University of Ljubljana

Search for Θ^+ pentaquark at Belle

hep-ex/0507014
submitted to PLB

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Belle Collaboration

- KEKB and Belle detector
- Inclusive production of Θ^+
- Exclusive production of Θ^+

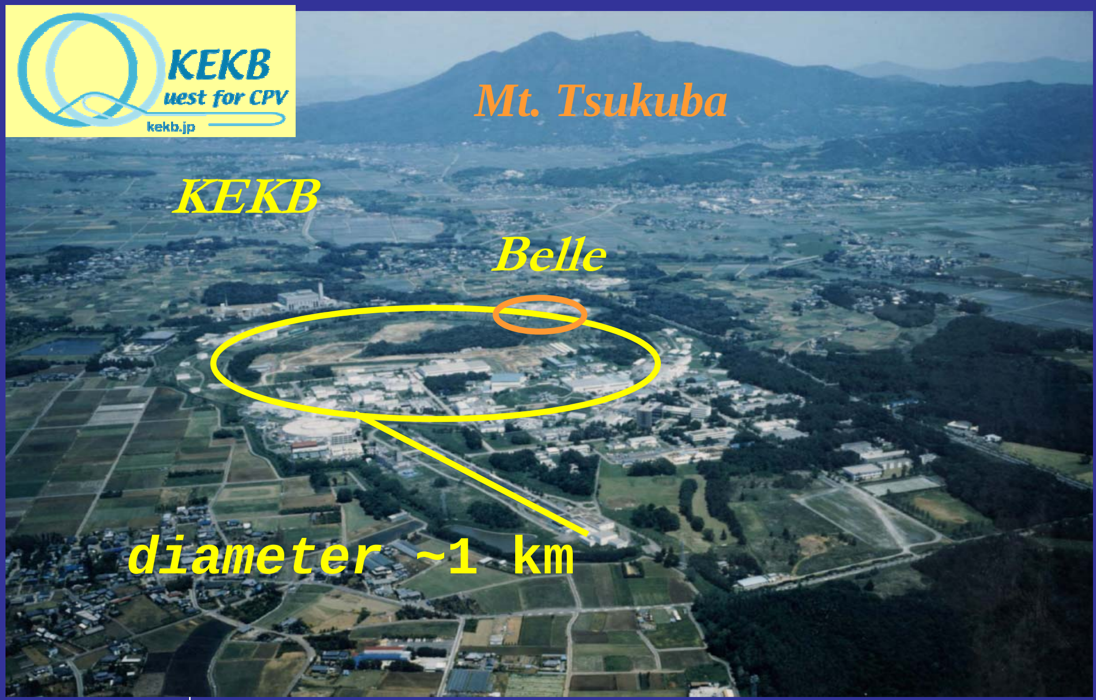
KEKB

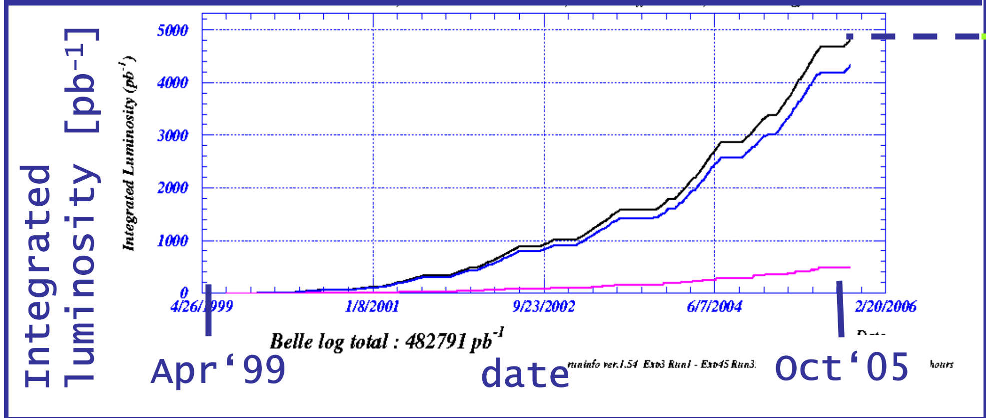
KEKB: asymmetric B factory

$e^+ \longrightarrow \Upsilon(4s) \longleftarrow e^-$

$p(e^+)=$ 3.5 GeV/c

$p(e^-)=$ 8.0 GeV/c



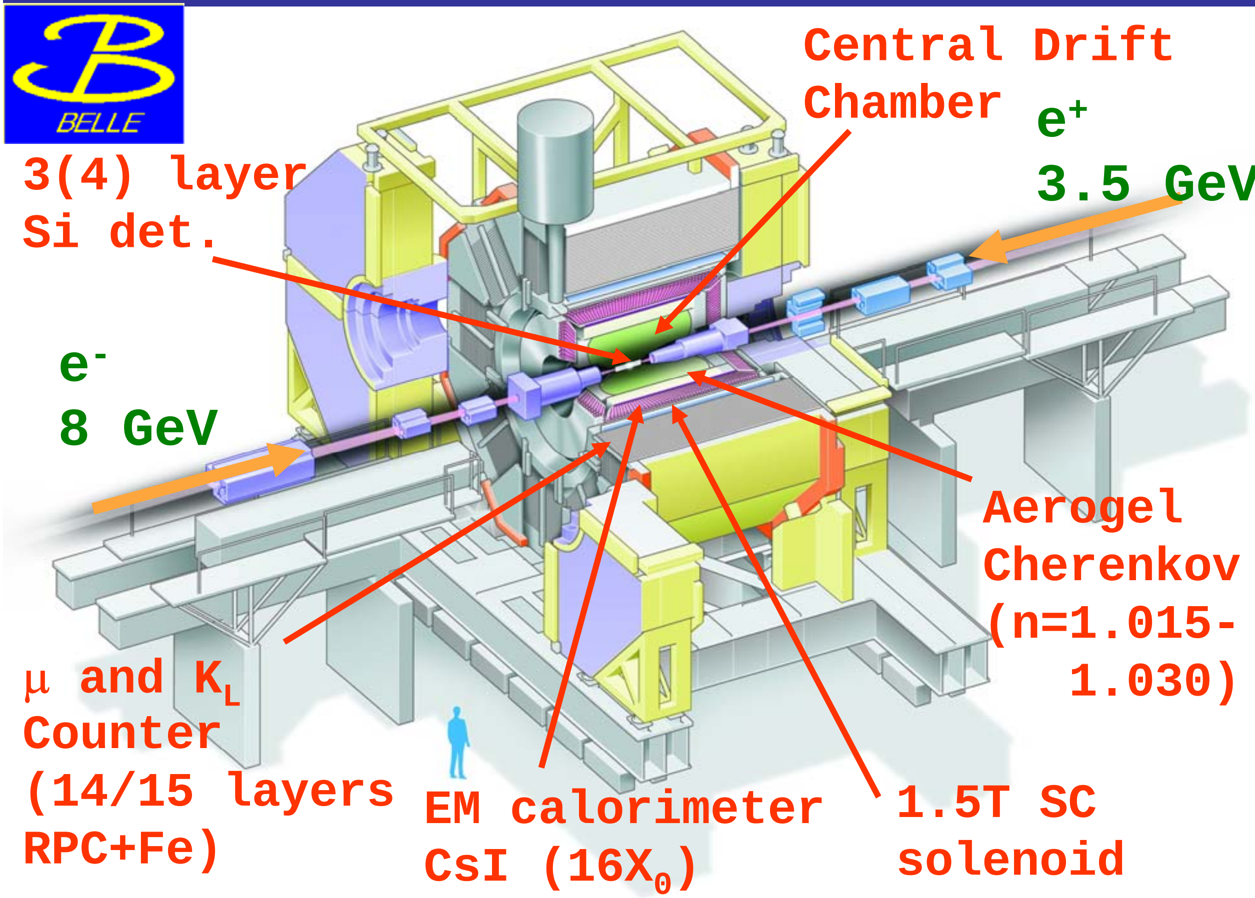


$\int L dt$ = 480 fb^{-1}

L_{peak} = $1.58 \times 10^{34}\ s^{-1}\ cm^{-2}$

Presented analysis:
$\int L dt$ = 357 fb^{-1}

Belle detector



$\sigma(p_t)/p_t = 0.3\% \sqrt{p_t^2+1}$

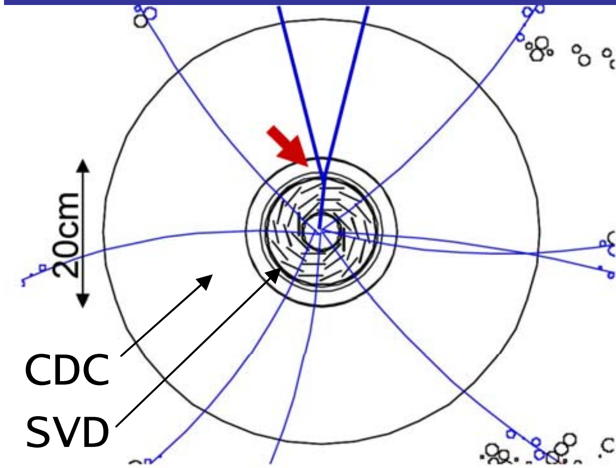
Particle ID

$\varepsilon(K^{\pm}) \sim 85\%$

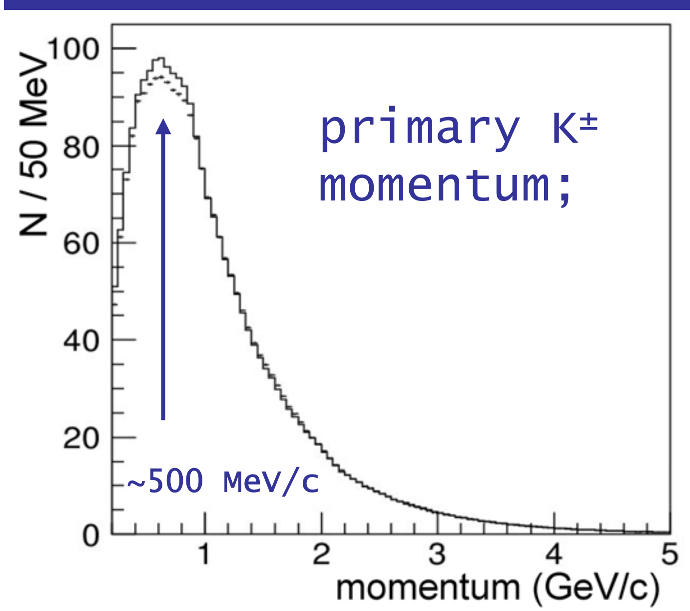
$\varepsilon(\pi^{\pm} \rightarrow K^{\pm}) <\sim 10\%$

@ $p<3.5$ GeV/c

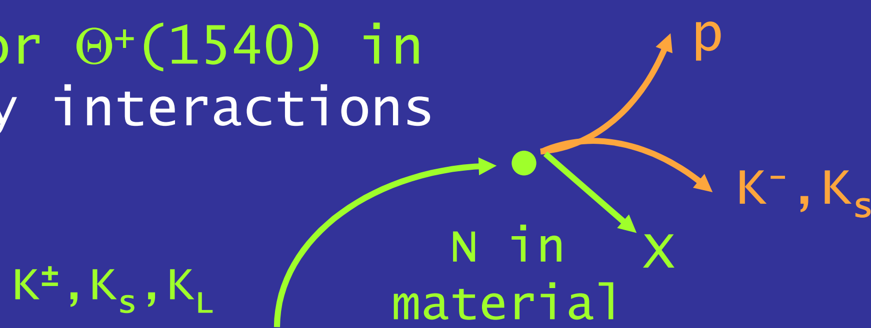
Measurement method



schematic view



- kaons produced in e^+e^- annihilation as projectiles
- search for $\Theta^+(1540)$ in secondary interactions



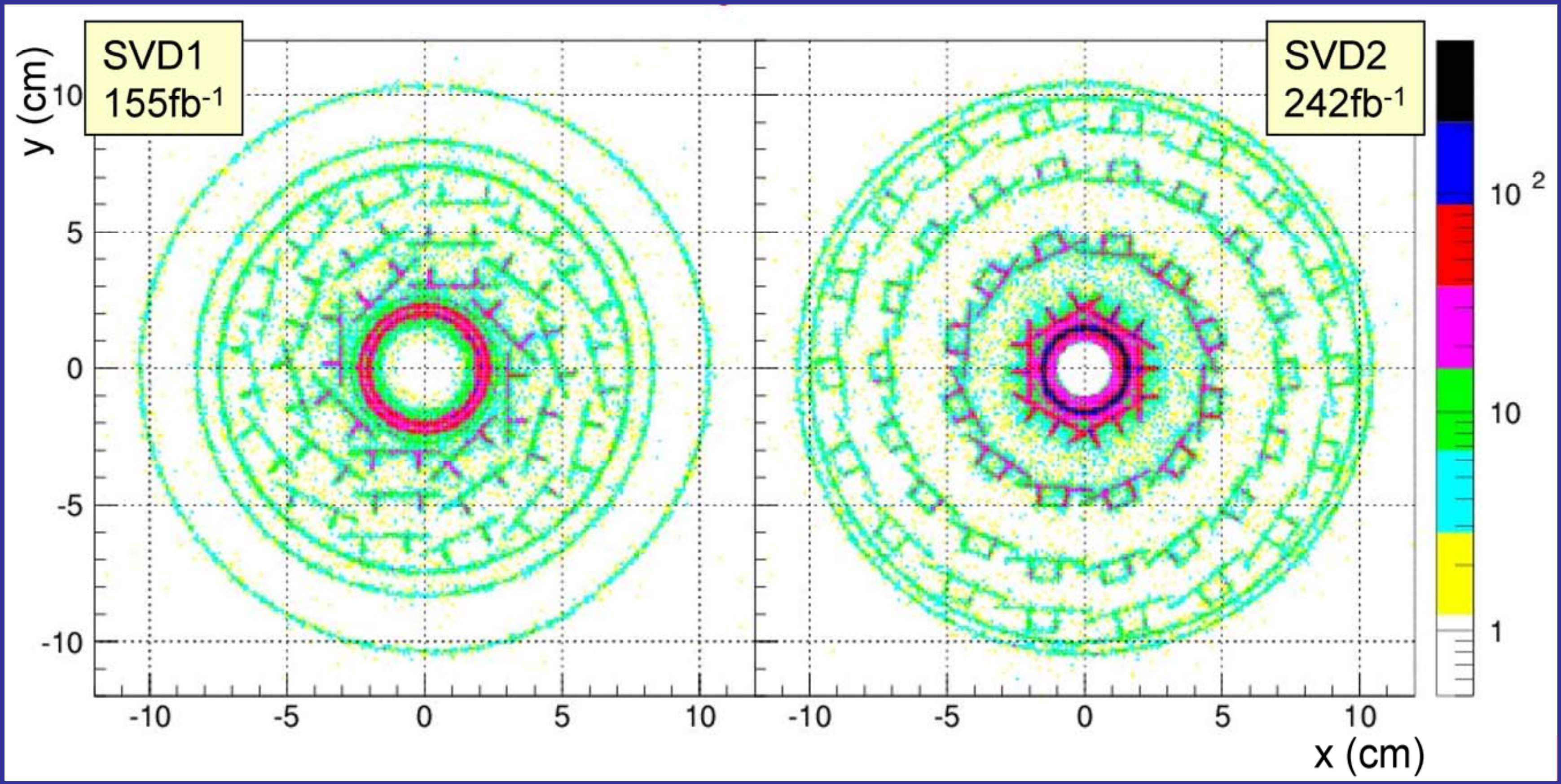
$\overset{(-)}{K^0}$	$K^\pm$	p	n	K^-	K_s
$d\bar{s}$	$u\bar{s}$	uud	udd	$u\bar{s}$	$d\bar{s}$
$\bar{d}s$	$\bar{u}s$				

Selection:

- identified p, $K^\pm$; not from IP ($\delta r>0.1$ cm);
- $K_s \to \pi^+\pi^-$;
  detached vtx, not from IP ($\delta r>0.1$ cm),
  3σ within $m(K_s)$
- pK detached vtx (1 cm < r < 11 cm);

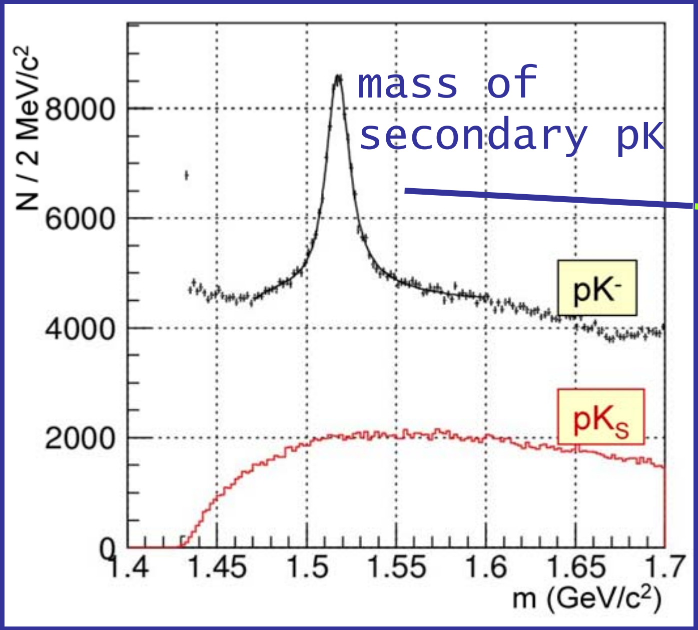
Measurement method

(x,y) coord. of pK_s secondary vertices =>
detector "tomography"



pK pairs arising from interactions with nucleons in detector material

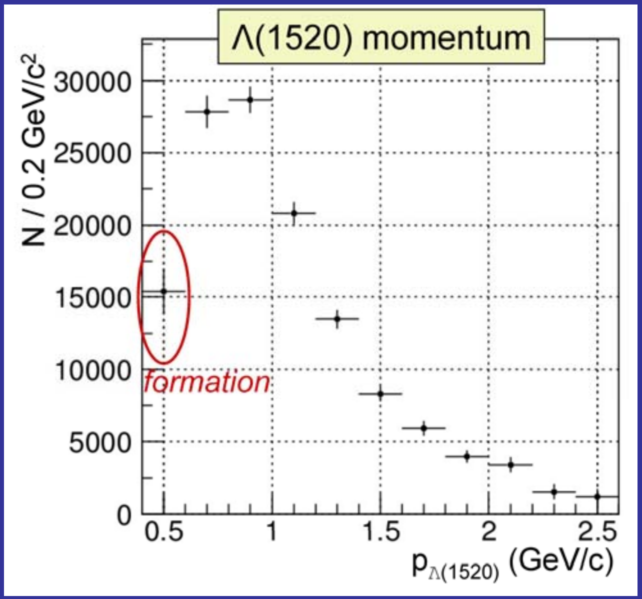
Inclusive production of Θ^+



inclusive ≡ analysis of $m(pK^-)$ and $m(pK_S)$;
no suppression of inelastic reactions,
no estimate of charge exchange $K^+n \to pK_S$

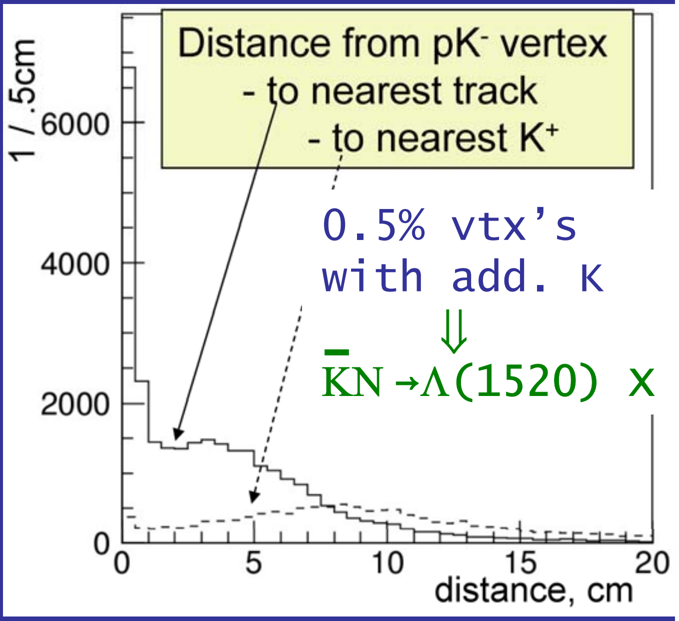
fit to threshold func.+
D-wave BW ⊕ resolution func.

$(4.02\pm0.08)\times10^4$ $\Lambda(1520)$ $(\pm2.5\ \Gamma)$
Γ and m consistent with PDG



$pK \to \Lambda(1520) \to pK$
formation,
$p(\Lambda) \sim 400$ MeV/c

$pK \to \Lambda(1520)\ X$
$\quad\hookrightarrow pK$
production



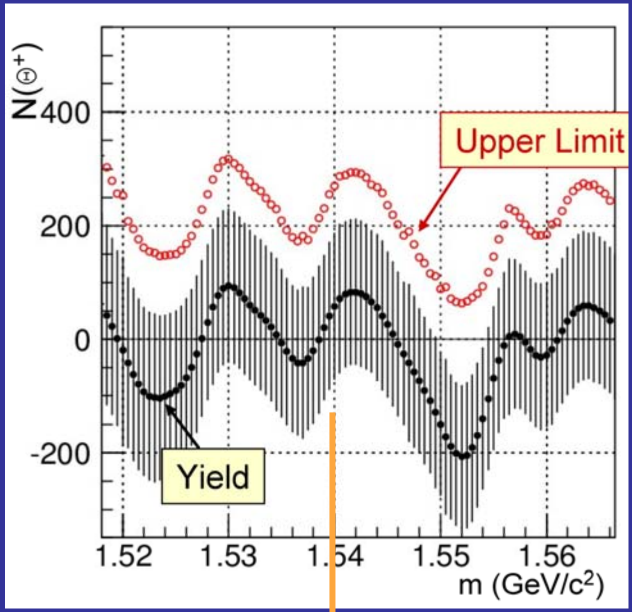
Inclusive production of Θ^+

fit $m(pK_s)$ to Gaussian
+ 3rd order polinomyal

σ~2 MeV/c^2 from
MC + small corr.
from $\Omega^- \rightarrow \Lambda K^-$

$$\frac{\sigma(KN \rightarrow \Theta(1540)^+ X)}{\sigma(\bar{K}N \rightarrow \Lambda(1520)X)} =$$

$$= \frac{N_{\Theta^+}}{N_{\Lambda^*}} \frac{\varepsilon_{pK^-}}{\varepsilon_{pK_s}} \frac{B(\Lambda^* \rightarrow pK^-)}{B(\Theta^+ \rightarrow pK^0)B(K^0 \rightarrow K_s \rightarrow \pi^+\pi^-)}$$



< 2.5% @ 90% C.L.

assuming $B(\Theta^+ \rightarrow pK_s)$=25%;
using $B(\Lambda^* \rightarrow pK^-)$=
½ $B(\Lambda^* \rightarrow NK)$= ½ (45±1)%;
ε's from MC;

Exp.	process	E[GeV]	$\sigma(\Theta^+)/\sigma(\Lambda^*)$
CDF	$pp \rightarrow \Theta^+X$	1960	<3%
HERA-B	$pA \rightarrow \Theta^+X$	42	<2%
SPHINX	$pA \rightarrow \Theta^+X$	12	<2%
Belle	$KA \rightarrow \Theta^+X$	~2	<2.5%
LEPS	$\gamma A \rightarrow \Theta^+X$	~2	~60%
HERMES	$eD \rightarrow \Theta^+X$	7	~200%

Exclusive production of Θ^+

exclusive ≡ search for $K^+n \rightarrow \Theta^+ \rightarrow pK_s$

motivated by DIANA result
Phys.Atom.Nucl. 66, 1715 (2003)

main steps

- suppression of inelastic reactions (additional π^0 or unrec. π^+ major bkg.; also contributions from $K_{s,L}p \rightarrow pK_s$)
- normalize to charge exchange $K^+n \rightarrow pK_s(N^{ch})$
- N^{ch} indirectly from elastic $K^+p \rightarrow K^+p$ (N^{el})
- interpretation $N_{\Theta+}/N^{ch} \Leftrightarrow \Gamma_{\Theta+}$
  Cahn, Trilling, PRD69, 11501 (2004)

$N_{\Theta+}/N^{ch} = 0.66 \pm 0.19$

⇓

$\Gamma_{\Theta+} = 0.9 \pm 0.3$ MeV

Exclusive production of Θ^+

number of charge exchange events:

$$N^{ch} = \int \underbrace{\Phi^{K+}(p_{K+},\theta)}_{K^+\ \text{flux}} \underbrace{\sigma^{ch}(m_{pKs})}_{\text{x-sect.}} \underbrace{M(R,\theta)}_{\text{material}} \underbrace{\varepsilon_{pKs}(m_{pKs}, p_{pKs}, R, \vartheta)}_{\text{reconstr. efficiency}} dR d\theta$$

$$\underbrace{P(m_{pKs}, p_{pKs})}_{\text{no-rescattering prob.}} \underbrace{S(E_N, p_F)}_{\text{nuclear spectral func.}} \delta(\sqrt{s} - m_{pKs}) dE_N d^3 p_F dp_{K+} B$$

MC may not reproduce M and ε accurately enough;
P and S model dependent;

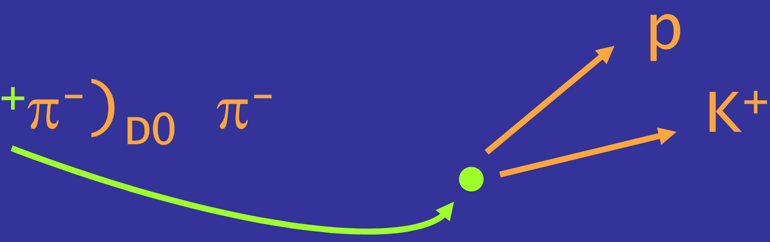
use data and estimate N^{ch} relative to N^{el}

$K^+ n \to p K_s$ $\qquad$ $K^+ p \to K^+ p$

Exclusive production of Θ^+

process enabling a "counting" of $K^+p \to pK^+$:

$D^{*-} \to D^0\pi^- \to (K^+\pi^-)_{D0}\ \pi^-$



$$N^{el}_{D^*} = \int \Phi^{K+}_{D^*}(p_{K+},\theta)\sigma^{el}(m_{pK+})M(R,\theta)\varepsilon_{pK+}(m_{pK+},p_{pK+},R,\vartheta)dRd\theta$$
$$P(m_{pK+},p_{pK+})S(E_N,p_F)\delta(\sqrt{s}-m_{pK+})dE_N d^3p_F dp_{K+}$$

ratio N^{ch}/N^{el}

$$N^{ch} = N^{el}_{D^*}\frac{\Phi^{K+}(m_{pK})\sigma^{ch}(m_{pK})\varepsilon_{pKs}(m_{pK})B}{\Phi^{K+}_{D^*}(m_{pK})\sigma^{el}(m_{pK})\varepsilon_{pK+}(m_{pK})}$$

Material and nuclear effects mostly cancel out

Exclusive production of Θ^+

reconstruction:

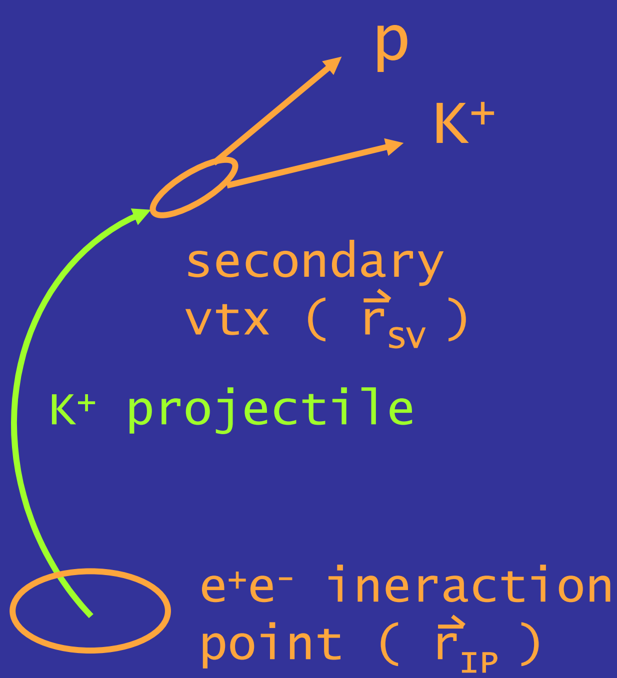
$D^{*-} \to D^0\pi^- \to (K^+\pi^-)_{D0}\ \pi^-$

relations:

- $E_N = m_N - 2\varepsilon - p_F^2/2m_N$

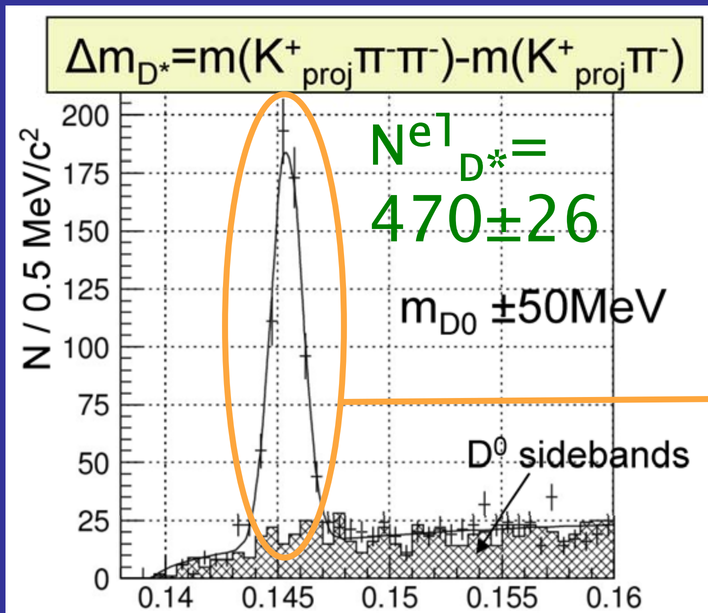
  $\varepsilon \sim 7$ MeV; Sibirtsev et al., EPJ A23, 491(2005)

- $E_K = E_{pK} - E_N$
- $\vec{p}_K = f(E_K, \vec{r}_{SV}, \vec{r}_{IP})$
- $\vec{p}_F = \vec{p}_{pK} - \vec{p}_K$



Solve iteratively for $\vec{p}_K$, $\vec{p}_F$

Exclusive production of Θ^+



Δm_{D*} from secondary pK^+ pairs combined with additional pions

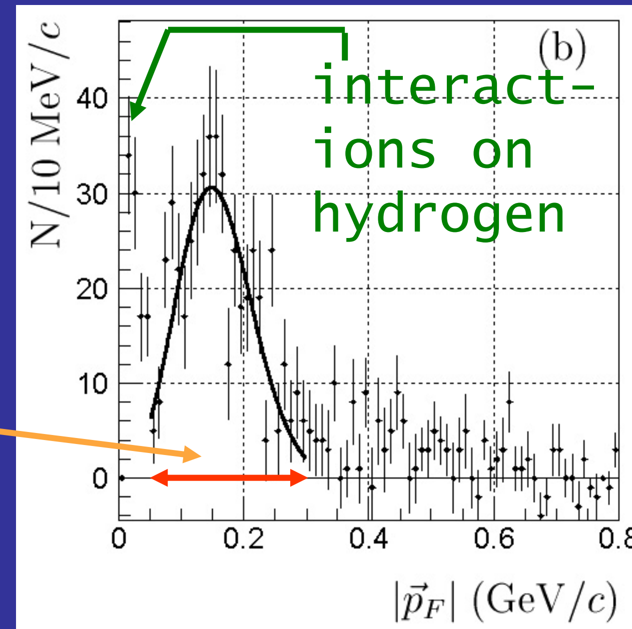
$$N^{ch} = N^{el}_{D*} \frac{\Phi^{K+} \sigma^{ch} \varepsilon_{pKs} B}{\Phi^{K+}_{D*} \sigma^{el} \varepsilon_{pK+}}$$

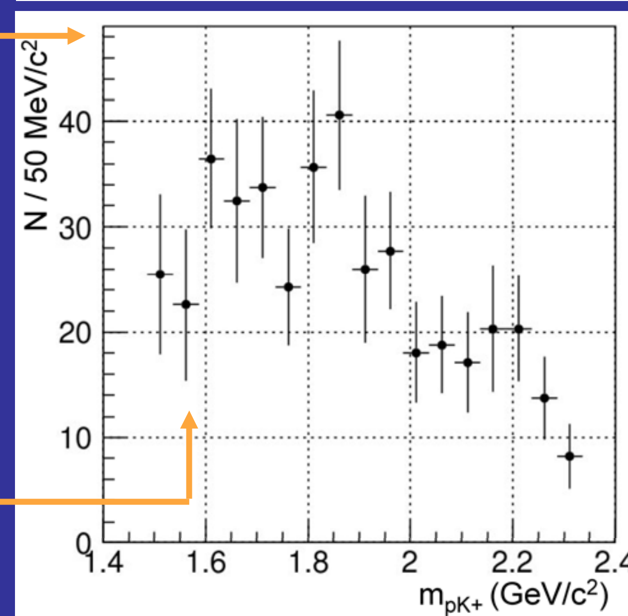
N^{el}_{D*} = 21 ± 7 (Θ^+ mass)

p_F for elastic events (D^0), bkg. subtracted

selected (enhanced elastic reactions)

in bins of m(pK^+)



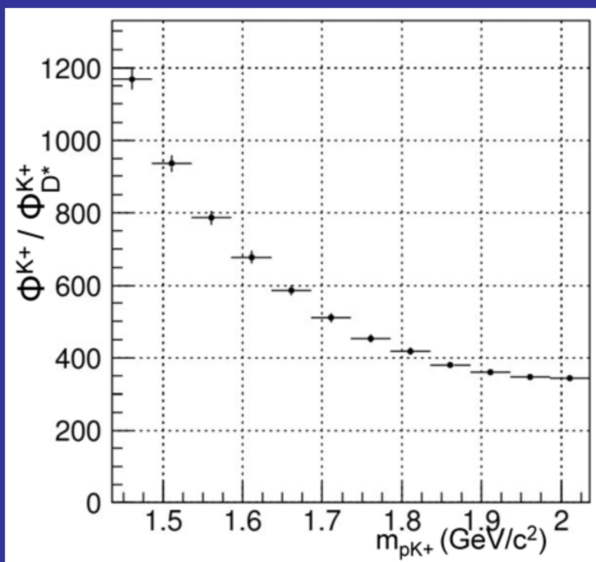


Exclusive production of Θ^+

$$N^{el}_{D^*}\frac{\Phi^{K+}\sigma^{ch}\varepsilon_{pKs}B}{\Phi^{K+}_{D^*}\sigma^{el}\varepsilon_{pK+}}$$

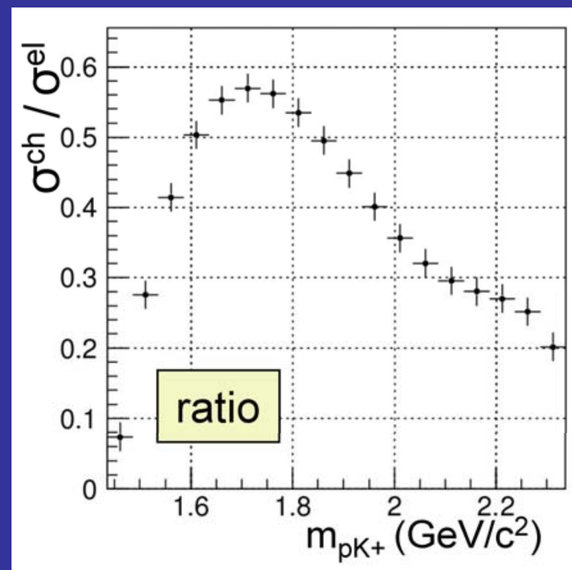
$$N^{el}_{D^*}\frac{\Phi^{K+}\sigma^{ch}\varepsilon_{pKs}B}{\Phi^{K+}_{D^*}\sigma^{el}\varepsilon_{pK+}}$$

$$N^{el}_{D^*}\frac{\Phi^{K+}\sigma^{ch}\varepsilon_{pKs}B}{\Phi^{K+}_{D^*}\sigma^{el}\varepsilon_{pK+}}$$



from ~20% of data uniform over running period

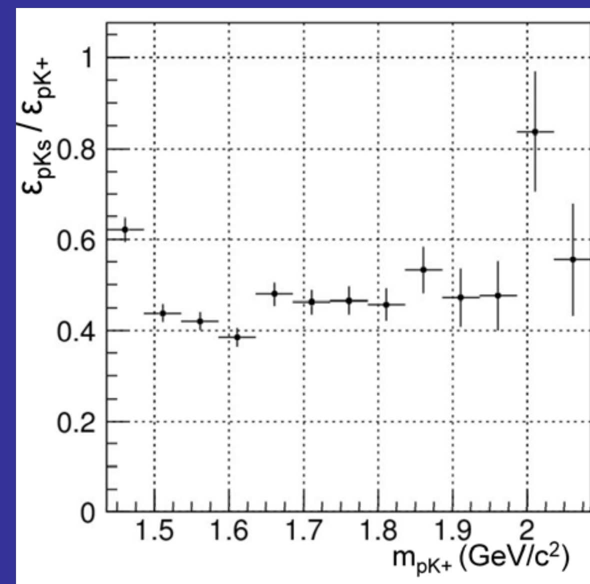
$\Phi^{K+}/\Phi^{K+}_{D^*}$= 850±20



from fit to published data; typical single experiment uncertainty

σ^{ch}/σ^{el}= 0.35±0.02

(Θ^+ mass)

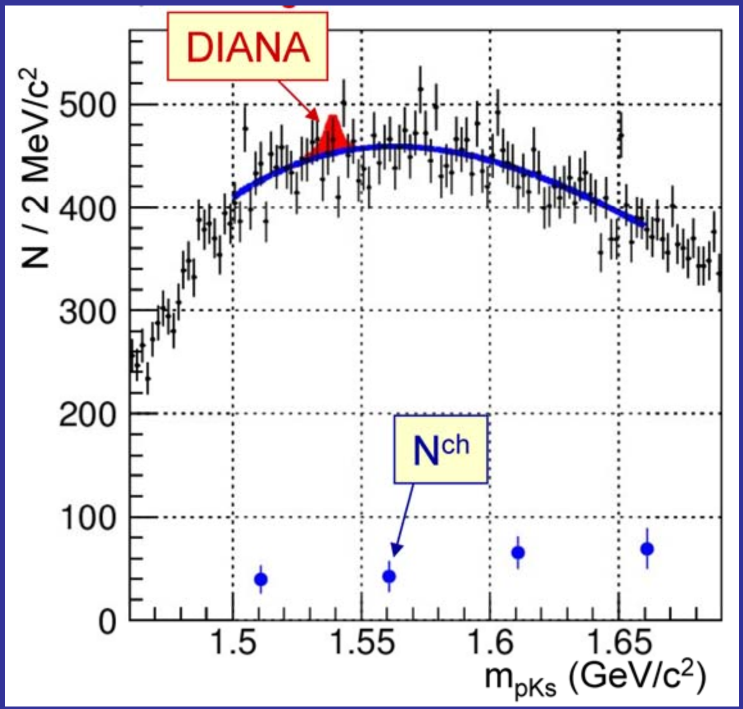


from MC

$\varepsilon^{pKs}/\varepsilon^{pK+}$= 0.43±0.05

Exclusive production of Θ^+

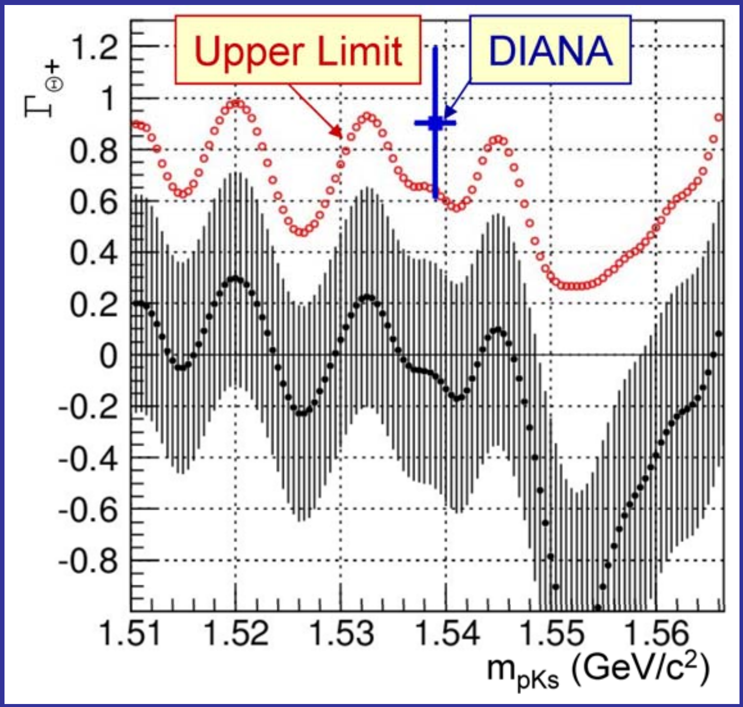
Fit $m(pK_s)$ for possible Θ^+ signal



- no vtx's with additional tracks
- 50 MeV/c < p_F < 300 MeV/c
- 3rd order polynom.+signal (σ=2 MeV/c^2)

$\Gamma_{\Theta+}$ < 0.64 MeV @ 90% C.L.

yield at various $m(pK_s)$ and UL



similar sensitivity as DIANA

DIANA:

$\Gamma_{\Theta+}$ = 0.9±0.3 MeV

Summary

- $\Theta(1540)^+$ signal searched for using kaon secondary interactions
- similar CM energy as in some positive result exp's

- inclusive search

$\sigma(KN \to \Theta(1540)^+X)/\sigma(\bar{K}N \to \Lambda(1520)X) < 2.5\%$ @90% C.L.

- exclusive search
- $K^+ n \to \Theta(1540)^+ \to p K_s$ yield normalized to total charge exchange $K^+ n \to p K_s$

- similar sensitivity to DIANA exp.

- $\Gamma_{\Theta+} < 0.64$ MeV @90% C.L. for $m(\Theta^+)=1540$ MeV/c^2
- $\Gamma_{\Theta+} < 1$ MeV @90% C.L. for $m(\Theta^+)\leq 1570$ MeV/c^2

Selection details, backup

PID

- p: $\mathcal{L}_{p/K} > 0.6$, $\mathcal{L}_{p/\pi} > 0.6$
- K±: $\mathcal{L}_{K/p} > 0.6$, $\mathcal{L}_{K/p} > 0.6$
- not identified as $e^{\pm}$
- $\mathcal{L}$: likelihood based on CDC, ACC, TOF

K_s

- $\pi^+\pi^-$ ±10 MeV (3σ) from m(K_s)
- z_{dist} at vtx < 1 cm
- δr of daughters > 0.1 cm
- $\theta(p(K_s), r(vtx,IP)) < 90^o$

typical resolution on sec. vtx ~400 μm (r)

pK vtx

- $\delta r(p,K^{\pm}) > 0.1$ cm
- z_{dist} at vtx < 1 cm
- $\theta(p(pK), r(vtx,IP)) < 90^o$

other

- 50 MeV/c < p_F < 300 MeV/c
- d/R > 0.1 (d – dist. to nearest track, R – radial coordinate of vtx)

angular cuts (DIANA) do not improve S/N or sensitivity after the p_F selection applied (suppression of 1.2, ε=93% ⇒ significance ~1.02)

Λ projectiles, backup

Formation:

$$p^2 = \frac{(m_\Lambda^2 - m_p^2 - m_K^2)^2}{4m_p^2} - m_K^2 \Rightarrow p \approx 400\ MeV/c$$

possible projectiles to produce $\Lambda(1520)$:
K^-, K_S, K_L, Λ (?)

$p(\Lambda) \geq 1.8$ GeV/c ($z \geq 0.35$) to produce $\Lambda(1520)$
@29 GeV fraction $\Lambda(z \geq 0.35)$ ~10%
$\sigma(e^+e^- \to \Lambda X)$~80 pb
$\sigma(e^+e^- \to K^0 X)$~470 pb
$\Rightarrow N(\Lambda)/N(K^0)$ ~ 2%
Tasso, PRD45, 3949 (1992)

$\sigma(K^-p \to \Lambda(1520))$~3 mb, $\sigma(\Lambda p$, total)~30mb
assuming equal prod. rate of K^0, K^-
$\Rightarrow \Lambda p \to \Lambda(1520)X$ / $Kp \to \Lambda(1520)X$ ~ 10%
(if $\sigma(\Lambda p$, total) saturated by $\Lambda(1520)$)

Fitted parameters of $\Lambda(1520)$:
$m = 1518.5 \pm 0.1$ MeV/c^2
$\Gamma = 13.5 \pm 0.4$ MeV
PDG:
$m = 1519.5 \pm 1.0$ MeV/c^2
$\Gamma = 15.6 \pm 1.0$ MeV

Λ projectiles contribute few % to $\Lambda(1520)$ production

Spectral function, backup

Energy of nucleon within a nuclei;

$E_q = \sqrt{q^2+m_N^2} - U(q,\rho)$

$U(q,\rho)$ – nuclear potential

Fermi momentum ~300 MeV/c $\Rightarrow$

$E_q \approx m_N + q^2/2m_N - U(q,\rho)$

if $U \propto 1/r$, virial theorem, $U \sim -2\, q^2/2m_N$

$E_q \approx m_N - q^2/2m_N$

checks:

use of $E_q \approx m_N - 2\varepsilon - q^2/2m_N$, with fixed ε

gives

- correct m_{D0}
- expected p_F distrib.

A. Sibirtsev et al.
EPJ A23, 491(2005)
Z.Phys. A358, 357(1997)

use of $E_q = m_N - E_R$

E_R (removal energy)

tuned to reproduce $m_{D0} \rightarrow E_R$=26 MeV

$E_R = 2\varepsilon + q^2/2m_N$, nucleons with higher momenta are more tightly bound

Θ^+ exclusive – integrals, backup

$$N^{ch} = \int \Phi^{K+}(p_{K+},\theta)\sigma^{ch}(m_{pKs})M(R,\theta)\varepsilon_{pKs}(m_{pKs}, p_{pKs}, R,\vartheta)dRd\theta$$

$$P(m_{pKs}, p_{pKs})S(E_N, p_F)\delta(\sqrt{s}-m_{pKs})dE_N d^3 p_F dp_{K+}B$$

all quantities depending only on m(pK) → factorize

- products Mε approx. independent of θ → decoupled from Φ
- fraction of recon. D* in p_F hydrogen peak w.r.t. all ~independent of p(pK); since fraction $\propto$ 1/P $\Rightarrow$ P ~ $\neq$ *F*(p(pK))

$$N^{ch} = \sigma^{ch}(m_{pKs})\varepsilon_{pKs}(m_{pKs})P(m_{pKs})\cdot$$

$$\cdot\int \Phi^{K+}(p_{K+})\varepsilon_{pKs}(p_{pKs})S(E_N, p_F)\delta(\sqrt{s}-m_{pKs})dE_N d^3 p_F dp_{K+}B$$

cancels in the ratio

remaining eff. dependence on p(pK) at given m(pK)

$S(E_N,p_F) = W(p_F)\delta(E_N-f(p_F))$;
$W(p_F)$ Fermi mom. distrib. (data);
$f(p_F)$ defined so that
$E_N = f(p_F) \Leftrightarrow$ max. of $S(E_N,p_F)$

Θ^+ exclusive – integrals, backup

$$N^{ch} = \sigma^{ch}(m_{pKs})\varepsilon_{pKs}(m_{pKs})P(m_{pKs})\cdot$$

$$\cdot\int \Phi^{K+}(p_{K+},\theta)\varepsilon_{pKs}(p_{pKs})W(p_F)\delta(E_N - f(p_F))\delta(\sqrt{s} - m_{pKs})dE_N d^3p_F dp_{K+} B$$

ratio N^{ch}/N^{el}

$$N^{ch} = N^{el}_{D*}\frac{\Phi^{K+}(m_{pK})\sigma^{ch}(m_{pK})\varepsilon_{pKs}(m_{pK})B}{\Phi^{K+}_{D*}(m_{pK})\sigma^{el}(m_{pK})\varepsilon_{pK+}(m_{pK})}$$

$$\frac{\Phi^{K+}(m_{pK})}{\Phi^{K+}_{D*}(m_{pK})} = \frac{\int \Phi^{K+}(p_{K+})\varepsilon_{pKs}(p_{pKs})W(p_F)\delta(\sqrt{s} - m_{pKs})d^3p_F dp_{K+}}{\int \Phi^{K+}_{D*}(p_{K+})\varepsilon_{pK+}(p_{pK+})W(p_F)\delta(\sqrt{s} - m_{pKs})d^3p_F dp_{K+}}$$

MC integration; p_F assumed isotropic w.r.t. p_K;
$\varepsilon(p(pK)) \rightarrow 3\%$ corr. to the ratio;
uncertainty dominated by assumed E_N, p_F relation

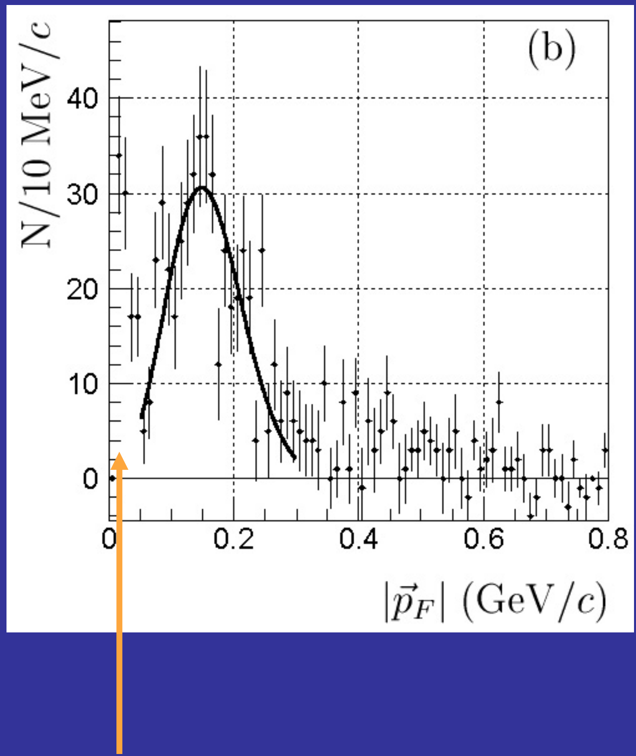
p_F distribution, backup

Fit to

$$p_F^2\left[1+\frac{4}{3}\left(\frac{p_F}{p_0}\right)^2\right]\exp(-p_F^2/p_0^2)$$

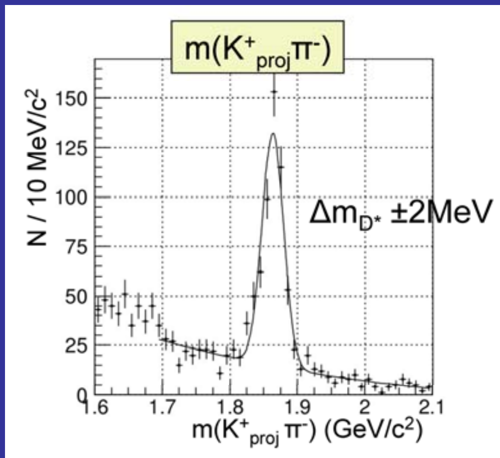
(oscillator model)

p_0=115±4 MeV/c
comparable to other measurements of p_F,
e.g. B.M. Abramov et al.,
JETP Lett. 71, 359(2000)



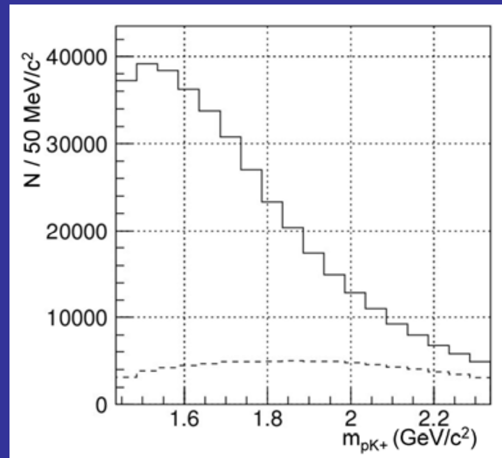
using $E_N=m_N$ ⇒
hydrogen peak exactly at 0

additional plots , backup



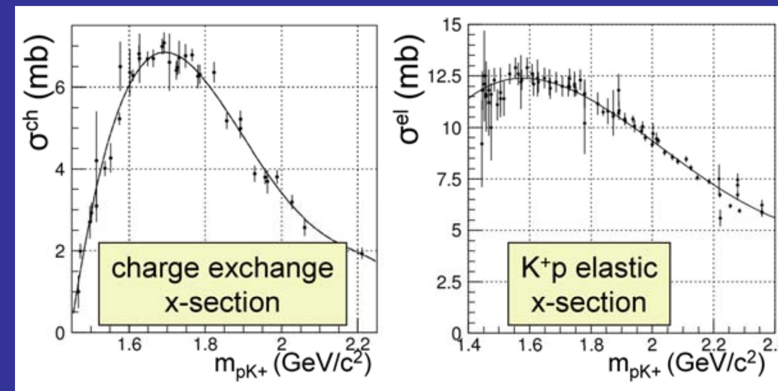
N^{el}_{D*}=470±26

σ=16 MeV/c^2



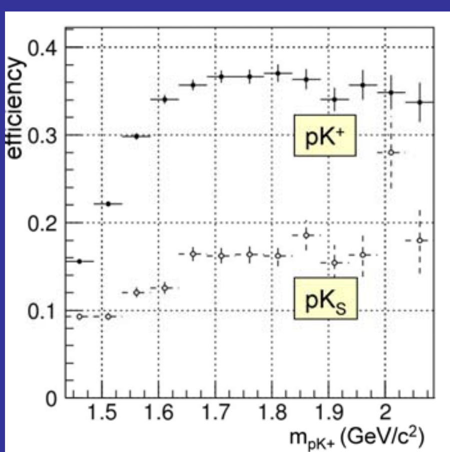
Φ^{K+}/Φ^{K+}_{D*}=
850±20

major uncertainty
from E_N, p_F relation



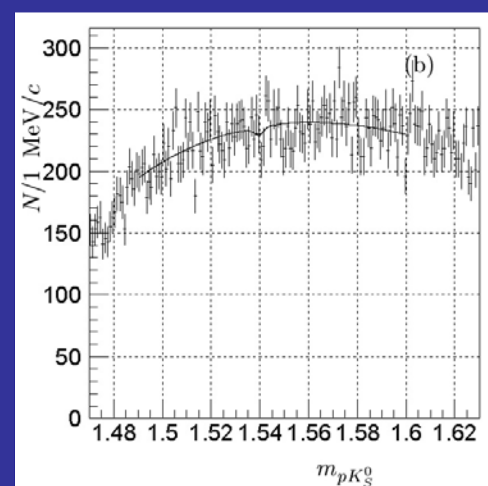
σ^{ch}/σ^{el}=
0.35±0.02

from fit to published
data; typical single
experiment uncertainty



$\varepsilon^{pKs}/\varepsilon^{pK+}$=
0.43±0.05

from Geant based MC;
uncertainties in
tracking and K_s eff.,
second. vtx eff., material
desc., reaction kinem.,
MC stat.



Fit to
m(pK_s)

sensitivity
to $\Gamma_{\Theta+}$
±0.42 MeV

$\Gamma_{\Theta+}$, backup

R.N. Cahn, G.H. Trilling, PRD69, 11501 (2004)

BW form

$\sigma(m) = B_i B_f \sigma_0 [\Gamma^2/4] / [(m-m_0)^2+\Gamma^2/4]$

σ_0=68 mb (J=1/2)

mass resolution broader than natural width ⇒

integral $I=\int \sigma(m)\, dm = 107$ mb $B_i B_f \Gamma$ ⟶

estimate of 26 signal evts in two 5 MeV bins,

bkg. level ~22 evts / bin

assumed bkg. from charge exchange, $\sigma^{ch}=4.1\pm0.3$ mb ⇒

I = (26/22) x 5 MeV x 4.1 mb = 24 mb MeV ⟶

$B_i=B_f=1/2$ ⟶

$\Gamma=0.9\pm0.3$ MeV

$K_s, K_L\ p \to \Theta^+ \to p\ K_s$, backup

A. Kaidalov, private comm.

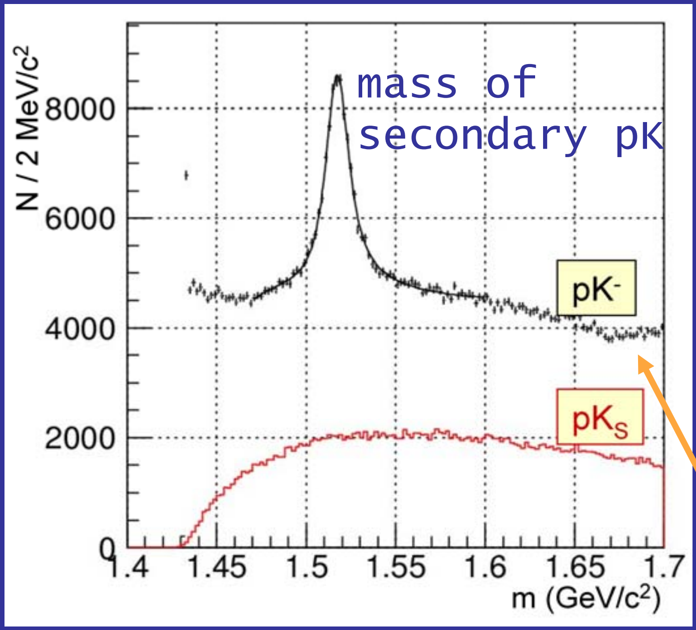
apart from charge exchange reactions also
$K_s\ p \to K_s\ p$ and $K_L\ p \to K_s\ p$ may contribute to signal

$K_L\ p \to \Theta^+ \to p\ K_s$
interference between amplitudes for same final state
can lead to "hole" in $\sigma(K_L\ p$, total) due to Θ^+

$\sigma(K_L\ p$, total) $\sim$ 2 mb $\Rightarrow$ negative interference < 1 mb
(also depending on decay angles)
$\sigma(K^+ n \to \Theta^+ \to p\ K_s) \sim 17$ mb (DIANA)
"hole" negligible

$K_s\ p \to \Theta^+ \to p\ K_s$ would also compensate for that

Other Σ states, backup



total $\sigma(pK^-)$ shows
two prominent structures
at 1520 MeV/c^2 and
at ~1800 MeV/c^2;
latter due to several
overllaping Λ and Σ states;
clearly seen, hard to interpret

look for Σ(1670) 4* resonance
m=1665-1685 (≈1670) MeV/c2
Γ=40-80 (≈60) MeV

Fit $m(pK_s)$ to sum of
3rd order polyn.+
D-wave BW

$N(\Sigma(1670))=(2.4\pm1.3)\times10^3$

Σ(1670)/Λ(1520) < 2 @90% C.L.

assuming $B(\Lambda^*\to pK^-)=$
$\frac{1}{2}\ B(\Lambda^*\to NK)=\frac{1}{2}\ (45\pm1)\%$;
$B(\Sigma(1670)\to p\bar{K}^0)=10\%$

Some additional statistics, backup

95% C.L. limits:

$\Gamma_{\Theta+}$ < 0.78 MeV (@ 1539 MeV/c^2)

< 1.11 MeV (wide range)

probability of stat. fluctuation
for the signal of the DIANA size
to the level observed by BELLE ~3%