Searches for Rare & Forbidden B and Charm decays with BaBar

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Representing the BaBar Collaboration at

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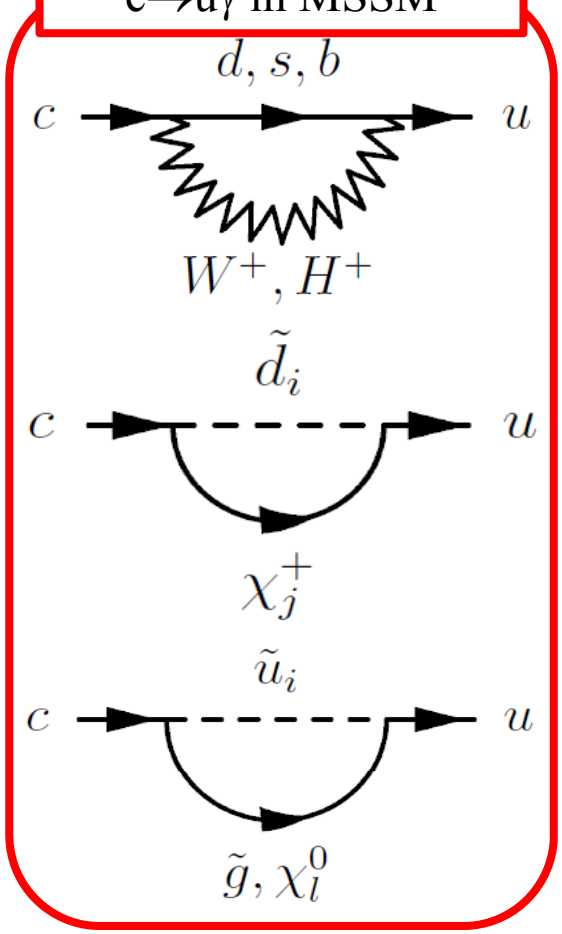
Rare B and Charm decays

- New physics (NP) can be revealed in low-energy flavor processes…especially in loops
- Particularly fruitful are processes with (very) small effects predicted by the Standard Model (SM)
- In general:
  - Induce (additional) flavor-changing neutral currents (FCNC)
  - Allow "forbidden" decays, i.e. baryon number violation (BNV), lepton number violation (LNV), lepton flavor violation (LFV)
- The particle in the loop can be very heavy…

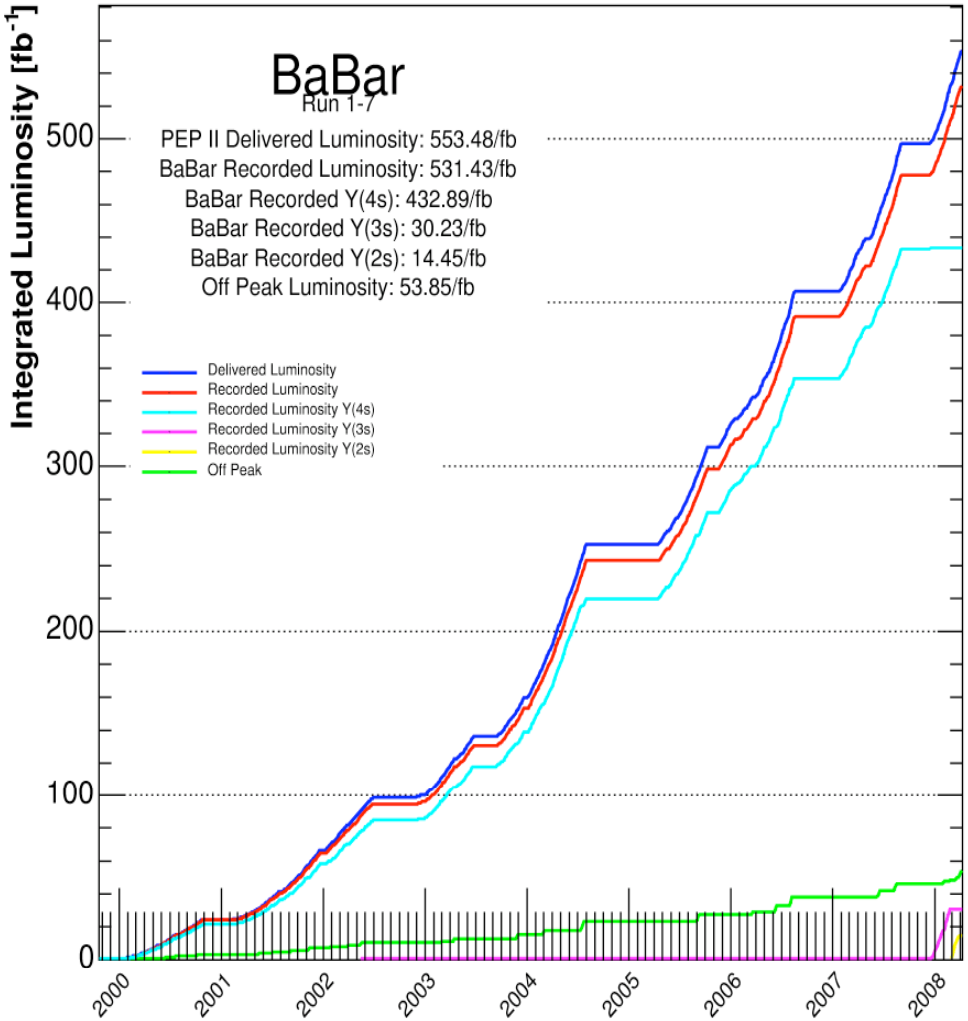
  can probe NP at the multi-TeV scale
- Huge datasets collected by B factories allow to explore NP in a clean environment… Luminosity frontier
- Complementary to direct searches at energy frontier
- Strong constraints already put on NP

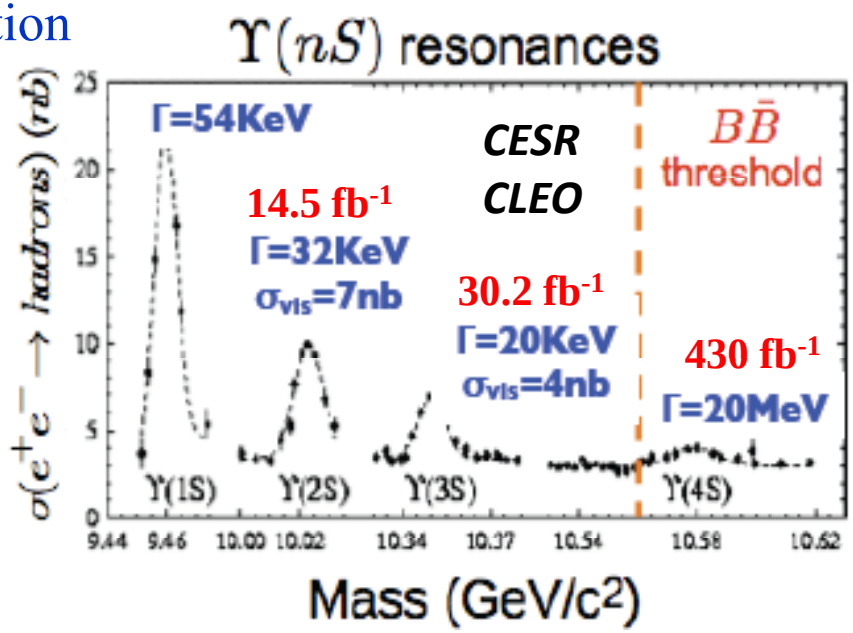
One-loop diagrams for c→uγ in MSSM



Data set

- 530 fb^{-1} recorded in the 9 years of operation





54 fb^{-1} Off-Υ(nS)
4 fb^{-1} above Υ(4S)

- ≈ 470×10^6 $B\bar{B}$ (0.5×Belle)
- ≈ 690×10^6 $c\bar{c}$
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 1.2×10^8 Υ(3S) (7×Belle+Cleo)
- ≈ 1.0×10^8 Υ(2S) (0.5×Belle+Cleo)

Outline

- B decays
  - FCNC decay $B \to K\nu\bar{\nu}$
  - FCNC decay $B \to \gamma\gamma$
  - BNV and LNV decay $B \to \Lambda_{(c)} l$
- Charm decays
  - FCNC decay $D \to \gamma\gamma$
  - BNV, LNV, LFV decays $X_c^+ \to h^\pm l^\mp l'^+$ with $X_c = D, D_s, \Lambda_c$
- Conclusions

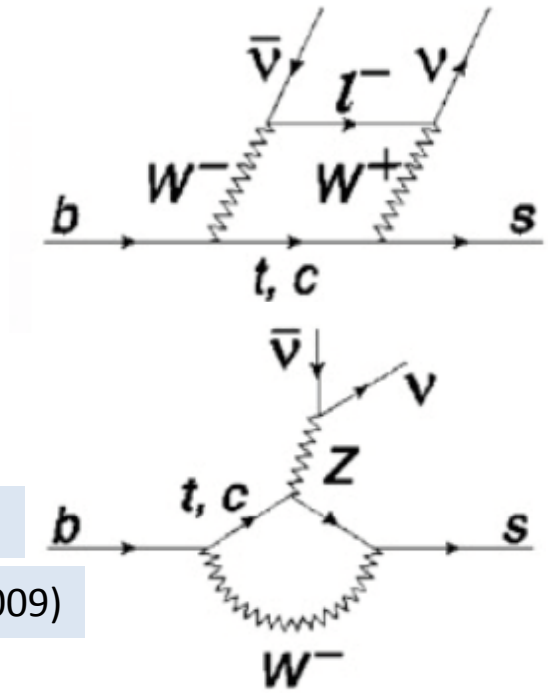
Other rare leptonic, radiative and semileptonic B and Charm decays:
✓ G. Eigen's talk at Parallel Session 6E
✓ A. Oyanguren's talk at this Parallel Session 8E

Rare and Forbidden B decays

Search for B →Kνν̄: motivation

- b → s FCNC process
- SM BF small: $\left(3.8^{+1.2}_{-0.6}\right)\times 10^{-6}$ PRD 63, 014015 (2001)
  $\left(4.5\pm 0.7\right)\times 10^{-6}$ JHEP 0204:022 (2009)
- Sensitive to NP: unparticles, MSSM at large tanβ, universal extra dimensions, WIMPs,…
- NP models predict BF up to a factor 10 larger

NPB465, 369 (1996) | JHEP 07, 072 (2007) | PRD 77, 014025 (2008)
PRD 73, 115006 (2006) | PRL 93, 201803 (2004) | PRD 79, 114001 (2009)

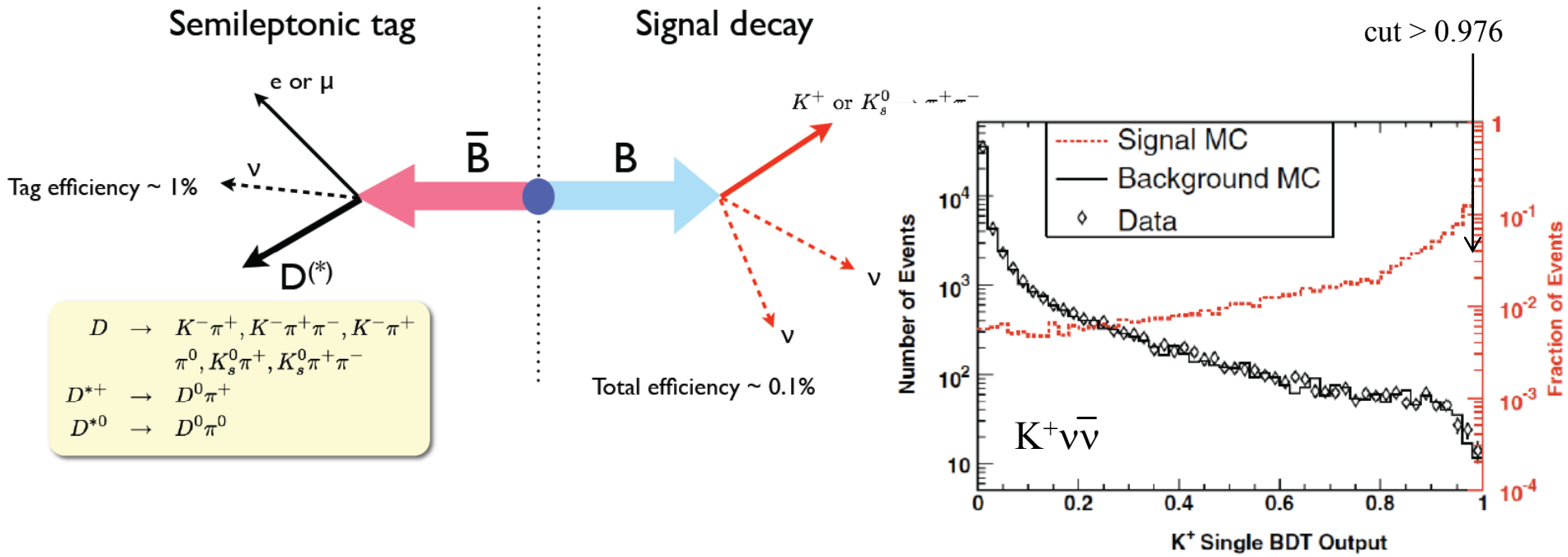


- Previous measurements

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

$B \to K\nu\bar{\nu}$: experimental technique

- Two neutrinos ⇒ few kinematical constraints on final state ⇒ reconstruct "other" B in event in semileptonic B decay
- Look for signal decay among remaining particles of event



- Apply K*(892), ρ^+ and a_1^+ vetos to reject combinatorial background
- Suppress remaining background using multivariate classifier (BDT)
- Uses 26 (K^+) or 38 (K^0) variables relating to i) *missing energy*, ii) *event shape*, iii) *signal kinematics*, and iv) *quality of reconstructed tag*

$B \to K\nu\bar{\nu}$: results

459x10^6 $B\bar{B}$ pairs

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	$187 \pm 10 \pm 46$

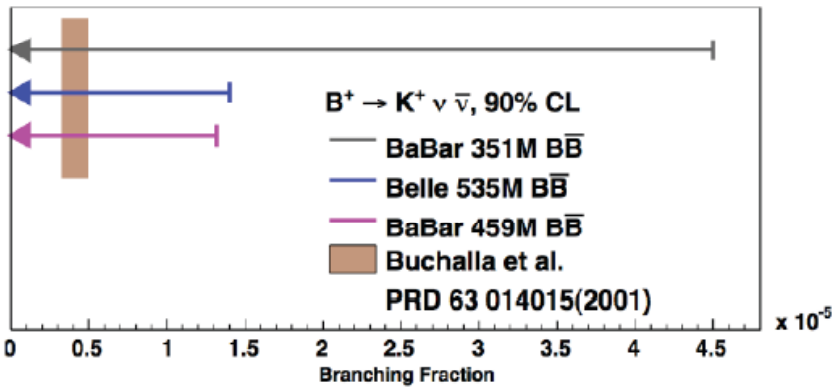
Observed events

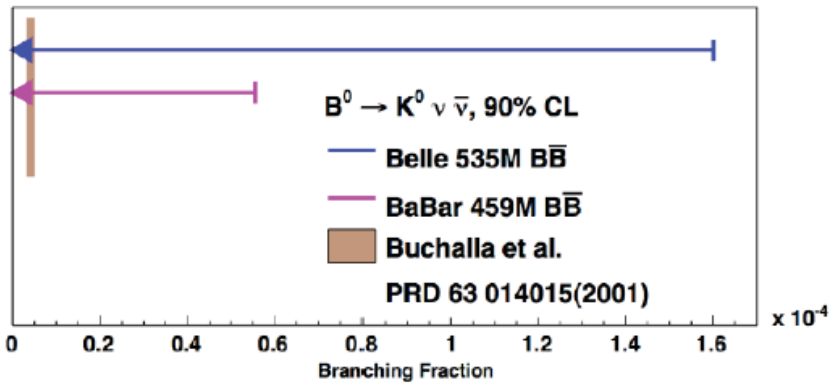
Mode	N_{obs}	N_{excess}	Prob.
K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$	38%
K^0	$6.1^{+4.0}_{-2.2}$	$2.2^{+4.1}_{-2.8}$	23%
low-q^2 K^+	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$	38%
high-q^2 K^+	164^{+13}_{-13}	-23^{+49}_{-48}	33%

Some NP models predict q^2-dependence

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

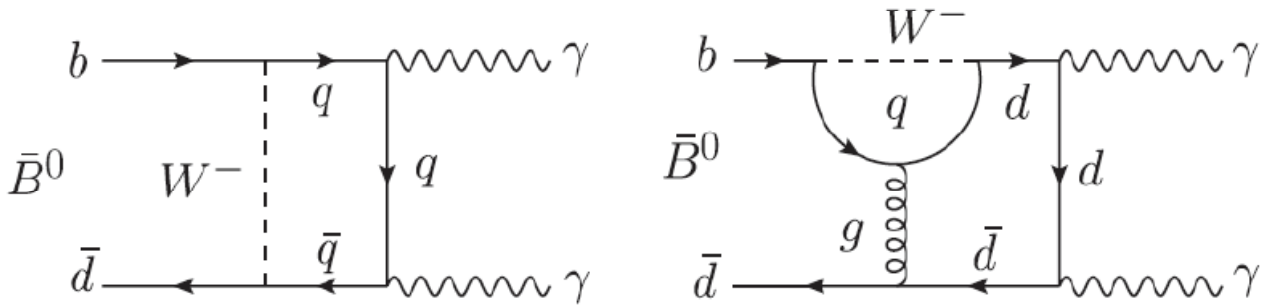




Best limits achieved to date

PRD 82, 112002 (2010)

Search for $B^0 \to \gamma\gamma$: motivation



- Involves $b \to d\gamma\gamma$ FCNC transition
- Additional CKM suppression compared to $b \to s\gamma\gamma$ FCNC transition ($B_s \to \gamma\gamma$)
- Very small SM BF ~ $\left(3.1^{+6.4}_{-1.6}\right)\times 10^{-8}$ JHEP 08, 054 (2002)
- Can significantly be enhanced by NP scenarios
  - Extended Higgs sector PRD 58, 095014 (1998)
  - SUSY with broken R-parity PRD 70, 035008 (2004)
- Previous measurements:

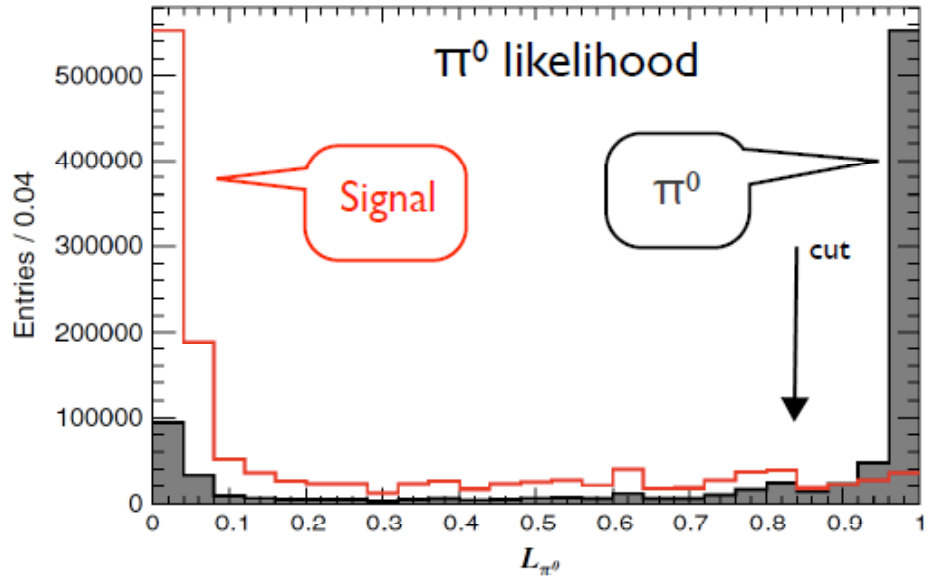
Upper Limit (90% CL)	Experiment	Data set	Reference
1.9×10^{-5}	L3	2.95×10^{6} $Z\to had$	PLB 363, 137 (1995)
1.7×10^{-6}	BaBar	19 fb^{-1}	PRL 87, 241803 (2001)
6.2×10^{-7}	Belle	104 fb^{-1}	PRD 73, 051107 (2006)

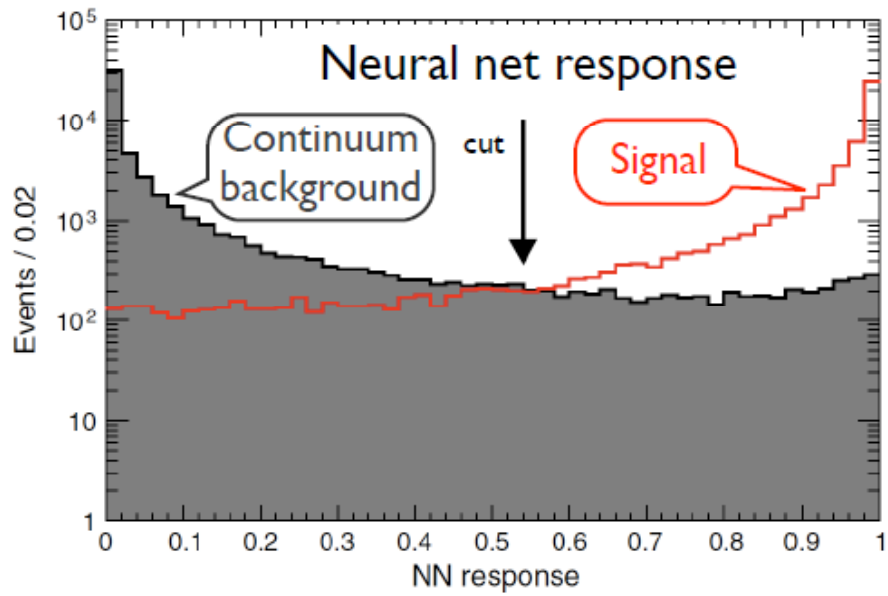
$B^0 \rightarrow \gamma\gamma$: experimental technique

- Two photons 1.5<E*<3.5 GeV
- Main background sources
  - Decays of π^0 and η decays
    - ✓ Reject with likelihood ratio based on m(γγ') and E(γ')
  - Out-of-time Bhabha event overlap
    - ✓ Reject with total energy and timing cuts
  - Generic continuum events
    - ✓ Multivariate classifier (NN) based on 19 input variables
- Perform 2-D likelihood fit to variables

$$m_{ES} = \sqrt{\left(\sqrt{s}/2\right)^2 - p_B^{*2}}$$

$$\Delta E = E_B^* - \sqrt{s}/2$$





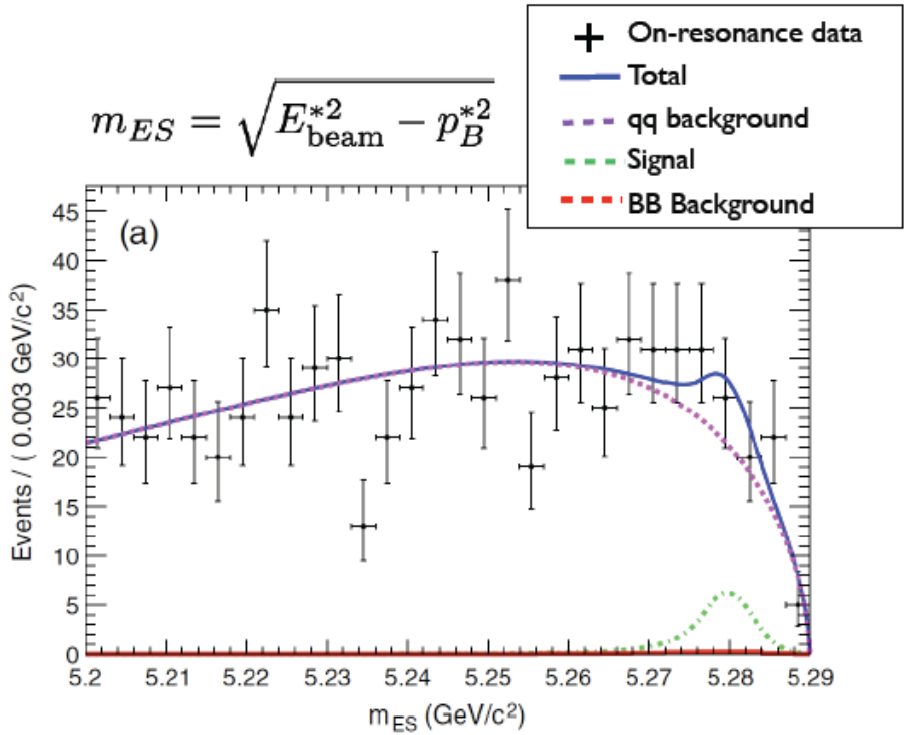
$B^0 \to \gamma\gamma$: results

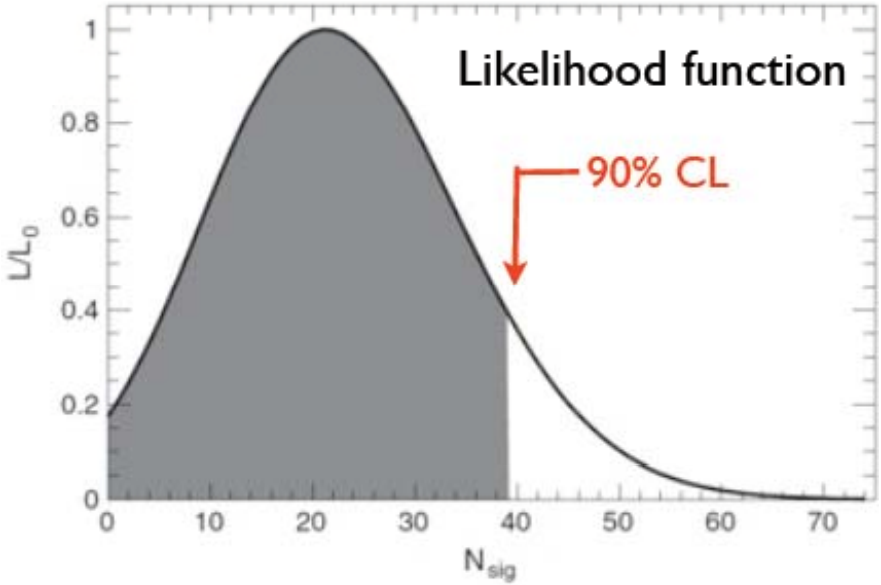
452x10⁶ $B\bar{B}$ pairs

- Signal Yield: $21.3^{+12.8}_{-11.8}$
- Signal efficiency: 26.7%
- Measured BF:

$$BF(B \to \gamma\gamma) = \left(1.7 \pm 1.1_{stat} \pm 0.2_{syst}\right) \times 10^{-7}$$

1.8σ significance





Upper limit (UL):

$$BF(B \to \gamma\gamma) < 3.2 \times 10^{-7} \text{ at } 90\% \text{ CL}$$

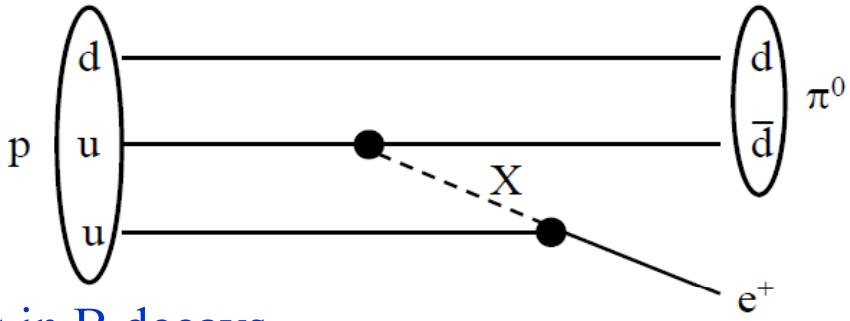
Improves by ×2 previous best limit

PRD 83, 032006 (2011)

Search for $B^0 \to \Lambda_{(c)} l$: motivation

l=e,μ

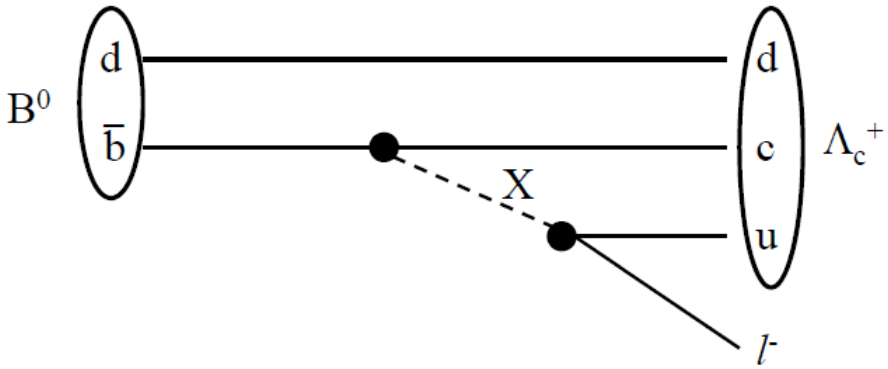
- SM quark-sector CP violation and BNV (non-pertubative *sphalerons*, B–L is conserved quantity) cannot explain observed matter-antimatter asymmetry
- GUTs predict proton decay, i.e. both BNV and LNV
  - New interaction with new gauge boson X with q=1/3
    - ✓ $X \to q + q$
    - ✓ $X \to q + l$



- Search for BNV (and LNV) extra sources in B decays
  - $B^0 \to \Lambda_c^+ l^-$
    - ✓ $BF_{SM}(B^0 \to \Lambda_c^+ l^-) < 4 \times 10^{-29}$

PRD 72, 095011 (2002)

  - $B^- \to \Lambda^0 l^-$
  - $B^- \to \bar{\Lambda}^0 l^-$



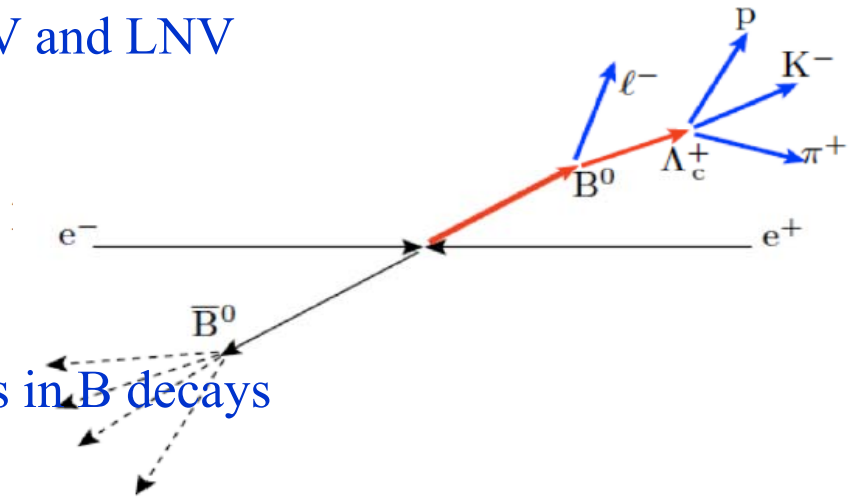
Search for $B^0 \to \Lambda_{(c)} l$: motivation

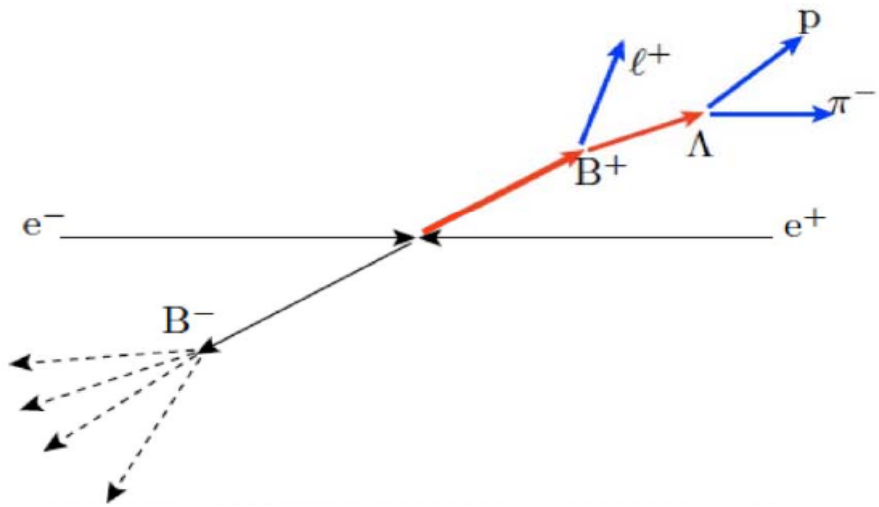
l=e,μ

- SM quark-sector CP violation and BNV (non-pertubative *sphalerons*, B–L is conserved quantity) cannot explain observed matter-antimatter asymmetry
- GUTs predict proton decay, i.e. both BNV and LNV
  - New interaction with new gauge boson X with q=1/3
    - ✓ $X \to q + q$
    - ✓ $X \to q + l$
- Search for BNV (and LNV) extra sources in B decays
  - $B^0 \to \Lambda_c^+ l^-$ where $\Lambda_c^+ \to pK^-\pi^+$
    - ✓ $BF_{SM}(B^0 \to \Lambda_c^+ l^-) < 4\times10^{-29}$

PRD 72, 095011 (2002)

  - $B^- \to \Lambda^0 l^-$ where $\Lambda^0 \to p\pi^-$
  - $B^- \to \bar{\Lambda}^0 l^-$ where $\bar{\Lambda}^0 \to \bar{p}\pi^+$
- First measurement of the BF for these BNV and LNV decays





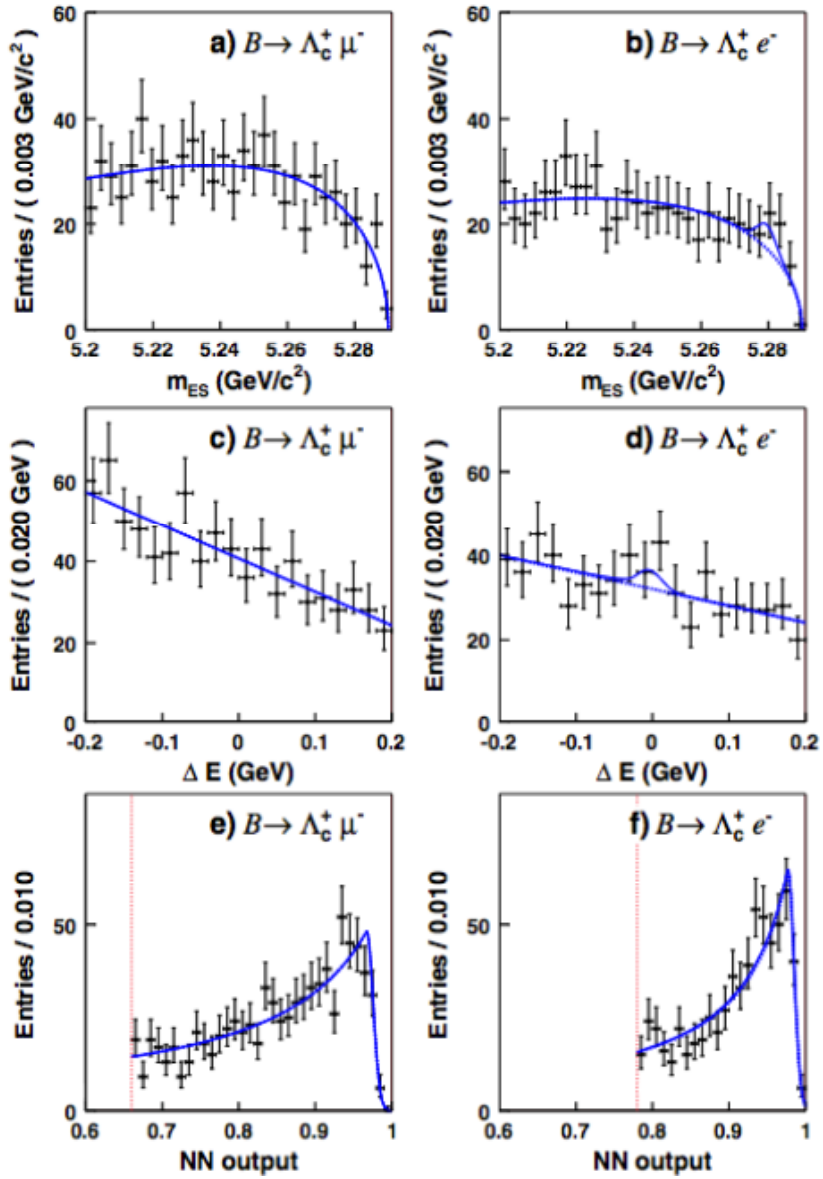
$B^0 \to \Lambda_{(c)} l$: technique and results

470x10^6 $B\bar{B}$ pairs

- PID for hadrons and leptons
- Background $e^+e^- \to e^+e^-\gamma$ ($\gamma \to e^+e^-$) rejected requiring more than 4 charged tracks in event
- Use NN (TMVA) based on 6 variables
- Perform 2-D likelihood fit to m_{ES} and ΔE variables. 3-D with TMVA output for Λ_c decay modes
- No significant signal yields observed

Decay mode	ε(%)	N_{cand}	BF(10^{-8}) UL
$B^0 \to \Lambda_c^+ \mu^-$	26.3 ± 0.9	180	814
$B^0 \to \Lambda_c^+ e^-$	25.7 ± 0.7	520	651
$B^- \to \Lambda \mu^-$	28.7 ± 0.9	6.2	320
$B^- \to \Lambda e^-$	27.2 ± 0.6	8.1	194
$B^- \to \bar{\Lambda} \mu^-$	31.3 ± 1.0	6.1	192
$B^- \to \bar{\Lambda} e^-$	30.0 ± 0.6	3.2	74

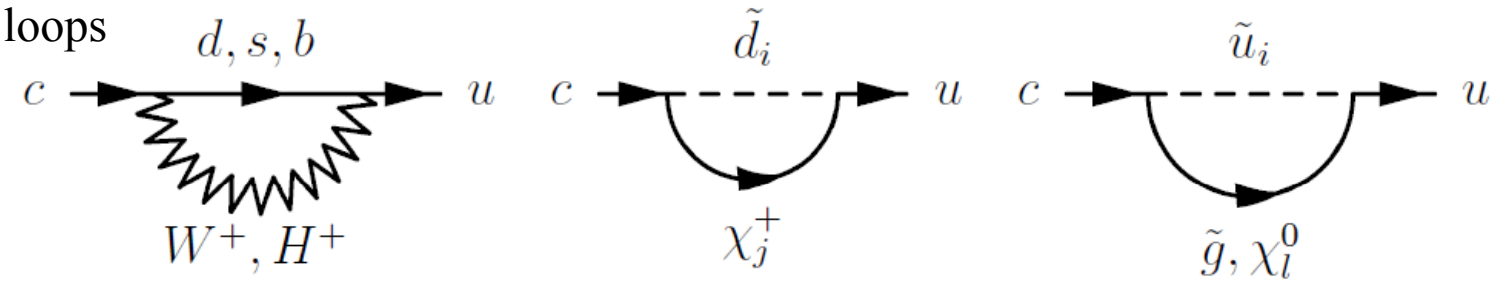
PRD 83, 091101(R) (2011)



Rare and Forbidden D decays

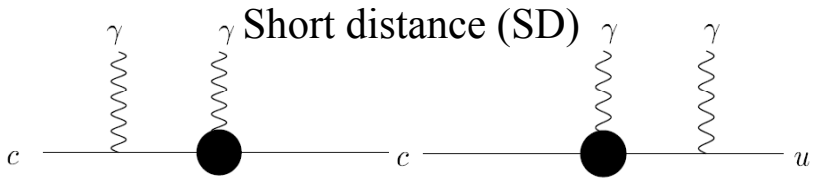
Search for $D^0 \to \gamma\gamma$: motivation

SM and MSSM loops

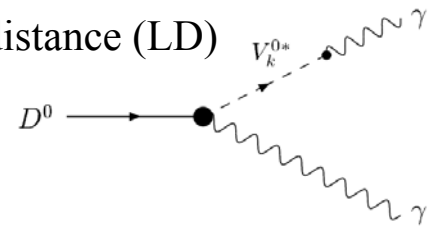


- FCNC, highly suppressed at loop level by GIM mechanism (light down quark sector)
- SM dominated by long distance contributions PRD 66, 014009 (2002)

Short distance (SD)



Long distance (LD)



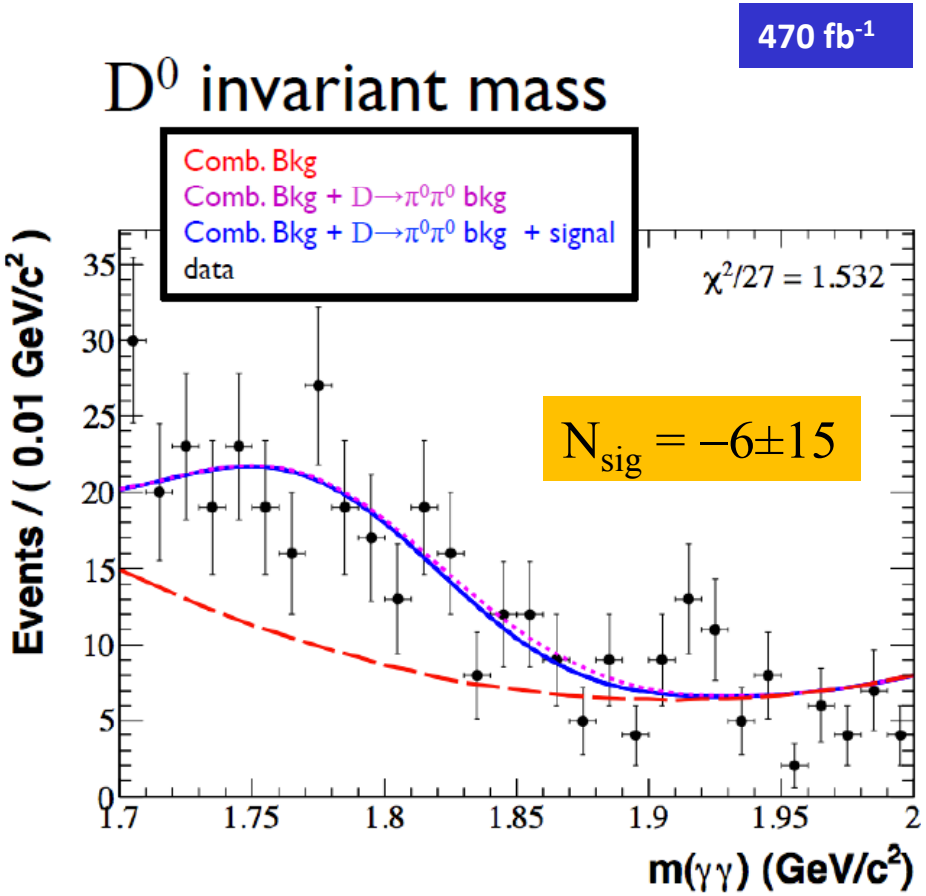
Theoretical predictions	
Mode	Value
$D^0 \to \gamma\gamma$ (SM,VMD)	$\approx (3.5\ ^{+4.0}_{-2.6}) \times 10^{-8}$
$D^0 \to \gamma\gamma$ (SM,HQχPT)	$(1.0 \pm 0.5) \times 10^{-8}$
$D^0 \to \gamma\gamma$ (MSSM)	6×10^{-6}

Experimental results	
Mode	Value
$D^0 \to \gamma\gamma$	$< 2.7 \times 10^{-5}$
	CLEO, PRL 90, 101801 (2003)
$D^0 \to \pi^0\pi^0$	$(8.0 \pm 0.8) \times 10^{-4}$
$D^0 \to K_S^0\pi^0$	$(1.22 \pm 0.05) \times 10^{-2}$

- SUSY can produce large enhancements up to ×200 $\Rightarrow$ >1000 expected events vs 6 SM PLB 500, 304 (2001)

$D^0 \to \gamma\gamma$: experimental technique

- Two photons $0.74<E^*<4$ GeV
- Require D^0 meson from $D^{*+}\to D^0\pi^+$ (D^{*+} tag)
- $p(D^*)>2.85$ GeV to reject $B\to D^0X$ decays
- Main background from $D^0\to\pi^0\pi^0$
  - π^0 veto
- Likelihood fit to D^0 invariant mass to extract signal
- Signal efficiency: 6.1%
- Also measure explicitly $D^0\to\pi^0\pi^0$ and reference mode $D^0\to K_S\pi^0$



Upper limit (UL):

$$BF(D^0 \to \gamma\gamma) < 2.4\times10^{-6} \text{ at } 90\% \text{ CL}$$

Preliminary

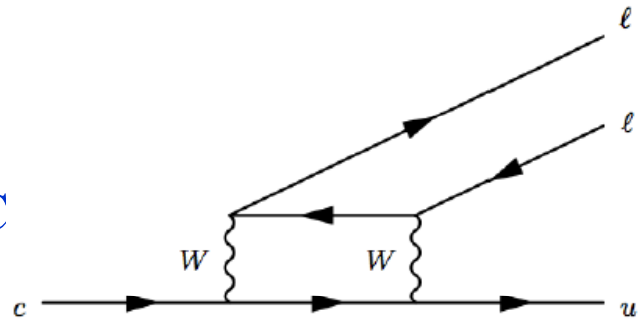
$\times$10 improvement wrt PDG

Search for $X_c \to hll$: motivation

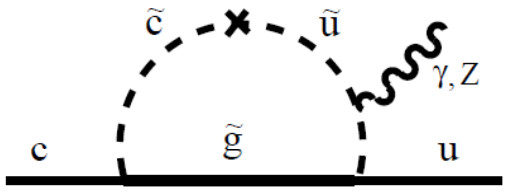
l=e,μ

- Search for decays of the form $X_c^+ \to h^{\pm} l^{\mp} l'^{+}$
  - $X_c = D^+, D_s^+$ or Λ_c^+
  - h = K or π for D and p for Λ_c^+
- For non-LFV/non-LNV decays, it is a charm FCNC transition, highly suppressed by GIM mechanism
  - $BF_{SM}(c \to ull) \sim 10^{-8}$

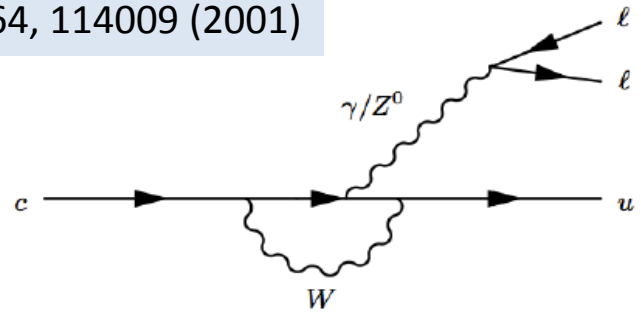
PRD 66, 014009 (2002) PRD 64, 114009 (2001)



- NP models (e.g. SUSY) can increase BF up to 10^{-5}



PRD 66, 014009 (2002)
PRD 73, 054026 (2006)
PRD 83, 114006 (2011)

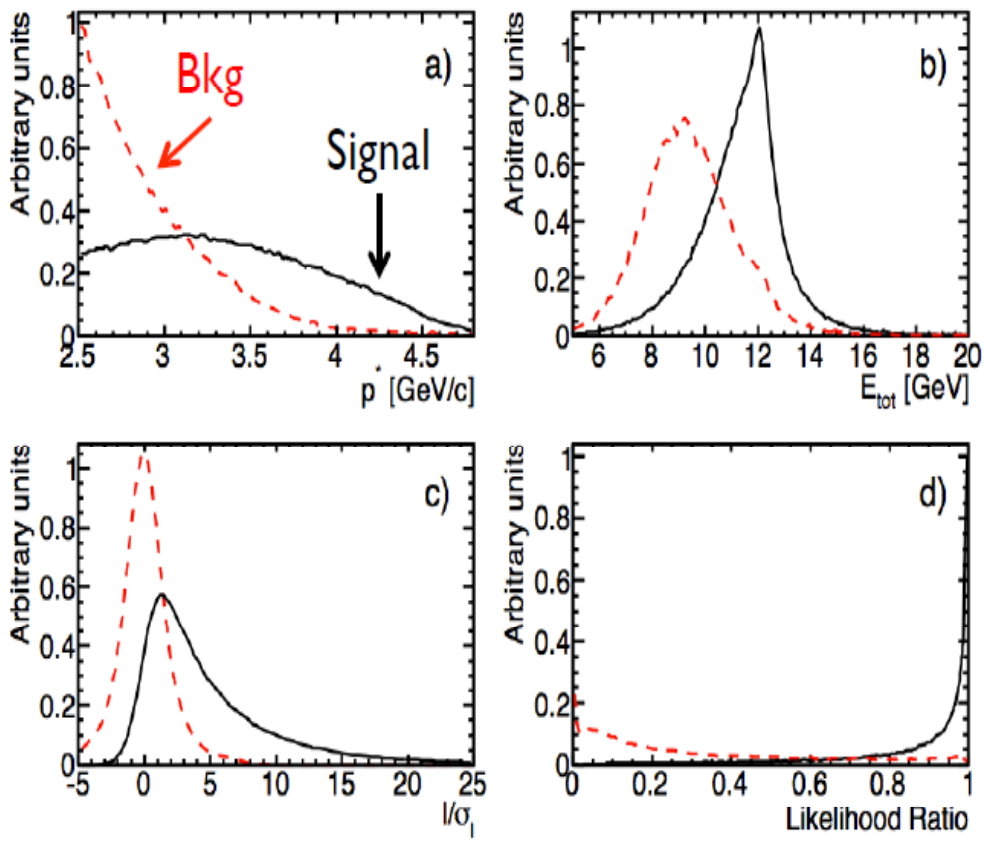


- FCNC transitions discussed by G. Eigen in Parallel Session 6E
- Can also look for "exotic" LFV decays
  - Essentially forbidden in the SM (can only occur through lepton mixing)
- and LNV decays
  - Forbidden in the SM

$X_c \rightarrow hll$: experimental technique

- LFV
  - 2 opposite charge leptons of different flavor
- LNV
  - 2 like-sign leptons ($\Delta L=2$)
- Main background sources:
  - QED events (Bhabha)
    - ✓ Rejected requiring at least 5 charged tracks
  - Semileptonic B and charm decays
    - ✓ Rejected by requiring the two leptons to be consistent with common origin
- Final candidate selection through a likelihood ratio
  - 3 discriminating variables

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



CM momentum of the X_c candidate
Total energy in the event
Flight length significance

$X_c \to hll$: results

384 fb^{-1}

- Likelihood fit to X_c invariant mass
- Efficiencies: 0.4%-6.8%
- Yields normalized to $D^+ / D_s^+ \to \pi^+ \phi_{K^+K^-}$

  $\Lambda_c^+ \to pK^-\pi^+$
- Most channels improve upon previous limits by ×10

Preliminary

1107.4465 [hep-ex] (2011). Sub. to PRD

Decay mode LFV	BF UL (10^{-6}) 90% CL	Previous UL
$D^+ \to \pi^+ e^+ \mu^-$	2.9	34 E791
$D^+ \to \pi^+ e^- \mu^+$	3.6	34 E791
$D^+ \to K^+ e^+ \mu^-$	1.2	68 E791
$D^+ \to K^+ e^- \mu^+$	2.8	68 E791
$D_s^+ \to \pi^+ e^+ \mu^-$	12	610 E791
$D_s^+ \to \pi^+ e^- \mu^+$	20	610 E991
$D_s^+ \to K^+ e^+ \mu^-$	14	630 E791
$D_s^+ \to K^+ e^- \mu^+$	9.7	630 E791
$\Lambda_c^+ \to p e^+ \mu^-$	9.9	
$\Lambda_c^+ \to p e^- \mu^+$	19	

Decay mode LNV	BF UL (10^{-6}) 90% CL	Previous UL
$D^+ \to \pi^- e^+ e^+$	1.9	1.1 CLEO-c
$D^+ \to \pi^- \mu^+ \mu^+$	2.0	4.8 FOCUS
$D^+ \to \pi^- e^+ \mu^+$	2.0	50 E791
$D^+ \to K^- e^+ e^+$	0.9	3.5 CLEO-c
$D^+ \to K^- \mu^+ \mu^+$	10	13 FOCUS
$D^+ \to K^- e^+ \mu^+$	1.9	130 E687
$D_s^+ \to \pi^- e^+ e^+$	4.1	18 CLEO-c
$D_s^+ \to \pi^- \mu^+ \mu^+$	14	29 FOCUS
$D_s^+ \to \pi^- e^+ \mu^+$	8.4	730 E791
$D_s^+ \to K^- e^+ e^+$	5.2	17 CLEO-c
$D_s^+ \to K^- \mu^+ \mu^+$	13	13 FOCUS
$D_s^+ \to K^- e^+ \mu^+$	6.1	680 E971
$\Lambda_c^+ \to \bar{p} e^+ e^+$	2.7	
$\Lambda_c^+ \to \bar{p} \mu^+ \mu^+$	9.4	
$\Lambda_c^+ \to \bar{p} e^+ \mu^+$	16	

Conclusions

- BaBar ended data-taking in 2008 but the large available dataset is still a very rich and fruitful playground for physics analysis

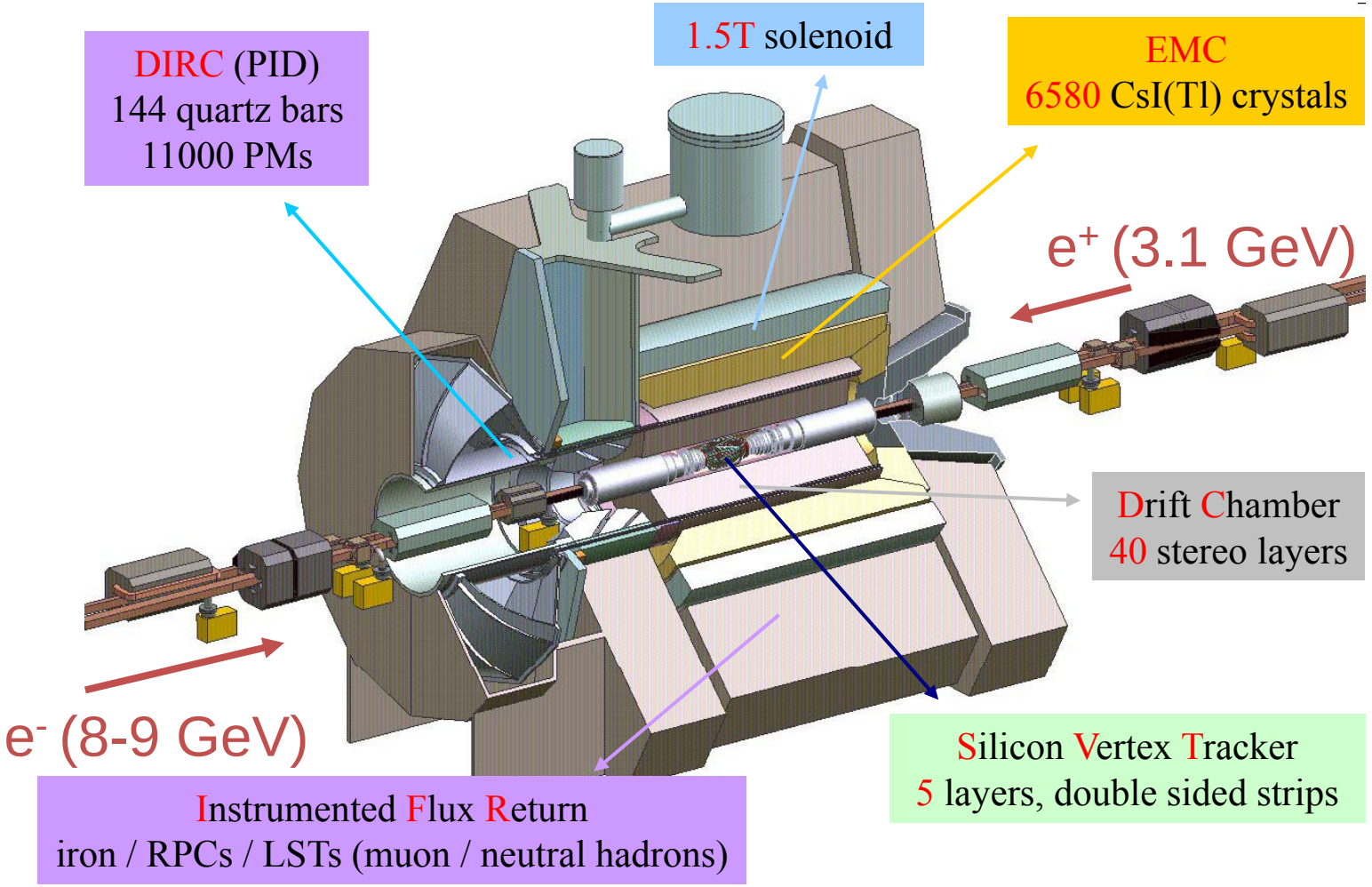
- Many rare and forbidden decay processes are sensitive to New Physics

- high statistics of B and Charm decays continues to make measurements of FCNC, BNV, LFV processes, which are powerful in constraining NP models
  - BF($B\to\gamma\gamma$) upper limit (UL) lowered by a factor 2
  - No evidence of BNV and LNV found in the first search for $B\to\Lambda_{(c)}\, l$
  - The UL on BF($B\to K\nu\bar{\nu}$) down to 10^{-5} level for both channels
  - The UL on BF($D\to\gamma\gamma$) improved by 1 order of magnitude, down to 10^{-6}
  - Most of LFV and LNV $X_c\to h\,ll$ BF ULs down by 1 order of magnitude

- New results still to come!
- We also look forward to many interesting flavor results from and , and looking a bit further down the road, from and

Bonus slides

BaBar detector



- Asymmetric B-factory: E_{cms} = 10.58 GeV $\quad e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L identification. Very stable over the 9 years of operation