Studies of missing energy decays at Belle II

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On behalf of the Belle II Collaboration

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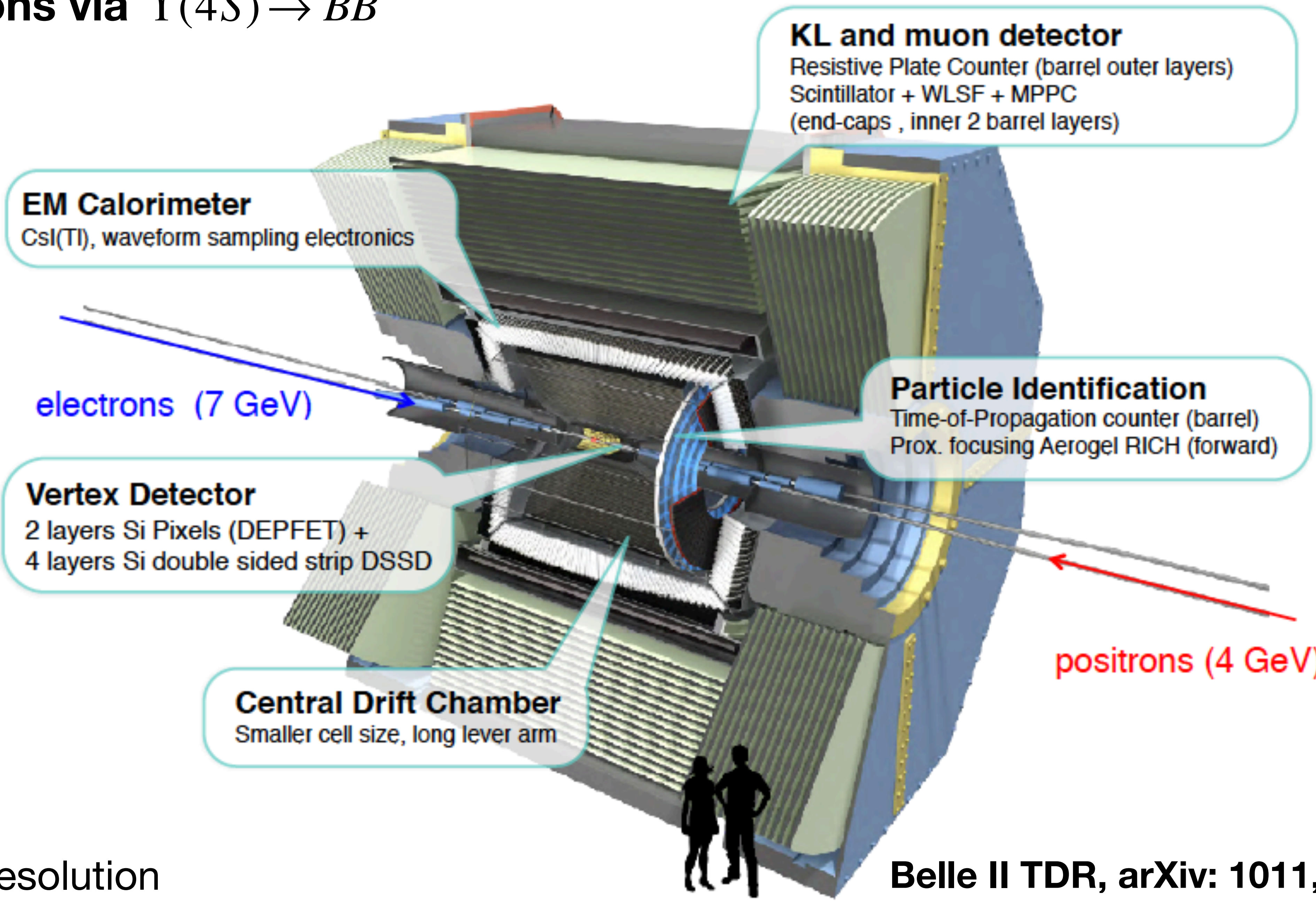
BelleII Detector

- **SuperKEKB: e^+e^- collider at sqrt(s) =10.58GeV, at KEK, Japan**
- **Produce B mesons via** $\Upsilon(4S) \rightarrow B\bar{B}$



Belle II TDR, arXiv: 1011, 0352

- Improve vertex resolution
- Particle ID: 4 σ K/pi separation at 1-3.5 GeV/c.
- EM Calorimeter: waveform sampling; low pileup, better resolution.
- KLM: RPC+Scintillators, better K_L efficiency.

Motivation

- (Semi-)Leptonic and rare *B* decays are important to probe new physics (NP). Anomalies are already observed in data.

- With 50 ab^{-1} collected at Belle II experiment one should be able to resolve the observed anomalies and search NP.

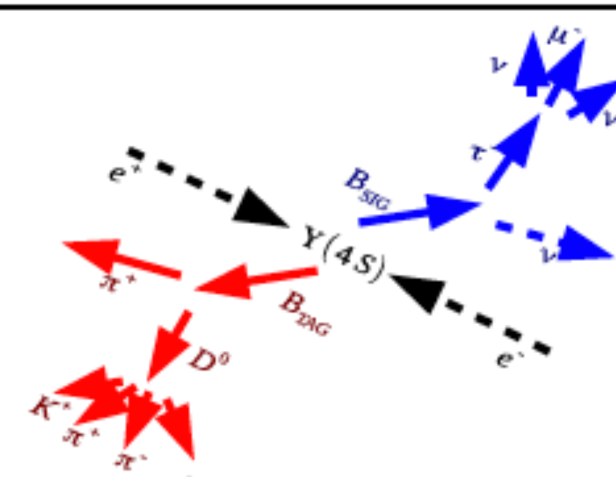
- Experimental challenging: one missing neutrino or multiple missing neutrinos.

- At *B*-factories, *B*-tagging tool is powerful, one *B* meson can be fully reconstructed (hadronic-tagging) providing constraints for the other *B*, suppressing backgrounds. Ideal place to measure rare decays with missing energy.

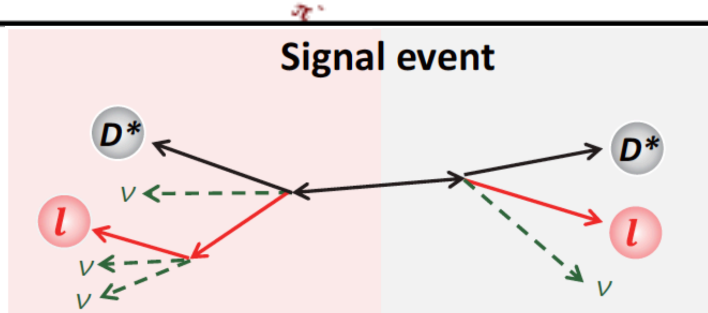
$$Br(\Upsilon(4S) \to B\bar{B} > 96\%)$$
$$p(e^-) + p(e^+) = p(B) + p(\bar{B})$$

One B meson fully reconstructed know flavor and momentum of the other

- **Allow to study decays with missing energy**
- **More than 2K hadronic decays available for full reconstruction**

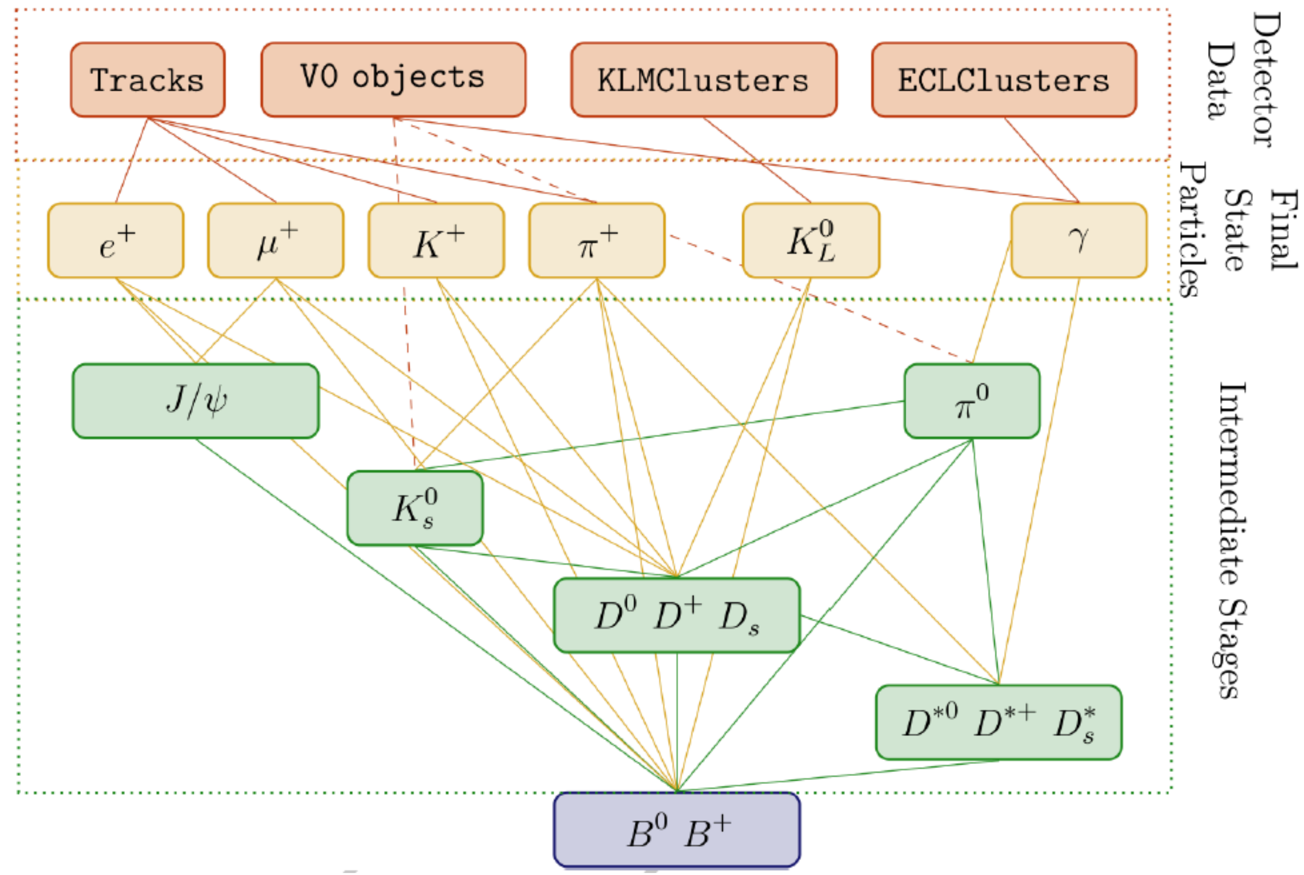


- Semi-leptonic tagging is also available, even has better sensitivities in some cases.



Full Event Interpretation (FEI)

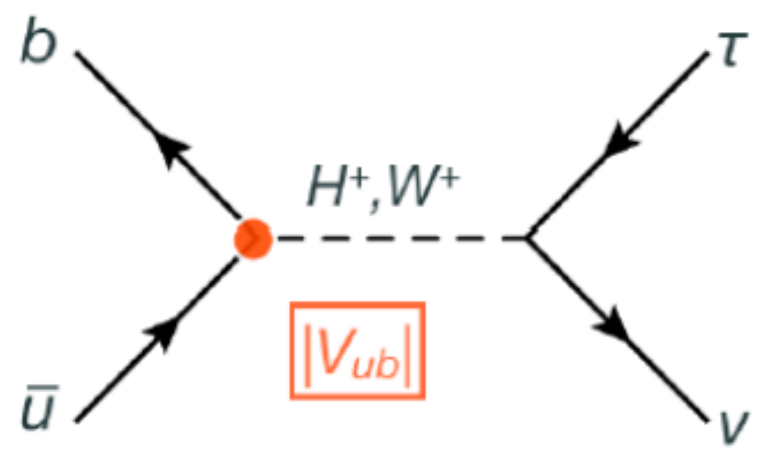
- Belle already employed Full Reconstruction (FR) successfully.
- Belle II: Full Event Interpretation (FEI): more inclusive, more automation and analysis-specific optimizations.
- Hierarchical approach
  - A multivariate classier (MVC) is trained for final-state particle candidates and intermediate particle candidates classification.
  - The MVC is trained for each employed decay channel.
  - Combine all information into a single value, the signal-probability.
- FEI can unify the hadronic and semi-leptonic and inclusive tagging into a single algorithm.



Tag-side efficiency:

Tag	FR[8] @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %

search NP in $B^+ \to \tau^+ \nu_\tau$



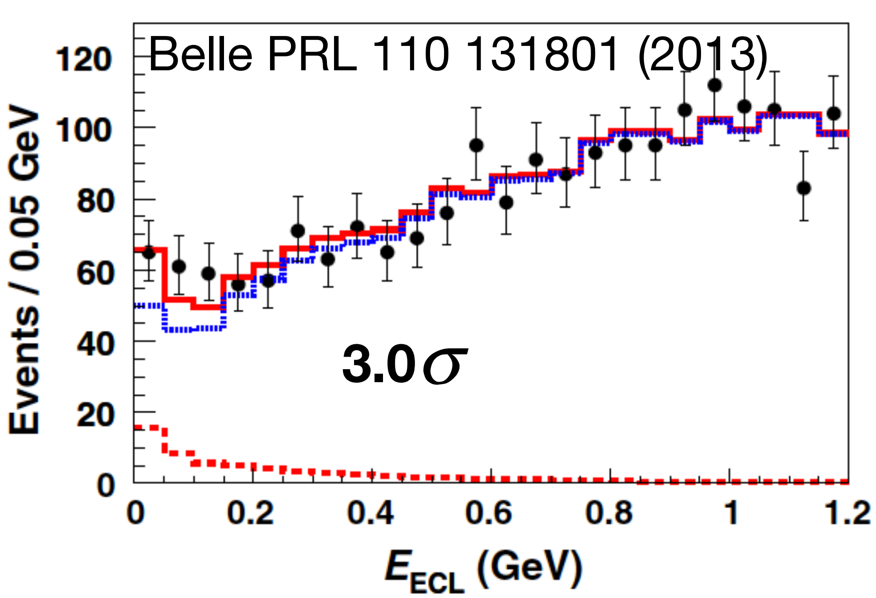
- Branching ratio depends strongly on the mass of the lepton due to helicity suppression. Thus $B^+ \to \tau^+ \nu_\tau$ is expected to have the largest leptonic branching fraction.
- NP could significantly suppress or enhance the branching ratio i.e. via exchange a charged Higgs boson from supersymmetry or from two-Higgs doublet models (2HDM).
- In the absence of NP, this channel provides a direct determination of the *B* decay constant f_B and the CKM matrix $|V_{ub}|$.

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}_{(B\to\tau\nu)} = \mathcal{B}_{SM} \times \left(1 - \tan^2\beta \frac{m_{B\pm}^2}{m_{H\pm}^2}\right)$$

- Hadronic tagging
- dominate backgrounds: $B^- \to D^{(*)0} \ell^- \bar{\nu}_\ell$

$$[0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$



tau decays:

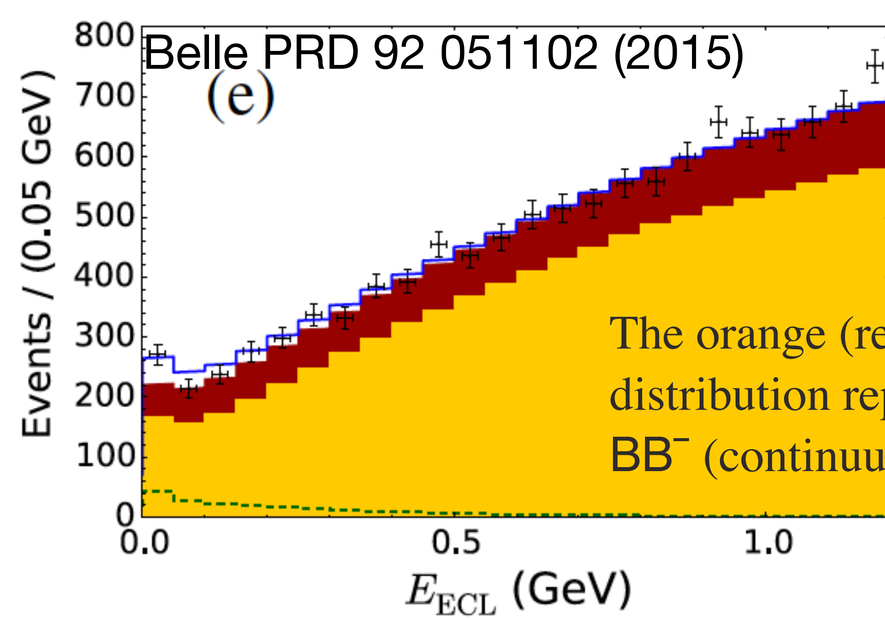
$$\tau^- \to l^- \bar{\nu}_l \nu_\tau$$

$$\tau^- \to \pi^- \nu_\tau$$

$$\tau^- \to \rho^- \nu_\tau$$

- Semi-leptonic tagging (agree with Had. tag and SM)

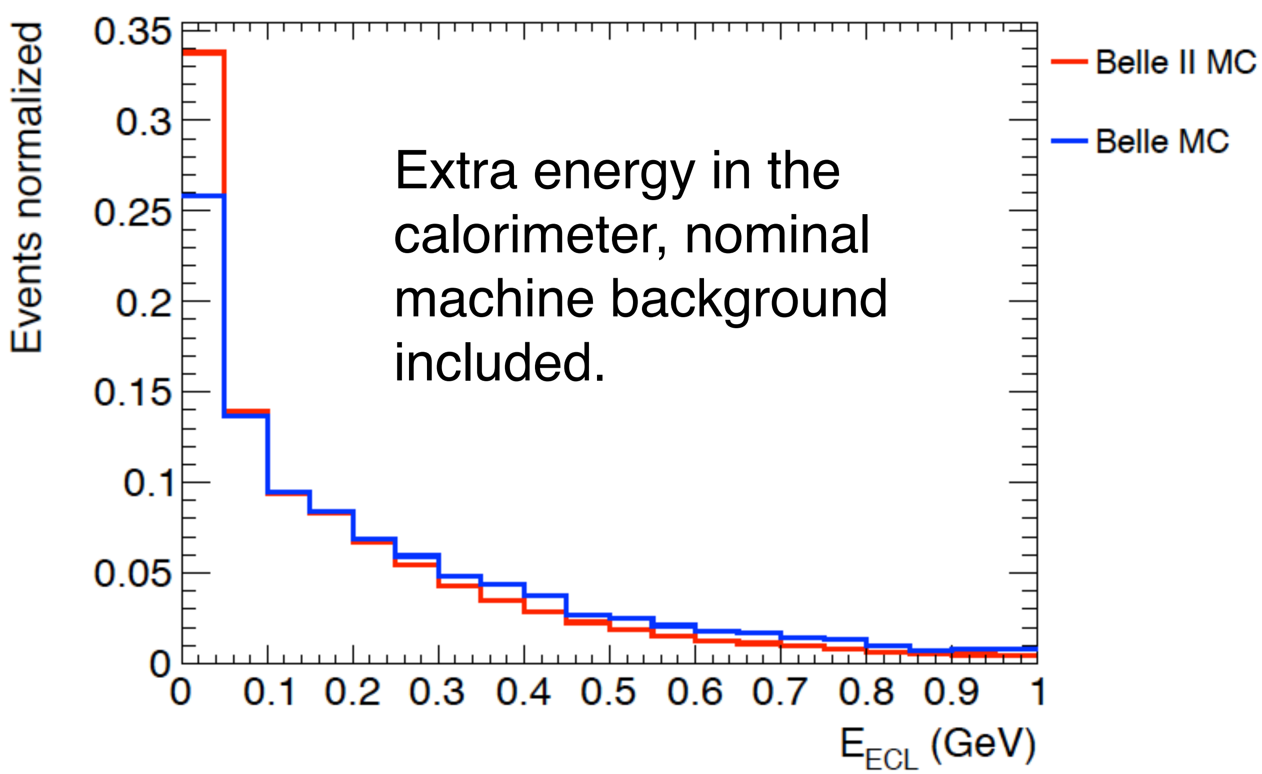
$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = [1.25 \pm 0.28(\text{stat.}) \pm 0.27(\text{syst.})] \times 10^{-4}$$



The orange (red) filled distribution represents the $B\bar{B}$ (continuum) background.

$B^+ \to \tau^+ \nu_\tau$ prospect at Belle II

- **Analysis on Belle II full simulation using hadronic B reconstruction.**
- **Signal yields extracted from fit to extra neutral energy.**
- **The extra energy resolution at Belle II is better than Belle despite the increased beam background.**



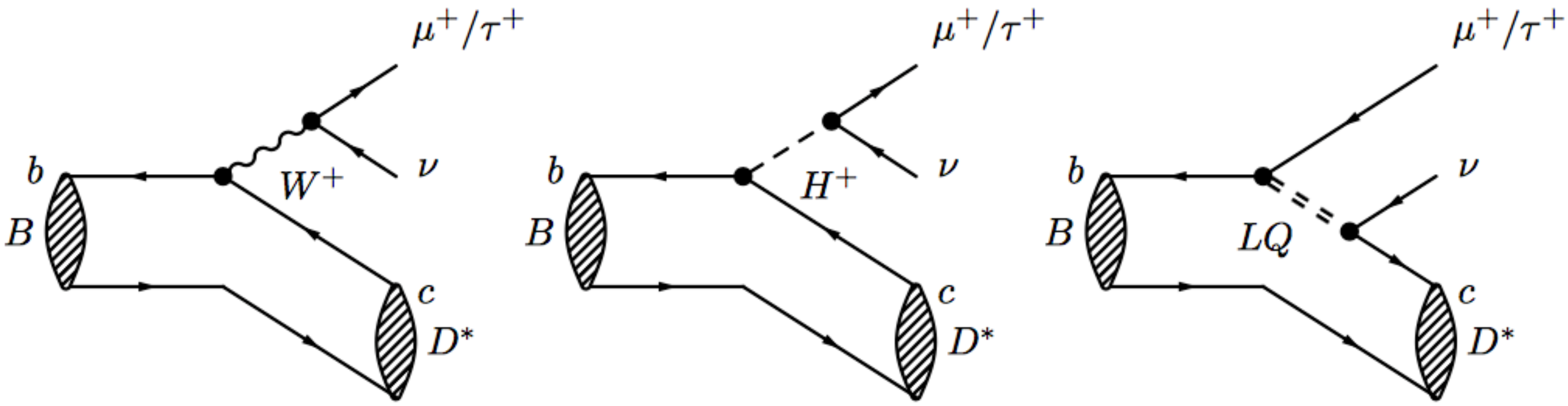
- **Comparison with Belle hadronic tag. 1 ab^{-1} equivalent statistics**

E_{ECL}		< 0.25 GeV
Belle II	# background events	1348
	# signal events	136
	signal efficiency (‰)	1.6
Belle	# background events	365
	# signal events	60
	signal efficiency (‰)	0.7

- **Extrapolation at full Belle II statistics**

	Integrated Luminosity (ab^{-1})	50
hadronic tag	statistical uncertainty (%)	4.1
	systematic uncertainty (%)	4.6
	total uncertainty (%)	6.2
semileptonic tag	statistical uncertainty (%)	2.7
	systematic uncertainty (%)	4.5
	total uncertainty (%)	5.3

Search NP in $B \to D^{(*)}\tau^+\nu_\tau$



- In the Standard Model (SM), the only difference between $B \to D^{(*)}\tau^+\nu_\tau$ and $B \to D^{(*)}\mu^+\nu_\mu$ is the mass of the lepton
- The ratio of them is sensitive to additional amplitudes, i.e. involving an intermediate charged Higgs boson.
- NP: type-II-2HDM (charged Higgs boson appears), Leptoquarks(LQ) model…
- NP could affect this decay topology in two ways:
  - Branching fraction
  - τ polarization

R(D^(*)) in $B \to D^{(*)}\tau^+\nu_\tau$

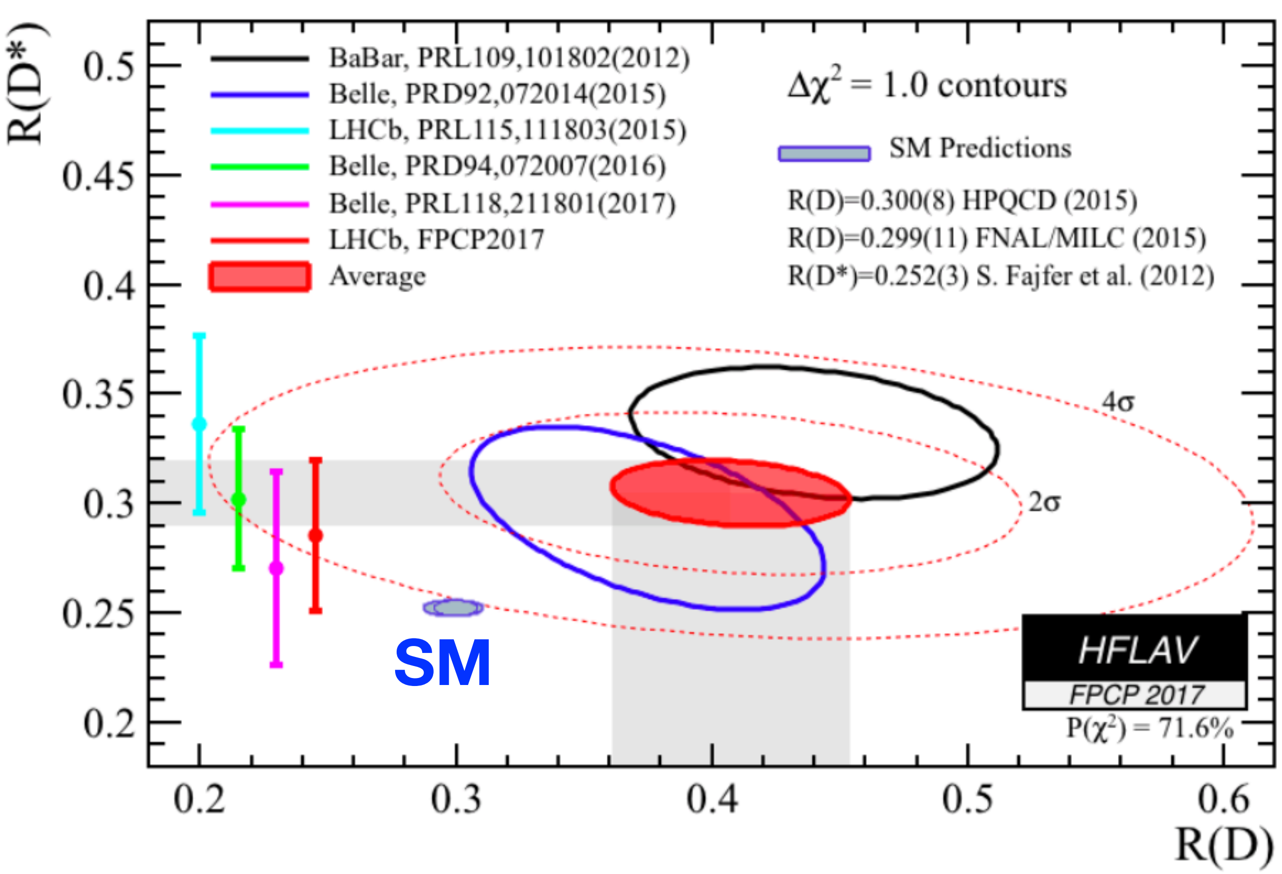
Test for lepton universality using the ratio typically:

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

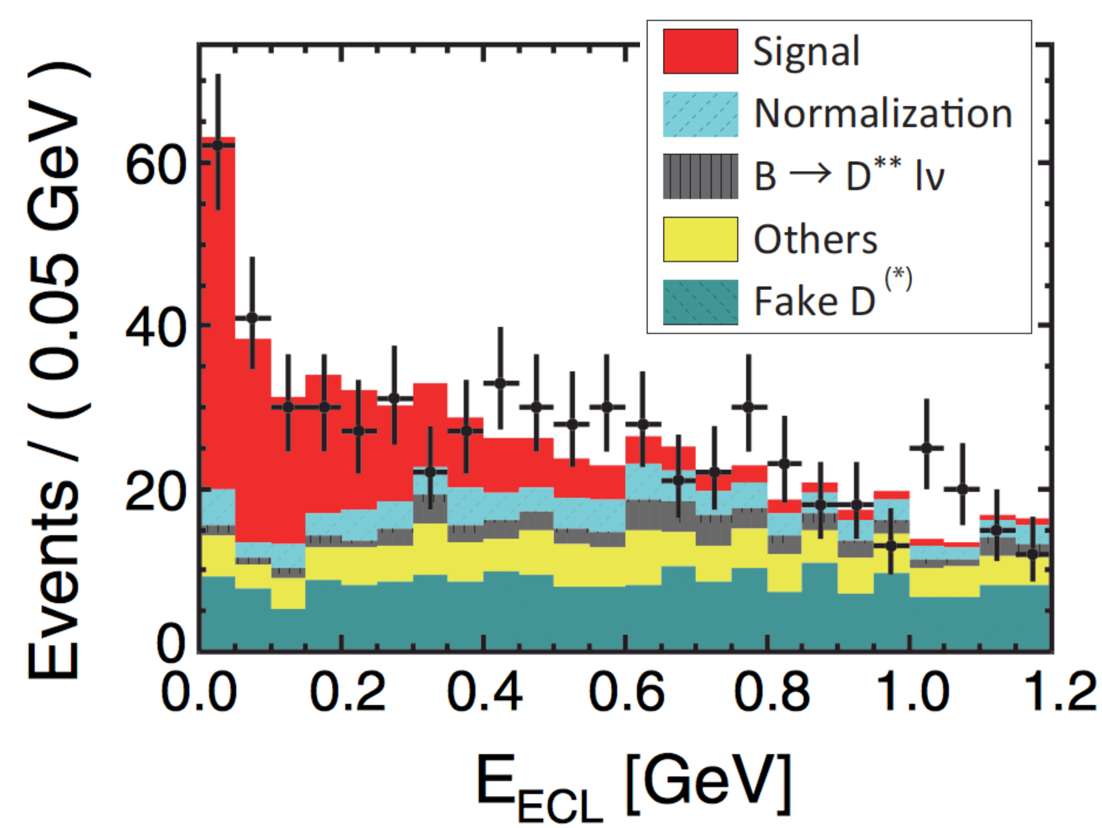
BaBar PRL 109 101802 (2012)
PRD 88 072012 (2013)
Belle PRD 92 072014 (2015)
PRD 94, 072007 (2016)
PRL 118, 211801 (2017)
arxiv1603.06711
LHCb PRL 115 111803 (2015)

SM: R(D) = 0.300 +- 0.008 Phys. Rev. D 92, 034506 (2015)
R(D*) = 0.252 +- 0.003 Phys. Rev. D 85, 094025 (2012)

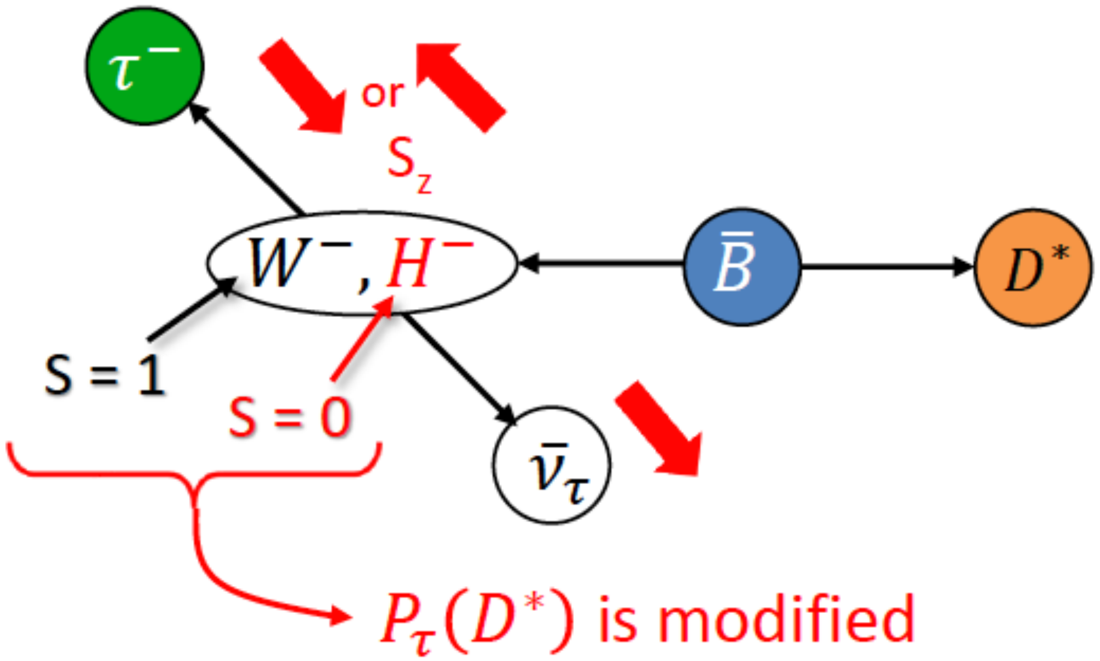
- Current world average for R(D^(*)) is in ~4.1σ tension with SM!



PRD 94 072007 (2016) SL tag



τ Polarization in $B \to D^{(*)}\tau^+\nu_\tau$

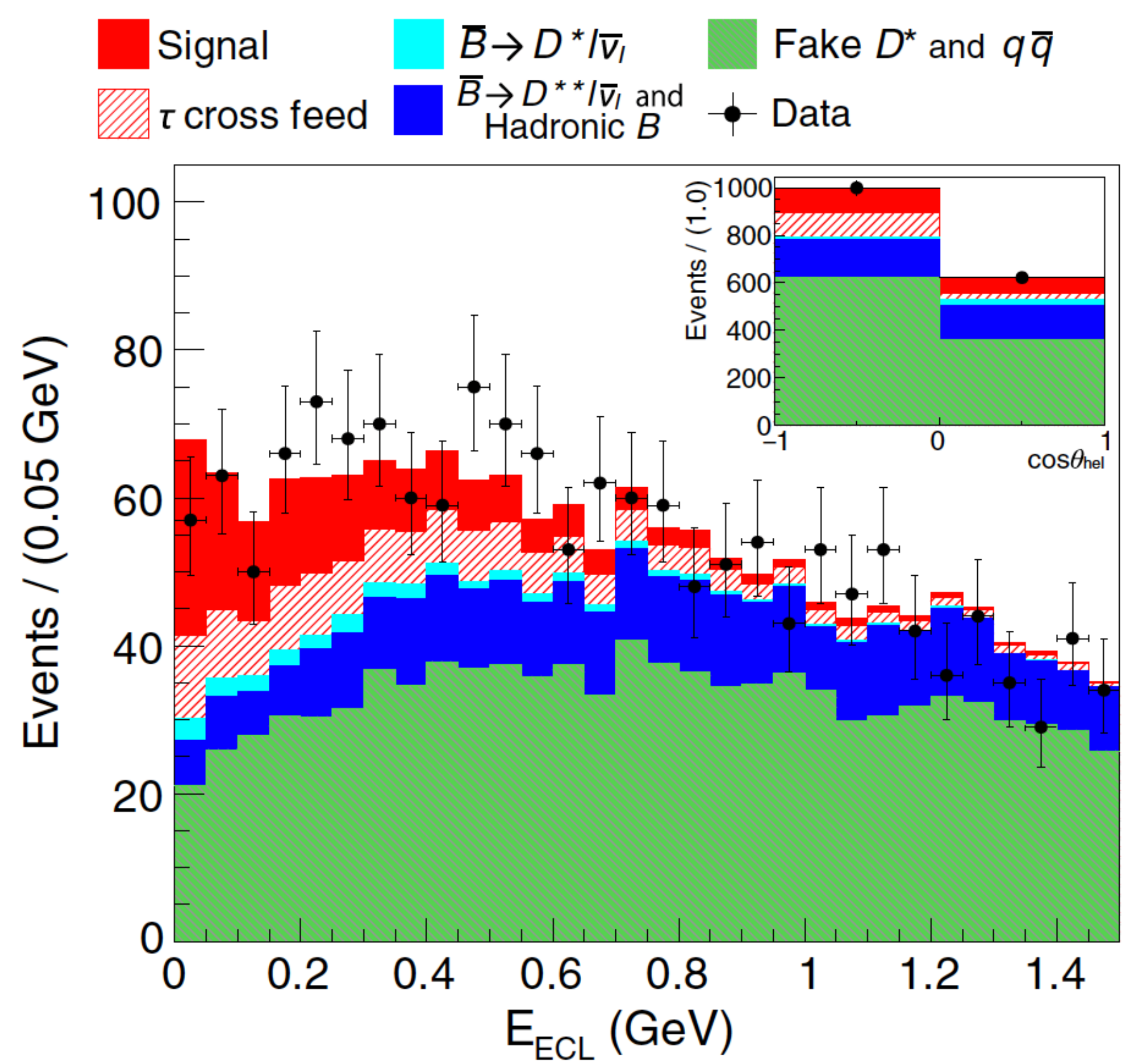


First measurement of the tau polarization in this decay.

First use tau had. decays in $B \to D^{(*)}\tau^+\nu_\tau$

$\tau^- \to \pi^-\nu_\tau$ $\tau^- \to \rho^-\nu_\tau$

Belle PRL 118, 211801 (2017) had. tag



$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

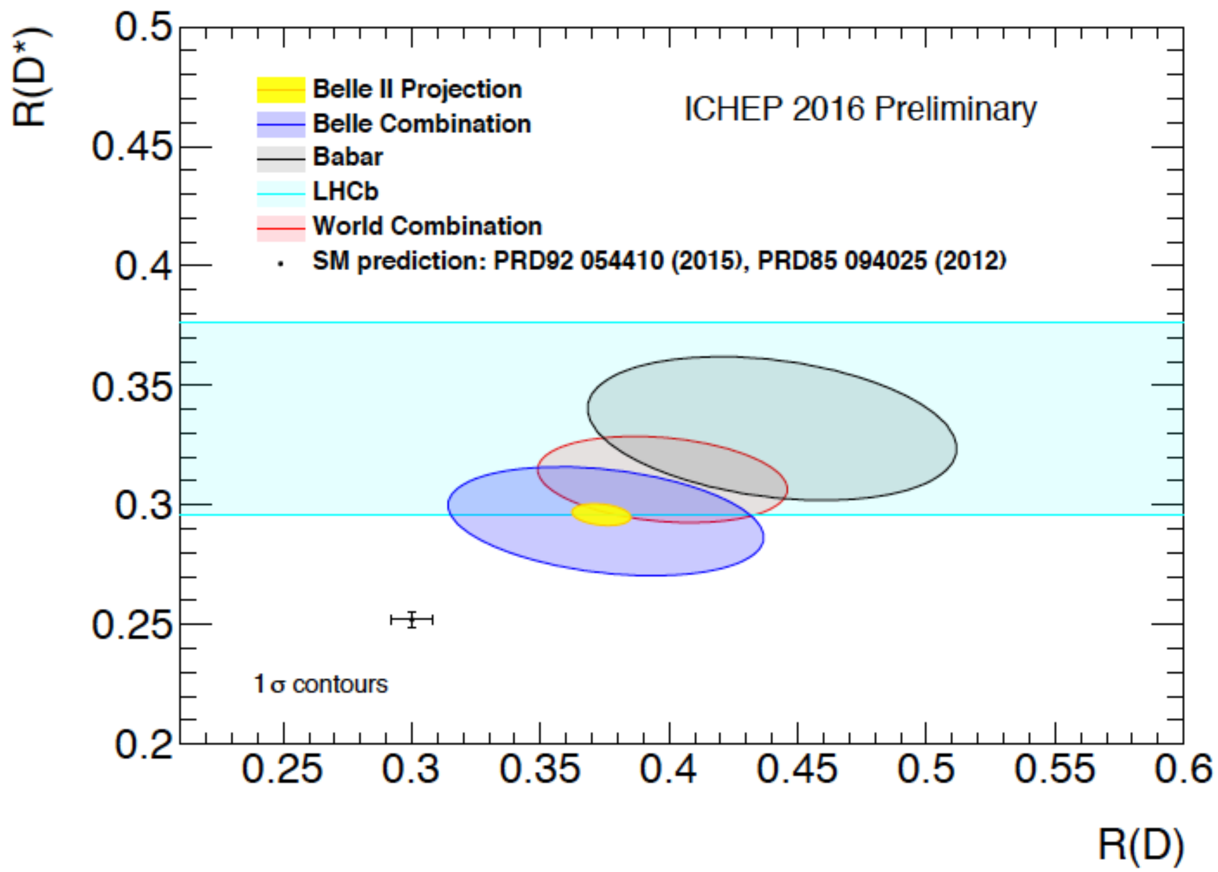
$\Gamma^{+(-)}$ for right-(left-)handed τ

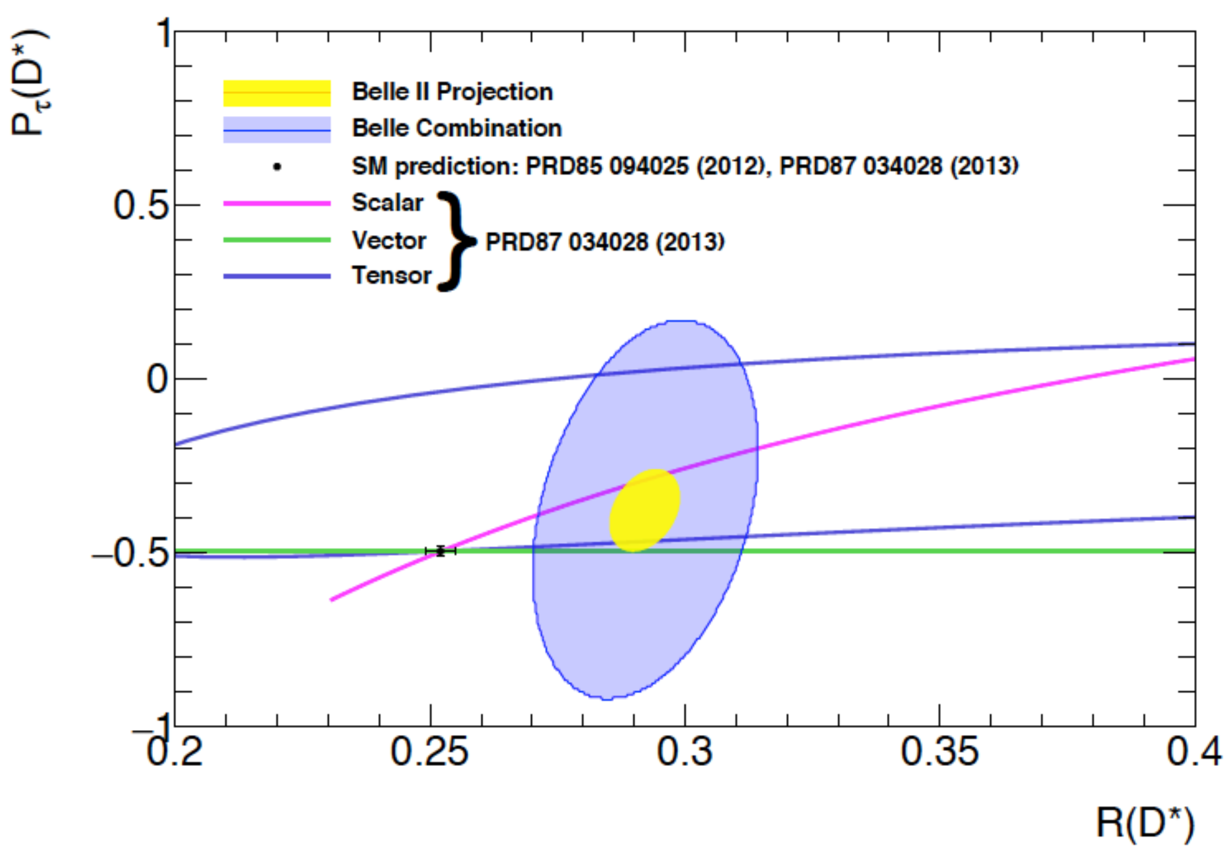
$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}).$$

Compatibility with the SM.

$P_\tau(D^*)_{SM} = -0.497 \pm 0.013$ Phys. Rev. D 87, 034028 (2013)

$B \to D^{(*)}\tau^+\nu_\tau$ prospect at Belle II





- Current measurements are statistically limited, dominant systematics from
  - limited MC -> larger at Belle II
  - limited knowledge of dominant bkg. (involving soft pions) —>dedicated studies with large data sample at Belle II
- With higher statistics, study polarization and q^2 distributions, essential to distinguish NP.

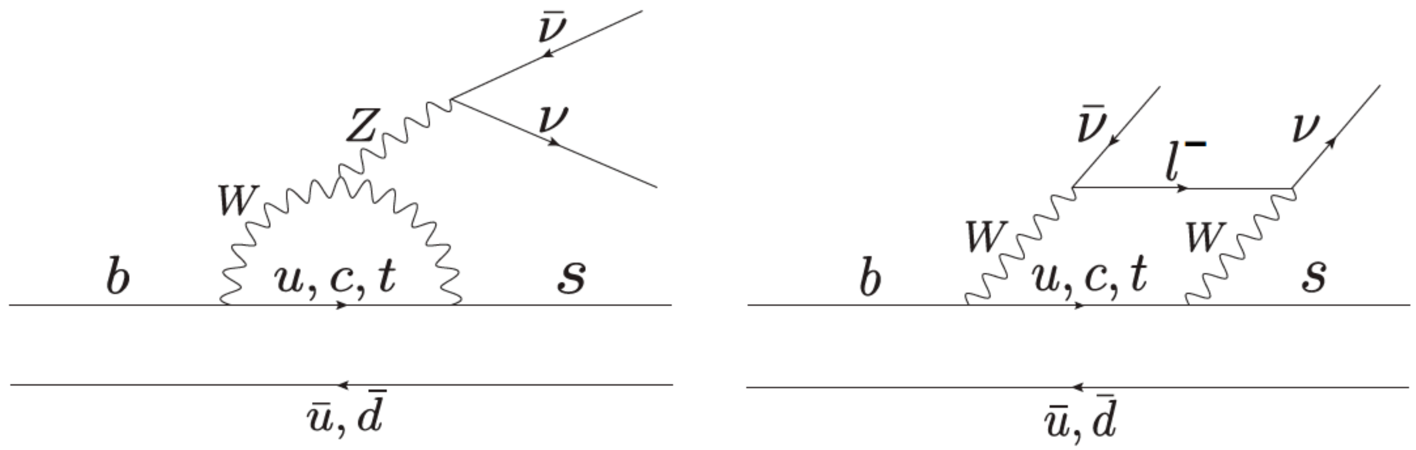
Uncertainties at Belle II

	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
R_D	$(6.0 \pm 3.9)\%$	$(2.0 \pm 2.5)\%$
R_{D^*}	$(3.0 \pm 2.5)\%$	$(1.0 \pm 2.0)\%$
$P_\tau(D^*)$	0.18 ± 0.08	0.06 ± 0.04

the first and the second values are the expected statistical and systematic errors.

FCNC $B \to K^{(*)}\upsilon\upsilon$

BaBar PRD 87, 112005(2013)
Belle PRD 87, 111103(R) (2013)
arxiv: 1702.03224

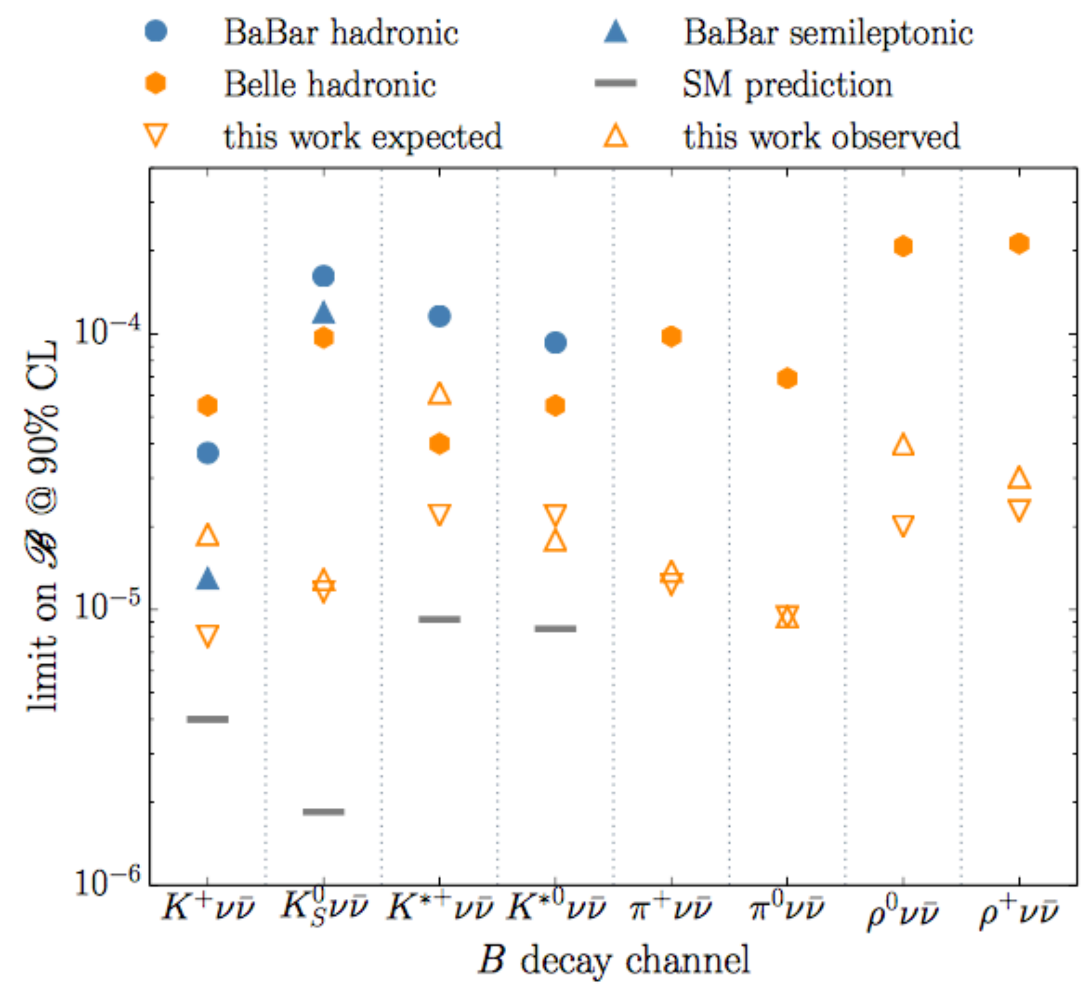


(a) penguin (b) box

- Flavor-changing neutral-current (FCNC) is prohibited in SM at tree-level, can occur via one-loop box or electroweak penguin diagrams.
- Golden mode at BelleII, theoretically very clean (in contrast to b—>sl$^+$l$^-$): free of uncertain long-distance effects ($\rho, J/\varphi, \varphi'$…)
- Highly sensitive to non-standard *Z*-coupling and other electroweak penguin effects.
- SM predictions [1] JHEP 02 184, 2015 [2] Belle2-MEMO-2016-007

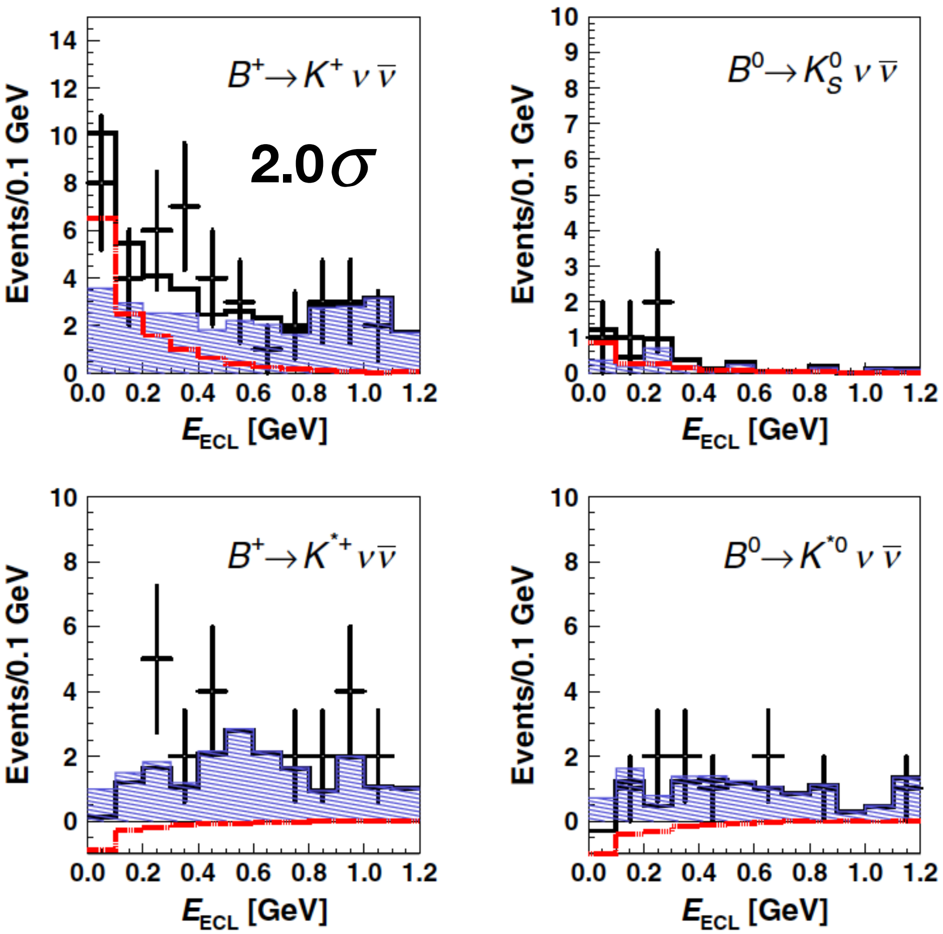
Mode	$\mathcal{B}$ $[10^{-6}]$ Ref. [2]	$\mathcal{B}$ $[10^{-6}]$ Ref. [1]
$B^+ \to K^+\nu\bar{\nu}$	$3.98 \pm 0.43 \pm 0.19$	4.68 ± 0.64
$B^0 \to K^0_S\nu\bar{\nu}$	$1.85 \pm 0.20 \pm 0.09$	2.17 ± 0.30
$B^+ \to K^{*+}\nu\bar{\nu}$	$9.91 \pm 0.93 \pm 0.54$	10.22 ± 1.19
$B^0 \to K^{*0}\nu\bar{\nu}$	$9.19 \pm 0.86 \pm 0.50$	9.48 ± 1.10

arXiv: 1702.03224 (semi-leptonic tagging)

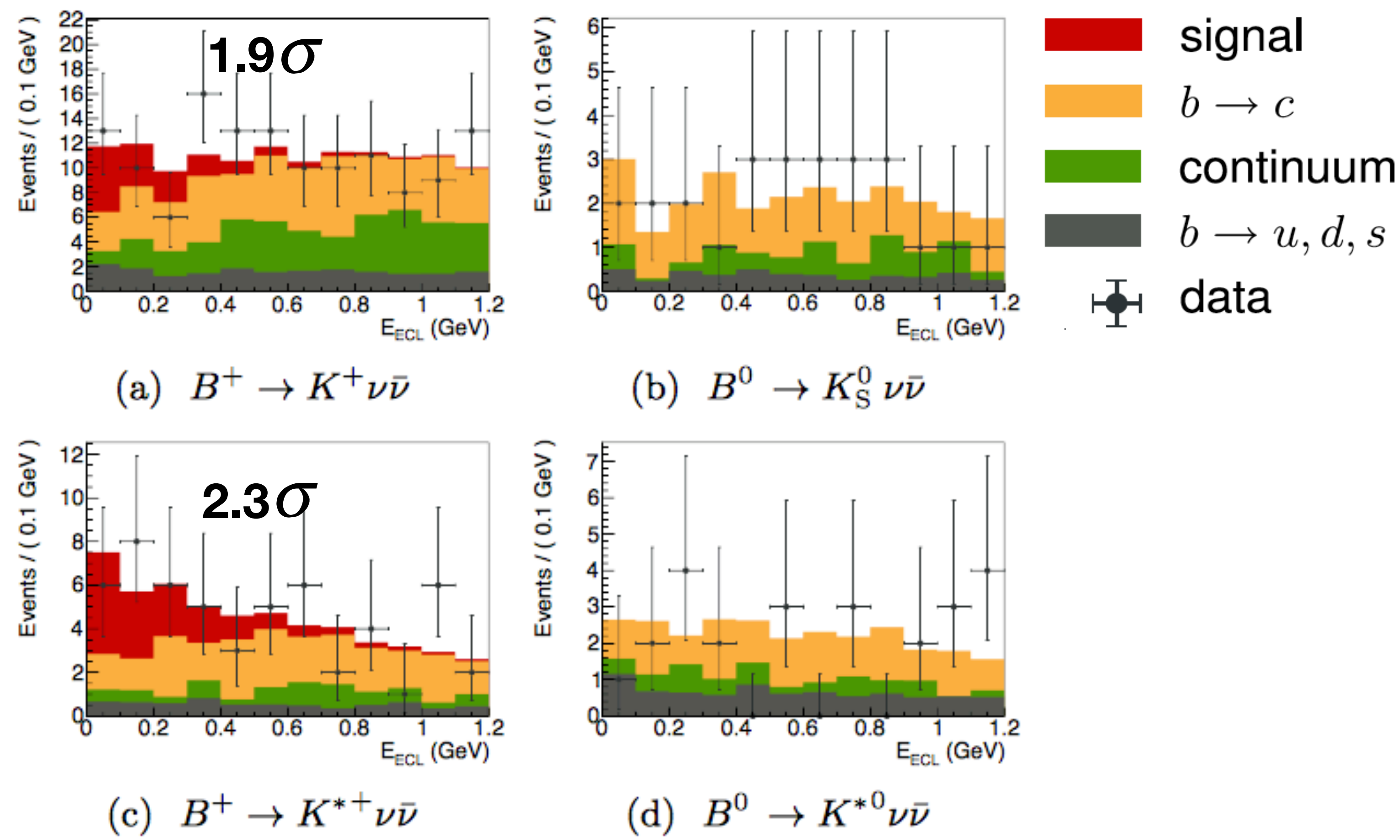


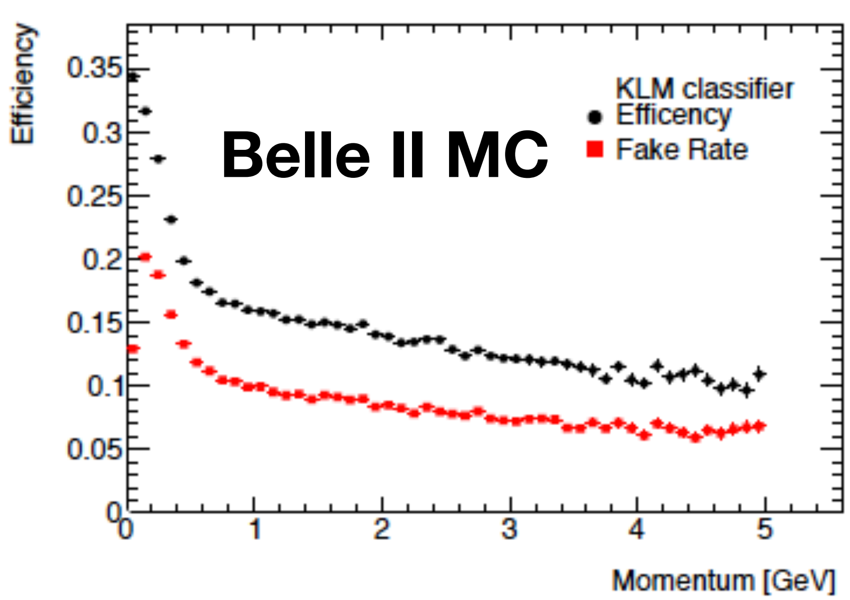
Background in $B \to K^{(*)}\nu\nu$

- Hadronic tagging PRD 87, 111103(R) (2013)



- Semi-leptonic tagging arxiv: 1702.03224





- With missing K_L, background can mimic signal.
- Require good background-rejection algorithm —> veto K_L^0
- Belle II will have better K_L^0 ID, better taking efficiencies, and 30% better K_S^0 efficiency.
- Systematics caused by statistical uncertainty of background model —> Belle II will allow more dedicated studies.

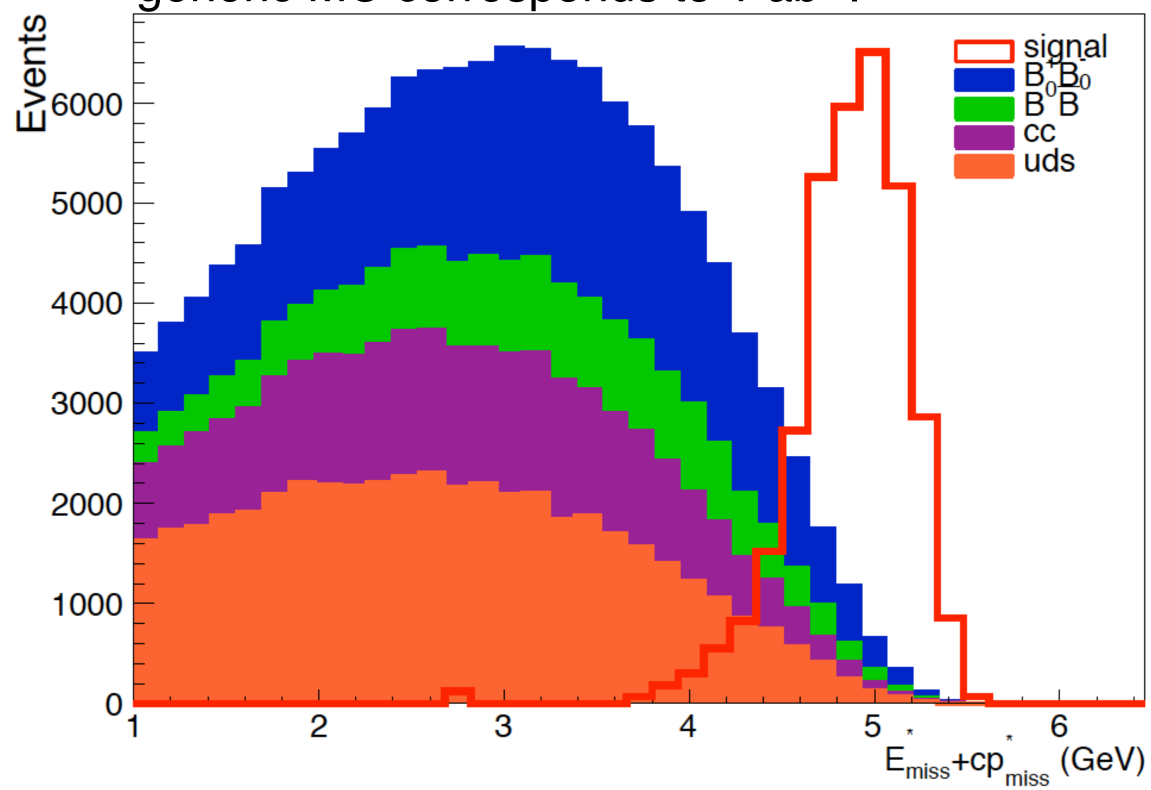
$B \to K^{(*)}\upsilon\upsilon$ sensitivity at Belle II

$B \to K^{+}\upsilon\upsilon \quad B \to K^{*}\upsilon\upsilon$

will be observed with about 18 ab^{-1}

- **With 50 ab^{-1}, the sensitivities of BF will be 12% and 11%.**
- **Once the K* modes are observed, measurements of differential BF and K* polarization will be important subjects.**

signal normalization is arbitrary.
generic MC corresponds to 1 ab^{-1}.



Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\rm Backg.}$ 711 fb^{-1} Belle	$N_{\rm Sig-exp.}$ 711 fb^{-1} Belle	$N_{\rm Backg.}$ 50 ab^{-1} Belle II	$N_{\rm Sig-exp.}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	4.68	5.68	21	3.5	2960	245	20%	22%
$B^0 \to K^0_S\nu\bar{\nu}$	2.17	0.84	4	0.24	560	22	94%	94%
$B^+ \to K^{*+}\nu\bar{\nu}$	10.22	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.48	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

Summary

- e^+e^- collider is the ideal place for studies on decays with large missing energy.

- Belle II will have the capability to perform studies of B meson decays with large missing energy in the final state (N_ν>1) with unprecedented precision.

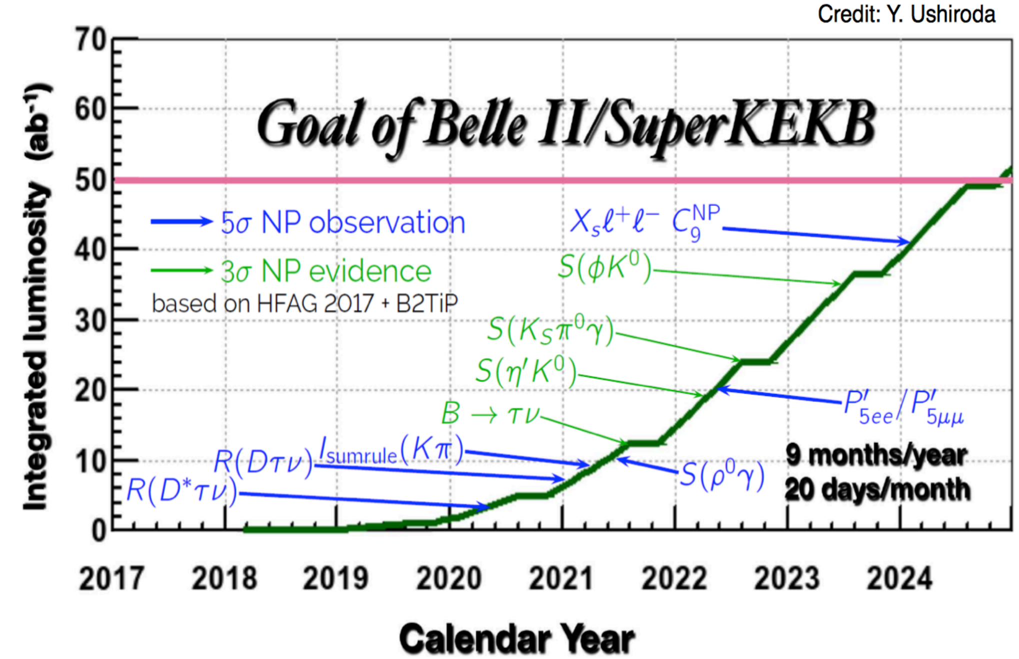
$$B^+ \to l^+\nu_l \qquad B \to D^{(*)}\tau^+\nu_\tau \qquad B \to h\upsilon\bar{\upsilon}$$

- Previously observed anomalies (such those observed in $B \to D^{(*)}\tau^+\nu_\tau$) can be resolved with few ab^{-1} of data, while very rare decays $B \to h\upsilon\bar{\upsilon}$ can be probed at 5 σ level with the full belle II data ($50ab^{-1}$).

- Belle II will have strong impact in the searches for new physics for the next decade.

- Belle II Physics Running: late 2018/ early 2019 (full detector). ⟶ Jake Bennett's talk

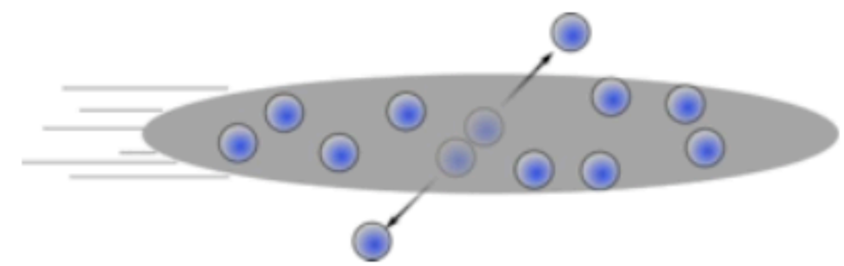
Credit: Y. Ushiroda



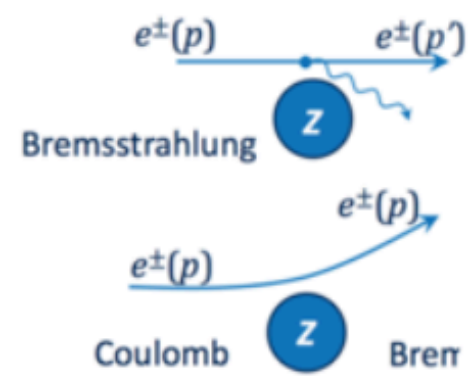
Extra

Belle II Beam Background

- **Touschek effect**
  - Intra bunch scattering
  - Rate ∝ the inverse beam size, number of bunches et.al
  - Suppressed with movable collimators

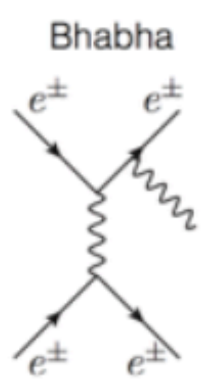


- **Beam gas**
  - Coulomb and bremsstrahlung scattering by the residual gas atoms
  - Rate ∝ the vacuum level and the beam current



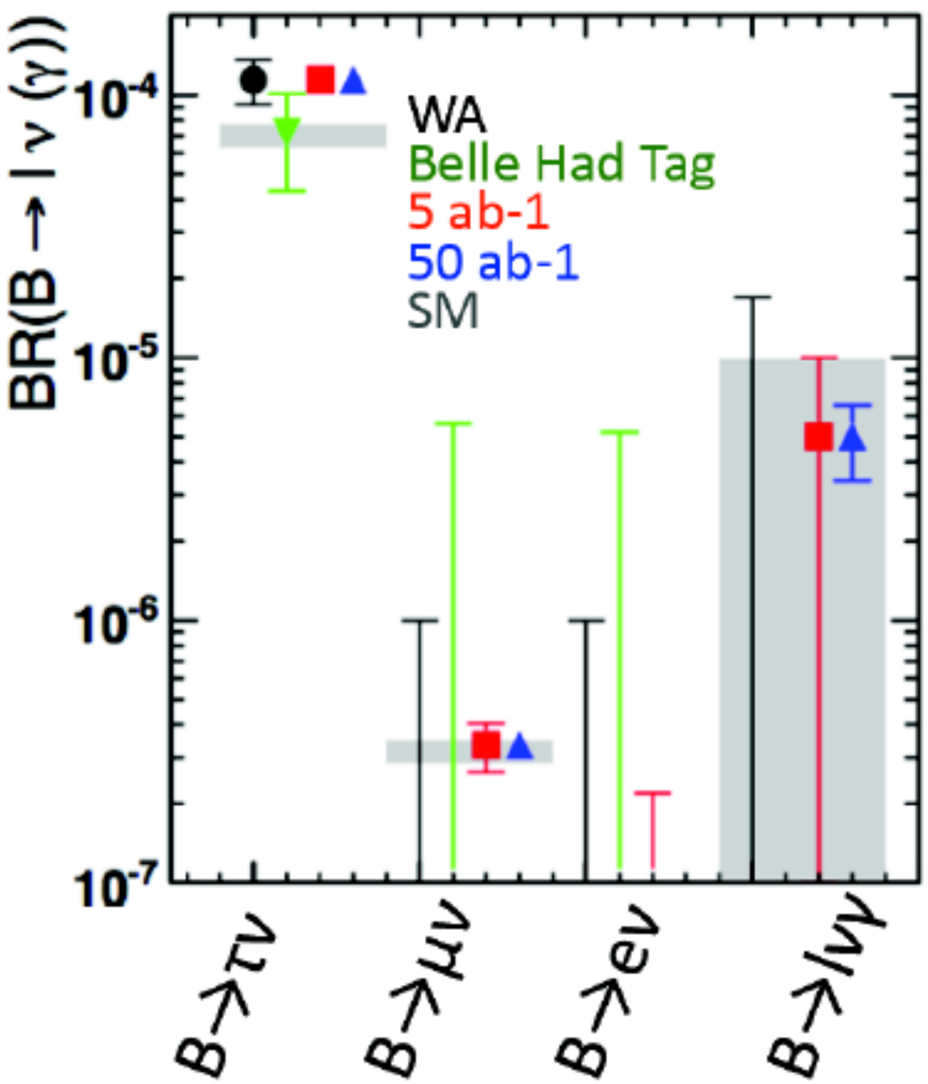
- **Synchrotron radiation**
  - Rate ∝ the beam energy squared and magnetic field squared

- **Physical backgrounds**
  - Bhabha ee→(γ)ee
  - Two photon: ee→eeee
  - Rate ∝ luminosity



Dominant when luminosity is high

$B^+ \to l^+ \nu_l$ prospect at Belle II



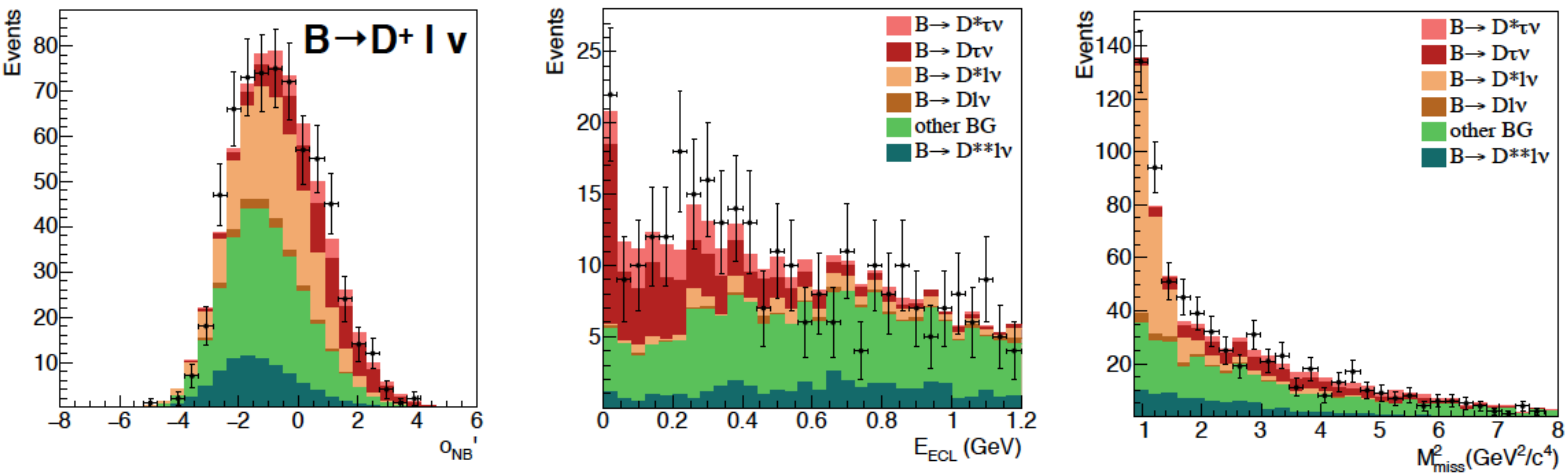
Belle II expected precision:

- $B \to \tau\nu$: 5 %
- $B \to \mu\nu$, $e\nu$, $l\nu\gamma$: 10 %

Expected errors with the Belle full data sample, and 5 ab^{-1} and 50 ab^{-1} of Belle II data.

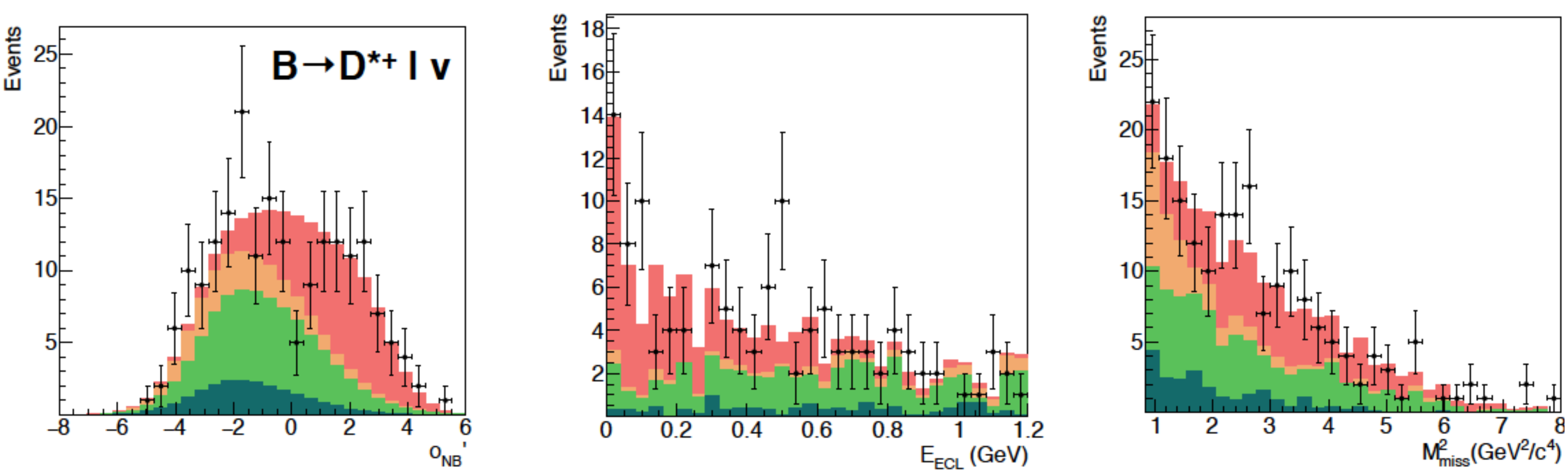
	Statistical	Systematic (reducible, irreducible)	Total Exp
$\mathcal{B}(B \to \tau\nu)$ (had. tagged)			
711 fb^{-1}	38.0	(14.2, 4.4)	40.8
5 ab^{-1}	14.4	(5.4, 4.4)	15.8
50 ab^{-1}	4.6	(1.6, 4.4)	6.4
$\mathcal{B}(B \to \tau\nu)$ (semileptonic tagged)			
711 fb^{-1}	24.8	$(18, {}^{+6.0}_{-9.6})$	${}^{+31.2}_{-32.2}$
5 ab^{-1}	8.6	$(6.2, {}^{+6.0}_{-9.6})$	${}^{+12.2}_{-14.4}$
50 ab^{-1}	2.8	$(2.0, {}^{+6.0}_{-9.6})$	${}^{+6.8}_{-10.2}$
$\mathcal{B}(B \to \mu\nu)$ (had. tagged)			
711 fb^{-1}	–	(16.2, 2.4)	$< 5.6 \times 10^{-6}$
5 ab^{-1}	–	(6.1, 2.4)	$< 8.0 \times 10^{-7}$
50 ab^{-1}	37	(1.9, 2.4)	37 (2.7σ)
$\mathcal{B}(B \to \mu\nu)$ (untagged)			
253 fb^{-1}	–	(16.4, 3.0)	$< 1.7 \times 10^{-6}$
5 ab^{-1}	–	(6.2, 3.0)	5σ
50 ab^{-1}		(2.0, 3.0)	$\gg 5\sigma$
$\mathcal{B}(B \to e\nu)$ (had. tagged)			
711 fb^{-1}		(15.8, 2.2)	$< 5.2 \times 10^{-6}$
5 ab^{-1}		(2.7, 2.2)	$< 7.4 \times 10^{-7}$
50 ab^{-1}		(0.8, 2.2)	$< 7.4 \times 10^{-8}$
$\mathcal{B}(B \to e\nu)$ (untagged)			
253 fb^{-1}		(15.8, 3.0)	$< 9.8 \times 10^{-7}$
5 ab^{-1}		(4.0, 3.0)	$< 2.2 \times 10^{-7}$
50 ab^{-1}		(1.1, 3.0)	$< 7.0 \times 10^{-8}$

Backgrounds in $B \rightarrow D^{(*)}\tau^{+}\nu_{\tau}$



$M^2{}_{miss}$> 0.85 GeV

$M^2{}_{miss}$> 2 GeV



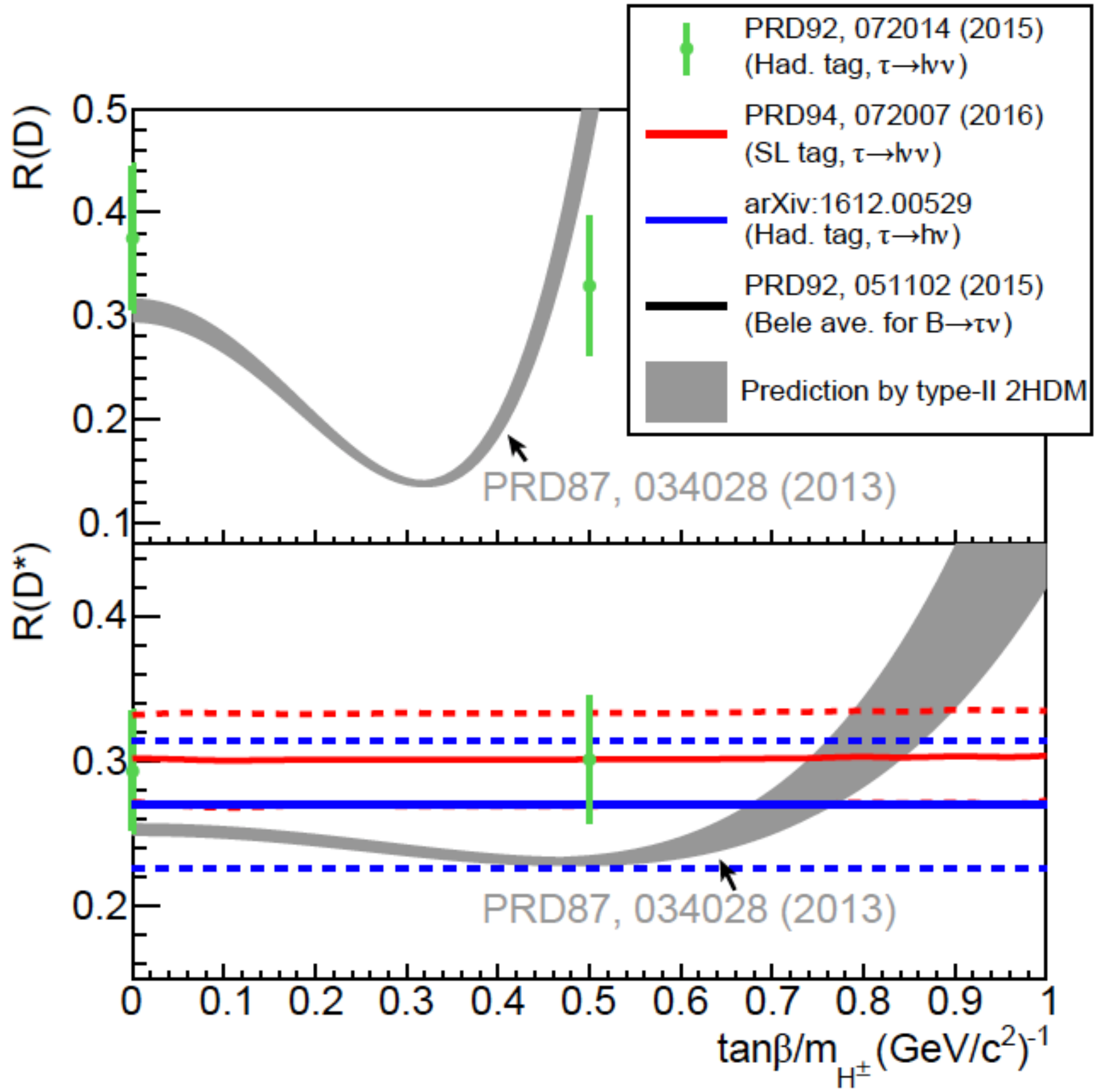
$B \to D^{(*)}\tau^+\nu_\tau$ Test type-II-2HDM

- Contribution from Type-II 2HDM

Ratio of VEV in two Higgs doublets

$$\mathcal{L}_{\rm eff} = -2\sqrt{2}G_F V_{ib}\left[O_{\rm SM} - m_b m_\tau \frac{\tan^2\beta}{m^2_{H^\pm}} O_S\right]\begin{cases} i = c \text{ for } \bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau \\ i = u \text{ for } B^- \to \tau^-\bar{\nu}_\tau \end{cases}$$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)
W.-S. Hou, Phys. Rev. D 48, 2342 (1993)

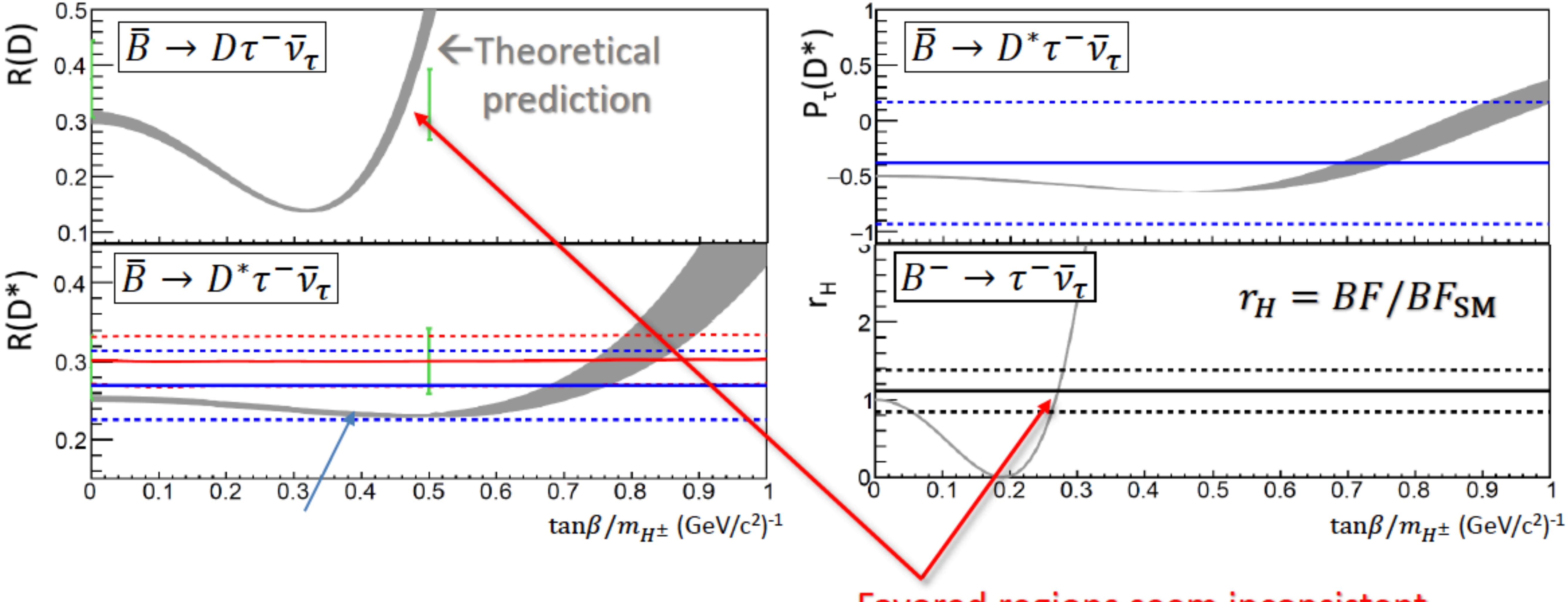


- All the results are consistent with, but always larger than the SM
- Large value of $\tan\beta/m_{H\pm}$ seems disfavored

Charged Higgs in Type-II 2HDM (2)

Results from Belle:
- $+$ $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with had. tag and $\tau^- \to l^-\bar{\nu}_l\nu_\tau$: **PRD 88, 072014 (2015)**
- $-$ $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with semilep. tag: **PRD 94, 072007 (2016)**
- $-$ $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with had. tag and $\tau^- \to h^-\nu_\tau$: **PRL 118, 211801 (2017)**
- $-$ $B^- \to \tau^-\bar{\nu}_\tau$ with had. tag + semilep. tag: **PRL 110, 131801 (2013), PRD 92, 051102(R) (2015)**

Efficiency is assumed to be uniform for tanβ/m_H

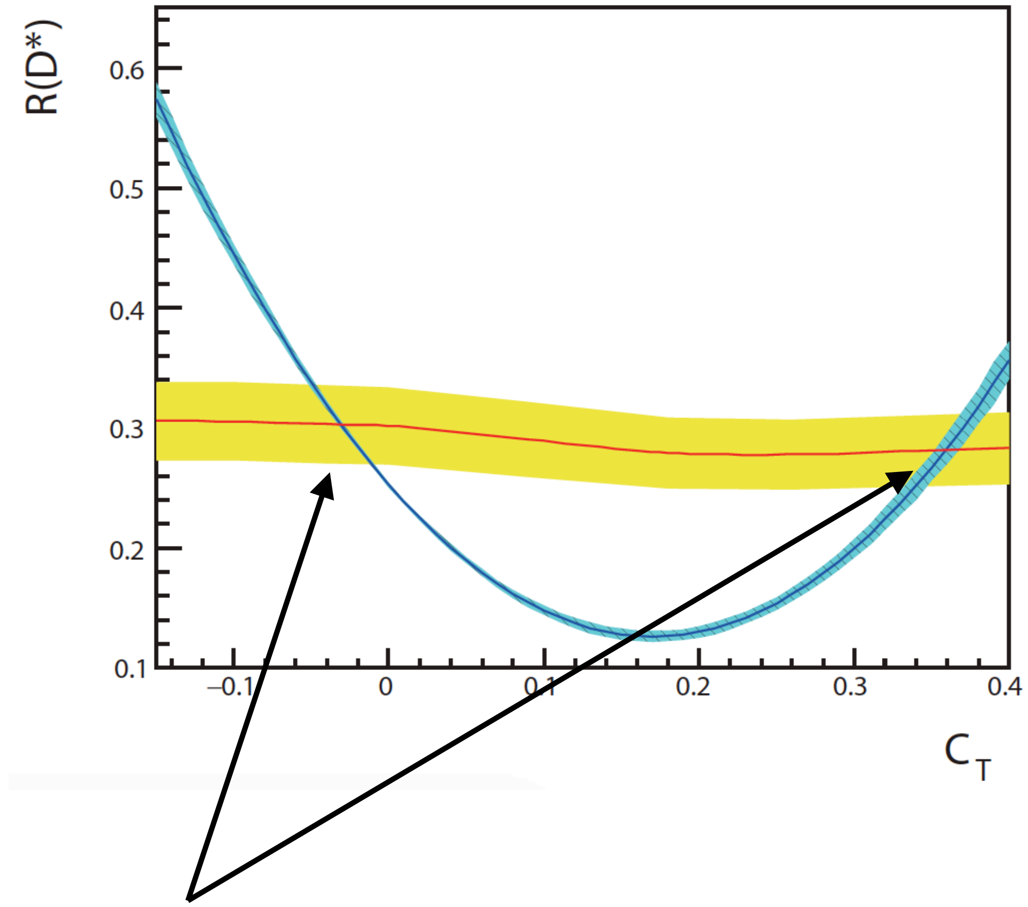


- All the results are consistent with, but always larger than the SM
- Large value of $\tan\beta/m_{H^\pm}$ seems disfavored

$B \to D^{(*)}\tau^+\nu_\tau$ Test R2-type LQ

- Leptoquarks(LQ) which couple to lepton-quark pair, carrying color, electric charge, baryon and lepton number. Unified description of leptons and quark.
- 6 LQ models in $b \to c\tau\upsilon$
- $B \to D^{(*)}\tau^+\nu_\tau$ is sensitive to the tensor operator
- R_2-type LQ model is good candidate for compatibility test.

arxiv1603.06711 belle pub#496

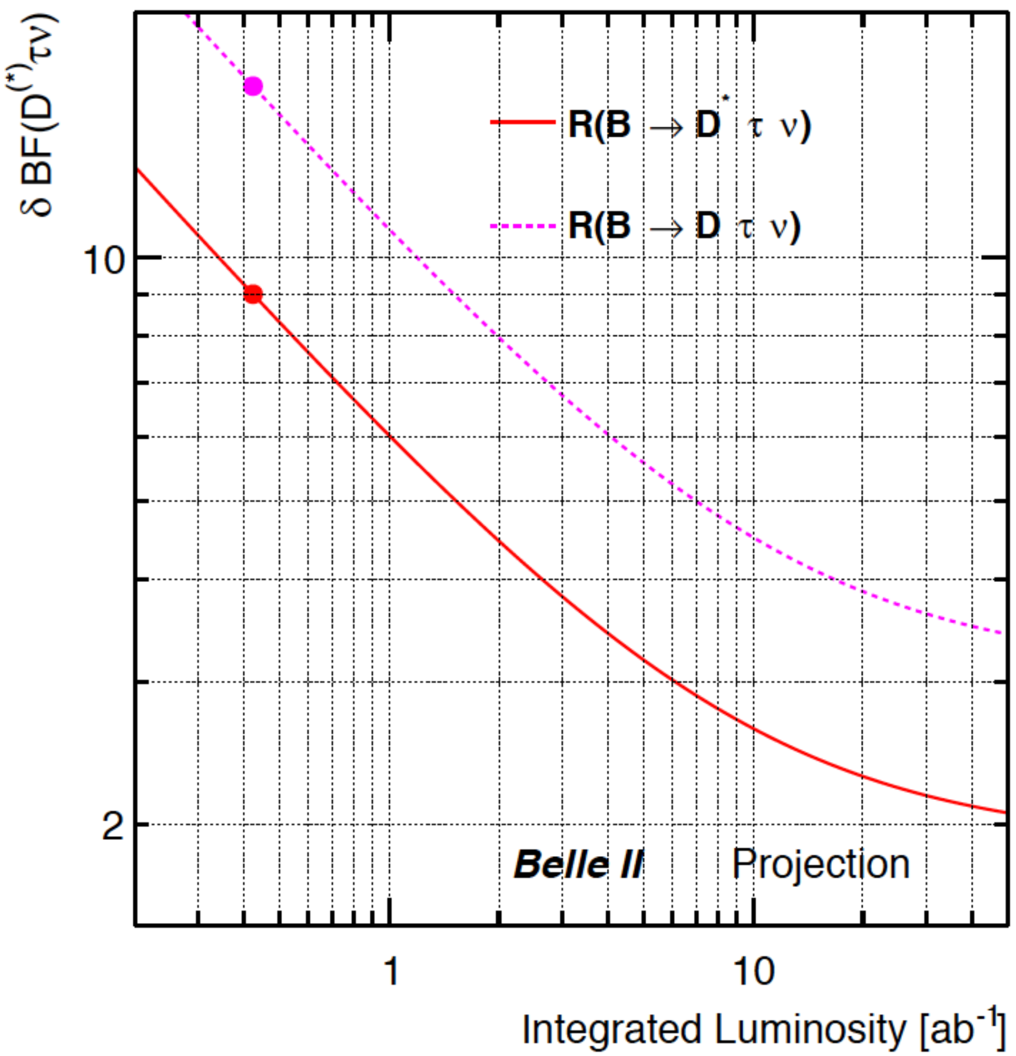


favored parameter points C_T=-0.030 and +0.360

Assignment of quantum numbers

	S_1	S_3	R_2	V_2	U_1	U_3
spin	0	0	0	1	1	1
$F = 3B + L$	-2	-2	0	-2	0	0
$SU(3)_C$	3^*	3^*	3	3^*	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	1/3	1/3	7/6	5/6	2/3	2/3
Operators	$(\mathcal{O}_{V_1}, \mathcal{O}_{S_2}, \mathcal{O}_T)$	$\mathcal{O}_{V_1}$	$(\mathcal{O}_{S_2}, \mathcal{O}_T)$	$\mathcal{O}_{S_1}$	$(\mathcal{O}_{V_1}, \mathcal{O}_{S_1})$	$\mathcal{O}_{U_3}$

$B \to D^{(*)}\tau^+\nu_\tau$ prospect at Belle II



Extrapolation of the Babar result. Errors are given in percent.

	Statistical	Systematic (reducible, irreducible)	Total Exp
$R(D)$			
423 fb^{-1}	13.1	(9.1, 3.1)	16.2
5 ab^{-1}	3.8	(2.6, 3.1)	5.6
50 ab^{-1}	1.2	(0.8, 3.1)	3.4
$R(D^*)$			
423 fb^{-1}	7.1	(5.2, 1.9)	9.0
5 ab^{-1}	2.1	(1.5, 1.9)	3.2
50 ab^{-1}	0.7	(0.5, 1.9)	2.1

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

- SL background modelling will dominate error @ 50 ab^{-1}.

- <u>Important to investigate with improved precision at Belle II</u>
  - Not only $R(D^{(*)})$ but also kinematics such as polarizations and q^2

$B \to h\upsilon\bar{\upsilon}$ sensitivity at Belle II

	Limit or total error
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (4.4 \pm 1.5) \times 10^{-6}$	
$0.711\ \mathrm{ab}^{-1}$	$< 5.5 \times 10^{-5}$
$5\ \mathrm{ab}^{-1}$	$< 2.1 \times 10^{-5}$
$50\ \mathrm{ab}^{-1}$	$< 0.7 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^0_S\nu\bar{\nu}) = (2.2 \pm 0.8) \times 10^{-6}$	
$0.711\ \mathrm{ab}^{-1}$	$< 9.7 \times 10^{-5}$
$5\ \mathrm{ab}^{-1}$	$< 3.7 \times 10^{-5}$
$50\ \mathrm{ab}^{-1}$	$< 1.2 \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) = (6.8 \pm 2.0) \times 10^{-6}$	
$0.711\ \mathrm{ab}^{-1}$	$< 5.5 \times 10^{-5}$
$5\ \mathrm{ab}^{-1}$	$< 2.1 \times 10^{-5}$
$50\ \mathrm{ab}^{-1}$	$< 0.7 \times 10^{-5}$
$\mathcal{B}(B^0 \to \pi^+\nu\bar{\nu}) \sim 1 \times 10^{-8}$	
$0.711\ \mathrm{ab}^{-1}$	$< 9.8 \times 10^{-5}$
$5\ \mathrm{ab}^{-1}$	$< 3.7 \times 10^{-5}$
$50\ \mathrm{ab}^{-1}$	$< 1.2 \times 10^{-5}$
$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu}) \sim 0.5 \times 10^{-8}$	
$0.711\ \mathrm{ab}^{-1}$	$< 6.9 \times 10^{-5}$
$5\ \mathrm{ab}^{-1}$	$< 2.6 \times 10^{-5}$
$50\ \mathrm{ab}^{-1}$	$< 0.8 \times 10^{-5}$