Searches for Lepton Number Violation processes in B decays

On behalf of the BaBar and Belle Collaborations

CKM 2012, 28th Sep. – 2nd Oct. 2012, Cincinnati, Ohio

Outline

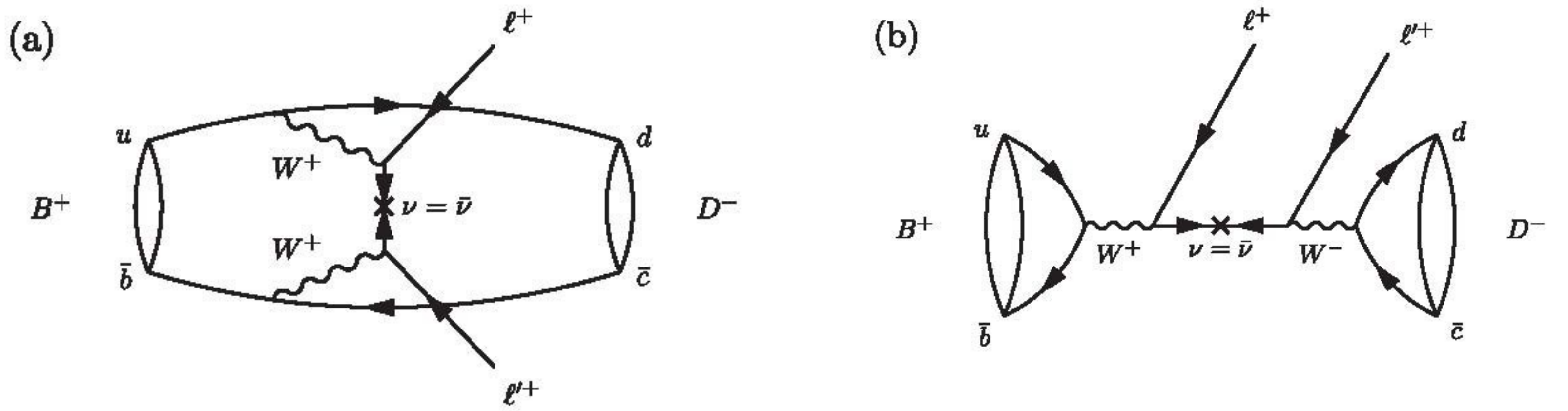
- Introduction/Motivation
- B Factory Searches
  - CLEO $B^+ \to V^-/h^- l^+l'^+$ PRD65, 111102 (2002)
  - BaBar $B^+ \to h^- l^+l^+$ PRD85, 071103 (2012)
  - BaBar $B^+ \to \Lambda_{(c)} l^+$ PRD83, 091101 (2011)
  - Belle $B^+ \to D^- l^+l'^+$ PRD84, 071106 (2011)
- Looking to the future
- Conclusion

Introduction/Motivation

- Charged Lepton Number L is approximately conserved in the Standard Model (SM) and can be violated at high energies by e.g. chiral anomalies.
- In GUT theories, quarks and leptons are part of the same multiplets so baryon number B and lepton number L are expected to be violated in almost all models.
- Lepton Number Violation (LNV) becomes possible if neutrinos are Majorana particles ($\Delta L=2$ process).
- Neutrino-less double beta decay ($0\nu\beta\beta$) releases about ~3MeV via t-channel Majorana neutrino exchange. Upper limits placed on Majorana electron neutrino mass ~1eV.

LNV in $B^+ \to h^- l^+ l^+$ processes

- Some theories suggest a new 4th generation neutrino.
- In $B^+ \to h^- l^+ l^+$ processes, can look for resonance production via Majorana neutrino exchange with masses in range 0.5 - 4.5 GeV.
- Caveat: do not know mass nor coupling.
- Can re-use many of the techniques used in $B \to K^{(*)} l^- l^+$ analyses.



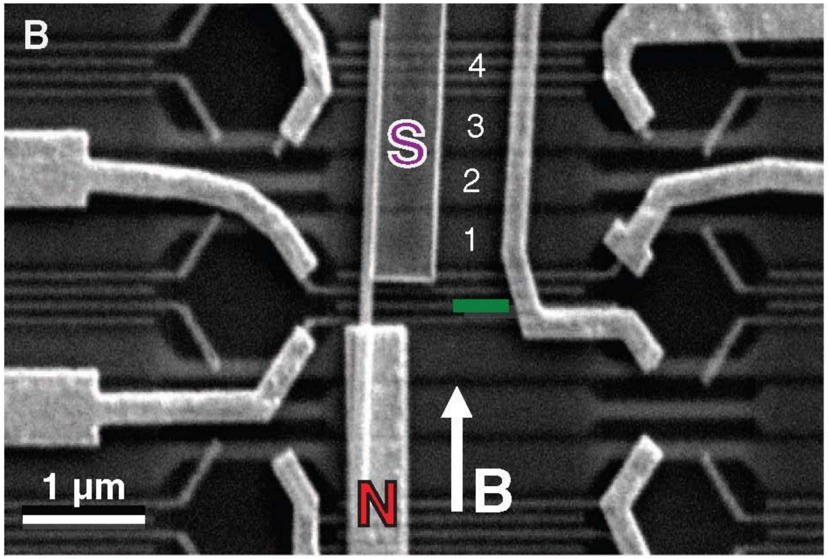
Science 336, 1003 (2012)

Are we too late?

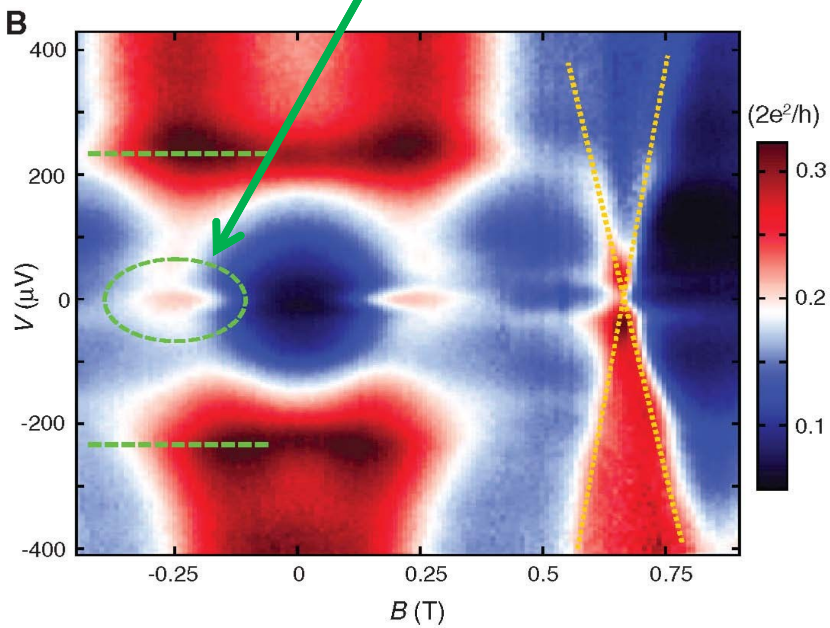
Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1*] K. Zuo,[1*] S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

Majorana fermions are particles identical to their own antiparticles. They have been theoretically predicted to exist in topological superconductors. Here, we report electrical measurements on indium antimonide nanowires contacted with one normal (gold) and one superconducting (niobium titanium nitride) electrode. Gate voltages vary electron density and define a tunnel barrier between normal and superconducting contacts. In the presence of magnetic fields on the order of 100 millitesla, we observe bound, midgap states at zero bias voltage. These bound states remain fixed to zero bias, even when magnetic fields and gate voltages are changed over considerable ranges. Our observations support the hypothesis of Majorana fermions in nanowires coupled to superconductors.

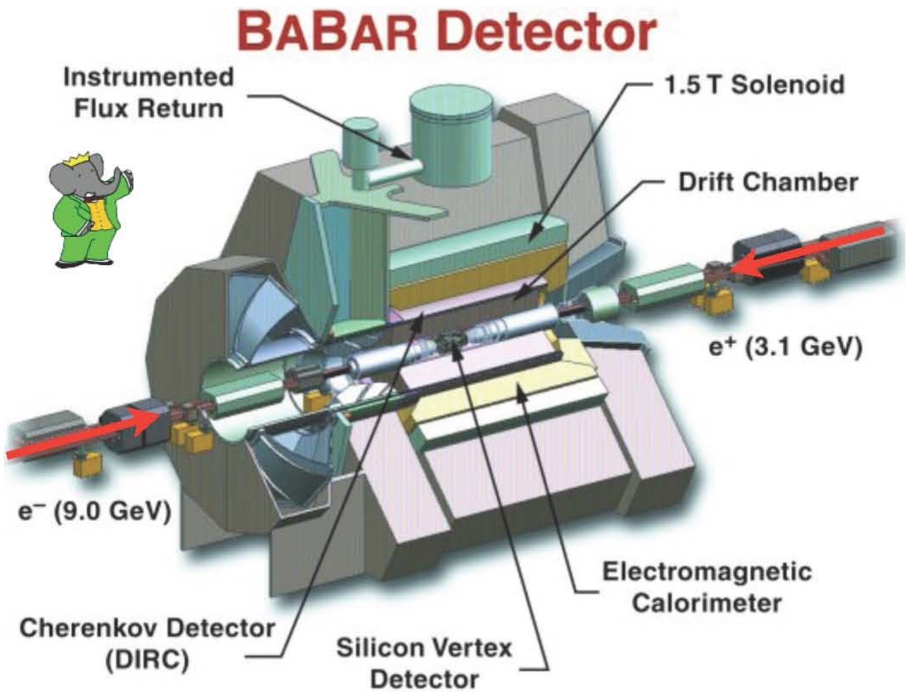


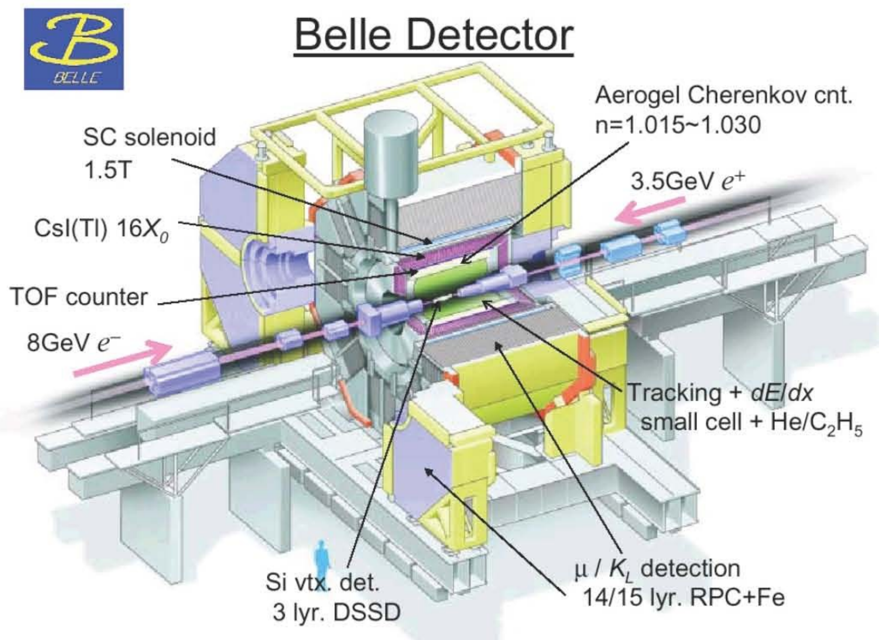
Is this the signal for a Majorana particle?



The BaBar and Belle Detectors

Common Features: asymmetric beam momenta, ϒ(4S) production, low multiplicity, low background, π/K particle identification, good muon and electron identification with wide coverage.



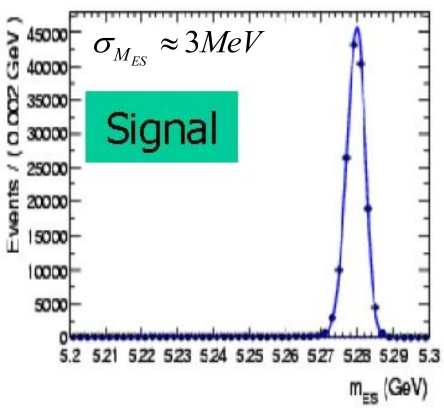


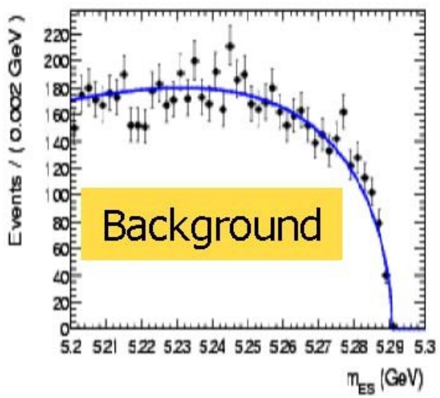
BaBar maximum ϒ(4S) dataset: ~470 x 10^6 $B\bar{B}$ pairs

Belle maximum ϒ(4S) dataset: ~770 x 10^6 $B\bar{B}$ pairs

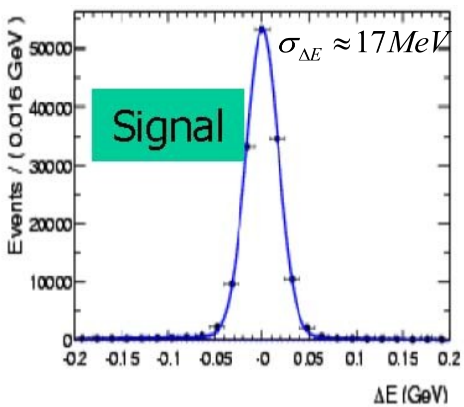
Common Analysis Techniques

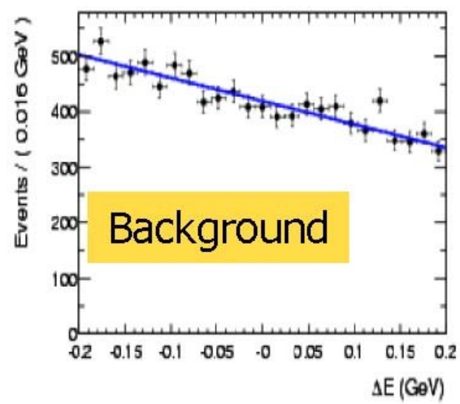
$$m_{ES} = m_{bc} = m_{cand} = \sqrt{E_{beam}^2 - p_B^2}$$



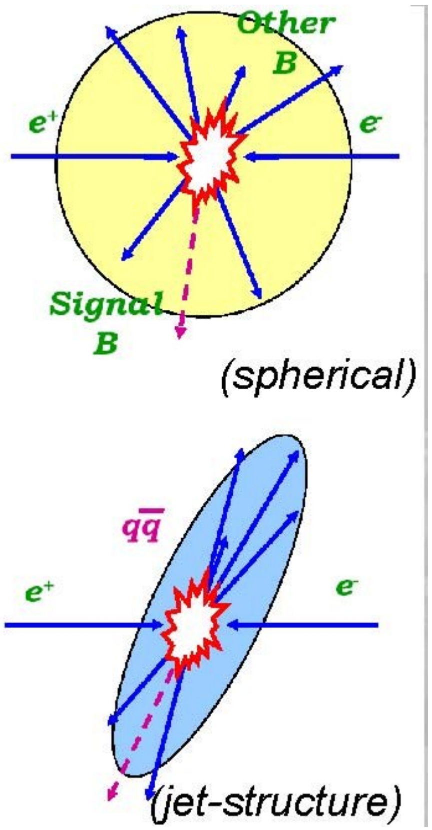


$$\Delta E = E_B - E_{beam}$$





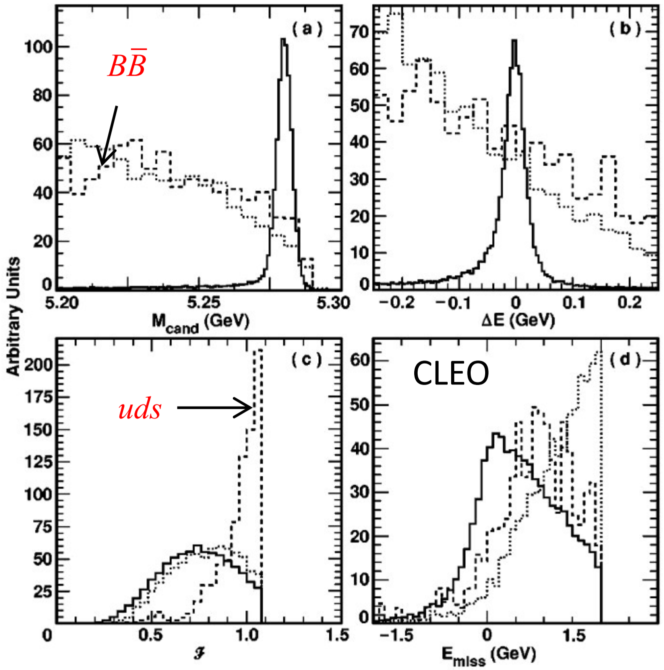
Event Topology



Plus Fisher Discriminants (F), Boosted Decision Trees (BDT), Neural Networks (NN) and unbinned Maximum Likelihood (ML) fits

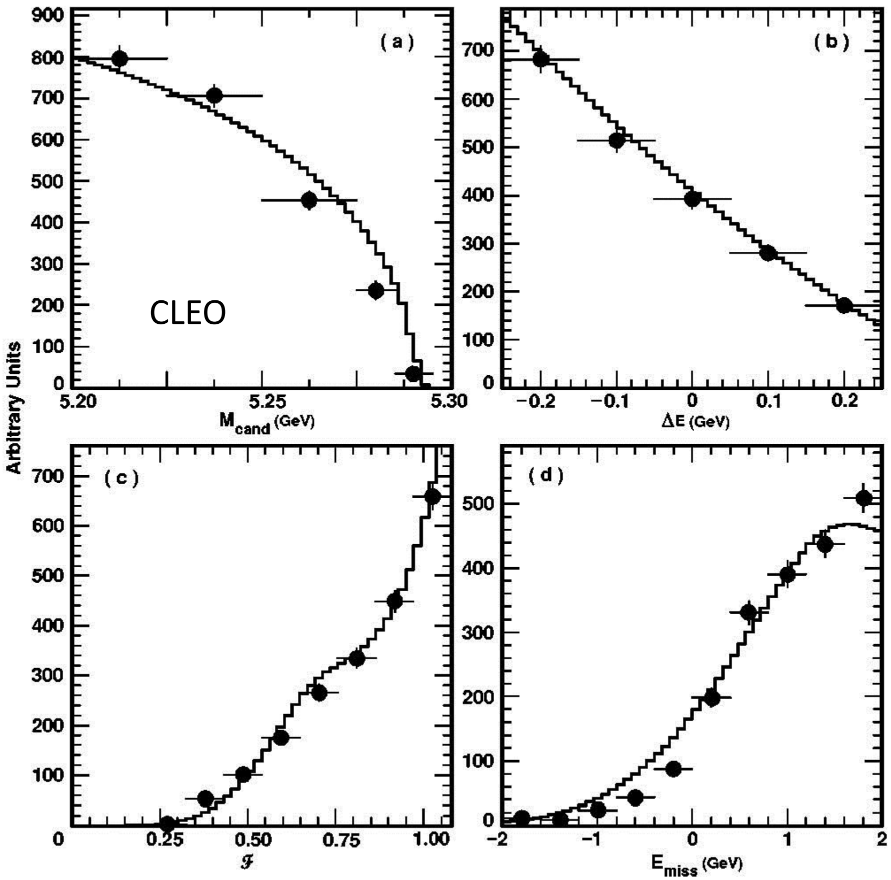
$B^+ \to h^- l^+ l^+$

- Based on CLEO search for $B \to K^{(*)} l^- l^+$.
- Look for 3 pairs of leptons ($e^+e^+, e^+\mu^+, \mu^+\mu^+$) and 4 hadronic final states ($h^- = K^-$, $K^{*-}(\to K^-\pi^0, K^0\pi^-)$,π^- and ρ^- (12 modes in total).
- Major backgrounds
  - Continuum (q=u,d,s,c)
  - Other B decays (e.g. B and D semi-leptonic).
  - Particle mid-identification e.g. K^- as μ^-.
- Reject background using ML with 4 variables taken from MC:
  - M_{cand}
  - ΔE
  - Fisher discriminant using 4 event shape variables.
  - E_{miss}
- MC Signal efficiency a few percent.



$B^+ \to h^- l^+ l^+$

- Upper limits are 90% integrals of log-likelihood increased by 1.28 times the systematics error (about 12%).



Fit to sum of modes

Decay Mode	Significance	Upper Limit ($\times 10^{-6}$)
$K^- e^+ e^+$	0.6σ	1.0
$K^{*-} e^+ e^+$	0.0	2.8
$\pi^- e^+ e^+$	0.0	1.6
$\rho^- e^+ e^+$	1.1	2.6
$K^- e^+ \mu^+$	0.0	2.0
$K^{*-} e^+ \mu^+$	0.0	4.4
$\pi^- e^+ \mu^+$	0.0	1.3
$\rho^- e^+ \mu^+$	0.3	2.2
$K^- \mu^+ \mu^+$	0.0	1.8
$K^{*-} \mu^+ \mu^+$	0.5	8.3
$\pi^- \mu^+ \mu^+$	0.0	1.4
$\rho^- \mu^+ \mu^+$	1.0	5.0

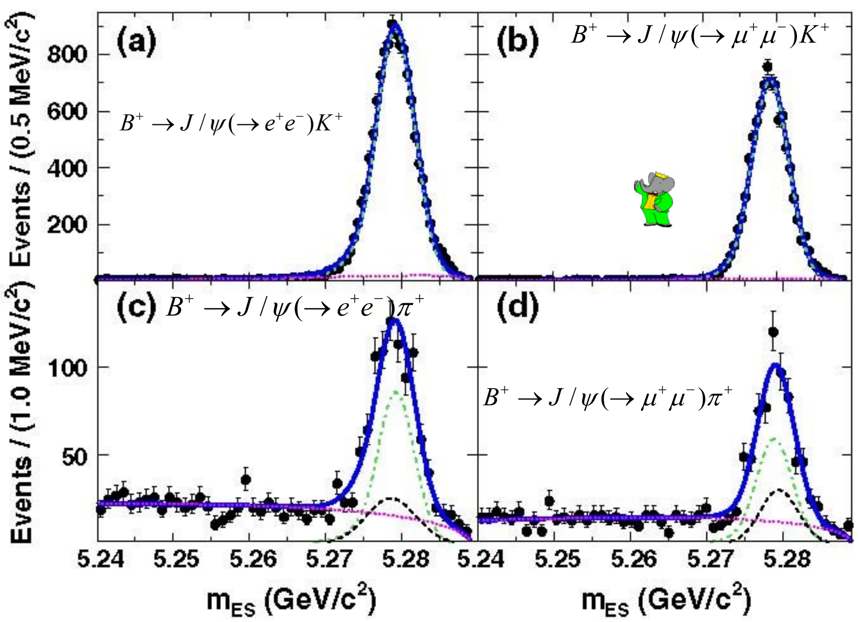
Black: superseded by LHCb/BaBar

Blue: still world's best

$B^+ \rightarrow h^- l^+ l^+$

- Based on BaBar measurement of $B \rightarrow K^{(*)} l^- l^+$.
- Look for 2 pairs of leptons ($e^+e^+, \mu^+\mu^+$) and 2 hadrons ($h^- = K^-, \pi^-$). 4 modes in total.
- Vetoes around the J/ψ and $\psi(2s)$ mass.
- Reject opposite-sign hadron-lepton pairs consistent with J/ψ or $\psi(2S)$ mass only for $B^+ \rightarrow \pi^- \mu^+ \mu^+$.
- Suppress continuum and B-decay backgrounds with 8 Boosted Decision Trees (BDT).
  - Electron v Muon
  - Continuum v. B-decay background
  - M_{ll} below or above J/ψ mass
- BDTs contains 18 variables (including ΔE)
- Combine to form a ratio R used in ML
- A cut on R is applied before the ML fit.

J/ψ control samples

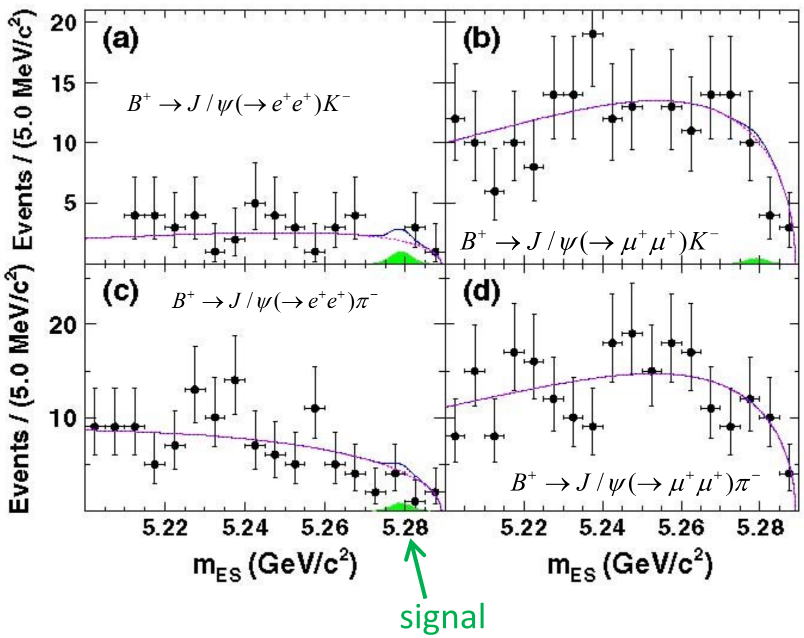


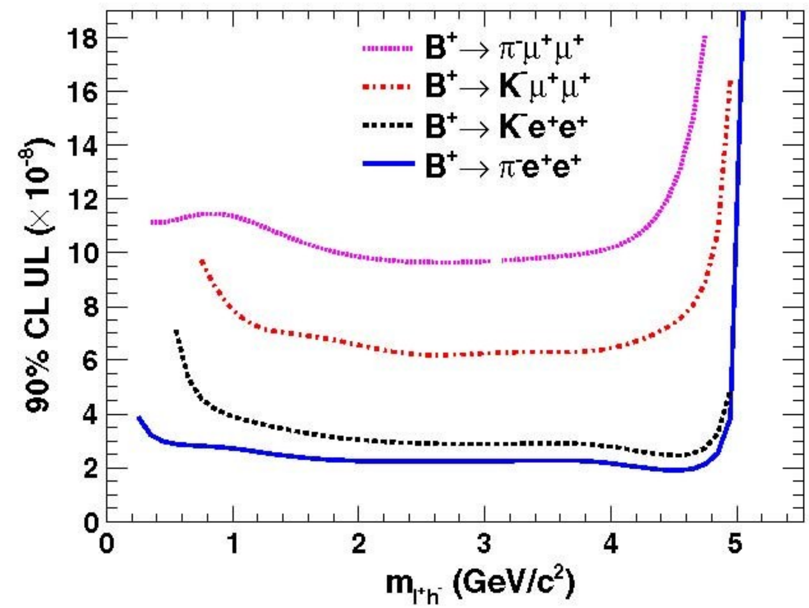
- ML fit uses 2 variables (R and M_{ES}) and 2 categories (signal and combined continuum/B-decay background).
- M_{ES} for signal is taken from $B^+ \rightarrow J/\psi (\rightarrow l^+ l^-) h^+$ control sample in data. Also used as a cross-check: branching fractions agree within 1σ of PDG numbers.

$B^+ \to h^- l^+ l^+$

- No significant signal seen

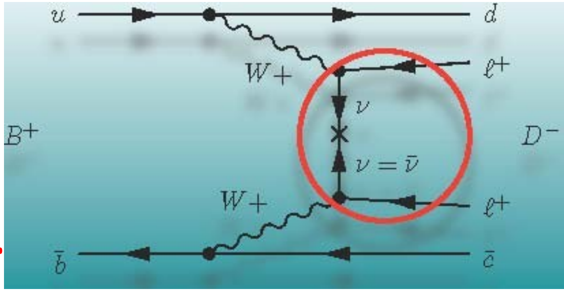
Decay Mode	Events	Yield	$\epsilon(\%)$	$S(\sigma)$	$\mathcal{B}(\times 10^{-6})$	$\mathcal{B}_{90\%}(\times 10^{-6})$
$B^+ \to \pi^- e^+ e^+$	123	$0.6^{+2.5}_{-2.7}$	47.8 ± 0.1	0.4	$0.27^{+1.1}_{-1.2} \pm 0.1$	2.3
$B^+ \to K^- e^+ e^+$	42	$0.7^{+1.8}_{-1.2}$	30.9 ± 0.1	0.5	$0.49^{+1.3}_{-0.8} \pm 0.1$	3.0
$B^+ \to \pi^- \mu^+ \mu^+$	228	$0.0^{+3.2}_{-2.0}$	13.1 ± 0.1	0.0	$0.03^{+5.1}_{-3.2} \pm 0.6$	10.7
$B^+ \to K^- \mu^+ \mu^+$	209	$0.5^{+3.5}_{-2.5}$	23.0 ± 0.1	0.2	$0.45^{+3.2}_{-2.7} \pm 0.4$	6.7





$B^- \to D^- l^+ l^+$

- V_{cb} ~ 10 x V_{ub} => BF could be as high as 10^{-7} in some Majorana models (e.g. JM Zhang and GL Wang, arXiv:1003.5570)
- Look for $D^- \to K^+\pi^-\pi^-$ and 3 lepton pairs ($e^+e^+, \mu^+\mu^+, e^+\mu^+$).
- $D^- \to K^+\pi^-\pi^-$ fitted to a vertex. M_D with ±10MeV of PDG value
- Form a likelihood ratio R_s from 4 likelihood variables
  - Fisher discriminant of Fox-Wolfram moments
  - $\cos(\theta_B)$, polar angle of B flight direction in c.m.
  - E_{miss} , missing energy
  - δZ, difference in impact parameter of 2 leptons.

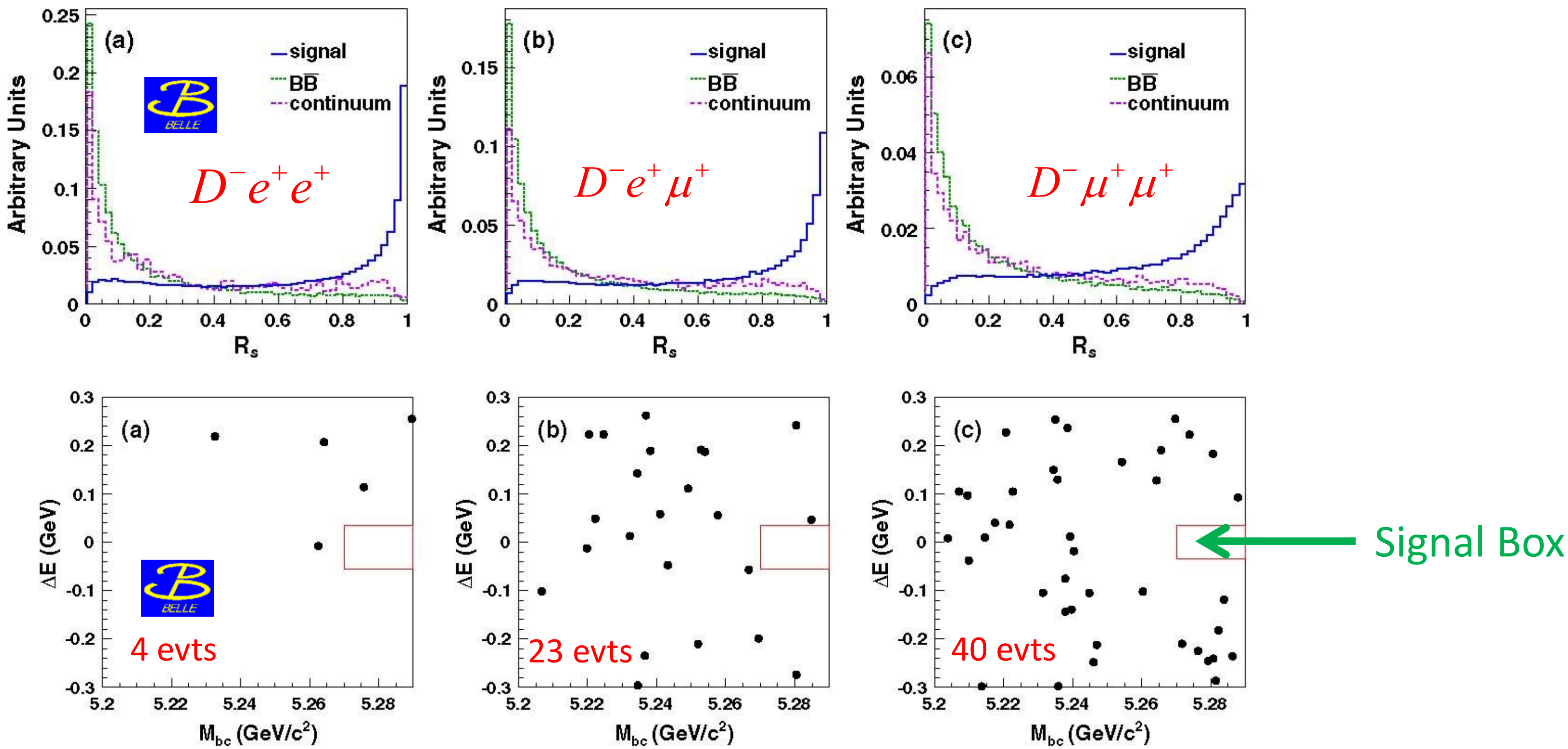


- Optimise cut on R_s using figure of merit FOM using MC signal efficiency and expected number of background events:

$$FOM = \varepsilon_{sig} \Big/ \sqrt{N_{bkg}}$$

- Rejects 99% of background. Signal efficiency 1.2%-1.9% signal.

$B^- \to D^- l^+ l^+$

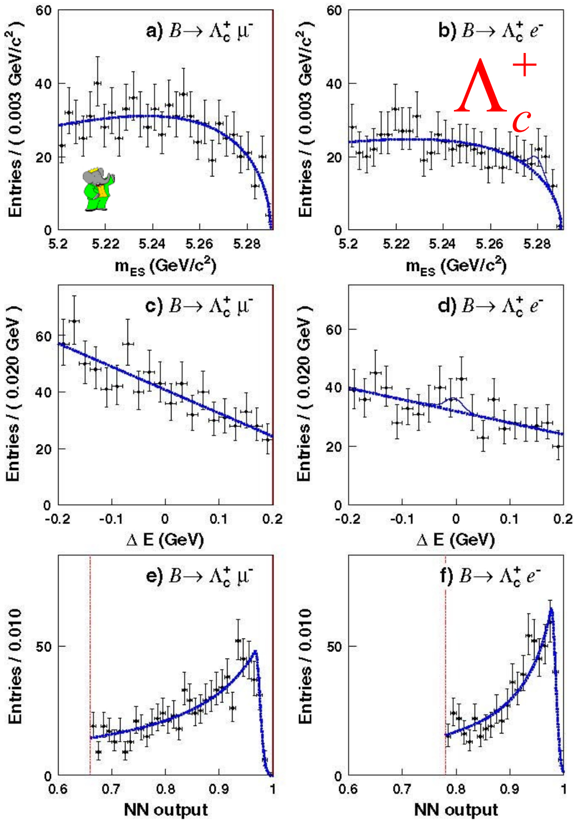


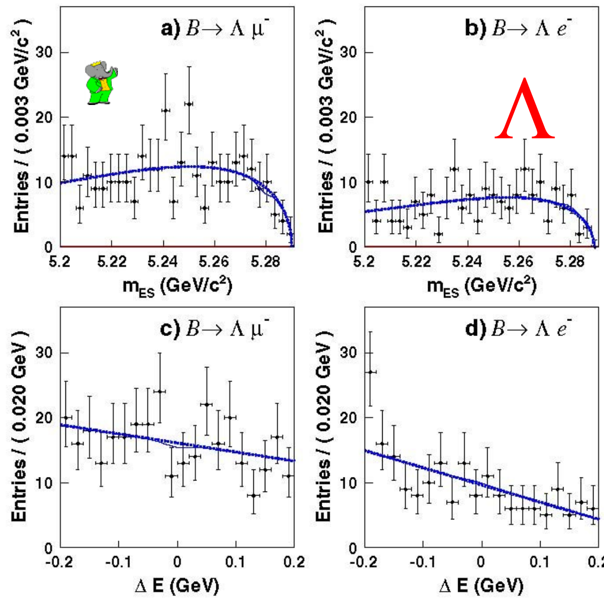
Mode	$\epsilon(\%)$	N_{obs}	N^{bkg}_{exp}	U.L. $(\times 10^{-6})$
$B^+ \to D^- e^+ e^+$	1.2	0	0.18 ± 0.13	< 2.6
$B^+ \to D^- e^+ \mu^+$	1.3	0	0.83 ± 0.29	< 1.8
$B^+ \to D^- \mu^+ \mu^+$	1.9	0	1.10 ± 0.33	< 1.1

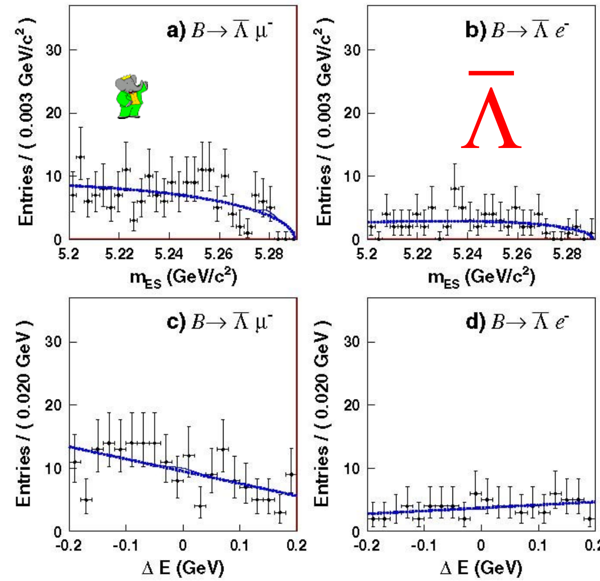
$B \to \Lambda l^+$

- Violate both Baryon and Lepton Number conservation. Highly suppressed.
- Analysis ignores any Λ polarisation.
- Only look at electron and muon modes.
- $\Lambda^+_c \to pK^-\pi^+$, $\Lambda \to p\pi^{-\,+}$, $\bar{\Lambda} \to \bar{p}\pi^+$. Tracks constrained to a common vertex and mass compatible with $\Lambda_{(c)}$.
- Repeat vertex constraint for B meson.
- Reject Λ with perpendicular flight distance < 0.2 cm (Λ $c\tau$ = 7.89cm).
- Demand >4 charged tracks to reject radiative Bhabhas where the photon converts to e^+e^-.
- Neural net (NN) with 6 event-shape variables for background rejection. ML based on M_{ES} and ΔE. NN is 3rd variable for Λ_c only.
- Systematics are included as a Gaussian constraint in the fit.

$B \to \Lambda l^+$



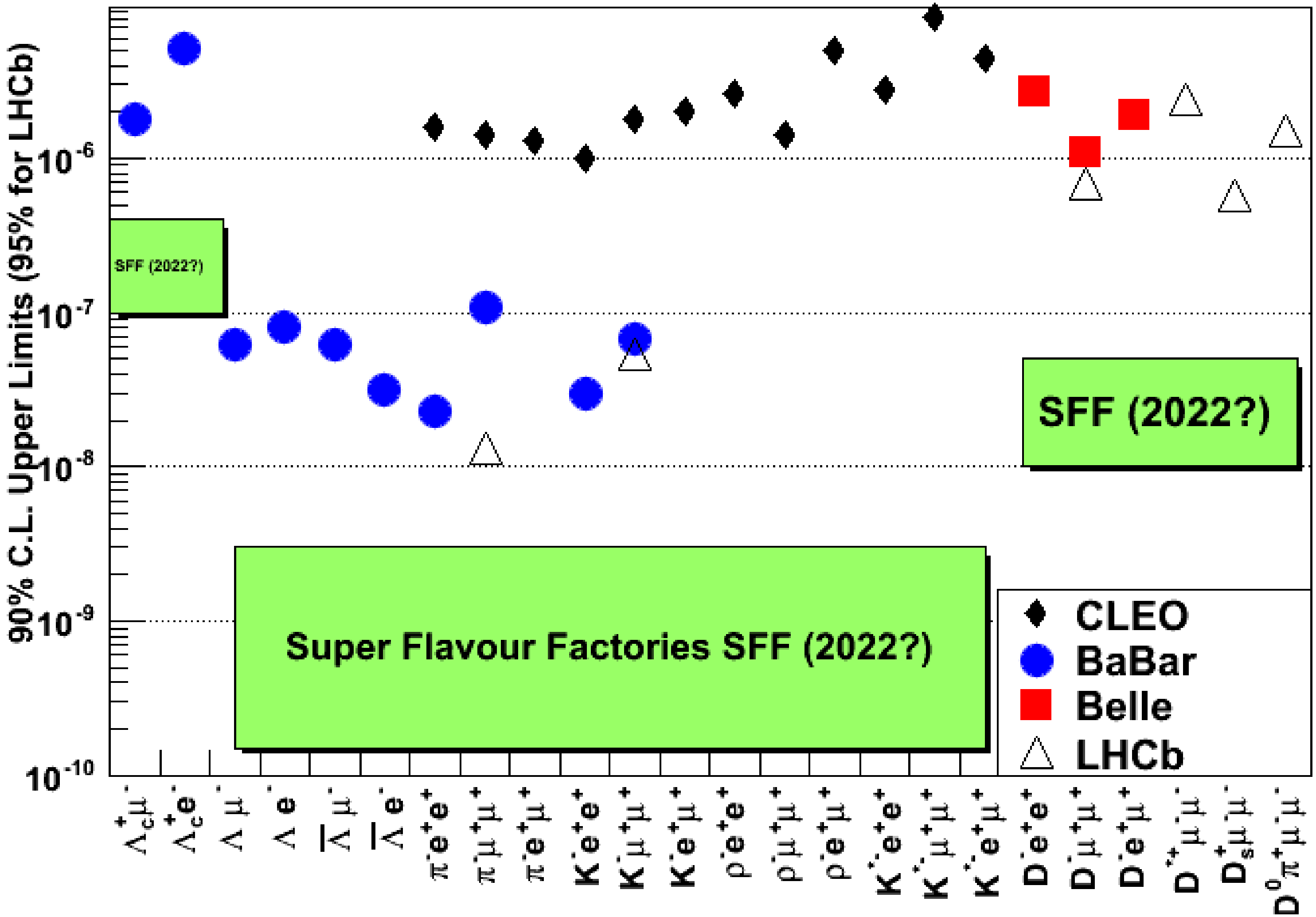




First measurements of upper limits

Decay Mode	N_{cand}	$\mathcal{B}(\times 10^{-8})$	$\epsilon(\%)$	$\mathcal{B}_{90\%}(\times 10^{-8})$
$B^0 \to \Lambda_c^+ \mu^-$	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

Summary of LNV results in B decays



(my extrapolations)

LNV in B meson decays conclusion

- The B Factories have improved the upper limits by 2 orders of magnitude (10^{-8}- 10^{-7}) since CLEO.
- Current limits closely follow LFV limits.
- There are still a number of searches (at least 8) from CLEO days that could be quickly made with current B Factory data.
- All-muon modes will continue to be improved over the next few years at LHCb.
- Super Flavour Factories should be able to get down to BF upper limits of 10^{-10}- 10^{-9} by 2022.