

SPECTROSCOPY OF HEAVY QUARKS AT BABAR

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Representing the BABAR Collaboration

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Spectroscopy of Heavy Quarks at BABAR

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for the *BABAR* Collaboration

Meson 2002

Cracow, Poland



bmb+f - Förderschwerpunkt

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Großgeräte der physikalischen
Grundlagenforschung



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Outline



- **BABAR**
- **Charmless Hadronic B -Decays**
 - ▷ Relevance for \mathcal{CP} violation
 - ▷ Decays into 2 pseudoscalars
 - ▷ Decays into 3 pseudoscalars
- **Charm decays into light mesons (scalar sector)**
 - ▷ $D_S^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$
 - ▷ $D_S^\pm \rightarrow \pi^+ \pi^- \pi^\pm$
- **Conclusion / Outlook**

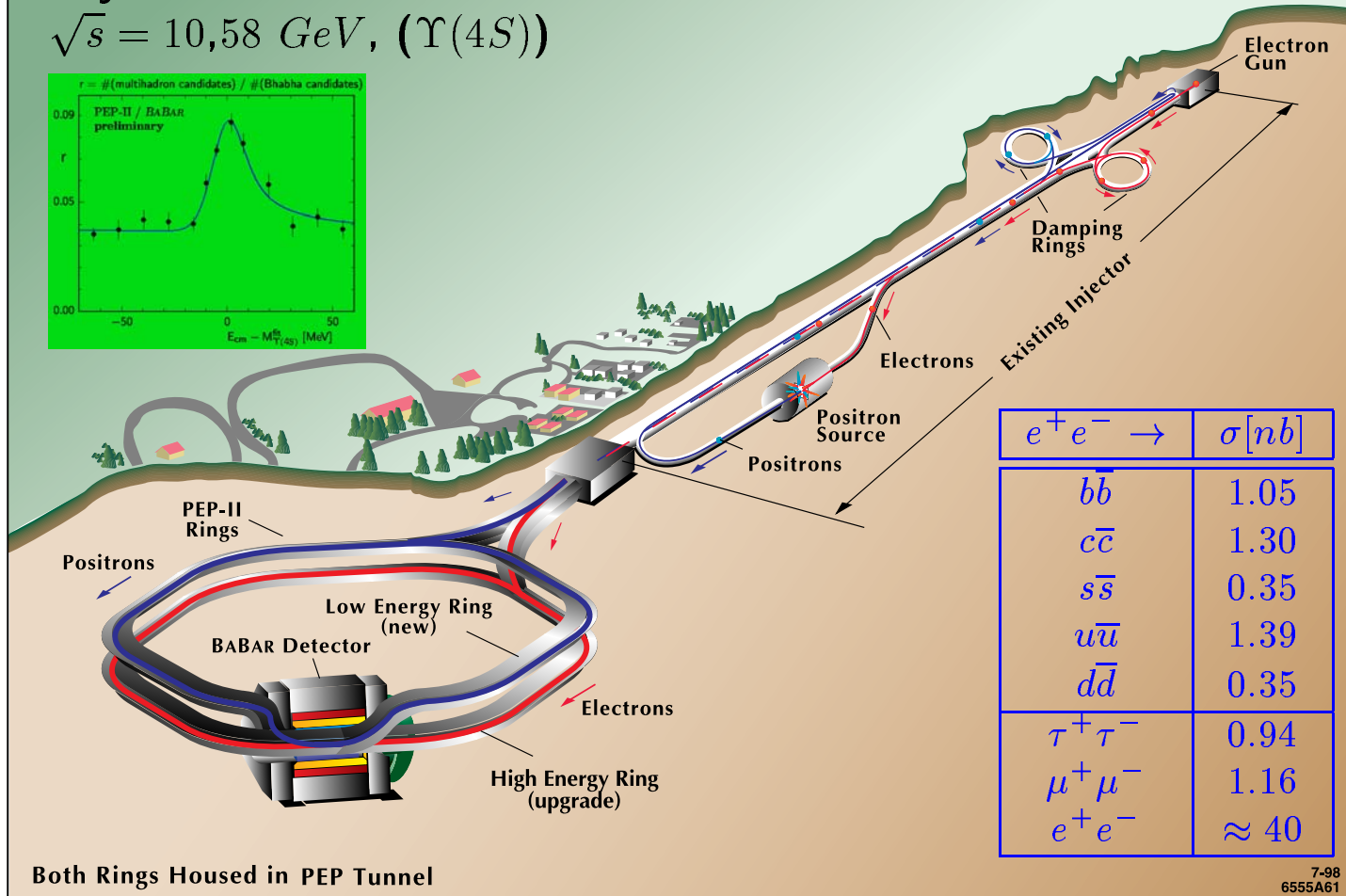
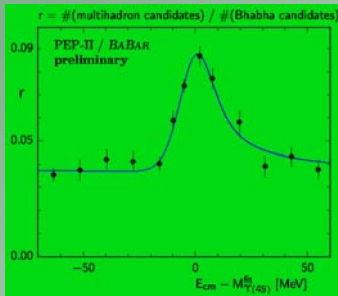


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PEP-II



Asymmetric e^+e^- -Collider $\sqrt{s} = 10,58 \text{ GeV}, (\Upsilon(4S))$



$e^+e^- \rightarrow$	$\sigma [nb]$
$b\bar{b}$	1.05
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	≈ 40

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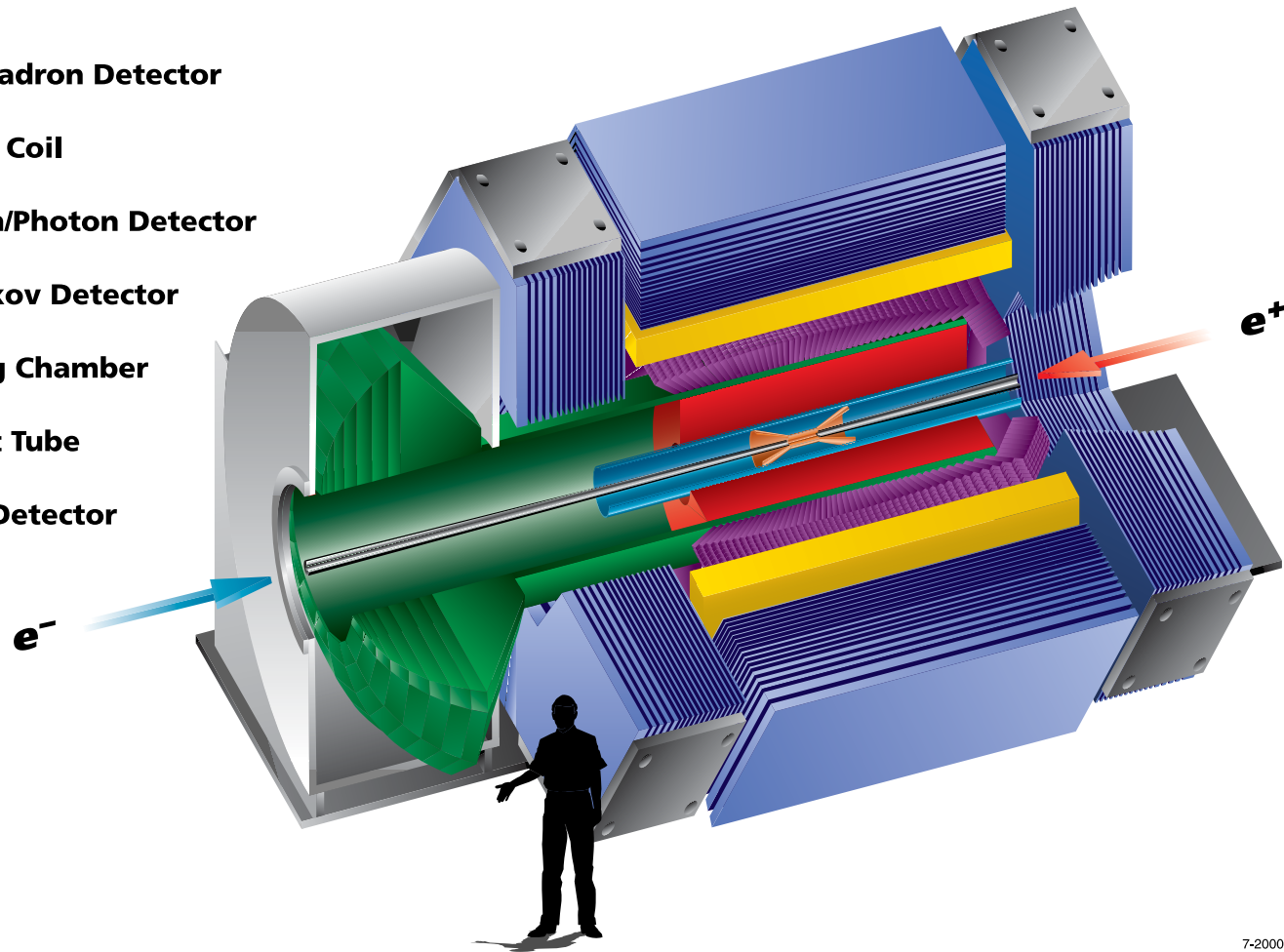
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BABAR Detector

-  Muon/Hadron Detector
-  Magnet Coil
-  Electron/Photon Detector
-  Cherenkov Detector
-  Tracking Chamber
-  Support Tube
-  Vertex Detector



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- **Asymmetric e^+e^- -Collider**
 - ▷ $\sqrt{s} = 10.58 \text{ GeV}$, ($\Upsilon(4S)$)
 - ▷ $b\bar{b}$ from resonance, $c\bar{c}$ from continuum

+ good vertex and track reconstruction

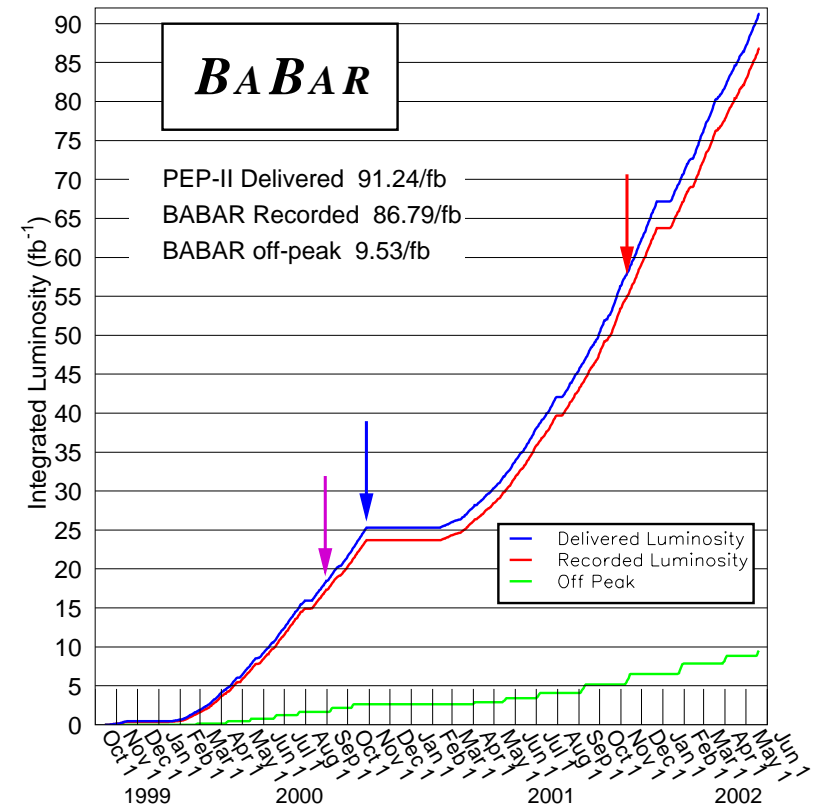
+ good particle identification

+ good energy resolution

+ high luminosity

- ▷ May 2002: $> 86 \text{ fb}^{-1}$
- ▷ more than 90 Mio. $b\bar{b}$ -events
- ▷ more than 110 Mio. $c\bar{c}$ -events

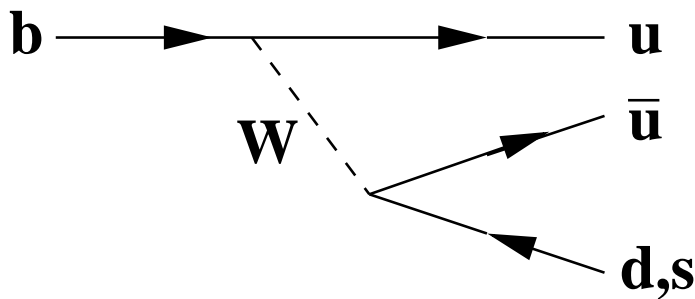
⇒ **Excellent opportunity for "beautiful/charming" physics and light meson spectroscopy**





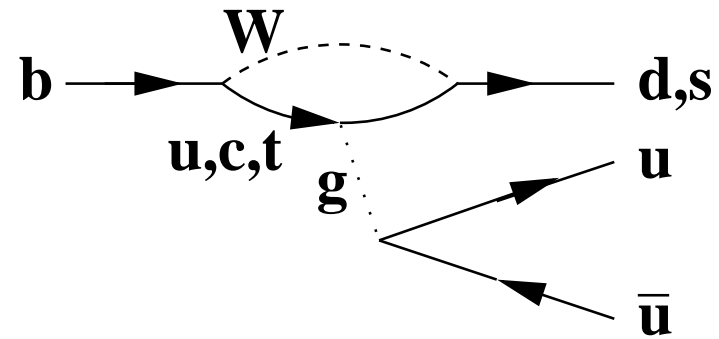
2 main categories of rare B -decays:

$b \rightarrow u$ transition
CKM suppressed:
 $|V_{ub}/V_{cb}| \approx 6 \times 10^{-3}$



- Interference \rightarrow Phases, CP violation ...

$b \rightarrow s, d$
Induced FCNC and
"Penguins"



- Penguins complicate CP measurements

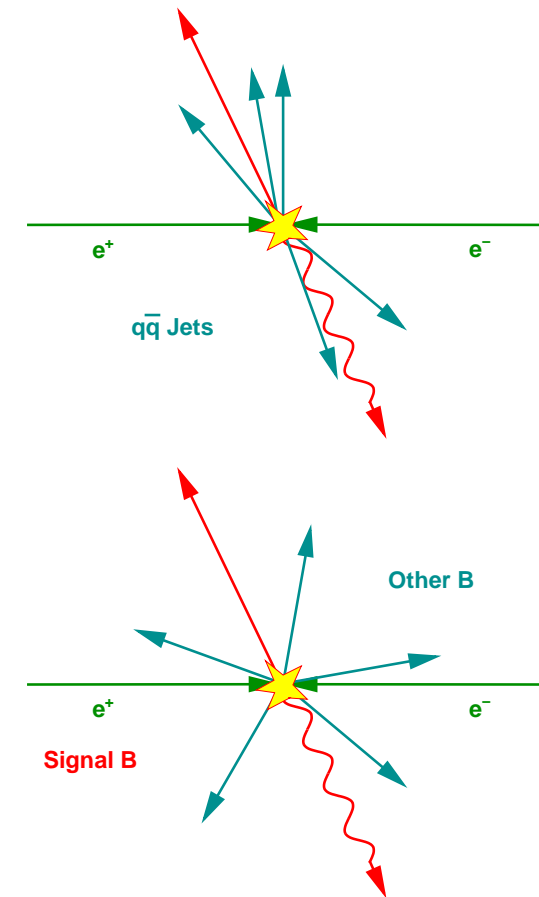


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B-Decays: Analysis Strategies



- Measure branching ratios / time dependent asymmetries
- Continuum background rejection:
 - ▷ Event shape
- B candidate selection:
 - ▷ ΔE , m_{ES}
- Signal extraction:
 - ▷ Cut and count, Maximum Likelihood fit, Neural Network
- All analyses blind!





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B-Decays: B Signal Variables



$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

B mesons \approx at rest ($p_B^* \approx 325 \text{ MeV}/c$)

- $q_{B1}^2 = q_{B2}^2 \Rightarrow \Delta E \equiv E_{beam}^* - E_B^*$ (CMS)

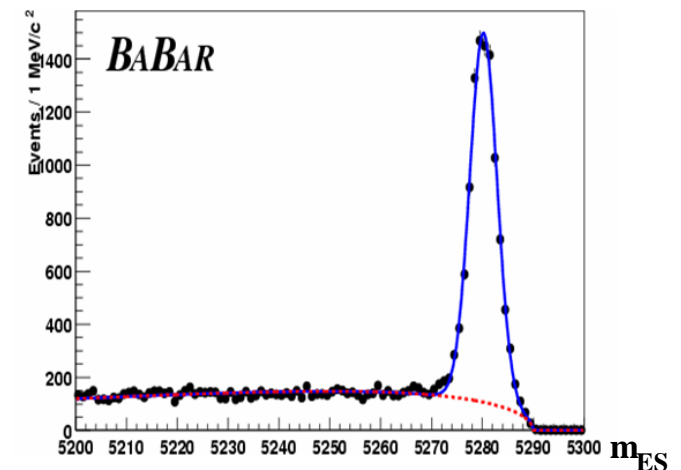
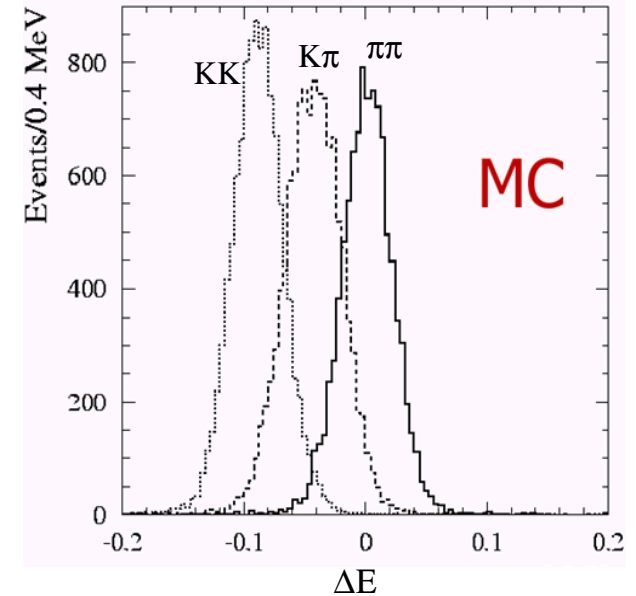
Typical: $\sigma(\Delta E) \approx 25 - 40 \text{ MeV}$

- $q_{B1}^2 = m_B^2$

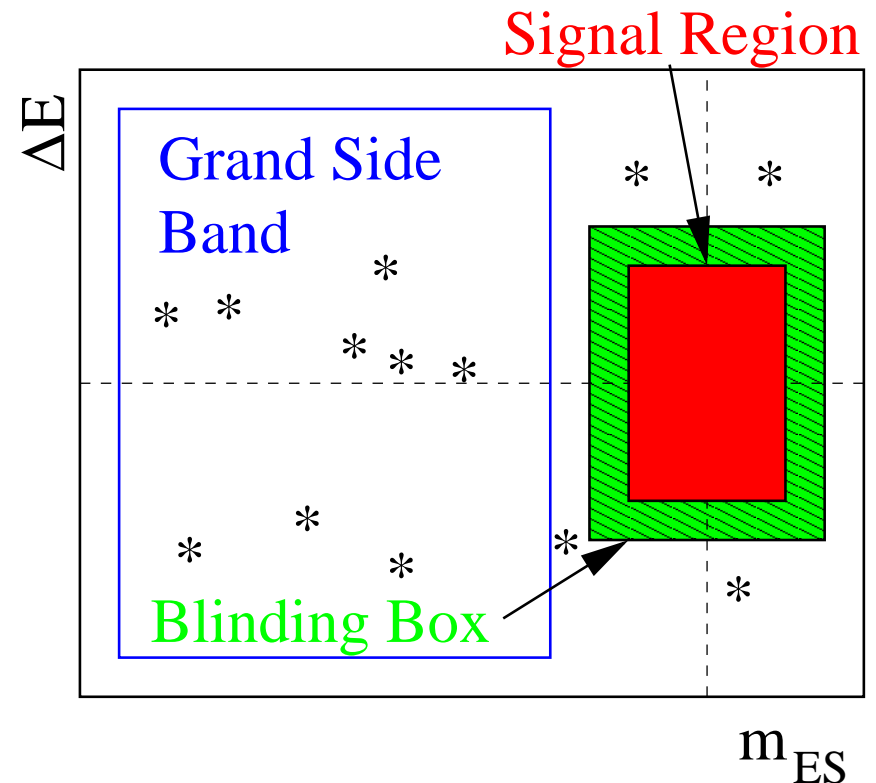
- Beam energy better known than B energy

$$\Rightarrow m_{ES} \equiv \sqrt{\left(\frac{1}{2}s + \vec{p}_0 \cdot \vec{p}_B\right)^2 / E_0^2 - p_B^2} \quad (\text{LAB})$$

Typical: $\sigma(m) \approx 2.8 \text{ MeV}/c^2$



- Cut optimisation
(signal MC and on-peak data GSB)
- Efficiency determination
(signal MC)
- Extrapolate background
GSB \rightarrow SR: $N(Bkg_{SR})$
(on-peak data GSB)
- Estimate $N(B\bar{B}_{SR})$ ($B\bar{B}$ MC)
- Signal: $N(SR) - N(Bkg_{SR}) - N(B\bar{B}_{SR})$





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B-Decays: Likelihood Fit

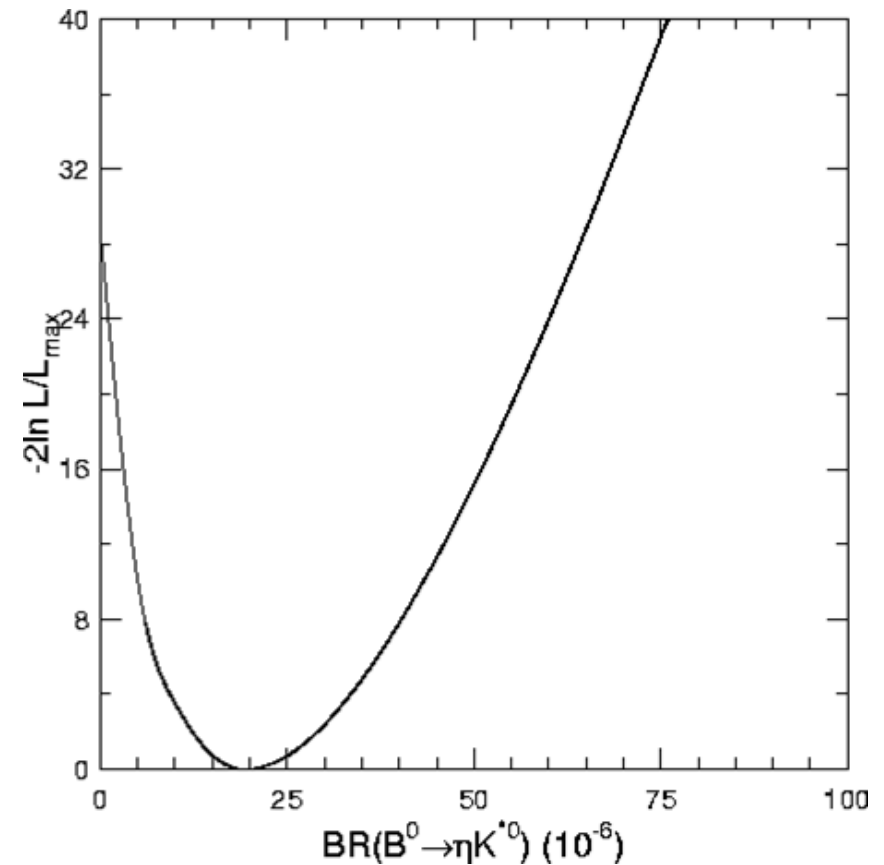


$$\mathcal{L} = \frac{e^{-(\sum n_j)} N!}{N!} \prod_{i=1}^N \mathcal{L}_i, \quad \text{where} \quad \mathcal{L}_i = \sum_{j=1}^m n_j P_j(\vec{x}_j)$$

- n_j : population for each species (signal and/or background)
- $P_j(\vec{x}_j)$: Probability density function evaluated with a set of observables \vec{x}_j (m_{ES} , ΔE , etc.)

- Statistical significance

$$S = \sqrt{\chi^2(\text{no signal}) - \chi^2(\text{minimum})}$$

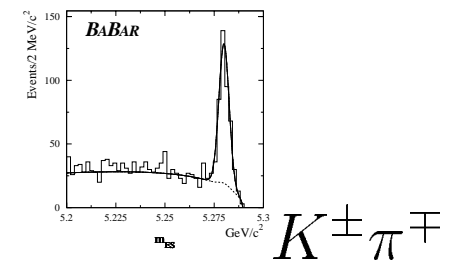
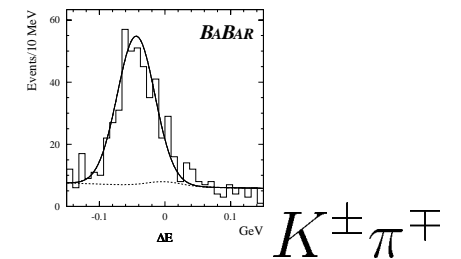
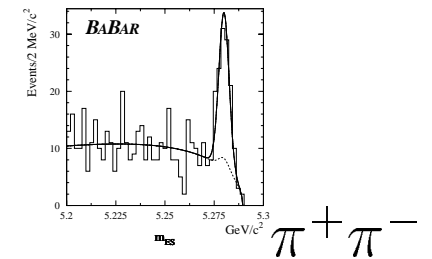
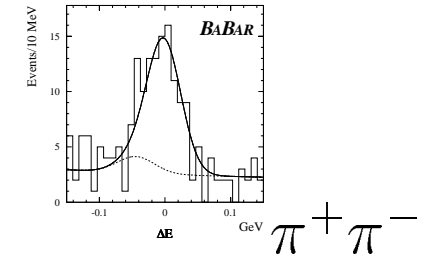


- Very important modes to constrain CKM angle α

▷ Time dependent asymmetry in $B^0(\overline{B}^0) \rightarrow \pi^+\pi^-$ measures $\sin(2\alpha_{eff})$

- In absence of penguins: $\alpha_{eff} = \alpha$
- Unfortunately: penguins are not small
- $B^+ \rightarrow \pi^+\pi^0$: \approx Pure Tree
- $B^+ \rightarrow \pi^+K^0$: \approx Pure Penguin
- $\mathcal{B}(B^+ \rightarrow \pi^+K^0) > \mathcal{B}(B^+ \rightarrow \pi^+\pi^0)$

- ML fit with ΔE , m_{ES} , etc.





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$B \rightarrow \pi\pi, K\pi, KK$ Branching Fractions



Mode	N_s	$\mathcal{B} [10^{-6}]$
$\pi^+\pi^-$	124_{-15}^{+16+7}	$5.4 \pm 0.7 \pm 0.4$
$\pi^+\pi^0$	62_{-16}^{+17+10}	$4.1_{-1.0}^{+1.1+0.8}$
$\pi^0\pi^0$	9.8 ± 8.7	< 3.4
$K^+\pi^-$	$403 \pm 24 \pm 15$	$17.8 \pm 1.1 \pm 0.8$
$K^+\pi^0$	$149 \pm 17_{-7}^{+8}$	$11.1_{-1.2}^{+1.3} \pm 1.0$
$K^0\pi^+$	$172 \pm 17 \pm 9$	$17.5_{-1.7}^{+1.8} \pm 1.3$
$K^0\pi^0$		$8.2_{-2.7}^{+3.1} \pm 1.2$
K^+K^-	$0.6_{-7.4}^{+8.0} (< 15)$	< 1.1
$K^+\bar{K}^0$	$-5.6_{-5.5}^{+2.8} \pm 2.5$	< 1.3
$K^0\bar{K}^0$		< 13



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Time-dependent CP in $B^0 \rightarrow \pi^+\pi^-$



- Decay distributions $f_+(f_-)$ if "other" B tagged as $B^0(\overline{B}^0)$
- $f_{\pm}(\Delta t) = \frac{e^{-\Delta t/\tau}}{4\tau} [1 \pm S_{\pi\pi} \sin(\Delta m_d \Delta t) \mp C_{\pi\pi} \cos(\Delta m_d \Delta t)]$
- Weak phase (only tree diagram)
 - ▷ $\lambda = \frac{q}{p} \frac{\overline{A}_f}{A_f} = \eta_f e^{-2i(\beta+\gamma)} = \eta_f e^{-2i\alpha}$
 - ▷ $C_{\pi\pi} = 0, \quad S_{\pi\pi} = \sin 2\alpha$
- Additional phase from penguin diagram
 - ▷ $|\lambda| \neq 1 \Rightarrow$ direct CP
 - ▷ $\text{Im}(\lambda) \neq \sin 2\alpha \Rightarrow \alpha \rightarrow \alpha_{eff}$
 - ▷ $C_{\pi\pi} \neq 0, \quad S_{\pi\pi} = \sin 2\alpha_{eff}$

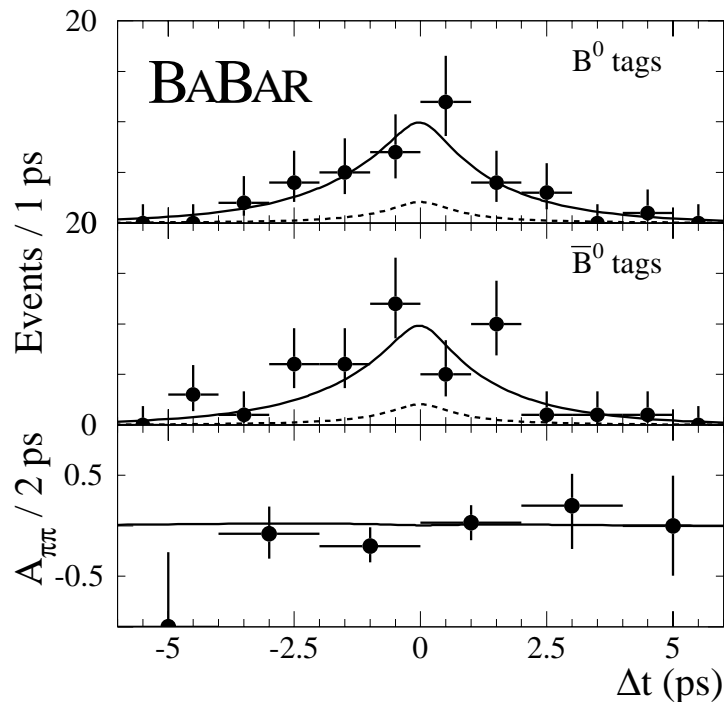


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$B^0 \rightarrow \pi^+\pi^-$ Asymmetry Results



- Measurement compatible with no \mathcal{CP} violation in $B^0 \rightarrow \pi^+\pi^-$
- Statistically limited due to small branching fraction
- Need $\approx 500 \text{ fb}^{-1}$ for $\sigma(S_{\pi\pi}) \approx 0.10 - 0.15$



$$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$$

$$C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$$

Data: 55.6 fb^{-1}



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Charge Asymmetry Results



Final state	A_{CP}		
$K^{\pm}\pi^{\mp}$	-0.05	± 0.06	± 0.01
$K_S\pi^{\pm}$	-0.17	± 0.10	± 0.02 ←
$\pi^{\pm}\pi^0$	-0.02	$\begin{matrix} +0.27 \\ -0.26 \end{matrix}$	± 0.10
$K^{\pm}\pi^0$	0.00	± 0.11	± 0.02

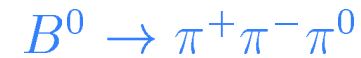
Belle:

$$A_{K^0\pi^{\pm}} = 0.46 \pm 0.15 \pm 0.02$$

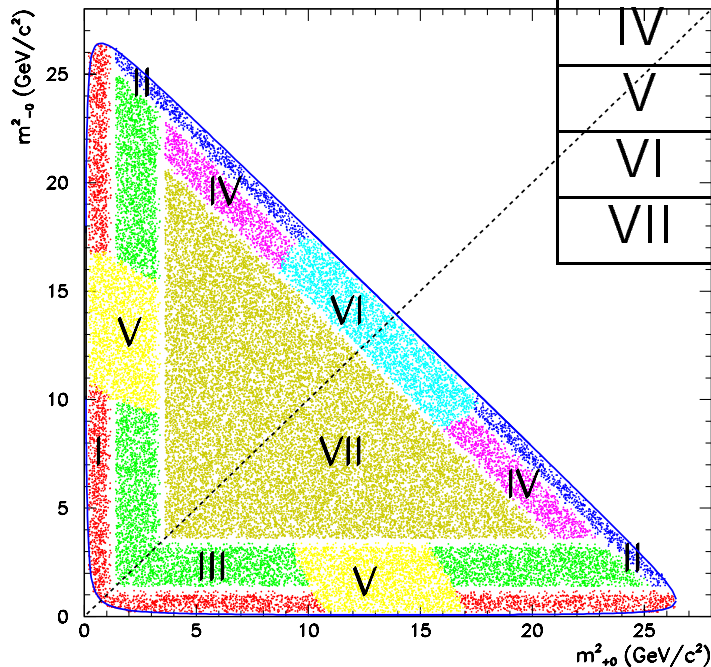
⇒ **3 σ direct CP asymmetry,**
not confirmed by BABAR



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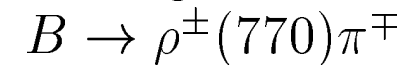
Zone	Main Contribution	ϵ [%]	Yield
I	$\rho^\pm(770)\pi^\mp$	13.5 ± 1.6	$89 \pm 16 \pm 6$
II	$\rho^0(770)\pi^0$	7.4 ± 0.9	$6.1 \pm 5.8 \pm 2.8$
II	$\rho^\pm(1450)\pi^\mp$	15.0 ± 2.1	$17.4 \pm 9.7 \pm 6.9$
IV	$\rho^0(1450)\pi^0$	8.7 ± 1.8	$-4.7 \pm 3.6 \pm 2.2$
V	(charged scalar) π^\pm	15.0 ± 2.3	$8.6 \pm 7.3 \pm 2.3$
VI	$f_0(400 - 1200)\pi^0$	6.7 ± 1.4	$-0.3 \pm 3.2 \pm 3.2$
VII	$\pi^\pm \pi^\mp \pi^0(NR)$	7.5 ± 1.0	$-4.2 \pm 7.3 \pm 3.8$



$m^2(\pi^- \pi^0)$ vs. $m^2(\pi^+ \pi^0)$

- Cuts optimized for each Dalitz region separately

Significant signal observed for



- Important for determination of α :
Enough info to disentangle penguins



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$B^0 \rightarrow \rho\pi$



$$\mathcal{B}(B^0 \rightarrow \rho^\pm(770)\pi^\mp) = (28.9 \pm 5.4 \pm 4.3) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow \rho^0(770)\pi^0) < 10.6 \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow \pi^+\pi^-\pi^0) < 7.3 \times 10^{-6}$$

- 2 Samples: $\rho^+\pi^-$ and $\rho^-\pi^+$
- Compute charge asymmetry:

$$\begin{aligned} A_{\rho\pi} &= \frac{\Gamma(\rho^+\pi^-) - \Gamma(\rho^-\pi^+)}{\Gamma(\rho^+\pi^-) + \Gamma(\rho^-\pi^+)} \\ &= -0.04 \pm 0.18 \pm 0.02 \end{aligned}$$

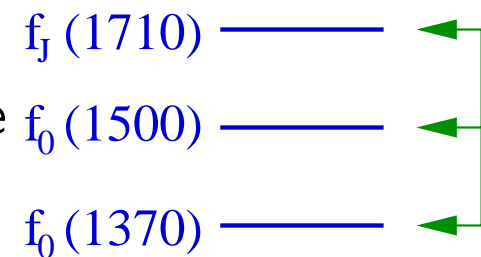
\Rightarrow no evidence for direct CP violation



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- **Search for exotic states in the spectrum of light mesons**
 - ▷ exotic states: glueballs (gg), hybrids ($q\bar{q}g$) and multiquark-states ($q\bar{q}q\bar{q}$)
 - ▷ glueball candidate $f_0(1500)$ found in $p\bar{p}$ -annihilation
 - ▷ $f_0(1500)$ may mix with conventional mesons of same quantum numbers: $f_0(1370)$, $f_J(1710)$ (if $J = 0$)
- **For the interpretation of the light meson spectrum it is crucial:**
 - ▷ to settle the spin of the $f_J(1710)$ and
 - ▷ to understand the production and decay of the $f_0(980)$



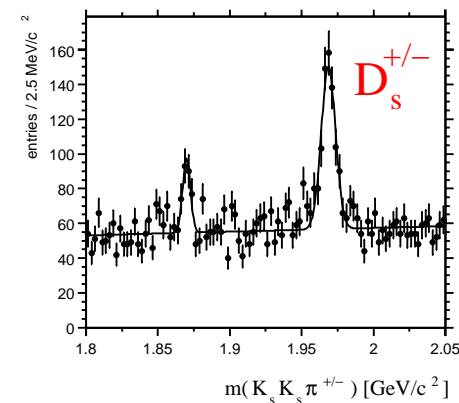
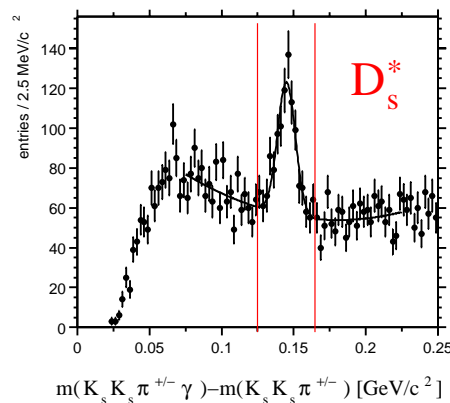
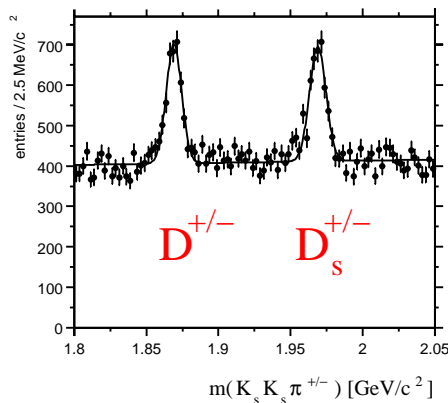


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$D_S^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$: Selection



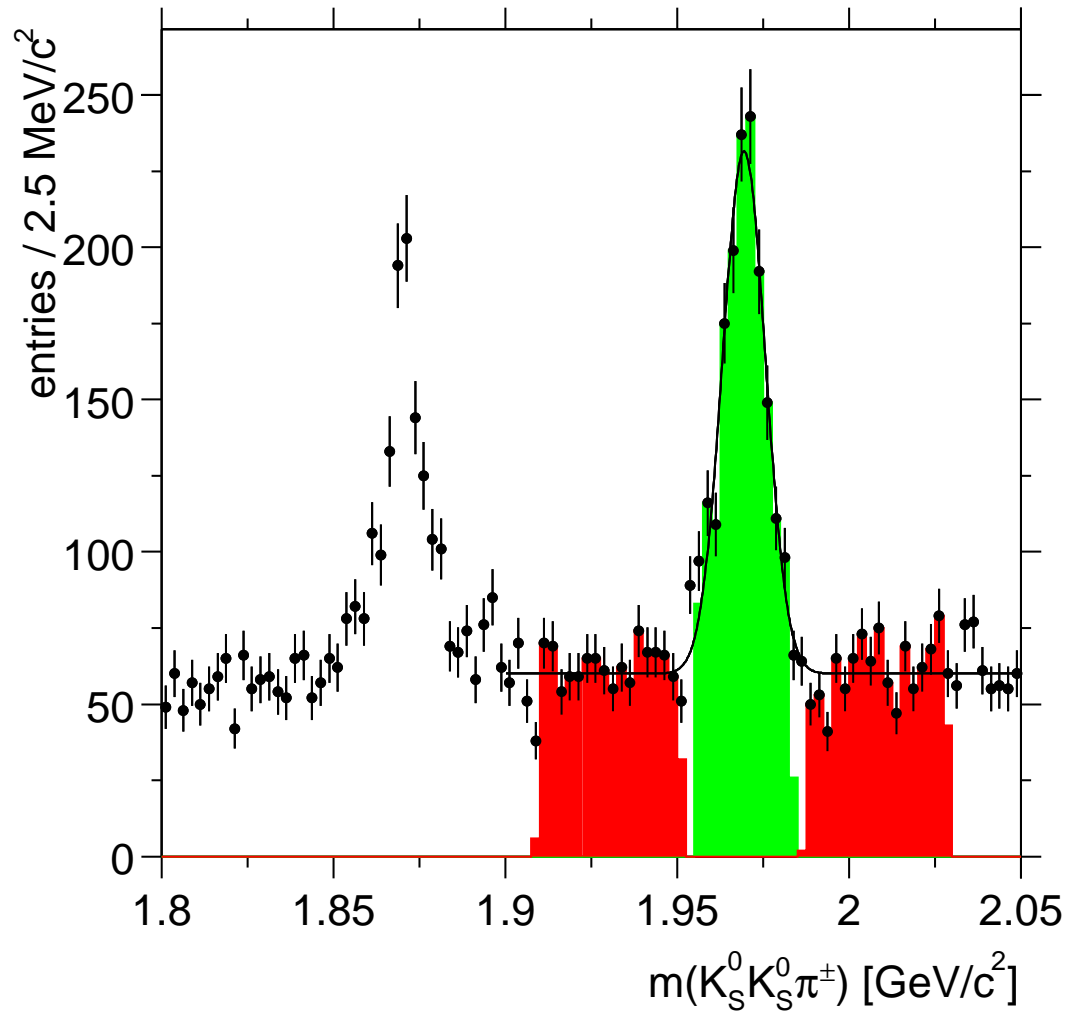
- **Data:** 18.4 fb^{-1}
- **Geometric vertex algorithms**
- D_S^\pm -candidates: **momentum cut** $p_{cms}(D_S^\pm) > 2.5 \text{ GeV}/c$
- **Further optimization**
 - ▷ vertex probability, lifetimes, mass windows, compatibility with interaction point
- **Strong increase of combinatorial background at low D_S^\pm -momenta**
 - ▷ **Additional constraint that D_S^\pm -mesons originate from $D_S^{*\pm} \rightarrow D_S^\pm \gamma$**





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$D_S^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$: Selection



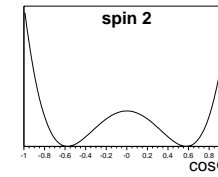
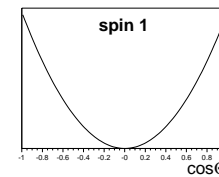
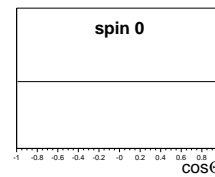
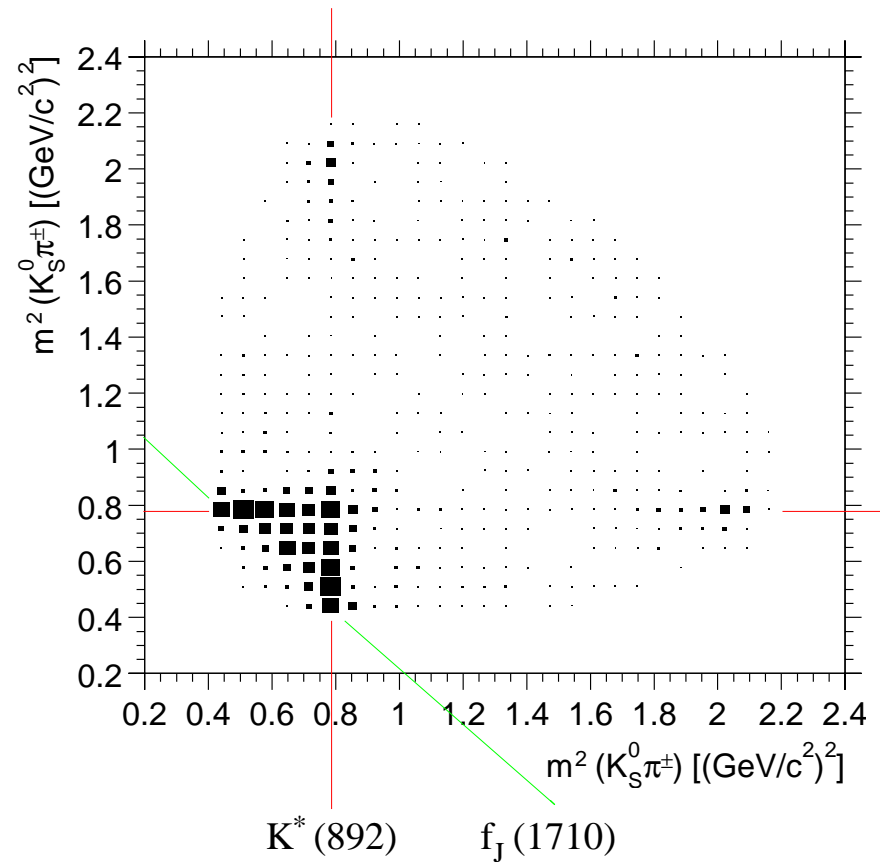
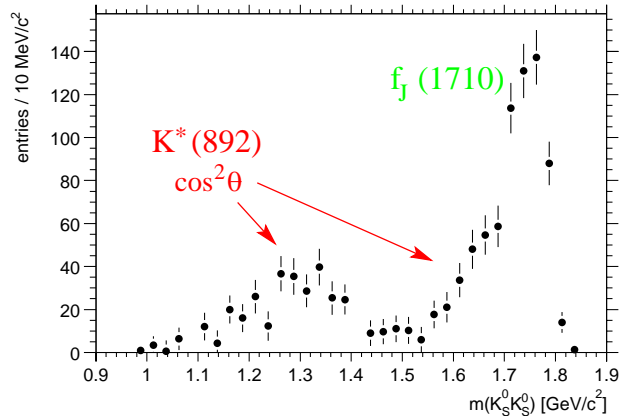
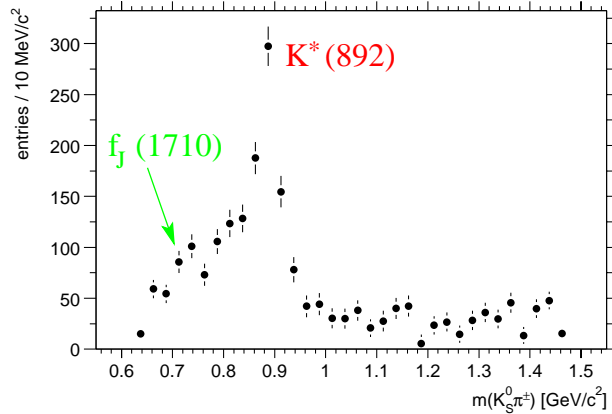
$N(D_S) = 1069.62866 \pm 46.62191$
 $\bar{m}(D_S) = 1.96942 \pm 0.00029$
 $\sigma(D_S) = 0.00622 \pm 0.00030$
 $C1_{\text{BACK}} = 59.99883 \pm 1.13149$

**More than 1000
entries in the
 D_S^\pm signal**



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$D_S^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$: Dalitz Analysis



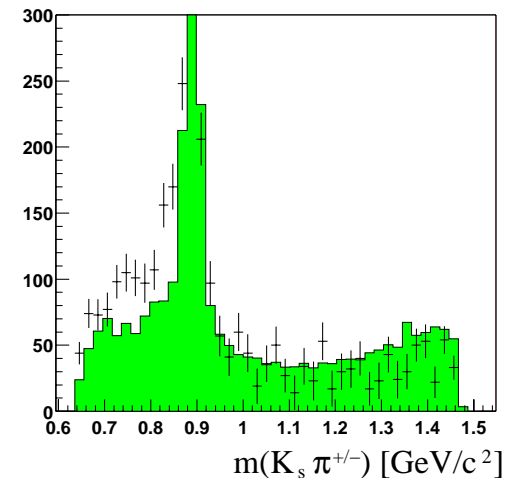
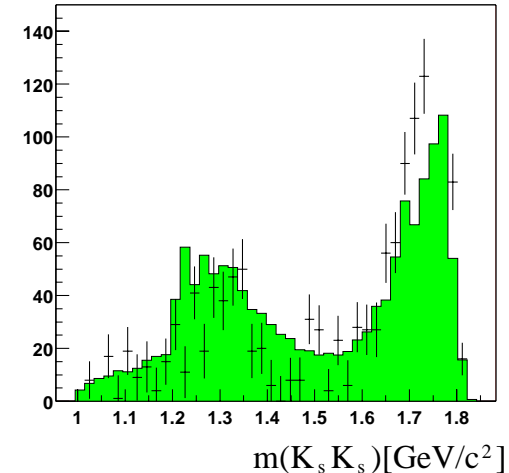


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$D_S^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$: Dalitz Analysis



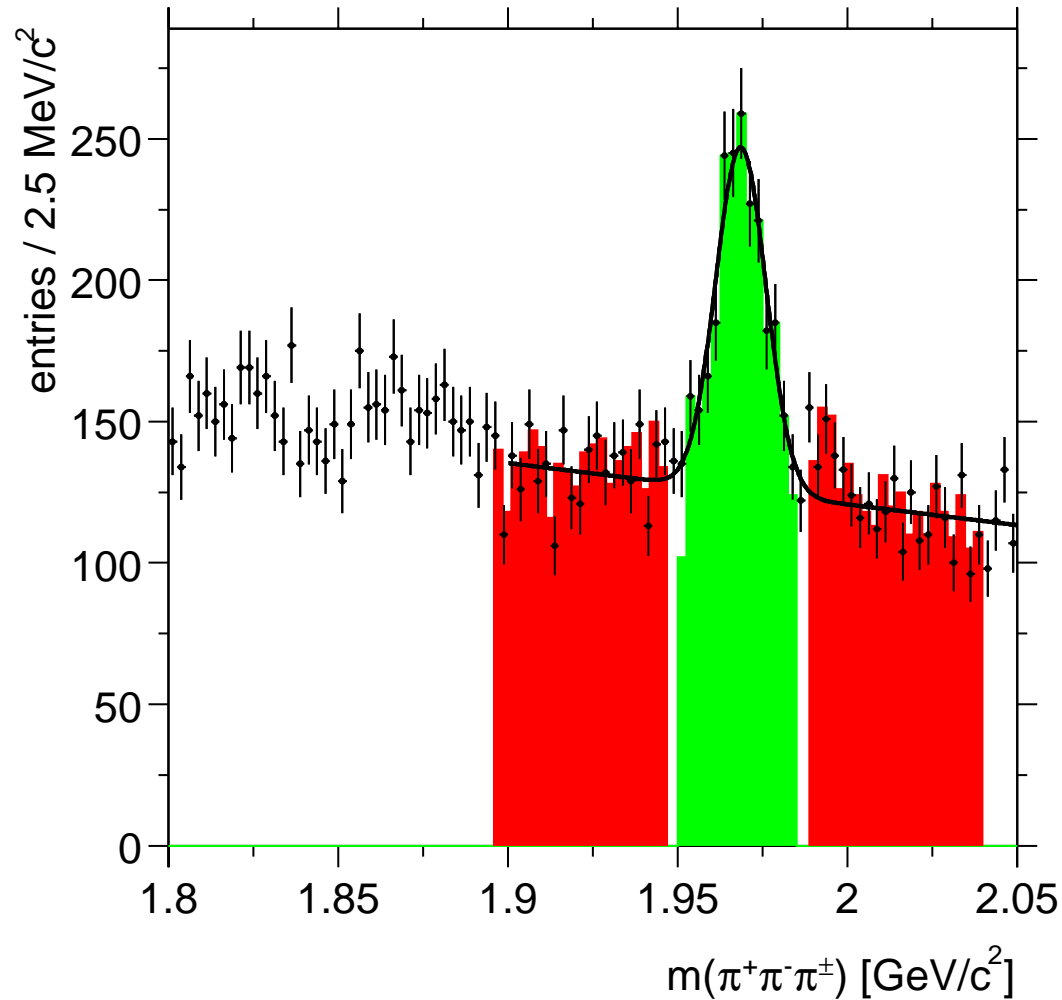
- Fit done with fixed masses and widths
- Fitting only with well known resonances ($K^*(892)$, $K_0^*(1430)$) fails to reproduce the distribution in the Dalitz plot
- There is need for an additional resonance at $m(K_S^0 K_S^0) \approx 1700 \text{ MeV}/c^2$





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$D_S^\pm \rightarrow \pi^+ \pi^- \pi^\pm$: Selection



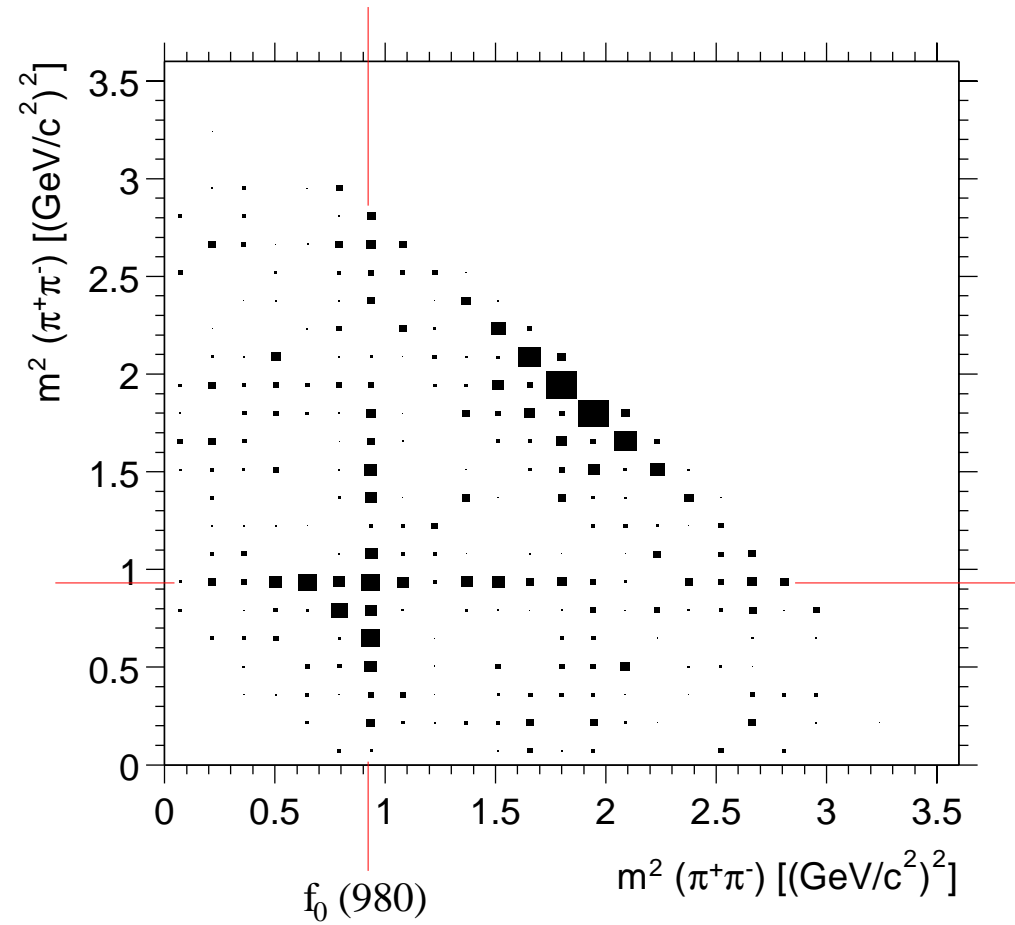
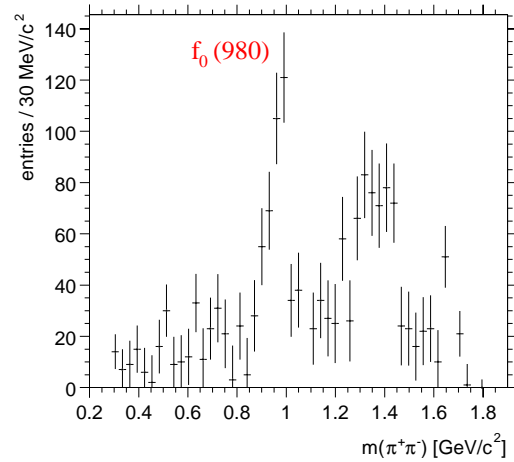
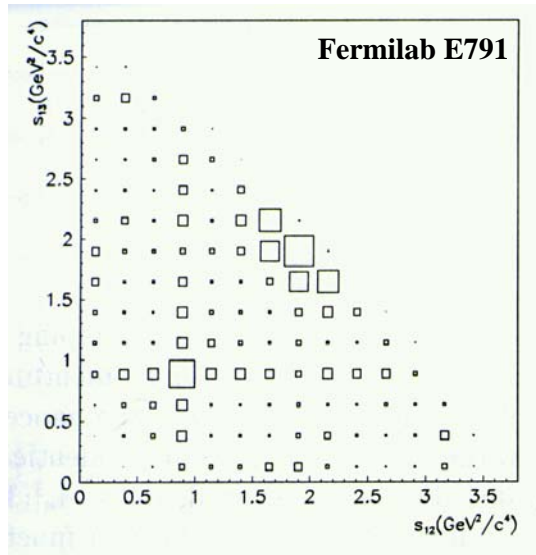
$N(D_S) = 902.90265 \pm 63.38998$
 $\bar{m}(D_S) = 1.96860 \pm 0.00052$
 $\sigma(D_S) = 0.00739 \pm 0.00062$
 $C1_{\text{BACK}} = 413.22238 \pm 64.07133$
 $C2_{\text{BACK}} = -146.27213 \pm 32.36530$

**About 900
entries in the
 D_S^\pm signal**



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$D_S^\pm \rightarrow \pi^+ \pi^- \pi^\pm$: Dalitz Analysis



- **Large data sample (Run1: $\approx 23 \cdot 10^6$ $B\bar{B}$ -pairs, $\approx 30 \cdot 10^6$ $c\bar{c}$ -pairs)**
- **Updated results: 55.6 fb^{-1}**
 - ▷ Sensitive to \mathcal{B} down to a few $\times 10^{-6}$
 - ▷ No evidence (yet) for direct \mathcal{CP} violation
 - ▷ First results from Dalitz analysis $D_S^\pm \rightarrow K_S^0 K_S^0 \pi^\pm$: strong contribution from $D_S^\pm \rightarrow f_J(1710) \pi^\pm$ necessary
- **Future**
 - ▷ End of Run: $\approx 100 \text{ fb}^{-1}$
 - ▷ Important to understand: Penguin/Tree contributions
 - ▷ Constraining (and measuring!) α
 - ▷ more data \Rightarrow more decay results + higher sensitivity