LES RENCONTRES DE PHYSIQUE DE LA VALEE D'AOSTE
1.03.2005

Pentaquarks – Experimental Review

Michael Danilov

ITEP, Moscow

It is a difficult task

More than 30 experiments

Þ apologies for personal bias in selection of topics

New results are expected soon

Þ Review will be obsolete in a few months (or earlier)

Many good reviews already (Hicks, Kubarovsky, …)

Þ I will use several slides form these reviews

But still easier than a theoretical review of about 300 papers!

Q+ observation in K+n mode by LEPC experiment

g C Þ K-Q+ Þ K- K+ n

Minimal quark content

uudd$\bar{s}$

Background level is estimated by a fit in a mass region above 1.59 GeV using shape from gp interactions

Assumptions:

- **Background is from non-resonant K+K- production off the neutron/nucleus**
- **… is nearly identical to non-resonant K+K- production off the proton**

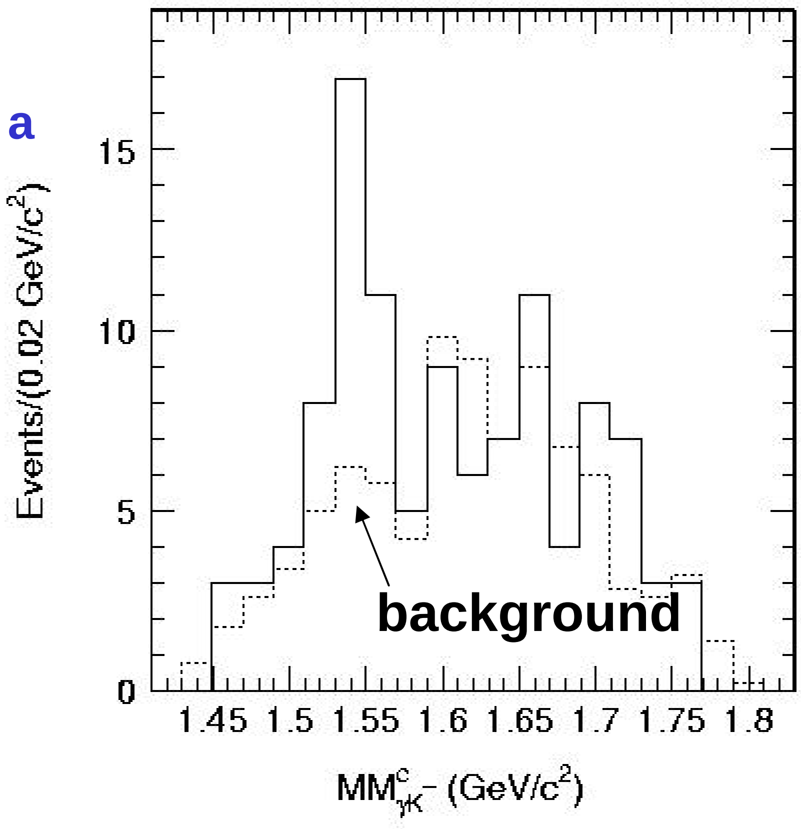
Phys.Rev.Lett. 91 (2003) 01 2002

hep-ex/0301020

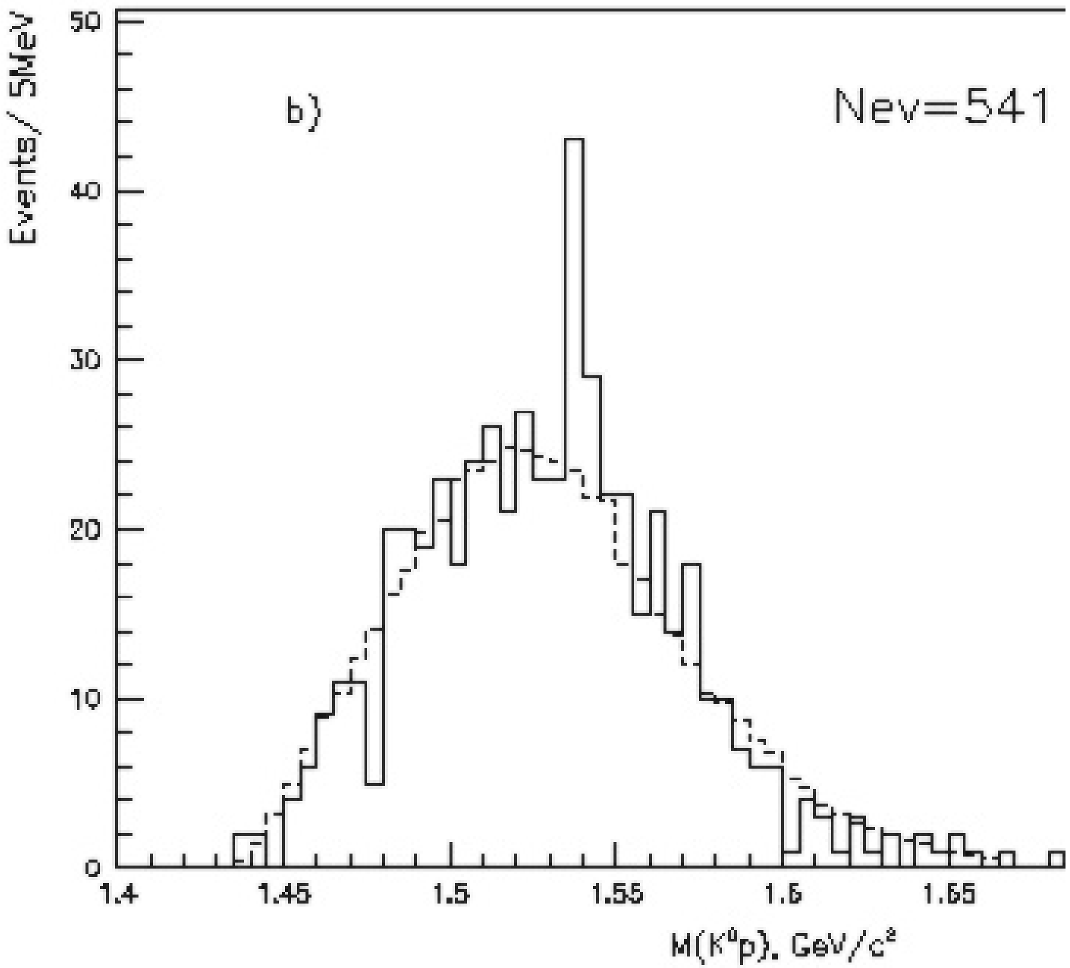
M = **1.54±0.01 MeV**

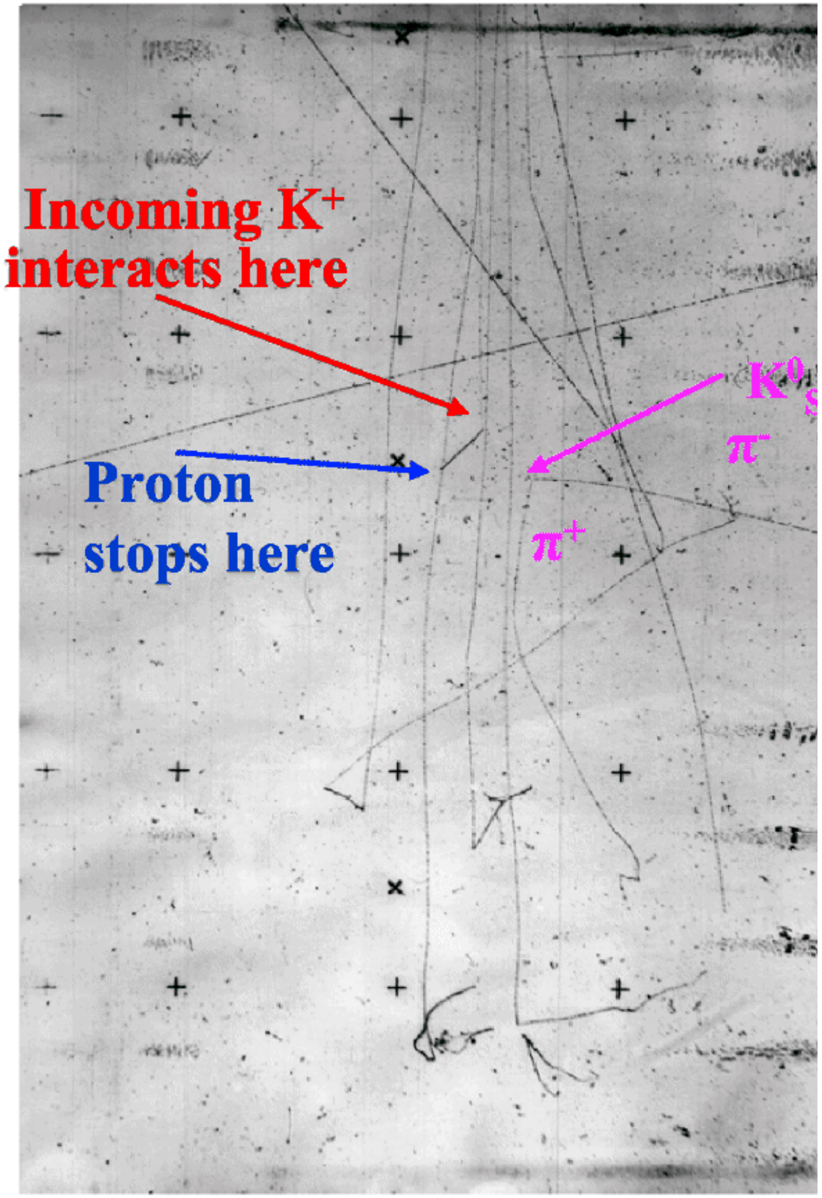
G **< 25 MeV**

Gaussian significance 4.6 s



DIANA: $K^{+}Xe \rightarrow Xe'\Theta^{+} \rightarrow K^{0}p$





Peak at 1.539 GeV

Statistical significance 4.4s.

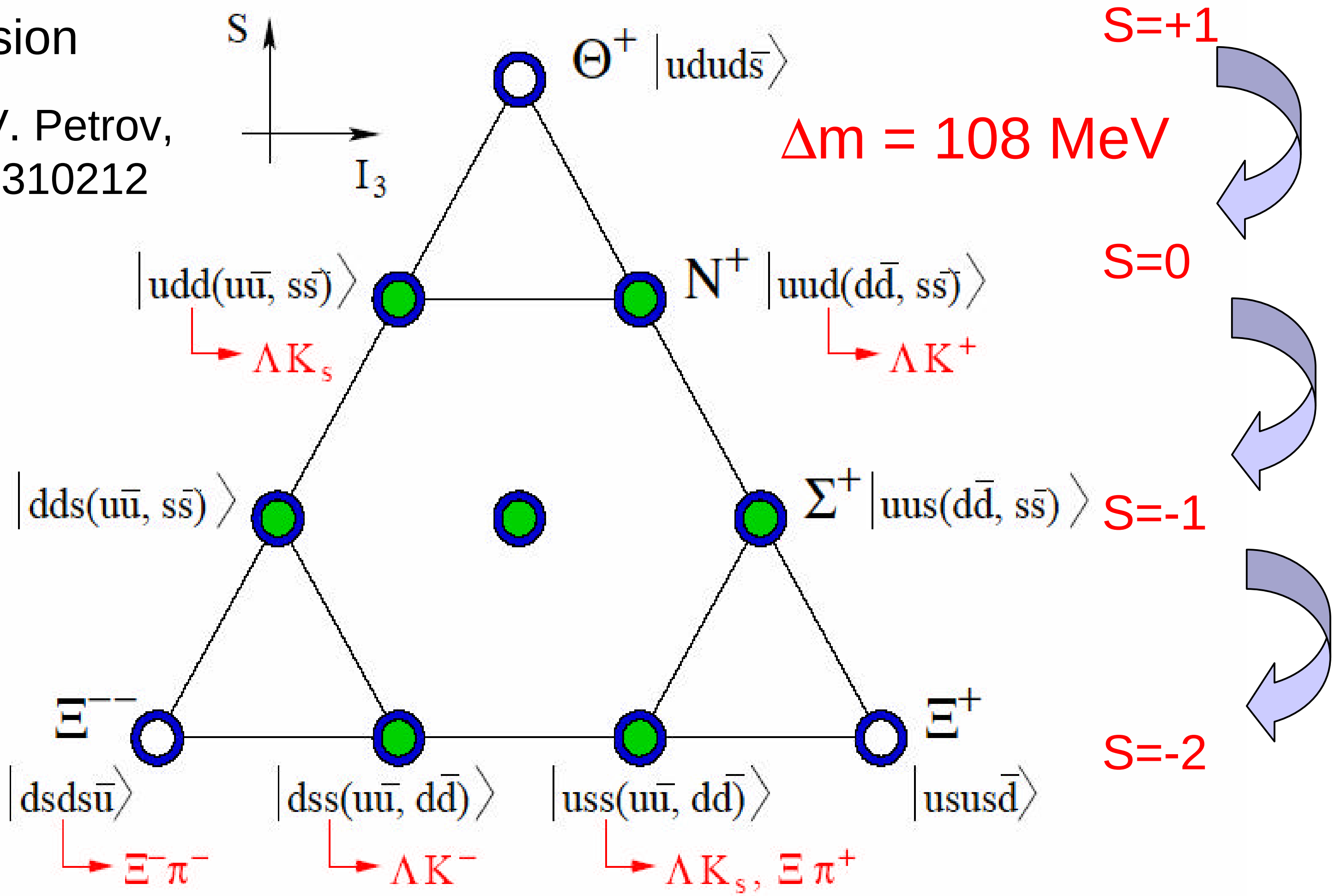
Measured width G < 9 MeV The best limit for width

Anti-decuplet in SM

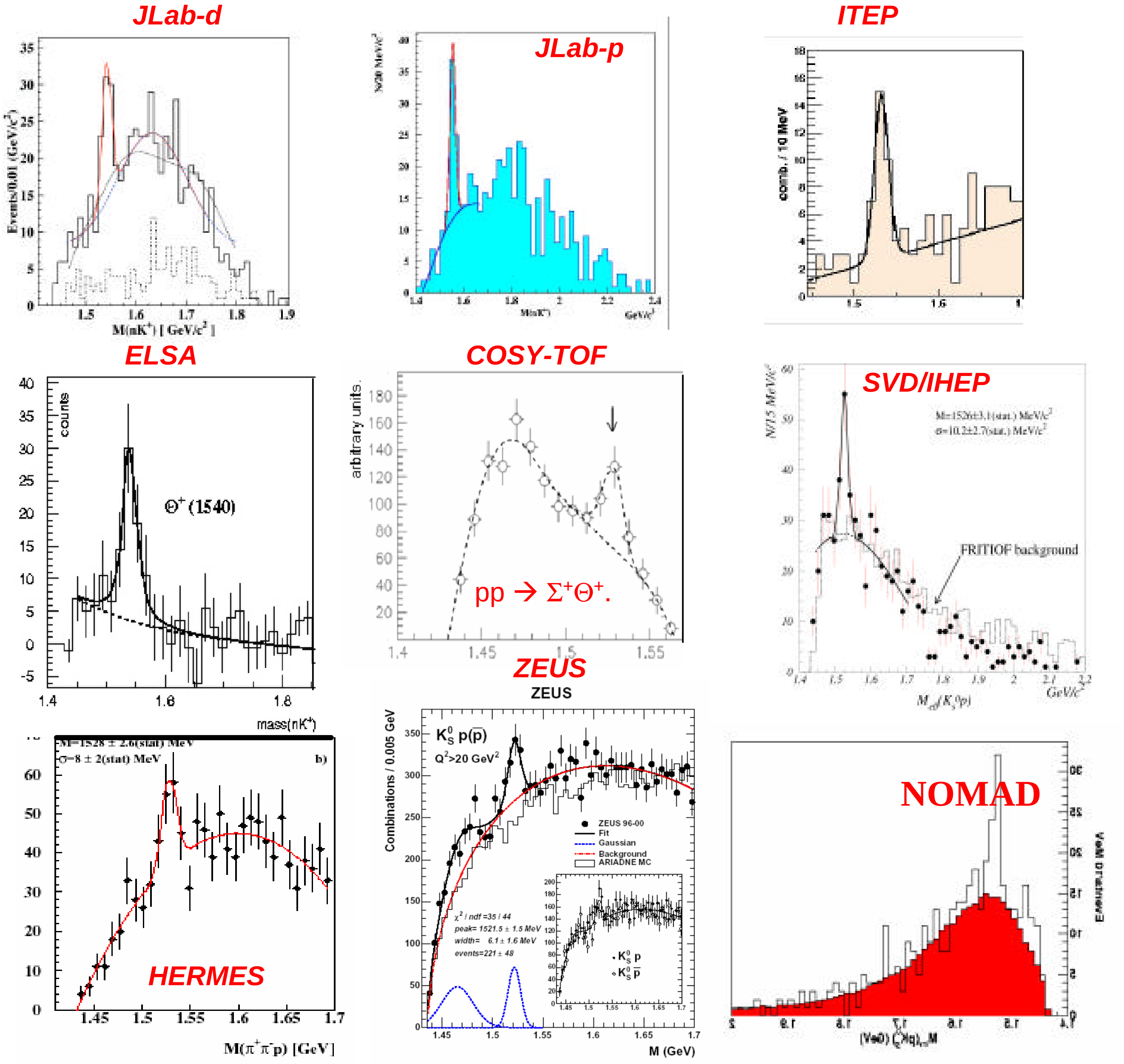
D. Diakonov, V. Petrov, M. Polyakov, Z.Phys.A359, 305 (1997)

updated version

D. Diakonov, V. Petrov, arXiv:hep-ph/0310212



Penta-Quark Confirmed by many experiments

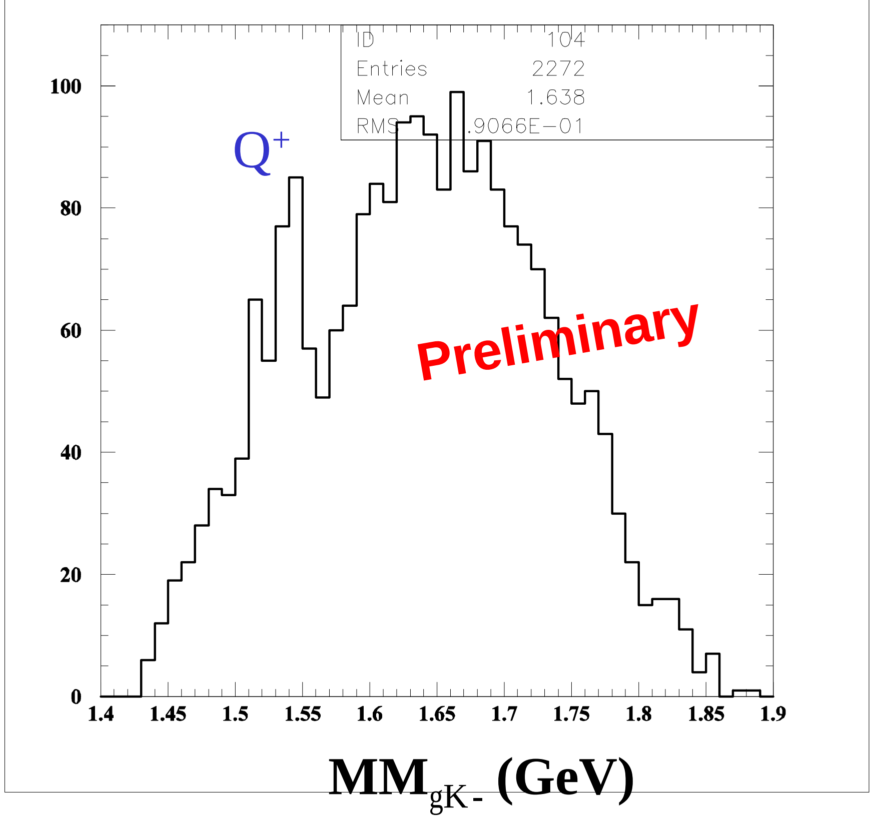


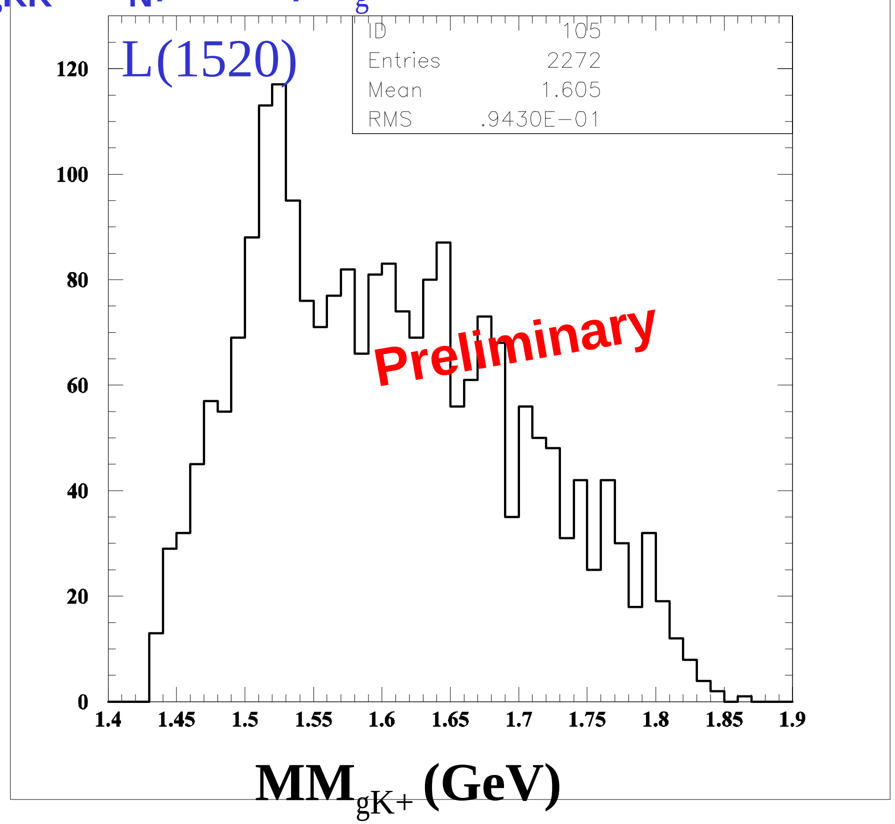
New data: LEPS deuterium*

(figures from Hicks seminar at DESY 01.02.2005)

Confirmation of the first observation in the “same” experiment

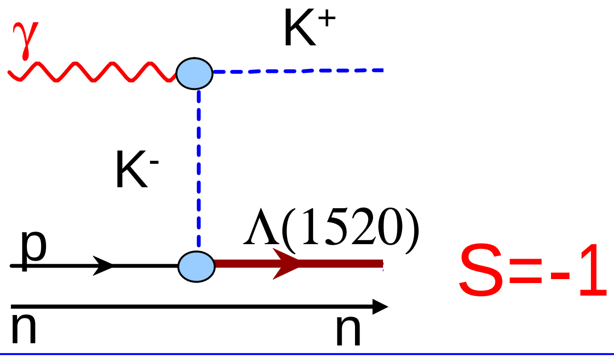
Minimal cuts: vertex, $MM_{gKK}=M_N$, no f, E_g < 2.35 GeV





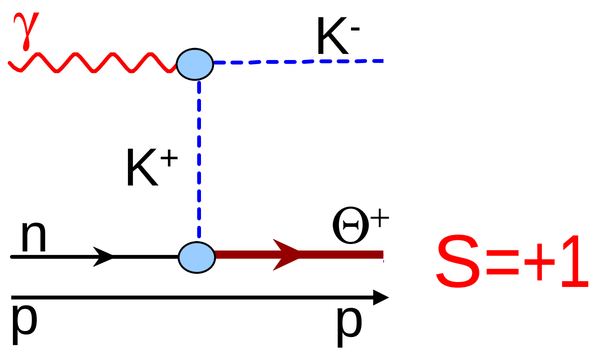
$$gN \rightarrow K^{-}K^{+}N$$

“Standard” baryon



$$\Lambda(1520) \rightarrow pK^{-}$$

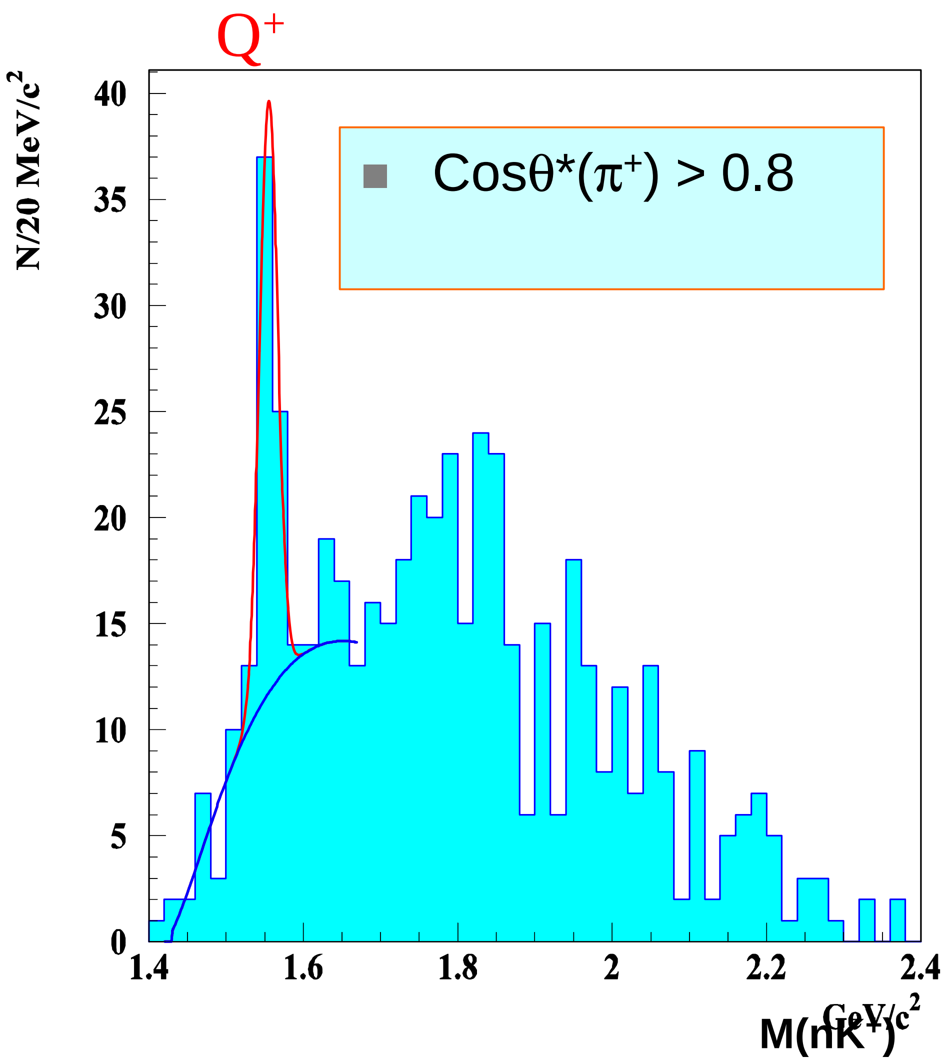
“Exotic”



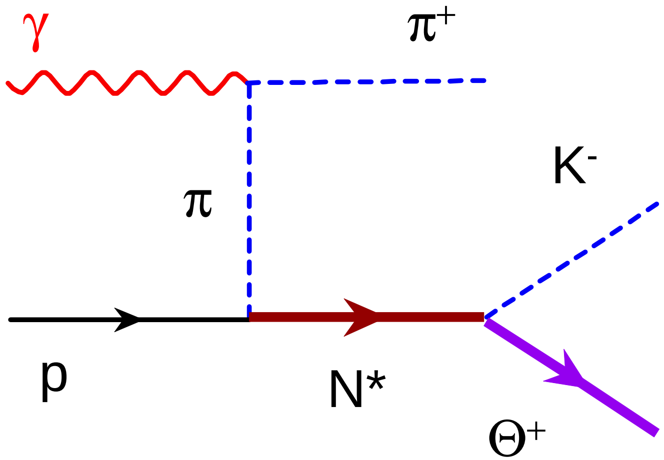
$$\Theta^{+} \rightarrow nK^{+}$$

Must correct for Fermi motion of target nucleon in the nucleus

CLAS: γp with forward going π^+

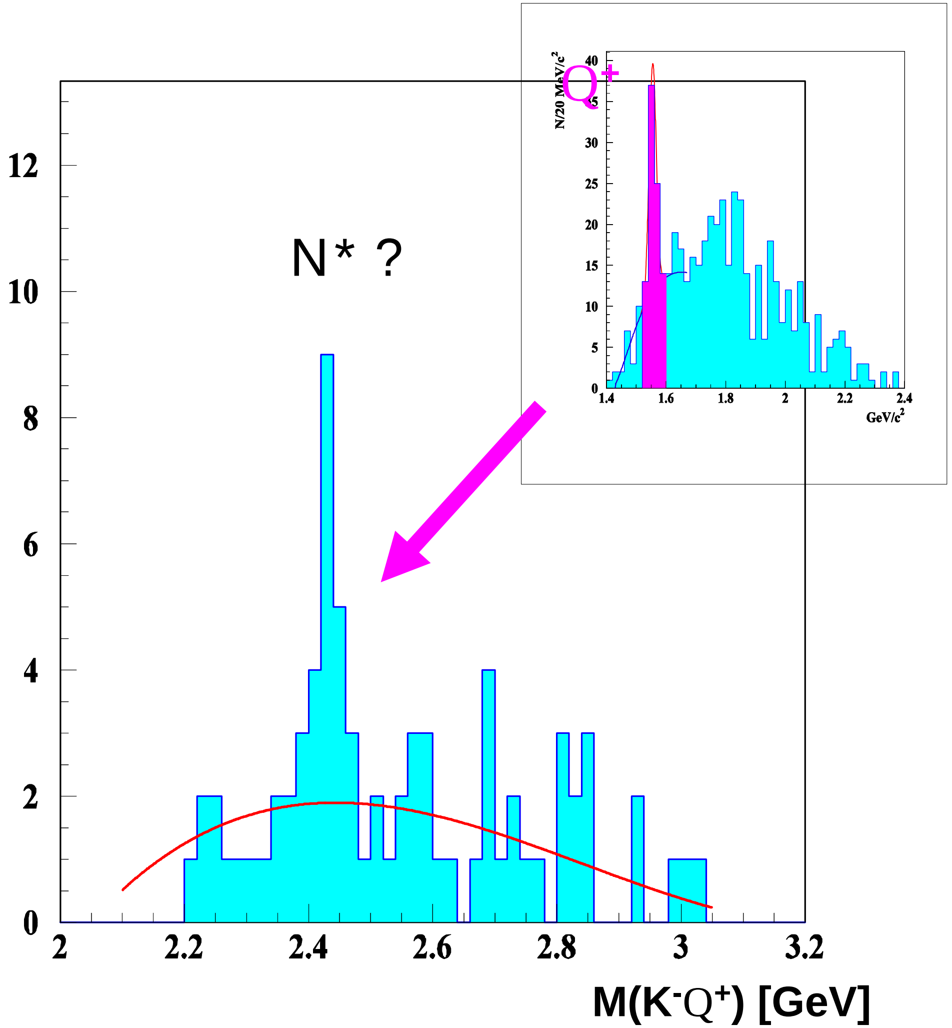


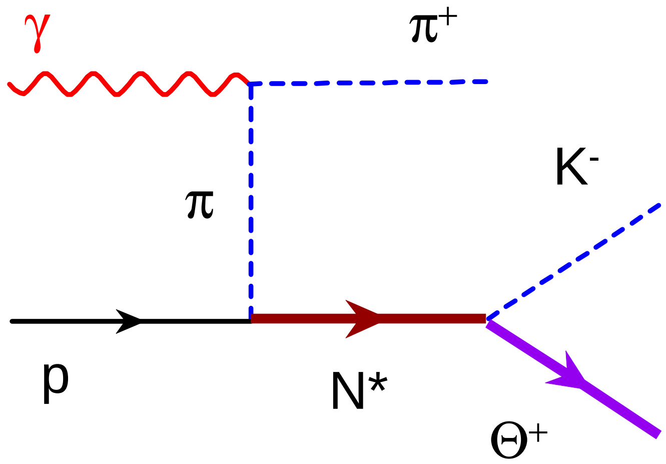
- **Fitted mass 1.555 GeV**
- G **< 28 MeV consistent with detector resolution**
- **Estimated significance 7.8** s
- **No peak without angular cut motivated by N* mechanism which selects ~5% of events**



$$\Theta^+ \rightarrow nK^+$$

CLAS-γp: Indication for a heavy N*(2430)?





There are no πN scattering data in the relevant energy range.

What is the width of Θ^+?

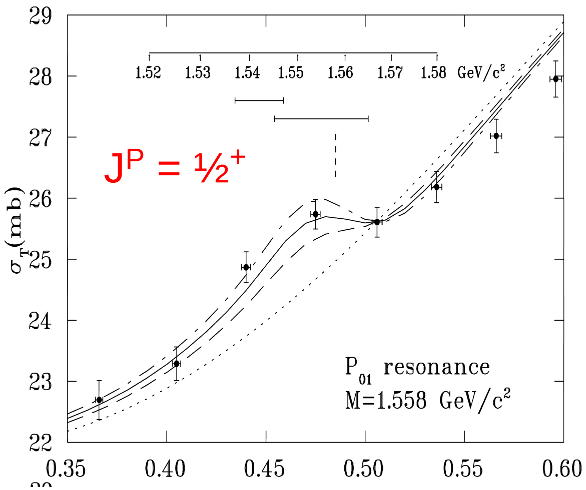
Widths seen in experimental analyses are dominated by resolution effects.
More precise information is obtained in analyses with theoretical constraints.

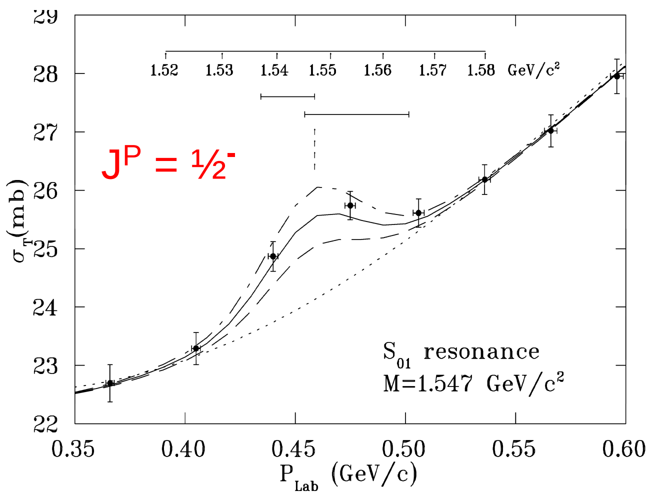
S. Nussinov et al., hep-ph/0307357 $\Gamma_\Theta <$ 6 MeV
R. Arndt et al., PRC68, 42201 (2003) $\Gamma_\Theta <$ 1 MeV
A. Sibirtsev, et al., hep-ph/0405099 (2004) $\Gamma_\Theta <$ 1 MeV (K$^+$d K^{o}pp)

$\Gamma \sim \int d\sigma/dM\, dM$

R. Cahn and G. Trilling, PRD69, 11401(2004) Γ_Θ = 0.9 +/- 0.3MeV (from DIANA results)

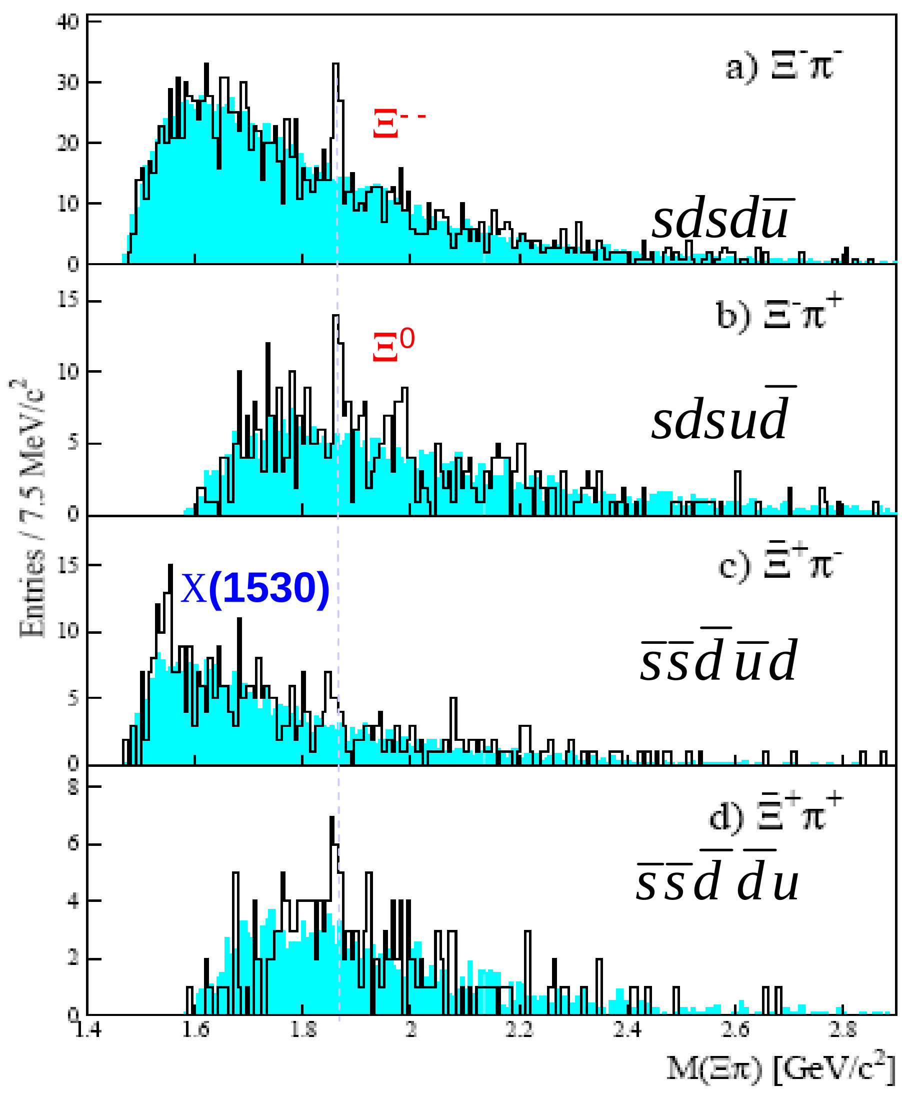
First positive identification of Θ^+ in K$^+$d, including double scattering.
W. Gibbs, nucl-th/0405024 (2004) Γ_Θ = 0.9 +/-0.2 MeV





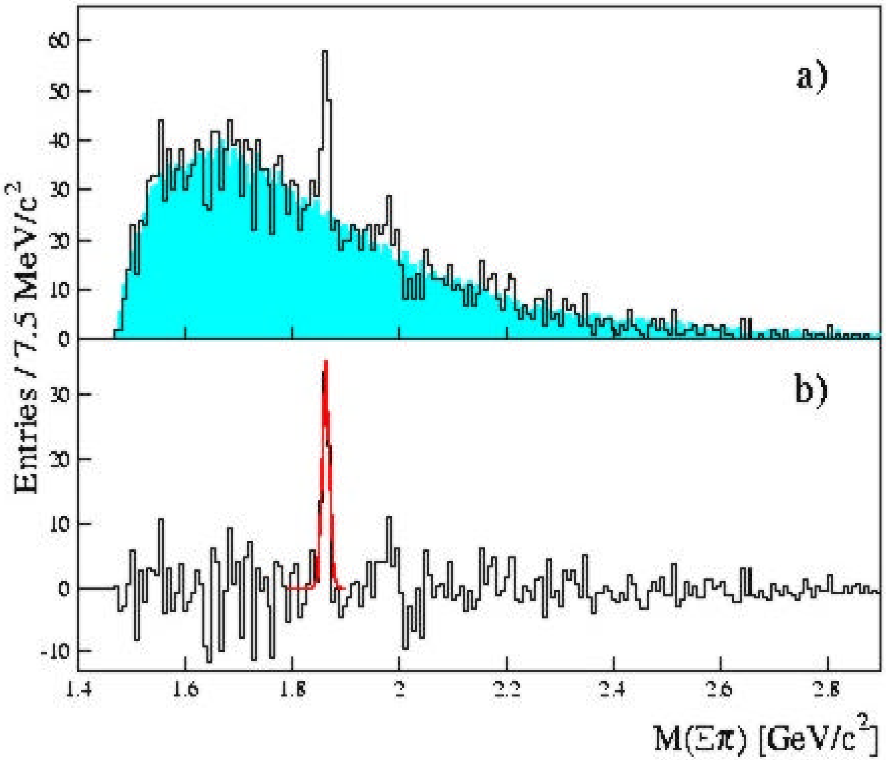
Such a small width is very unusual for strong decays

NA49 claim for $X^{- -}$ and X^{0} states

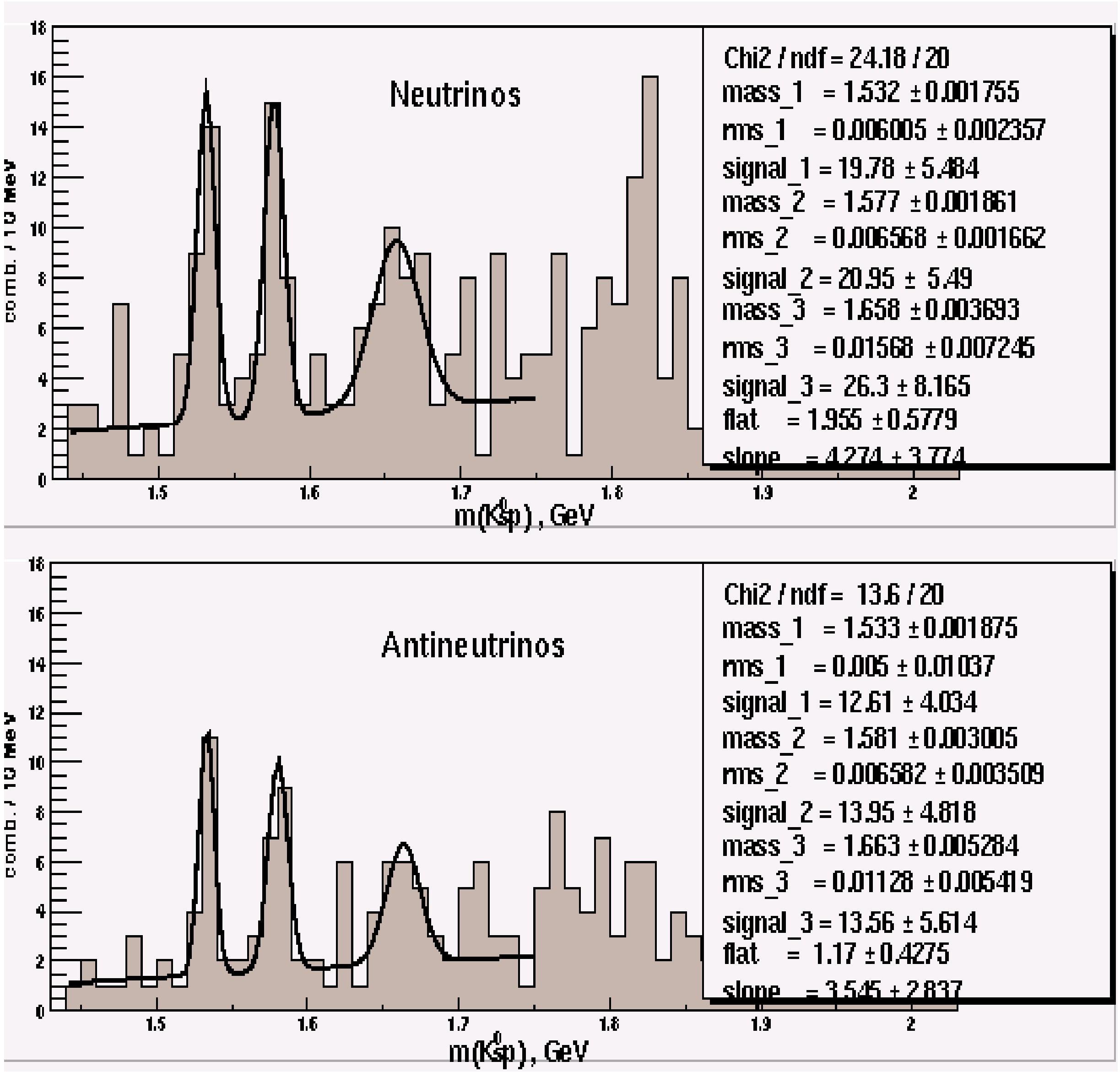


Signal for Exotic S = -2, Q=-2, and *Non*-exotic S=-2, Q=0 at
M=1.862± 0.002 GeV

Combined significance 5.6 s



$K^0_S p$ resonances in neutrino interactions (Asratyan et al)



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 (5σ)

Significance above 5σ

Evidence for 1573 state in CLAS data?

Observation of charm pentaquark

Opposite sign D*p mass distribution in DIS

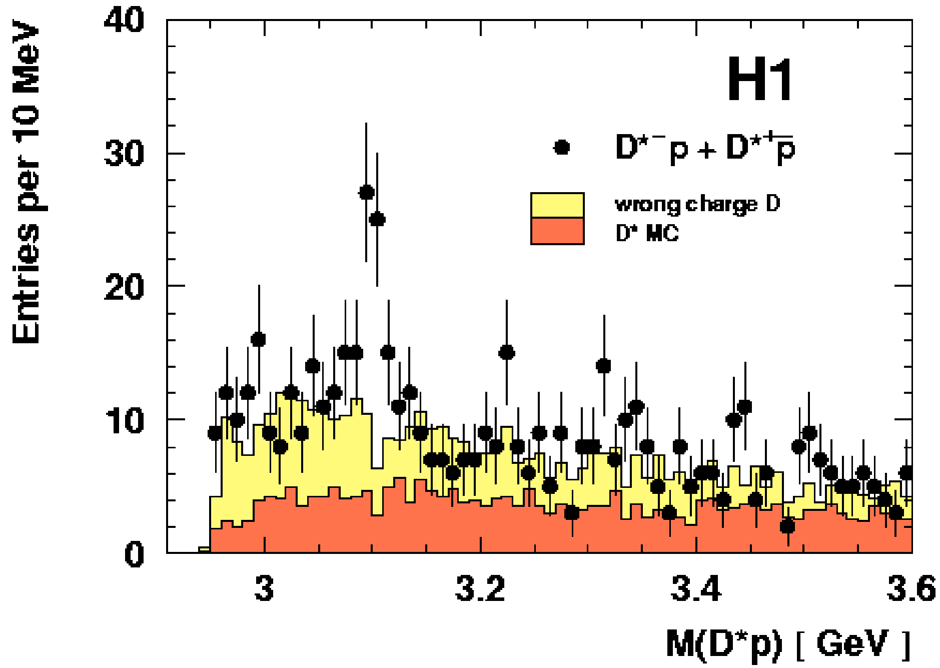
Apply mass difference technique

$M(D^*p)=m(Kpp\ p)-m(Kpp)+M_{PDG}(D^*)$

no enhancement in D* Monte Carlo

no enhancement in wrong charge D

Background well described by D* MC and "wrong charge D" from data



narrow resonance at M=3099± 3(stat.) ± 5 (syst.) MeV

- signal visible in different data taking periods

Summary of Positive Results

(Compiled by Airapetian)

Experiment	$\Theta^+(1540)$ $(uudd\bar{s})$	$\Xi^{--}(1862)$ $(ddss\bar{s})$	$D^{*-}p(3100)$ $(uudd\bar{c})$	Reaction
LEPS	1540 ± 11.2			$\gamma^{12}C(n) \rightarrow nK^+K^-$
DIANA	1539 ± 3.6			$K^+Xe \rightarrow \Theta^+X$
CLAS (D)	1542 ± 5.4			$\gamma d \rightarrow \pi^+K^-K^+n$
SAPHIR	1540 ± 4.5			$\gamma p \rightarrow nK^+K^0$
ITEP $(\nu' s)$	1533 ± 5.83			$\nu A \rightarrow \Theta^+X$
CLAS (P)	1555 ± 10.05			$\gamma p \rightarrow \pi^+K^-K^+n$
HERMES	1528 ± 3.106			$eD \rightarrow \Theta^+X$
ZEUS	1521.5 ± 3.176			$ep \rightarrow \Theta^+X$
SVD-2	1526 ± 4.24			$pA \rightarrow \Theta^+X$
COSY-TOF	1530 ± 6.0			$pp \rightarrow \Sigma^+K^0p$
JINR	1545.1 ± 12.36			$pC_3H_8 \rightarrow \Theta^+X$
LPI	1541 ± 4.58			$np \rightarrow npK^+K-$
HLBC/JINR	1532 ± 6			$CC \rightarrow \Theta^+X$
NOMAD	1528.7 ± 2.5			$\nu A \rightarrow \Theta^+X$
NA49		1862 ± 2		$pp \rightarrow \Xi^{--}X$
H1			3099 ± 6	$ep \rightarrow D^{*-}pX$
LEPS	*NEW*			$\gamma D \rightarrow nK^+K^-$

? Certainly high statistic data are needed

Summary of Null Results

(Compiled by Airapetian)

(For some reason he has not included BELLE, COMPAS, and L3)

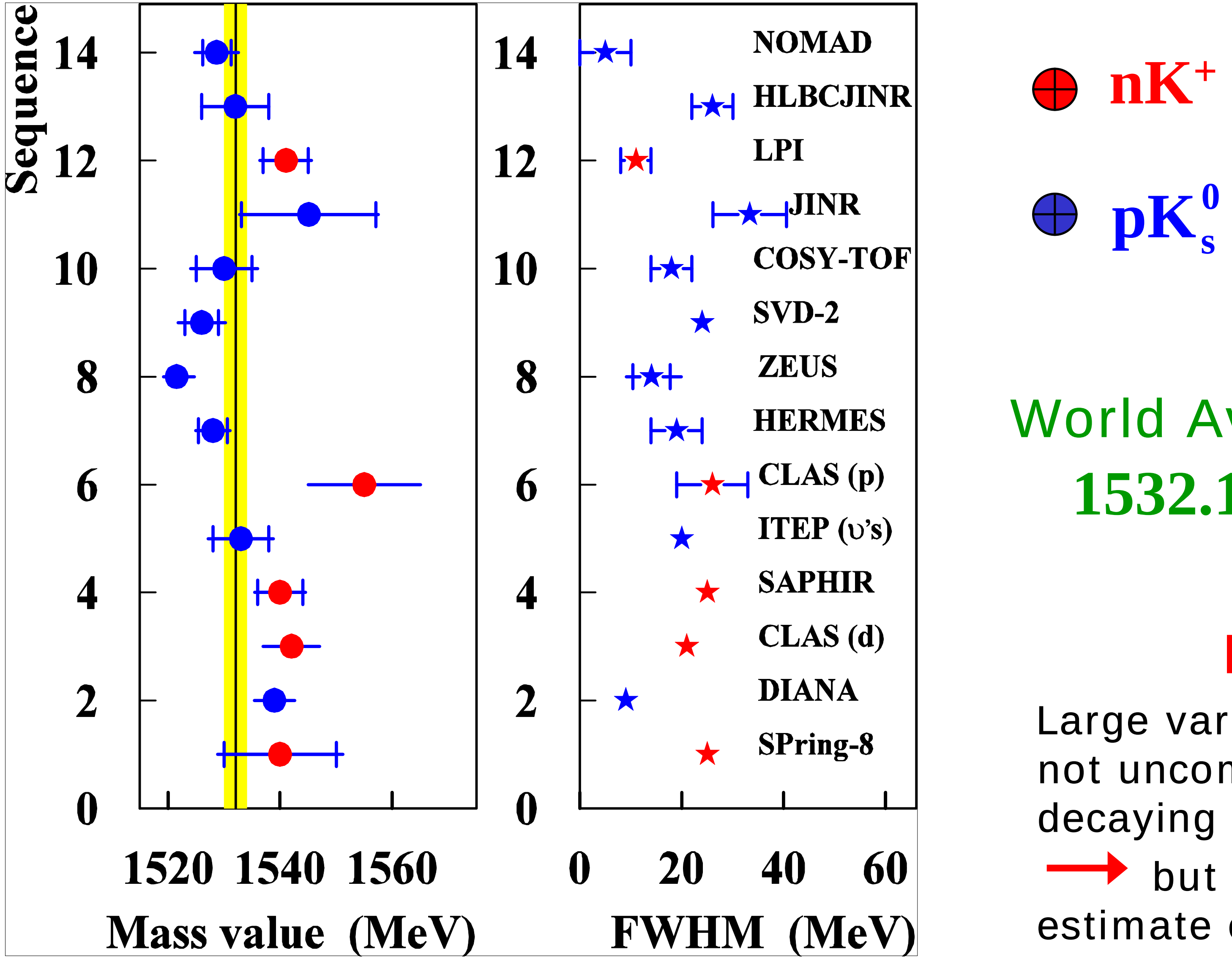
Experiment	$\Theta^+(1540)$ $(uudd\bar{s})$	$\Xi^{--}(1862)$ $(ddss\bar{s})$	$\Theta_c(3100)$ $(uudd\bar{c})$	Reaction
HERA-B*	NO	NO		$pA \to \Theta^+ X,\ \Xi^{--} X$
E690	NO	NO		$pp \to \Theta^+ X,\ \Xi^{--} X$
CDF*	NO	NO	NO	$p\bar{p} \to \Theta^+ X,\ \Xi^{--} X,\ \Theta_c X$
HyperCP	NO			$\pi, K, p \to \Theta^+ X$
BaBar*	NO	NO		$e^+e^- \to \Theta^+ X,\ \Xi^{--} X$
ZEUS	yes	NO	NO	$ep \to \Theta^+ X,\ \Xi^{--} X,\ \Theta_c X$
ALEPH+	NO	NO	NO	$e^+e^- \to \Theta^+ X$
DELPHI	NO			$e^+e^- \to \Sigma^- K^0 p$
PHENIX*	NO			$AuAu \to \Theta^+ X$
FOCUS			NO	$\gamma A \to \Theta_c X$
BES*	NO			$e^+e^- \to J/\Psi \to \Theta^+ \overline{\Theta^-}$
WA89+		NO		$\Sigma^- A \to \Xi^{--} X$
SPHINX*	NO			$pC(N) \to \Theta^+ \bar{K}^0 + C(N)$
HERMES	yes	NO		$ep \to \Theta^+ X,\ \Xi^{--} X$

Experiments	17 YES	17 NO
Experiments with ITEP	5 YES	5 NO
My (former) PhD students	0.5 YES	13.5 NO Statistically significant!

Scientific questions can not be answered by majority vote

What are the arguments Pro&Contra?

Contra: Large spead in Mass and Width (compilation by Airapetian)

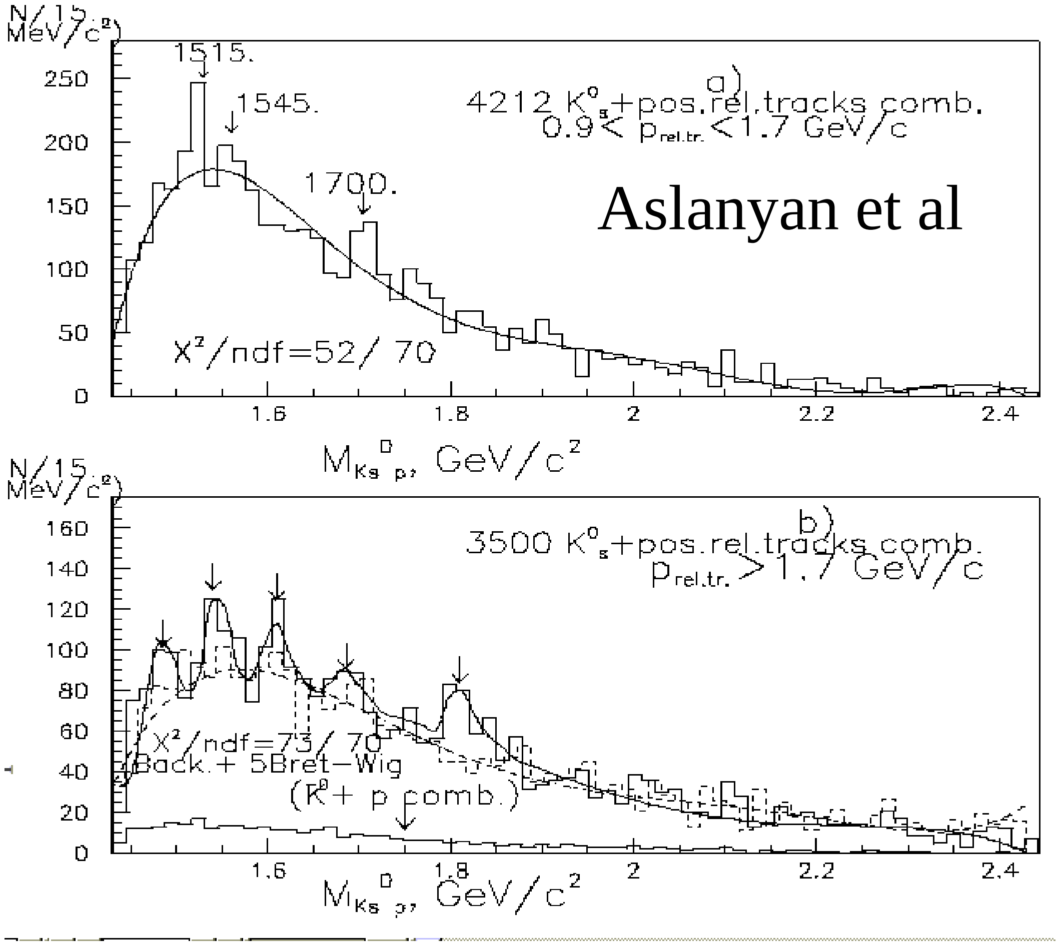


World Average:
1532.1±2.1 MeV

Pro:

Large variation in mass not uncommon for new, decaying particles
→ but need to better estimate exp. Uncertainties

Contra: Some experiments use arbitrary cuts



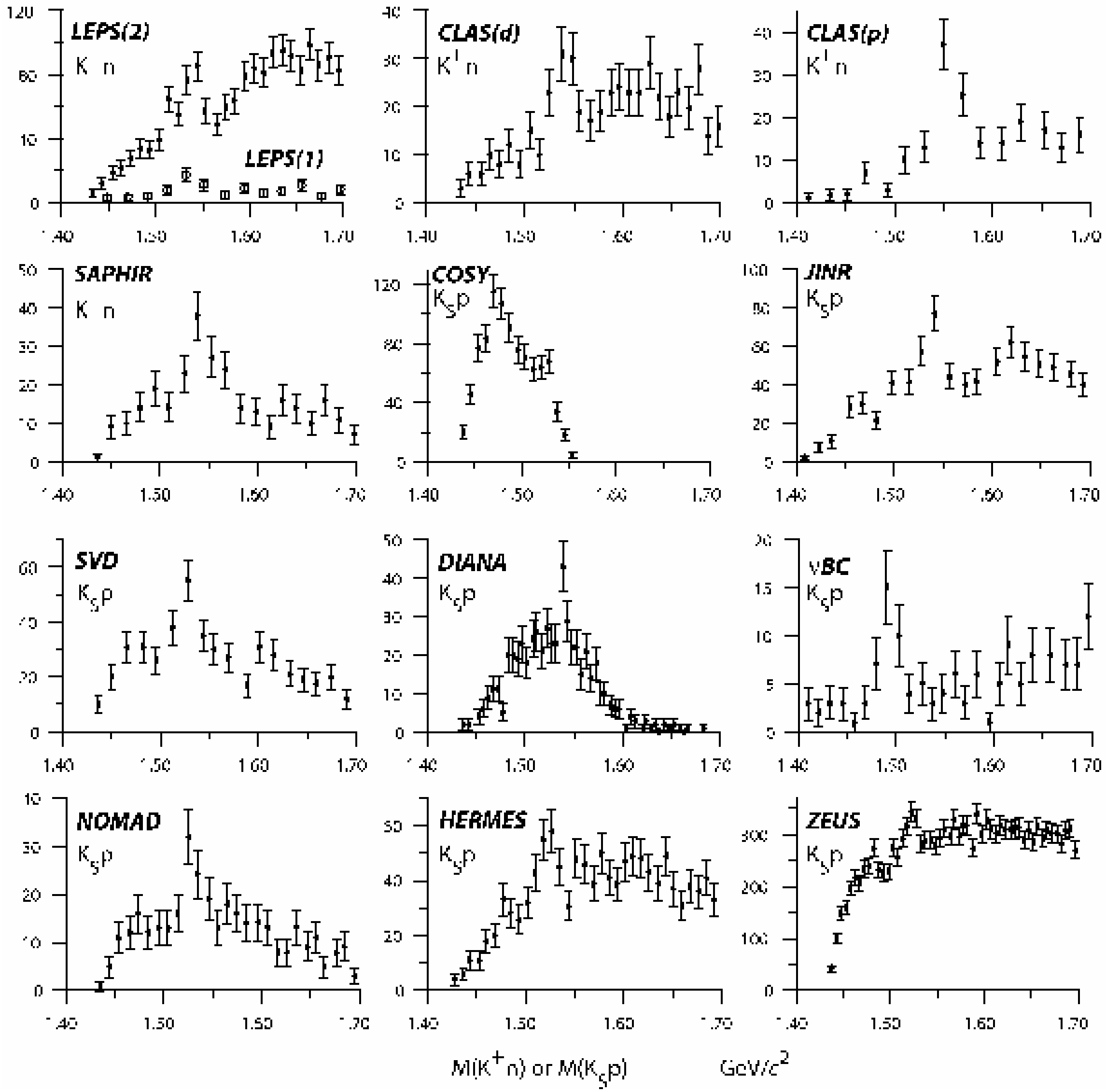
No corresponding peaks in the first plot?

Þ **Cut away this momentum interval**

Pro: many experiments do not

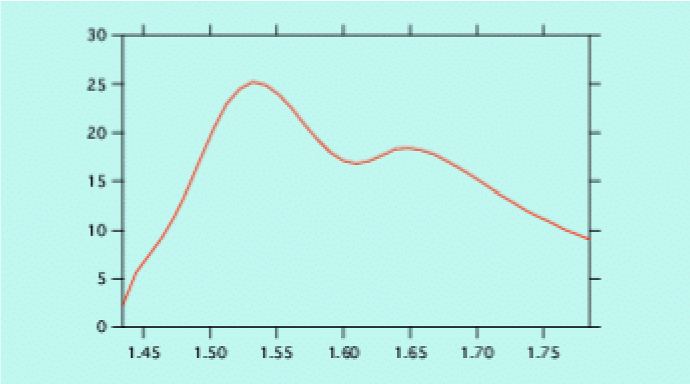
Contra: Statistical significance is overestimated

Positive results with stat errors (Dzierba et al)

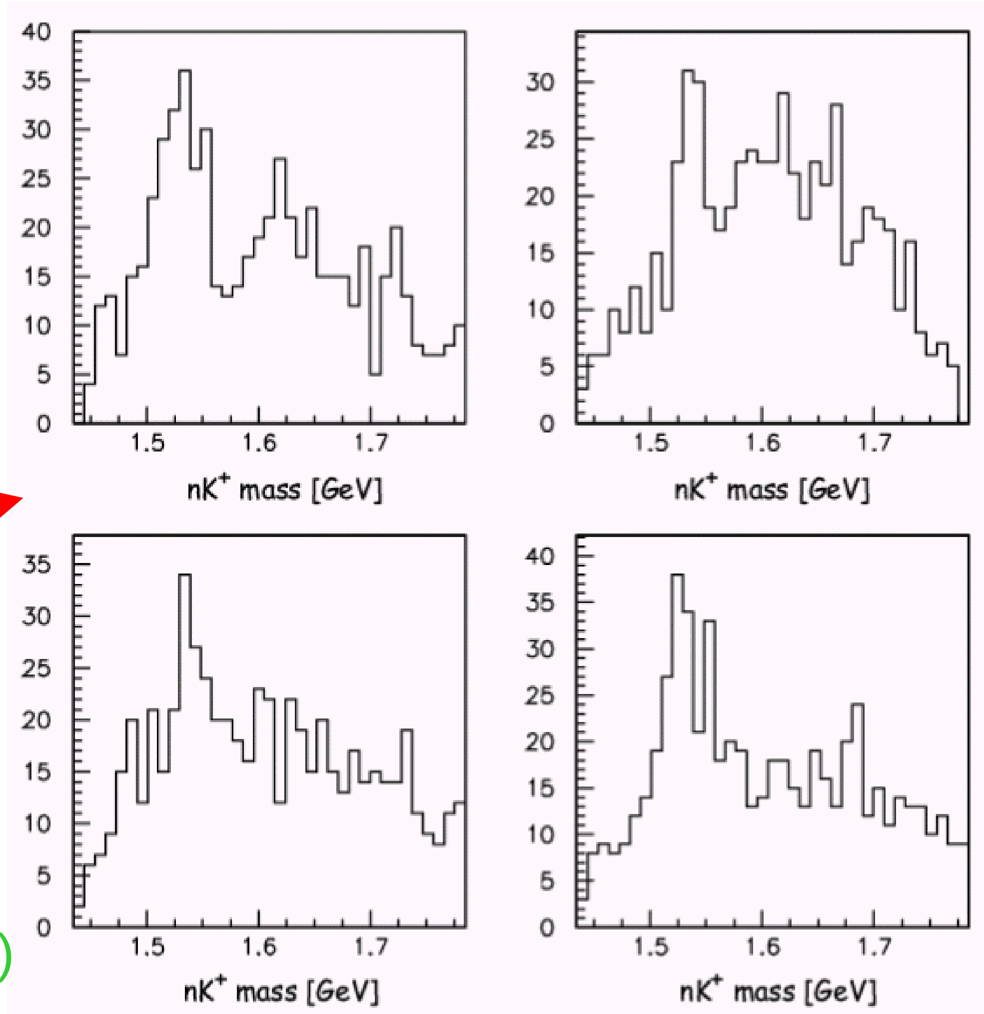


Pro: but still high enough

Contra: Broad kinematic reflection from a2/f2 fluctuates to narrow peak



3 out of 20 histograms with 600events each and 1 real distribution (Dzierba et al.)



Pro: **a2/f2 cross section too small for this**

(Y. Oh et al., hep-ph/0412363)

Contra: Ghost tracks from ? can give a peak around 1.5 GeV

Pro: Such tracks (if exist) can be removed

Contra: Pentaquark yields is very high in some experiments
1.4% of D* come from pentaquark in H1
4% of K^0p come form pentaquark in HERMES

Pro: Just so

Contra: Many experiments with much higher statistic and better mass resolution do not see pentaquarks

Pro: Pentaquark production is heavily suppressed at high energies or in particular processes

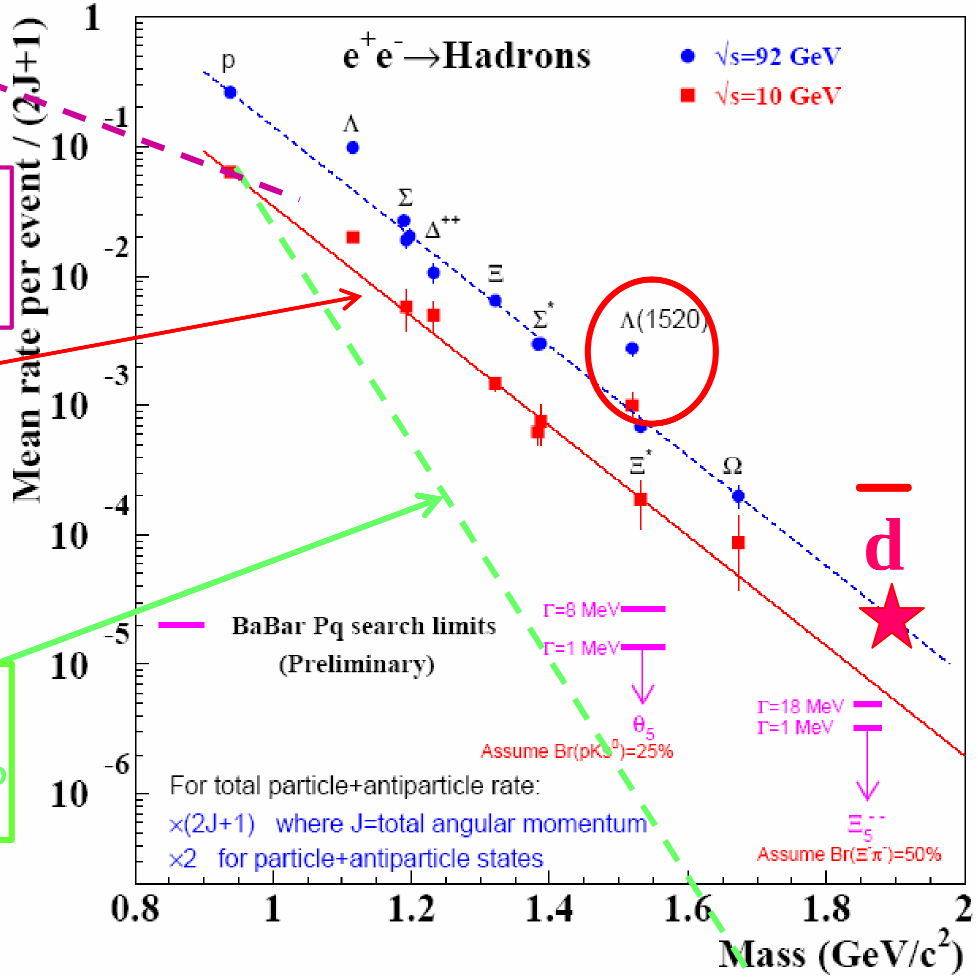
Disagreement between experiments is the main question.
Let us try to answer it (at least partially)

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)

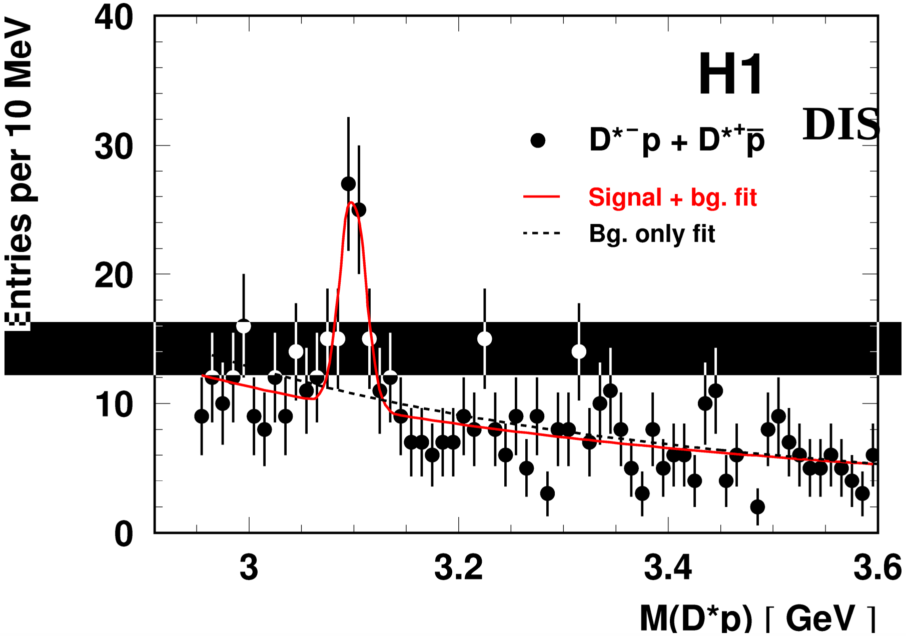
Baryons:
~ 10^{-4} /GeV/c^2
(need two more pairs)

Antideutrons (ARGUS, ϒ)
(need 6 more pairs!)?

Pentaquarks:
~ 10^{-6} /GeV/c^2 (?)
(need 4 more pairs)

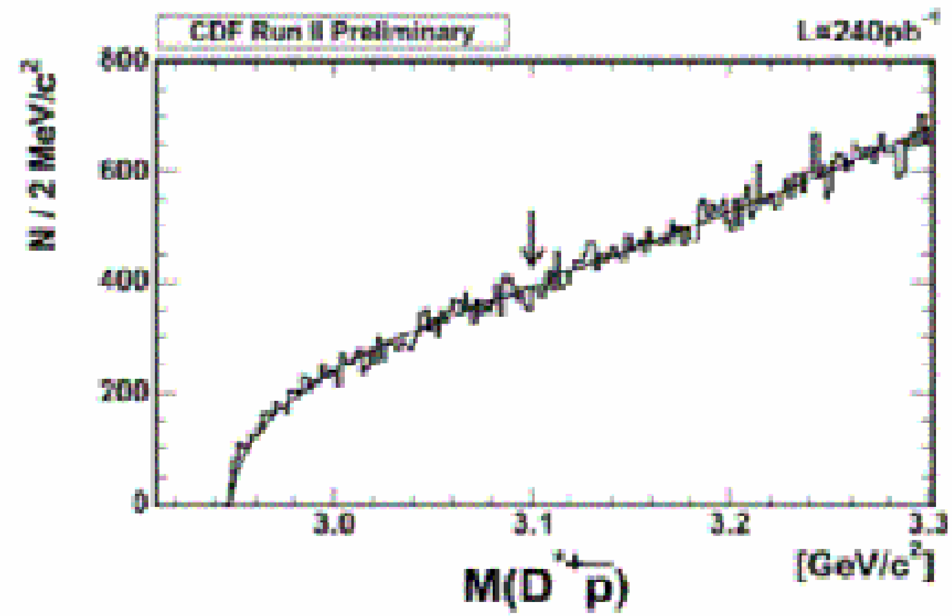
we don't know the production mechanism!!

A charmed pentaquark



Peak at 3099±3±5 MeV
(51ev. significance 5.4-6.2 s)
1.46% D* come from q_c
Peak at the same mass is seen also in photoproduction

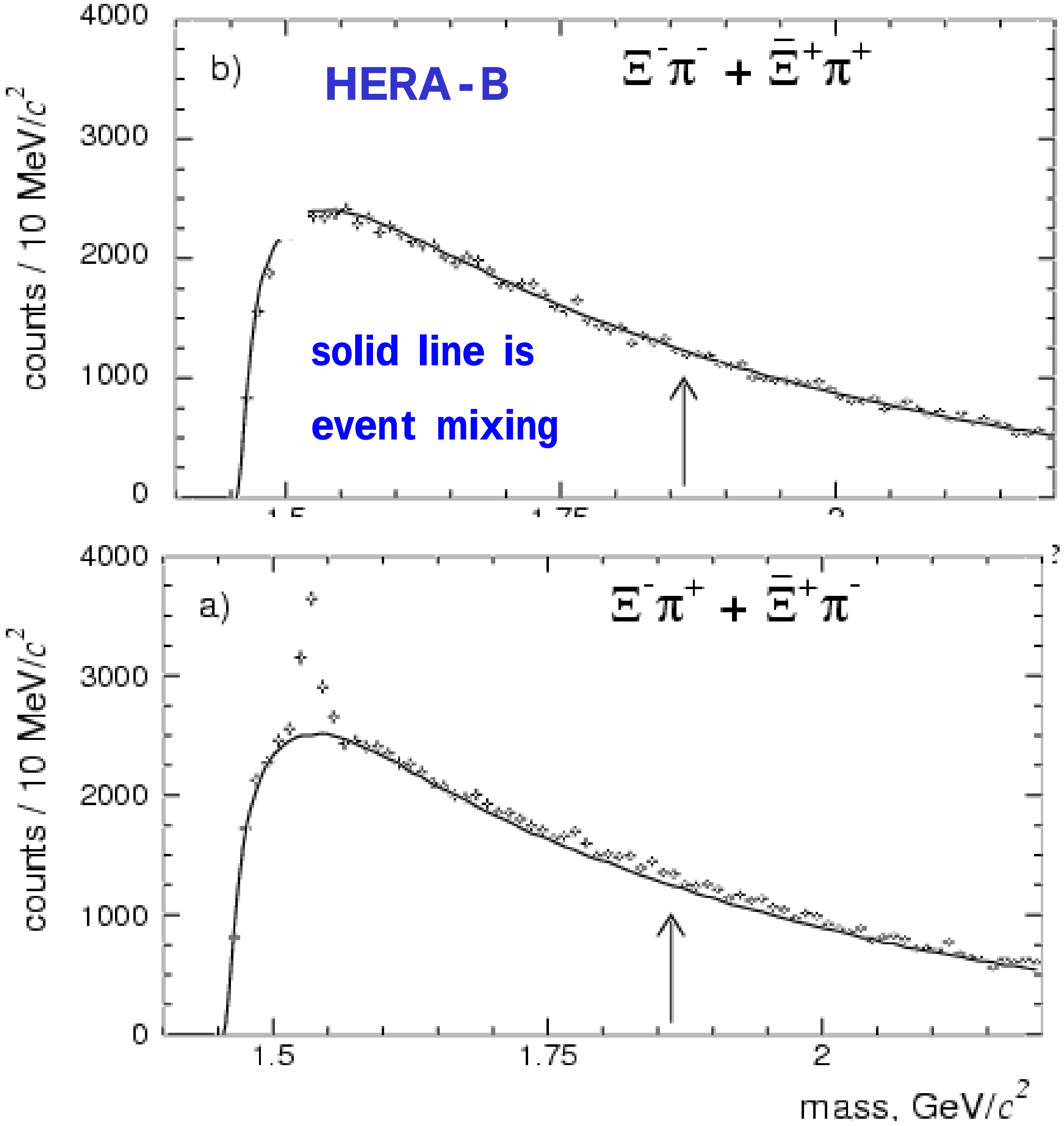
However ZEUS does not see it
(<0.35% of D* come from q_c)



CDF has 0.5M D* and 15k D**
(H1 has ~3.4k D*)
But CDF does not see q_c
(Nev<29 for a narrow state)

ALEPH, COMPAS, FOCUS, BELLE, WA89 do not see q_c

X^{--}(1862)



No evidence for resonances at 1862 MeV in the same process but twice larger Ecms

HERA-B has better resolution (6.6 MeV) and 10 times higher Ξ^0(1530) statistics than NA49:

$$R = \frac{\sigma B\,(X^{--}(1862))}{\sigma(\Xi^0(1530))} < 4\%\ @95\%$$

NA49: R~ 18%

E690: R<0.3%

CDF, BaBar, ALEPH, COMPASS, FOCUS, WA89, and ZEUS also do not see X^{--}(1862) signal

Q^+: Negative results

Many experiments do not see Q^+

BES, BaBar, ALEPH, DELPHI,HERA-B, SPHINX, E690, HyperCP, CDF, COMPASS,...

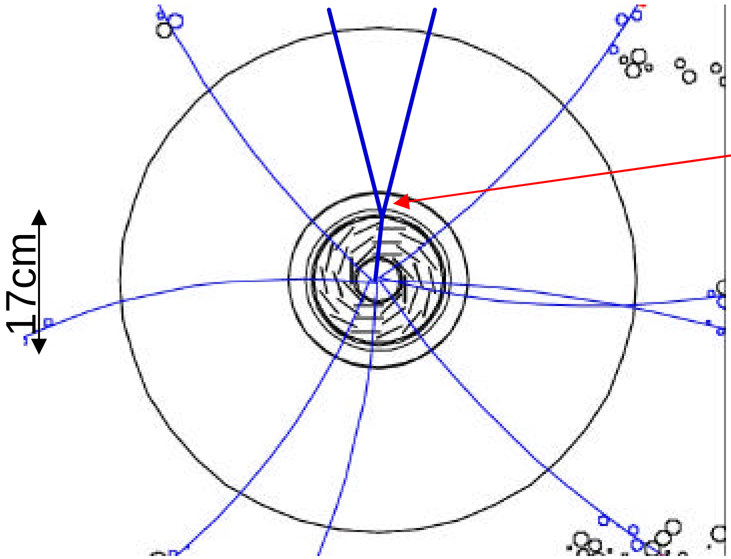
However comparison with positive results which are mainly at low energies is difficult (different processes, different energies, often no information to compare with: no cross sections, yield ratios etc.)

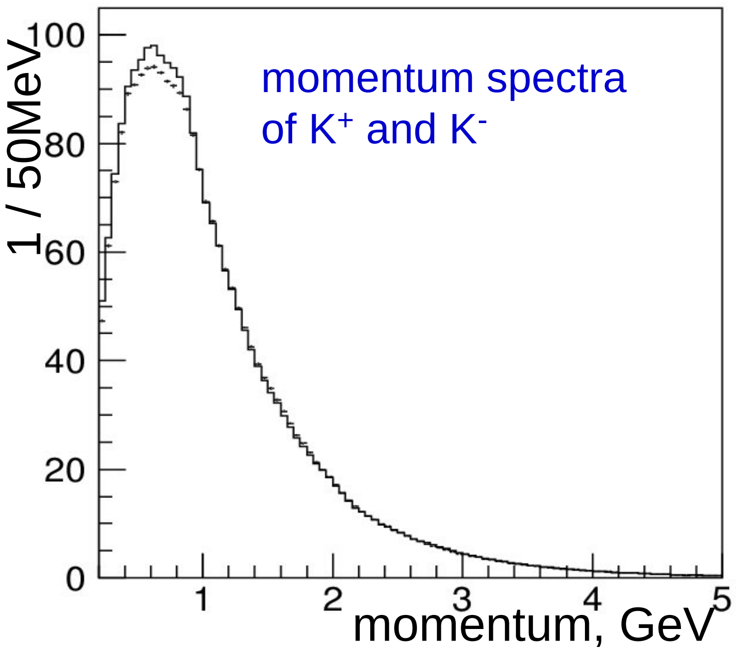
In some cases experiment contradicts theoretical estimates for example HERA-B upper limit on Q^+/L_{1520} relative yield is 30 times smaller than theoretical predictions and two orders of magnitude smaller than in photoproduction experiments

However accuracy of predictions is not known and extrapolation to low energies is uncertain. There are theoretical predictions of fast decrease of cross section with energy

One needs high statistics experiment at low energies

Search for pentaquarks using kaon interactions in the detector material (BELLE).





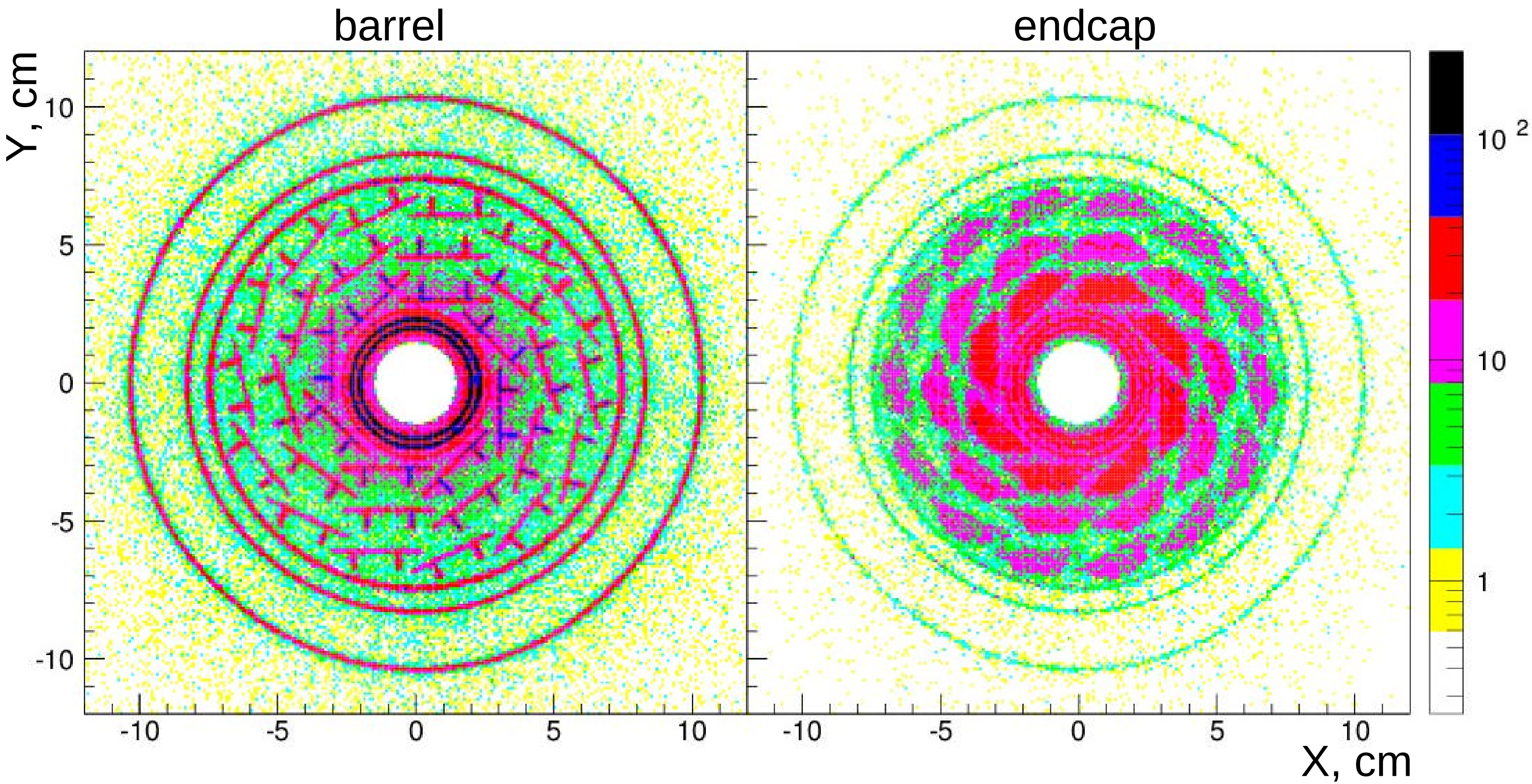
- Small fraction of kaons interacts in the detector material. Select secondary pK pairs to search for the pentaquarks.

- Momentum spectrum of the projectile is soft.
  ⇒ low energy regime, similar to most experiments which observed pentaquark.

- Projectile is not reconstructed.
  ⇒ K_S flavor is not fixed.
  ⇒ can not distinguish between elastic and inelastic scattering.

- Secondary pK pairs selection:
  - p, $K^{\pm}$ do not originate from e^+e^- interaction point, identified based on dE/dx, TOF and Cherenkov info
  - K_S? p^+p^- detached vertex, momentum is not pointing to e^+e^- interaction point
  - detached common pK vertex

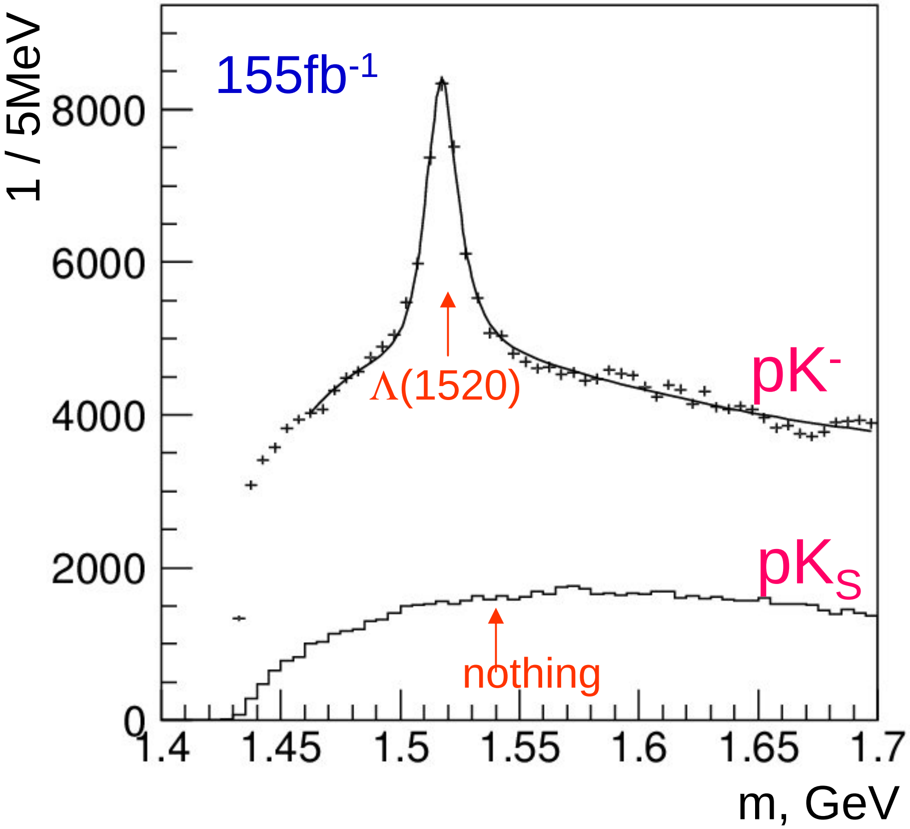
XY Distribution of Secondary pK^- Vertices in Data

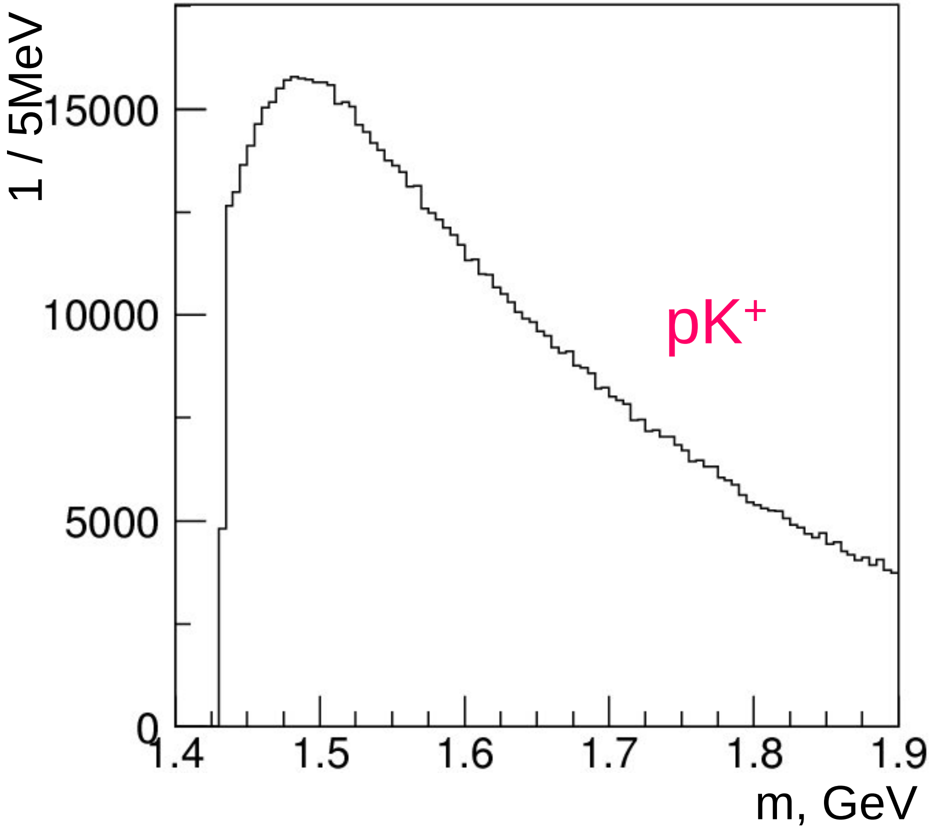


"Strange particle tomography" of the detector.

⇒ Selected pK vertices originate from nuclear interactions.

Mass Spectra of Secondary pK Pairs





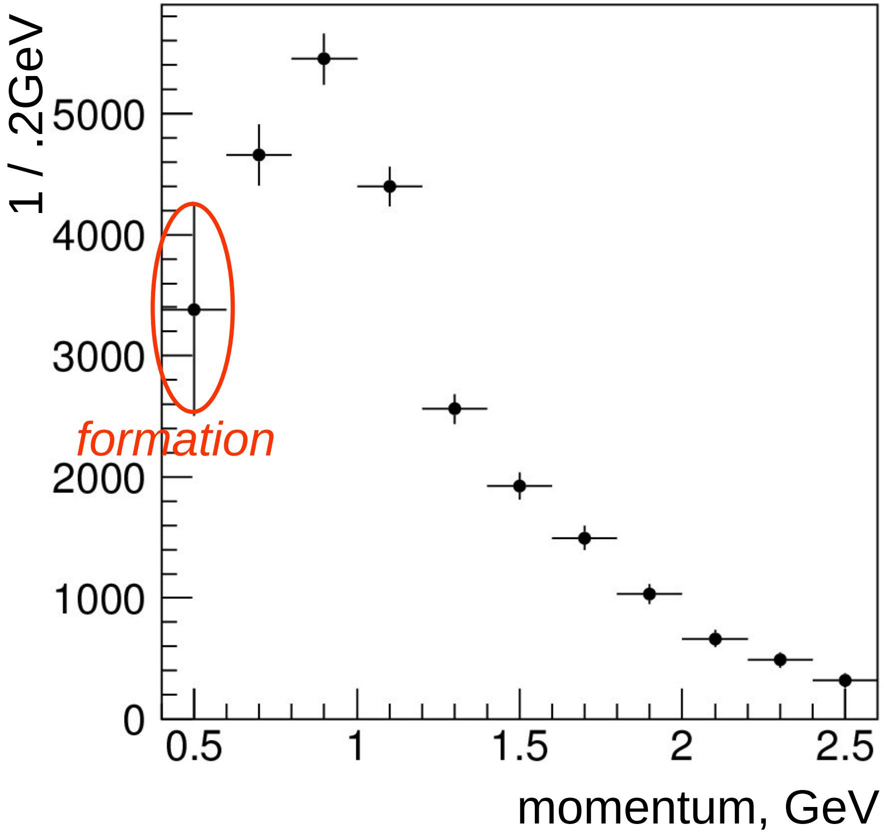
Fit M(pK^-) to D-wave BW ⊕ resolution function + threshold function.

⇒ L(1520) yield is 15519±412 events

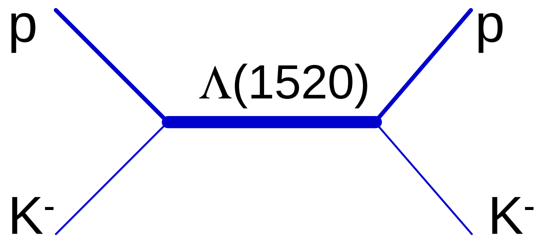
M=1518.5±.2MeV in agreement with PDG'02 value 1519.5±1.0MeV

$$\frac{s(KN \circledR\ Q^+(1540)\ X)}{s(\bar{K}N \circledR\ L(1520)\ X)}$$ **< 2% at 90%CL**

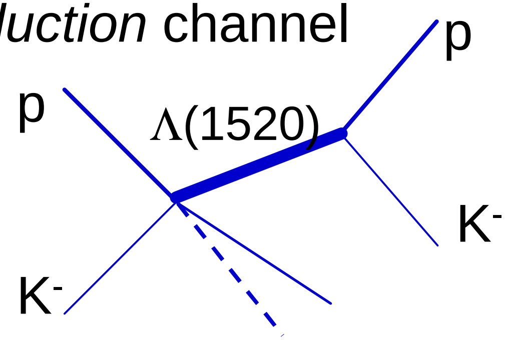
Λ(1520) Momentum Spectrum



formation channel: $p(pK^-)$~500MeV



production channel



Λ(1520) momentum spectrum is hard ⇒ *production* channel dominates.

HERMES vs BELLE

Peak at:

M= 1527 ± 2.3 MeV

σ= 9.2 ± 2 MeV

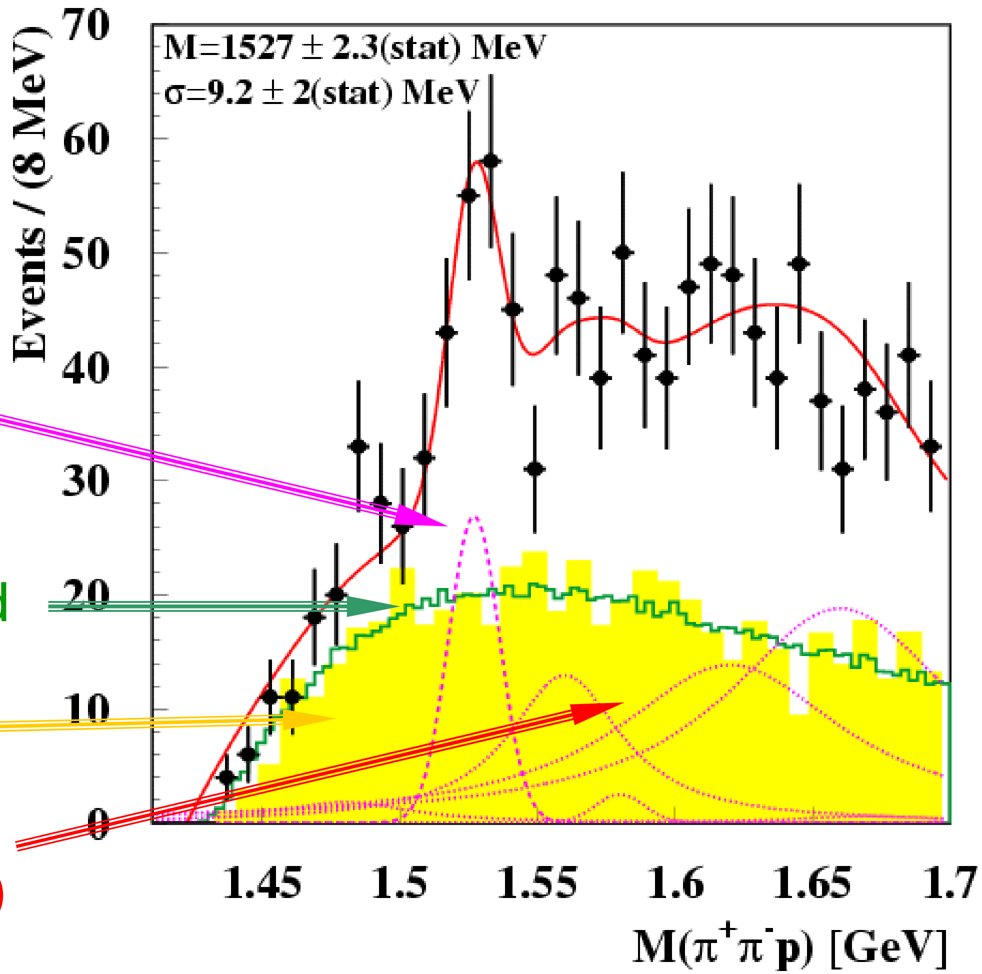
Significance:

$N_s / dN_s = 4.3$

mixed event background

PYTHIA6

excited Σ* hyperons
(not included in Pythia6)



Q^+ / L**(1520) ~ 1.6 – 3.5** **BELLE: R<0.02**

Q^+ **/p K_s ~ 4 %** **BELLE:** Q^+ **/p K_s <0.06%**

Clear Contradiction

BELLE vs DIANA

Kaons at BELLE are soft $\Rightarrow$ considerable overlap with DIANA
Number of expected $K^+ n \Rightarrow \Theta^+ \Rightarrow pK_s$ for Γ_Θ =1MeV comparable to BELLE upper limit (my rough estimate)
If inelastic Θ yield is smaller than elastic one $\Rightarrow$ No contradiction
However for Λ(1520) inelastic yield is much larger than elastic one

BELLE vs Low Energy Photoproduction Experiments

BELLE kaon spectrum is comparable to virtual kaon spectrum in photoproduction experiments
It is strange to have more than order of magnitude difference in relative Θ and Λ(1520) yields
However quantitative estimates are difficult

Conclusions(not politically correct)

1. Evidence for X(1862) is much weaker than arguments against
2. Evidence for Q_c(3099) contradicts more statistically significant result at the same energy and same process and several experiments at different energies
3. Evidence for Q^+ at high and medium energy is much weaker than negative results especially from BELLE at low energy and many experiments at high energy.
   Most probably some experiments are wrong.
4. There is no contradiction with DIANA and photo production experiments if Q^+ cross section drops fast with energy
   High statistic low energy experiments are required to settle the problem. They are coming soon (Jlab, LEPS, KEK, BELLE,…).