Leptonic and Radiative B Meson Decays at Belle

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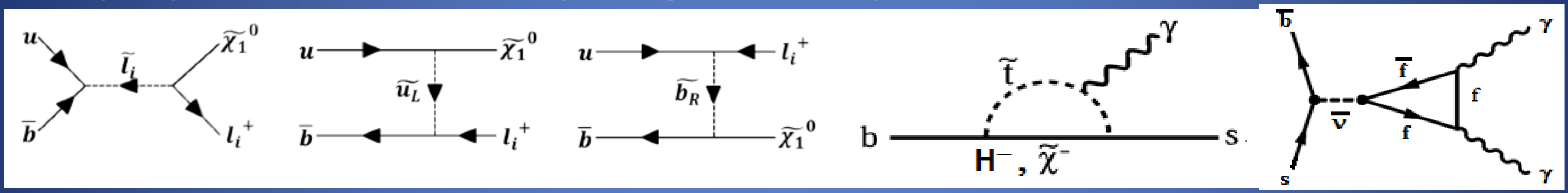
EPS-HEP 2015

23-29 July, Vienna, Austria

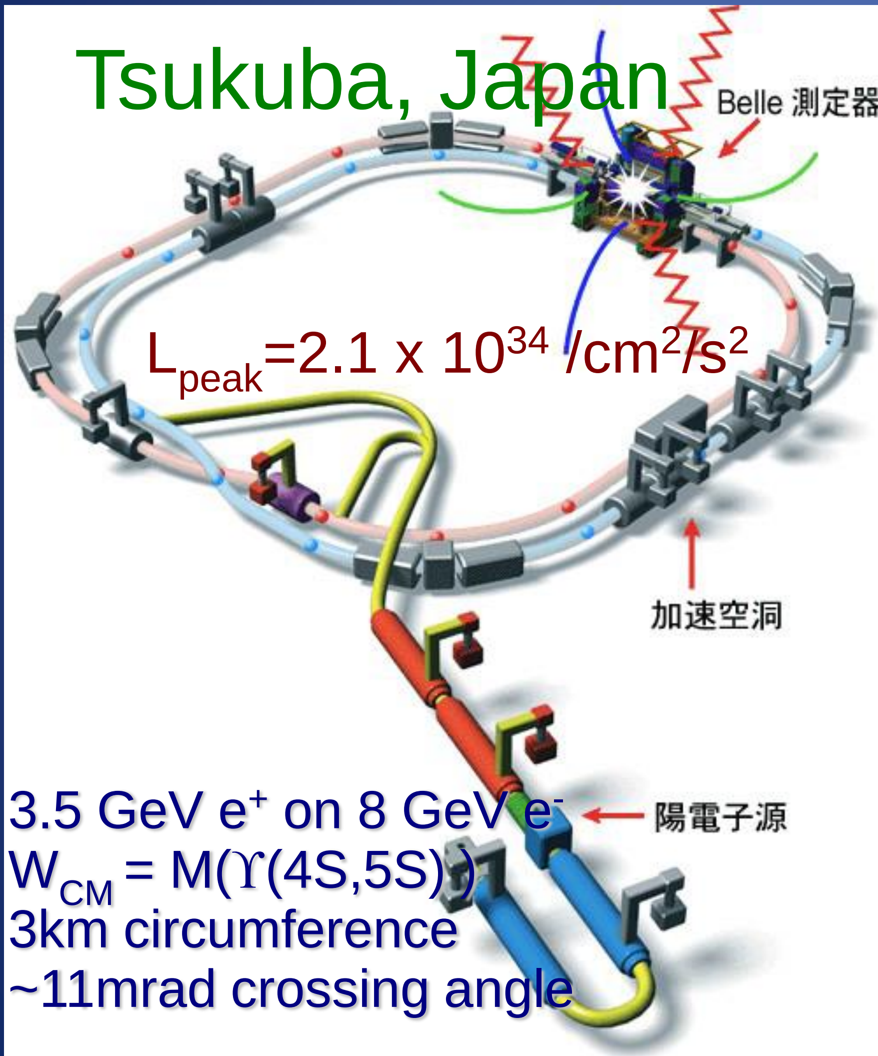
Introduction

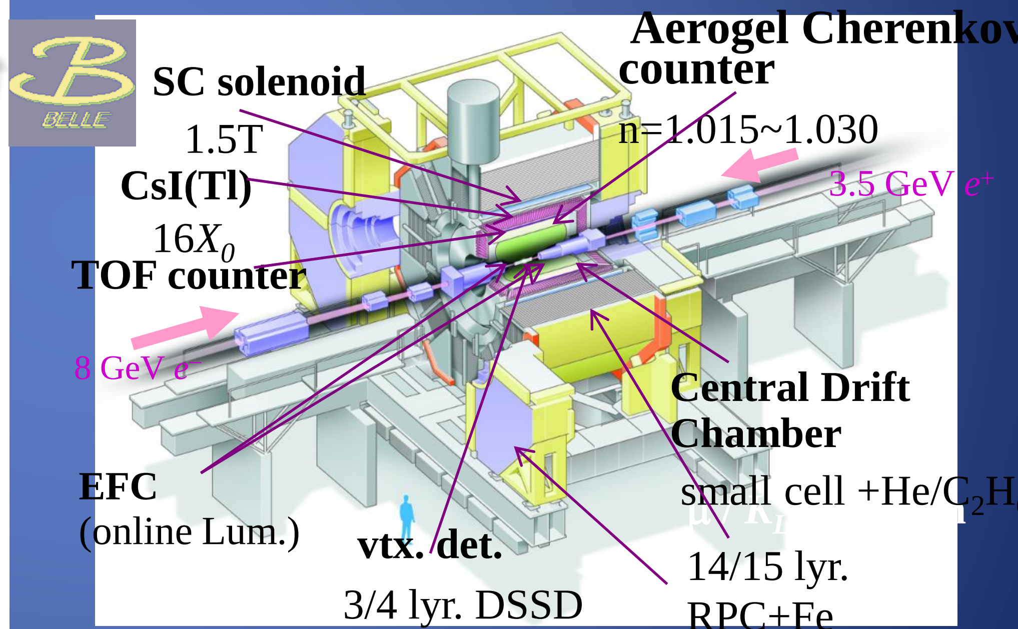
- Leptonic and radiative B decays are sensitive to new physics in tree or penguin loop.



  - Small SM branching fraction ($\mathcal{B}$)
  - More precise theoretical predictions
- Topics covered in this talk
  - Search for massive invisible particles
  - Search for $B^+ \to \ell^+ \nu \gamma$, ($\ell$ = e, μ)
  - Update on $B_s^0 \to \phi \gamma$ and search for $B_s^0 \to \gamma\gamma$

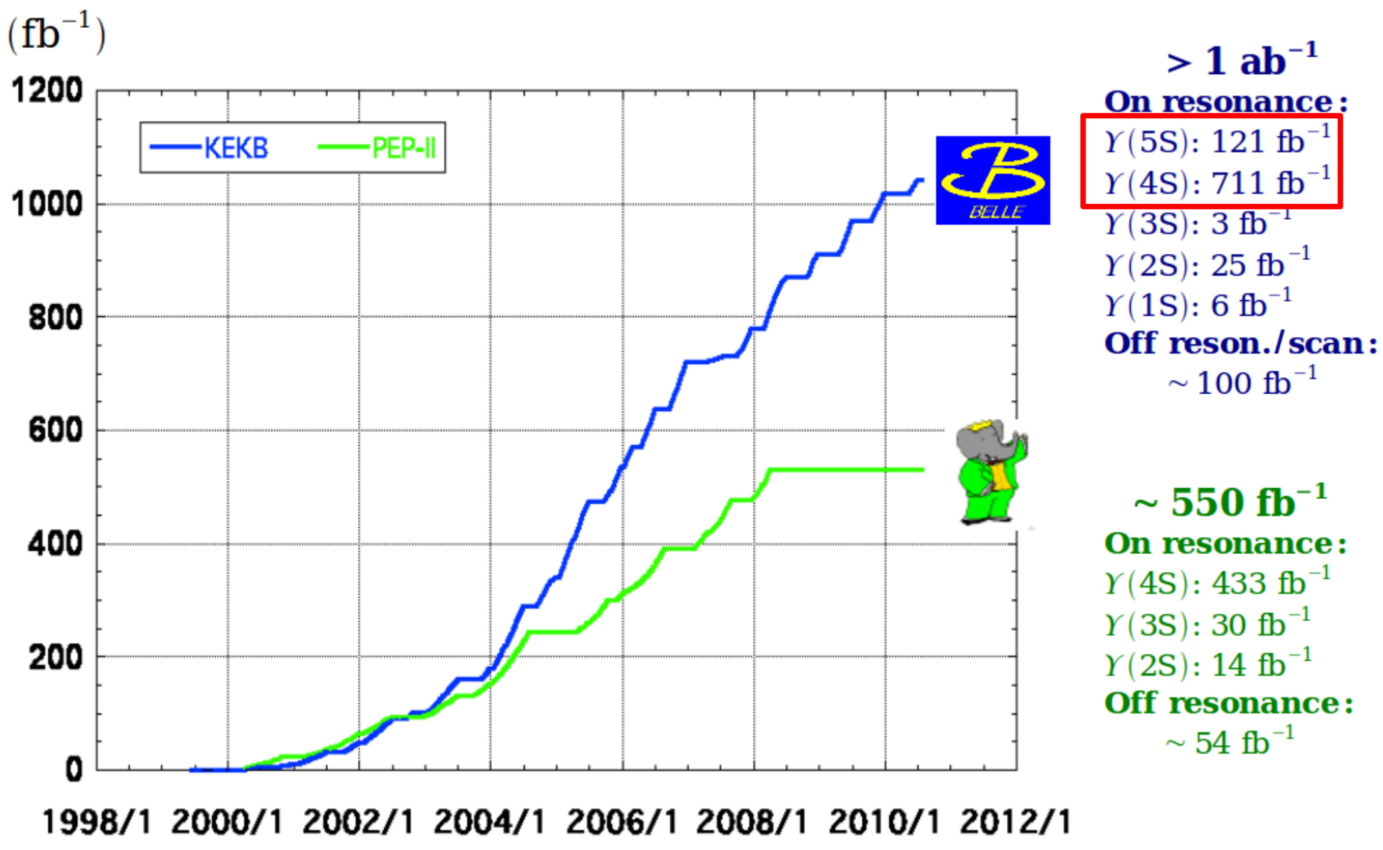
KEKB and Belle Detector





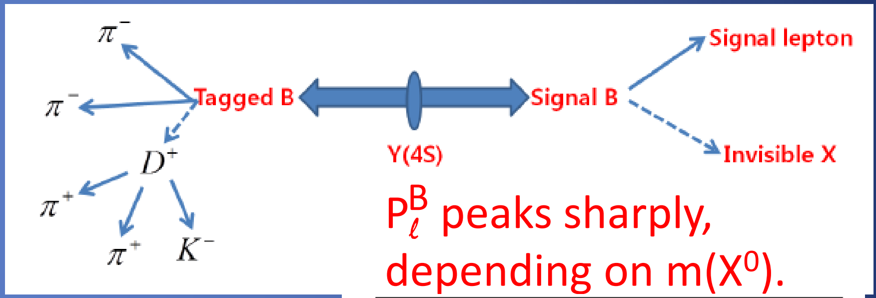
Data samples

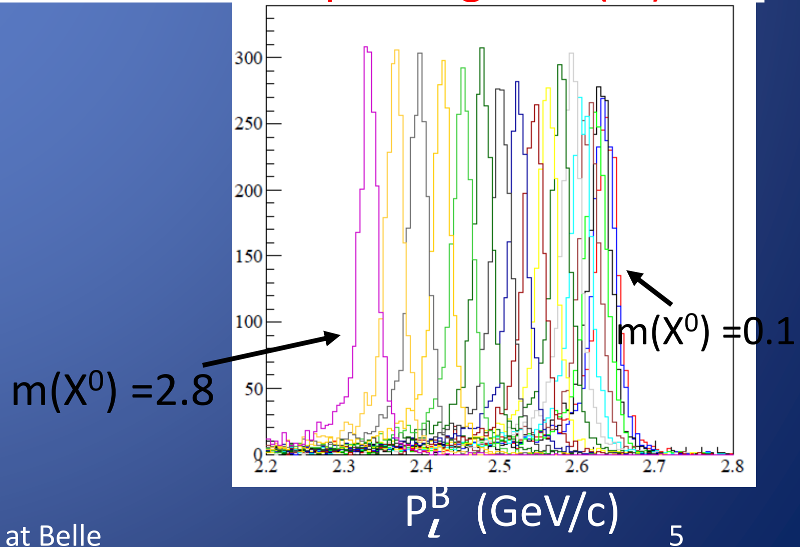
Integrated luminosity of B factories



Search for massive invisible spin-1/2 particle X^0 in $B^+ \to \ell^+ X^0$

- Analysis strategy:
  - Require hadronic B_{tag} (1104 modes) using NeuroBayes.
  - Select $1.8 < P_\ell^B < 3.0$ GeV/c (ℓ = e or μ)
  - Apply $|\cos\theta_T| < 0.9$ (0.8) for $e^+ X^0$ ($\mu^+ X^0$) to suppress continuum background.
  - Demand $E_{Ecl} < 0.5$ GeV

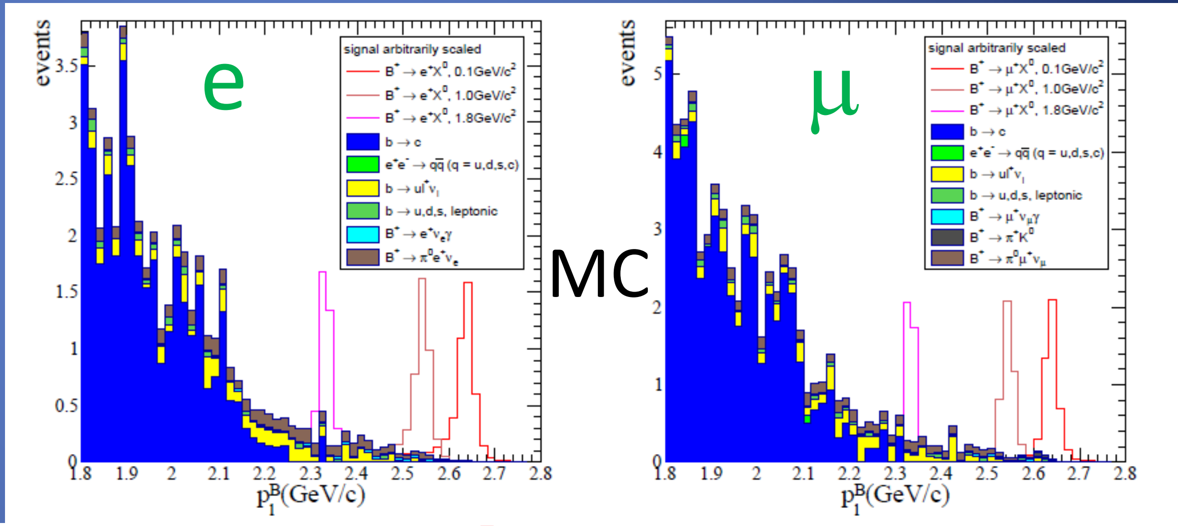


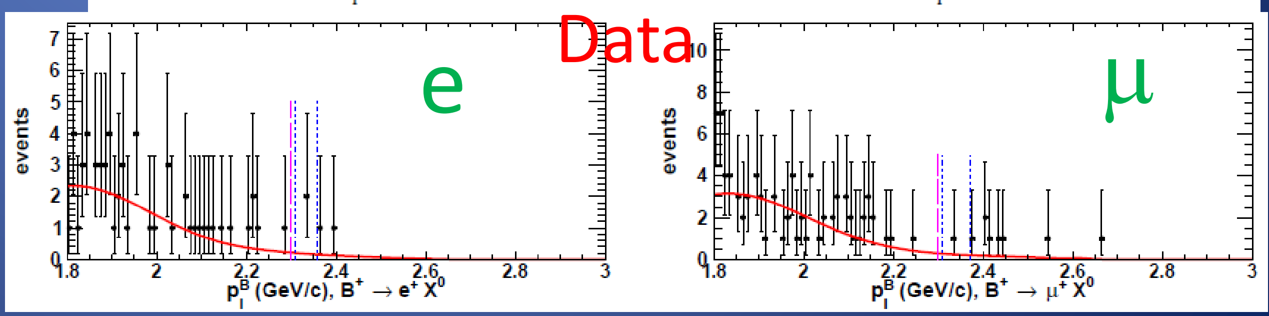


Signal Extraction, $B^+ \to \ell^+ X^0$

- Use MC and data to estimate the numbers of bkg.
  - Fit MC P_ℓ^B distribution in side-band region (1.8–2.3 Gev/c) to estimate yields in signal regions.
  - Correct for data-MC difference
- $N_{sig} = N_{obs} - N_{exp}^{bkg}$
- Backgrounds:

■ $b \to c$
■ $e^+e^- \to qq$
■ $b \to u\, \ell^+ \nu$
■ $b \to u, d, s$, leptonic
■ $b \to \ell^+ \nu \gamma$
■ $b \to \pi^0 \ell^+ \nu$



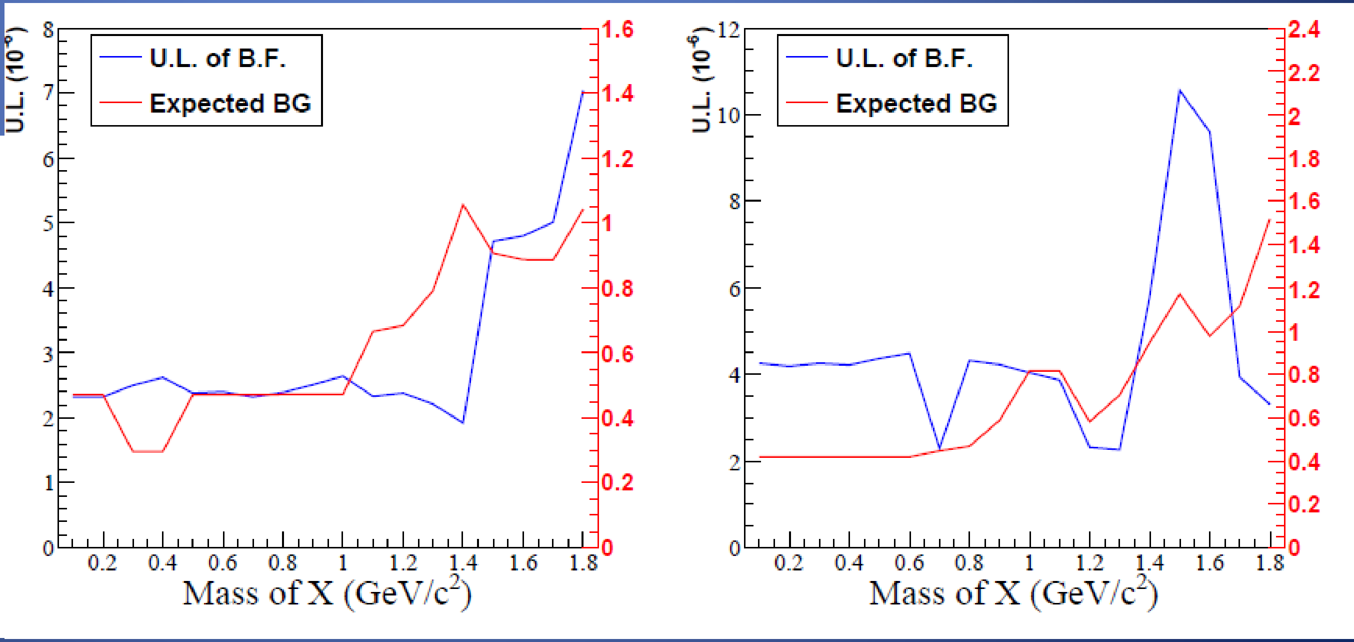


Preliminary Results of $B^+ \to \ell^+ X^0$

- No significant signals are observed; the obtained $\mathcal{B}$ ($B^+ \to \ell^+ X^0$) upper limits @90% C.L. using POLE package are $(2–11) \times 10^{-6}$ for $0.1 < m(X^0) < 1.8$ GeV/c^2

Syst. errors.

Source	$B^+ \to e^+ X^0$	$B^+ \to \mu^+ X^0$
$N_{B^+B^-}$	1.8%	1.8%
Tracking	0.35%	0.35%
ϵ_{tag} correction	6.4%	6.4%
p_l^B shape	3.6%	3.6%
Lepton ID	1.0-1.1%	0.8-0.9%
MC statistics	1.8-2.0%	1.8-1.9%
Total	7.9%	7.8%

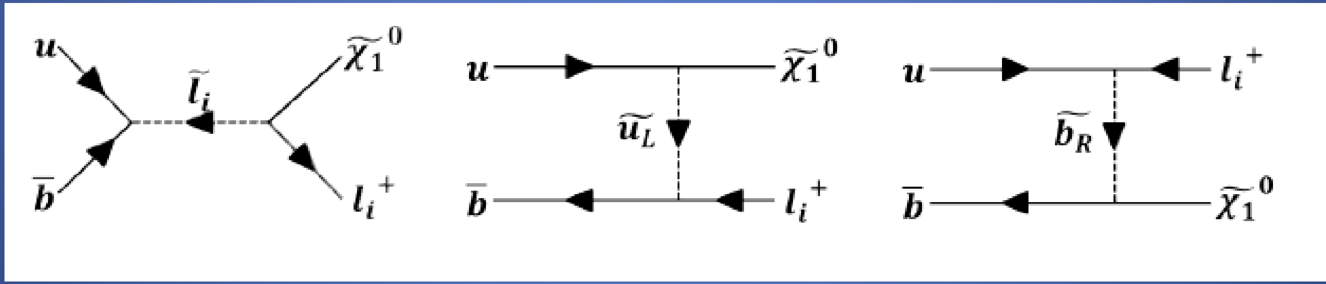


Bound on SUSY-related parameter

- Assume R-parity violation, ξ_i can be expressed as,

$$\xi_i = \lambda'^2_{i13}\left(\frac{1}{2M^2_{\tilde{l}_i}} + \frac{1}{12M^2_{\tilde{u}_L}} + \frac{1}{6M^2_{\tilde{b}_R}}\right)^2 = \frac{8\pi(m_u+m_b)^2\mathcal{B}(B^+\to l_i^+X^0)}{\tau_{B^+}g'^2 f_B^2 m_{B^+}^2 p^B_{l_i}(m^2_{B^+}-m^2_{l_i}-m^2_{X^0})}$$

λ': R-parity violating coupling constant; g': weak decay coupling c.

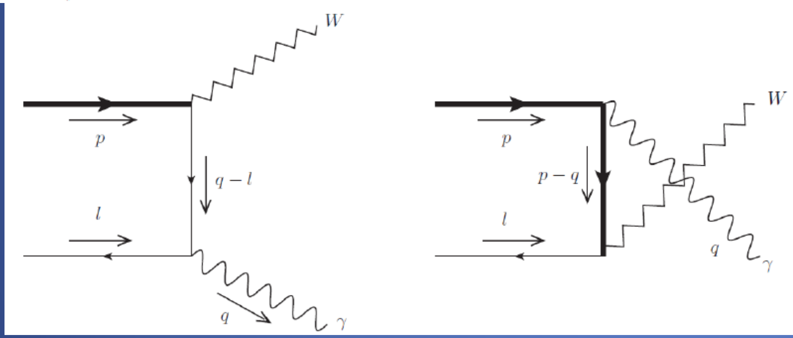


- Best limits: $\xi_i < 4\text{x}10^{-14}$ for $m(X^0) = 0.1$ GeV/c^2 (for e)
  $\xi_i < 4\text{x}10^{-14}$ for $m(X^0) = 0.7$ GeV/c^2 (for μ)

Search for in $B^+ \to \ell^+ \nu \gamma$

- The differential branching fraction is expressed as ,

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 |V_{ub}|^2}{48\pi^2} m_B^4 (1 - x_\gamma) x_\gamma^3 \left[F_A^2 + F_V^2 \right]$$



1. $x_\gamma = 2E\gamma/m_B$
2. F_A and F_V are form factors
3. λ_B , the B meson light-cone parameter, in F_A and F_V is a key param. for charmless B decays.

- Compared to $B^+ \to \ell^+ \nu$,
  1. no helicity suppression
  2. additional α_{em}
- SM branching fraction ~ $O(10^{-6})$ M. Beneke and J. Rohrwild Eur. Phys. J. C. 71, 1818 (2011)
- Best limits from BaBar $\mathcal{B}(B^+ \to e^+ \nu \gamma) < 17 \times 10^{-6}$

  PRD 80, 111105 (2009) $\mathcal{B}(B^+ \to \mu^+ \nu \gamma) < 26 \times 10^{-6}$

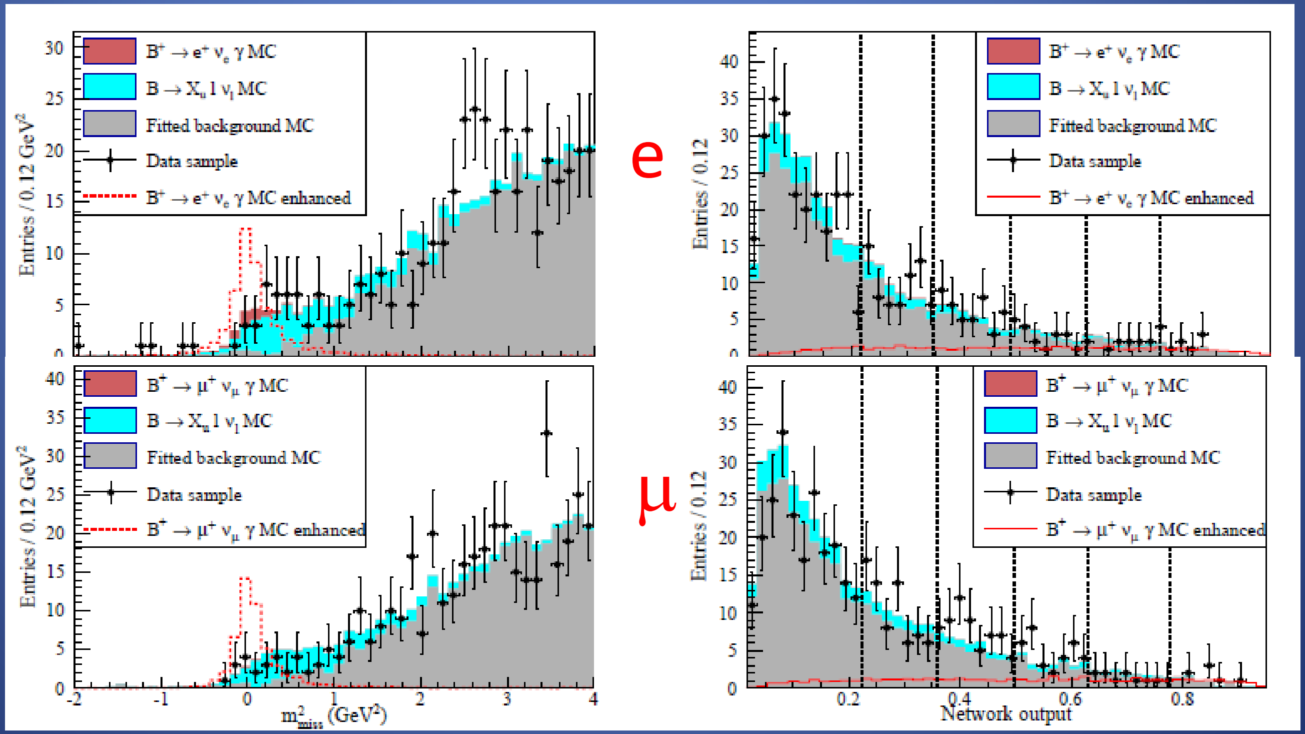
Analysis strategy, $B^+ \to \ell^+ \nu \gamma$

- Require a hadronic B tag with a lepton and a photon.
- $P_{miss} > 800$ MeV/c, $\cos\Theta_{\gamma\ell} < 0.6$, $\cos\Theta_{\gamma\nu} > -0.9$
- Two thresholds on E_γ^{sig}, 400 MeV & 1 GeV (nominal).
- Signal-background separation: m^2_{miss} & other variables
  - Remaining ECL energy
  - $\cos\Theta_{\gamma\ell}$ & $\cos\Theta_{\gamma\nu}$
  - $m(\gamma\gamma)$ with E_γ threshold from 0-100 MeV to distinguish γs from $B^+ \to \ell^+ \nu\pi^0$ and $\ell^+ \nu\eta$

⇒ Neural Network

Signal Extraction, $B^+ \to \ell^+ \nu \gamma$

- Perform unbinned likelihood fit on m^2_{miss} in 6 NN bins with 3 components: signal, measured $B \to X_u \ell^+ \nu$, other backgrounds.



Results, $B^+ \to \ell^+ \nu \gamma$

PRD 91, 112009 (2015)

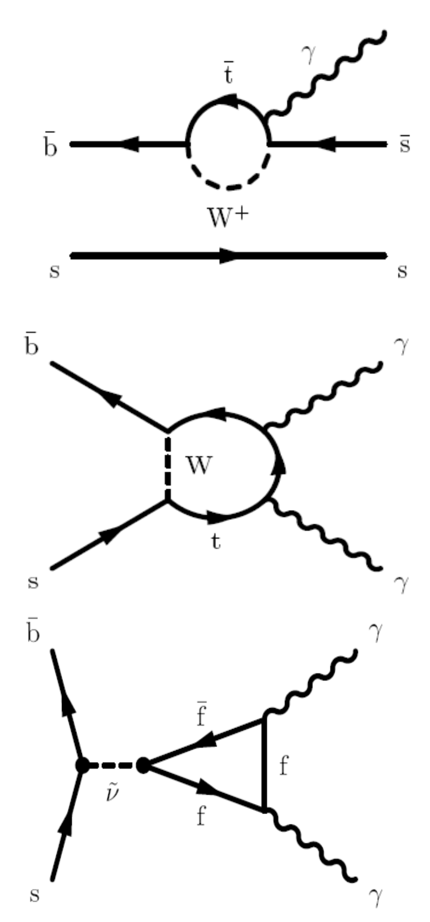
- No significant signals are observed. Provide best limits.
- $\lambda_B > 260$ MeV at 90% C.L.

	Nominal analysis with $E_\gamma^{\rm sig} > 1\,$GeV						
	MC expectation			Data measurement			
Mode	Yield	Significance (σ)	$\mathcal{B}$ limit (10^{-6})	Yield	$\mathcal{B}$ (10^{-6})	Significance (σ)	$\mathcal{B}$ limit (10^{-6})
$B^+ \to e^+\nu_e\gamma$	$8.0 \pm 4.5\ ^{+1.1}_{-1.4}$	2.1	< 7.5	$6.1^{+4.9}_{-3.9}{}^{+1.1}_{-1.4}$	$3.8^{+3.0}_{-2.4}{}^{+0.5}_{-0.6}$	1.7	< 6.1
$B^+ \to \mu^+\nu_\mu\gamma$	$8.7 \pm 4.6\ ^{+1.1}_{-1.6}$	2.2	< 6.9	$0.9^{+3.6}_{-2.6}{}^{+1.1}_{-1.6}$	$0.6^{+2.1}_{-1.5}{}^{+0.1}_{-0.1}$	0.4	< 3.4
$B^+ \to \ell^+\nu_\ell\gamma$	$16.5 \pm 6.5\ ^{+1.8}_{-2.3}$	2.9	< 4.8	$6.6^{+5.7}_{-4.7}{}^{+1.8}_{-2.3}$	$2.0^{+1.7}_{-1.4}{}^{+0.2}_{-0.3}$	1.4	< 3.5

	Secondary analysis with $E_\gamma^{\rm sig} > 400\,$MeV						
	MC expectation			Data measurement			
Mode	Yield	Significance (σ)	$\mathcal{B}$ limit (10^{-6})	Yield	$\mathcal{B}$ (10^{-6})	Significance (σ)	$\mathcal{B}$ limit (10^{-6})
$B^+ \to e^+\nu_e\gamma$	$12.4 \pm 6.2\ ^{+1.9}_{-2.4}$	2.1	< 6.8	$11.9^{+7.0}_{-6.0}{}^{+1.9}_{-2.4}$	$4.9^{+2.9}_{-2.5}{}^{+0.8}_{-1.0}$	2.0	< 9.3
$B^+ \to \mu^+\nu_\mu\gamma$	$11.9 \pm 6.0\ ^{+1.9}_{-2.3}$	2.2	< 6.2	$-0.1^{+5.2}_{-4.1}{}^{+1.9}_{-2.3}$	-	-	< 4.3
$B^+ \to \ell^+\nu_\ell\gamma$	$24.9 \pm 8.7\ ^{+3.1}_{-3.6}$	2.9	< 4.3	$11.3^{+8.4}_{-7.4}{}^{+3.1}_{-3.6}$	$2.3^{+1.7}_{-1.5}{}^{+0.3}_{-0.3}$	1.5	< 5.0

Search for $B_s^0 \to \gamma\gamma$ & update on $B_s^0 \to \phi\gamma$

- Update $\mathcal{B}(B_s^0 \to \phi\gamma)$ with full Belle data.
  - Stringent constraint by $B \to X_s\gamma$ & exclusive decays
  - SM $\mathcal{B}$ = $4\text{x}10^{-5}$ with 30% theory error
    Best $\mathcal{B}$ =$(35.1\pm3.5\pm1.2)\text{x}10^{-6}$ is provided by LHCb,
    Nucl. Phys. B867, 1 (2013)
- The decay $B_s^0 \to \gamma\gamma$ has not been observed.
  - Belle previous limit, $\mathcal{B} < 8.7\text{x}10^{-6}$ @90% C.L.
  - $\mathcal{B}$ is also constrained by $B \to X_s\gamma$ in R-parity conser. SUSY, but may not in R-parity violating case. $\Rightarrow$
- At Υ(5S), $f_{B_s^*\bar{B}_s^*} = (87.0\pm0.7)\%$, $f_{B_s^*\bar{B}_s}$ = $(7.3\pm1.4)\%$



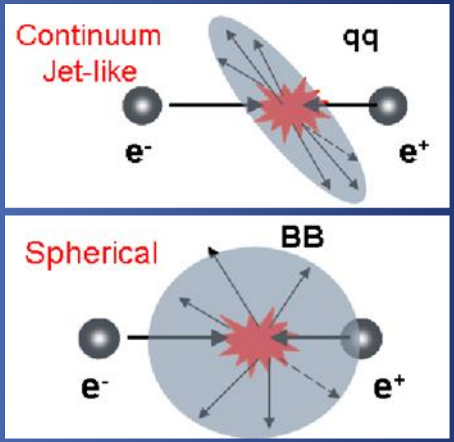
PRD70, 035008(2004)

Anlaysis method, $B_s^0 \to \phi\gamma$, $\gamma\gamma$

- Select $\phi \to K^+K^-$, good quality photon with π^0 veto.
- Identify B candidates with M_{bc} and ΔE.

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

$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{P}_B|^2}$$

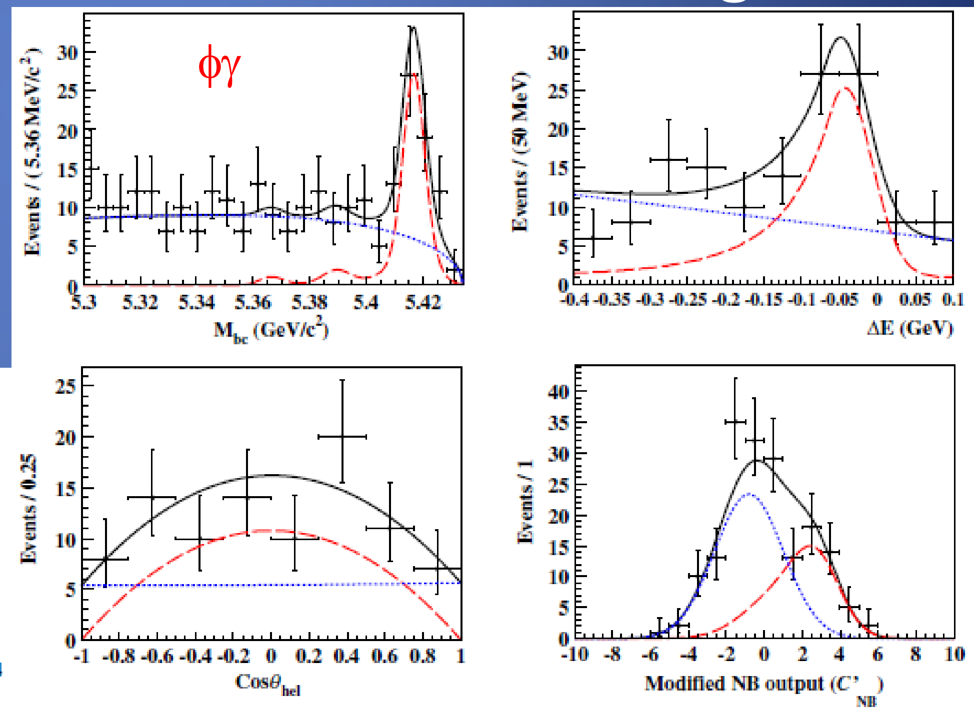


- Distinguish signals from background using shape variables: FWM and $\cos\theta_T$ in NN $\Rightarrow \mathcal{C}_{NB}$
  - $\gamma\gamma$: tighter cut on $\mathcal{C}_{NB.}$ Perform 2-D M_{bc}–ΔE fit.
  - $\phi\gamma$: loose cut on $\mathcal{C}_{NB}$ and modify it as $\mathcal{C}'_{NB} = \log\left(\frac{\mathcal{C}_{NB} - \mathcal{C}_{NBmin}}{\mathcal{C}_{NBmax} - \mathcal{C}_{NB}}\right)$
    Perform 4-D fit on M_{bc}, ΔE, $\cos\theta_{hel}$, $\mathcal{C}'_{NB}$

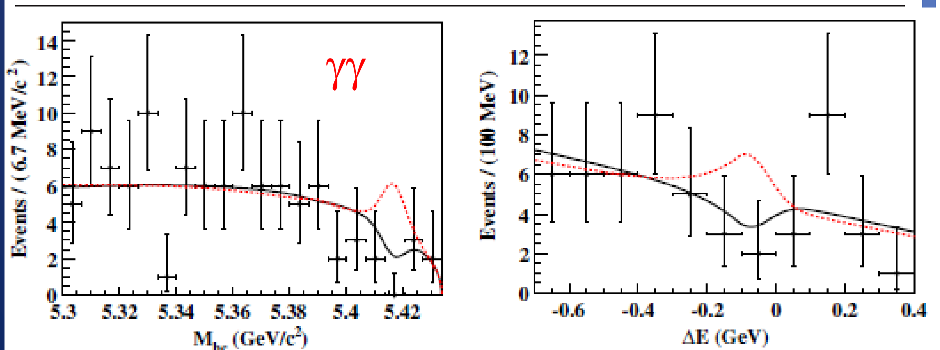
Results, $B_s^0 \to \phi\gamma$, $\gamma\gamma$

PRD 91, 011101 (2015)

- Calibrate signal PDFs using $B^0 \to K^*\gamma$ and $B_s \to D_s\pi$
- Signal PDFs = $(f_{B_s^*\bar{B}_s^*})$ x $(B^*B_s^*\ \mathrm{PDF}) + (f_{B_s^*\bar{B}_s})$ x $(B_s^*B_s\ \mathrm{PDF})$
  $+\ (f_{B_s\bar{B}_s})$ x $(B_sB_s\ \mathrm{PDF})$
- Background PDFs includes continuum and $b\bar{b}$ bkg.



	$B_s^0 \to \phi\gamma$	$B_s^0 \to \gamma\gamma$
$\epsilon(\%)$	36.1 ± 0.1	14.0 ± 0.1
N	91^{+14}_{-13}	$-3.9^{+3.7}_{-2.6}$
$\mathcal{B}(10^{-6})$	$36 \pm 5(\mathrm{stat.}) \pm 3(\mathrm{syst.}) \pm 6(f_s)$	< 3.1 (90% C.L.)



Summary

- We present search results for leptonic and radiative B decays using full $\Upsilon(4S)$ and $\Upsilon(5S)$ samples:
  - No massive X^0 particles are observed between 0.1 and 1.8 GeV/c^2. $\mathcal{B}(B^+ \to \ell^+ X^0) < (1.96\text{-}10.56) \times 10^{-6}$
  - No significant $B^+ \to \ell^+ \nu \gamma$ signals are observed. $\mathcal{B}(B^+ \to e^+ \nu \gamma) < 6.1 \times 10^{-6}$; $\mathcal{B}(B^+ \to \mu^+ \nu \gamma) < 3.4 \times 10^{-6}$
  - $\mathcal{B}(B_s \to \phi\gamma) = (36 \pm 5(\text{stat}) \pm 3\,(\text{syst}) \pm 6\,(\text{fs})) \times 10^{-6}$ consistent with LHCb result and SM expectation.
  - No $B_s \to \gamma\gamma$ signal is observed, $\mathcal{B} < 3.1 \times 10^{-6}$

BACK UP

$\mathcal{B}$ ($B^+ \to \ell^+ X^0$) Upper limits

	p_l^B selection (GeV/c)	ϵ_s[%]	N_{obs}	N_{exp}^{bkg}	$\mathcal{B}^{90}$	selection (GeV/c)	ϵ_s[%]	N_{obs}	N_{exp}^{bkg}	$\mathcal{B}^{90}$
M_{X^0}	$B^+ \to e^+ X^0$ for M_{X^0}					$B^+ \to \mu^+ X^0$ for M_{X^0}				
0.1 GeV/c^2	2.52-2.70	0.11	0	0.471 ± 0.173	$< 2.32 \times 10^{-6}$	2.58-2.68	0.12	1	0.420 ± 0.151	$< 4.26 \times 10^{-6}$
0.2	2.52-2.70	0.11	0	0.471 ± 0.173	$< 2.32 \times 10^{-6}$	2.58-2.68	0.12	1	0.420 ± 0.151	$< 4.19 \times 10^{-6}$
0.3	2.55-2.68	0.11	0	0.296 ± 0.115	$< 2.50 \times 10^{-6}$	2.58-2.68	0.12	1	0.420 ± 0.151	$< 4.26 \times 10^{-6}$
0.4	2.55-2.68	0.11	0	0.296 ± 0.115	$< 2.62 \times 10^{-6}$	2.58-2.68	0.12	1	0.420 ± 0.151	$< 4.22 \times 10^{-6}$
0.5	2.52-2.70	0.11	0	0.471 ± 0.173	$< 2.38 \times 10^{-6}$	2.58-2.68	0.11	1	0.420 ± 0.151	$< 4.37 \times 10^{-6}$
0.6	2.52-2.70	0.11	0	0.471 ± 0.173	$< 2.40 \times 10^{-6}$	2.58-2.68	0.11	1	0.420 ± 0.151	$< 4.49 \times 10^{-6}$
0.7	2.52-2.70	0.11	0	0.471 ± 0.173	$< 2.32 \times 10^{-6}$	2.56-2.63	0.11	0	0.447 ± 0.153	$< 2.29 \times 10^{-6}$
0.8	2.51-2.62	0.11	0	0.472 ± 0.163	$< 2.39 \times 10^{-6}$	2.54-2.61	0.11	1	0.469 ± 0.162	$< 4.32 \times 10^{-6}$
0.9	2.51-2.62	0.10	0	0.472 ± 0.163	$< 2.51 \times 10^{-6}$	2.52-2.60	0.11	1	0.588 ± 0.201	$< 4.23 \times 10^{-6}$
1.0	2.51-2.62	0.096	0	0.472 ± 0.163	$< 2.64 \times 10^{-6}$	2.49-2.58	0.11	1	0.817 ± 0.266	$< 4.04 \times 10^{-6}$
1.1	2.47-2.57	0.099	0	0.666 ± 0.207	$< 2.33 \times 10^{-6}$	2.49-2.58	0.12	1	0.817 ± 0.266	$< 3.87 \times 10^{-6}$
1.2	2.45-2.53	0.096	0	0.684 ± 0.206	$< 2.38 \times 10^{-6}$	2.48-2.53	0.10	0	0.582 ± 0.179	$< 2.32 \times 10^{-6}$
1.3	2.43-2.51	0.098	0	0.792 ± 0.237	$< 2.21 \times 10^{-6}$	2.45-2.50	0.10	0	0.705 ± 0.211	$< 2.26 \times 10^{-6}$
1.4	2.41-2.51	0.10	0	1.056 ± 0.318	$< 1.92 \times 10^{-6}$	2.42-2.48	0.11	2	0.947 ± 0.282	$< 5.78 \times 10^{-6}$
1.5	2.39-2.46	0.093	1	0.907 ± 0.277	$< 4.72 \times 10^{-6}$	2.40-2.47	0.11	5	1.171 ± 0.351	$< 10.56 \times 10^{-6}$
1.6	2.37-2.43	0.092	1	0.887 ± 0.277	$< 4.80 \times 10^{-6}$	2.37-2.42	0.10	4	0.977 ± 0.295	$< 9.60 \times 10^{-6}$
1.7	2.34-2.39	0.088	1	0.886 ± 0.283	$< 5.01 \times 10^{-6}$	2.34-2.39	0.10	1	1.116 ± 0.337	$< 3.94 \times 10^{-6}$
1.8	2.31-2.36	0.087	2	1.042 ± 0.335	$< 7.04 \times 10^{-6}$	2.31-2.37	0.11	1	1.518 ± 0.452	$< 3.31 \times 10^{-6}$

Form factors to compute $\mathcal{B}(B^+ \to \ell^+ \nu \gamma)$

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 |V_{ub}|^2}{48\pi^2} m_B^4 (1 - x_\gamma) x_\gamma^3 \left[F_A^2 + F_V^2 \right]$$

where

$$F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) + \left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2} \right]$$

and

$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma, \mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_l f_B}{E_\gamma} \right].$$