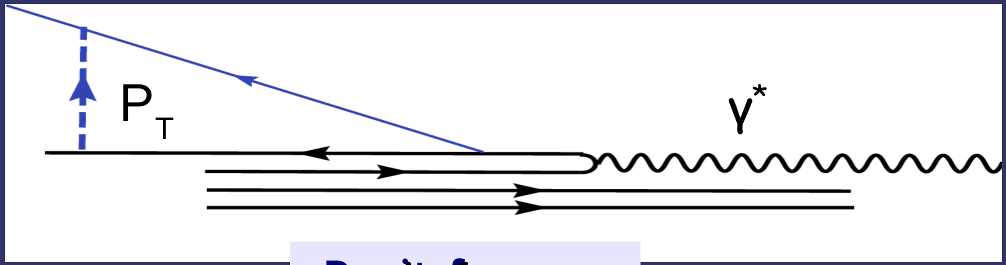


ZEUS results

Most protons are concentrated in the region p ~ 0.8-2 GeV:

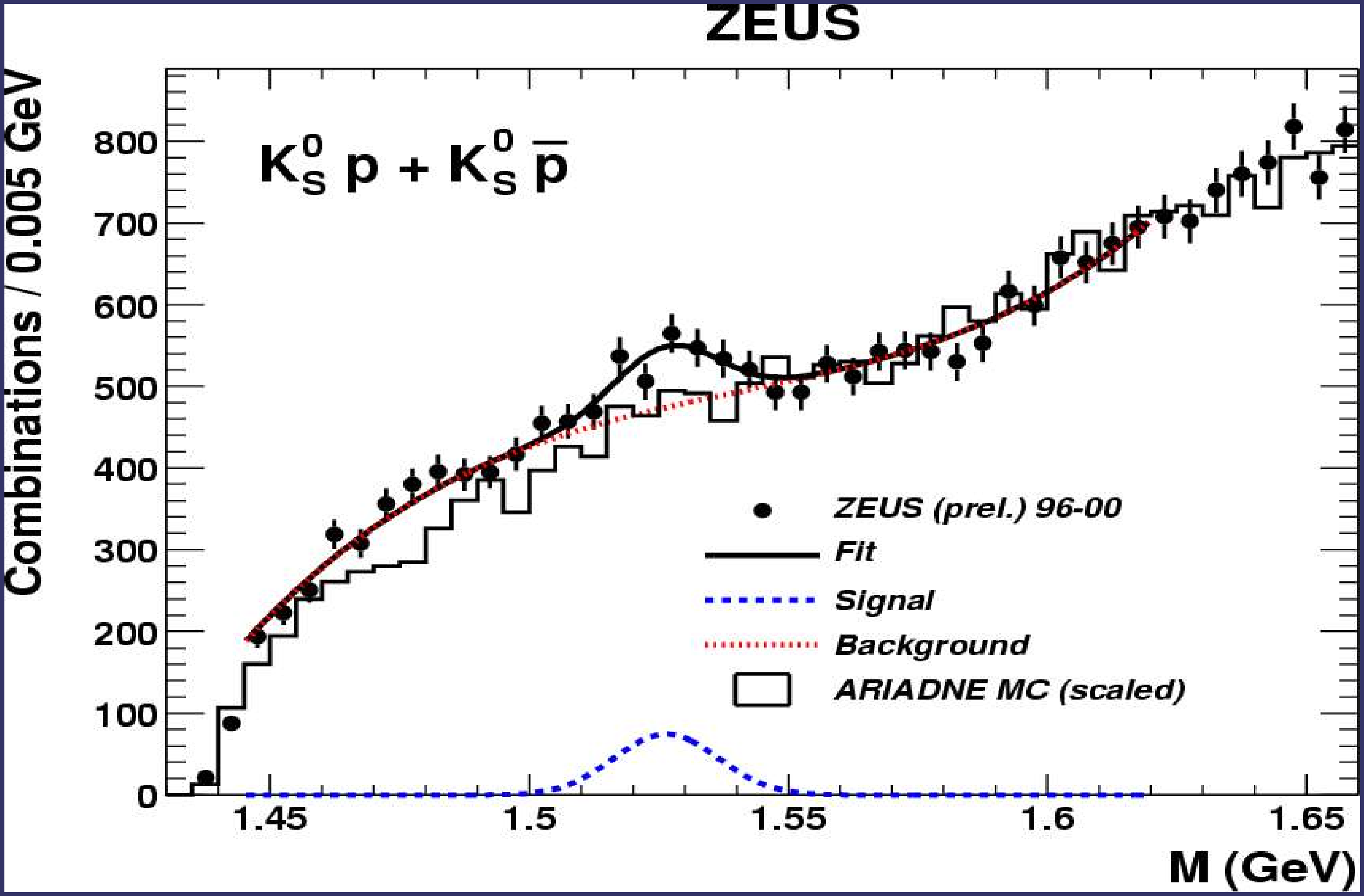
☞ Large pion background

- Reject tracks with p>1.3 GeV inside the dE/dX band;
- Assign pion mass to proton candidate, reconstruct $K^0\pi$ mass, rejects pions; from K^* : 800 <$M(K^0\pi)$ <980 MeV;
- E(proton)>E(K^0);
- P_T>0.5 GeV in the Breit frame to look at gluon-rich DIS region (applied posteriori!)



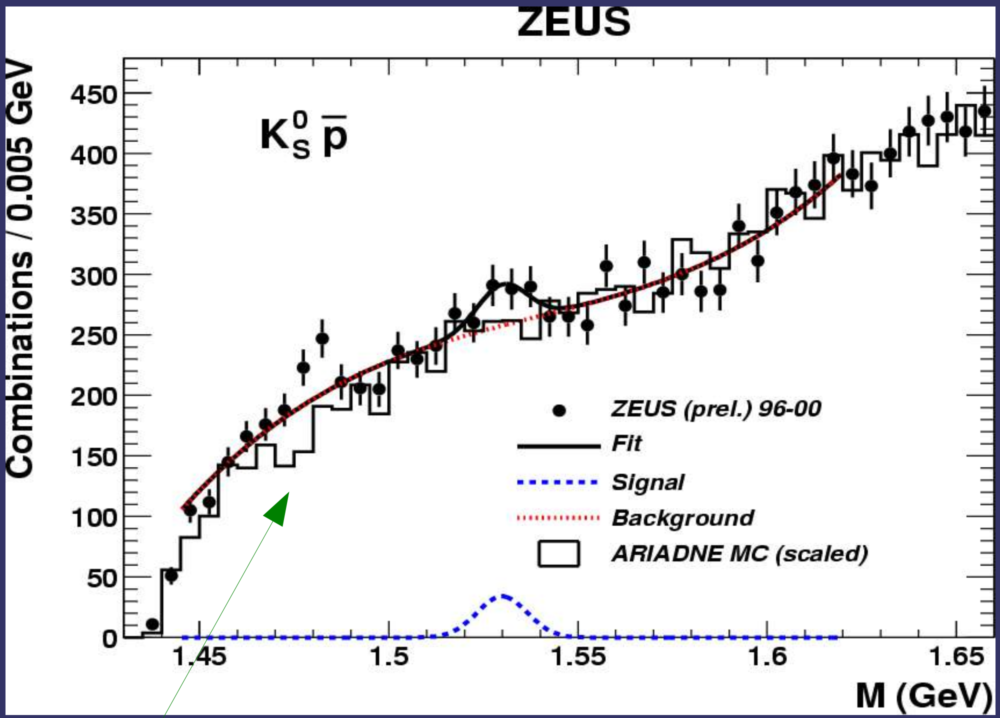
Breit frame

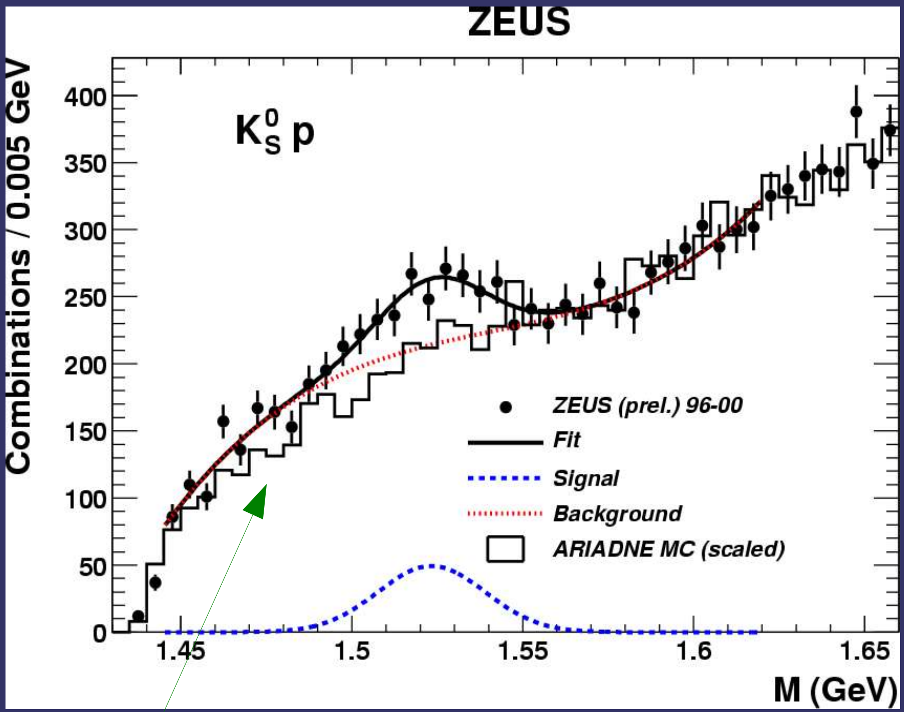
ZEUS results



Combined sample: 372±75 candidates
peak=1527±2(stat.) MeV, W=10 ±2(stat.) MeV

ZEUS results





Σ(1480) bump?

Σ(1480) bump?

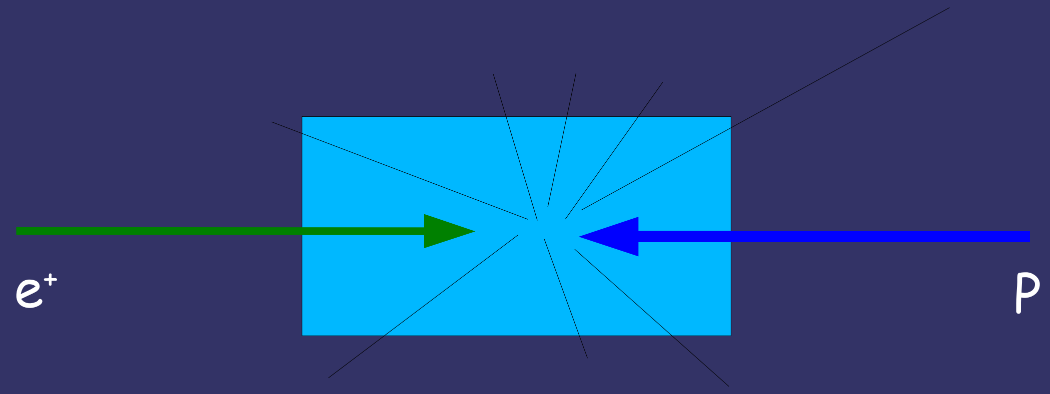
K^0-antiprotons: 126±50 candidates
peak=1529±3(stat.) MeV, W=7 ±3 (stat) MeV

K^0-protons: 393±86 candidates
peak=1523±3(stat.) MeV, W=16 ±3(stat) MeV

Note: if the width is fixed to ~ 10 MeV, the fit is still OK

ZEUS results

- A signal at 1527±2(stat.) MeV, with a Gaussian width of 10±2 MeV:
  - ~ 5 σ statistical significance (from Gaussian fit);
  - exists for both K^0-protons and K^0-antiproton channels (antipentaquark);
  - consistent with the predicted pentaquark (1530 MeV, <15 MeV width);
  - Systematics need to be estimated (~ a few MeV);
  - PRELIMINARY result!
- First evidence in HEP colliding experiment;
- First measurement in central fragmentation region



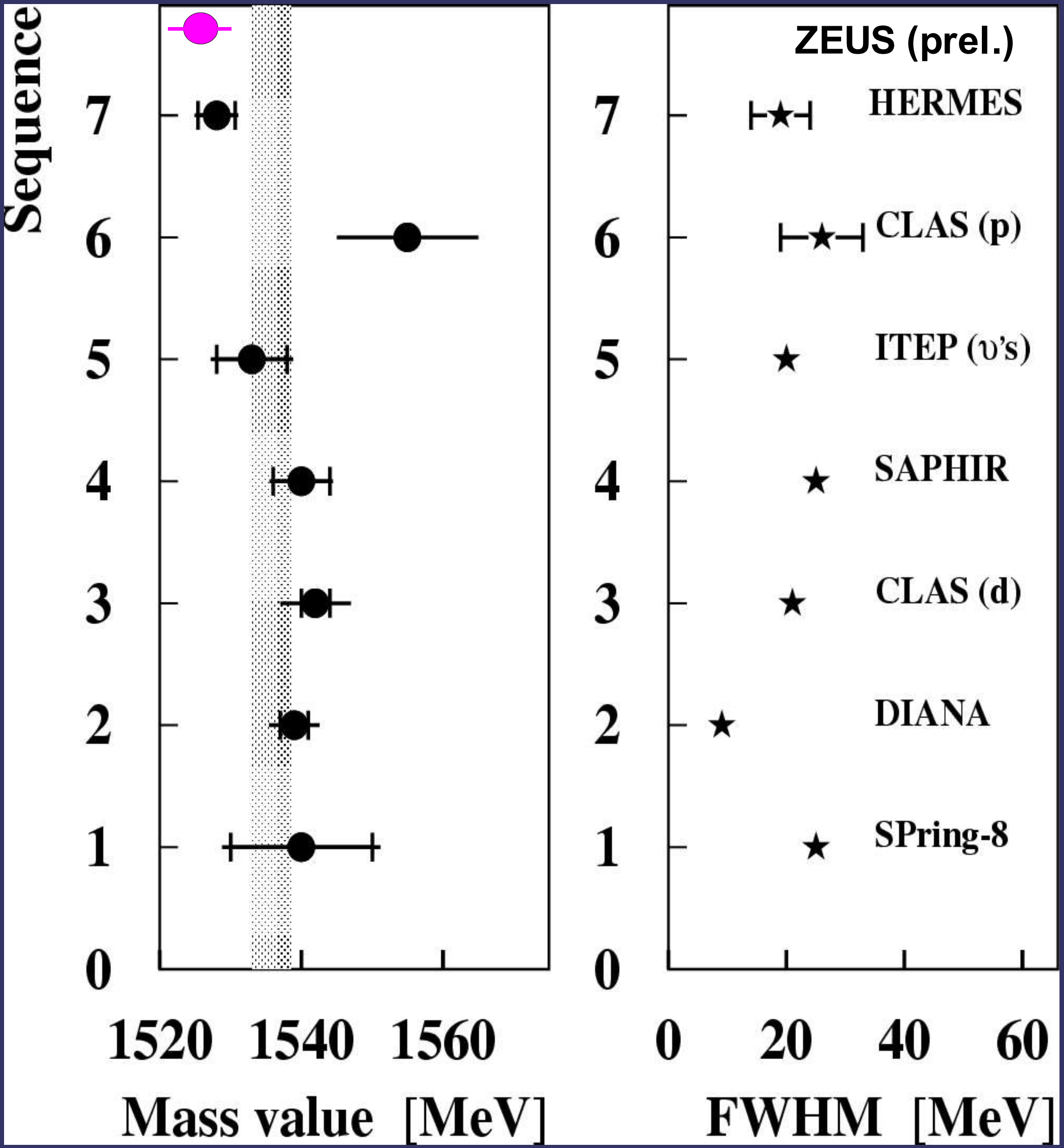
Summary

- Word average

  (without ZEUS prel.)

  1536.2 ± 2.6 MeV

- HERA results prefer smaller pentaquark mass;
- Inclusion of the ZEUS result shifts the mass to a lower value



Summary

- HERA data provide many precise tests of theoretical models describing various aspects of particle productions – careful analysis of pre-upgrade data still producing a wealth of important results;
- Many challenges to describe multihadron production; BE – universal feature of hadronisation; LPHD is not applicable for particle correlations at small p_t;
- Identified hadrons: First insight into the strange sea; Universal power low for different particle species? Strangeness withing the LUND model is not understood;
- HERMES and ZEUS – consistent results for pentaquark masses; First measurement by a HEP colliding experiment in central fragmentation region → can this disfavor some pentaquark models?