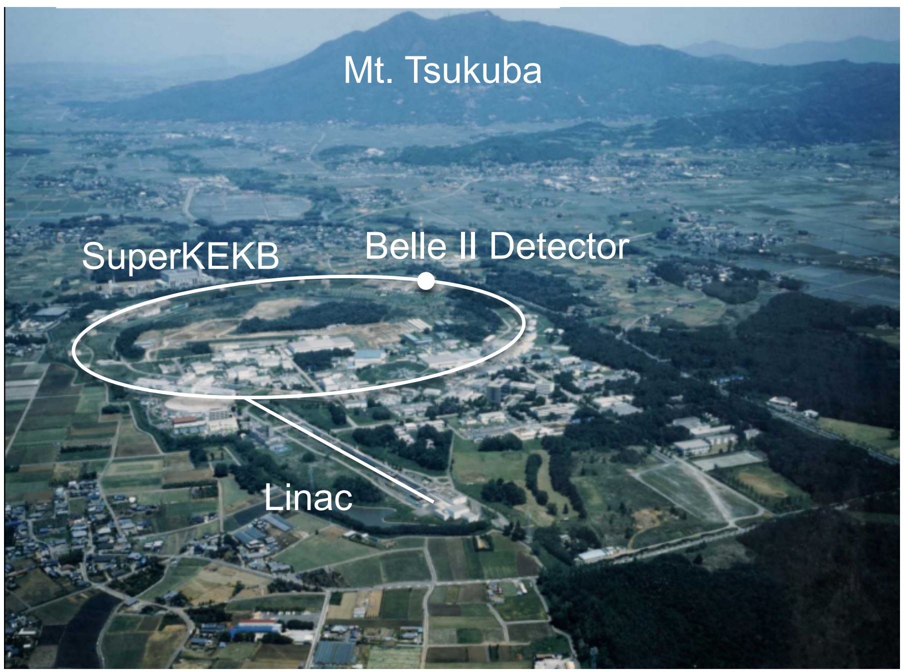
LFV, lepton universality, and rare decay searches at e^+e^- colliders

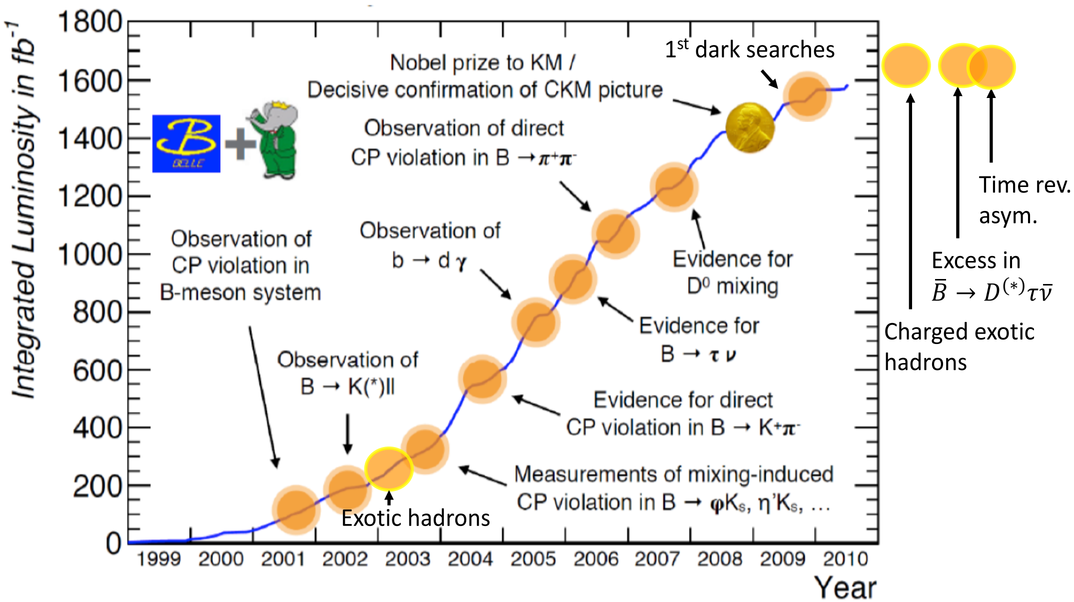
Mario Merola (Università di Napoli Federico II and INFN)

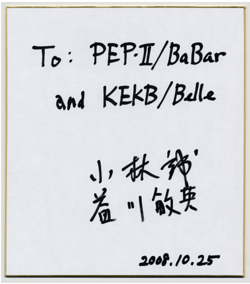
On behalf of the Belle II Collaboration

BLV2019, 21-24 October 2019, Madrid



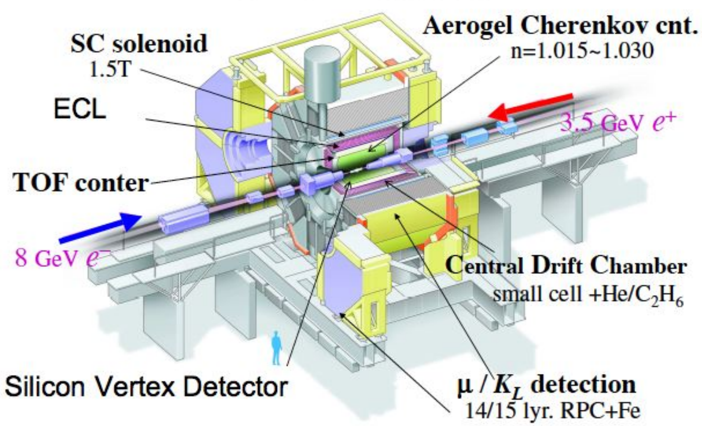
Babar and Belle achievements



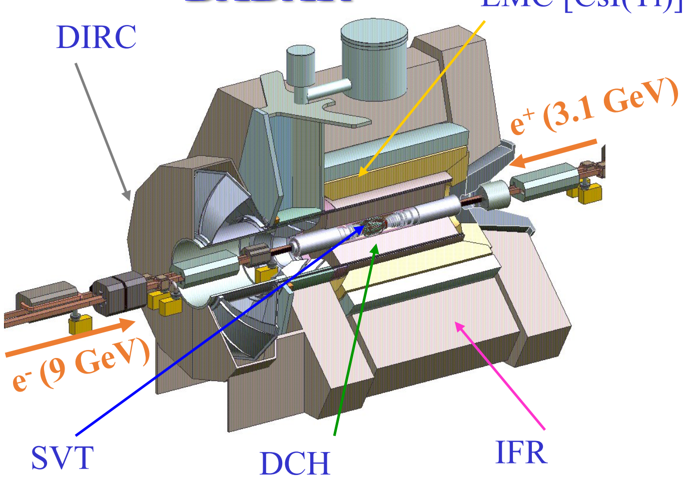


Kobayashi, Maskawa nobel prize in 2008

Belle Detector

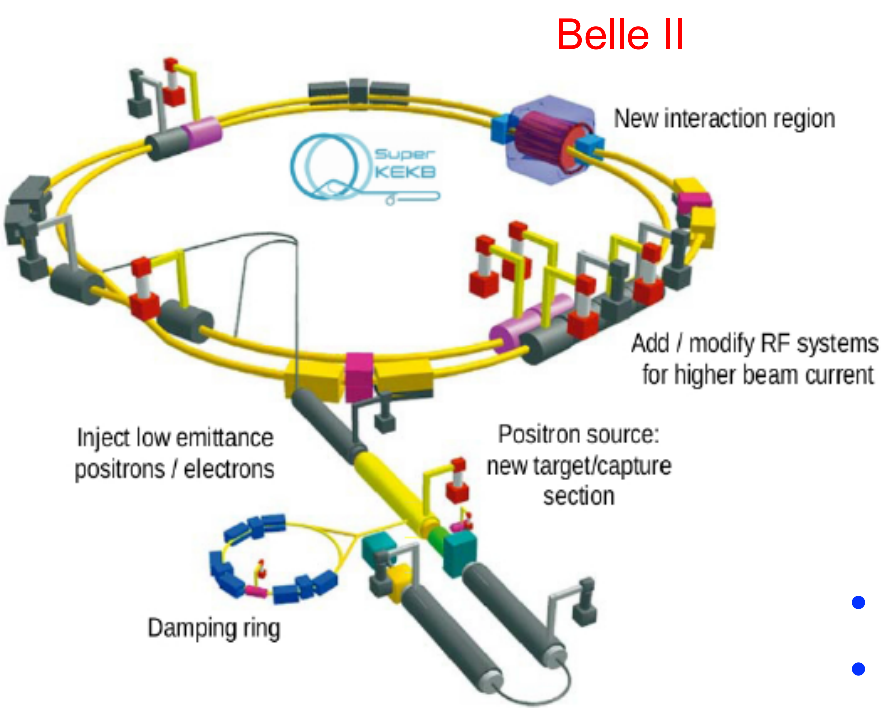


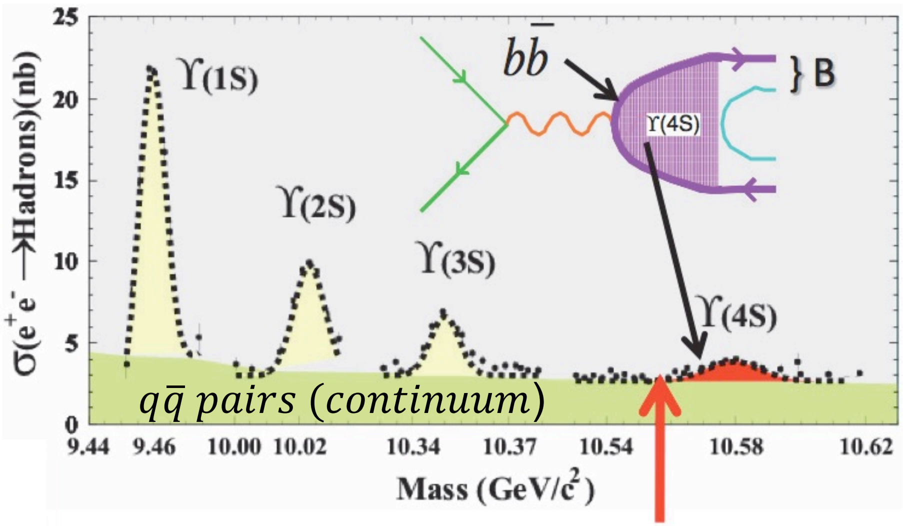
BABAR



SuperKEKB

- **Electron-positron collider** situated at KEK (Tsukuba, Japan), upgrade of KEKB
- **e^+e^-** (4 GeV + 7 GeV) → **$B\bar{B}$** mainly at $\sqrt{s_{cm}}$=10.58 GeV (peak of Υ(4S) resonance)

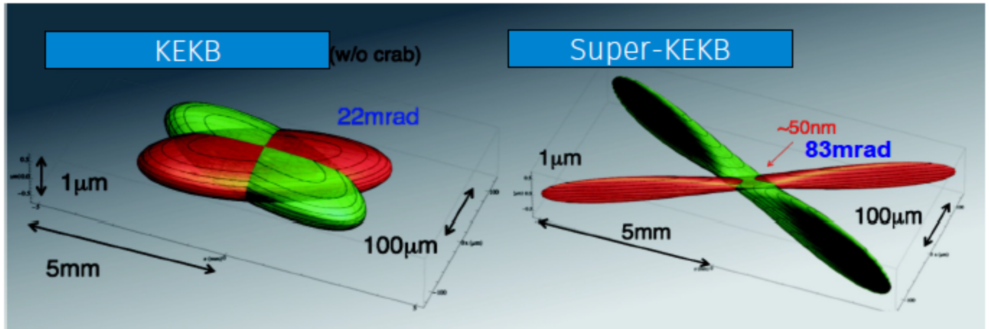




- **B-factory** (10^9 pairs per ab^{-1})
- **tau and charm factory** (10^9 pairs per ab^{-1})

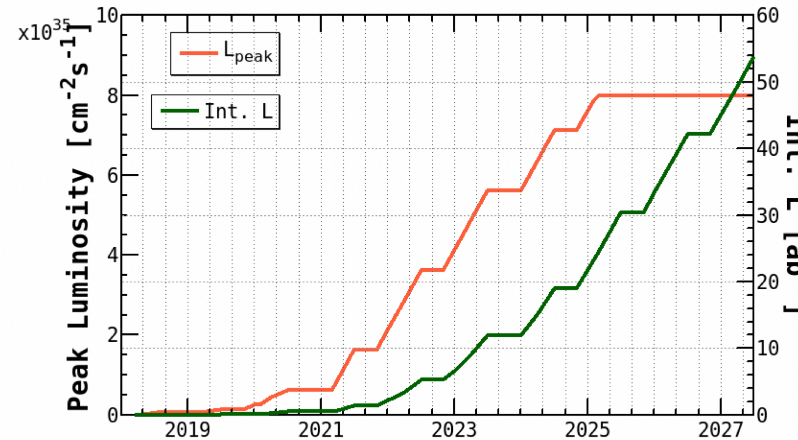
From KEKB to SuperKEKB

Nano-beam scheme firstly proposed by P. Raimondi for SuperB



	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm-2s-1)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^34
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^34

factor 20 factor 2-3



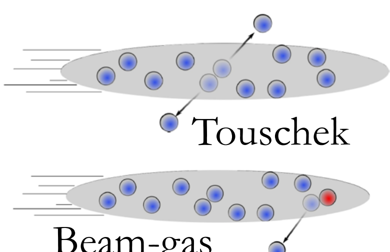
Factor ~ 40-50 in the luminosity

beam current

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

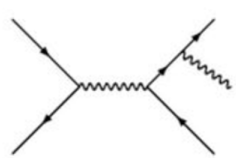
vertical beta function at IP

Higher backgrounds

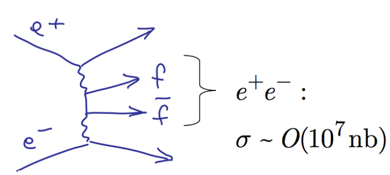


Touschek

Beam-gas



Radiative Bhabha



2-photon-processes

- Radiation damage
- Occupancy in inner detectors
- Fake hits and pile-up

From Belle to Belle II

Belle Upgrade:

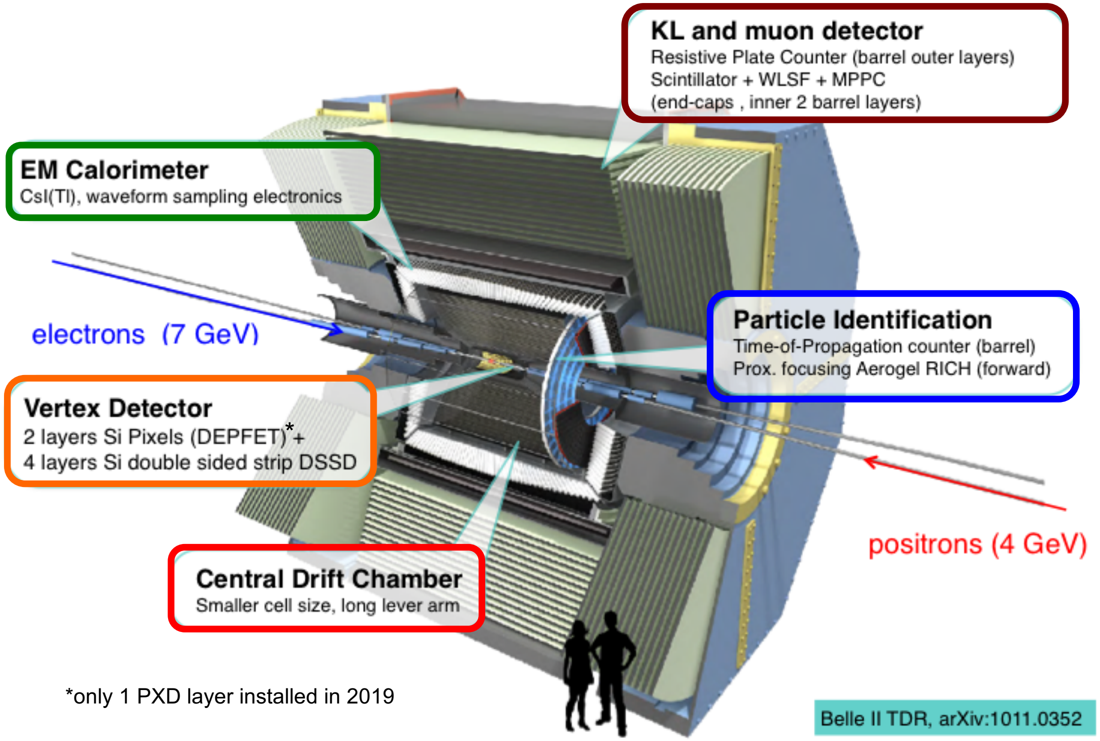
- **Extended VXD region:** PXD and SVD (silicon pixel and strips detectors)

- **Extended Drift Chamber region**

- **ECL:** CsI(Tl) crystals. **New electronics** (waveform sampling and fitting)

- **TOP and ARICH detectors: better hermeticity** with new PID detector in the forward region

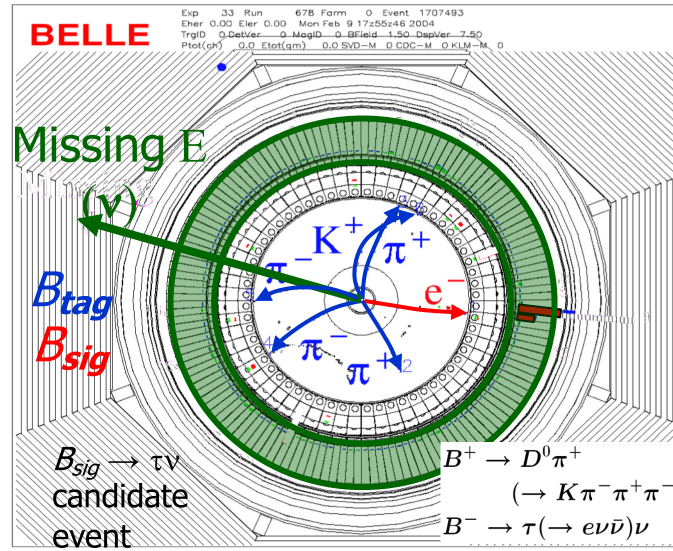
- **KLM detector: RPCs and scintillators** (some RPCs layers substituted with scintillators to resist neutron background)



- improved IP and secondary vertex resolution
- better K/π separation and flavor tagging
- robust against machine background
- higher K_S, π^0 and slow pions reconstruction efficiency

Unique capabilities of e^+e^- B factories

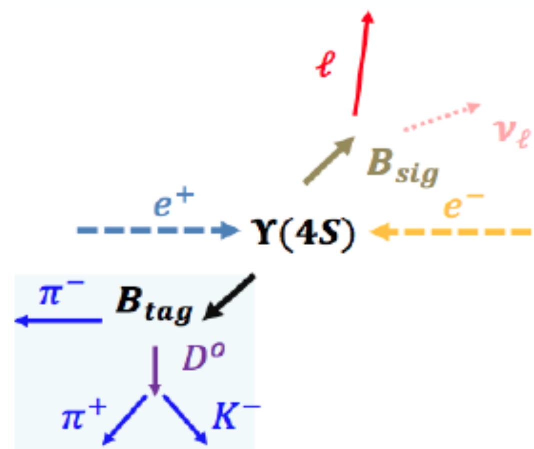
- **Beam energy constraint:** can be adjusted for different resonances $\Upsilon(nS)$
- **Clean experimental environment:** high B, D, K, τ lepton and neutral final states reconstruction efficiency.
- **BB produced in quantum correlated state:** high flavour tagging efficiencies (36% vs 3% @LHCb)



The **full reconstruction of one B (B_{tag})** constraints the 4-momentum of the other (B_{sig})

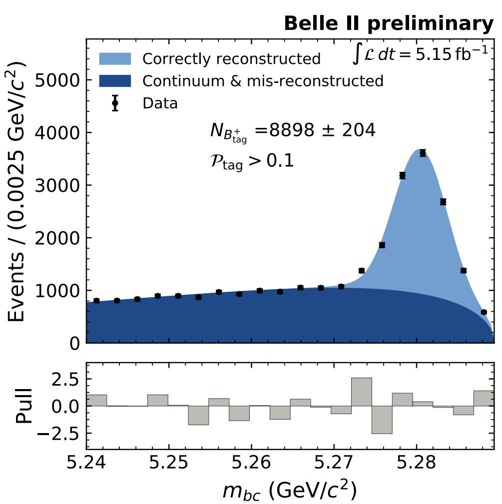
Reconstruction of **channels with missing energy**

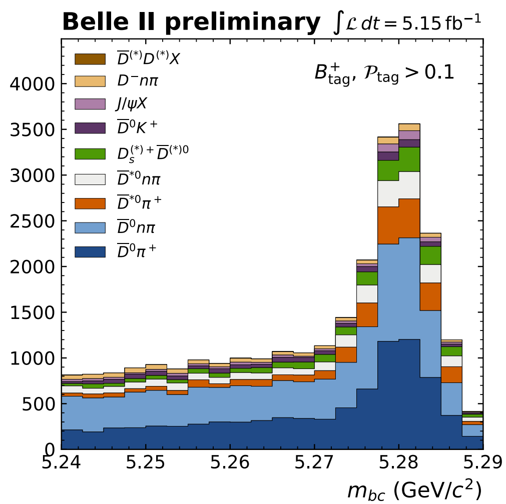
$$p_\nu = p_{e^+e^-} - p_{B_{tag}} - p_{B_{sig}}$$



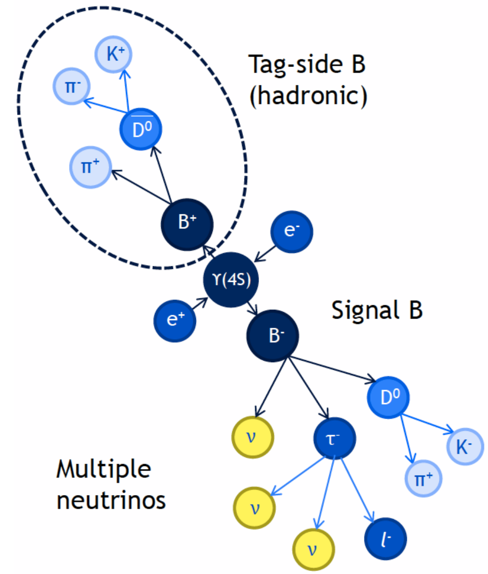
Tag side reconstruction: Full Event Interpretation (FEI)

- It is a development of the Full Reconstruction (FR) used in Belle, and uses a multivariate technique to reconstruct the B-tag side (semileptonic or hadronic) through O(10³) decay modes in a Υ(4S) decay.
- Tested on Belle II early data





$$M_{bc} \equiv \sqrt{\frac{s}{4} - {p_B^*}^2}$$



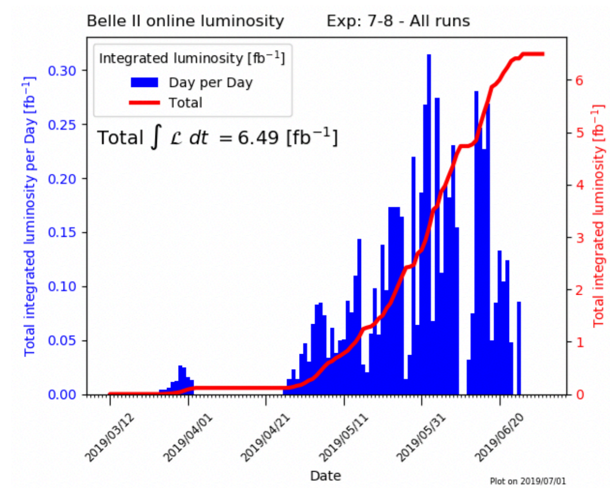
Tag algorithm	Efficiency B±/B⁰ (%)	Purity (%)
BaBar (SER)	0.4/0.2	30
Belle (FR)	0.28/0.18	10
Belle II (FEI)	0.76/0.46	10

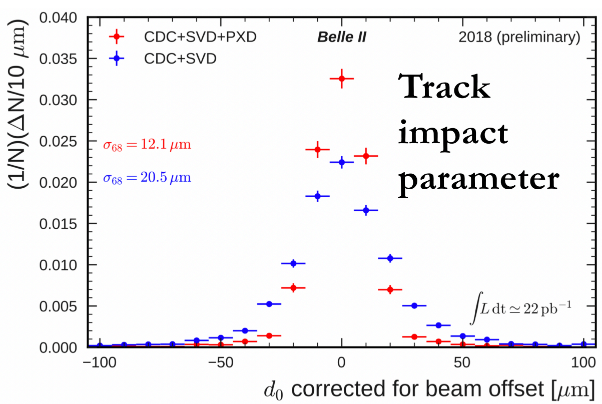
Performances with hadronic tag

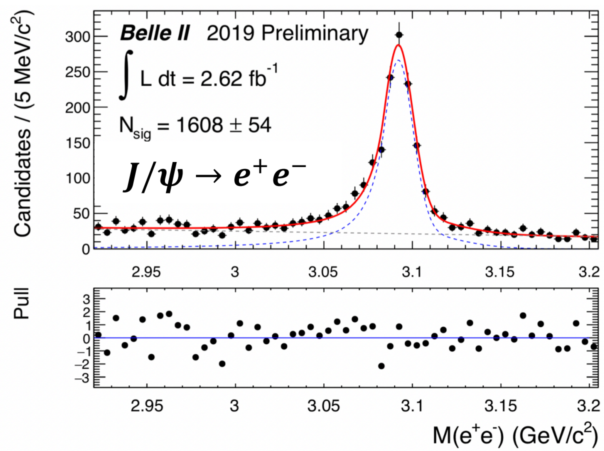
Belle FR: NIM A 654, 432-440 (2011)
Belle II FEI: Keck, T., Abudinén, F., Bernlochner, F.U. et al. Comput Softw Big Sci (2019) 3: 6.
https://doi.org/10.1007/s41781-019-0021-8

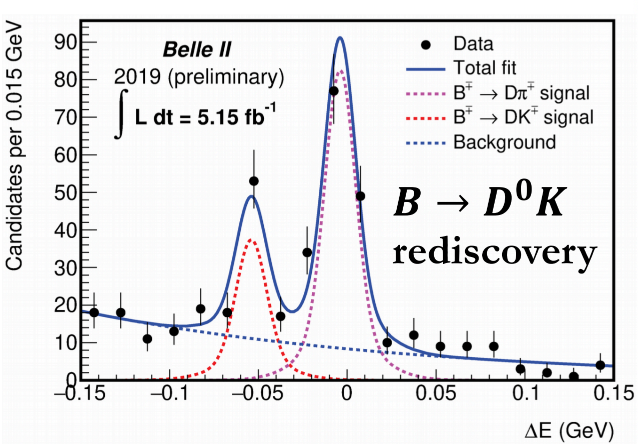
Belle II status and recent results

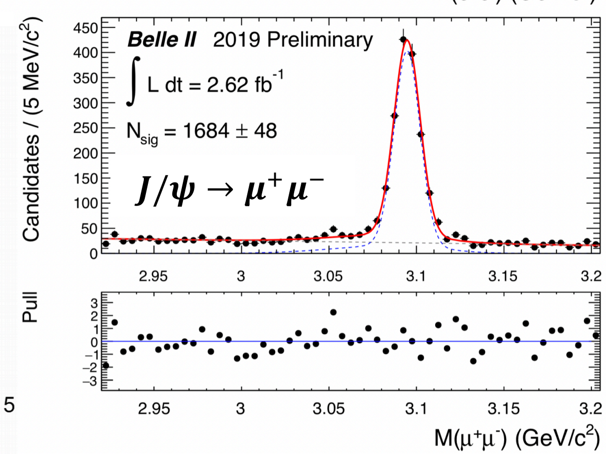
- **Phase 1 (2016-2018)**: no collisions, beam background studies
- **Phase 2 (2018)**: collisions, no vertex detector, dark sector studies
- **Phase 3 (2019-2027)**: full detector, superKEKB peak luminosity in 2019 $1.2\times 10^{34}/(cm^2 \cdot s)$ (half of the KEKB peak)

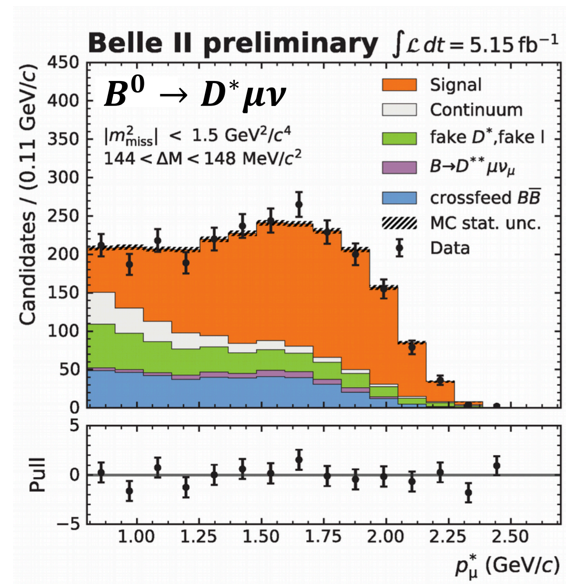












LFV, LFU, rare decays

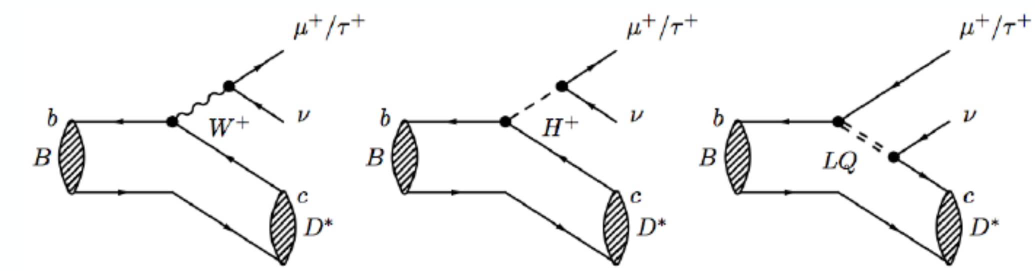
- **Semileptonic B decays with missing energy**
  - $B \to X\ell\nu$, measurement of $R(D), R(D^*)$
- **FCNC B decays with leptons in the final state**
  - $B \to X_s\ell^+\ell^-$, measurement of $R(K), R(K^*), P_5'$
- **Tau lepton decays**
  - $\tau \to 3\ell, \tau \to \ell\gamma, \tau \to \ell h$

Other channels as $B \to K^{(*)}\nu\bar{\nu}, B \to \ell\nu\ (\gamma)$ **in the backup slides**

Belle II physics reach projections summarized in the
Belle II Physics Book
(https://arxiv.org/abs/1808.10567, soon available on PTEP)

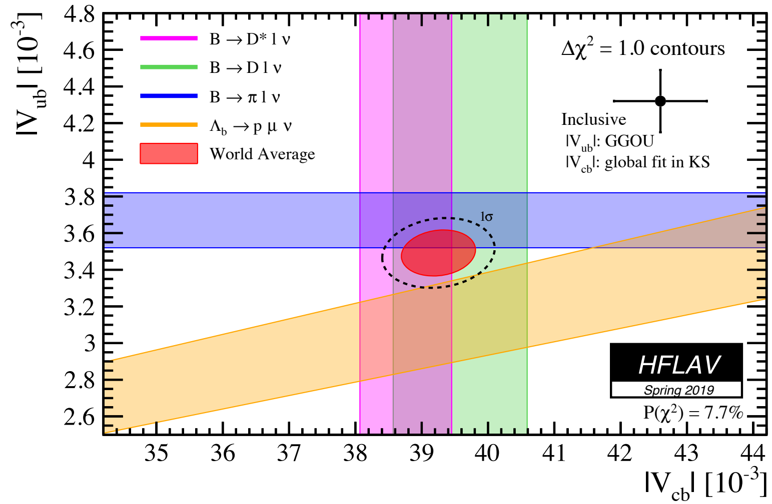
Semileptonic decays: $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}l\nu$

Clear test of the SM LFU: **NP** (charged Higgs in 2HDM models or Leptoquarks) **can affect the BR, the tau polarization P_τ and $|V_{cb}|$**



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

arXiv:1909.12524



Inclusive vs exclusive tension

Advantages of measuring $R(D^{(*)})$:

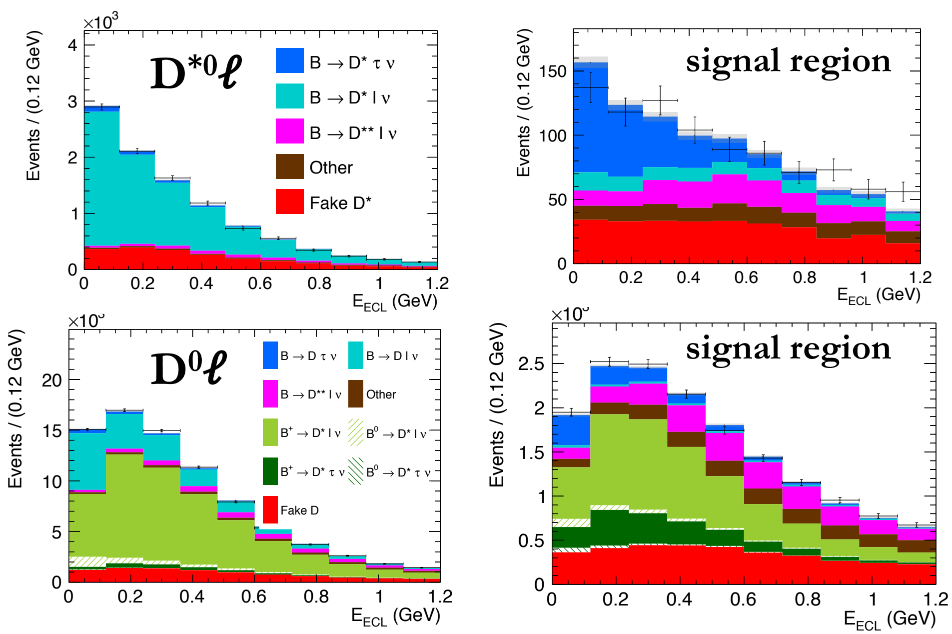
- **experimentally** we eliminate the uncertainties on the tagging efficiencies
- **theoretically** we eliminate the uncertainties on $|V_{cb}|$ and on the semileptonic form factors → **complementary to the inclusive / exclusive searches**

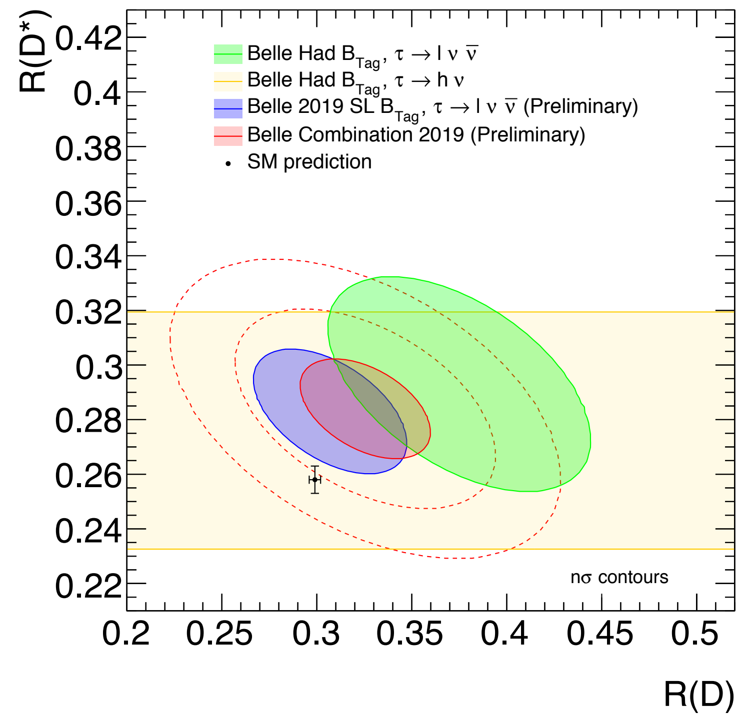
Belle measurements of $R(D^{(*)})$

- Simultaneous fit to the E_{ECL} distribution of the signal ($D^{(*)}\tau\nu$) and normalization modes ($D^{(*)}\ell\nu$)

arXiv:1904.08794 (2019) **SL tag**

E_{ECL} is the extra energy left in the calorimeter after the signal and tag B are reconstructed





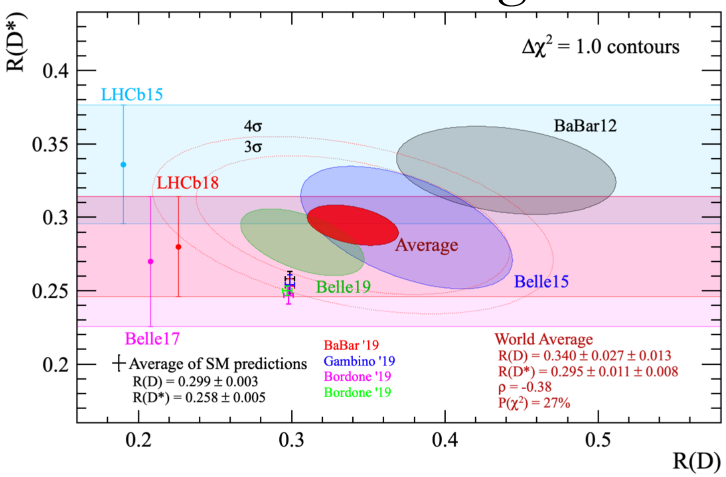
Signal and normalization separation is based mainly on the missing mass and the angle between B meson and $D^{(*)}$l system

New Belle combination is 2σ from the SM

$$\mathcal{R}(D^*) = \frac{1}{2\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)} \cdot \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \cdot \frac{N_{\rm sig}}{N_{\rm norm}}$$

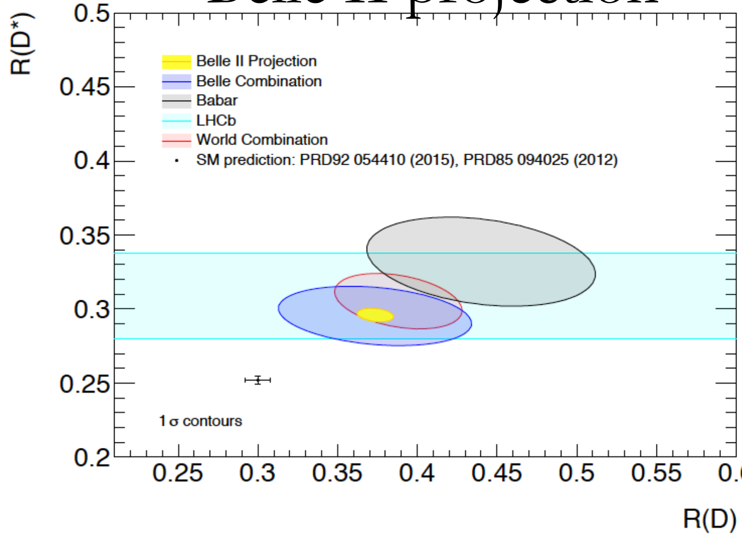
R(D$^{(*)}$) Belle II projections

World average



Current combination: 3.1σ from the SM

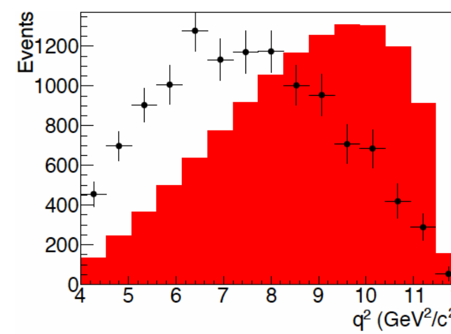
Belle II projection



	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

Projections based on Belle SL tag measurement (before 2019)

Main systematics: D** modelling, soft pions, yield of fake D* candidates. **Studies of B → D**lν and B → D**τν planned**



– NP $H^{\pm}$ type II at $\tan\beta/m_{H^{\pm}} = 0.5 (GeV/c^2)^{-1}$

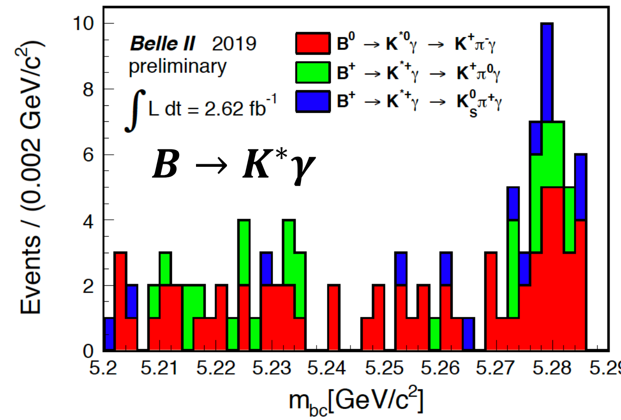
- Pseudo-data SM

50 ab^{-1} projection of q^2 spectrum in $B \to D^{(*)}\tau\nu$

Differential distributions can be measured to constrain NP

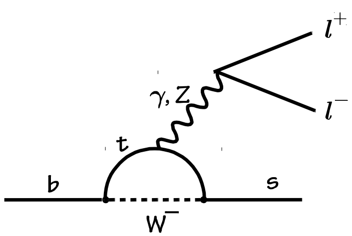
FCNC $B \to X_s \ell\ell$

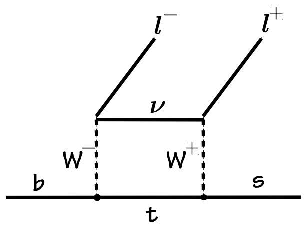
- **Very rare in the SM**: $\mathfrak{B}(B \to K^{(*)} ll) \sim 10^{-(6\text{-}8)}$
- **Sensitive to NP** (supersymmetry, 2HDM models, fourth generation, extra dimensions…)



- Experimentally we measure the ratios:

$$R_K^{(*)} = \frac{\mathfrak{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathfrak{B}(B \to K^{(*)}e^+e^-)}$$

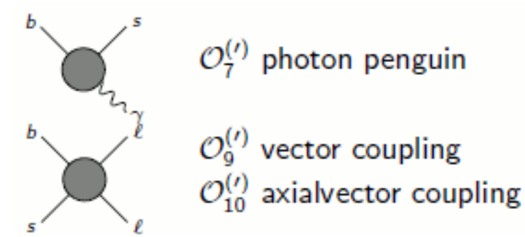




- Effective, model independent, hamiltonian:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i O_i$$

C_i: Wilson coefficients, encode short distance physics
O_i: Operators describing long-distance physics

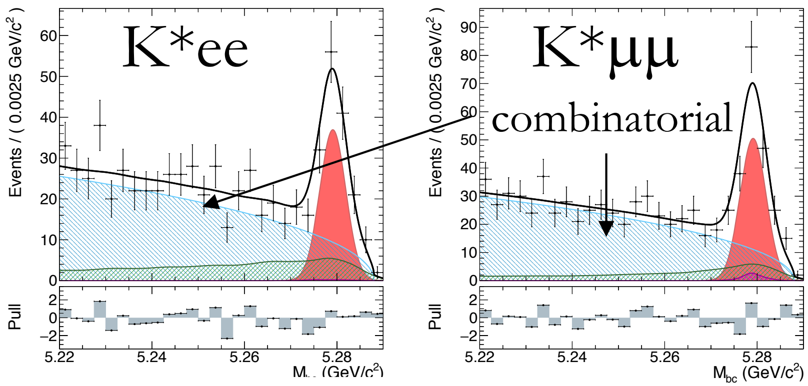


- Measurement of parameters related to angular distributions of the decay products (P_5', $Q_5 = P_5'^{e} - P_5'^{\mu}$) (see Ben Grinstein's plenary talk for details)

FCNC B → $K^{(*)}\ell\ell$: recent Belle studies

- B → $K^{*}\ell\ell$

arXiv:1904.02440 (Belle 2019)

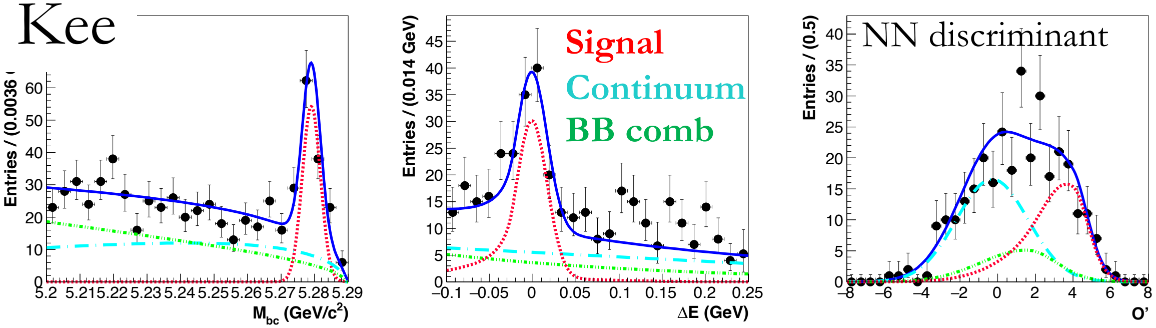


- Signal extraction with fit to M_{bc} distributions
- Dominant background: combinatorial
- Peaking background: charmonium $J/\psi K^*$
- Main systematics: lepton efficiency and peaking background

$$M_{bc} \equiv \sqrt{\frac{s}{4} - p_B^{*\,2}}$$

- B → $K\ell\ell$

arXiv:1908.01848 (Belle 2019)

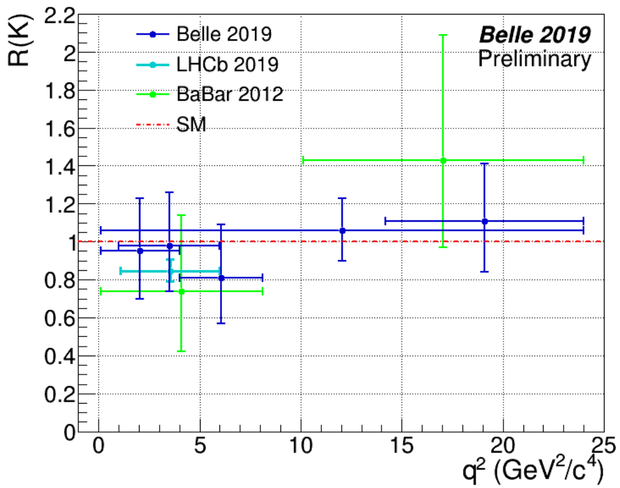


$$\Delta E \equiv E_B^* - \sqrt{s}/2$$

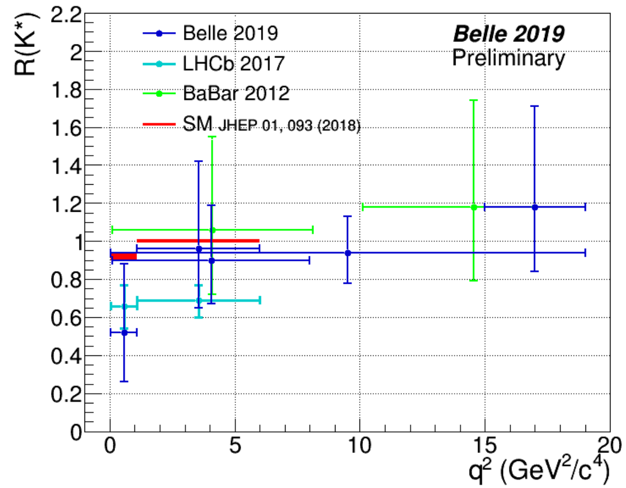
- Signal extraction with 3D fit to M_{bc}, ΔE, NN discriminant
- NN discriminant built using kinematic and angular variables
- Main systematics: lepton identification, B counting, NN discriminant

FCNC $B \to K^*\ell\ell$: summary and projections

arXiv:1908.01848 (Belle 2019)



arXiv:1904.02440 (Belle 2019)



Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
R_K ($[1.0, 6.0]\,\mathrm{GeV}^2$)	28%	11%	3.6%
R_K ($> 14.4\,\mathrm{GeV}^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	26%	10%	3.2%
R_{K^*} ($> 14.4\,\mathrm{GeV}^2$)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	32%	12%	4.0%
R_{X_s} ($> 14.4\,\mathrm{GeV}^2$)	28%	11%	3.4%

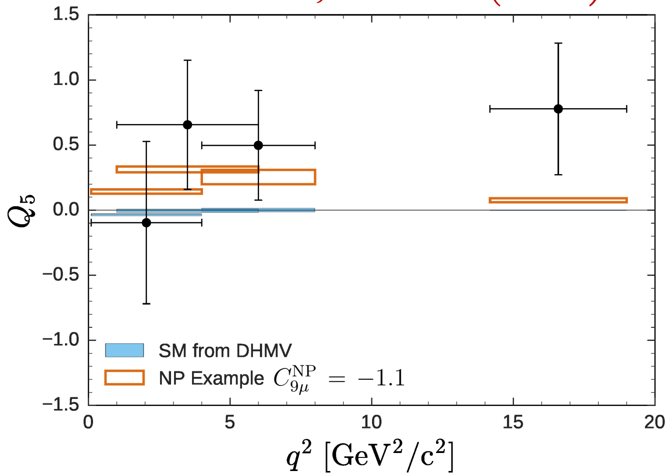
Belle II projections

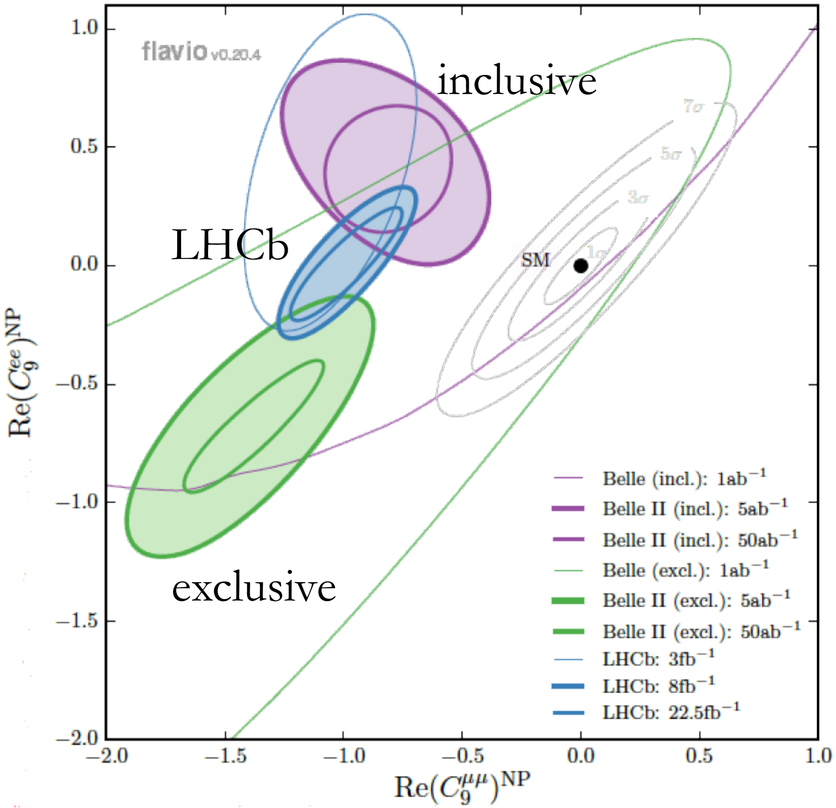
- Differential distributions in q^2 (dilepton invariant mass squared)
- Latest Belle result closer to the SM expectation (~1)
- Measurements still dominated by statistical uncertainty
- Inclusive studies of $B \to X_s\ell\ell$ possible: reduce hadronic uncertainties

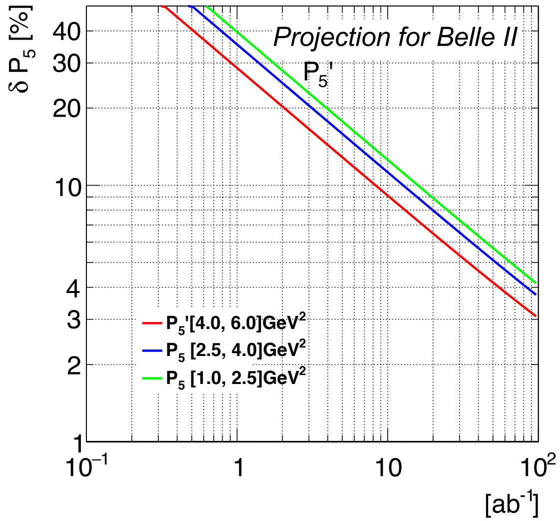
FCNC $B \to X_s \ell\ell$: perspectives on C_9, P_5'

- Angular variables sensitive to NP
- LHCb measurement dominated by systematics
- Exploit Full Event Interpretation to perform fully inclusive searches

PRL118, 111801 (2017)



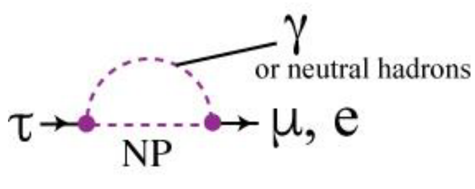


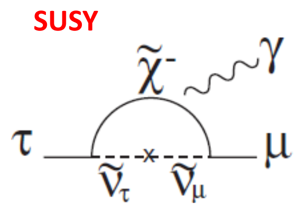


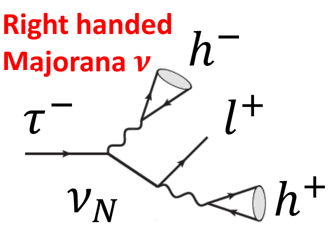
5σ confirmation of NP possible with 20 ab^{-1} at Belle II

LFV in tau decays

- LFV in tau decays is a **clear test of the SM**: expected **BR ~ 10^{-45}** (**NP predicts BR up to 10^{-8}**)







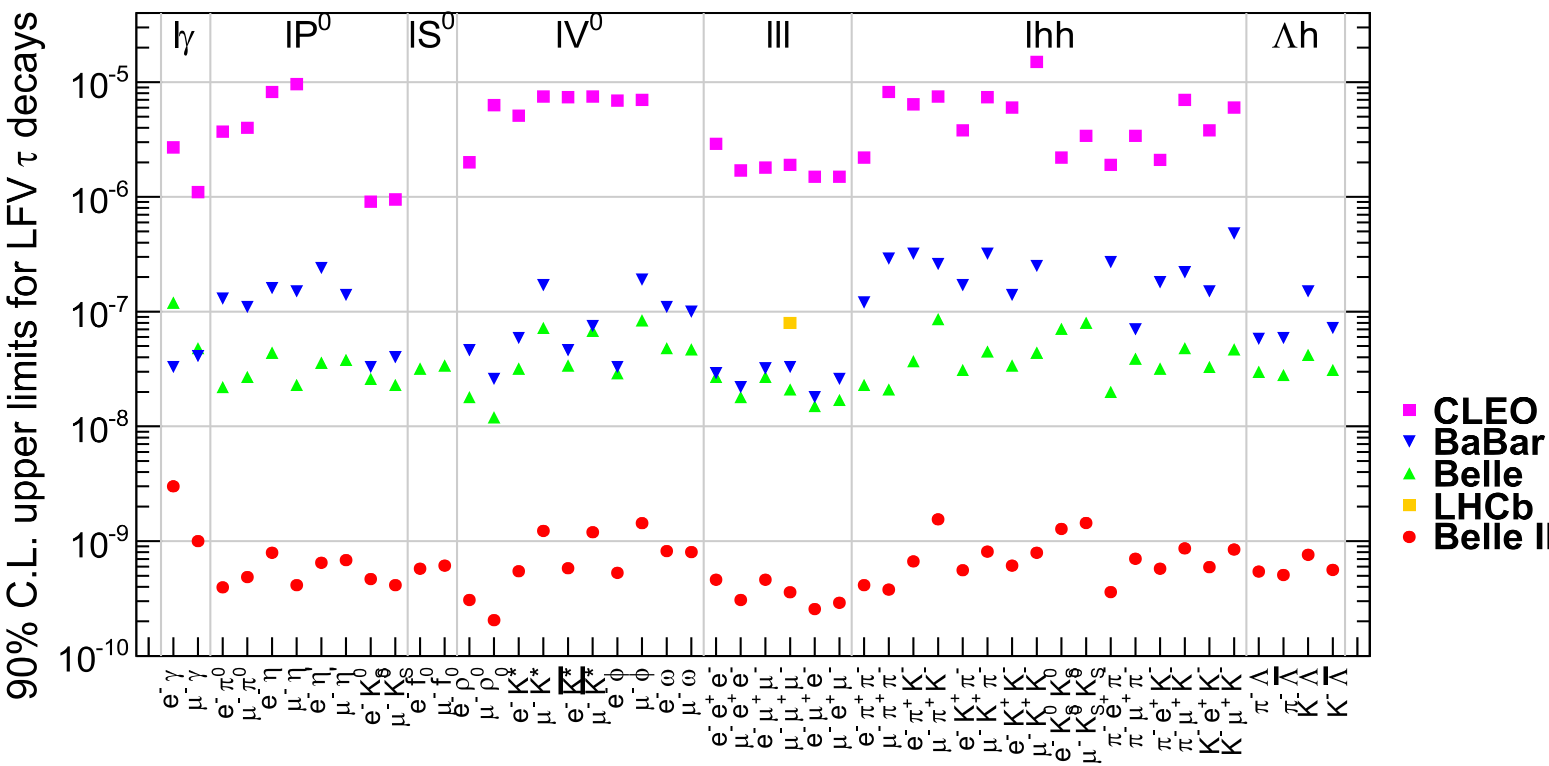
- Searches in different channels may provide discrimination among **NP models**

(M.Blanke, et al., JHEP 0705, 013(2007), C.Yue, et al.,PLB547, 252 (2002))

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\left(\frac{\tau \to \mu\mu\mu}{\tau \to \mu\gamma}\right)$	$\sim 2 \times 10^{-3}$	0.06~0.1	0.4~2.3	~16
$\left(\frac{\tau \to \mu ee}{\tau \to \mu\gamma}\right)$	$\sim 1 \times 10^{-2}$	$\sim 1 \times 10^{-2}$	0.3~1.6	~16
Br ($\tau \to \mu\gamma$)	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

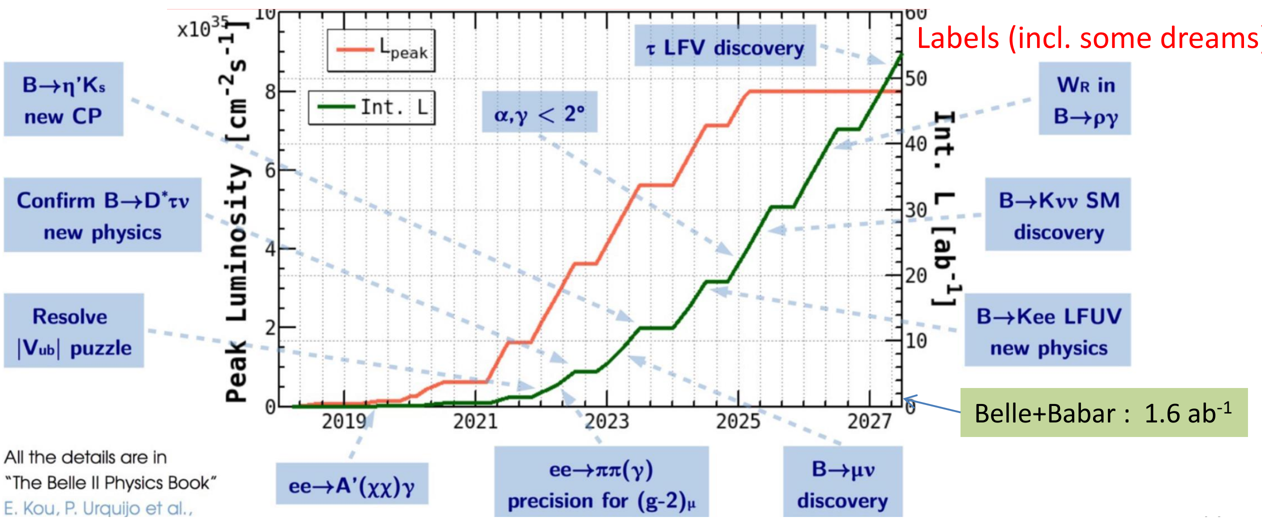
Upper limits on tau LFV modes

At Belle II an improvement of **2 orders of magnitude** is expected with full dataset



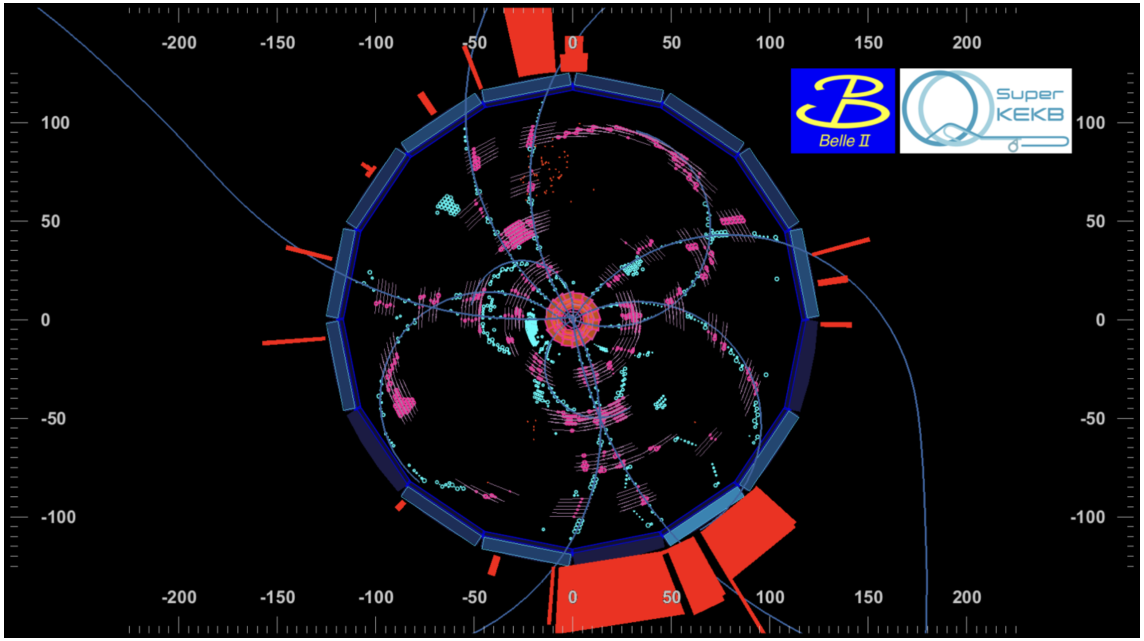
Conclusions

- Within the next **three-five years of data taking Belle II** will collect **5-20 ab^{-1}** and will be able to address the Lepton Flavour Universality Violation by precisely measuring **R(D$^{(*)}$), R(K$^{(*)}$), P$_5$'**
- With **full dataset** Belle II will also be able to potentially discover LFV in the tau lepton sector
- In addition Belle II will also have the sensitivity to shed light on anomalies in the $B \to X_u \ell \nu$ decays and investigate other rare processes suppressed in the SM ($B \to \ell\nu$, $B \to K^{(*)}\nu\bar{\nu}$, $B \to \nu\bar{\nu}$, etc.)



All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

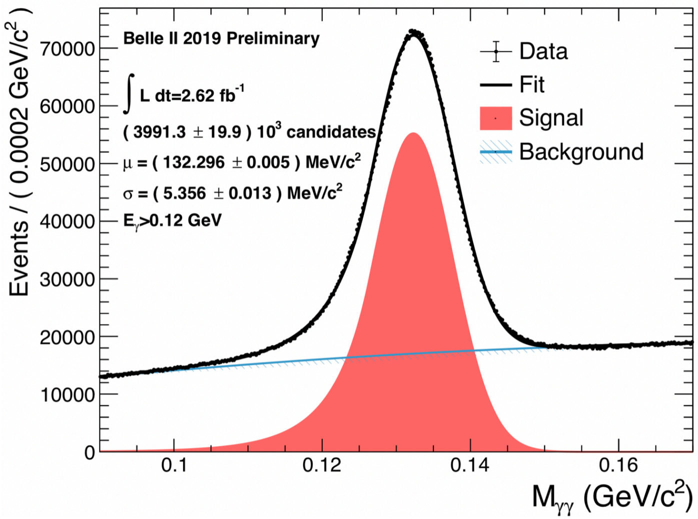
Thanks !



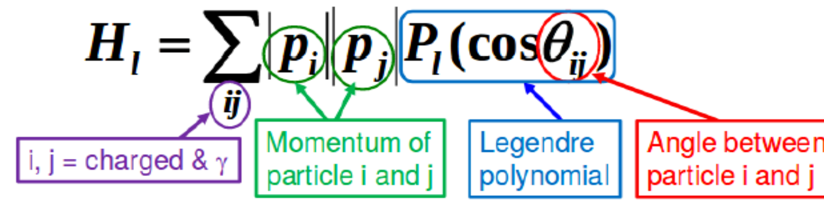
Backup

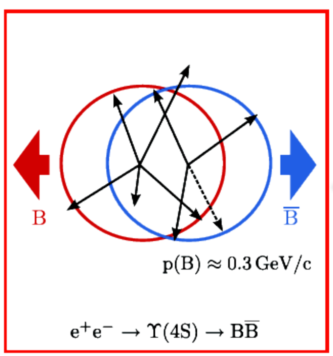
Belle II first data

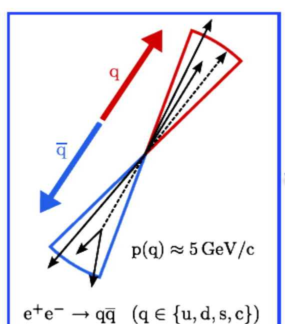
π^0 invariant mass

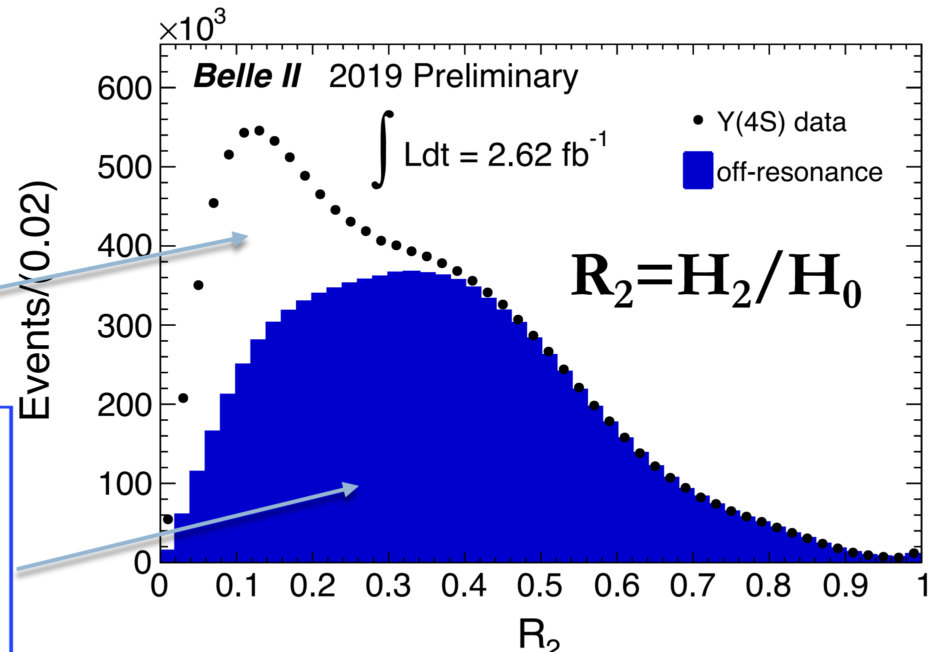


R_2 is the ratio between H_2 and H_0



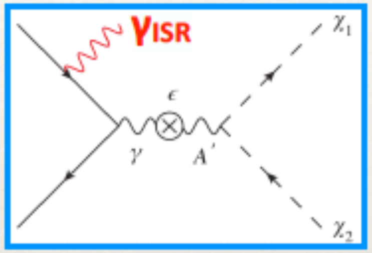




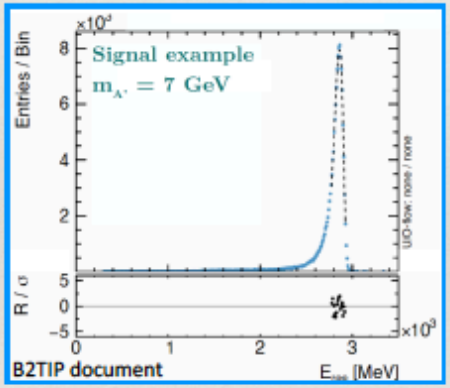


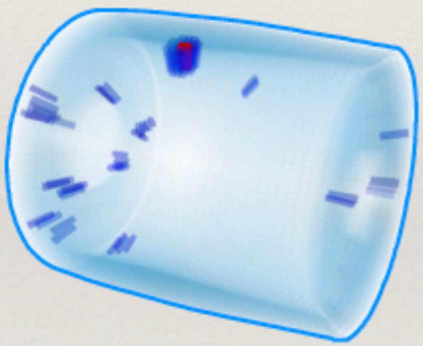
Early physics: the dark sector

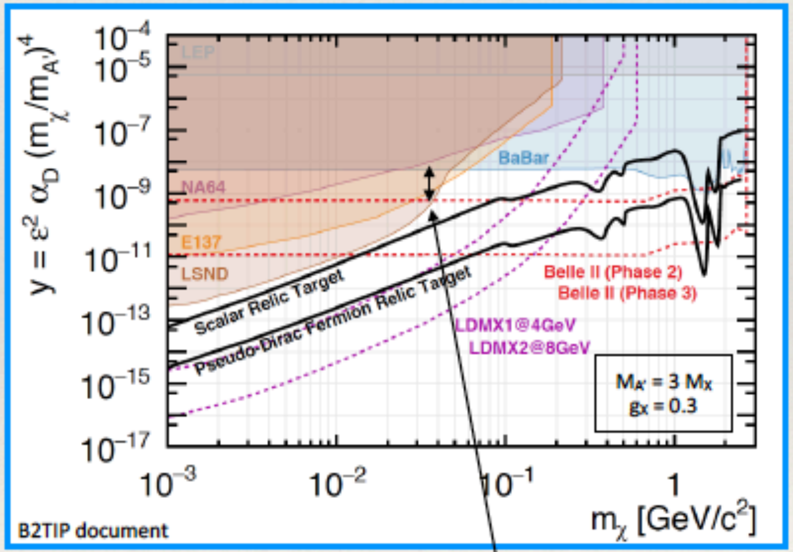
- Light dark matter and light mediator searches in Belle II:
  - Dark photons, dark higgs, axion-like particles (ALPs), mass scale ~GeV or sub-GeV.
  - Production, e.g.: $e^+e^- \to M+X$, $e^+e^- \to Y(ns) \to M+X$, $e^+e^- \to B+X \to K+M+X$.



- Example: on-shell dark photon decaying to invisible DM:
  - Signal: single, mono-energetic, high-E photon & peak in recoil mass.
  - Single Photon trigger with 1 GeV threshold.







- Particularly relevant with Phase 2 data:
  - Low luminosity and lower beam background allow to open up triggers.
  - Small dataset can still give world best sensitivity.

Belle II calo more hermetic than BaBar

FEI Calibration

FEI validated on Belle real data

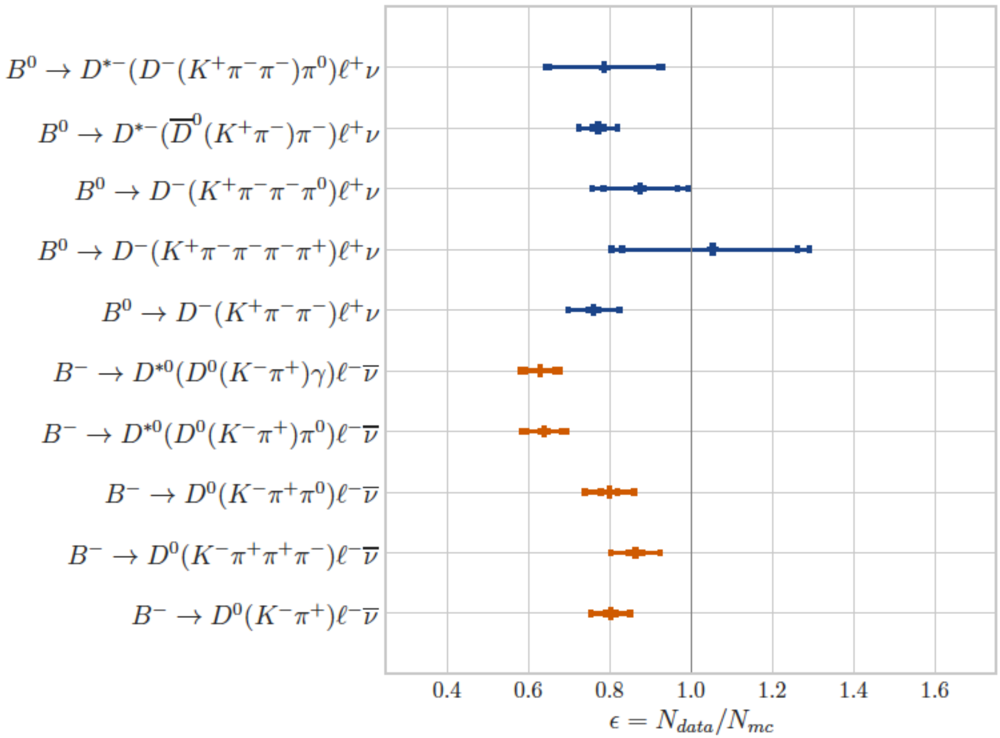
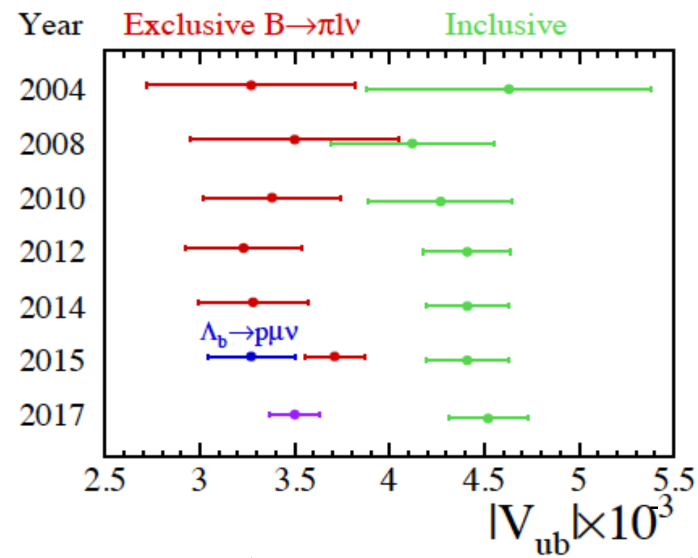


Figure 4.18.: The overall efficiency correction calculated by measuring the known branching fractions of 10 control channels on converted Belle data [76].

Thomas Keck's master thesis

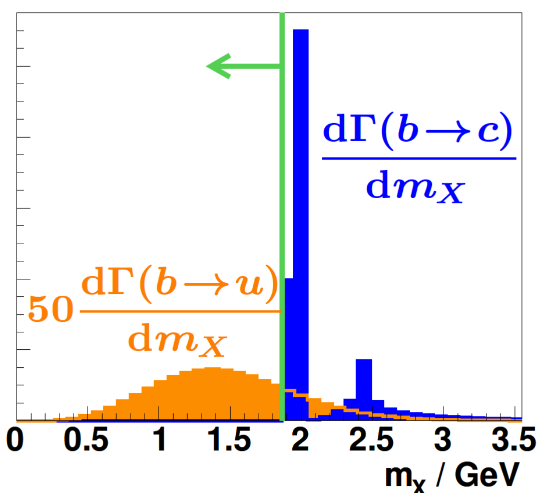
Semileptonic decays: $B \to X_u l\nu$



Tension between inclusive and exclusive **|V**

Measurement of $|V_{ub}|$ from inclusive and exclusive B decays

- **Inclusive decays measurement**
  - Hadronic tag
  - Exploit kinematic endpoints to reduce $B \to X_c l\nu$ bkg



$$|V_{ub}|^2 = \Delta\mathcal{B}_{u\ell\nu}/(\tau_B\Delta\mathcal{R})$$

Measured BR in fiducial phase space region

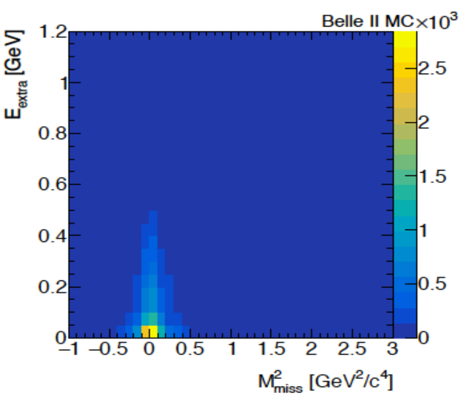
B meson lifetime

Predicted partial decay rate

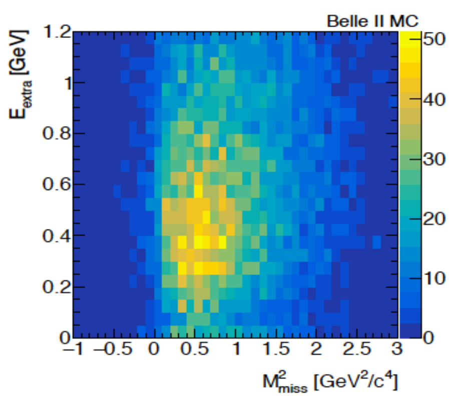
Semileptonic decays: $B \to X_u l \nu$

Belle II Full Simulation study

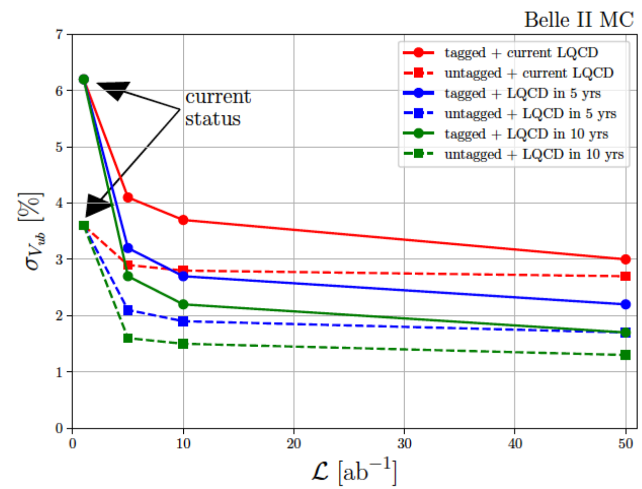
- $B^0 \to \pi\, l\, \nu$ decay
  - Untagged or tagged (with FEI)
  - Exploit missing mass and extra energy in the calorimeter
  - $\mathcal{B} \sim f_i |V_{ub}|^2$; form factors f_i computed with LQCD (PRD 91, 074510 (2015))



signal



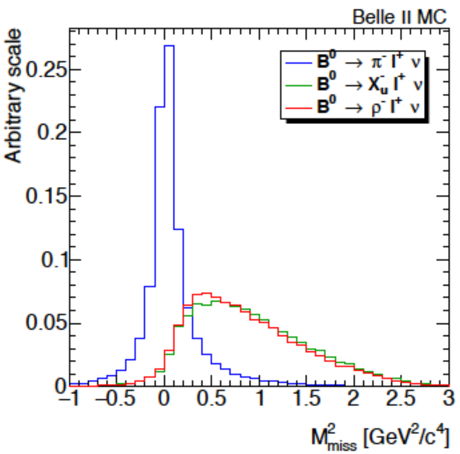
background



$B \to \pi\, l\, \nu$ projections

Belle II @ 50 ab^{-1}: ~3% (inclusive) / ~2% (exclusive $\pi\, l\, \nu$) uncertainty

Semileptonic decay: $B^0 \to \pi l \nu$



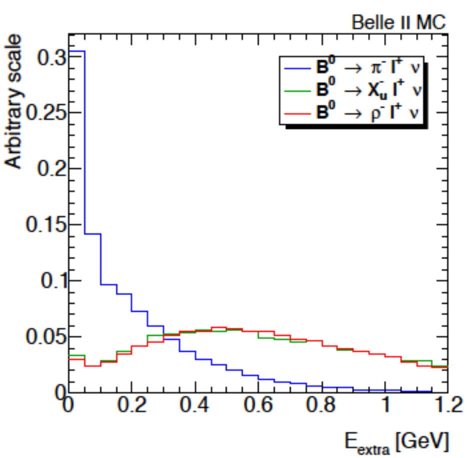


Table 54: Summary of systematic uncertainties on the branching fractions of $B^0 \to \pi^- \ell^+ \nu_\ell$ decays in hadronic tagged and untagged Belle analyses with 711 fb^{-1} [271] and 605 fb^{-1} [269] data samples, respectively. The estimated precision limit for some sources of systematic uncertainties is given in brackets.

Source	Error (Limit) [%]	
	Tagged [%]	Untagged
Tracking efficiency	0.4	2.0
Pion identification	–	1.3
Lepton identification	1.0	2.4
Kaon veto	0.9	–
Continuum description	1.0	1.8
Tag calibration and $N_{B\bar{B}}$	4.5 (2.0)	2.0 (1.0)
$X_u \ell \nu$ cross-feed	0.9	0.5 (0.5)
$X_c \ell \nu$ background	–	0.2 (0.2)
Form factor shapes	1.1	1.0 (1.0)
Form factor background	–	0.4 (0.4)
Total	5.0	4.5
(reducible, irreducible)	(4.6, 2.0)	(4.2, 1.6)

LQCD: current is the world avergage by FLAG group

- 5 yr w/o EM": We assume a factor of 2 reduction of the lattice QCD uncertainty in the next ve years and that the uncertainty of the EM correction is negligible (e.g. for processes insensitive to the EM correction).
- 5 yr w/ EM": The lattice QCD uncertainty is reduced by a factor of 2, but we add in quadrature 1% uncertainty from the EM correction19.
- 10 yr w/o EM": We assume a factor of 5 reduction of the lattice QCD uncertainty in the next ten years. It is also assumed that the EM correction will be under control and its uncertainty is negligible.
- 10 yr w/ EM": We assume lattice QCD uncertainties reduced by a factor of 5, but add in quadrature 1% uncertainty from the EM correction.

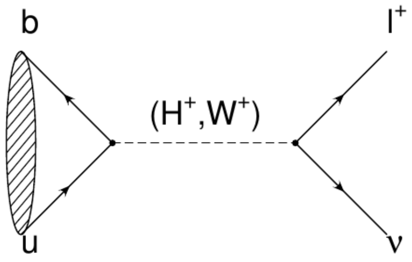
$R(D^{(*)})$ Belle measurement

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} composition	0.76	1.41
Fake $D^{(*)}$ calibration	0.19	0.11
B_{tag} calibration	0.07	0.05
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12
Lepton efficiency and fake rate	0.36	0.33
Slow pion efficiency	0.08	0.08
MC statistics	4.39	2.25
B decay form factors	0.55	0.28
Luminosity	0.10	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.35	0.13
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.15	0.14
Total	5.21	4.94

Leptonic B decays

- Helicity suppressed decays

$$BR_{SM}\left(B \rightarrow \ell\, \nu\right) = \frac{G_F^2 m_B \tau_B}{8\pi} f_B^2 \,|V_{ub}|^2 m_\ell^2 \left[1 - \frac{m_\ell^2}{m_B^2}\right]^2$$



	SM Prediction
$\mathcal{B}\left(B^+ \to e^+\nu_e\right)$	$(1.09 \pm 0.21) \cdot 10^{-11}$
$\mathcal{B}\left(B^+ \to \mu^+\nu_\mu\right)$	$(4.65 \pm 0.91) \cdot 10^{-7}$
$\mathcal{B}\left(B^+ \to \tau^+\nu_\tau\right)$	$(1.03 \pm 0.2) \cdot 10^{-4}$

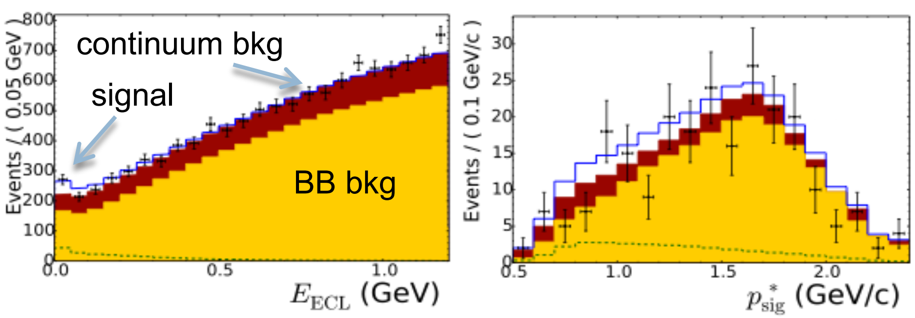
- Sensitive to NP contributions, e.g. type III Higgs doublet model [PhysRevD.86.054014]

- Clean theoretically, hard experimentally: only $B \to \tau\nu$ has been measured

Belle combination

$$\mathcal{B} = [0.91 \pm 0.19(\text{stat.}) \pm 0.11(\text{syst.})] \times 10^{-4}$$
(evidence at ~4.6 σ level)

Belle PRD 92, 051102 (2015), SL tag

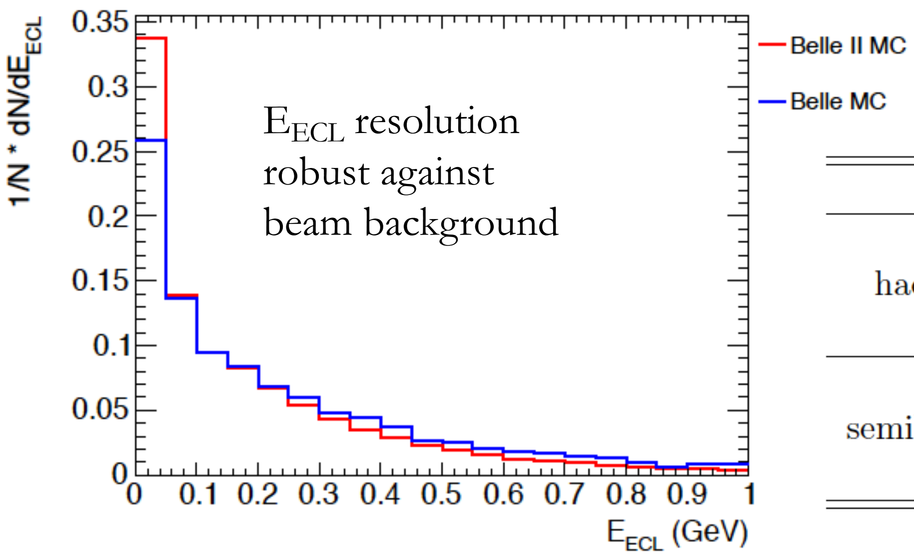


Leptonic B decays: $B \to \tau\nu$

Belle II full simulation study

- Hadronic tag with FEI
- 1-prong τ decays (μνν, eνν, πν, ρν)
- Dedicated study on machine background impact
- ML fit to extra energy E_{ECL}

Extra energy in the calorimeter



Main systematic uncertainties: background E_{Extra} PDF, branching fractions of the peaking backgrounds, tagging efficiency, and K^0_L veto efficiency

	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29.2	13.0	4.1
	systematic uncertainty (%)	12.6	6.8	4.6
	total uncertainty (%)	31.6	14.7	6.2
semileptonic tag	statistical uncertainty (%)	19.0	8.5	2.7
	systematic uncertainty (%)	17.9	8.7	4.5
	total uncertainty (%)	26.1	12.2	5.3

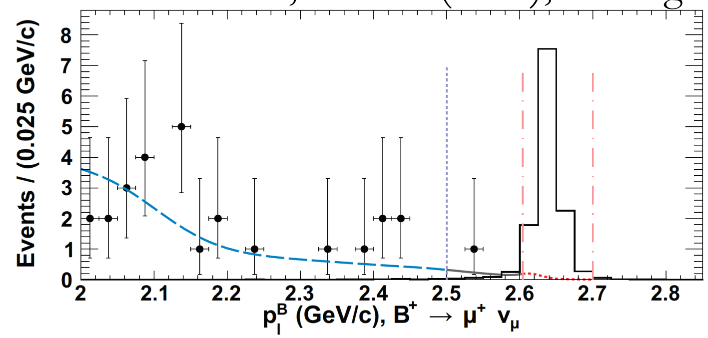
Observation at ~3 ab^{-1}

Leptonic B decays: $B \to \mu\nu$ and radiative $B \to l\nu\gamma$

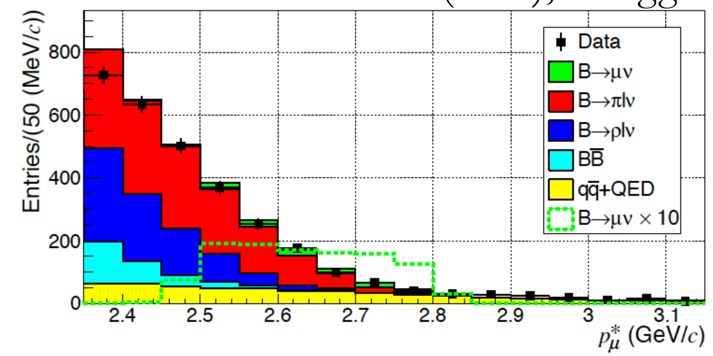
$B \to \mu\nu$

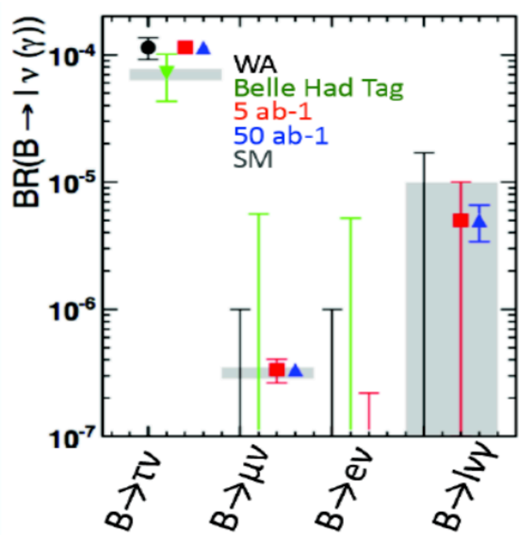
- Two body decay: $p^*_\mu = m_B/2$ in B rest frame
- Tagging $\to$ better p^*_μ resolution but small statistics
- ~2.4σ measurement

Belle PRD 91, 052016 (2015), had tag



Belle arXiv:1712.04123 (2018), untagged





$B \to l\nu\gamma$

- Radiative decay lifts the helicity suppression
- Allows a measurement of $\lambda_B \to$ crucial input to QCD factorization predictions of charmless hadronic B decays

Leptonic radiative B → lνγ

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

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

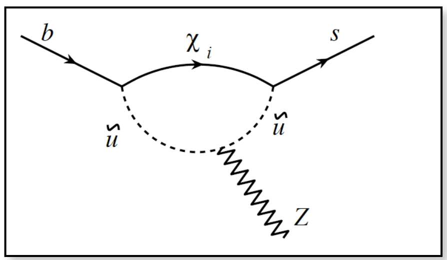
$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma} \right],$$

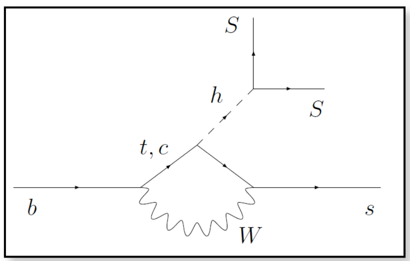
Beneke and Rohrwild, 2011, https://doi.org/10.1140/epjc/s10052-011-1818-8

Flavour changing neutral current $B \rightarrow K^{(*)}\nu\bar{\nu}$

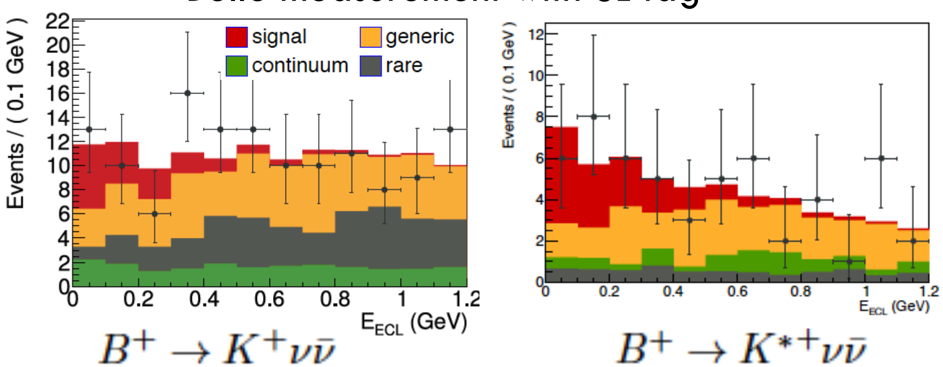
- Prohibited in the SM at tree level: penguin + box diagrams
- BR ~ $10^{-5} \div 10^{-6}$; NP contribution can increase the BR by factor 50
  - non standard Z-couplings (SUSY)
  - New missing energy sources (DM, extra dim.)

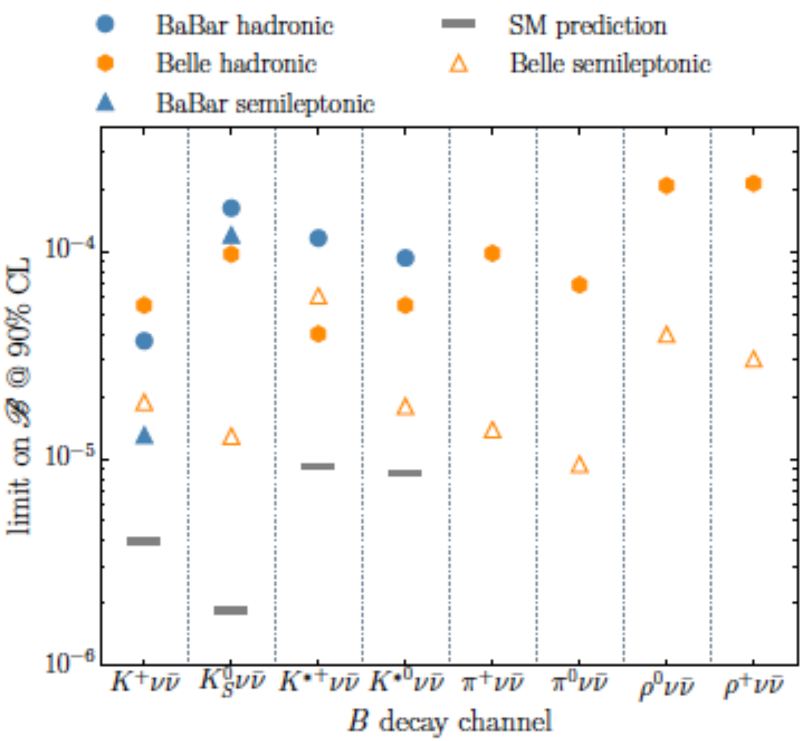
Belle PRD(R) 96, 091101 (2017)





Belle measurement with SL tag

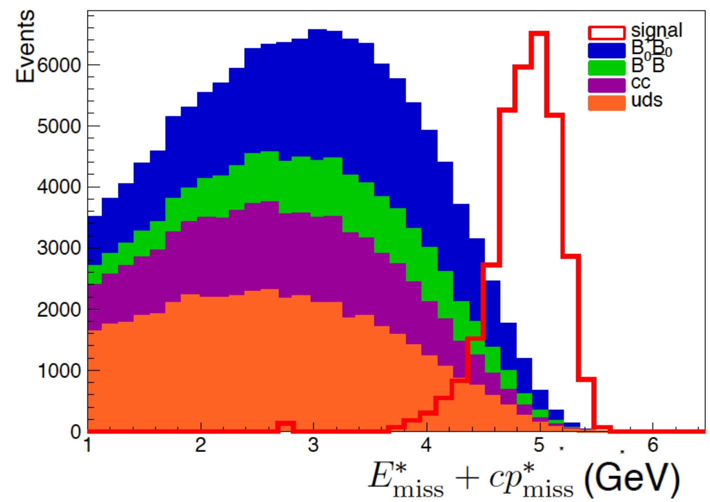




Flavour changing neutral current $B \to K^{(*)}\nu\bar{\nu}$

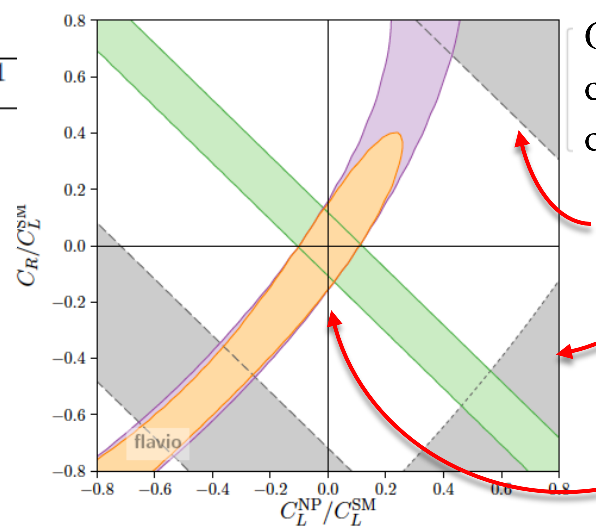
Belle II full simulation study

- Hadronic tag with FEI
- $K^* \to K\pi^0$
- Powerful discriminating variable $E^*_{miss} + cp^*_{miss}$
- Projections performed with a cut and count analysis in extra energy signal window



Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\nu\bar{\nu})$	30%	11%
$Br(B^0 \to K^{*0}\nu\bar{\nu})$	26%	9.6%
$Br(B^+ \to K^{*+}\nu\bar{\nu})$	25%	9.3%

Observation at ~18 ab^{-1}



Constraints on new physics contributions to Wilson coefficients C_L, C_R

90% CL excluded by Belle and Babar

68% CL allowed by Belle II at 50 ab^{-1}

Flavour changing neutral current $B \to K^{(*)}\nu\bar{\nu}$

In BSM right handed operator for neutrinos $Q_R^\ell = (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_{\ell L}\gamma^\mu \nu_{\ell L})$

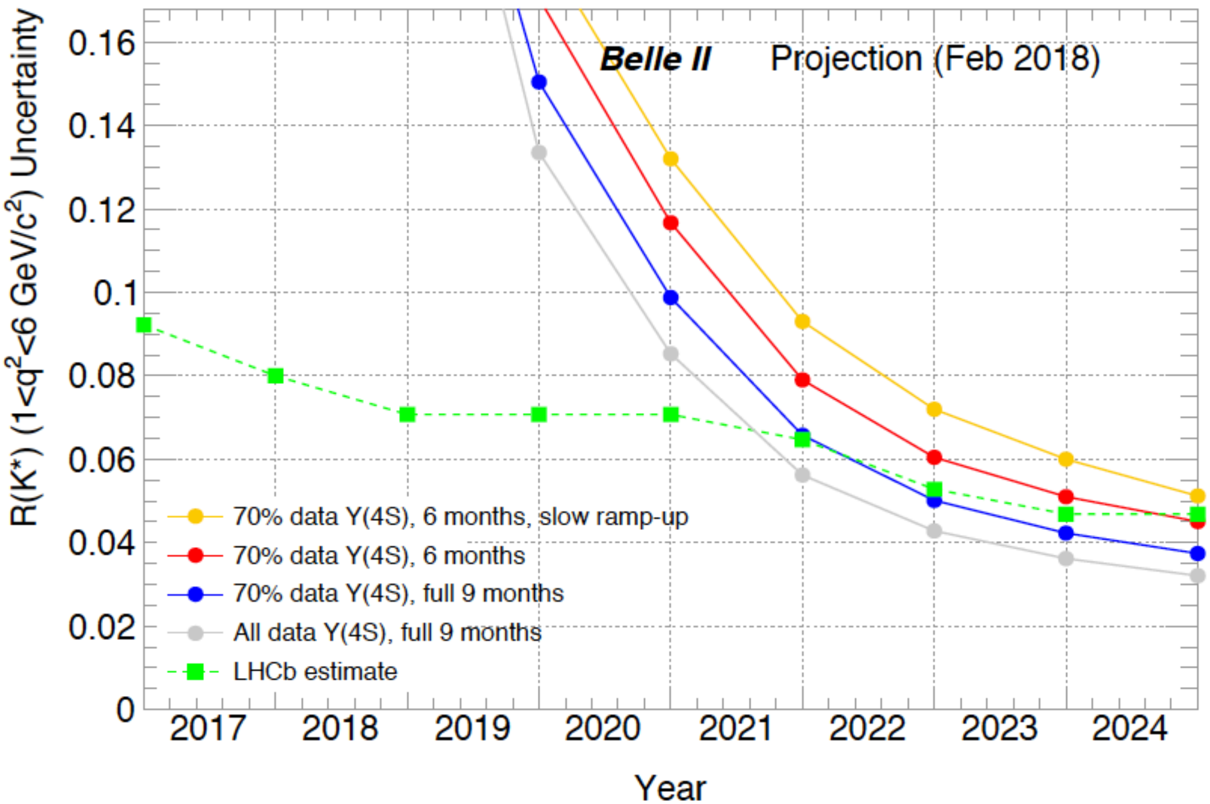
$$\frac{\mathrm{Br}(B \to K\nu\bar{\nu})}{\mathrm{Br}(B \to K\nu\bar{\nu})_{\mathrm{SM}}} = \frac{1}{3}\sum_\ell (1 - 2\,\eta_\ell)\,\epsilon_\ell^2\,,$$

$$\frac{\mathrm{Br}(B \to K^*\nu\bar{\nu})}{\mathrm{Br}(B \to K^*\nu\bar{\nu})_{\mathrm{SM}}} = \frac{1}{3}\sum_\ell (1 + \kappa_\eta \eta_\ell)\,\epsilon_\ell^2\,,$$

$$\epsilon_\ell = \frac{\sqrt{|C_L^\ell|^2 + |C_R^\ell|^2}}{|C_L^{\mathrm{SM}}|}\,,$$

$$\eta_\ell = \frac{-\mathrm{Re}\left(C_L^\ell C_R^{\ell *}\right)}{|C_L^\ell|^2 + |C_R^\ell|^2}\,.$$

B → sll : R(K*)



LHCb values based on naive run-1 extrapolation (not official)
Belle II scenarios due to operating conditions at KEK

** Consider it as a sketch to show Belle II can provide confirmation of any persistent anomaly.

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ ($[1.0, 3.5]\,\mathrm{GeV}^2$)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ ($[3.5, 6.0]\,\mathrm{GeV}^2$)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s \ell^+ \ell^-)$ ($> 14.4\,\mathrm{GeV}^2$)	23%	10%	4.7%

B → sll : R(K*)

Differential rate

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

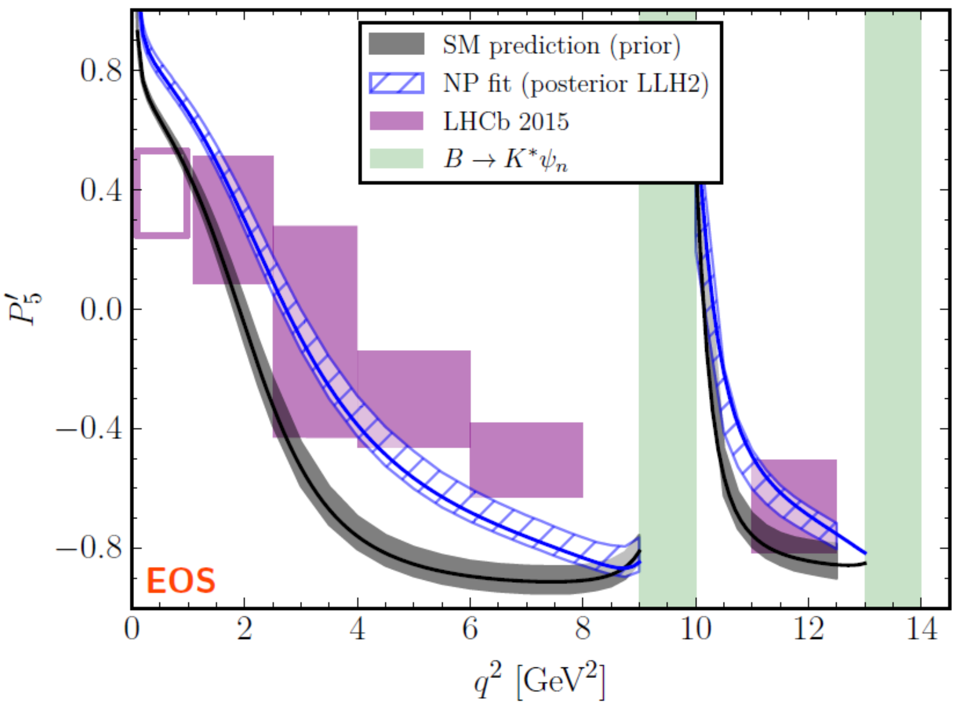
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}},$$

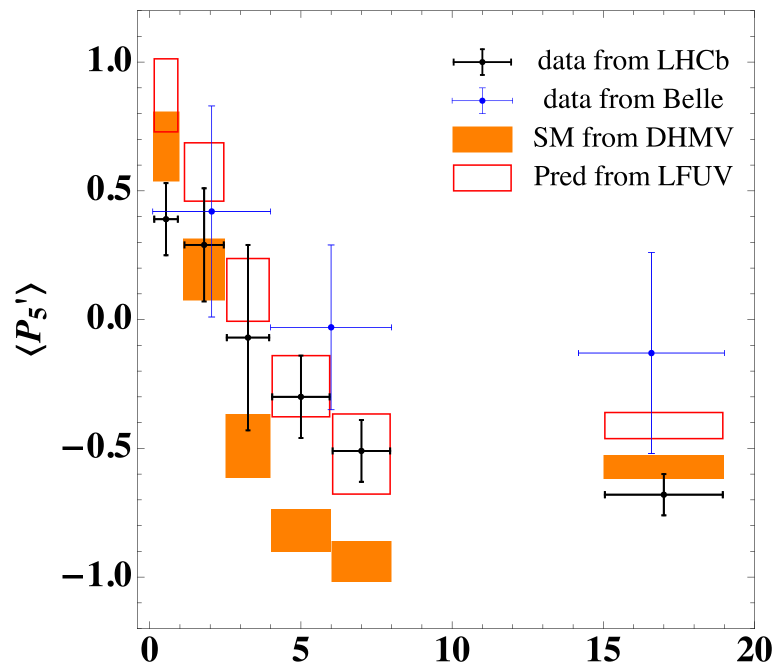
Prospects for tauonic EW penguins

Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 6.5	< 2.0
$Br(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 30	< 9.6
$Br(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 8.1	–
$Br(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	< 2.1
$Br(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	–	< 3.3
$Br(B^0 \to \tau^\pm e^\mp) \cdot 10^5$	–	< 1.6
$Br(B^0 \to \tau^\pm \mu^\mp) \cdot 10^5$	–	< 1.3

$B \to K^{(*)}\tau^+\tau^-$ hard to measure even with 50 ab^{-1} at Belle II (SM BR $\sim 10^{-7}$)

P_5'


SM prediction (prior)
NP fit (posterior LLH2)
LHCb 2015
$B \to K^* \psi_n$
EOS
P_5'
q^2 [GeV^2]
0.8
0.4
0.0
−0.4
−0.8
0
2
4
6
8
10
12
14


data from LHCb
data from Belle
SM from DHMV
Pred from LFUV
$\langle P_5' \rangle$
1.0
0.5
0.0
−0.5
−1.0
0
5
10
15
20

Physics prospects: Belle II vs LHCb

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K^0_S\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	**	0.03	Belle II/LHCb

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 2018	LHCb 50 fb^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$	2.9%	0.9%		
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$	3.5%	2.3%		
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	30%	25%		
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	$-32 \pm 21 \pm 9$	11	6		
	$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-3}]$	3.4*			0.5	0.1
	A_Γ $[10^{-2}]$	0.22	0.1	0.03	0.02	0.005
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	0.29	0.09		
	$A_{CP}(D^0 \to K^0_S\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$	0.08	0.03		
Charm Mixing	$x(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	0.14	0.11		
	$y(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	0.08	0.05		
	$\lvert q/p\rvert(D^0 \to K^0_S\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	0.10	0.07		
	$\phi(D^0 \to K^0_S\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	6	4		
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7		
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12		
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3		

Belle II Physics Book

- B2TiP Report (600p)
  - https://confluence.desy.de/display/BI/B2TiP+ReportStatus
- To be published in PTEP / Oxford University Press & printed.
  - Belle II Detector, Simulation, Reconstruction, Analysis tools
  - Physics working groups
  - New physics prospects and global fit code

PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (319 pages)
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The Belle II Physics Book

Emi Kou[1], Phillip Urquijo[2], The Belle II collaboration[3], and The B2TiP theory community[4]

[1] *LAL*
* *E-mail: kou@lal.in2p3.fr*
[2] *Melbourne*
* *E-mail: purquijo@unimelb.edu.au*
[3] *Addresses of authors*
[4] *Addresses of authors*

The report of the Belle II Theory Interface Platform is presented in this document.

Contents **PAGE**