Pentaquark Searches at BaBar

Tetiana Berger-Hryn'ova, SLAC
For the BaBar Collaboration

Outline

- **Search for Θ^+ in Electro- and Hadro-Production**

- **Inclusive Search for Strange-Pentaquark Production in e^+e^- Annihilation**

- **Inclusive Search for anti-Charm Pentaquark Production in e^+e^- Annihilation**

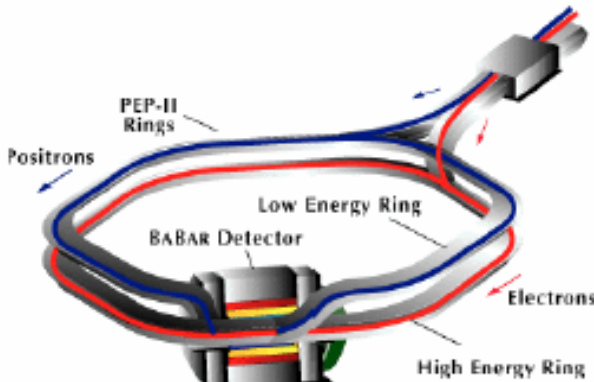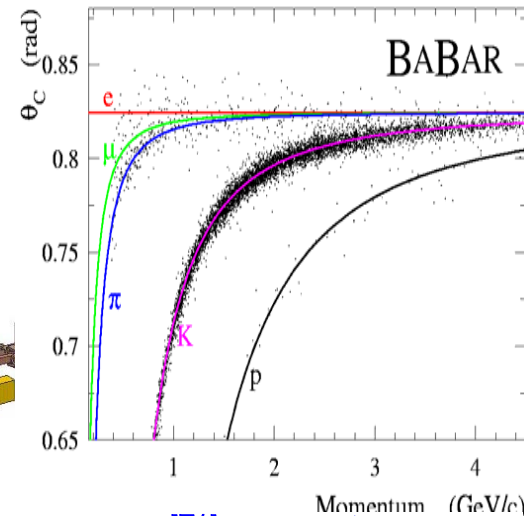- **Search for $\Theta^{*++}(pK^+)$ in B decay to the $p-K^+$ final state**

Tetiana Berger-Hryn'ova

SLAC

BaBar/PEP-II

- **PEP-II** is an asymmetric e^+e^- collider with a CM energy of 10.58 GeV.
- Peak luminosity = $1.0 \ 10^{34} \ cm^{-2}s^{-1}$
- Integrated luminosity = ~310 fb^{-1}

BaBar DIRC
- Fused Silica Cherenkov radiator
- Covers 80% of solid angle
- Particle ID above 600 MeV/c

Cherenkov Angle
(Kaon from $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ sample)
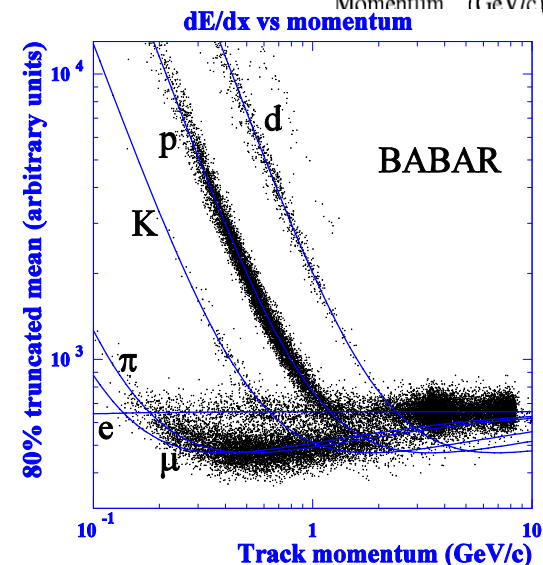

BaBar SVT
- 5 layers of double-sided Silicon strip sensors.

BaBar EMC
- 6580 CsI(Tl) crystals
- E resolution ~2 % at high E.

BaBar DCH
- 40 layers, axial and stereo wires.
- Covers 92% of solid angle
- $\delta p_t/p_t$ ~ 0.5 -1.5 %
- Particle ID up to 1.3 GeV/c

dE/dx vs momentum

Pentaquark 2005

Tetiana Berger-Hryn'ova

Search for Θ^+ in Electro- & Hadro-Production

Electro- and Hadro-Production

Evidence of Θ^+ found in:
- real/virtual photoproduction (*)
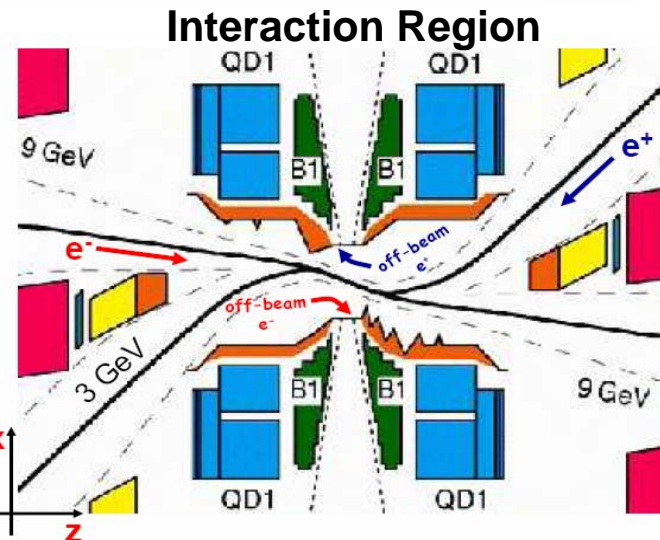- hadroproduction on hydrogen or nuclear target

No signal in CLAS: ~6x more data!

~40x more data!

Experiment	Reaction	$\sigma's$
LEPS(1)*	$\gamma^{12}C \rightarrow K^+ K^- X$	4.6
LEPS(2)*	$\gamma d \rightarrow K^+ K^- X$	
CLAS(d)*	$\gamma d \rightarrow K^+ K^- (n)p$	5.2
CLAS(p)*	$\gamma p \rightarrow K^+ K^- \pi^+ (n)$	7.8
SAPHIR*	$\gamma p \rightarrow \bar{K}^0 K^+ (n)$	4.8
COSY	$pp \rightarrow \Sigma^+ K^0 p$	4-6
JINR	$p(C_3H_8) \rightarrow K_S^0 pX$	5.5
SVD	$pA \rightarrow K_S^0 pX$ A=(C, Si, Pb)	5.6
DIANA	$K^+ Xe \rightarrow K^0 p(Xe)'$	4.4
νBC(ITEP)	$\nu Ne \rightarrow K_S^0 pX$	6.7
NOMAD	$\nu_\mu A \rightarrow K_S^0 pX$ A=(Fe, Al, Pb)	4.4
HERMES*	$e^+ d \rightarrow K_S^0 pX$	~ 5
ZEUS*	$e^- p \rightarrow e K_S^0 pX$	~ 5

Study $\Theta^+ \rightarrow pK_S^0$ production in interactions with the material of the BABAR inner detector!

- Hadroproduction: interactions of hadrons produced in e^+e^- annihilation with detector material
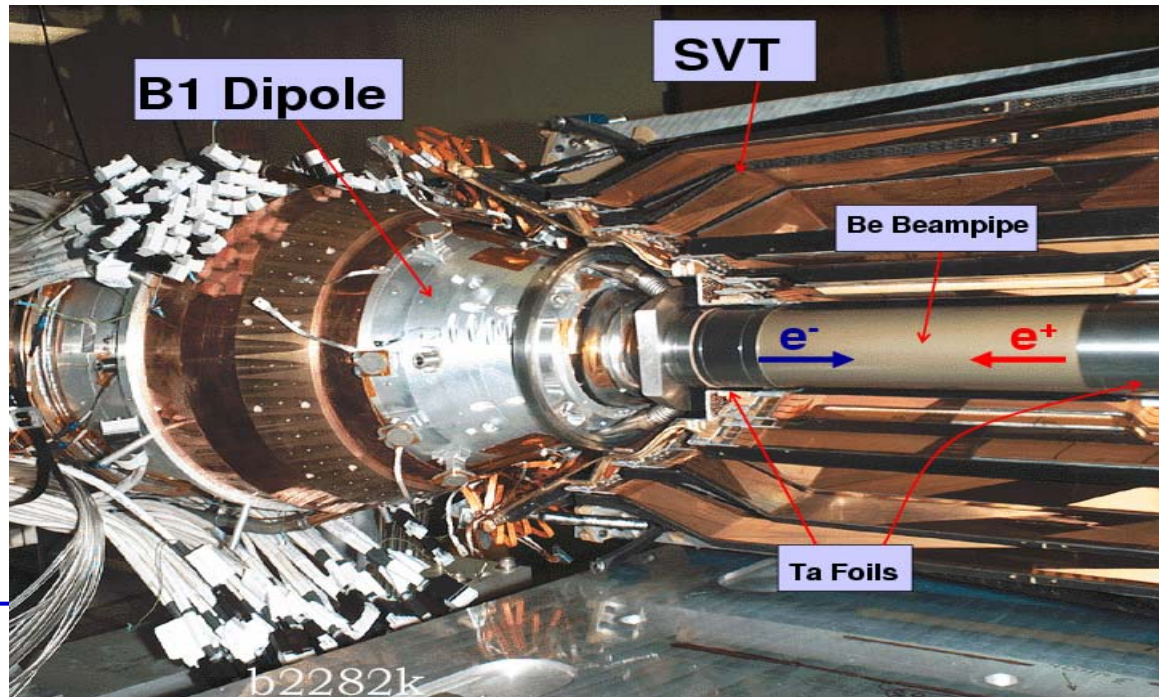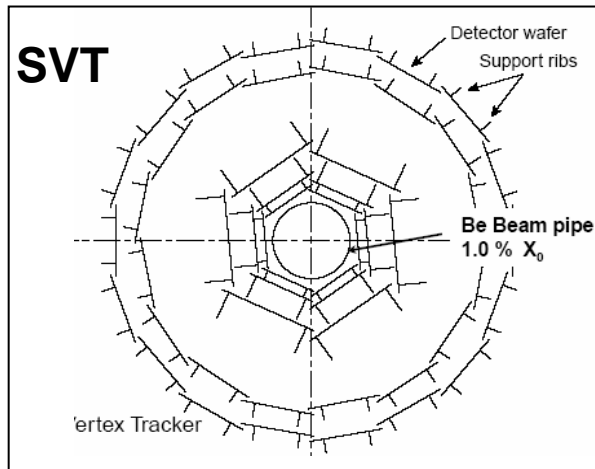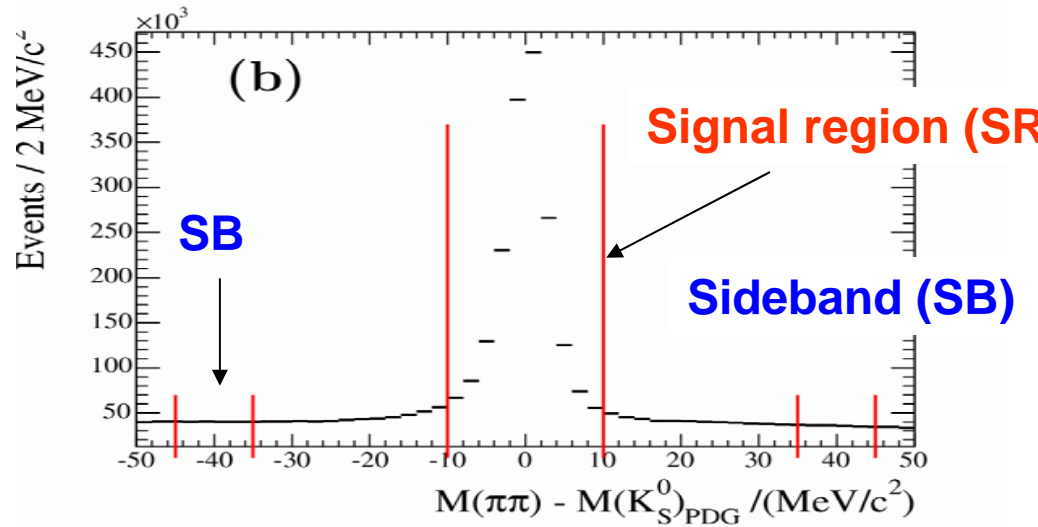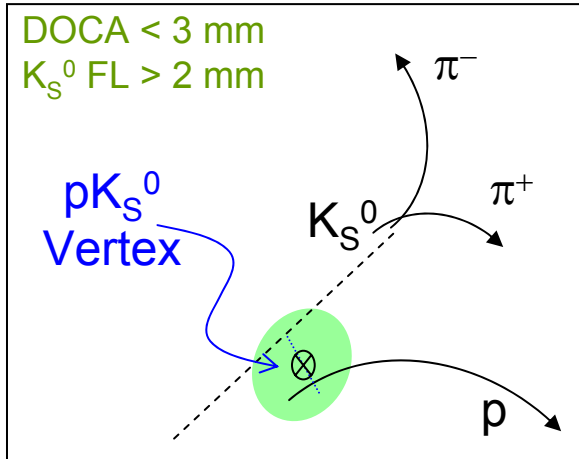- Electroproduction: off-beam e^- and e^+ bent into beampipe (Be) in horizontal plane

Compare with BABAR results

Interaction Region

Pentaquark 2005

Tetiana Berger-Hryn'ova

pK$_s^0$ reconstruction/Detector Material

Preliminary 233 fb^{-1} e$^+$ e$^-$ data

DOCA < 3 mm
K$_s^0$ FL > 2 mm

π^-

pK$_s^0$ Vertex

K$_s^0$

π^+

p

Events / 2 MeV/c^2

(b)

Signal region (SR

SB

Sideband (SB)

$M(\pi\pi) - M(K_s^0)_{PDG}$ /(MeV/c^2)

SVT

Detector wafer
Support ribs

Be Beam pipe
1.0 % X$_0$

Vertex Tracker

B1 Dipole
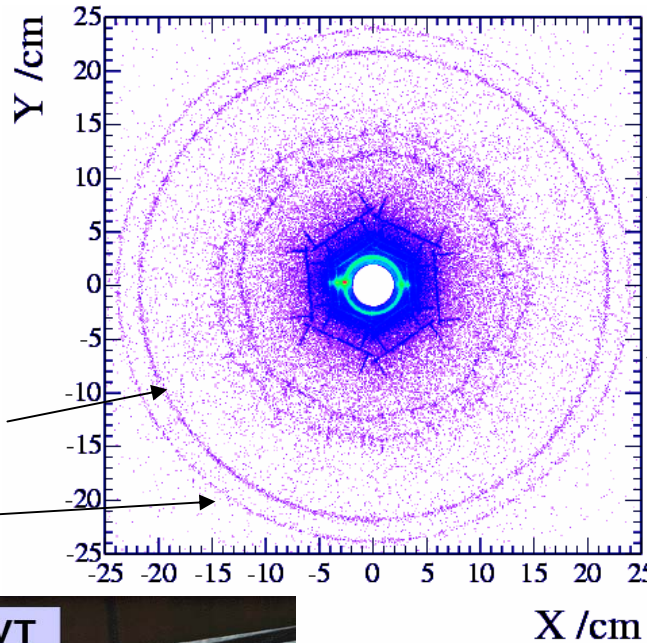
SVT

Be Beampipe

e$^-$

e$^+$

Ta Foils

b2282k

Pentaquark 2005

Detector Tomography with pK_s^0 Vertices

Preliminary 233 fb^{-1} e$^+$ e$^-$ data

SVT
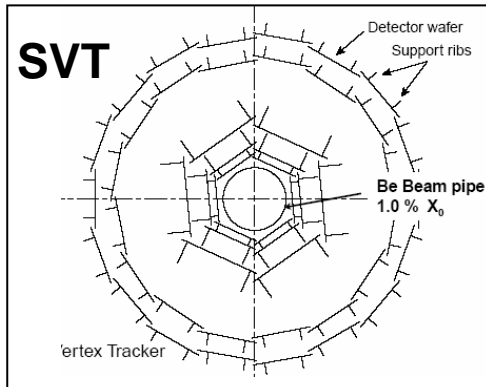
SVT support tube

DCH inner wall

beampipe

B1 Dipole

SVT

Be Beampipe

e$^-$ e$^+$

Ta Foils

b2282k

Ta

Fe   Be   Ta

-0.2 < y < 0.7 cm

-3.1 < x < -2.2 cm

z profile e- side

Tetiana Berger-Hryn'ova

pK$_S^0$ Mass Distribution

Signal region (SR)

SB

Sideband (SB)
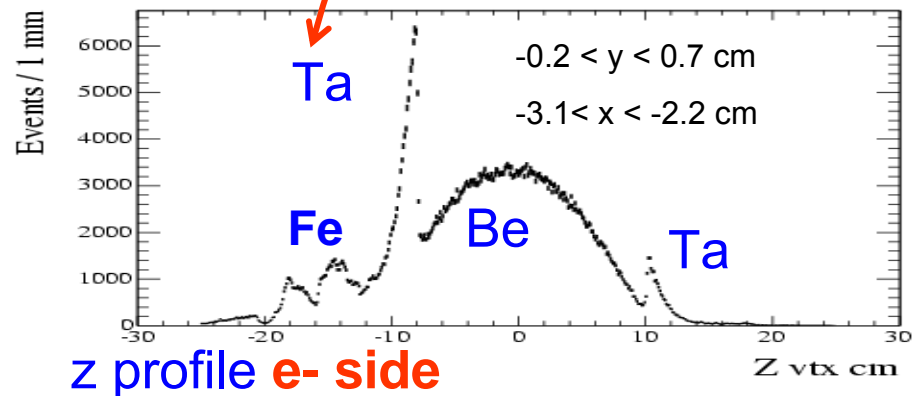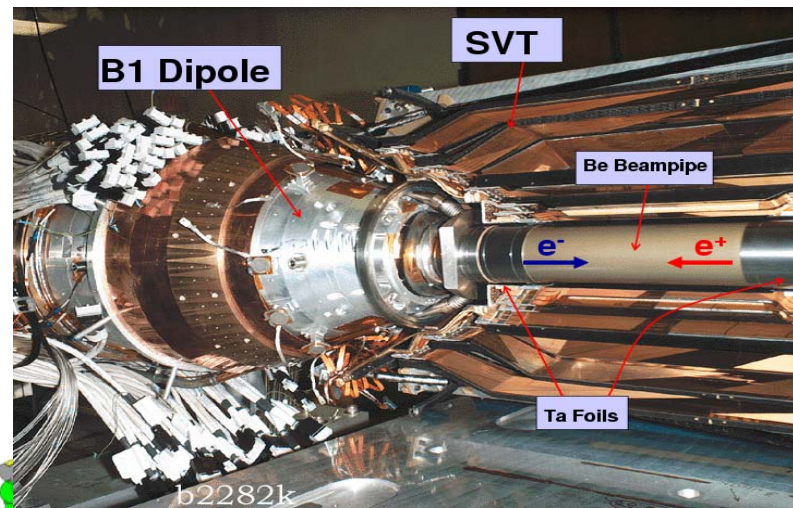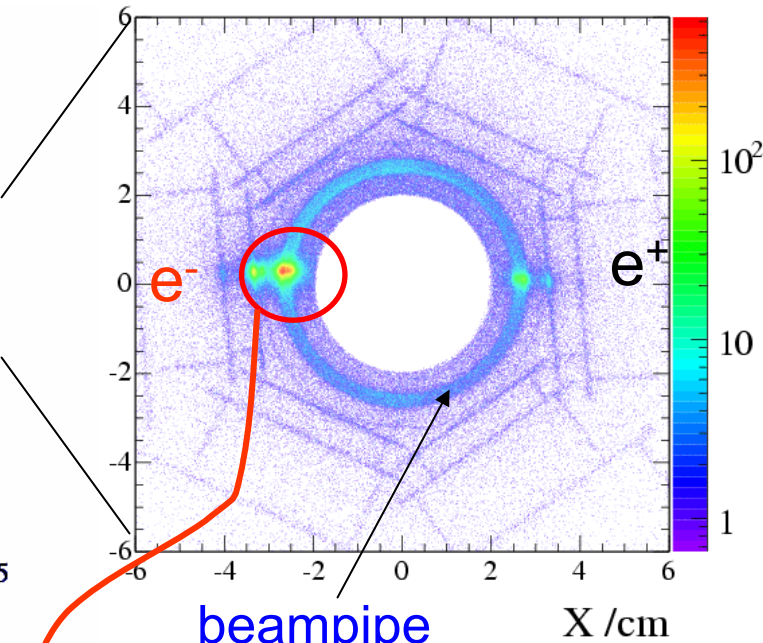
Preliminary 233 fb^{-1} e$^+$ e$^-$ data
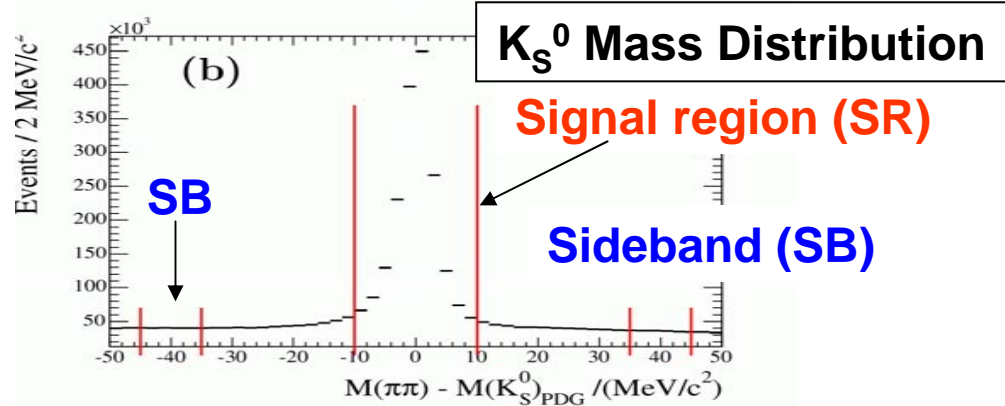
All vertices (e- and h-production)   Vertices from e-Be interaction (e-production)

SR

BABAR preliminary

No Θ^+ signal

SB

M(K$_S^0$p)/GeV/c^2

BABAR preliminary   SR

No Θ^+ signal

SB
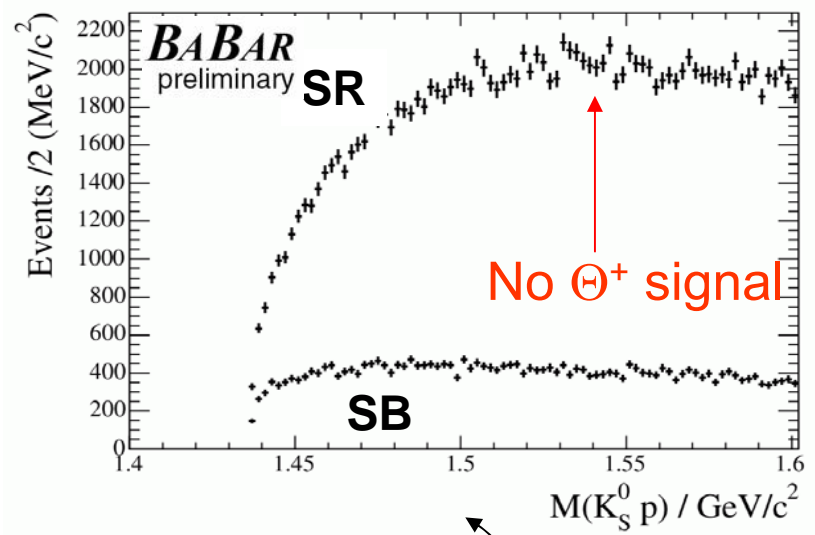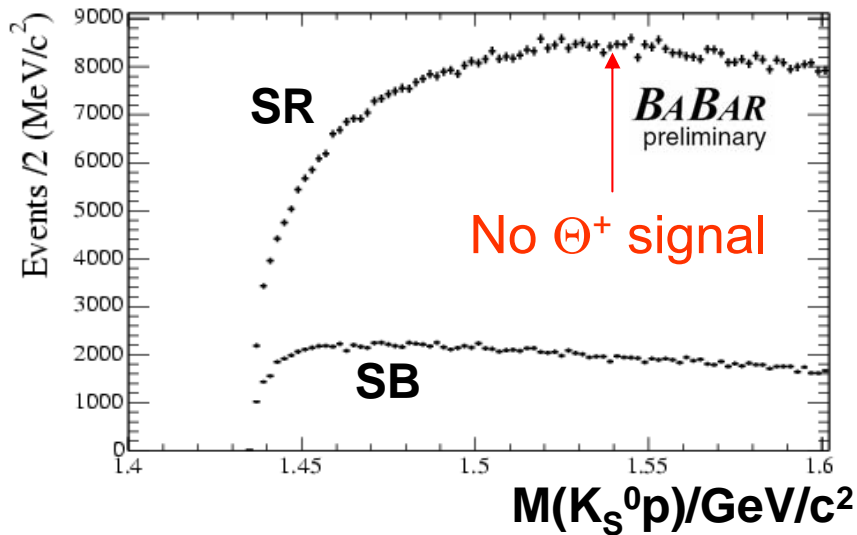
- Remove candidates with associated baryons (p,−,d,t)
- Look for other associated tracks

π^-

π^+

p,p,d,t; **$\pi^\pm$, K$^\pm$**

K$_S^0$

p

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC
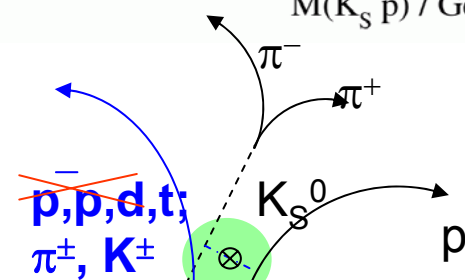
Association of $\pi^{\pm}$, $K^{\pm}$ with (p, K_s^0) Vtx

All vertices (same for e⁻Be with fewer events)

Preliminary 233 fb⁻¹ e⁺ e⁻ data

Pentaquark 2005

Tetiana Berger-Hryn'ova
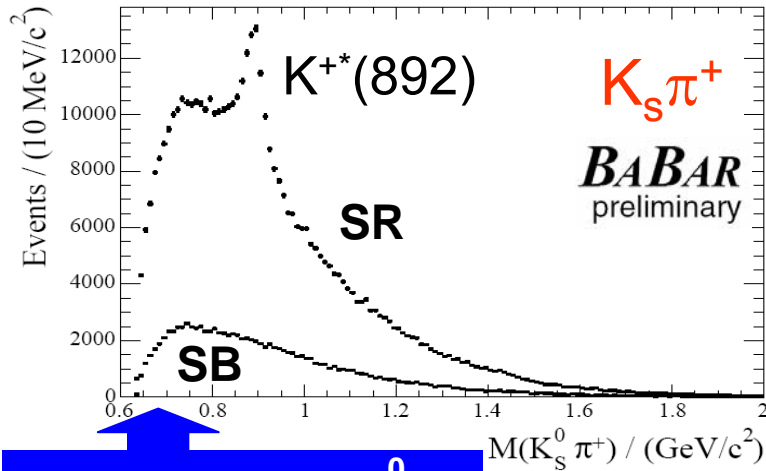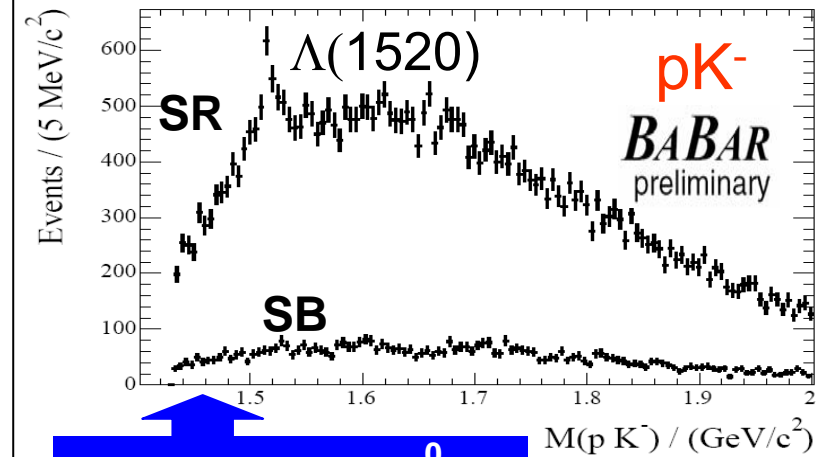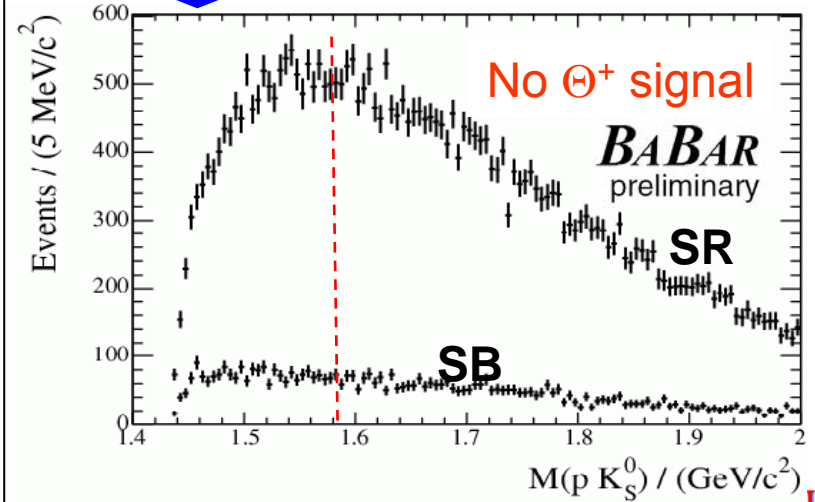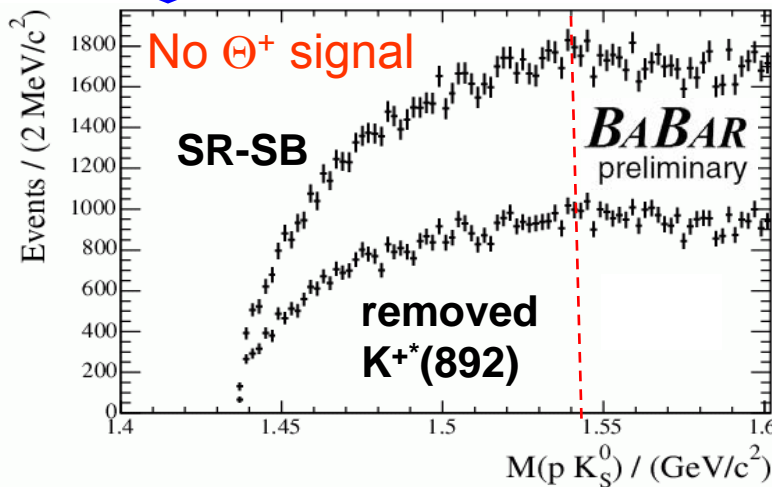
e⁻Be Electroproduction

HERMES $(e^+d \to K_S^0 p + X)$ ZEUS $(e^\nwarrow p \to e^\nwarrow K_S^0 p + X)$
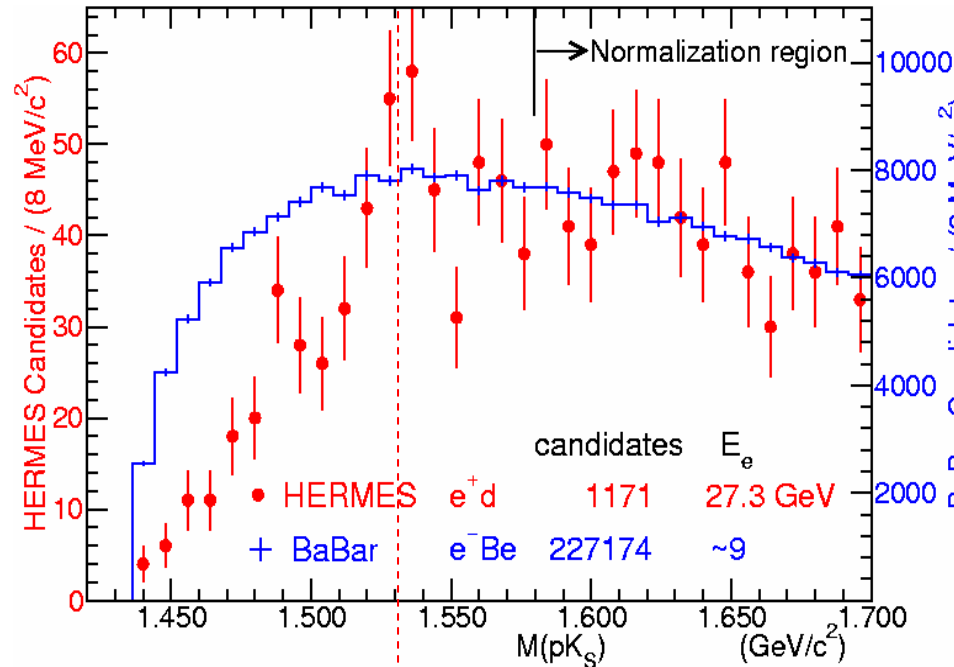
M=1528±3 MeV
~5σ
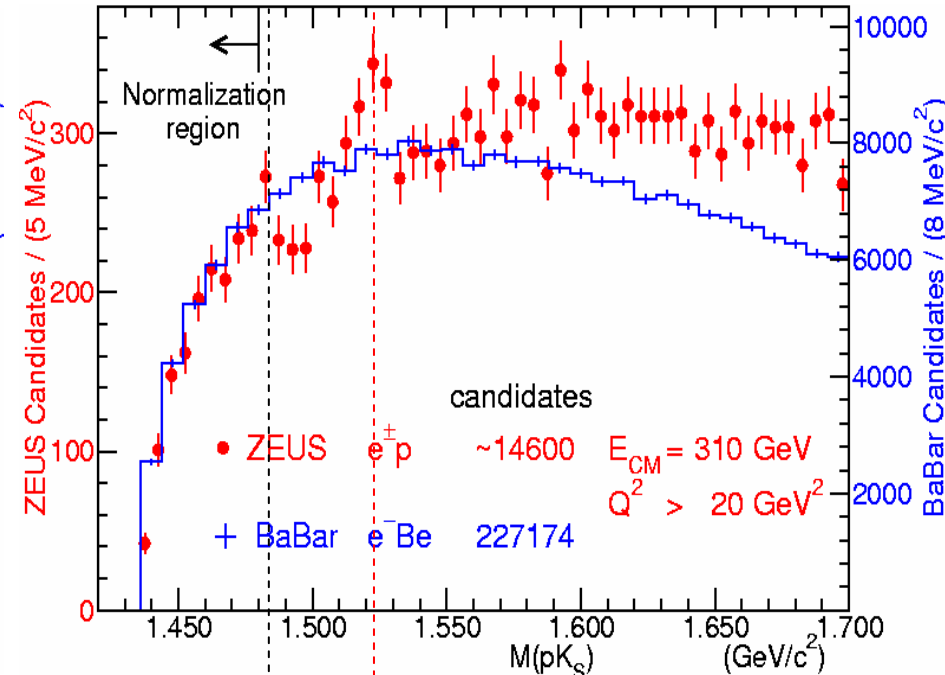
M=1522±3 MeV
~5σ

$\Sigma^*(1480)$

Possible acceptance loss in low mass region:
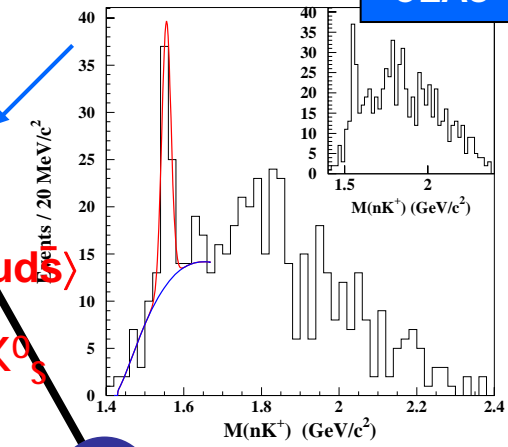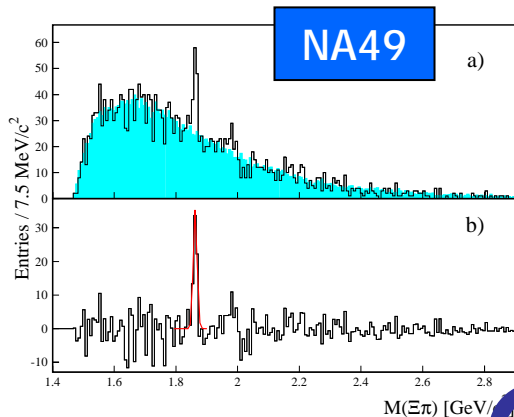(PID requires p(p) >4.1 GeV/c; p(K_S^0)>3 GeV/c)

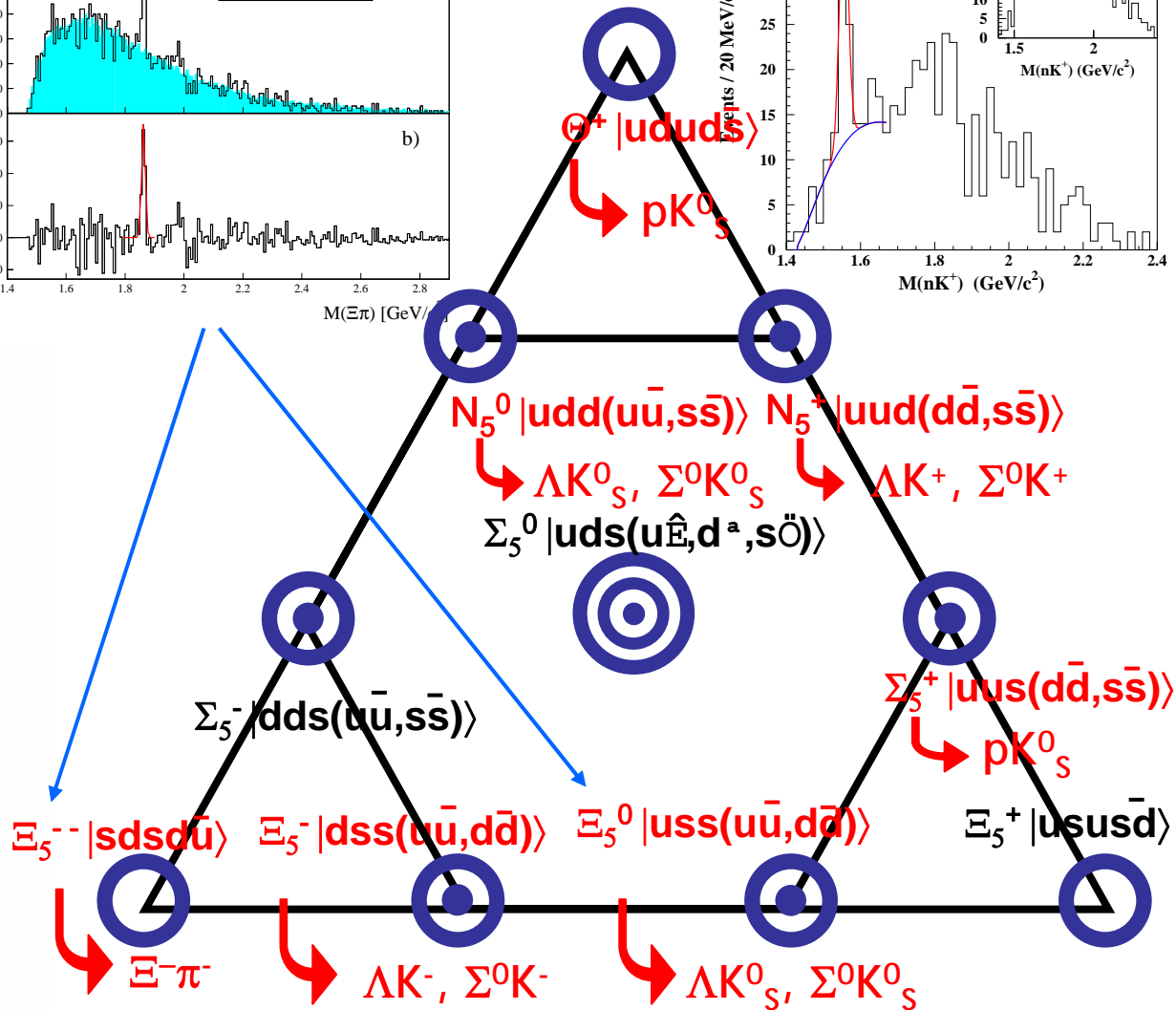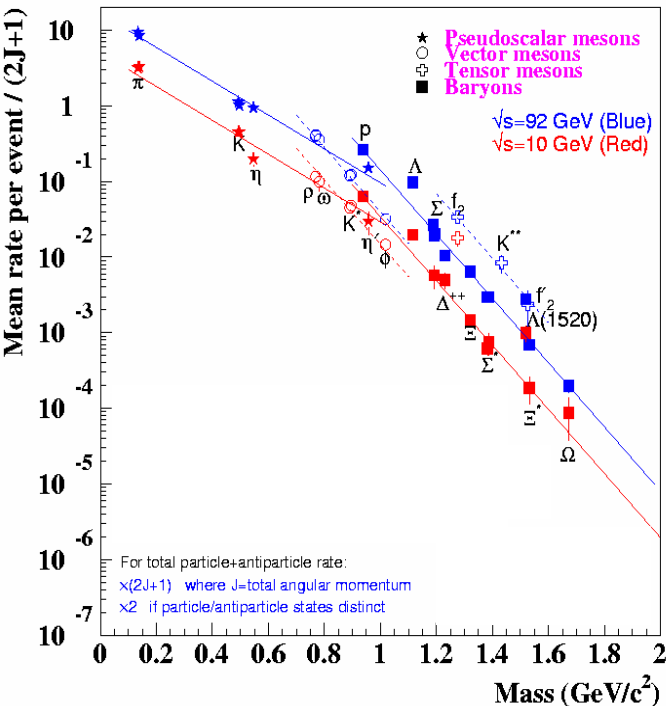Fit uses $\Sigma^*(1480)$ [PDG 1star]

SLAC
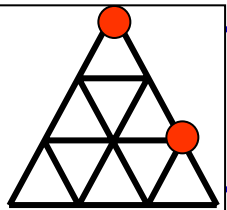
e⁺e⁻ Inclusive Pentaquark Searches

Overview

- Exotic resonances: Θ^+, seen by several and $\Xi_5^{0,--}$ seen by one experiments.

- Fits into several models; $\overline{10}+8$ multiplet of $SU(3)_f$ is favored.

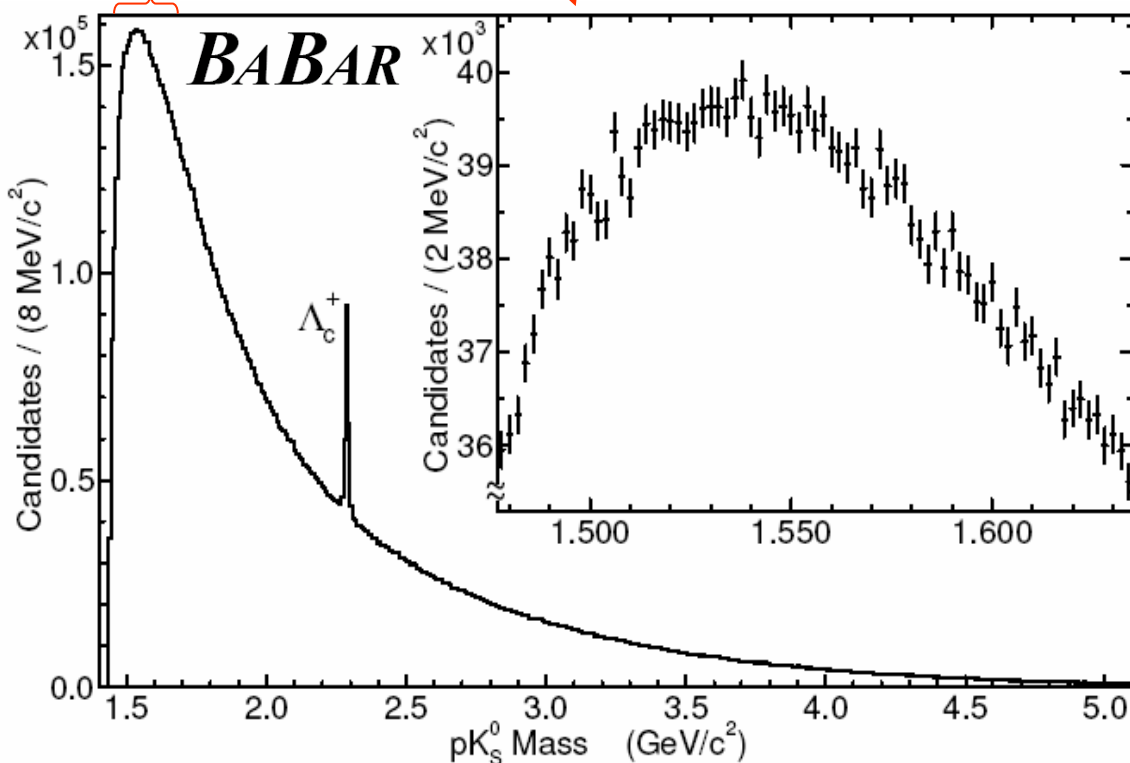- Production could be similar to baryons of same mass.

Hadron production in $e^+e^- \rightarrow$ Hadrons

NA49

$\Theta^+ \, |udud\bar{s}\rangle$

↳ pK^0_S

$N_5^0 \, |udd(u\bar{u},s\bar{s})\rangle$ $N_5^+ \, |uud(d\bar{d},s\bar{s})\rangle$

↳ $\Lambda K^0_S, \Sigma^0 K^0_S$ ↳ $\Lambda K^+, \Sigma^0 K^+$

$\Sigma_5^0 \, |uds(u\hat{E},d^a,s\ddot{O})\rangle$

$\Sigma_5^- \, |dds(u\bar{u},s\bar{s})\rangle$

$\Sigma_5^+ \, |uus(d\bar{d},s\bar{s})\rangle$

↳ pK^0_S

$\Xi_5^{--} \, |sdsd\bar{u}\rangle$ $\Xi_5^- \, |dss(u\bar{u},d\bar{d})\rangle$ $\Xi_5^0 \, |uss(u\bar{u},d\bar{d})\rangle$ $\Xi_5^+ \, |usus\bar{d}\rangle$

↳ $\Xi^-\pi^-$ ↳ $\Lambda K^-, \Sigma^0 K^-$ ↳ $\Lambda K^0_S, \Sigma^0 K^0_S$

Mean rate per event / (2J+1)

★ Pseudoscalar mesons
○ Vector mesons
✠ Tensor mesons
■ Baryons

$\sqrt{s}$=92 GeV (Blue)
$\sqrt{s}$=10 GeV (Red)

π, K, η, ρ ω, K* η' ϕ, p, Λ, Σ f_2, K**, Δ^{++}, f'_2, Λ(1520), Ξ, Σ^*, Ξ^*, Ω

For total particle+antiparticle rate:
×(2J+1) where J=total angular momentum
×2 if particle/antiparticle states distinct

Mass (GeV/c^2)

$M(\Xi\pi)$ [GeV] a) b)

$M(nK^+)$ (GeV/c^2)

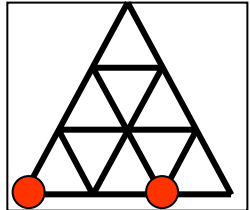# Search for $\Theta^+/\Sigma_5^+ \rightarrow pK_S^0$

- Proton selection using dE/dx and Cherenkov, clean over wide momentum range.
- Use $K^0_S \rightarrow \pi^+\pi^-$.
- 3×10^6 reconstructed decays
- Expected Resolution (HWHM) on Θ^+ mass ~ **2 MeV** (from MC)
- Can also look for Σ_5^+.

→ **~98K Λ_C's in data sample**
→ **Resolution 5-7 MeV at Λ_C**

No Σ_5^+
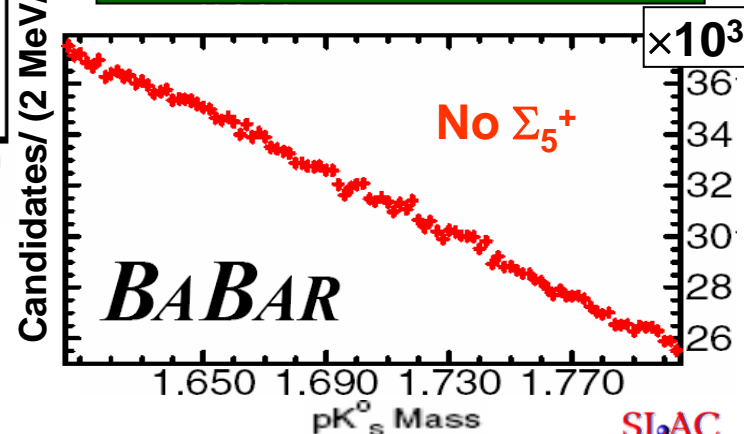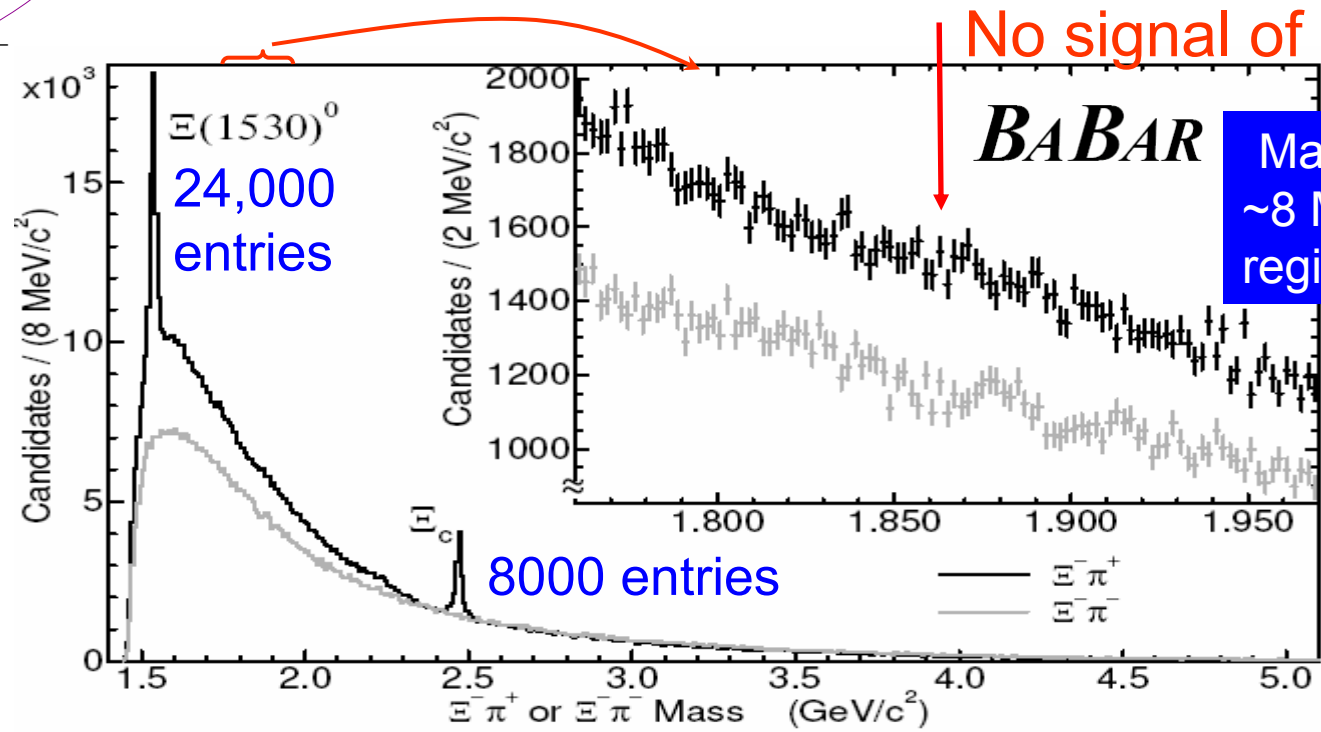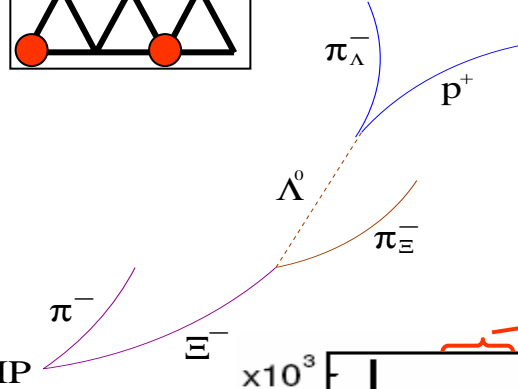
Upper Limits of total cross section:
$\Theta^+ + \Theta^-$: for $\Gamma=1(8)$MeV $\Rightarrow 171(363)$fb

Search for $\Xi_5^{0/--} \rightarrow \Xi^-\pi^{\pm}$

- Geometrical selection of two displaced vertices
- Good p and π selection (dE/dx, θ_c)
- Select masses near the nominal Λ^0 and Ξ^- masses
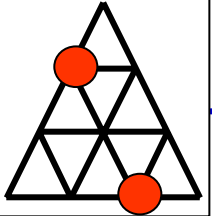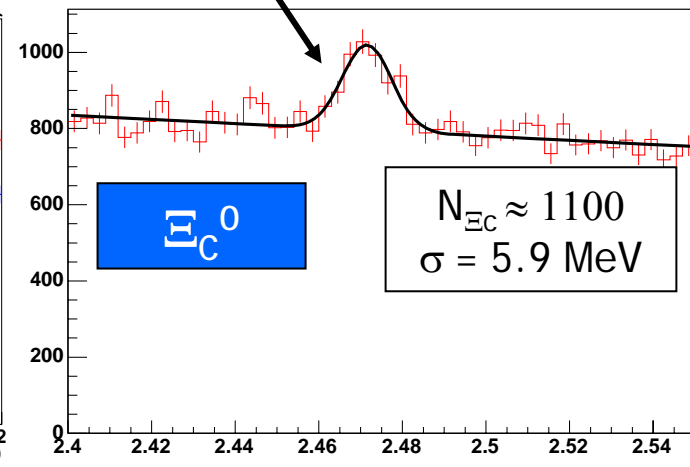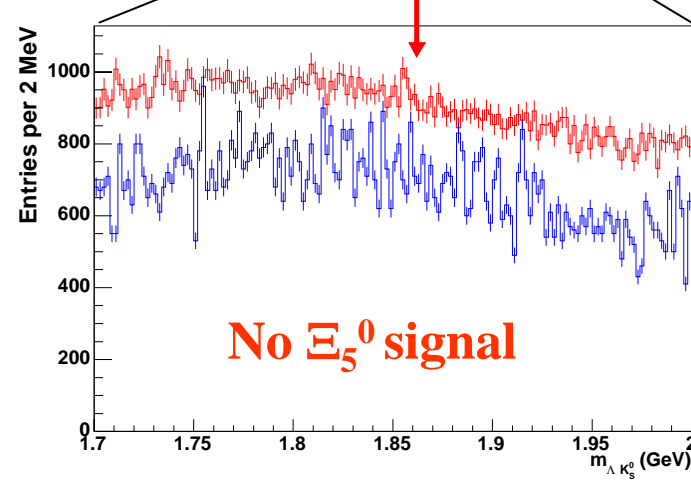- Control signals: $\Xi^{*0}(1530) \rightarrow \Xi^-\pi^+$, $\Xi_c(2470) \rightarrow \Xi^-\pi^+$

No signal of Ξ_5^0 / Ξ_5^{--}
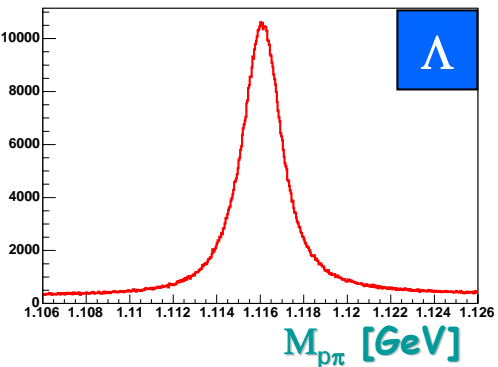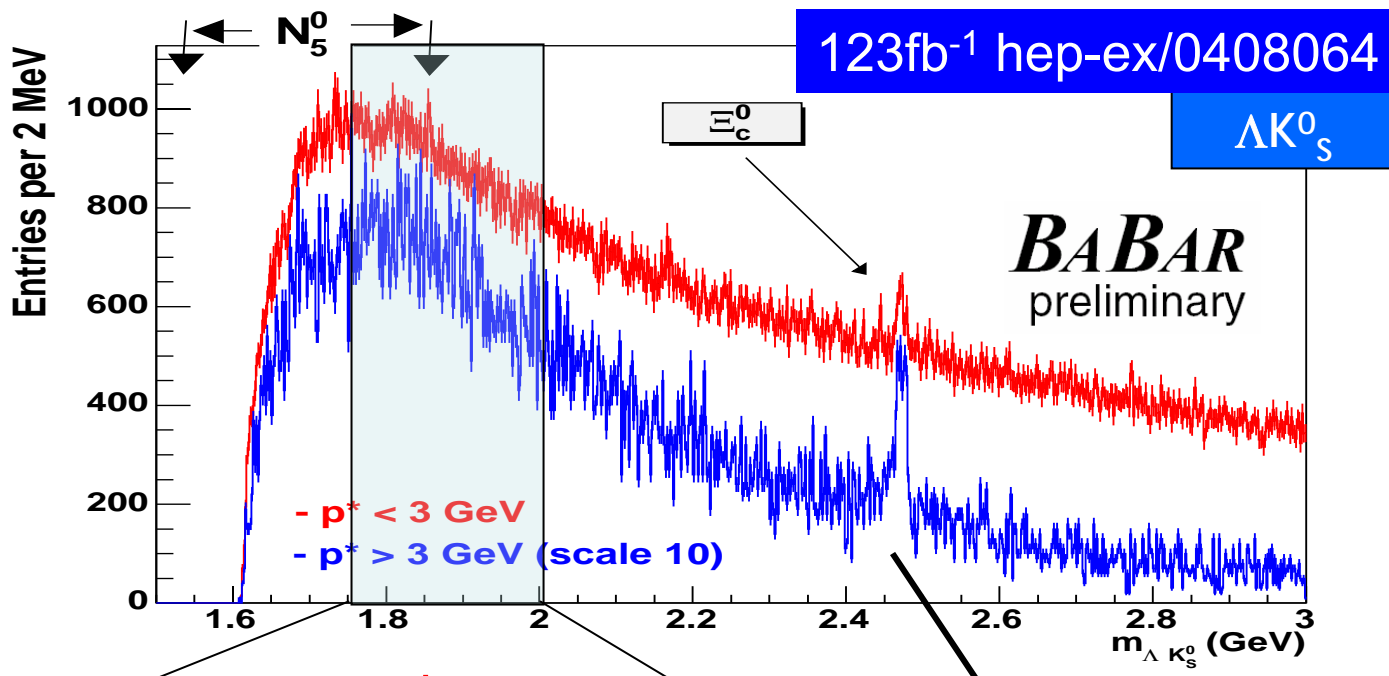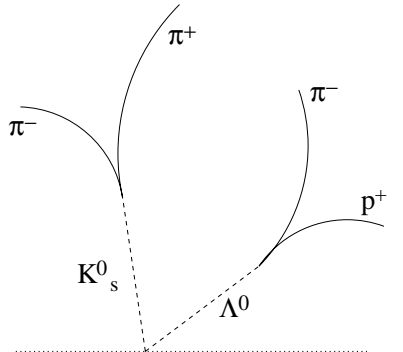

24,000 entries

$\Xi(1530)^0$

8000 entries

Ξ_c

BABAR

Mass resolution ~8 MeV/c^2 in Ξ_5 region (r.m.s)

U. L. on total cross section: $\Xi_5^{++}+\Xi_5^{--}$: for Γ=1(18)MeV $\Rightarrow$ 25(36) fb

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Search for $\Xi_5^0/N_5^0 \rightarrow \Lambda K_S^0$

123fb^{-1} hep-ex/0408064

ΛK_S^0

N_5^0

Ξ_c^0

BABAR preliminary

- p* < 3 GeV
- p* > 3 GeV (scale 10)

$m_{\Lambda K_S^0}$ (GeV)

Λ

$M_{p\pi}$ [GeV]

K_S^0

$M_{\pi\pi}$ [GeV]

No Ξ_5^0 signal

$m_{\Lambda K_S^0}$ (GeV)

Ξ_c^0

$N_{\Xi_C} \approx 1100$
$\sigma = 5.9$ MeV

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Search for $N_5^+ \to \Lambda K^+$, $\Xi_5^- \to \Lambda K^-$

ΛK^+

N_5^+

- p* < 3 GeV
- p* > 3 GeV (scale 10)

Λ_c^+ feed-down

Λ_c^+

BABAR preliminary

ΛK^-

Ω^-

- p* < 3 GeV
- p* > 3 GeV (scale 10)

BABAR preliminary

DATA

$N_{\Lambda C} \approx 600$
$\sigma = 5.3$ MeV

Λ_c^+ Cabibbo-Suppressed Decay

Ω^-

$N_\Omega \approx 6300$
$\sigma = 3.0$ MeV

No Ξ_5^- signal

Pentaquark 2005

Tetiana Berger-Hryn'ova
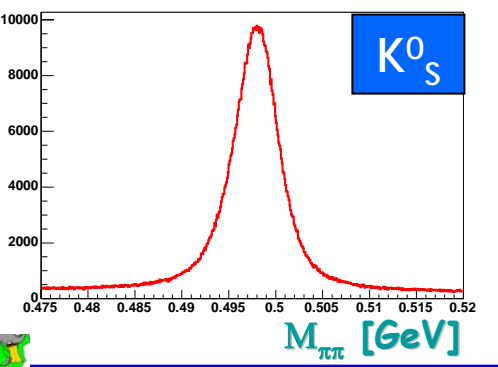
Search for $N_5^+/\Xi_5^- \to \Sigma^0 K^\pm$, $\Xi_5^0/N_5^0 \to \Sigma^0 K_s^0$

Results (e⁺e⁻ Annihilations)
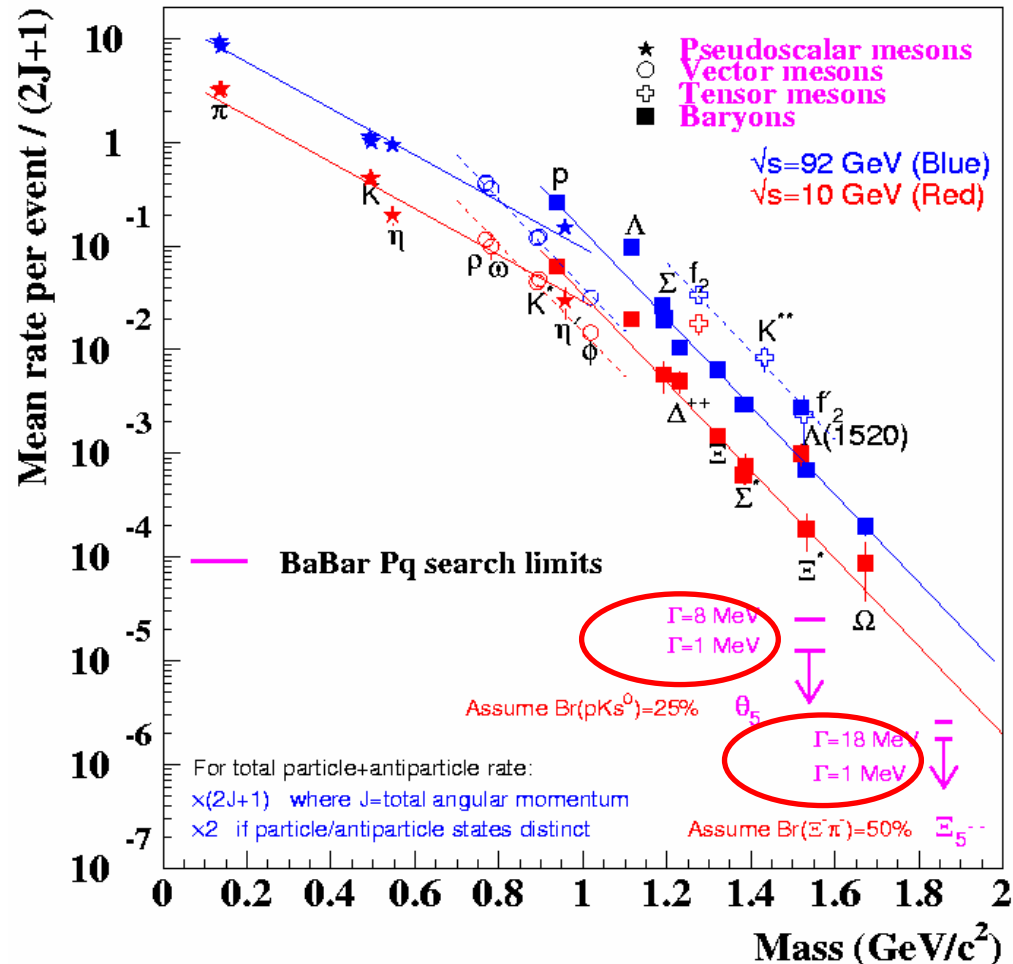
- No signal for any pentaquark state observed

- Assumptions
  - $J=1/2$
  - $BF(\Theta^+ \rightarrow pK_s^0)=25\%$
  - $BF(\Xi_5^{--} \rightarrow \Xi^-\pi^+)=50\%$
  - BF for Ξ_5^- and Ξ_5^0 very unclear
  - Intrinsic width 1-18 MeV/c^2

- Limits on production times branching fraction 4-15x lower than production rates for conventional baryons

Hadron production in e⁺e⁻→Hadrons

Pentaquark 2005

Tetiana Berger-Hryn'ova

$\Theta_c{}^0$ Pentaquark Search

SU(4) 60-plet

C

I

Y

15-plet C=+2

$(cdcd\hat{E})$

anti-15 + 6-plet C=+1

$(cdsd\hat{E})$

$\Xi^+(usus\,^a)$

$\Xi^{--}(sdsd\hat{E})$

anti-decupltet (10) + octet (8) C=0

$\Theta^+(udud\ddot{O})$

anti-6-plet C=-1

$\Theta_c{}^0(udud\cancel{E})$

H1

- $D^{*-}p + D^{*+}\bar{p}$
— Signal + bg. fit
···· Bg. only fit

Entries per 10 MeV

40

30

20

10

0

3   3.2   3.4   3.6

$D^0 \rightarrow K^-\pi^+$ **mode only**

$M(\bar{D}^*p)$ [GeV]
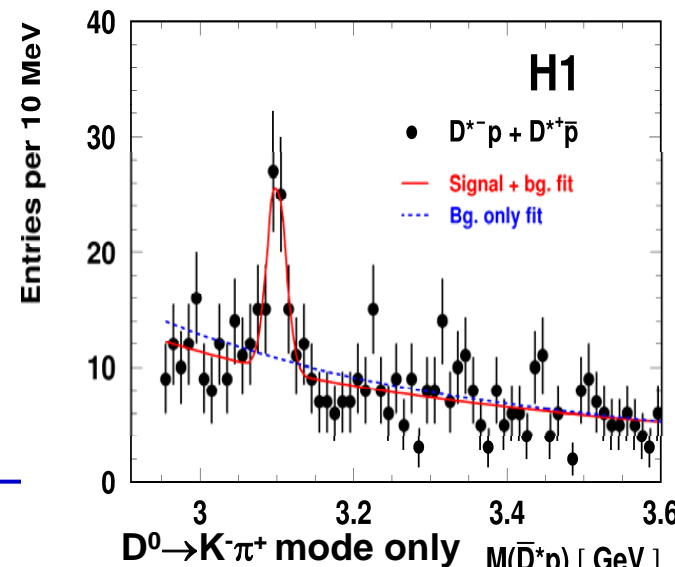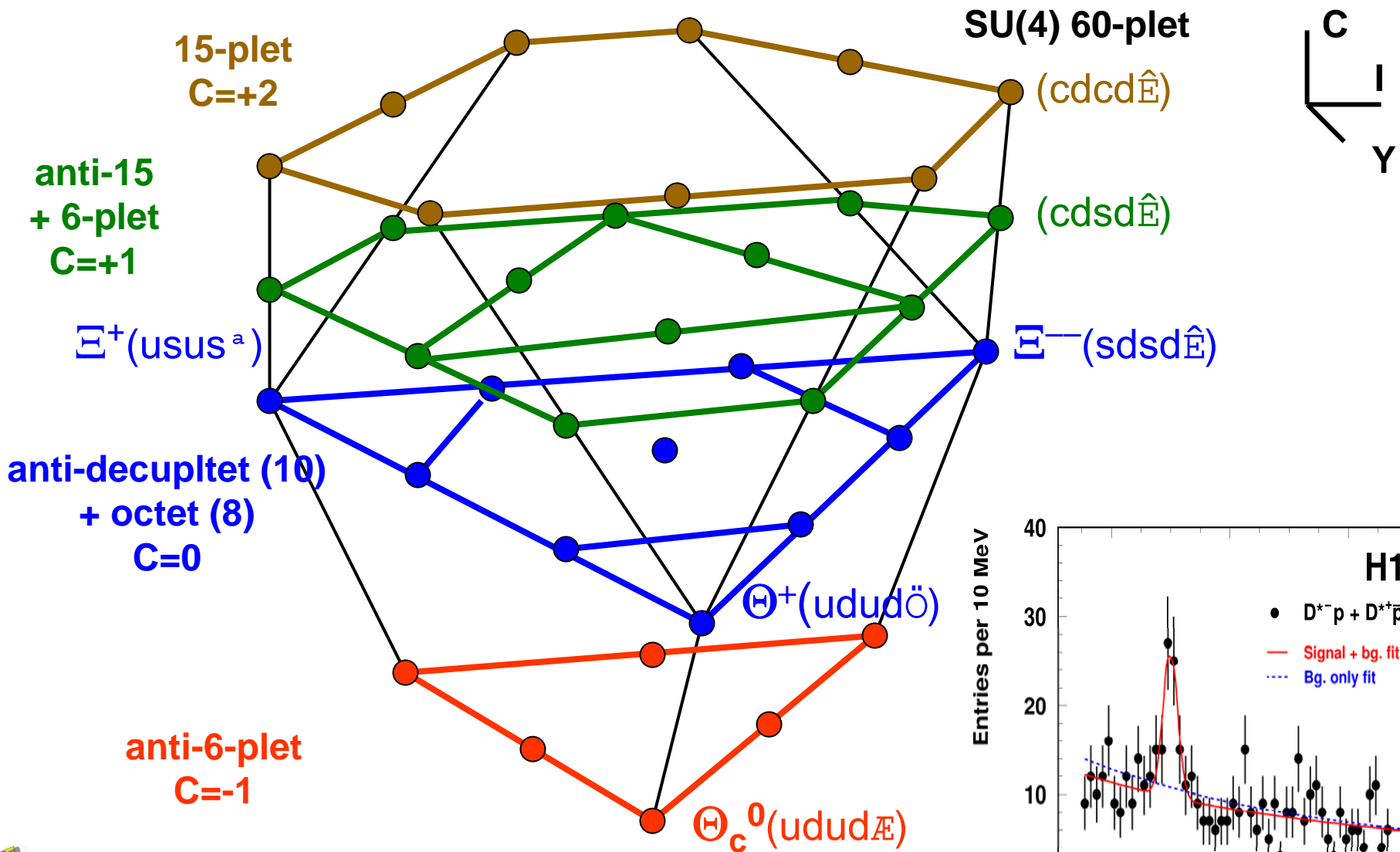
Search for $\Theta_c^0 \rightarrow pD^{*-}(\overline{D}^0(K^+\pi^-, K^+\pi^-\pi^+\pi^-)\pi^-)$

BaBar Preliminary 123 fb^{-1} e$^+$ e$^-$ data, see hep-ex/0510044 for details

Reconstruct ~750k of D^{*-}

D^{*-}($\overline{D}^0 \rightarrow K^+\pi^-$)

After cuts
~55k D^{*-}
~4k bkgr

After cuts
~73k D^{*-}
~62k bkgr

D^{*-}($\overline{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-$)
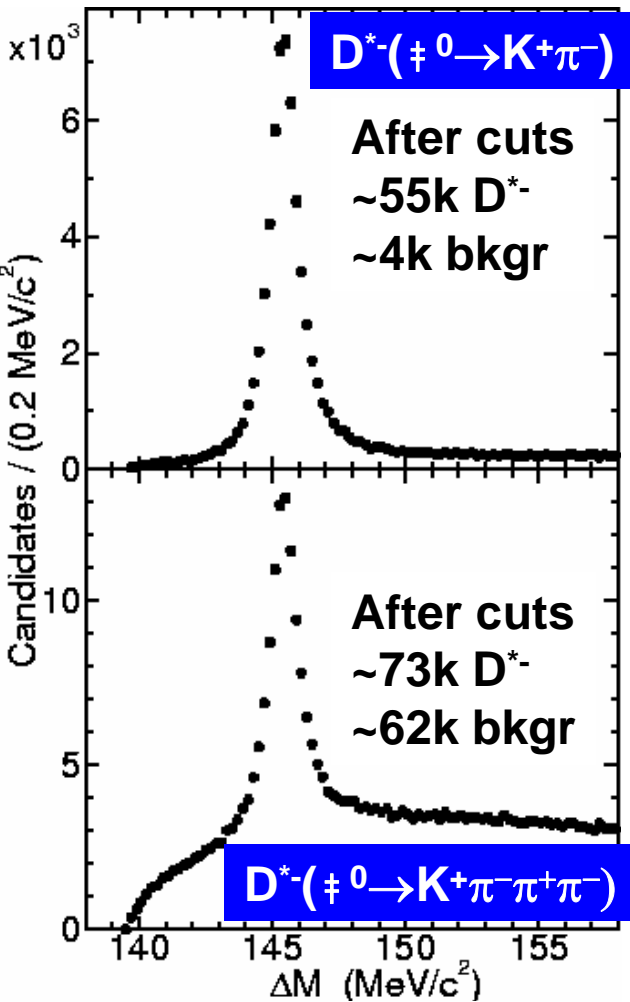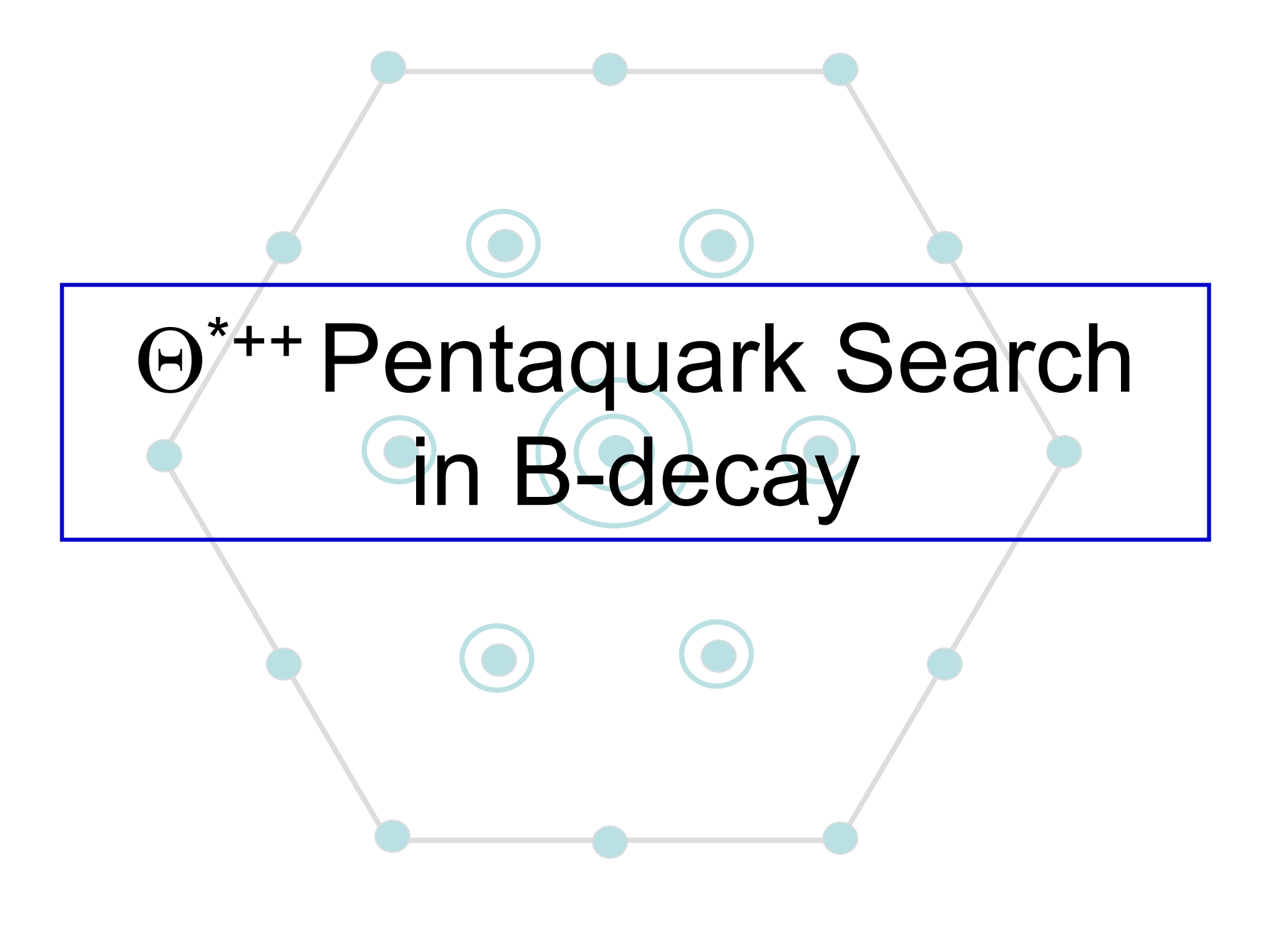
with proton requirement

BaBar preliminary
— D^0 -> Kπ mode
— D^0 -> K3π mode
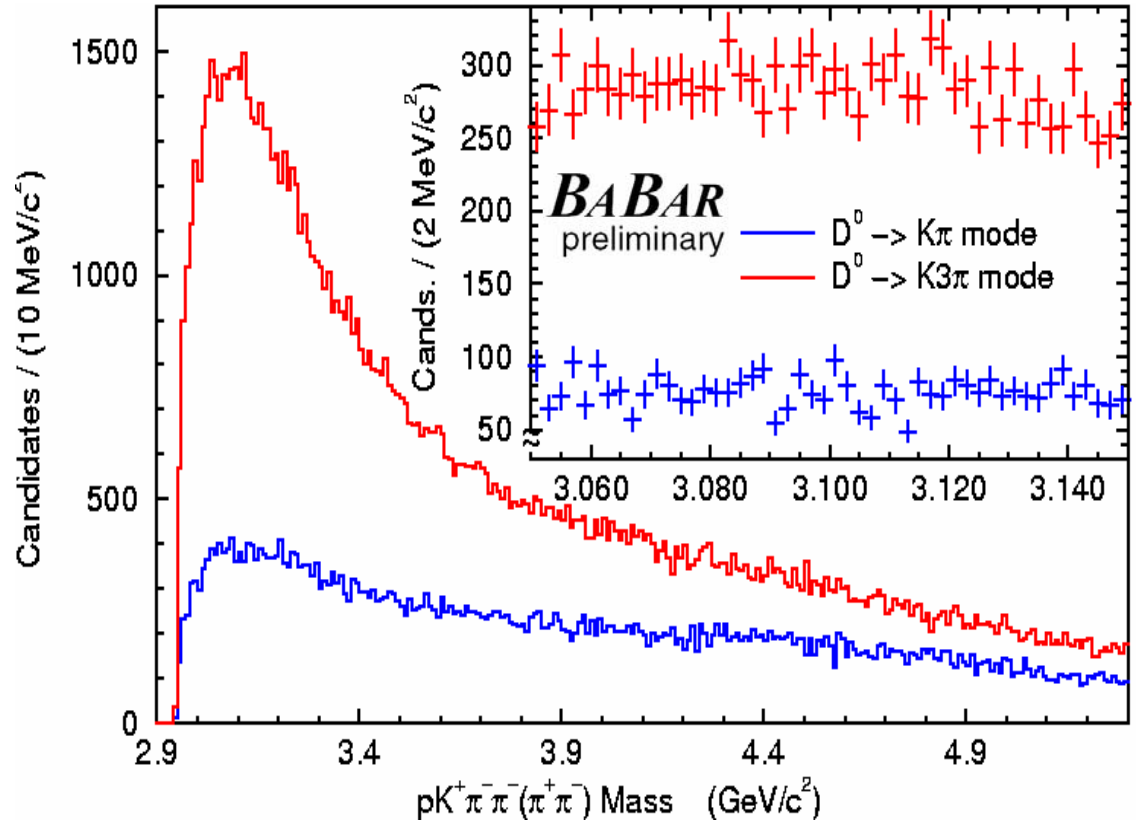
Expected Resolution (HWHM) on
Θ_c mass ~ **3 MeV** (from MC)

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Θ^{*++} Pentaquark Search in B-decay

Current Status

$uddd\ddot{o}$ $uudd\ddot{o}$ $\underline{uuud\ddot{o}}$ Θ^*

$uddd\,\hat{u}$ $uuud\,\cancel{E}$ Δ^*

$ddds\,\hat{u}$ $uuus\,\cancel{E}$ X_{1s}

$ddss\,\hat{u}$ $uuss\,\cancel{E}$ X_{2s}

$dsss\,\hat{u}$ $usss\,\cancel{E}$ Ω^*
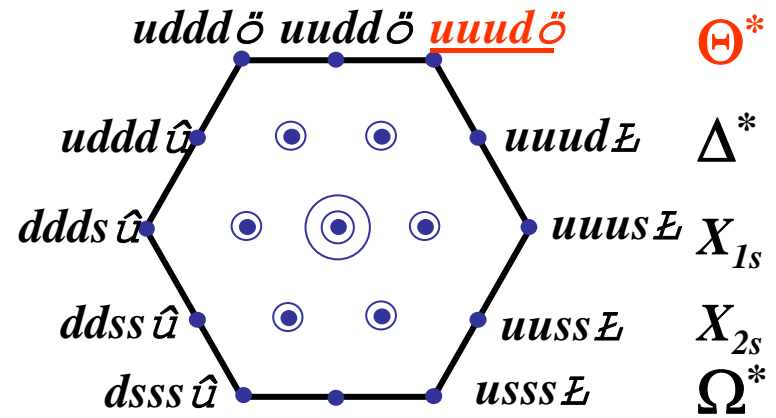
- Theory: $\Theta^{*++} \to K^+ p$ mode dominant
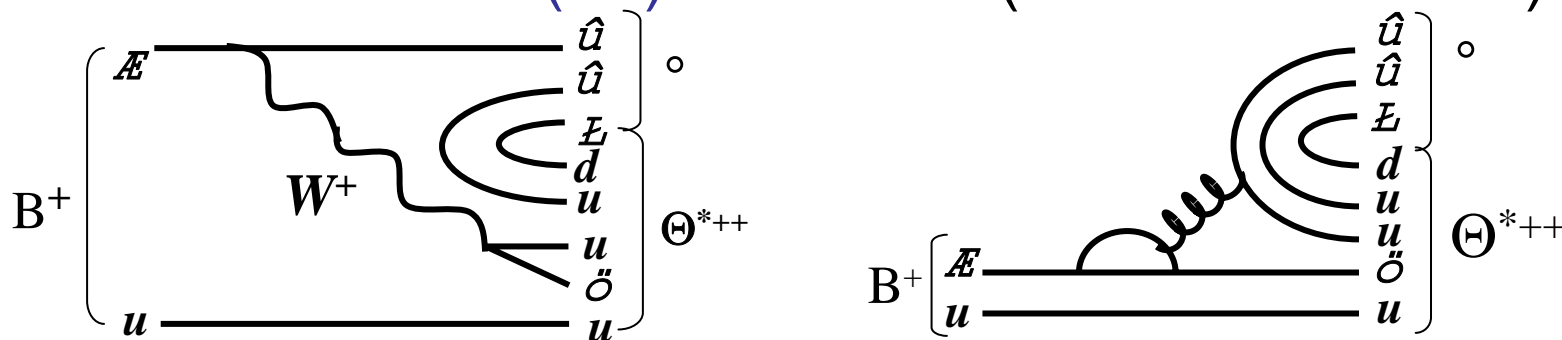 $m_{\Theta^{*++}}$ = 1.6-1.7 GeV/c^2 & $\Gamma_{\Theta^{*++}}$= 37-66 MeV

- Not seen by CLAS, HERMES, SAPHIR, ZEUS

- A hint from STAR? (at ~1.53GeV/c^2, Γ~20MeV); isospin partner not seen in BaBar inclusive search with ~3-10 times statistics

- In K$^+$p scattering: no sign of Θ^{*++}; constrains $\Gamma(\Theta^{*++})$<15MeV

- Previous searches in B decays (idea: Phys.Lett.B, **587** 62(2004))

  – By-product of the B$^\pm \to$ p−K$^\pm$ analysis, very low background

  – BaBar 81fb^{-1} [hep-ex/0408037]: $\mathcal{B}(B^+ \to \Theta^{*++}−) \times \mathcal{B}(\Theta^{*++} \to pK^+)$< 1.5×10^{-7} @ 90% CL for narrow state with m(Θ^{*++})=1.43-1.85 GeV/c^2

  – BELLE 140fb^{-1} [Phys Lett B 617(2005),141]: $\mathcal{B}(B^+ \to \Theta^{*++}−) \times \mathcal{B}(\Theta^{*++} \to pK^+)$< 0.9×10^{-7} @ 90% CL for narrow state at m(Θ^{*++})=1.71 GeV/c^2 [search region: 1.6-1.8]

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Analysis Overview

- Data Samples
  - 210 fb^{-1} on the Υ(4S) resonance (232 M B$^{\pm}$ mesons)

- Isolate B$^{\pm}\rightarrow$p$-$K$^{\pm}$ final state, search for Θ^{*++} in m$_{pK+}$

B decay

q°
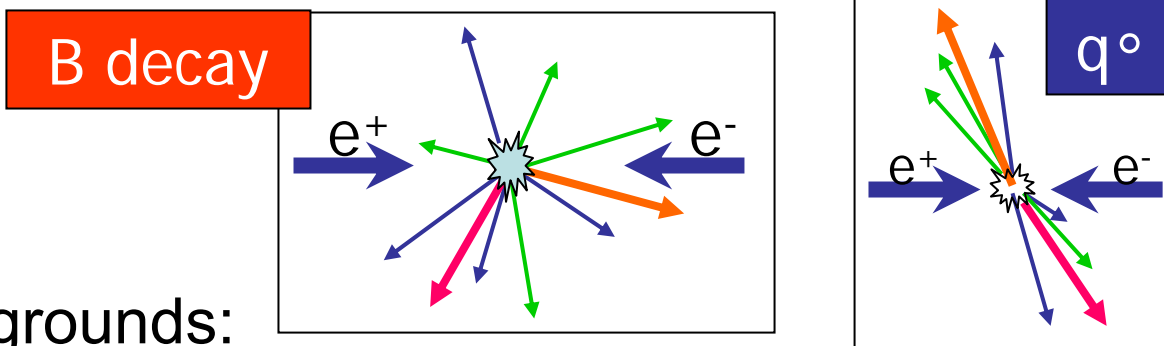
- Major Backgrounds:
  - Baryons from e$^+$e$^-\rightarrow$q°, where q=u,d,s,c (suppress topologically)
  - Allowed B decays: B$^{\pm}\rightarrow$XK$^{\pm}$, X$\rightarrow$p$-$ (X=η_c,J/ψ,χ_c,ψ(2S))

Tetiana Berger-Hryn'ova

B→ppK Dalitz Plot

B signal

BABAR

$E^*_B - E^{*\,expected}_B$ (GeV)

ΔE (GeV)

$\sim m_B$

m_{ES} (GeV/c^2)

$m^2_{pK^+}$, GeV^2/c^4

BABAR

m_{p}

η_c

J/ψ

$\psi(2S)$

$\chi_{c[0-2]}$

Θ^{*++} **region**

$m^2_{pK^+}$, GeV^2/c^4
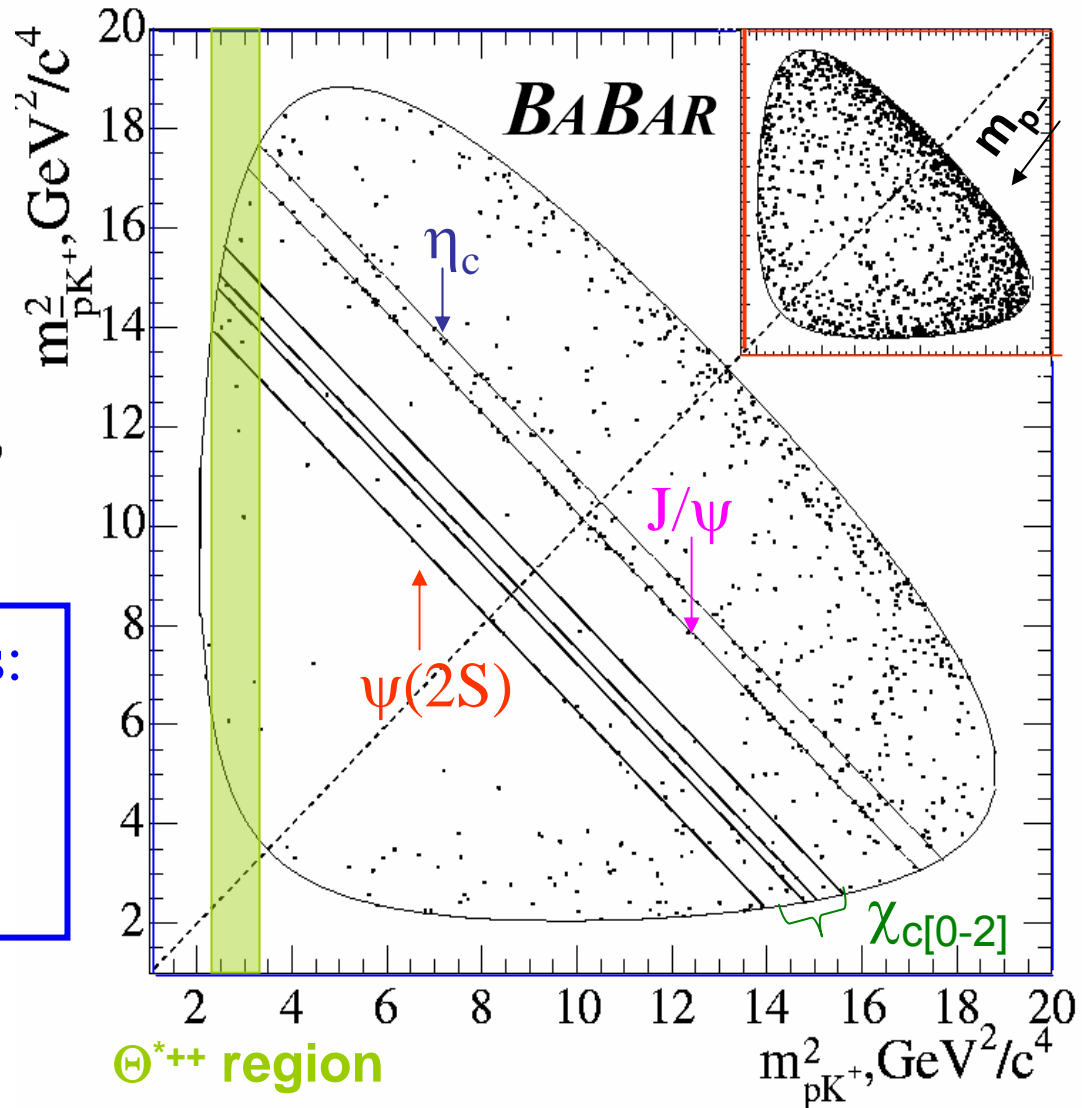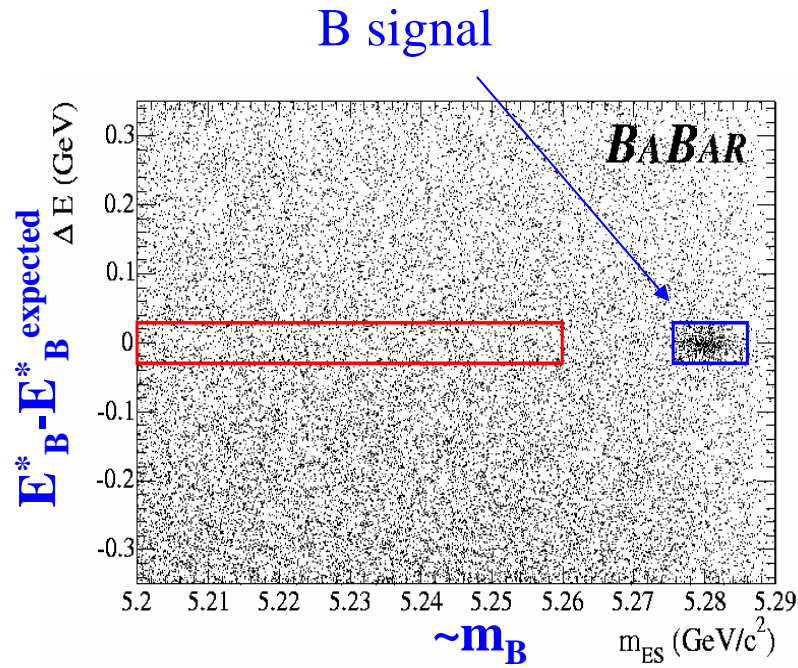
p°K$^+$ signal box 780 events:
~566±29 signal events
~ 202±5 combinatorial background

Sideband: 1661 events

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC
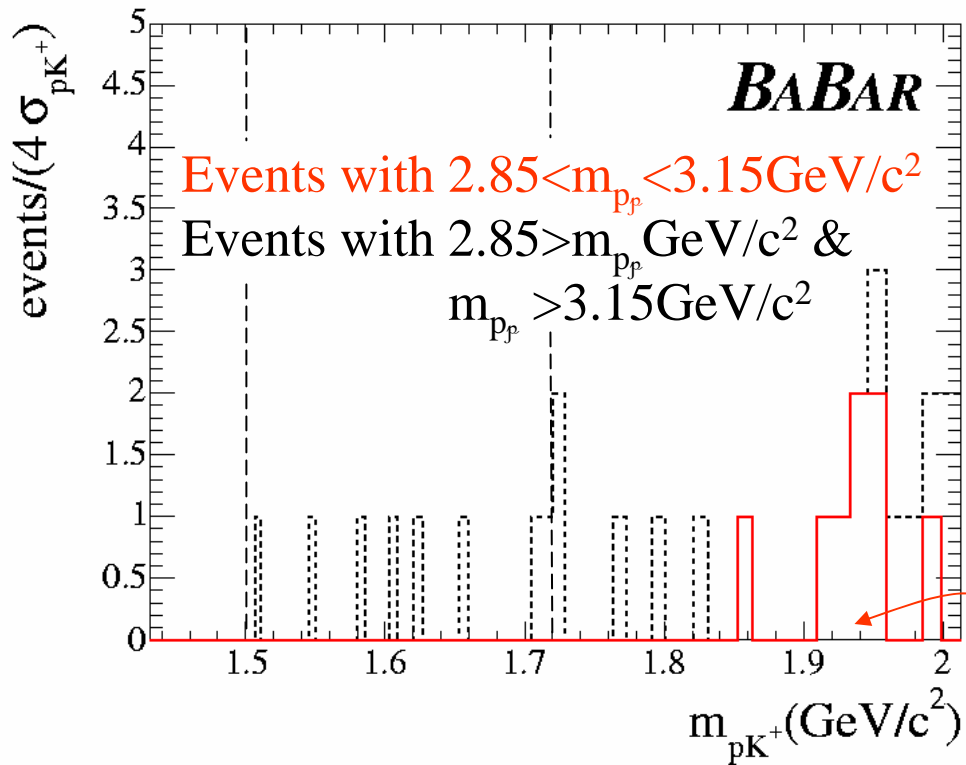
Θ^{*++} Search
(PRD **72**, 051101(R) 2005)

BaBar

Events with $2.85 < m_{p\bar{p}} < 3.15 \text{GeV}/c^2$

Events with $2.85 > m_{p\bar{p}} \text{GeV}/c^2$ & $m_{p\bar{p}} > 3.15 \text{GeV}/c^2$

events/(4 σ_{pK^+})

$m_{pK^+}(\text{GeV}/c^2)$

For $m_{pK^+} < 3\text{GeV}/c^2$:
σ_{pK+} varies from 1-3MeV/c^2
and $\varepsilon_{av}=20.5\pm0.1\%$

Remove from UL calculation

Mass Region, GeV/c^2	$\mathcal{B}(B^+ \to \Theta^{*++}\bar{p}) \times \mathcal{B}(\Theta^{*++} \to pK^+)$ UL $\times 10^{-7}$ @ 90% CL
$1.4 < m_{pK+} < 1.5$	0.5
$1.5 < m_{pK+} < 1.7$	0.9
$1.7 < m_{pK+} < 2.0$	1.2

assuming narrow (<1GeV) Θ^*++ resonance!

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Conclusions

- BaBar Pentaquark searches have yielded negative results
- High statistics, excellent mass resolution:
  - Hadro- and Electro-Production in Detector Material
    - No $\Theta^+ \rightarrow pK_s$ found
  - Inclusive Search in e^+e^- Annihilations
    - No evidence found for eight members of strange anti-decuplet and octet, and anti-charm Θ_c^0
    - Limits below expectation for baryons (factor 1-15) for Θ^+, Ξ_5^{--}
- Low statistics/low background, excellent mass resolution:
  - No Θ^{*++} observed in $B^+ \rightarrow p-K^+$: limit set on product of BF
- Pentaquark Searches highlight potential for study of charmed and non-charmed Baryons at BaBar
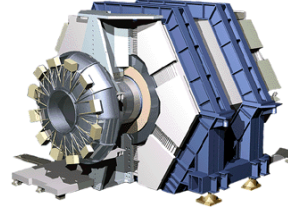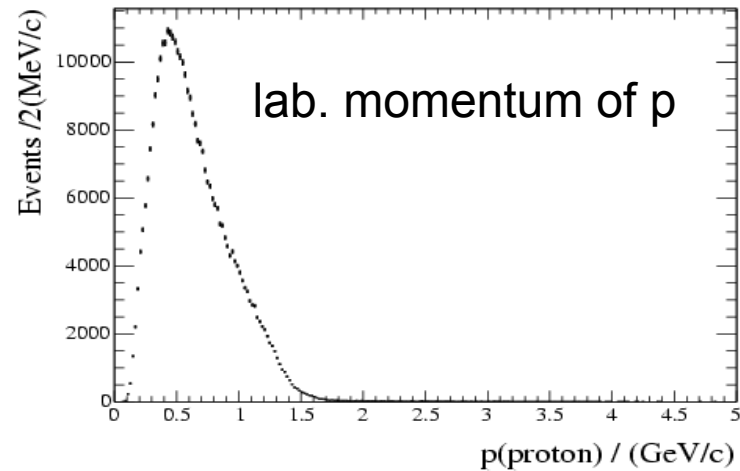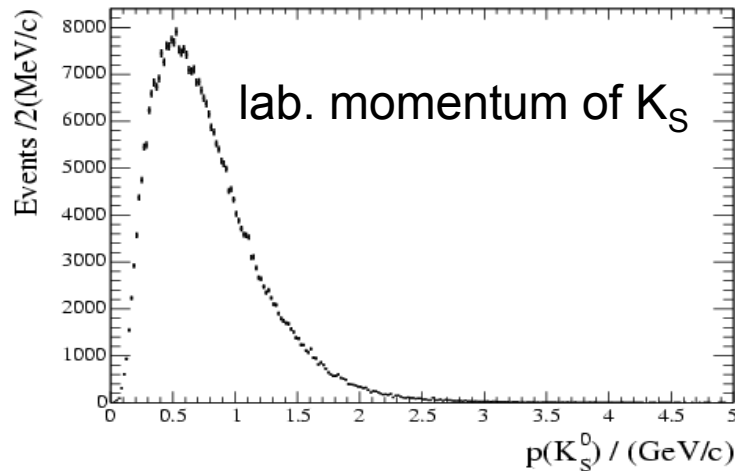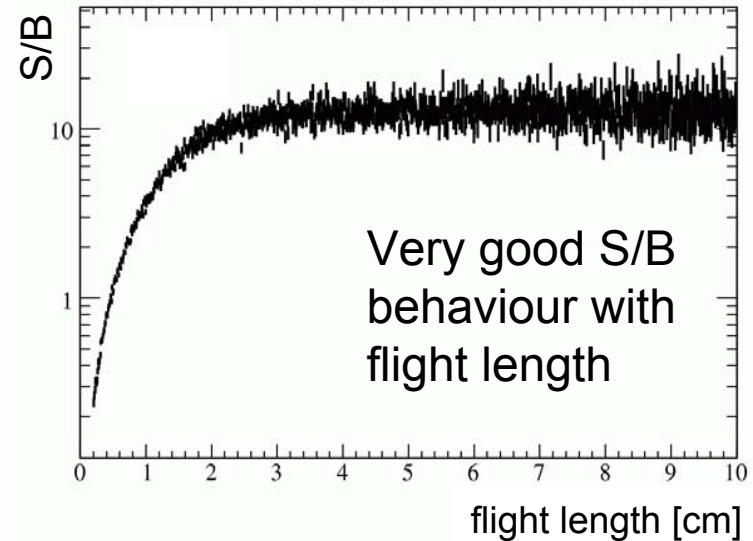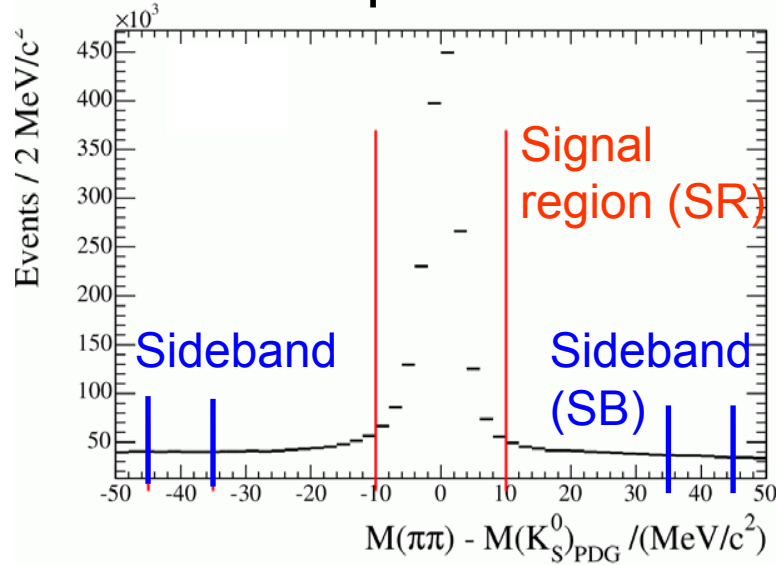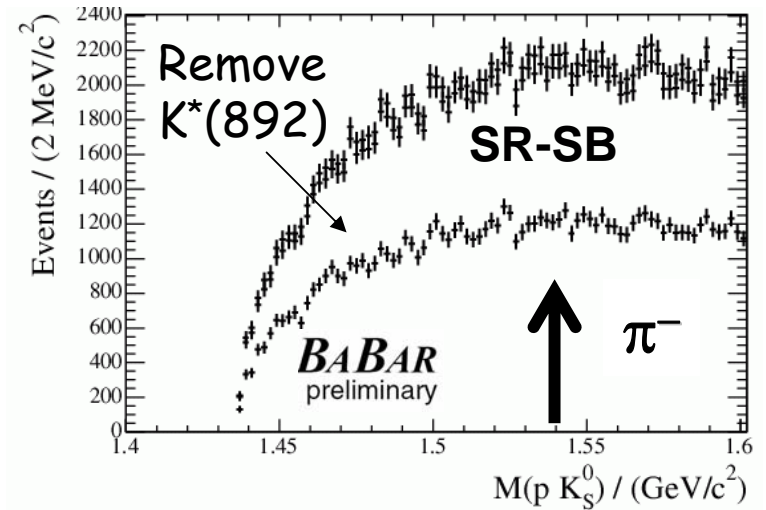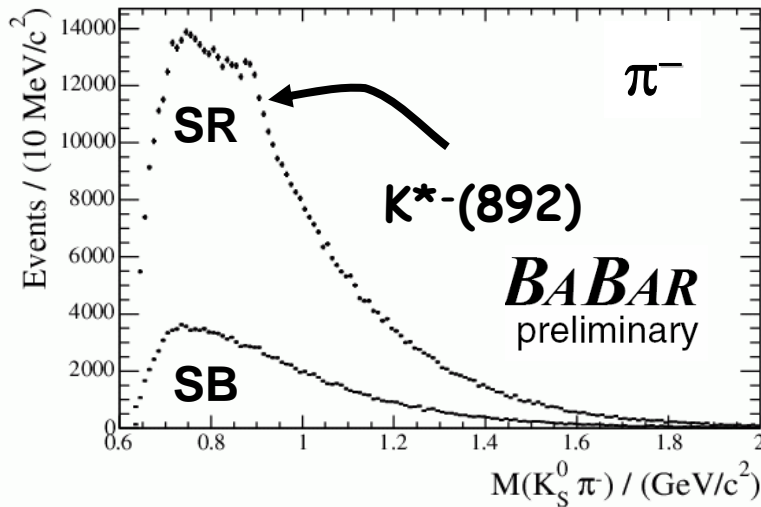
Backup Slides

p and K_s^0 Samples

- Clean samples of selected p and $K_s \to \pi^+ \pi^-$ candidates

Signal region (SR)

Sideband

Sideband (SB)

$M(\pi\pi) - M(K_S^0)_{PDG} \, /(\text{MeV}/c^2)$

Very good S/B behaviour with flight length

flight length [cm]

lab. momentum of K_S

$p(K_S^0) \, / \, (\text{GeV}/c)$

lab. momentum of p

$p(\text{proton}) \, / \, (\text{GeV}/c)$

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Combine p or K$_S$ with identified π^- or K$^+$

No Θ^+ Seen

Pentaquark 2005

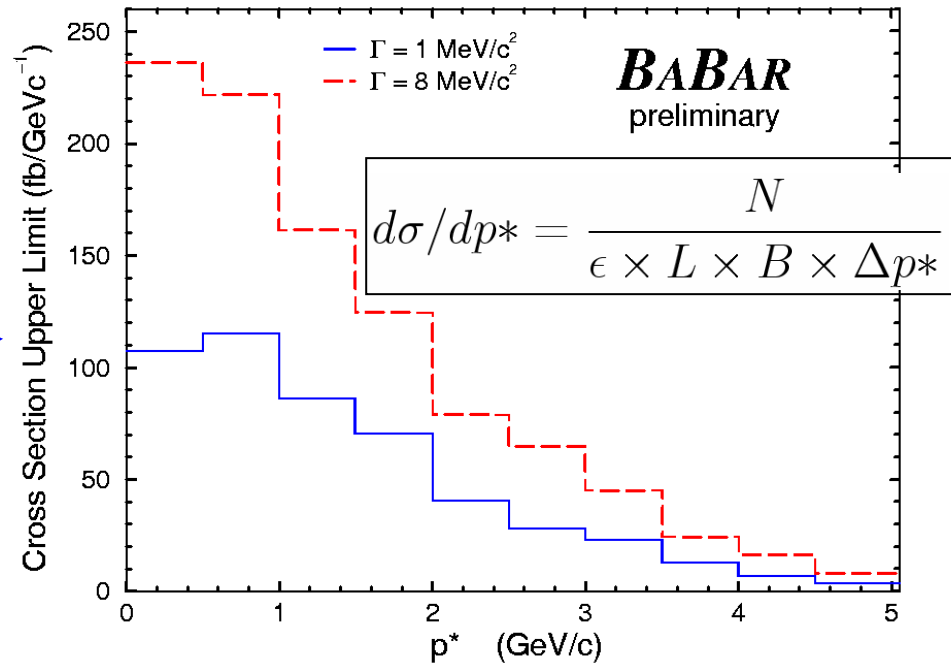Tetiana Berger-Hryn'ova

Zeus Comparison

Pentaquark 2005   Tetiana Berger-Hryn'ova
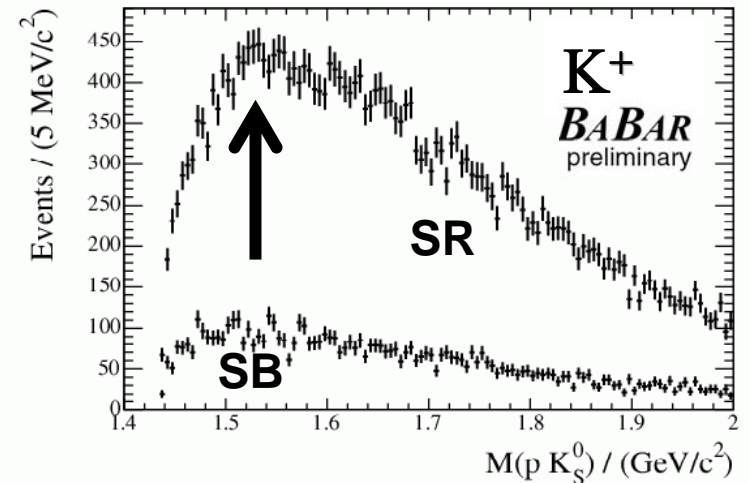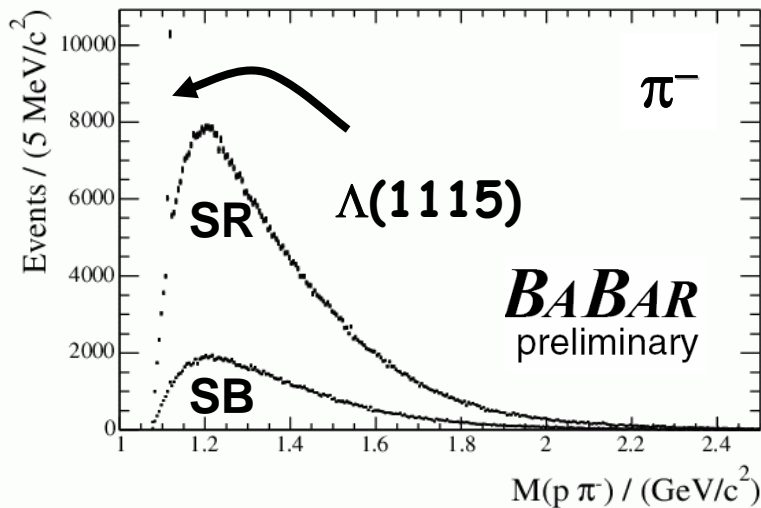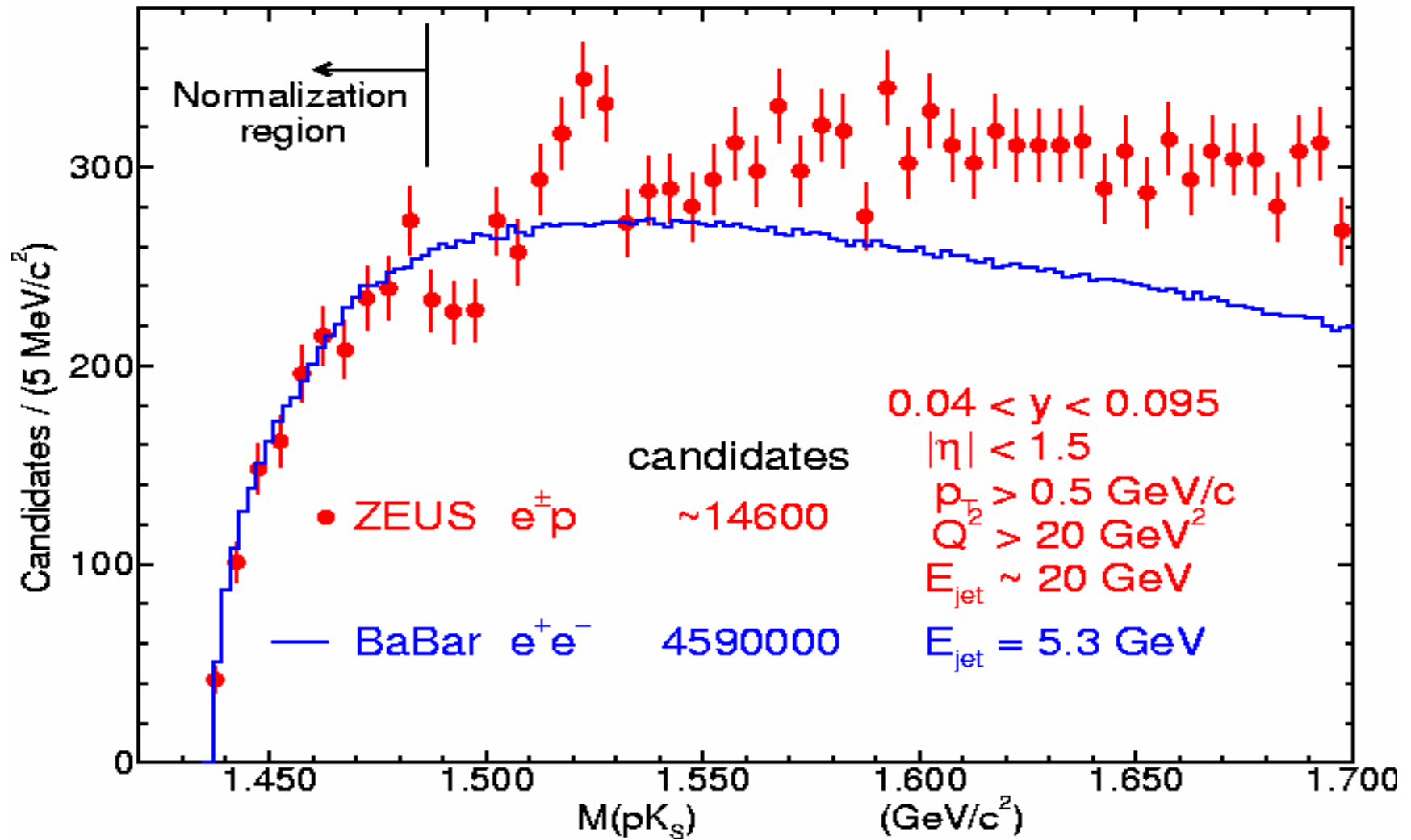
Upper Limits for Production Cross Section

Sample Bin: 3.0 GeV < p* < 3.5 GeV

p* 3→3.5 GeV/c

Sig. Events = 33.2 +38.9 −58.9
χ^2/Ndof = 181.67/173
M(Θ') = 1540 GeV
$\Gamma(\Theta^*)$ = 1 MeV

yield

BABAR preliminary

$\Gamma = 1$ MeV/c^2
$\Gamma = 8$ MeV/c^2

BABAR preliminary

$$d\sigma/dp* = \frac{N}{\epsilon \times L \times B \times \Delta p*}$$

$\Gamma = 1$ MeV/c^2
$\Gamma = 8$ MeV/c^2
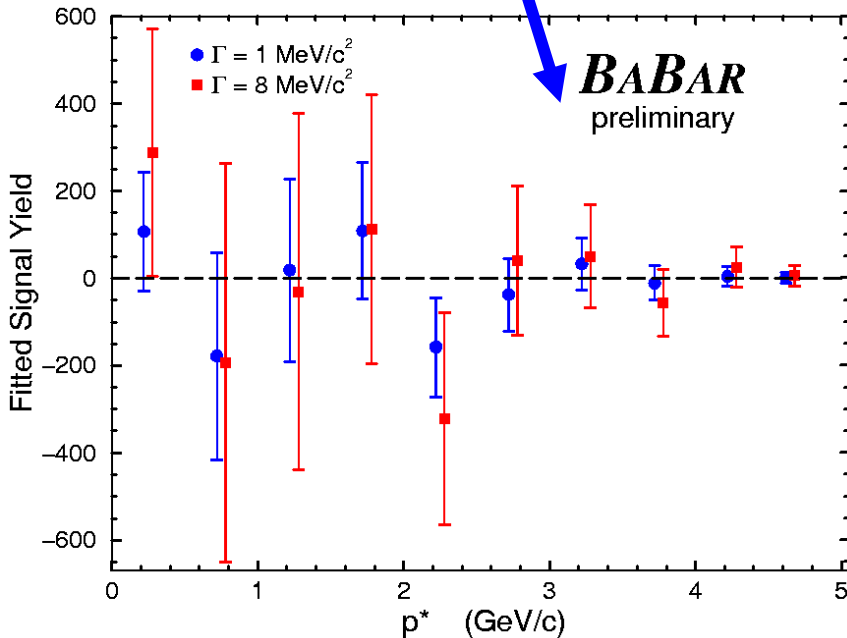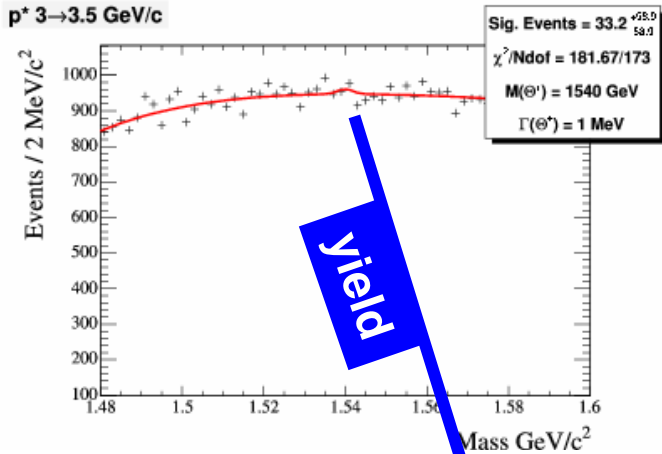
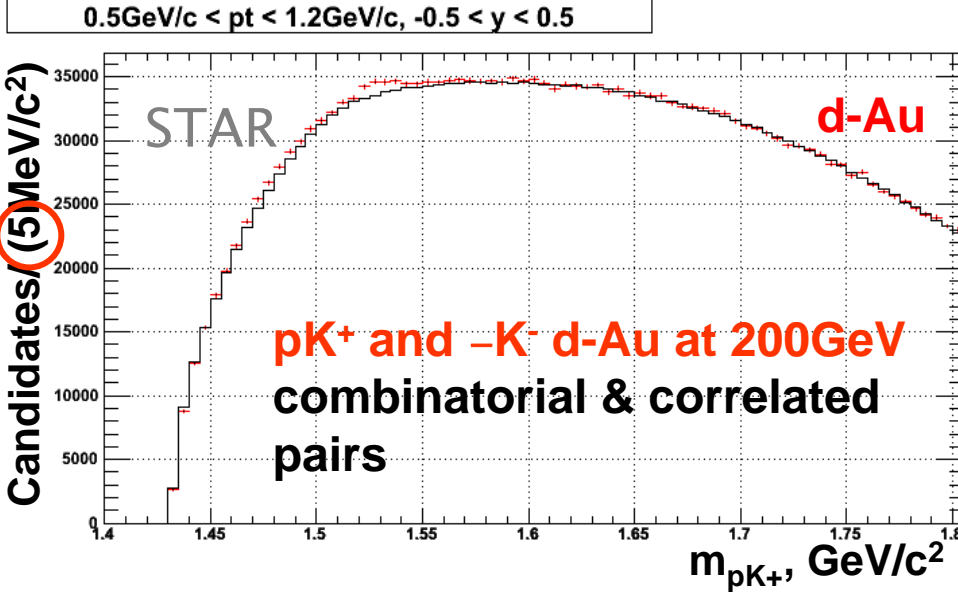**UL @ 95% CL on production Xsection:**

$\Gamma = 1$	$\Gamma = 8$ MeV
< 182.8	< 363.1 fb
< 5.4x10^{-5}	< 10.7x10^{-5} per q° event
< 17.9x10^{-5}	< 35.0x10^{-5} per Υ(4S)

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Search for Θ_c^0

Pentaquark 2005

Tetiana Berger-Hryn'ova

SLAC

Hints of a signal?

0.5GeV/c < pt < 1.2GeV/c, -0.5 < y < 0.5

STAR

d-Au

Candidates/(5MeV/c²)

pK⁺ and −K⁻ d-Au at 200GeV
combinatorial & correlated
pairs

m_{pK+}, GeV/c²

×10³

Candidates (2 MeV/c²)

$B\!A\!B\!A\!R$

Suppressed
Zero!

m_{pKs} [GeV/c²]

STAR Preliminary

0.5GeV/c < pt < 1.2GeV/c, -0.5 < y < 0.5

d-Au   Bkgr subtracted

Θ^{++}?

Mon Apr 11 13:24:39 2005   Invariant Mass (GeV/c^2)

Au-Au   Bkgr subtracted

Θ^{++}?
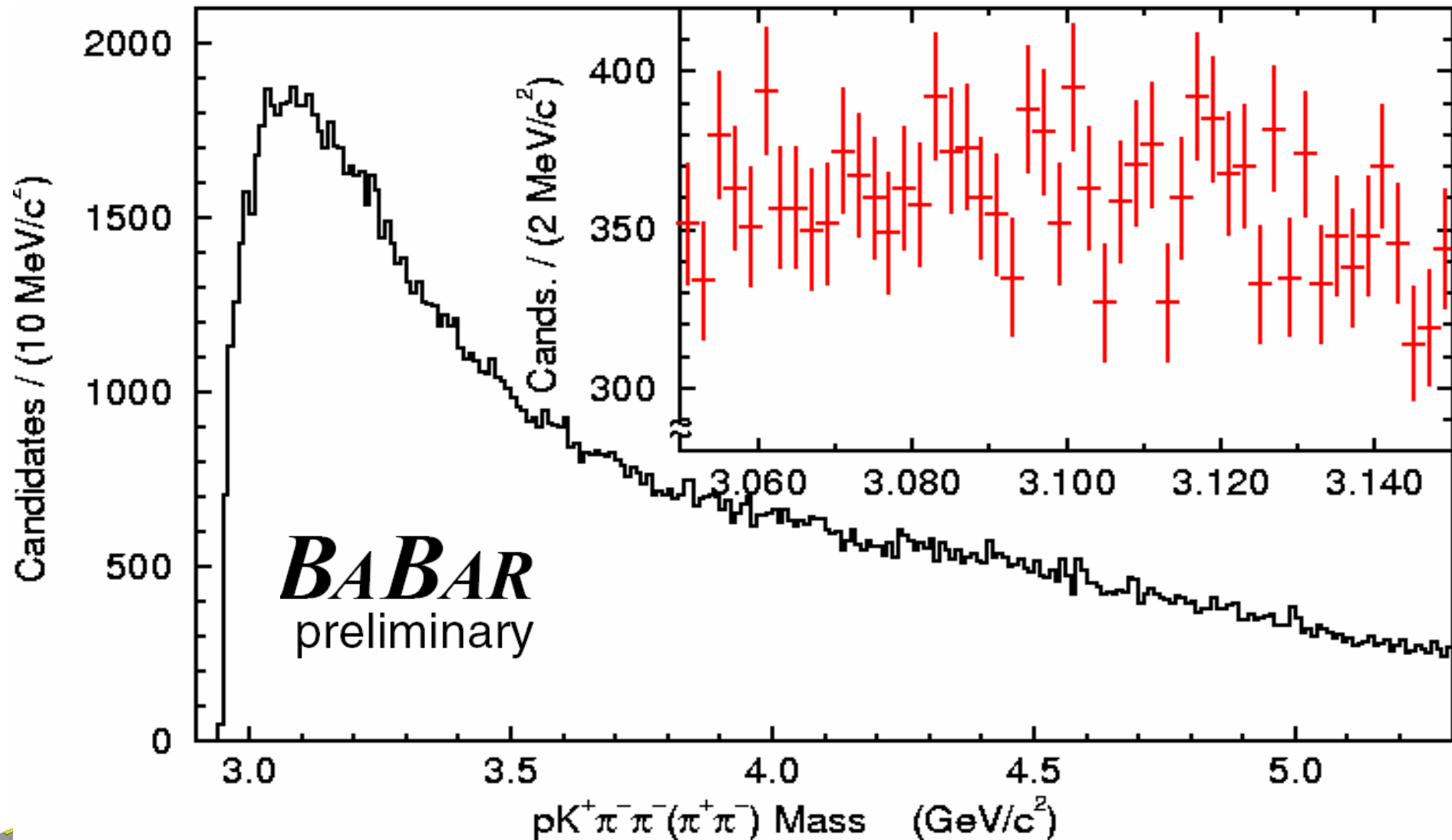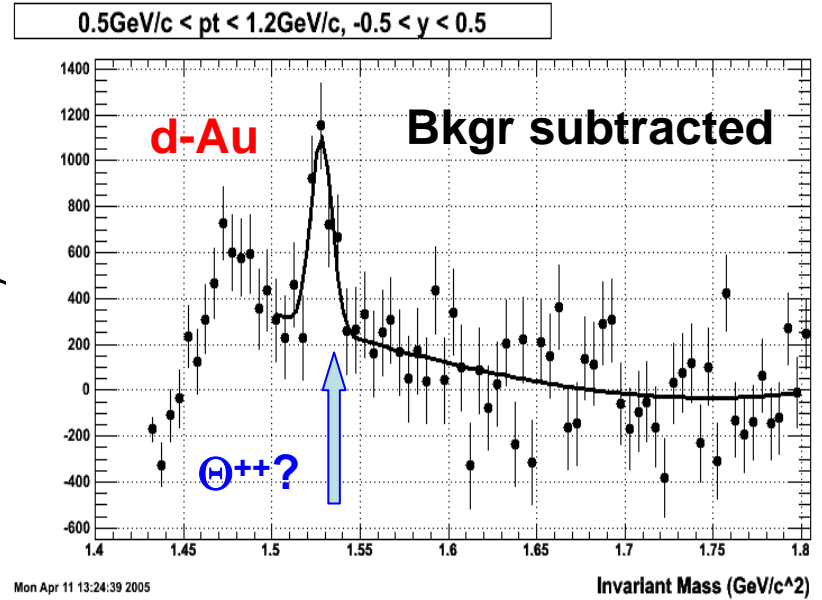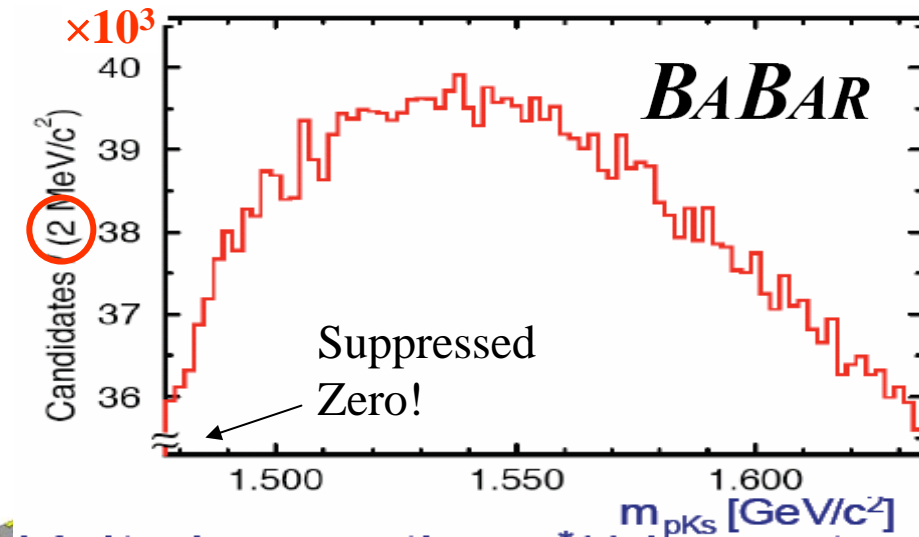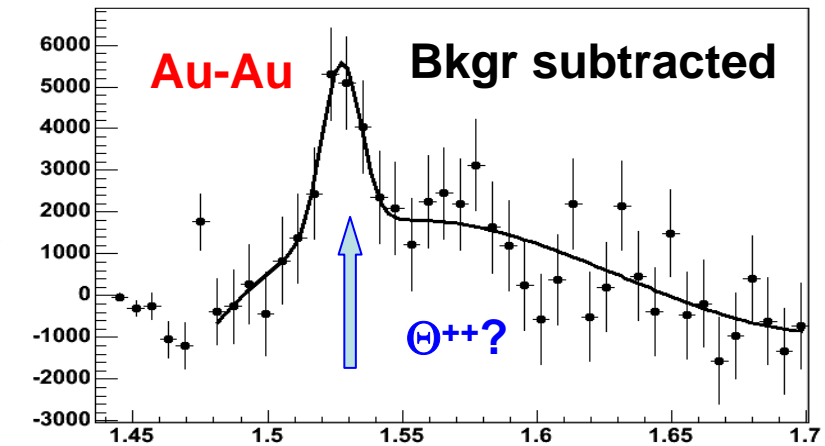
From Volker D Burkert's talk at LP05

**Puzzle: BaBar didn't observe the Θ^{*++} isovector partner Θ^{*+} in the
search of pK^0_S resonances**

33

SLAC

e$^+$e$^-$→q°
Background Suppression

B decay

q°

Background

Signal MC

94%

67%

Fisher Discriminant
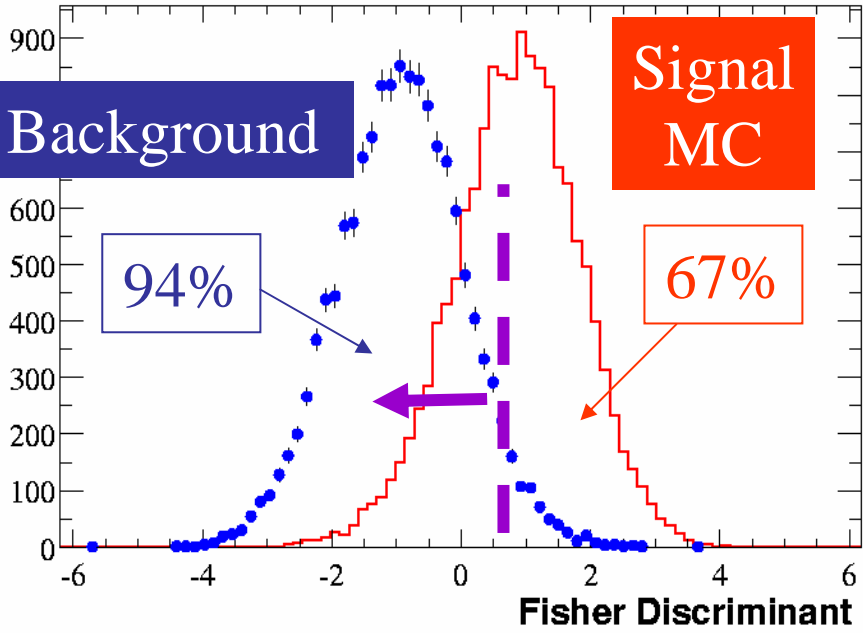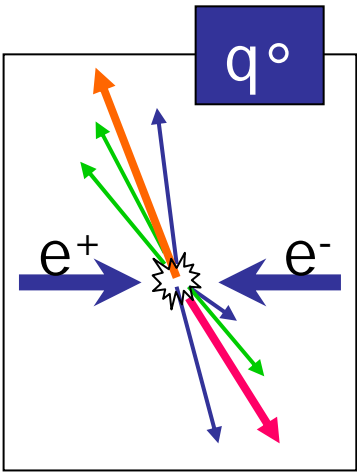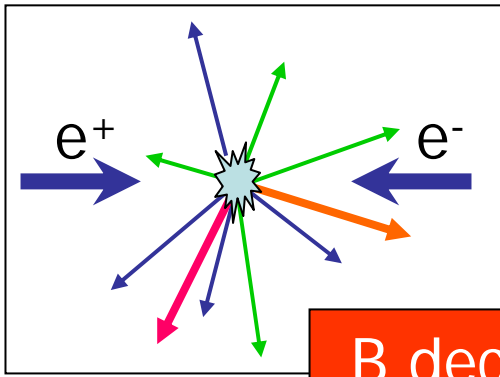
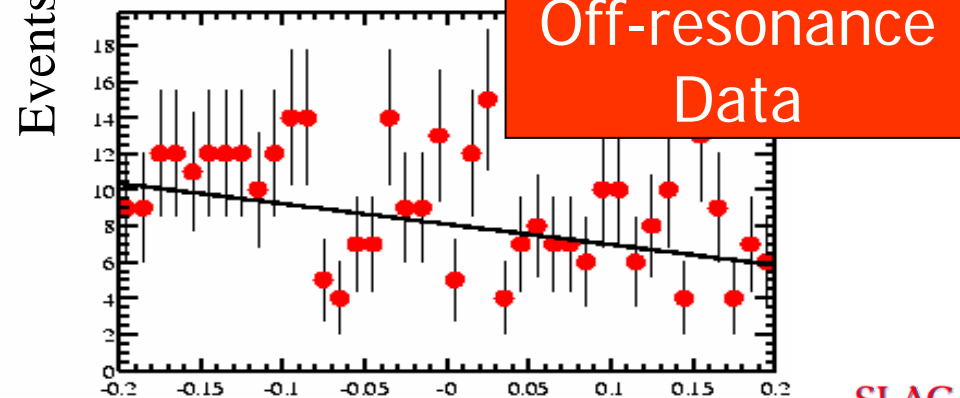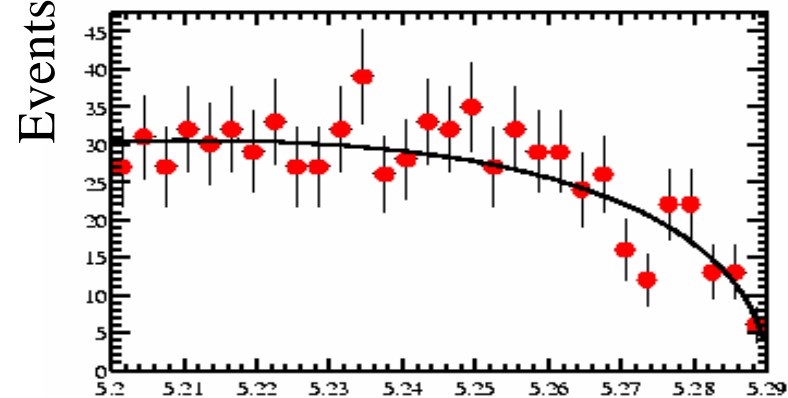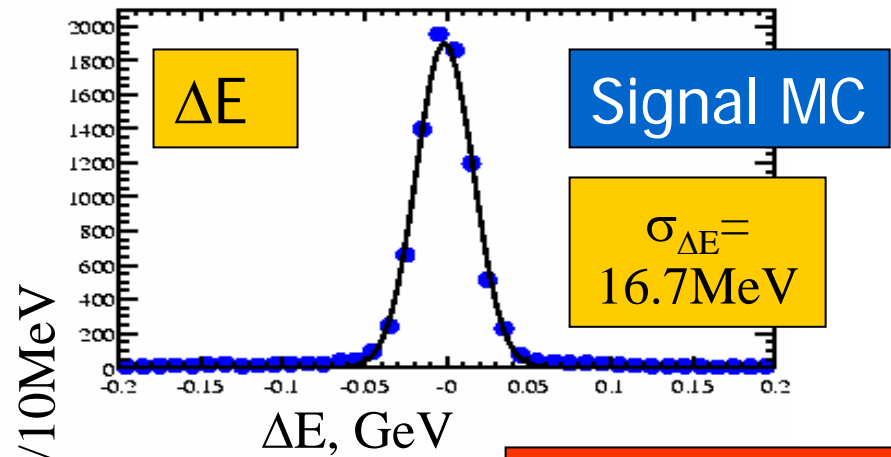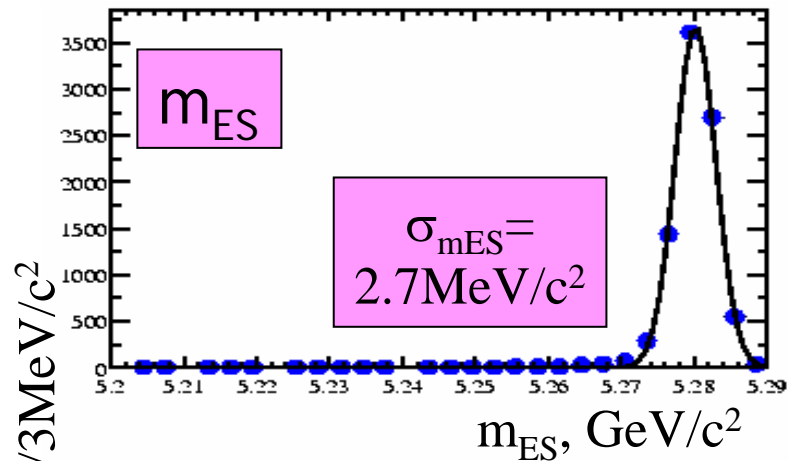$$L_2 = \sum_i | p_i^* | (3\cos^2 \theta_{Thr_{B,i}} - 1)\big/ 2,$$

$$L_0 = \sum_i | p_i^* |,$$

(i = photons and tracks which are not part of the B$_{pfK}$) and angles between the B$_{pfK}$ thrust (momentum) and z axis combined into Fisher Discriminant

Pentaquark 2005
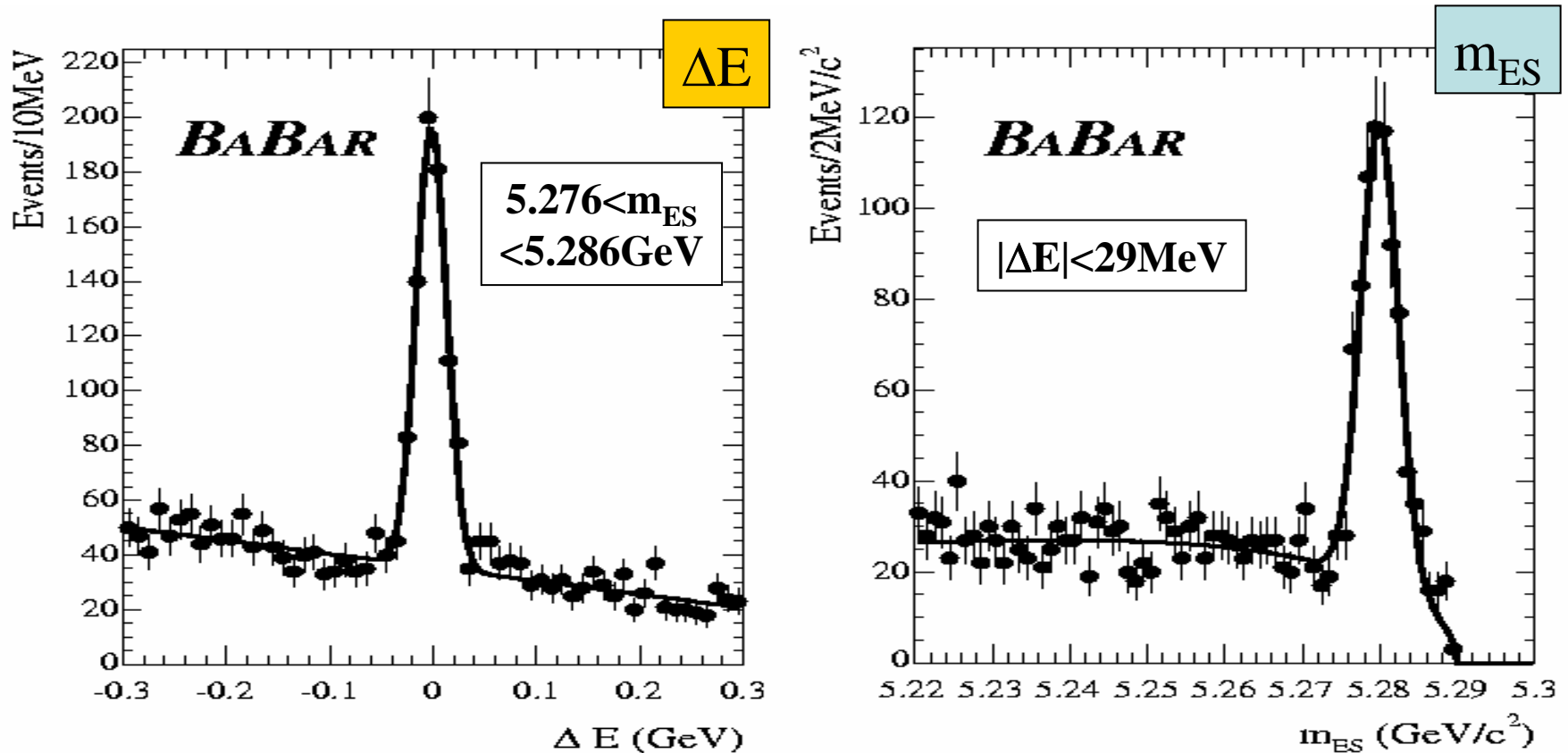
Tetiana Berger-Hryn'ova

SLAC

B reconstruction

$$m_{ES} = \sqrt{\left(\frac{E_{CM}^2}{2} + \vec{p}_i \cdot \vec{p}_B\right)^2 \Big/ E_i^2 - p_B^2}$$

$$\Delta E = E_B^* - \frac{E_{CM}}{2}$$

m_{ES}

$\sigma_{mES} = 2.7\text{MeV/c}^2$

Events/3MeV/c^2

m_{ES}, GeV/c^2

ΔE

Signal MC

$\sigma_{\Delta E} = 16.7\text{MeV}$

Events/10MeV

ΔE, GeV

Off-resonance Data

Tetiana Berger-Hryn'ova

SLAC

B$^\pm \to$ p–K$^\pm$ Signal Event Yield

Event estimate in the signal region for 1D fits to data:

ΔE fit: 566±29 events && m$_{ES}$ fit: 588±32 events

Expected Charmonium contribution: ~229±33