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On Pentaquarks

Introduction: Mesons, Baryons, Pentaquarks

Experimental Evidence for the T^+ Pentaquark

Lack of Evidence

2. Generation Experiments

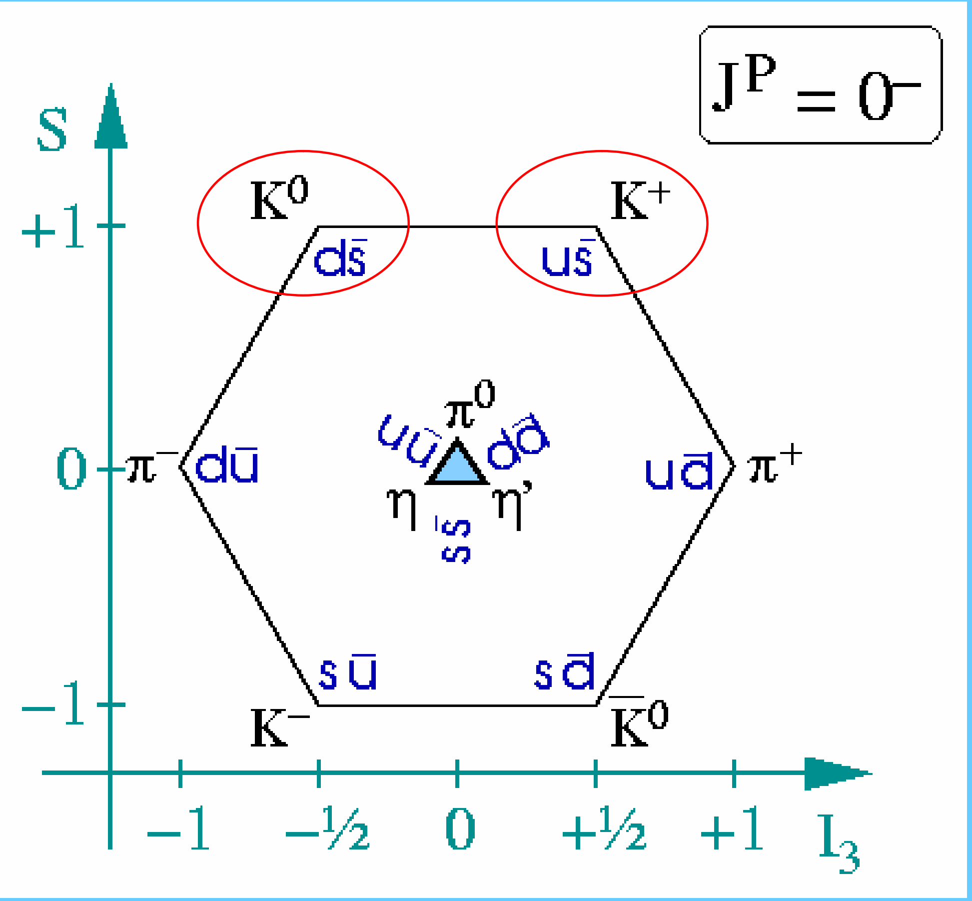
Conclusion and Final Remarks

Dedicated to John R. Huizenga on the occasion of the 85th recurrence of his birthday

Mesons

Quantum-Chromo-Dynamics (QCD) predicts mesons to be composed of pairs of quarks and antiquarks of three flavors: up, down, strange.
Mesons can be grouped as octets in a representation of strangeness (S) vs. 3-component of isospin (I_3)

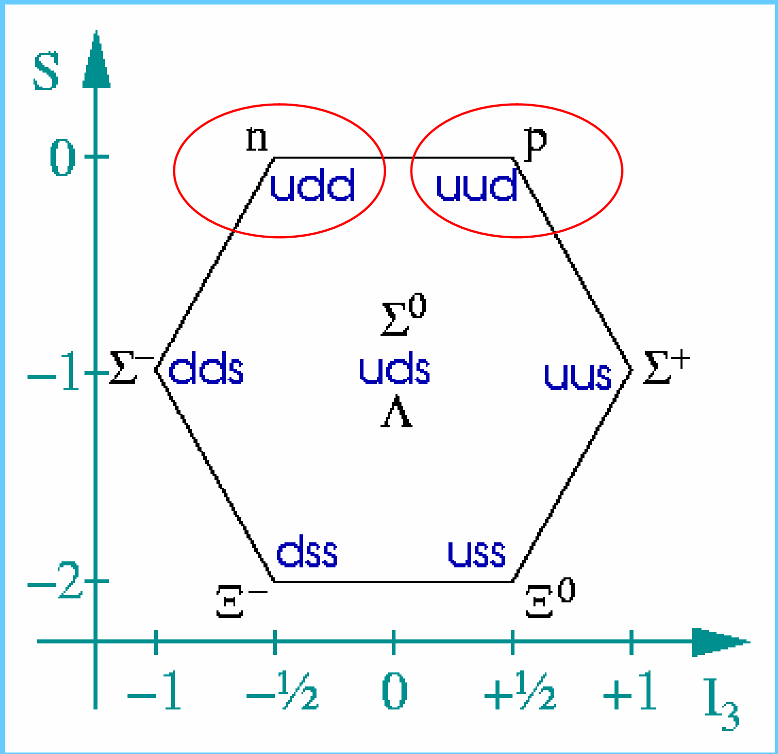
K^0 decays as
$K_S \rightarrow p^+ p^-$

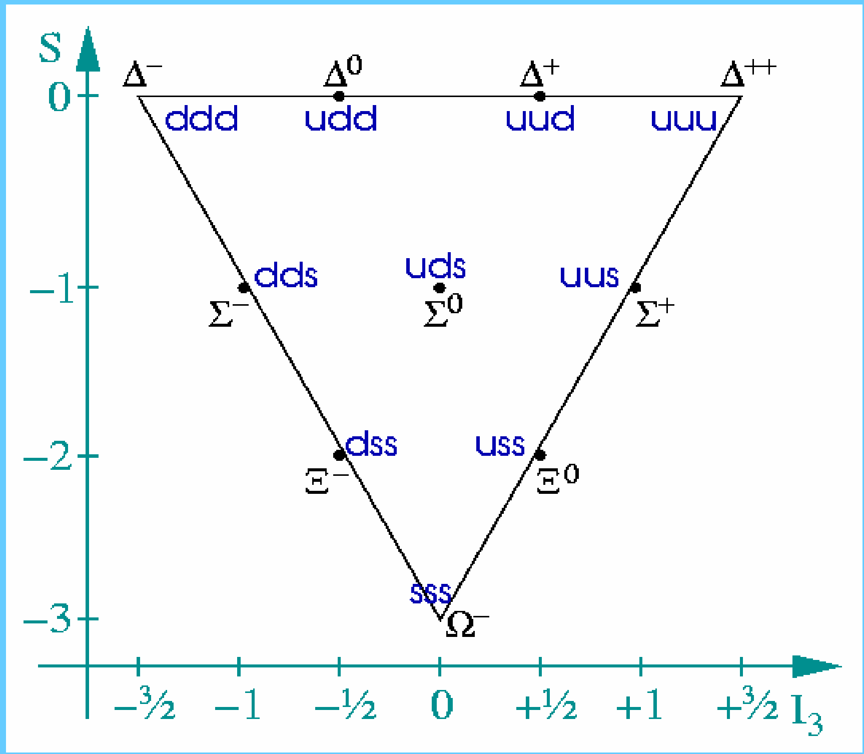


Octet

Baryons

QCD predicts baryons to be composed of three quarks with flavor: up, down, strange. Baryons can be grouped as octet and decuplet in a representation of strangeness (S) vs. 3-component of isospin (I_3)





Octet

Decuplet

Pentaquarks

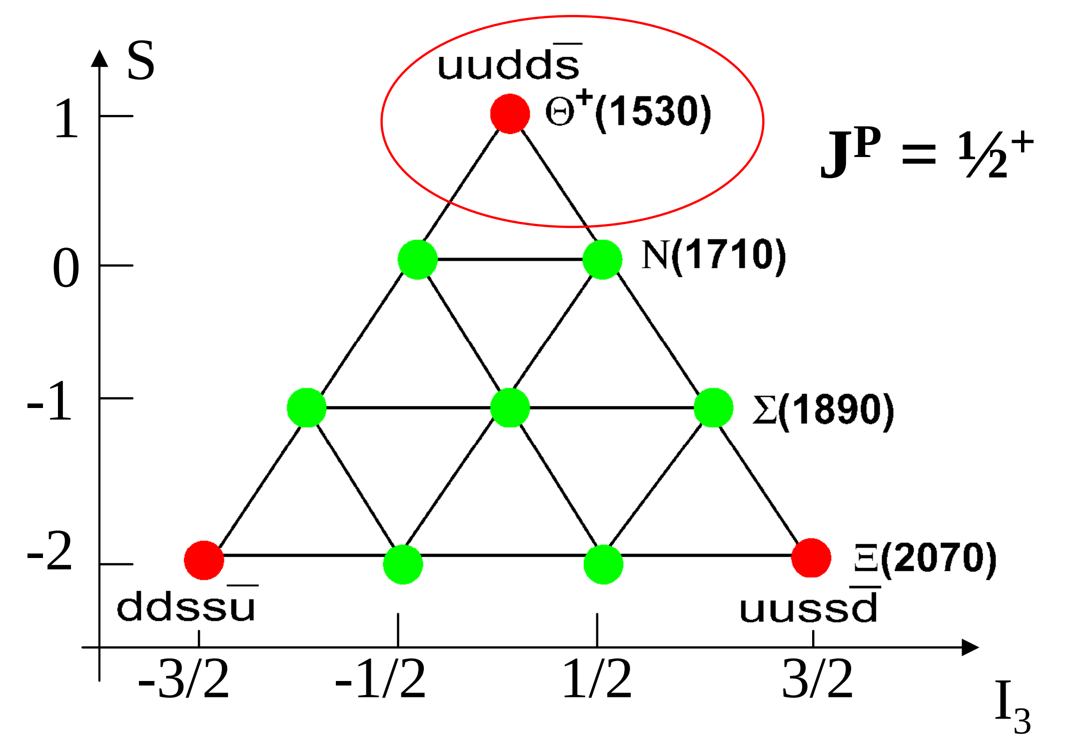
Other states are not ruled out by QCD: pentaquark states

Non-exotic pentaquarks: antiquark has the same flavor as one of the other quarks, difficult to distinguish from ordinary baryons

Exotic pentaquarks: antiquark differs in flavor from the other four quarks; unique identification possible due to conservation laws

Decay mode:
pK^0 or nK^+
uud ds udd us

mass:
~ 1530 MeV/c²
width:
< 15 MeV/c²



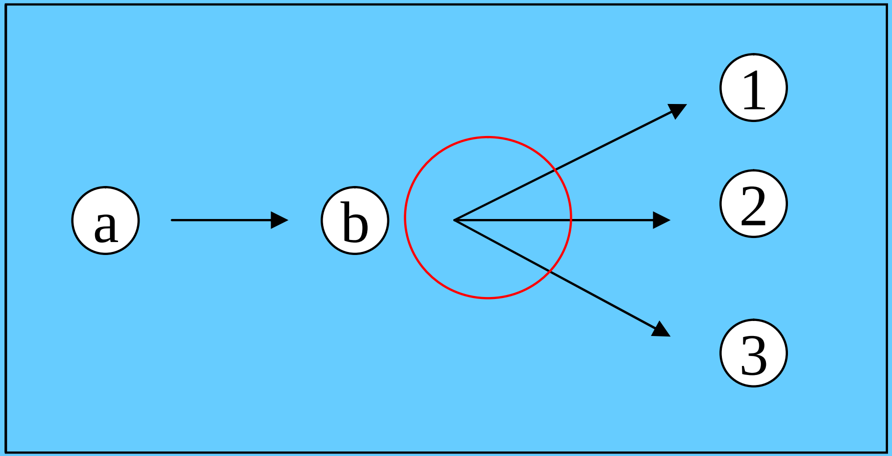
Exotic baryon: S = 1

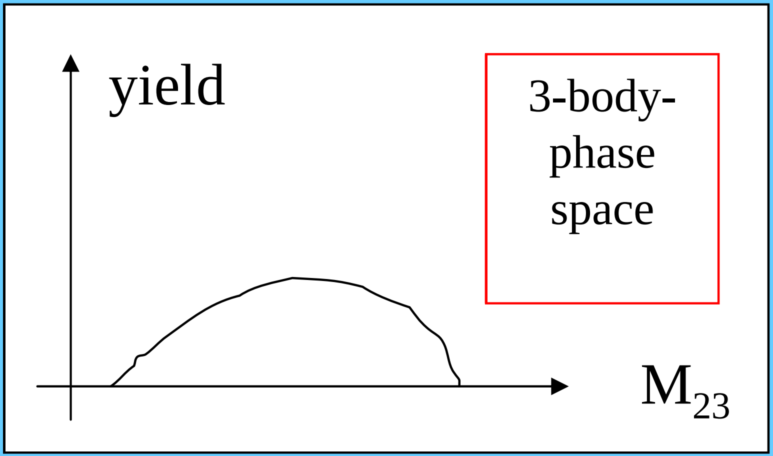
D. Diakonov, V. Petrov and M. Polyakov Z. Phys. A 359 (97) 305

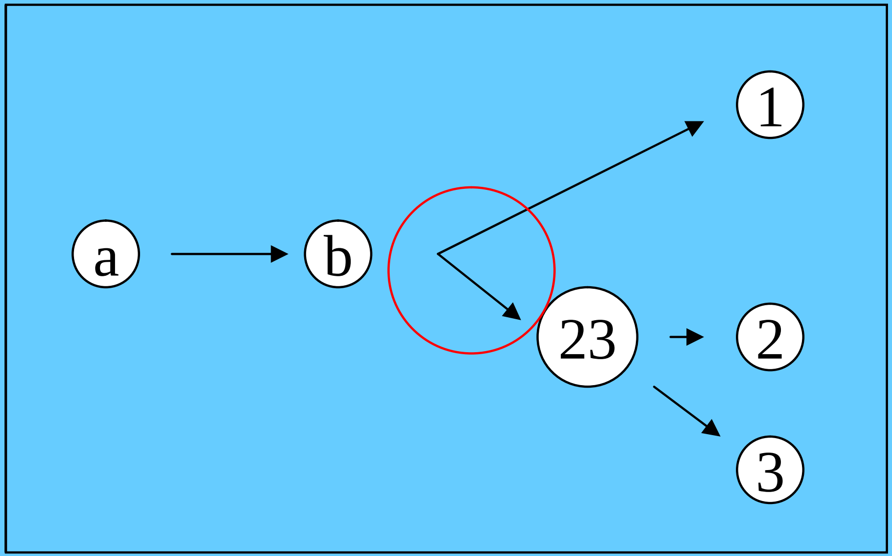
Anti-decuplet

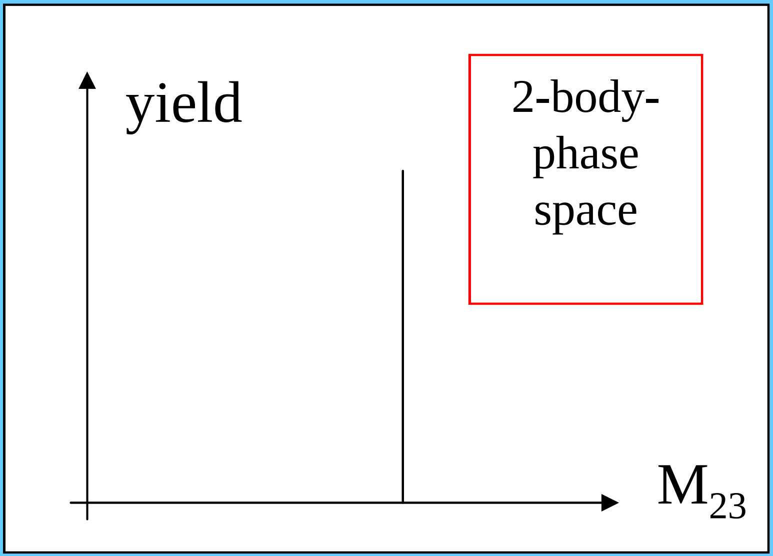
Kinematics for reactions
$a + b \rightarrow 1 + 2 + 3$

Invariant mass
$$M_{ij}^2 = (\mathcal{P}_i + \mathcal{P}_j)^2 / c^2$$





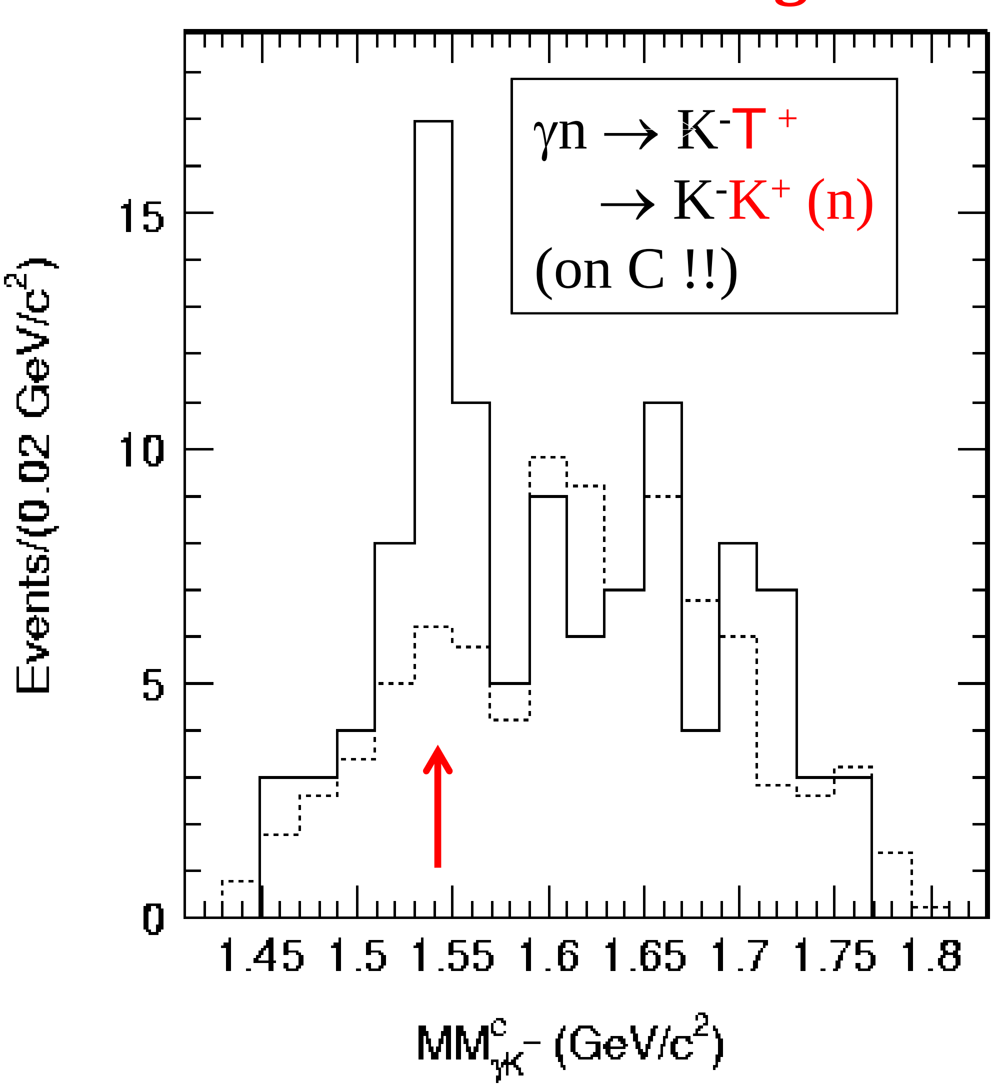




Missing mass, e. g. M_1, can be calculated if M_2 and M_3 have been identified

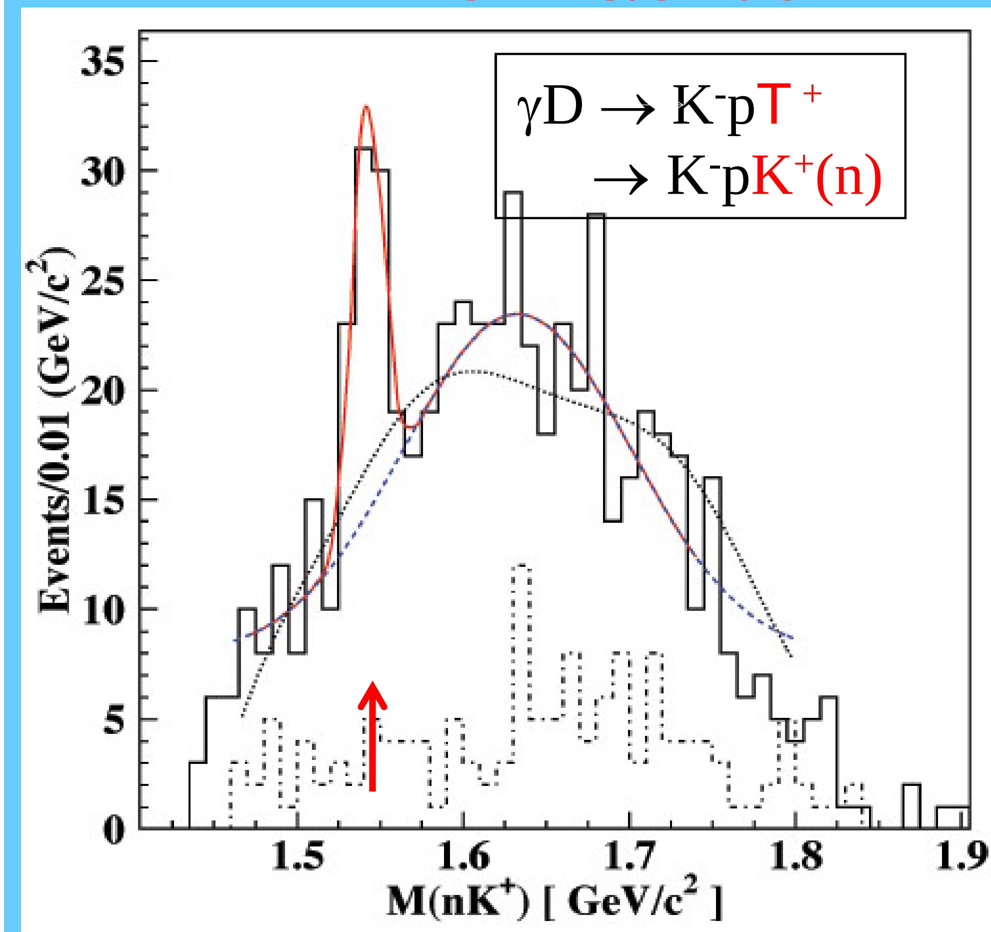
Experimental evidence for T^+ from electromagnetic probes (I)

LEPS/SPring8



Phys. Rev. Lett. 91(2003)012002

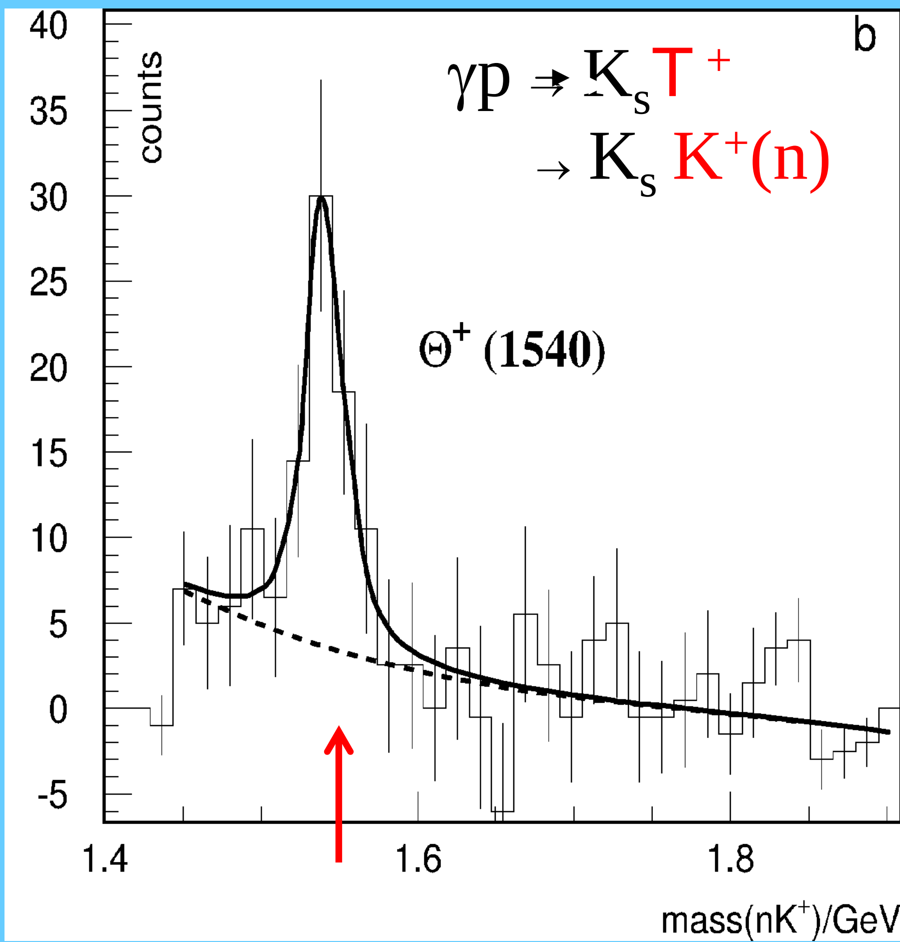
CLAS/JLab



Phys. Rev. Lett. 91(2003)252001

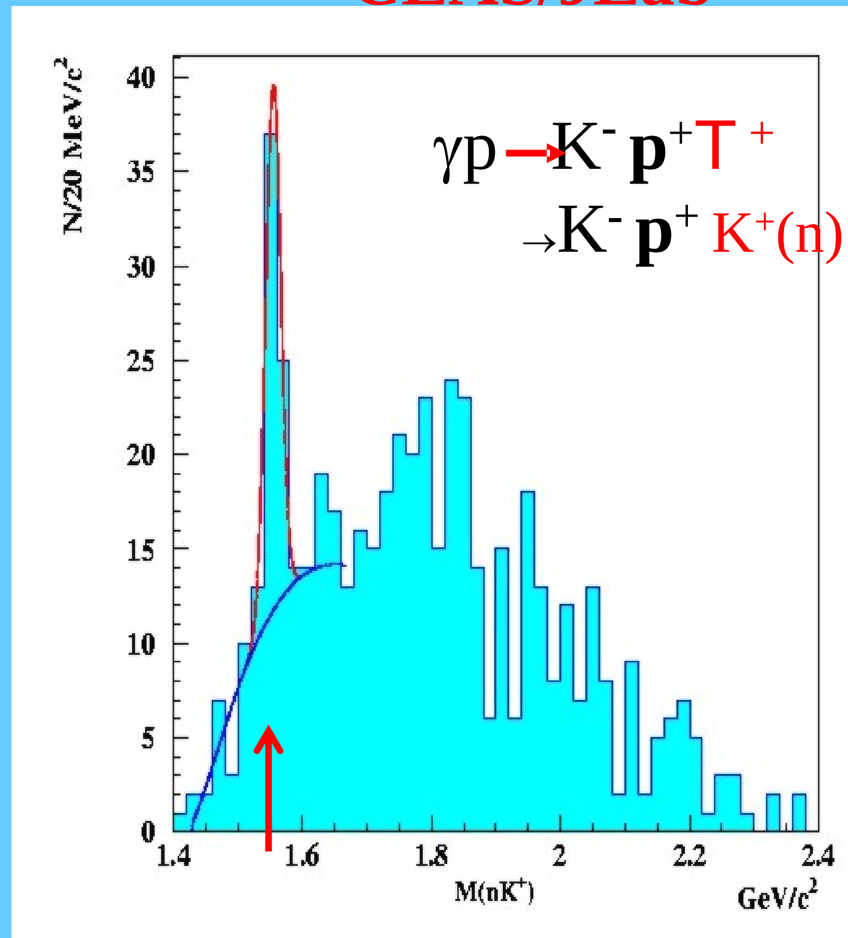
Experimental evidence for T$^+$ from electromagnetic probes (II)

SAPHIR/ELSA



Phys. Lett. B572(2003)127

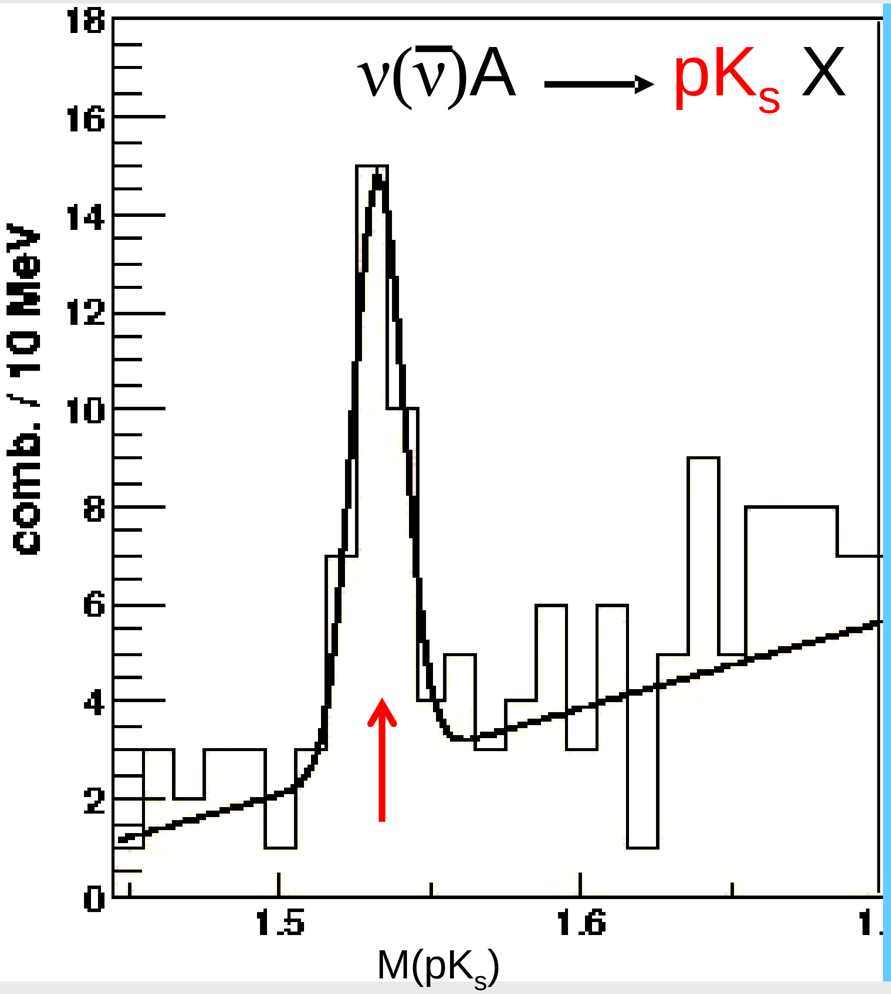
CLAS/JLab



Phys. Rev. Lett 92(2004)032001

Experimental evidence for T^+ from neutrino interactions

ITEP

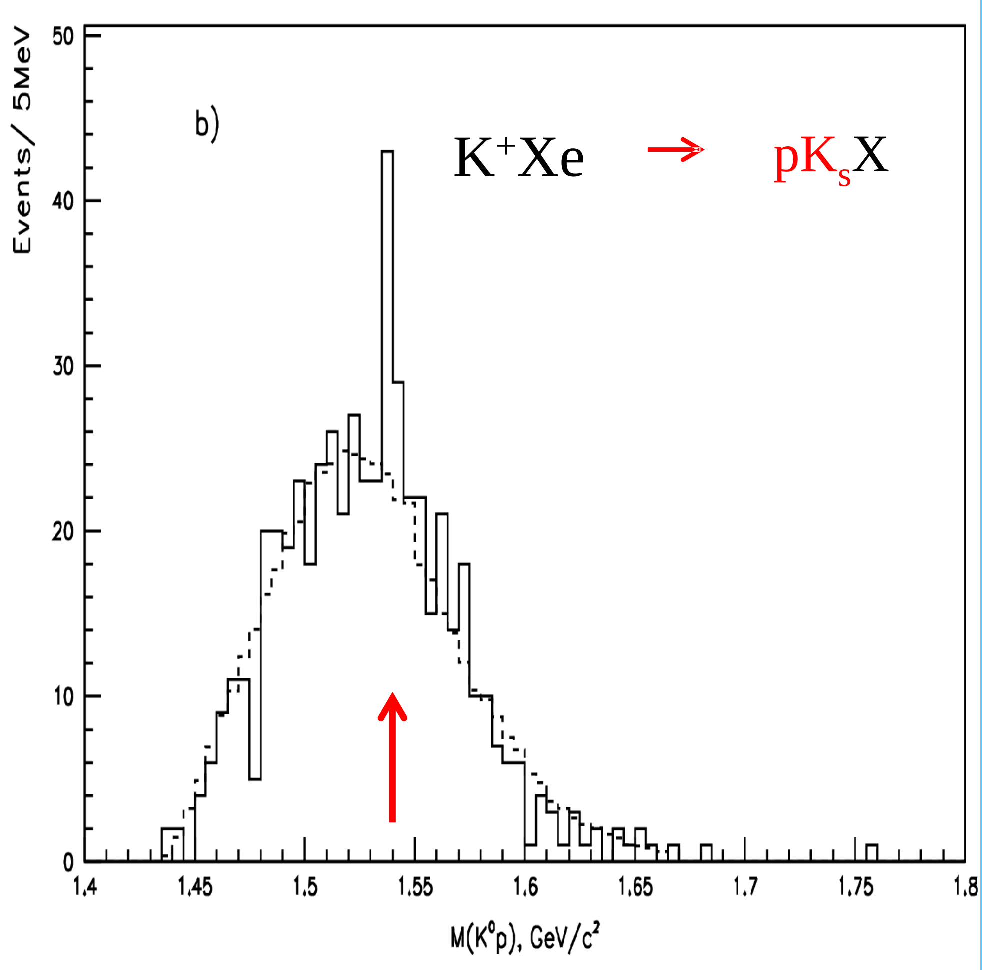


Phys.A.Nucl. 67(2004)682

- Analysis of bubble chamber data:
  - FNL: 15-feet chamber
  - CERN: BEBC
  - filled with H_2, D_2, Ne
  - 120000 ν_μ and $\bar{\nu}_\mu$ CC events
- Results of combined D_2 and Ne data

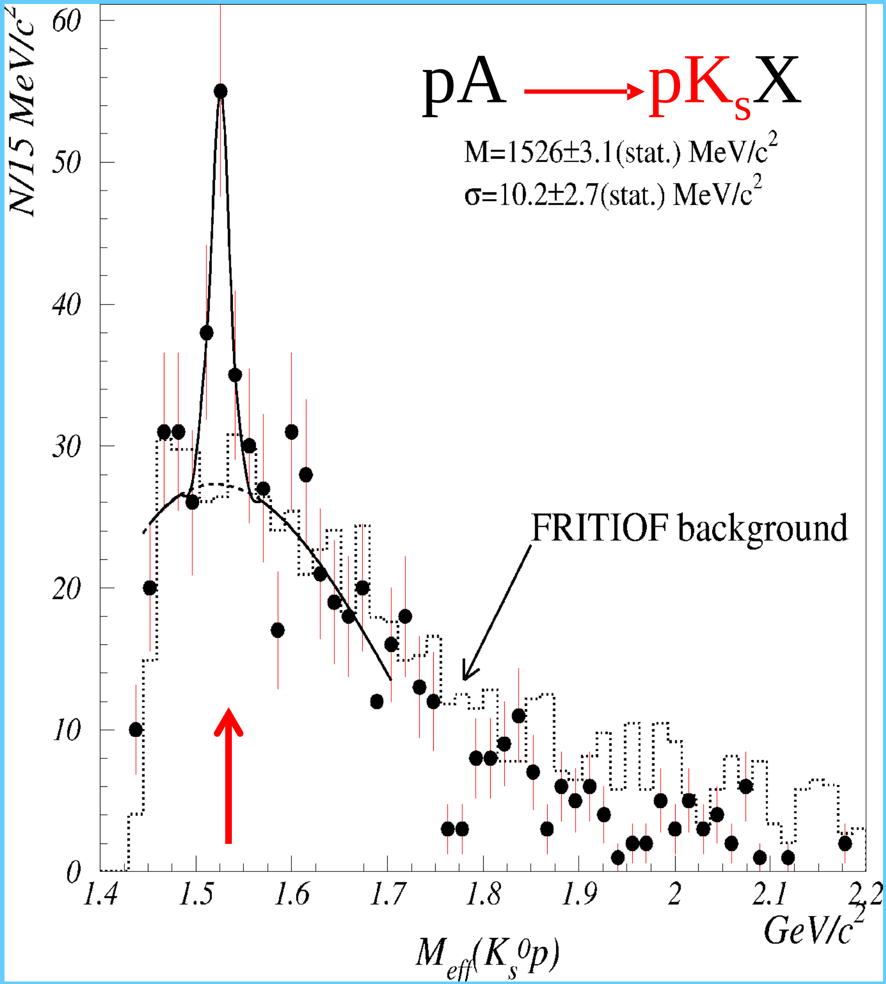
Experimental evidence for Θ^+ from hadronic probes (I)

DIANA



Phys.A.Nucl. 66 (2004)500

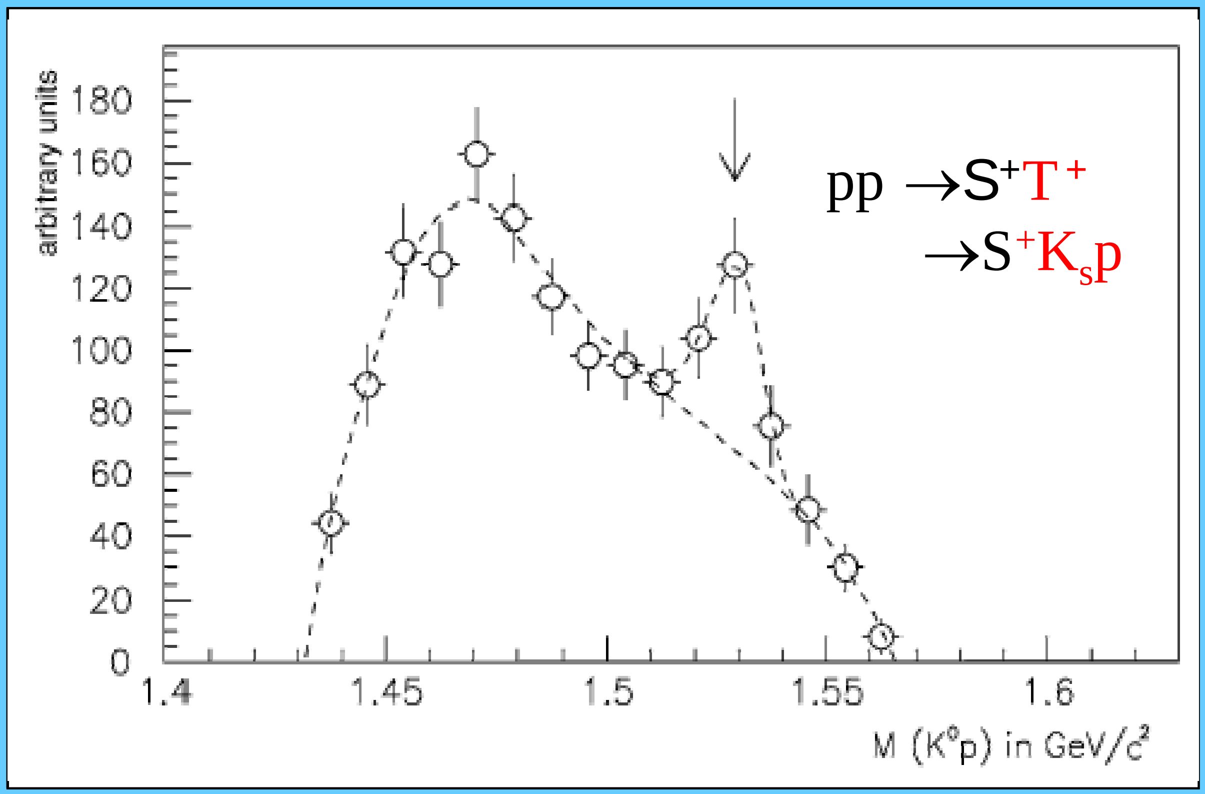
SVD/IHEP



hep-ex/0401024 (2004)

Experimental evidence for Θ^+ from hadronic probes (II)

COSY-TOF



Phys. Lett. B 595(2004)27

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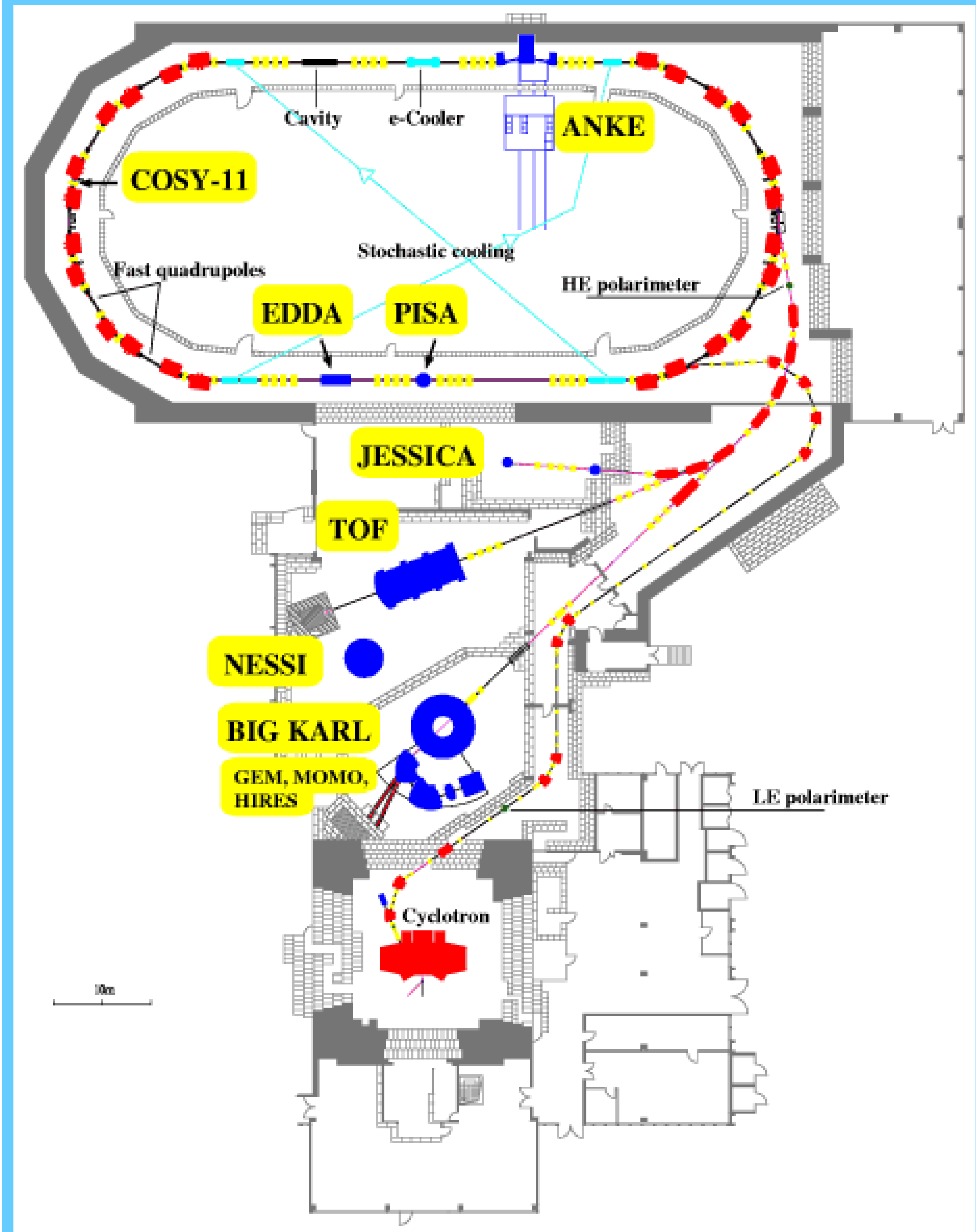


- 184 *m* circumference
- 10^{11} protons per filling
  @ 620 *MeV* (25 *mA*, T ~ 600 *ns*)
- Pc_{MAX} = 3,65 *GeV*
- $\Delta p/p \cong 10^{-4}$, $\varepsilon = \pi$ *mm mrad*
  (1 *mm* Ø · 0,18°) ***beam cooling***
- up to 80% polarization

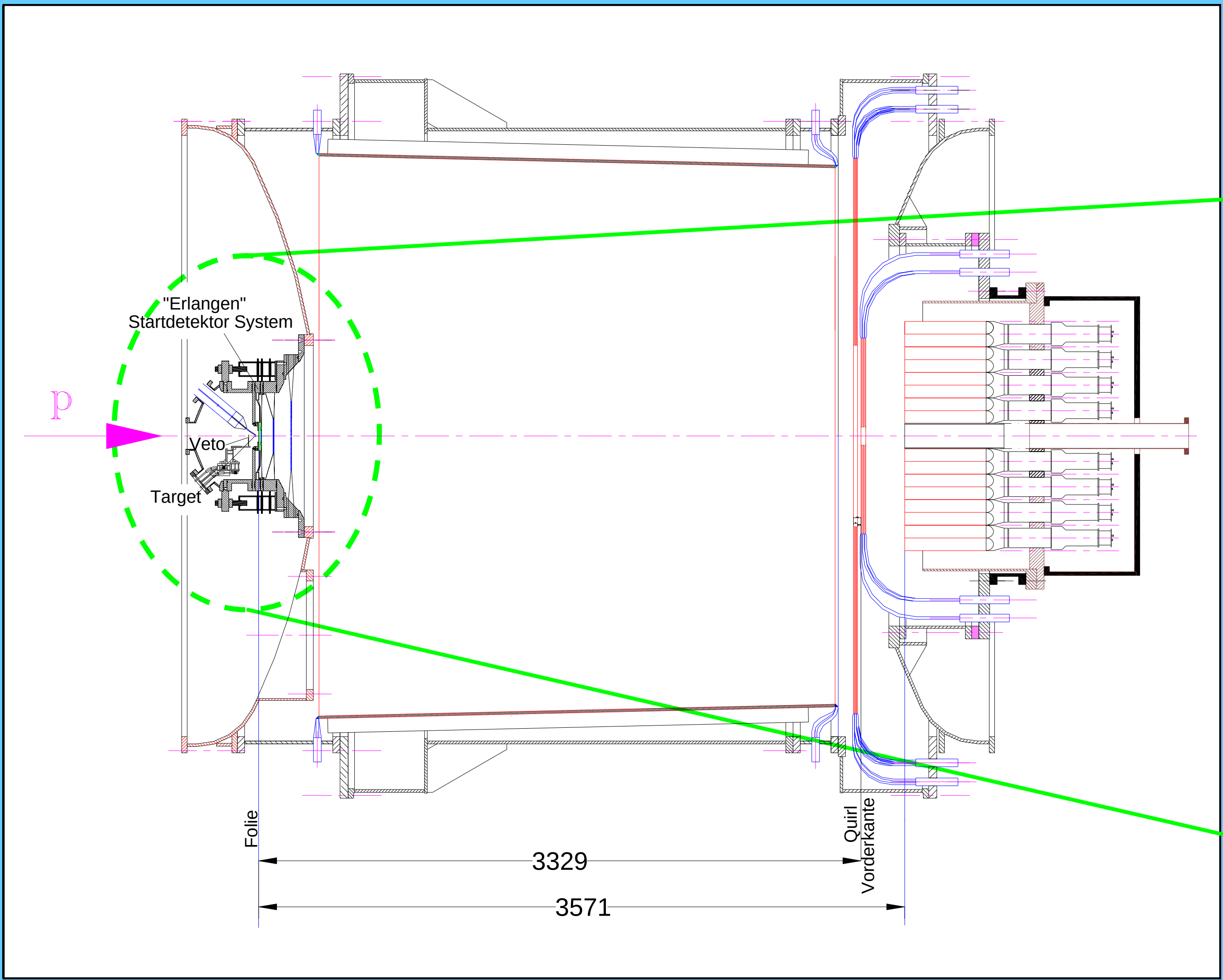
Extracted beam:

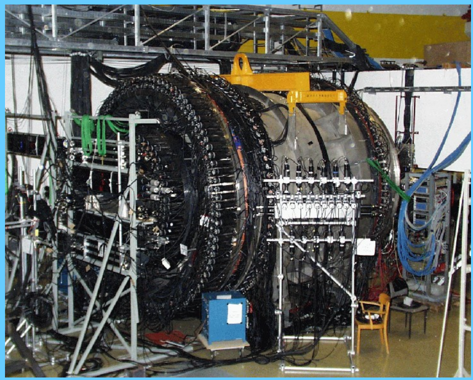
- $10^5 \ldots 10^9$ protons /*s* in spill
- 1 *s*...>2 *min* spill, 5 *s* inter-spill
  OR $2 \cdot 10^9$ p in 200 *ns*
- Quasi-DC, polarized

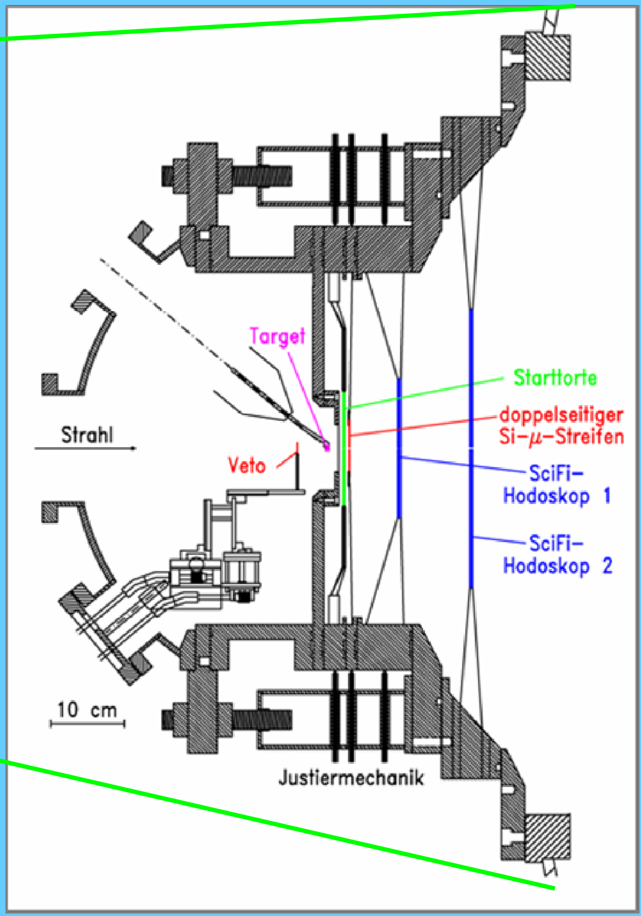
The COSY-TOF experiment

high-acceptance Time-of-Flight spectrometer

with vertex tracking







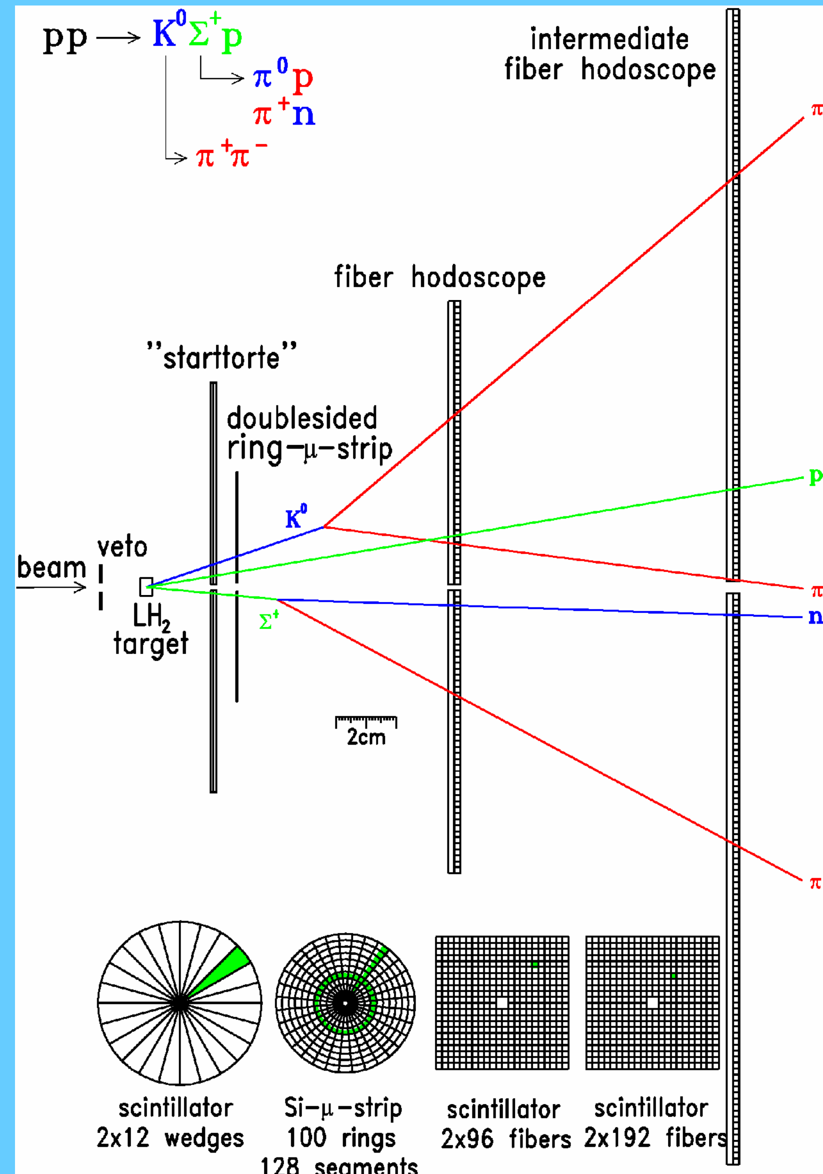
The COSY-TOF experiment

COSY-TOF designed to identify strangeness
(pp →pK$^+$Λ, pK^{0}S$^+$, pK$^+$S^0, nK$^+$S$^+$)

reaction identification:

- primary track → proton
- delayed decay “V“ of $K_S \rightarrow \pi^+\pi^-$

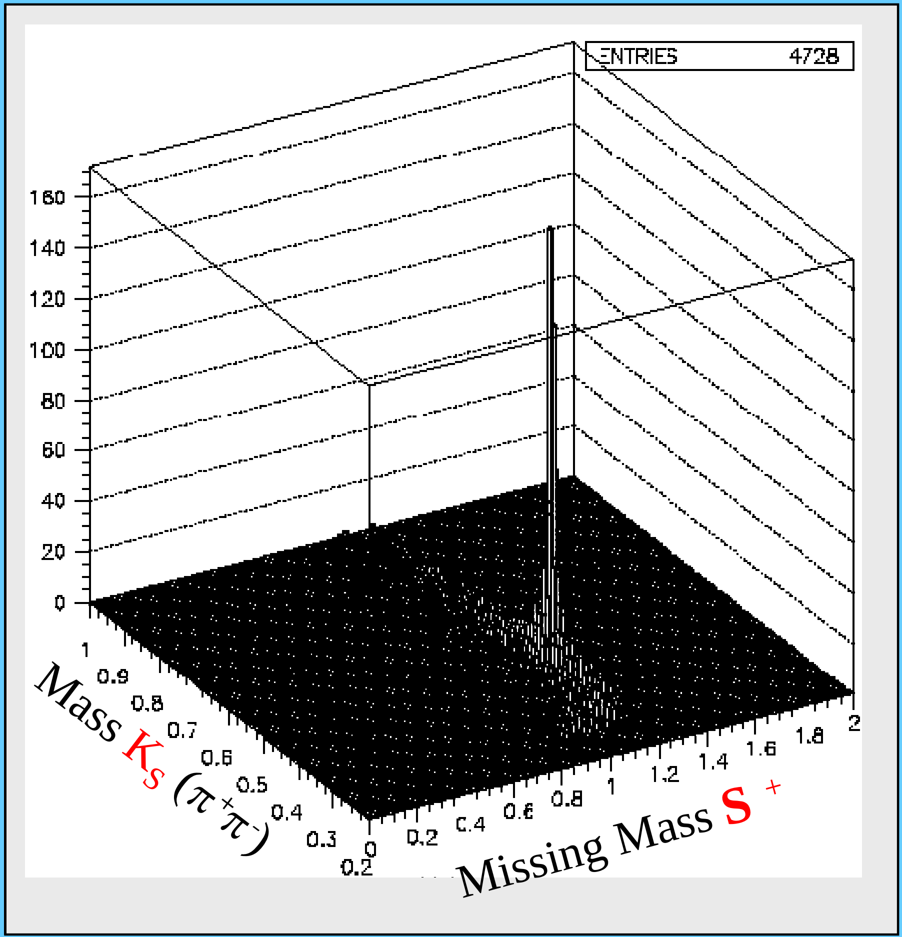
  without start scintillators / Si
- decay of Σ^+, kink
- time-of-flight of proton



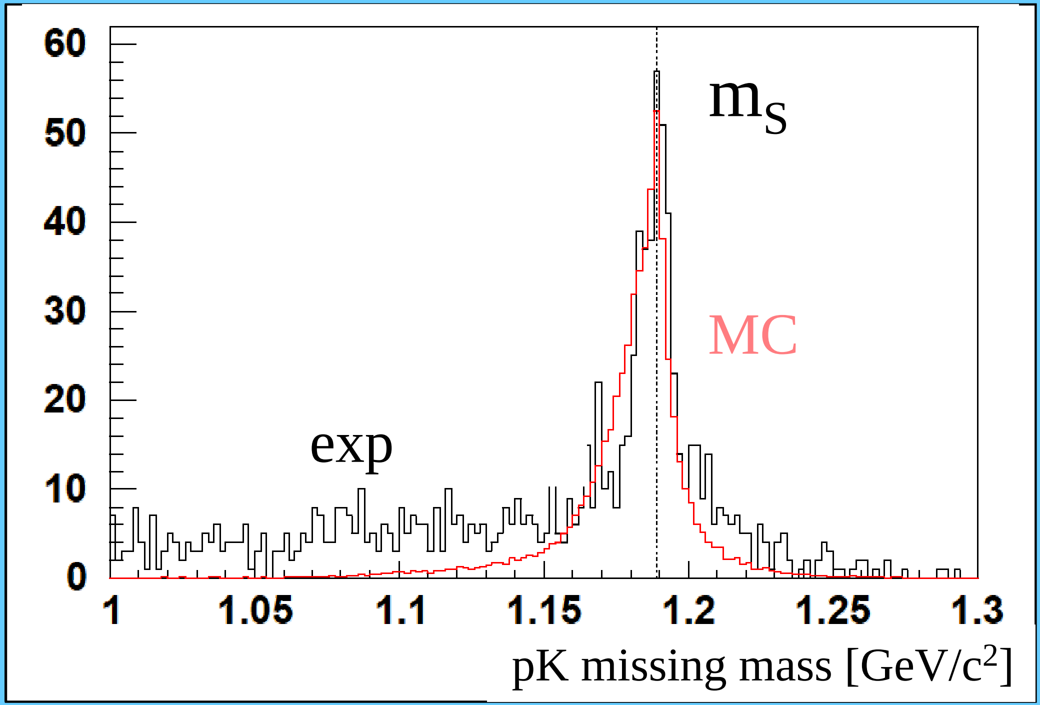
pp →pK$_S$S$^+$: search for the T$^+$

pp → $pK_S\Sigma^+$: reaction identification

using geometry only



and using ToF

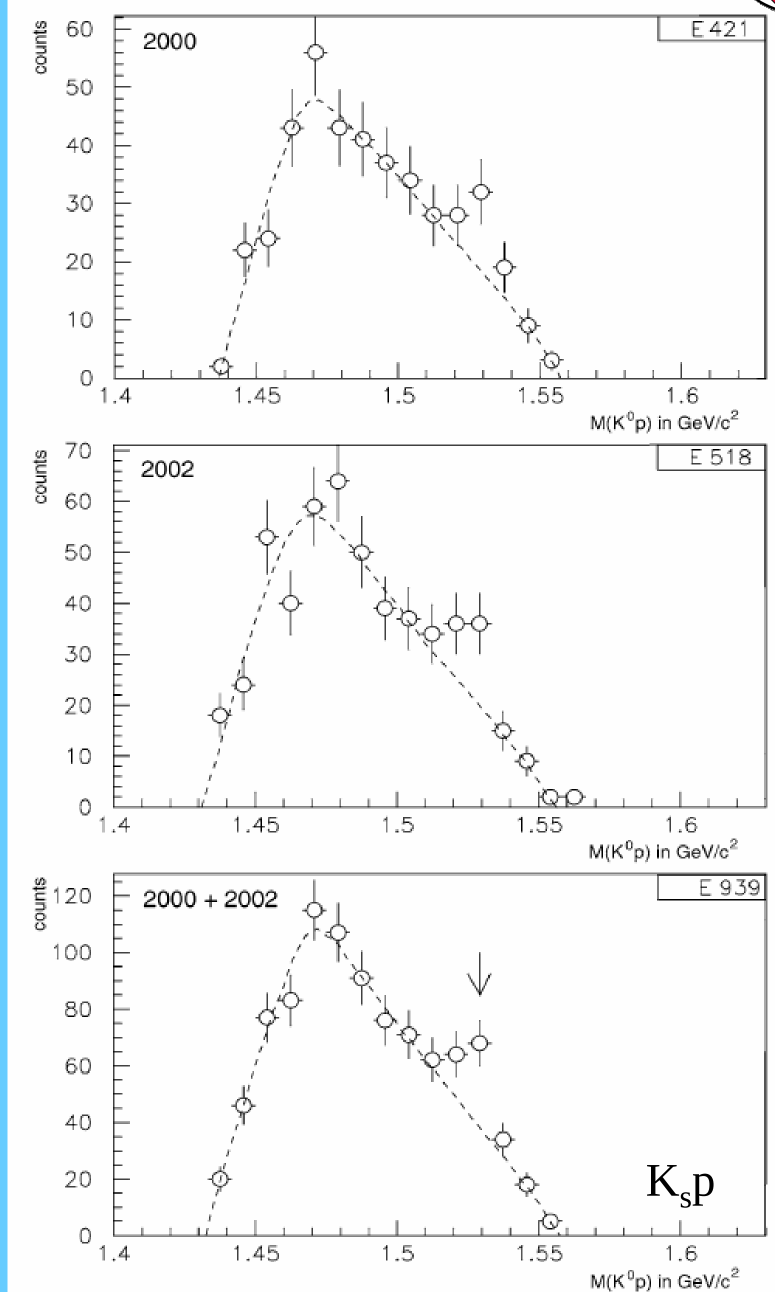


Missing mass of primary p and K → Σ^+

pp → pK_sS^+: Results

COSY-TOF collaboration
PLB595 (2004) 27

Sum of two experiments (2000 and 2002) yields about 1000 events of pp →pK_SS^+

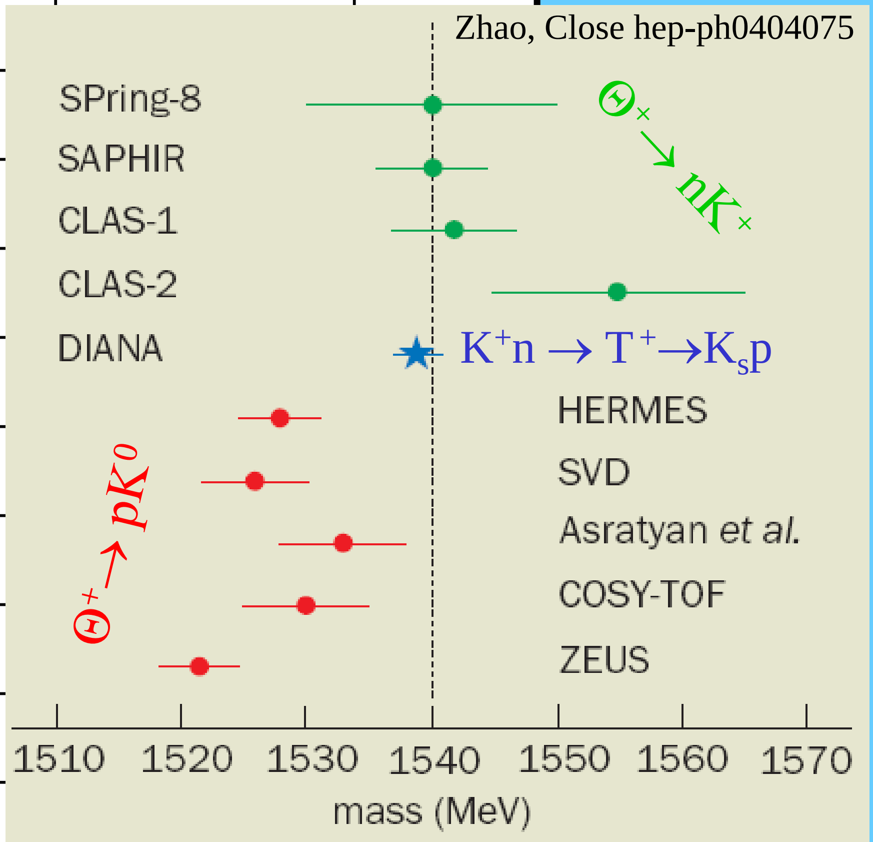


Excursion in K_sp spectrum at

mass = (1530 ± 5) MeV/c²
width < 18 MeV/c² (FWHM)
compatible with detector resolution
statistical significance of 4-6 s
cross section $(0.4\pm0.1_{stat}\pm0.1_{sys})$ μb

Summary of Evidences

	Reaction	Mass / MeV	Width/MeV	s *
LEPS	$\gamma C \rightarrow K^+K^- X$	1540 ± 10		
CLAS-1	$\gamma d \rightarrow K^+K^-p(n)$	1542 ± 5		
SAPHIR	$\gamma p \rightarrow K^+K_s(n)$	1540 ± 6		
CLAS-2	$\gamma p \rightarrow p^+K^-K^+(n)$	1555 ± 10		
HERMES	$e^+d \rightarrow K_sp X$	1528 ± 3		
ZEUS	$e^+p \rightarrow e'K_sp X$	1522 ± 3		
ITEP	$\nu A, \bar{\nu}A$ □K_spX	1533 ± 5		
DIANA	$K^+Xe \rightarrow K_sp X$	1539 ± 2		
SVD/ITEP	$pA \rightarrow K_sp X$	1526 ± 3		
COSY	$pp \rightarrow K_spS^+$	1530 ± 5		



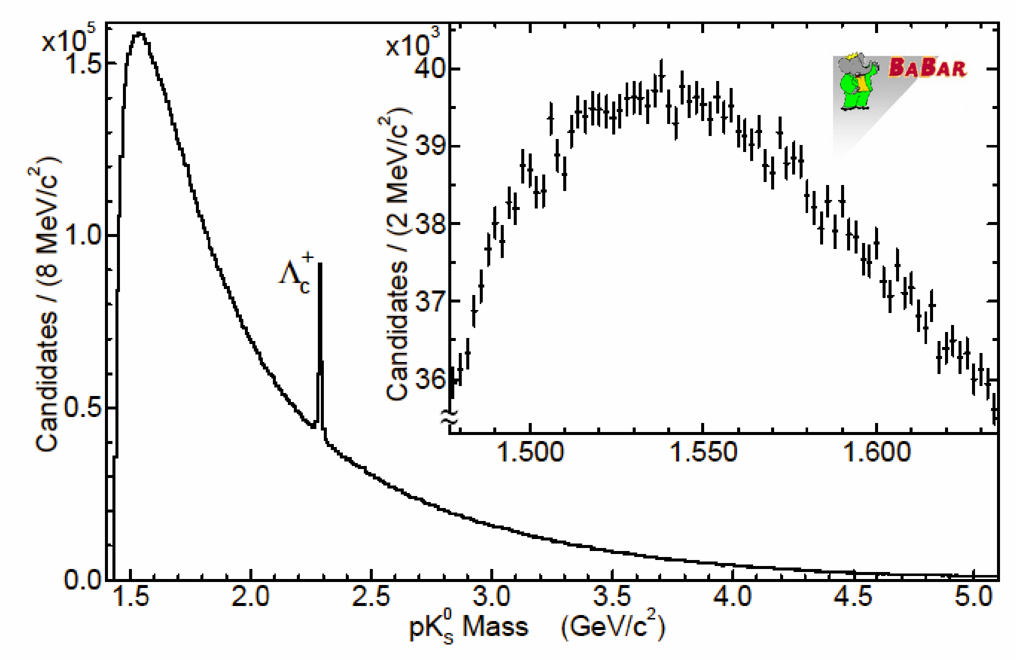
*Gaussian statistical significance: estimated background fluctuation

Lack of experimental evidence

BaBaR, Delphi, BES, CDF, HyperCP, E690, HERA-B, Aleph, Phenix

Common features:

- large data samples
- excellent resolution
- high energy
- inclusive
- e^+e^- or hadronic probes



Problems and (possible) solutions in pentaquark searches

- **Most of the positive experiments performed so far suffer from**
  - small data samples → limited statistical significance
  - limited acceptance → only certain region of phase space probed
  - poorly understood competing reactions (background!) → cuts tailored to enhance signal to background ratio
  - cuts which may produce artificial structures if signal and background deviate from pure phase space in different way

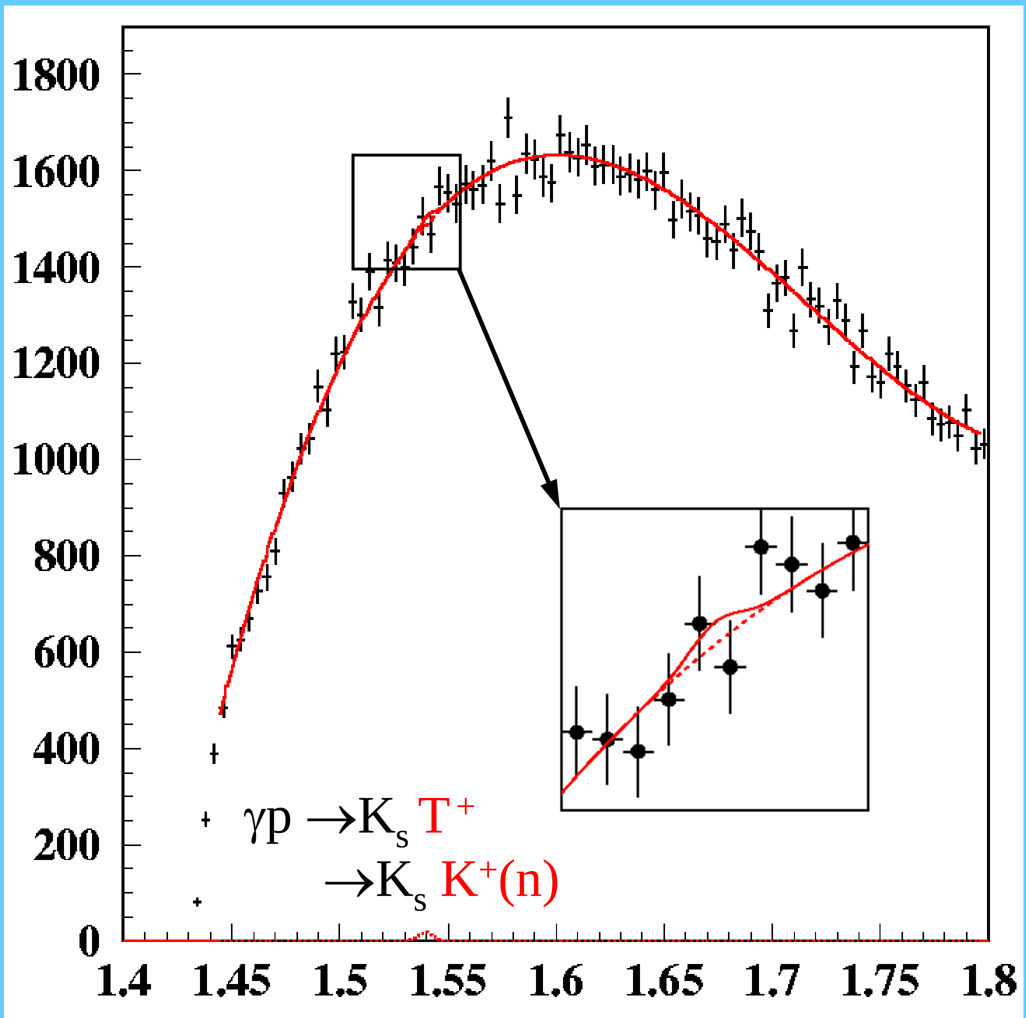
- **Needed: 2. generation experiments with**
  - large data samples
  - experiments with nearly 4π acceptance (COSY-TOF)
  - Dalitz plots to reveal the full dynamics: partial wave analyses
  - detailed Monte Carlo simulation of competing reactions (physics simulations) and their analyses with the same program used for data analysis

- **If pentaquarks, e. g. the Θ^+, exist, mass, width and parity need to be determined**

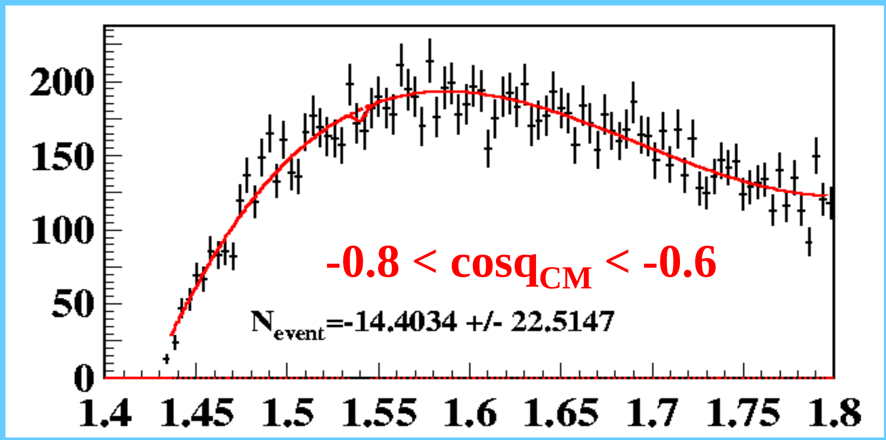
2. Generation experiments

• CLAS	γd, γp
• LEPS	γd
• CB@ELSA (Saphir follow up)	γp
• BELLE	e^+e^-, K^+A
• COSY-TOF	pp

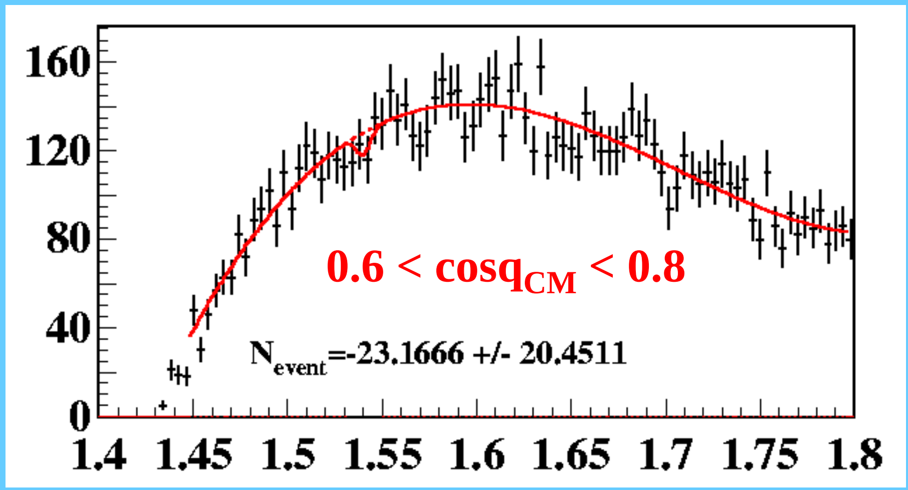
2. Generation experiments
CLAS: Upper limit on the T^+ yield



M(nK+)(GeV)



M(nK+)(GeV)

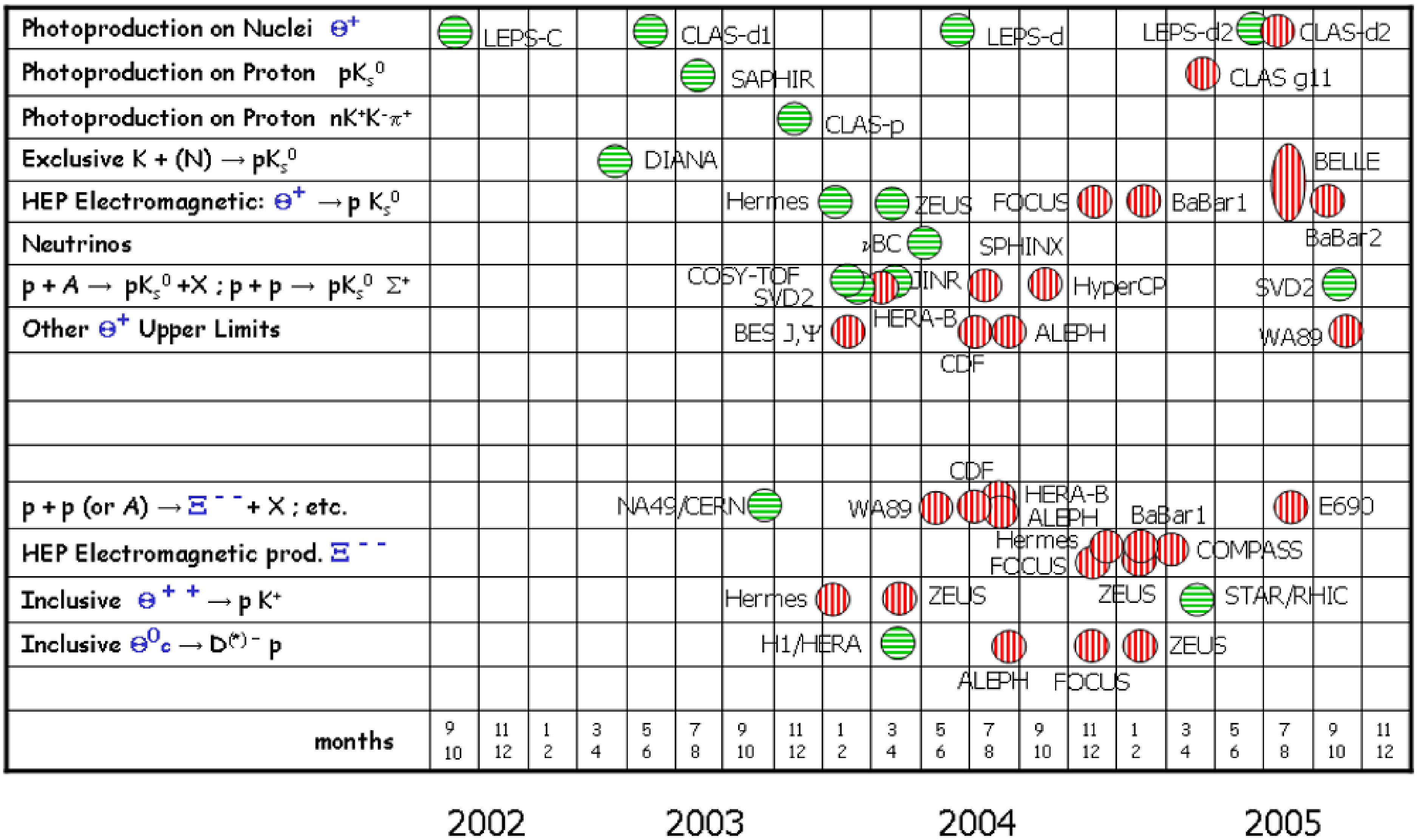


M(nK+)(GeV)

From: DeVita for the CLAS–Collaboration APS Meeting April 2005

Pentaquark Exp’ts Timeline

Reinhard Schumacher (PANIC05)



Conclusion

- Several experiments have shown evidence for a manifestly exotic (S = +1) pentaquark T^+(1530)
- Several experiments lack evidence for T^+(1530)
- The pentaquark T^+ (1530) has not been convincingly proven to be alive or dead
- If it exists, it likely is an isoscalar, spin ½ baryon of unknown parity
- "Should the T^+ pentaquark not survive the next few years of intense scrutiny we will have to examine why so many experiments observed the signal in the first place"

  (Volker D. Burkert, CLAS collaboration at JLab)