Measurements of R(D$^{(*)}$) and other missing energy modes at Belle II

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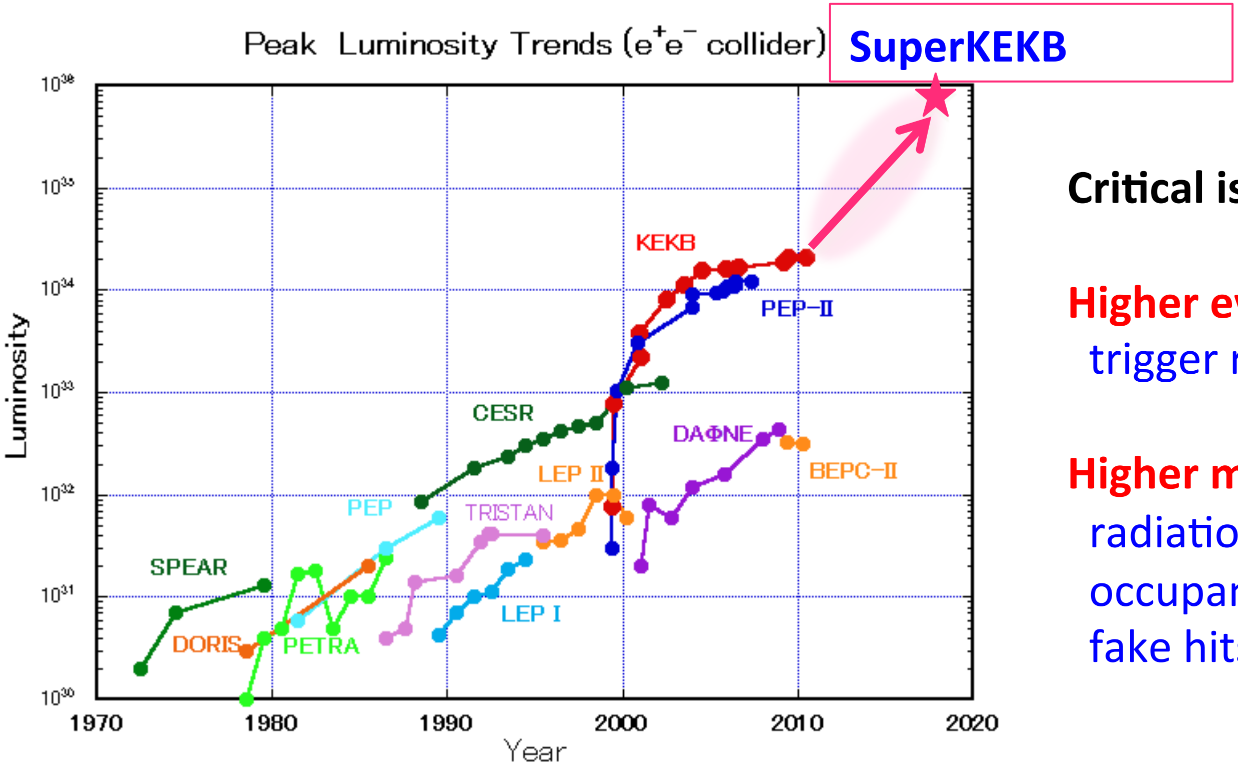
on behalf of the Belle II Collaboration

Outline:

- Belle II and SuperKEKB status
- Missing energy modes reconstruction strategy at Belle II
- Lepton Flavour Universality test with R(D$^{(*)}$)
- B $\rightarrow \tau \nu$ and B $\rightarrow K^{(*)} \nu \nu$

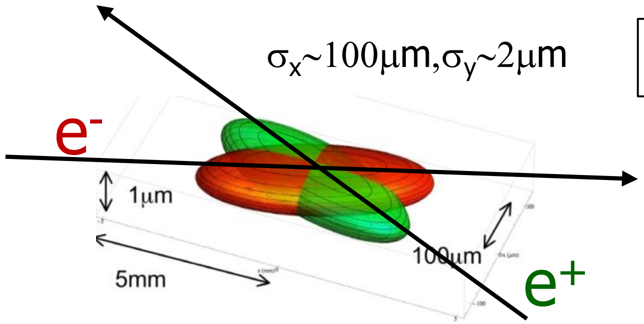
From KEKB → SuperKEKB



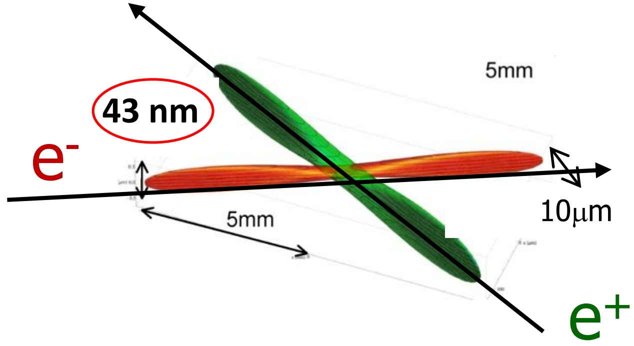
Critical issues at L = 8 x 10^{35} $cm^{-2}s^{-1}$

Higher event rate (x40)
- trigger rate, DAQ, computing

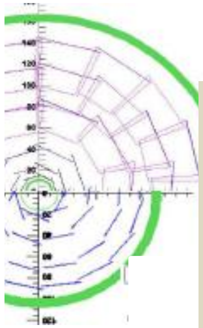
Higher machine backgrounds
- radiation damage
- occupancy
- fake hits and pile-up in the calorimeter



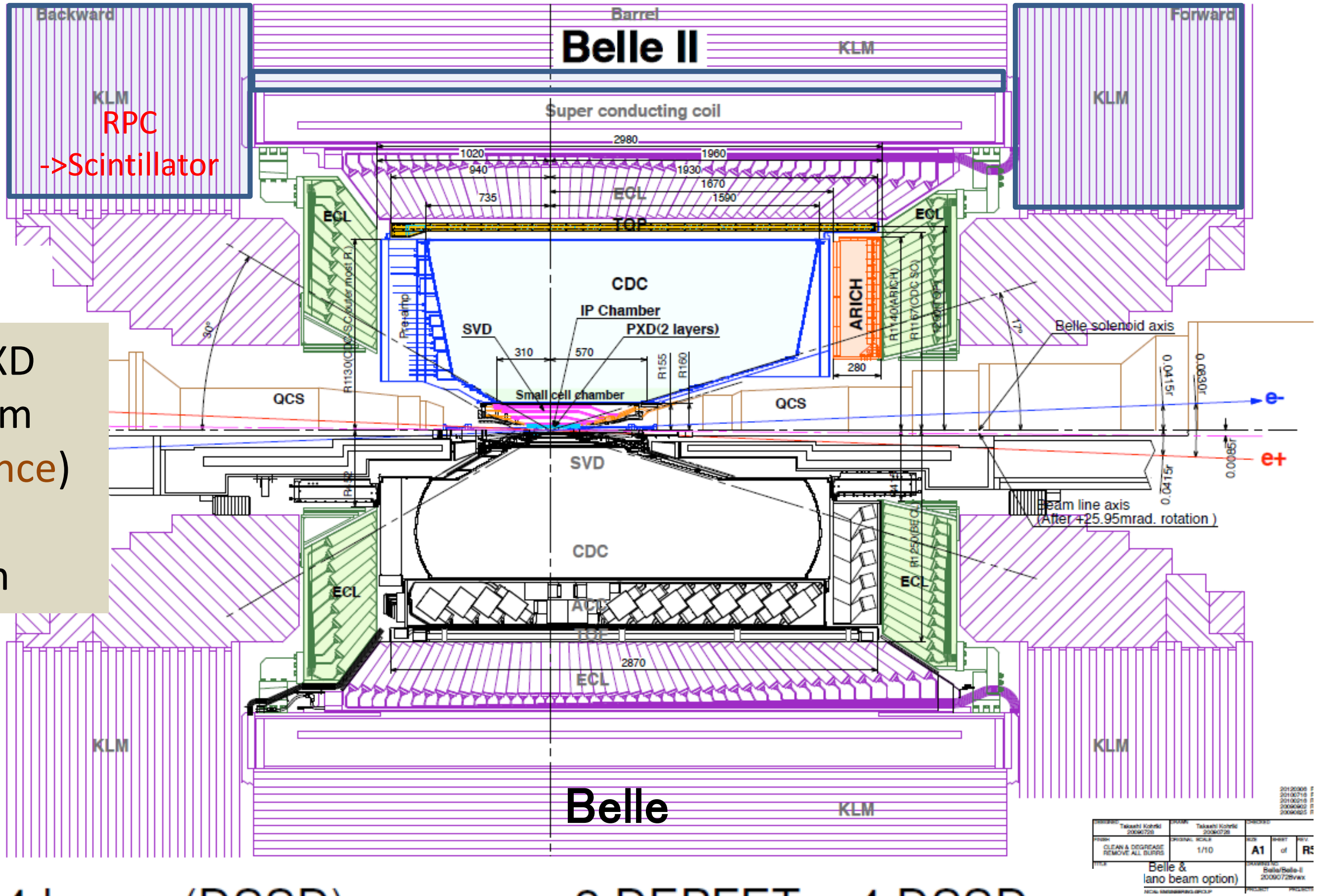
Nano-Beam scheme



Belle → Belle II

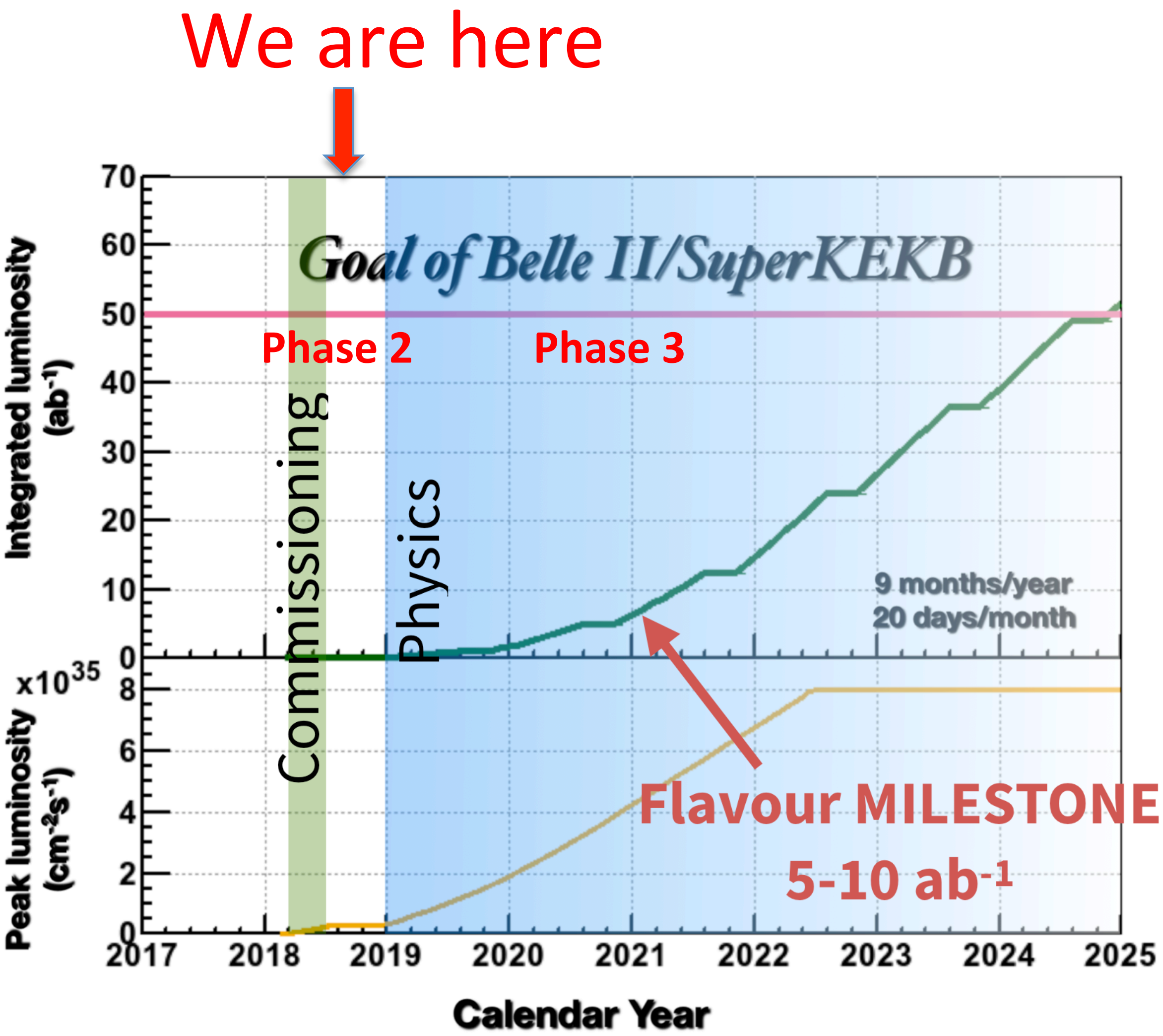


Belle II VXD
R=14-140mm
(Ks acceptance)
Belle SVD
R=20-88mm



SVD 4 layers (DSSD) → 2 DEPFET + 4 DSSD
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH (Better K/p separation)
ECL: waveform sampling
KLM: RPC → Scintillator+SiPM

Belle II data taking



Phase 2:

Ended on July 17 2018
Peak luminosity: 0.5 x 10^{34} $cm^{-2}s^{-1}$
Recorded int. lum.: 500 pb^{-1}
→ 5 × 10^{-4} Belle+Babar dataset

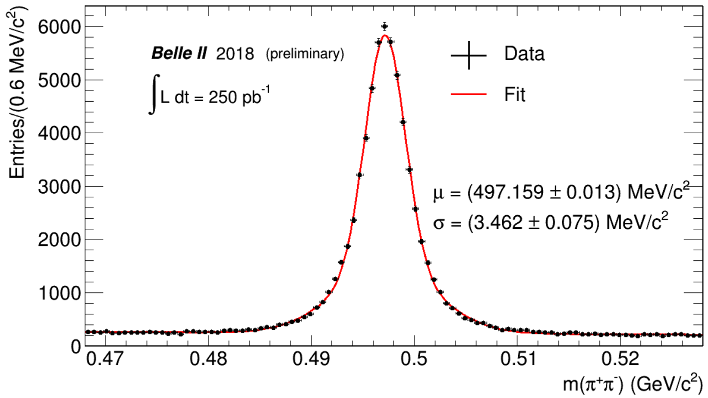
Commisioning run w/o vertex
understand machine backgrounds
and detector

Phase 3:
Physics run with complete detector
Begins early 2019

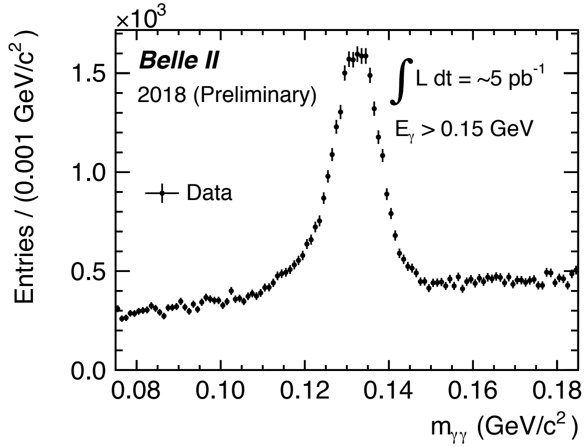
Will collect 50 x Belle data
by 2025

Belle II performances in Phase 2

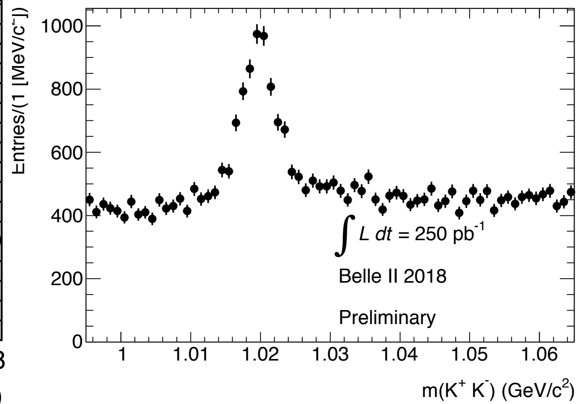
$K_s \rightarrow \pi\, \pi$



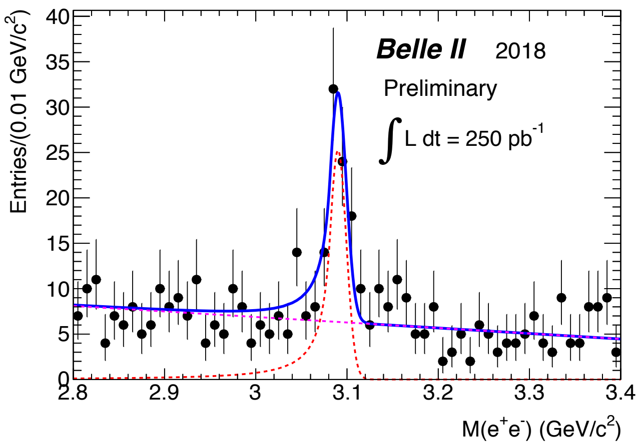
$\pi^0 \rightarrow \gamma\gamma$



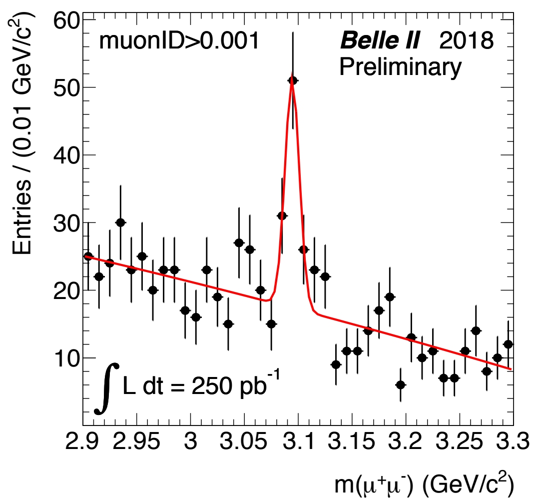
$\phi \rightarrow K\, K$



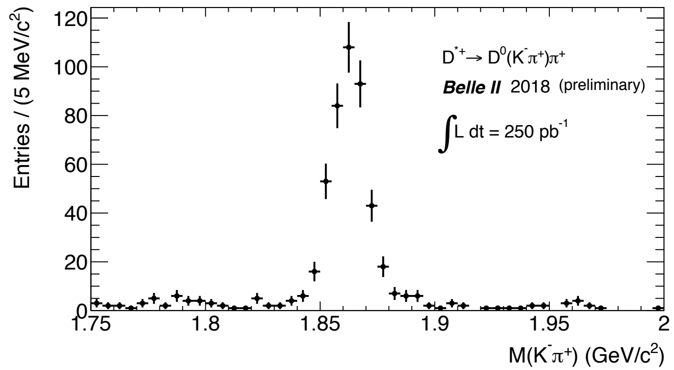
$J/\psi^0 \rightarrow e\, e$



$J/\psi^0 \rightarrow \mu\, \mu$

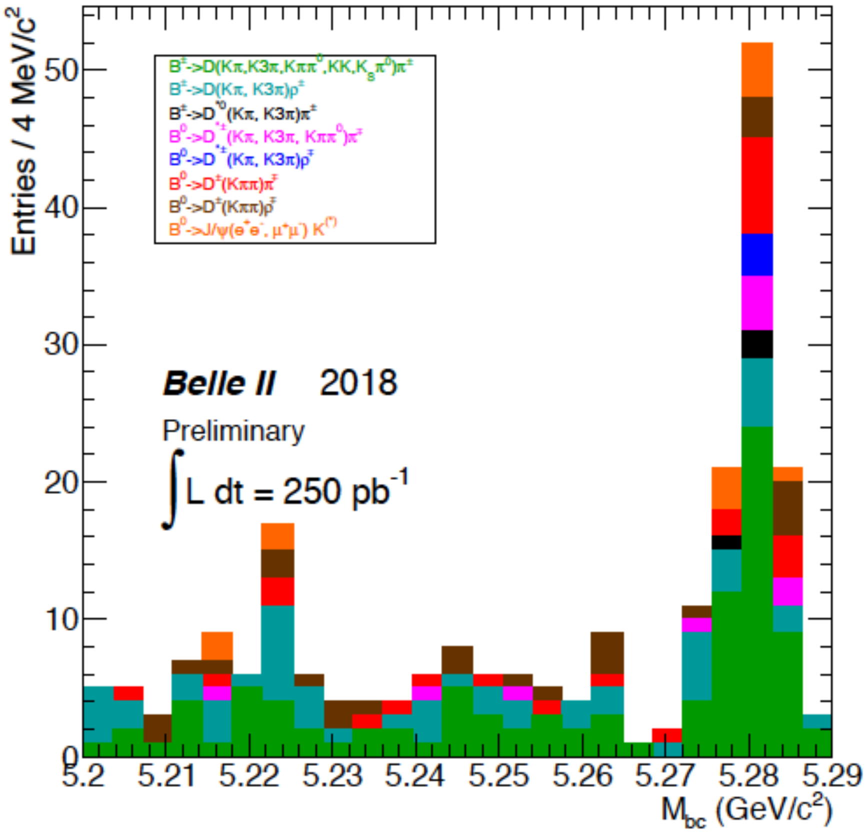


$D \rightarrow K\, \pi$

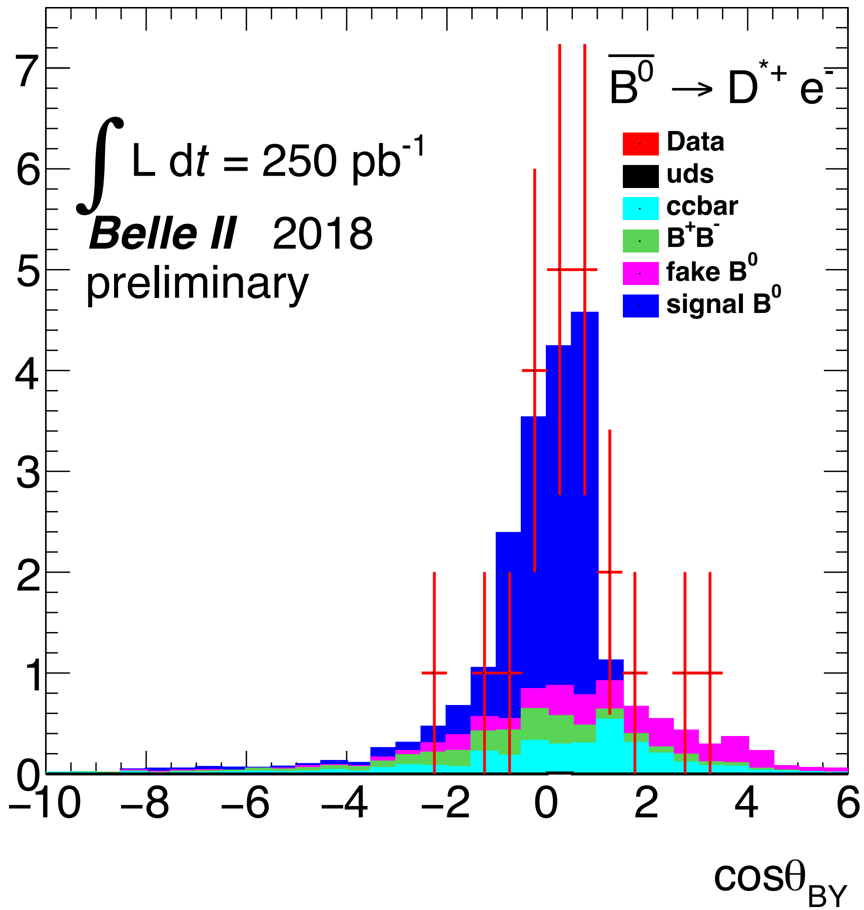


Seen few B meson decays

Hadronic B decay modes

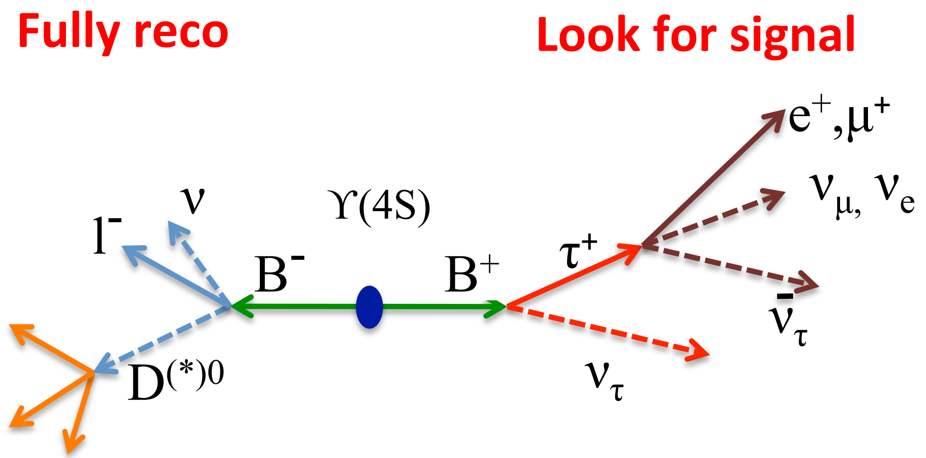


Semileptonic B decay modes

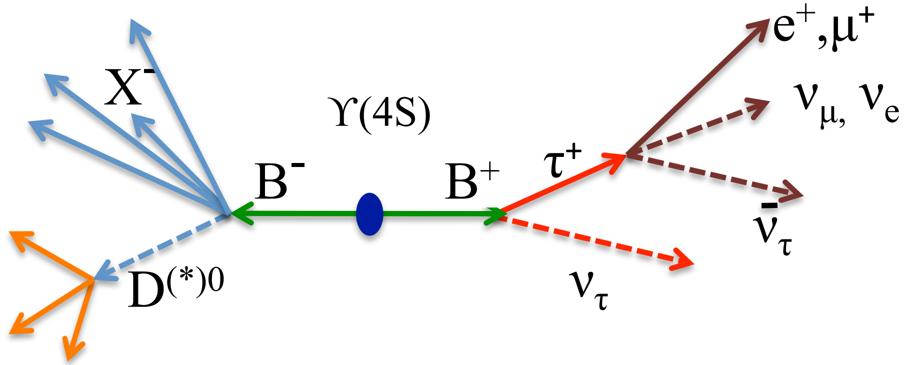


Strategy to reconstruct missing energy modes

- For signal with weak exp. signature
  - Decay with missing momentum (many neutrinos in the final state)
  - Inclusive analyses
- background rejection improved by fully reconstructing the companion B (tag)



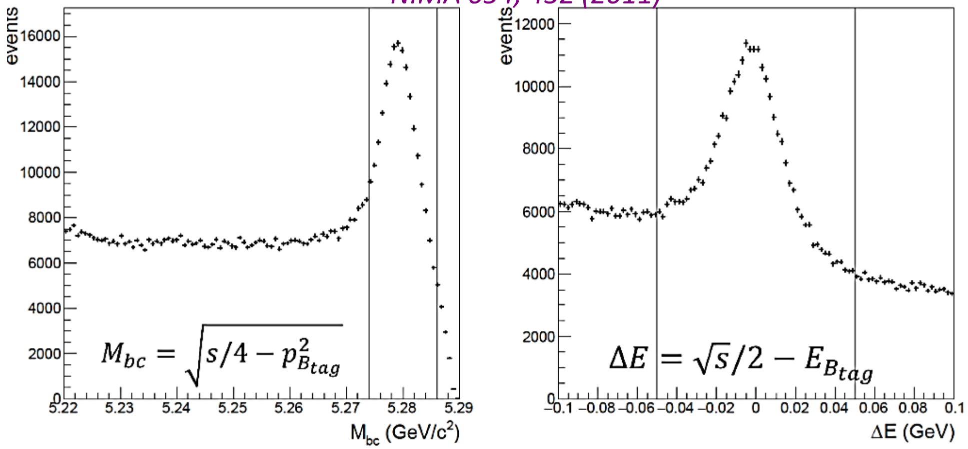
- Tag with semileptonic decays
  - PRO: Higher efficiency ε_{tag} >O(1%)
    CON: more backgrounds,
    B momentum unmeasured
- Tag with hadronic decays
  - PRO: much cleaner events,
    B momentum reconstructed
    CON: smaller efficiency ε_{tag} <O(1%)



B reconstruction strategy

$$\boldsymbol{M_{bc}} = \sqrt{E^2_{\text{beam}} - \vec{p}^{\,2}_{B_{\text{tag}}}} \qquad \boldsymbol{\Delta E} = E_{\text{beam}} - E_{B_{\text{tag}}}$$

NIMA 654, 432 (2011)



Algorithm	MVA	Eff.	Purity
Belle (2007)	Cut	0.1	0.25
Belle (2011)	NeuroBayes	0.2	0.25
Belle II FEI (2017)	Fast BDT	0.5	0.25

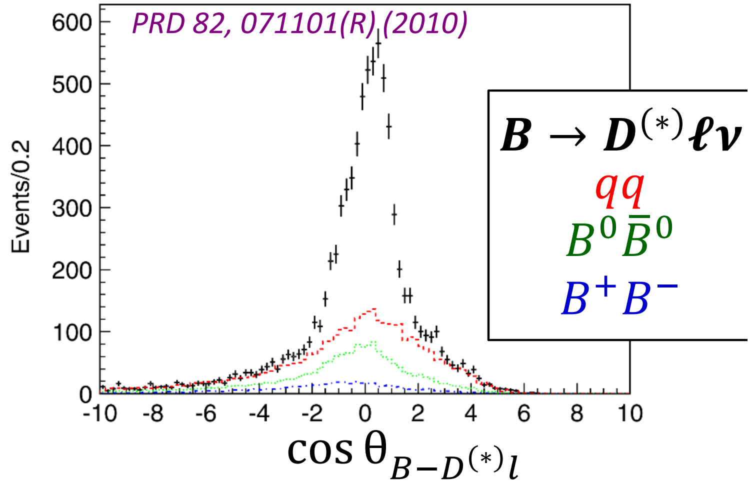
Developed at B-factories to reconstruct thousands of combination of
B → D X , D →Y hadronic decays

BaBar determined the purity on data to rank the decay modes

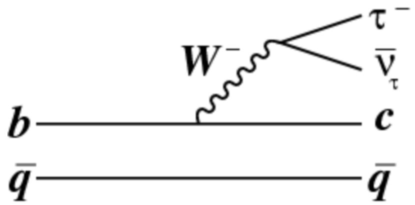
Belle pioneered a multilevel MV classifier further developed in Belle II

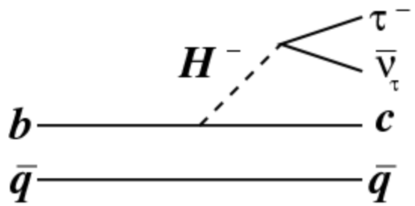
"Tagging" extended to B → D l ν decays

$$\cos\theta_{B-D^{(*)}l} = \frac{2E_{beam}E_{D^{(*)}l} - m_B^2 - m^2_{D^{(*)}l}}{2\, p_B\, p_{D^{(*)}l}}$$



B → $D^{(*)}$ τν



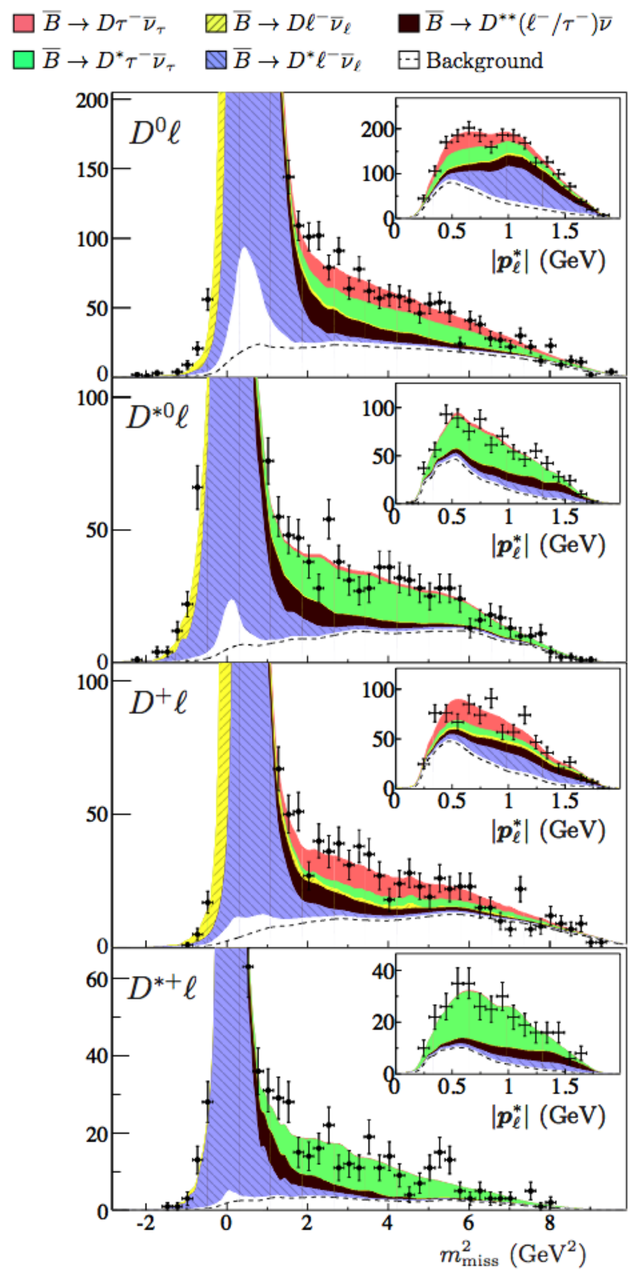


Standard Model prediction theoretically clean
Yield and q^2 distribution from a form factor

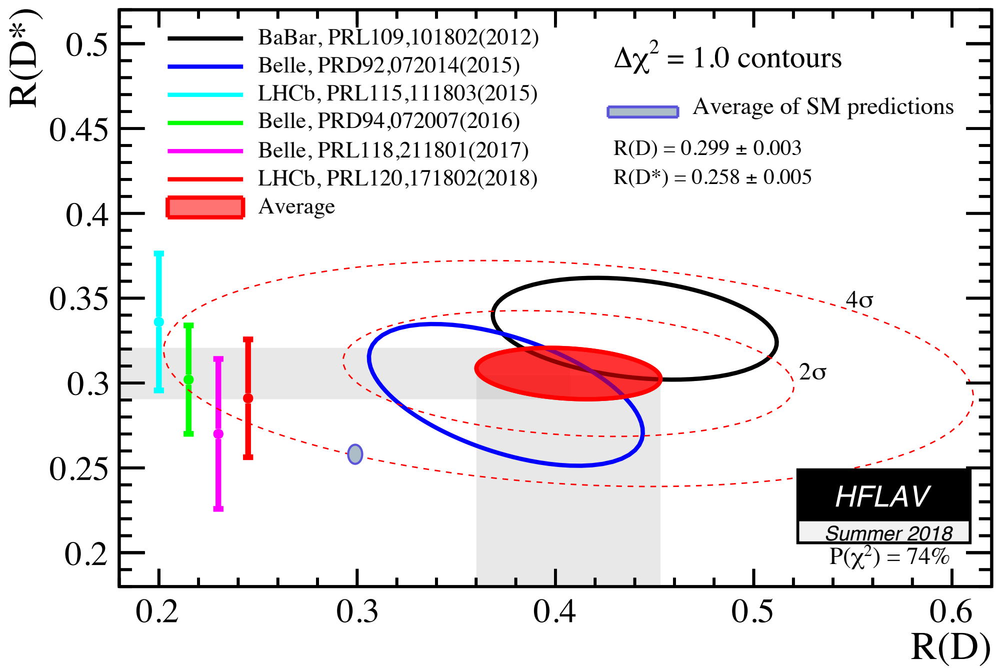
Simplest case of New Physics from Charged Higgs

Measure a ratio R = B(B→ $D^{(*)}$ τ ν)/B(B→$D^{(*)}$lν)
Experimentally hard: signature is not a peak on a smooth background!

Data driven methods to control the backgrounds
(most dangerous B → D** l ν background)

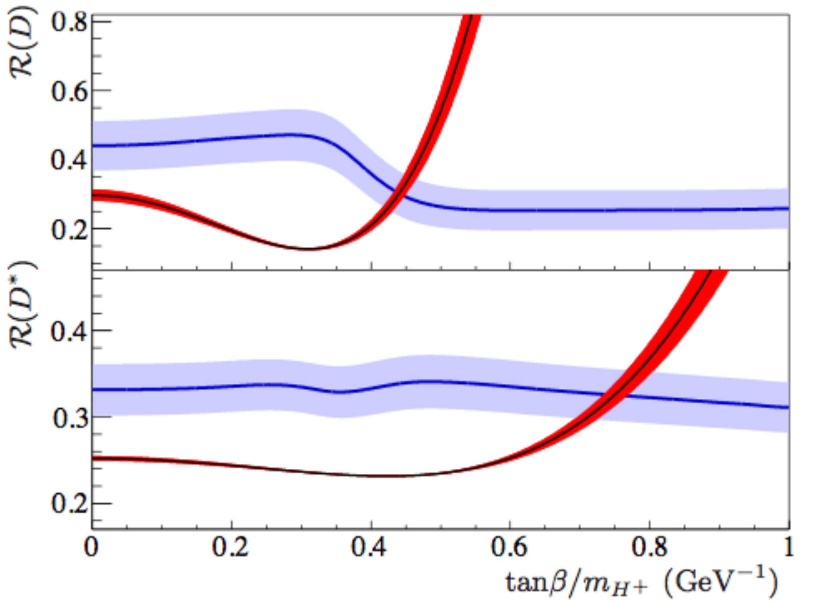


Hints of Lepton Flavour Universality violation



HFlav Combination

Phys. Rev. Lett. 109, 101802 (2012)

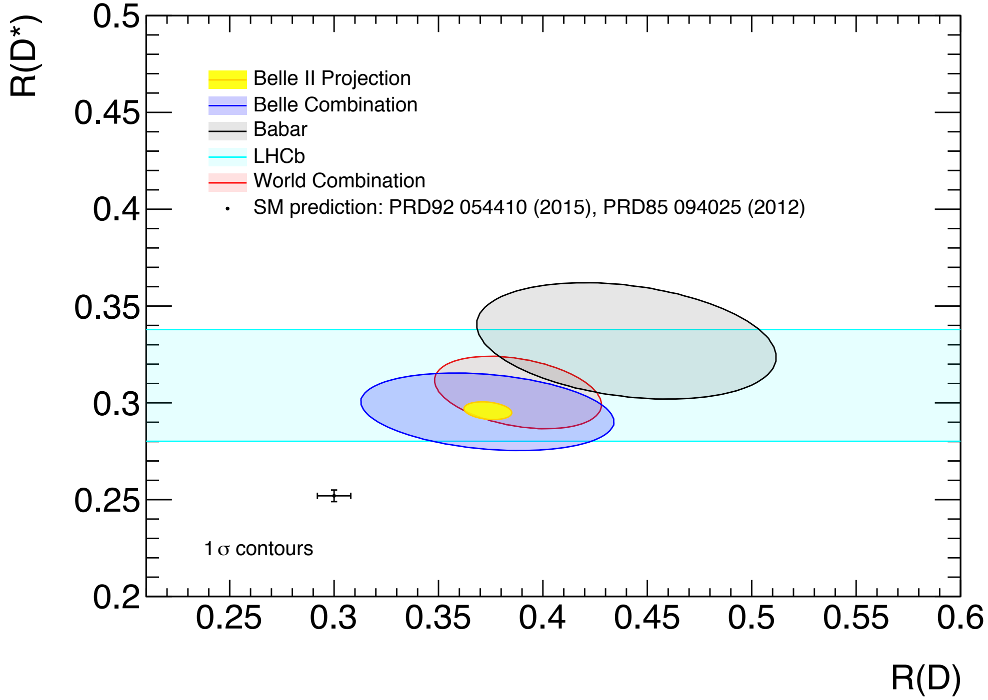


4σ away from SM prediction pointing to Lepton Flavour Universality violation
Simplest NP extensions like 2HDM type II not sufficient

Many theoretical models on the market to explain the measurements

- Extending the interactions adding scalar, vector, tensor coefficients to be fitted
- Specific new physics models like LQ, additional gauge bosons…

Current measurements and Belle II projection



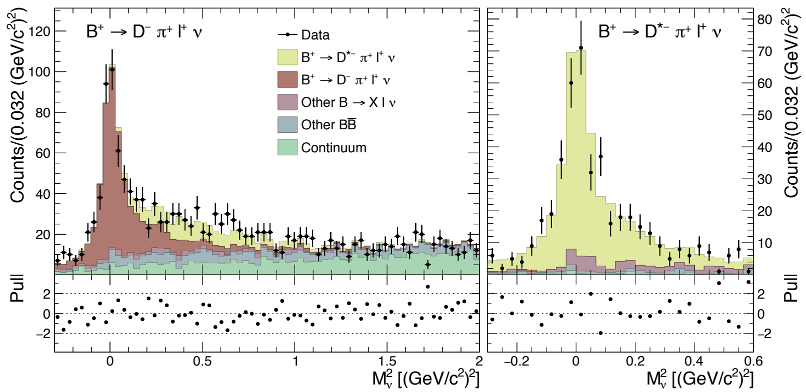
Belle II will greatly improve the statistical uncertainty on R(D) and R(D*)

We will confirm the excess early.
After 10% of data taking we expect
- 3% uncertainty on R(D*)
- 6% uncertainty on R(D)

Ultimate precision 2% and 3% limited by systematics

Biggest contribution to systematics is the uncertainty in D** component.
→ In Belle II we will improve studying in detail B → D** l ν decays

A simultaneous R(D), R(D*) and R(D**) determination may be feasible

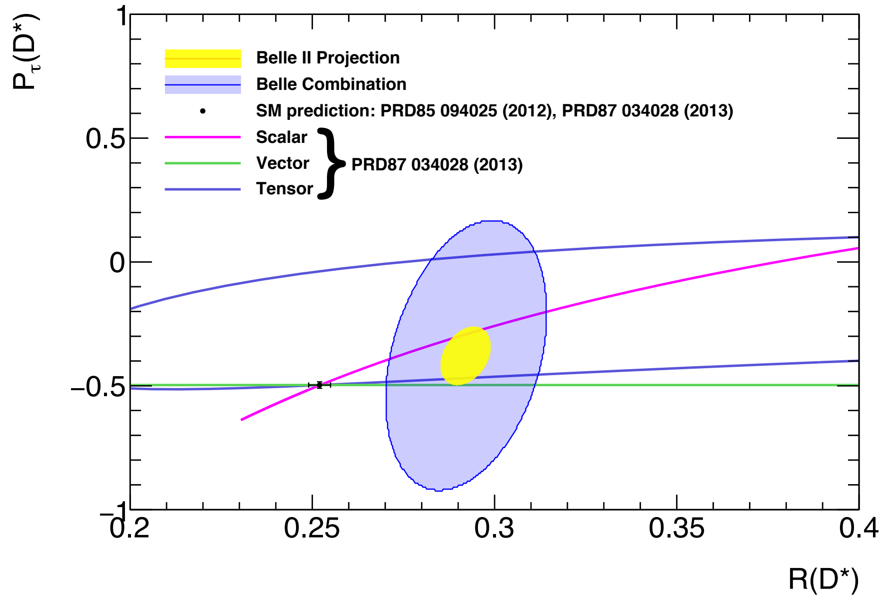


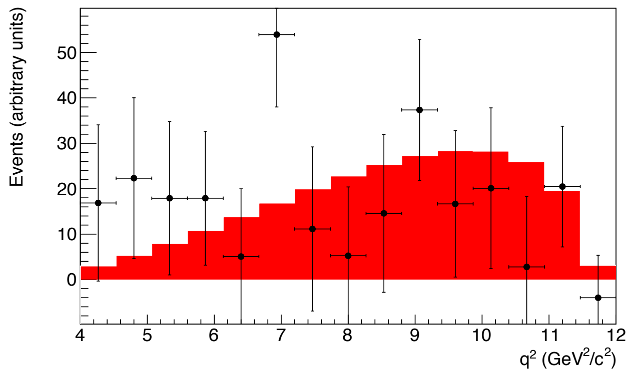
q^2 distribution and τ polarization

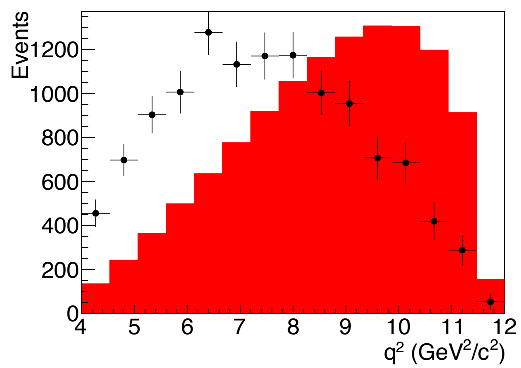
Differential distribution can be measured to constrain NP contributions

Detailed measurement of q^2 and other kinematical distribution including polarization of the τ by means of its hadronic decays

Already pionereed by Belle
Phys. Rev. Lett. 118, 211801
Phys. Rev. D 97, 012004







Belle II pseudo-data (points with error bars) are generated in the SM hypothesis

Block histograms is a 2HDM-type II benchmark

Testing LFU with b → u semileptonic decays

$$R(\pi) = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell)}$$

Feasibility already demonstrated with Belle.
No statistically significant signal observed
Phys. Rev. Lett. 118, 211801 (2017)

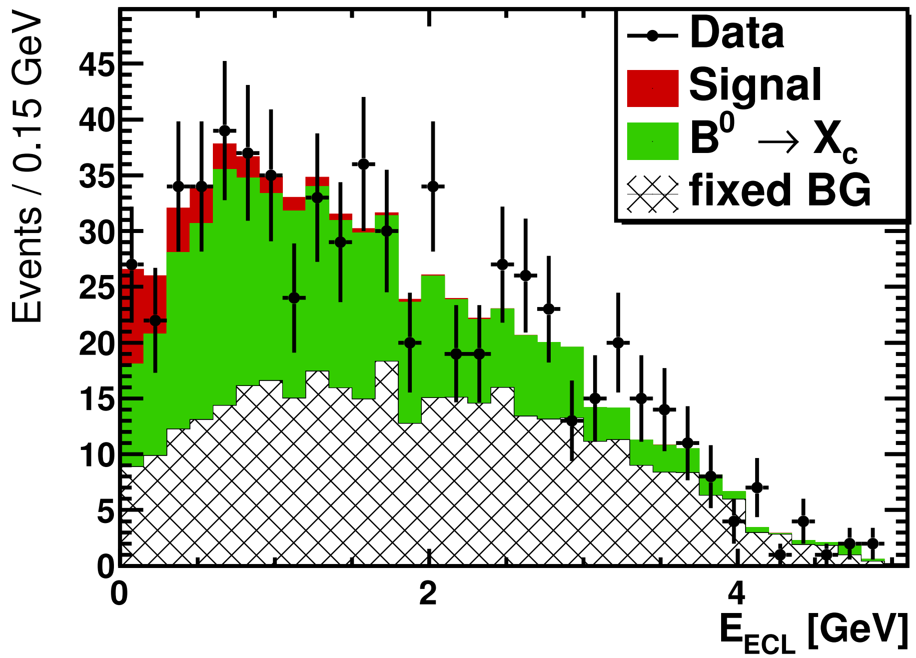
$$\mathcal{B}(B \to \pi\tau\bar{\nu}) < 2.5 \times 10^{-4}.$$

Corresponding central value:

$$\mathcal{B}(B \to \pi\tau\bar{\nu}) = (1.52 \pm 0.72 \pm 0.13)$$

Belle II extrapolation

$$R_\pi^{5\,\mathrm{ab}^{-1}} = 0.64 \pm 0.23\,,$$
$$R_\pi^{50\,\mathrm{ab}^{-1}} = 0.64 \pm 0.09\,.$$

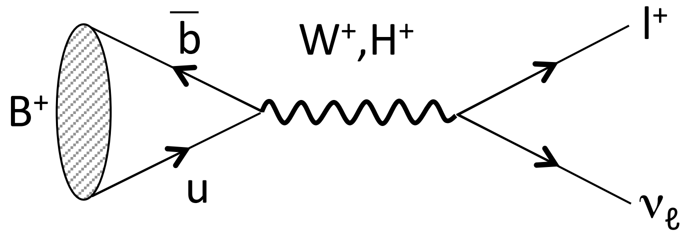


LFU with leptonic decays

Very clean theoretically, hard experimentally

SM is helicity suppressed

Sensitive to NP contribution (charged Higgs)



$$\mathcal{B}(B \to l\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}(B \to l\nu) = \mathcal{B}(B \to l\nu)_{SM} \times r_H$$

$$r_H = (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$ *in 2HDM type II*

Belle II can test LFU also with

$$R^{\tau\mu} = \frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}$$

$$R^{\tau e} = \frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}$$

$$R^{\tau\pi} = \frac{\Gamma(B \to \tau\nu)}{\Gamma(B \to \pi l\nu)}$$

Mode	SM BR	Current meas.	Belle II 5 ab-1	Belle II 50 ab-1
τν	10^{-4}	20% uncertainty	15%	6%
μν	10^{-6}	40% uncertainty*	20%	7%
eν	10^{-11}	Beyond reach	-	-

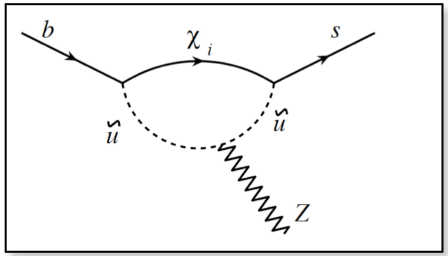
Belle II Full simulation with expected background conditions (hadronic tags only) S.L. tag expected to have similar sensitivity

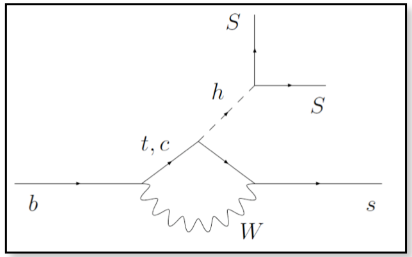
Extrapolation of untagged Belle analysis

* arxiv:1712.04123 2.4σ excess $[2.9,10.7]\times10^{-7}$ at 90% C.L.

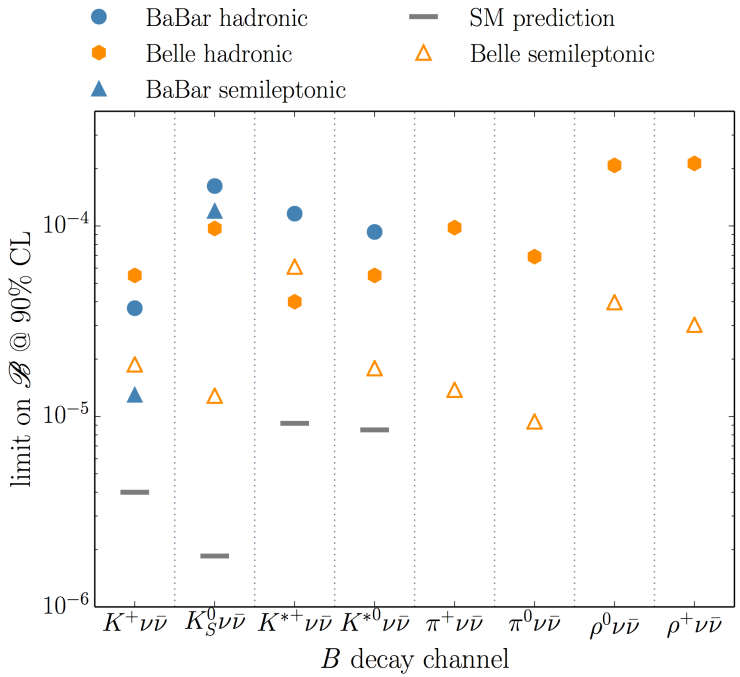
$B \to K^{(*)} \nu \nu$

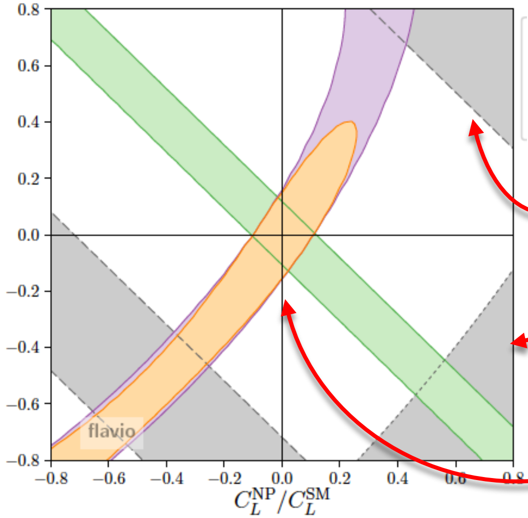
Suppressed in the SM : BRs 10^{-5} – 10^{-6} may be enhanced by NP





Current limits





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}

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%

Conclusions

- Unique capabilities of Belle II detector to measure B decays with missing energy
- We expect to collect 5 ab^{-1} in the first two years of data taking and address LFU violation measuring R(D) and R(D*).
- Detailed measurements of the differential spectra will help to discriminate among NP models
- Moreover Belle II will measure precisely purely leptonic B decays and FCNC processes $B \rightarrow K^{(*)} \nu \nu$