UNIVERSITAT DE BARCELONA

BABAR

Searches for Rare & Forbidden B and Charm decays with BaBar

Eugeni Graugés

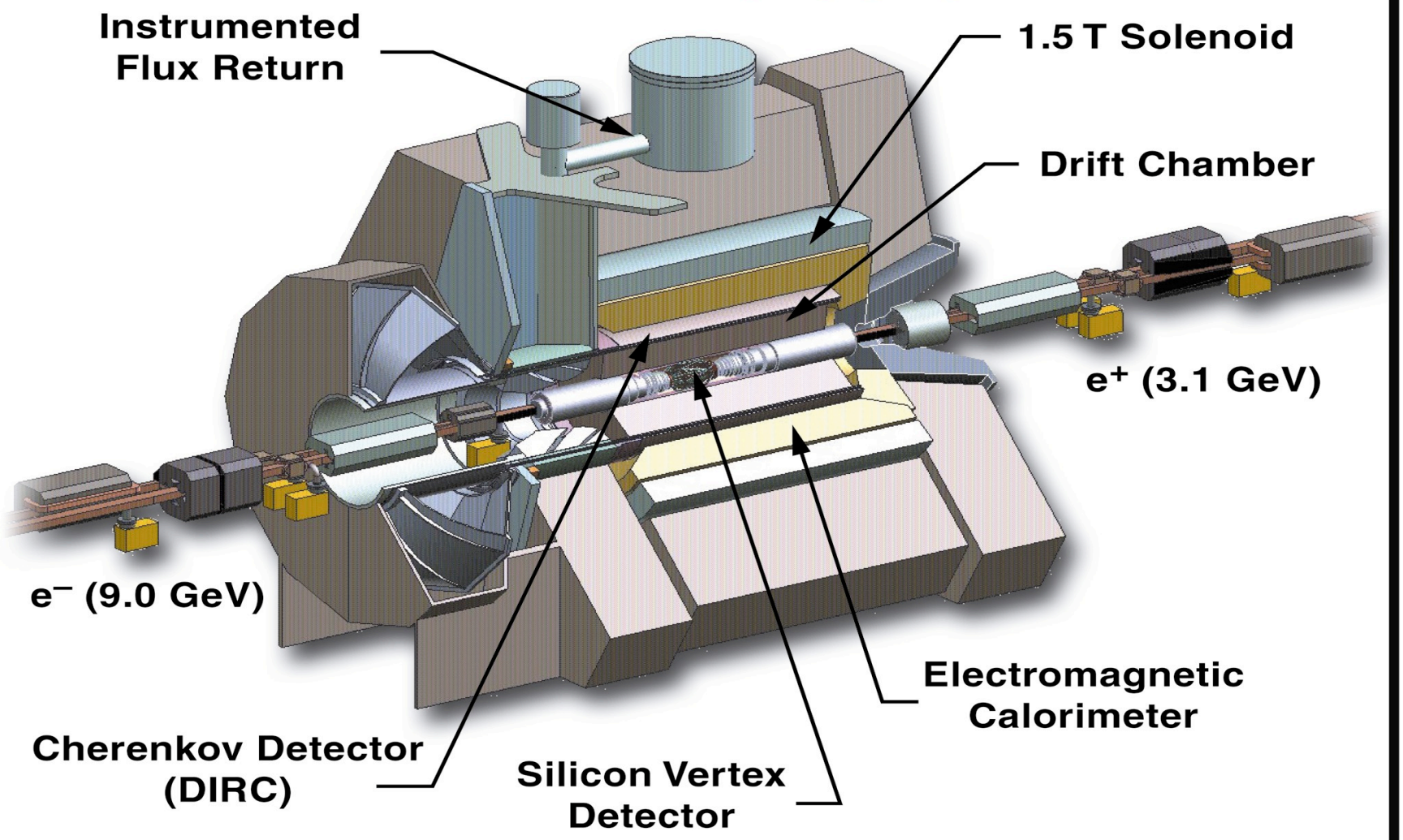
Universitat de Barcelona

Europhysics Conference On High Energy Physics: EPS- HEP2011

Outline:

- The BaBar Detector & Dataset
- B Physics
  - $B \rightarrow \gamma\gamma$
  - $B \rightarrow \Lambda_{(c)}\, \ell^-$
  - $B \rightarrow K\upsilon\upsilon$
- Charm Physics
  - $D \rightarrow \gamma\gamma$
  - $X_c \rightarrow h\, \ell^+\ell^-$
- Conclusions

BABAR Detector



Dataset:

530/fb recorded in 9 years of operation :

~470M BB pairs but also:

7 x (Belle + Cleo) ϒ(3s)

0.5 x (Belle + Cleo) ϒ(2s)

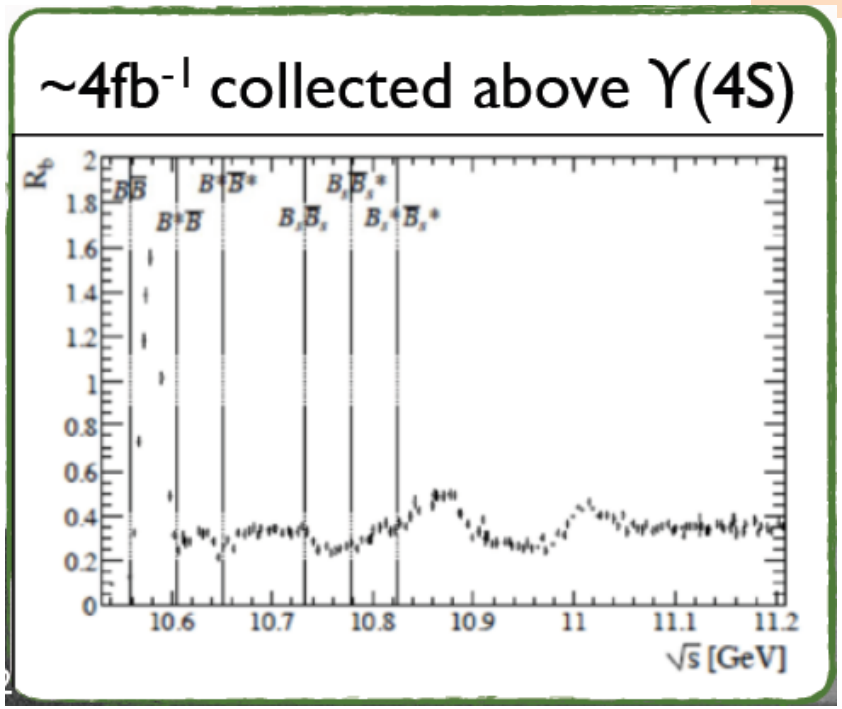
Not only BB pairs:

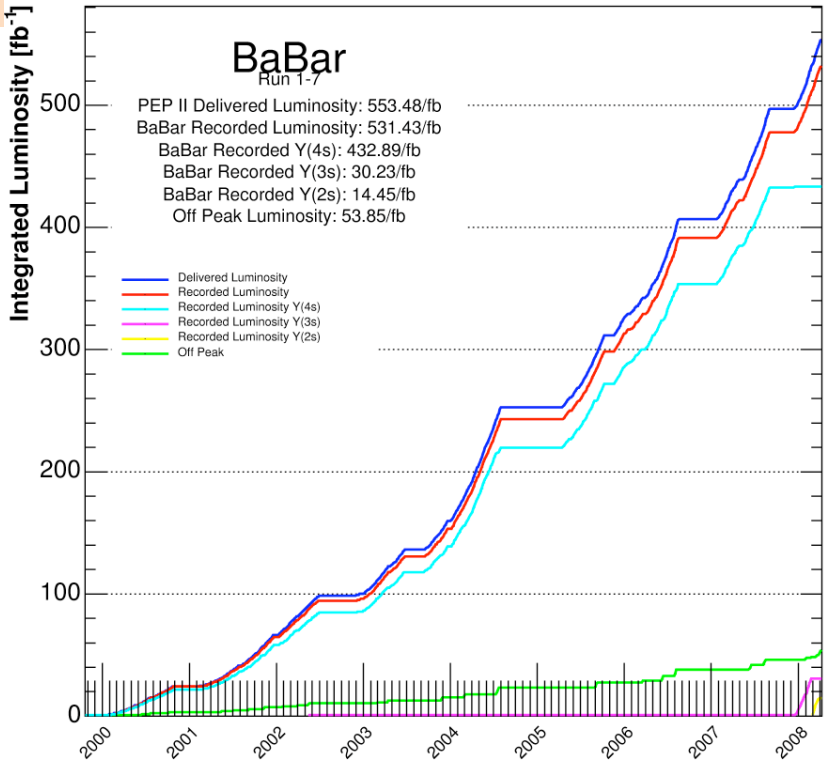
690M cc pairs

500M τ τ pairs

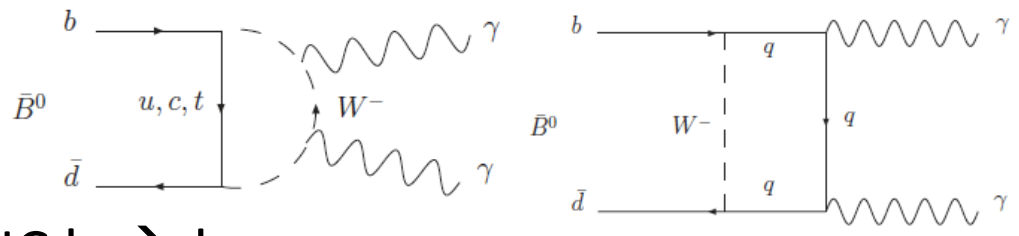
sample	fb^{-1}
$\Upsilon(4S)$	430
$\Upsilon(3S)$	30.2
$\Upsilon(2S)$	14.5
Off-$\Upsilon(nS)$	54

As of 2008/04/11 00:00





$B \rightarrow \gamma\gamma$



- $B \rightarrow \gamma\gamma$ is an effective FCNC $b \rightarrow d\gamma\gamma$
- Process supressed due to additional CKM and EM vertex factors: @L.O. SM BF ~$3.1^{+6.4}_{-1.6} \times 10^{-8}$ [JHEP0208:54 (2002)]
- Different NP scenarios can enhance the BF
  - Extended Higgs sector: PRD58,095014(1998)
  - Susy with broken R-parity: PRD70,0355008 (2004)

– Previous measurements:

Experiment	B($B \rightarrow \gamma\gamma$)	Dataset	Ref.
L3	$< 1.9 \times 10^{-5}$	2.95×10^6 ($Z \rightarrow$had)	Acciarri et al. Phys. Lett. B, 363, 1995
BaBar	$< 1.7 \times 10^{-6}$	19 fb^{-1}	Aubert et al. PRL 87, 24, 2001
Belle	$< 6.1 \times 10^{-7}$	104 fb^{-1}	Villa et al. PRD 73, 2006

$B \to \gamma\gamma$

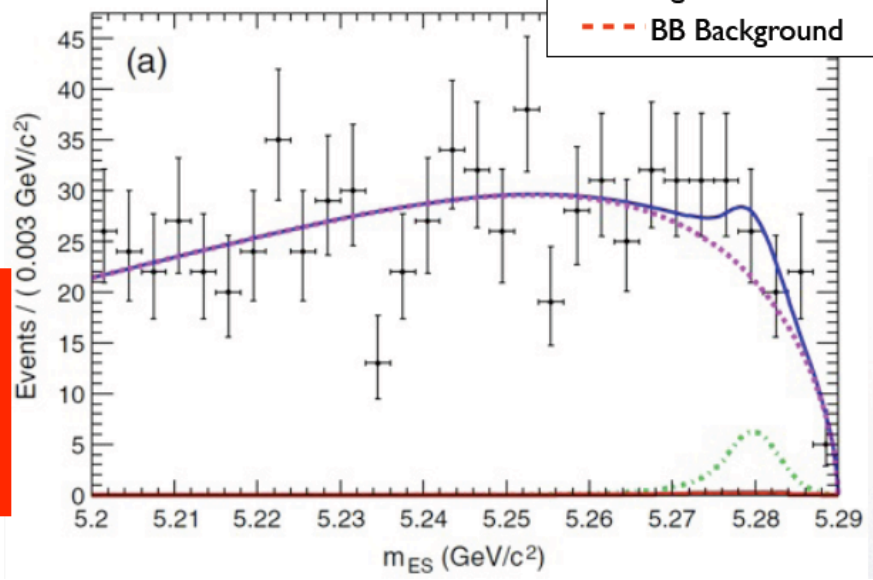
Phys. Rev. D 83, 032006 (2011)
467M BB pairs

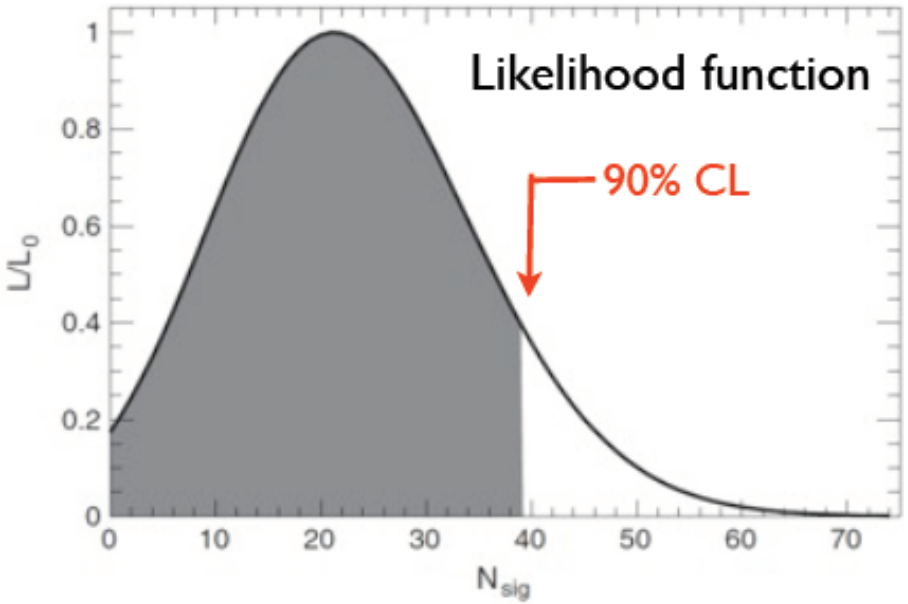
- 2-D likelihood fit to m_{ES} and ΔE
- Signal Yield: $21\ ^{+12.8}_{-11.8}$ events

Measured BF x 10^{-7}: (1.9σ sig)

$$B(B \to \gamma\gamma) = (1.7 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}})$$

$$m_{ES} = \sqrt{E^{*2}_{\text{beam}} - p^{*2}_{B}}$$





Upper limit:

$$B(B \to \gamma\gamma) < 3.3 \times 10^{-7} \text{ at } 90\%\ \text{CL}$$

$B \rightarrow \Lambda_{(c)}\, \ell^-$ $(\ell = \mu, e)$

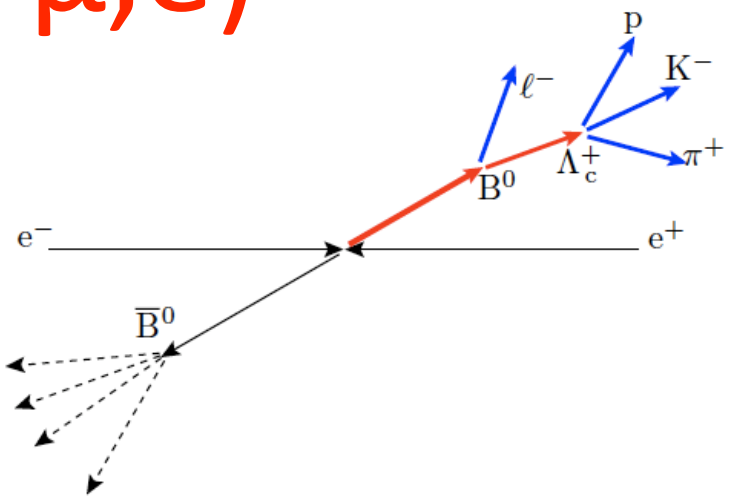
Phys. Rev. D 83, 091101(R) (2011)

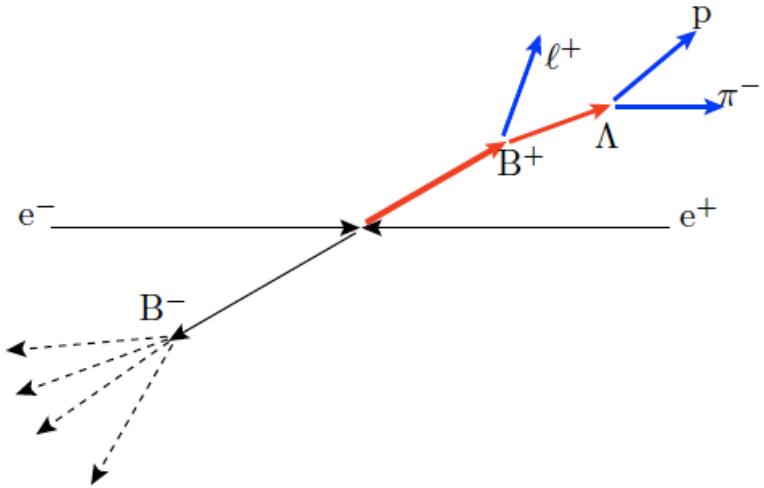
arXiv:1101.3830v2 [hep-ex

- An explanation for matter-Antimatter universe asymmetry would require:
  - CP violation (CPV)
  - Baryon number violation (BNV)
- Are there any extra sources of CPV… or BNV?
- BNV searches in B decays:
  - $B^0 \rightarrow \Lambda^+_c\, \ell^-$ where the $\Lambda^+_c \rightarrow \mathbf{p}K^-\pi^+$

    BF ($B^0 \rightarrow \Lambda^+_c\, \ell^-$) < 4×10^{-29}

    [PRD 72, 095001, 2005]
  - $B^- \rightarrow \Lambda^0\, \ell^-$ where the $\Lambda^0 \rightarrow \mathbf{p}\pi^-$
  - $B^- \rightarrow \Lambda^0$-bar ℓ^- where the Λ^0-bar $\rightarrow$ **p-bar** π^+

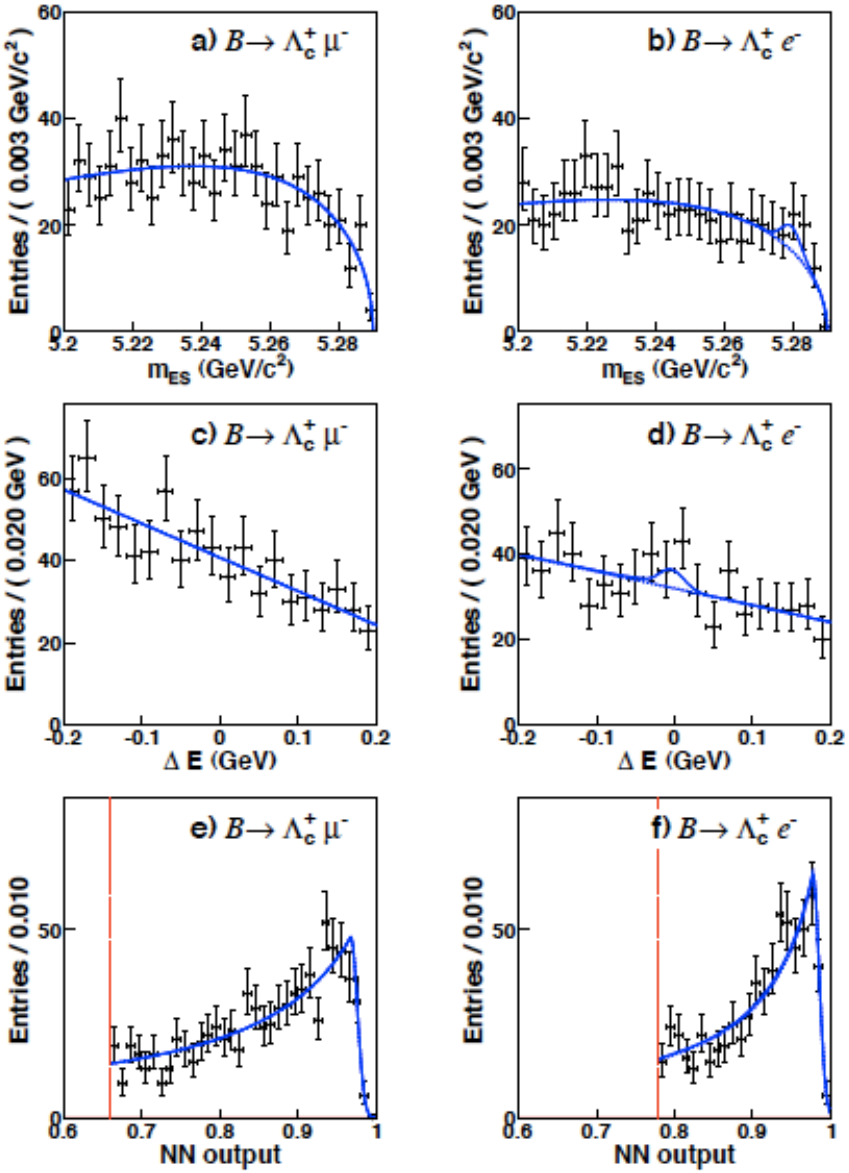




$B \to \Lambda_{(c)} \ell^-$

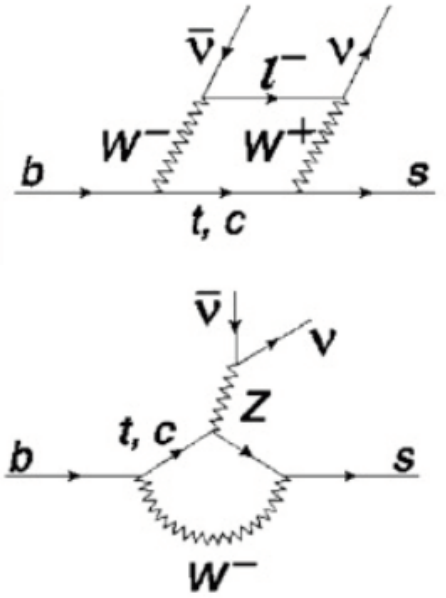
- Dataset: 429/fb @ Y(4s) (~470M BB pairs)
- Blind analysis
- Unbinned extended likelihood fit to get the signal yield
- 2D PDF in $m_{ES}/\Delta E$ plane (3D with TMVA output for Λ_c decay modes)
- Background e+e-→e+e-γ (γ→e+e-) rejected requiring more than 4 ch. trks in the event.
- Some BB and continuum irreducible background after selection

Decay mode	$N_{\rm cand}$	$\mathcal{B}$ $(\times 10^{-8})$	ϵ (%)	$\mathcal{B}_{90\%}$ $(\times 10^{-8})$
$B^0 \to \Lambda_c^+ \mu^-$	814	-4^{+71}_{-56}	26.3 ± 0.9	180
$B^0 \to \Lambda_c^+ e^-$	651	190^{+130}_{-90}	25.7 ± 0.7	520
$B^- \to \Lambda \mu^-$	320	$-2.3^{+3.5}_{-2.5}$	28.7 ± 0.9	6.2
$B^- \to \Lambda e^-$	194	$1.2^{+3.7}_{-2.6}$	27.2 ± 0.6	8.1
$B^- \to \bar{\Lambda} \mu^-$	192	$1.5^{+2.6}_{-1.7}$	31.3 ± 1.0	6.1
$B^- \to \bar{\Lambda} e^-$	74	$-0.9^{+0.7}_{-0.0}$	30.0 ± 0.6	3.2



B → Kνν

- b→s FCNC transition analogous to B →Kl^+l^-, and so sensitive to NP
- Small SM BF ~3.8 x 10^{-6}
- Some NP models predict BF up to a factor 10 larger



Previous Upper limits on BF

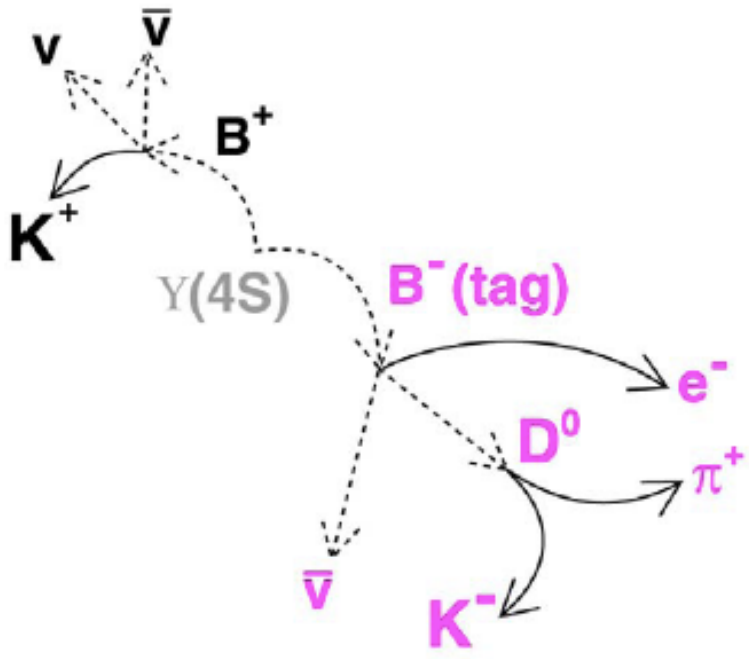
Mode	Upper Limit (90% CL)	Experiment	Dataset (fb^{-1})	Reference
$B^+ \to K^+\nu\nu$	1.4 x 10^{-5}	Belle	492	PRL 99, 221802 (2007)
$B^+ \to K^+\nu\nu$	5.2 x 10^{-5}	BaBar	82	PRL 94, 101801 (2005)
$B^0 \to K^0\nu\nu$	1.6 x 10^{-4}	Belle	492	PRL 99, 221802 (2007)

B → Kνν

- Few kinematic handles to reconstruct B →Kνν

→Reconstruct the "other B" in the event in *semileptonic* B decay

- Look for signal decay among remaining particles of the event



$$
\begin{aligned}
D &\rightarrow K^-\pi^+, K^-\pi^+\pi^-, K^-\pi^+\pi^0, K^0_S\pi^+, K^0_S\pi^+\pi^- \\
D^{*+} &\rightarrow D^0\pi^+ \\
D^{*0} &\rightarrow D^0\pi^0
\end{aligned}
$$

B → Kνν

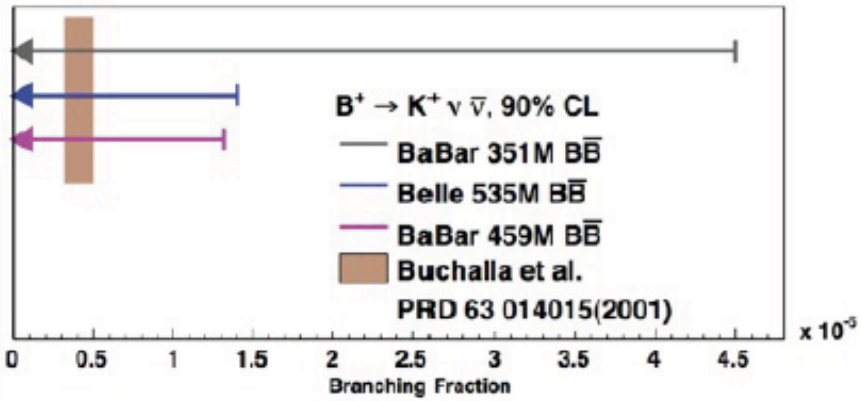
Observed events

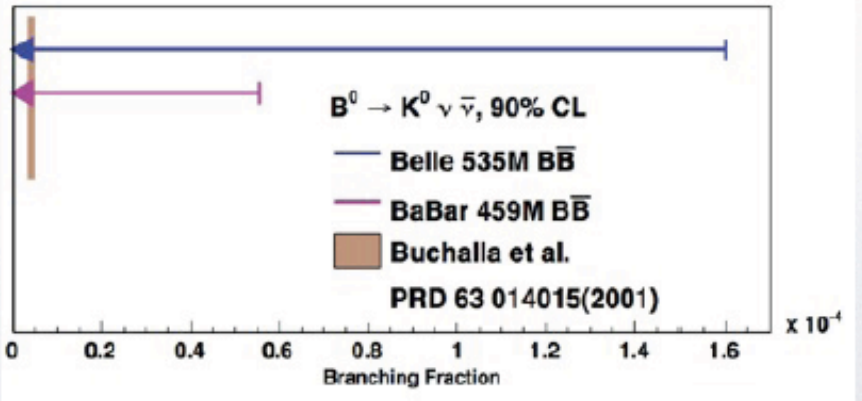
N_{obs} - N_{BG}

Mode	N_{obs}	N_{excess}
K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$
K^0	$6.1^{+4.0}_{-2.2}$	$2.2^{+4.1}_{-2.8}$
low-q^2 K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$
high-q^2 K^+	164^{+13}_{-13}	-23^{+49}_{-48}

Upper limits

Mode	BF	90% CL	95% CL
	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$
K^+	$0.2^{+0.8}_{-0.7}$	1.3	1.6
K^0	$1.7^{+3.1}_{-2.1}$	5.6	6.7
Comb. K^+, K^0	$0.5^{+0.7}_{-0.7}$	1.4	1.7
Low-q^2 K^+	$0.2^{+0.6}_{-0.5}$	0.9	1.1
High-q^2 K^+	$-1.8^{+3.8}_{-3.8}$	3.1	4.6





Best limits achieved to date

Phys. Rev. D **82**, 112002 (2010)

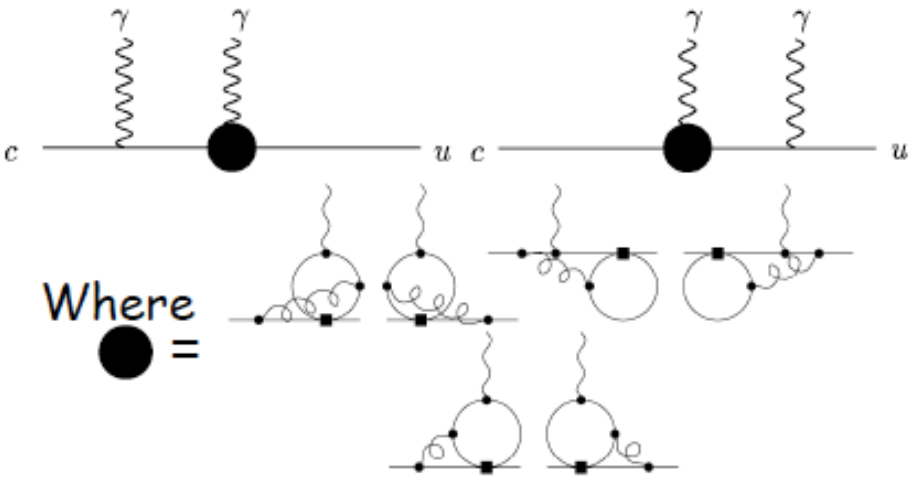
$D \to \gamma\gamma$

- FCNC, GIM-suppressed charm loop diagrams:

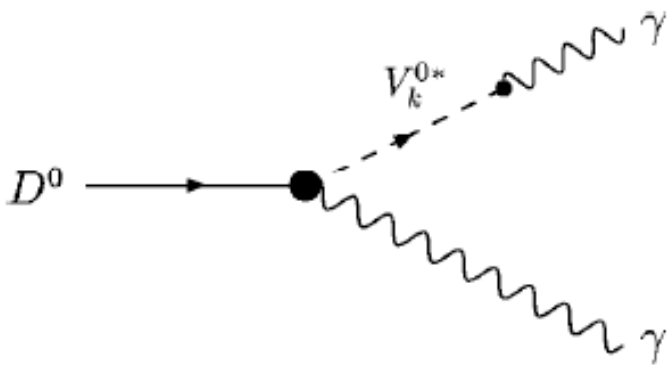
Look for NP contributing into the loops

SM dominated by long distance contributions (PR D66, 014009, 2002)

Short Distance



Long Distance



Mode	Value
$D^0 \to \gamma\gamma$ (SM,VMD)	$\approx (3.5\ ^{+4.0}_{-2.6}) \times 10^{-8}$
$D^0 \to \gamma\gamma$ (SM,HQχPT)	$(1.0 \pm 0.5) \times 10^{-8}$
$D^0 \to \gamma\gamma$ (MSSM)	6×10^{-6}

Experimental results

Mode	Value
$D^0 \to \gamma\gamma$	$< 2.7 \times 10^{-5}$
$D^0 \to \pi^0\pi^0$	$(8.0 \pm 0.8) \times 10^{-4}$
$D^0 \to K_s^0\pi^0$	$(1.22 \pm 0.05) \times 10^{-2}$

D → γγ

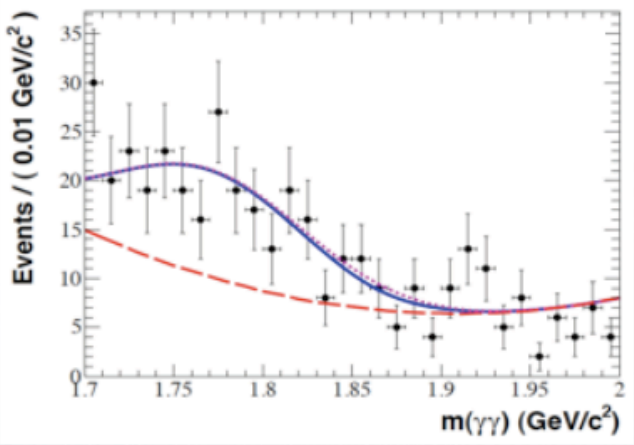
Comb bkg
Comb bkg + D0 →$\pi^0\pi^0$
Comb bkg + D0 →$\pi^0\pi^0$ + signal
data

Preliminary, 407.5 fb^{-1}

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

x 10 improvement wrt PDG

$D^0 \to \gamma\gamma$

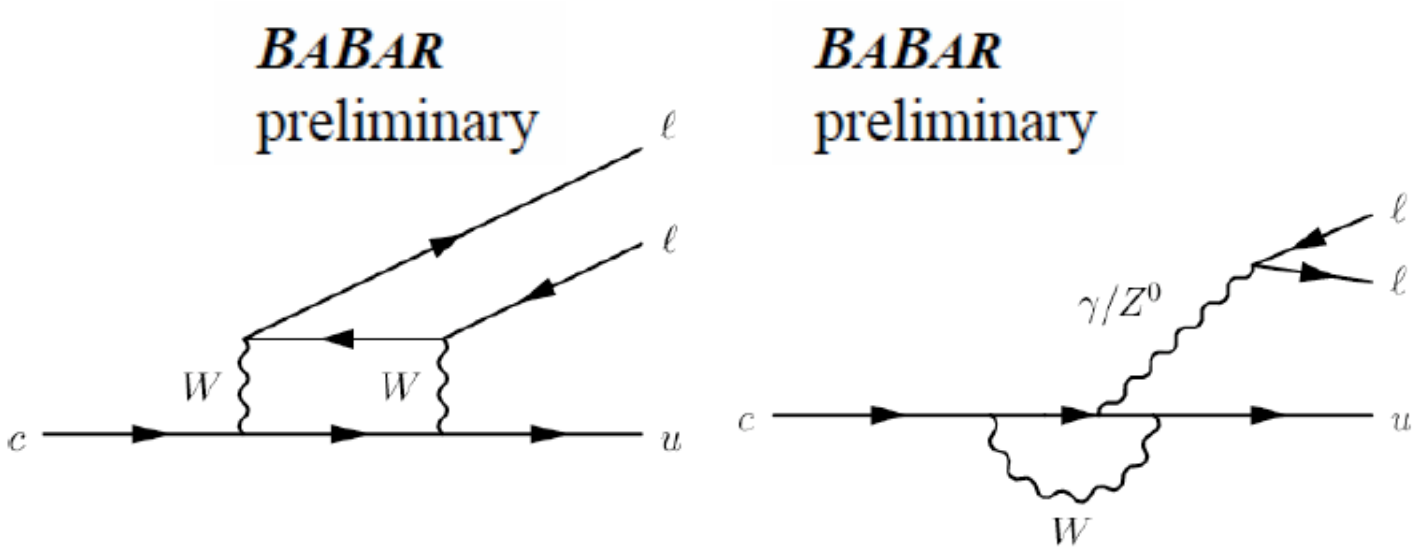


N_{sig} = -6 ±15

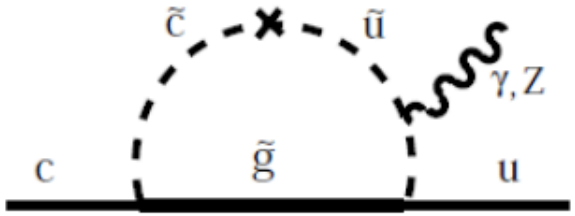
Main systematics from neutral pion veto

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

$X_c \rightarrow h \ell^+\ell^-$



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



➔➔➔➔

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

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

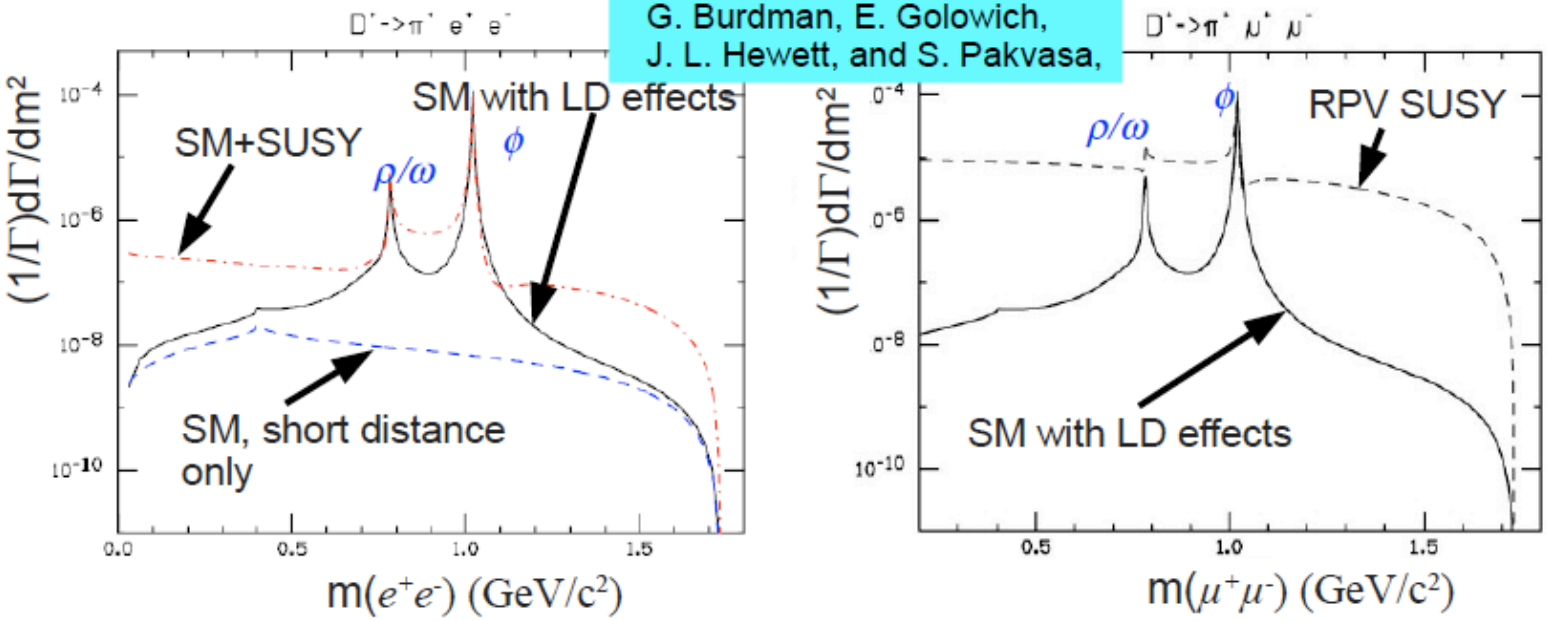
3

$X_c \rightarrow h \ell^+\ell^-$

Predictions and Resonance Bkgd

- 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

$X_c \rightarrow h\,\ell^+\ell^-$

- 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		
$D^+ \to \pi^+ e^+ e^-$	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		

Decay mode	BF UL (10^{-6}) 90% CL		
$D^+ \to \pi^- e^+ e^+$	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		

BABAR
preliminary

Conclusions:

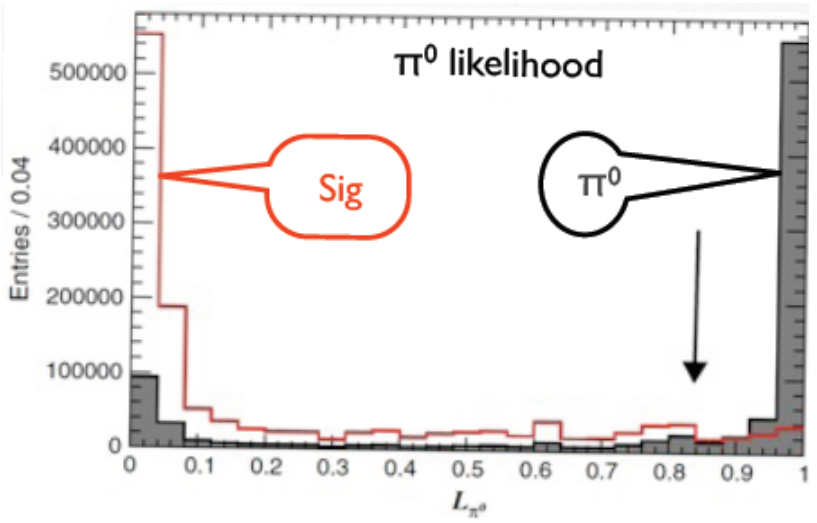
- BaBar stopped taking data in 2008, but the available dataset is still a very rich and fruitful playground for physics analysis.
- BaBar was not only a B-factory, but also a charm (tau) factory (and a much more: isr, etc…)
- Beauty and Charm sectors are a very appealing place to look for FCNC, LFV, BNV modes that could reveal NP beyond the SM:
  - $B \rightarrow \gamma\gamma$ BF upper limit lowered a factor 2
  - No evidence of BNV found in the search for $B \rightarrow \Lambda_{(c)}\, \ell^-$
  - The UL on $B \rightarrow K\upsilon\upsilon$ down to 10^{-5} level for both channels
  - The $D \rightarrow \gamma\gamma$ improved 1 order of magnitude down to 10^{-6}
  - Most $X_c \rightarrow h\, \ell^+\ell^-$ channels BF UL also down by 1 order of magnitude

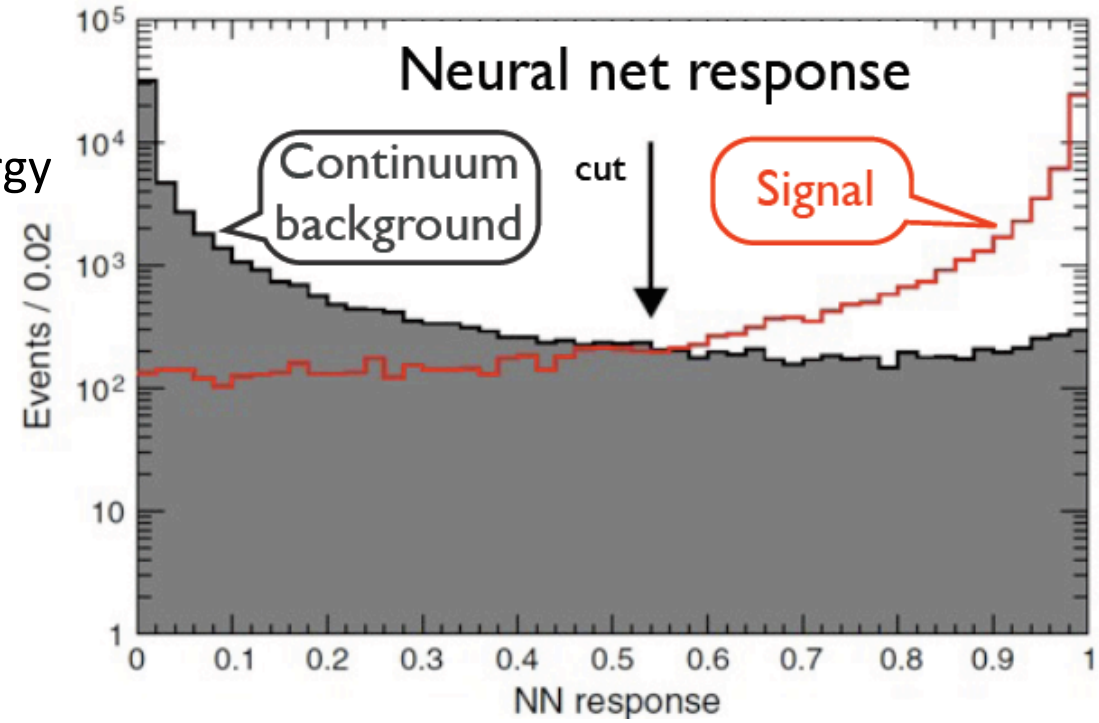
BACKUP

B → γγ

B→γγ background sources:

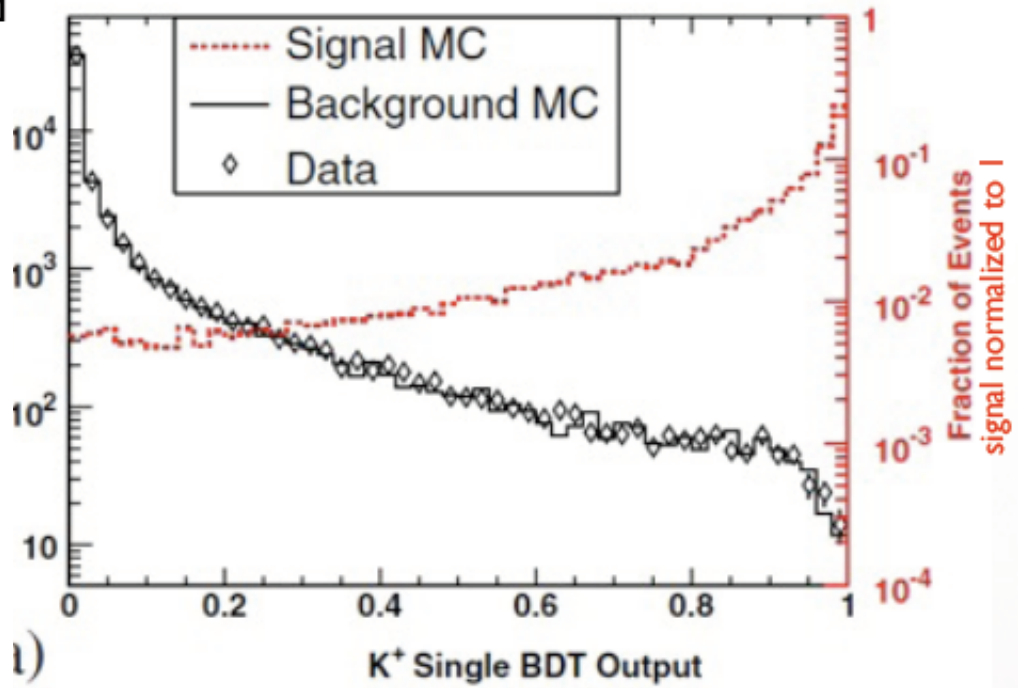
- Decays of π^0 and η's
  - Rejected with Likelihood ratio based on m(γγ') and Eγ'
- Out-of-time Bhabha event overlap
  - Rejected with total energy and timing cuts
- Generic continuum events
  - Multivariate classifier (NN) based on 19 input variables





B → Kνν

- Suppress high remaining background using multivariate classifier: Bagged Decision Trees (BDT)
- Ensemble of BDTs trained on simulated signal and background events
- Trees use 26 (K^+) or 38 (K^0) variables relating to i) *missing energy*, ii) *event shape*, iii) *signal kinematics* and iv) *quality of reconstructed tag*
- Selection optimized for signal significance: $s/(s+b)^{1/2}$



Expected events

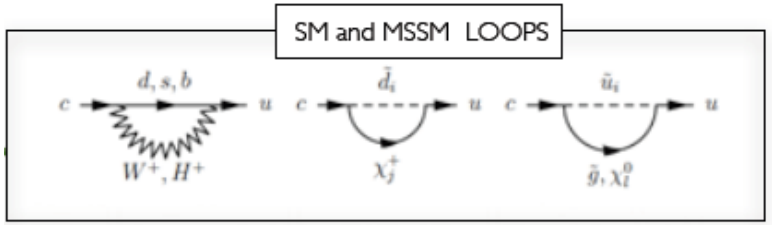
Mode	ϵ (in %)	N_{sgnl}	N_{bkgd}
K^+	0.16	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$
K^0_S	0.06	0.5 ± 0.1	$3.9 \pm 1.3 \pm 0.4$
low-q^2 K^+	0.24	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$
high-q^2 K^+	0.28	2.1 ± 0.3	$187 \pm 10 \pm 46$

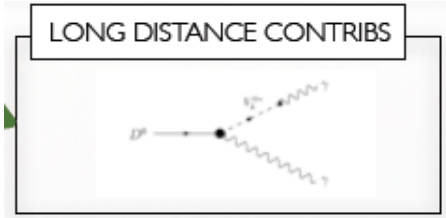
D → γγ

- FCNC, GIM-suppressed charm loop diagrams:

SM dominated by long distance contributions (PR D66, 014009, 2002)

Look for NP contributing into the loops





Mode	Value
$D^0 \to \gamma\gamma$ (SM,VMD)	$\approx (3.5\ ^{+4.0}_{-2.6}) \times 10^{-8}$
$D^0 \to \gamma\gamma$ (SM,HQχPT)	$(1.0 \pm 0.5) \times 10^{-8}$
$D^0 \to \gamma\gamma$ (MSSM)	6×10^{-6}

Experimental results

Mode	Value
$D^0 \to \gamma\gamma$	$< 2.7 \times 10^{-5}$
$D^0 \to \pi^0\pi^0$	$(8.0 \pm 0.8) \times 10^{-4}$
$D^0 \to K^0_s\pi^0$	$(1.22 \pm 0.05) \times 10^{-2}$

Strategy:

D^{*+} tag: D from $D^* \to \pi D$

Normalized to $D \to K\pi$

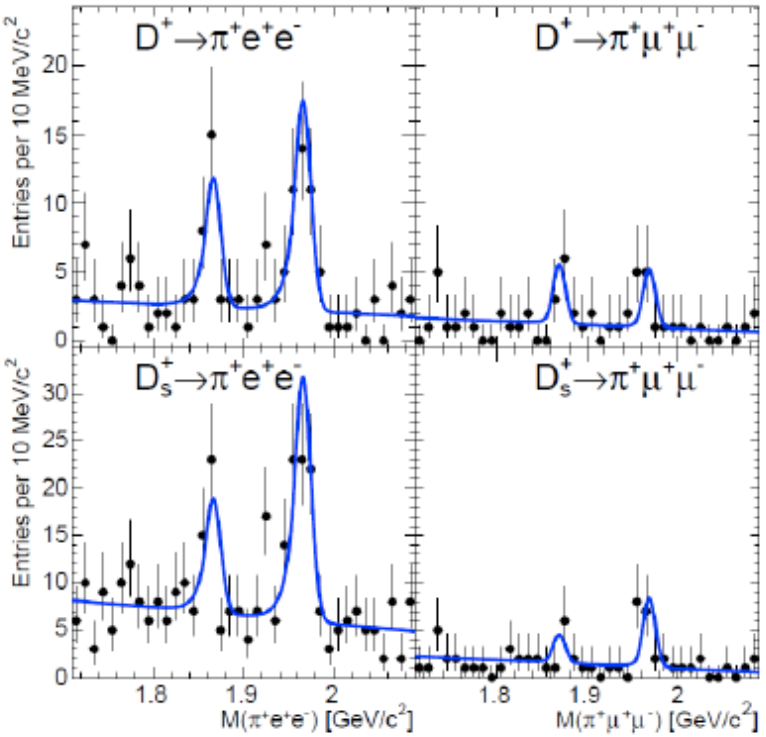
	$D^0 \to \gamma\gamma$	$D^0 \to \pi^0\pi^0$
selection efficiency		
signal	15.2 %	6.1%
normalization	12.0%	7.6%

$X_c \rightarrow h\, \ell^+\ell^-$

Fit Results – Control Modes

BABAR preliminary

- 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 $D_s^+ \rightarrow \pi\phi$, $\phi \rightarrow e^+e^-$



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