16th Conference on Flavor Physics & CP Violation

FPCP 2018

14 -18 July 2018, Hyderabad, India

Rare decays: a window on new physics

NIBEDITA DASH

IIT BHUBANESWAR

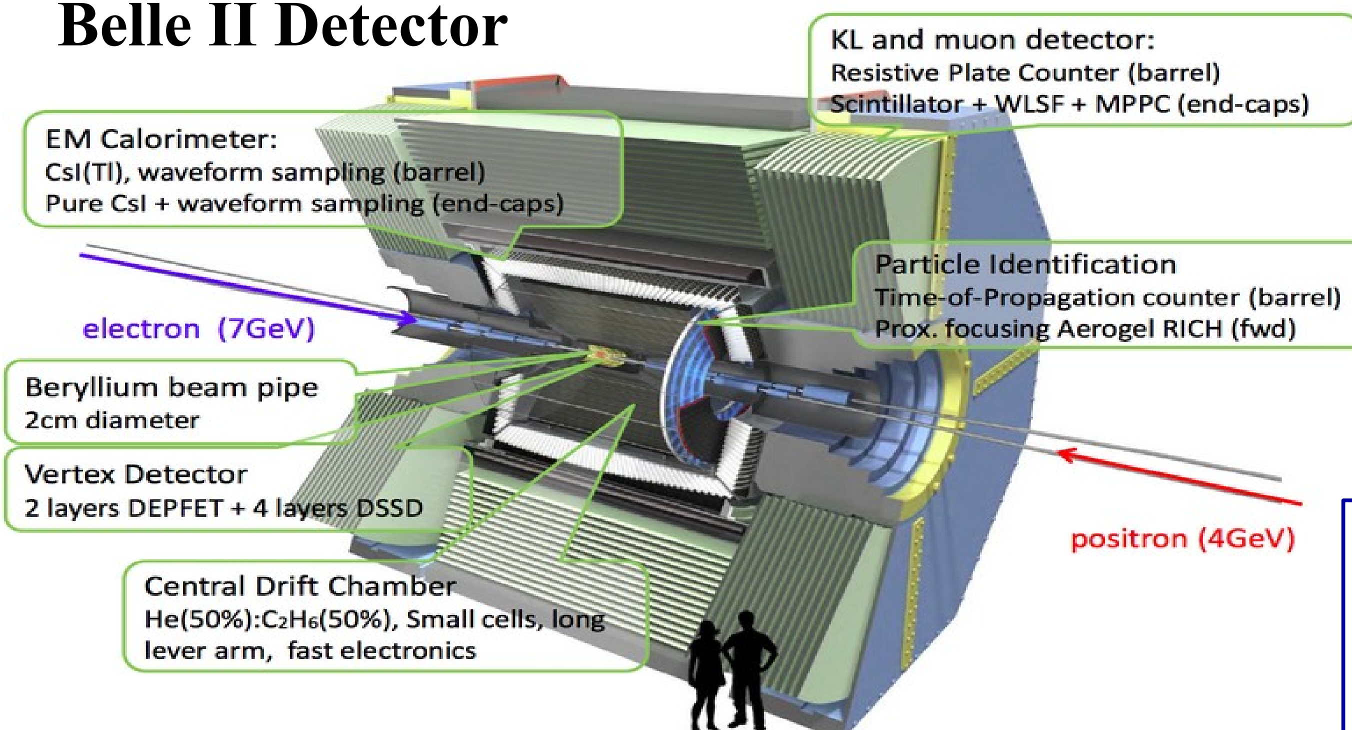
(On Behalf of the Belle II Collaboration)

Talk Outline :

- Introduction
- b →(s,d) γ
- b →(s,d)l+l-
- b → (s,d) νν
- Summary

- B-factories had a successful operational period (10 years) 1.5 ab^{-1} (1.25 x 10^9 Bpairs)
- Observation of CPV in B meson system and confirmation of CKM picture, first evidence for mixing in the D meson system, first evidence for exotic states X(3872) ....
- Still room for NP.
- Belle II, as a next generation flavor factory, aims to search for NP in the flavour sector, and to further reveal the nature of QCD.

Belle II Detector



- All subdetectors are upgraded
- First Pixel layer closer to IP
  → Better vertex resolution
- Larger Vertex Detector
  → Better Ks efficiency
- TOP and ARICH
  → better K/π separation.
- Better performance than Belle even under 20 times higher bkgs.

Phase 2 : ongoing w/o VXD
Till mid-July
Phase 3 : Full detector operation
by end of 2018

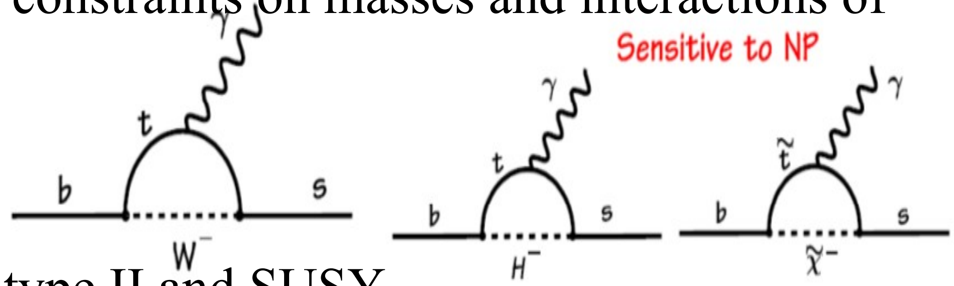
****Already covered by Vishal Bhardwaj**
Detail will be covered by Thomas Browder on 18th in Review Talk

- FCNC $b \to s$ and $b \to d$ processes continue to be of great importance to precision flavor physics
- Final states having color singlet leptons and photons are both theoretically and experimentally clean, radiative and electroweak (EW) penguin B decays are ideal place to search for NP
- Belle II physics program in this area will focus on process such as inclusive measurements of $B \to X_{(s,d)} \gamma$, $B \to X_{(s,d)} ll$ as well as decay $B \to K^{(*)} \nu\nu$
- Belle II will be very capable of B-meson decays into final states containing pairs of photons, neutrinos or taus (Fully-inclusive measurements)
- Belle II will provide an independent test of anomalies recently uncovered by the LHCb and Belle experiments in the angular analysis of $B \to K^* \mu^+ \mu^-$ and in the determination of R(K).

**** Most of the Belle results are covered by S. Sandilya**

$\bar{B} \rightarrow X_{(s,d)}\gamma$

The inclusive $\bar{B} \rightarrow X_{(s,d)}\gamma$ decays provide important constraints on masses and interactions of many possible BSM scenarios and SUSY theories.



The inclusive $B \rightarrow X_{(s,d)}\gamma$ B.F. is sensitive to $|C_7|$ and in the new physics models such as 2HDM type II and SUSY.

Precise prediction is available (for the CP- and IA branching ratios) for $E_\gamma > 1.6$ GeV :

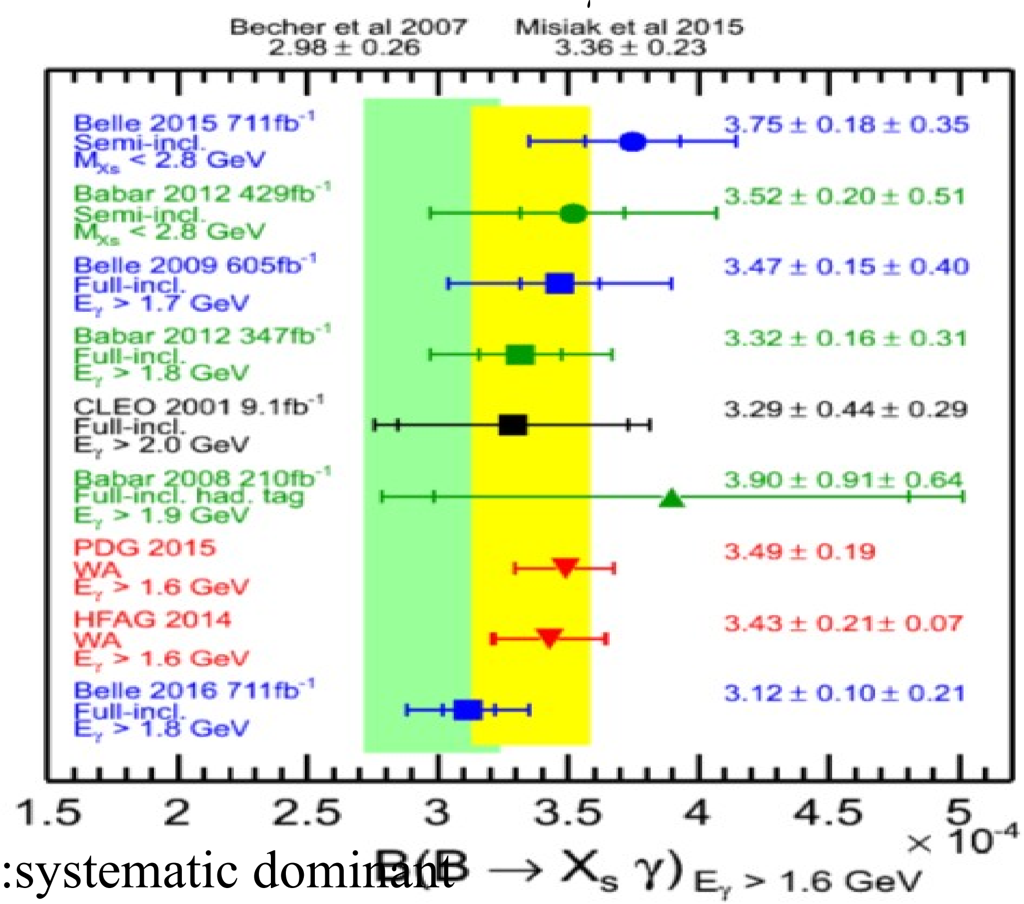
$$\mathrm{Br}^{\mathrm{SM}}_{s\gamma} = (3.36 \pm 0.23) \cdot 10^{-4},$$
$$\mathrm{Br}^{\mathrm{SM}}_{d\gamma} = (1.73^{+0.12}_{-0.22}) \cdot 10^{-5}.$$

PRL 114, 221801 (2015)

$$\mathrm{Br}^{\mathrm{exp}}_{s\gamma} = (3.27 \pm 0.14) \cdot 10^{-4},$$
$$\mathrm{Br}^{\mathrm{exp}}_{d\gamma} = (1.41 \pm 0.57) \cdot 10^{-5}.$$

JHEP, 04, 168 (2015)

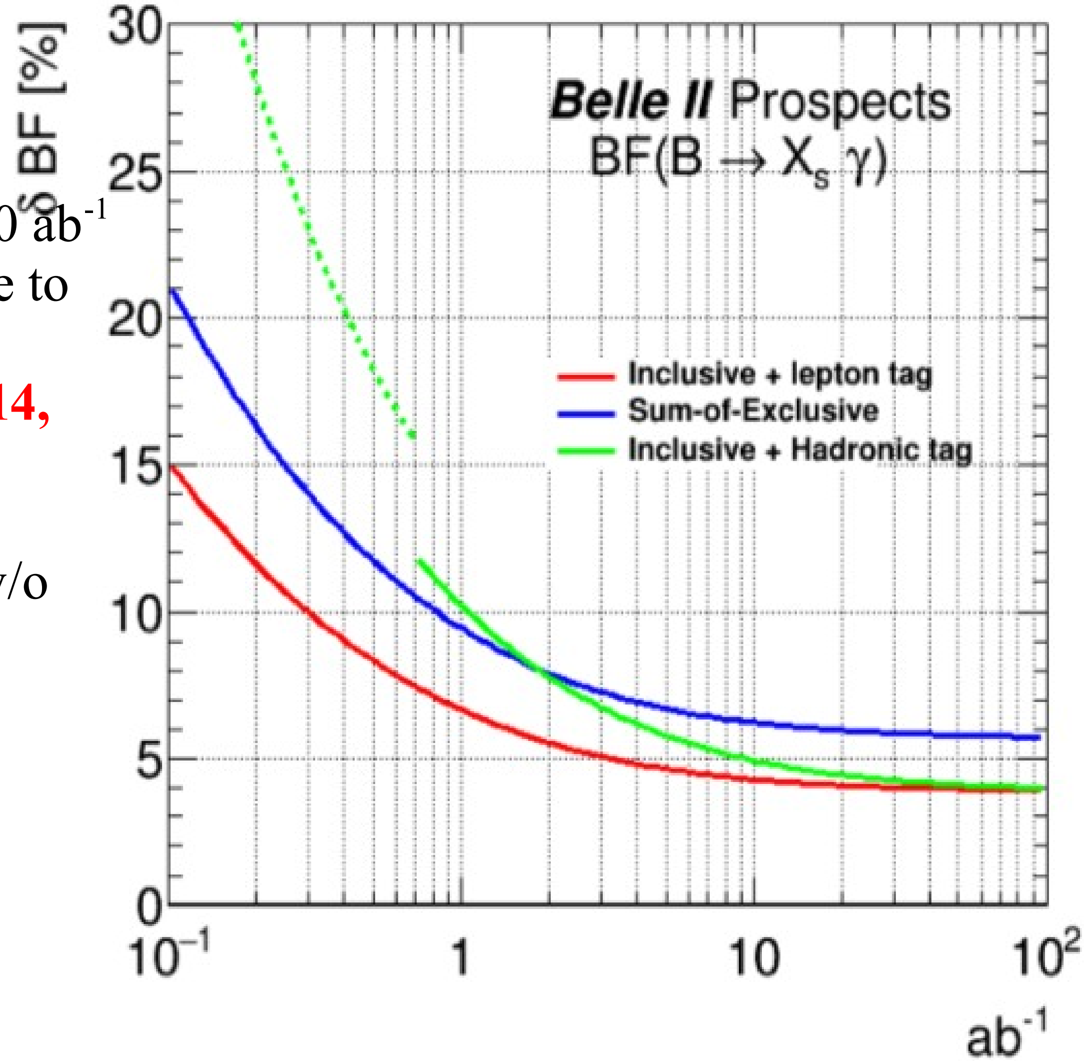
- Systematically dominated



- Exp. and theory are consistent – puts a strong limit on new physics.
- The newest Belle result with fully inclusive method has only 7.3% uncertainty:systematic dominant

Charged Higgs mass (2HDM type-II) > 580GeV in 95% C.L.

- Mission at Belle II is to reduce the systematic uncertainty with more data.
- 3.9% total error will be reachable with 50 ab^{-1} -which is comparable to uncertainty due to non-perturbative effect (which is hard to reduce) in theory. **[Misiak et. al PRL 114, 221801 (2015)].**
- BF with E_γ >1.6GeV can be measured w/o extrapolation



Lowering the photon energy threshold will however increase the size of the systematic uncertainty due to hadronic backgrounds.

(5-10 ab^{-1} will be recorded in ~ 2-3 years)

$\bar{B} \to X_{(s,d)}\gamma$: Rate Asymmetry

- In addition to BFs, asymmetry in decay rates **(isospin asym. and CP asym.)** are also sensitive to BSM contributions
- The direct CP asymmetry in the time-integral rates is defined as:

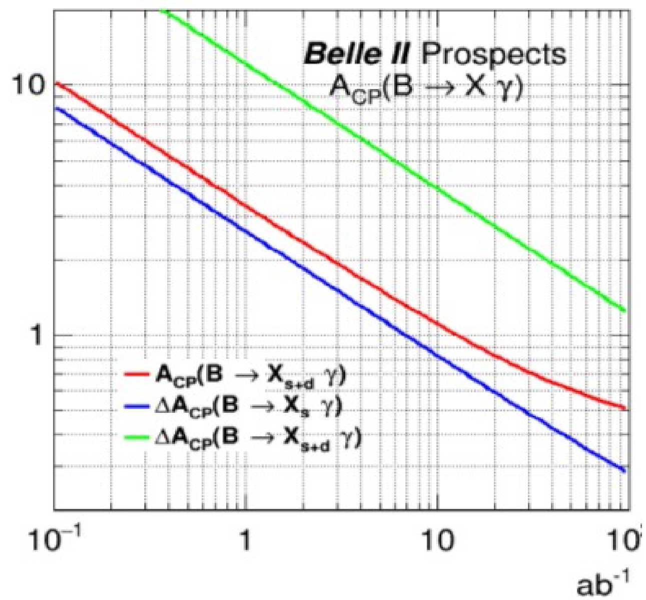
$$A_{CP} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}.$$

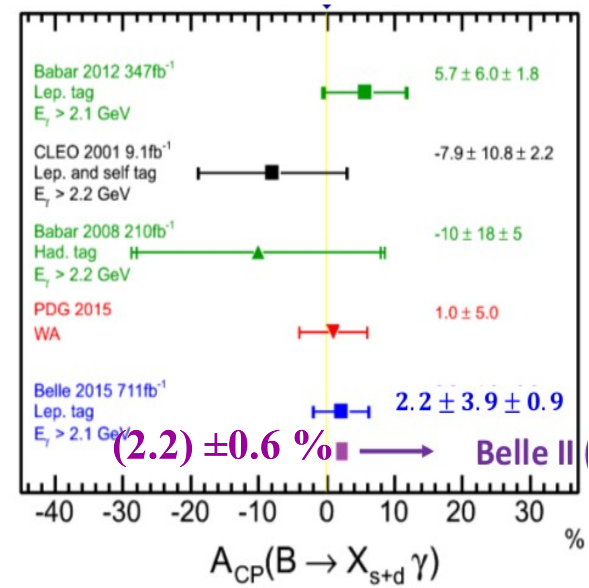
$$\Delta A_{CP}(B \to X_q\gamma) = A_{CP}(B^+ \to X_q^+\gamma) - A_{CP}(B^0 \to X_q^0\gamma)$$

- SM predicts : $B \to X_s\gamma$ and $B \to X_d\gamma$

  $A^{SM}_{CP(s\gamma)} = [-0.6, 2.8]$ %

  $A^{SM}_{CP(d\gamma)} = [-62, 14]$ %





- A_{CP} for the sum of $b \to s\gamma$ & $b \to d\gamma$ is predicted to be very small (close to zero, thanks to the unitarity of the CKM matrix)
- ΔA_{CP} sensitive to phases in C_7 and C_8

  In the SM , phases in C_7 and C_8 are zero $\to \Delta A_{CP} = 0$
- If either is deviated from null, clear NP signal!

Uncertainty in :
A_{CP} : ±0.6 % → 3.7σ
ΔA_{CP}: ±0.4 %
} if the central value not change

BaBar's measurement $\Delta A_{CP}(X_s\gamma) = +(5.0 \pm 3.9 \pm 1.5)\%$]

most of systematic cancels,
statistically dominated @ Belle II (50 ab^{-1})

[Belle II : +(5.0± 0.37)%]

T. Hurth, E. Lunghiand W. Porod, Nucl.Phys. B704 (2005) 56–74, M. Benzke et. al, PRL 106, 141801 (2011)

b→qγ Exclusive modes

Isospin asymmetry is defined as :

$$a_I^{\bar{0}-} = \frac{c_V^2\,\Gamma(\bar{B}^0 \to \bar{V}^0\gamma) - \Gamma(B^- \to V^-\gamma)}{c_V^2\,\Gamma(\bar{B}^0 \to \bar{V}^0\gamma) + \Gamma(B^- \to V^-\gamma)}$$

$c_{\rho 0}^{\ 2} = 2$ and $c_{K*}^{\ 2} = 1$ are isospin-symmetry factors

To accumulate more statistics, CP-averaged IAs can be defined as: $\bar{a}_I = (a_I^{\bar{0}-} + a_I^{0+})/2.$

$\bar{a}_I^{SM}(K^*\gamma) = (4.9 \pm 2.6)\%$

$\bar{a}_I^{SM}(\rho\gamma) = (5.2 \pm 2.8)\%$

PRD 88 (2013), 094004

$\bar{a}_I^{exp}(K^*\gamma) = (5.2 \pm 2.6)\%$

$\bar{a}_I^{exp}(\rho\gamma) = (30^{-13}_{+16})\%$

HFLAV 2017

considerable uncertainty

The observable with reduced uncertainty

$$1 - \delta_{a_I} = \frac{\bar{a}_I(\rho\gamma)}{\bar{a}_I(K^*\gamma)} \sqrt{\frac{\bar{\Gamma}(B \to \rho\gamma)}{\bar{\Gamma}(B \to K^*\gamma)}} \left|\frac{V_{ts}}{V_{td}}\right| ,$$

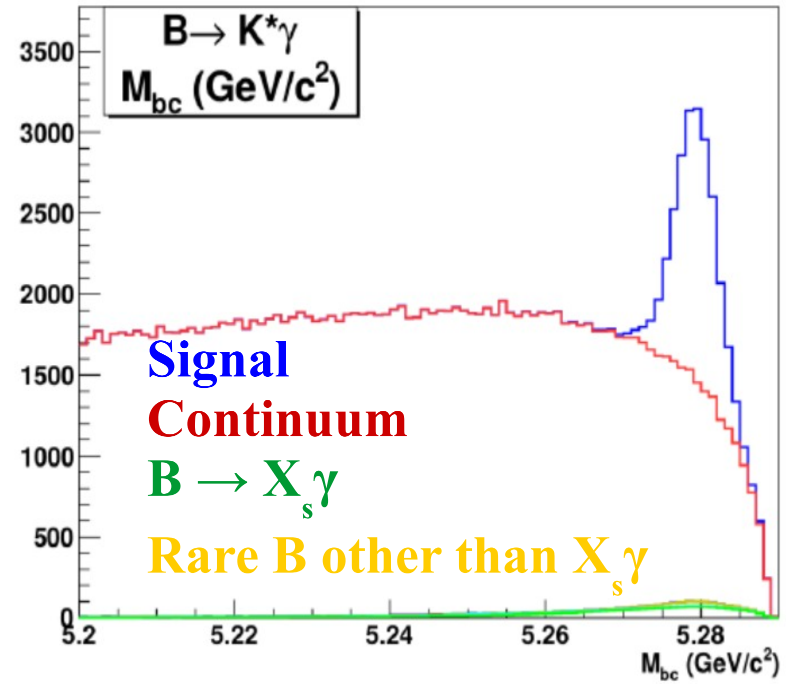
$\delta_{aI}^{SM} = 0.10 \pm 0.11$

$\delta_{aI}^{exp} = -4.0 \pm 3.5$

Can be improved at Belle II with more statistics.

b→ sγ :Time dependent CPV

- Mixing-induced CP asymmetry in an exclusive **b→ sγ** mode such as B → K*($K_s\pi^0$)γ is an excellent probe for particular class of NP scenario

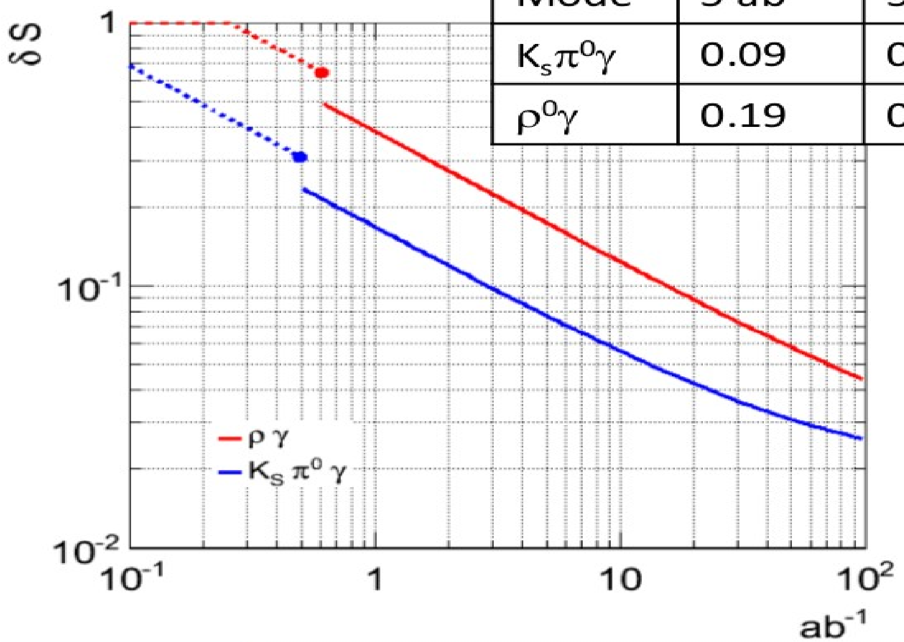


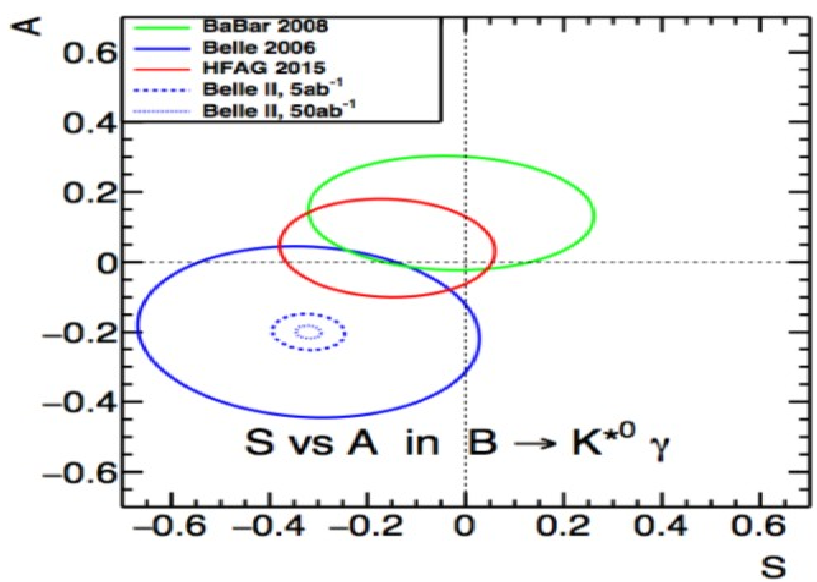
- In the SM, expected asymmetry $|S_{CP}|$

$$\approx \frac{2m_s}{m_b}\sin(2\phi_1) \sim \text{a few \%}.$$

- At Belle II, significant improvement in the determination of $A_{CP}(t)$ in $K_s\pi^0\gamma$ is expected
  - Larger VXD than Belle (6cm → 11.5cm).
  - 30% more Ks
  - Effective tagging efficiency
- Expected errors for S measurements of $K_s\pi^0\gamma$ and $\rho^0\gamma$

Mode	5 ab^{-1}	50 ab^{-1}
$K_s\pi^0\gamma$	0.09	0.030
$\rho^0\gamma$	0.19	0.064

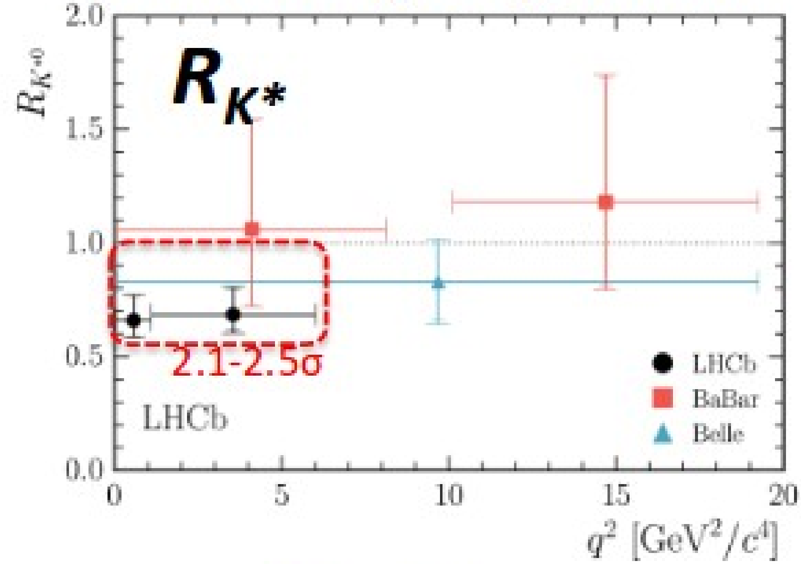


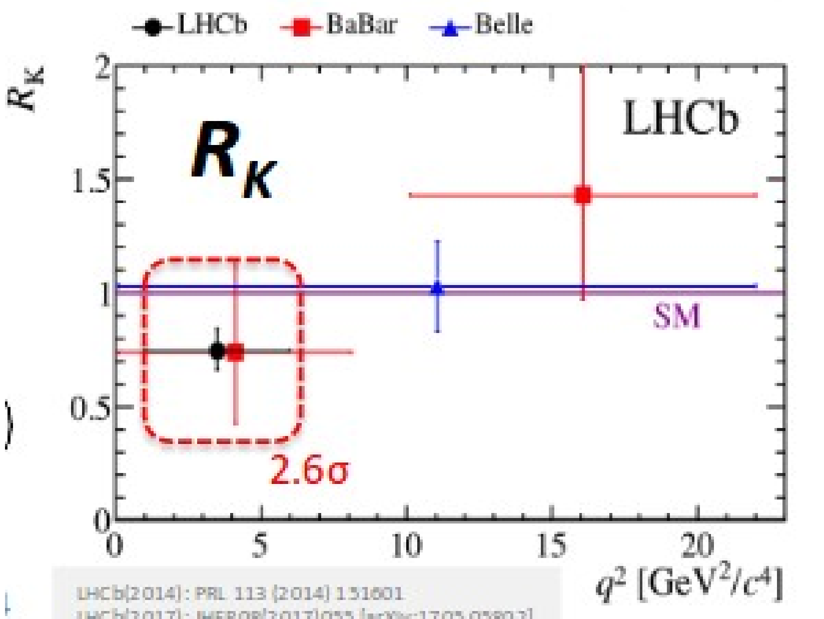


16σ deviation with 50 ab^{-1}.

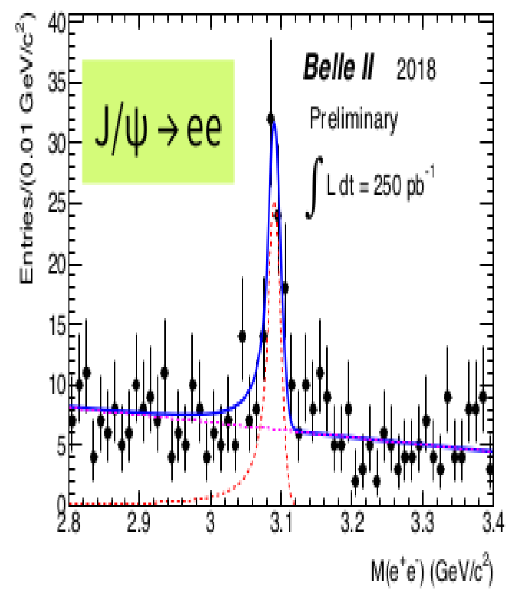
$B \to K^{(*)}$ ll proceeds via one loop diagram, and LU holds in SM

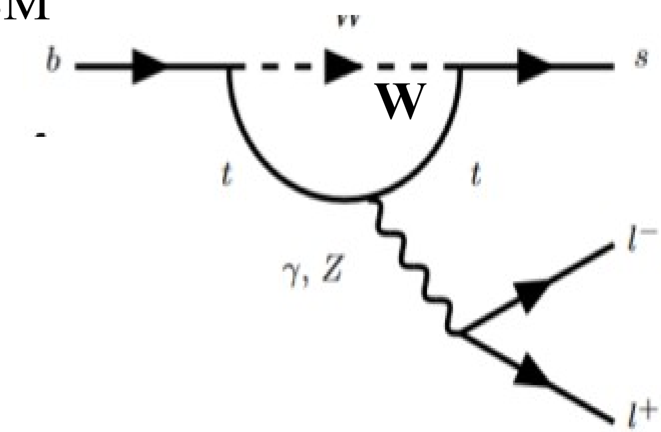
Current R_{K^*}, R_K results

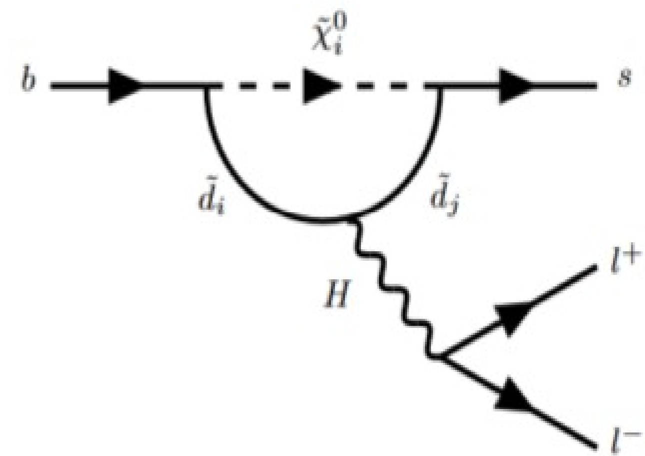




Ratio of $B \to K^{(*)} \mu \mu$ and $B \to K^{(*)} ee$



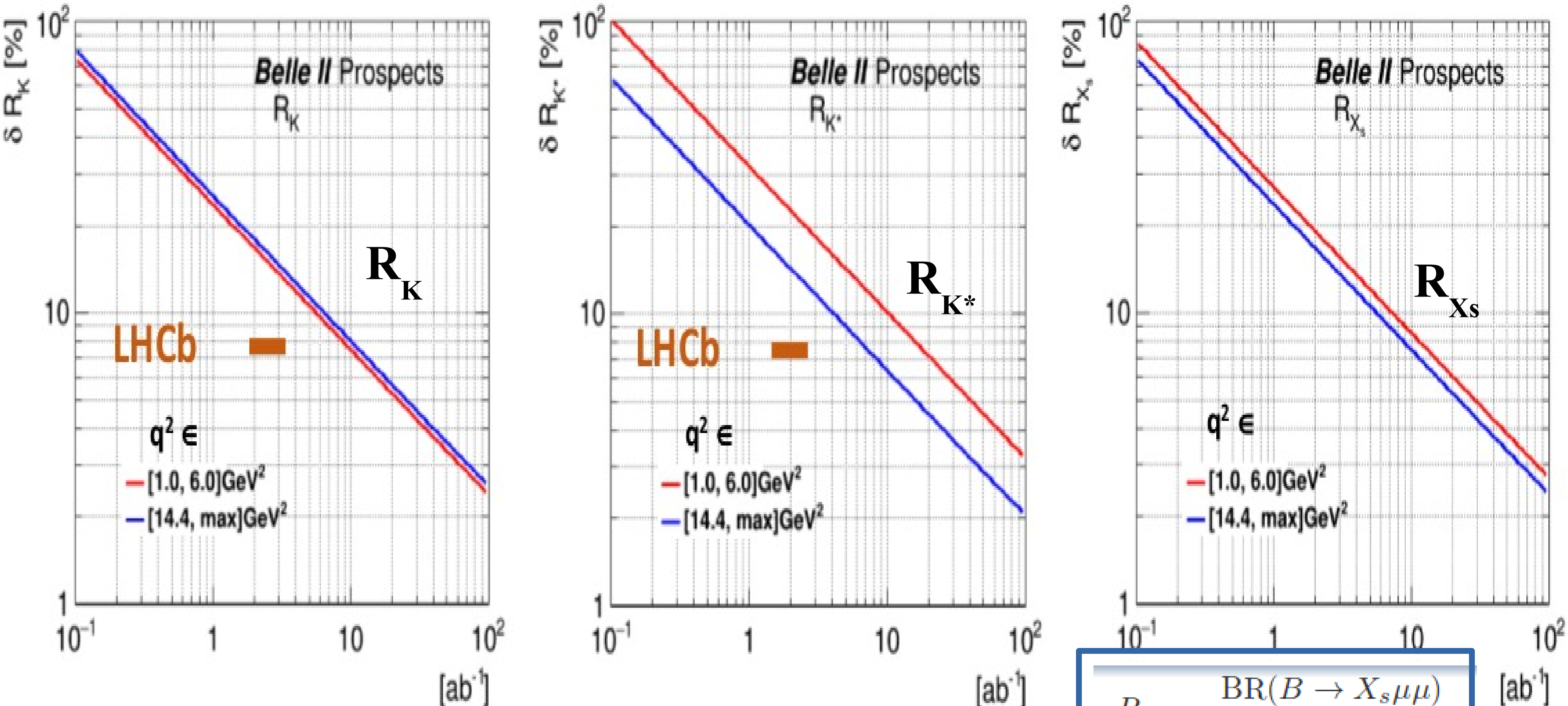




- However electron mode is challenging at LHCb, especially for high q^2
- Belle II:
  - electron and muon modes have similar efficiency
  - Both low and high q^2 regions are possible
  - All ratios R(K), R(K*), R(X_s) are possible

LU test : R(K), R(K*), R(X$_s$)

Expected uncertainty of R measurement at Belle II



$$R_{X_s} = \frac{\mathrm{BR}(B \to X_s \mu\mu)}{\mathrm{BR}(B \to X_s ee)}$$

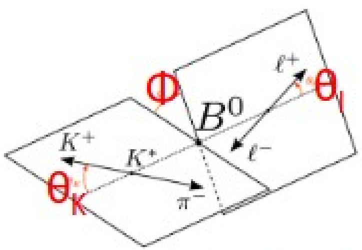
- The errors reach to 0.04 for all K, K* and Xs modes in Belle II (with 50 ab^{-1})
- Errors are still statistically limited (systematic error ~ 0.4%)

Belle II should be able to confirm the R(K$^{(*)}$) anomaly with a significance of 5σ, if it is indeed due to new physics.

Angular Analysis $B \to K^* l^+ l^-$

Full decomposition of angular distribution

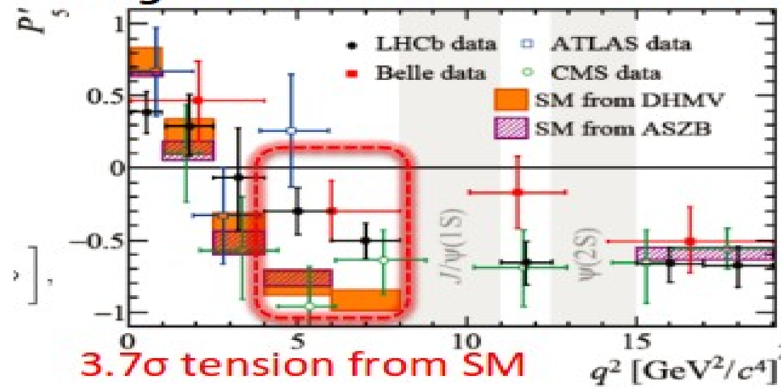
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi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



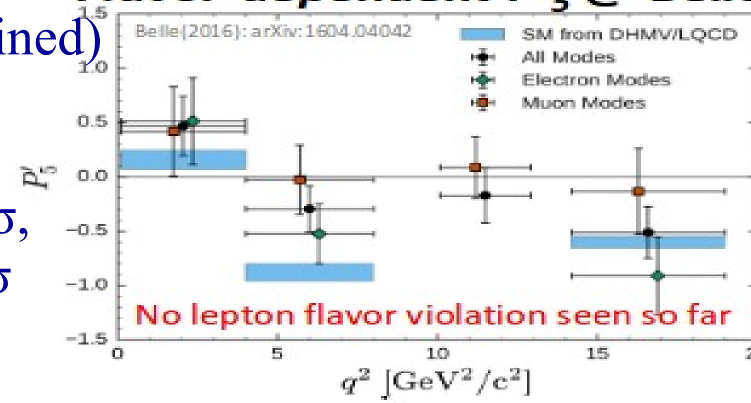
Optimized observable

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

P'₅ measurement results



Flavor-dependent P'₅ @ Belle



2.5σ (combined) tension

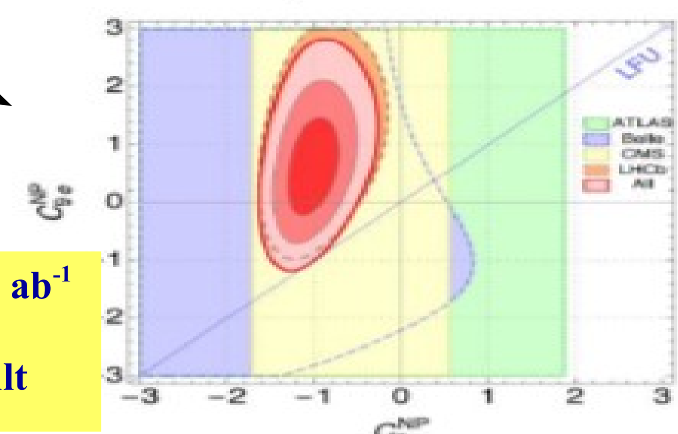
μ mode 2.6σ, e mode 1.1σ

- Global fits including P'_5 Q_5 $R(K^*)$, $B_s \to \mu\mu$, $B \to s\gamma$ suggests $C_{9\mu}^{NP} \approx -1.1$
- Belle II and LHCb will be comparable for this process.
- electron mode more efficiently and can also explore $Q_{4,5}$
- Projection of uncertainties at Belle II for P'_5

q^2 (GeV²c⁻⁴)	Belle	Belle II
0.1 – 4	0.42	0.06
4 – 8	0.28	0.04
10.09 – 12	0.34	0.05
14.18 – 19	0.25	0.03

Low q^2 region

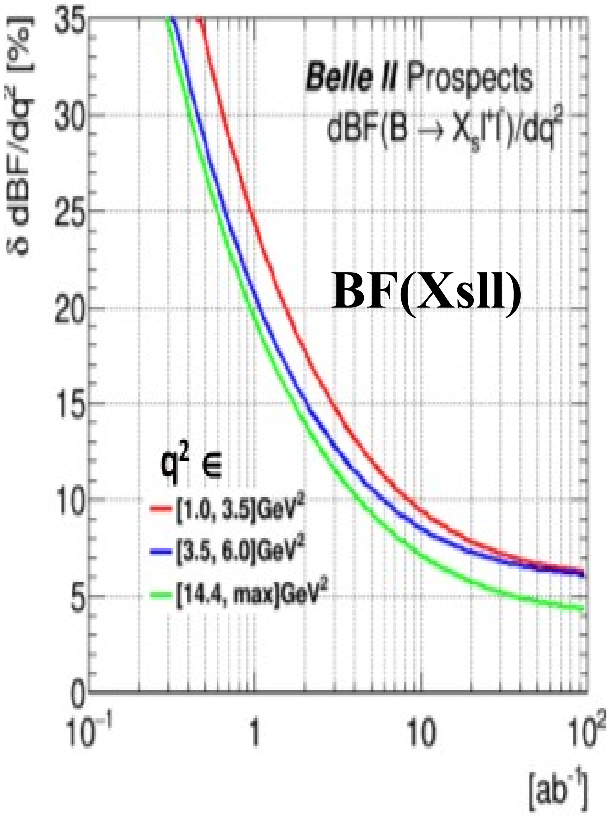
4% error with 50 ab⁻¹ comparable with LHCb 22fb⁻¹ result

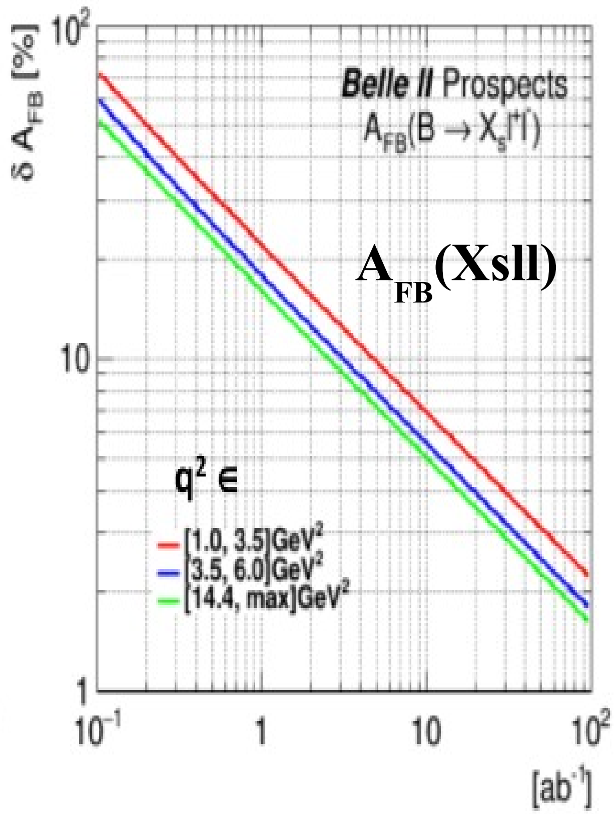


Capdevila, Crivellin, Descotes-Genon Matias, Virto, arXiv:1704.05340

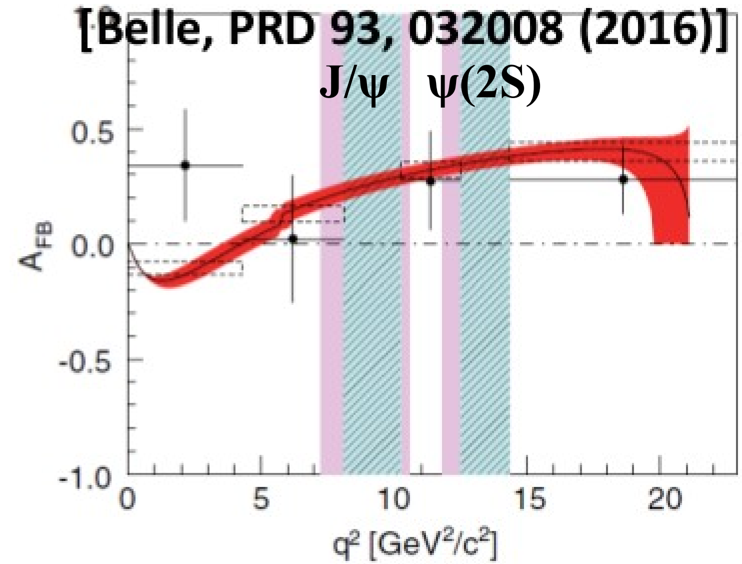
$B \to X_s l^+ l^-$

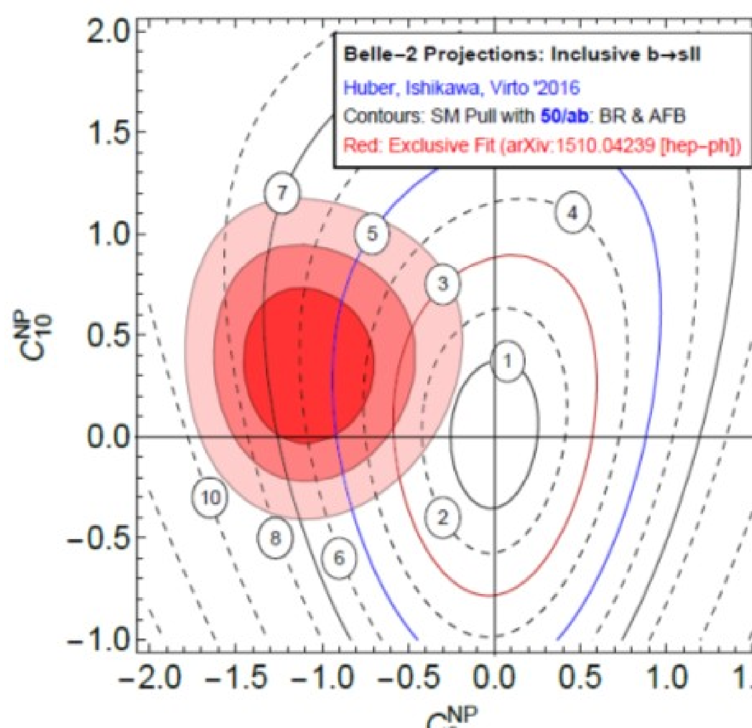
- Measurement of BF and A_{FB} in $B \to X_s l^+ l^-$ at Belle
- Sum-of-exclusive method is utilized
- Tension in low q^2 region
- Measurement can be improved at Belle II.





l+l- Fwd-Bwd Asymmetry A_{FB})



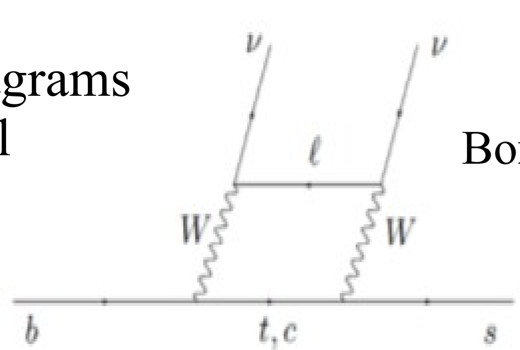


- Decay rate dBF/dq^2, A_{FB} Sensitive to C_9 and C_{10}
- Precise theory prediction available

T. Huber, J. Virto, A. Ishikawa

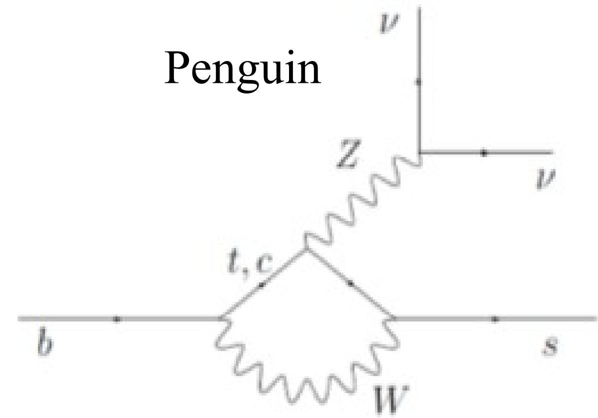
b → sνν

- Proceeds via penguin or box diagrams
- Theoretically very clean channel (no charm loops)



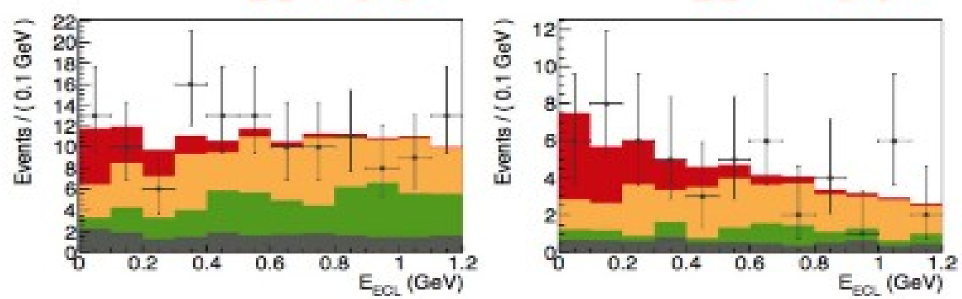
Box

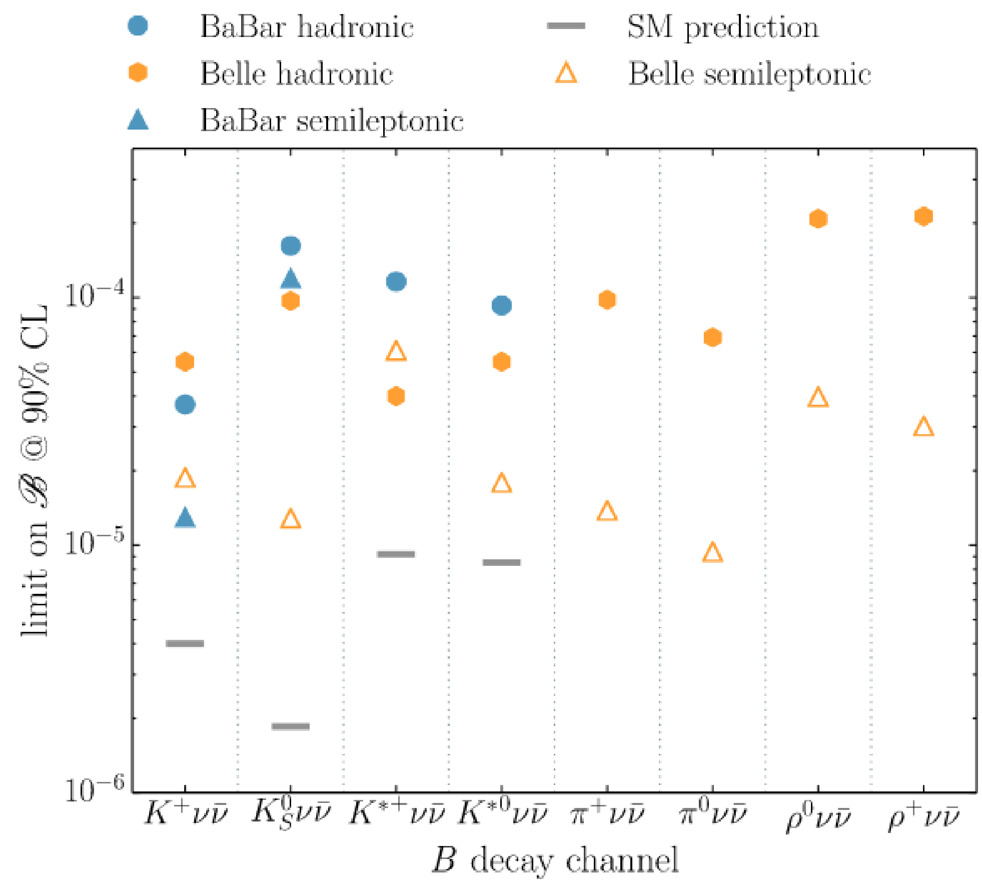
Penguin



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

[JHEP 02 184, 2015]





- Belle updated b→(s,d)νν measurement with semileptonic tag

[PRD96, 091101(R)]

- Most stringent limits till date in most channels
- Close to SM prediction in $K^{(*)}$ mode Golden channel for Belle II

**** well explained by S. Sandilya**

$b \to s\nu\nu$: Belle II prospects

- Brighter prospects for Belle II to observe this decay.

Expected uncertainty at Belle II

	stat only	total
$B^+ \to K^+ \nu\nu$	10%	11%
$B^+ \to K^{*+} \nu\nu$	8%	9%
$B^+ \to K^{*0} \nu\nu$	8%	10%

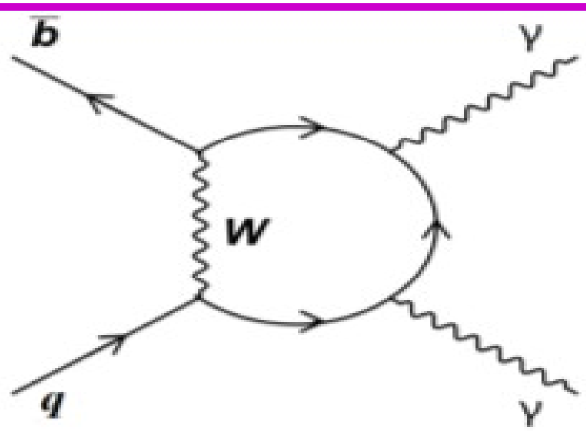
- Belle II extrapolation based on Belle hadronic and SL tag analyses, assuming 100%
- observation with about 18 ab^{-1}
- precision on the branching fraction at 50 ab^{-1}
- BF($B \to K(*)\nu\nu$) is measurable at Belle II with about 10% uncertainty.

Summary

- Many detector components and electronics replaced, software and analysis also improved
- Belle II has a rich physics program, complementary to existing experiments and energy frontier programs
- Belle II experiment will contribute strongly to apply further constraint on BSM and to understand the current anomalies, with abundant rare B decay data:
  1.Radiative penguin B decays
  2. Semileptonic penguin B decays
- Moreover, Belle II has a sufficient ability to discover other interesting decay channels: $B \rightarrow K^{(*)}\nu\nu$

Extra

Double-Radiative Decays



$B_q \to \gamma\gamma$

SM prediction

$$\mathrm{Br}(B_s \to \gamma\gamma)_{\mathrm{SM}} \in [0.5, 3.7] \cdot 10^{-6},$$

$$\mathrm{Br}(B_d \to \gamma\gamma)_{\mathrm{SM}} \in [1.0, 9.8] \cdot 10^{-8},$$

[JHEP 08 (2002) 054]

Exp. status

$$\mathrm{Br}(B_s \to \gamma\gamma)_{\mathrm{exp}} < 3.1 \cdot 10^{-6},$$

[Belle, PRD 91, 011101 (2015)]

$$\mathrm{Br}(B_d \to \gamma\gamma)_{\mathrm{exp}} < \begin{cases} 3.2 \cdot 10^{-7}, \\ 6.2 \cdot 10^{-7}, \end{cases}$$

90% CL UL

[BaBar, PRD 83, 032006 (2011)]
[Belle, , PRD 73, 051107 (2006)]

- Belle II will be able to discover $B_d \to \gamma\gamma$ with the anticipated 50 ab^{-1} at Υ(4S)
- large data at Υ(5S) $B_s \to \gamma\gamma$ can be observed

$B \to X_s\gamma\gamma$

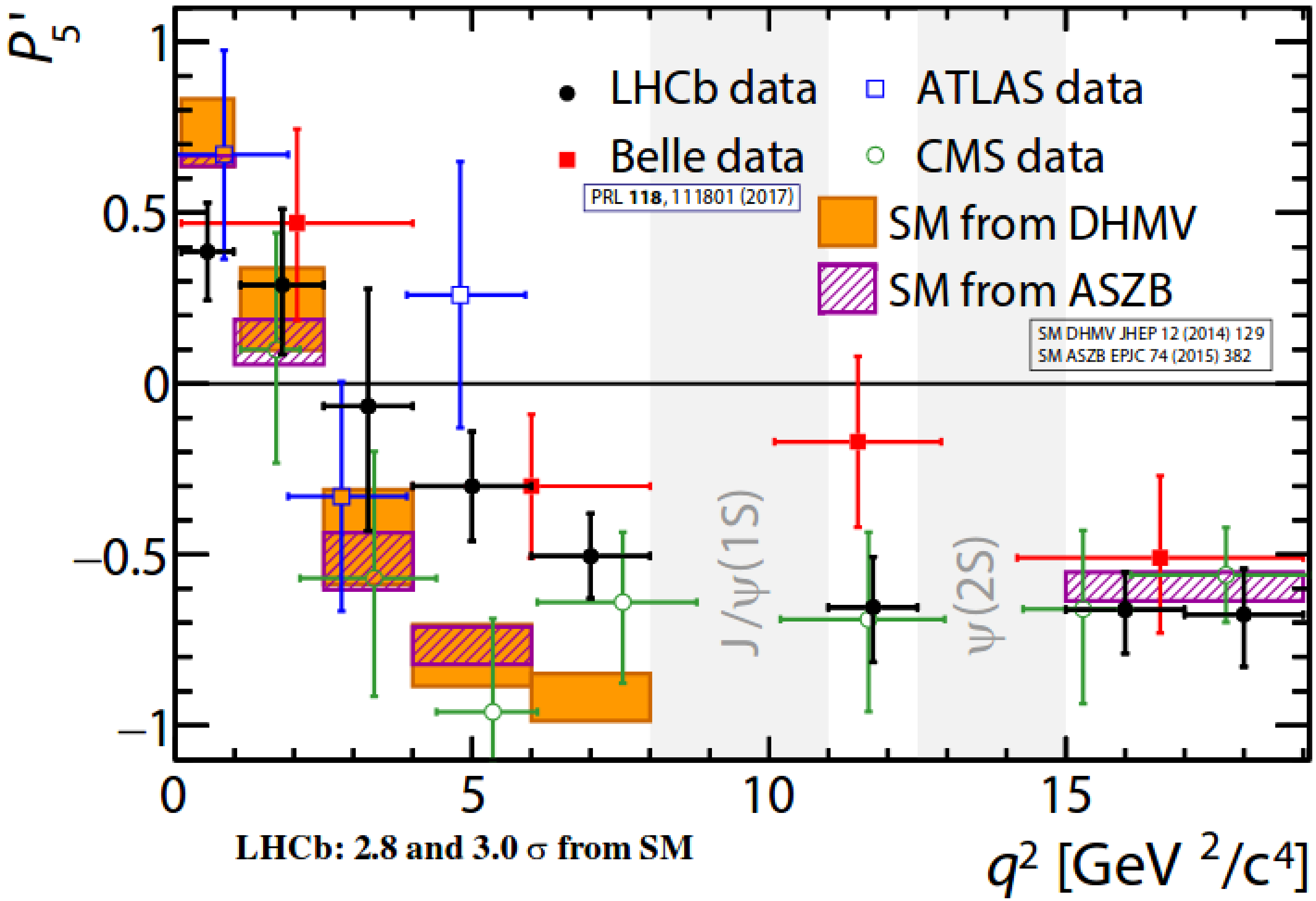
$B \to X_s\gamma\gamma$ decays are suppressed by $\alpha_s/4\pi$ compared to $B \to X_s\gamma$

$$\mathrm{Br}(B \to X_s\gamma\gamma)_{\mathrm{SM}}^{c=0.02} = (0.9 \pm 0.3) \cdot 10^{-7},$$

[PRD 93, 014037 (2016)]

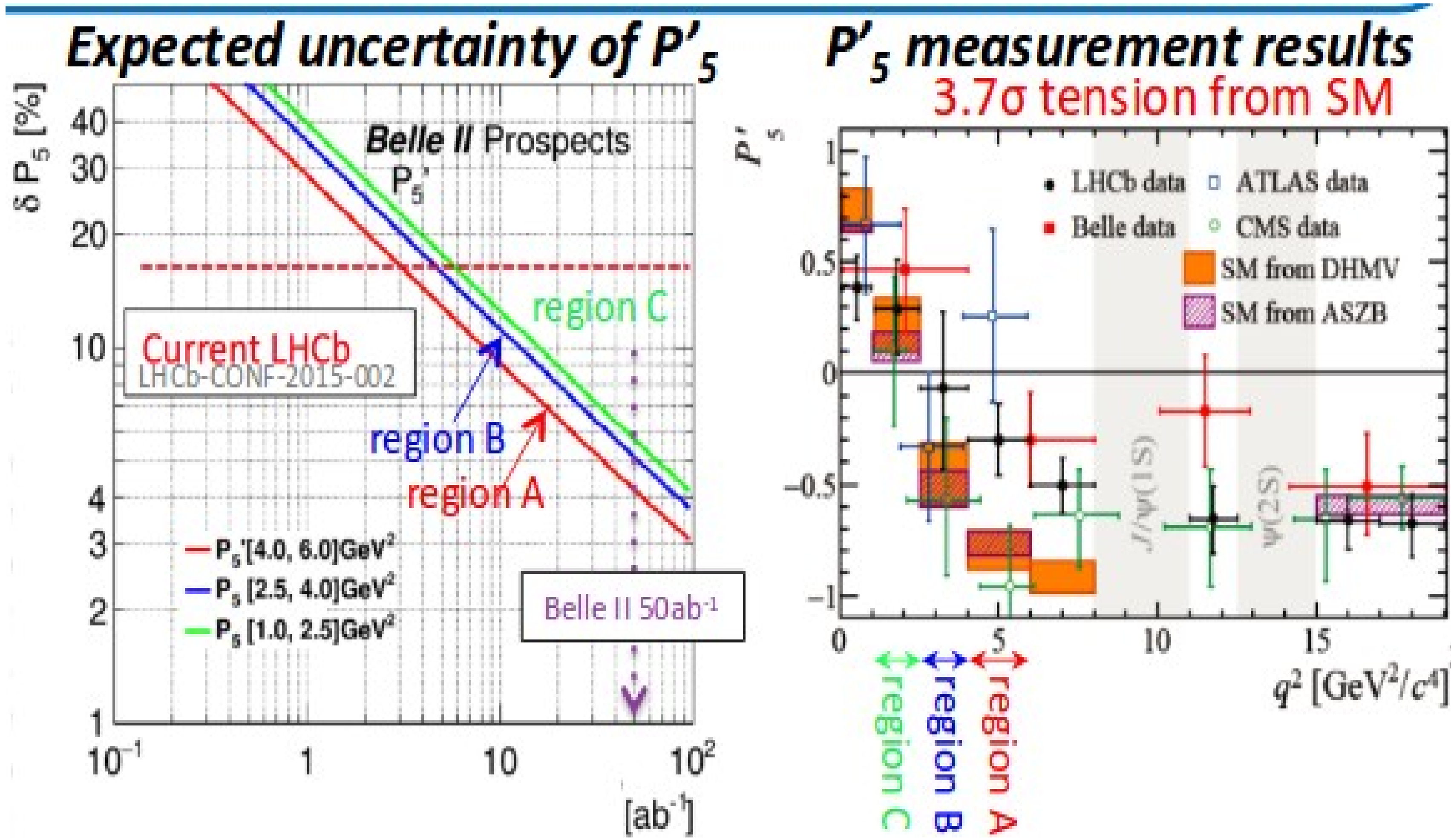
- Measurements of the double-radiative decay mode would allow to put bounds on 1PI type corrections.
- One can study more complicated distributions like, double differential rate ($d^2\Gamma/dE_1 dE_2$) and forward backward asymmetry : sensitive to BSM physics

Lepton Flavour dependent Angular Analysis B->K*ll



LHCb: 2.8 and 3.0 σ from SM

Lepton Flavour dependent Angular Analysis



4% error with 50 ab^{-1}

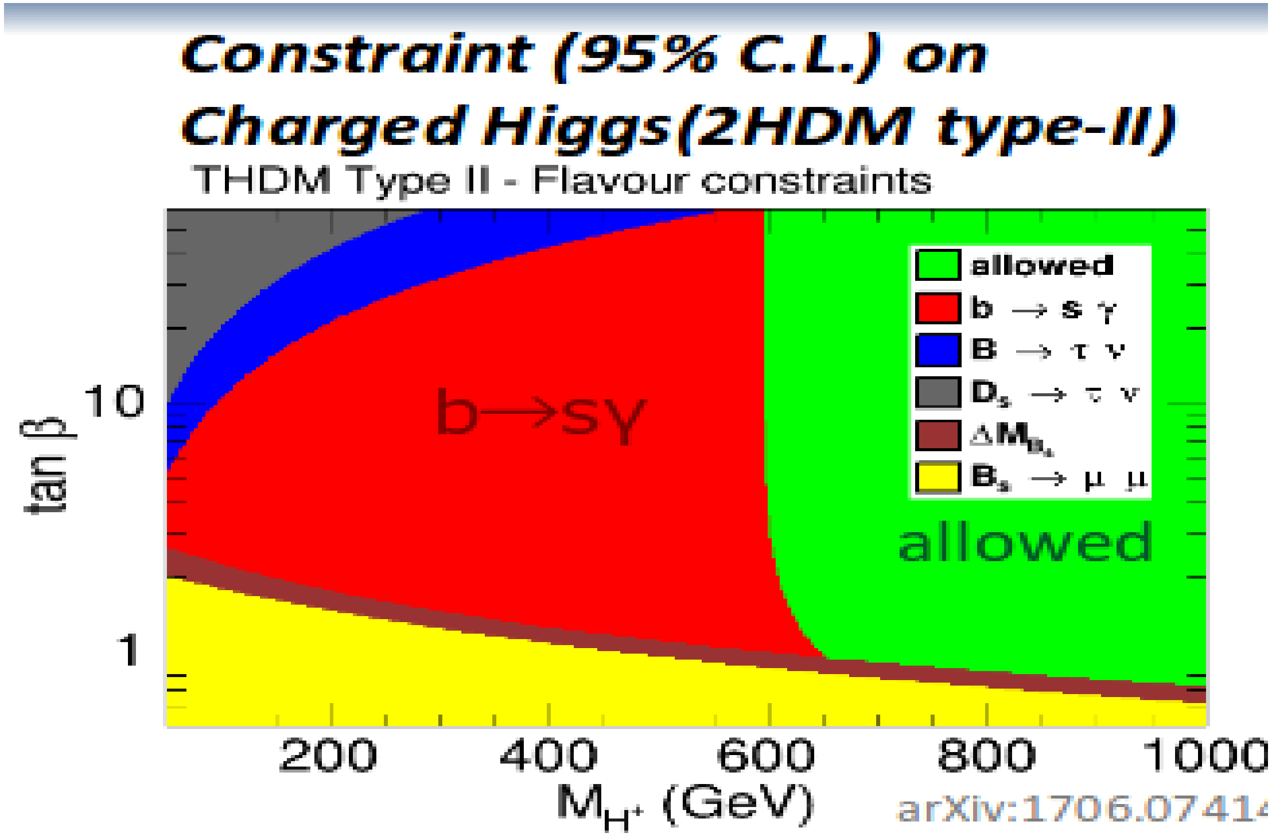
– comparable with LHCb $22fb^{-1}$ result

Belle II Projected Sensitivity to (some of) Angular Observables

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
F_L $(1 < q^2 < 2.5\ \mathrm{GeV}^2)$	0.19	0.063	0.025
F_L $(2.5 < q^2 < 4\ \mathrm{GeV}^2)$	0.17	0.057	0.022
F_L $(4 < q^2 < 6\ \mathrm{GeV}^2)$	0.14	0.046	0.018
F_L $(q^2 > 14.2\ \mathrm{GeV}^2)$	0.088	0.027	0.009
P_5' $(1 < q^2 < 2.5\ \mathrm{GeV}^2)$	0.47	0.17	0.054
P_5' $(2.5 < q^2 < 4\ \mathrm{GeV}^2)$	0.42	0.15	0.049
P_5' $(4 < q^2 < 6\ \mathrm{GeV}^2)$	0.34	0.12	0.040
P_5' $(q^2 > 14.2\ \mathrm{GeV}^2)$	0.23	0.088	0.027

Belle II Theory Interface Platform (B2TIP)
(https://confluence.desy.de/display/BI/B2TiP+WebHome)

6th Belle II Theory Interface Platform (B2TiP) Workshop, KEK
https://kds.kek.jp/indico/event/27330/


Constraint (95% C.L.) on
Charged Higgs(2HDM type-II)
THDM Type II - Flavour constraints
allowed
b → s γ
B → τ ν
D_s → τ ν
ΔM_Bs
B_s → μ μ
b→sγ
allowed
tan β
10
1
200
400
600
800
1000
M_H+ (GeV)
arXiv:1706.0741