Recents Charm Results from the B factories

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Outline

- Introduction:
  - Charm Physics and searches for Physics beyond the Standard Model
- Recent results from the B factories:
  - BaBar
    - Search for CP violation in $D^+ \to K_S\pi^+$;
    - Search for T/CP violation in $D_{(s)}^+ \to K_S K^+\pi^+\pi^-$;
    - Search for flavor-changing neutral current (FCNC) processes *(in backup slides)*:
      - $D^0 \to \gamma\gamma$;
      - $c \to u l^+ l^-$ transitions.
  - Belle
    - Evidence of CP violation in $D^+ \to K_S\pi^+$;
    - Search for CP violation in $D^0 \to K_S\pi^0$, $K_S\eta$, $K_S\eta'$;
    - Search for CP violation in D meson decays $D_{(s)}^+ \to \pi^+\phi$;
    - Search for CP violation in D meson decays $D^+ \to \pi^+\eta^{(\prime)}$.
- Summary

Introduction

Charm Physics and searches for Physics beyond the Standard Model

- Recent evidence of CP violation (CPV) in D^0 decays has renewed the interest for searching new physics in the charm sector:
  - observed asymmetries are marginally compatible with the SM but not conclusive for establishing new Physics.
- Some hot topics in Charm Physics:
  - Search for CP violation in Single Cabibbo Suppressed (SCS) decays, uniquely sensitive to new physics through tree-penguin interference:
    - measure CP asymmetries in individual decay modes and keep improving precision;
    - measure additional decay modes with similar quark transitions: $c \rightarrow u\ d\ \bar{d}$, $c \rightarrow u\ s\ \bar{s}$.
  - Search for Flavor Changing Neutral Current (FCNC) decays, highly suppressed in the standard model: *(in backup slides)*
    - however difficult to calculate SM long distance contributions.

Understanding origin of CPV in SCS decays

- Enrico Franco, Satoshi Mishima and Luca Silvestrini arXiv:1203.3131
- Gino Isidori, Jernej F. Kamenik Zoltan Ligeti and Gilad Perez arXiv:1111.4987

. Another important experimental handle to decide whether the observed signal can or cannot be accommodated in the SM would be observing or constraining CP violation in other decay modes. corresponding to the same quark-level transitions.

Decays that are accessible at the B factories, not a complete list!

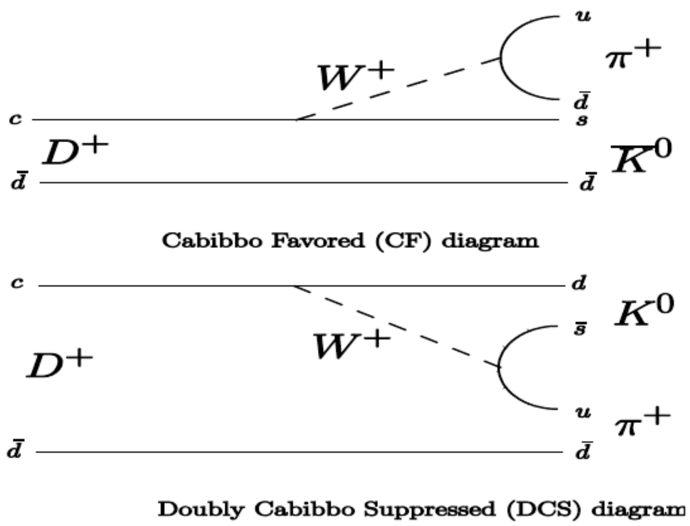
- $D^0 \to \pi^+\pi^-, \pi^+\pi^-\pi^0, 2\pi^+2\pi^-, 2\pi^0$
- $D^+ \to \pi^+\pi^0, \pi^+\eta, \pi^+\eta', 2\pi^+\pi^-, 2\pi^+\pi^-\pi^0$
- $D_s^+ \to K_s\pi^+, K^+\pi^+\pi^-, K_s\pi^+\pi^0, K^+\pi^0, K^+\eta, K^+\eta'$
- $\Lambda_c^+ \to p\pi^+\pi^-, p2\pi^+2\pi^-$
- $D^0 \to K^+K^-, K^+K^-\pi^0, K_sK^-\pi^+, K_sK^+\pi^-$
- $D^+ \to K_sK^+, \pi^+\Phi, K^+K^-\pi^+\pi^0, K_sK^+\pi^+\pi^-$
- $D_s^+ \to 2K^+K^-$
- $\Lambda_c^+ \to pK^+K^-$

CP violation in D decays with a K_S in final state

- CP asymmetry in charm decays with a K_S in the final state is expected to be (-0.332±0.006)% due to CPV in K^0-$\bar{K}^0$ mixing.
- Sizable difference from this value would indicate CP violation in the Δc transition (very small in the SM) indicating possible new physics effects.

Example: $D^+ \rightarrow K_S^0 \pi^+$

$$A_{CP}^{D^+\to K_S^0\pi^+} \equiv \frac{\Gamma(D^+\to K_S^0\pi^+)-\Gamma(D^-\to K_S^0\pi^-)}{\Gamma(D^+\to K_S^0\pi^+)+\Gamma(D^-\to K_S^0\pi^-)} = A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}, \quad (1)$$



Recent results

Search for CP violation in $D^+ \to K_S \pi^+$

$$A_{CP} = \frac{\Gamma(D^+ \to K_S^0\pi^+) - \Gamma(D^- \to K_S^0\pi^-)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^- \to K_S^0\pi^-)}$$

Direct CP asymmetry from K_S mixing: **-0.332**±0.006%

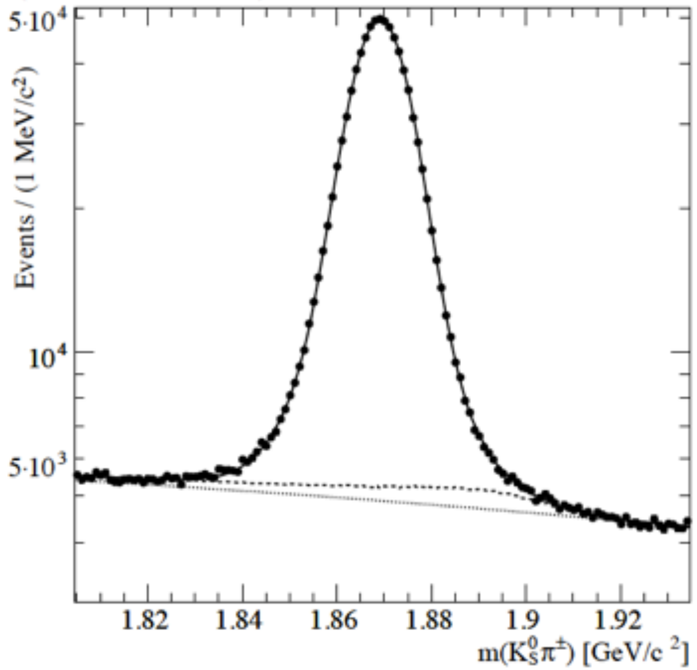
New Physics affecting doubly Cabibbo-suppressed Feynman diagram could cancel or enhance it to % level

Phys.Rev.D 83:071103,2011 469 fb^{-1}

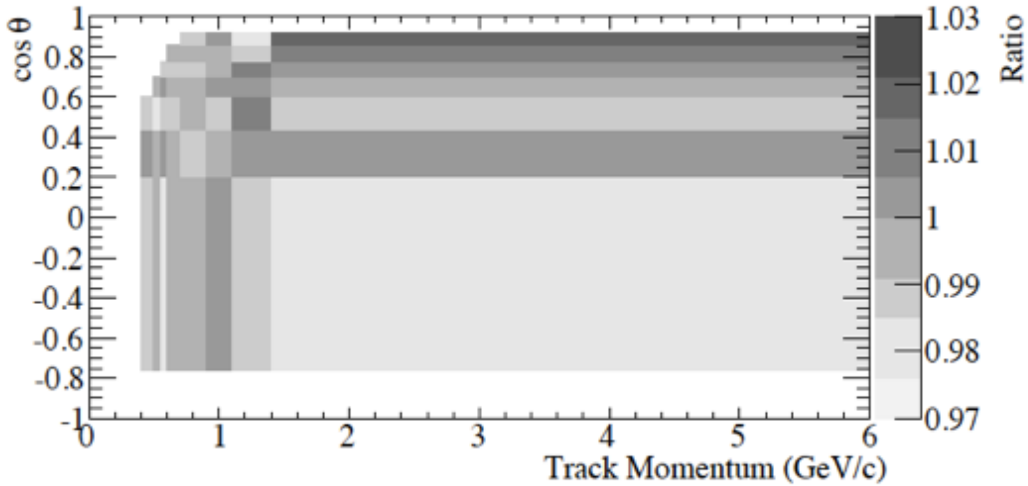
New Idea

Fit: Signal, reflection bkg and combinatorial bkg

$(807.4 \pm 0.1) \times 10^3$ signal events.



New data-driven method to determine charge asymmetry in track reconstruction.
Use tracks from $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ *process, free of any physics-induced charge asymmetry.*

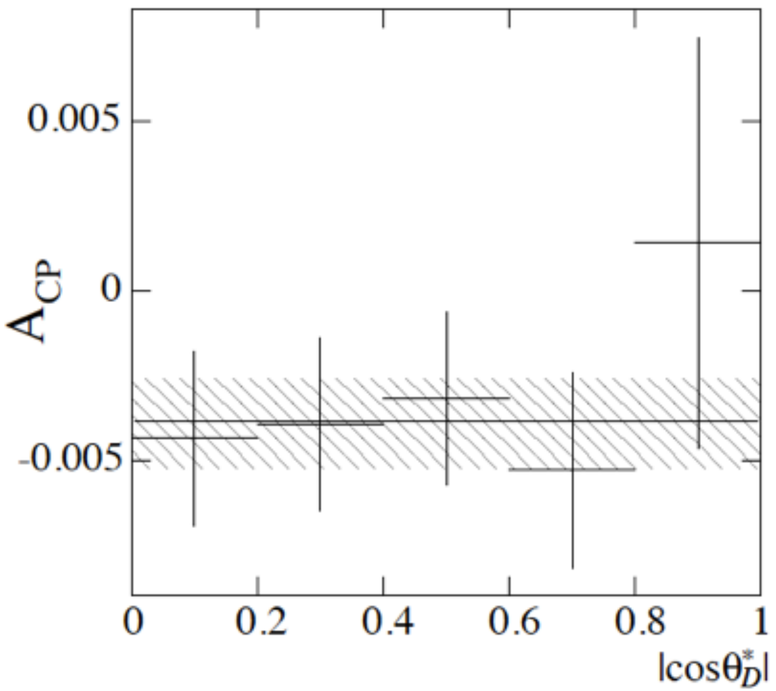


Ratio of detection efficiency: π^+/π^-

Search for CP violation in $D^+ \to K^0_S \pi^+$

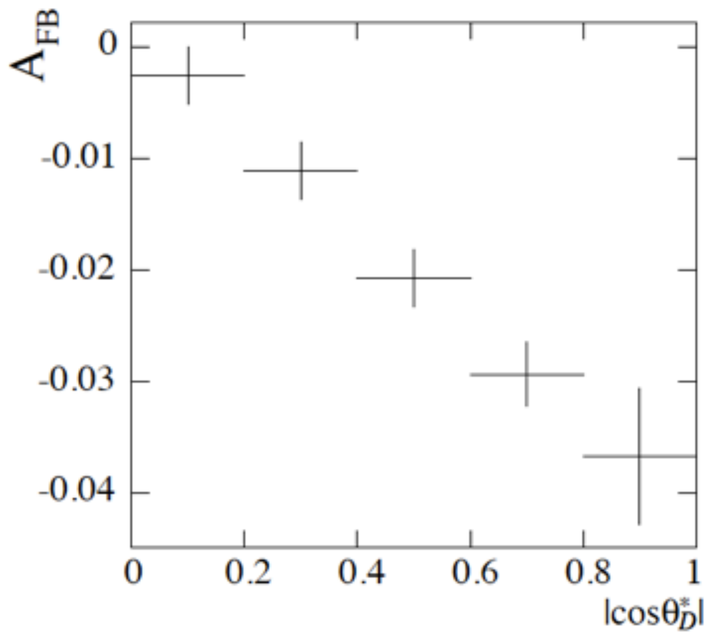
CP violation asymmetry

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



FW-BW asymmetry due to γ-Z interference and to detector efficiency asymmetry

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



$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\,\%$$ ***Phys.Rev.D 83:071103,2011*** 469 fb^{-1}

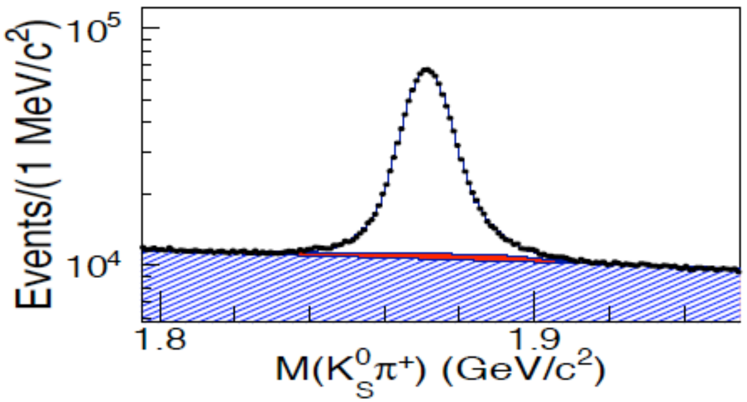
Consistent with SM prediction $(-0.332 \pm 0.006)\%$

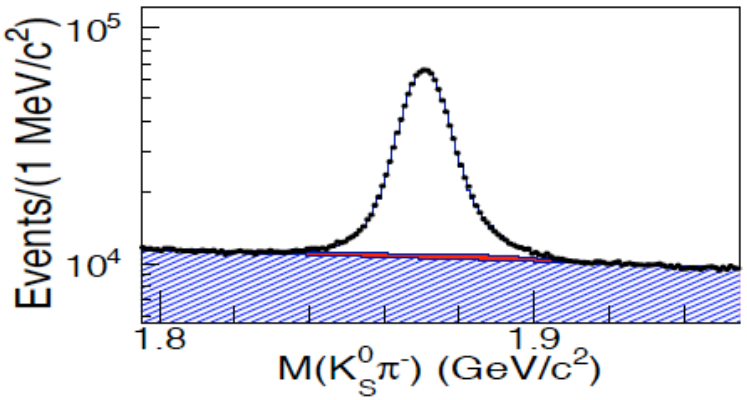
Search for CP violation in $D^+ \to K^0_S \pi^+$

$$A_{\rm rec}^{D^+\to K^0_S\pi^+} = \frac{N_{\rm rec}^{D^+\to K^0_S\pi^+} - N_{\rm rec}^{D^-\to K^0_S\pi^-}}{N_{\rm rec}^{D^+\to K^0_S\pi^+} + N_{\rm rec}^{D^-\to K^0_S\pi^-}}$$

$$A_{\rm rec}^{D^+\to K^0_S\pi^+} = A_{CP}^{D^+\to K^0_S\pi^+} + A_{FB}^{D^+}(\cos\theta_{D^+}^{\rm CMS}) + A_{\epsilon}^{\pi^+}(p_{T\pi^+}^{\rm lab}, \cos\theta_{\pi^+}^{\rm lab})$$

arXiv:1203.6409v1 977 fb^{-1} 1738 K





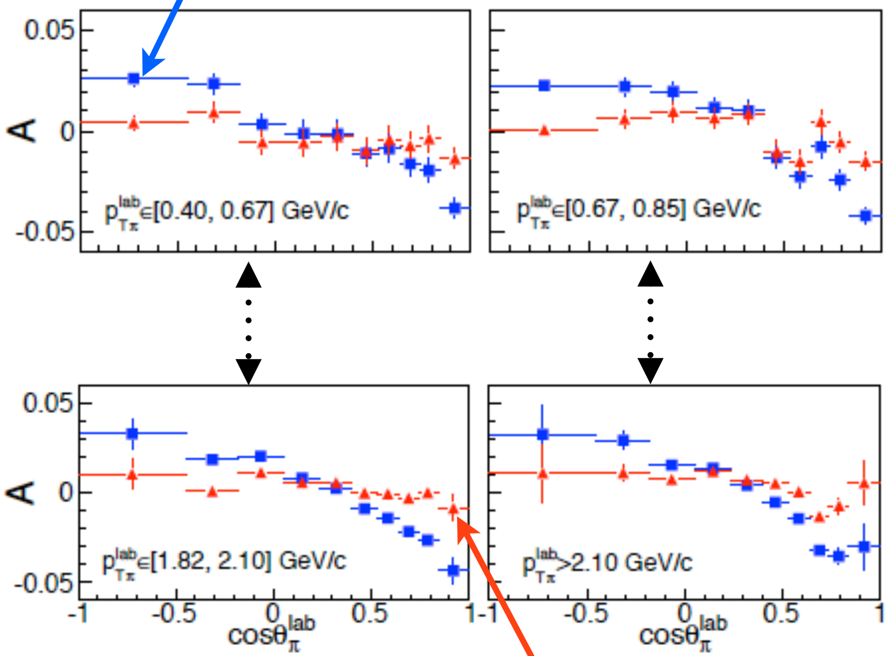
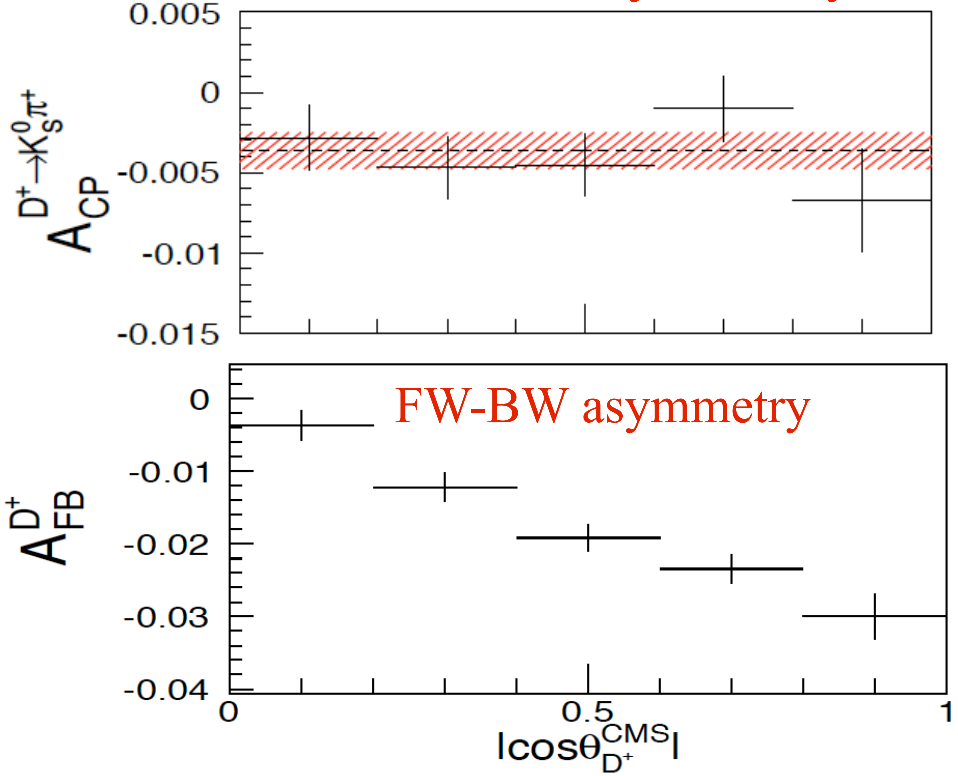


FIG. 2: $A_\epsilon^{\pi^+}$ map in bins of $p_T^{\rm lab}$ and $\cos\theta^{\rm lab}$ of the π^+ obtained with the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ samples (triangles). The $A_{\rm rec}^{D^+\to K^-\pi^+\pi^+}$ map is also shown (rectangles) for comparison, include A_{FB}, $A_\epsilon^{K^-}$, and $A_\epsilon^{\pi^+}$

Search for CP violation in $D^+ \to K^0_S \pi^+$

CP violation asymmetry



Systematic errors

Source	$\sigma_{A_{CP}}$ (%)
$A_\epsilon^{\pi^+}$ determination	0.064
Fitting	0.003
$\cos\theta_{D^+}^{CMS}$ binning	0.008
$A_{\mathcal{D}}$ correction	0.016
Total	0.067

- *A_D is due to different K^0-$\overline{K^0}$ interaction with material*
- *Asymmetry due to neutral kaons to be corrected with acceptance effects as a function of K_S decay time by (1.040±0.005)* Y. Grossman and Y. Nir, arXiv:1110.3790

$$A_{CP}^{D^+\to K_S^0\pi^+} = -0.363 \pm 0.094 \pm 0.067\ (\%)$$

3.2 standard deviations away from zero

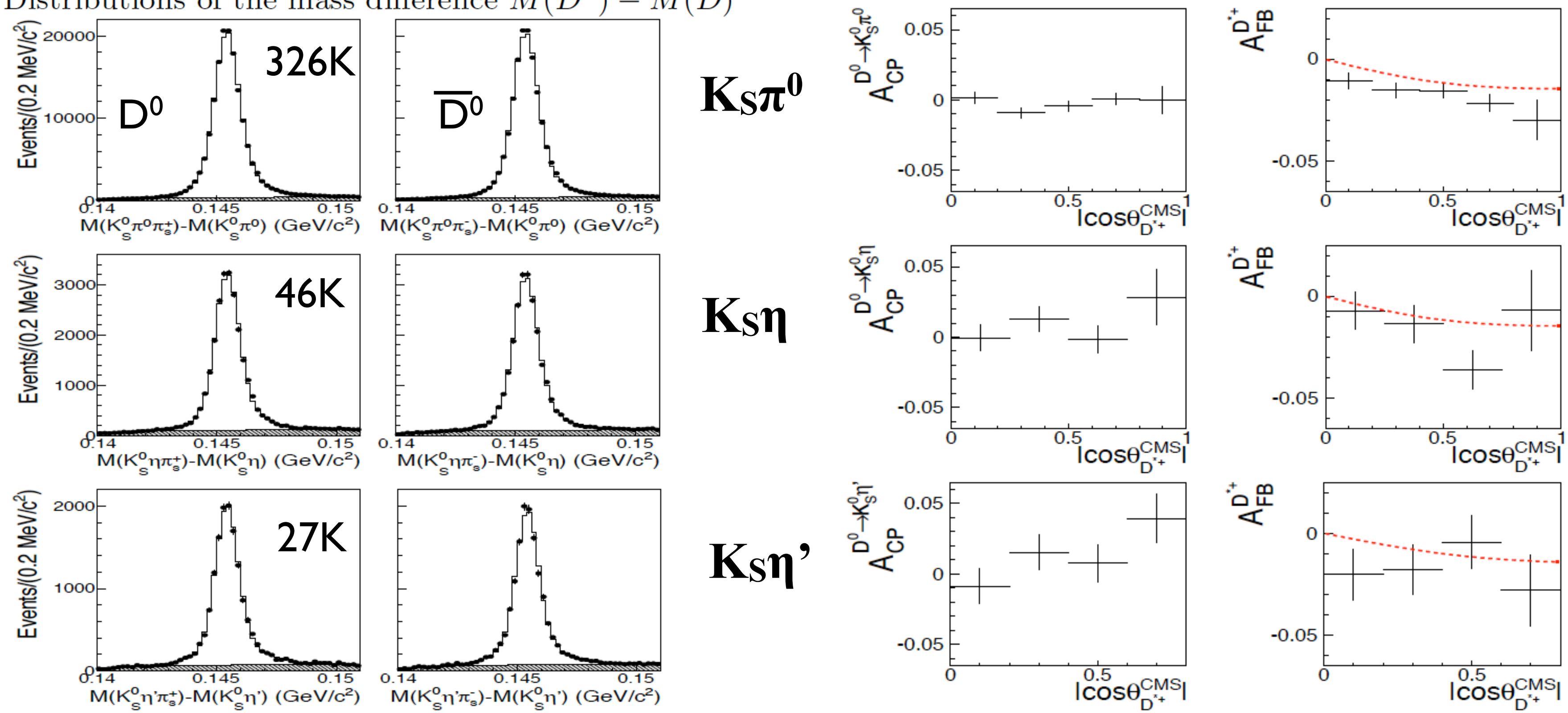
977 fb^{-1}

arXiv:1203.6409v1

Phys. Rev. Lett. 106, 211801 (2011) 791 fb^{-1}

Search for CPV in $D^0 \to K^0_S P^0$ decays

Distributions of the mass difference $M(D^*) - M(D)$

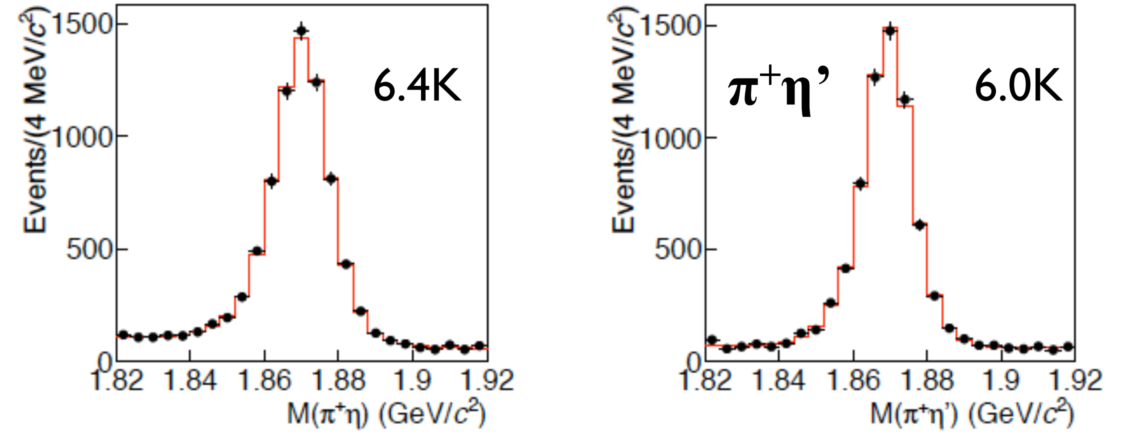


	Belle (%)
$A_{CP}^{D^0 \to K^0_S \pi^0}$	$-0.28 \pm 0.19 \pm 0.10$
$A_{CP}^{D^0 \to K^0_S \eta}$	$+0.54 \pm 0.51 \pm 0.16$
$A_{CP}^{D^0 \to K^0_S \eta'}$	$+0.98 \pm 0.67 \pm 0.14$

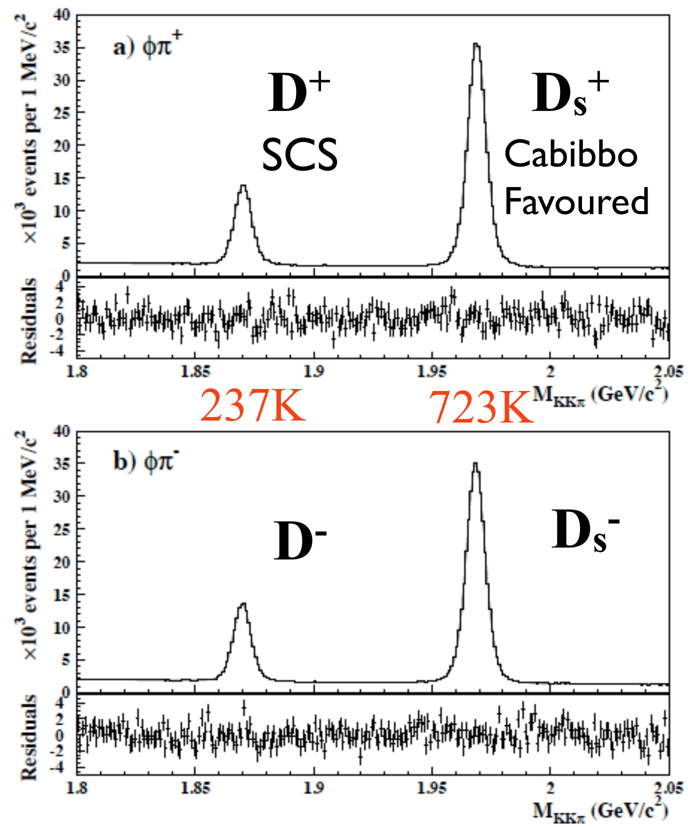
Source	$K^0_S\pi^0$ (%)	$K^0_S\eta$ (%)	$K^0_S\eta'$ (%)
$A_\epsilon^{\pi_s^+}$ determination	0.08	0.08	0.08
Fitting	0.02	0.12	0.10
$\cos\theta^{CMS}_{D^{*+}}$ binning	<0.01	0.01	0.03
$K^0/\bar{K}^0$-material effects	0.06	0.06	0.06
Total	0.10	0.16	0.14

Search for CP violation in SCS $D^+ \to \pi^+\eta^{(\prime)}$ and $D^+ \to \pi^+\phi$ decays

$D^+ \to \pi^+\eta$, $\eta \to \pi^+\pi^-\pi^0$ **$D^+ \to \pi^+\eta'$, $\eta' \to \pi^+\pi^-\eta_{\gamma\gamma}$**



$D^+ \to \pi^+\phi$, $\phi \to K^+K^-$



791 fb^{-1} **Phys. Rev. Lett. 107, 221801 (2011)**

$$A_{CP}^{D^+\to\pi^+\eta} = (+1.74 \pm 1.13 \pm 0.19)\%$$

$$A_{CP}^{D^+\to\pi^+\eta'} = (-0.12 \pm 1.12 \pm 0.17)\%.$$

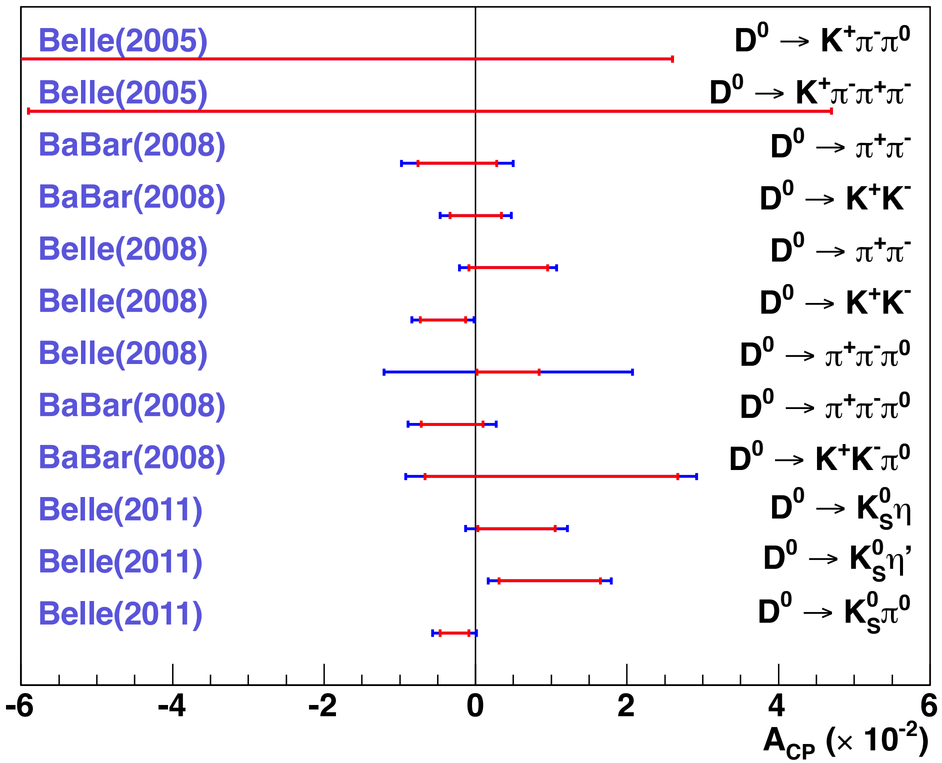
955 fb^{-1} arXiv:1110.0694v2

$$A_{CP}^{D^+\to\phi\pi^+} = (+0.51 \pm 0.28 \pm 0.05)\%$$

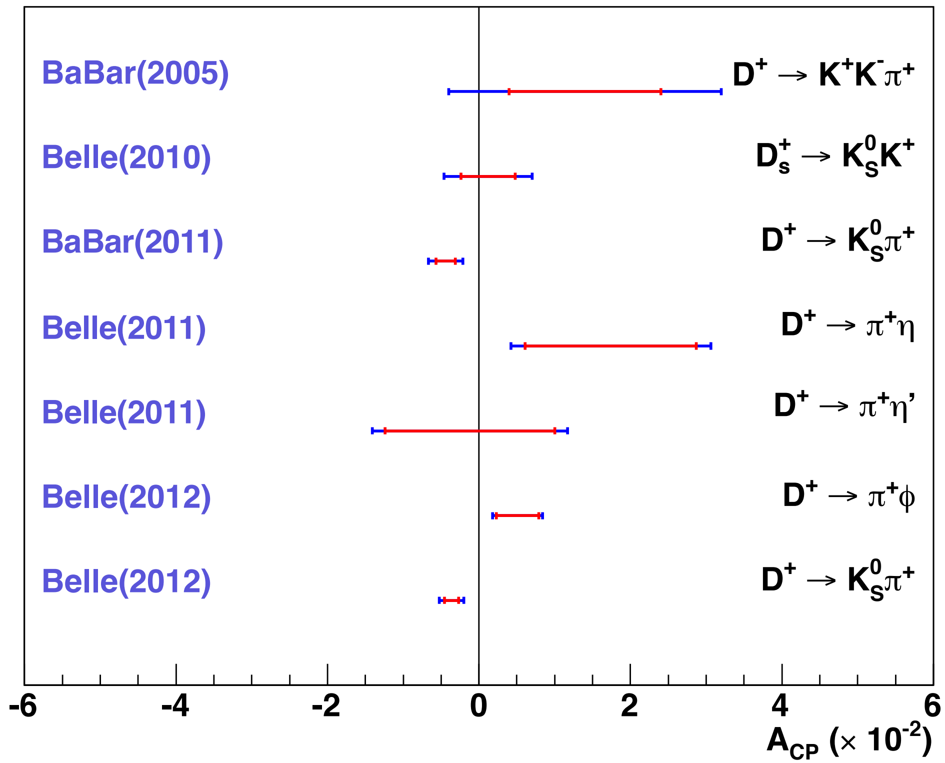
assuming no CPV in CF $D_s^+ \to \pi^+\phi$

Time-integrated CPV measurements at the B factories

D^0 modes: direct + indirect CPV



$D_{(s)}^+$ modes: direct CPV



At the B factories was found evidence of CP violation in $D^+ \to K_S^0\pi^+$ decays.
Systematic errors kept under control below the 10^{-3} level.

Search for CPV using T-odd correlations in $D_{(s)}^+ \to K^+ K_S \pi^+ \pi^-$ decays

***I.I. Bigi hep-ph/0107102** (2001)*

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)

- It is a measurement of T violation and of CP violation assuming CPT is conserved.
- T-odd observable: $C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$

$$A_T = \frac{\Gamma(D_{(s)}^+, C_T > 0) - \Gamma(D_{(s)}^+, C_T < 0)}{\Gamma(D_{(s)}^+, C_T > 0) + \Gamma(D_{(s)}^+, C_T < 0)}$$

measured on D^+

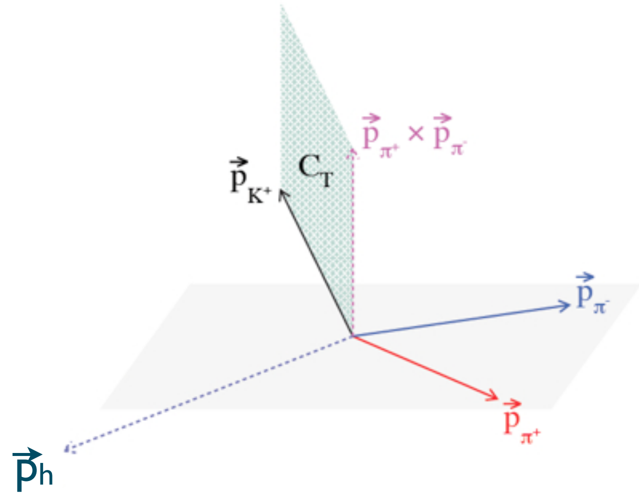
- Final state interaction (FSI) could introduce fake T-odd asymmetries $A_T \neq 0$.

- T-violating observable, removes FSI effects:

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

measured on D^-

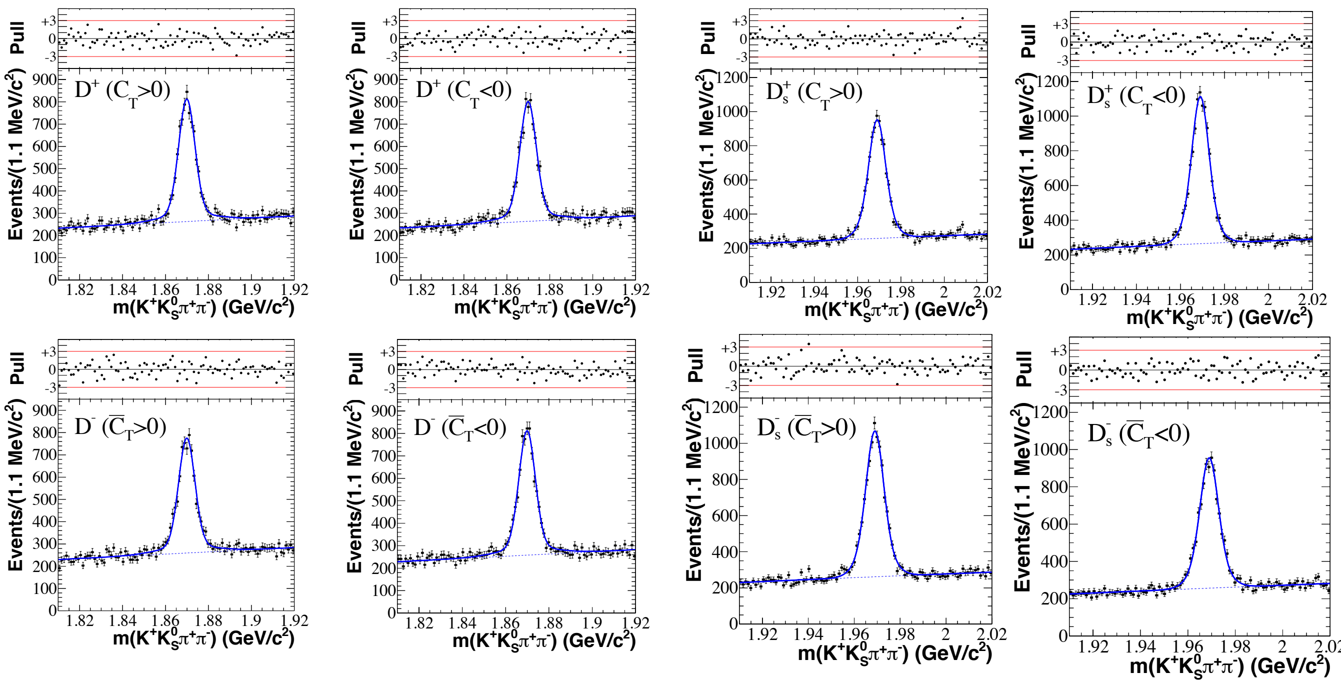
$D_{(s)}^+$ rest frame



$D^+ \to K^+ K_S \pi^+ \pi^-$ and $D_s^+ \to K^+ K_S \pi^+ \pi^-$ events

D^+ Fit projections in signal region *D_s^+*

520 fb^{-1}



Phys. Rev. D 84, 031103 (RC) (2011)

- Inclusive $D_{(s)}^+$ reconstruction;
- $p^*(D) > 2.5$ GeV/c;
- use data sidebands for bkg parameterization;
- 20,000 D^+ Cabibbo suppressed and 30,000 D_s^+ Cabibbo favored decays;

Systematic errors

x 10^{-3}

	$\mathcal{A}_T(D^+)$	$A_T(D^+)$	$\bar{A}_T(D^-)$	$\mathcal{A}_T(D_s^+)$	$A_T(D_s^+)$	$\bar{A}_T(D_s^-)$
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

Final results

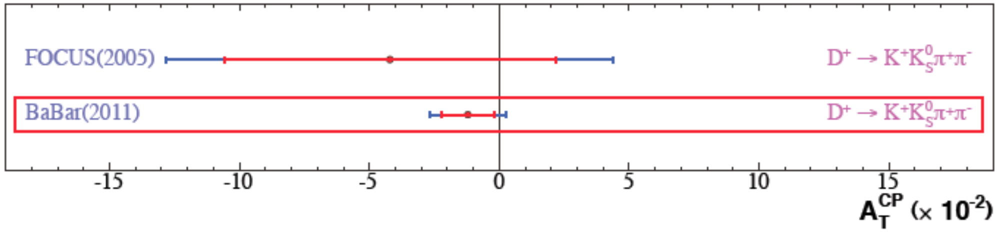
Phys. Rev. D 84, 031103 (RC) (2011) 520 fb^{-1}

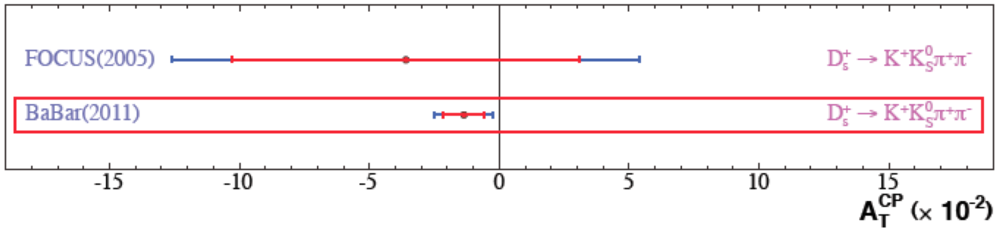
$$A_T(D^+) = (+11.2 \pm 14.1_{\rm stat} \pm 5.7_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(D^-) = (+35.1 \pm 14.3_{\rm stat} \pm 7.2_{\rm syst}) \times 10^{-3}$$
$$A_T(D_s^+) = (-99.2 \pm 10.7_{\rm stat} \pm 8.3_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{\rm stat} \pm 10.7_{\rm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

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

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

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





Conclusions

- Recent evidence of CPV in Charm decays has renewed the interest for searching for new physics in the Charm sector.
- The B factories are contributing in the understanding and possibly constraining the SM effects by measuring CPV observables and studying also decay modes that are not easily accessible at the LHC.
- An overview of the recent B factories results has been presented covering CP violation searches in Charm decays.
- Evidence of CPV in $D^+ \to K_S \pi^+$ was found at the B factories (3.2σ Belle, 2.9σ BaBar).
- Present results are in agreement with Standard Model expectations within the uncertainties.

Backup slides

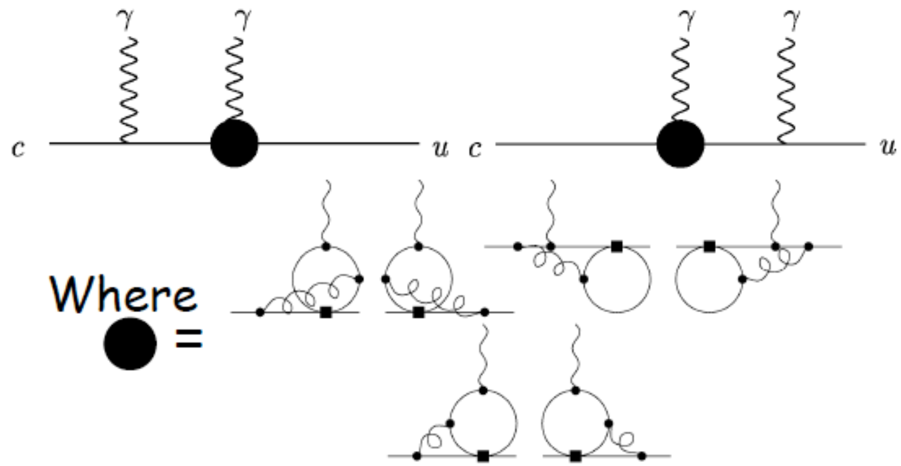
Physics motivations for studying $D^0 \to \gamma\gamma$ decay

- FCNC Decay
  - Forbidden at the tree-level
  - 1-loop GIM suppressed

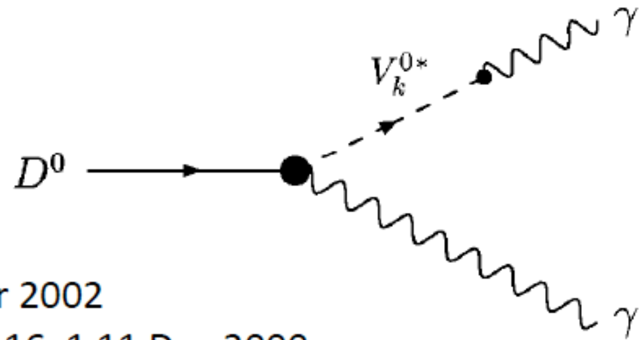
- Dominated by long distance effects [1]
  - Short-range (2-loop dominate):
    $B(D^0 \to \gamma\gamma) \approx 3 \times 10^{-11}$
  - Long-range (VMD contribution dominates):
    $B(D^0 \to \gamma\gamma) \approx 3.5 \times 10^{-8}$

- However, possible 10^2 enhancement from new physics (gluino-exchange of MSSM) [2]
- Within the range of BaBar sensitivity.
- Excellent (but difficult) mode to search for new physics

Short Distance



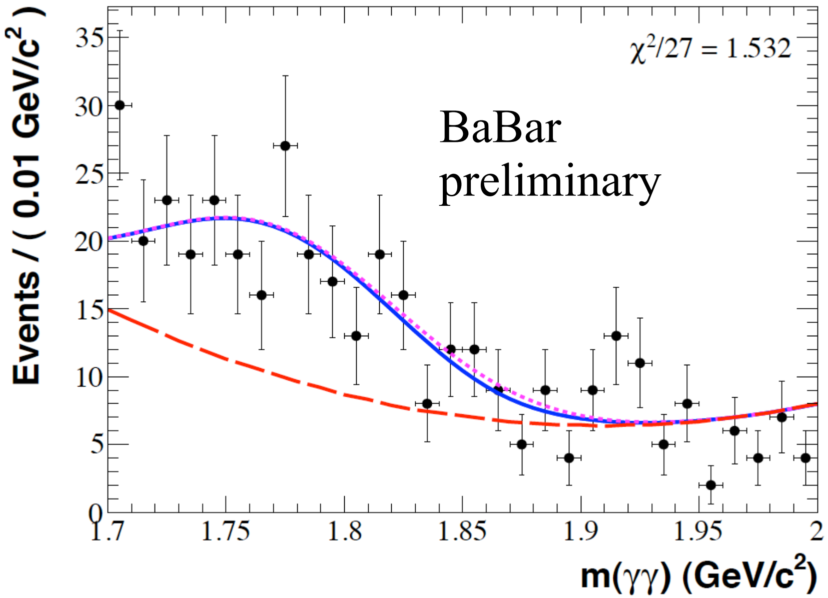
Long Distance

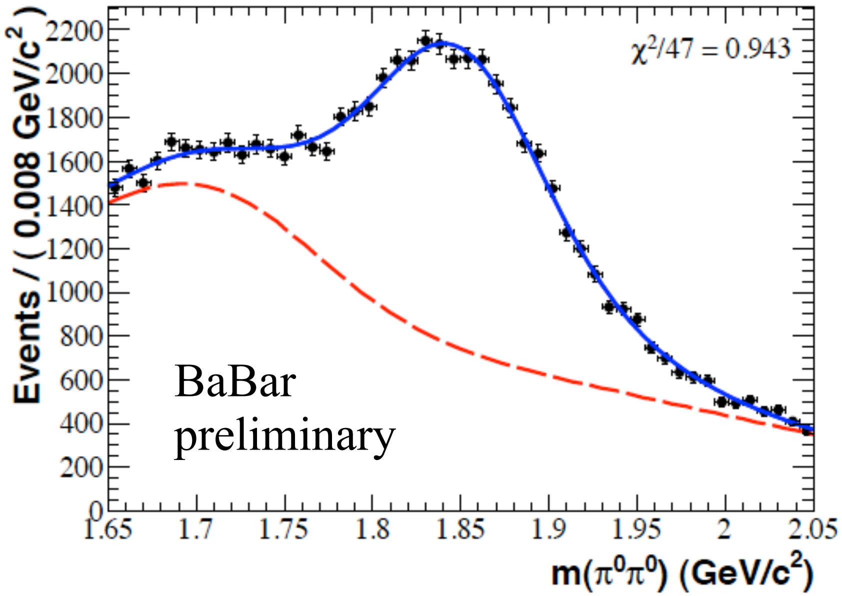


[1] Burdman et al. hep-ph/0112235v2 1 Mar 2002
[2] S. Prelovsek and D. Wyler, hep-ph/0012116v1 11 Dec 2000

Search for $D^0 \to \gamma\gamma$ and BR measurement of the $D^0 \to \pi^0\pi^0$ decay

arXiv:1110.6480v1 470.5 fb^{-1}





Use $D^0 \to K^0_S\pi^0$ as BR normalizing mode

Systematic	$\sigma(D^0 \to \gamma\gamma)$ (%)	$\sigma(D^0 \to \pi^0\pi^0)$ (%)
Tracking (K^0_S) and Vertexing	0.96	0.96
Photon Reconstruction	0.60	3.00
π^0 Veto	1.80	-
D^{*+} Fragmentation	0.02	0.03
Signal Shape	*	0.20
Background Shape	*	0.80
Cut selection	*	2.50
$D^0 \to K^0_s\pi^0$ Signal Shape	0.53	0.17
$D^0 \to K^0_s\pi^0$ Background Shape	0.01	0.63
$D^0 \to K^0_s\pi^0$ Cut selection	0.76	0.76
Total Systematic Uncertainty	*	4.23

$$B(D^0 \to \pi^0\pi^0) = (8.4 \pm 0.1 \pm 0.4 \pm 0.3) \times 10^{-4}$$

comparable precision with CLEO measurement

$$B(D^0 \to \gamma\gamma) < 2.4 \times 10^{-6}$$

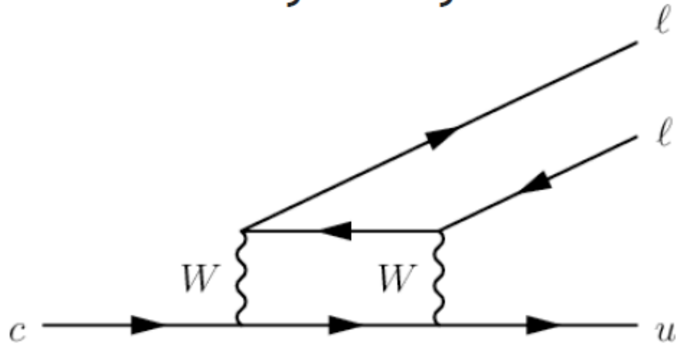
at the 90% confidence level.

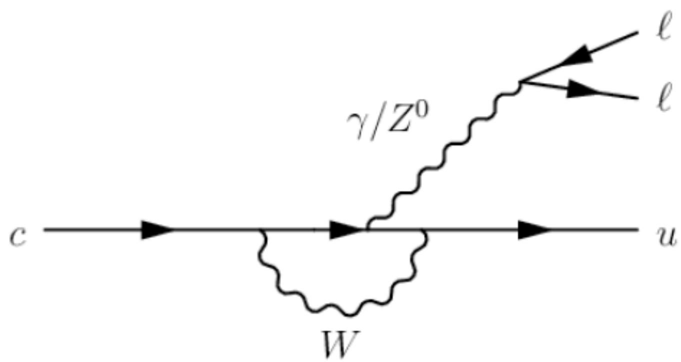
- About factor of 10 improvement on previous CLEO measurement

Physics interest in searching for FCNC decays

Search for Flavor-Changing Neutral-Current (FCNC) decays

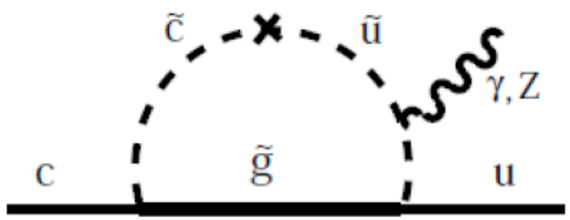
FCNC decays only occur in loop diagrams in SM:





Charm decays heavily GIM suppressed in SM: BF($c \to ull$)~10^{-8}

New physics can introduce new particles into loop



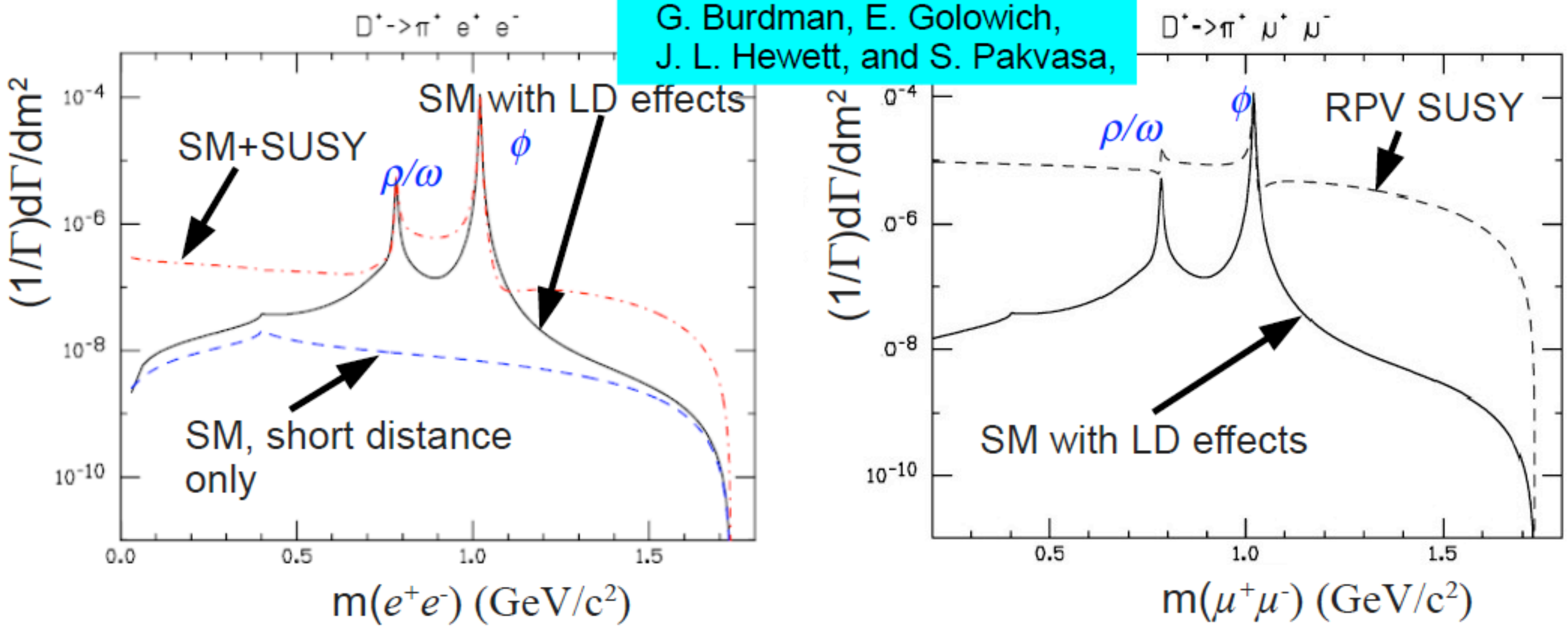
Some models increase BF($c \to ull$) to 10^{-6}–10^{-5}

Also look for exotic decays violating lepton flavor and/or lepton number

Standard Model predictions for signal and bkg

- While FCNC predicted to be low in SM, do have contribution from leptonic decays of intermediate resonances in $D_{(s)}^{+} \rightarrow h^{+}V,\ V \rightarrow l^{+}l^{-}$

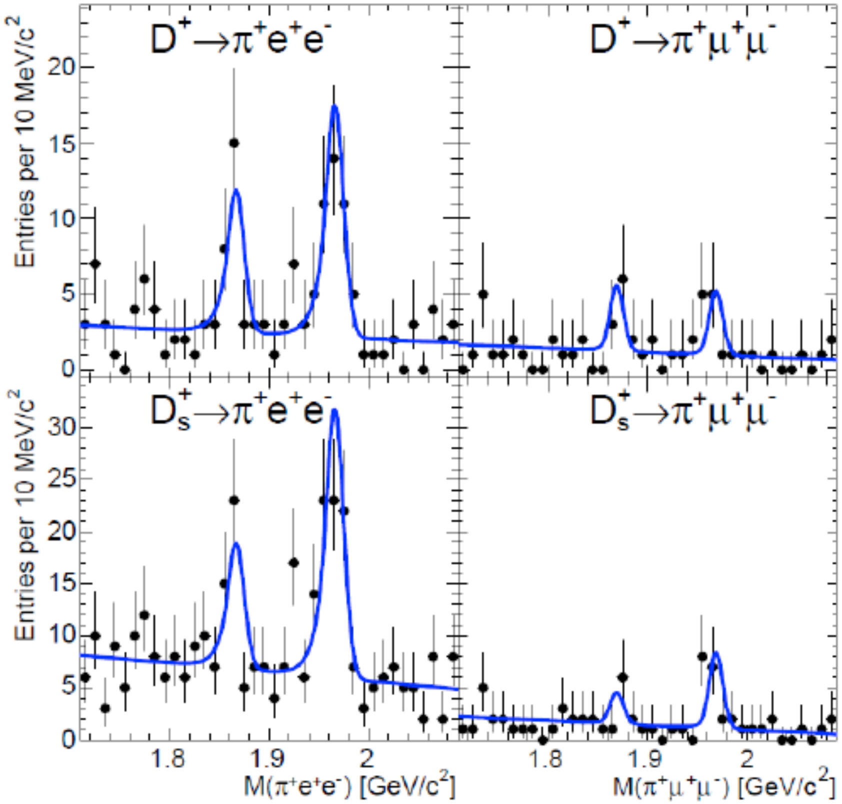
PRD 66, 014009 (2002)
G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa,



At current sensitivity, only ϕ resonance contributes
Can be removed by cut on $l^{+}l^{-}$ invariant mass

Validating the analysis using control modes

- Before unblinding, checked procedure using ϕ resonance
  - Reverse l^+l^- mass cut:
    $0.995 < m(e^+e^-) < 1.030$ GeV/c^2
    $1.005 < m(\mu^+\mu^-) < 1.030$ GeV/c^2
- Significant signal seen in 3 of 4 modes
- Yield is about as expected
  - 1.5σ low in $D_s^+ \to \pi\phi$, $\phi \to e^+e^-$



384 fb^{-1} **Phys. Rev. D 84, 07200 (2011)**

Decay mode	Yield (events)	Efficiency (%)	Expected yield (events)
$D^+ \to \pi^+\phi_{e^+e^-}$	$21.8 \pm 5.8 \pm 1.5$	5.65	22.2 ± 1.1
$D^+ \to \pi^+\phi_{\mu^+\mu^-}$	$7.5 \pm 3.4 \pm 1.4$	1.11	4.5 ± 0.4
$D_s^+ \to \pi^+\phi_{e^+e^-}$	$62.8 \pm 9.9 \pm 3.0$	6.46	79 ± 3
$D_s^+ \to \pi^+\phi_{\mu^+\mu^-}$	$12.7 \pm 4.3 \pm 2.6$	1.07	13.1 ± 1.2

Fit results and comparison with previous limits

- Most channels improve upon previous limits
  - Many modes by more than order of magnitude
  - Dimuon modes have the worst limits (lowest efficiency)

Decay mode	BF UL (10^{-6}) 90% CL	Previous limit	Experiment
$D^+ \to \pi^+ e^+ e^-$	1.1	5.9	CLEO-c
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5	3.9	D0
$D^+ \to \pi^+ e^+ \mu^-$	2.9	34	E791
$D^+ \to \pi^+ \mu^+ e^-$	3.6	34	E791
$D_s^+ \to \pi^+ e^+ e^-$	13	22	CLEO-c
$D_s^+ \to \pi^+ \mu^+ \mu^-$	43	26	FOCUS
$D_s^+ \to \pi^+ e^+ \mu^-$	12	610	E791
$D_s^+ \to \pi^+ \mu^+ e^-$	20	610	E791
$D^+ \to K^+ e^+ e^-$	1.0	3.0	CLEO-c
$D^+ \to K^+ \mu^+ \mu^-$	4.3	9.2	FOCUS
$D^+ \to K^+ e^+ \mu^-$	1.2	68	E791
$D^+ \to K^+ \mu^+ e^-$	2.8	68	E791
$D_s^+ \to K^+ e^+ e^-$	3.7	52	CLEO-c
$D_s^+ \to K^+ \mu^+ \mu^-$	21	36	FOCUS
$D_s^+ \to K^+ e^+ \mu^-$	14	630	E791
$D_s^+ \to K^+ \mu^+ e^-$	9.7	630	E791
$\Lambda_c^+ \to p e^+ e^-$	5.5	340	E653
$\Lambda_c^+ \to p \mu^+ \mu^-$	44		
$\Lambda_c^+ \to p e^+ \mu^-$	9.9		
$\Lambda_c^+ \to p \mu^+ e^-$	19		

New results

Decay mode	BF UL (10^{-6}) 90% CL	Previous limit	Experiment
$D^+ \to \pi^- e^+ e^+$	1.9	1.1	CLEO-c
$D^+ \to \pi^- \mu^+ \mu^+$	2.0	4.8	FOCUS
$D^+ \to \pi^- \mu^+ e^+$	2.0	50	E791
$D_s^+ \to \pi^- e^+ e^+$	4.1	18	CLEO-c
$D_s^+ \to \pi^- \mu^+ \mu^+$	14	29	FOCUS
$D_s^+ \to \pi^- \mu^+ e^+$	8.4	730	E791
$D^+ \to K^- e^+ e^+$	0.9	3.5	CLEO-c
$D^+ \to K^- \mu^+ \mu^+$	10	13	FOCUS
$D^+ \to K^- \mu^+ e^+$	1.9	130	E687
$D_s^+ \to K^- e^+ e^+$	5.2	17	CLEO-c
$D_s^+ \to K^- \mu^+ \mu^+$	13	13	FOCUS
$D_s^+ \to K^- \mu^+ e^+$	6.1	680	E791
$\Lambda_c^+ \to \bar{p} e^+ e^+$	2.7		
$\Lambda_c^+ \to \bar{p} \mu^+ \mu^+$	9.4		
$\Lambda_c^+ \to \bar{p} \mu^+ e^+$	16		

New results

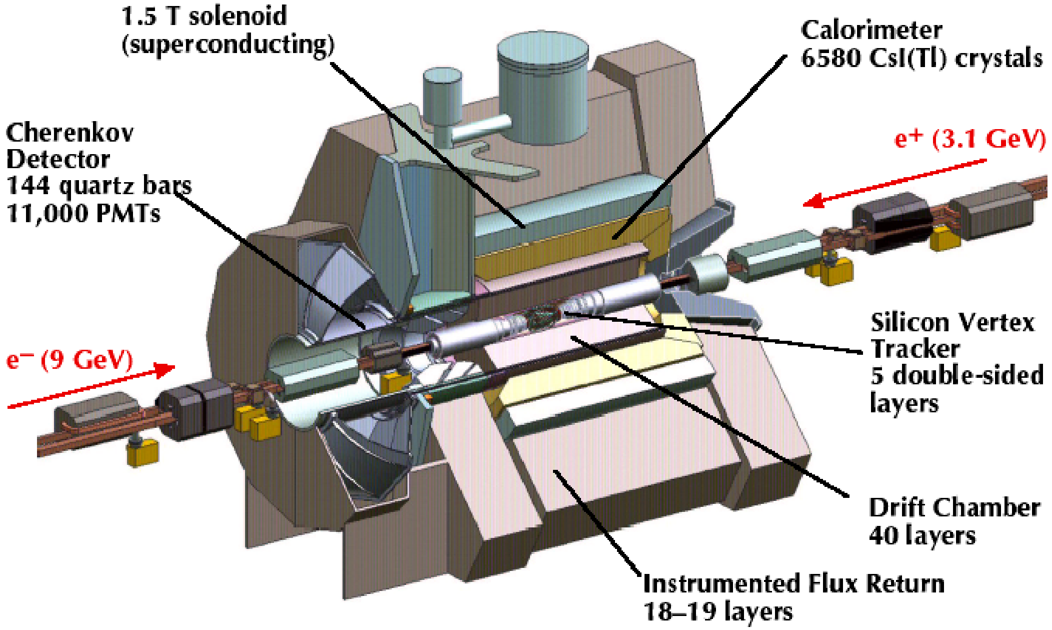
Phys. Rev. D 84, 07200 (2011) 384 fb^{-1}

New Limits approach theoretically interesting region

The BaBar experiment

PEP-II is an asymmetric-energy B factory at SLAC running mostly at the $\Upsilon(4S)$ (10.58 GeV) with a center-of-mass boost with $\beta\gamma=0.55$

The BaBar Detector



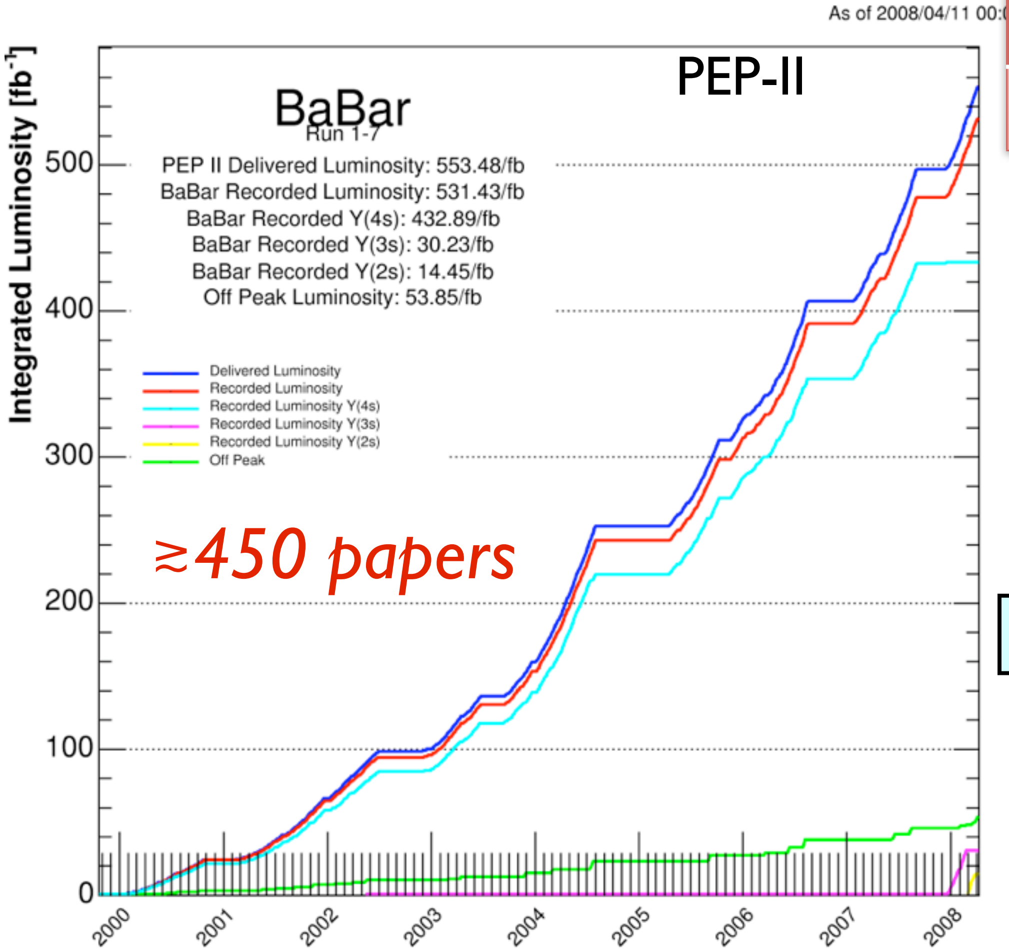
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T\ +\ 0.45\ \%$, $\sigma(z_0)$=65 μm@ 1GeV/c

DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

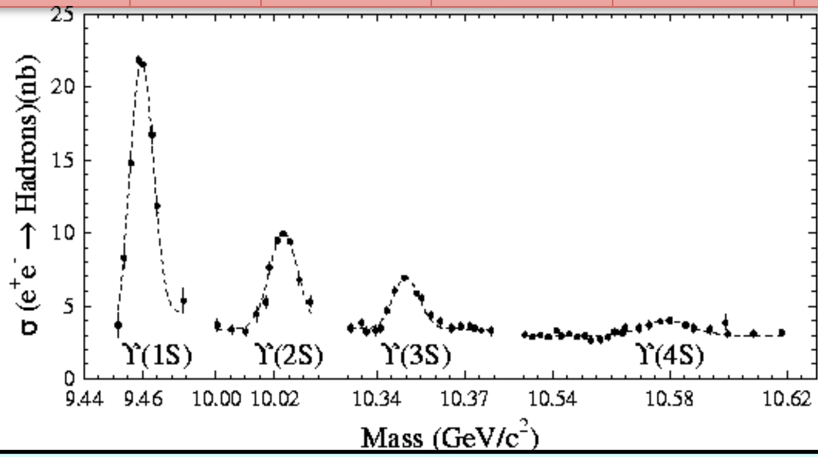
The BaBar dataset



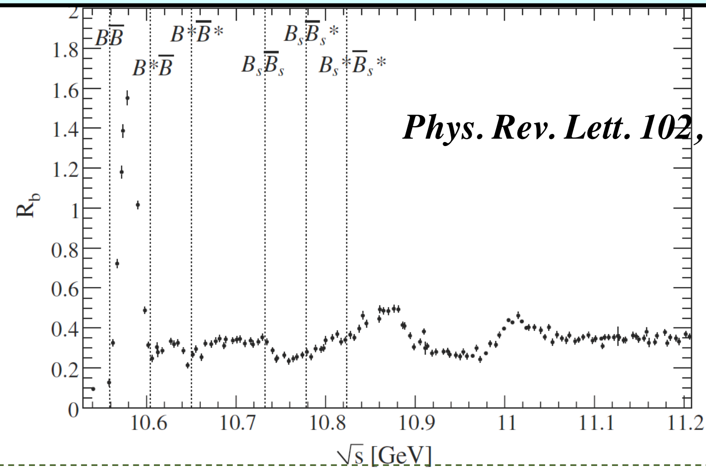
≳450 papers

Recorded luminosity ~530 fb^{-1}
Peak luminosity ~12x10^{33} cm^{-2}s^{-1}

	Υ(1S)	Υ(2S)	Υ(3S)	Υ(4S)	Υ(5S)
BaBar	-	14 fb^{-1}	30 fb^{-1}	433 fb^{-1}	-



Offpeak (10.54GeV) + Scan above Υ(4S): 53.9 fb^{-1}



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