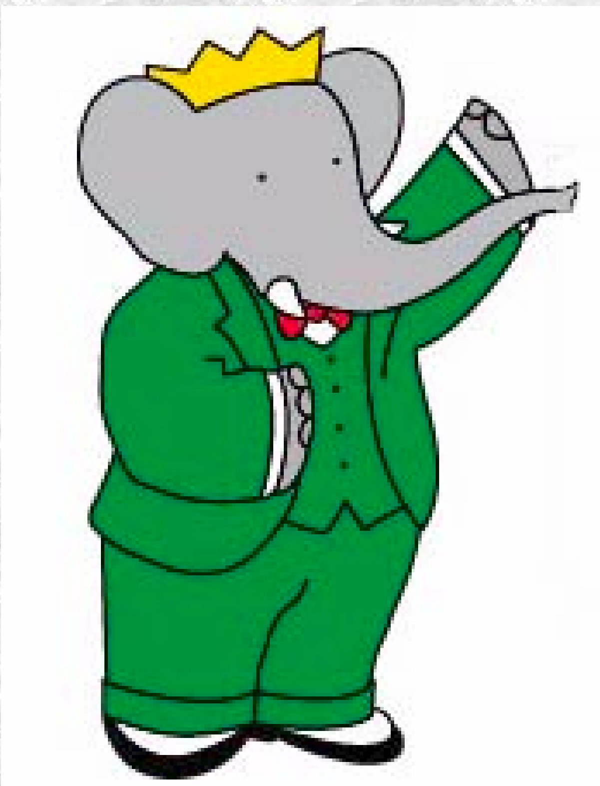
Rare B Decays at BaBar and Belle



BELLE

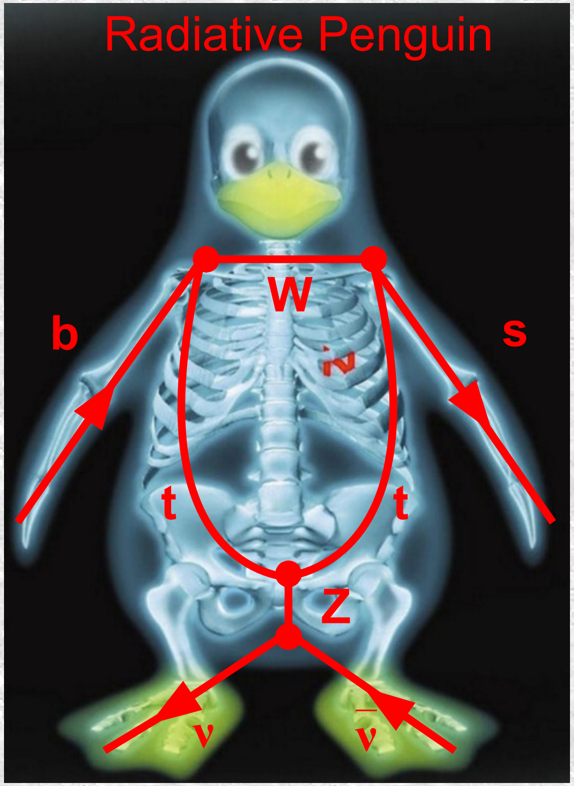
Dana Lindemann
On Behalf of the
BaBar Collaboration

Beauty 2013: Bologna, Italy
April 9, 2013

SLAC
NATIONAL ACCELERATOR LABORATORY

Outline

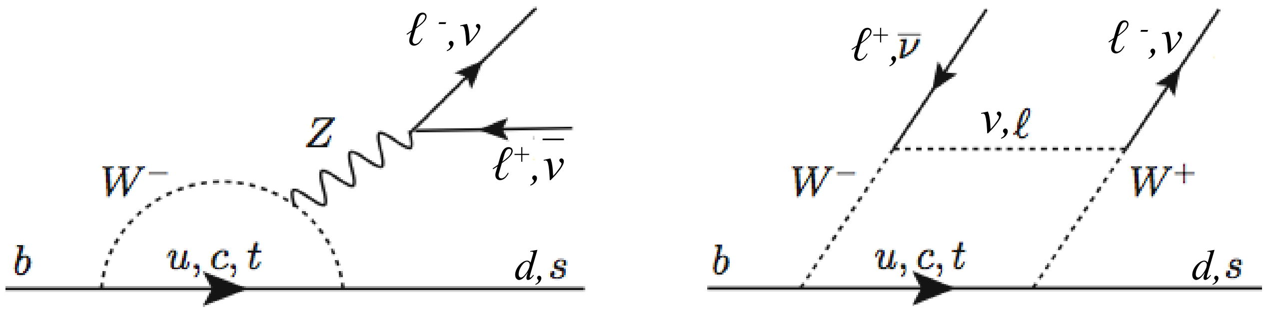
- Preliminary results of Rare B decay searches
  (using full BaBar/Belle datasets)



- Belle: $B \rightarrow h^{(*)}\nu\bar{\nu}$ arXiv: 1303:3719
- BaBar: $B \rightarrow K^{(*)}\nu\bar{\nu}$ and J/ψ, $\psi(2S) \rightarrow \nu\bar{\nu}$ arXiv: 1303:7465
- BaBar: $B \rightarrow \pi\ell^+\ell^-$, $\eta\ell^+\ell^-$ arXiv: 1303:6010
- Belle: Heavy Neutrinos arXiv: 1301:1105

Penguin Decay Motivations

Flavor-Changing Neutral Current processes are not allowed at tree-level in SM



SM expectations:

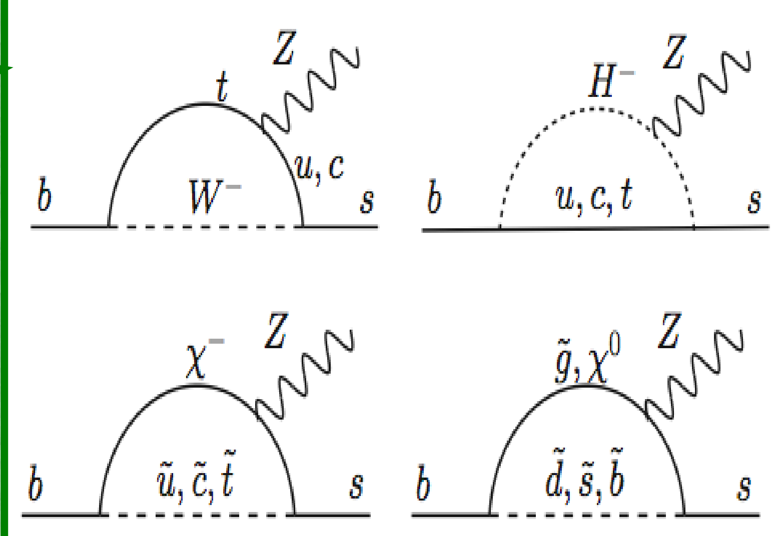
$BR(B \to K^{(*)} \nu\bar{\nu}) \sim 10^{-6}$

b→d further suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ compared to b→s :

$BR(B \to \pi/\eta\ \ell^+\ell^-) \sim 10^{-8}$

$BR(B \to \pi/\rho\ \nu\bar{\nu}) \sim 10^{-7}$

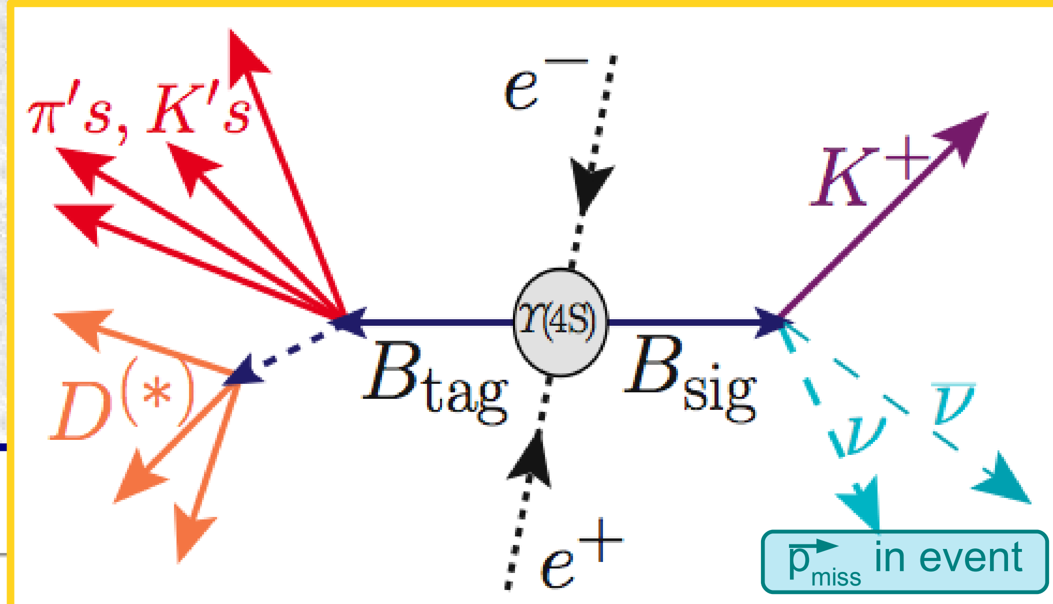
- Theoretically well-understood → precision tests of the SM
- Branching Fractions can be enhanced at same order as SM:
  - Non-standard Z or Z' couplings
  - New Physics entering in loops
  - New Physics with invisible signatures
- New Physics can also alter other observables
- Only $B \to \pi^+\mu^+\mu^-$ observed by LHCb



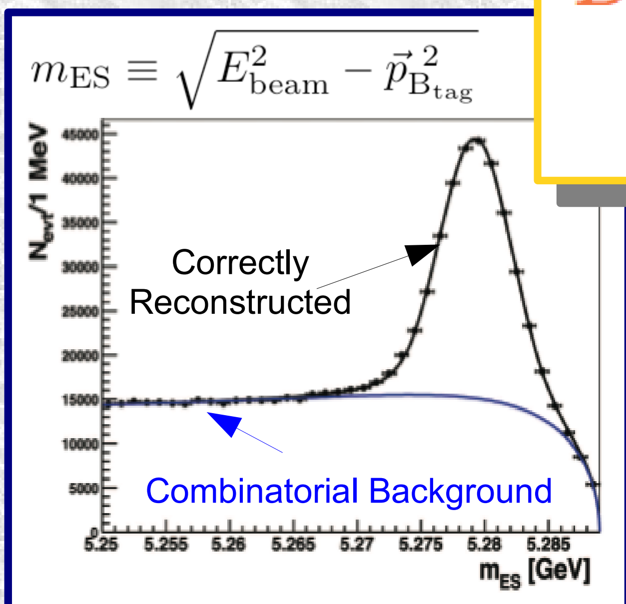
Hadronic Tag Reconstruction

- $B \rightarrow h^{(*)} \nu\bar{\nu}$ experimentally challenging: "detect" neutrinos via p_{miss}
- Exploit $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ production by reconstructing both B's

① Fully reconstruct B_{tag} in hadronic modes



② Look for signal decay in rest of the event



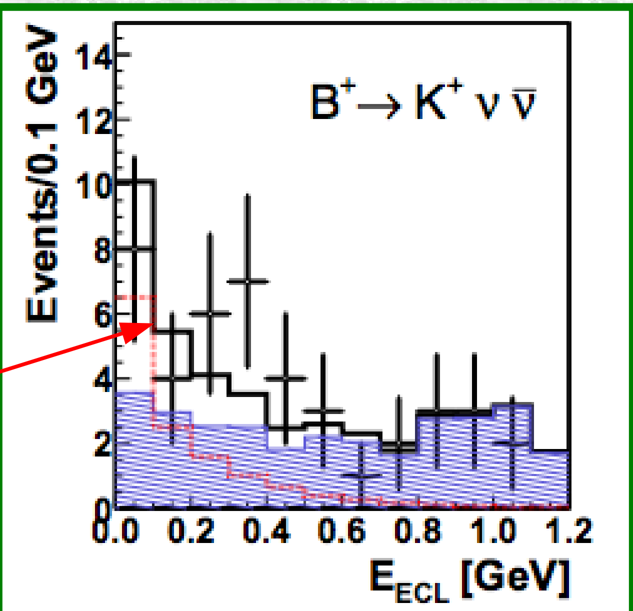
- High purity B samples
- B_{sig} 4-vector is determined
- Low reconstruction efficiency, but ~2x efficiency over past algorithms

$B \to h^{(*)} \nu\nu$ at Belle

9 channels:

- $B^+ \to K^+ \nu\bar{\nu}$
- $B^0 \to K_s^0 \nu\bar{\nu}$ ($K_s^0 \to \pi^+\pi^-$)
- $B^+ \to K^{*+} \nu\nu$
  ($K^{*+} \to K^+\pi^0, K_s^0\pi^+$)
- $B^0 \to K^{*0} \nu\bar{\nu}$ ($K^{*0} \to K^+\pi^-$)
- $B^+ \to \pi^+ \nu\bar{\nu}$
- $B^0 \to \pi^0 \nu\bar{\nu}$
- $B^+ \to \rho^+ \nu\bar{\nu}$ ($\rho^+ \to \pi^+\pi^0$)
- $B^0 \to \rho^0 \nu\bar{\nu}$ ($\rho^0 \to \pi^+\pi^-$)
- $B^0 \to \varphi \nu\bar{\nu}$ ($\varphi \to K^+K^-$)

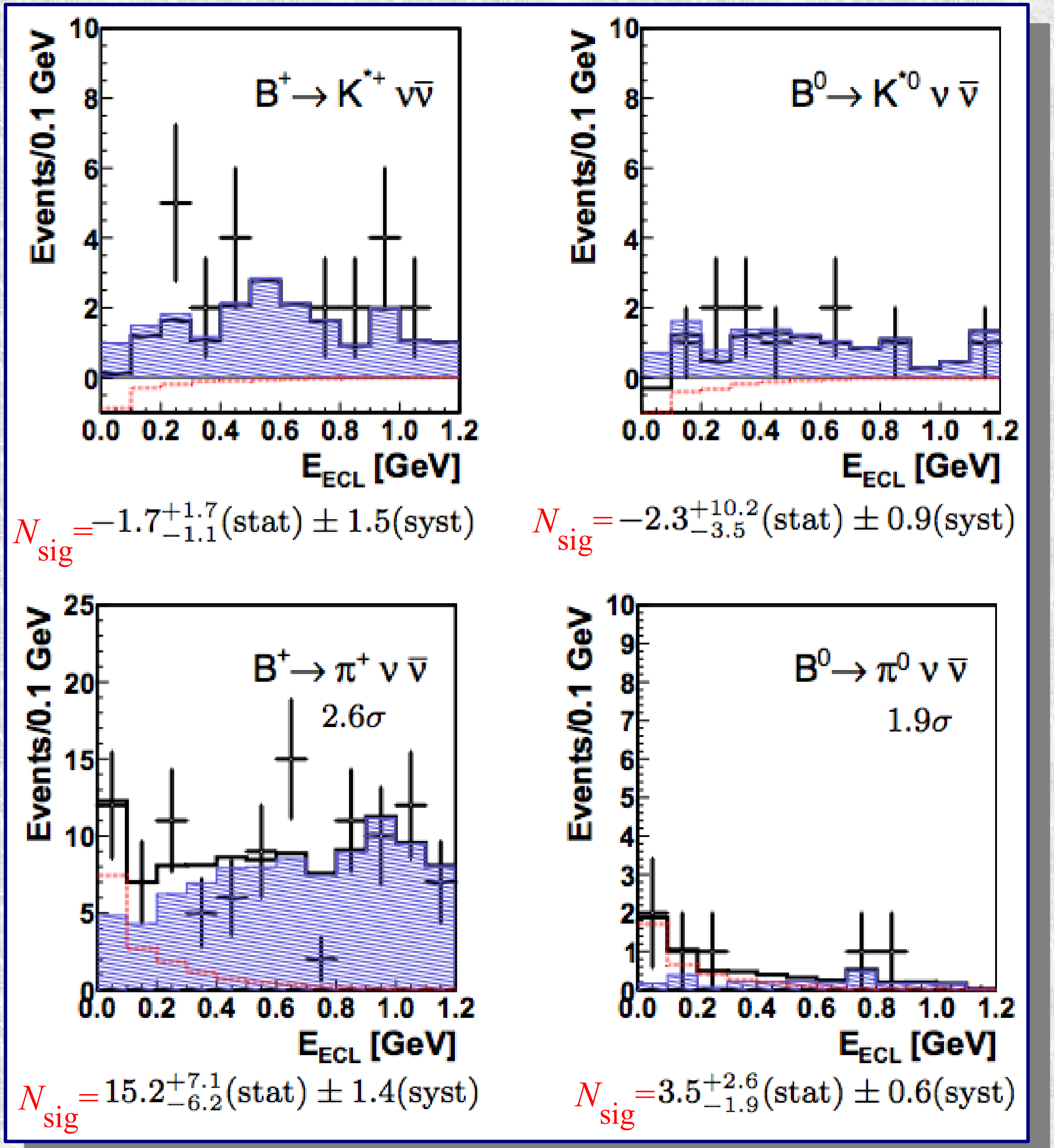
- Event Selection:
  - B_{tag} reconstruction
  - ID or reconstruct $h^{(*)}$ candidate
  - No extra tracks or π^0 in event
  - $1.6 < h^{(*)}$ momentum < 2.5 GeV/c in B_{sig} rest frame
    (except $B \to \varphi\nu\bar{\nu}$: lacks theoretical FF calcs)
  - Extended Binned Max LH fit to E_{ECL} ($=E_{extra}$)



- Extra energy in calorimeter
- Peaks at 0 for signal events

arXiv: 1303:3719
772 $B\bar{B}$

B→h(*)νν Results



Belle Preliminary!

x10^{-5}

Mode	BF Upper Limit 90%CL	Previous Belle/BaBar
$B^+ \to K^+\nu\bar{\nu}$	< 5.5	1.3
$B^0 \to K^0_s\nu\bar{\nu}$	< 9.7	5.6 (x0.5)
$B^+ \to K^{*+}\nu\bar{\nu}$	< 4.0	8
$B^0 \to K^{*0}\nu\bar{\nu}$	< 5.5	12
$B^+ \to \pi^+\nu\bar{\nu}$	< 9.8	10
$B^0 \to \pi^0\nu\bar{\nu}$	< 6.9	22
$B^+ \to \rho^+\nu\bar{\nu}$	< 21.3	15
$B^0 \to \rho^0\nu\bar{\nu}$	< 20.8	44
$B^0 \to \phi\nu\bar{\nu}$	< 12.7	5.8

Best Limits to date

- Best limits for $B \to K^*\nu\bar{\nu}$, $B \to \pi\nu\bar{\nu}$, $B \to \rho^0\nu\bar{\nu}$
- $B \to K^*\nu\bar{\nu}$ limits within factor of ~5 of SM predictions (0.7-1.3x10^{-5})

arXiv: 1303:7465
471 $B\bar{B}$

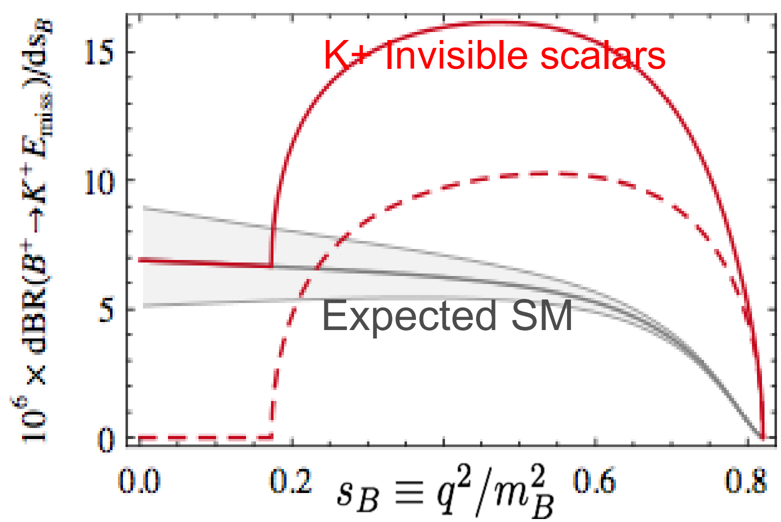
$B \to K^{(*)} \nu\bar{\nu}$ at BaBar

- 4 channels:
  - $B \to K^+ \nu\bar{\nu}$
  - $B \to K^0 \nu\bar{\nu}$ ($K^0 \to K_s^0 \to \pi^+\pi^-$)
  - $B \to K^{*+} \nu\bar{\nu}$ ($K^{*+} \to K^+\pi^0, K_s^0\pi^+$)
  - $B \to K^{*0} \nu\bar{\nu}$ ($K^{*0} \to K^+\pi^-, K_s^0\pi^0$)

- Event Selection:
  - B_{tag} Reconstruction
  - $K^{(*)}$ reconstruction
  - No additional tracks
  - Suppress continuum bkg using LHR of event-shape variables
  - Restrict to low values of E_{extra}

Kinematic variable: $s_B = q^2/m_B^2$

- Normalized invariant mass of $\nu\bar{\nu}$
- Report 2 results:
  - Cut & count in $s_B < 0.3$ for SM sensitivity
    ($K^{(*)}$ momentum of $\gtrsim$1.7 (1.8) GeV/c)
  - Partial BFs over full kinematic spectrum for New Physics sensitivity



Altmannshofer, Buras, Straub, Wick
JHEP 0904:022 (2009)

$B \to K^{(*)}\nu\nu$ Results

arXiv: 1303:7465
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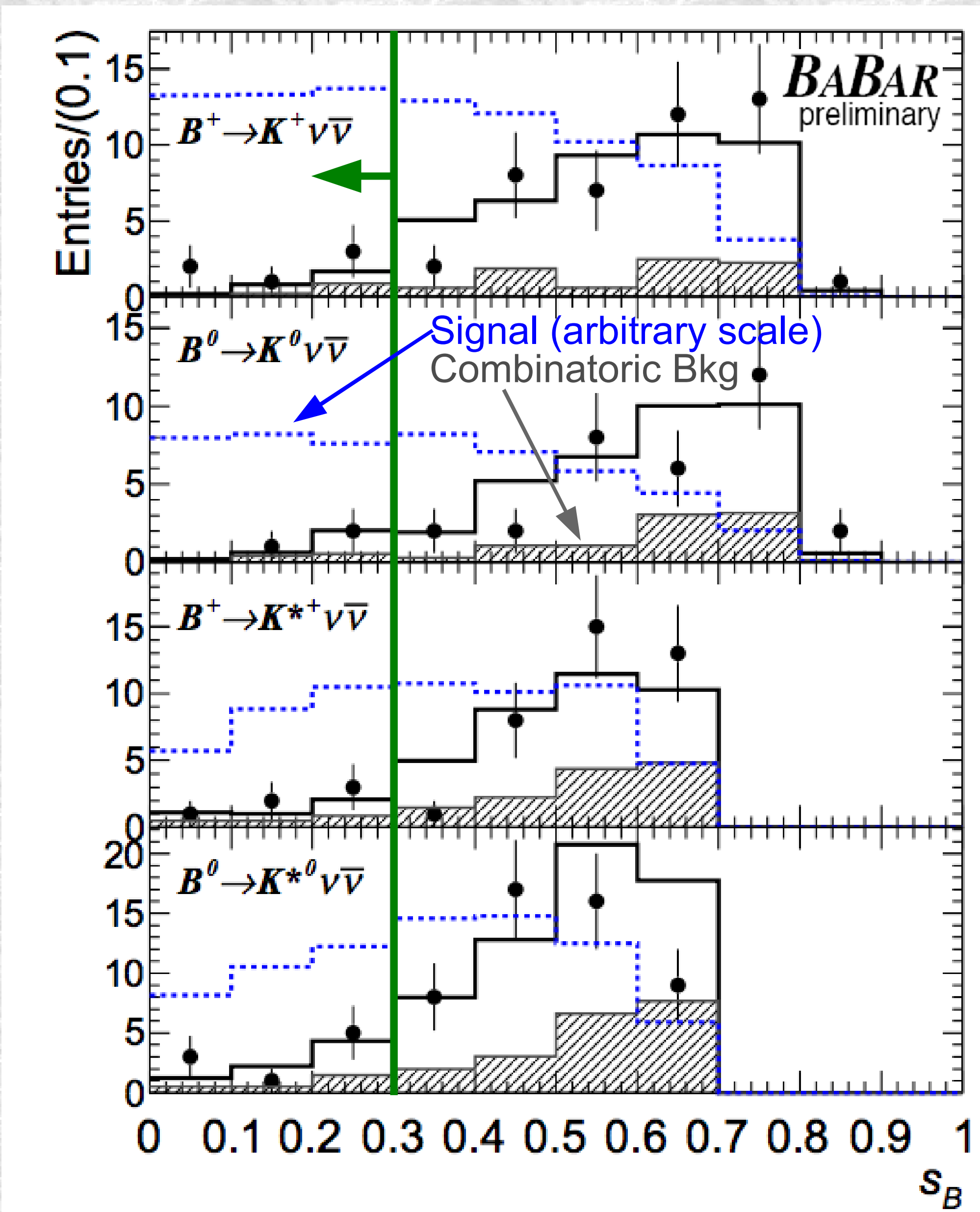
BaBar Preliminary!



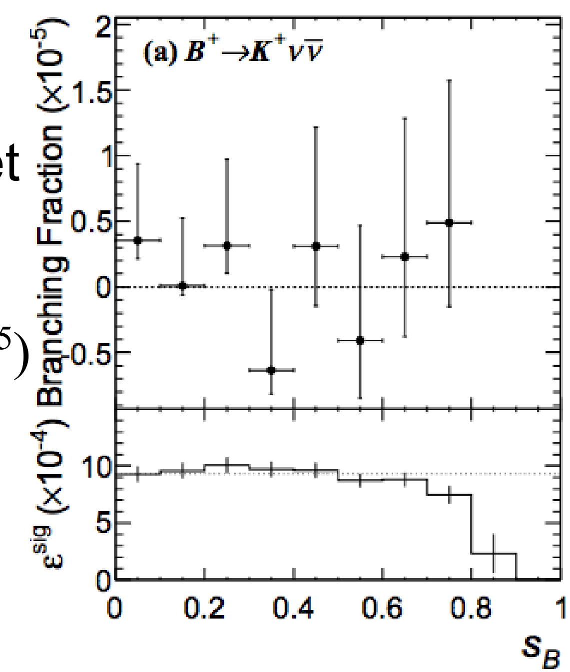
Branching fraction UL at 90% CL with $s_B < 0.3$

$K^+\nu\bar{\nu}$	$K^0\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$
(>0.4, < 3.7)	< 8.1	< 11.6	< 9.3
(>0.2, < 3.2)		< 7.9	

$\times 10^{-5}$

- Best $B \to K^0\nu\bar{\nu}$ Limits using hadronic B_{tag}'s
- First lower limits at 90% CL on $B \to K\nu\bar{\nu}$ (excess less than 2σ)

- Partial BF's set BF upper limits on several NP models at $O(10^{-5})$ (see backups)



arXiv: 1303:7465
471 $B\bar{B}$

$B \to K^{(*)}\nu\bar{\nu}$: NP Constraints

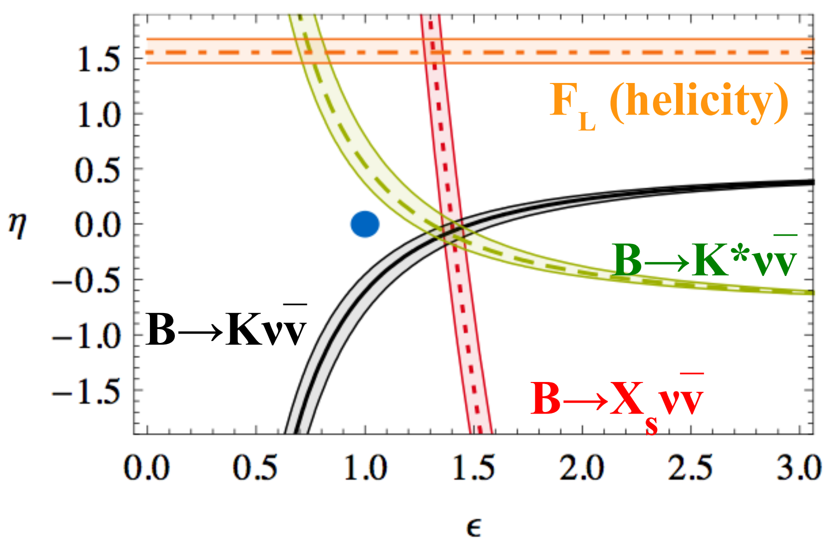
Wilson Coefficients describing $q\bar{q} \to \nu\bar{\nu}$:

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\mathrm{SM}}^\nu|}$$

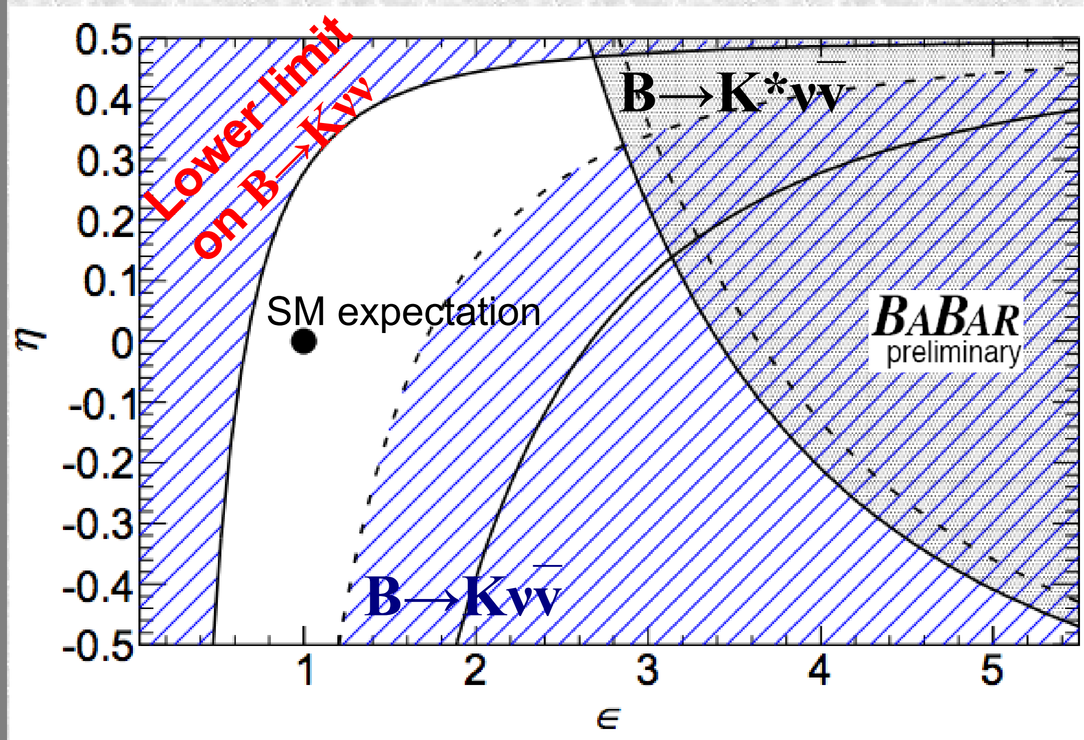
$$\eta = \frac{-\mathrm{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

RH current = 0 in SM

New Physics scenario with invisible scalar contributions
(Only theoretical uncertainties shown)



Altmannshofer, Buras, Straub, Wick, JHEP 0904:022 (2009)



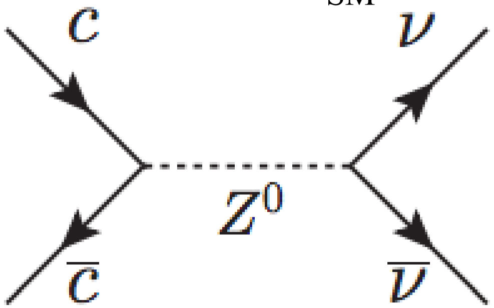
2012 BaBar constraints
Most stringent SL-tag constraints:
$B+ \to K+\nu\bar{\nu} < 1.3 \times 10^{-5}$
$B+ \to K^*+\nu\bar{\nu} < 9.0 \times 10^{-5}$

BaBar PRD 82, 112002 (2010)
BaBar PRD 78, 072007 (2008)

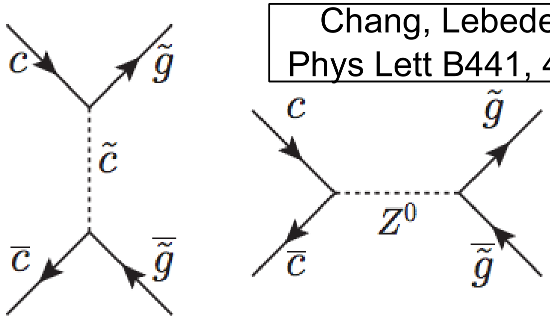
arXiv: 1303:7465
471 $B\bar{B}$

J/ψ, $\psi(2S) \to \nu\bar{\nu}$ at BaBar

- Narrow $c\bar{c}$ resonances to invisible decays can only occur in the SM via Z^0
  - $BR(J/\psi \to \nu\bar{\nu})_{SM} \approx 2.5 \times 10^{-8}$

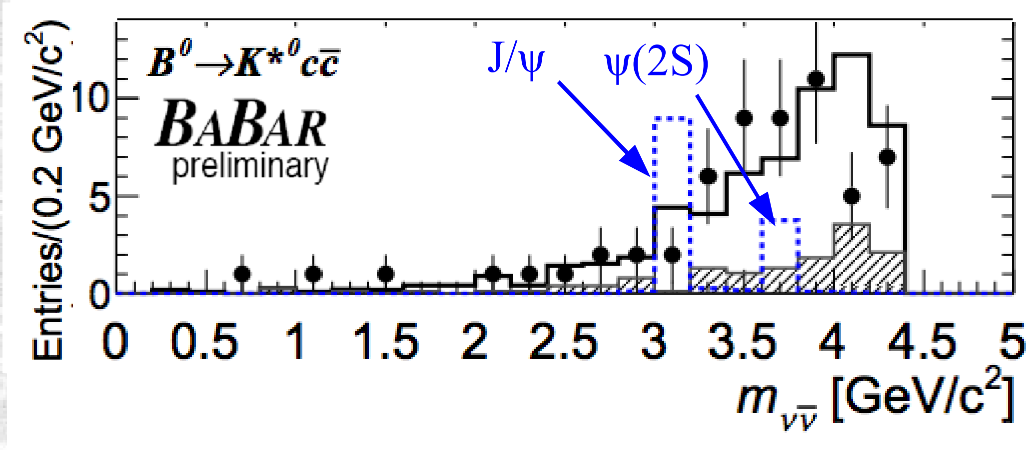


- New Physics (*e.g.* SUSY, low-mass dark matter) can increase or decrease BF
  - $BR(\psi \to \chi^0\bar{\chi}^0) \sim 10^{-5}$



Chang, Lebedev, & Ng, Phys Lett B441, 419 (1998)

- Extension of $B \to K^{(*)}\nu\bar{\nu}$ analysis
- Same event selection, but restrict $m_{\nu\bar{\nu}}$ (*i.e.* s_B) to mass of J/ψ and $\psi(2S)$



BaBar Preliminary!

$J/\psi \to \nu\bar{\nu} < 3.9 \times 10^{-3}$

$\psi(2S) \to \nu\bar{\nu} < 15.5 \times 10^{-3}$

First ever search!

$B \to \pi/\eta\ \ell^+\ell^-$ at BaBar

arXiv:1303:6010
471 $B\bar{B}$

SM expected rates:

$$\mathcal{B}(B^+ \to \pi^+\ell^+\ell^-) = (1.96\text{–}3.30) \times 10^{-8}$$

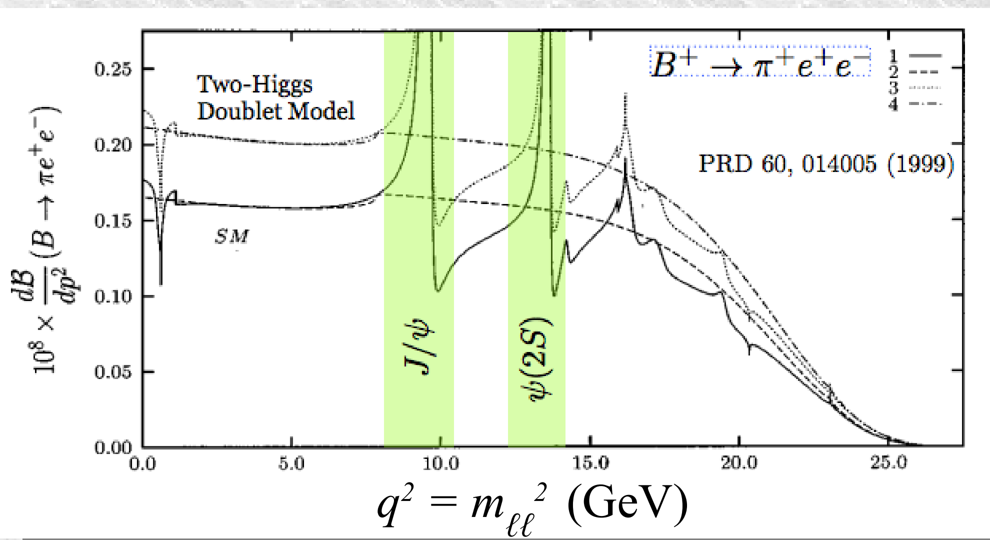
$$\mathcal{B}(B^0 \to \eta\ell^+\ell^-) = (2.5\text{–}3.7) \times 10^{-8}$$

Expect ~10 signal events in full BaBar dataset of 471 $B\bar{B}$

6 channels (where $\ell = e$ or μ):

- $B^0 \to \pi^0\ \ell^+\ell^-$
- $B^+ \to \pi^+\ \ell^+\ell^-$
- $B^0 \to \eta\ \ell^+\ell^-$ ← First ever search!

($\eta \to \pi^+\pi^-\pi^0$ or $\eta \to \gamma\gamma$)



- **Inclusive** Event Selection:
  - (No B_{tag} reco necessary)
  - Lepton pair + π or η candidate
  - $m_{\ell\ell}$ veto on J/ψ and $\psi(2S)$, used as high-statistics control sample
  - Continuum and $B\bar{B}$ background suppressed with 4 neural nets
  - Suppression of $e^+e^- \to e^+e^- q\bar{q}$

arXiv:1303:6010
471 $B\bar{B}$

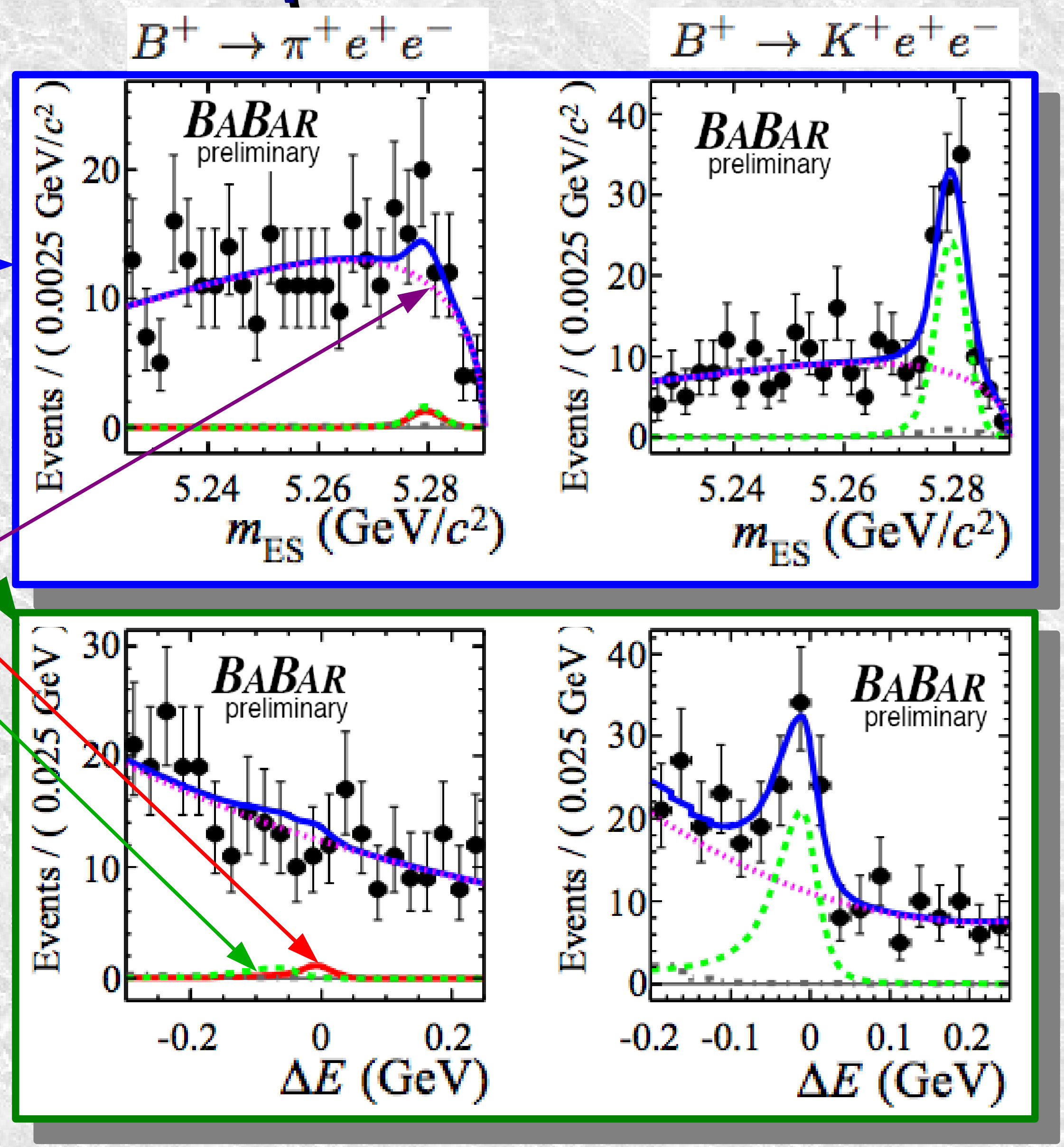
Fit to B→π/η ℓ⁺ℓ⁻

- 2D unbinned max likelihood fit:

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

$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$

Combinatoric Bkg
Signal
B→K⁺ℓ⁺ℓ⁻



- Large B→K⁺ℓ⁺ℓ⁻ bkg (mis-IDed π)
  - Simultaneous fit with π⁺ℓ⁺ℓ⁻
  - Provides BF validation
- Also did lepton-flavor and/or isospin constrained fits to combine channels

arXiv:1303:6010
471 $B\bar{B}$

$B \to \pi/\eta\ \ell^+\ell^-$ Results

BaBar Preliminary!

Branching Fraction UL at 90% CL

Mode	$\mathcal{B}\,(10^{-8})$	Upper limit (10^{-8})	Previous BABAR (10^{-8})	Belle (10^{-8})
$B^+ \to \pi^+ e^+ e^-$	$4.3^{+5.9}_{-4.7} \pm 2.0$	12.5	18	8.0
$B^0 \to \pi^0 e^+ e^-$	$1.2^{+5.4}_{-4.0} \pm 0.2$	8.4	14	22.7
$B^0 \to \eta e^+ e^-$	$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8	-	-
$B^+ \to \pi^+ \mu^+ \mu^-$	$-0.6^{+4.4}_{-3.2} \pm 0.9$	5.5	28	6.9
$B^0 \to \pi^0 \mu^+ \mu^-$	$-0.3^{+5.3}_{-3.6} \pm 0.6$	6.9	51	18.4
$B^0 \to \eta \mu^+ \mu^-$	$-2.0^{+9.7}_{-6.6} \pm 0.4$	11.2	-	-
$B \to \pi e^+ e^-$	$4.0^{+5.1}_{-4.2} \pm 1.6$	11.0	-	-
$B \to \pi \mu^+ \mu^-$	$-0.7^{+4.1}_{-3.1} \pm 1.2$	5.0	-	-
$B^+ \to \pi^+ \ell^+ \ell^-$	$1.6^{+3.6}_{-3.0} \pm 1.2$	6.6	12	4.9
$B^0 \to \pi^0 \ell^+ \ell^-$	$0.5^{+3.6}_{-2.9} \pm 0.3$	5.3	12	15.4
$B \to \pi \ell^+ \ell^-$	$1.6^{+3.2}_{-2.7} \pm 1.0$	6.4	9.1	6.2
$B^0 \to \eta \ell^+ \ell^-$	$-2.8^{+6.6}_{-5.2} \pm 0.3$	5.9	-	-

Best Limits to date

First ever limits

Constrained by: both ℓ-flavor isospin

$2.4 \pm 0.6 \pm 0.2$

LHCb (1 fb^{-1}) observation
JHEP12 125 (2012)

- Best limits to date for $B^0 \to \pi^0\ \ell^+\ell^-$
- First search for $B^0 \to \eta\ \ell^+\ell^-$
- Limits within a factor of 2-3 of SM predictions

arXiv: 1301:1105
772 $B\bar{B}$

Heavy Neutrinos at Belle

- Neutrino oscillations
- Dark Matter
- Baryogenesis
- Smallness of observed m_ν due to see-saw mechanism?

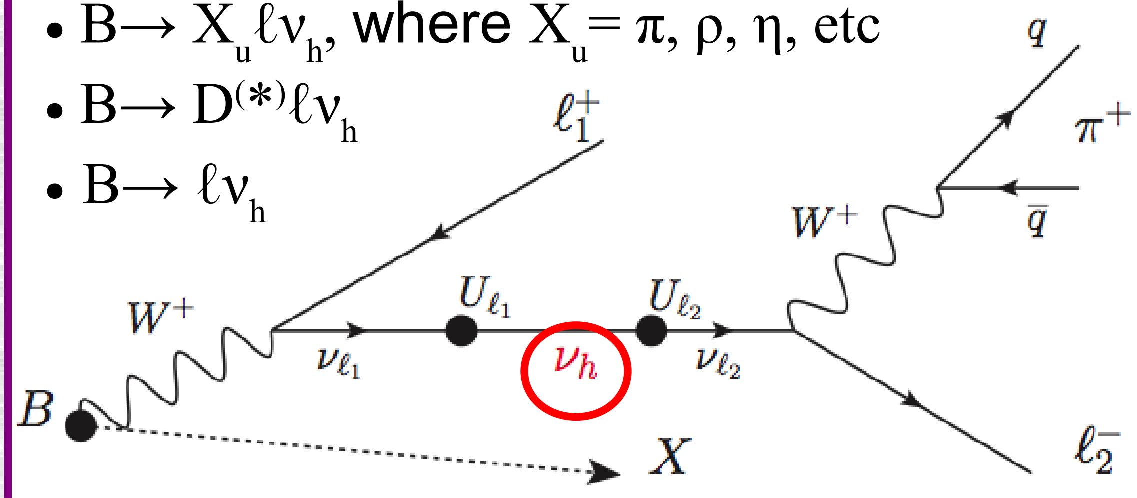
Could be explained with heavy right-handed neutrinos (*e.g.*, νMSM)

Gorbunov & Shaposhniko
JHEP 0710, 015 (2007)

- $|U_{e,\mu}|$ = lepton mixing with ν_h (similar to quark sector CKM)
- **Long expected flight** so partial reconstruction used to boost efficiency

Search for $\nu_h \rightarrow \ell^+\pi^-$ in the decays:

- $B \rightarrow X_u \ell \nu_h$, where $X_u = \pi, \rho, \eta$, etc
- $B \rightarrow D^{(*)} \ell \nu_h$
- $B \rightarrow \ell \nu_h$



Heavy Neutrinos at Belle

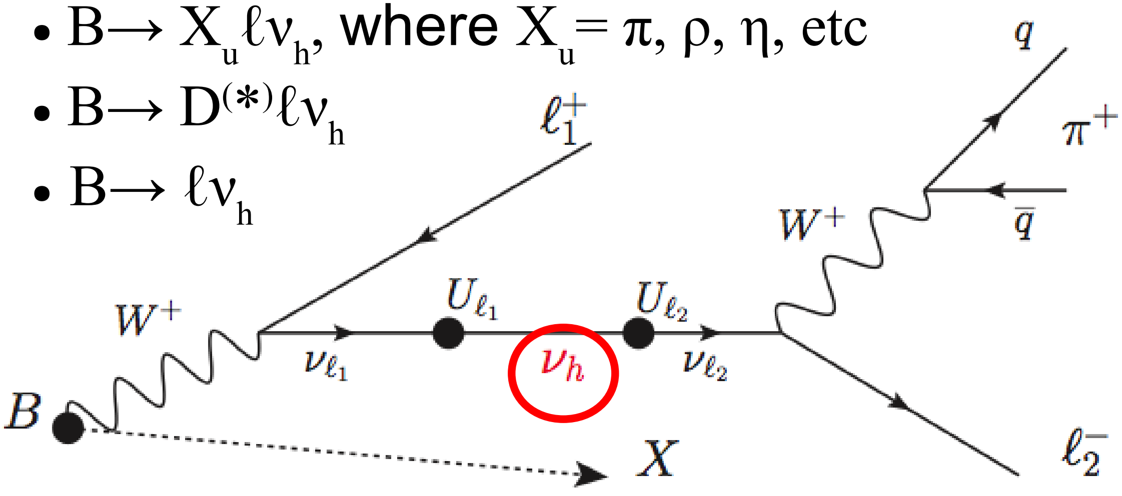
arXiv: 1301:1105
772 $B\bar{B}$

Event Selection:

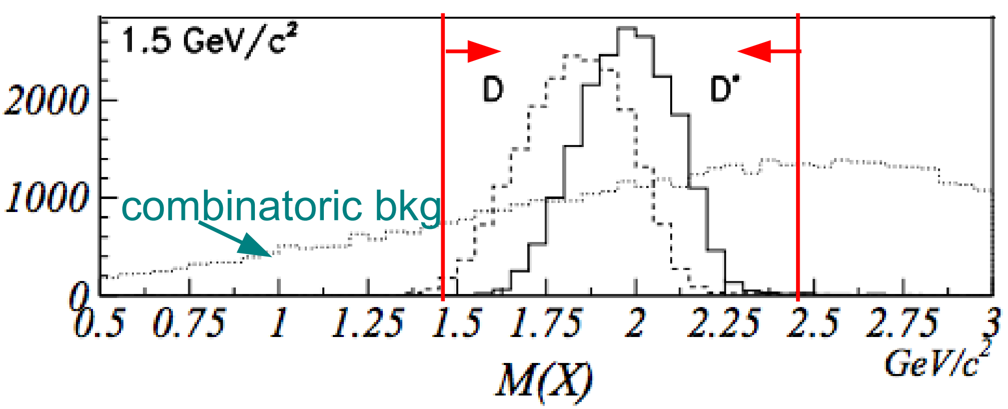
- Find $\ell^{\pm}(\ell^{+}\pi^{-})$ candidates
  - Unrestricted 2^{nd} lepton charge (Dirac fermions produce oppositely charged ℓ's)
- $(\ell^{+}\pi^{-})$ must form vertex displaced from IP, 2^{nd} lepton originates from IP
- 2 mass regions
  - If $M(\nu_h) < 2$ GeV/c^2, only reconstruct $B\to D^{(*)}\ell\nu_h$
- D mass constraint for $B\to D^{(*)}\ell\nu_h$ decays

Search for $\nu_h\to\ell^{+}\pi^{-}$ in the decays:

- $B\to X_u\ell\nu_h$, where $X_u = \pi, \rho, \eta$, etc
- $B\to D^{(*)}\ell\nu_h$
- $B\to \ell\nu_h$



For $B\to D^{(*)}\ell\nu_h$ decays:

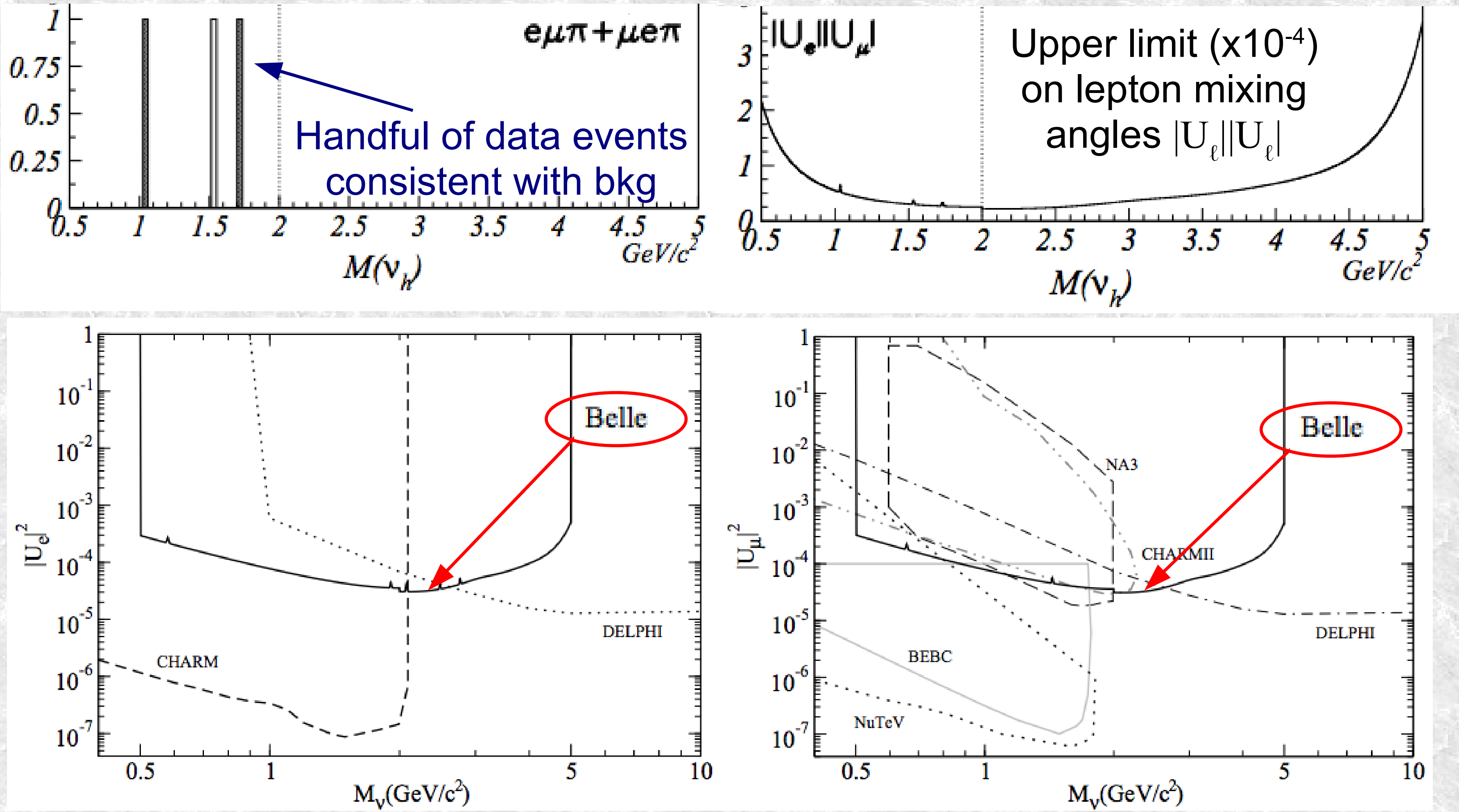


$$M_X^2 \equiv (E_{CM} - E_{\ell\ell\pi})^2 - P_{\ell\ell\pi}^2 - P_B^2$$

Heavy Neutrinos Results

arXiv: 1301:1105
772 $B\bar{B}$

- Bins of 3 MeV, and extrapolate within empty regions using fits
  - At M_ν = 2.0 GeV/c²: $|U_{e,\mu}|^2 < 3.1 \times 10^{-5}$ and $|U_e||U_\mu| < 2.2 \times 10^{-5}$
    - $BR(B\to X\ell\nu_h) \cdot BR(\nu_h\to\ell\pi^+) < 7.5 \times 10^{-7}$



Conclusions

- New results on rare B decays from BaBar and Belle
  - Best limits for $B \to K^* \nu \bar{\nu}$, $B \to \pi \nu \bar{\nu}$, $B \to \rho^0 \nu \bar{\nu}$
  - First lower limits for $B \to K \nu\nu$ & partial BFs for NP sensitivity
  - First search for $\psi(2S) \to \nu \bar{\nu}$
  - Best limits for $B \to \pi^0 \ell^+ \ell^-$
  - First search for $B \to \eta \ell^+ \ell^-$
  - New B-factory Heavy Neutrinos Search
- No evidence of signal in any mode, consistent with SM & tighter constraints on New Physics scenarios
- Belle II sensitivity expected to reach SM-expected BF values for $B \to K^{(*)} \nu \bar{\nu}$ and $B \to \pi/\eta \ell^+ \ell^-$

Back-ups

arXiv: 1303:7465
471 $B\bar{B}$

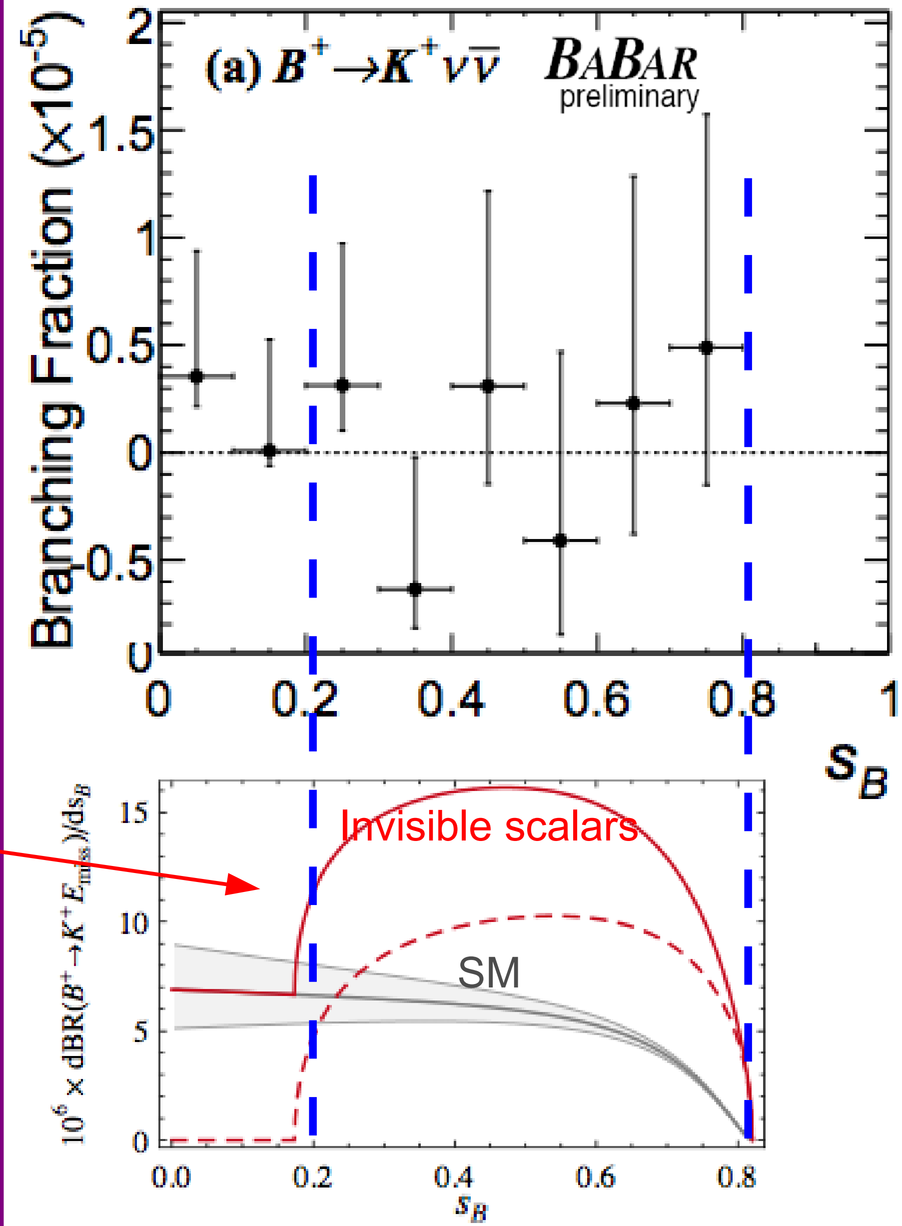
$B \to K^{(*)} \nu\bar{\nu}$ Partial BFs

- Partial branching fractions in $s_B = 0.1$ bins
- Provides model-independent sensitivity to New Physics models
- Places upper limits on branching fractions of several NP models at $O(10^{-5})$

BF in bin • ϵ fraction

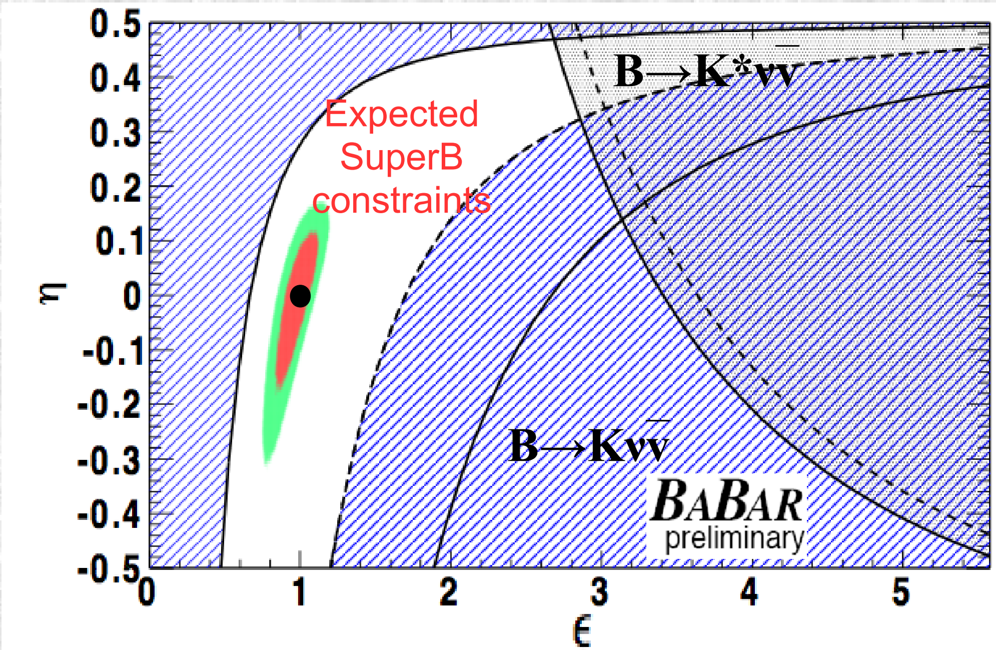
$$\Delta\mathcal{B} = \frac{N_{\rm bin}^{\rm obs} - N_{\rm bin}^{\rm bkg}}{N_B\,\epsilon_{\rm bin}^{\rm sig}} \cdot \frac{\epsilon_{\rm bin}^{\rm sig}}{\epsilon_{\rm full}^{\rm sig}}$$

- Invisible Scalars Model example:
  - ϵ fraction: ~85% in s_B bins 0.2-0.8
  - Divide "sum" of bins by ϵ fraction: BF central value = $(0.35^{+3.1}_{-1.5})\times 10^{-5}$
  - Corresponds to 90% CL BF Upper Limit of $\sim 4.2\times 10^{-5}$ for this model

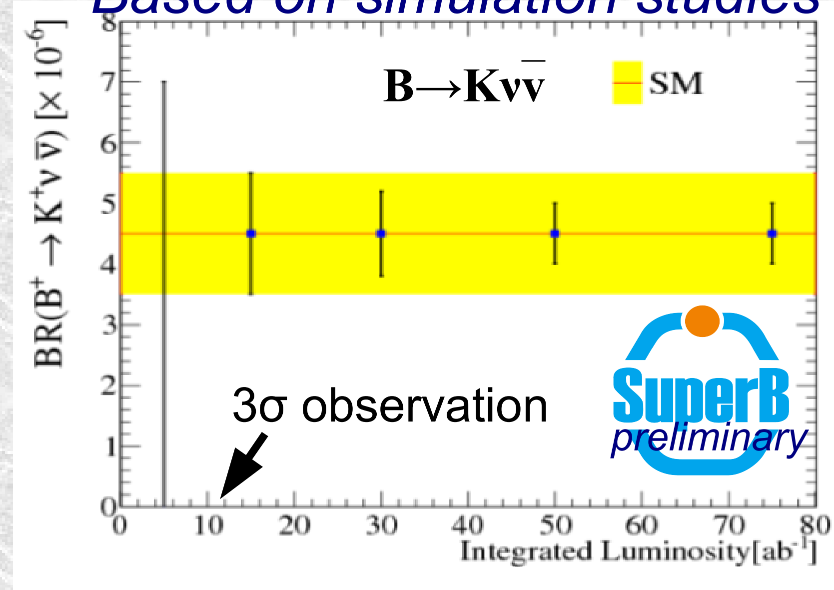


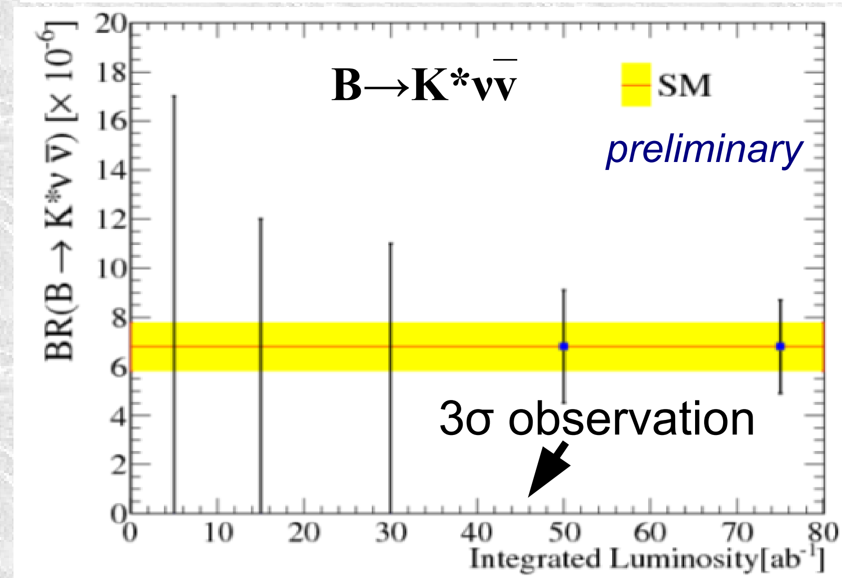
Altmannshofer, Buras, Straub, Wick, JHEP 0904:022 (2009)

$B \to K^{(*)}\nu\nu$ at Belle II
(assuming ~SuperB precision)



Based on simulation studies





arXiv:1008.1541

- Predict 15-20% precision on BF at 75 ab^{-1}
- Expect to measure F_L (polarization fraction) of $B \to K^*\nu\bar{\nu}$ to ~50% precision (currently unmeasured)
- Belle II expects ~50 ab^{-1} in 10 years of running

arXiv: 1303:3719
772 $B\bar{B}$

$B \to h^{(*)}\nu\nu$ Details

Mode	N_{tot}	N_{sig}	Significance	$\epsilon, 10^{-4}$	Upper limit	Expected limit
$B^+ \to K^+\nu\bar{\nu}$	43	$13.3^{+7.4}_{-6.6}(\text{stat}) \pm 2.3(\text{syst})$	2.0σ	5.68	$< 5.5 \times 10^{-5}$	2.2×10^{-5}
$B^0 \to K^0_s\nu\bar{\nu}$	4	$1.8^{+3.3}_{-2.4}(\text{stat}) \pm 1.0(\text{syst})$	0.7σ	0.84	$< 9.7 \times 10^{-5}$	7.3×10^{-5}
$B^+ \to K^{*+}\nu\bar{\nu}$	21	$-1.7^{+1.7}_{-1.1}(\text{stat}) \pm 1.5(\text{syst})$	–	1.47	$< 4.0 \times 10^{-5}$	5.8×10^{-5}
$B^0 \to K^{*0}\nu\bar{\nu}$	10	$-2.3^{+10.2}_{-3.5}(\text{stat}) \pm 0.9(\text{syst})$	–	1.44	$< 5.5 \times 10^{-5}$	4.6×10^{-5}
$B^+ \to \pi^+\nu\bar{\nu}$	107	$15.2^{+7.1}_{-6.2}(\text{stat}) \pm 1.4(\text{syst})$	2.6σ	3.39	$< 9.8 \times 10^{-5}$	3.8×10^{-5}
$B^0 \to \pi^0\nu\bar{\nu}$	6	$3.5^{+2.6}_{-1.9}(\text{stat}) \pm 0.6(\text{syst})$	1.9σ	1.66	$< 6.9 \times 10^{-5}$	3.6×10^{-5}
$B^+ \to \rho^+\nu\bar{\nu}$	90	$11.3^{+6.3}_{-5.4}(\text{stat}) \pm 4.1(\text{syst})$	1.7σ	1.35	$< 21.3 \times 10^{-5}$	10.2×10^{-5}
$B^0 \to \rho^0\nu\bar{\nu}$	31	$1.6^{+5.0}_{-4.1}(\text{stat}) \pm 0.4(\text{syst})$	0.4σ	0.64	$< 20.8 \times 10^{-5}$	15.7×10^{-5}
$B^0 \to \phi\nu\bar{\nu}$	3	$1.4^{+2.9}_{-0.9}(\text{stat}) \pm 0.8(\text{syst})$	0.5σ	0.58	$< 12.7 \times 10^{-5}$	8.7×10^{-5}

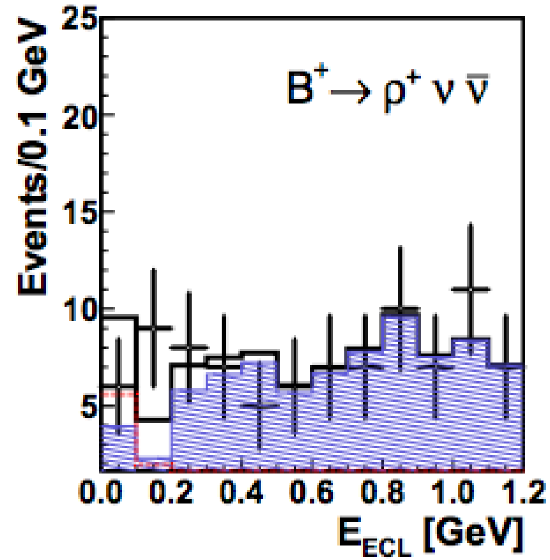
arXiv: 1303:3719
772 $B\bar{B}$

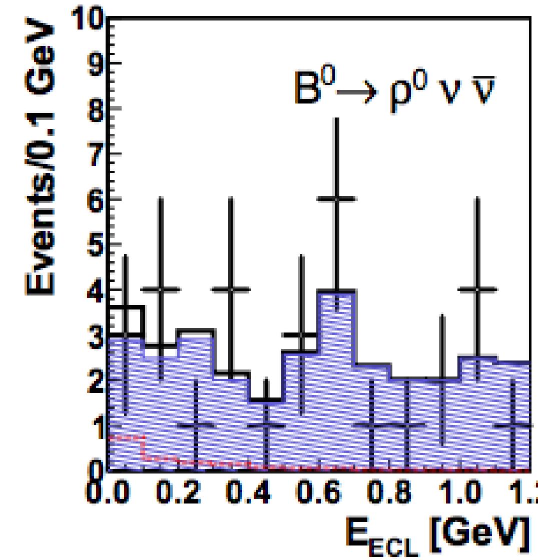
$B \to h^{(*)}\nu\nu$ Systematics

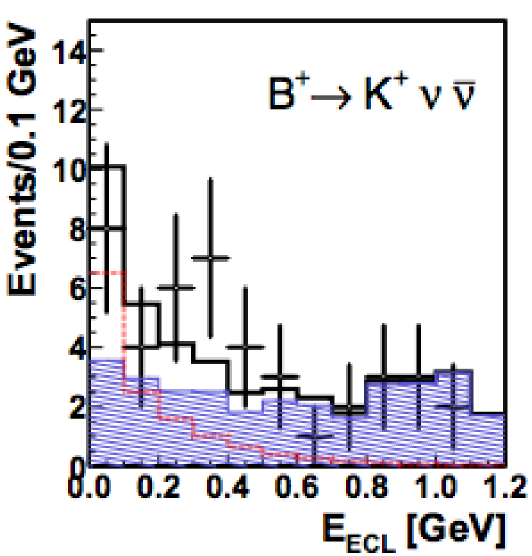
Channel	$K^+\nu\bar{\nu}$	$K_S^0\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$	$\pi^+\nu\bar{\nu}$	$\pi^0\nu\bar{\nu}$	$\rho^+\nu\bar{\nu}$	$\rho^0\nu\bar{\nu}$	$\phi\nu\bar{\nu}$
Signal yield [events]									
Background model	2.1	0.9	1.5	0.5	0.9	0.4	4.0	0.4	0.5
Fit bias	–	–	0.2	0.6	–	0.4	–	0.1	0.6
Signal normalization [%]									
Track and π^0 rejection	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
$B_{\rm tag}$ correction	4.2	4.5	4.2	4.5	4.2	4.5	4.2	4.5	4.5
Signal MC statistics	1.2	3.5	3.7	2.8	1.5	2.1	2.3	3.3	2.6
Track, π^0 and K_S^0 reconstruction efficiency	0.3	2.3	4.1	0.4	0.4	4.0	4.2	0.7	1.4
Particle identification	2.0	4.0	2.0	4.0	2.0	–	2.0	4.0	4.0
$N_{B\bar{B}}$	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Form factors	2.0	5.4	3.8	6.4	1.9	1.6	2.9	4.5	7.5

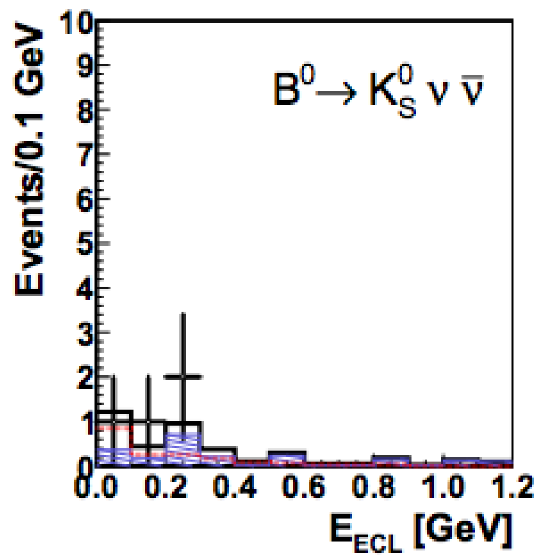
More $B \to h^{(*)} \nu\nu$ Plots

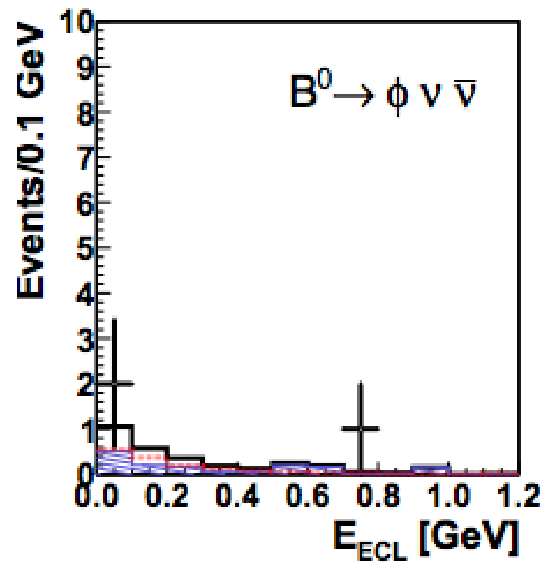
arXiv: 1303:3719
772 $B\bar{B}$











arXiv: 1303:7465
471 $B\bar{B}$

$B \to K^{(*)}\nu\nu$ Details

BABAR preliminary

	$B^+ \to K^+\nu\bar{\nu}$	$B^0 \to K^0\nu\bar{\nu}$
$N_i^{\rm comb}$	$1.1 \pm 0.4 \pm 0.0$	$0.9 \pm 0.4 \pm 0.1$
$N_i^{\rm peak}$	$1.8 \pm 0.4 \pm 0.1$	$2.0 \pm 0.5 \pm 0.2$
$N_i^{\rm bkg}$	$2.9 \pm 0.6 \pm 0.1$	$2.9 \pm 0.6 \pm 0.2$
$\varepsilon_i^{\rm sig}$ $(\times 10^{-5})$	$43.8 \pm 0.7 \pm 3.0$	$10.3 \pm 0.2 \pm 1.2$
$N_i^{\rm obs}$	6	3
Limits	$(> 0.4, < 3.7) \times 10^{-5}$	$< 8.1 \times 10^{-5}$
$\mathcal{B}_i$	$(1.5^{+1.7+0.4}_{-0.8-0.2}) \times 10^{-5}$	$(0.14^{+6.0+1.7}_{-1.9-0.9}) \times 10^{-5}$
Combined Limits	$(> 0.2, < 3.2) \times 10^{-5}$	
$\mathcal{B}(B \to K\nu\bar{\nu})$	$(1.4^{+1.4+0.3}_{-0.9-0.2}) \times 10^{-5}$	

	$B^+ \to [K^+\pi^0]\nu\bar{\nu}$	$B^+ \to [K_S^0\pi^+]\nu\bar{\nu}$	$B^0 \to [K^+\pi^-]\nu\bar{\nu}$	$B^0 \to [K_S^0\pi^0]\nu\bar{\nu}$
$N_i^{\rm comb}$	$0.8 \pm 0.3 \pm 0.0$	$1.1 \pm 0.4 \pm 0.0$	$2.0 \pm 0.5 \pm 0.1$	$0.5 \pm 0.3 \pm 0.0$
$N_i^{\rm peak}$	$1.3 \pm 0.4 \pm 0.1$	$1.2 \pm 0.4 \pm 0.1$	$5.0 \pm 0.8 \pm 0.5$	$0.2 \pm 0.2 \pm 0.0$
$N_i^{\rm bkg}$	$2.0 \pm 0.5 \pm 0.1$	$2.3 \pm 0.5 \pm 0.1$	$7.0 \pm 0.9 \pm 0.5$	$0.7 \pm 0.3 \pm 0.0$
$\varepsilon_i^{\rm sig}$ $(\times 10^{-5})$	$6.0 \pm 0.2 \pm 0.5$	$4.9 \pm 0.2 \pm 0.4$	$12.2 \pm 0.3 \pm 1.4$	$1.2 \pm 0.1 \pm 0.1$
$N_i^{\rm obs}$	3	3	7	2
Limits	$< 17.0 \times 10^{-5}$	$< 19.4 \times 10^{-5}$	$< 8.9 \times 10^{-5}$	$< 86 \times 10^{-5}$
$\mathcal{B}_i$	$(3.5^{+10.4+2.5}_{-3.2\ -1.2}) \times 10^{-5}$	$(3.0^{+12.5+3.1}_{-3.9\ -1.5}) \times 10^{-5}$	$(0.08^{+6.6+2.3}_{-3.1-1.5}) \times 10^{-5}$	$(23^{+47+15}_{-11-4}) \times 10^{-5}$
Combined Limits	$< 11.6 \times 10^{-5}$		$< 9.3 \times 10^{-5}$	
$\mathcal{B}(B^{+/0} \to K^{*+/0}\nu\bar{\nu})$	$(3.3^{+6.2+1.7}_{-3.6-1.3}) \times 10^{-5}$		$(2.0^{+5.2+2.0}_{-4.3-1.7}) \times 10^{-5}$	
Combined Limits	$< 7.9 \times 10^{-5}$			
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	$(2.7^{+3.8+1.2}_{-2.9-1.0}) \times 10^{-5}$			

arXiv: 1303:7465
471 $B\bar{B}$

J/ψ, $\psi(2S) \rightarrow \nu\bar{\nu}$ Details

BABAR preliminary

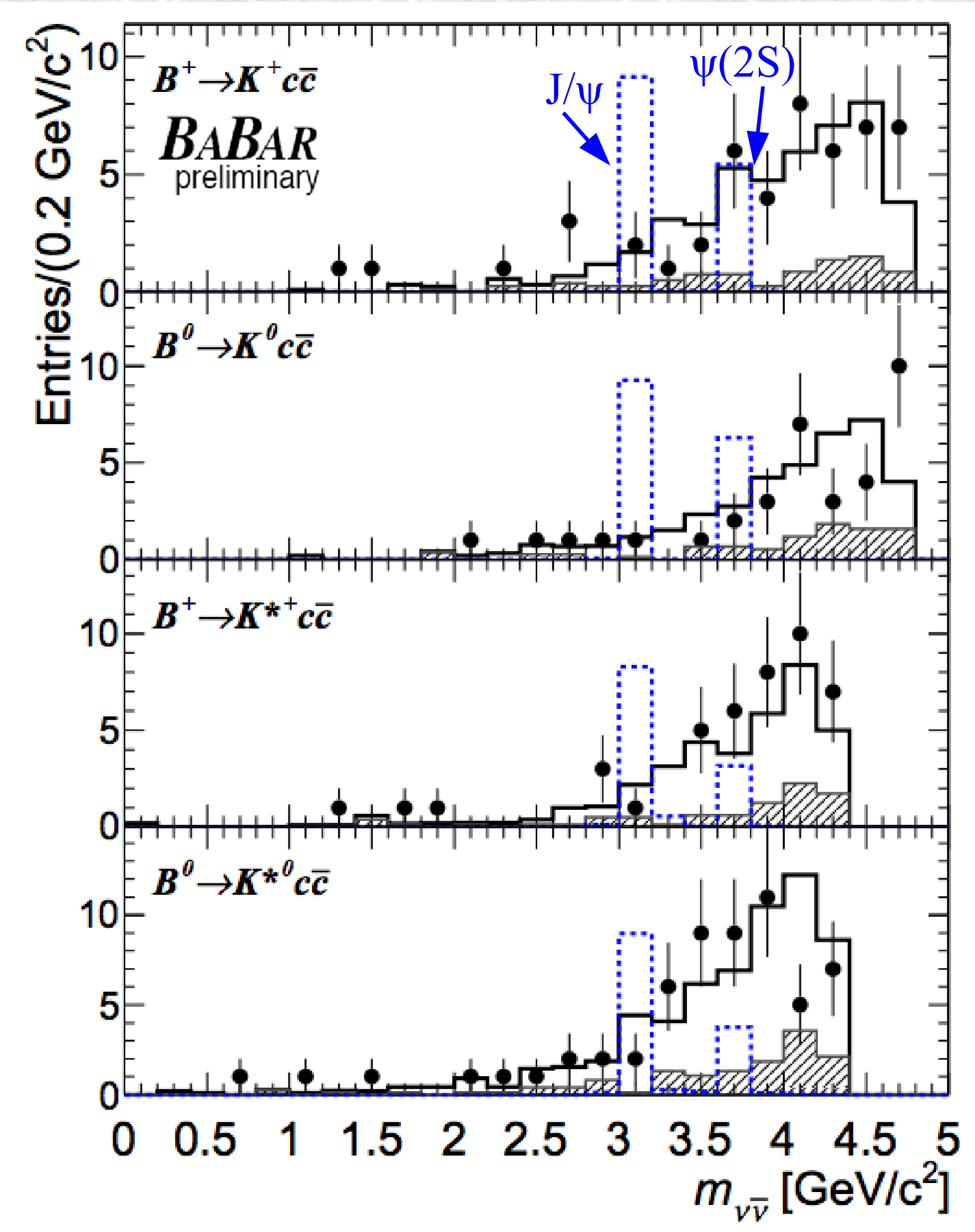
Channel	$J/\psi \rightarrow \nu\overline{\nu}$ K^+	K^0	$K^{*+} \rightarrow K^+\pi^0$	$K^{*+} \rightarrow K^0_S\pi^+$	$K^{*0} \rightarrow K^+\pi^-$	$K^{*0} \rightarrow K^0_S\pi^0$
$N_i^{\rm peak}$	$0.4 \pm 0.2 \pm 0.0$	$0.7 \pm 0.3 \pm 0.1$	$0.8 \pm 0.3 \pm 0.1$	$0.4 \pm 0.2 \pm 0.0$	$2.6 \pm 0.5 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$N_i^{\rm bkg}$	$0.5 \pm 0.2 \pm 0.0$	$0.7 \pm 0.3 \pm 0.1$	$0.8 \pm 0.3 \pm 0.1$	$0.8 \pm 0.3 \pm 0.0$	$2.8 \pm 0.5 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$\varepsilon_i^{\rm sig}$ ($\times 10^{-8}$)	$95.3 \pm 4.4 \pm 5.5$	$19.3 \pm 1.0 \pm 2.1$	$20.9 \pm 1.5 \pm 1.7$	$12.4 \pm 0.8 \pm 1.0$	$36.2 \pm 1.9 \pm 4.0$	$1.8 \pm 0.2 \pm 0.2$
$N_i^{\rm obs}$	1	0	1	0	0	1
$\mathcal{B}(J/\psi \rightarrow \nu\overline{\nu})$	$(0.2^{+2.7+0.5}_{-0.9-0.4}) \times 10^{-3}$					
Limit	$< 3.9 \times 10^{-3}$					

Channel	$\psi(2S) \rightarrow \nu\overline{\nu}$ K^+	K^0	$K^{*+} \rightarrow K^+\pi^0$	$K^{*+} \rightarrow K^0_S\pi^+$	$K^{*0} \rightarrow K^+\pi^-$	$K^{*0} \rightarrow K^0_S\pi^0$
$N_i^{\rm peak}$	$1.4 \pm 0.4 \pm 0.1$	$0.6 \pm 0.3 \pm 0.1$	$1.4 \pm 0.4 \pm 0.1$	$1.0 \pm 0.3 \pm 0.1$	$3.5 \pm 0.7 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$N_i^{\rm bkg}$	$1.6 \pm 0.4 \pm 0.1$	$0.7 \pm 0.3 \pm 0.1$	$1.4 \pm 0.4 \pm 0.1$	$1.5 \pm 0.4 \pm 0.1$	$3.9 \pm 0.7 \pm 0.3$	$0.6 \pm 0.2 \pm 0.1$
$\varepsilon_i^{\rm sig}$ ($\times 10^{-8}$)	$57.2 \pm 3.5 \pm 3.3$	$13.1 \pm 1.2 \pm 1.4$	$8.1 \pm 1.7 \pm 0.7$	$4.9 \pm 1.1 \pm 0.4$	$14.2 \pm 1.2 \pm 1.6$	$0.6 \pm 0.1 \pm 0.1$
$N_i^{\rm obs}$	3	1	1	3	5	1
$\mathcal{B}(\psi(2S) \rightarrow \nu\overline{\nu})$	$(5.6^{+7.4+1.6}_{-4.6-1.4}) \times 10^{-3}$					
Limit	$< 15.5 \times 10^{-3}$					

arXiv: 1303:7465
471 $B\bar{B}$

J/ψ, $\psi(2S) \rightarrow \nu\bar{\nu}$ Plots

BaBar Preliminary!



$$\frac{\mathcal{B}(J/\psi \rightarrow \nu\bar{\nu})}{\mathcal{B}(J/\psi \rightarrow e^+e^-)} < 6.6 \times 10^{-2}$$

$$\frac{\mathcal{B}(\psi(2S) \rightarrow \nu\bar{\nu})}{\mathcal{B}(\psi(2S) \rightarrow e^+e^-)} < 2.0$$

arXiv: 1303:7465
471 $B\bar{B}$

$K^{(*)}$, J/ψ, $\psi(2S)\rightarrow\nu\bar{\nu}$ Systematics

Source	K^+	$[K^+\pi^0]$	$[K^0_S\pi^+]$	K^0	$[K^+\pi^-]$	$[K^0_S\pi^0]$
ε_i^{sig} normalization	3.5	3.5	3.5	8.9	8.9	8.9
N_i^{bkg} normalization	2.3	2.3	2.3	6.0	6.0	6.0
K^0_S reconstruction	–	–	1.4	1.4	–	1.4
K^* reconstruction	–	2.8	2.8	–	2.8	2.8
π^0 reconstruction	–	3.0	–	–	–	3.0
E_{extra}	4.5	6.0	6.5	6.0	6.0	6.5

Source	K^+	$[K^+\pi^0]$	$[K^0_S\pi^+]$	K^0	$[K^+\pi^-]$	$[K^0_S\pi^0]$
$B\to K^{(*)}\nu\bar{\nu}$						
N_i^{peak} B's	2.8	2.8	2.8	2.8	2.8	2.8
s_B resolution	3.6	3.6	3.6	3.6	3.6	3.6
Total N_i^{peak} syst.	6.8	8.9	8.8	9.7	10.0	10.9
Total N_i^{comb} syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total ε_i^{sig} syst.	6.7	8.8	8.8	11.4	11.7	12.4
$J/\psi\to\nu\bar{\nu}$						
N_i^{peak} B's	3.5	3.5	3.5	3.5	3.5	3.5
$m_{\nu\bar{\nu}}$ resolution	1.1	2.1	0.4	0.7	0.3	1.3
Total N_i^{peak} syst.	6.2	8.6	8.4	9.3	9.6	10.5
Total N_i^{comb} syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total ε_i^{sig} syst.	5.8	8.3	8.0	10.8	11.1	11.9
$\psi(2S)\to\nu\bar{\nu}$						
N_i^{peak} B's	2.8	2.8	2.8	2.8	2.8	2.8
$m_{\nu\bar{\nu}}$ resolution	0.8	2.4	1.0	0.9	1.8	3.1
Total N_i^{peak} syst.	5.8	8.5	8.1	9.1	9.5	10.7
Total N_i^{comb} syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total ε_i^{sig} syst.	5.8	8.4	8.1	10.9	11.2	12.2

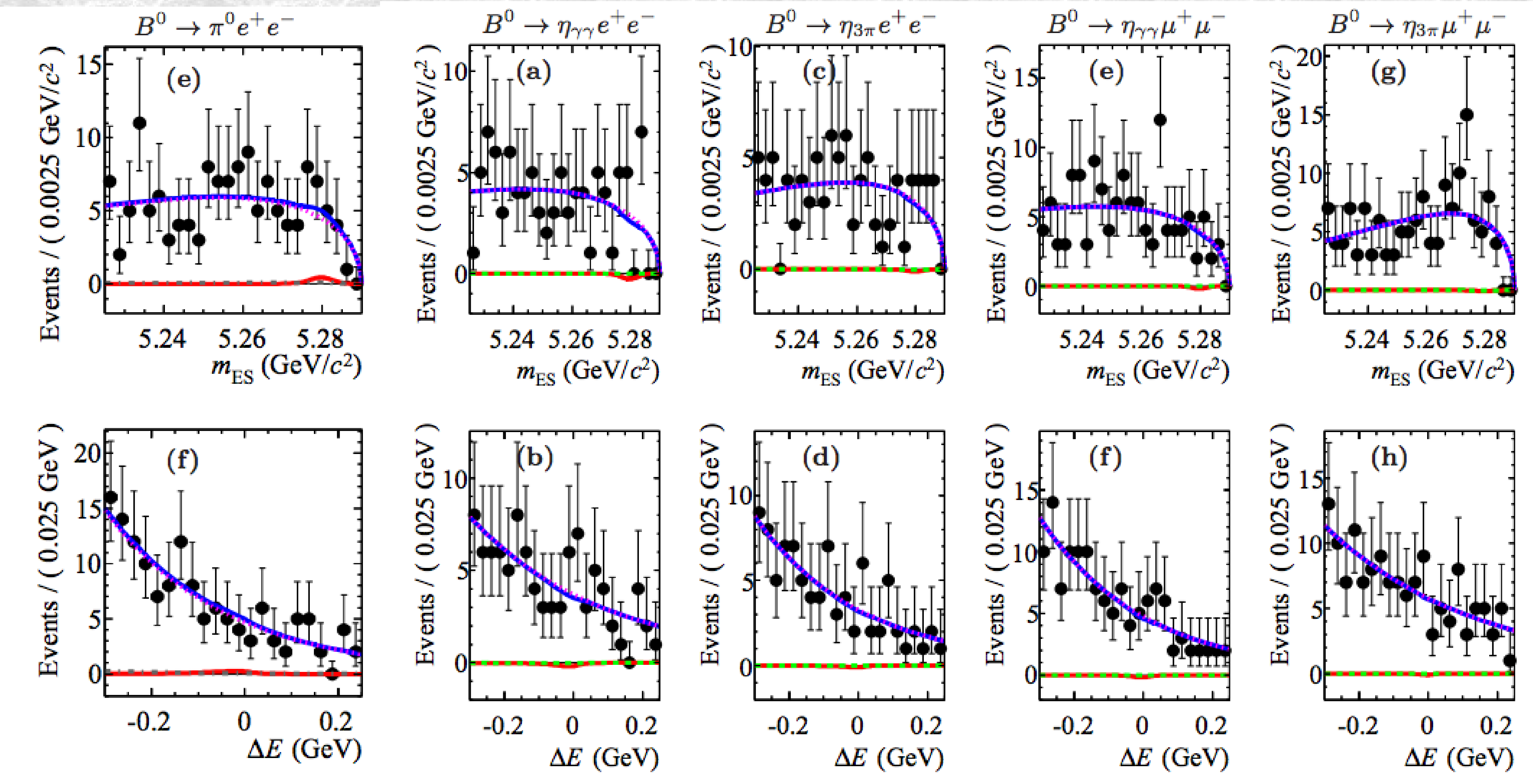
arXiv:1303:6010
471 $B\bar{B}$

$B \to \pi/\eta\ \ell^+\ell^-$ Details

Mode	ε	Yield	$\mathcal{B}\,(10^{-8})$	Upper Limit (10^{-8})
$B^+ \to \pi^+ e^+ e^-$	0.199	$4.2^{+5.7}_{-4.6}$	$4.3^{+5.9}_{-4.7} \pm 2.0$	12.5
$B^0 \to \pi^0 e^+ e^-$	0.163	$1.0^{+3.2}_{-1.1}$	$1.2^{+5.4}_{-4.0} \pm 0.2$	8.4
$B^0 \to \eta e^+ e^-$			$-4.0^{+10.0}_{-8.0} \pm 0.6$	10.8
$B^0 \to \eta_{\gamma\gamma} e^+ e^-$	0.164	$-1.2^{+3.1}_{-2.4}$		
$B^0 \to \eta_{3\pi} e^+ e^-$	0.115	$-0.5^{+1.2}_{-1.0}$		
$B^+ \to \pi^+ \mu^+ \mu^-$	0.140	$-0.5^{+3.1}_{-2.3}$	$-0.6^{+4.4}_{-3.2} \pm 0.9$	5.5
$B^0 \to \pi^0 \mu^+ \mu^-$	0.115	$-0.2^{+2.0}_{-0.7}$	$-1.0^{+5.0}_{-3.4} \pm 0.6$	6.9
$B^0 \to \eta \mu^+ \mu^-$			$-2.0^{+9.7}_{-6.6} \pm 0.4$	11.2
$B^0 \to \eta_{\gamma\gamma} \mu^+ \mu^-$	0.102	$-0.4^{+1.7}_{-1.3}$		
$B^0 \to \eta_{3\pi} \mu^+ \mu^-$	0.063	$-0.1^{+0.7}_{-0.4}$		
$B \to \pi e^+ e^-$			$4.0^{+5.1}_{-4.2} \pm 1.6$	11.0
$B \to \pi \mu^+ \mu^-$			$-0.9^{+3.9}_{-3.0} \pm 1.2$	5.0
$B^+ \to \pi^+ \ell^+ \ell^-$			$2.5^{+3.9}_{-3.3} \pm 1.2$	6.6
$B^0 \to \pi^0 \ell^+ \ell^-$			$1.2^{+3.9}_{-3.3} \pm 0.2$	5.3
$B^0 \to \eta \ell^+ \ell^-$			$-2.8^{+6.6}_{-5.2} \pm 0.3$	6.4
$B \to \pi \ell^+ \ell^-$			$2.5^{+3.3}_{-3.0} \pm 1.0$	5.9

$B \to \pi/\eta\ \ell^+\ell^-$ Plots

arXiv:1303:6010
471 $B\bar{B}$



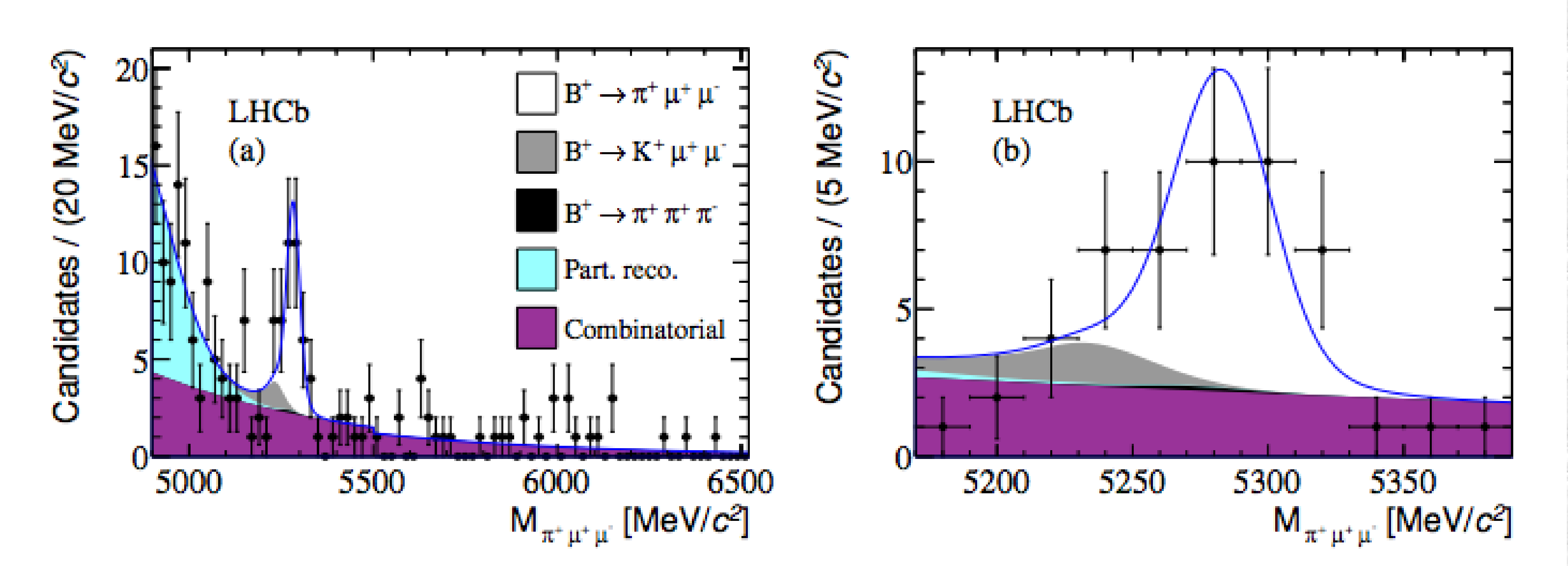
arXiv:1303:6010
471 $B\bar{B}$

$B \to \pi/\eta\ \ell^+\ell^-$ Systematics

	$\pi^+e^+e^-$	$\pi^0e^+e^-$	$\pi^+\mu^+\mu^-$	$\pi^0\mu^+\mu^-$	$\eta_{\gamma\gamma}e^+e^-$	$\eta_{3\pi}e^+e^-$	$\eta_{\gamma\gamma}\mu^+\mu^-$	$\eta_{3\pi}\mu^+\mu^-$
$N_{B\overline{B}}$	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
$\pi^0/\eta_{\gamma\gamma}$ eff.	-	3.0%	-	3.0%	3.0%	3.0%	3.0%	3.0%
Tracking eff.	0.9%	0.6%	0.9%	0.6%	0.6%	1.2%	0.6%	1.2%
lepton PID	1.3%	1.3%	1.4%	1.4%	1.4%	1.4%	1.5%	1.5%
$\pi^\pm$ PID	2.5%	-	3.5%	-	-	2.3%	-	3.7%
NN cut	1.4%	1.3%	1.5%	1.5%	1.4%	1.3%	1.5%	1.5%
Wilson coeff.	2.7%	2.3%	1.0%	1.9%	3.1%	3.1%	0.3%	0.9%
FF model	9.1%	7.7%	0.7%	7.1%	3.4%	1.3%	0.2%	1.6%
Total	10.1%	8.8%	4.4%	8.2%	5.9%	5.6%	3.8%	5.7%

Mode	$\pi^+e^+e^-$	$\pi^0e^+e^-$	$\pi^+\mu^+\mu^-$	$\pi^0\mu^+\mu^-$	ηe^+e^-	$\eta\mu^+\mu^-$
Fixed parameters	1.9	0.2	0.6	0.3	0.6	0.4
Non-parametric shapes	< 0.1	< 0.1	0.7	0.5	0.1	0.1
Hadronic peaking bkg yields	-	-	< 0.1	< 0.1	-	-
Non-hadronic peaking bkg yields	-	-	< 0.1	< 0.1	-	-
Total	1.9	0.2	0.9	0.6	0.6	0.4

LHCb Observation

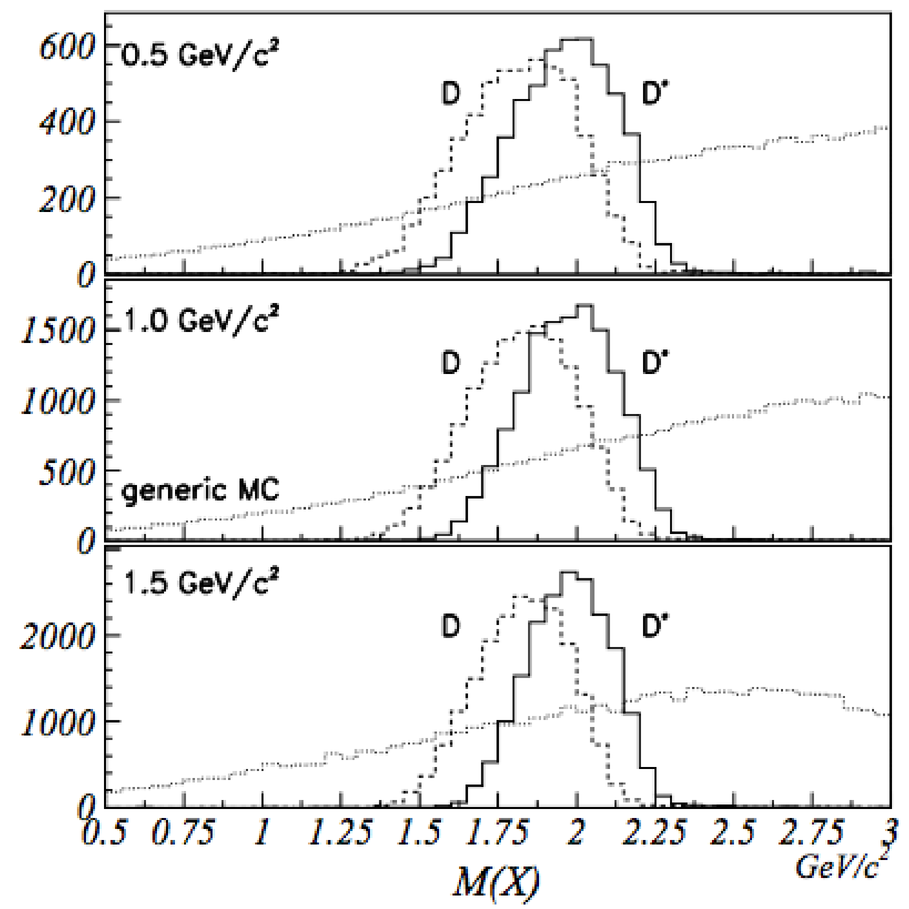


LHCb (1 fb^{-1})
JHEP12 125 (2012)

Heavy Neutrinos Systematics

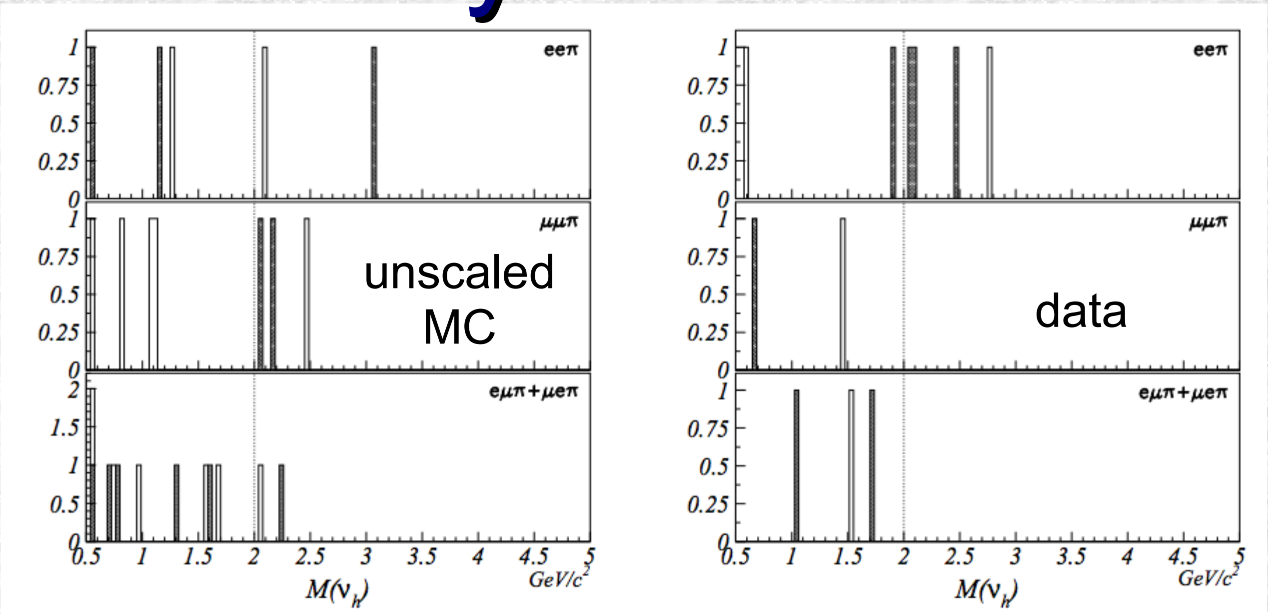
arXiv: 1301:1105
772 $B\bar{B}$

Requirement	Systematic uncertainty, %
Tracking per track	8.7
$\mathcal{R}_e(\ell_1)$	2.2
$\mathcal{R}_\mu(\ell_1)$	4.9
$\mathcal{R}_e(\ell_2)$	3.0
$\mathcal{R}_\mu(\ell_2)$	3.1
$d\phi$	5.8
dr	3.7
dz_{vtx}	10.0
χ_1^2	2.9
χ_2^2	10.1
dr_{fh}	2.9
Lepton veto	1.8
Proton veto*	1.6
Recoil mass*	4.1
Total	31.6 (31.9*)



arXiv: 1301:1105
772 $B\bar{B}$

Heavy Neutrinos Plots



filled histogram =
opposite sign leptons
open histogram =
same sign leptons