# $R(D^{(*)})$ and other missing energy B decays at the Belle II Experiment


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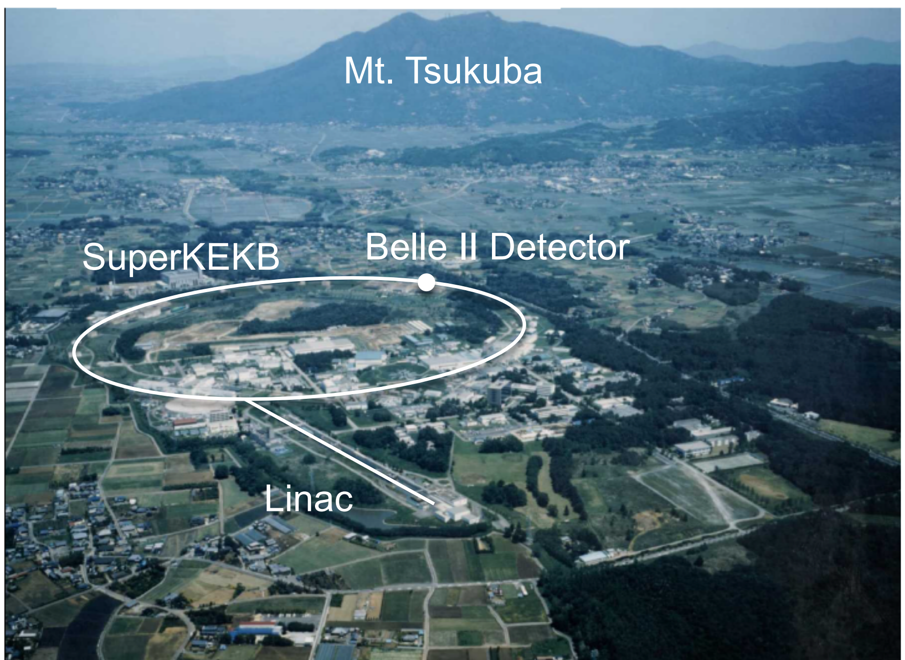
*On behalf of the Belle II Collaboration*

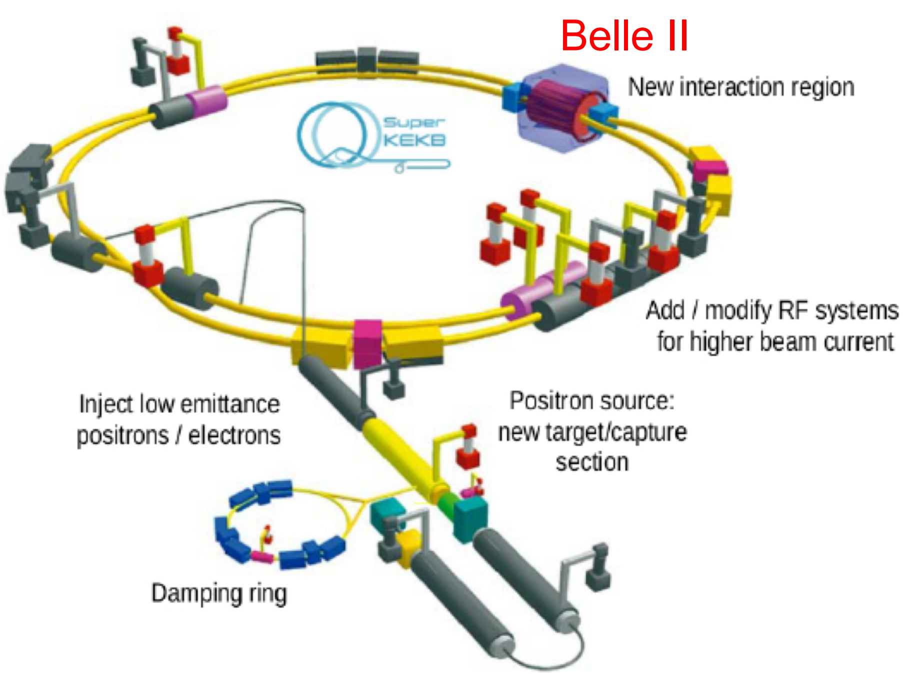

***Beach2018, 17-23 June, Peniche***

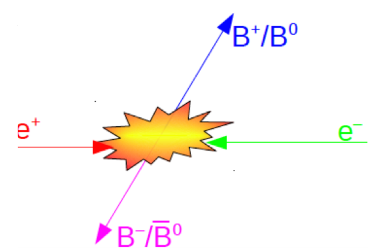



# SuperKEKB



- **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)
- **First collisions recorded on 26 April**




$10^{10}$ BB pairs per year @ full luminosity

Cross sections at Υ(4S)

| Physics process | Cross section (nb) |
|---|---|
| $\Upsilon(4S) \to B\bar{B}$ | 1.2 |
| $e^+e^- \to$ continuum | 2.8 |
| $\mu^+\mu^-$ | 0.8 |
| $\tau^+\tau^-$ | 0.8 |
| Bhabha ($\theta_{\rm lab} \geq 17°$) | 44 |
| $\gamma\gamma$ ($\theta_{\rm lab} \geq 17°$) | 2.4 |
| $2\gamma$ processes [b] | $\sim 80$ |
| Total | $\sim 130$ |

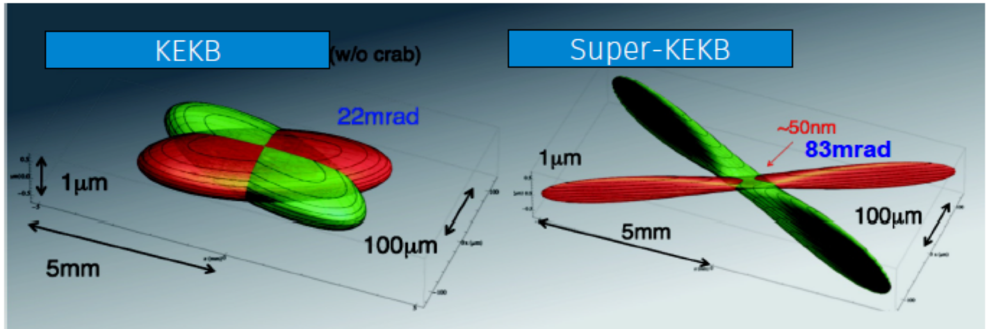
[a] The rate is pre-scaled by a factor of 1/100.

[b] $\theta_{\rm lab} \geq 17°$, $p_t \geq 0.1{\rm GeV}/c$

# From KEKB to SuperKEKB



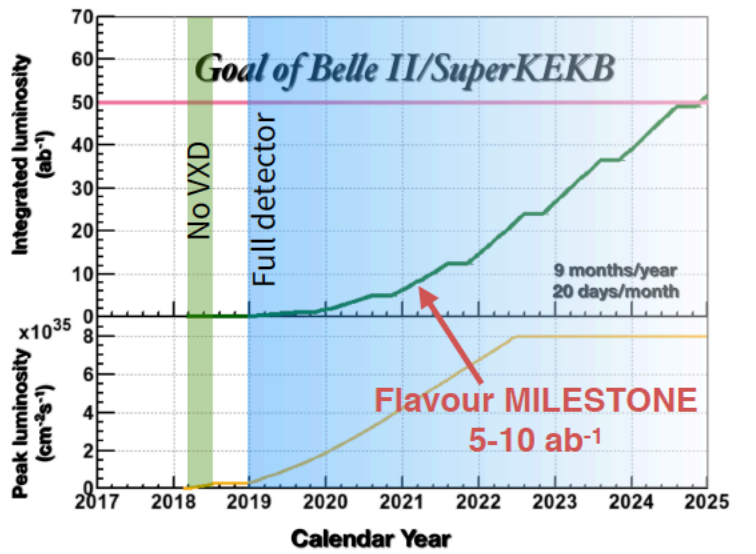
*Nano-beam scheme firstly proposed by P. Raimondi for SuperB*




| | 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 10³⁴ |
| SuperKEKB | 4.0/7.0 | 0.27/0.30 | 3.2/2.5 | 41.5 | 3.6/2.6 | 80 x 10³⁴ |

factor 20 — factor 2-3

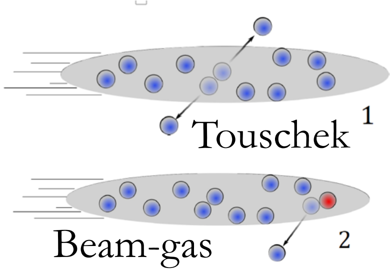
**Factor ~ 40-50 in the luminosity**

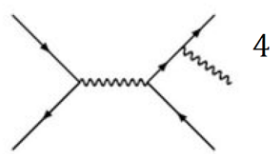



$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

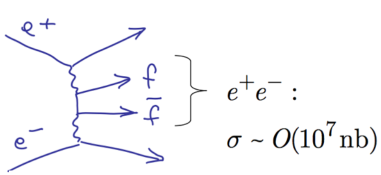
beam current ($I_{\pm}$); vertical beta function at IP ($\beta_{y\pm}^*$)

## Higher backgrounds




Radiative Bhabha




2-photon-processes

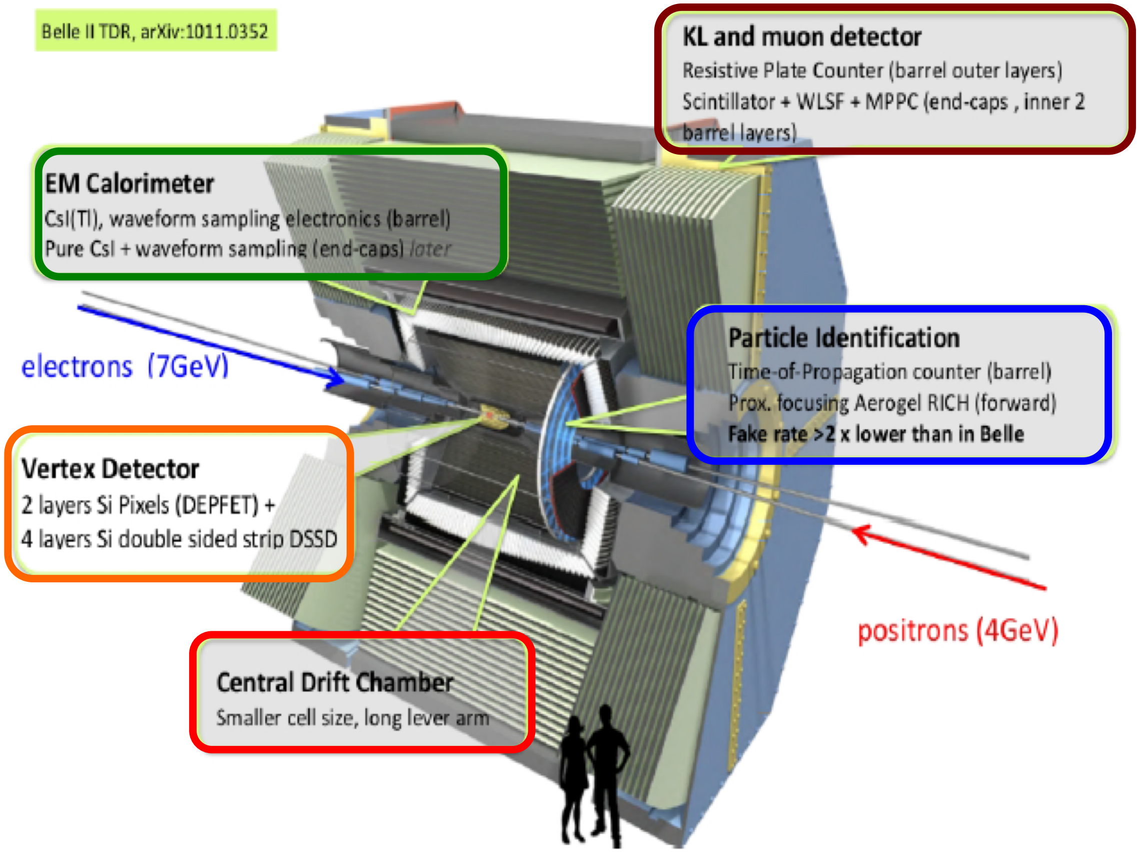
- Radiation damage
- Occupancy in inner detectors
- Fake hits and pile-up

# From Belle to Belle II



**Belle Upgrade**:

- **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)

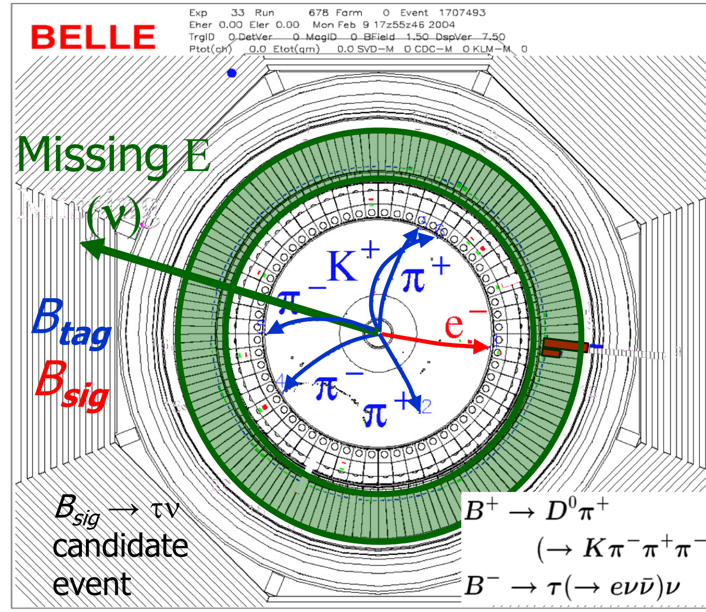



- improved IP and secondary vertex resolution
- better K/π separation and flavor tagging
- robust against machine background
- higher $K_S$, $\pi^0$ and slow pions reconstruction efficiency

# Unique capabilities of $e^+e^-$ B factories - Belle II



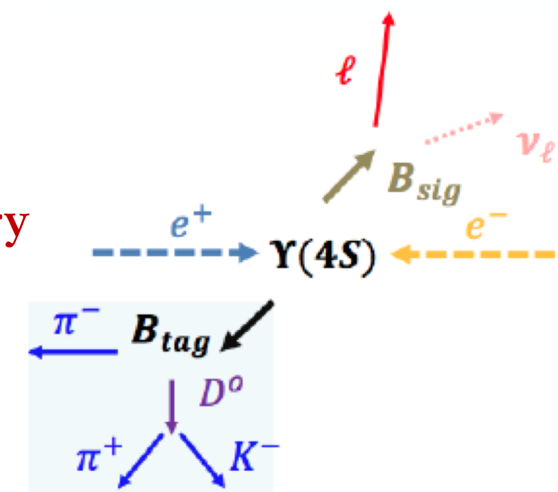
- **Beam energy constraint:** can be adjusted for different resonances Υ(nS)
- **Clean experimental environment:** high B, D, K, τ lepton and neutral final states reconstruction efficiency.
- **BB produced in quantum correlated state:** high flavour tagging efficiencies (34% vs 3% @LHCb)




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

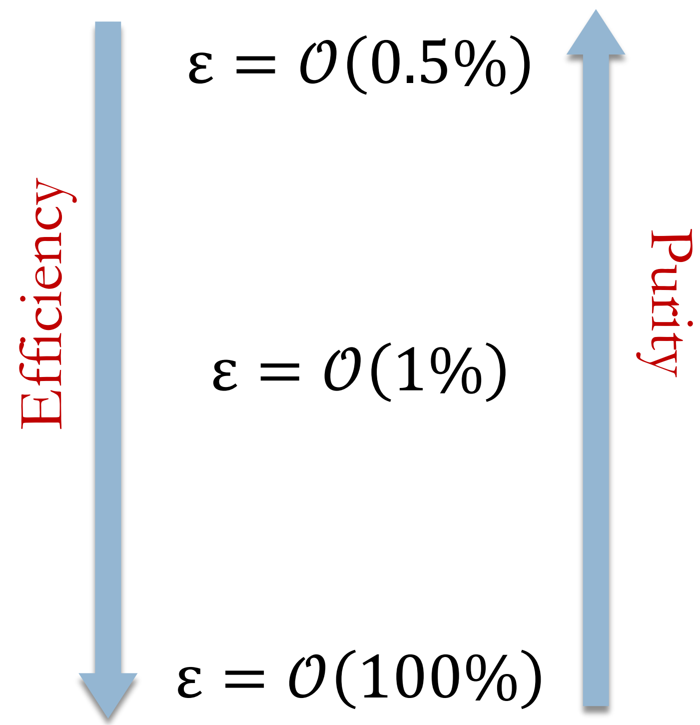
Reconstruction of **channels with missing energy**

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



# B tag reconstruction strategy

- **Hadronic tagging**
  - \- Low efficiency
  - \+ B tag completely reconstructed
- **Semileptonic tagging**
  - \- More backgrounds, B momentum unmeasured
  - \+ Higher efficiency
- **Inclusive tagging (no tagging)**
  - B-tag not explicitly reconstructed
  - Reconstruct the signal and then use the Rest of Event (ROE) to constrain the neutrino momentum



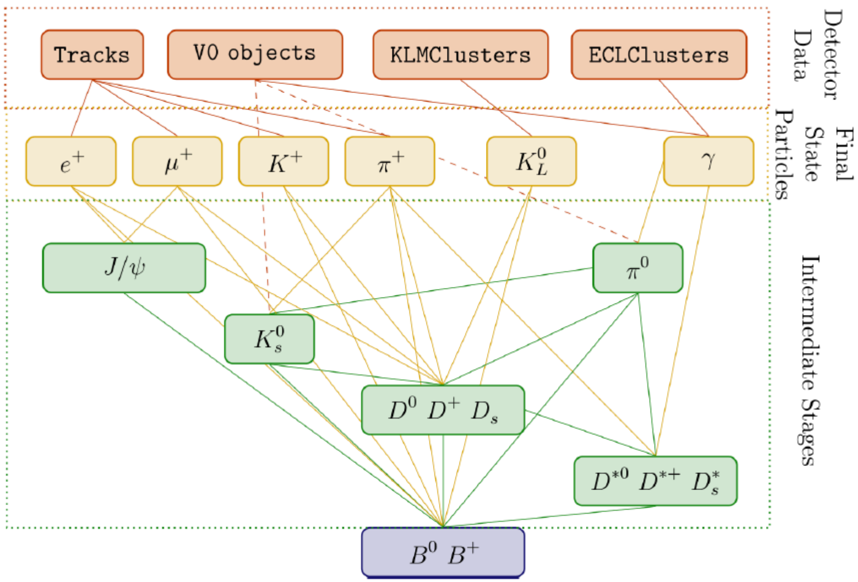
# Tag side reconstruction: Full Event Interpretation (FEI)



- It is an extension of the Full Reconstruction (FR) used in Belle, and uses a multivariate technique to reconstruct the B-tag side through O($10^3$) decay modes in a Υ(4S) decay.

- Hierarchical approach: train multivariate classifiers (MVC) on FSP, then reconstruct intermediate particles and build new dedicated MVC. For each candidate a signal probability is defined, which represents the "goodness" of its reconstruction. It uses:

- PID, tracks momenta, impact parameters;
- Cluster info, energy and direction;
- Invariant masses, daughter momenta, vertex quality;
- Classifier output of the daughters




| Tag algorithm date | MVA | Efficiency (%) | Purity |
|---|---|---|---|
| Belle (2007) | Cut-based | 0.1 | 0.25 |
| Belle FR (2011) | Neurobayes | 0.2 | 0.25 |
| Belle II FEI (2017) | Boosted Decision Trees | 0.5 | 0.25 |

FEI performances with had tag

**Belle FR:** NIM A 654, 432-440 (2011)
**Belle II FEI:** https://ekp-invenio.physik.uni-karlsruhe.de/record/48602/files/EKP-2015-00001.pdf

# Missing energy B meson decays



- Semileptonic decays ($B \to D^{(*)}\tau\nu$ / $D^{(*)}l\nu$ )
- Leptonic decay to tau leptons ($B \to \tau\nu$)
- Penguin electroweak decays ($B \to K^{(*)}\nu\nu$)

BR ~2÷5%

branching ratio

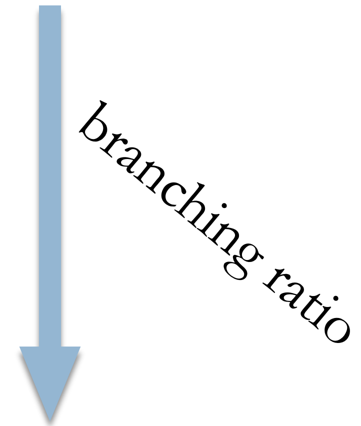
BR ~$10^{-6}$

*Belle II full simulation studies summarized in the Belle II Physics Book to be published in 2018*

# Missing energy B meson decays

- **Semileptonic decays ($B \rightarrow D^{(*)}\tau\nu$ / $D^{(*)}l\nu$)**
- **Leptonic decay to tau leptons ($B \rightarrow \tau\nu$)**
- Penguin electroweak decays ($B \rightarrow K^{(*)}\nu\nu$)

BR $\sim 2 \div 5\%$



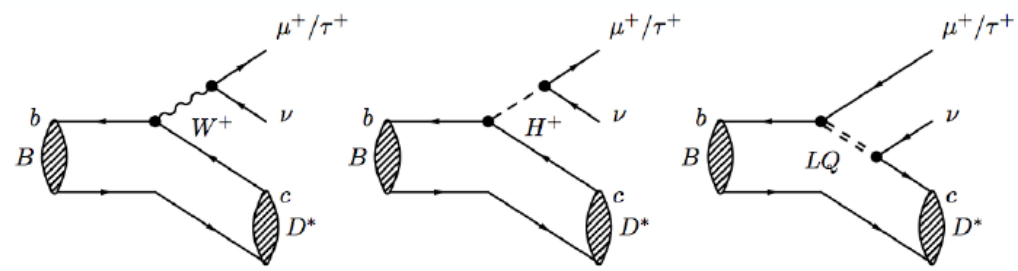

BR $\sim 10^{-6}$

**Updates expected by the next Beach Conference !**

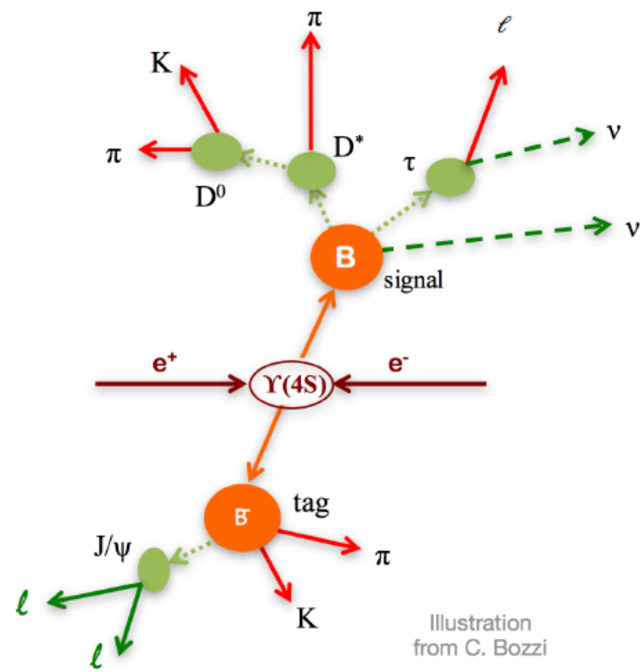
# Semileptonic decays: $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}l\nu$



Clear test of the SM LFU: **NP** (charged Higgs in 2HDM models or Leptoquarks) **can affect the BR and the tau polarization $P_\tau$**




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



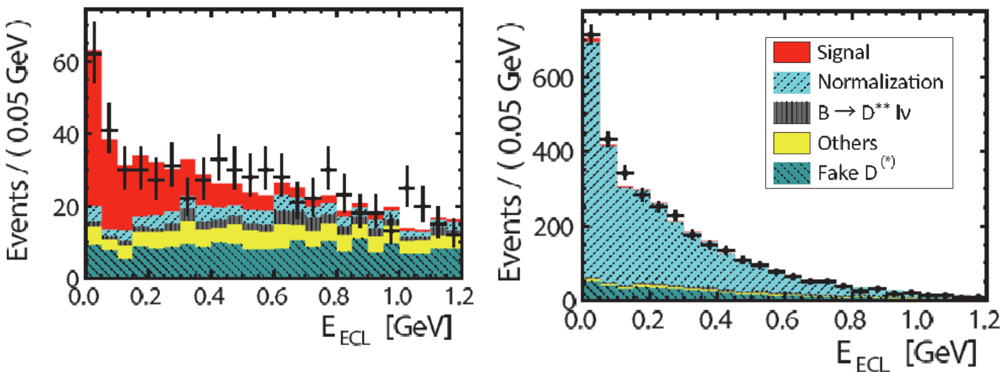

**Advantages of measuring R(D$^{(*)}$):**

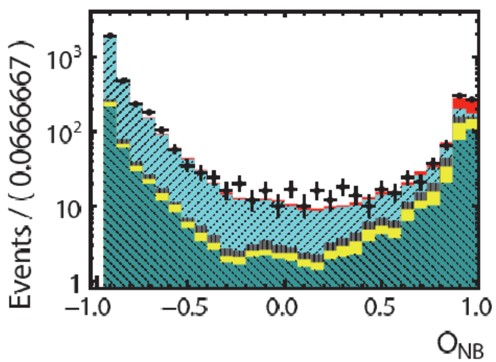
- **experimentally** we eliminate the uncertainties on the tagging efficiencies
- **theoretically** we eliminate the uncertainties on $|V_{cb}|$ and on the semileptonic form factors

# Belle measurements of R(D*) and $P_\tau$

## Measurement of R(D*)

(Belle PRD 94, 072007(2016) **SL tag**)



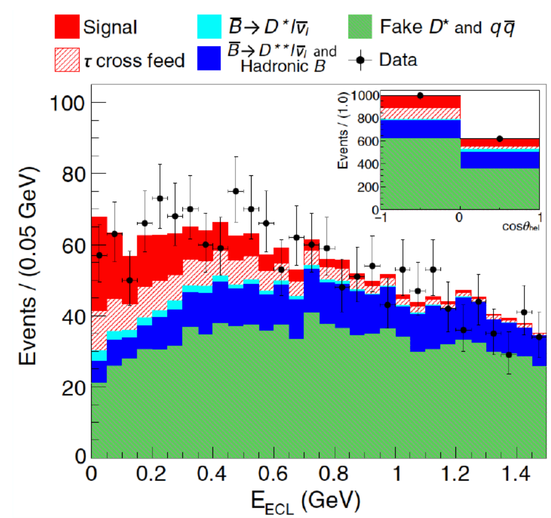

$E_{ECL}$ is the extra energy left in the calorimeter after the signal and tag B are reconstructed

Signal and normalization separation is based on the missing mass and the angle between B meson and D*l system

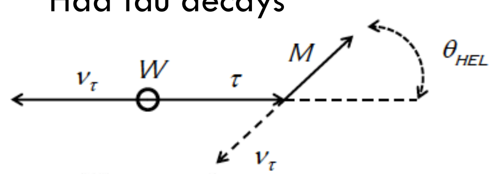
$$\mathcal{R}(D^*) = \frac{1}{2\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)} \cdot \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \cdot \frac{N_{\text{sig}}}{N_{\text{norm}}}$$

## Measurement of $P_\tau$

Belle PRL 118, 211801 (2017) **Had tag**




Had tau decays

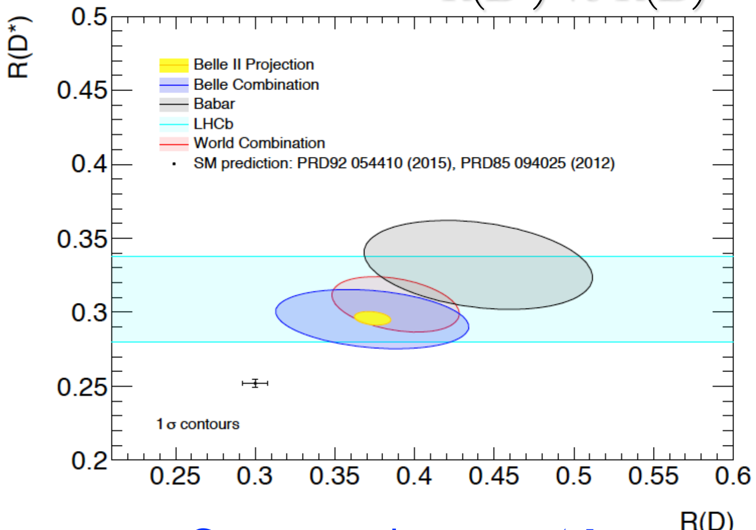



Extract the fractions with positive and negative tau helicity

Results in the next page

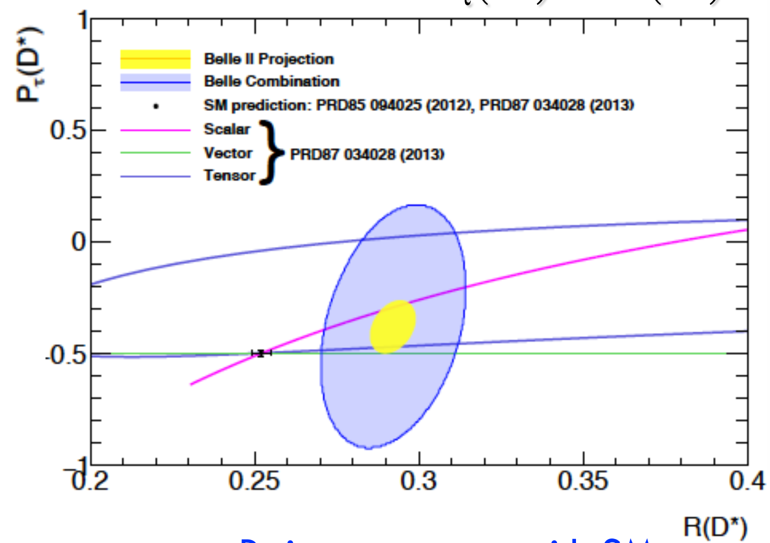
# $R(D^{(*)})$ and $P_\tau$ measurements and Belle II projections

$R(D^*)$ vs $R(D)$




Current combination: 4.1σ from the SM

$P_\tau(D^*)$ vs $R(D^*)$



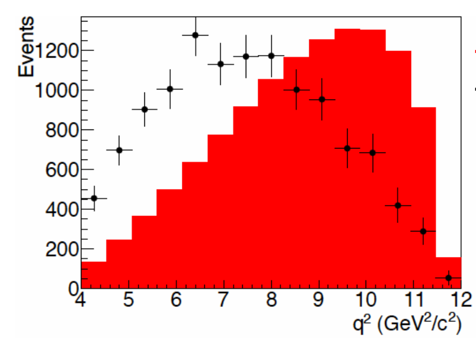

$P_\tau$ in agreement with SM

| | 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

Belle II full simulation studies in progress

Main systematics: $B \to D^{**}l\nu$ modelling, hadronic B decay composition, yield of fake D* candidates

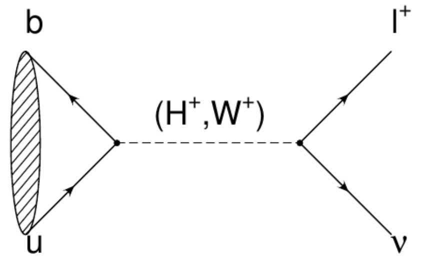



50 $ab^{-1}$ projection of subtracted $q^2$ spectrum in $B \to D^{(*)}\tau\nu$

# Leptonic B decays

- Helicity suppressed decays

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




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

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

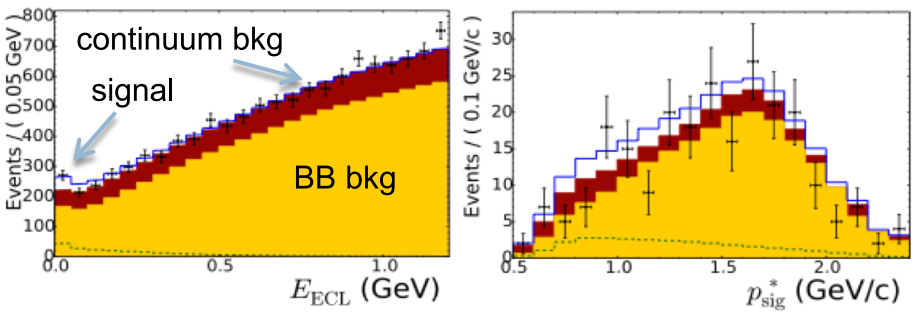
- Clean theoretically, hard experimentally: only B → τν has been measured

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

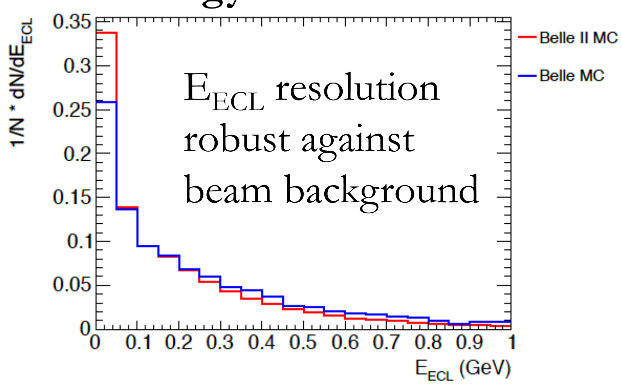


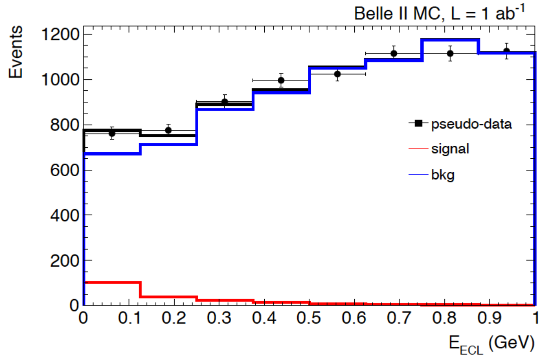
# Leptonic B decays: $B \to \tau\nu$

## 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

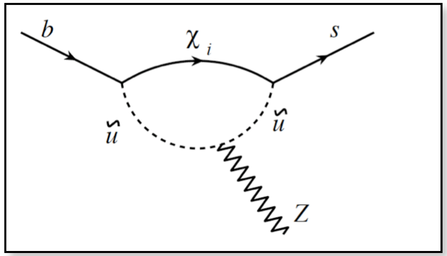
| | Integrated Luminosity ( $ab^{-1}$) | 1 | 5 | 50 |
|---|---|---|---|---|
| hadronic tag | statistical uncertainty (%) | 29.2 | 13.0 | 4.1 |
| | systematic uncertainty (%) | 12.6 | 6.8 | 4.6 |
| | total uncertainty (%) | 31.6 | 14.7 | 6.2 |
| semileptonic tag | statistical uncertainty (%) | 19.0 |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

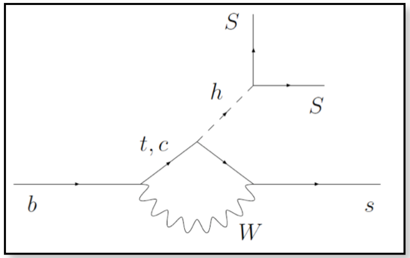
Observation at ~3 $ab^{-1}$

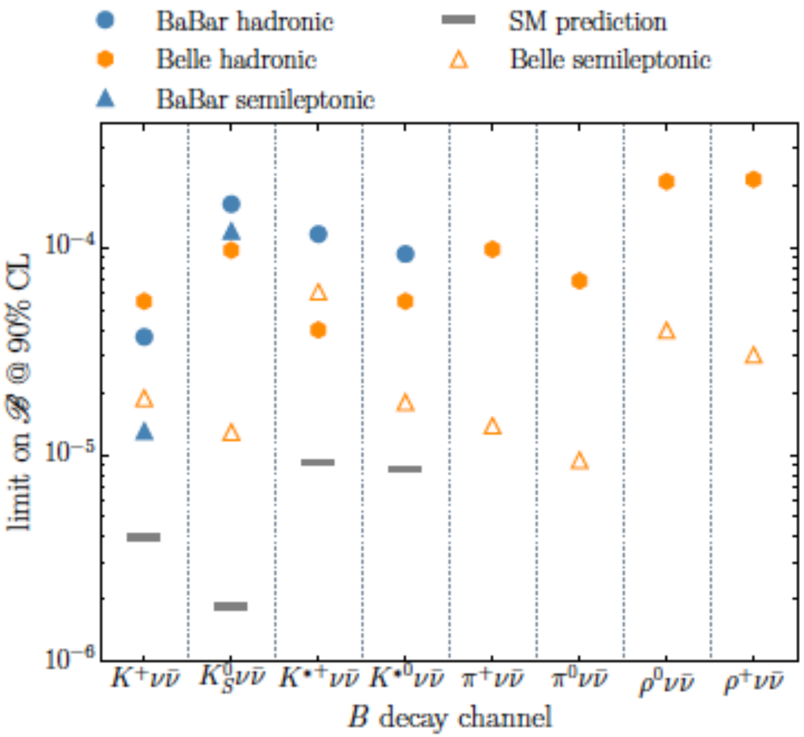
# Flavour changing neutral current $B \to K^{(*)}\nu\bar{\nu}$

- 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.)

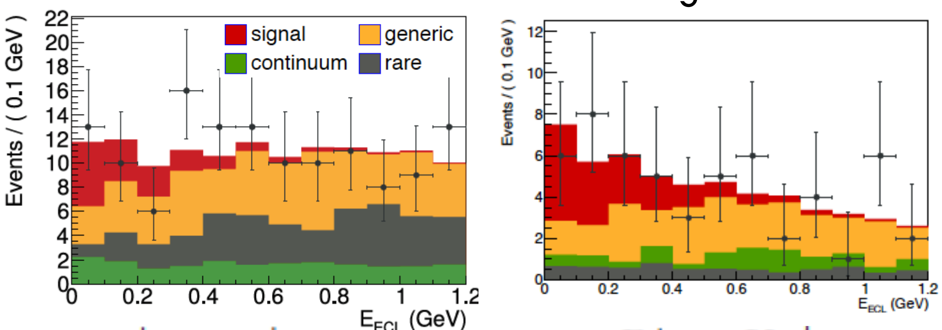
Belle PRD(R) 96, 091101 (2017)




Belle measurement with SL tag

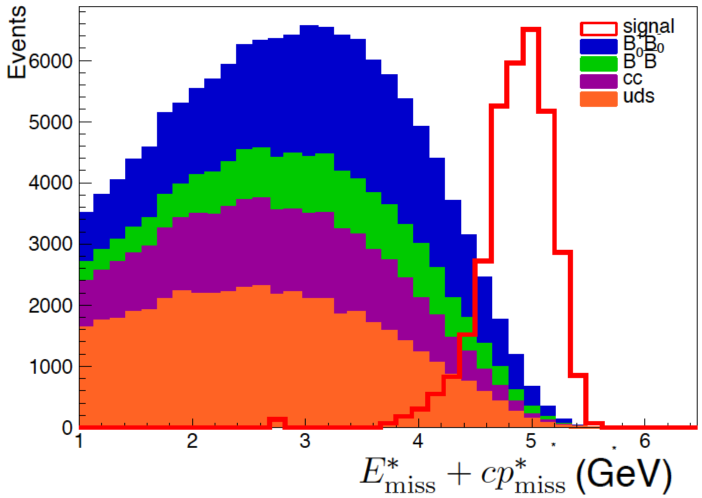



$B^+ \to K^+\nu\bar{\nu}$ $B^+ \to K^{*+}\nu\bar{\nu}$

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

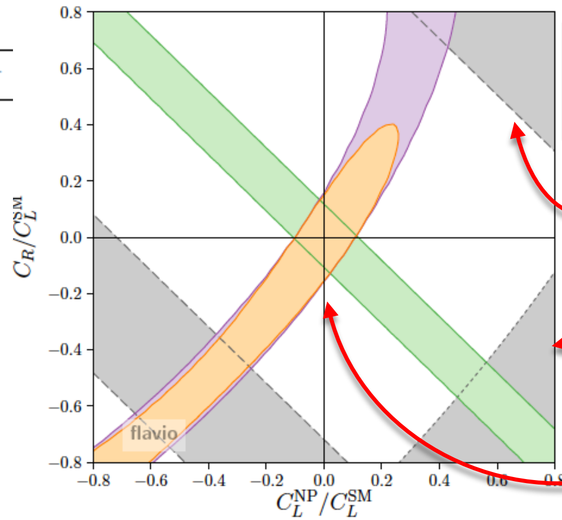
## Belle II full simulation study

- 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 $ab^{-1}$

# Conclusions



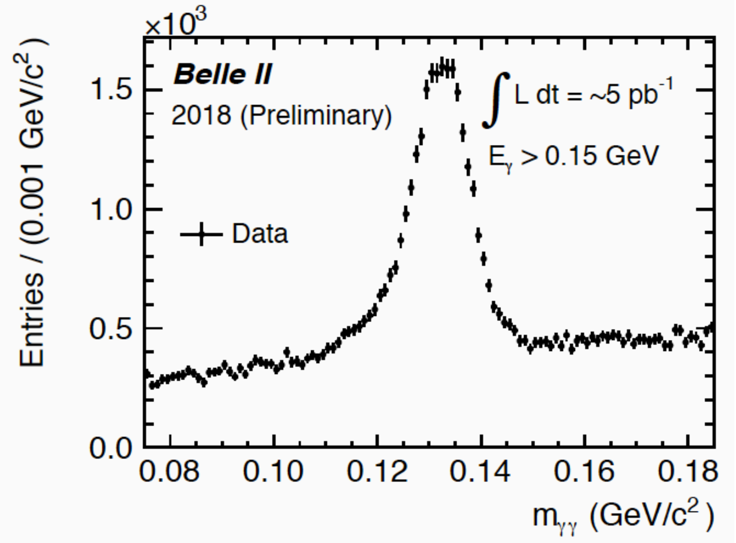
- Unique capabilities of Belle II to study **B decays with missing energy in the final state**
- Within the first **two years of data taking** Belle II will collect **5 to 10 $ab^{-1}$** and will be able to address the Lepton Flavour Universality Violation by precisely measuring **R(D)** and **$R(D^*)$**
- Belle II will also be able to test new physics scenarios precisely measuring **leptonic B decays into taus** (first two years) and **FCNC processes** (with less than half of the total dataset)
- In addition Belle II will also have the sensitivity to shed light on the **$|V_{ub}|$ puzzle** from inclusive and exclusive semileptonic decays and investigate other rare processes suppressed in the SM ($B \rightarrow l\nu\gamma$, $B \rightarrow l\nu$, $B \rightarrow \nu\nu$)

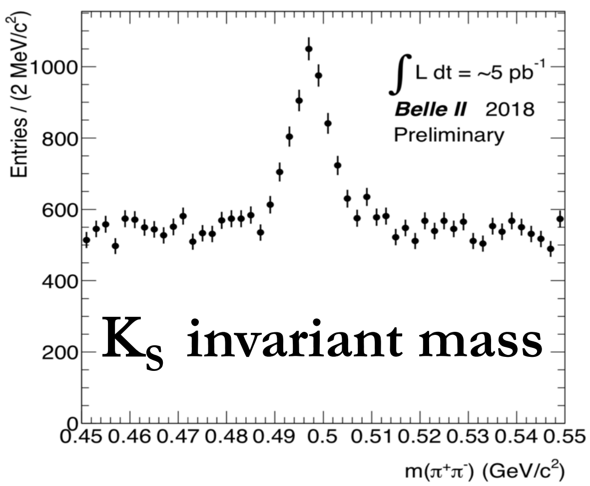
# Thanks !

# Backup

# First data (particles re-discovery)

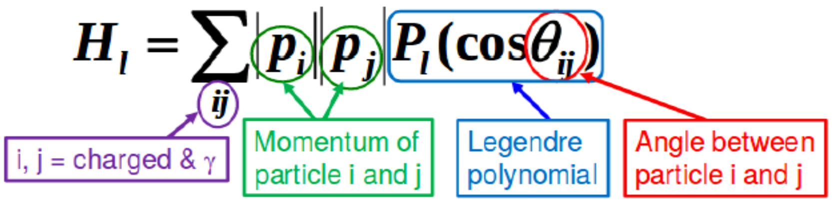
## $\pi^0$ invariant mass

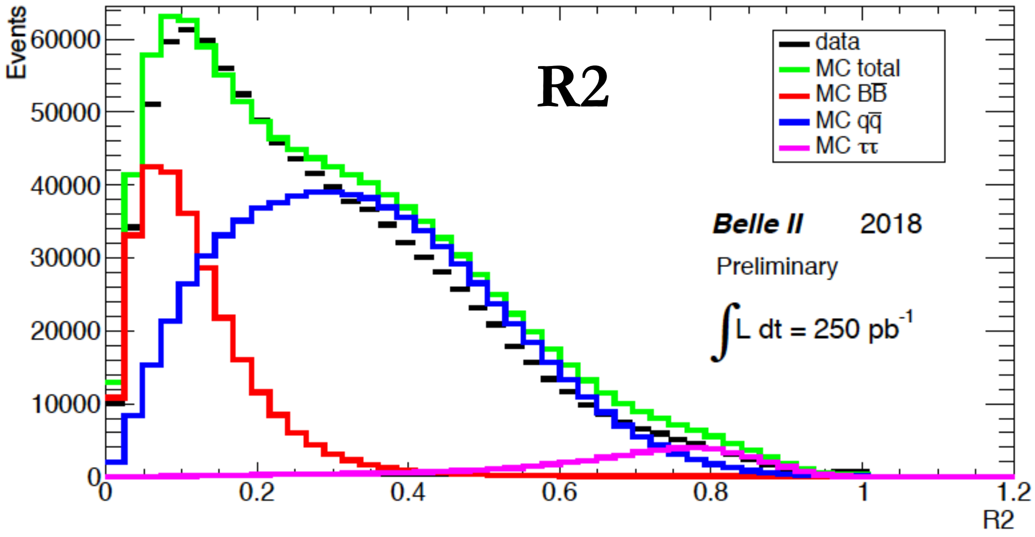



**R2** is the ratio between $H_2$ and $H_0$

$$H_l = \sum_{ij} |p_i||p_j| P_l(\cos\theta_{ij})$$



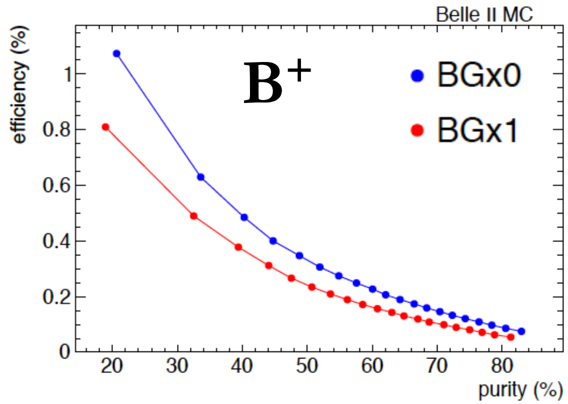



# Improvement in Belle II algorithms: background rejection



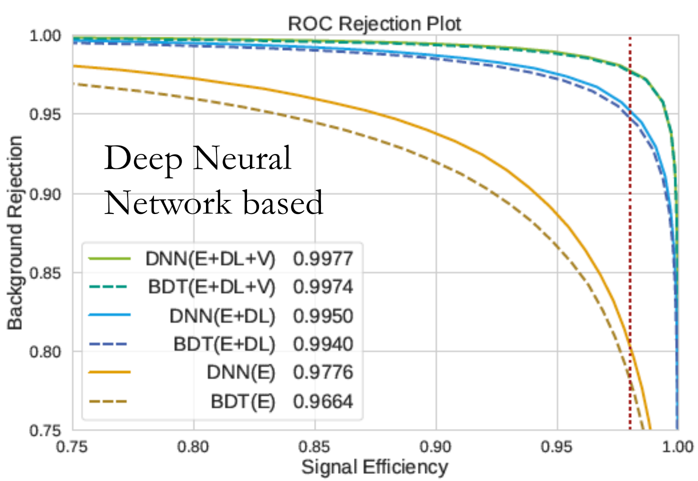
## FEI performance with hadronic B-tag reconstruction

| Tag algorithm date | MVA | Efficiency | Purity |
|---|---|---|---|
| Belle (2007) | Cut-based | 0.1 | 0.25 |
| Belle FR (2011) | Neurobayes | 0.2 | 0.25 |
| Belle II FEI (2017) | Boosted Decision Trees | 0.5 | 0.25 |

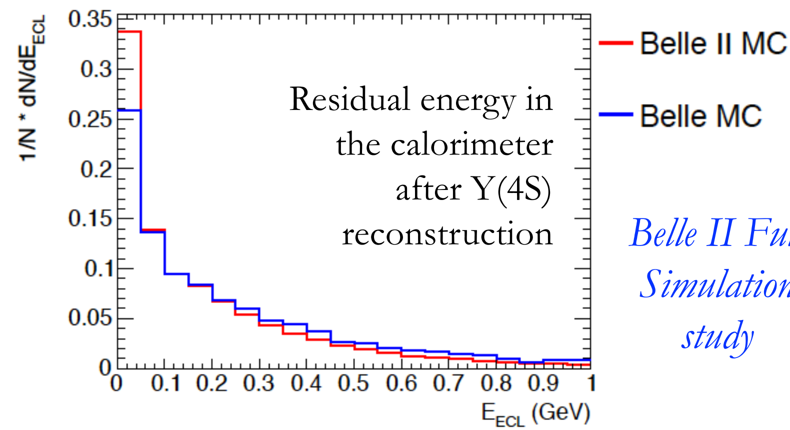



*Belle II Full Simulation study*

## Rejection of the continuum $e^+e^- \to q\bar{q}$ background



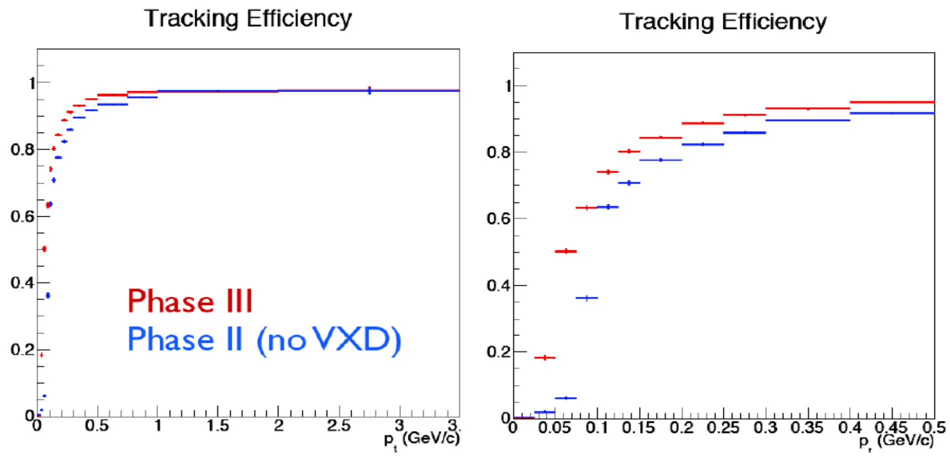

## Beam background rejection MVA using ECL clusters info




*Belle II Full Simulation study*

# Phase II

## Tracking without VXD

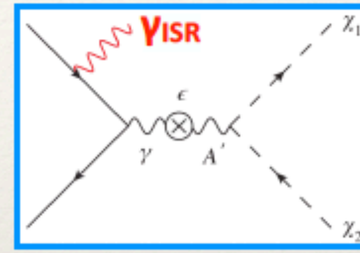



What can we do with phase II data ?

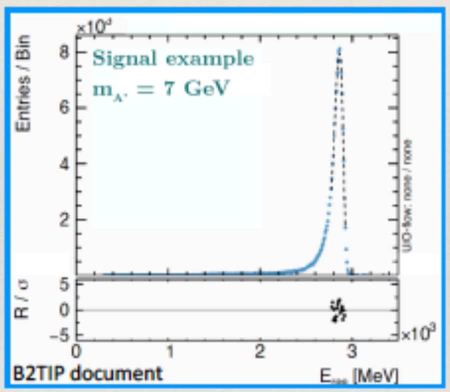
- Background studies
- Detector and trigger performance studies
- Simulation validation
- Exercising of calibration and alignment procedures
- Reconstruction algorithm tuning
- **Physics measurements (quarkonia and dark sector)**

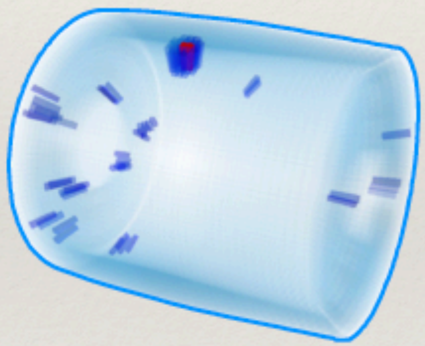
# Early physics: the dark sector

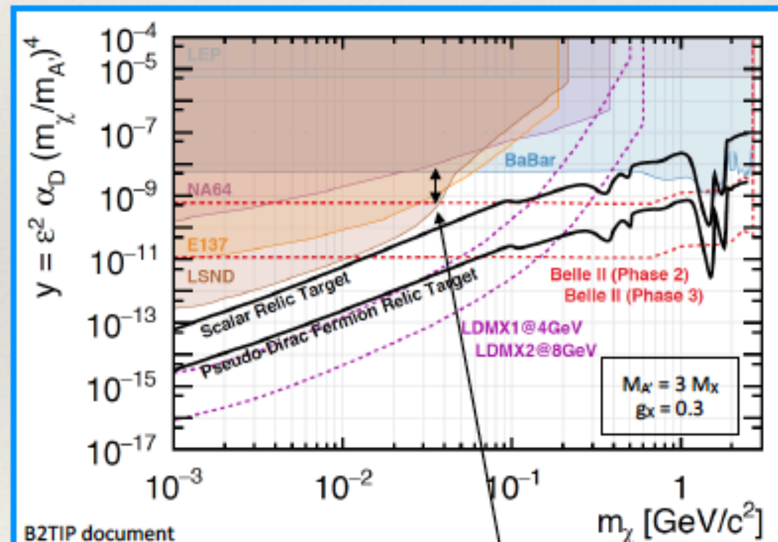
- Light dark matter and light mediator searches in Belle II:
  - Dark photons, dark higgs, axion-like particles (ALPs), mass scale ~GeV or sub-GeV.
  - Production, e.g.: $e^+e^- \rightarrow M+X$, $e^+e^- \rightarrow Y(ns) \rightarrow M+X$, $e^+e^- \rightarrow B+X \rightarrow K+M+X$.




- 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.



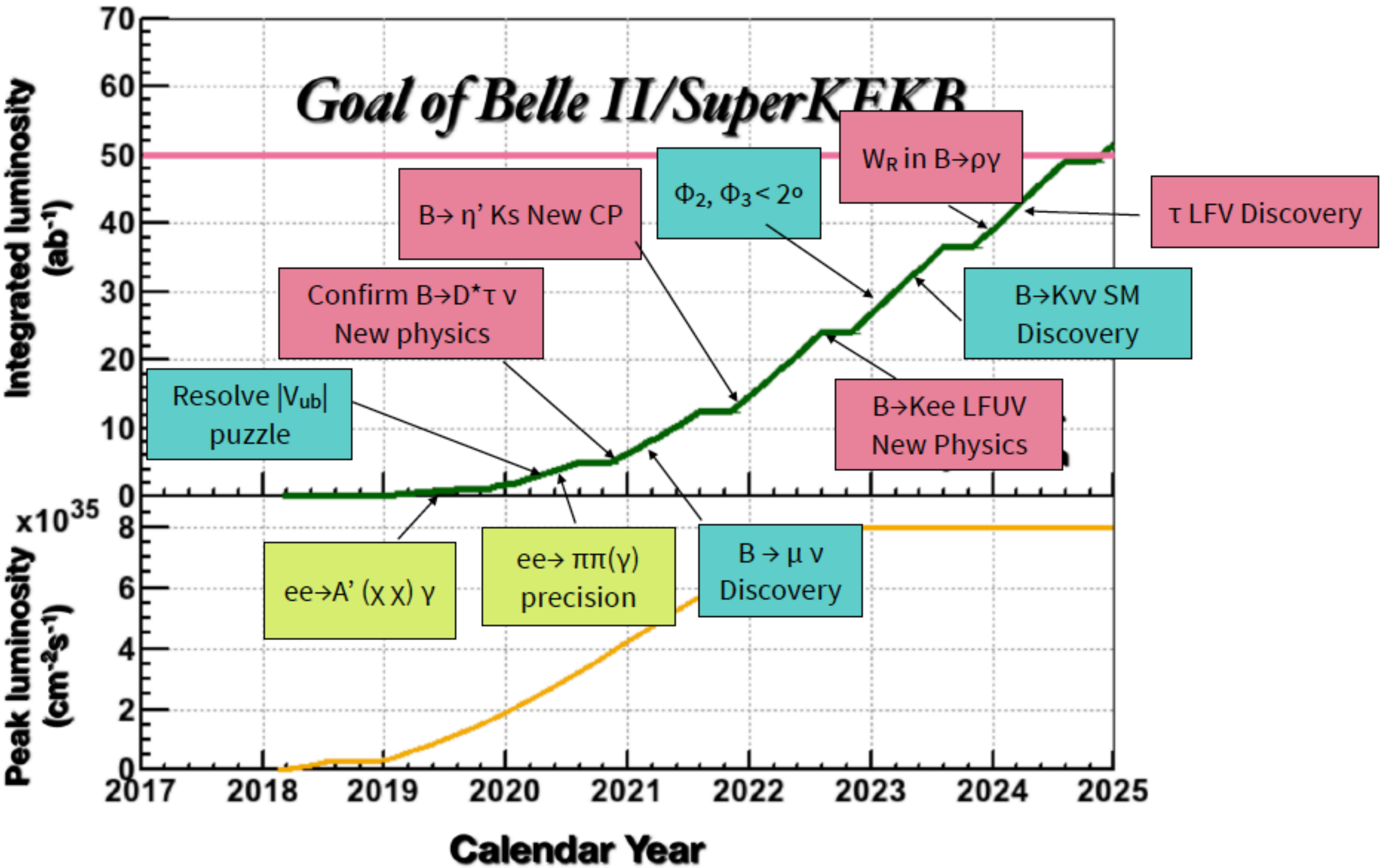






- Particularly relevant with Phase 2 data:
  - Low luminosity and lower beam background allow to open up triggers.
  - Small dataset can still give world best sensitivity.

Belle II calo more hermetic than BaBar

# Roadmap


Goal of Belle II/SuperKEKB
Integrated luminosity (ab-1)
Peak luminosity (cm-2s-1)
x1035
Calendar Year
2017
2018
2019
2020
2021
2022
2023
2024
2025
Resolve |Vub| puzzle
Confirm B→D*τ ν New physics
B→ η' Ks New CP
Φ2, Φ3 < 2o
WR in B→ργ
τ LFV Discovery
B→Kνν SM Discovery
B→Kee LFUV New Physics
ee→A' (χ χ) γ
ee→ ππ(γ) precision
B → μ ν Discovery

# FEI Calibration

FEI validated on Belle real data

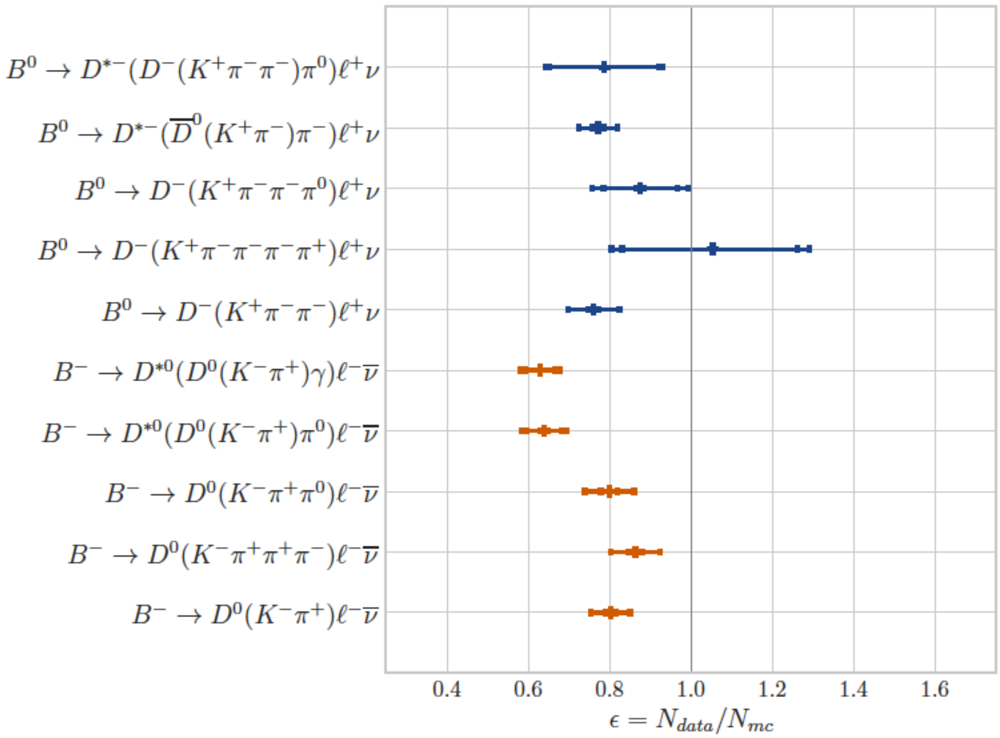



Figure 4.18.: The overall efficiency correction calculated by measuring the known branching fractions of 10 control channels on converted Belle data [76].

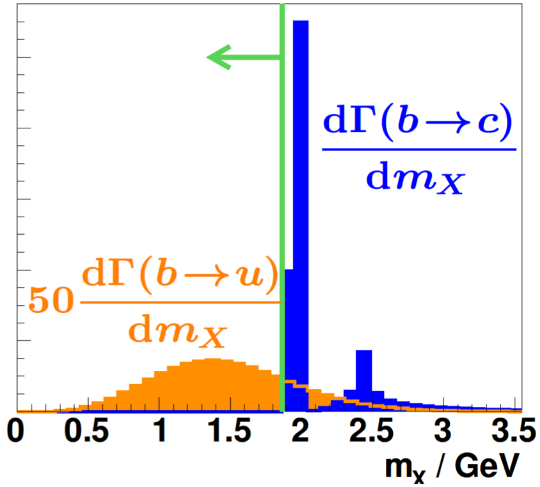
*Thomas Keck's master thesis*

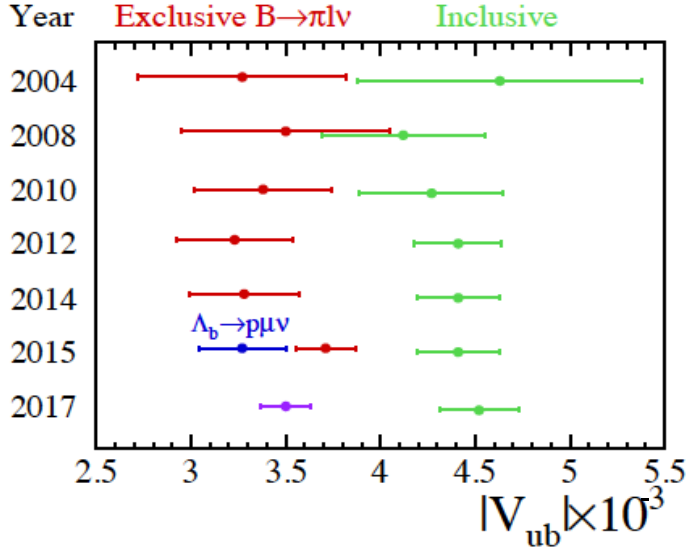
# Semileptonic decays: $B \rightarrow X_u l\nu$



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

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




Tension between inclusive and exclusive $|V_{ub}|$ measurements

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

Measured BR in fiducial phase space region

B meson lifetime

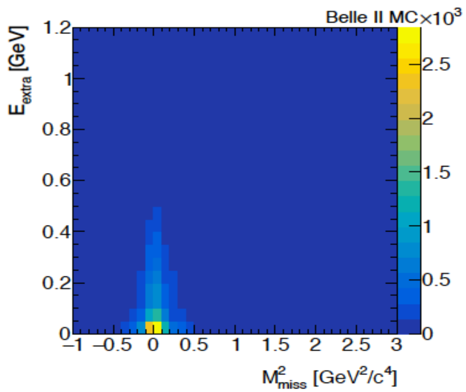
Predicted partial decay rate

# Semileptonic decays: $B \rightarrow X_u l\nu$

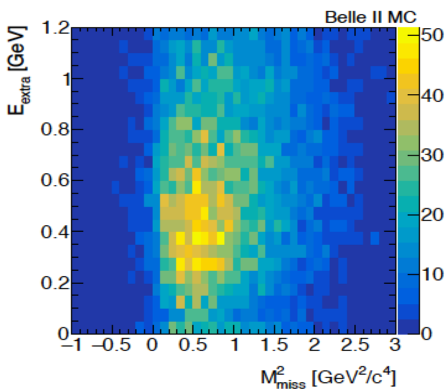


*Belle II Full Simulation study*

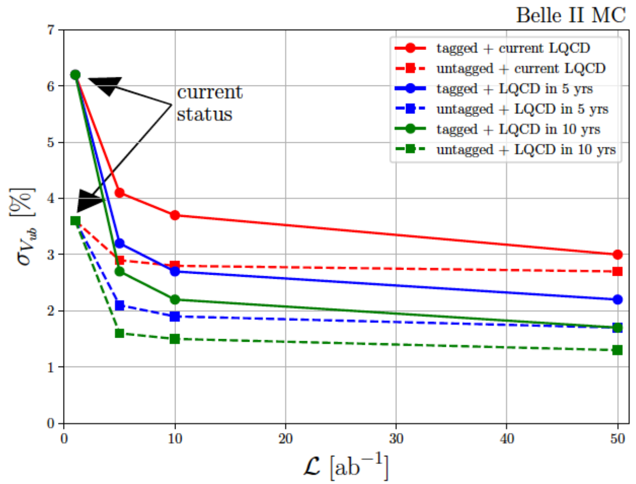
- $B^0 \rightarrow \pi\, l\, \nu$ decay
  - Untagged or tagged (with FEI)
  - Exploit missing mass and extra energy in the calorimeter
  - $\mathcal{B} \sim f_i |V_{ub}|^2$; form factors $f_i$ computed with LQCD (PRD 91, 074510 (2015))




signal



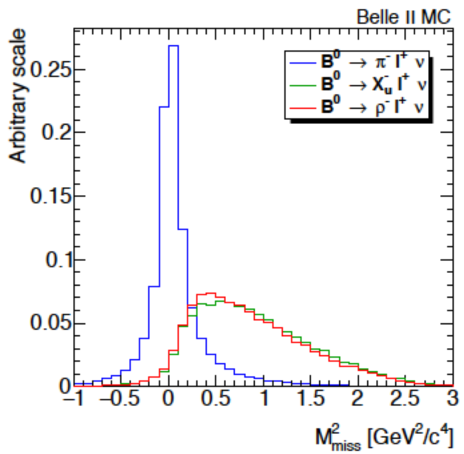

background




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

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

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



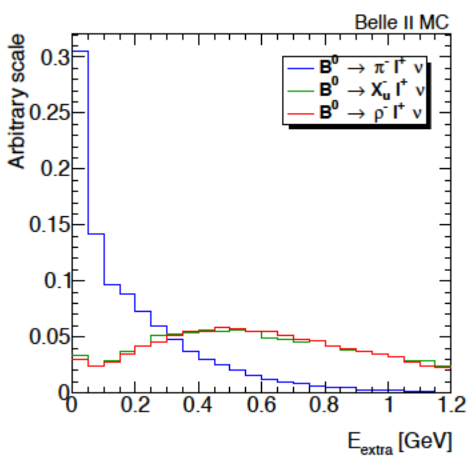




Table 54: Summary of systematic uncertainties on the branching fractions of $B^0 \to \pi^- \ell^+ \nu_\ell$ decays in hadronic tagged and untagged Belle analyses with 711 fb$^{-1}$ [271] and 605 fb$^{-1}$ [269] data samples, respectively. The estimated precision limit for some sources of systematic uncertainties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



Belle PRD 94, 072007(2016) SL tag

| | $\mathcal{R}(D^*)$ [%] | | |
|---|---|---|---|
| Sources | $\ell^{\rm sig} = e, \mu$ | $\ell^{\rm sig} = e$ | $\ell^{\rm sig} = \mu$ |
| MC size for each PDF shape | 2.2 | 2.5 | 3.9 |
| PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$ | $^{+1.1}_{-0.0}$ | $^{+2.1}_{-0.0}$ | $^{+2.8}_{-0.0}$ |
| PDF shape of $B \to D^{**}\ell\nu_\ell$ | $^{+1.0}_{-1.7}$ | $^{+0.7}_{-1.3}$ | $^{+2.2}_{-3.3}$ |
| PDF shape and yields of fake $D^{(*)}$ | 1.4 | 1.6 | 1.6 |
| PDF shape and yields of $B \to X_c D^*$ | 1.1 | 1.2 | 1.1 |
| Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$ | 1.2 | 1.5 | 1.9 |
| Modeling of semileptonic decay | 0.2 | 0.2 | 0.3 |
| $\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$ | 0.2 | 0.2 | 0.2 |
| Total systematic uncertainty | $^{+3.4}_{-3.5}$ | $^{+4.1}_{-3.7}$ | $^{+5.9}_{-5.8}$ |

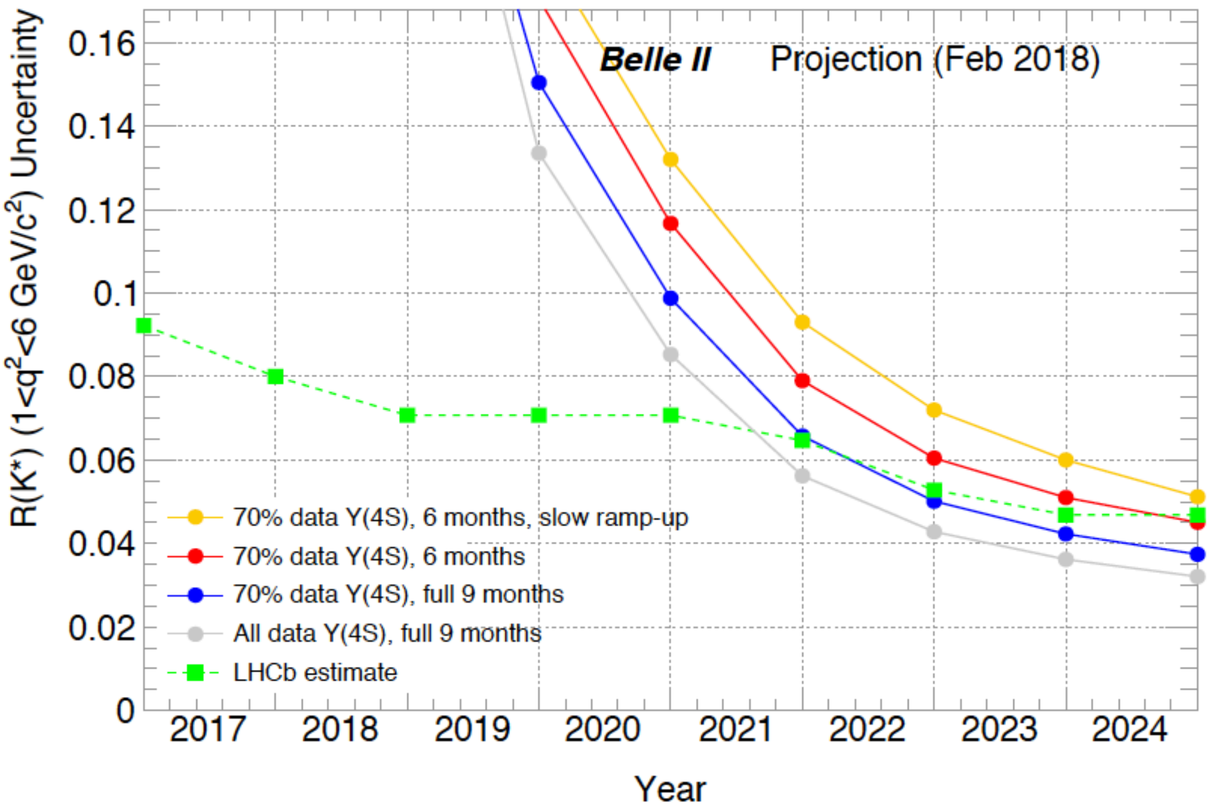
# Semitauonic decays: R(D) and R(D*)

| Experiment | Tag method | τ mode | $R_D$ | $R_{D^*}$ | ρ |
|---|---|---|---|---|---|
| Belle 07* | Inclusive | e ν ν, π ν | 0.38±0.11 | 0.34±0.08 | - |
| Belle 10* | Inclusive | l ν ν, π ν | | | |
| Babar 12 | Hadronic | l ν ν | 0.440±0.058±0.042 | 0.332±0.024±0.018 | -0.27 |
| **Belle 15** | **Hadronic** | **l ν ν** | **0.375±0.064±0.026** | **0.293±0.038±0.015** | **-0.32** |
| **Belle 16** | **Semileptonic** | **l ν ν** | **IN PROGRESS** | **0.302±0.030±0.011** | **-** |
| **Belle 17** | **Hadronic** | **π ν, ρ ν** | **-** | **0.270±0.035±0.027** | **-** |
| LHCb 16 | - | l ν ν | - | 0.336±0.027±0.030 | - |
| LHCb 17 | | 3 π ν | - | 0.286±0.019±0.033 | - |
| **Belle ave.** | **SL+Had** | **-** | **0.374±0.061** | **0.292±0.020±0.012** | **-0.29** |

| | Experiment | SL tag $R_{D^*}$ | Had tag $R_{D^*}$, τ→h ν | Had tag $R_{D^*}$, τ→l ν ν | Had tag $R_D$, τ→l ν ν |
|---|---|---|---|---|---|
| 1 | MC statistics | 2.2 | 3.5 | - | - |
| **2** | **B → D** l ν modelling** | **+1, -1.7** | **2.4** | **1.5** | **4.2** |
| 3 | B → D* l ν | +1.3, -0.2 | 2.3 | - | - |
| **4** | **D** decay modes** | **(in 2)** | **(in 2)** | **1.3** | **3.0** |
| **5** | **Hadronic B decays** | **1.1** | **7.3** | - | - |
| **6** | **B → D** τ ν** | **(in 2)** | **(in 2)** | - | - |
| 7 | Fake $D^{(*)}$ | 1.4 | 0.2 | 0.3 | 0.5 |
| 8 | Fake lepton | - | - | 0.6 | 0.5 |
| 9 | Lepton ID | 1.2 | 1.8 | 0.5 | 0.5 |
| 10 | τ Br | 0.2 | 0.3 | 0.2 | 0.2 |
| 11 | Other | - | 2.3 | - | - |
| | Total | 3.5 | 9.9 | 5.2 | 7.1 |

# $B \rightarrow sll$ : 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.

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



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

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

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

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

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

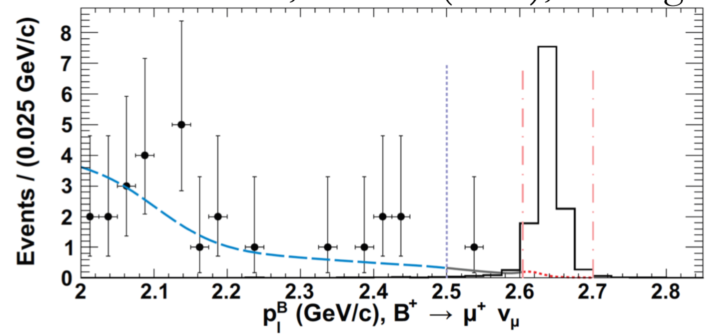
# Leptonic B decays: B → μν and radiative B → lνγ



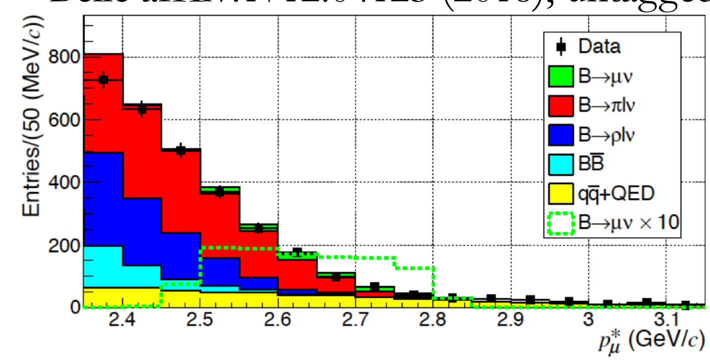
## B → μν

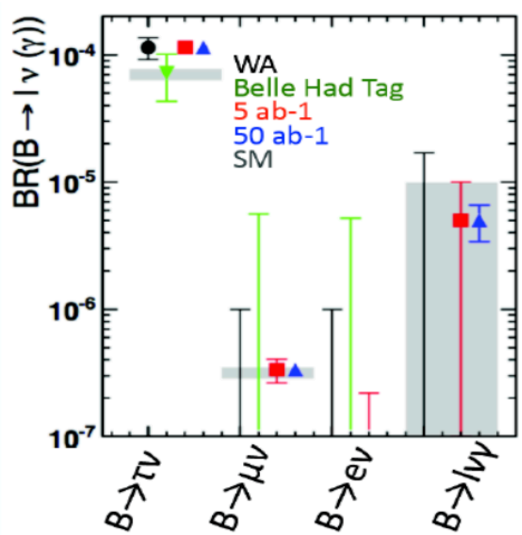
- Two body decay: $p_\mu^* = m_B/2$ in B rest frame
- Tagging → better $p_\mu^*$ resolution but small statistics
- ~2.4σ measurement

Belle PRD 91, 052016 (2015), had tag




Belle arXiv:1712.04123 (2018), untagged




## B → lνγ

- Radiative decay lifts the helicity suppression
- Allows a measurement of $\lambda_B$ → 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

# Physics prospects: Belle II vs LHCb



| Observables | Expected th. accuracy | Expected exp. uncertainty | Facility (2025) |
|---|---|---|---|
| UT angles & sides | | | |
| $\phi_1$ [°] | *** | 0.4 | Belle II |
| $\phi_2$ [°] | ** | 1.0 | Belle II |
| $\phi_3$ [°] | *** | 1.0 | Belle II/LHCb |
| $\|V_{cb}\|$ incl. | *** | 1% | Belle II |
| $\|V_{cb}\|$ excl. | *** | 1.5% | Belle II |
| $\|V_{ub}\|$ incl. | ** | 3% | Belle II |
| $\|V_{ub}\|$ 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 |
| $S(B \to K_S^0\pi^0\gamma)$ | *** | 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 |
| $\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$ | *** | 15% | Belle II |
| $\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$ | *** | 20% | Belle II |
| $R(B \to K^*\ell\ell)$ | ** | 0.03 | Belle II/LHCb |

| | Observables | Belle or LHCb* | Belle II | | LHCb | |
|---|---|---|---|---|---|---|
| | | (2014) | 5 $ab^{-1}$ | 50 $ab^{-1}$ | 2018 | 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 |
| | $A_\Gamma$ $[10^{-2}]$ | 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 | | |
| | $A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$ | $-0.21 \pm 0.16 \pm 0.09$ | 0.08 | 0.03 | | |
| Charm Mixing | $x(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$ | $0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$ | 0.14 | 0.11 | | |
| | $y(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$ | $0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$ | 0.08 | 0.05 | | |
| | $\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$ | $0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$ | 0.10 | 0.07 | | |
| | $\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°] | $-6 \pm 11 \pm {}^{4}_{5}$ | 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)
DOI: 10.1093/ptep/0000000000

## The Belle II Physics Book

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

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