Low energy QCD phenomena and spectroscopy

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Outline:

- Chiral symmetry & spectroscopy
- pentaquarks: pro & contra
- postdictions
- implications

Villars, September 24

Main phenomena in strong interactions

Spontaneous breakdown of chiral symmetry

- Pions are light
- Nucleons are heavy
- Nuclei exist
- Very rarely is taken into account in spectroscopy
- What is the microscopic mechanism of SBChS? Instanton? Vortex? -> Can be checked in high energy processes.

Confinement

Linear potential ?

Not for QCD ! String is broken at 0.3 fm.
But this definition is used actively in quark model spectroscopy.

Confinement in QCD = absence of fractionally charged hadrons

Quantum Chromodynamics

$$L_{QCD} = -\frac{1}{4g^2} F^a{}_{\mu\nu} F^{a\mu\nu} + \sum_{f=1}^{6} \bar{\psi}_f (i\gamma_\mu \nabla^\mu - m_f)\psi_f$$

$$F_{\mu\nu}{}^a = \partial_\mu A_\nu{}^a - \partial_\nu A_\mu{}^a \cdot$$

Contains everything about strong interactions: from pions to uranium nuclei !

$$m_u \approx 4MeV, m_d \approx 7MeV$$

Proton =uud, its mass is 940 MeV

How it comes that nucleon is more than 60 times heavier its constituents ?

Chiral Symmetry of QCD

QCD in the chiral limit, i.e. Quark masses ~ 0

$$L_{\mathrm{QCD}} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}(i\gamma^\mu \partial_\mu + \gamma^\mu A_\mu)\psi$$

Global QCD-Symmetry → Lagrangean invariant under:

$$SU(2)_V : \quad \psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix} \rightarrow \psi' = \exp\left\{-i\alpha^A \tau^A\right\} \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}$$

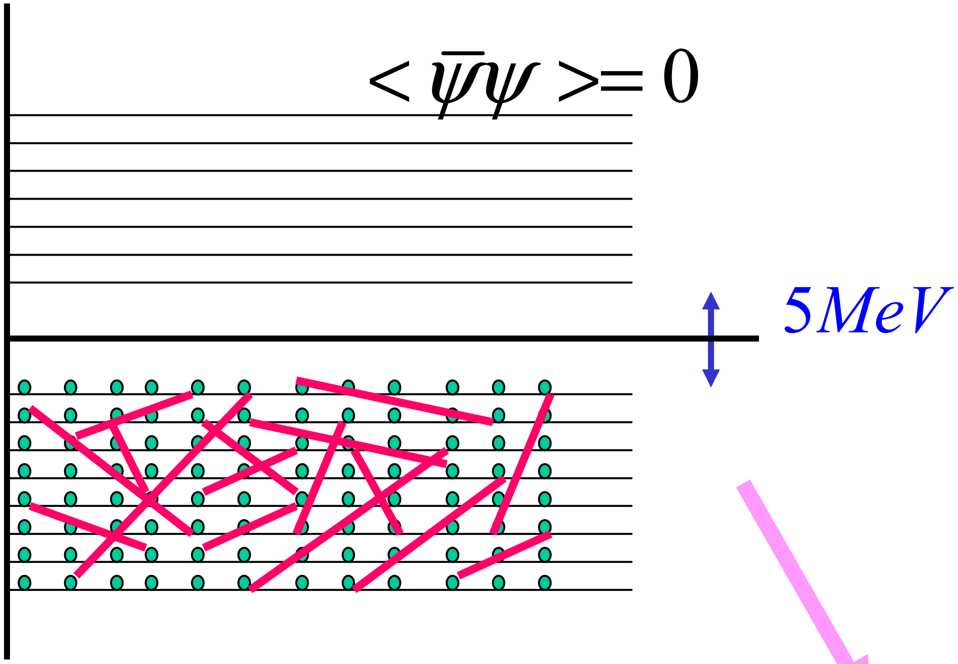
hadron multiplets

$$SU(2)_A : \quad \psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix} \rightarrow \psi' = \exp\left\{-i\alpha^A \tau^A \gamma_5\right\} \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}$$

No Multiplets Symmetry is sponteneousl broken

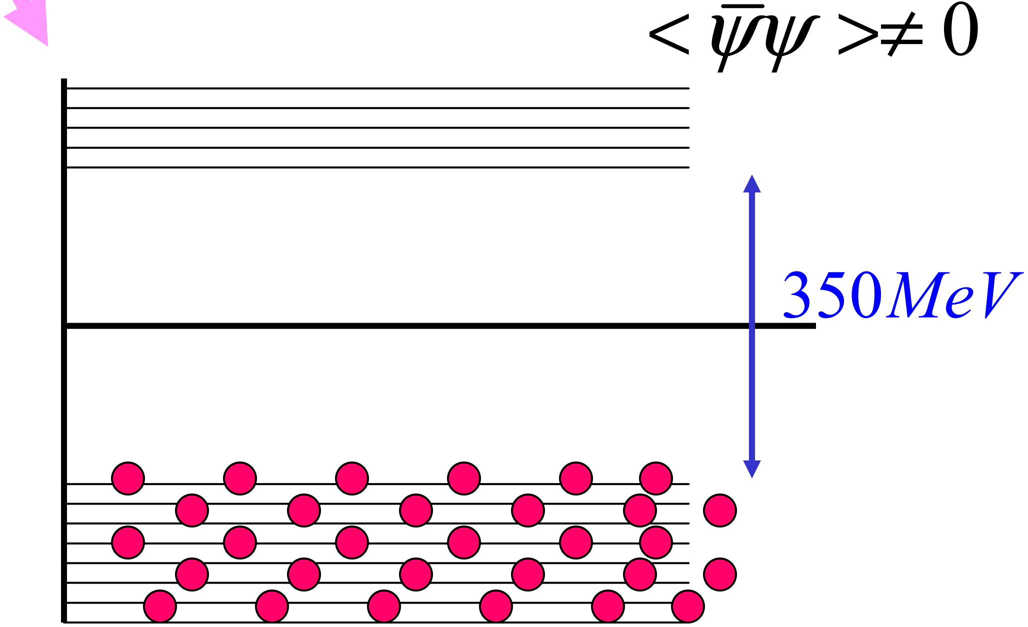
Symmetry of Lagrangean is not the same as the symmetry of eigenstates

Spontaneous Chiral symmetry breaking

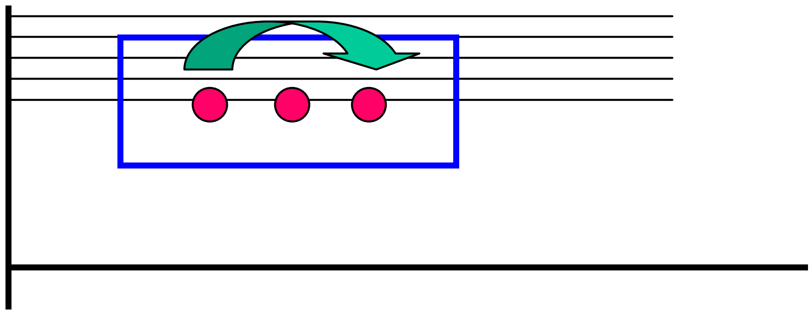


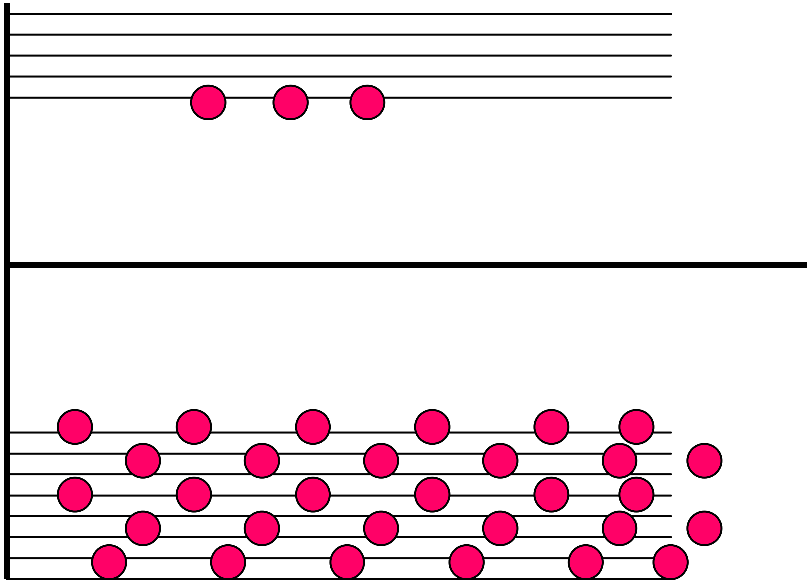
current-quarks (~5 MeV) → Constituent-quarks (~350 MeV)

Particles → Quasiparticles



Quark-Model

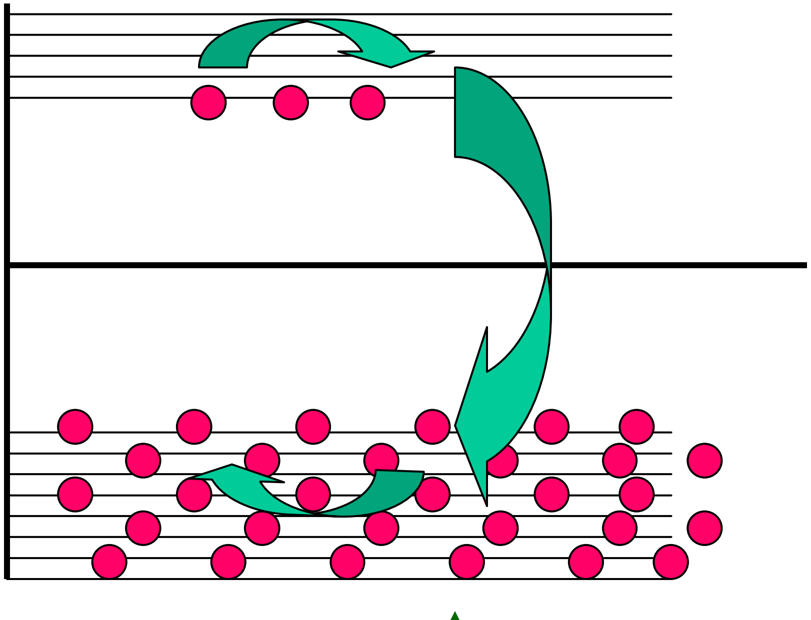




Nucleon

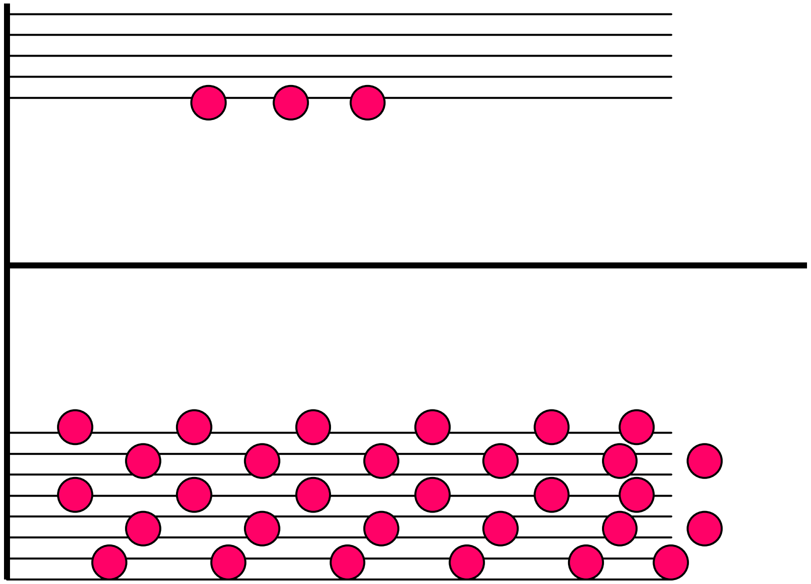
- **Three massive quarks**
- **2-particle-interactions:**
- confinement potential
- gluon-exchange
- meson-exchage
- (non) relativistisc
- **chiral symmetry is not respected**
- Succesfull spectroscopy (?)

Chiral Soliton



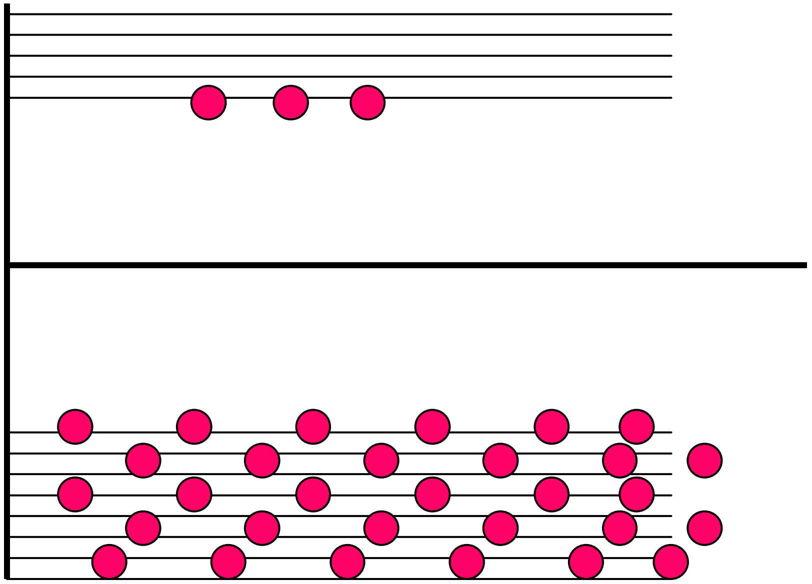
Mean Goldstone-fields (Pion, Kaon)

Large N_c-Expansion of QCD

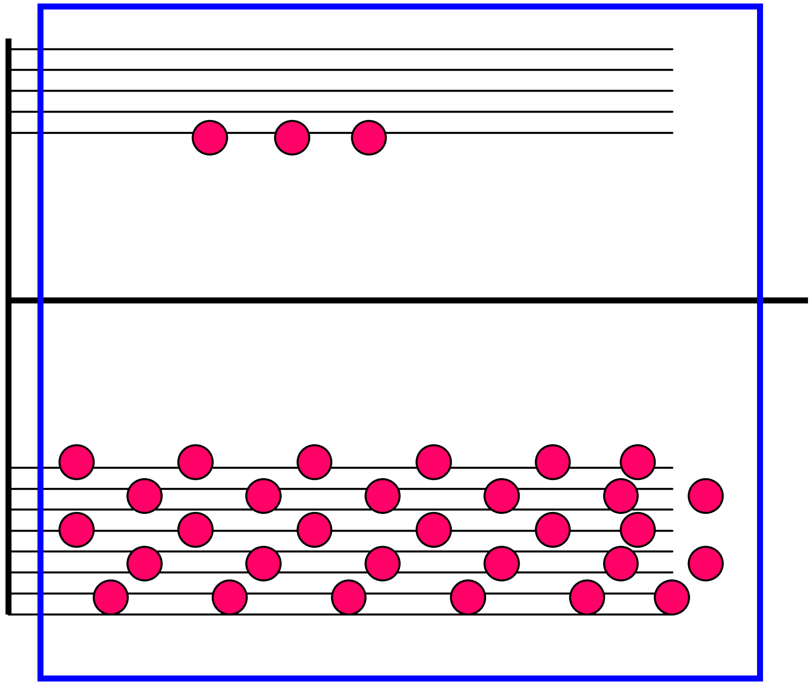


Nucleon

Chiral Soliton



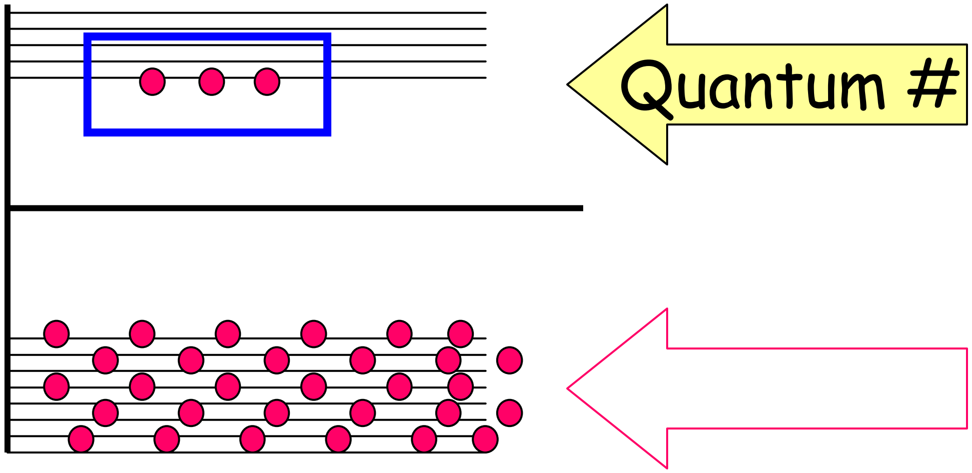
Nucleon



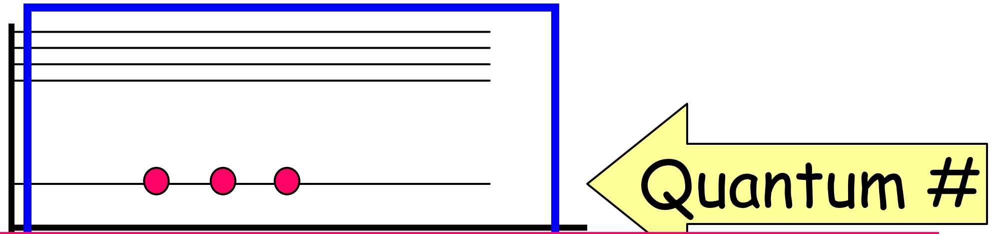
- **Three massive quarks**
- interacting with each other
- interacting with Dirac sea
- relativistic field theory
- spontaneously broken chiral symmetry is full accounted

Quantum numbers

Coupling of spins, isospins etc. of 3 quarks



mean field → non-linear system → soliton → rotation of soliton



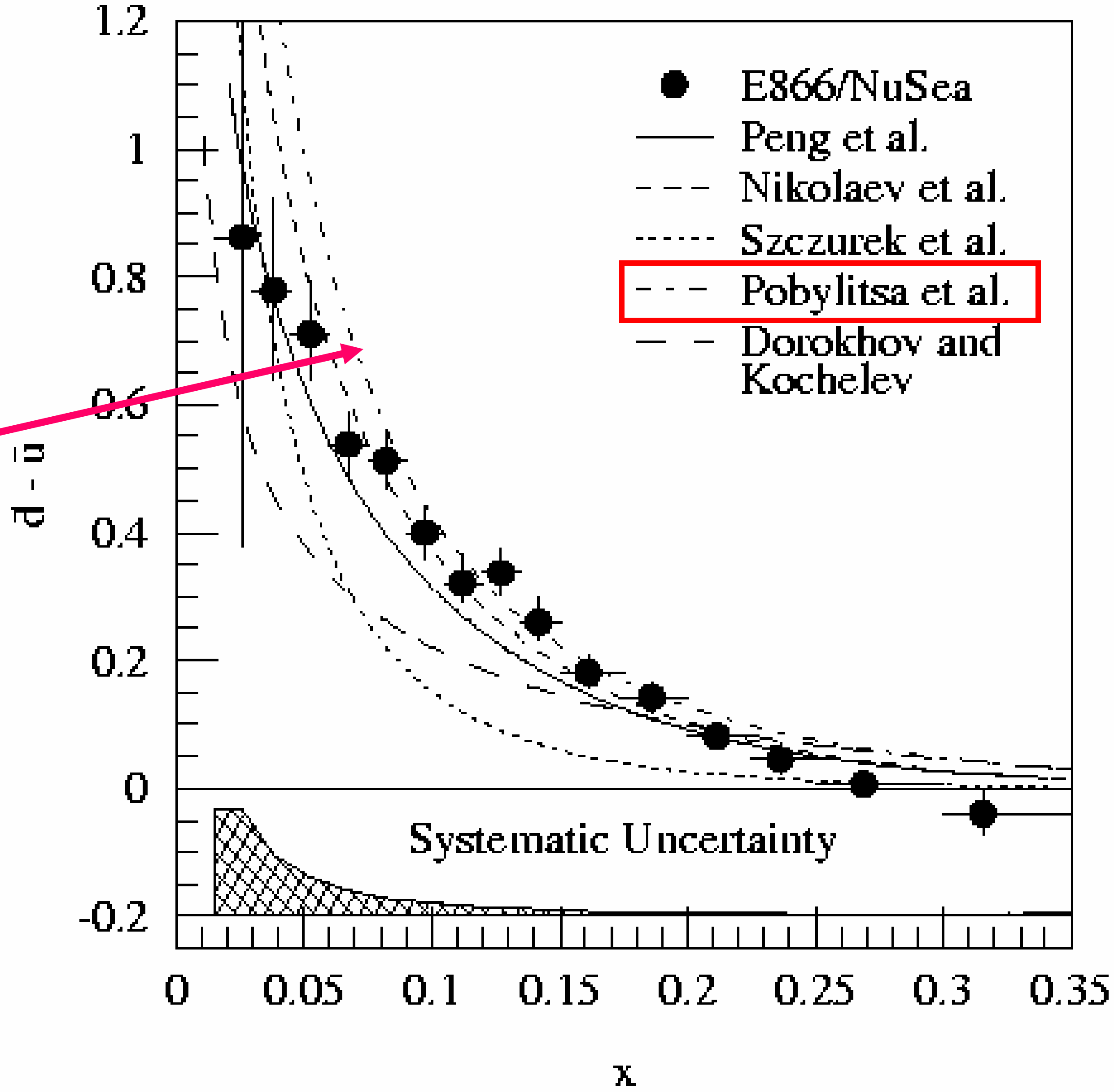
Coherent :1p-1h,2p-

Natural way for light baryon exotics. Also usual „3-quark“ baryons should contain a lot of antiquarks

Antiquark distributions: unpolarized flavour asymmetry

$\bar{d}(x) - \bar{u}(x)$

Pobylitsa et al



Soliton picture predicts large polarized flavour asymmetry

SU(3): Collective Quantization

$$L_{coll} = M_0 + \frac{I_1}{2}\sum_{a=1}^{3}\Omega^a\Omega^a + \frac{I_2}{2}\sum_{a=4}^{7}\Omega^a\Omega^a + \frac{\sqrt{3}}{2}\Omega^8$$

$$J^a = \frac{\partial L}{\partial \Omega^a} \qquad \hat{H}_{coll} = \frac{1}{2I_1}\sum_{a=1}^{3}\hat{J}^a\hat{J}^a + \frac{1}{2I_2}\sum_{a=4}^{7}\hat{J}^a\hat{J}^a + \text{constraint}$$

$$J^8 = -\frac{N_c B}{2\sqrt{3}} \qquad Y' \equiv -\frac{2\hat{J}^8}{\sqrt{3}} = 1$$

$$\left[\hat{J}^a, \hat{J}^b\right] = if^{abc}\hat{J}^c$$

Known from delta-nucleon splitting

$$\xcancel{3}, \xcancel{\overline{3}}, \xcancel{6}, 8, 10, \overline{10}, 27, \ldots$$

$$\mathrm{J{=}T} \rightarrow \frac{1^+}{2} \quad \frac{3^+}{2} \quad \frac{1^+}{2} \quad \ldots.$$

$$\Delta_{10\text{-}8} = \frac{3}{2I_1} \qquad \Delta_{\overline{10}\text{-}8} = \frac{3}{2I_2}$$

$$\Delta_{\overline{10}\text{-}10} = \frac{3}{2I_2} - \frac{3}{2I_1}$$

Spin and parity are predicted !!!

General idea: 8, 10, anti-10, etc are various excitations of <u>the same</u> mean field → properties are interrelated

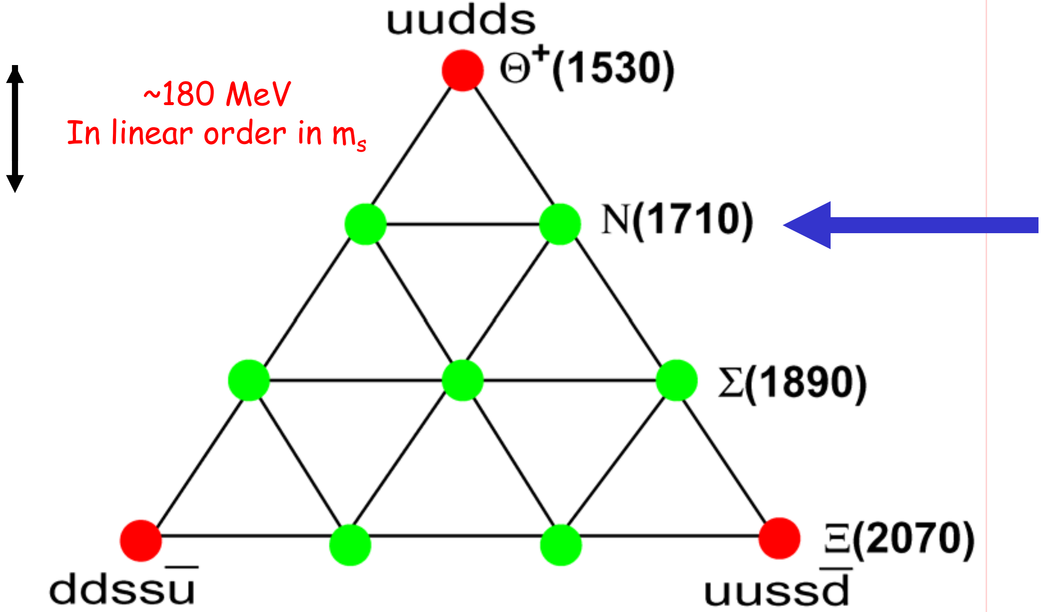
Example [Gudagnini '84]

$$8(m_{\Xi^*} + m_N) + 3m_\Sigma = 11m_\Lambda + 8m_{\Sigma^*}$$

Relates masses in 8 and 10, accuracy 1%

To fix masses of anti-10 one needs to know the value of I_2 which is not fixed by masses of 8 and 10

DPP'97



~180 MeV
In linear order in m_s

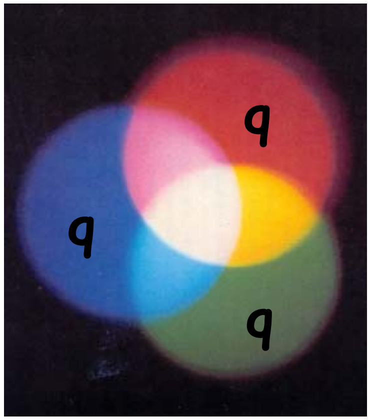
Input to fix I_2

$J^p = 1/2^+$

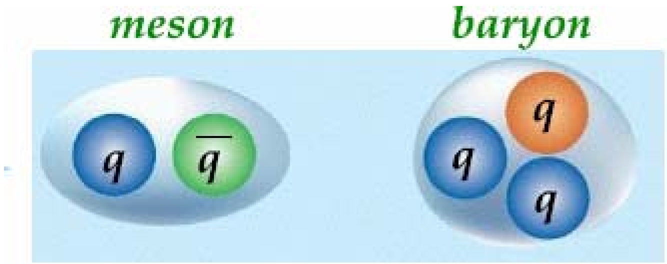
Mass is in expected range (model calculations of I_2)
P_{11}(1440) too low, P_{11}(2100) too high

Decay branchings fit soliton picture better

Quarks are confined inside colourless hadrons



Mystery remains:
Of the many possibilities for combining quarks with colour into colourless hadrons, only two configurations were found, till now…



Particle Data Group **1986** reviewing evidence for *exotic baryons states*

"…The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another ***15 years*** *before the issue is decided.*

PDG dropped the discussion on pentaquark searches after **1988**.

Baryon states

All baryonic states listed in PDG can be made of 3 quarks only

* classified as octets, decuplets and singlets of flavour SU(3)
* Strangeness range from S=0 to S=-3

A baryonic state with S=+1 is explicitely EXOTIC

- Cannot be made of 3 quarks
- Minimal quark content should be $qqqq\bar{s}$, hence pentaquark
- Must belong to higher SU(3) multiplets, e.g anti-decuplet

observation of a S=+1 baryon implies a new large multiplet of baryons (pentaquark is always ocompanied by its large family!) ⬅ important

Searches for such states started in 1966, with negative results till autumn 2002 [16 years after 1986 report of PDG !]

Searches were for heavy and wide states

Theoretical predictions for pentaquarks

1. Bag models [R.L. Jaffe '77, J. De Swart '80]
$J^p = 1/2^-$ lightest pentaquark
Masses higher than 1700 MeV, width ~ hundreds MeV

Mass of the pentaquark is roughly 5 M +(strangeness) ~ 1800 MeV
An additional q –anti-q pair is added as constituent

2. Soliton picture [Diakonov, Petrov '84, Chemtob'85, Praszalowicz '87, Walliser '92]
Exotic anti-decuplet of baryons with lightest S=+1
$J^p = 1/2^+$ pentaquark with mass in the range 1500-1800 MeV.

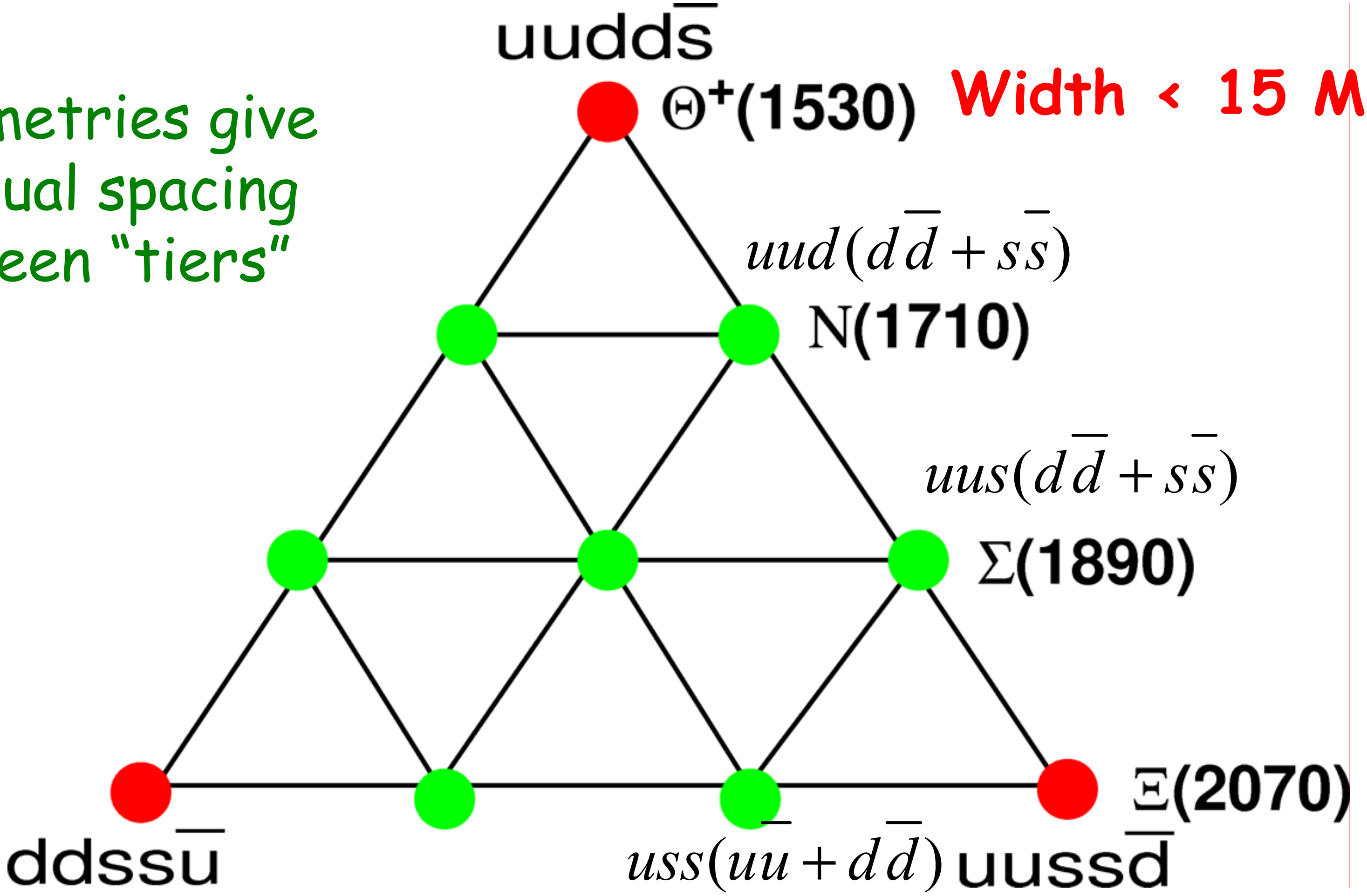
Mass of the pentaquark is rougly 3 M +(1/baryon size)+(strangeness) ~ 1500MeV
An additional q –anti-q pair is added in the form of excitation of nearly massless chiral field.

The question what is the width of the exotic pentaquark
In Skyrme model has not been address untill 1997

It came out that it should be „anomalously" narrow!
Light and narrow pentaquark is expected ->
drive for experiments
[D. Diakonov, V. Petrov, M. P. '97]

The Anti-decuplet

Symmetries give
an equal spacing
between "tiers"

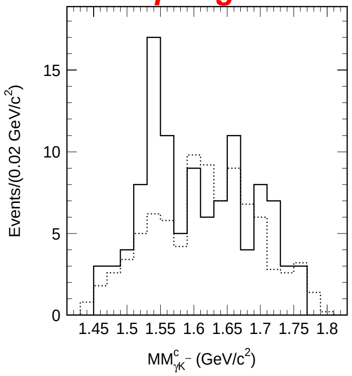


Width < 15 MeV !

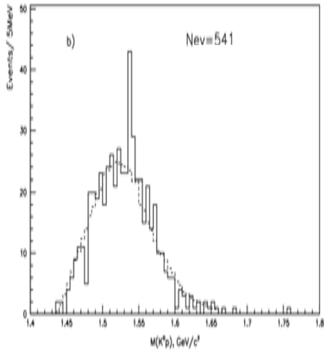
Diakonov, Petrov, MVP 1997

2003 – Dawn of the Pentaquark

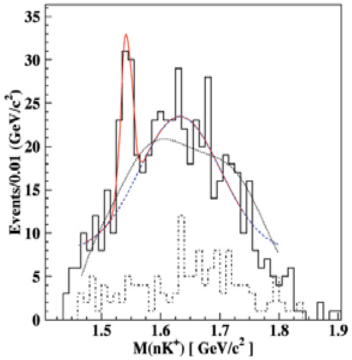
Spring8



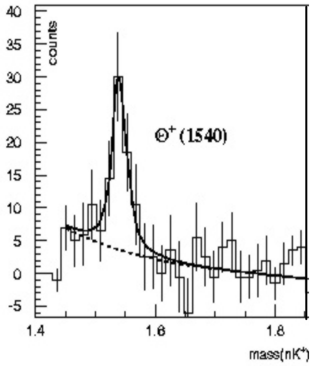
DIANA

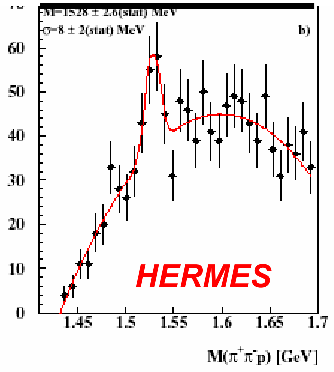


JLab-d

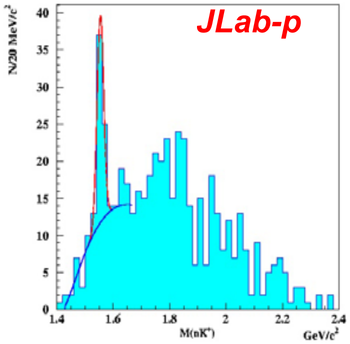


ELSA



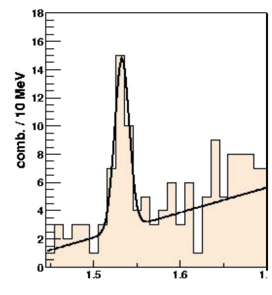


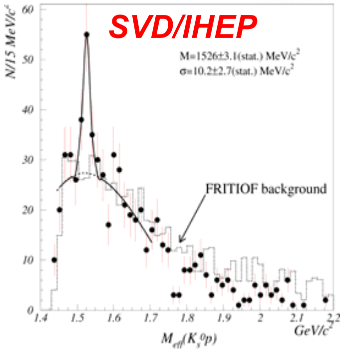
HERMES



JLab-p

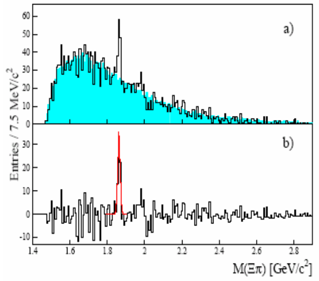
ITEP

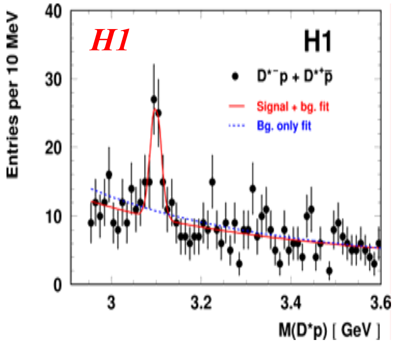




SVD/IHEP

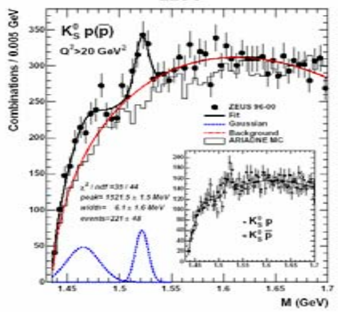
CERN/NA49



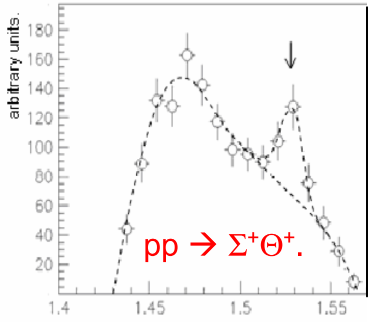


H1

ZEUS



COSY-TOF



pp → $\Sigma^+\Theta^+$.

So, what is the problem?

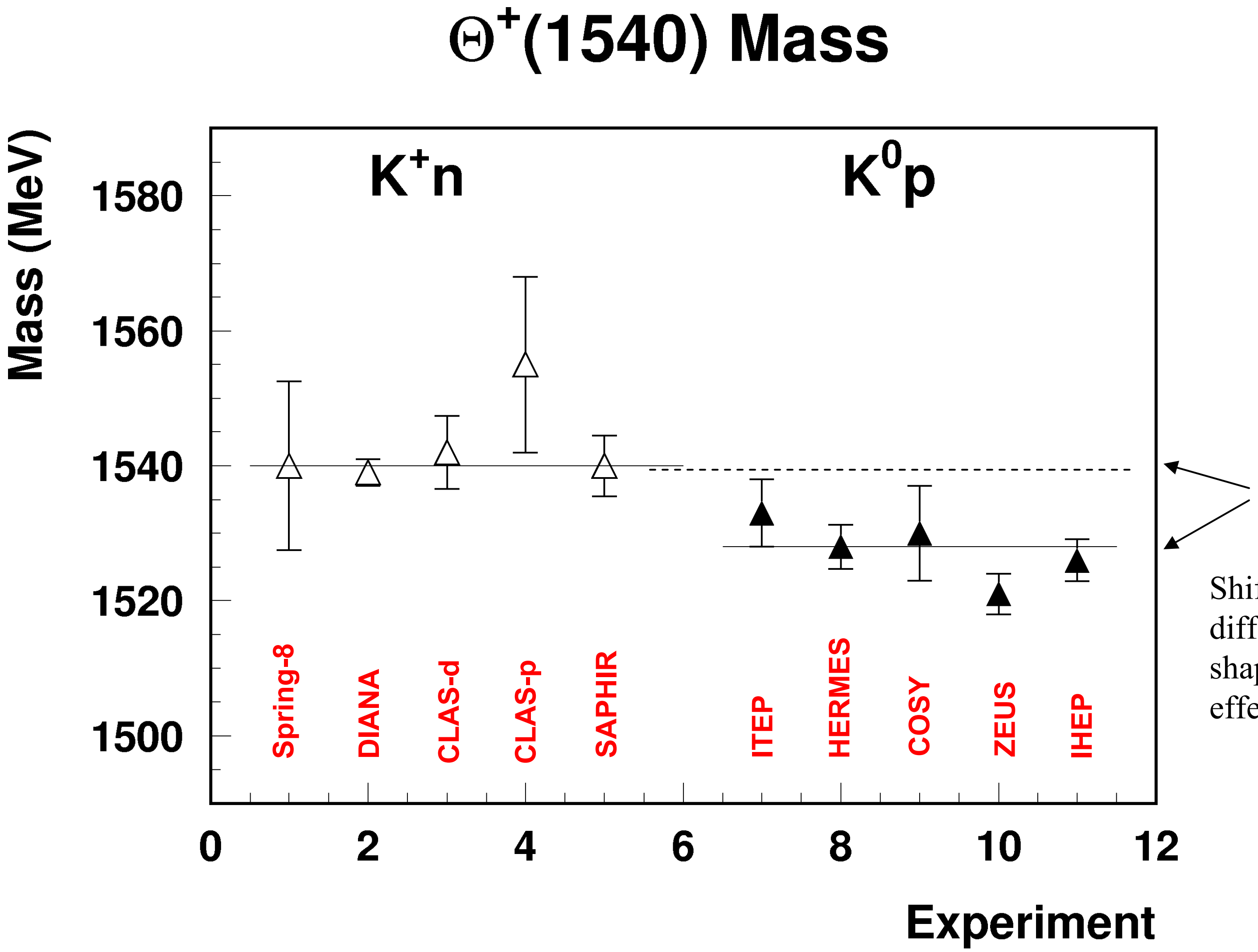
- If Pentaquark baryons exist it is the most important finding in hadronic physics since the J/Ψ discovery. It is absolutely necessary to obtain fully convincing experimental data.

- Many experiments see positive Θ^+ signal with specific kinematical cuts, taken together they represent an impressive significance. However, few experiment have fully convincing results:
  - significance is often optimistically estimated ~4–6σ
  - background estimates are not always justified
  - masses are not fully consistent (1525–1555) MeV
  - are kinematical reflections excluded?

- Many high energy experiments present null results. This adds a level of uncertainty until we understand the sensitivities in various experiments.

- The very narrow width of ~1 MeV is not understood, although models have been developed that allow Θ^+ widths of < 1 MeV.

Summary of Experimental Masses



ΔM ~ 12 MeV

Shift could be due to different background shapes and interference effects.

Do we see Theta$^+$ at all ?

Experiments that do not see Θ^+:

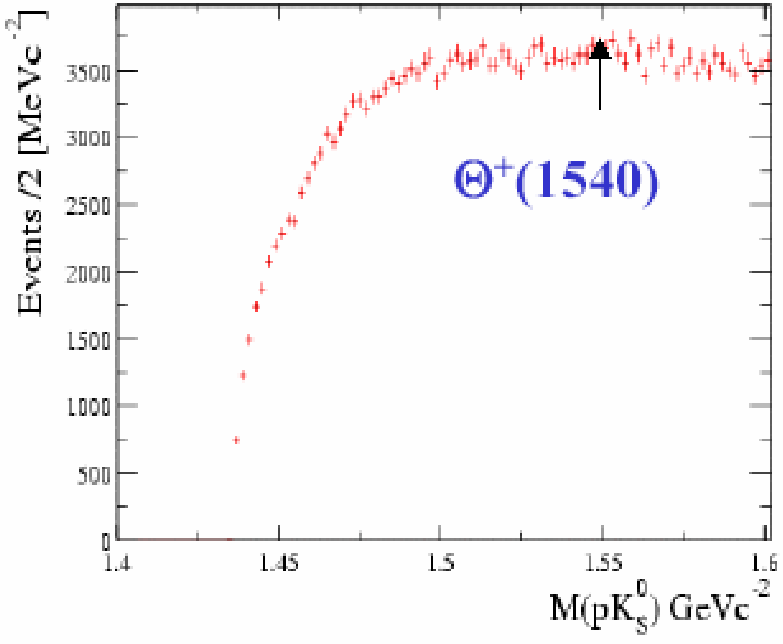
- HERA-B
- STAR & PHENIX (RHIC) - ?
- Opal, Aleph, Delphi (LEP)
- BES (Beijing)
- SPHINX
- CDF, Hyper-CP (Fermilab), E690
- BaBar
- BELLE
- Phase shifts from old K-scattering exps.

mostly high energy inclusive

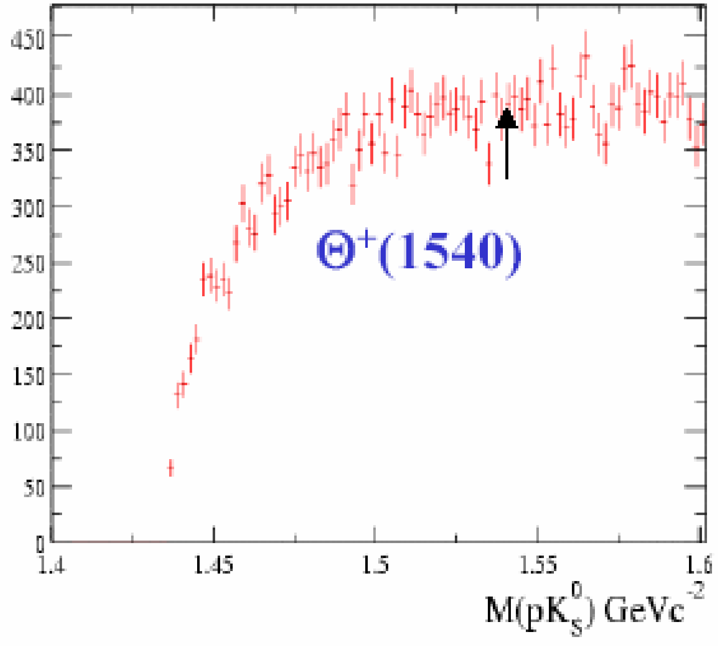
$\Theta^+(p\,K_s)(1540)$ Invariant Mass

No signal observed in any p* region (SFL > 0.0 cm)

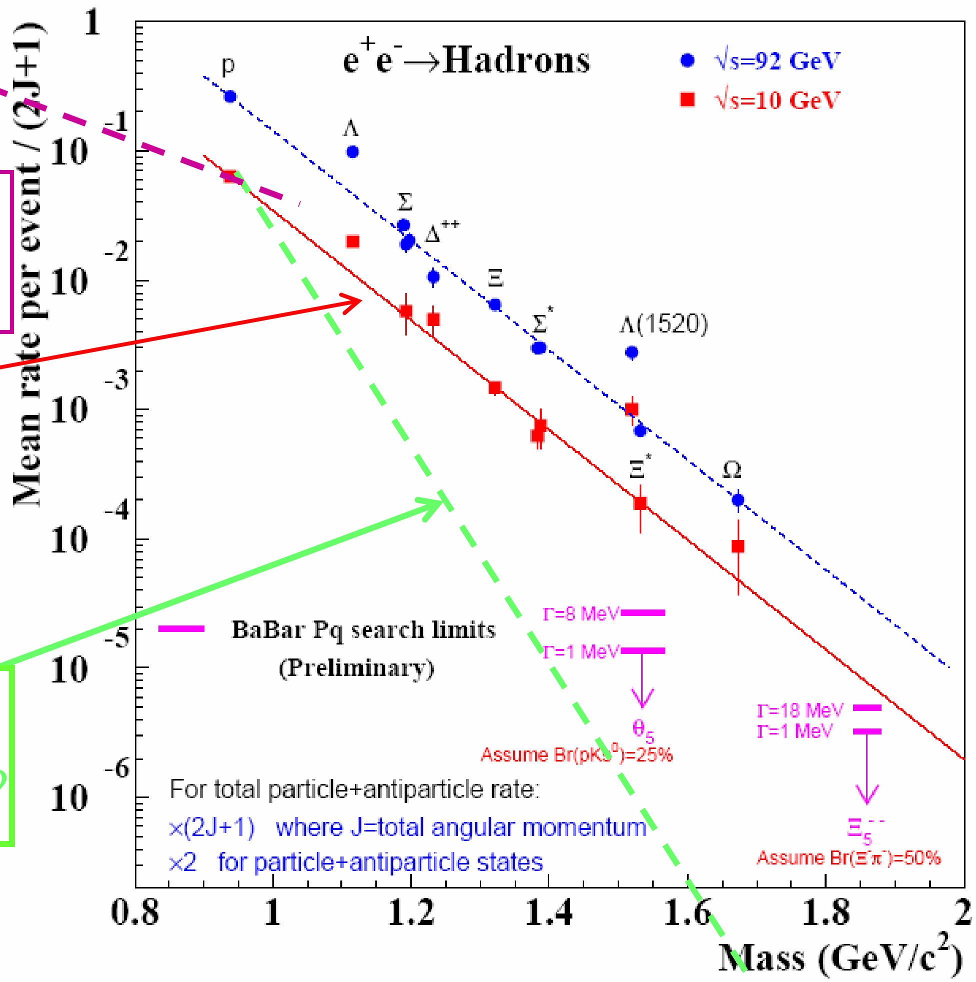
$0.0 < p^* < 0.5$ GeV/c



$3.5 < p^* < 4.0$ GeV/c



Hadron production in e^+e^-



Slope for p.s. mesons

Slope for baryons

Slope for Pentaquark??

Slope:

Pseudoscalar mesons:
~ 10^{-2}/GeV/c^2 (need to generate one $q\bar{q}$ pair)

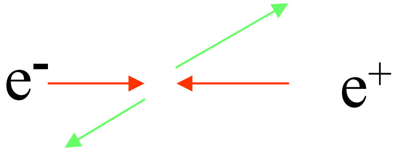
Baryons:
~ 10^{-4} /GeV/c^2
(need to generate two pairs)

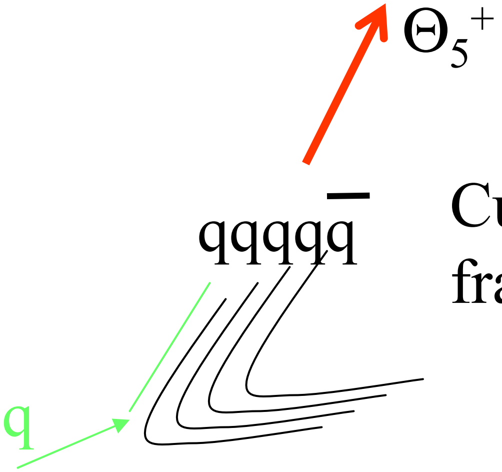
Pentaquarks:
~ 10^{-8} /GeV/c^2 (?) (need to generate 4 pairs)

⟶ Pentaquark production in direct e^+e^- collisions likely requires orders of magnitudes higher rates than available.

Pentaquarks in Quark Fragmentation?

Pentaquarks in e^+e^- (BaBaR)?





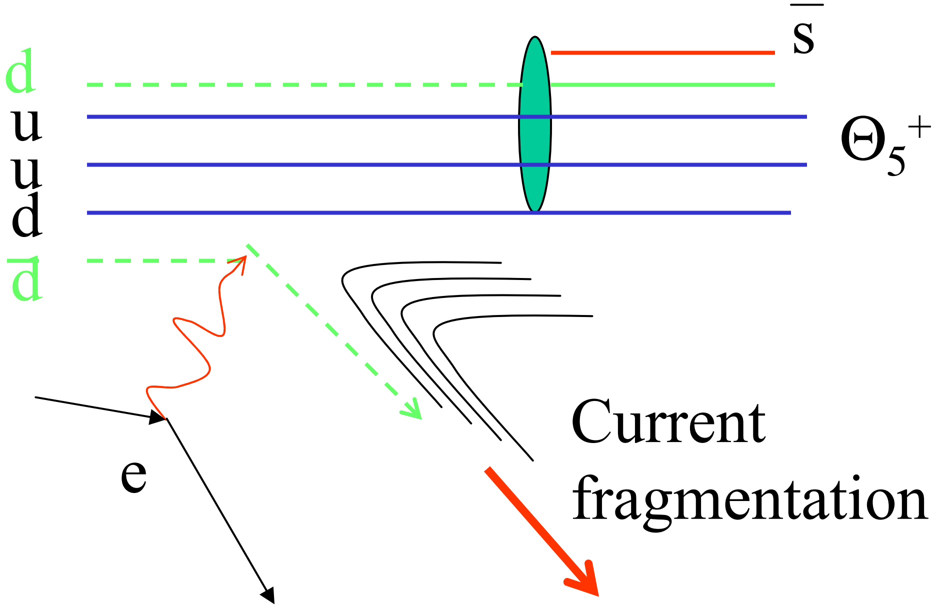
Current fragmentation

Pentaquark production **suppressed**

Pentaquarks in ep ? (ZEUS, H1, HERMES)

Target fragmentation

Pentaquarks **not suppressed**



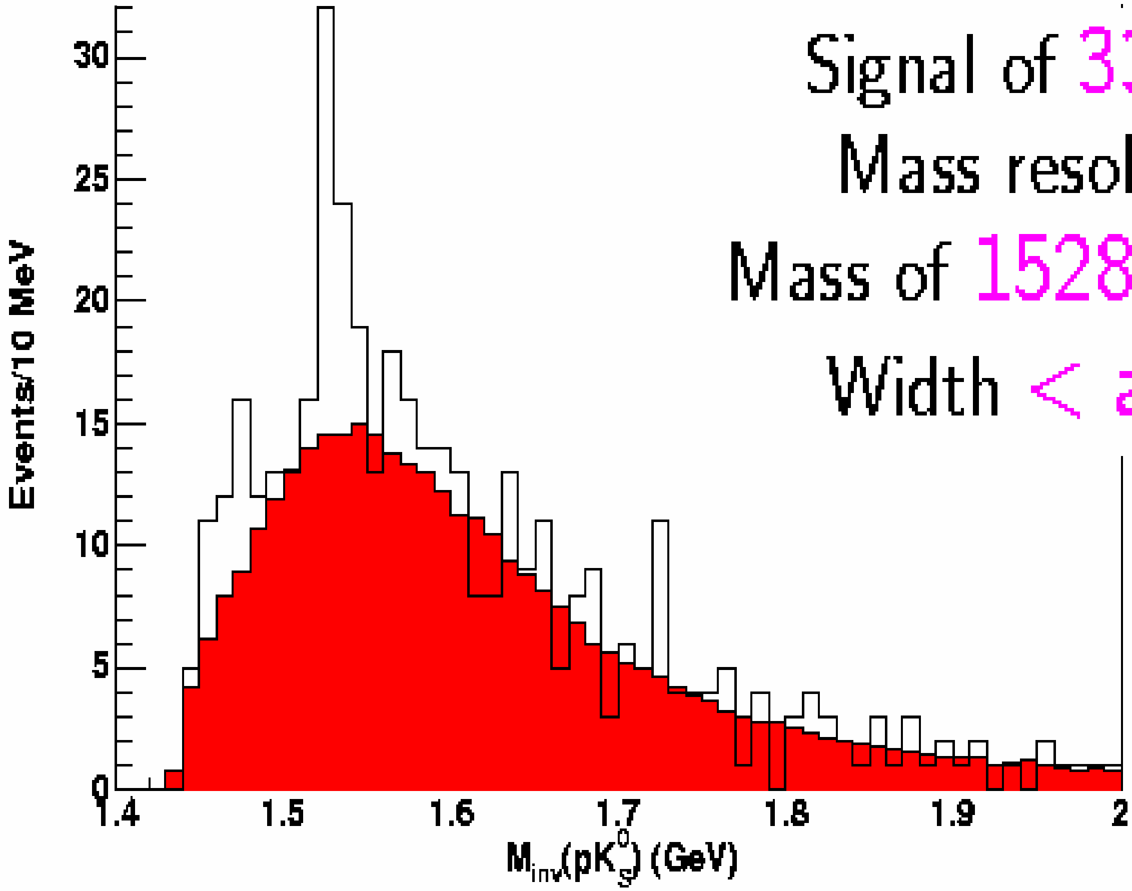
Current fragmentation

Pentaquarks **suppressed**

Recent confirmation of $\Theta^+(1530)$

Neutrino 2004
Paris
June 13th-19th, 2004

Leslie Camilleri
CERN



Signal of 33 events → $4.3\,\sigma$.

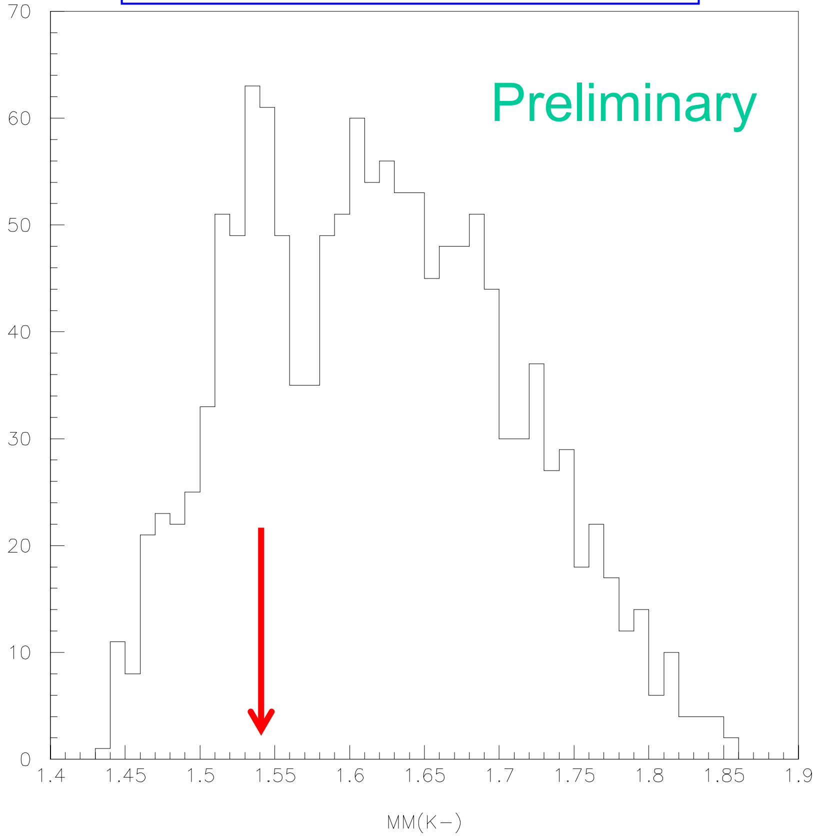
Mass resolution: 9 MeV/c^2

Mass of 1528.7 ± 2.5 MeV/c^2

Width < a few MeV/c^2

LEPS-2/Spring8: deuterium target

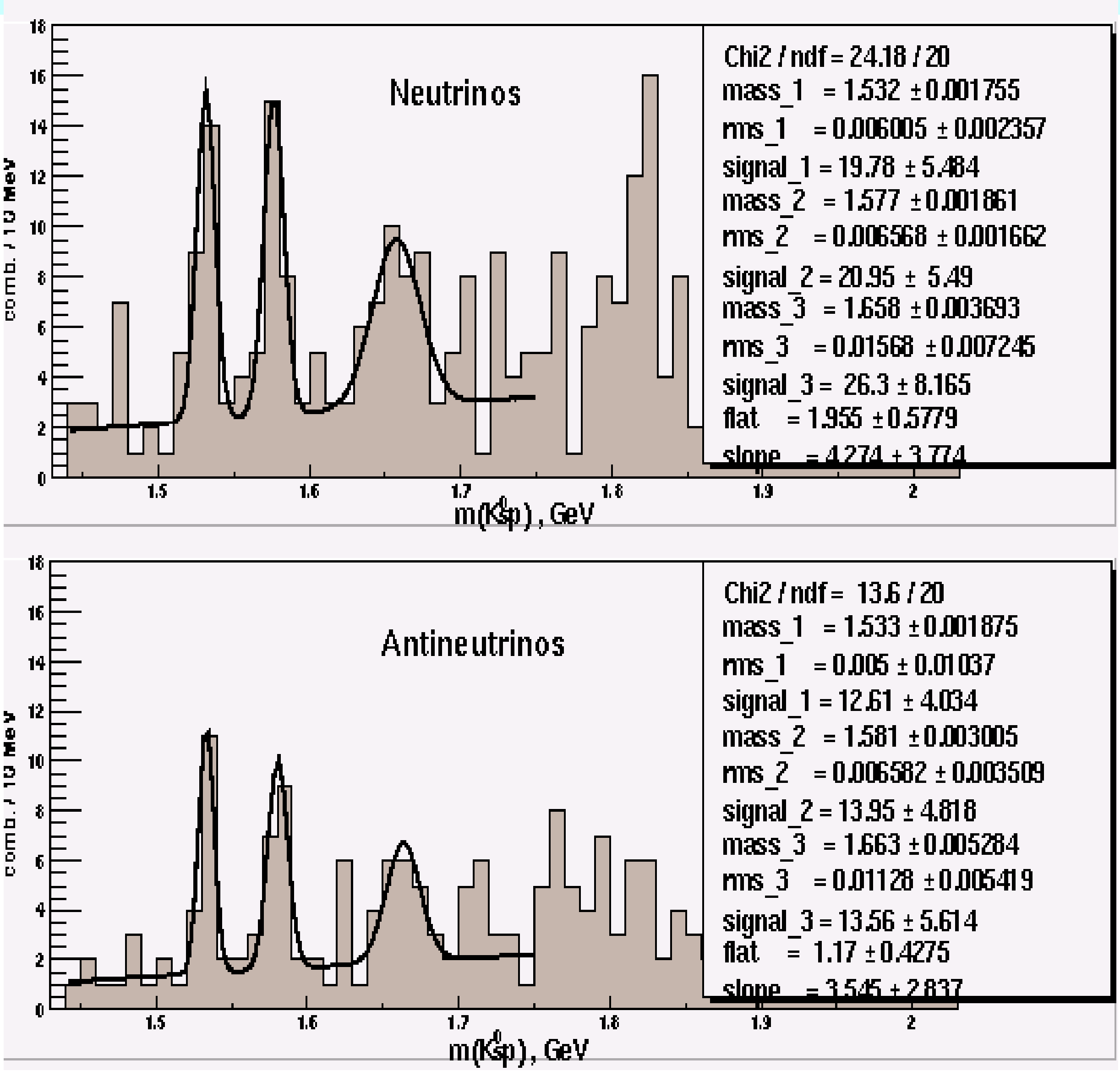
$$\boxed{\gamma n \rightarrow K^- K^+ n}$$



- Dedicated experiment
- Aimed for 4x statistics of 2003 result
- Announced at N*2004

Confirmation of the first measurement in the "same" experiment!

$K^0{}_s p$ resonances in neutrino interactions



Yields of 3 peaks (relative to all events) are close in neutrino and antineutrino beams.

Masses of 3 peaks:
1533.1 ±1.0MeV(7.5σ)
1573.7 ±1.4MeV(5.5σ)
1659 ±5MeV(7.5σ)

Significance above 5σ

Evidence for 1573 state in CLAS data?

What's next ?

- Θ^+(1540)
  - ✓Spin, **parity**, isospin
  - ✓Total decay width
  - ✓ Cross section in various reactions
  - ✓ Production mechanism

- Search for other exotic Pentaquark States Ξ^{--}, Ξ^+ in electromagnetic interactions

- Search for non-exotic Pentaquark states (P_{11}(1440), P_{11}(1710), Σ's …?), what are their signatures to distinguish them from the q^3 states? What are production mechanisms? How they interact with usual baryons and mesons?

- Excited states of Θ^+(1540) ? Are they also narrow ?

Unexpected D_{sJ} Mesons

Discovery by BaBar & CLEO of narrow $D_{sJ}(2317)$ and $D_{sJ}(2457)$ – a big surprise

Masses much lower than potential model P-level predictions

⇒ speculations about 4-quark, DK-molecule and $D_s\pi$ atom, …

However D_{sJ} properties are consistent with two lowerst P-level states

$D_{sJ}(2457)$ has $J^P=1^+$ (BELLE)

No $D_s\pi^0$ decay ⇒ rules out $0^+, 1^-$

$D_s\,\gamma$ decay ⇒ rules out $0^+, 0^-$

Helicity in $B\to\bar{D}\,D_{sJ}(2457)$ prefer J=1

$D_{sJ}(2317)$ consistent with 0^+

Flat decay angle distribution

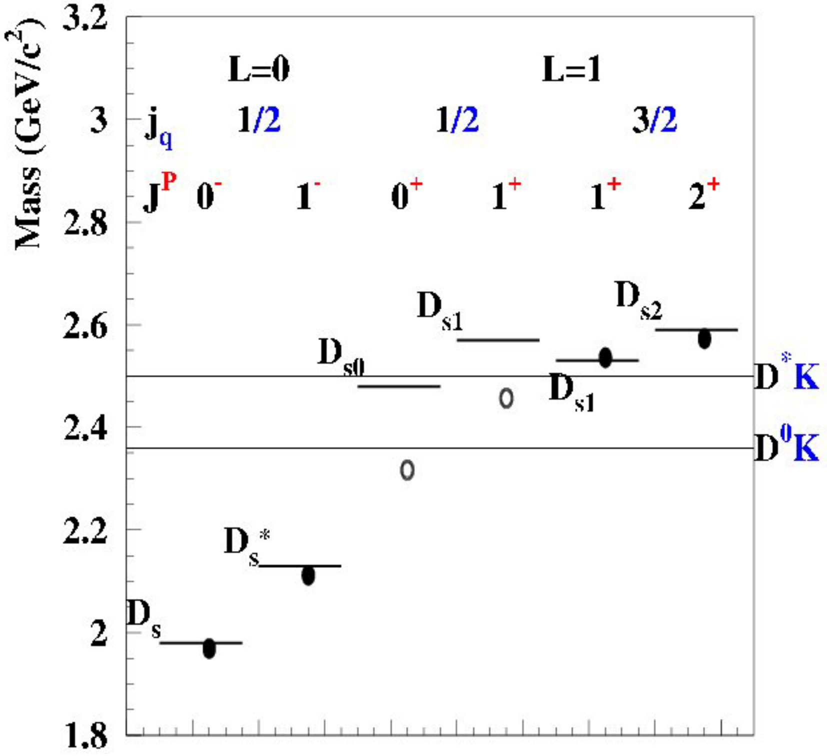
No $D_s\pi^+\pi^-$ and $D_s\,\gamma$ decays

New SELEX $D_{sJ}(2632)$ creates new problems

It is narrow $\Gamma<17$ MeV

$\Gamma(D^0K^+)/\Gamma(D_s\eta)=0.16\pm0.06$

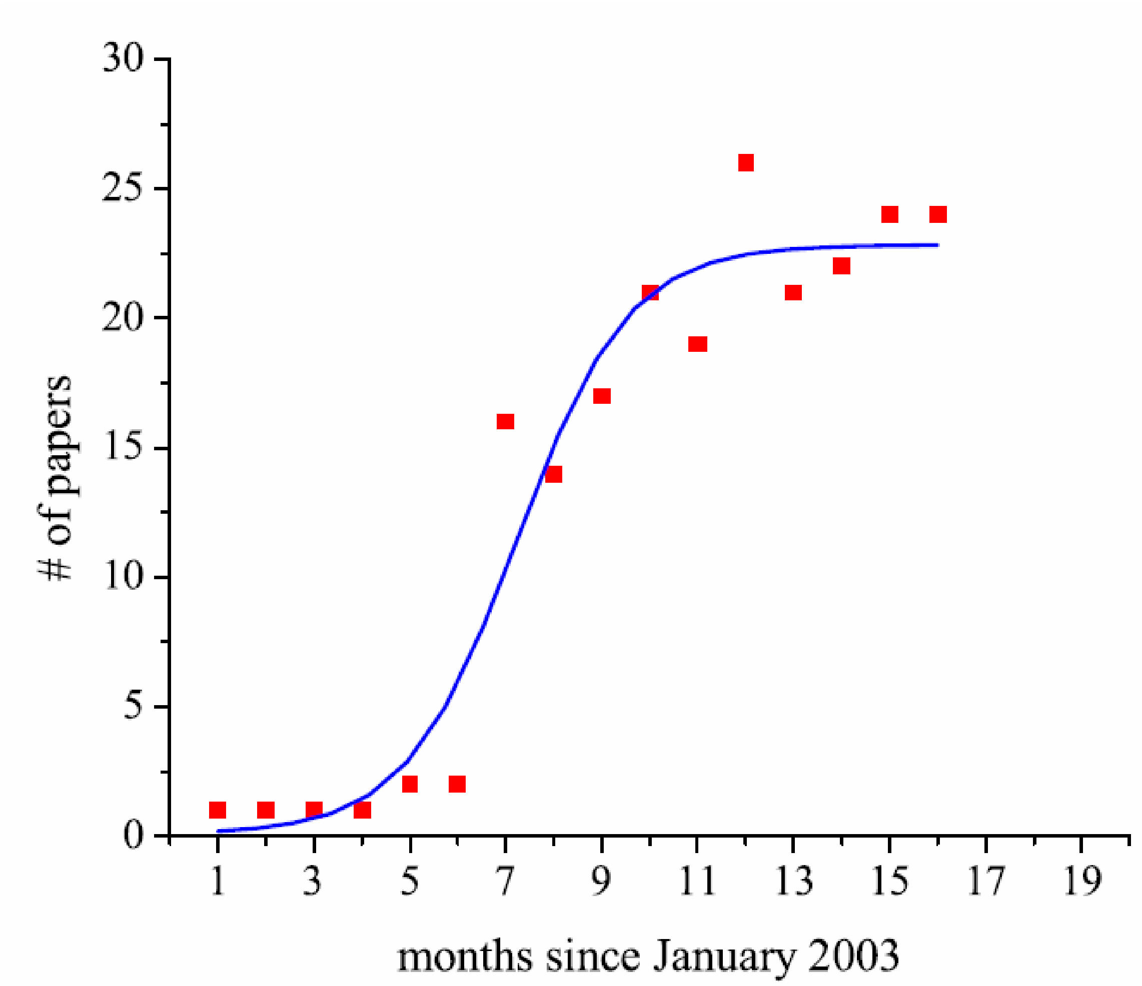
Production rate larger than for $D_{sJ}(2573)$



Actually these states were predicted as a chiral Doubler of usual D mesons
[Bardeen, Hiller; Nowak, Rho, Zahed `93]

$M(0+) - M(0-) \sim$ constituent quark mass

Exotics activity



Is it a phase transition ?

Theory Postdictions

Super radiance resonance
Diamond lattice of gluon strings
Θ+(1540) as a heptaquark

QCD sum rules, parity =- 1, or P=+1
Lattice QCD P=-1 or P=+1
di-quarks + antiquark, P=+1
colour molecula, P=+1
Constituent quark models, P=-1 or P=+1

Exotic baryons in the large Nc limit
Anti-charmed Θ , and anti-beauty Θ
Θ produced in the quark-gluon plasma and nuclear matter
SU(3) partners of Θ

Constituent quark model

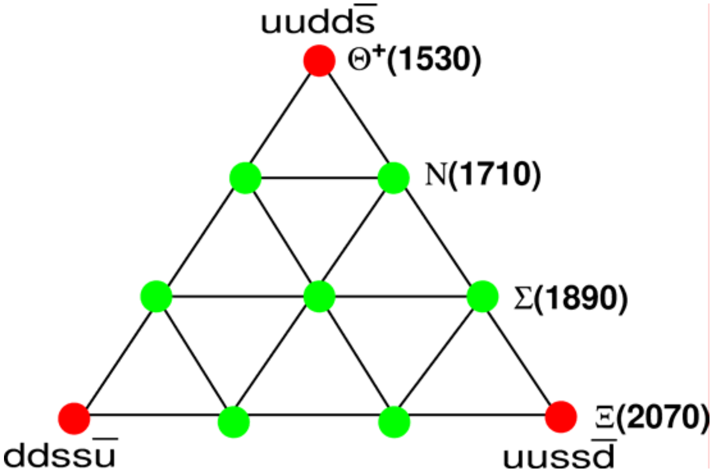
If one employs flavour independent forces between quarks (OGE) natural parity is negative, although P=+1 possible to arrange

With chiral forces between quarks natural parity is P=+1
[Stancu, Riska; Glozman]

- No prediction for width
- Implies large number of excited pentaquarks

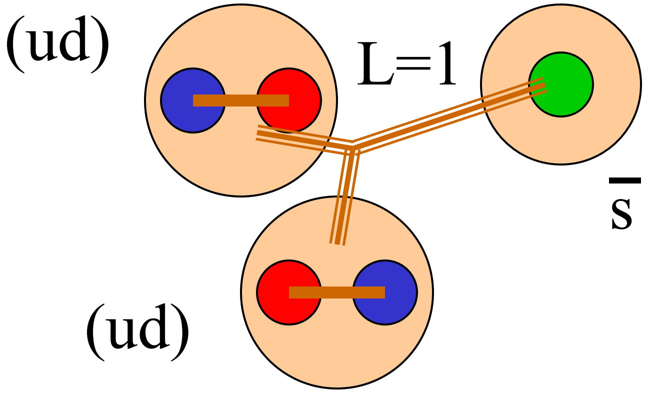
Missing Pentaquarks ?
(And their families)

Mass difference $\Xi - \Theta \sim 150$ MeV



Diquark model [Jaffe, Wilczek]

No dynamic explanation of
Strong clustering of quarks



Dynamical calculations suggest large mass
[Narodetsky et al.; Shuryak, Zahed]

$J^P=1/2^+$ is assumed, not computed

$J^P=3/2^+$ pentaquark should be close in mass [Dudek, Close]

Anti-decuplet is accompanied by an octet of pentaquarks.
P11(1440) is a candidate

No prediction for width

Mass difference $\Xi - \Theta \sim 150$ MeV -> Light Ξ pentaquark

Implications of the Pentaquark

- Views on what hadrons “made of” and how do they “work” may have fundamentally changed
  - renaissance of hadron physics
  - need to take a fresh look at what we thought we knew well. E.g. strangeness and other “sea’s” in nucleons.
  - presently many labs over the globe drastically reoriented their physics programmes

- Quark model & flux tube model are incomplete and should be revisited. Also we have to think what questions we have to ask lattice QCD.

- Does Θ start a new Regge trajectory? -> implications for high energy scattering of hadrons !

- Can Θ become stable in nuclear matter? -> physics of compact stars! New type of hypernuclei !

- Width of $\Theta \sim$ (quark condensate)^2, can be used as a probe of chiral symmetry restoration ? D-meson chiral doubler.

- Predicted Θ pentaquark is light NOT because it is a sum of 5 constituent quark masses but rather a collective excitation of the mean chiral field. It is narrow for the same reason

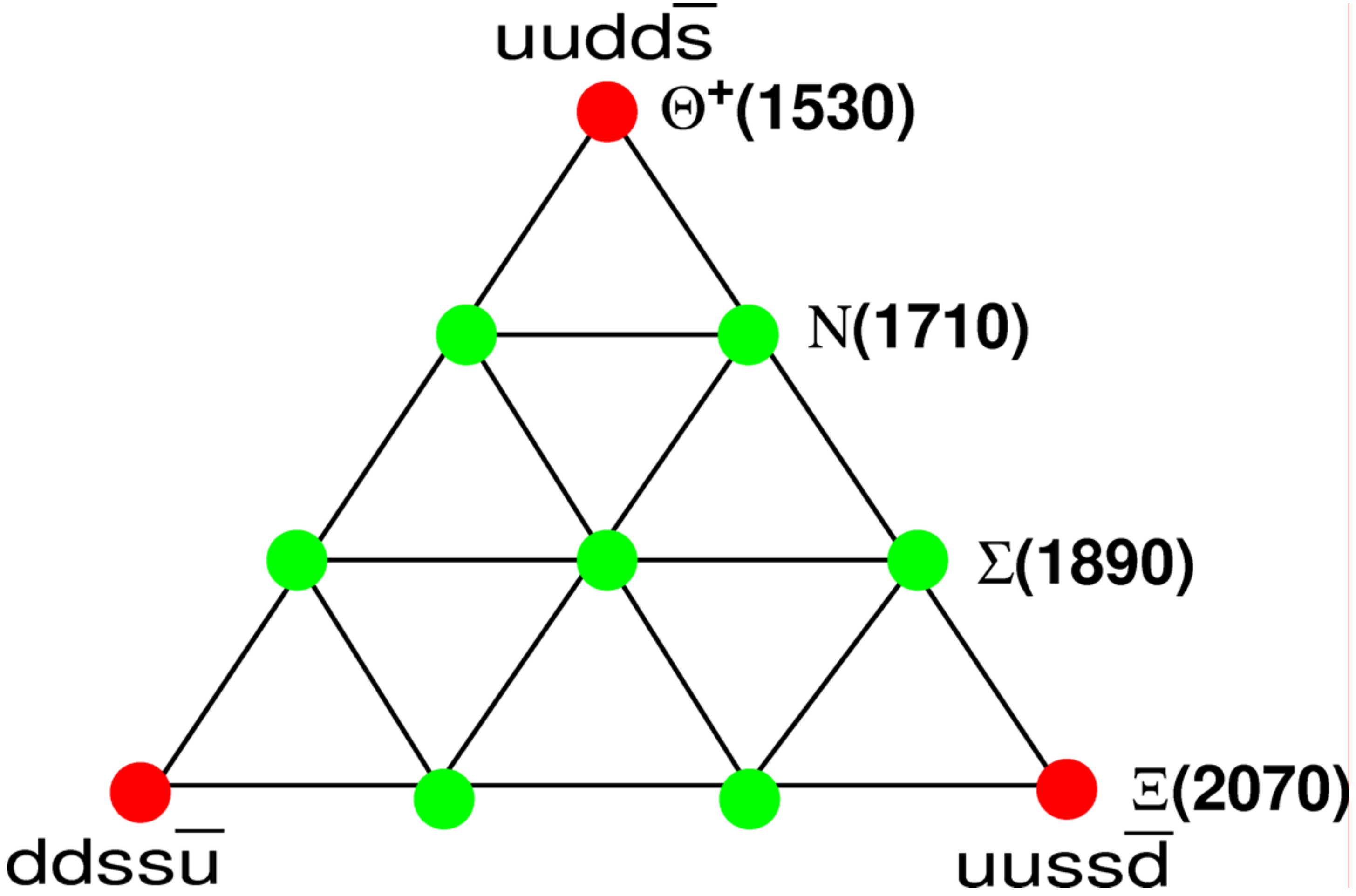
- Where are family members accompaning the pentaquark Are these "well established 3-quark states"? Or we should look for new "missing resonances"? Or we should reconsider fundamentally our view on spectroscopy?

- Study at SBChS at high energies. E.g. in hard exclusive processes.

- Study of chiral anomaly, e.g. in Primakoff processes.

Surely new discoveries are waiting us
around the corner !

Non strange partners revisited



Non strange partners revisited

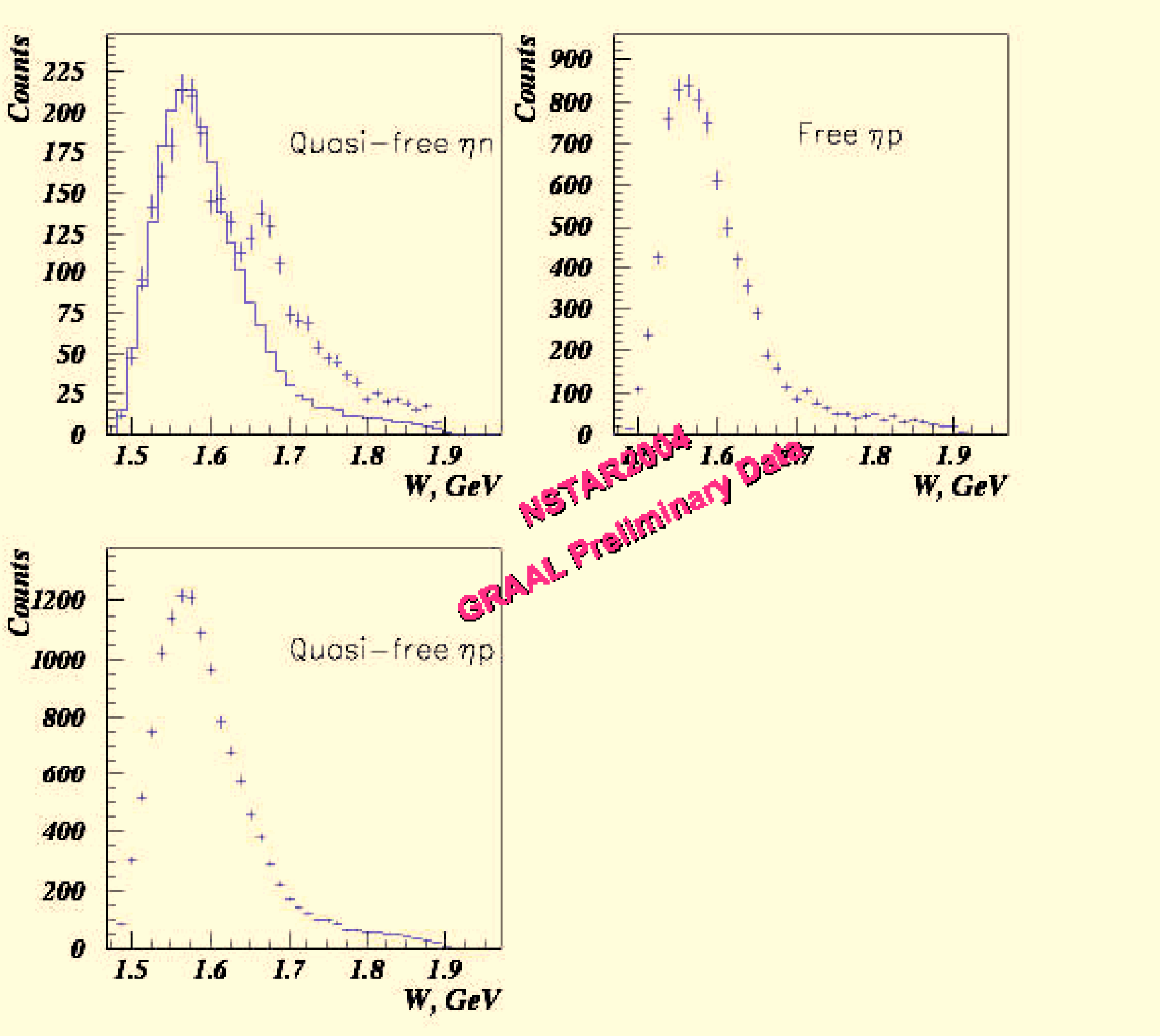
N(1710) is not seen anymore in most recent πN scattering PWA [Arndt et al. 03]

If Θ is extremely narrow N* should be also narrow 10-20 MeV. Narrow resonance easy to miss in PWA. There is a possiblity for narrow N*(1/2+) at 1680 and/or 1730 MeV [Arndt, et al. 03]

In the soliton picture mixing with usual nucleon is very important. π N mode is suppressed, ηN and $\pi\Delta$ modes are enhanced.

Anti-decuplet nature of N* can be checked by photoexcitation. It is excited much stronger from the neuteron, not from the proton [Rathke, MVP]

GRAAL results: comparison of eta N photoproduction on the proton and neutron [V. Kouznetsov]



Preliminary results of STAR pentaquark searches in the Λ K0s channel

Observation of a possible narrow peak at 1734 MeV in Λ K0s inv.mass

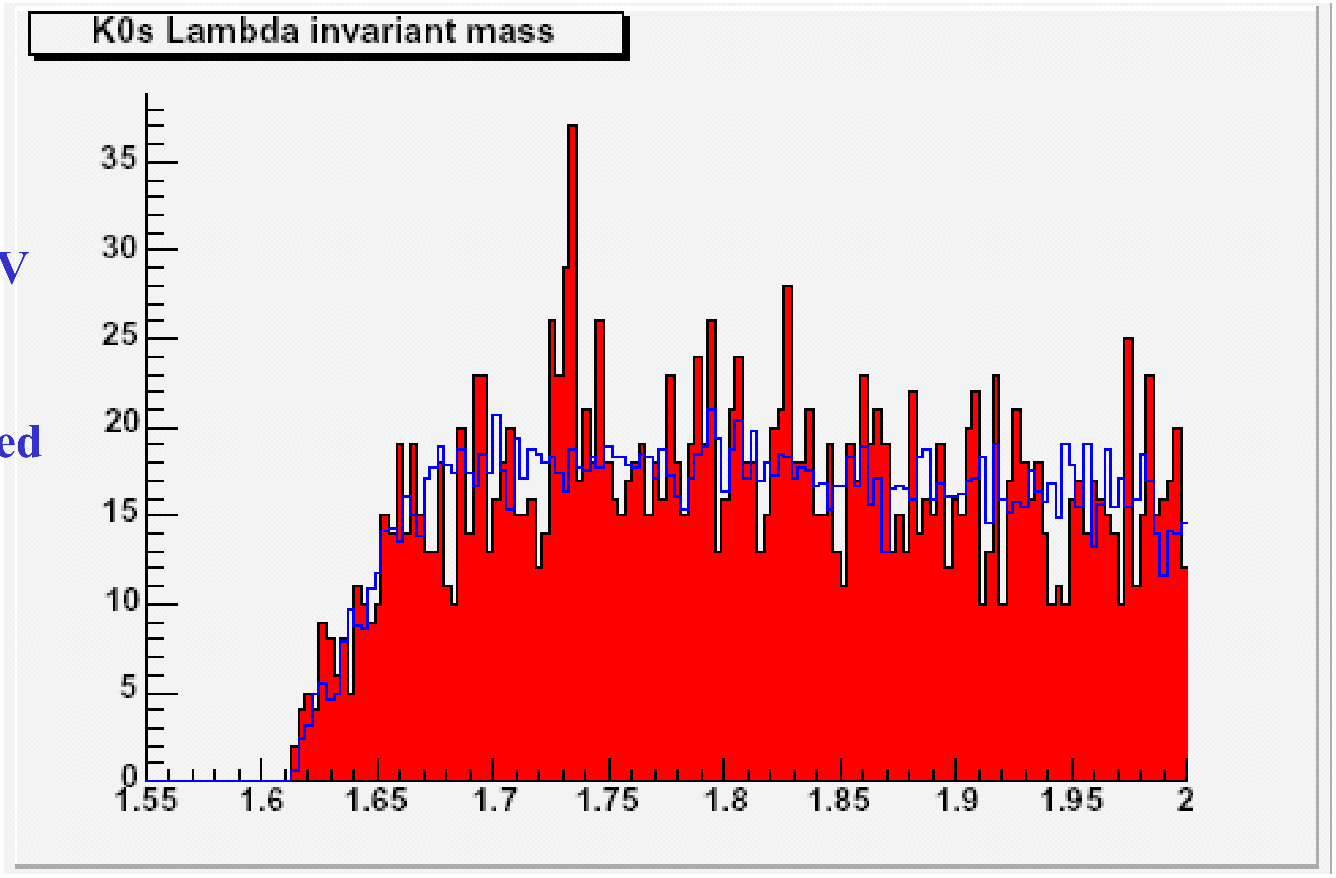
Au+Au min. bias √(s)NN=200 GeV   Cut out upper ~10% of σ(tot) to suppress background

Region +- 3 MeV (~1.5 σ) around maximum: S/√(B)=30.6/ √(35.4)= 5.15, S/√(S+B)=3.77,
Mass = 1733.6 +-0.5 MeV +-5 MeV (syst),   Γ< 4.6 +-2.4 MeV (Gauss,1 MeV bin)

STAR Au+Au coll. 200 GeV preliminary

Bin size 3 MeV

Blue line: mixed event background



Best Significance obtained in semiperipheral ev.: S/√(B)=19.36/ √(10.64)=5.93