Recent Results on Radiative and Electroweak Penguin B Decays at Belle

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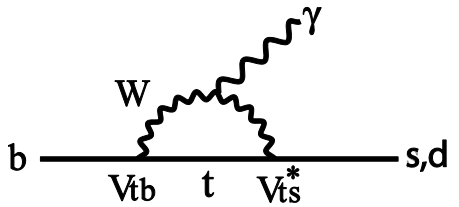
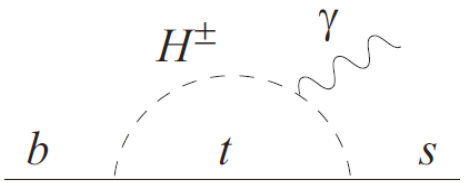
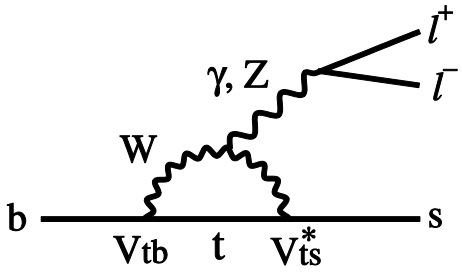
Introduction

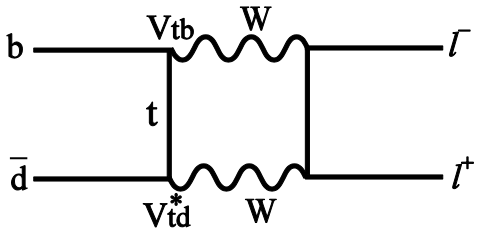
- Loop processes are sensitive to physics Beyond the Standard Model (BSM) since unobserved new particles might be able to enter in the loop.





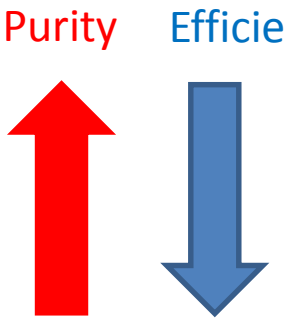
- Radiative and Electroweak Penguin B decays are experimentally and theoretically clean due to final states having color singlet photons or leptons.



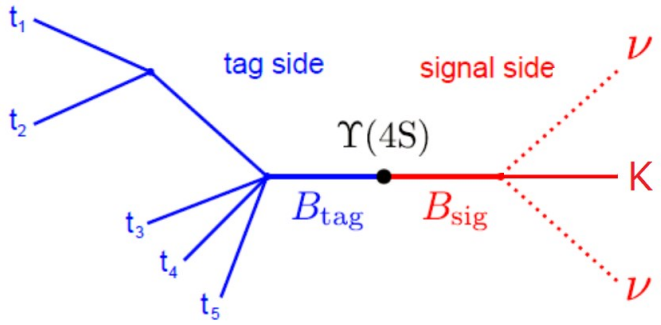


Tagging Methods

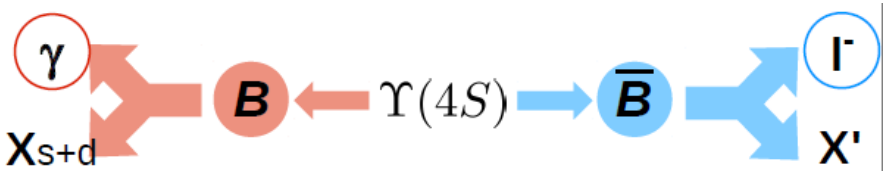
- Two B mesons are produced from Y(4S).
- For some analyses, one of the B meson is tagged
  - To study/search for decays with multiple neutrinos : B→Kνν
  - To know the flavor of the other B meson : A_{CP}(B→X_{s+d} γ)
  - To improve the sensitivity : BF(B→X_sγ)
- There are several tagging methods
  - Hadronic tagging : reconstruct hadronic B decays
  - Semileptonic tagging : reconstruct semileptonic B decays
  - Lepton tagging : just require a hard lepton from B decays



Hadronic tagging



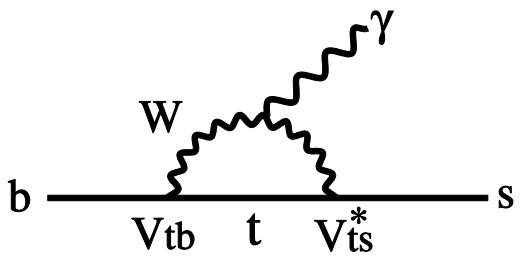
Lepton tagging

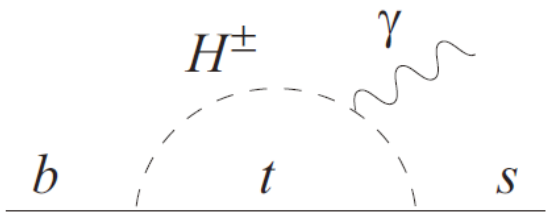


Radiative Decays

BF(B→$X_s\gamma$)

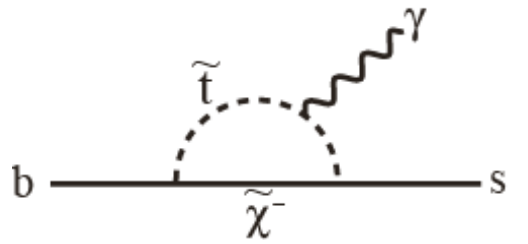
- Branching fraction of Inclusive B→$X_s\gamma$ is very sensitive to BSM.
  - Charged Higgs in 2HDM
    - Constructive to SM amplitude
    - Almost no tanβ dependence
  - SUSY
    - Constructive or destructive to SM
    - Depending on SUSY parameters
- Very precise prediction available.
  - 7% precision





$$\mathcal{B}_{s\gamma}^{\rm SM} = (3.36 \pm 0.23) \times 10^{-4}$$

$$\text{for } E_0 = 1.6\,\text{GeV}$$



M. Misiak et al, Phys. Rev. Lett. 114, 221801 (2015)

T.Saito, A. Ishikawa, et al (Belle Collaboration) PRD 91, 052004 (2015)

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Measurement of BF(B→$X_s\gamma$)

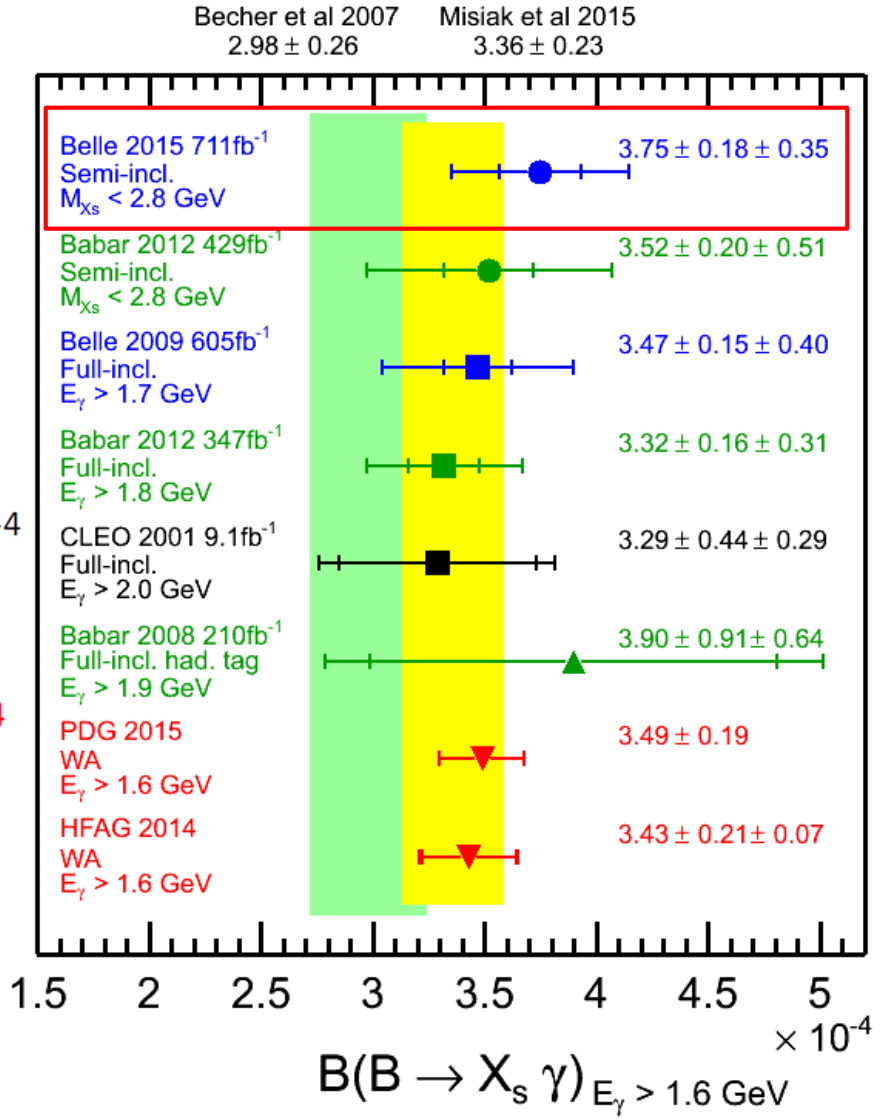
- Sum of exclusive method adopted
  - 38 Xs decay modes
    - Kπ, K2π, K3π, K4π, Kη, Kηπ, Kηππ, 3K, 3Kπ
  - Mass of hadronic system <2.8 GeV
    - corresponding to Eγ > 1.9GeV
  - BF measured in each MXs bin and then combined

$$B(B \to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}$$

  - Extrapolated to E_γ > 1.6GeV

$$B(B \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$$

- Best measurement with sum of exclusive method
  - Second best for all measurements



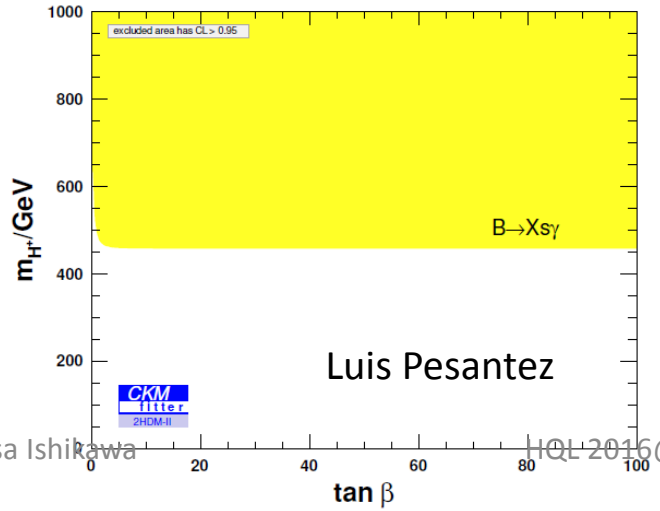
Limit on Charged Higgs in 2HDM

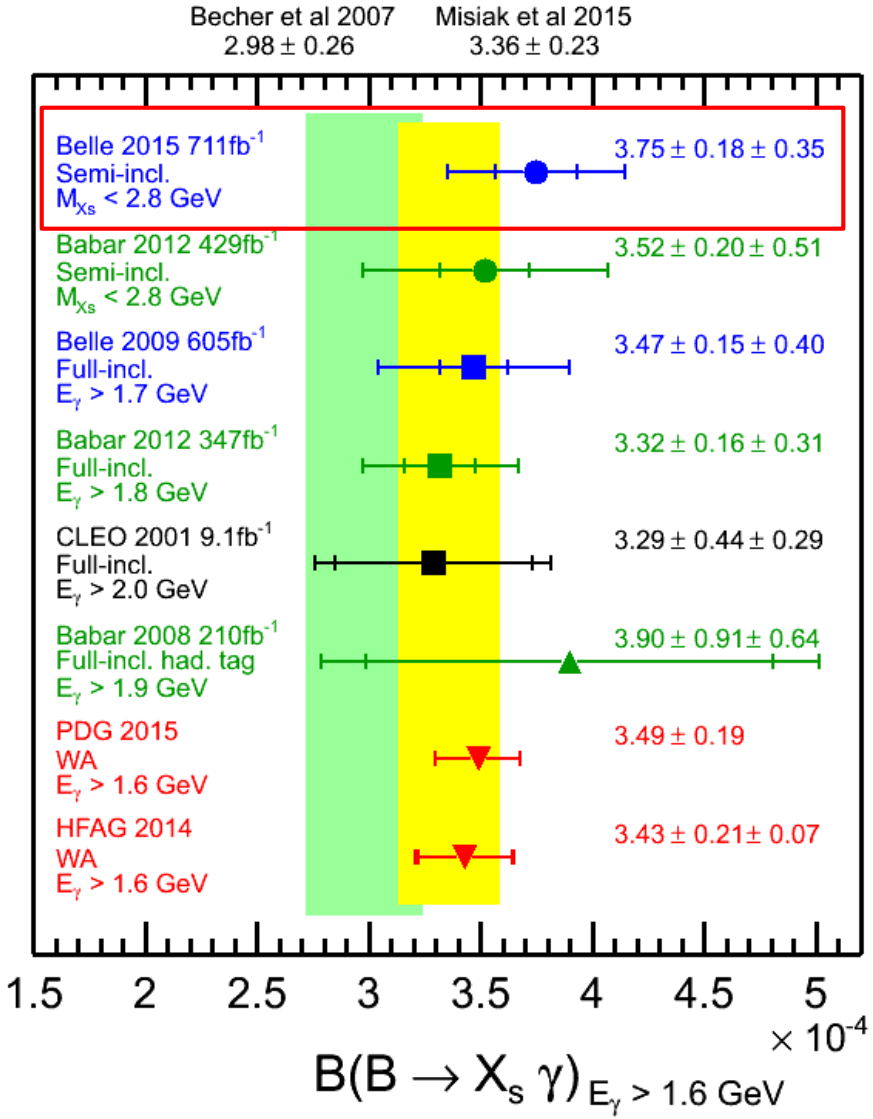
- World Average is consistent with the prediction by M. Misiak et al

$$\mathcal{B}_{s\gamma}^{\rm exp} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$
$$\mathcal{B}_{s\gamma}^{\rm SM} = (3.36 \pm 0.23) \times 10^{-4}$$

- This can be used to constrain charged Higgs mass in 2HDM

$$M_{H^\pm} > 480\,\text{GeV}$$ at 95% CL





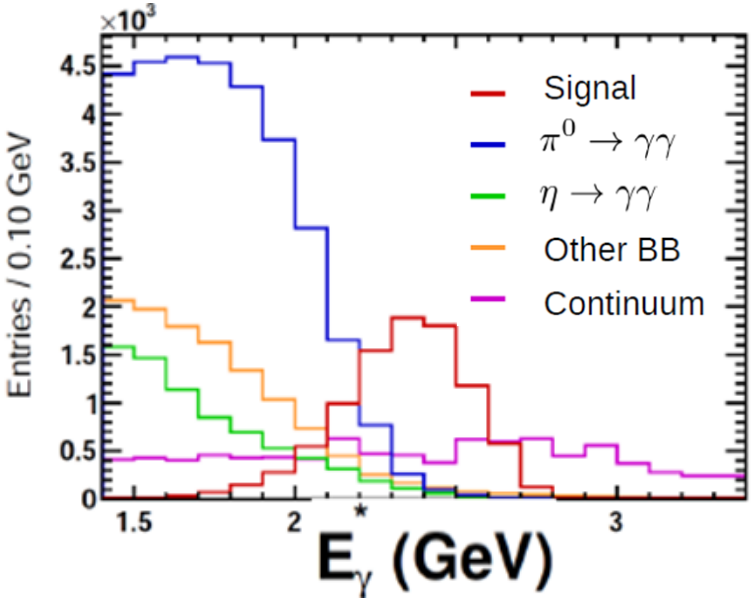
Direct CP Asymmetry in $B \rightarrow X_{s+d}\gamma$

- Theoretical prediction is very precise thanks to Unitarity of the CKM matrix.
  - If deviated from 0, clear new physics signal

Channel	A_{CP}(SM)
$B \rightarrow X_s\gamma$	[-0.6% , +2.8%]
$B \rightarrow X_d\gamma$	[-62% ,+14%]
$B \rightarrow X_{s+d}\gamma$	0

M. Benzke et al, PRL 106, 141801 (2011)

- Inclusively reconstruct photon with $1.7 < E_\gamma < 2.8$GeV
  - Veto for asymmetric decays of $\pi^0(\eta) \rightarrow \gamma\gamma$
- High momentum lepton to tag flavor of the other B
  - Correction of mixing applied



L. Pesantez et al (Belle Collaboration) PRL 114, 151601 (2015)
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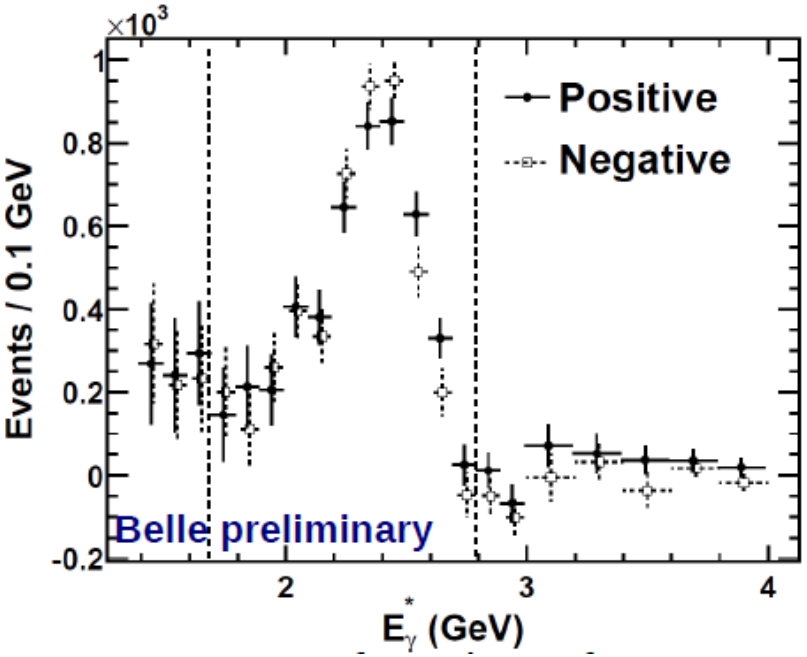
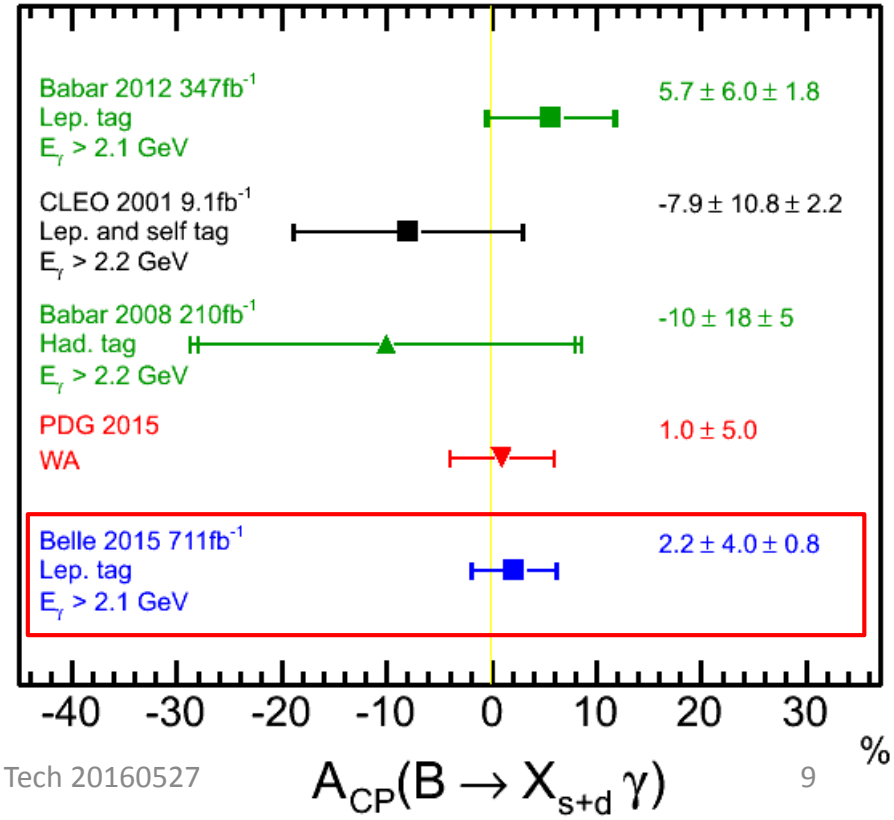
Result for $A_{CP}(B \rightarrow X_{s+d}\gamma)$

- Belle performed world best measurement
  - Even better than PDG 2015!
- The result is consistent with null
- Still statistical error dominates → Belle II





Z. King et al (Belle Collaboration) to appear in PRD, arXiv:1603.06546

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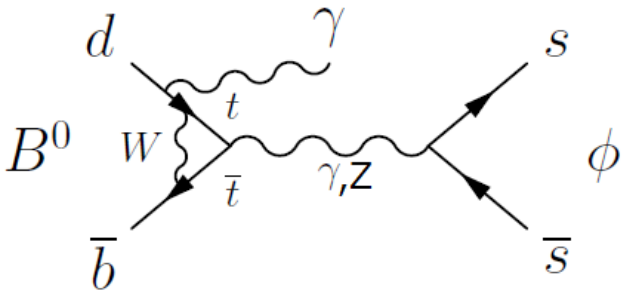
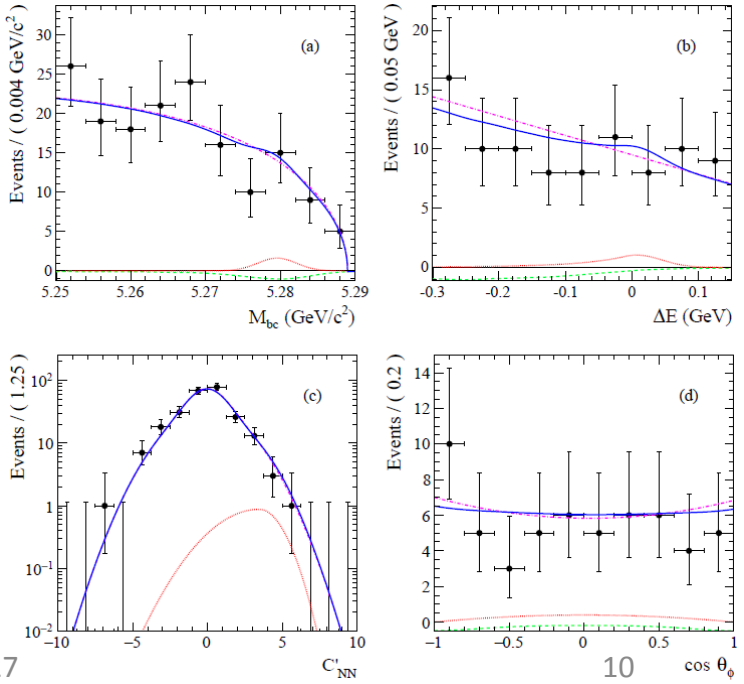
Search for B→φγ

- Proceeds via b→d penguin annihilation
  - Suppressed by V_{td}
  - Prediction : B(B→φγ) ~ O($10^{-11\sim12}$)
- Dominant continuum background suppressed by Neural Net
- Simultaneous fit to M_{bc}, ΔE, NN, $\cos\theta_{hel}$ to extract signal yield.
  - Consistent with null
- Set a limit on BF

$$\mathcal{B}(B^0 \to \phi\gamma) < 1.0 \times 10^{-7}$$ 90% C.L.

  - Almost one order of magnitude better than previous search





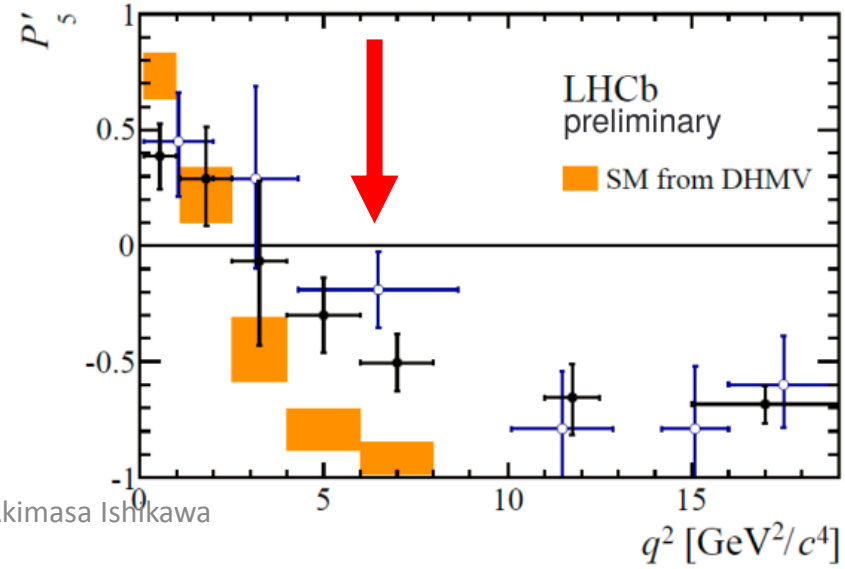
Electroweak Penguin Decays

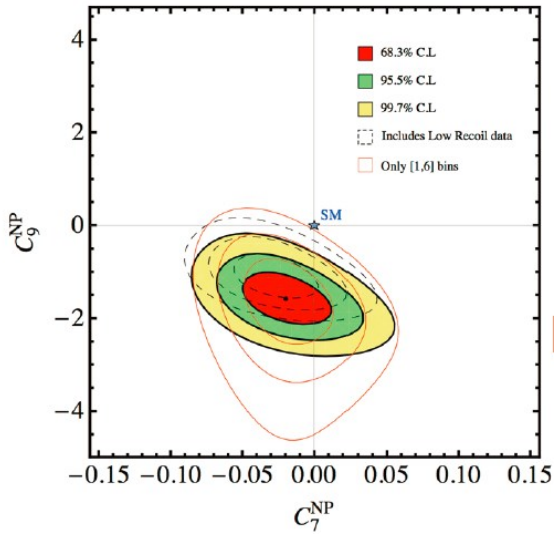
$b \rightarrow s l^+ l^-$ and $b \rightarrow (s,d) \nu\nu$

Full Angular Analysis of $B^0 \rightarrow K^{*0} l^+ l^-$

- LHCb reported 3.4σ deviation from a SM prediction in P_5' for $4 < q^2 < 8 GeV^2$ which was obtained from full angular analysis of $B^0 \rightarrow K^{*0} \mu\mu$
  - There is a discussion that the deviation can be explained by a charm loop
- Global fit to radiative and EW penguin B decays gives Wilson coefficient C_9 deviated about -1 from SM values
  - Driven by P5', F_L, B(Bs→φμμ) etc.
- Independent analyses/checks are desired.

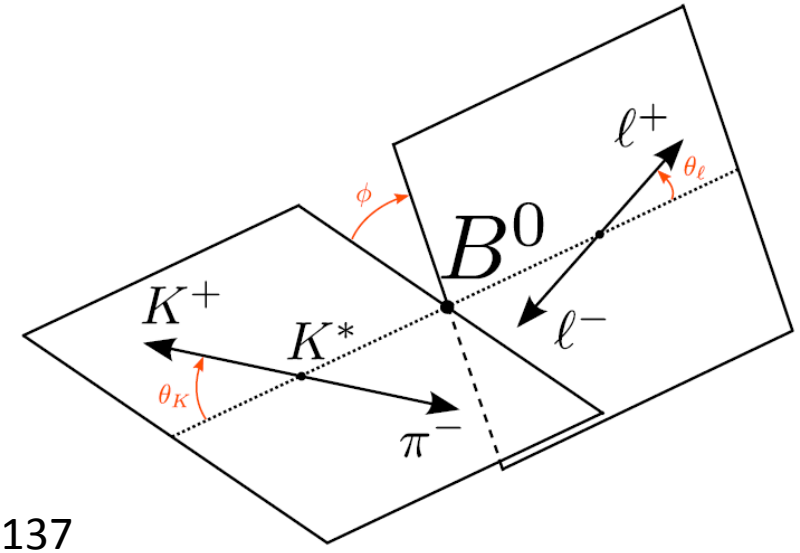
S.Descotes-Genon et al, PRD 88 074002 (2013)





Differential Decay Width for B→K*ll

- Differential decay width as a function of 4 variables, q^2, θ_l, θ_K, and ϕ, is expressed in terms of form factor independent observables, P_i'.



S. Descotes-Genon et al. JHEP 05 (2013) 137

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

A. Abdesselam, et al (Belle Collaboration), arXiv:1604.04042

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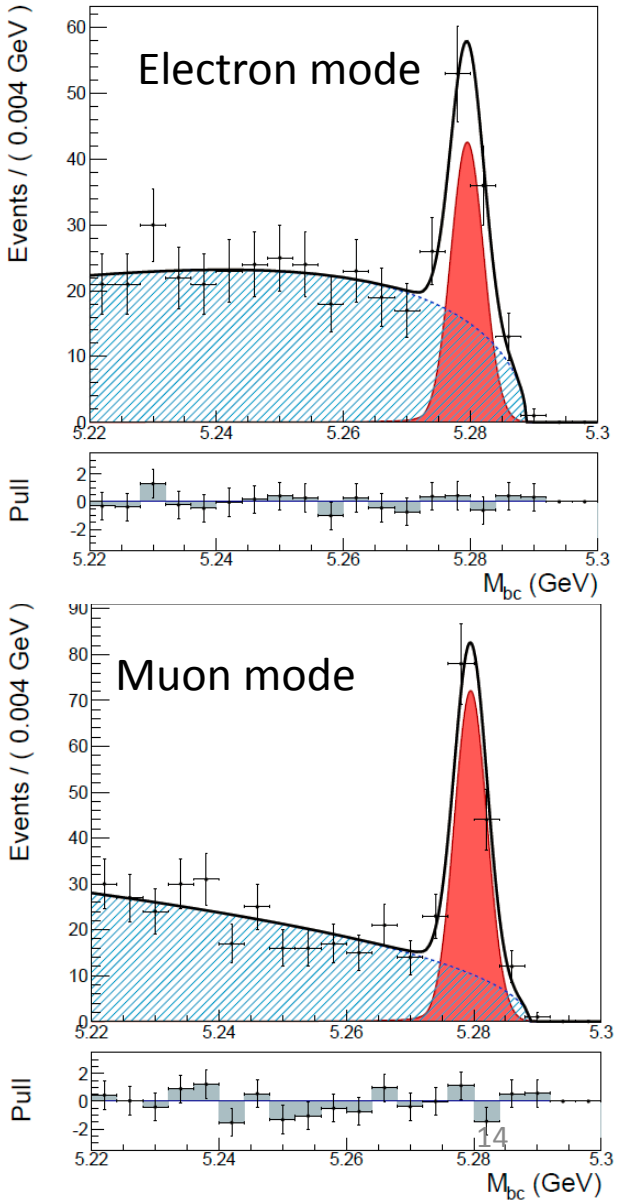
Analysis of $B^0 \rightarrow K^* l^+ l^-$

- Only neutral B^0 used
- Neural Net based selections were adopted to improve the sensitivity
  - 69±12 and 118±12 signal events were reconstructed for electron and muon modes.
- Since the number of signal events is small, folding method was adopted to extract P_4', P_5', P_6' and P_8' as LHCb did in 2013.

$$P_5', S_5 : \begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \theta_L \rightarrow \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

- The fit is performed in bins of q^2



A. Abdesselam, et al (Belle Collaboration), arXiv:1604.04042

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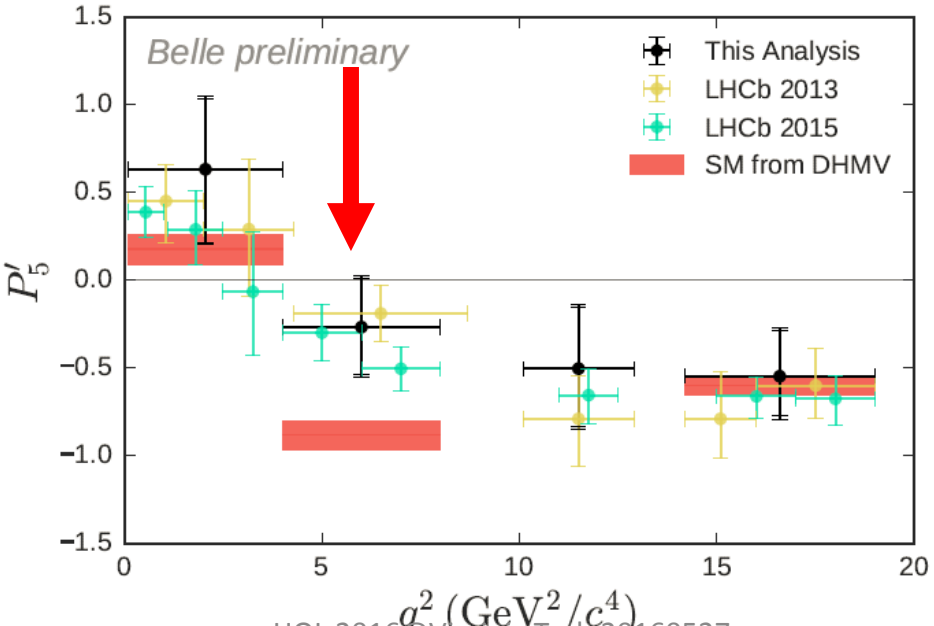
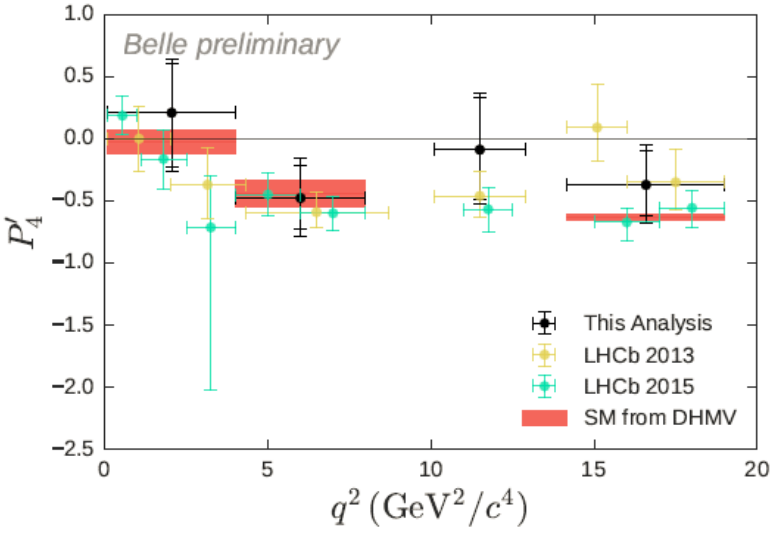
Result for P_5'

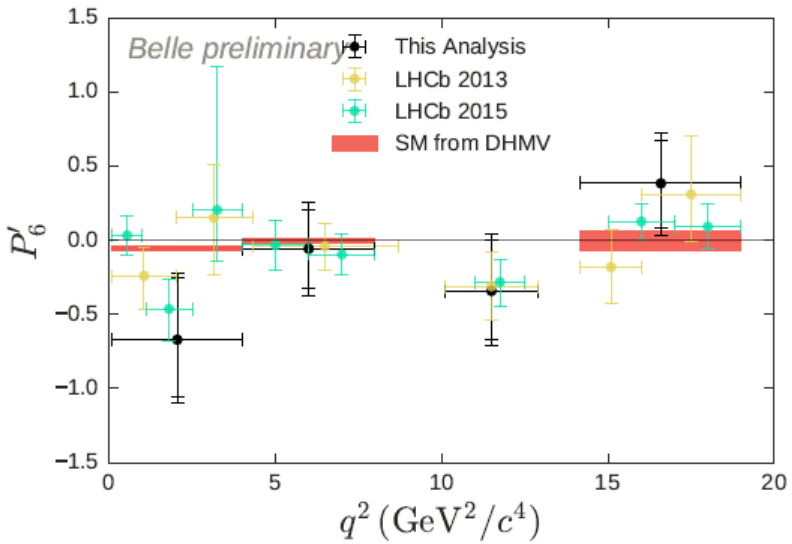
- The result for $4 < q^2 < 8$ GeV^2 is 2.1σ deviated from a theoretical prediction with the same direction as LHCb observed.

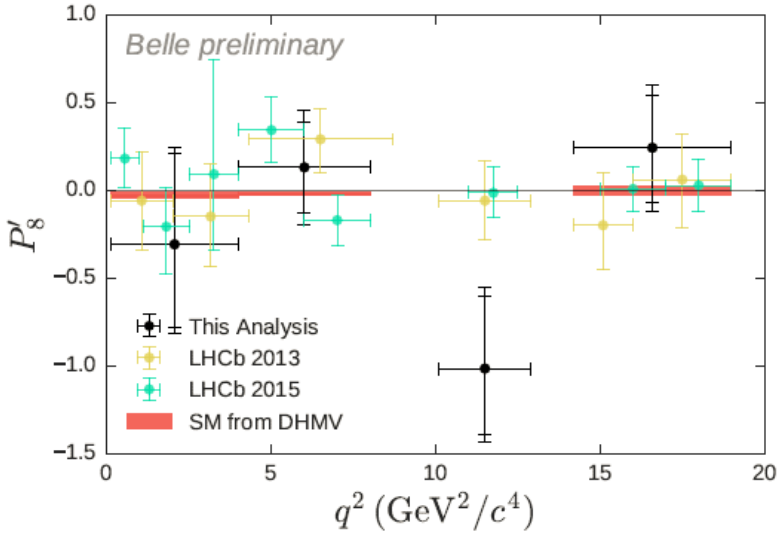


Results for P_4', P_6' and P_8'

Consistent with theoretical predictions







Y. Sato, A. Ishikawa, et al. (Belle Collaboration) PRD 93 032008 (2016)

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Measurement of $A_{FB}(B \rightarrow X_s l^+ l^-)$

- A_{FB} in exclusive $B \rightarrow K^* l^+ l^-$ decays was measured by many experiments while A_{FB} in inclusive decays was not yet.
- Different systematic uncertainties in inclusive decays than those in exclusive decays.
  - Important tool for independent check of C_9 deviation
- Precise prediction possible but experimentally it was hard to measure.

Y. Sato, A. Ishikawa, et al. (Belle Collaboration) PRD 93 032008 (2016)

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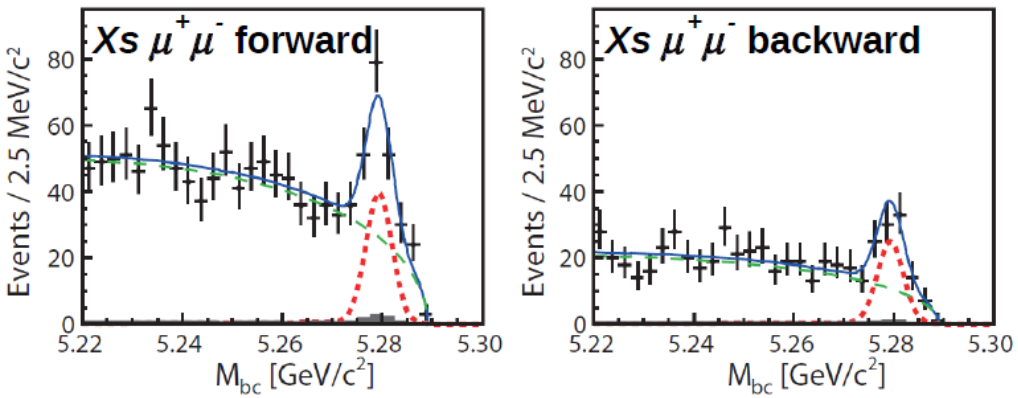
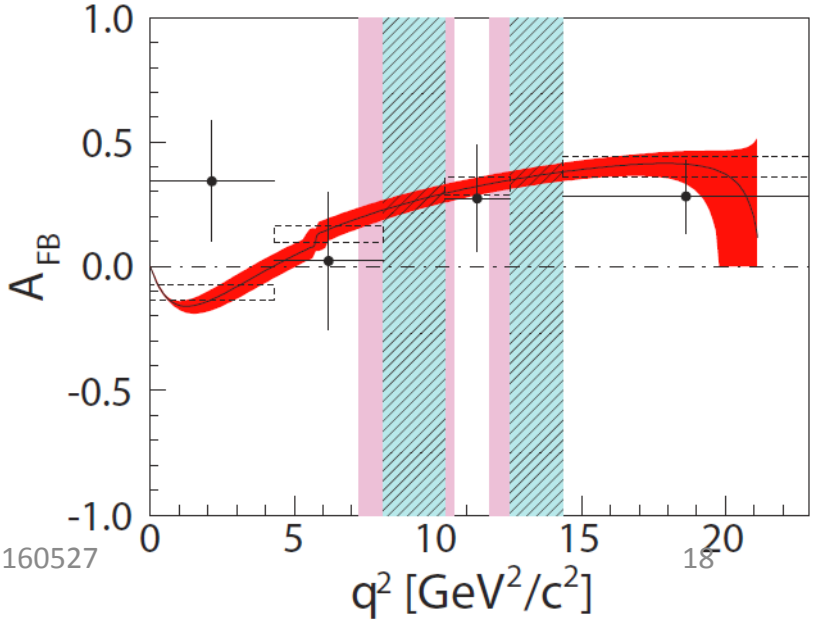
$A_{FB}(B \rightarrow X_s l^+ l^-)$ with Semi-Inclusive Technique

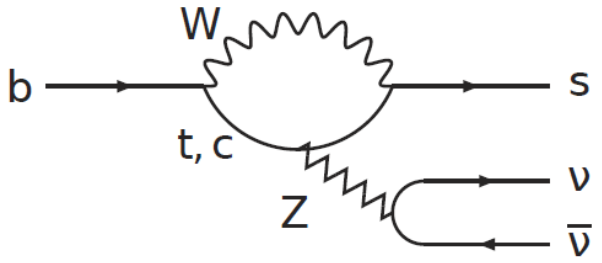
- Reconstruct 36 decay modes
- 20 self-tag decay modes used to measure A_{FB}
- The result is consistent with a SM prediction within error.
- Still statistically dominated ➔ Belle II



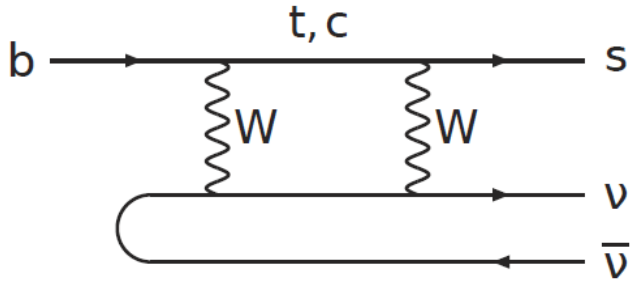


Search for B→hνν

- If C_9 is deviated from the SM value, vector current in b→sνν could be also affected in some BSM models.



- Proceeds via penguin or box diagrams
- Theoretically very clean.
  - No charm loop as in b→sl⁺l⁻
- Experimentally, need to tag the other B meson due to final states having multiple neutrinos.
- Hadronic B decays are used for tag side.



A. Buras, et al. JHEP 02 184 (2015)

Mode	$\mathcal{B}$ $[10^{-6}]$
$B^+ \to K^+ \nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$
$B^0 \to K^0_S \nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$
$B^+ \to K^{*+} \nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$
$B^0 \to K^{*0} \nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$

O. Lutz, et al (Belle Collaboration) PRD 87 111103(R) (2013)

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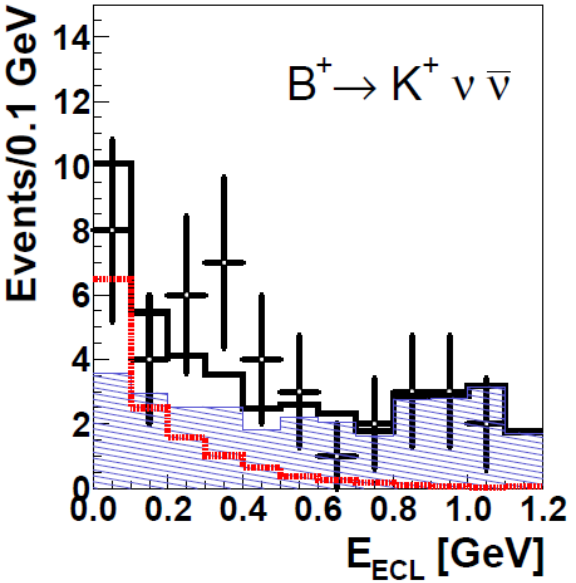
Results on B→hνν

- 1104 exclusive hadronic decays are used for tagging
  - Typical tagging efficiencies for B^+ and B^0 are 0.3% and 0.2%, respectively.
- Reconstruct h candidates
- Vetoing K_L using K_L and muon detector
- Momentum requirement
  - P_h > 1.6GeV
- Extra energy in ECL used for signal extraction



- Best upper limits on BF for
  - h = K*$^+$, π^+, π^0, ρ^+
- About 5 times larger UL than prediction for B→K*νν ➔ Belle II

Mode	Upper limit
$B^+ \to K^+ \nu\bar{\nu}$	$< 5.5 \times 10^{-5}$
$B^0 \to K^0_s \nu\bar{\nu}$	$< 9.7 \times 10^{-5}$
$B^+ \to K^{*+} \nu\bar{\nu}$	$< 4.0 \times 10^{-5}$
$B^0 \to K^{*0} \nu\bar{\nu}$	$< 5.5 \times 10^{-5}$
$B^+ \to \pi^+ \nu\bar{\nu}$	$< 9.8 \times 10^{-5}$
$B^0 \to \pi^0 \nu\bar{\nu}$	$< 6.9 \times 10^{-5}$
$B^+ \to \rho^+ \nu\bar{\nu}$	$< 21.3 \times 10^{-5}$
$B^0 \to \rho^0 \nu\bar{\nu}$	$< 20.8 \times 10^{-5}$
$B^0 \to \phi \nu\bar{\nu}$	$< 12.7 \times 10^{-5}$

Summary

- Radiative and EW penguin B decays are sensitive to BSM.
- We performed BSM searches using many observables.
  - Full angular analysis of B→K*l+l- shows 2.1σ deviation of P_5' in the $4<q^2<8 GeV^2$ bin as the same direction as LHCb.
  - Independent checks of the deviation of Wilson coefficient C_9 is very important using $B \to X_s l^+ l^-$ and/or $B \to K^{(*)} \nu\nu$ which need very high statistics ➔ Belle II

- Still important analyses are in pipeline. Some of which to be presented at ICHEP 2016 @ Chicago.
- Stay tuned!

Acknowledgement

- This talk is supported by Grants-in-Aid for Scientific Research B, No. ??????, “World best sensitivities of new physics searches with Electroweak Penguin B decays and development of light and fast-readout pixel detector” from the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

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D. Dutta, et al (Belle Collaboration) PRD 91, 011101(R) (2015)
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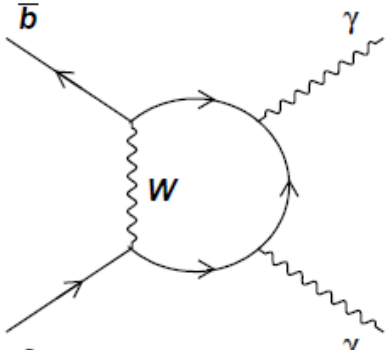
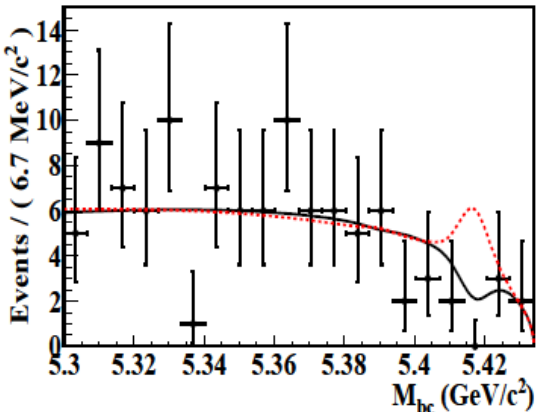
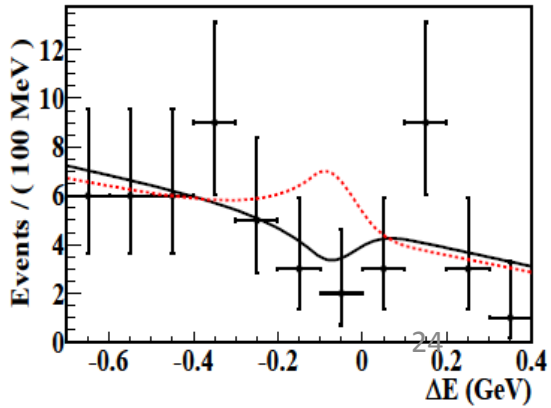
Search for $B_s \rightarrow \gamma\gamma$



- Sensitive to RPV SUSY
  - RP conserving SUSY effect to $B_s \rightarrow \gamma\gamma$ is constrained by $B(b \rightarrow s\gamma)$
- Prediction on BF is ~10^{-6}
- Measured on Y(5S)
  - $Y(5S) \rightarrow Bs^{(*)}Bs^{(*)}$
- Two hard photons
- Simultaneous fit to M_{bc} and ΔE
- Set a limit on BF
  - $< 3.1 \times 10^{-6}$
- Exclude large contribution of RPV SUSY





D. Dutta, et al (Belle Collaboration) PRD 91, 011101(R) (2015)
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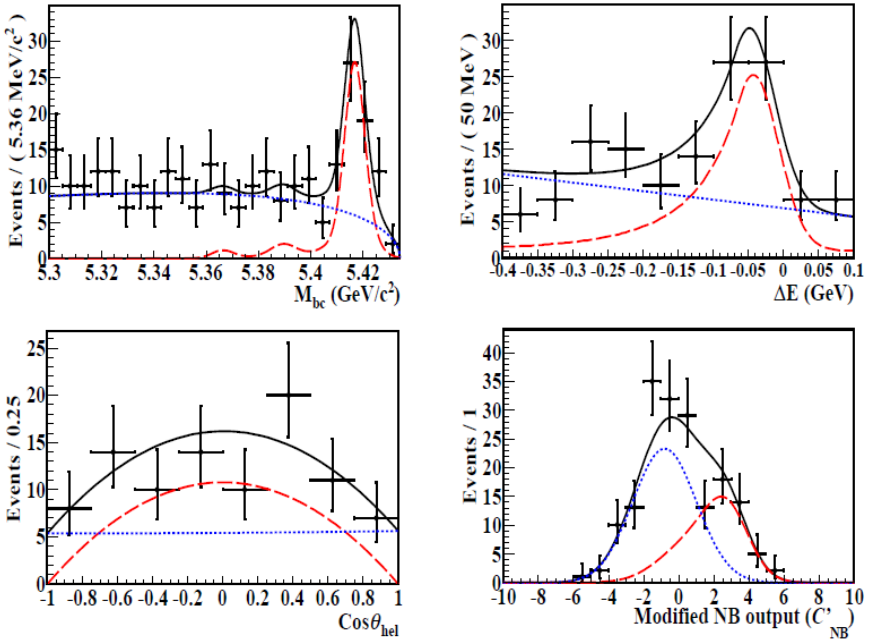
Measurement of $B_s \rightarrow \phi\gamma$

- Counter part of $B \rightarrow K^*\gamma$
- Measured on Y(5S)
  - $Y(5S) \rightarrow Bs^{(*)}Bs^{(*)}$



$$\mathcal{B}(B_s^0 \to \phi\gamma) = (3.6 \pm 0.5(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.6(f_s)) \times 10^{-5}$$