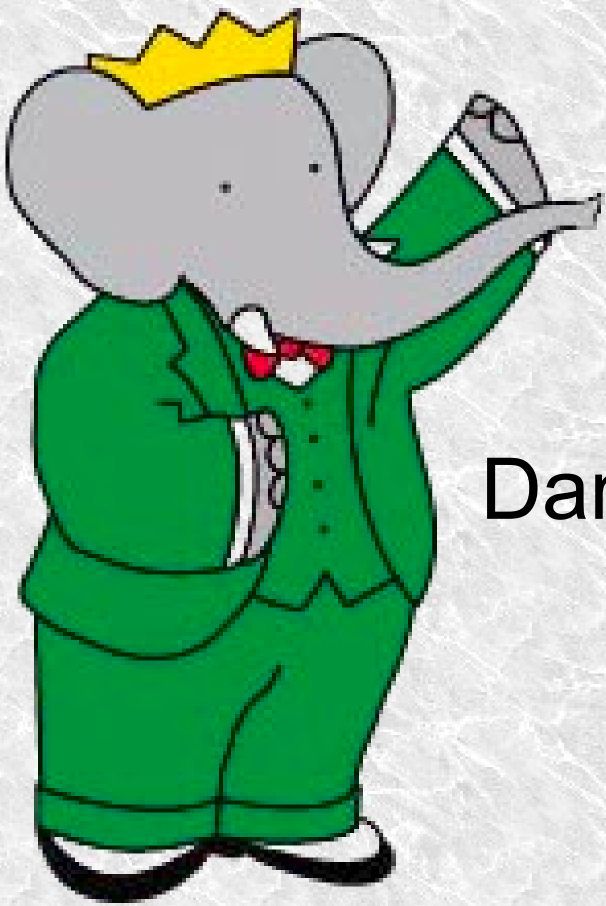
Searches for New Physics in $B \to D^{(*)}\tau\nu$, $B \to \tau\nu$, and Rare Electroweak Penguin Decays at BaBar



Dana Lindemann, SLAC

SLAC Seminar
August 27, 2013

SLAC
NATIONAL ACCELERATOR LABORATORY

Recent Results
based on full BaBar dataset

~470 million $B\bar{B}$ (429 fb^{-1})

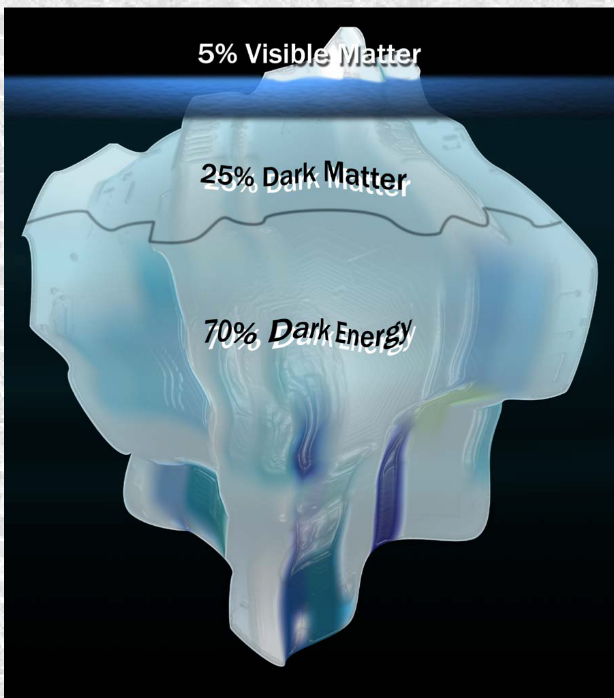
- Leptonic & Semileptonic B decays
  - $B \to \tau\nu$ PRD 88, 031102 (2013)
  - $B \to D^{(*)}\tau\nu$ PRL 109, 101802 (2012) and Additional extra studies submitted to PRD, arXiv:1303.0571
- Rare B decays via electroweak penguin decays
  - $B \to K^{(*)}\nu\bar{\nu}$ PRD 87, 112005 (2013)
  - $B \to \pi\,\ell^+\ell^-$, $\eta\,\ell^+\ell^-$ accepted by PRD, arXiv: 1303.6010

Standard Model + ??

- Standard Model extremely successful model!
  - M_W and M_Z: Spontaneous symmetry breaking

(A) Higgs found!

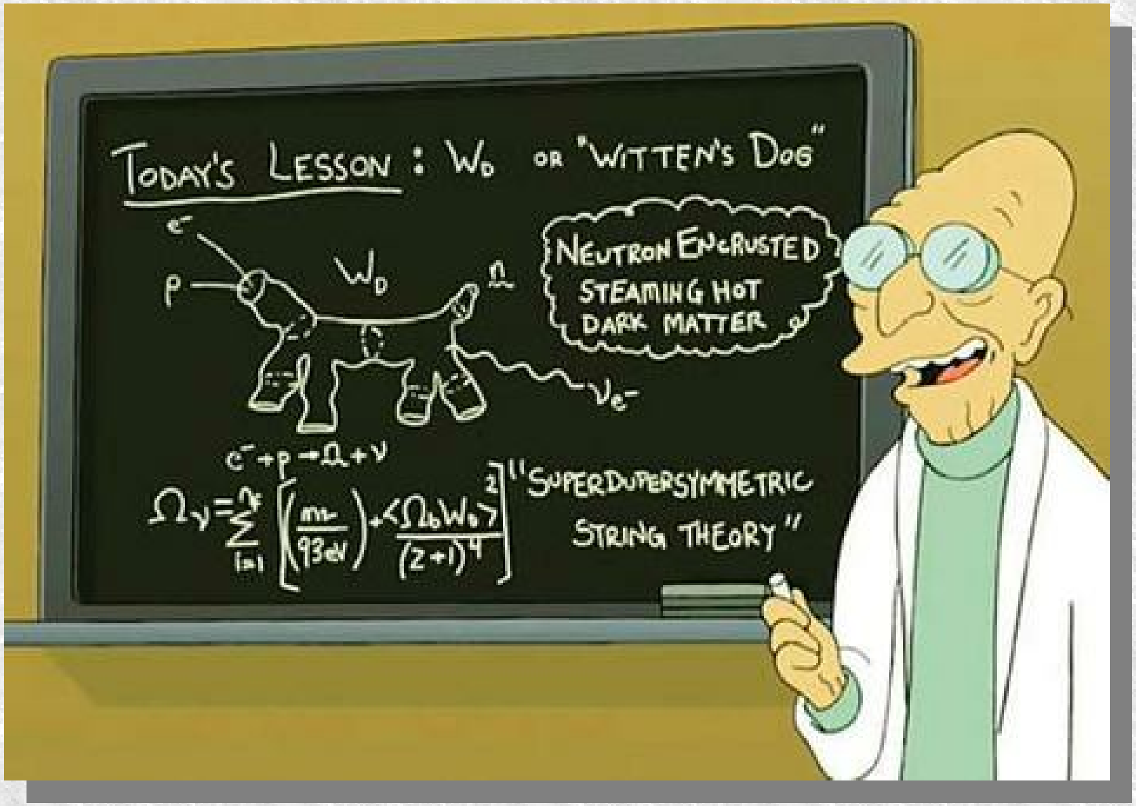
- Except... (to name a few):
  - Cosmological evidence of non-baryonic Dark Matter

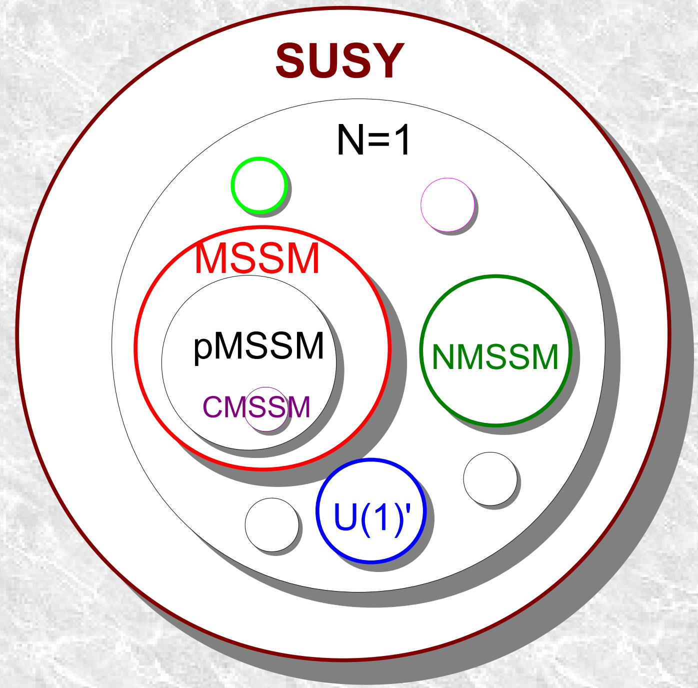


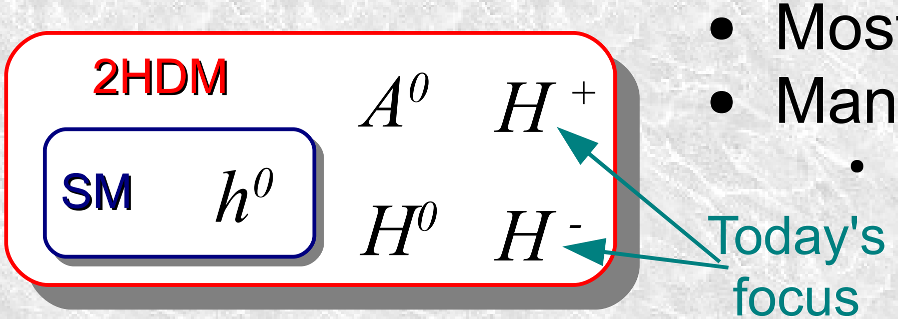
- CP-violation source for baryogenesis
- Hierarchy problem: Planck scale vs. Weak scale
- Unification of electroweak + strong forces

Standard Model + New Physics

New Physics (NP) models may alleviate most of these short-comings



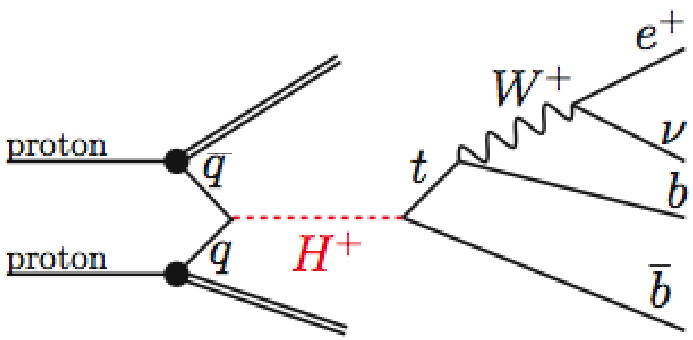




- Most NP models predict additional particles
- Many predict additional Higgs bosons
  - *e.g.* Two-Higgs Doublet Model (2HDM), as in the Higgs sector of MSSM

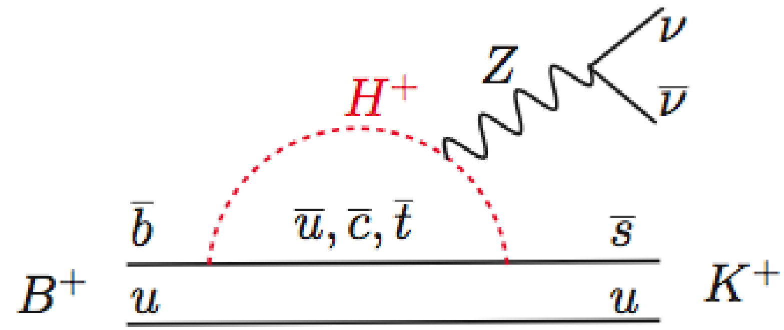
Searching for NP Particles

Direct production or Indirect detection



- Requires very high energy
- Has a limited reach
- Enables detailed study of particle

i.e. LHC, Tevatron



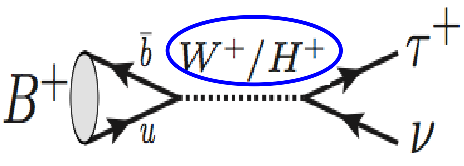
- Requires high precision to measure rare processes
- Can probe much higher mass scales (few TeV)

i.e. B-Factories (BaBar, Belle, Belle II), LHCb

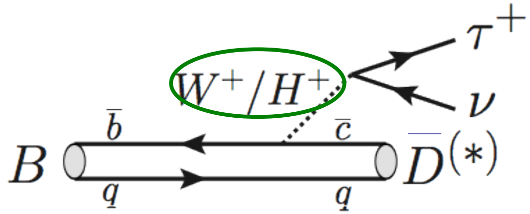
Complementary Methods

Comparison of Channels

$B \to \tau\nu$



$B \to D^{(*)}\tau\nu$

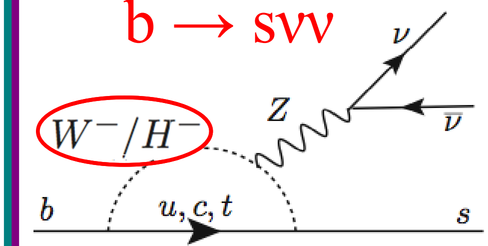


- H^+ enters at tree level $\to$ access to NP parameters ($\tan\beta/m_H$)
- H^+ - ℓ coupling $\propto$ $m_\ell \to$ large NP effects in τ channels

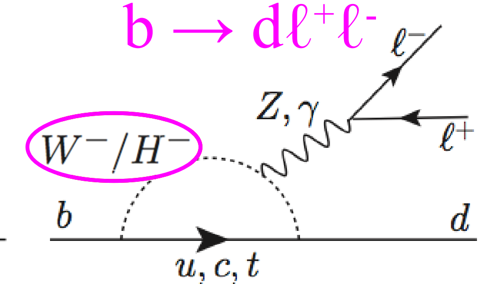
- Large δ_{SM} ~ 25% (f_B, $|V_{ub}|$)
- BF ~ 10^{-4}
- e/μ modes strongly helicity-suppressed

- Small δ_{SM} ~ 5% (FFs, $|V_{cb}|$)
- BF ~ 2%
- $D^{(*)}$ provides constraint

$b \to s\nu\bar{\nu}$



$b \to d\ell^+\ell^-$



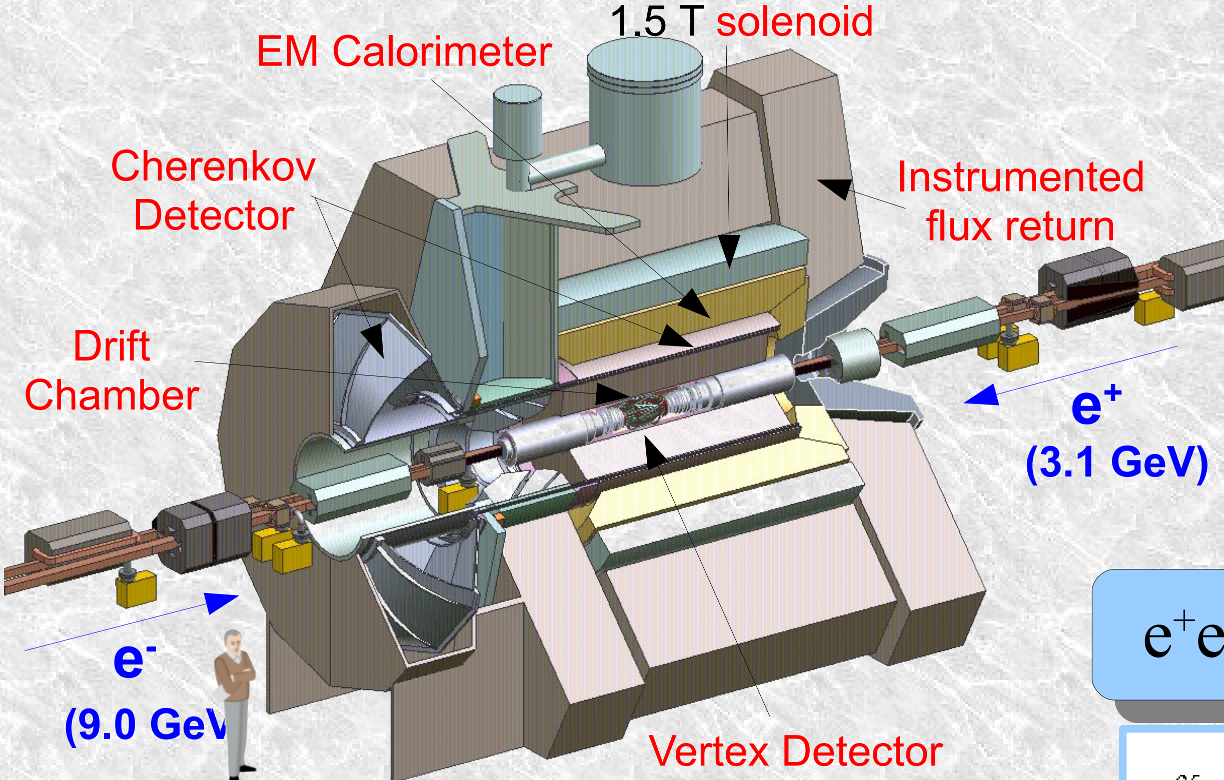
- NP at loop level $\to$ probe multiple NP models up to TeV scales
- Small SM BF rates $\to$ sensitive to enhancements from NP (including Z')

- δ_{SM} ~ 15% (excl. mode FFs)
- BF ~ 10^{-6}
- $\nu\bar{\nu}$ sensitive to dark-matter candidates

- δ_{SM} ~ 15% (excl. mode FFs)
- BF ~ 10^{-8}
- $\ell^+\ell^-$ mode fully reconstructable

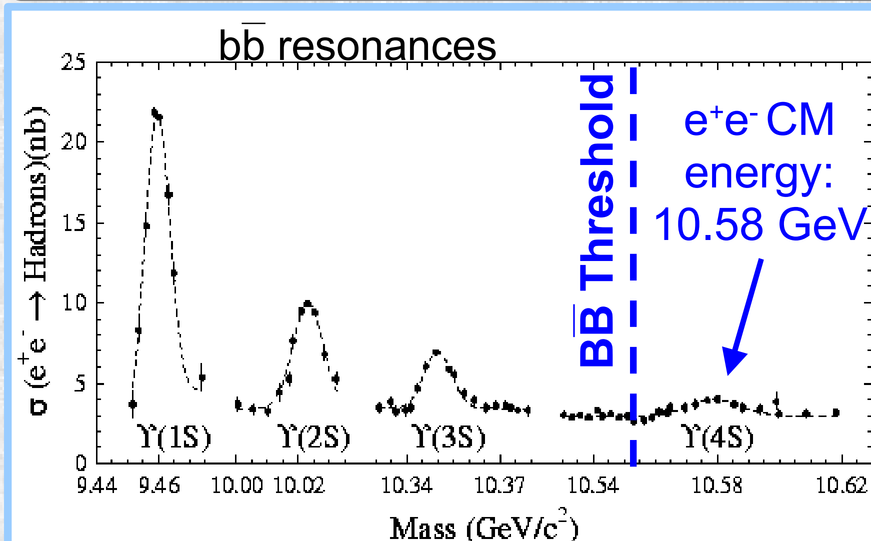
All are sensitive to charged Higgs – BF enhancements/reductions are at leading order!

The BaBar Experiment



- PEP-II storage rings at SLAC
- Data-taking 2000-2008
- Full dataset = ~470 million $B\overline{B}$ (429 fb^{-1})

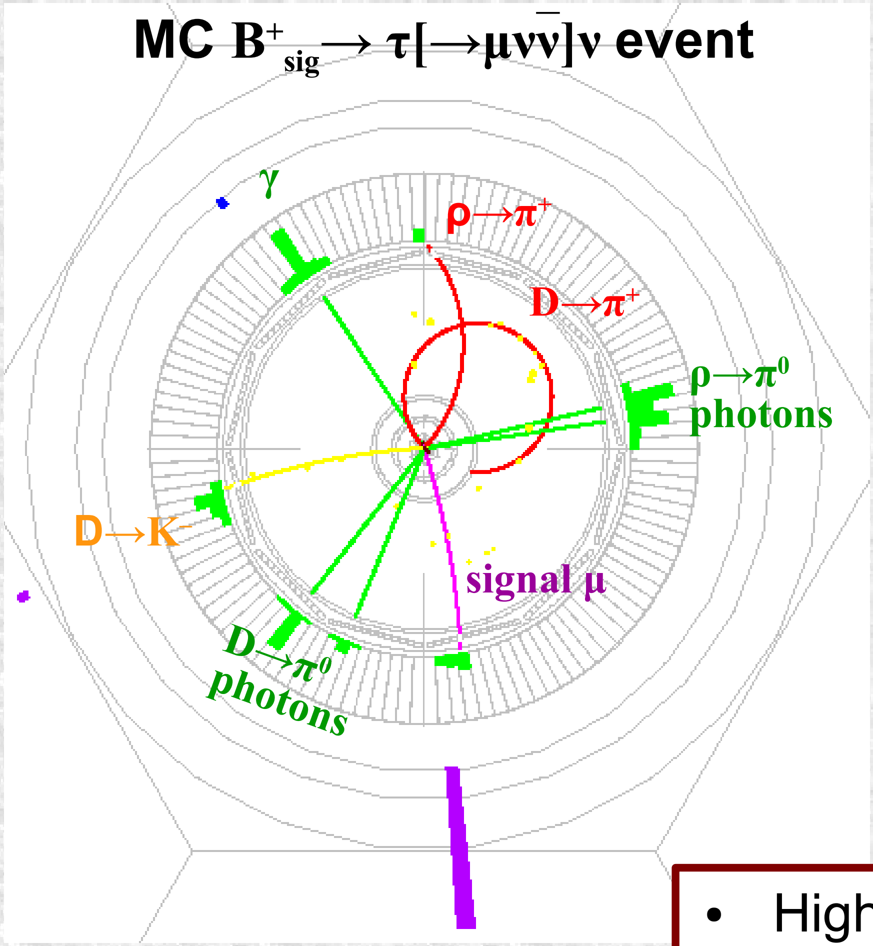
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-, B^0\overline{B}^0$$

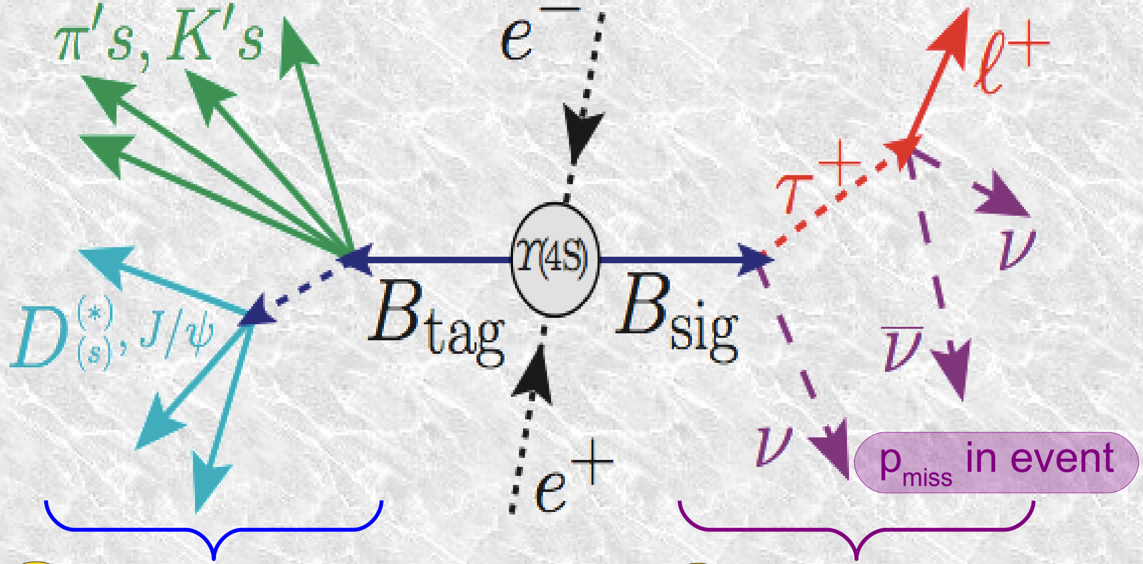


- Good lepton and π/K identification
- ~ Hermetic detector (91% coverage) (neutrino "detection" via p_{miss})
- Clean environment (rare decay searches)

Hadronic-Tag Reconstruction

- Multiple neutrinos → experimentally challenging
- Exploit $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$ production by reconstructing both B's





1 Hadronic tag reconstruction: Fully reconstruct B_{tag} in hadronic modes

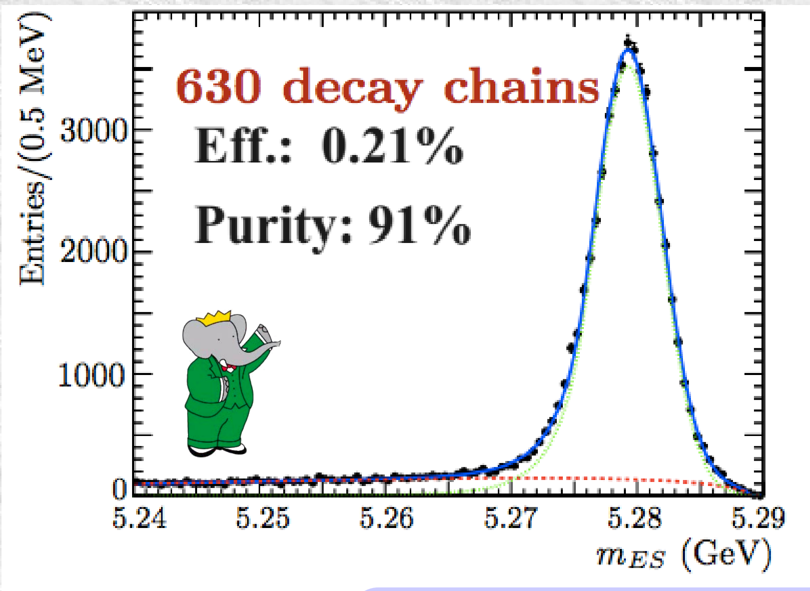
2 Check if rest of event (+ p_{miss}) consistent with signal decay

- High purity B samples with suppressed backgrounds
- B_{sig} 4-vector is determined

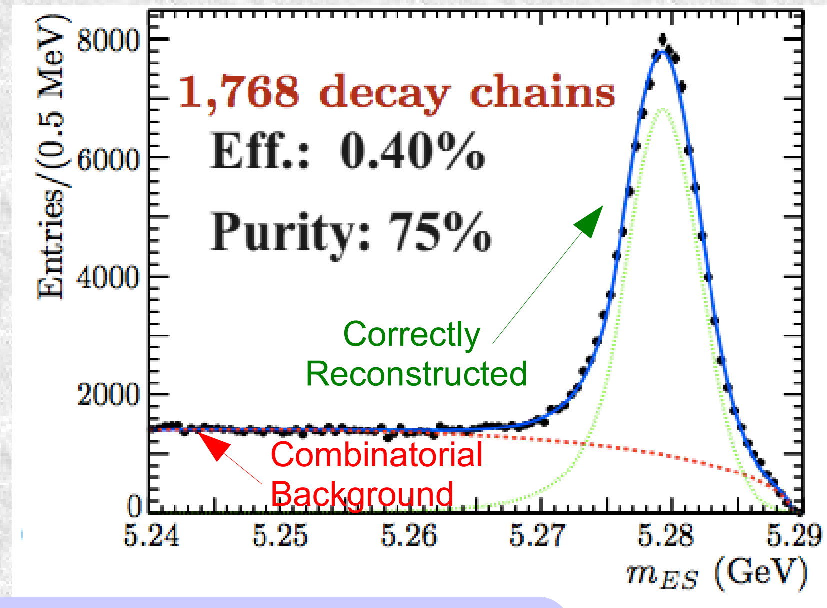
Improved Tagging

Low reconstruction efficiency but ~2x efficiency over past algorithms

Old B_{tag}: D, D^*



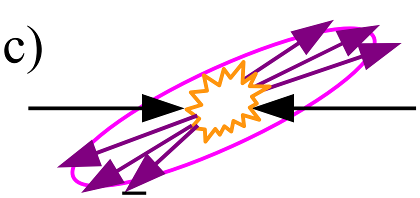
New B_{tag}: $D, D^*, D_s^+, D_s^{*+}, J/\psi$



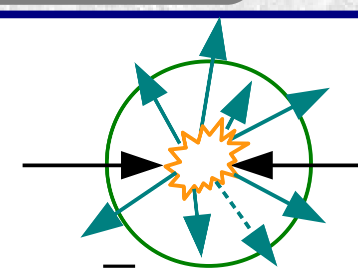
Energy-substituted B-meson mass ≈ 5.28 GeV/c^2

$$m_{\mathrm{ES}} \equiv \sqrt{E_{\mathrm{beam}}^2 - \vec{p}_{\mathrm{B_{tag}}}^{\,2}}$$

Suppress $e^+e^- \to q\bar{q}$ ($q = u,d,s,c$) background using Event-Shape variables



$q\bar{q}$ (γ)$\to$ jetlike

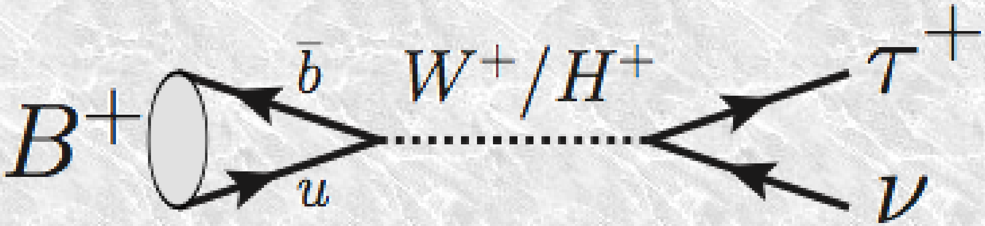


$B\bar{B} \to$ spherical

$B \rightarrow \tau \nu$

PRD 88, 031102 (2013)

$B^+ \to \tau^+ \nu$ in SM and Beyond



No uncertainties from hadronic (QCD) final-states!

$$\boxed{\mathcal{B}(B \to \ell\nu)_{\mathrm{SM}} = \frac{G_F^2 m_B \tau_B}{8\pi} \underbrace{m_\ell^2}(1 - \frac{m_\ell^2}{m_b^2})^2 \underbrace{f_B^2 |V_{ub}|^2}}$$

Helicity-suppressed

$$\mathcal{B}(B \to e\nu)_{\mathrm{SM}} \approx 10^{-11}$$

$$\mathcal{B}(B \to \mu\nu)_{\mathrm{SM}} \approx 10^{-7}$$

$$\boxed{\mathcal{B}(B \to \tau\nu)_{\mathrm{SM}} \approx 10^{-4}}$$

$|V_{ub}|$ and f_B dominate SM uncertainty

f_B = B decay constant (lattice QCD)

Charged Higgs can enhance or suppress SM rate:

$$\mathcal{B}(B \to \tau\nu)_{\mathrm{2HDM}} = \mathcal{B}_{\mathrm{SM}} \times (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$

W.S. Hou, PRD 48, 2342 (1993)

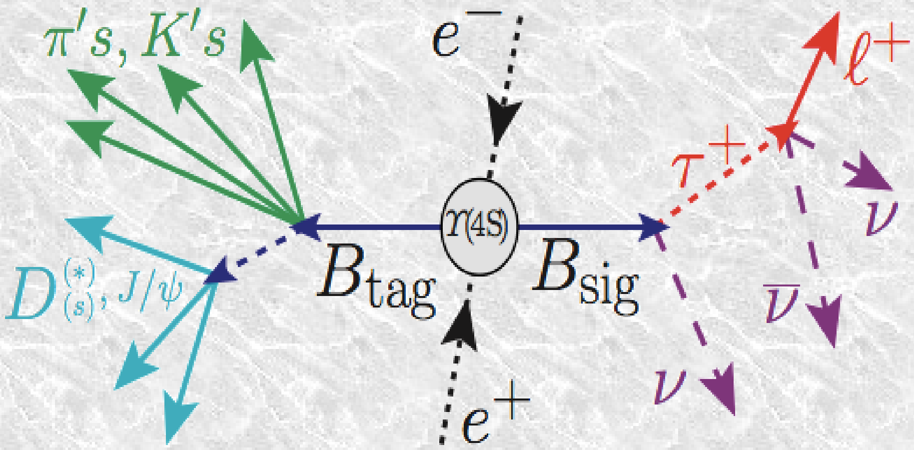
$$\mathcal{B}(B \to \tau\nu)_{\mathrm{SUSY}} = \mathcal{B}_{\mathrm{SM}} \times (1 - \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta} \frac{m_B^2}{m_H^2})^2$$

Akeroyd and Recksiegel, J. Phys G29, 2311 (2003)

where $|\epsilon_0| < \mathcal{O}(0.01)$

PRD 88, 031102 (2013)

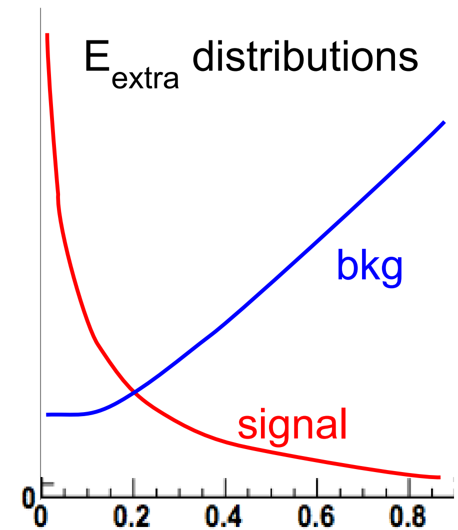
$B^+ \rightarrow \tau^+ \nu$ Event Selection



Event Selection

- Reconstruct hadronic B_{tag}
- Reconstruct 1-prong τ decay modes
  - $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, and $\rho\nu \rightarrow \pi^+\pi^0\nu$
  - ~70% of total τ decay modes
- 2-variable LH ratio for $\pi\nu$ (p^*_π and $\cos\theta_{miss}$)
- 4-variable LH ratio for $\rho\nu$ ($\cos\theta_{miss}$, $m_{\pi 0}$, $m_{\pi\pi 0}$, p^*_ρ)
- Suppress continuum background using event-shape variables

- Key variable: E_{extra}
  - Sum of all neutral energy not associated with B_{sig} or B_{tag}
  - Should be ~0 for signal
  - Misreconstructions, split-offs, & beam bkgs produce excess

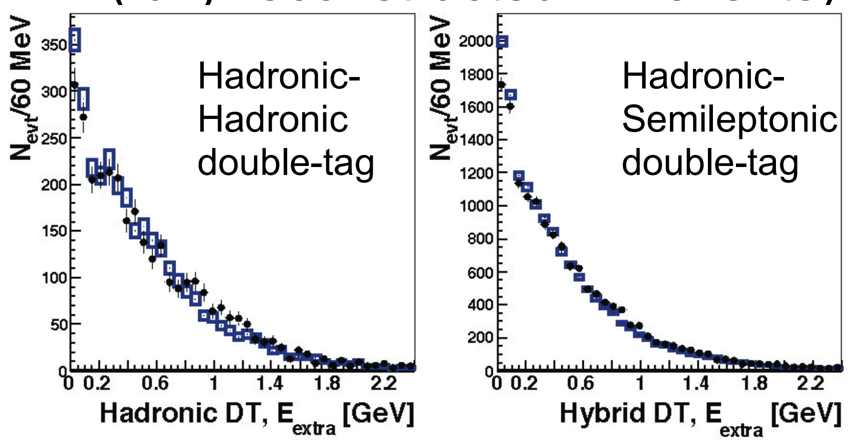


PRD 88, 031102 (2013)

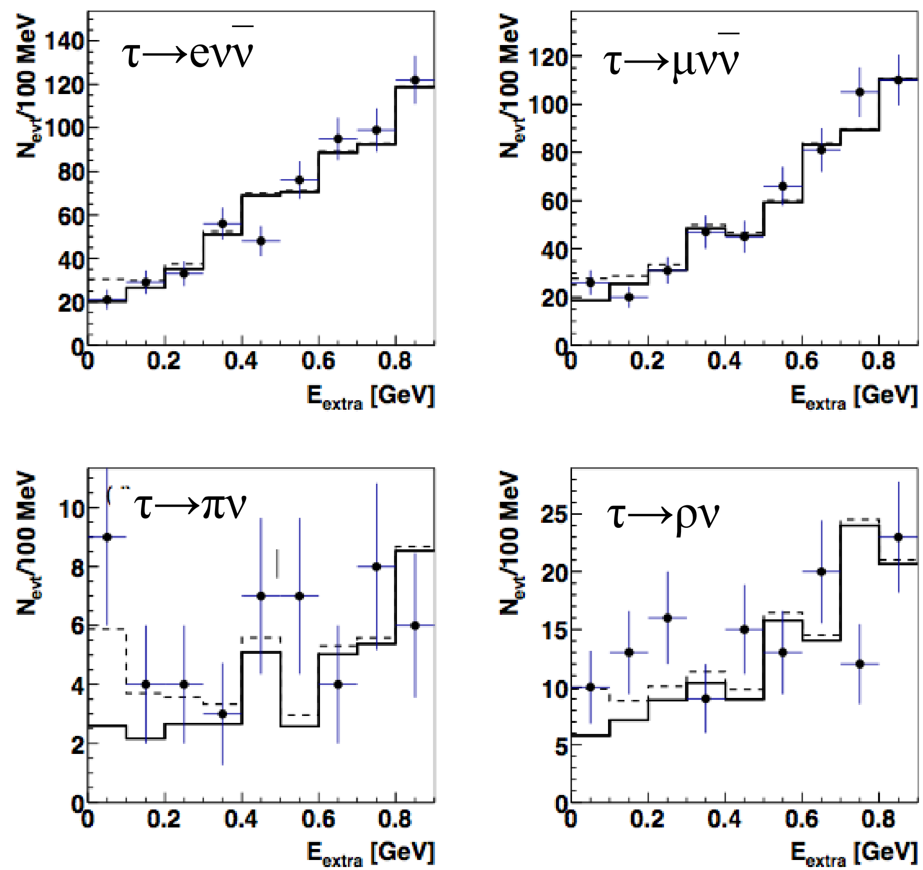
$B^+ \to \tau^+ \nu$: Corrections & Fits

- Unbinned maximum likelihood fit to E_{extra}
- Signal and peaking background PDFs taken from MC
- Combinatorial background PDF taken from m_{ES} sidebands in data

- Validate E_{extra} with data using double-tagged samples (fully reconstructed $B\bar{B}$ events)



Results of all channels, separately



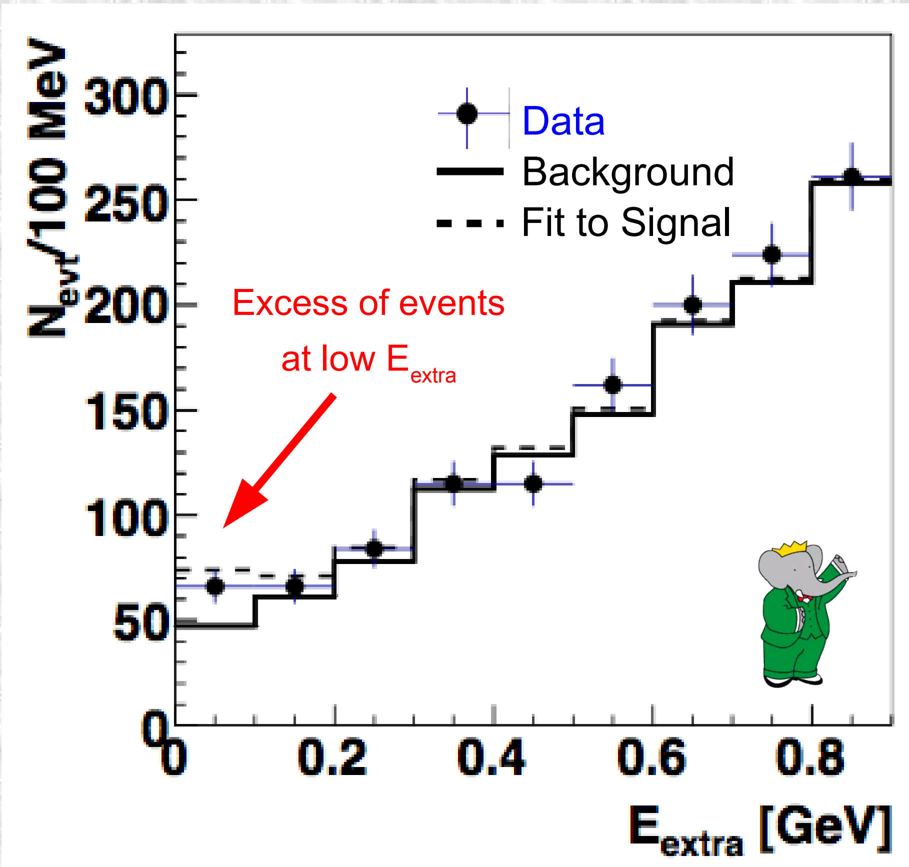
Decay Mode	Signal yield	$\mathcal{B}(\times 10^{-4})$
$\tau^+ \to e^+\nu\bar{\nu}$	4.1 ± 9.1	$0.35^{+0.84}_{-0.73}$
$\tau^+ \to \mu^+\nu\bar{\nu}$	12.9 ± 9.7	$1.12^{+0.90}_{-0.78}$
$\tau^+ \to \pi^+\nu$	17.1 ± 6.2	$3.69^{+1.42}_{-1.22}$
$\tau^+ \to \rho^+\nu$	24.0 ± 10.0	$3.78^{+1.65}_{-1.45}$

stat errors only

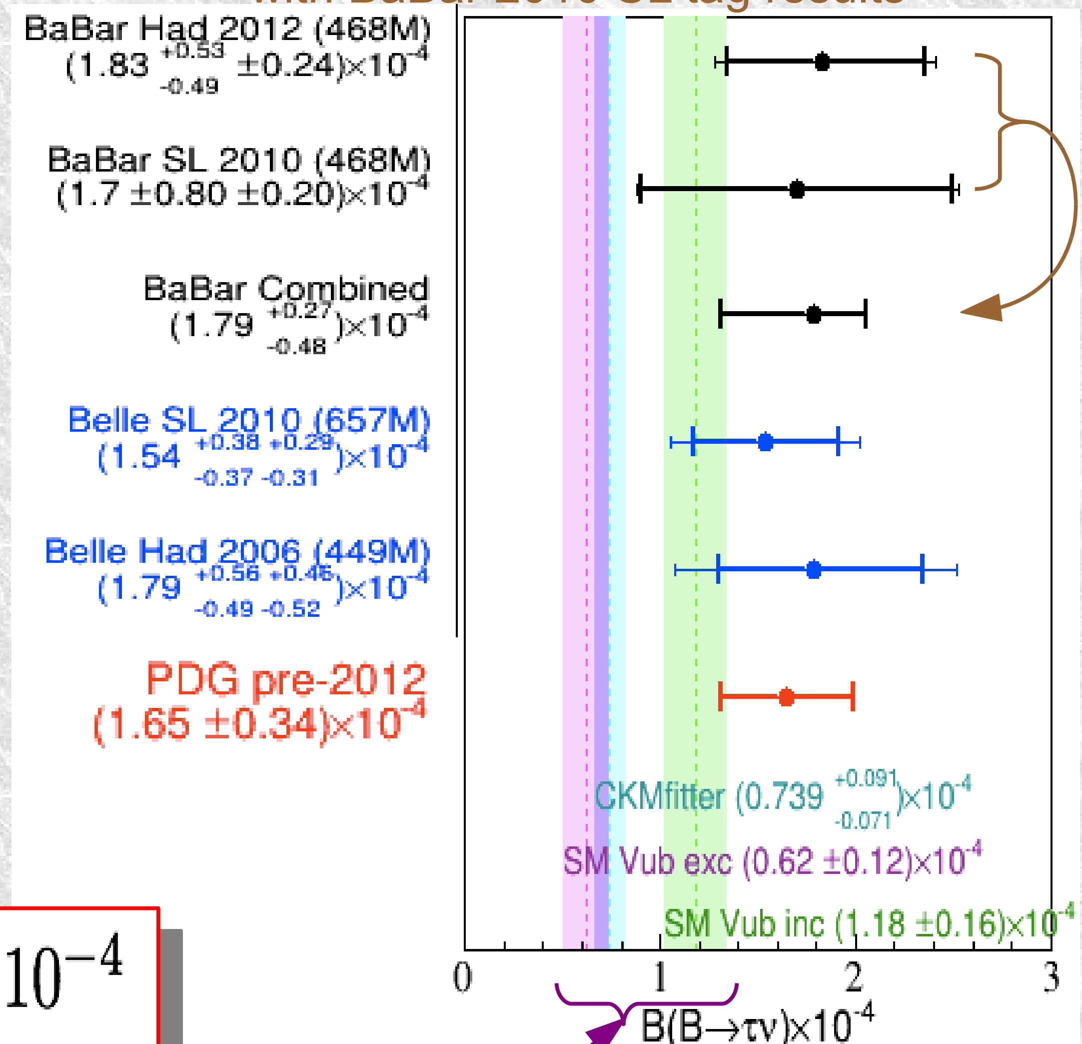
PRD 88, 031102 (2013)

$B^+ \to \tau^+ \nu$: Combined Modes

All τ modes are fit simultaneously



These hadronic tag results are combined with BaBar 2010 SL tag results



$$\mathcal{B}(B \to \tau\nu) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$$

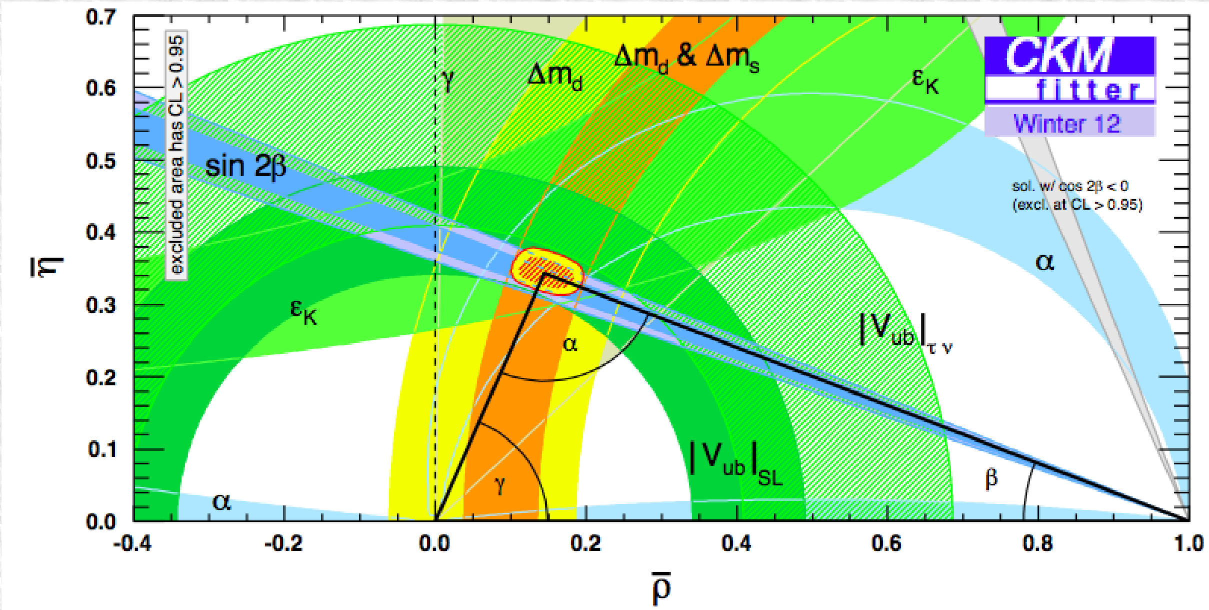
Exclusion of null hypothesis at 3.8 σ (incl. syst.)

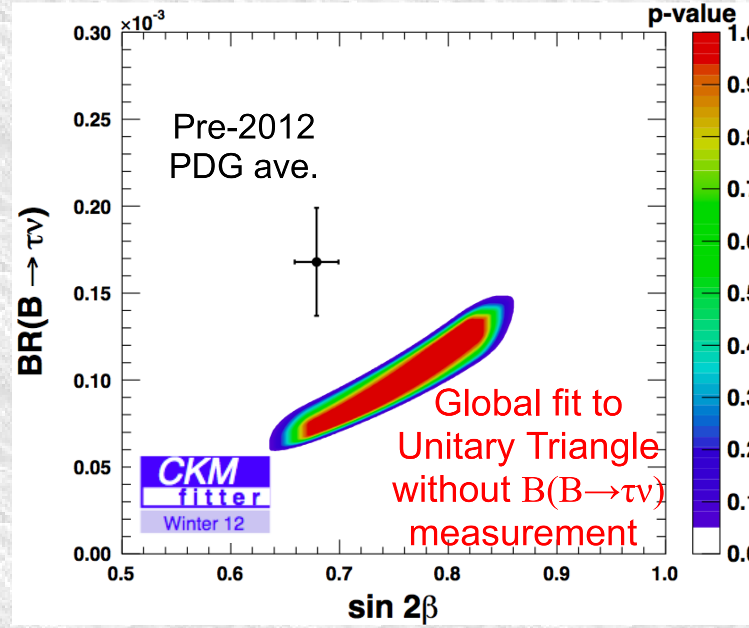
SM prediction depends on how $|V_{ub}|$ is obtained

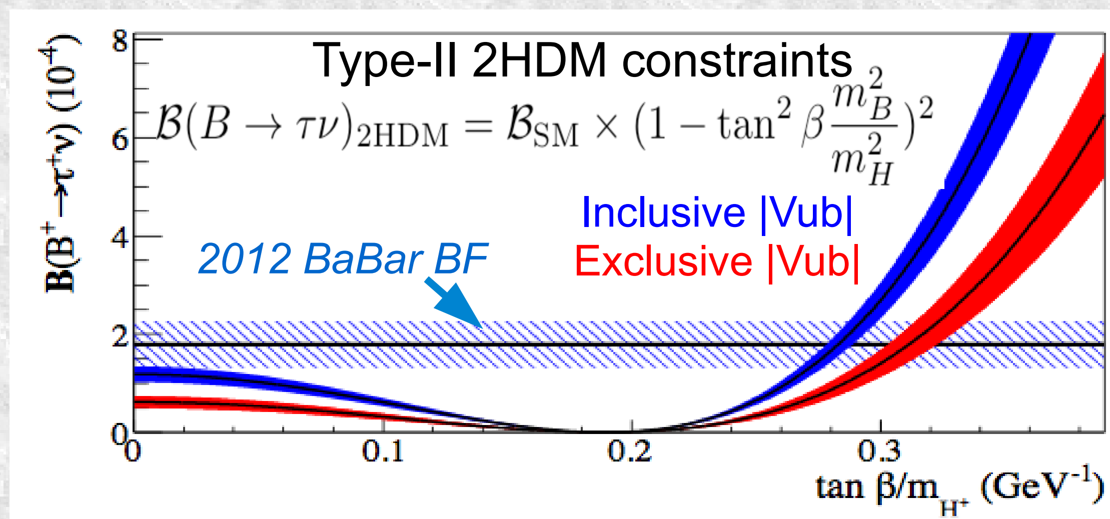
Excess in $B^+ \to \tau^+ \nu$ (Pre-2012)

PRD 88, 031102 (2013)

Results are in excess of SM values and with other Unitarity Triangle measurements







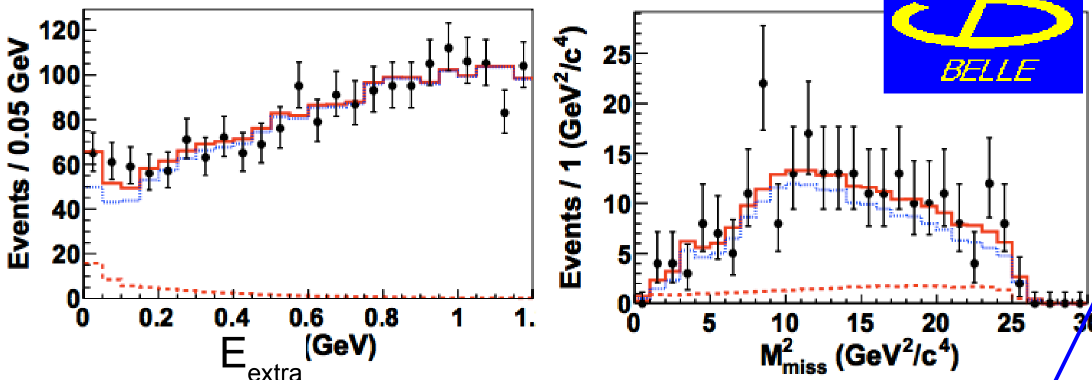
Hints of New Physics?

Or just statistical fluctuations and/or under-estimation of backgrounds?

2012 Belle Results

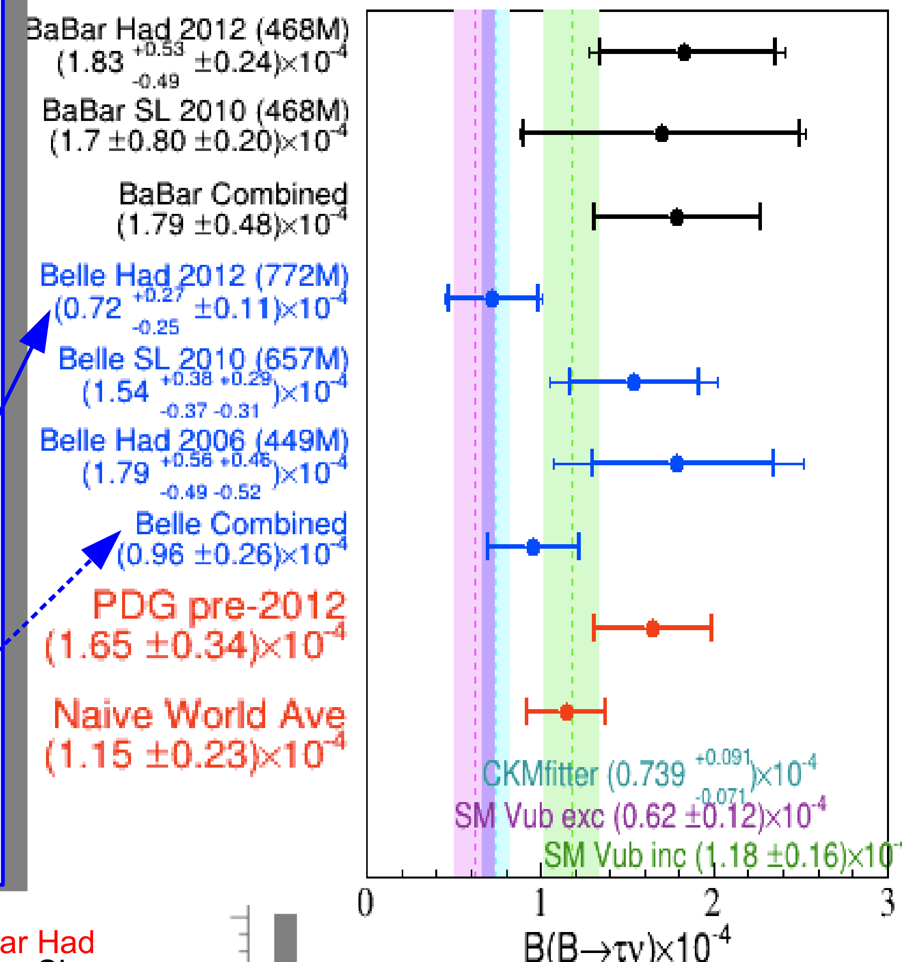
PRL 110, 131801 (2013)
772 million $B\bar{B}$

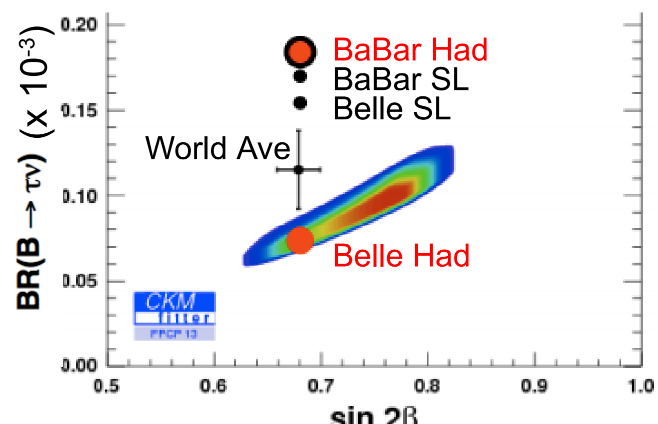
- Improved hadronic tag reconstruction
- 2D fit to E_{extra} + Missing Mass^2



Sub-mode	N_{sig}	ϵ (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	16^{+11}_{-9}	3.0	$0.68^{+0.49}_{-0.41}$
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	26^{+15}_{-14}	3.1	$1.06^{+0.63}_{-0.58}$
$\tau^- \to \pi^- \nu_\tau$	8^{+10}_{-8}	1.8	$0.57^{+0.70}_{-0.59}$
$\tau^- \to \pi^- \pi^0 \nu_\tau$	14^{+19}_{-16}	3.4	$0.52^{+0.72}_{-0.62}$
Combined	62^{+23}_{-22}	11.2	$0.72^{+0.27}_{-0.25}$

combined with SL





BaBar SL: PRD 81, 051101 (2010)
Belle Had: PRL 110,131801(2013)
Belle SL: PRD 82, 071101 (2010)
Belle Had: PRL 97, 251802 (2006)

$B^+ \to \tau^+ \nu$ at Belle II

- Current world $B \to \tau\nu$ precision:

$$\left(\frac{\delta\mathcal{B}}{\mathcal{B}}\right)_{1.1ab^{-1}} \approx 20\%$$

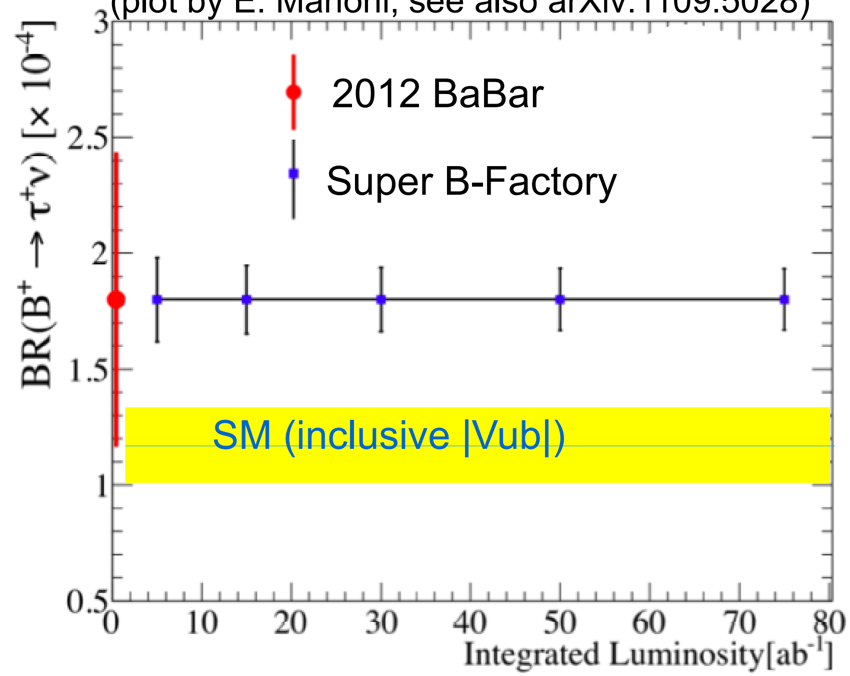
  - δ_{syst} dominated by statistical origin that scales with luminosity

- Belle II $B \to \tau\nu$ precision:

$$\left(\frac{\delta\mathcal{B}}{\mathcal{B}}\right)_{50ab^{-1}} \approx 3-4\%$$

  - limited by experimental systematics such as beam backgrounds

Based on simulation studies for SuperB
(plot by E. Manoni, see also arXiv:1109.5028)



BF($B \to \mu\nu$)/BF($B \to \tau\nu$) ratio independent of $f_B|V_{ub}|$

- Belle II $B \to \mu\nu$ precision

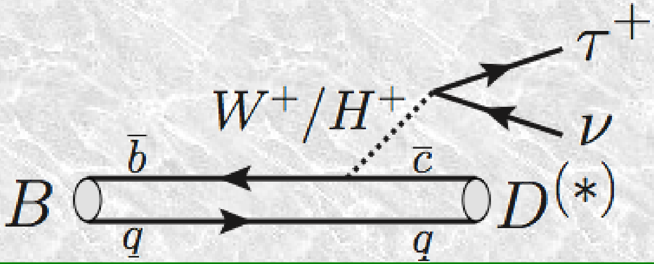
$$\left(\frac{\delta\mathcal{B}}{\mathcal{B}}\right)_{50ab^{-1}} \approx 5-6\%$$

  - currently unobserved
  - experimentally clean! (2-body decay, only 1 neutrino)
  - ~5ab^{-1} needed for 5σ discovery! arXiv:1002.5012

$B \rightarrow D^{(*)} \tau\nu$

PRL 109, 101802 (2012) and
More detailed studies submitted to PRD, arXiv:1303.0571

$B\to D^{(*)}\tau\nu$ in SM and Beyond



$$\mathcal{B}(B^0 \to D^- \tau\nu)_{\rm SM} = 0.69 \pm 0.04$$

$$\mathcal{B}(B^0 \to D^{*-} \tau\nu)_{\rm SM} = 1.41 \pm 0.07$$

Chen & Geng, JHEP 0610, 053 (2006)

- Larger rates and lower hadronic uncertainties than $B\to\tau\nu$
- 3 body decay permits study of other observables sensitive to NP (q^2 distributions, D* and τ polarization)

$$\frac{d\mathcal{B}}{dq^2} = \frac{G_F^2 \tau_B |V_{cb}|^2 |p^*_{D^{(*)}}| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\underbrace{\left(|H_+|^2 + |H_-|^2 + |H_0|^2\right)}_{\text{Helicity amplitudes common to } e,\, \mu,\, \tau} \left(1 + \frac{m_\tau^2}{2q^2}\right) + \underbrace{\frac{3m_\tau^2}{2q^2} |H_s|^2}_{\text{Helicity amplitude only relevant for } \tau} \right]$$

$D^{(*)}$ momentum in CM frame

momentum transfer to $\tau\nu$

Helicity amplitudes common to e, μ, τ
Only H_0 affects $D(\ell/\tau)\nu$

Helicity amplitude only relevant for τ

- Spin-0 Higgs doesn't couple to all helicity states $\rightarrow$ affects D and D* differently

$$R(D^{(*)}) = \frac{\overbrace{\Gamma(B\to D^{(*)}\tau\nu_\tau)}^{\text{signal}}}{\underbrace{\Gamma(B\to D^{(*)}\ell\nu_\ell)_{\ell=e,\mu}}_{\text{normalization}}}$$

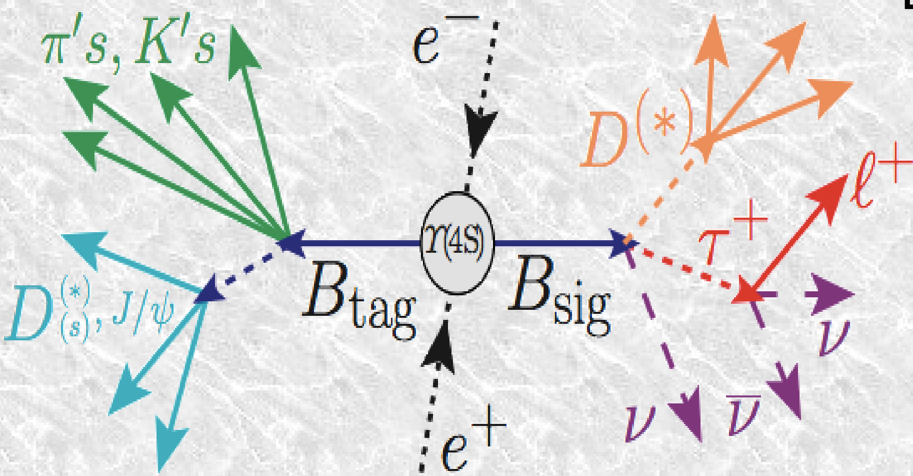
Several uncertainties cancel in ratio:
theoretical and experimental

$|V_{cb}|$, Form factors

Leptonic signal decays have same final event topology and similar efficiency as normalization decays

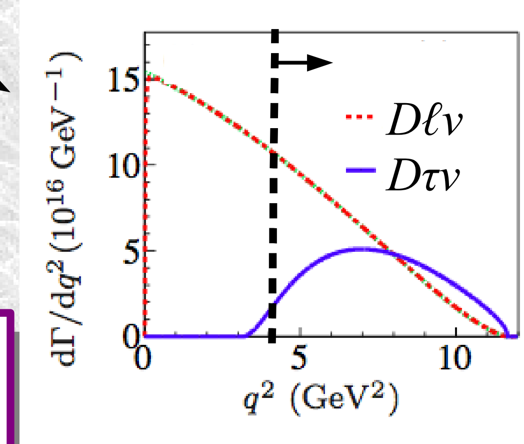
$B \rightarrow D^{(*)}\tau\nu$ Event Selection

PRL 109, 1018022 (2012)



Event Selection:

- Reconstruct hadronic B_{tag}
- Reconstruct D^0, D^{*0}, D^+, D^{*+} candidates
- Exactly one leptonic track ($\tau \rightarrow e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$)
- Boosted Decision Trees to reduce bkgs:
  - E_{extra}, $m_{D(*)}$, event-shape, etc.
- $q^2 > 4\ \mathrm{GeV}^2$ to reduce bkg & $B \rightarrow D^{(*)}\ell\nu$
- $p_{miss} > 200\ \mathrm{MeV}$

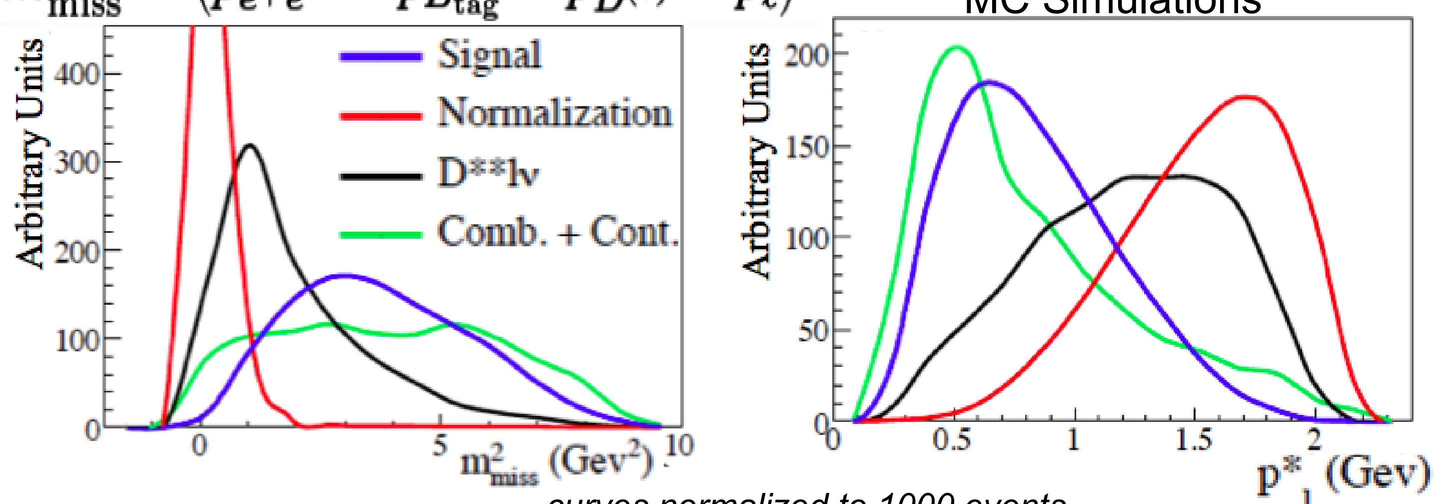


Key variables to discriminate signal from normalization:

m^2_{miss} and **p^*_ℓ** in B_{sig} rest frame

$$m^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}} - p_\ell\right)^2$$

MC Simulations



curves normalized to 1000 events

PRL 109, 1018022 (2012)

$B \to D^{(*)}\tau\nu$ Fit Strategy

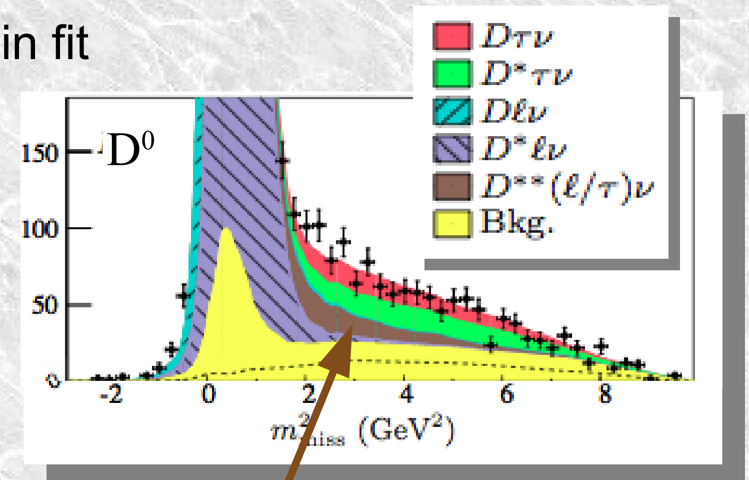
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} = \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} \cdot \frac{\epsilon_{\mathrm{norm}}}{\epsilon_{\mathrm{sig}}}$$

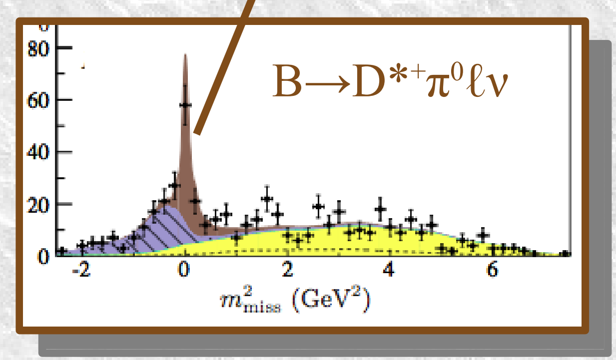
from MC simulation

- 2D unbinned maximum likelihood fit to $\mathbf{m^2_{miss}}$ and $\mathbf{p^*_\ell}$
  - 56 fully 2D PDFs, derived from MC and shapes fixed in fit

- Control samples to correct MC distributions:
  - $e^+e^- \to q\bar{q}(\gamma)$: Off-peak data (40 MeV below $\Upsilon(4S)$)
  - Normalization decays: q^2 sidebands
  - $B\bar{B}$ Combinatorial: m_{ES} and E_{extra} sidebands

- Simultaneously fitted yields:
  - 4 signal & 4 normalization channels: D^0, D^{*0}, D^+, D^{*+}
  - 4 $D^{(*)}\pi^0\ell\nu$ channels (to estimate $D^{**}\ell\nu$ contribution)

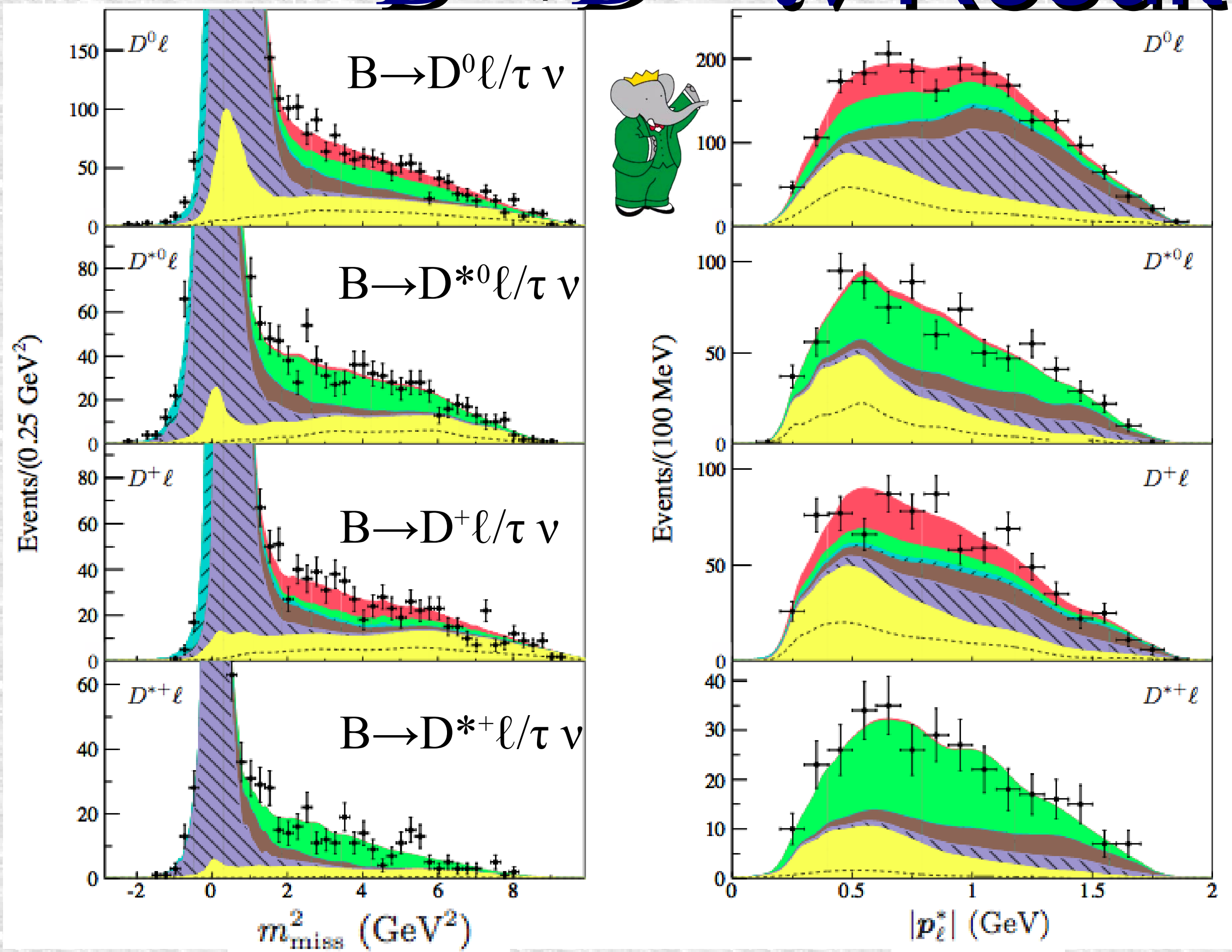




Simultaneous fit

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

PRL 109, 1018022 (2012)



- Largest systematic due to bkg PDFs
- Statistical uncertainty dominates

	Decay	$N_{\rm sig}$	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{\rm stat}$
	$B^- \to D^0\tau^-\overline{\nu}_\tau$	314 ± 60	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.12 \pm 0.04$	5.5
	$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.11 \pm 0.06$	11.3
	$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	177 ± 31	$0.469 \pm 0.084 \pm 0.053$	$1.01 \pm 0.18 \pm 0.11 \pm 0.04$	6.1
	$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	$0.355 \pm 0.039 \pm 0.021$	$1.74 \pm 0.19 \pm 0.10 \pm 0.06$	11.6
Isospin constrained	$\overline{B} \to D\tau^-\overline{\nu}_\tau$	489 ± 63	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.10 \pm 0.04$	8.4
	$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$	888 ± 63	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.10 \pm 0.06$	16.4

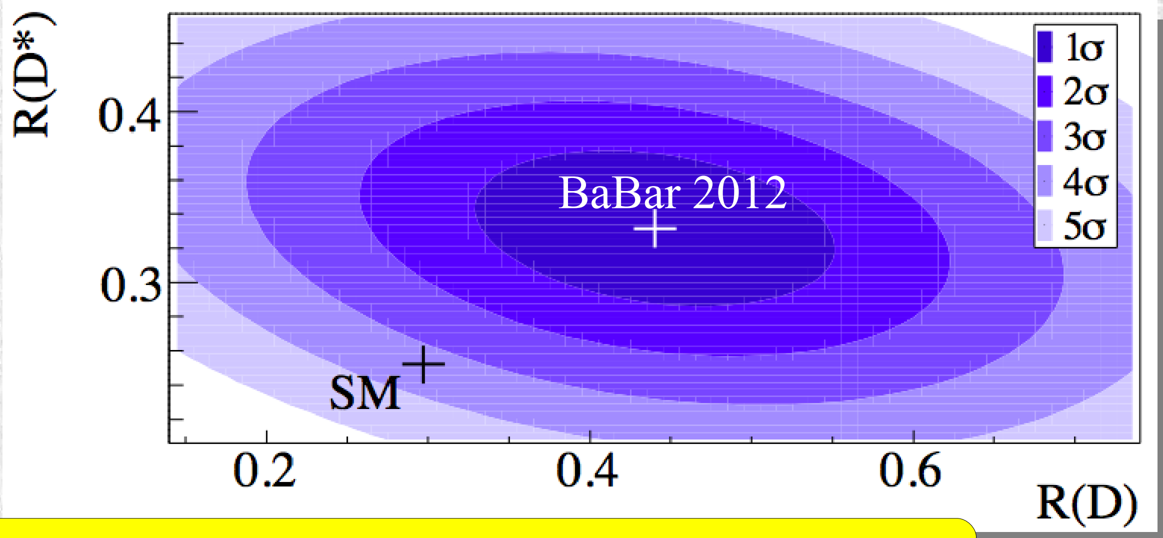
First observation!!

$B \to D^{(*)}\tau\nu$ Results versus SM

PRL 109, 1018022 (2012)

$$R(D) = \left\{ \begin{array}{ll} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{array} \right\} 2.0\sigma$$

$$R(D^*) = \left\{ \begin{array}{ll} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{array} \right\} 2.7\sigma$$



R(D) and R(D*) not independent due to D* → D feed-down: -27% correlation

Combined $R(D^{(*)})$ deviation from SM: 3.4σ

New Lattice QCD value:

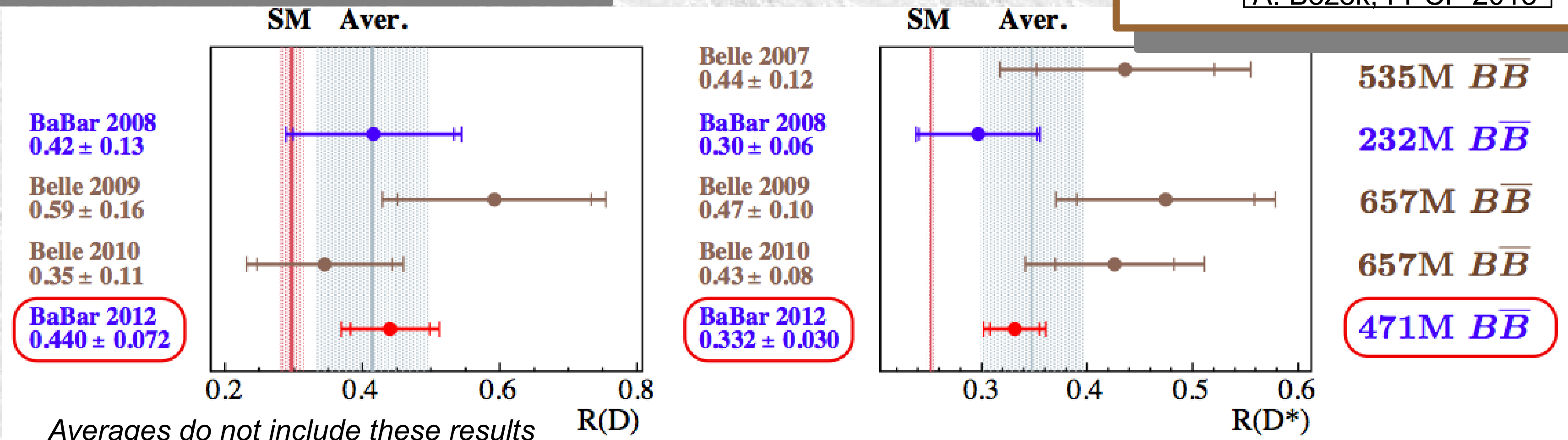
Bailey, et al, PRL 109, 071802 (2012)

$R(D) = 0.316 \pm 0.012 \pm 0.007$

$\to$ **$R(D^{(*)})$ deviation = 3.2σ**

Belle's conservative $R(D^{(*)})$ estimates also show excess over SM

A. Bozek, FPCP 2013

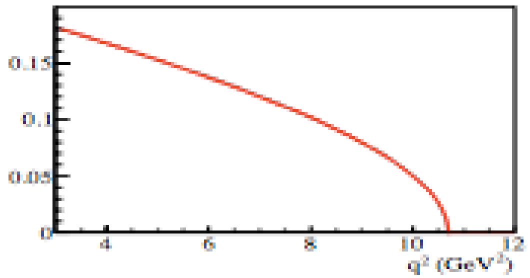


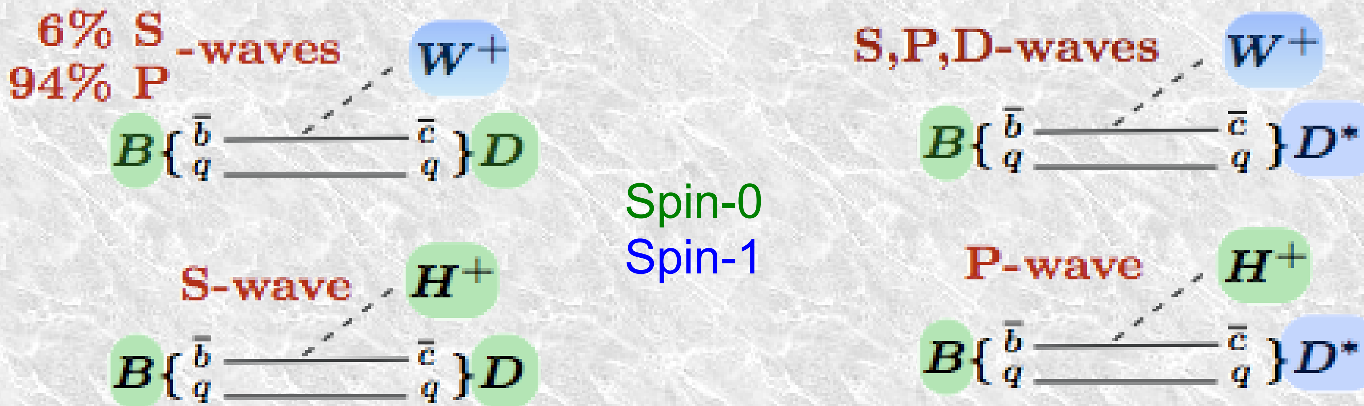
Effect of H^+ on q^2 of $B\to D^{(*)}\tau\nu$

- q^2 spectrum impacted by scalar helicity: $H_s^{2HDM} \approx H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_{H^+}^2}\frac{q^2}{1 \mp m_c/m_b}\right)$

+ for $B\to D^*\tau\nu$, - for $B\to D\tau\nu$

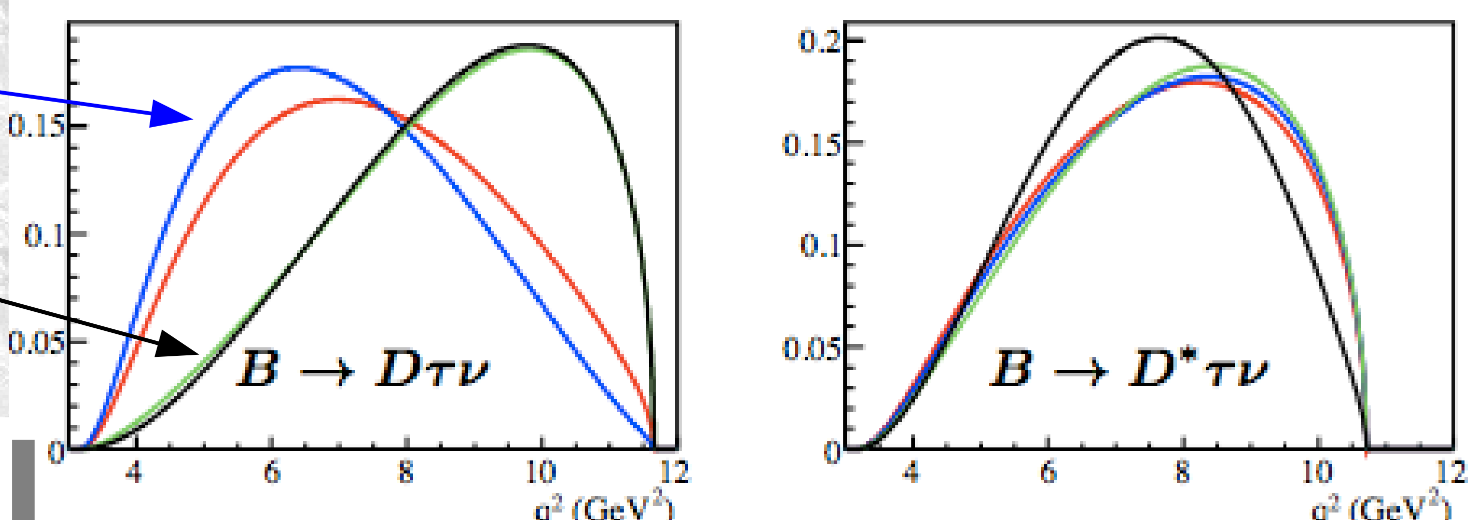
P-waves have lower q^2 spectra due to additional factor of $|p^*_D|^2$ in decay rate

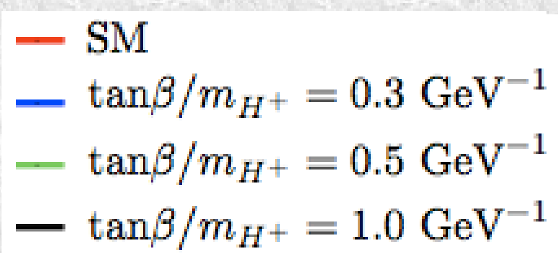




Destructive interference until H^+ and SM contributions are equal (~0.31 GeV^{-1})

Higgs contribution dominates at high $\tan\beta/m_{H^+}$





$B\to D\tau\nu$ more affected by spin-0 contribution than $B\to D^*\tau\nu$

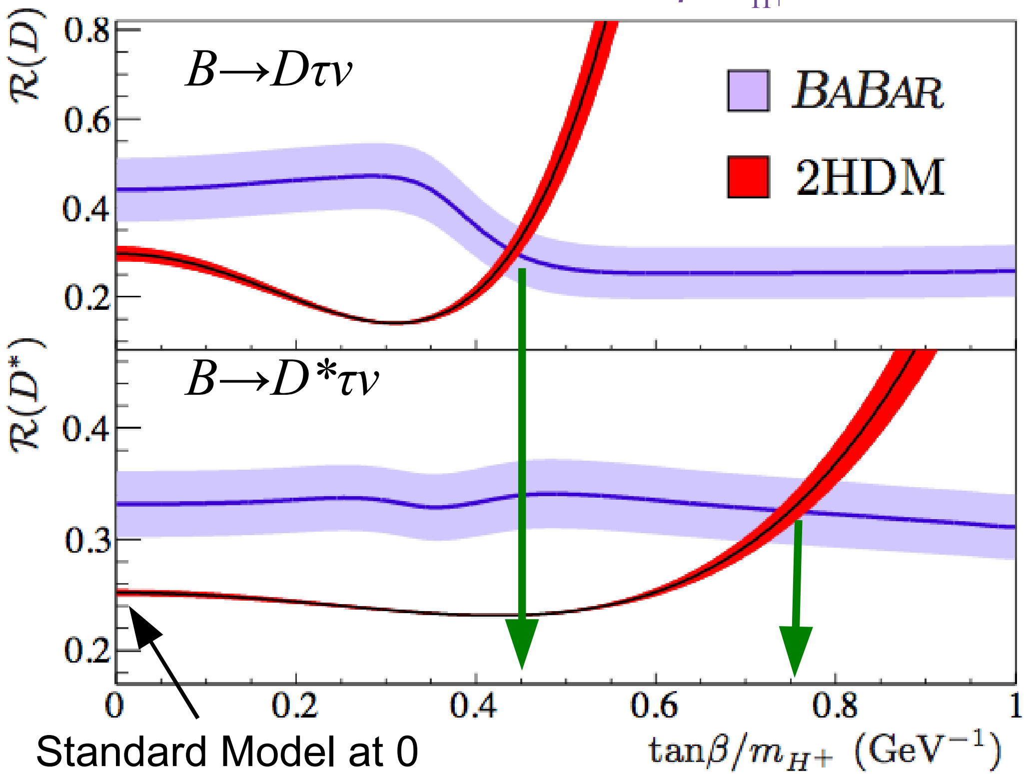
PRD 109, 1018022 (2012)

Type-II 2HDM

$B \to D^{(*)}\tau\nu$

$$H_s^{2HDM} \approx H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_{H^+}^2}\frac{q^2}{1 \mp m_c/m_b}\right)$$

PDFs re-calculated in 2HDM context for all values of $\tan\beta/m_{H+}$

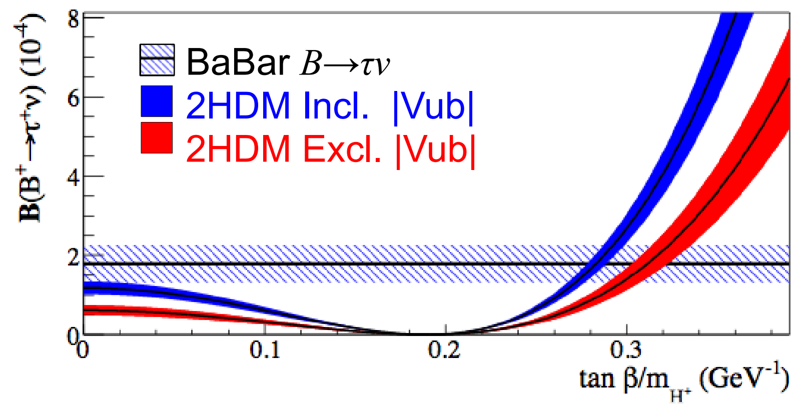


$$R(D): \tan\beta/m_{H+} = 0.44 \pm 0.02$$

$$R(D^*): \tan\beta/m_{H+} = 0.75 \pm 0.04$$

$B \to \tau\nu$

$$\mathcal{B}(B \to \tau\nu)_{2HDM} = \mathcal{B}_{SM} \times (1 - \tan^2\beta\frac{m_B^2}{m_H^2})^2$$

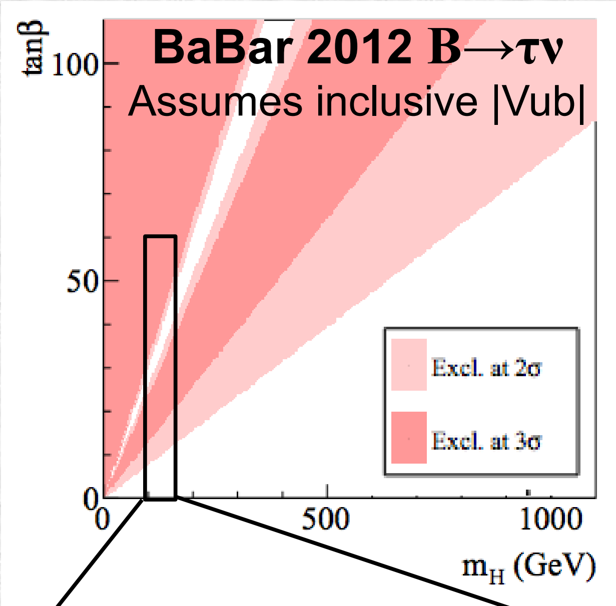


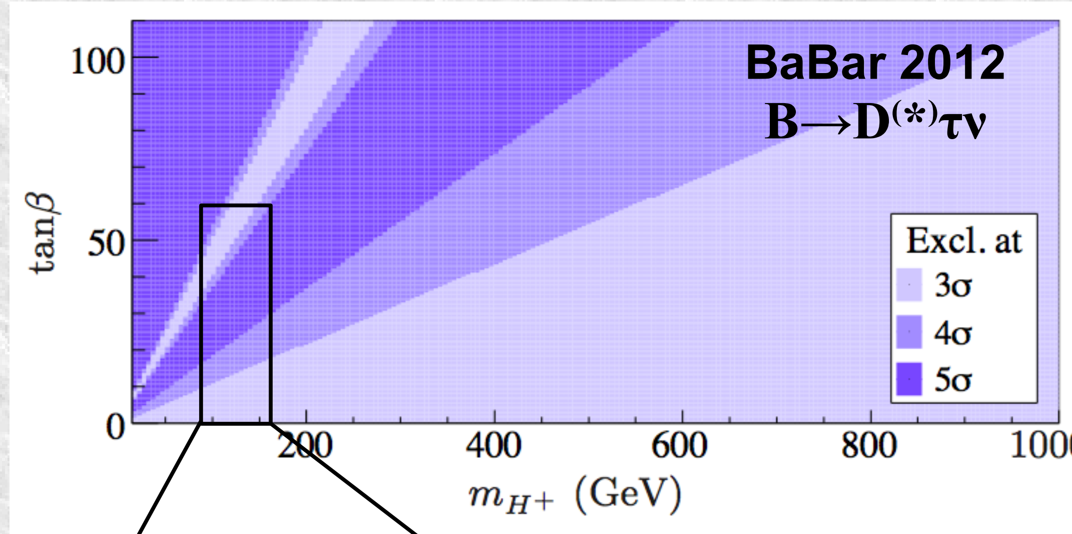
Combination of R(D) and R(D*) excludes Type-II 2HDM in full $\tan\beta$-m_H parameter space with probability of >99.8% (~3.1σ)

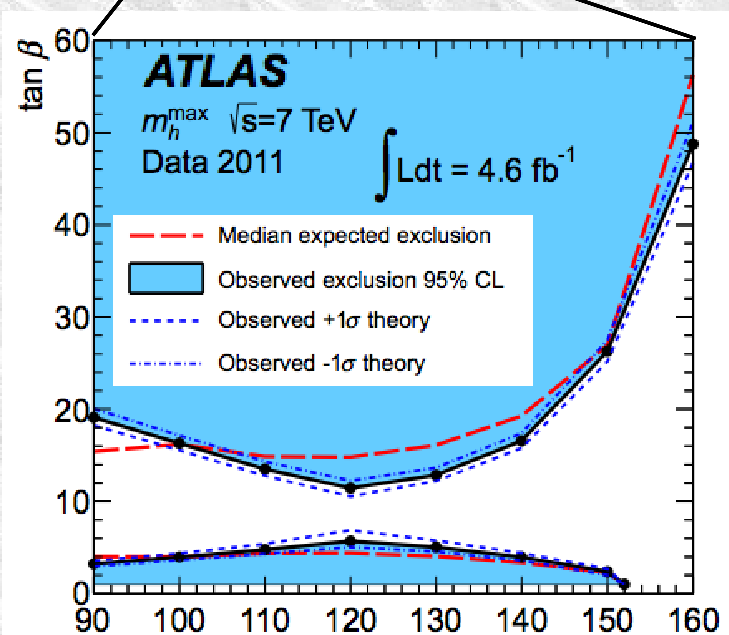
(with m_{H+} >15 GeV,

$m_{H+} \lesssim$ 300GeV already excluded by $B \to X_s\gamma$)

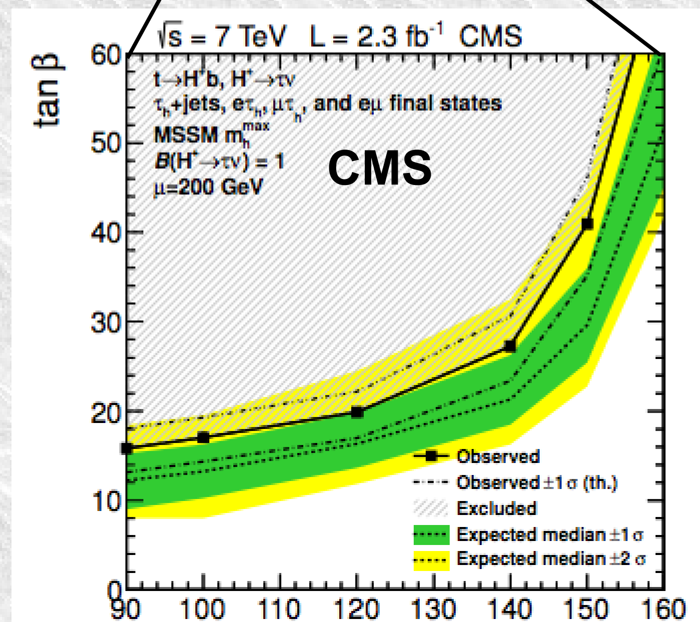
Exclusion reach of Type-II 2HDM







JHEP 1206, 039 (2012)



JHEP 07, 143 (2012)

$B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ searches are complementary to $t \to bH^+$, $\hookrightarrow \tau\nu$ searches at LHC

Type-III 2HDM

arXiv:1303.0571
submitted to PRD

Type-II 2HDM:
one Higgs doublet couples to **up** quarks, one to **down** & **leptons**.

Subset of Type-III

$S_L = 0$

$S_R = -m_b m_\tau \frac{\tan\beta^2}{m_H^2}$

Type-III 2HDM: More general charged Higgs model

$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + \boldsymbol{S_R} (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) \right] + \boldsymbol{S_L} (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$

Datta et al, PRD 86, 034027 (2012); Crivellin et al, arXiv:1206.2634

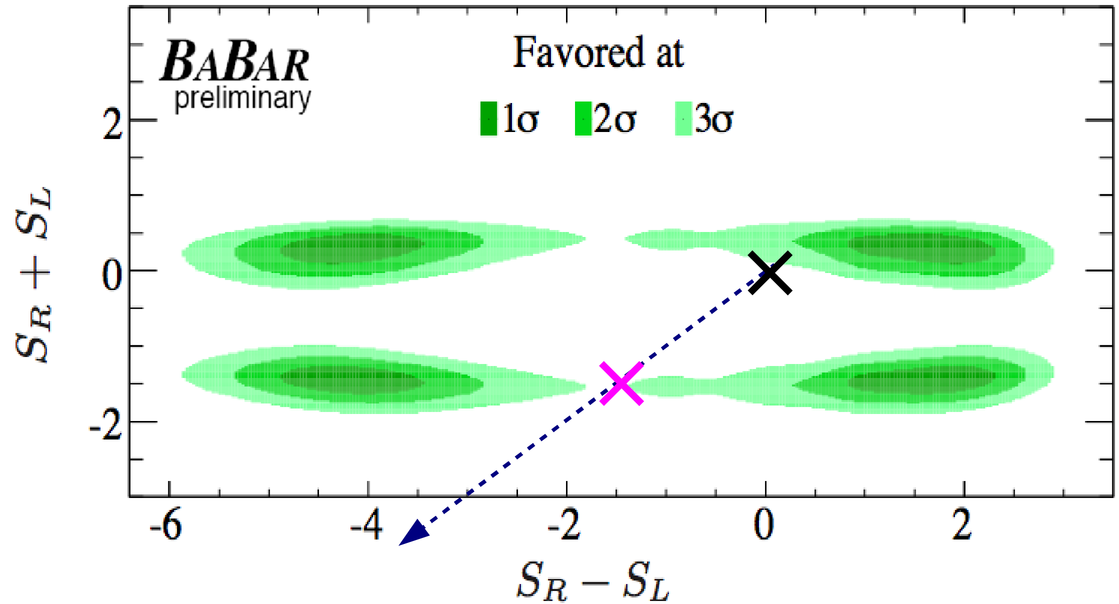
R(D) and R(D*) depend on 2 independent NP parameters ($S_R \pm S_L$)

$$\mathcal{R}(D) = \mathcal{R}(D)_{\rm SM} + A'_D {\rm Re}(\boldsymbol{S_R} + \boldsymbol{S_L}) + B'_D |\boldsymbol{S_R} + \boldsymbol{S_L}|^2$$

$$\mathcal{R}(D^*) = \mathcal{R}(D^*)_{\rm SM} + A'_{D^*} {\rm Re}(\boldsymbol{S_R} - \boldsymbol{S_L}) + B'_{D^*} |\boldsymbol{S_R} - \boldsymbol{S_L}|^2$$

- Type-II has no solution for both R(D) and R(D*)
- Type-III has **4 solutions** for real $S_R \pm S_L$

(more for complex values)



- - Type-II: $S_R + S_L = S_R - S_L$

× SM value

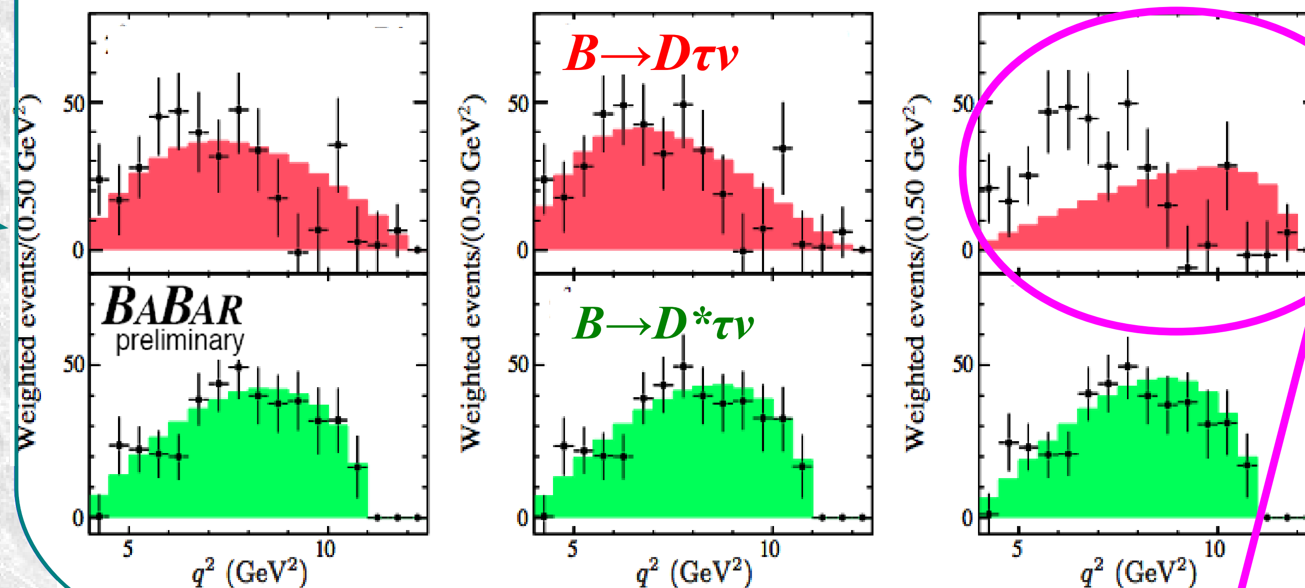
× Measured value for R(D) in Type-II: $S_R \pm S_L = -1.51$

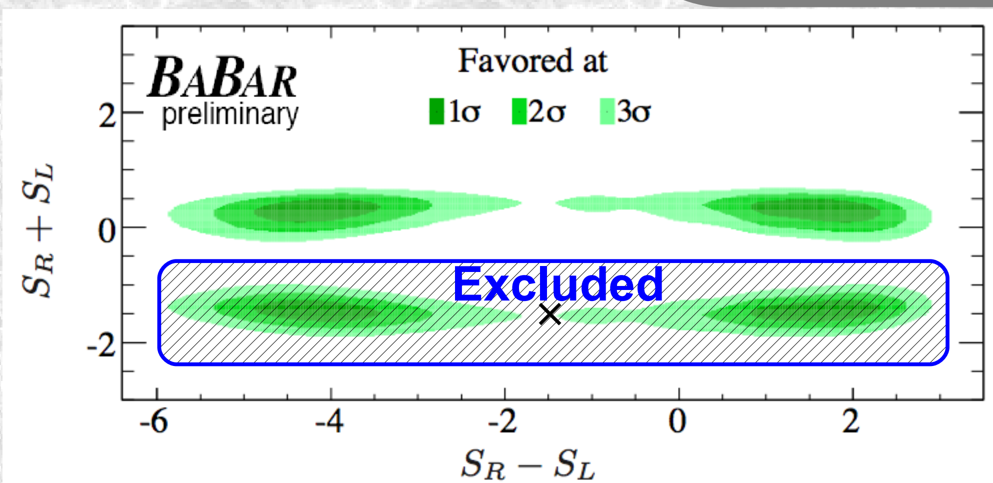
Type-III 2HDM Exclusions

arXiv:1303.0571
submitted to PRD

$\tan\beta/m_{H+}$ affects (bkg-subtracted, efficiency corrected) signal q^2 distributions

SM	$\tan\beta/m_{H+}$ = 0.30 GeV^{-1}	$\tan\beta/m_{H+}$ = 0.45 GeV^{-1}
($S_R \pm S_L$ = 0)	($S_R \pm S_L$ = -0.67)	($S_R \pm S_L$ = -1.51)



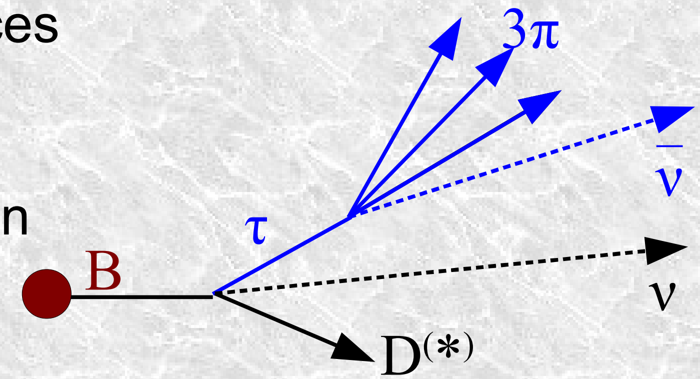


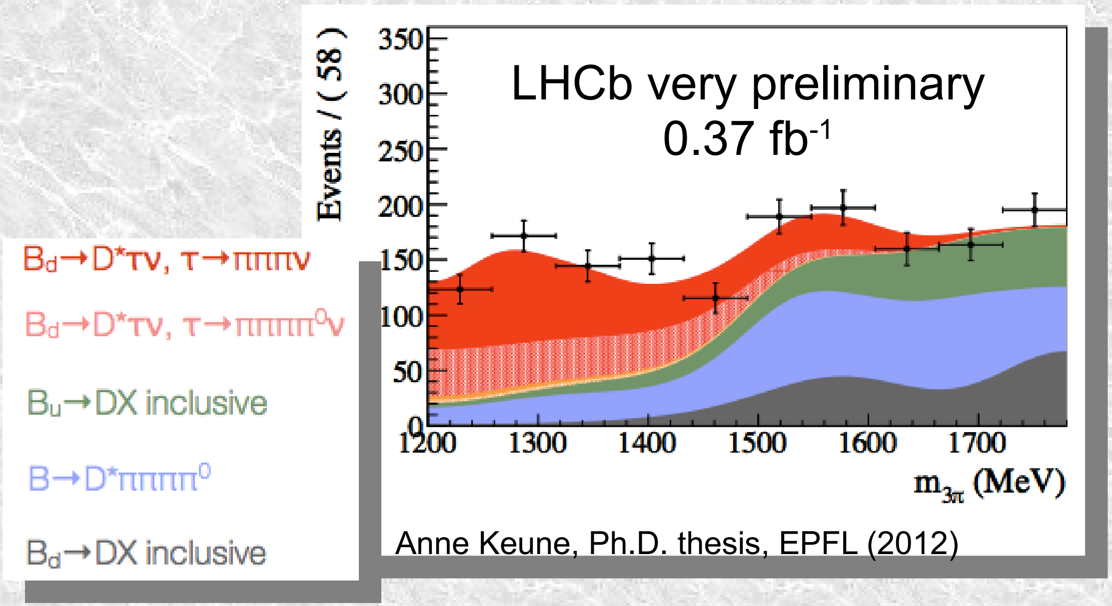
p-values of q^2 plots	$\overline{B} \to D\tau^-\overline{\nu}_\tau$	$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$
SM	83.1%	98.8%
$\tan\beta/m_{H+} = 0.30\,\text{GeV}^{-1}$	95.7%	98.9%
$\tan\beta/m_{H+} = 0.45\,\text{GeV}^{-1}$	0.4%	97.9%

p-value (with syst.) excludes solutions around $S_R \pm S_L \approx -1.5$ with >2.9σ

$B \to D^{(*)}\tau\nu$ at LHCb?

- Undefined initial state in $p\bar{p}$ collisions → no kinematic B-tagging, no m^2_{miss}
- Large boost in forward direction & excellent vertexing resolution
  → sufficient separation between B and τ vertices
  - $\tau \to \pi\pi\pi\bar{\nu}$ to define τ decay vertex
  - D + "slow" π provide τ birth vertex & τ direction





Anne Keune, Ph.D. thesis, EPFL (2012)

Possible yield at 3 fb^{-1} (assuming $\sigma(b\bar{b})$ =250μb, BF($B \to D^*\tau\nu$)=1.2% and ε=0.01%)
$N(B \to D^*\tau\nu,\ D^* \to D^0\pi,\ D^0 \to K\pi,\ \tau \to \pi\pi\pi\bar{\nu})$ ~ 1800 events (compared to 888 at BaBar)

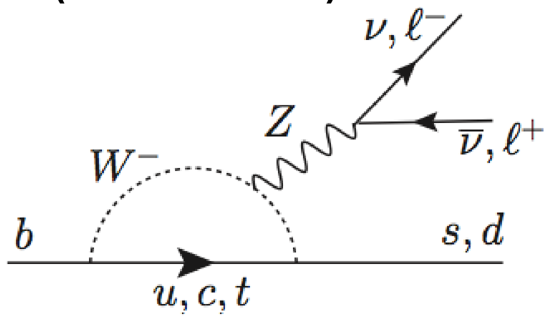
Malcolm John talk at "Workshop on B → D** decays and related issues" (November 2012)

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

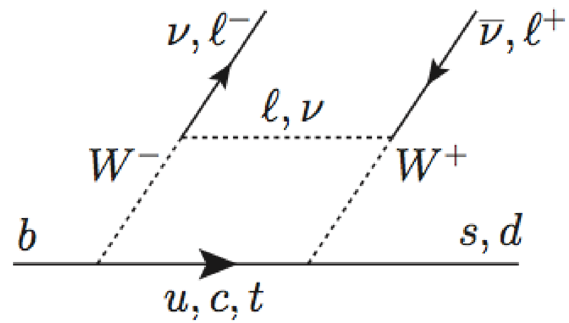
PRD 87, 112005 (2013)

Electroweak Penguin Decays in SM

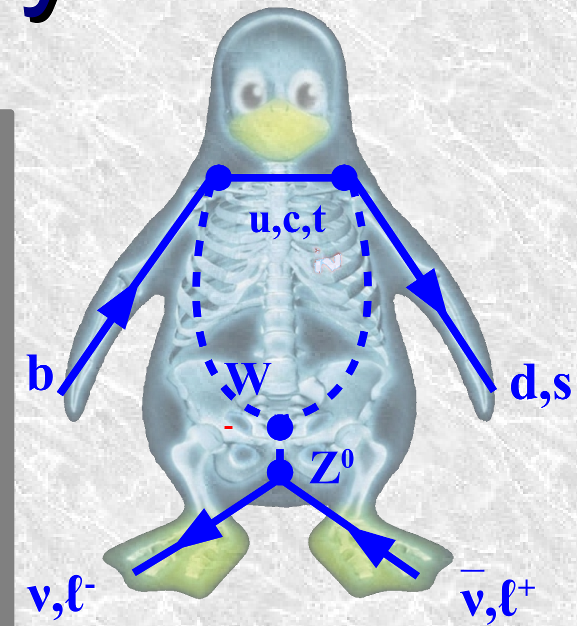
Flavor-Changing Neutral Current (FCNC) processes ($b \rightarrow s$ or d) are not allowed at tree-level in SM



weak "penguin" diagram



box diagram

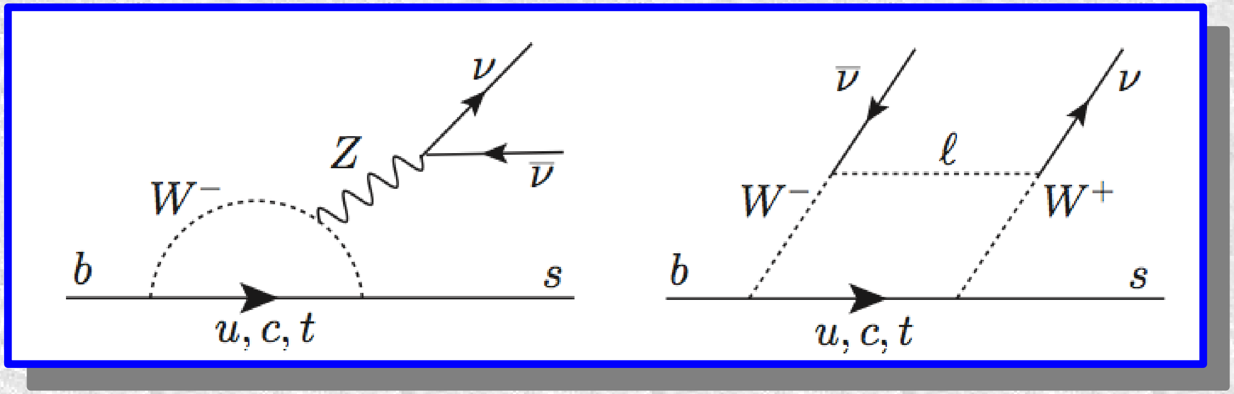


Radiative Penguin

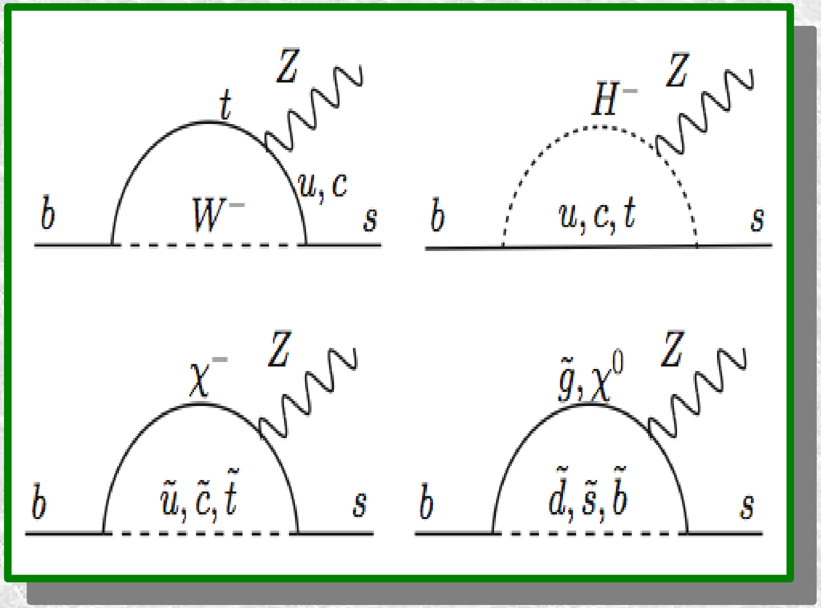
SM expectations

- Dominated by top-quark exchange → $BR(B \rightarrow K^{(*)} \nu\overline{\nu})$ suppressed by $|V_{ts}|^2$
  - $BF(B \rightarrow K^{(*)} \nu\overline{\nu}) \sim 10^{-6}$
- $b \rightarrow d$ further suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ compared to $b \rightarrow s$
  - $BF(B \rightarrow \pi/\eta\ \ell^+\ell^-) \sim 10^{-8}$
  - $\ell^+\ell^-$ modes also have EM penguin (γ) → long-distance theoretical uncertainties
- Exclusive searches → largest uncertainties from $B \rightarrow K^{(*)}/\pi/\eta$ form-factors

Penguin Decays Beyond SM



- Theoretically well-understood → precision tests of SM
- New Physics can enhance Branching Fraction at leading order:
  - New Physics entering in loops
  - Non-standard Z or Z' couplings
  - Invisible NP in addition to neutrinos



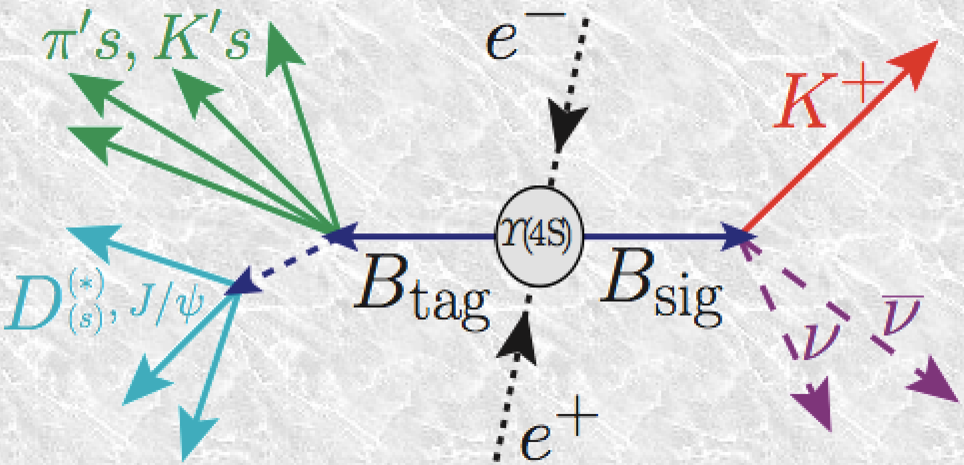
- New Physics can modify angular/momentum distributions, lepton flavor ratios, CP asymmetries

PRD 87, 112005 (2013)

$B \to K^{(*)} \nu\bar{\nu}$ Event Selection

$$\mathcal{B}(B \to K\nu\bar{\nu})_{\mathrm{SM}} = (3.6 - 5.3) \times 10^{-6}$$
$$\mathcal{B}(B \to K^*\nu\bar{\nu})_{\mathrm{SM}} = (6.8 - 13) \times 10^{-6}$$

Altmannshofer et al, JHEP 0904, 022 (2009)
Hurth et al, Nucl. Phys. B 808, 326 (2009)
Bartsch et al, JHEP 0911, 011 (2009)



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

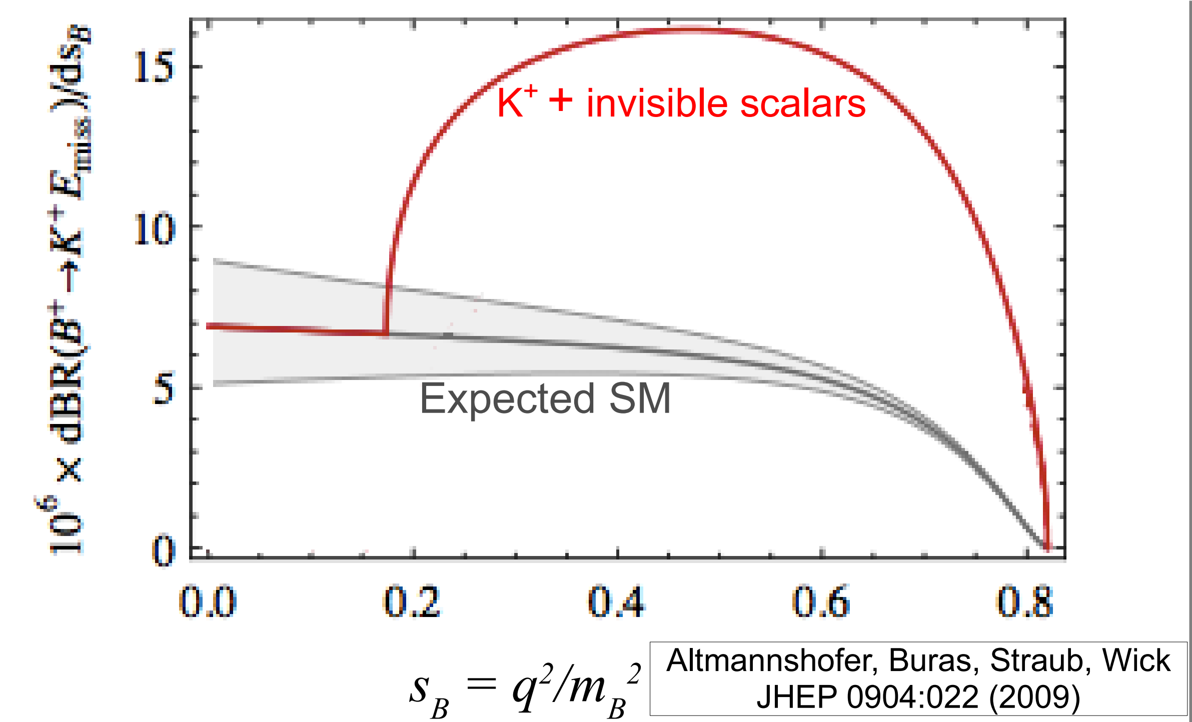
Event Selection:
- B_{tag} and $K^{(*)}$ reconstruction
- No additional tracks
- Suppress continuum bkg using LH ratio of event-shape variables
- Restrict to low values of E_{extra}
- Correct MC to data using m_{ES} sidebands

PRD 87, 112005 (2013)

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

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

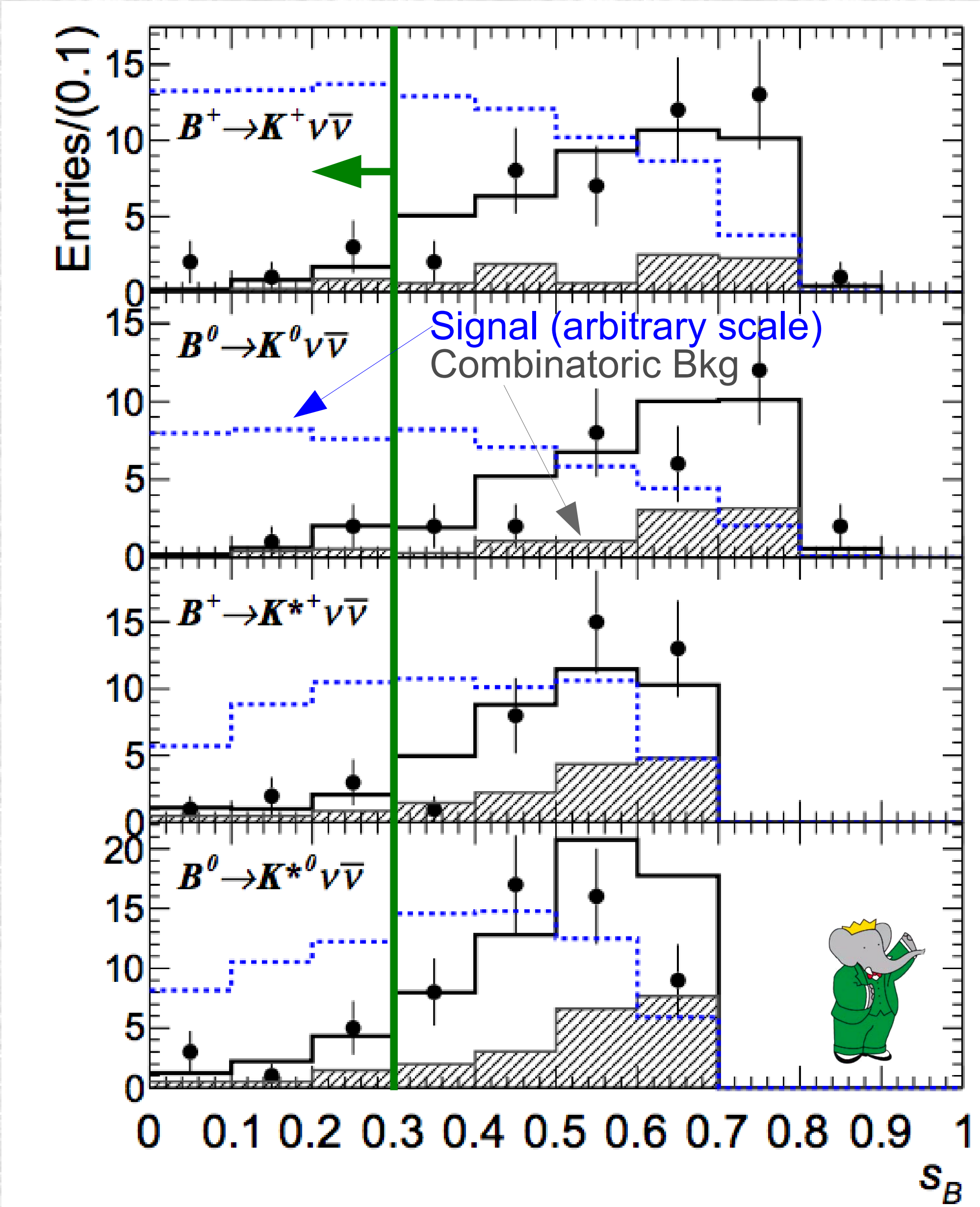
- Normalized invariant mass of $\nu\bar{\nu}$
- Report 2 results:
  - Cut & count in $s_B < 0.3$ for SM sensitivity
    - K (K*) momentum of $\gtrsim$ 1.7 (1.8) GeV/c
  - Partial BFs over full kinematic spectrum for New Physics sensitivity



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

PRD 87, 112005 (2013)

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



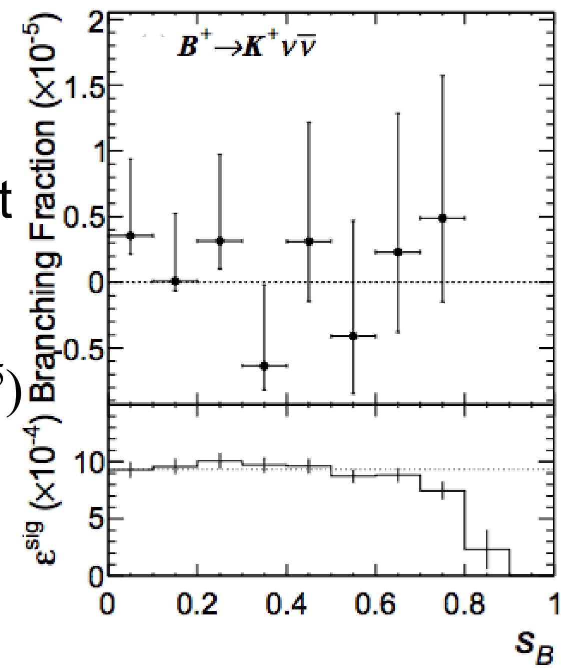
Branching fraction UL at 90% CL with $s_B < 0.3$

$K^+\nu\bar{\nu}$	$K^0\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$
(>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 ~2σ)

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



PRD 87, 112005 (2013)

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

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

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

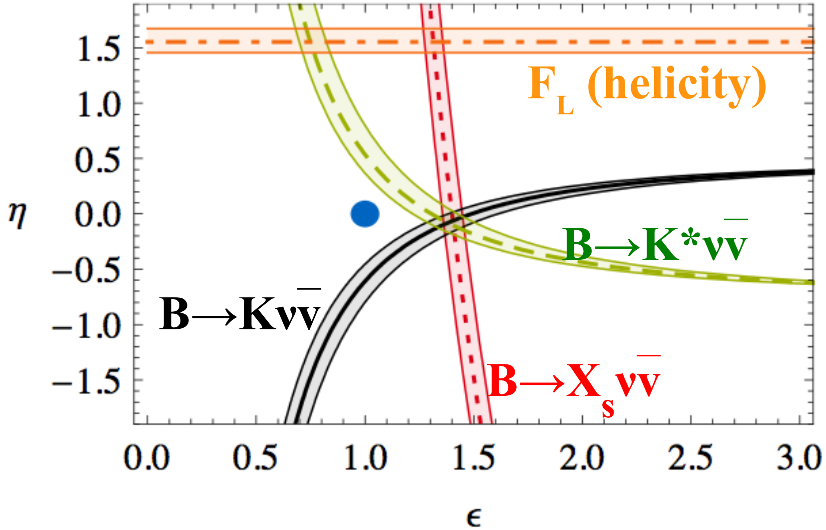
$$\eta = \frac{-\mathrm{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

RH current

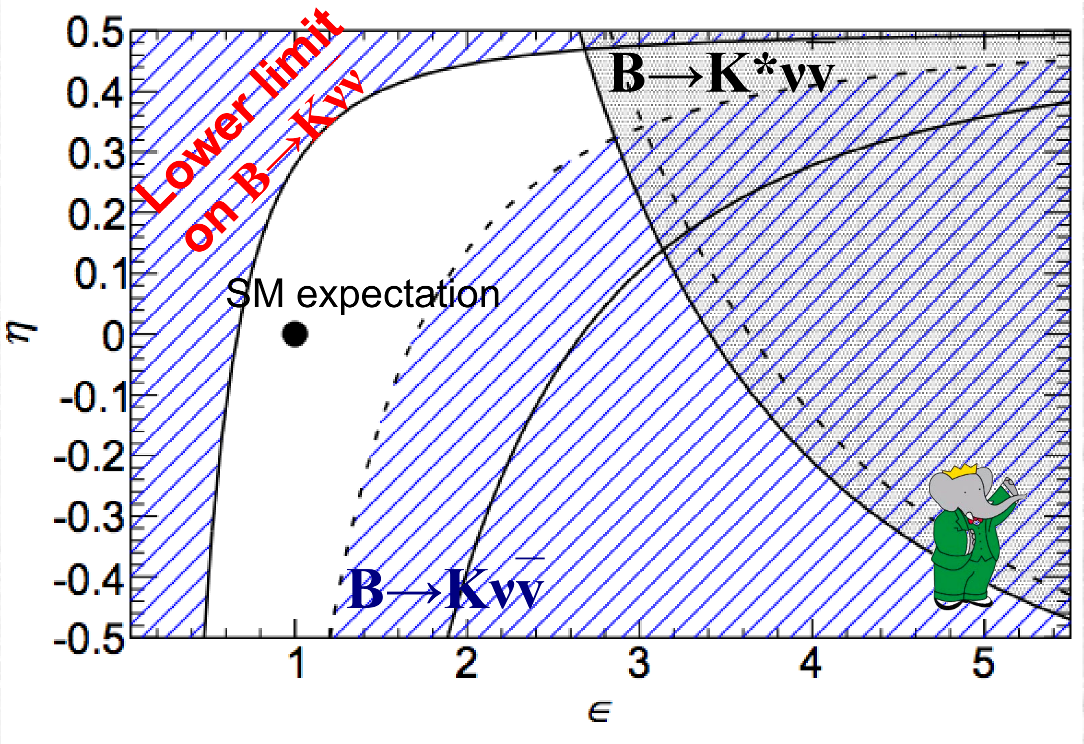
$C_R = 0$ in SM

New Physics scenario with invisible scalar contributions

(*Only theoretical uncertainties shown*)



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



These constraints

SL-tag constraints:

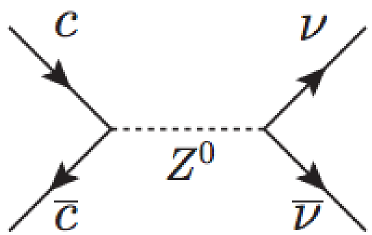
- $B+ \to K+\nu\bar{\nu} < 1.3 \times 10^{-5}$
- $B+ \to K^*+\nu\bar{\nu} < 9.0 \times 10^{-5}$

PRD 87, 112005 (2013)

$B \to K^{(*)}\psi$; $J/\psi,\ \psi(2S) \to \nu\bar{\nu}$

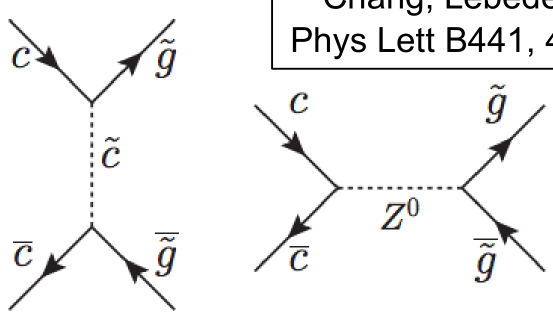
- Narrow $c\bar{c}$ resonances to invisible decays can only occur in the SM via Z^0

$BF(J/\psi \to \nu\bar{\nu})_{SM} \approx 2.5 \times 10^{-8}$

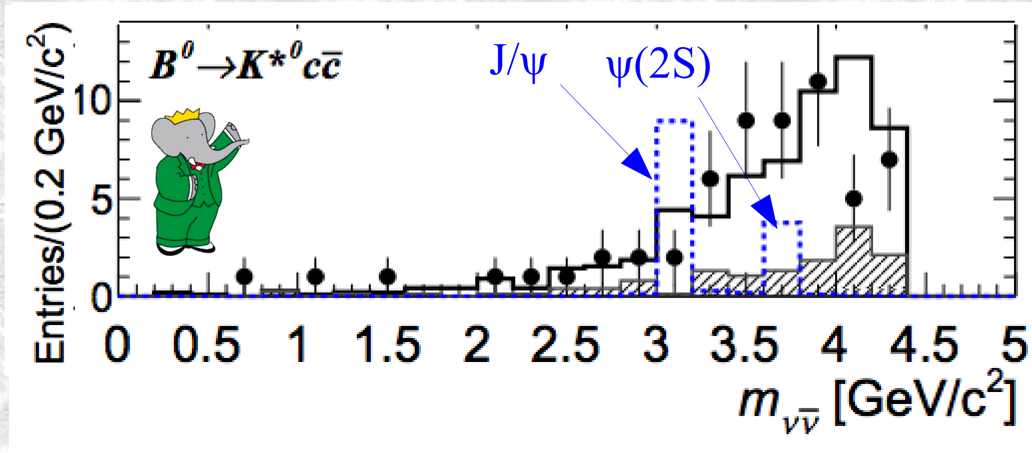


- New Physics (*e.g.* SUSY, low-mass dark matter) can increase or decrease BF
  - *i.e.* $BF(\psi \to \chi^0\bar{\chi}^0) \sim 10^{-5}$

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



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



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

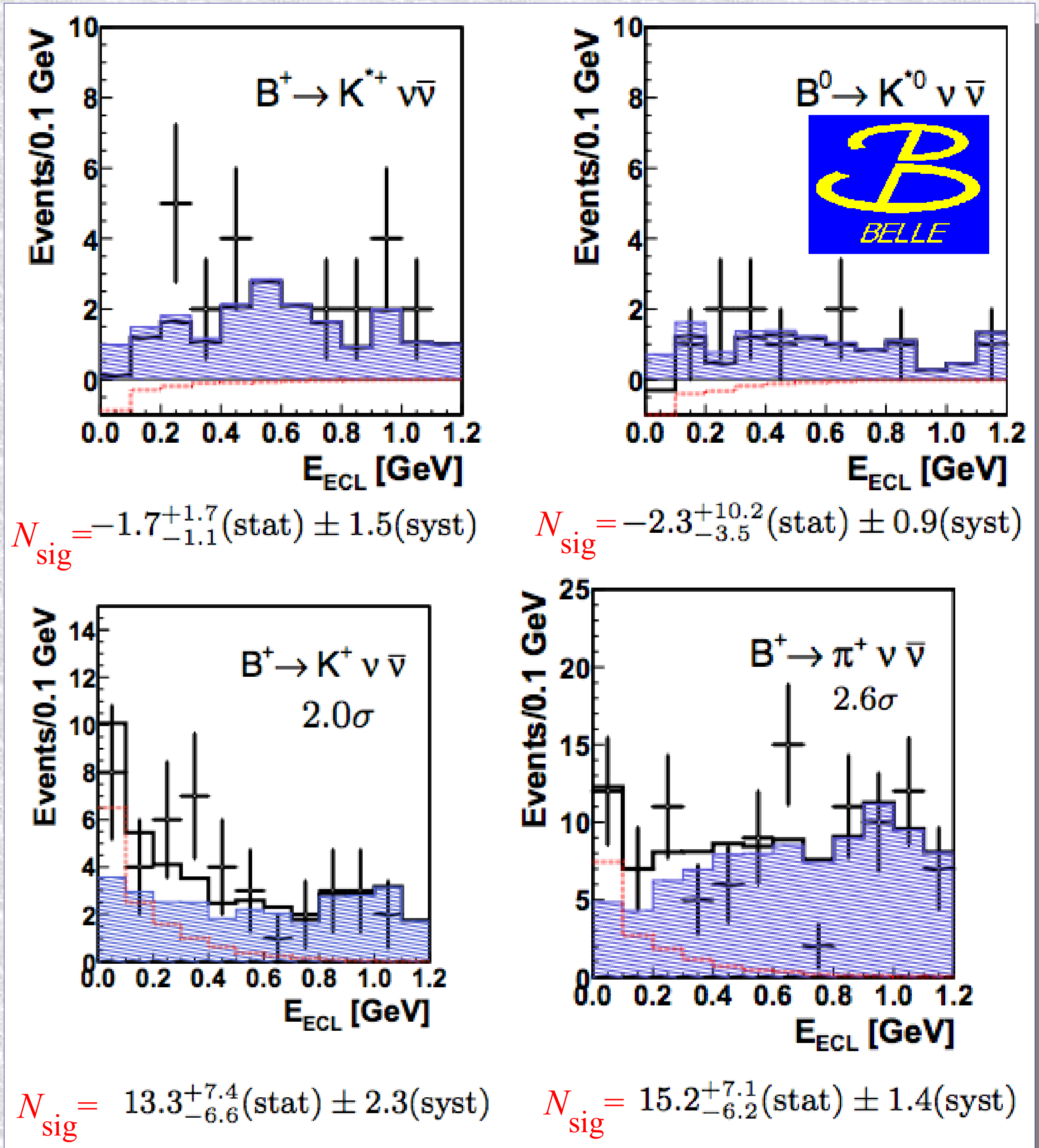
$\psi(2S) \to \nu\bar{\nu} < 15.5 \times 10^{-3}$

at 90% CL

First ever search!

PRD 87, 111103 (2013)
772 million $B\bar{B}$

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



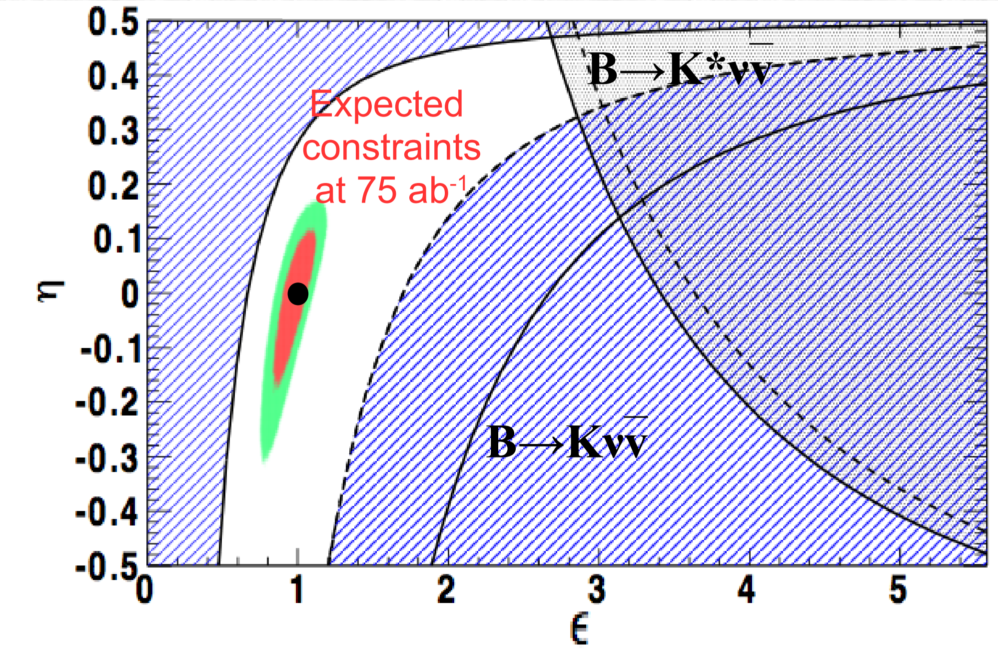
$\times 10^{-5}$

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

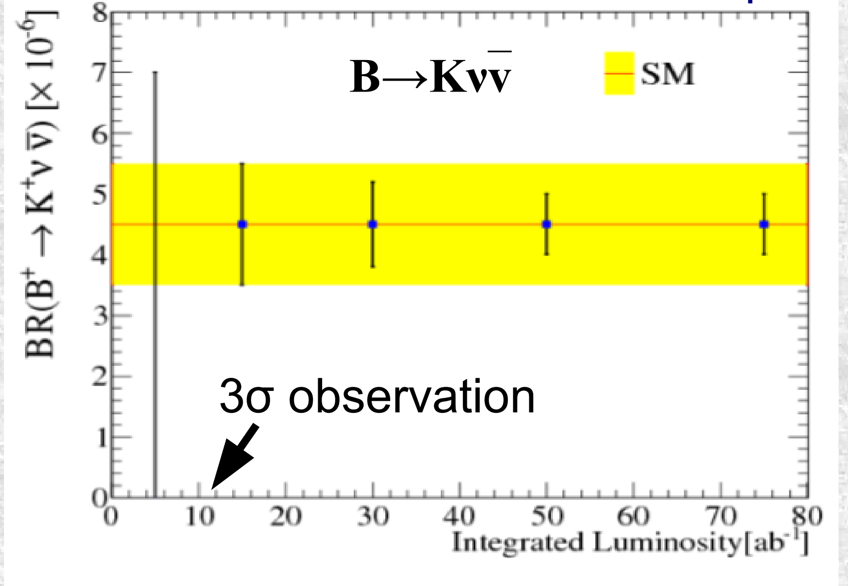
Best Limits to date

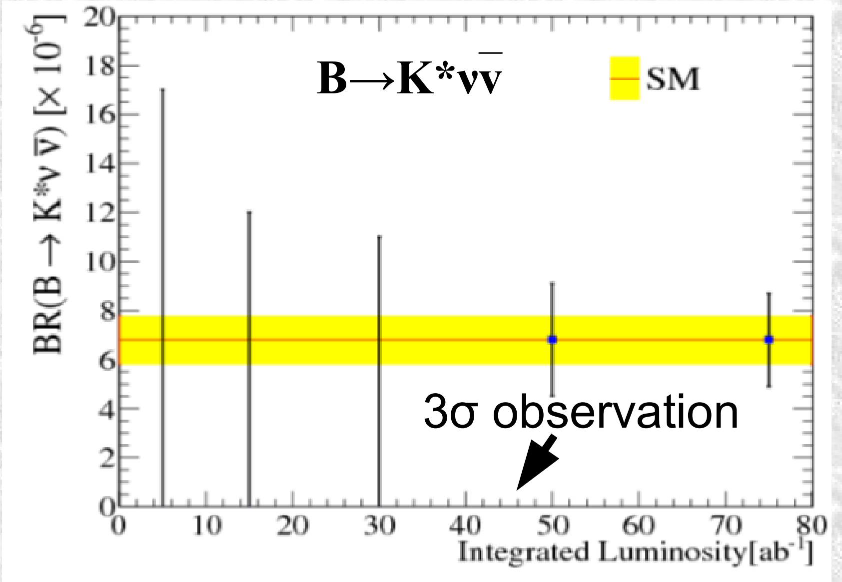
- Signal yield < 0 for $B \to K^*\nu\bar{\nu}$
  - Best limits for $B \to K^*\nu\bar{\nu}$
- Best limits for $B \to \pi\nu\bar{\nu}$, $B \to \rho^0\nu\bar{\nu}$

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



Based on simulation studies for SuperB





- Predict 15-25% precision on BF at 50 ab^{-1}
- Expect to measure F_L (polarization fraction) of $B \to K^* \nu\bar{\nu}$ to ~50% precision (currently unmeasured)

arXiv:1008.1541

$B \rightarrow \pi/\eta\ \ell^{+}\ell^{-}$

accepted by PRD, arXiv: 1303:6010

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

SM expected rates (excluding charmonium):

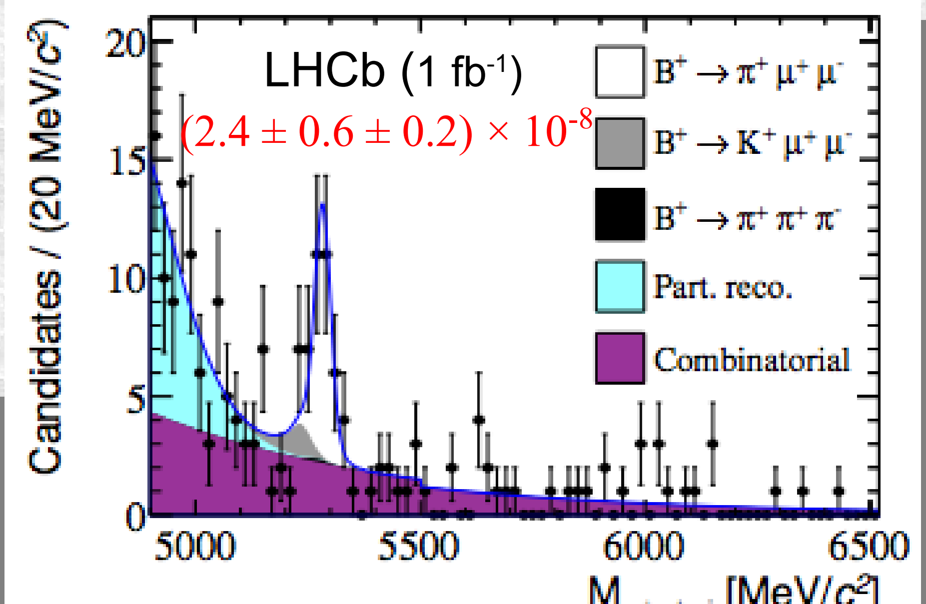
$$\mathcal{B}(B^+ \to \pi^+\ell^+\ell^-) = (1.96\text{–}3.30) \times 10^{-8}$$

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

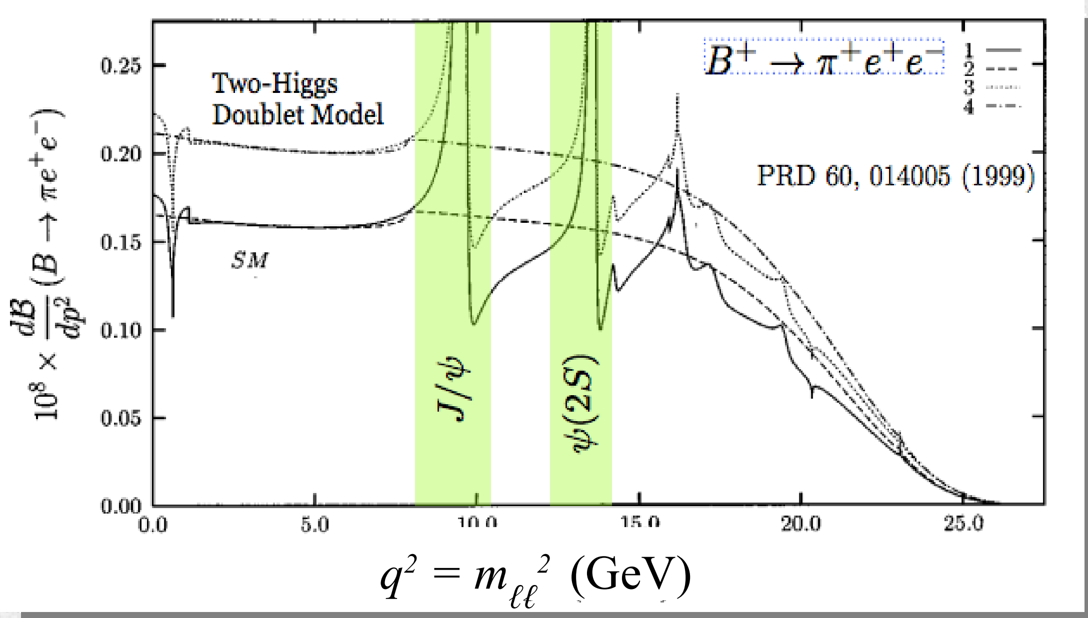
Aliev & Savci, PRD 60, 014005 (1999)
Erkol & Turan, Eur. Phys. Jour. C 28, 243 (2003)

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

$B \to \pi^+\mu^+\mu^-$ recently observed at LHCb



JHEP12 125 (2012)



arXiv:1303.6010

$B\to\pi/\eta\ \ell^+\ell^-$ Event Selection

6 channels (where $\ell = e$ or μ):

- $B^0\to\pi^0\ \ell^+\ell^-$
- $B^+\to\pi^+\ \ell^+\ell^-$
- $B^0\to\eta\ \ell^+\ell^-$

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

First ever search!

Fully reconstructable final state
(No B_{tag} reco necessary)

- Lepton pair + π or η candidate
- $p_\ell > 300$ MeV/c
- Continuum and $B\bar{B}$ bkg suppressed using neural nets for ee and $\mu\mu$ modes (4 NN total)
  - Event topology, kinematics, E_{miss}

Background specific vetos:

- Charmonium
  - $m_{\ell\ell}$ veto on J/ψ and $\psi(2S)$
  - Used as high-statistics control sample
- Two-photon events: $e^+e^-\to e^+e^-q\bar{q}$
- Hadronic decays: (e.g. $B\to\pi^-\pi^+\pi^-$)
- Charm: $B\to D\pi$, $D\eta$; $D\to\pi\pi$, $K\pi$, $\eta\pi$, with hadrons mis-IDed as muons

arXiv:1303.6010

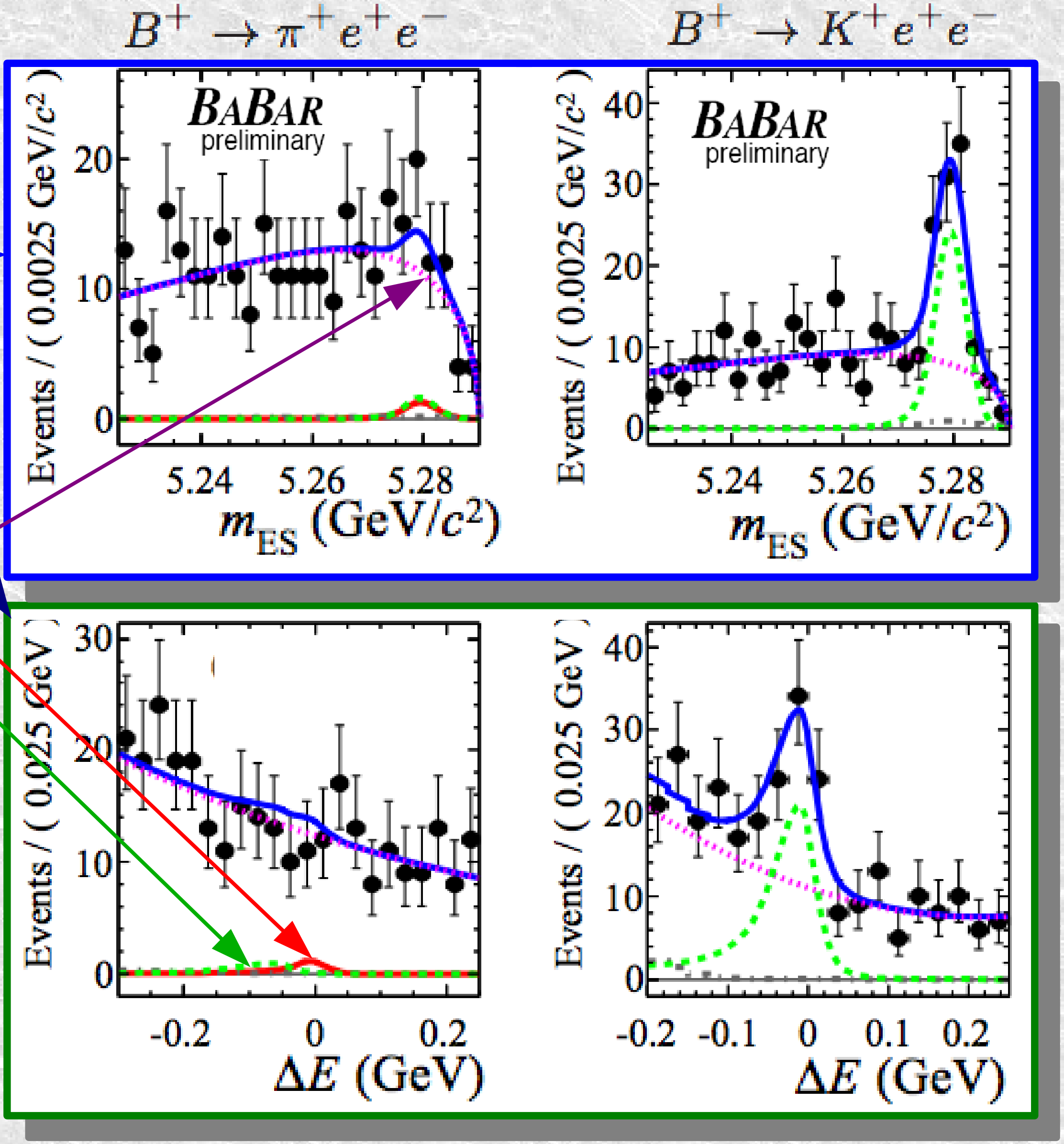
Fit to $B \to \pi/\eta\ \ell^+\ell^-$

- 2D unbinned max likelihood fit:

$$m_{ES} = \sqrt{E_{\rm beam}^{*2} - p_B^{*\,2}}$$

$$\Delta E = E_B^* - E_{\rm beam}^*$$

Combinatoric Bkg
Signal
$B \to K^+\ell^+\ell^-$

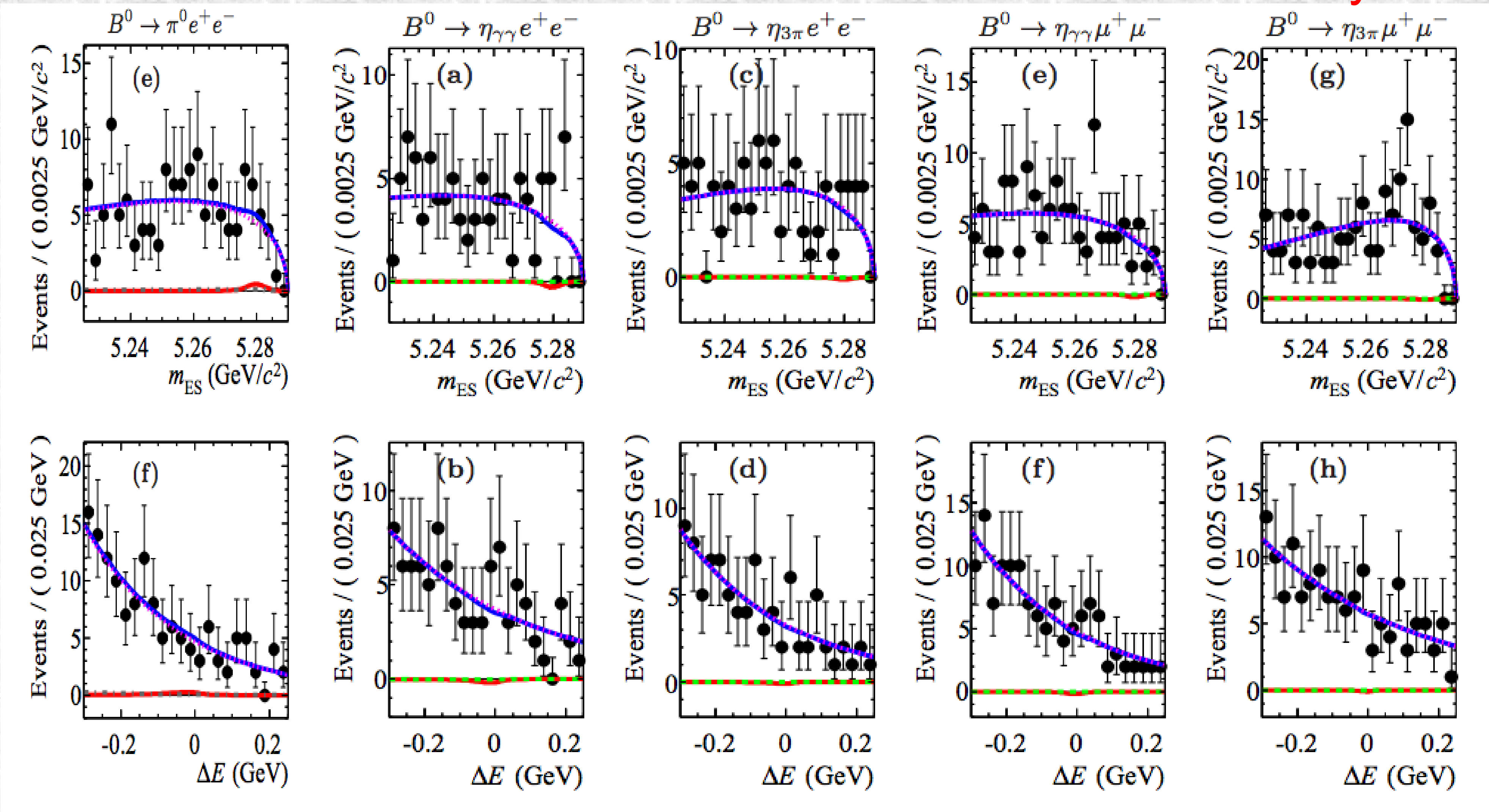


- Large $B \to K^+\ell^+\ell^-$ bkg
  - From K's misidentified as π's
  - Simultaneous fit with $\pi^+\ell^+\ell^-$
  - Provides BF validation
- Also, lepton-flavor and/or isospin-constrained fits to combine channels

arXiv:1303.6010

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

BaBar Preliminary



No significant signal observed

arXiv:1303.6010

B→π/η ℓ⁺ℓ⁻ 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 (LHCb: $2.4 \pm 0.6 \pm 0.2$)	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

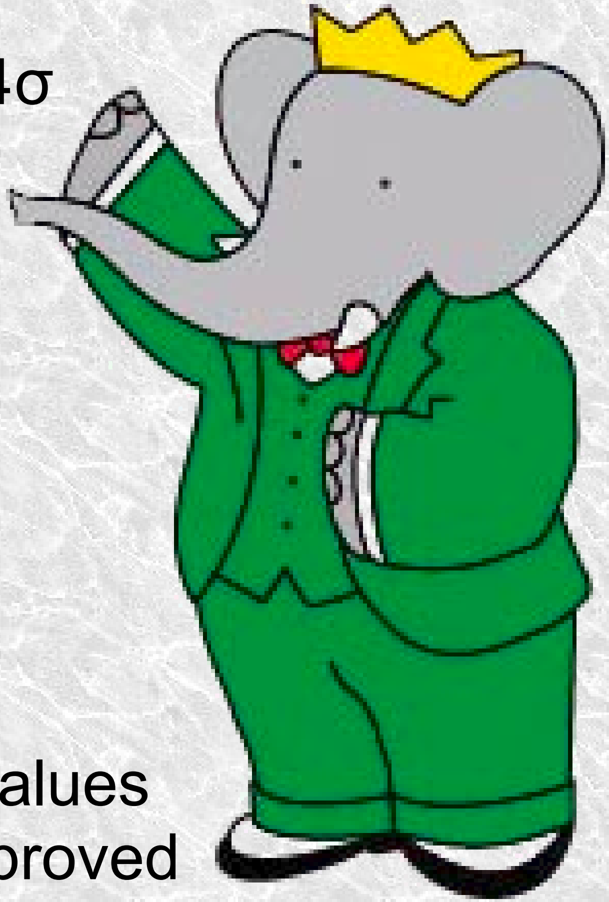
First ever limits

Constrained by: both ℓ-flavor isospin

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

Conclusions

- New results from BaBar on B decays sensitive to New Physics
  - $BR(B \to \tau\nu)$ observed at 3.8σ
  - $R(D^{(*)})$ from $B \to D^{(*)}\tau\nu$ excludes SM by 3.4σ
    - Excludes Type-II 2HDM by 3.1σ
    - Constrains Type-III 2HDM model
  - First lower limits for $B \to K\nu\bar{\nu}$
    - First search for $\psi(2S) \to \nu\bar{\nu}$
  - Best limits for $B \to \pi^0\ell^+\ell^-$
    - First search for $B \to \eta\ell^+\ell^-$
- Belle II sensitivity expected to reach SM BF values for $B \to K^{(*)}\nu\bar{\nu}$ and $B \to \pi/\eta\ell^+\ell^-$ and provide improved precision of $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ measurements



Back-ups

$B \to \tau\nu$ Details

Decay Mode	$\epsilon_k (\times 10^{-4})$	Signal yield	$\mathcal{B} (\times 10^{-4})$
$\tau^+ \to e^+ \nu\bar{\nu}$	2.47 ± 0.14	4.1 ± 9.1	$0.35^{+0.84}_{-0.73}$
$\tau^+ \to \mu^+ \nu\bar{\nu}$	2.45 ± 0.14	12.9 ± 9.7	$1.12^{+0.90}_{-0.78}$
$\tau^+ \to \pi^+ \nu$	0.98 ± 0.14	17.1 ± 6.2	$3.69^{+1.42}_{-1.22}$
$\tau^+ \to \rho^+ \nu$	1.35 ± 0.11	24.0 ± 10.0	$3.78^{+1.65}_{-1.45}$
combined		62.1 ± 17.3	$1.83^{+0.53}_{-0.49}$

Variable	e^+	μ^+	π^+	ρ^+
$\mathcal{P}$		$> 10\%$		
Cluster energy (MeV)		> 60		
$\mathcal{R}2$	< 0.57	< 0.56	< 0.56	< 0.51
$\lvert \cos\theta_{TB} \rvert$	< 0.95	< 0.90	< 0.65	< 0.8
L_P			> 0.30	> 0.45

Source of systematics	$\mathcal{B}$ uncertainty (%)
Additive	
Background PDF	10
Signal PDF	2.6
Multiplicative	
Tag-B efficiency	5.0
B counting	1.1
Electron identification	2.6
Muon identification	4.7
Kaon identification	0.4
Tracking	0.5
MC statistics	0.6
Total	13

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

Source	Uncertainty (%) $R(D)$	$R(D^*)$	ρ
$D^{**}\ell\nu$ background	5.8	3.7	0.62
MC statistics	5.0	2.5	-0.48
Cont. and $B\overline{B}$ bkg.	4.9	2.7	-0.30
$\varepsilon_{sig}/\varepsilon_{norm}$	2.6	1.6	0.22
Systematic uncertainty	9.5	5.3	0.05
Statistical uncertainty	13.1	7.1	-0.45
Total uncertainty	**16.2**	**9.0**	**-0.27**

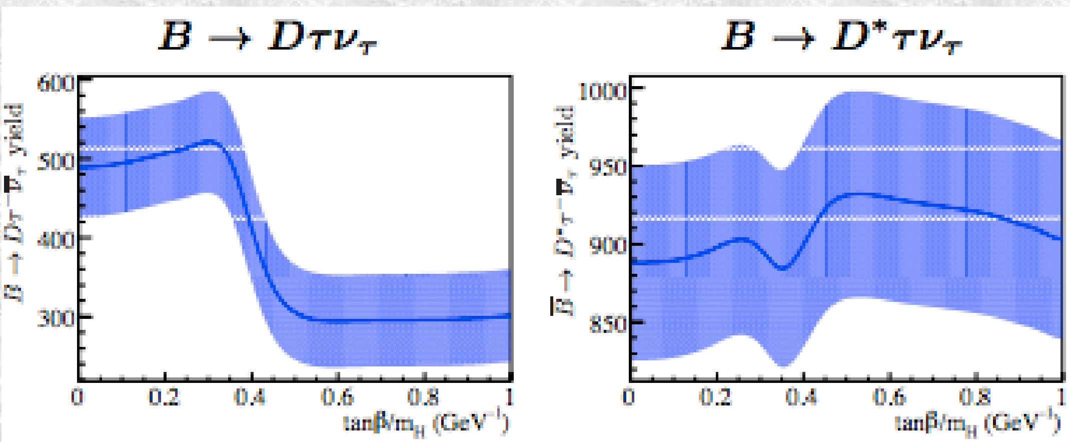
Correlation between $R(D)$ and $R(D^*)$

- **Largest syst.** due to **backgrounds**
- **Small** uncertainty on **efficiency ratio $\varepsilon_{sig}/\varepsilon_{norm}$**
- **Statistical** uncertainty **dominates**

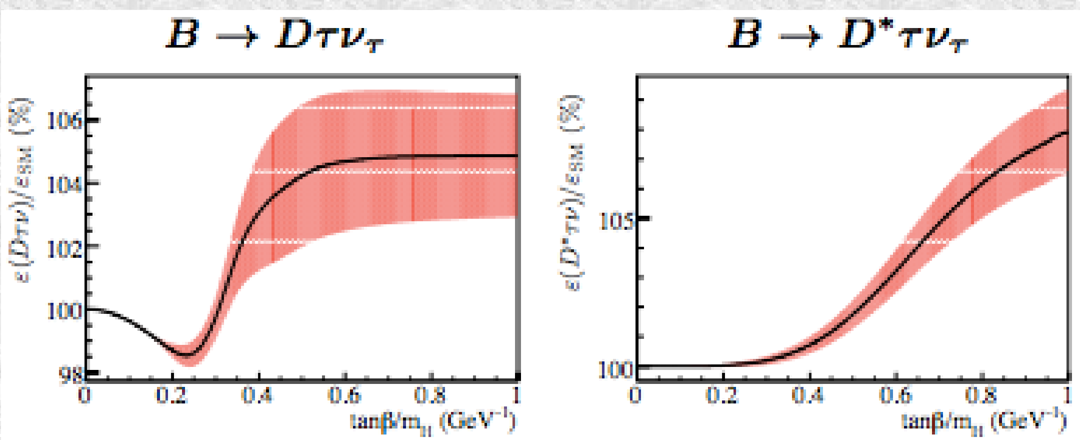
2HDM yields & efficiencies

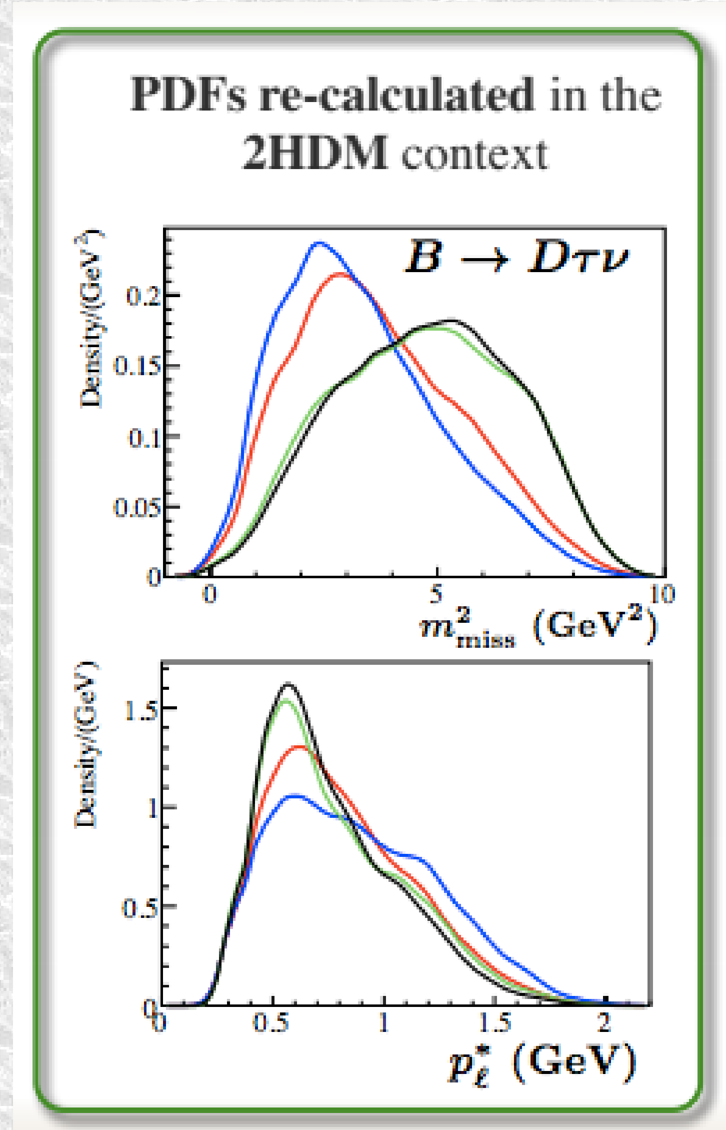
- PDFs re-calculated in 2HDM context for all values of $\tan\beta/m_{H+}$

Fitted Yields



Efficiencies





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

A. Bozek's averages shown at KEK-FF 2013:

(naive averages for inclusive and exclusive hadronic tags)

$R(D) = 0.430 \pm 0.091$

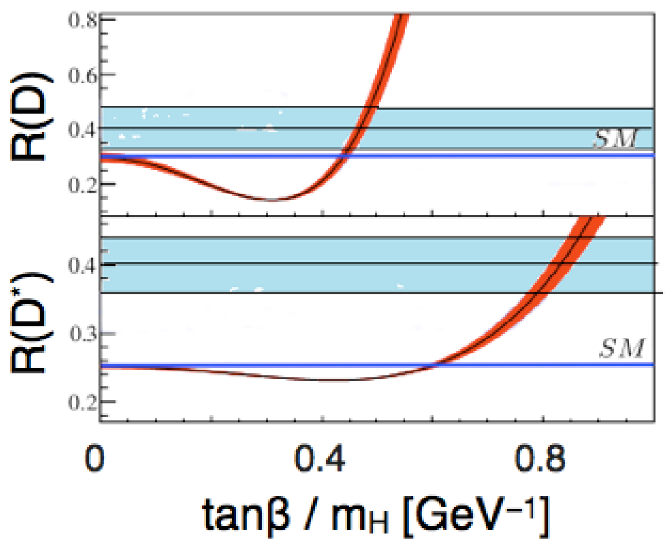
$R(D^*) = 0.405 \pm 0.047$

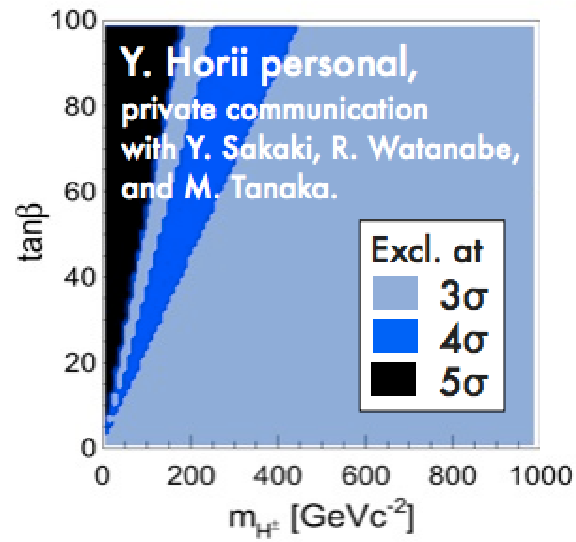
PRL 99 (2007) (535×10^6)
PRD 82 (2010) (657×10^6)
hep-ex/0910.4301 (657×10^6)

SM deviations:
$R(D)$: 1.4σ
$R(D^*)$: 3.0σ
Combined: 3.3σ

Correlation btw $R(D)$ and $R(D^*)$ neglected conservatively.

Constraint on Type-II 2HDM:





Experimental $R(D^{(*)})$ dependence on $\tan\beta/m_H$ not considered.
Experimental correlation between $R(D)$ and $R(D^*)$ not considered.

Belle and *BABAR* average deviation from SM

- $R(\overline{D}^*)$ 3.8σ
- $R(\overline{D})$ 2.4σ
- $R(\overline{D}^{(*)})$ 4.8σ

Y. Horii @ Beauty 2013
A. Bozek @FPCP 2013

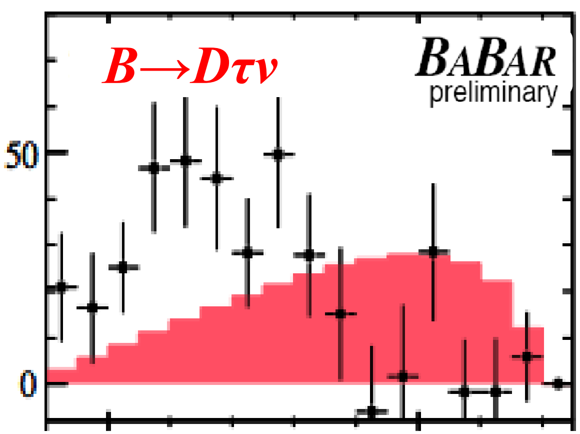
arXiv:1303.0571
submitted to PRD

$B \to D^{(*)} \tau \nu$ Summary

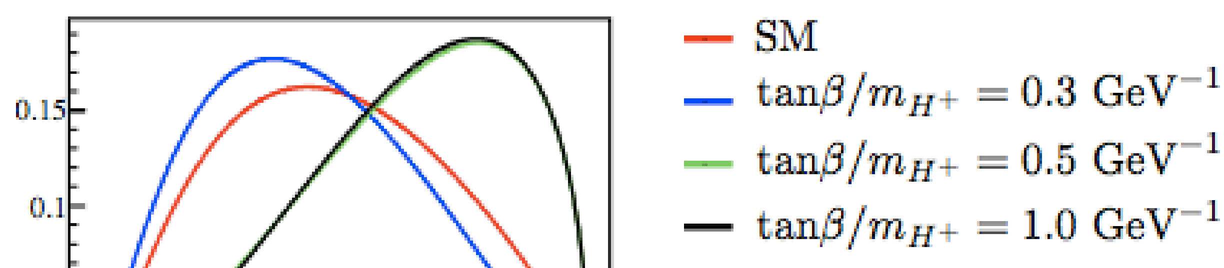
	R(D)	R(D*)	R(D)/R(D*)	q² spectrum
SM	✗ (2.0 σ)	✗ (2.7 σ)	✗ (3.4 σ)	✓
Type II 2HDM	✓	✓	✗ (3.1 σ)	~
Type III 2HDM	✓	✓	✓	~
Non-0 spin NP	✓	✓	✓	✓

- Type-III 2HDM can account for R(D), R(D*), **and** $B \to \tau \nu$ deviations without fine-tuning
- 2 of 4 real solutions, as well as **non-real solutions**, still possible

q^2 data distribution consistent with non-zero spin NP (P-wave contribution)



$\tan\beta/m_{H+} = 0.45\ \mathrm{GeV}^{-1}$



Spin-0

PRD 87, 112005 (2013)

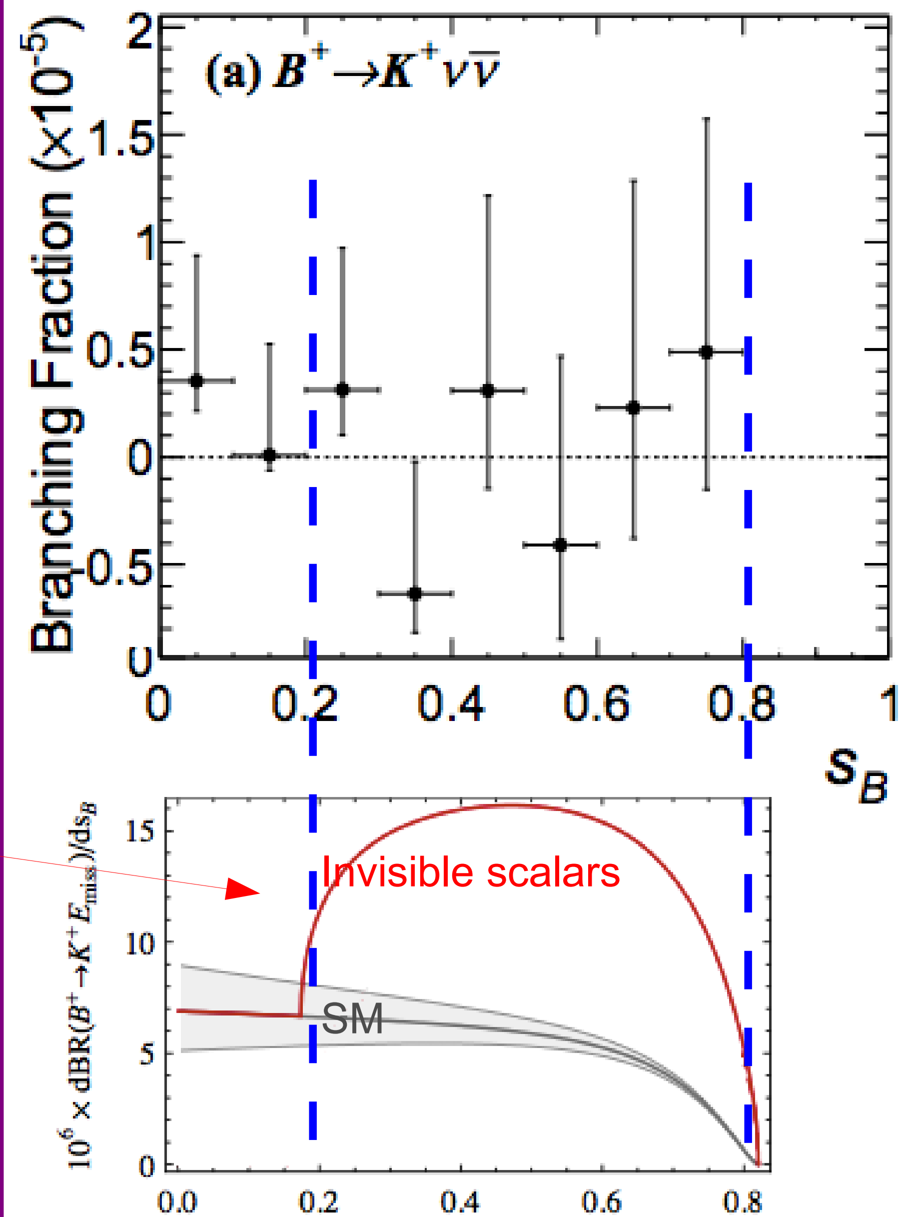
$B \to K^{(*)} \nu\bar{\nu}$ Partial BFs

- 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

$$\Delta\mathcal{B} = \frac{N^{\mathrm{obs}}_{\mathrm{bin}} - N^{\mathrm{bkg}}_{\mathrm{bin}}}{N_B\,\epsilon^{\mathrm{sig}}_{\mathrm{bin}}} \cdot \frac{\epsilon^{\mathrm{sig}}_{\mathrm{bin}}}{\epsilon^{\mathrm{sig}}_{\mathrm{full}}}$$

- 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)

PRD 87, 112005 (2013)

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

	$B^+ \to K^+\nu\bar{\nu}$	$B^0 \to K^0\nu\bar{\nu}$
N_i^{comb}	$1.1 \pm 0.4 \pm 0.0$	$0.9 \pm 0.4 \pm 0.1$
N_i^{peak}	$1.8 \pm 0.4 \pm 0.1$	$2.0 \pm 0.5 \pm 0.2$
N_i^{bkg}	$2.9 \pm 0.6 \pm 0.1$	$2.9 \pm 0.6 \pm 0.2$
ε_i^{sig} $(\times 10^{-5})$	$43.8 \pm 0.7 \pm 3.0$	$10.3 \pm 0.2 \pm 1.2$
N_i^{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	$(> 0.2, < 3.2) \times 10^{-5}$	
$\mathcal{B}(B \to K\nu\bar{\nu})$	$(1.4^{+1.4+0.3}_{-0.9-0.2}) \times 10^{-5}$	

	$B^+ \to [K^+\pi^0]\nu\bar{\nu}$	$B^+ \to [K^0_S\pi^+]\nu\bar{\nu}$	$B^0 \to [K^+\pi^-]\nu\bar{\nu}$	$B^0 \to [K^0_S\pi^0]\nu\bar{\nu}$
N_i^{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^{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^{bkg}	$2.0 \pm 0.5 \pm 0.1$	$2.3 \pm 0.5 \pm 0.1$	$7.0 \pm 0.9 \pm 0.5$	$0.7 \pm 0.3 \pm 0.0$
ε_i^{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^{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	$< 7.9 \times 10^{-5}$			
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	$(2.7^{+3.8+1.2}_{-2.9-1.0}) \times 10^{-5}$			

PRD 87, 112005 (2013)

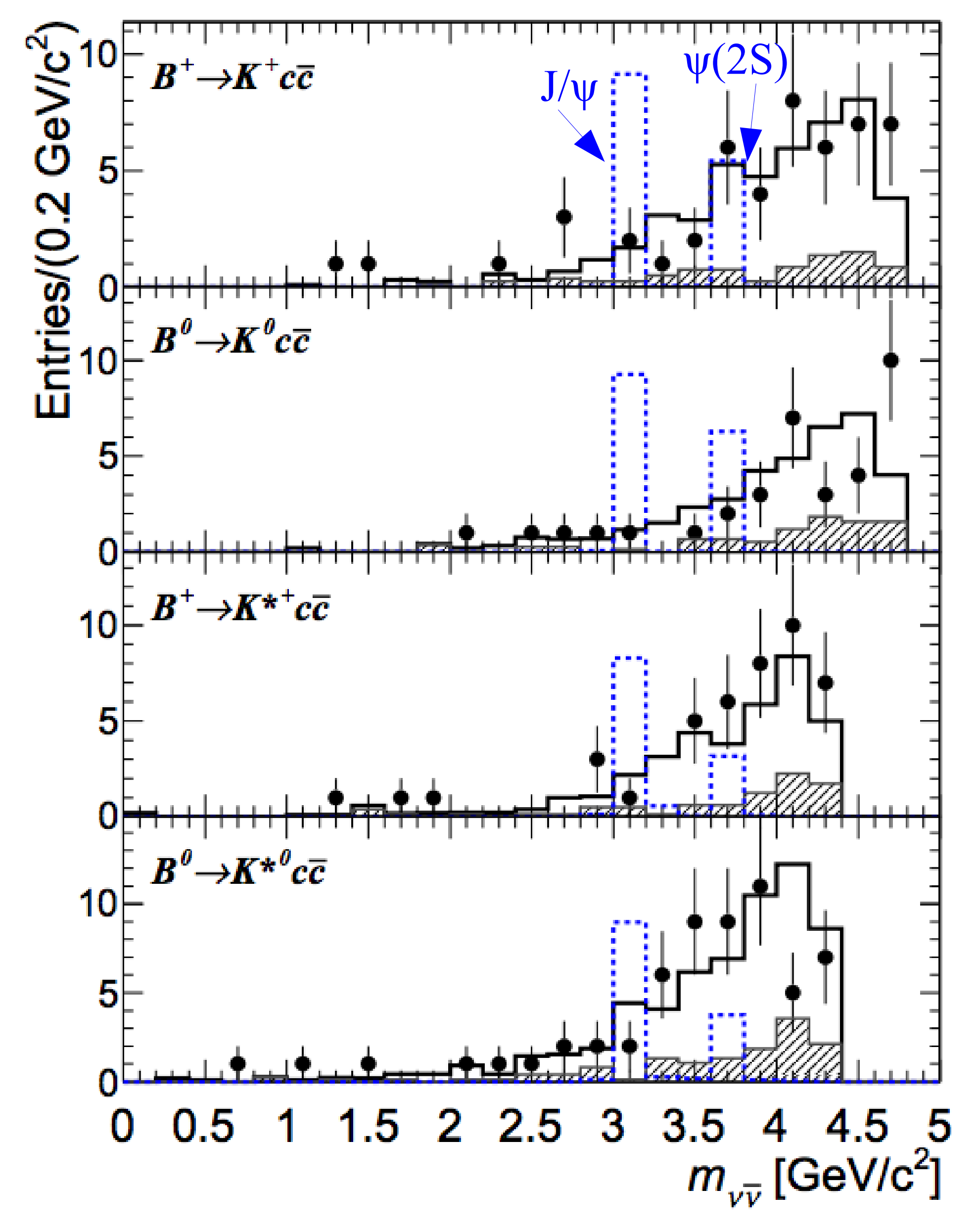
J/ψ, $\psi(2S) \rightarrow \nu\bar{\nu}$ Details

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

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

PRD 87, 112005 (2013)

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



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

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

PRD 87, 112005 (2013)

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

Source	K^+	$[K^+\pi^0]$	$[K^0_S\pi^+]$	K^0	$[K^+\pi^-]$	$[K^0_S\pi^0]$
$\varepsilon_i^{\rm sig}$ normalization	3.5	3.5	3.5	8.9	8.9	8.9
$N_i^{\rm bkg}$ 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
$E_{\rm extra}$	4.5	6.0	6.5	6.0	6.0	6.5

Source	K^+	$[K^+\pi^0]$	$[K^0_S\pi^+]$	K^0	$[K^+\pi^-]$	$[K^0_S\pi^0]$
$B\rightarrow K^{(*)}\nu\bar{\nu}$						
$N_i^{\rm peak}$ 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 $N_i^{\rm peak}$ syst.	6.8	8.9	8.8	9.7	10.0	10.9
Total $N_i^{\rm comb}$ syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total $\varepsilon_i^{\rm sig}$ syst.	6.7	8.8	8.8	11.4	11.7	12.4
$J/\psi\rightarrow\nu\bar{\nu}$						
$N_i^{\rm peak}$ 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 $N_i^{\rm peak}$ syst.	6.2	8.6	8.4	9.3	9.6	10.5
Total $N_i^{\rm comb}$ syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total $\varepsilon_i^{\rm sig}$ syst.	5.8	8.3	8.0	10.8	11.1	11.9
$\psi(2S)\rightarrow\nu\bar{\nu}$						
$N_i^{\rm peak}$ 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 $N_i^{\rm peak}$ syst.	5.8	8.5	8.1	9.1	9.5	10.7
Total $N_i^{\rm comb}$ syst.	2.3	2.3	2.3	6.0	6.0	6.0
Total $\varepsilon_i^{\rm sig}$ syst.	5.8	8.4	8.1	10.9	11.2	12.2

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

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