"PentaQuarks: Experimental Review"

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"An Observer's *view* of PentaQuark Experiments"

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"PentaQuarks: damn peaks or statistics"

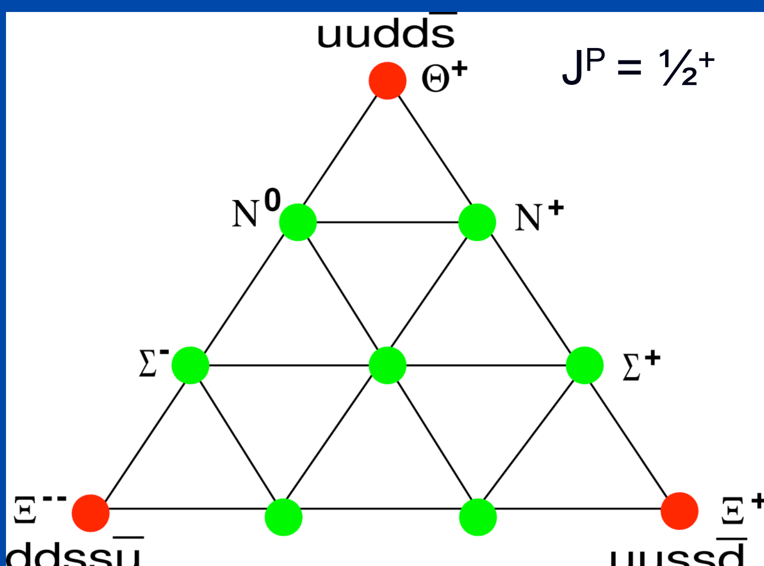
(after Samuel Clemmens)

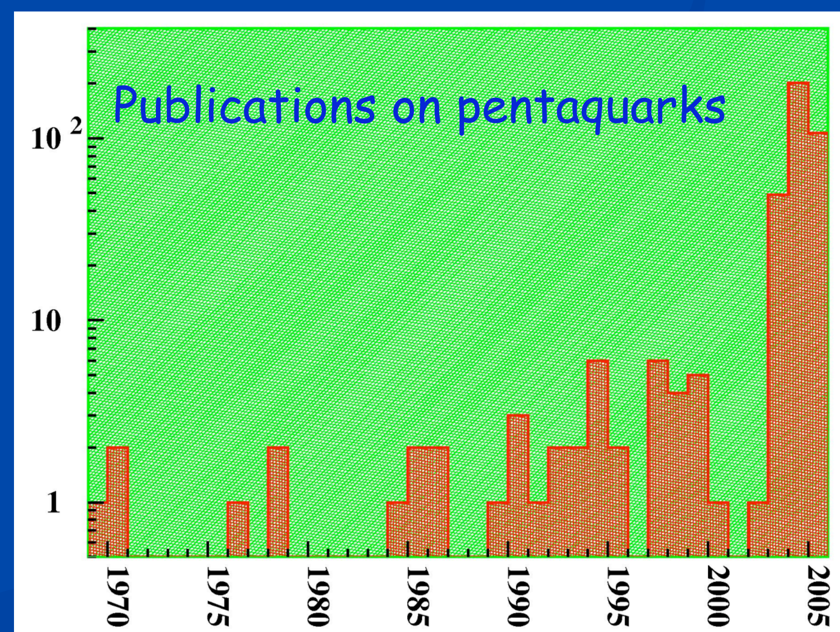
A.M. Sandorfi
Brookhaven National Lab

Pentaquark history

- General idea of five-quark states has been around since late 60's. Predicted masses range from 1500 to 1800 MeV, widths ~hundreds MeV.
  - Bag models [R.L. Jaffe '76, J. De Swart '80], lightest pentaquark $J^P = 1/2^-$;
  - Soliton models [Diakonov, Petrov '84, Chemtob'85, Praszalowicz '87. Walliser'92]
- A new wave of experimental searches was motivated by predictions in χSM model: Diakonov, Petrov, Polyakov. Z.Physics A359 (1997).

Anti-decuplet $q^4\bar{q}$ states





Θ^+ : M = 1530 MeV, Γ < 15 MeV

V. Burkert, *NSTAR'05*

The consequences of finding narrow *pentaQuarks:*

- QCD does not rule out $q^4\ \bar{q}$ states;
  if they could be shown to definitely not exist ⇒ something missing from QCD
- why a narrow width ?
  what aspects of their structure keep them together so long ?
  - meson+baryon molecule
  - diquark+ diquark+antiquark

  ⇒ another potentially useful handle on non-perturbative QCD
- the bottom line:

It sure would be fun if they're real !!!

Suggested properties of the Θ^+

- Spin = 1/2 (3/2 ?)
- Parity = + (– ?)
- Isospin = 0
- **Strangeness = +1**

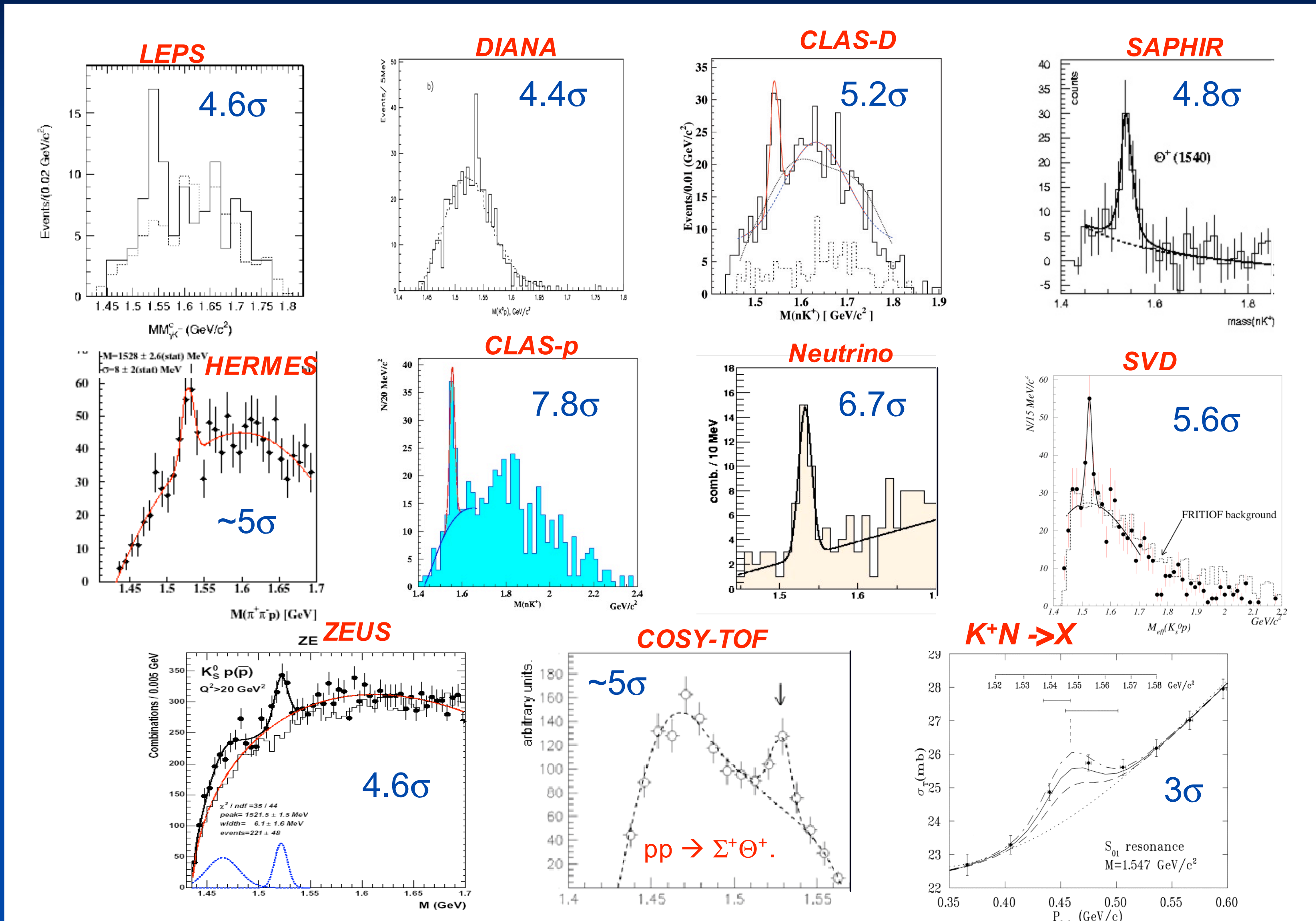
Decay channels

- quark structure: $uudd\bar{s}$

$$uudd\bar{s} \rightarrow (udd)(u\bar{s}) \equiv nK^+$$

$$uudd\bar{s} \rightarrow (uud)(d\bar{s}) \equiv pK^0$$

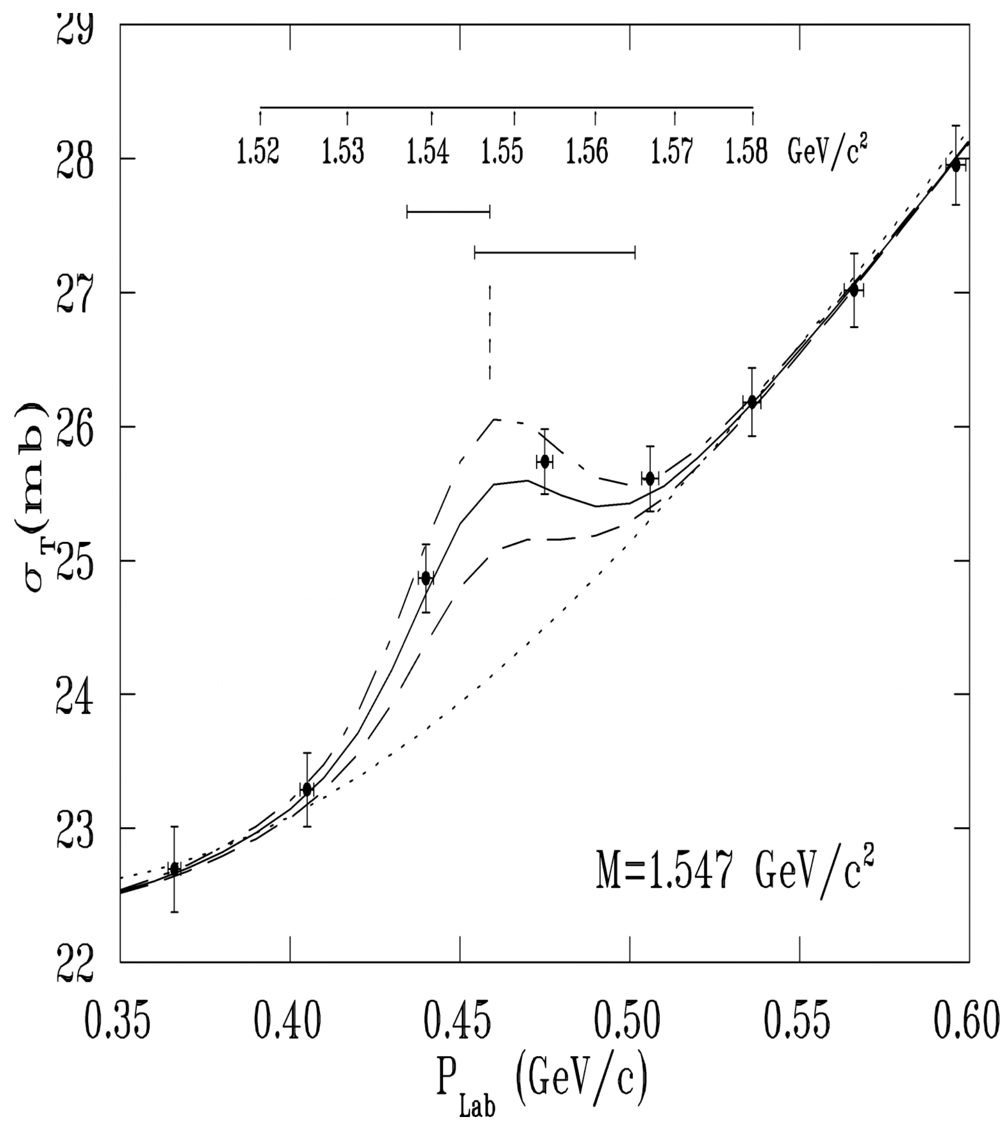
The initial evidence for the Θ^+



Limits on the Θ^+ width:

- all positive results show peaks consistent with exp. resolution

W. Gibbs, PRC70, 054208 ('04)

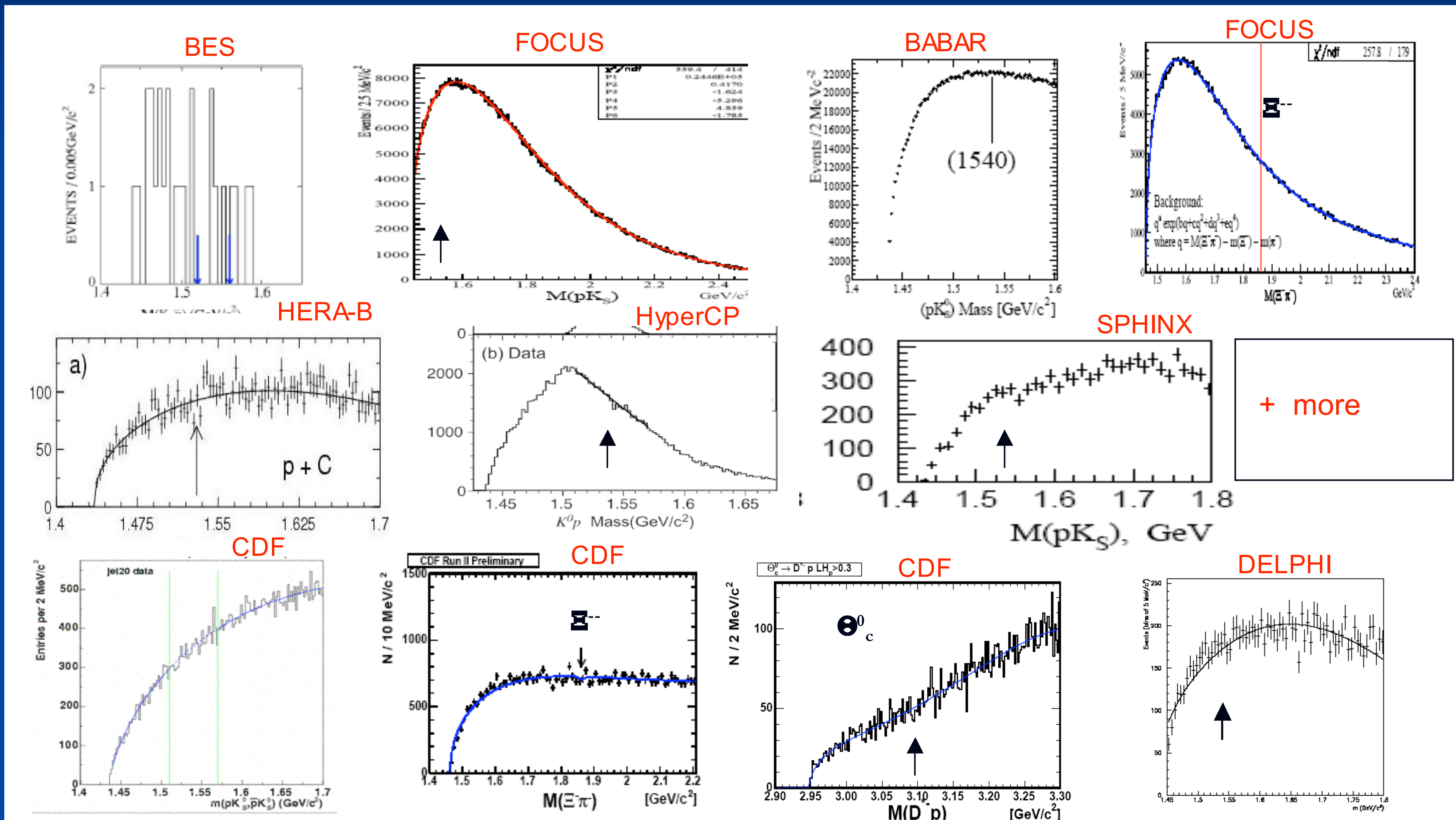


- reanalysis of K^+N scattering data base:
  - data base is noisy at low K^+ momenta;
  - analysis of selected sample:

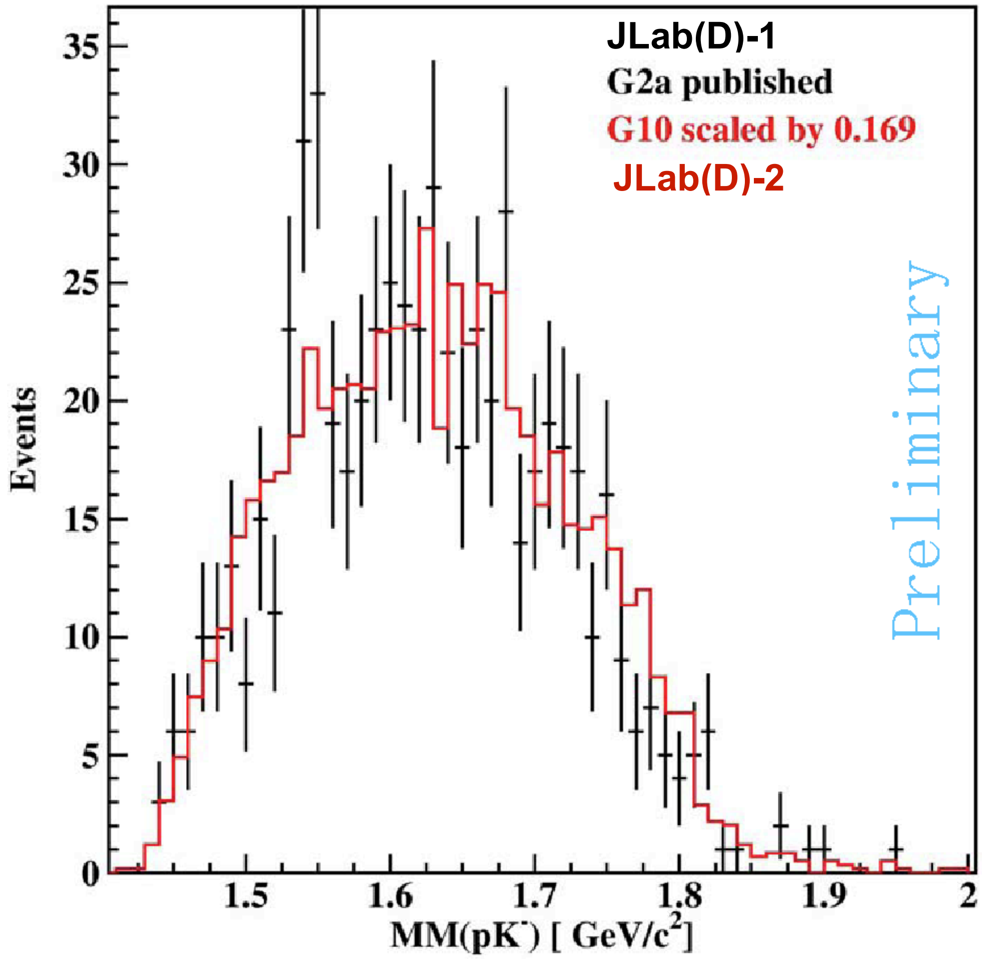
⇒ **Γ_Θ = 0.9 ± 0.3 MeV**

  - amazingly narrow;
  - even, *unbelievably* narrow?

Non-evidence for Pentaquarks



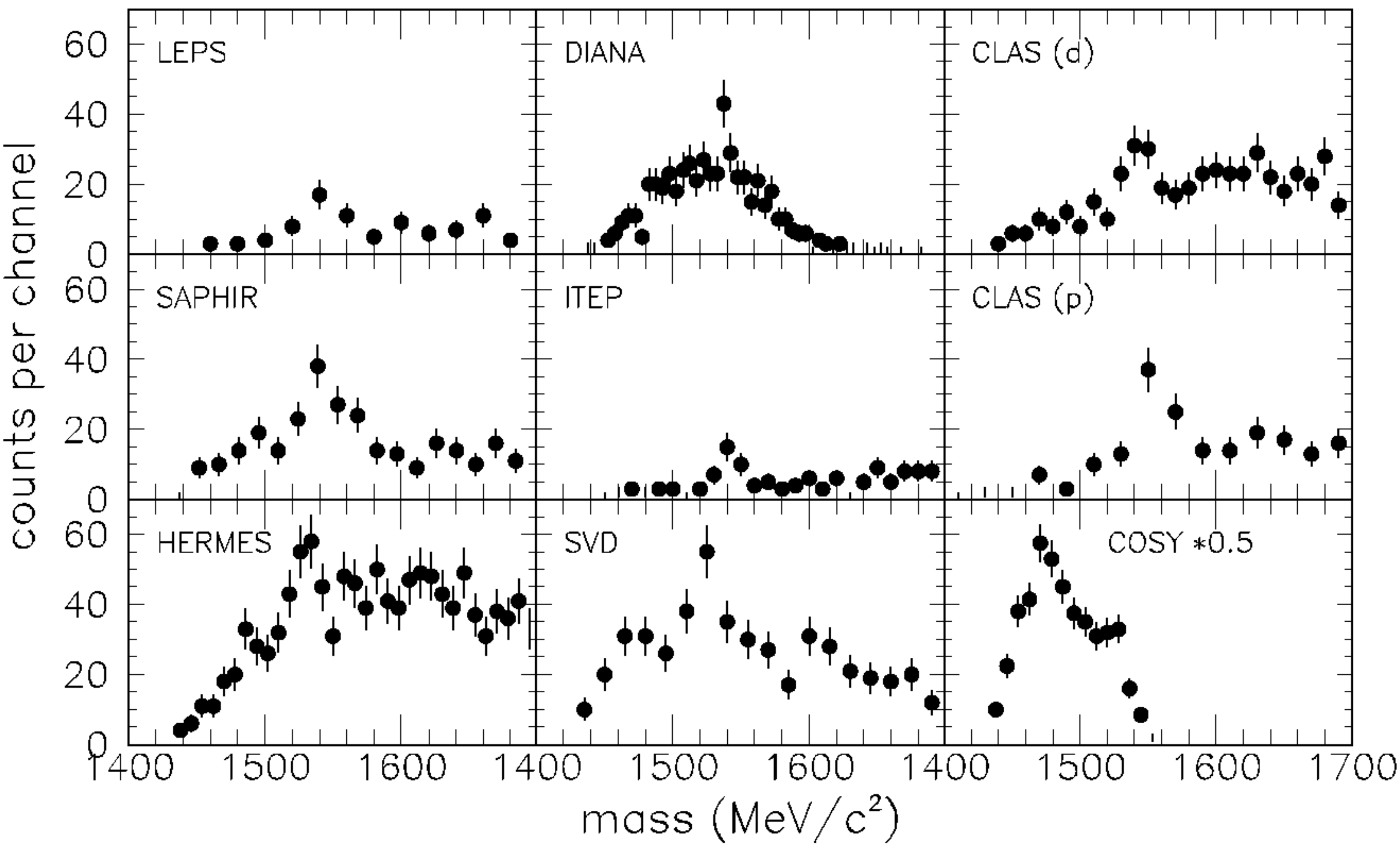
New and old CLAS data (γ D)



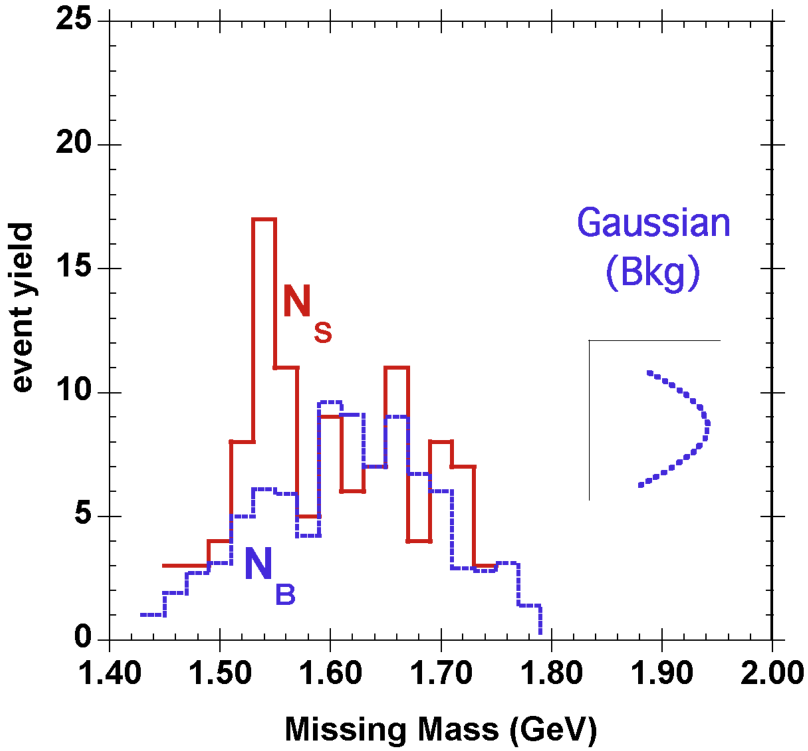
"The statistical significance in the published data is an unlucky coincidence of a statistical fluctuation and an underestimate of the background in the mass region of 1.54 GeV/c^2."

- G10 mass distribution can be used as a background for refitting the published spectrum.

Evidence for the Θ^+, without *curves to guide the eye*



from hep-exp/0504027



Bkg distributed as a Gaussian
with mean μ_B = N_B and $\sigma_{Bkg} = \sqrt{N_B}$:

$$\frac{1}{\sigma_{Bkg}\sqrt{2\pi}} e^{-(Y-\mu_B)^2/2\sigma_{Bkg}^2}$$

- probability of reaching $N_P = N_S + N_B$

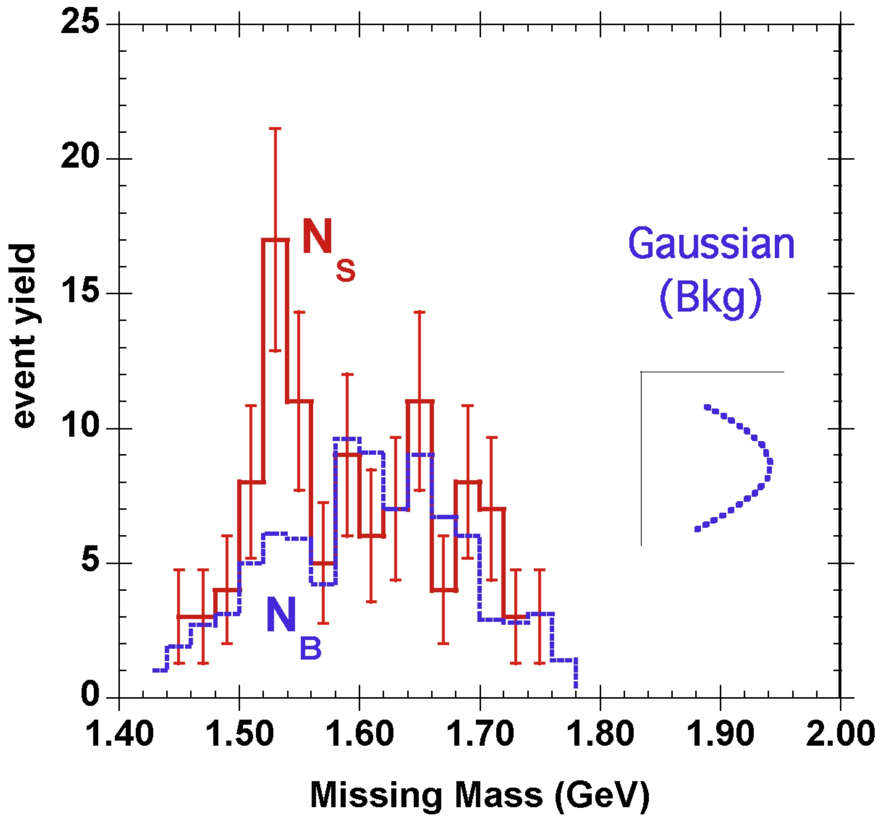
$$\Rightarrow \frac{1}{\sigma_{Bkg}\sqrt{2\pi}} e^{-(N_S)^2/2\sigma_{Bkg}^2}$$

- how far out is this, in units of σ ?

$$e^{-(K\sigma_B)^2/2\sigma_{Bkg}^2} = e^{-(N_S)^2/2\sigma_{Bkg}^2}$$

Probability of finding *exactly*

$N_P = N_S + N_B$ ⟷ $\Rightarrow K = N_S \big/ \sqrt{N_B}$



A more meaningful *statistical significance*

- probability of Bkg fluctuating up into the range $N_P \pm \sqrt{N_P}$

$$\Rightarrow \frac{1}{\sigma_{Bkg}\sqrt{2\pi}} \int_{N_P-\sqrt{N_P}}^{N_P+\sqrt{N_P}} e^{-(Y-N_B)^2/2N_B}\, dy$$

$$N_P = N_S + N_B$$

Q: how far out is this, in units of σ ?

$$K = \left\{ -2 \cdot \ln\left[\int_{N_P-\sqrt{N_P}}^{N_P+\sqrt{N_P}} e^{-(Y-N_B)^2/2N_B}\, dy \right] \right\}^{1/2}$$

$$\in \left[\frac{N_S}{\sqrt{N_S+2N_B}}, \frac{N_S}{\sqrt{N_S+N_B}} \right]$$

Statistics for published Θ^+ observations

	Reaction	$N_P = N_S + N_B$	N_B	Fluctuation to $N_P = N_S + N_B$ $= N_s / \sqrt{N_B}$	Fluctuation to $N_P \pm \sqrt{N_P}$
LEPS-1	$\gamma C \to K^+ K^- X$	36	17	4.6	3.1
DIANA	$K^+ Xe \to K^o_S pXe'$	72	43	4.4	2.9
JLab(D)-1	$\gamma D \to K^+ K^- pn$	103	59	5.8	4.4
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HERMES	$e^+ D \to K^o_S pX$	201±15	148	4.3	2.7
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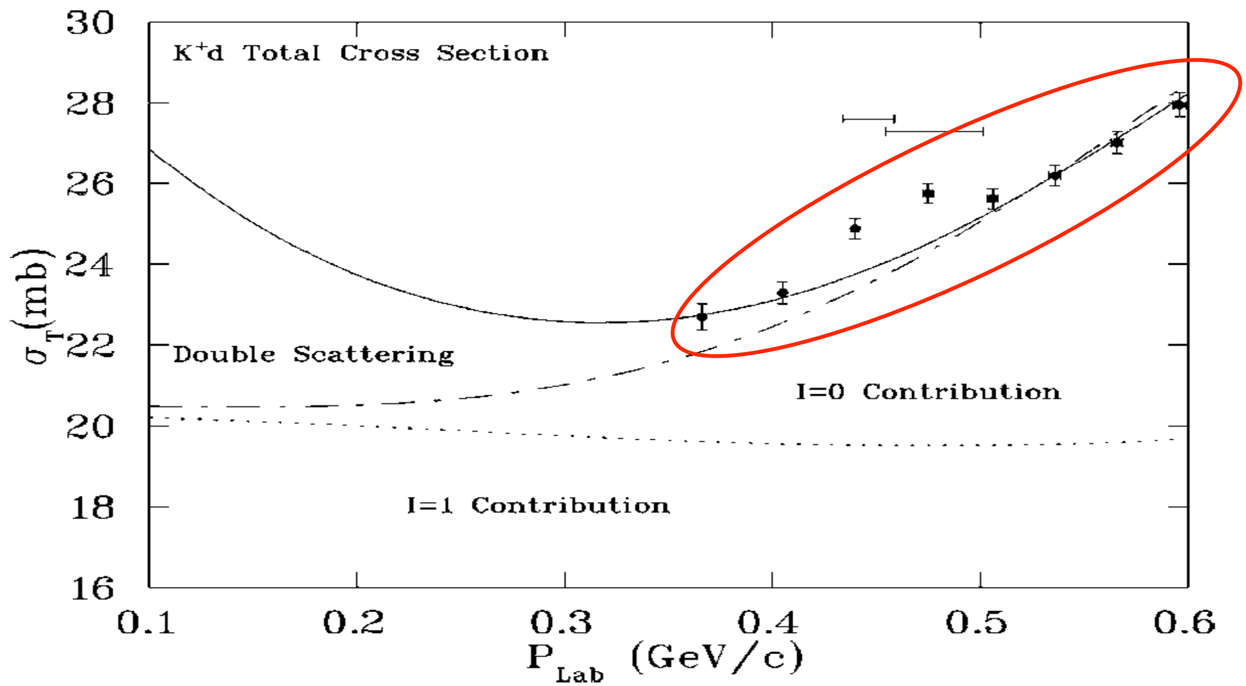
K^+N scattering analysis

W. Gibbs, PRC**70**(04)

- **I=0 from K^+D**
- **I=1 from K^+p**

- **8 points come from 1 out of 4 data sets;**
- **renormalized to another set with larger errors**

- **significance depends critically on shape of I=0 cross section**



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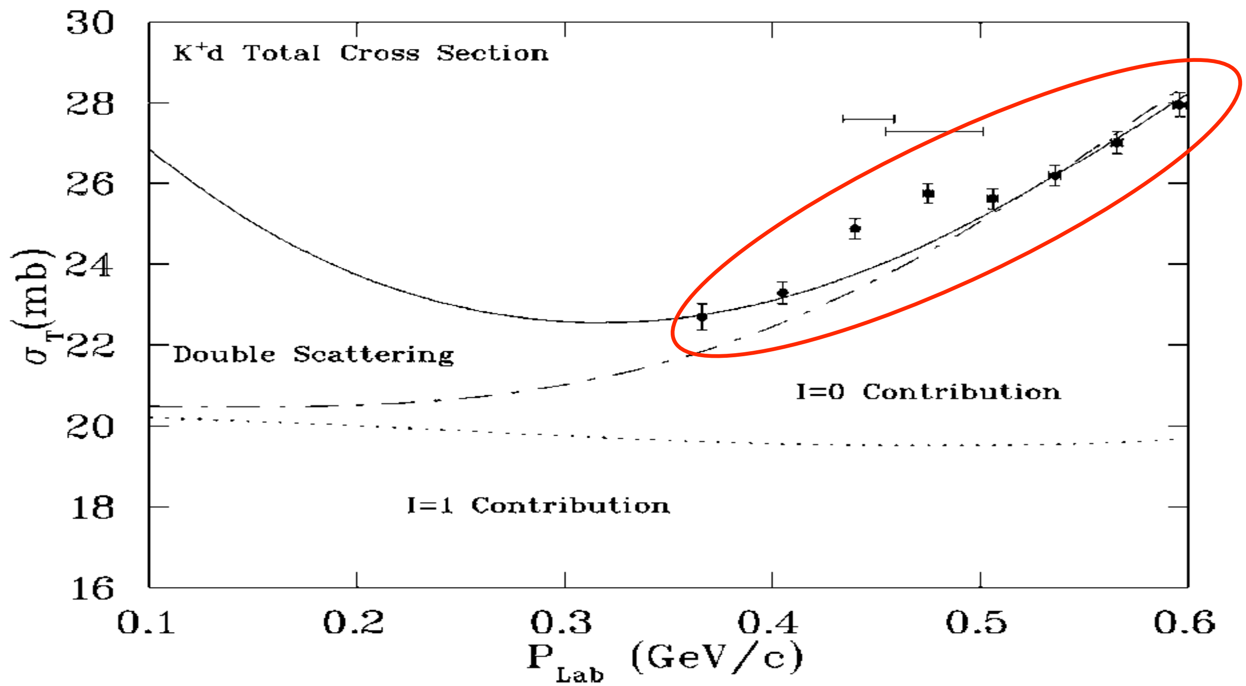
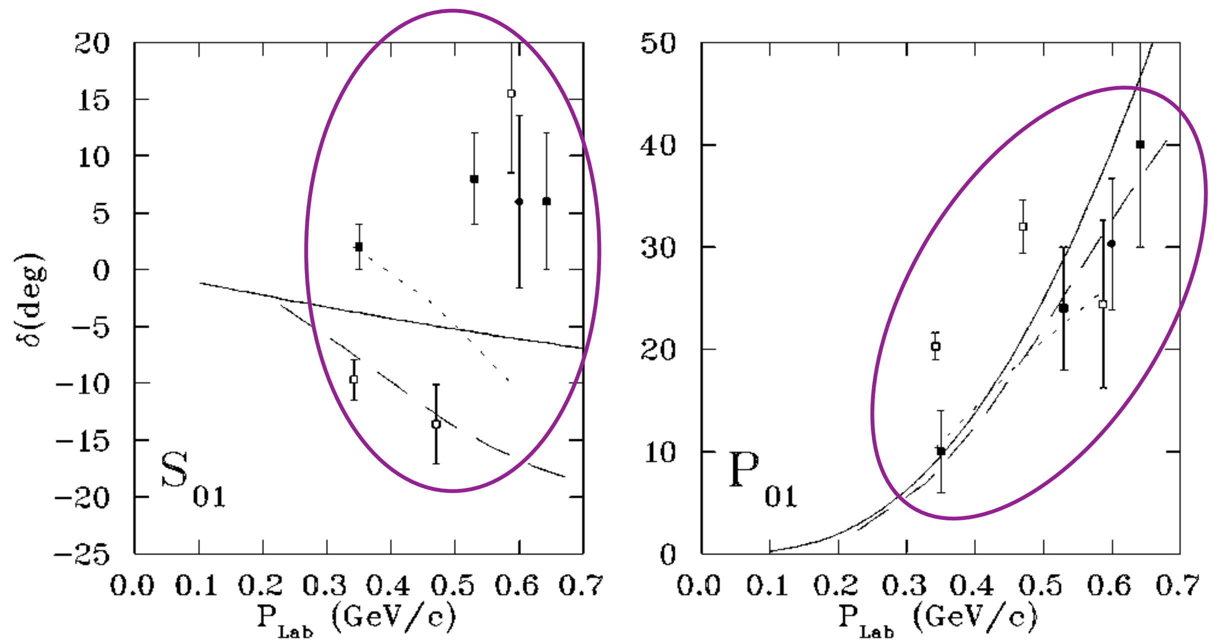
- **significance depends critically on shape of I=0 cross section**

- **scatter in single-energy solutions ⇔ scatter in data sets**

- **intriguing result, BUT !?!**





Statistics for published Θ^+ observations

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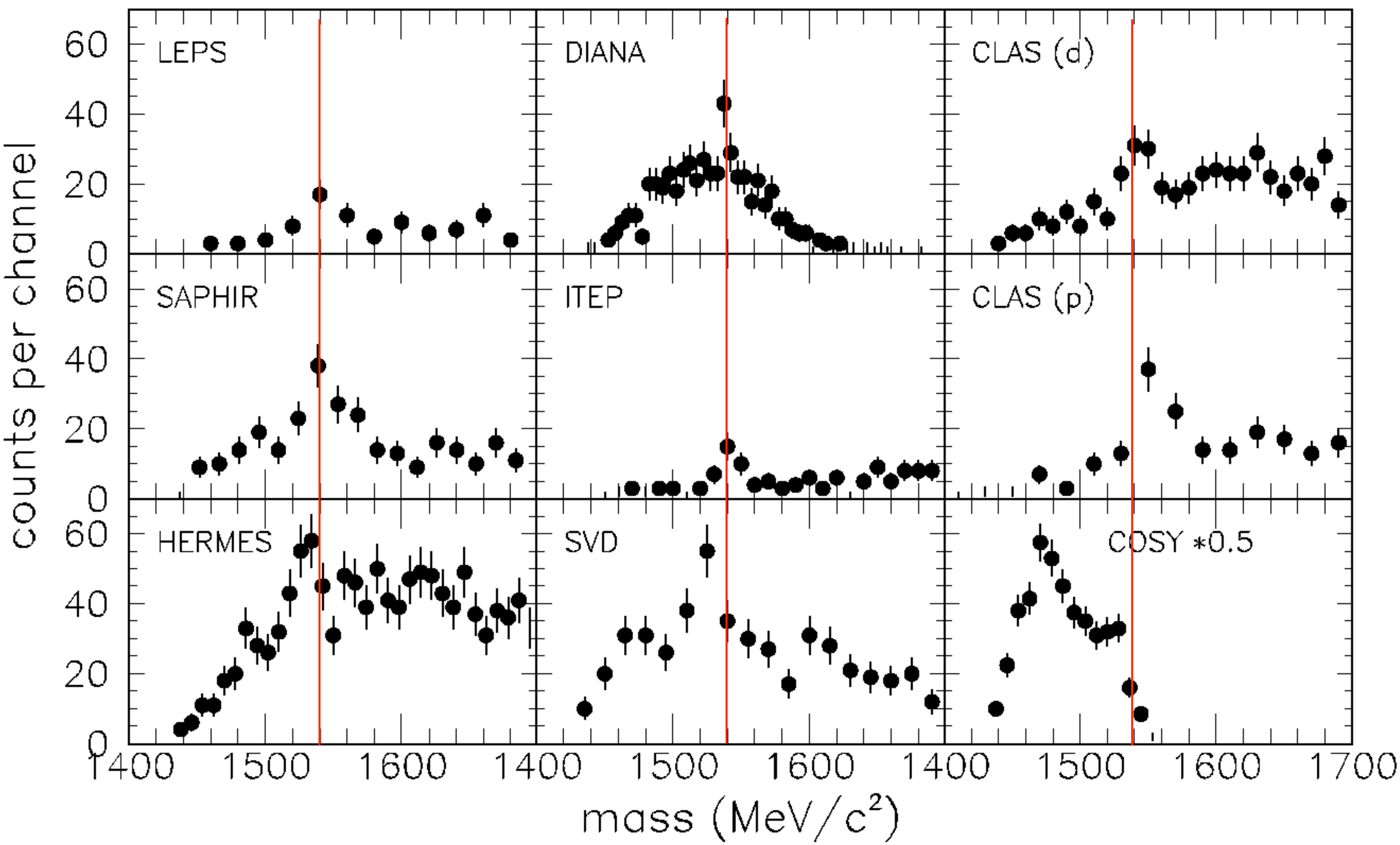
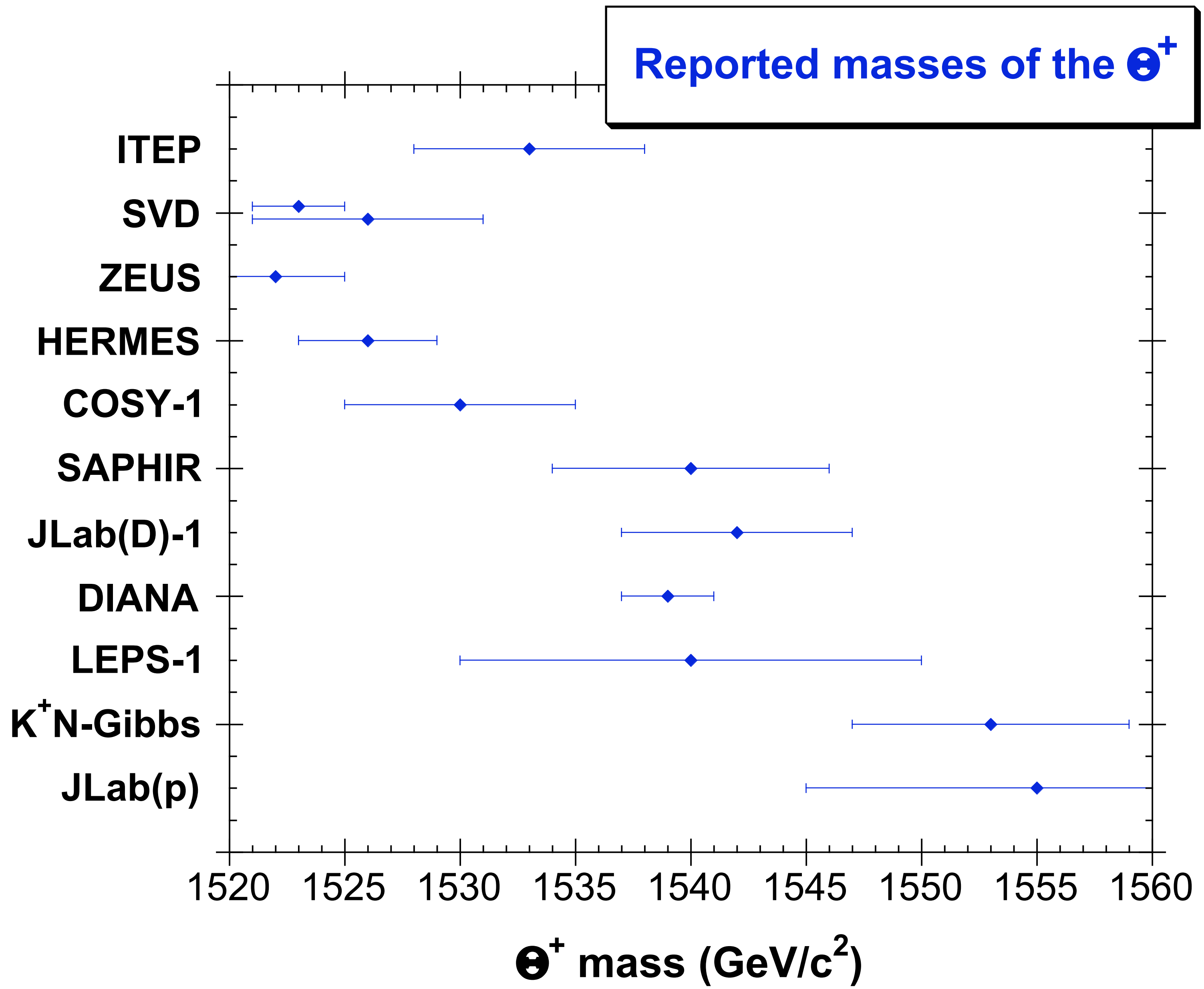
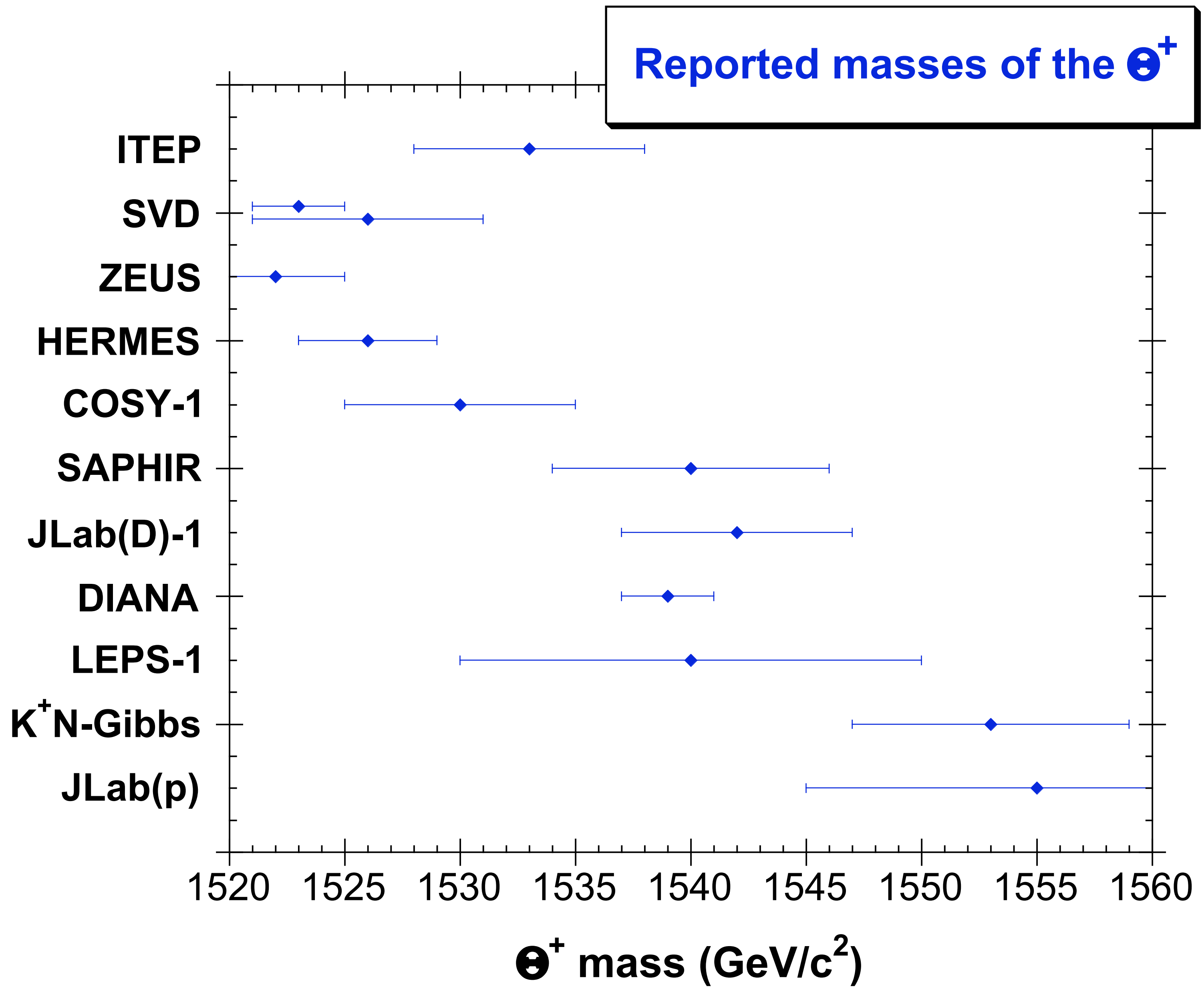


from hep-exp/0504027


Reported masses of the Θ+
ITEP
SVD
ZEUS
HERMES
COSY-1
SAPHIR
JLab(D)-1
DIANA
LEPS-1
K+N-Gibbs
JLab(p)
1520
1525
1530
1535
1540
1545
1550
1555
1560
Θ+ mass (GeV/c2)

are all these experiments really measuring the same thing ?



Suggested properties of the Θ^+

- Spin = 1/2 (3/2 ?)
- Parity = + (– ?)
- Isospin = 0
- **Strangeness = +1**

Decay channels

S=+1 guaranteed

$(udd)(u\bar{s}) \equiv nK^+$

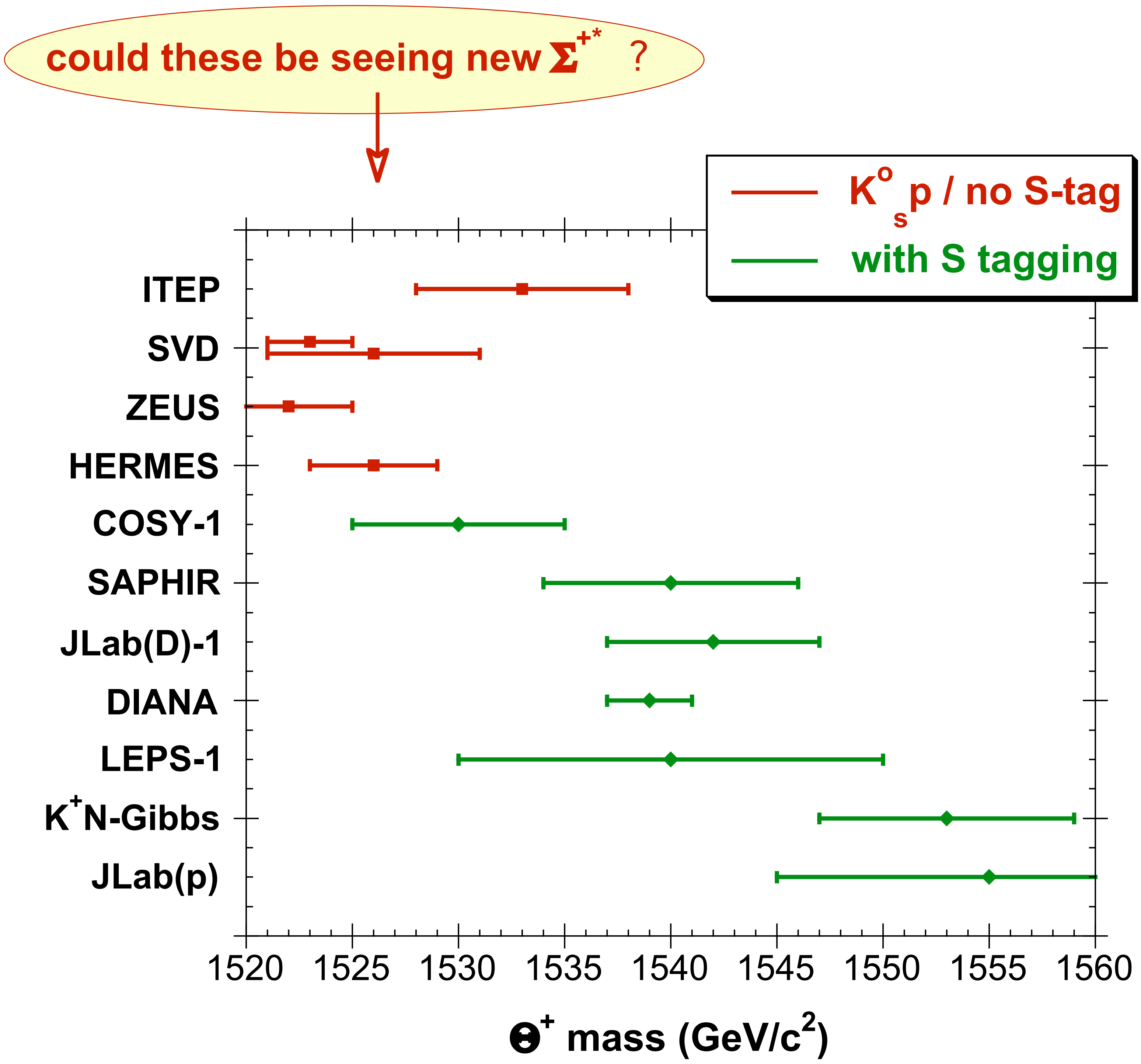
- quark structure: $uudd\bar{s}$

$(uud)(d\bar{s}) \equiv pK^0$

S=+1 or -1

if K_S^0 detected

(needs a Strangeness tag)



could these be seeing new Σ+* ?
K°s p / no S-tag
with S tagging
ITEP
SVD
ZEUS
HERMES
COSY-1
SAPHIR
JLab(D)-1
DIANA
LEPS-1
K+N-Gibbs
JLab(p)
1520 1525 1530 1535 1540 1545 1550 1555 1560
Θ+ mass (GeV/c2)

Statistics for published Θ^+ observations

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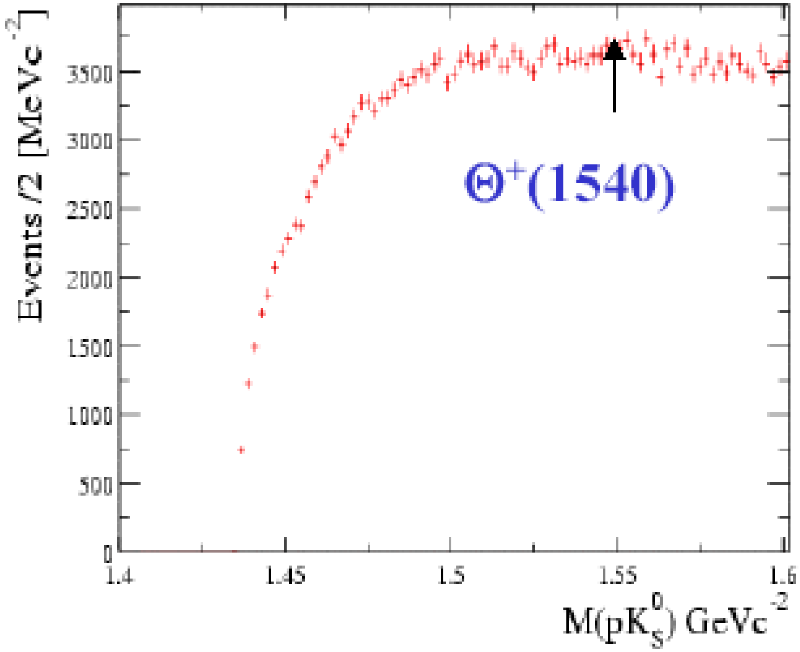
<u>Published</u> Null Experiments

Group	Reaction	Limit	Sensitivity?
BES e^+e^-	J/Ψ --> $\Theta\Theta^*$	$<1.1\times10^{-5}$	No?
Belle e^+e^-	$\Psi(2S)$ --> pK^0	$<0.6\times10^{-5}$	??
BaBar e^+e^-	$\Upsilon(4S)$ -->pK_s^0	$<1.1\times10^{-4}$	??
ALEPH	e^+e^- ->Z -> pK_s^0	$<0.6\times10^{-5}$	??
HERA-B	pA --> pK_s^0X	$<0.02\times\Lambda^*$	No?
CDF	pp* --> pK_s^0X	$<0.03\times\Lambda^*$	No?
HyperCP	pCu --> pK_s^0X	<0.3% K^0p	No?
PHENIX	AuAu -->n^*K^-	not given	??
Belle	K^+Si -->pK_s^0X	$<0.02\times\Lambda^*$	Yes?

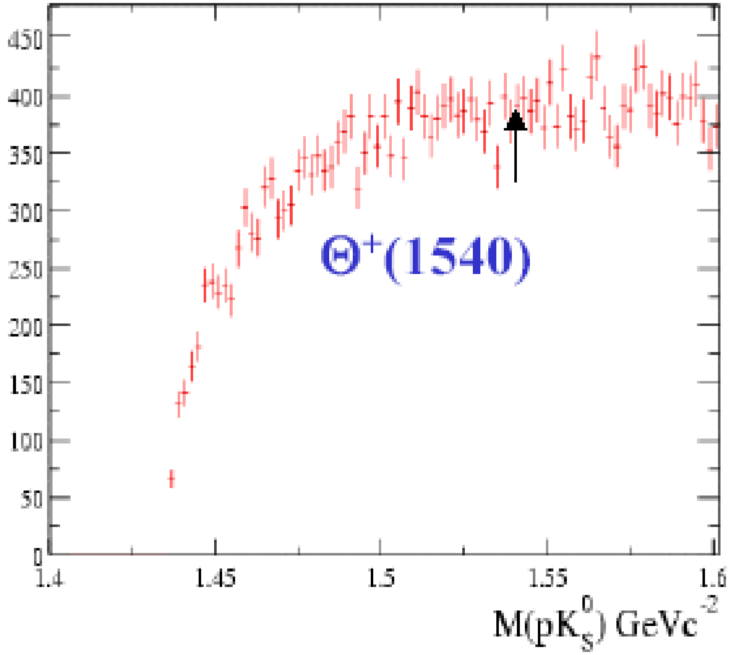
$\Theta^+(p\,K_s)(1540)$ Invariant Mass

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

0.0 < p* < 0.5 GeV/c

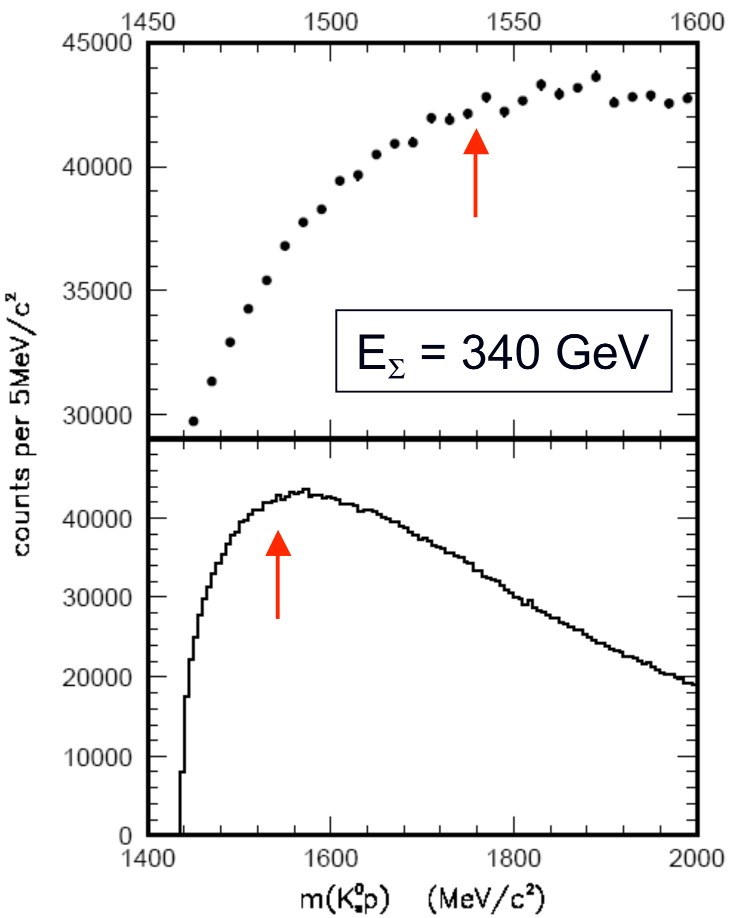


3.5 < p* < 4.0 GeV/c



WA89

$\Sigma^{-}A \rightarrow K_{s}pX$



Null experiments

- tremendous statistics !
- no S=+1 tagging
- no sign of any structures at all
  - why not Σ^* ?
- fragmentation dominates at very high energies
  - could this inhibit production of exotics with complex structure?

2^{nd} generation, dedicated pentaQuark-search experiments:

- JLab/CLAS G10 experiment: $\gamma + D \rightarrow p + K^- + \underline{K^+ + (n)}$

  Θ^+ ?

- JLab/CLAS G11 experiment: $\gamma + p \rightarrow K^o_s + \underline{K^+ + (n)}$

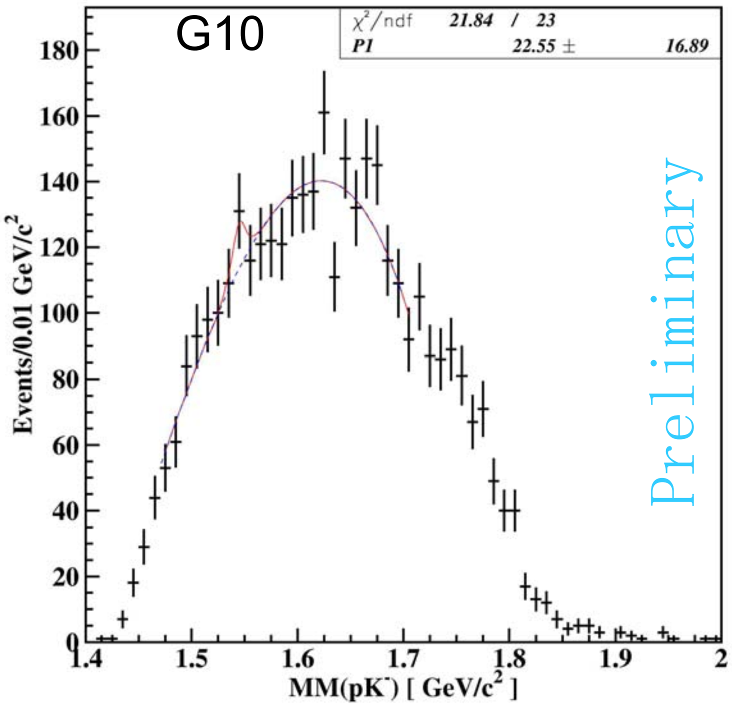
  $K^o_s \downarrow \pi^+ \pi^-$; Θ^+ ?

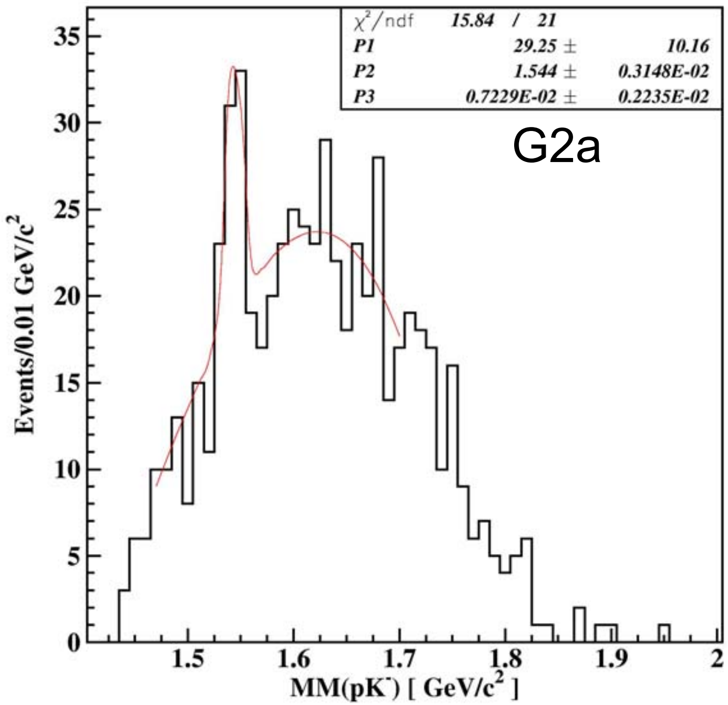
- LEPS-2 experiment: $\gamma + D \rightarrow \Lambda(1520) + \underline{K^+ + (n)}$

  $\Lambda(1520) \downarrow p + K^-$; Θ^+ ?

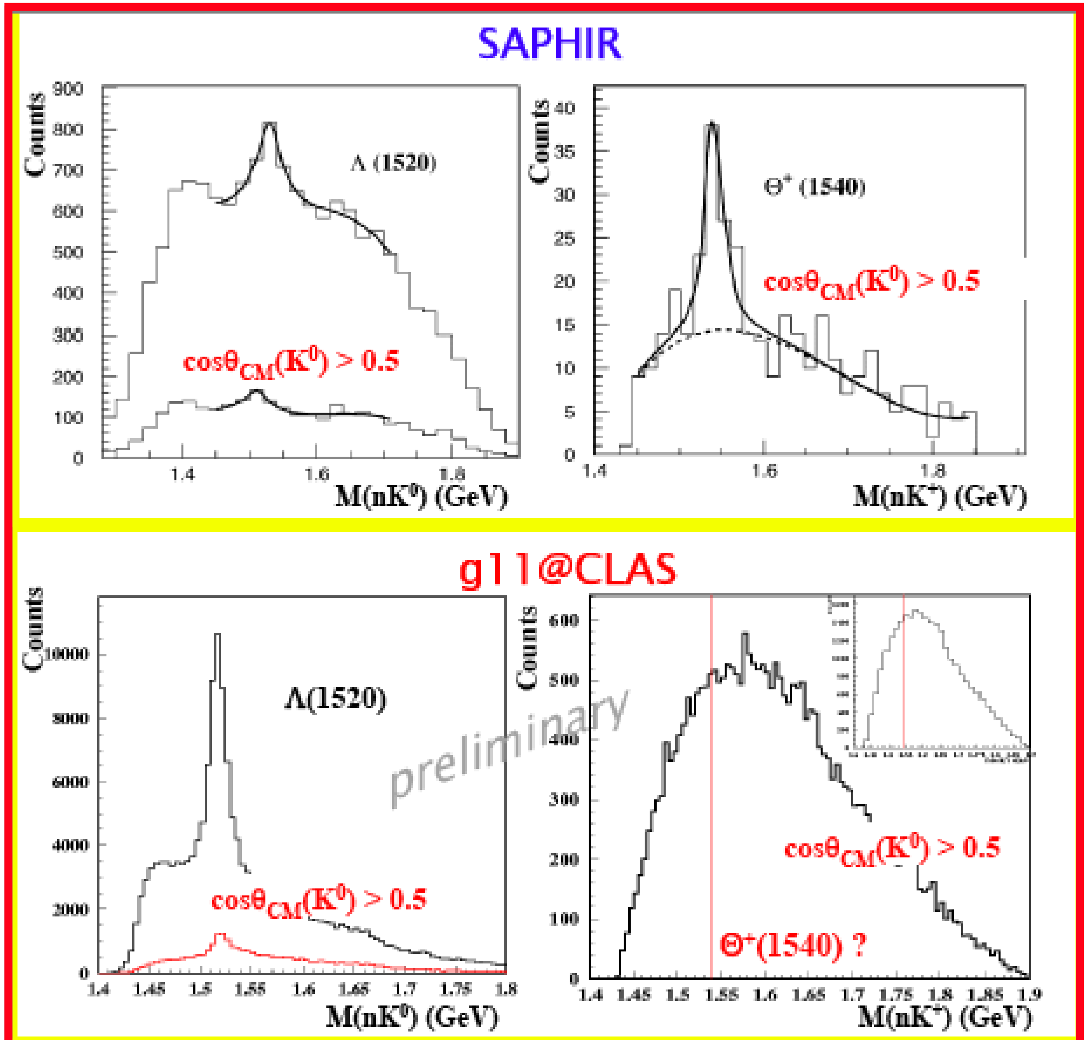
Fit to the MM(pK$^-$) distributions

- The same 3rd degree polynomial as a background in both fits (for g2a function was scaled by x5.9).
- For the fit to the g10 distribution Gaussian, the sigma was fixed to the known CLAS resolution (determined from MC and fits to other peaks).





Comparison to SAPHIR



SAPHIR

$N(\Theta^+)/N(\Lambda^*) \sim 9\%$

CLAS

$N(\Theta^+)/N(\Lambda^*) < 0.5\%$

(95%CL)

Statistics for published Θ^+ observations

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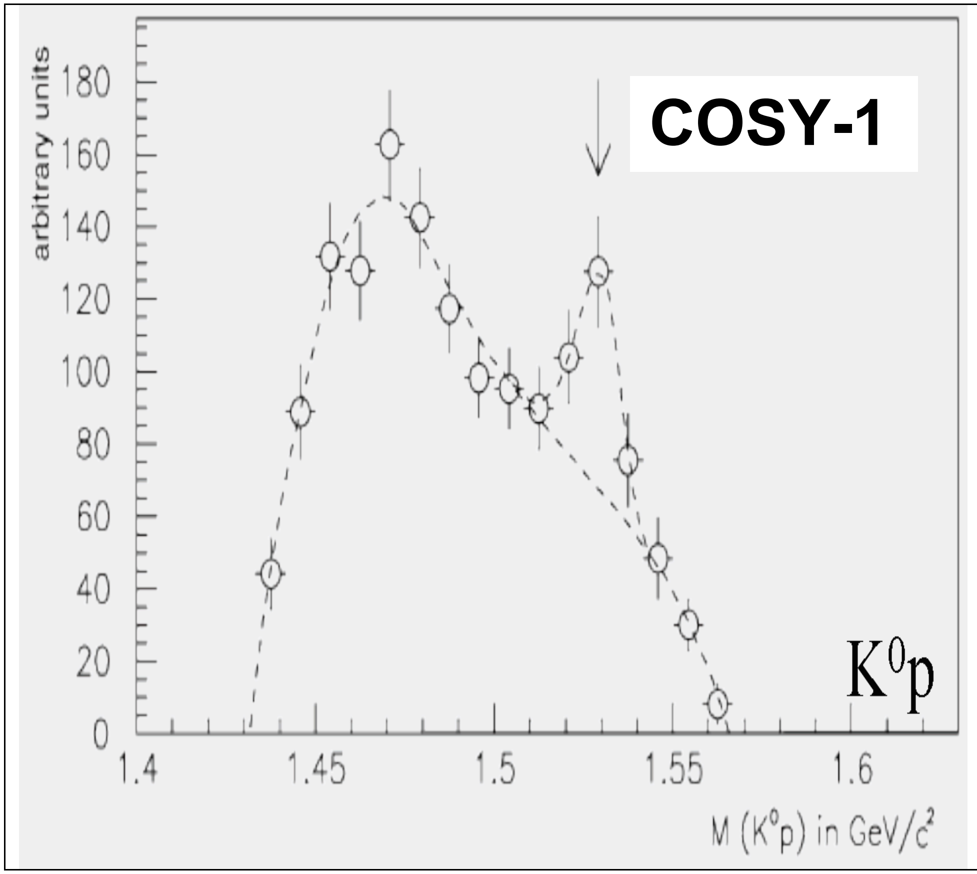
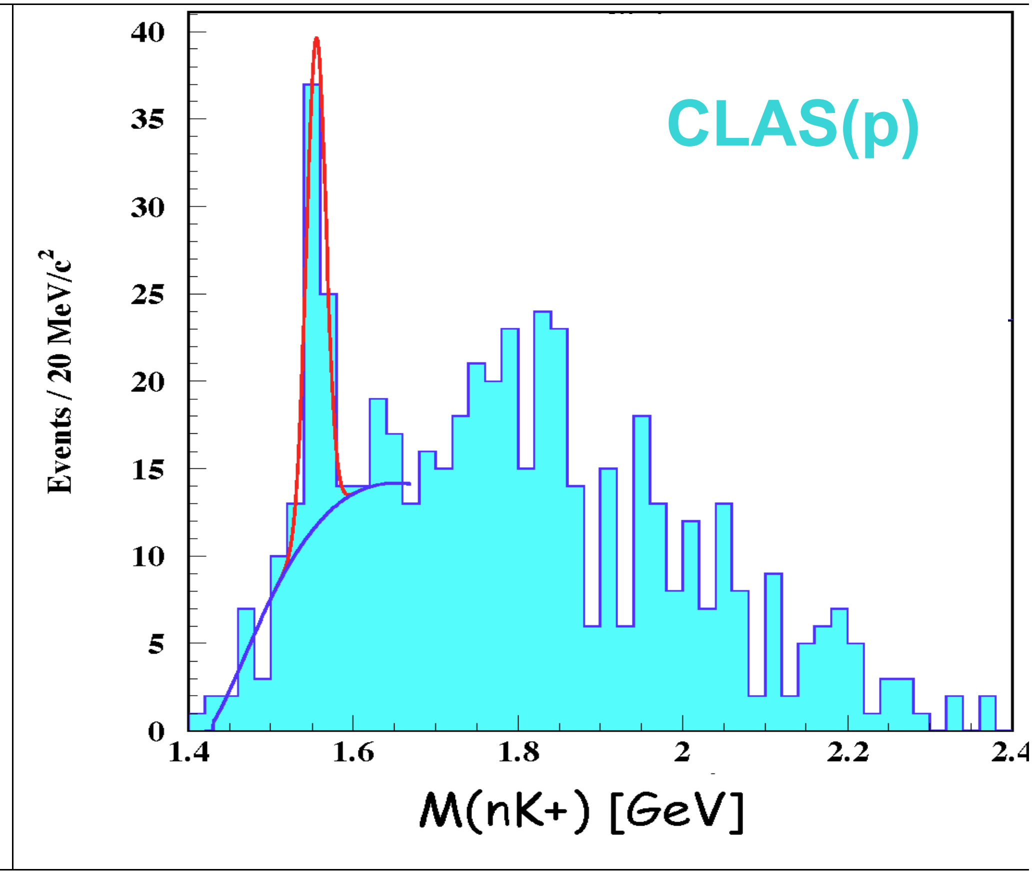
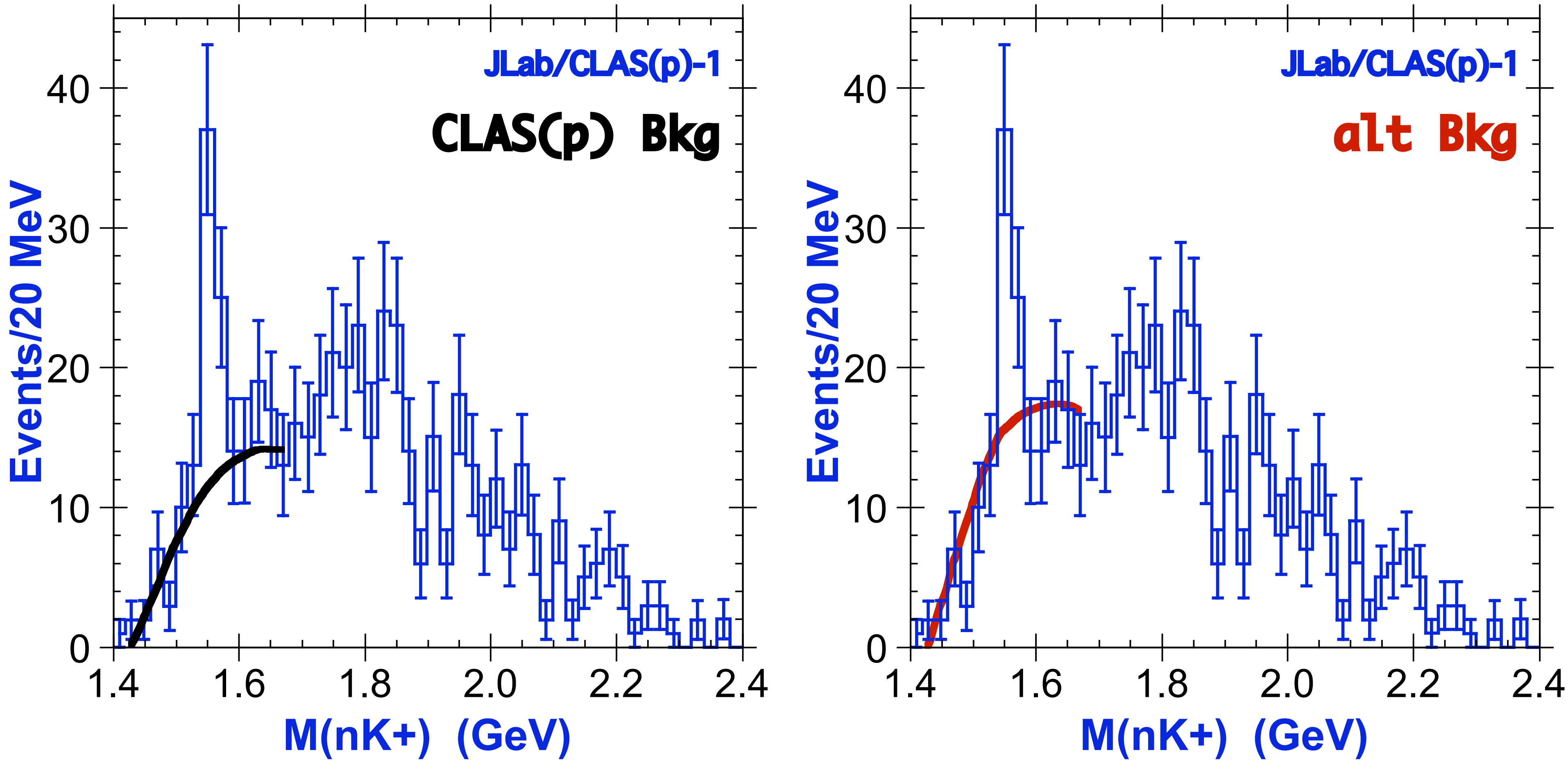
the survivors :





- Statistical significance of these peaks depends strongly on the assumed background
- Backgrounds are reasonable fits, but are not calculated

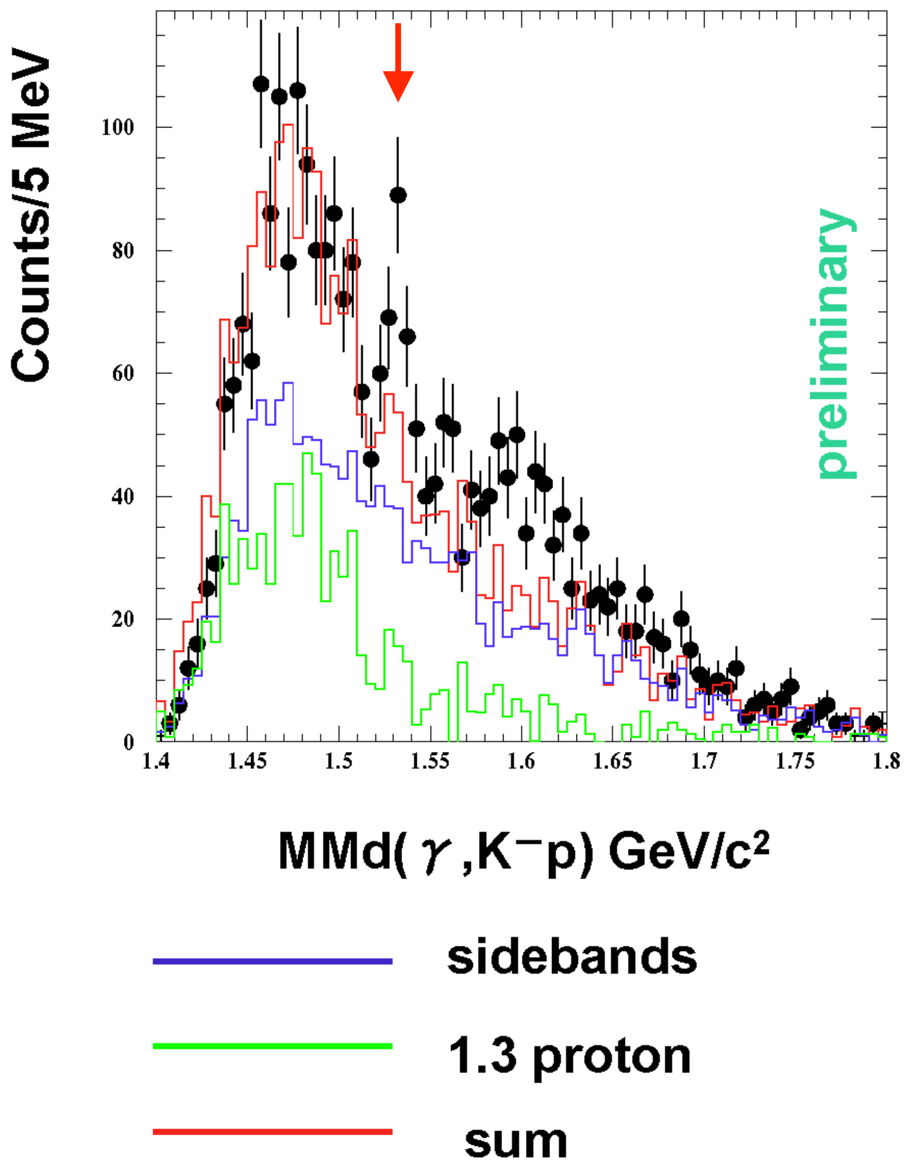
Sensitivity to the Background



statistical significance : K = 4.7

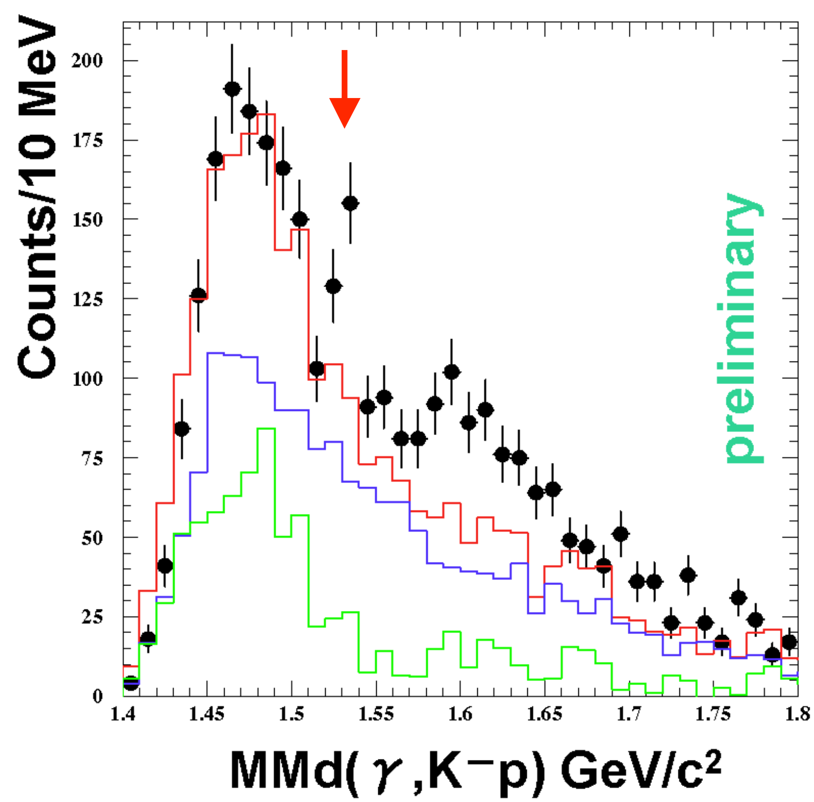
K = 2.1

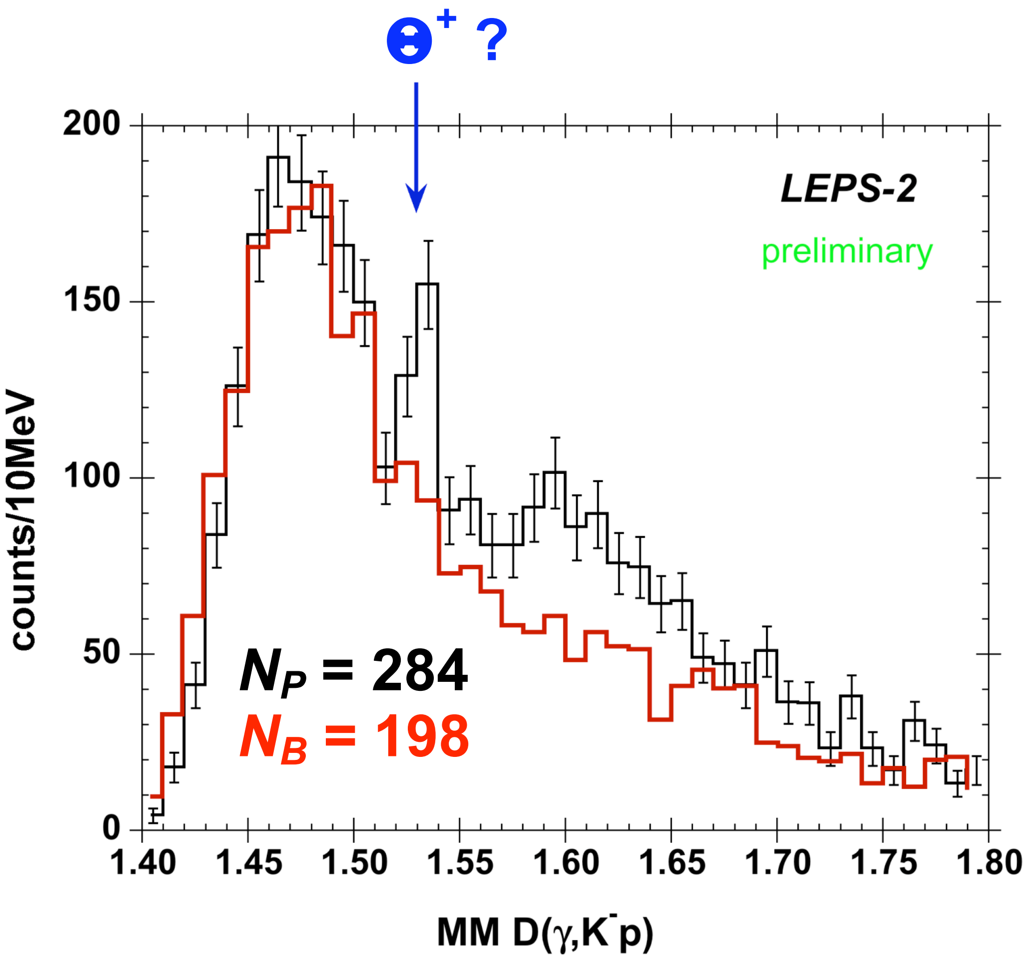
LEPS-2 : $K^{-}p$ missing mass spectrum



Excesses are seen at 1.53 GeV and at 1.6 GeV above the background level.

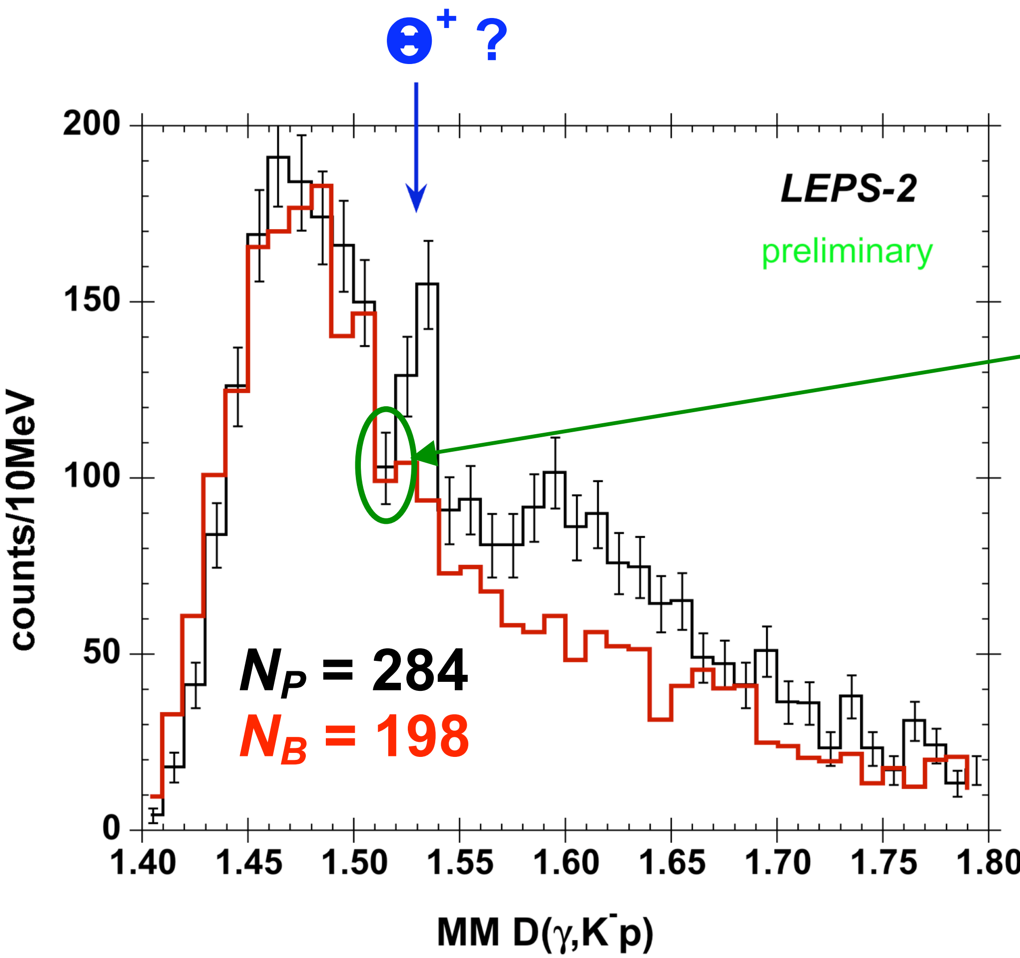
1.53-GeV peak: $\dfrac{S}{\sqrt{S+B}} \sim 5$





- Statistical significance $\equiv$ $$K = \left\{ -2 \cdot \ln \left[\int_{N_P - \sqrt{N_P}}^{N_P + \sqrt{N_P}} e^{-(Y - N_B)^2 / 2N_B} dy \right] \right\}^{1/2}$$

$$= 4.7$$



- fixing the background is crucial
- **significance depends strongly on one low point**

- Statistical significance $\equiv K = \left\{ -2 \cdot \ln \left[\int_{N_P-\sqrt{N_P}}^{N_P+\sqrt{N_P}} e^{-(Y-N_B)^2/2N_B} dy \right] \right\}^{1/2}$

= 4.7

Statistics for Θ⁺ observations

	Reaction	$N_P = N_S + N_B$	N_B	Strangeness tag	Fluctuation to $N_P \pm \sqrt{N_P}$
LEPS-1	$\gamma C \rightarrow K^+ K^- X$	36	17	yes	3.1
DIANA	$K^+ Xe \rightarrow K^o_S pXe'$	72	43	yes	2.9
JLab(D)-1	$\gamma D \rightarrow K^+ K^- pn$	103	59	**yes**	**4.4**
SAPHIR	$\gamma p \rightarrow K^o_S K^+ n$	111	56	**yes**	**5.9**
COSY-1	$pp \rightarrow K^o_S p\Sigma^+$	279±18	200	**yes**	**4.0**
HERMES	$e^+ D \rightarrow K^o_S pX$	201±15	148	no	2.7
ZEUS	$e^+ p \rightarrow e^+ K^o_S pX$	1283±36	1072	no	**5.0**
JLab(p)	$\gamma p \rightarrow \pi^+ K^+ K^- n$	89	47	**yes**	**4.6**
SVD(I)	$pA \rightarrow K^o_S pX$	128	81	no	**3.8**
SVD(II)	$pA \rightarrow K^o_S pX$	1127	940	no	**4.6**
ITEP	$\nu A \rightarrow K^o_S pX$	36	11	no	**5.8**
KN-Gibbs	$K^+ D \rightarrow X$	~13770	~13140	yes	5.1
LEPS-2	$\gamma D \rightarrow pK^- K^+ n$	284	198	**yes**	**4.7**

other (non-Θ^+) sightings

- Ξ^{--} (1862), $|sdsd\bar{u}\rangle$

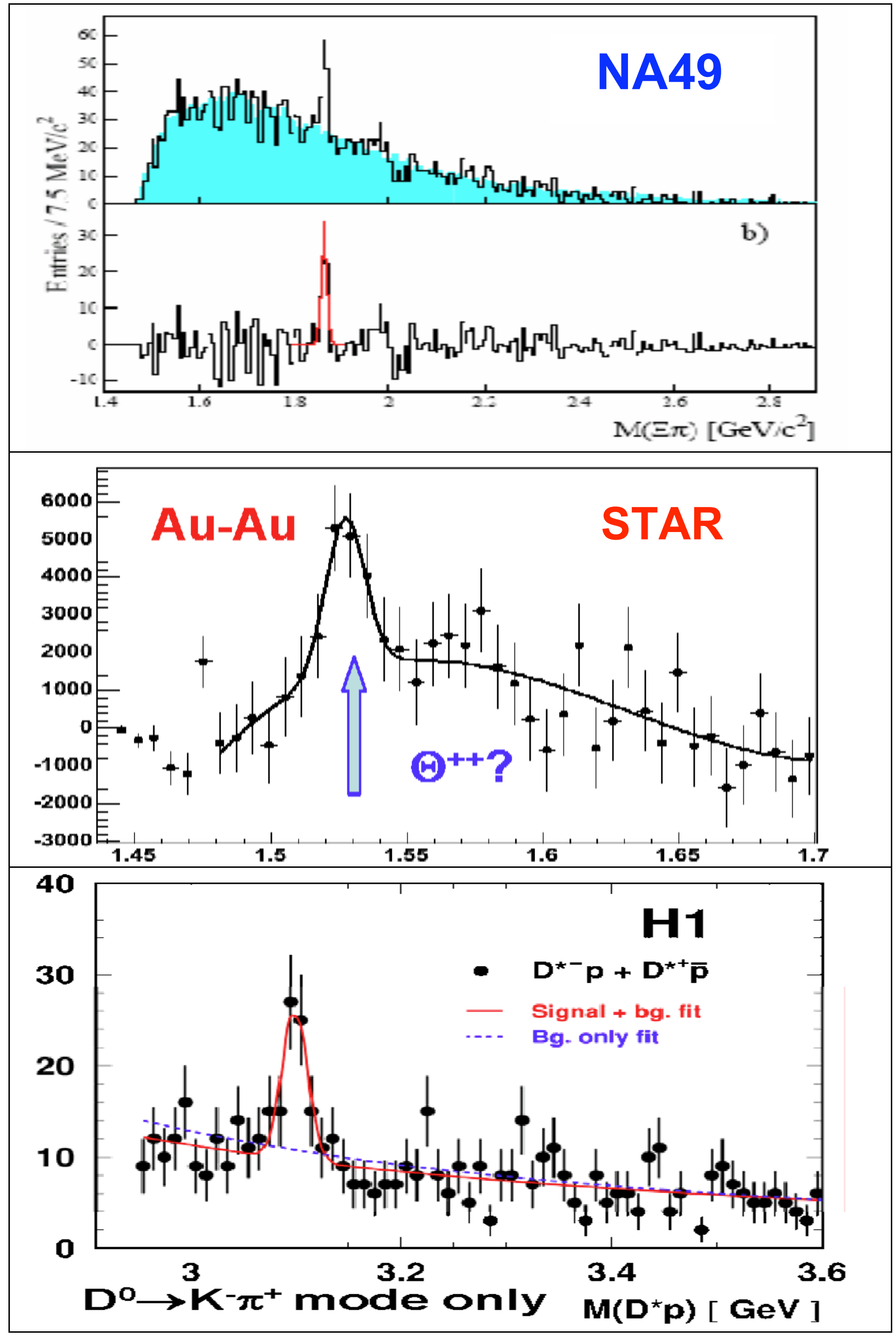
  NA49 ✔
  BaBar ✘

- Θ^{++} (1525), $|uuud\bar{s}\rangle$

  STAR: *D+Au; Au+Au* **✔**
  BaBar, JLab/Hall-A ✘

- Θ^{o}_{c} (3100), $|udud\bar{c}\rangle$

  H1 ✔
  BaBar, FOCUS, …✘



Some concluding remarks:

- pentaQuarks are, potentially, extremely interesting
  - a $^{+}$ would be the 1st S=+1 baryon !

- the $^{+}$ sits in precarious condition:

  - of 11 original sightings and 3 follow-up exps, all but 3 are in dispute

Some concluding remarks:

- pentaQuarks are, potentially, extremely interesting
  - a $^{+}$ would be the 1st S=+1 baryon !
- the $^{+}$ sits in precarious condition:
  - of 11 original sightings and 3 follow-up exps, all but 3 are in dispute

    So far, there are few ***damn peaks***, but lots of ***statistics*** !

  - the surviving JLab(p), COSY-1 and LEPS-2 exps lack a calculated background; their background subtractions seem reasonable, but the statistics of small numbers can be tricky – *eg*. JLab(D)
- sightings of the $^{++}$, $^{--}$ and $^{o}_{c}$ have not been confirmed, and all are in dispute
- the burden of proof rests with the few positive experiments, who must identify a reproducible mechanism for seeing a "*pentaQuark*"

Necessary requirements of any future experiments:

- essential to have a *strangeness tag* for *S=+1*
- *essential* to provide firm production cross sections or limits
- essential to have the theoretical support for *calculated backgrounds*

Outlook:

- upcoming experiments (underway or *on the books*):
  - LEPS at SPring-8 — *p*
  - COSY(2) — *pp* — W. Eyrich in the parallel session
  - JLab/CLAS — p
  - JLab/ Hall A — D
  - KEK — KD