Recent *BABAR* Charm Physics Results

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Outline

- *BABAR* has a wide Charm physics program and published many results in the last months:

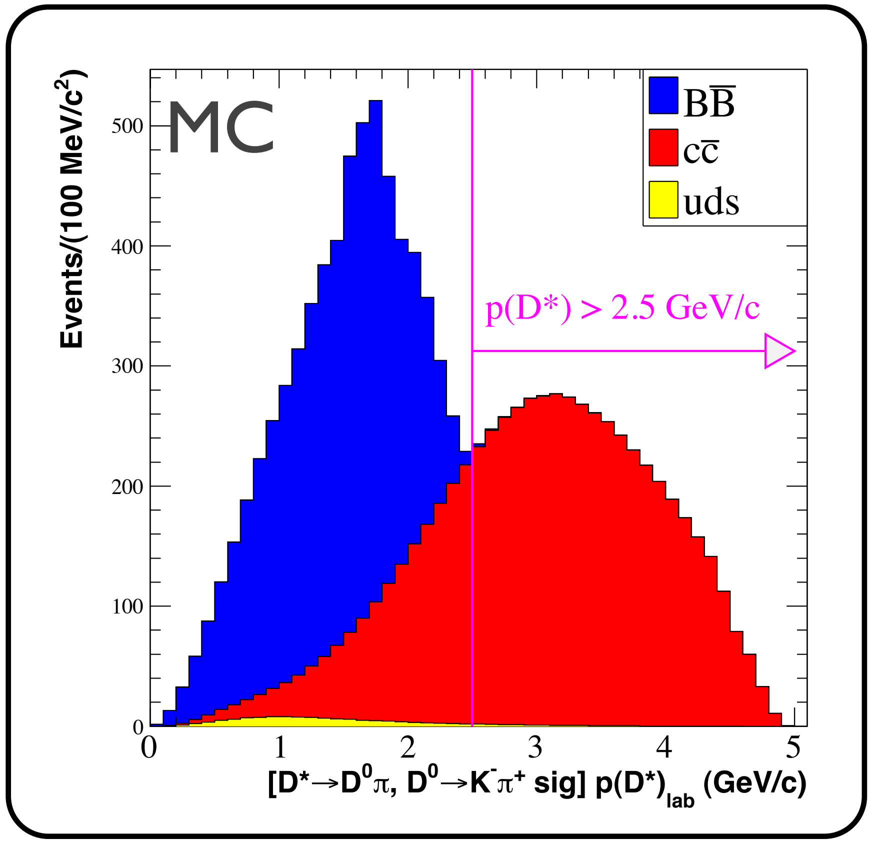
This talk

  - Precision measurements ($D_{s1}(2535)^+$)
  - Dalitz plot analysis ($D_s^+ \to K^+K^-\pi^+$)
  - *CP* violation ($D^+ \to K^0_S\pi^+$, $D_{(s)}^+ \to K^+K^0_S\pi^+\pi^-$)
  - Rare decays ($D^0, D^+, \Lambda_c \to X\, l^+l^-$, $D^0 \to \gamma\gamma, \pi^0\pi^0$)

See Eugeni's talk this afternoon

Charm and *B* factories

- Why reconstructing Charm decays at *B* factories:
  - $e^+e^- \to c\bar{c}$, cross section @*10.6 GeV* is 1/4 total hadronic
  - require $p^*(D) > 2.5$ *GeV/c* to reduce background
  - $D^{*+} \to D^0\pi^+$ provides D^0 flavor
  - Likelihood or *BDT* optimization when *D** not reconstructed



- *CPV* measurements drawback: Electroweak Forward-Backward asymmetry

Mass and width of $D_{s1}(2535)^+$

Phys. Rev. D83, 072003 (2011)

BABAR (385fb^{-1})

- Masses and widths of D_{sj} mesons are not always in agreement with potential model calculations (HQET)

R.N. Cahn and J.D. Jackson, Phys. Rev. D68, 037502 (2003)

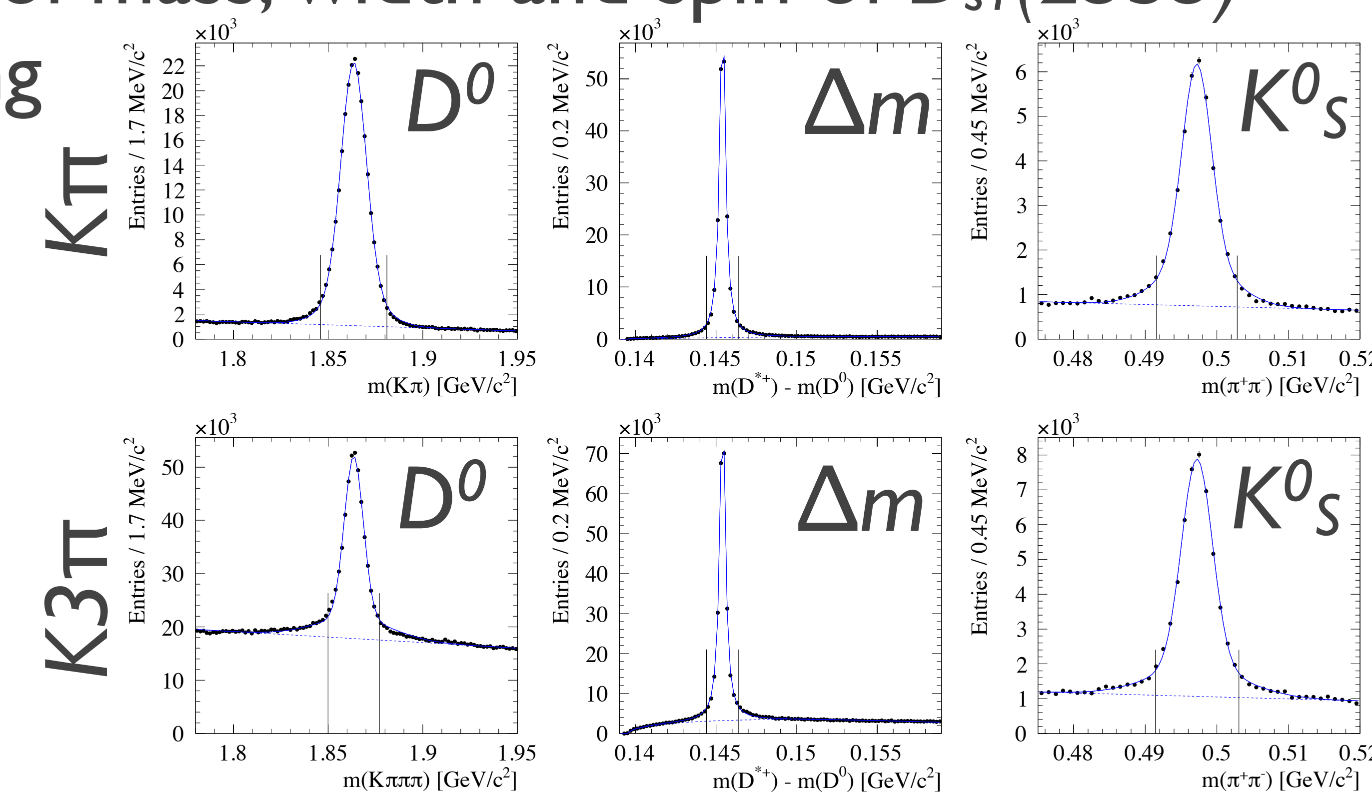
- Many theoretical alternative explanations: D^*K molecules, chiral partners, unitarized chiral models, tetraquarks and lattice calculations.

for a review see: P. Colangelo, F. de Fazio and R. Ferrandes Mod. Phys. Lett. A19, 2083 (2004)
E. S. Swanson, Phys. Rep. 429, 243 (2006)

- This first precise measurement of mass, width and spin of $D_{s1}(2535)^+$ may help in better understanding the D_{sj} mesons.

$$D^+_{s1} \to D^{*+} K^0_S$$
$$K^0_S \to \pi^+\pi^-$$
$$D^{*+} \to D^0\pi^+$$
$$D^0 \to K^-\pi^+$$
$$D^0 \to K^-\pi^+\pi^+\pi^-$$

$p^*(D_{s1})>2.7$ GeV/c



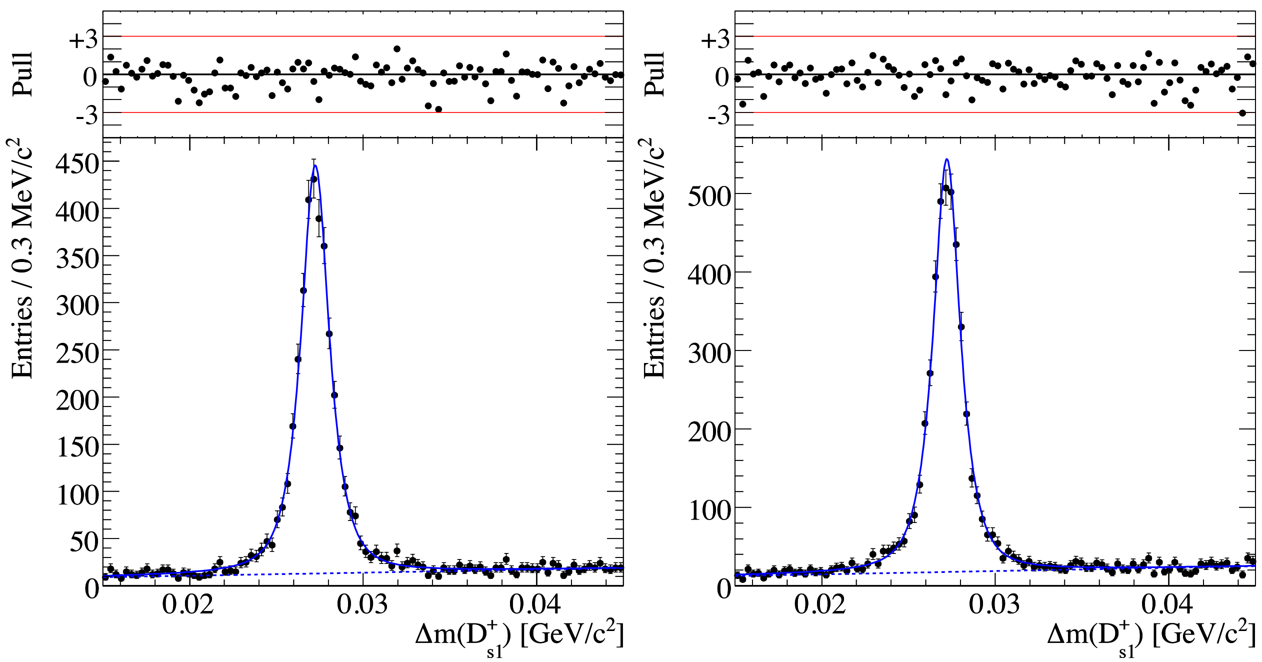
Mass and width of $D_{s1}(2535)^+$

Phys. Rev. D83, 072003 (2011)

BABAR ($385 fb^{-1}$)

- Fit to $\Delta m = m(D_{s1}^+) - m(D^{*+})$ using a relativistic Breit-Wigner convolved with the resolution function (multi-Gaussian ansatz)

$D^0 \to K^-\pi^+$ $\quad$ $D^0 \to K^-\pi^+\pi^+\pi^-$



- Systematics:
  1) Resolution model — main $\Delta\Gamma_{sys}$: p^* dep.
  2) Fit procedure
  3) Reconstruction — main Δm_{sys}: material density

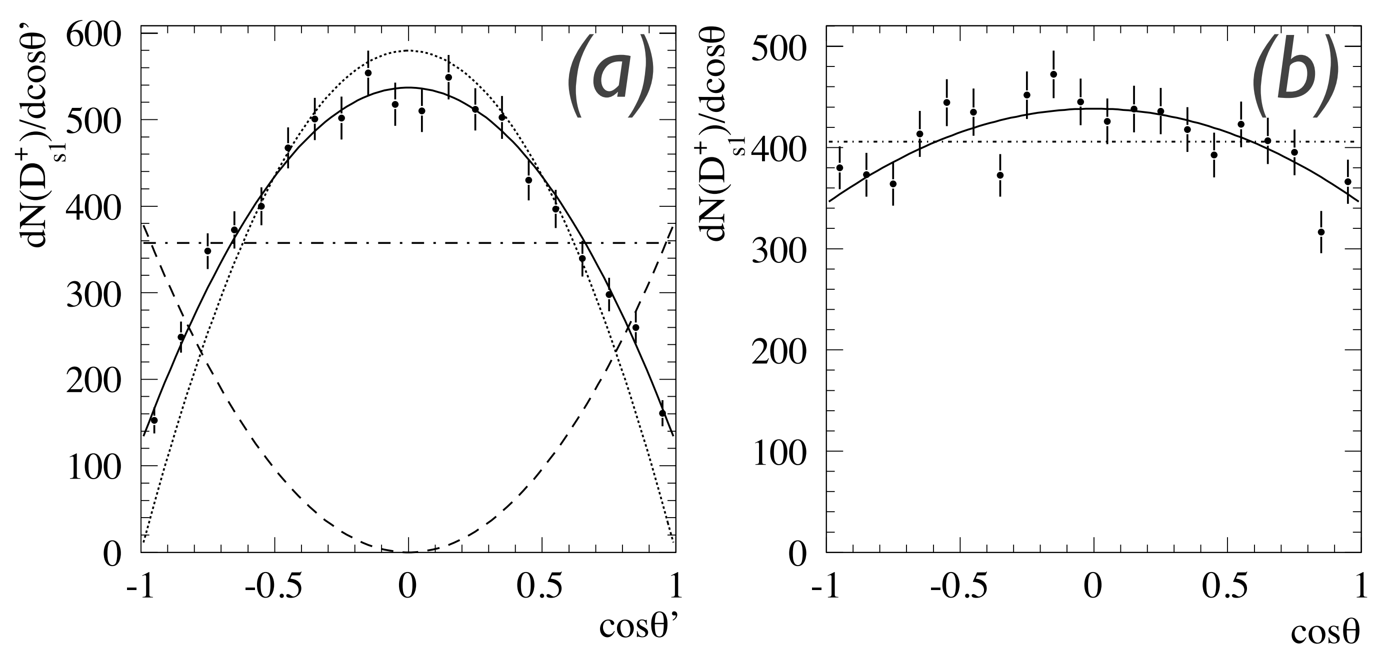
$m(D_{s1}^+) = 2535.08 \pm 0.01 \pm 0.15$ MeV/c^2

$\Gamma(D_{s1}^+) = 0.92 \pm 0.03 \pm 0.04$ MeV/c^2

first measurement!

- Angular analysis:
  Distribution of efficiency corrected D_{s1}^+ events to D^0 helicity angle (a) and D^* helicity angle (b).

  confirms $J^P = 1^+$



Dalitz plot analysis of $D_s^+ \to K^+K^-\pi^+$

Phys. Rev. D83, 052001 (2011)

BaBar ($384 fb^{-1}$)

- Scalar mesons are still a puzzle in light meson spectroscopy: are $a_0(980)$ or $f_0(980)$ 4-quarks states due to their proximity to KK threshold?

  F. E. Close and N. A. Tornqvist, J. Phys. G28, R249 (2002)

- We need to understand $\pi\pi$ and KK S-waves:

  $D_s^+ \to \pi^+\pi^-\pi^+$ → *BaBar* Collaboration, Phys. Rev. D79, 032003 (2009)

  $D_s^+ \to K^+K^-\pi^+$

- The measurement of KK S-wave is of great importance for the precise measurement of CP violation in B_s oscillations using $B_s \to J/\psi\phi$

  S. Stone and L. Zhang, Phys. Rev. D79, 074024 (2009)
  Y. Xie et al., J. High Energy Phys. 09 074 (2009)

Dalitz plot analysis of $D_s^+ \to K^+K^-\pi^+$

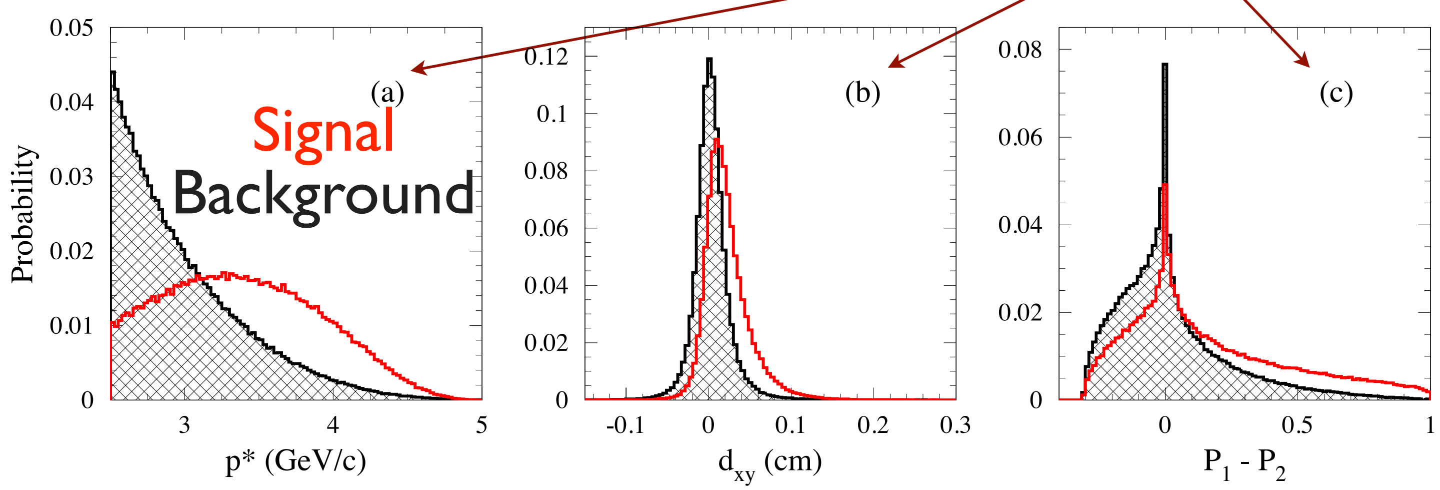
Phys. Rev. D83, 052001 (2011)

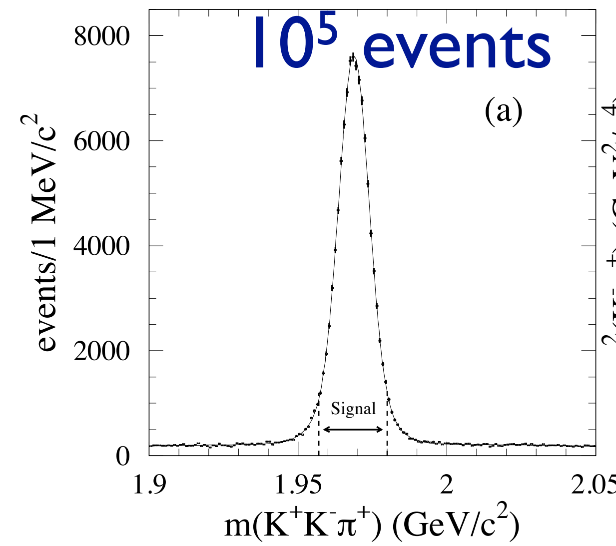
BABAR ($384 fb^{-1}$)

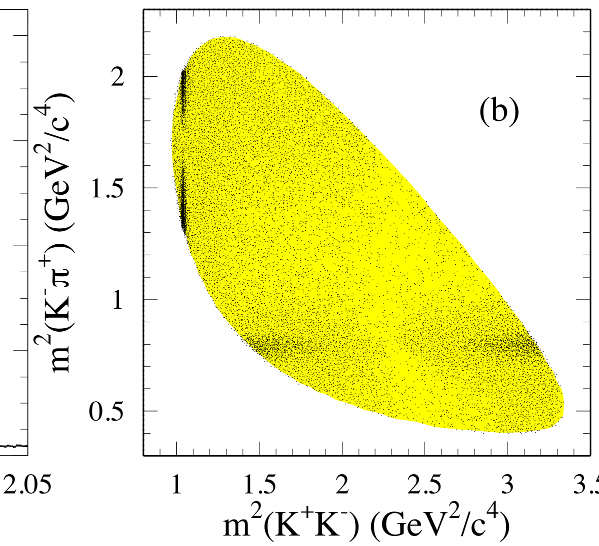
$p^*(D_s^+)>2.5$ GeV/c

$$D_s^*(2112)^+ \to D_s^+\gamma$$
$$\hookrightarrow K^+K^-\pi^+$$

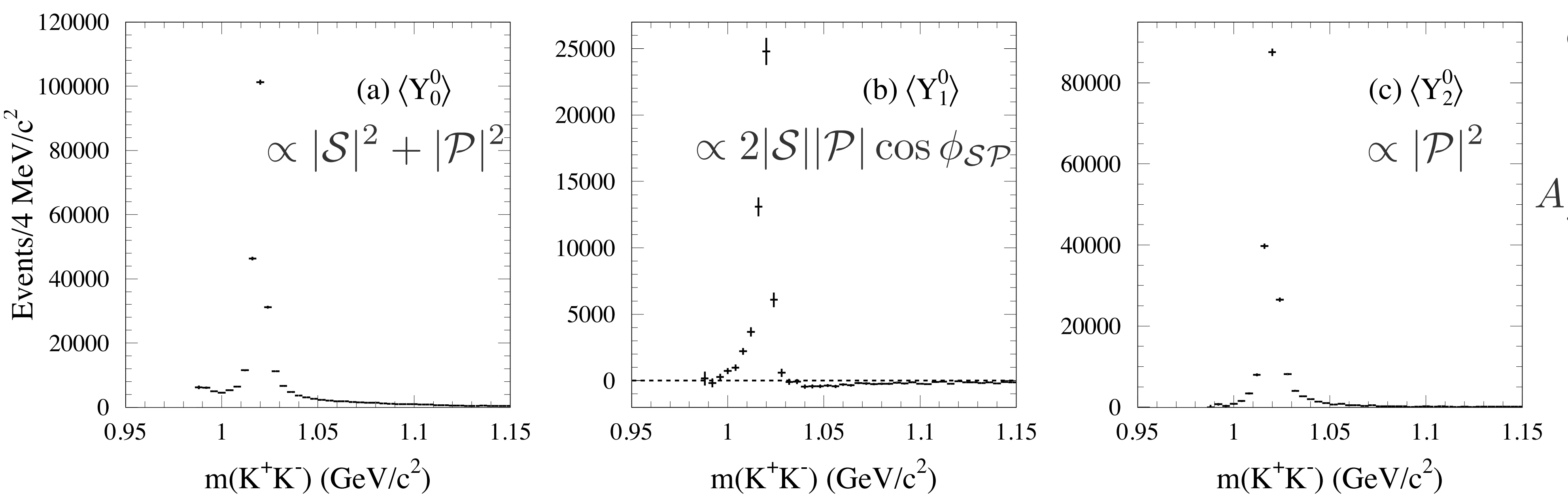
Likelihood Ratio + $\Delta m = m(KK\pi\gamma) - m(KK\pi)$







- Partial wave analysis of the K^+K^- threshold to retrieve a model-independent description of K^+K^- S-wave.
  Projections on Legendre moments used to separate $|S|$ from $|P|$ wave contributions.



- Effective parametrization of $f_0(980)$ from isolated S:

$$A_{f_0(980)} = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma_0 \rho_{KK}}$$
$$m_0 = (0.922 \pm 0.003_{\text{stat}})\ \text{GeV}/c^2$$
$$\Gamma_0 = (0.24 \pm 0.08_{\text{stat}})\ \text{GeV}$$
$$\rho_{KK} = 2p/m$$

Dalitz plot analysis of $D_s^+ \to K^+K^-\pi^+$

Phys. Rev. D83, 052001 (2011)

BABAR ($384 fb^{-1}$)

- Dalitz plot analysis:

$$\mathcal{L} = \prod_{n=1}^{N}\left[f_{sig}\eta(x,y)\frac{\sum_{i,j} c_i c_j^* A_i(x,y)A_j^*(x,y)}{\sum_{i,j} c_i c_j^* I_{A_i A_j^*}} + (1-f_{sig})\frac{\sum_i k_i B_i(x,y)}{\sum_i k_i I_{B_i}}\right]$$

purity (f_{sig}); signal pdf; background pdf — Evaluated from sidebands; efficiency ($\eta(x,y)$); complex amplitudes; normalization integrals

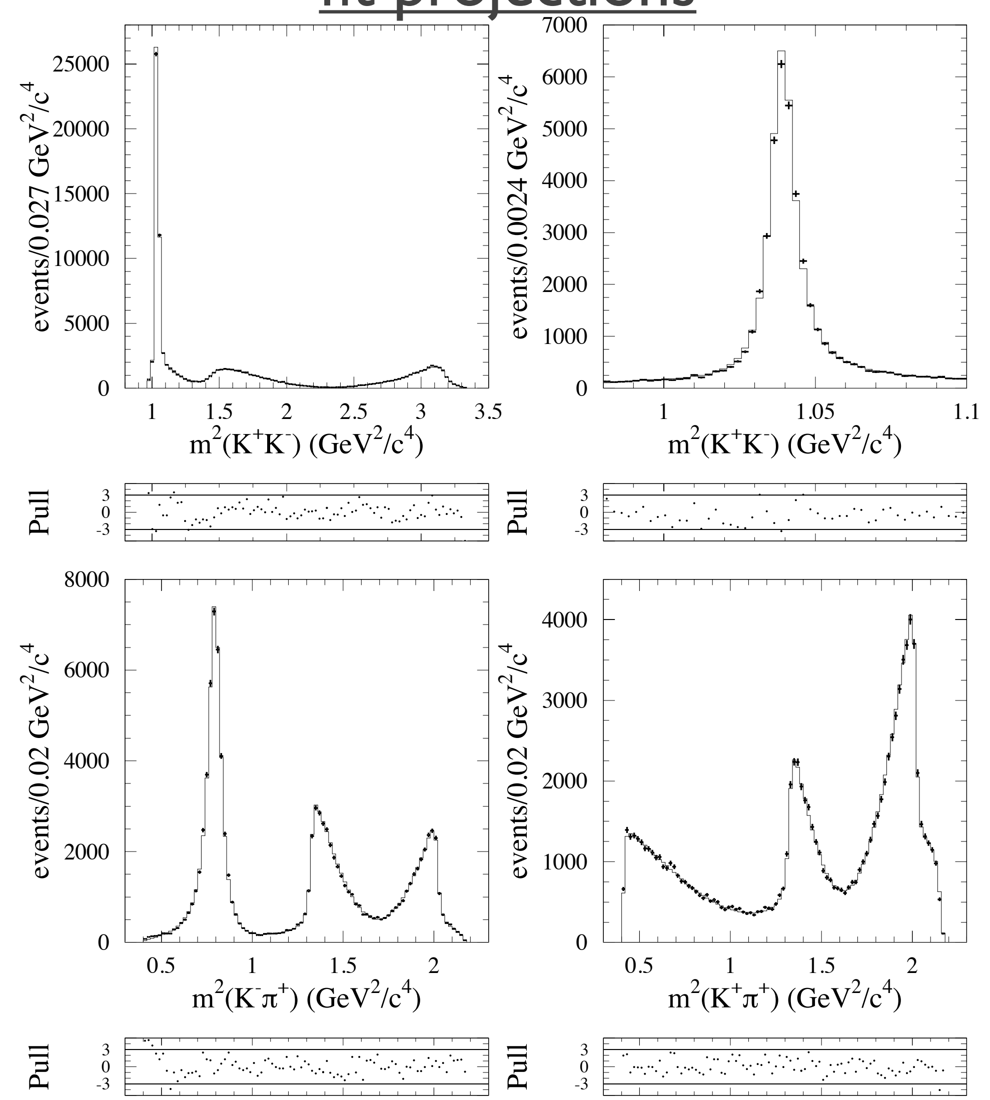
- Model:

Decay mode	Decay fraction(%)	Amplitude	Phase (rad.)
$\bar{K}^*(892)^0K^+$	$47.9 \pm 0.5 \pm 0.5$	1. (fixed)	0 (fixed)
$\phi(1020)\pi^+$	$41.4 \pm 0.8 \pm 0.5$	$1.15 \pm 0.01 \pm 0.26$	$2.89 \pm 0.02 \pm 0.04$
$f_0(980)\pi^+$	$16.4 \pm 0.7 \pm 2.0$	$2.67 \pm 0.05 \pm 0.20$	$1.56 \pm 0.02 \pm 0.09$
$\bar{K}_0^*(1430)^0K^+$	$2.4 \pm 0.3 \pm 1.0$	$1.14 \pm 0.06 \pm 0.36$	$2.55 \pm 0.05 \pm 0.22$
$f_0(1710)\pi^+$	$1.1 \pm 0.1 \pm 0.1$	$0.65 \pm 0.02 \pm 0.06$	$1.36 \pm 0.05 \pm 0.20$
$f_0(1370)\pi^+$	$1.1 \pm 0.1 \pm 0.2$	$0.46 \pm 0.03 \pm 0.09$	$-0.45 \pm 0.11 \pm 0.52$
Sum	$110.2 \pm 0.6 \pm 2.0$	χ^2/NDF=2843/(2305-14)=1.24	

systematic errors obtained varying within reasonable range fixed parameters in the fit.
Goodness of fit tested using adaptive binning.

- Compared to previous analysis from *E687* (700 ev.) and *CLEO-c* (12000 ev.), the use of a model-independent parametrization overcomes the uncertainties introduced by the coupling constants in the Flatté and gives a more accurate description of the Dalitz plot and total fit fractions.

fit projections



CPV in *D* decays

- Standard Model: *CP* violation from *KM* phase in *CKM* quark mixing matrix:

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{\lambda^2}{2} - \boxed{i\eta A^2\lambda^4} & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

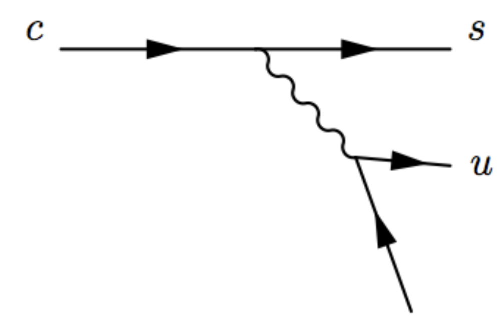
- Charmed Mesons:
  - *CP* violation is *CKM* suppressed $\mathcal{O}(10^{-3})$ or less
  - The presence of a K^0_S introduces *CPV* of (-0.332±0.006)% from *CPV* in $K^0/\overline{K}^0$ mixing
  - Experimental Sensitivity $\mathcal{O}(10^{-3})$

1% Signal = New Physics

New Physics Scenario

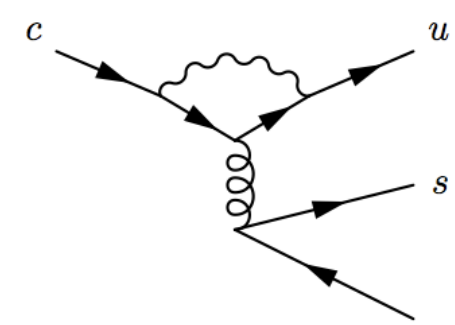
CPV ~ 1% Strong Evidence for non-*SM* processes

- Direct *CP* violation at tree level («1%)
  - extra quarks in *SM* vector-like representations
  - supersymmetry without *R*-parity models
  - two Higgs doublet models



(a) *Tree diagram.*

- Direct *CP* violation at one-loop (1%)
  - *QCD* penguin and dipole operators
  - *FCNCs* in supersymmetric flavor models.



(b) *Penguin diagram.*

Singly Cabibbo Suppressed (*CS*) decays are uniquely sensitive to $c \rightarrow uq\bar{q}$ and are more likely to show the effect if present

Details:
Grossman, Kagan and Nir, Phys. Rev. D75, 036008 (2007)
Bigi, hep-ph/0104008 (2001)
Buccella et al., Phys. Rev. D51,3478 (1995)

Direct *CP* violation

$$A_{CP}^{rec} = \frac{\Gamma_D - \Gamma_{\bar{D}}}{\Gamma_D + \Gamma_{\bar{D}}}$$

Γ = yields

- In asymmetric detectors like *BABAR* and *BELLE*, forward-backward asymmetry could bias these measurements
- *FB* asymmetry = *EW*+*EM* currents interference

$$N_c/N_{\bar{c}} = f(\cos\theta^*)$$

- We need to estimate *FB* asymmetry contribution A_{FB}
- Another source of asymmetry is the different interaction between particles of different charge and the detector A_{ϵ}
- The asymmetry measured is then

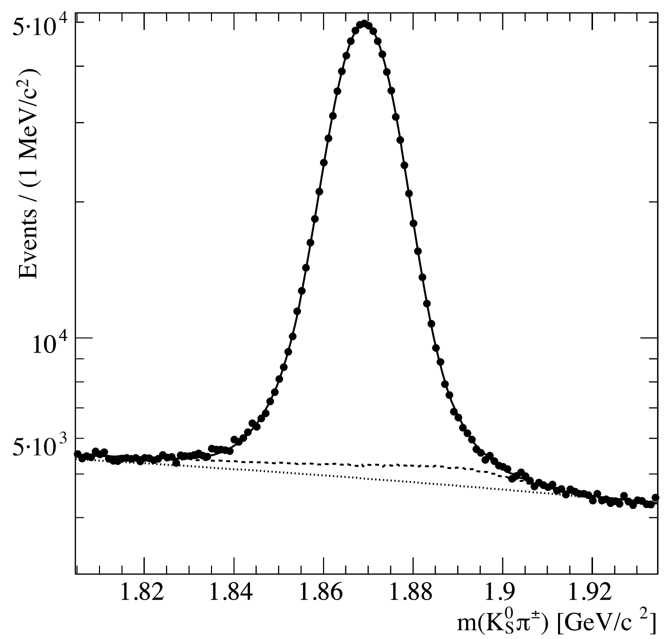
Need to quantify this part to retrieve A_{CP}

$$A_{CP}^{rec} = A_{CP} + \boxed{A_{FB} + A_{\epsilon}}$$

$D^+ \to K^0_S \pi^+$

Phys. Rev. D83, 071103(R) (2011)

BABAR (469fb^{-1})



- Signal optimization maximizing $S/\sqrt{(S+B)}$ using *BDT* on *MC*:
  Vars: $\tau_T(D^\pm)$, $L_T(D^\pm)$, $p^*(D^\pm)$, $p(K^0_S)$, $p_T(K^0_S)$, $p(\pi^\pm)$, $p_T(\pi^\pm)$
- binned maximum likelihood fit: $(807\pm1)\times10^3$ events

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}} = A_{CP} + A_{FB} + A_\epsilon^\pi$$

control sample of $B\overline{B}$ decays → efficiency map on $p(\pi)$ and $\cos\theta(\pi)$ introduces a bias (+0.05)% in A_{CP}, included in systematics

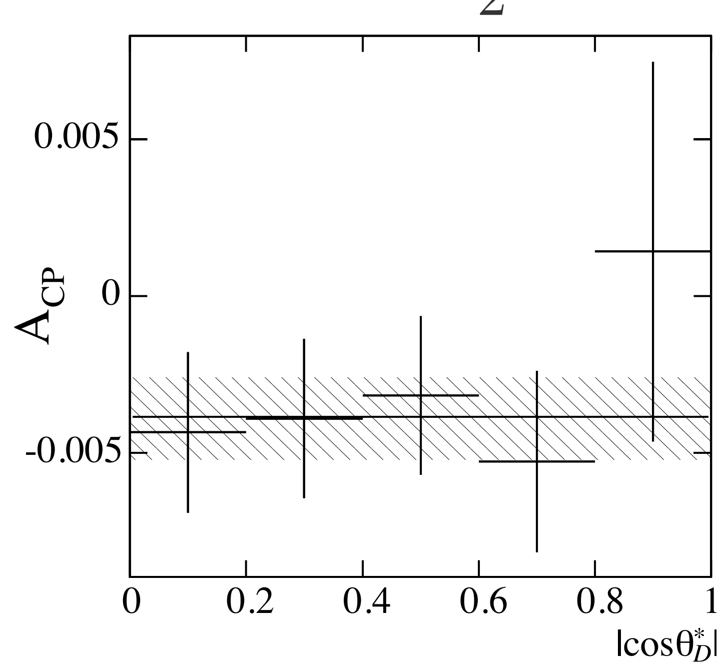
$$A_{FB} = \frac{A(+|\cos\theta_D^*|) - A(-|\cos\theta_D^*|)}{2}$$

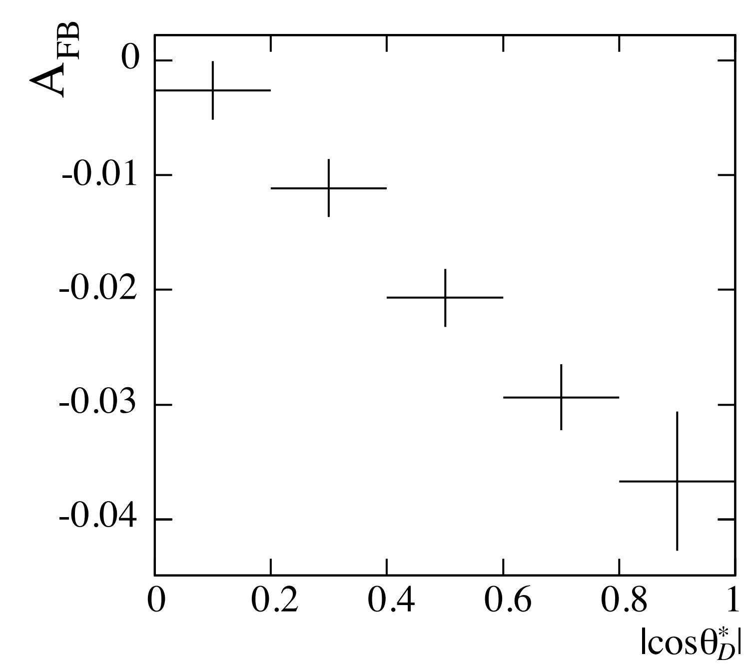
$$A_{CP} = \frac{A(+|\cos\theta_D^*|) + A(-|\cos\theta_D^*|)}{2}$$

A corrected for π efficiency weighting D^- candidates

systematics

evaluation $A_\epsilon^{\pi^+}$	0.08%
$K^0/\overline{K}^0$ regeneration	0.06%
fit model	0.01%
total	0.10%





final result:

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%$$

consistent to 0 (2.7σ) and to *SM* pred. (-0.332±0.006)%

T-odd Correlations

W. Bensalem, A. Datta and D. London, Phys. Rev. D66, 094004 (2002)
W. Bensalem and D. London, Phys. Rev. D64, 116003 (2001)
W. Bensalem, A. Datta and D. London, Phys. Lett. B538, 309 (2002)
I. Bigi and H.-B. Li, Int. J. Mod. Phys. A24, 657 (2009)

- Asymmetry in a *T*-odd observable→*T* violation→*CPV* (assuming *CPT* invariance)
- *T*-odd observable (*v* = spin or momentum)

$$A_T = \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}$$

← measured on D^+

- Final State Interactions (*FSI*) may fake the measurement producing $A_T \neq 0$
- To remove *FSI* effects

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T)$$

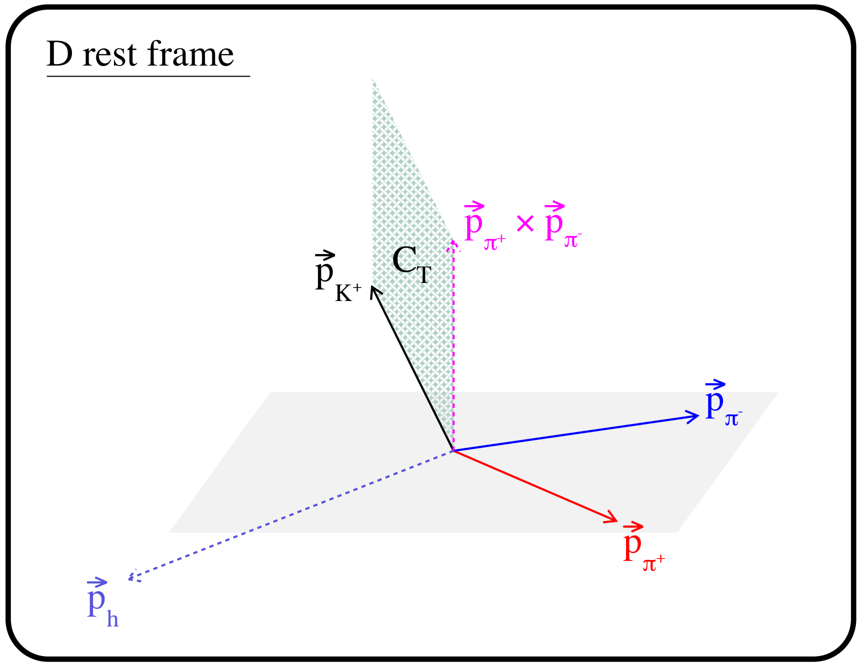
measured on D^- (→ $\bar{A}_T$)

T violation observable

- In $D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$

$$C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

T-odd observable

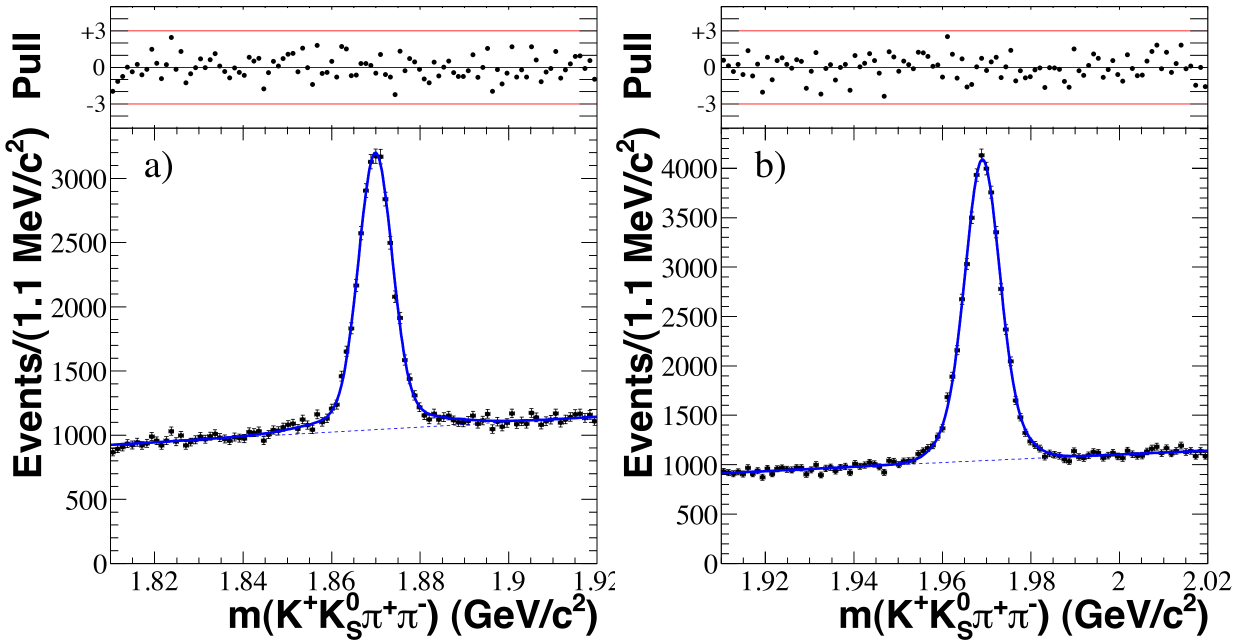


$D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$

hep-ex/1105.4410

submitted to PRD-RC

BABAR (520fb^{-1})



- Blind Analysis
- Inclusive $D_{(s)}^+$ reconstruction
- $p^*(D)>2.5$ GeV/c
- 20,000 D^+ and 30,000 D_s^+ decays

- Peaks optimized by means of likelihood ratio
- 3 variables: $p^*(D)$, P_1-P_2, $L_T(D)$

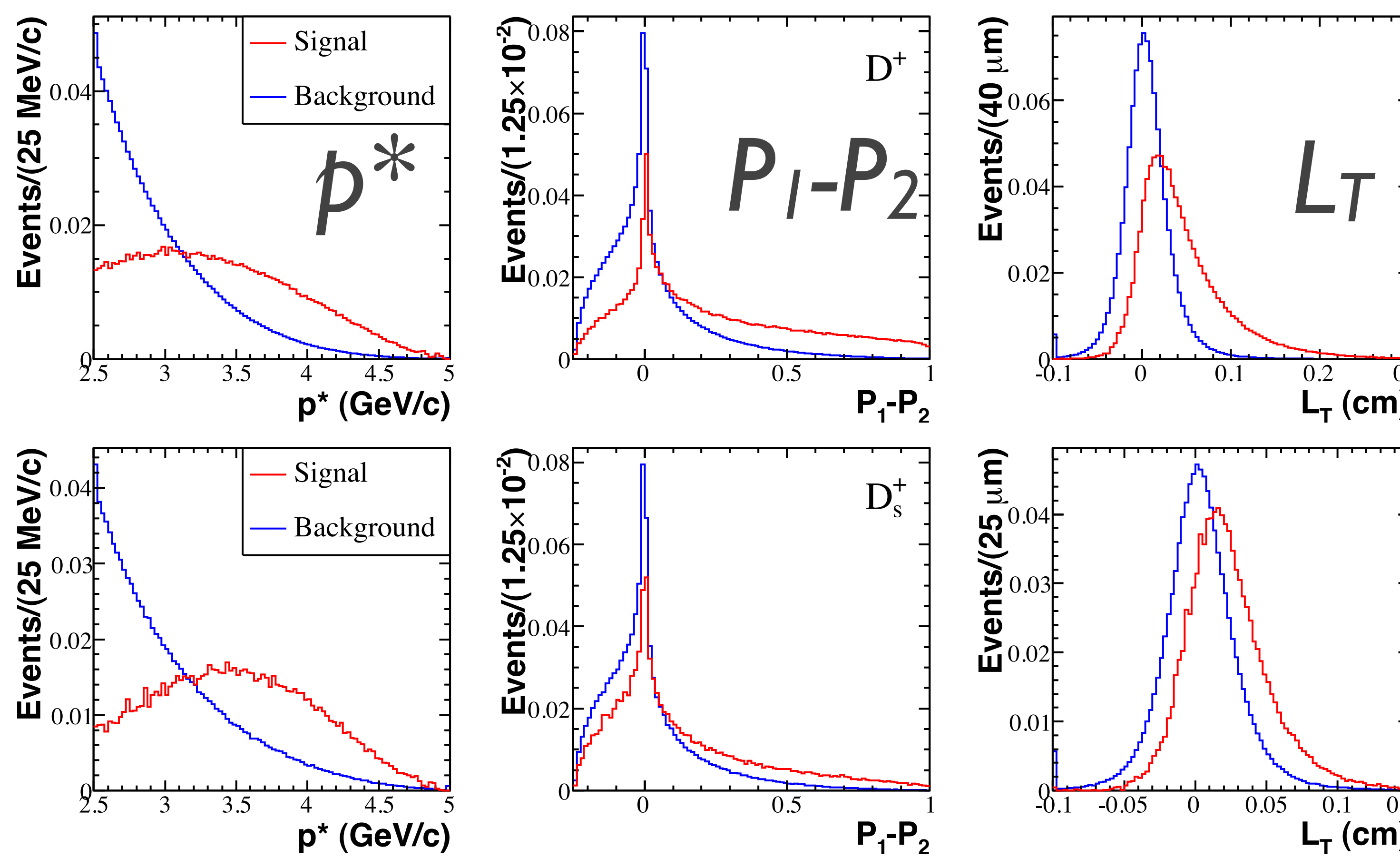
  P_1=nominal fit probability

  P_2=fit probability constraining D vtx to *IR*

  $L_T(D)$=transverse D decay length
- signal distributions from

  $D^+ \to K^0_S \pi^+ \pi^+ \pi^-$

  $D_s^+ \to K^- K^0_S \pi^+ \pi^+$
- background from data sidebands

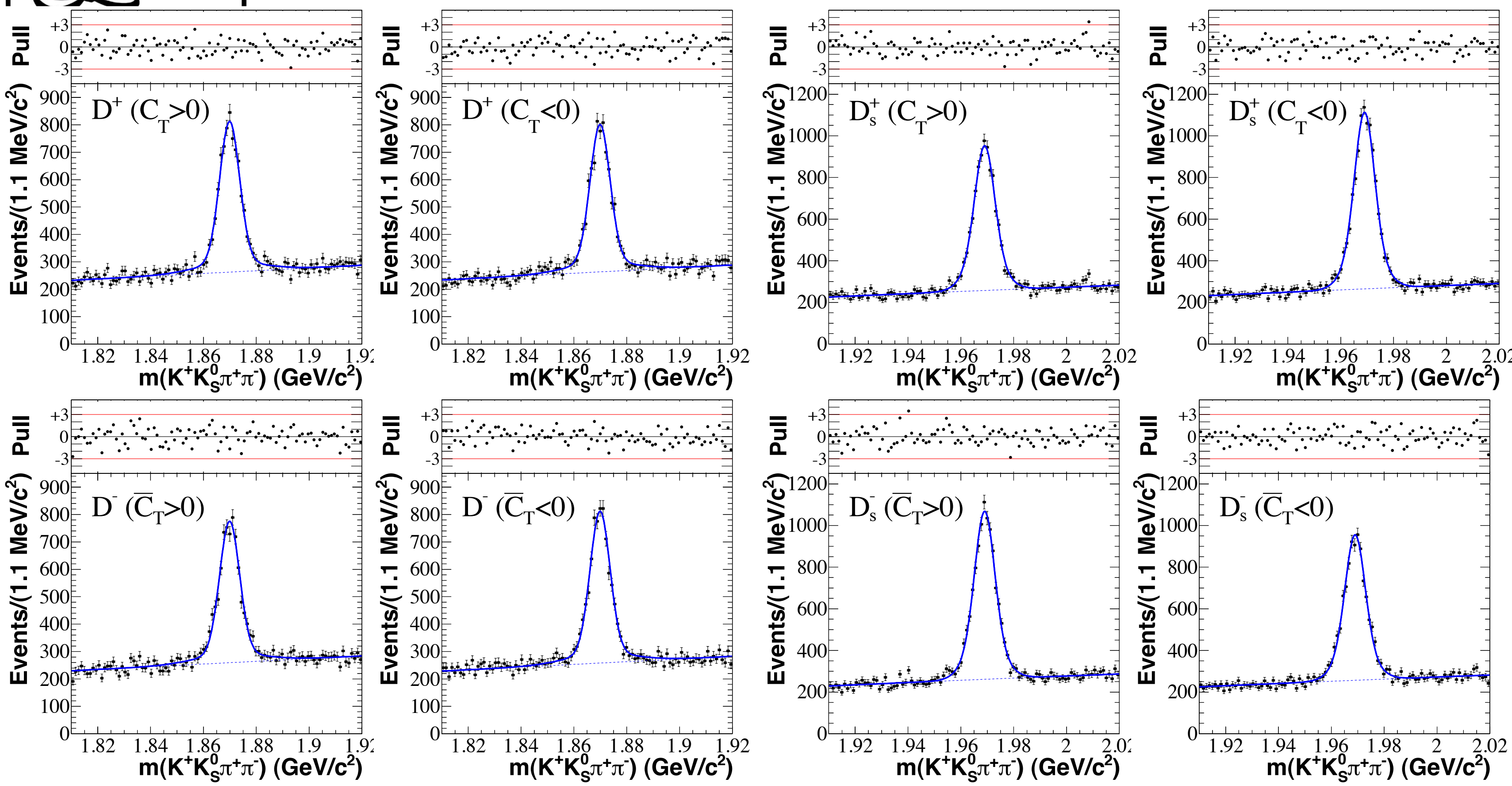


$D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$ cont.

hep-ex/1105.4410

submitted to PRD-RC

BABAR ($520 fb^{-1}$)



- Dataset split depending on $D_{(s)}$ charge and C_T value
- Simultaneous binned maximum likelihood fit
- Peak: 2 Gaussians with common mean
  Background: line(D^+), 2nd order polynomial (D_s^+)

systematics

x 10^{-3}

Effect	$\mathcal{A}_T(D^+)$	$A_T(D^+)$	$\bar{A}_T(D^-)$	$\mathcal{A}_T(D_s^+)$	$A_T(D_s^+)$	$\bar{A}_T(D_s^-)$
1) Reconstruction	2.05	2.84	1.26	1.00	1.00	1.27
2) Likelihood Ratio	1.08	3.41	5.58	2.46	7.77	8.16
3) Fit Model	1.30	1.14	1.46	0.10	0.78	0.70
4) Particle Identification	3.70	3.33	4.08	2.22	2.47	6.73
Total	4.56	5.66	7.18	3.43	8.25	10.67

$D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$ cont.

hep-ex/1105.4410 submitted to PRD-RC

BaBar (520fb^{-1})

- Final Results

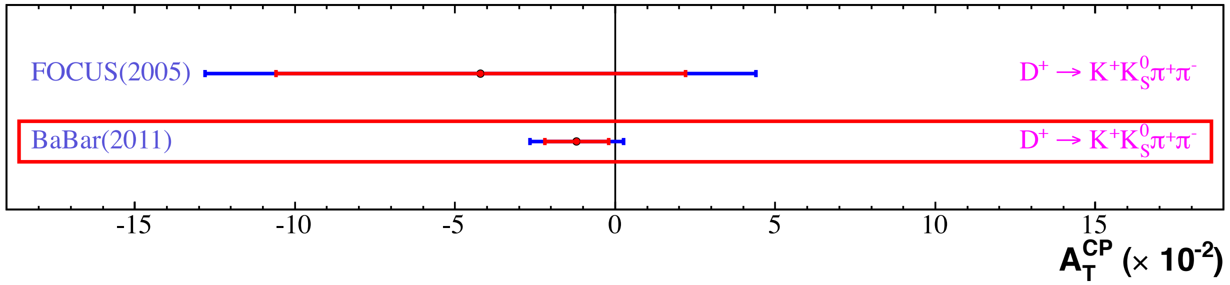
$$\bar{A}_T(D^+) = (+11.2 \pm 14.1_{\rm stat} \pm 5.7_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(D^-) = (+35.1 \pm 14.3_{\rm stat} \pm 7.2_{\rm syst}) \times 10^{-3}$$
$$A_T(D_s^+) = (-99.2 \pm 10.7_{\rm stat} \pm 8.3_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{\rm stat} \pm 10.7_{\rm syst}) \times 10^{-3}$$

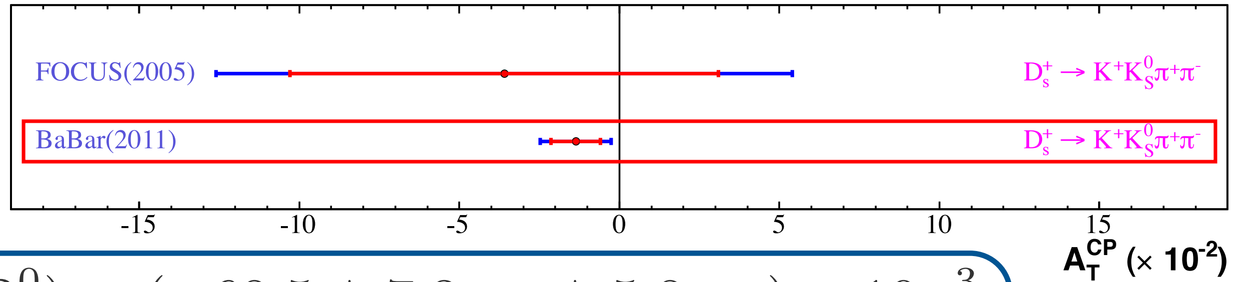
Final state interaction effects seem to be larger in D_s^+ than D^+ decays

Gronau and Rosner, hep-ph/1107.1232 (2011)

$$\mathcal{A}_T(D^+) = (-12.0 \pm 10.0_{\rm stat} \pm 4.6_{\rm syst}) \times 10^{-3}$$
$$\mathcal{A}_T(D_s^+) = (-13.6 \pm 7.7_{\rm stat} \pm 3.4_{\rm syst}) \times 10^{-3}$$

T violation parameter consistent to 0. Factor 10 better than previous result.





similar *BaBar* analysis $D^0 \to K^+K^-\pi^+\pi^-$ (2010)

Phys. Rev. D81, 111103(R) (2010)

$$A_T(D^0) = (-68.5 \pm 7.3_{\rm stat} \pm 5.8_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(\bar{D}^0) = (-70.5 \pm 7.3_{\rm stat} \pm 3.9_{\rm syst}) \times 10^{-3}$$
$$\mathcal{A}_T(D^0) = (+1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}$$

Conclusions

- The *BABAR* Collaboration is still producing excellent Charm physics results.
- The huge *BABAR* dataset of Charm decays allows to perform the best precision measurements and the most detailed Dalitz plot analysis.
- Searching for *CP* violation, we have reached the limit of the *B* factories, obtaining sensitivities of 10^{-3}, but the *CP* violation from $c \rightarrow s$ transition didn't show up yet, neither from *SM* or *NP*.
- Still many analysis are in the pipeline and new results are expected soon.