Prospects of semileptonic B decays at Belle II

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Outline

Semileptonic B decays at Belle II with focus on:

- Lepton Flavour Universality

- Measurement of |Vub| with exclusive and inclusive decays

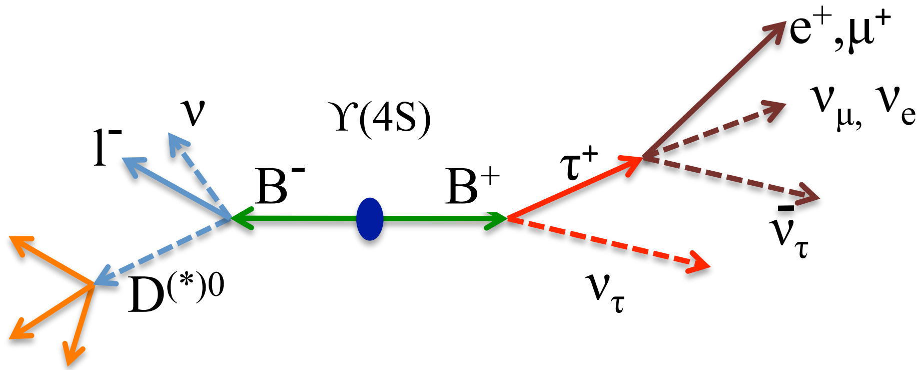
For a thorough description of the Belle II Physics Program and the status of the Belle II experiment →Peter Krizan's talk

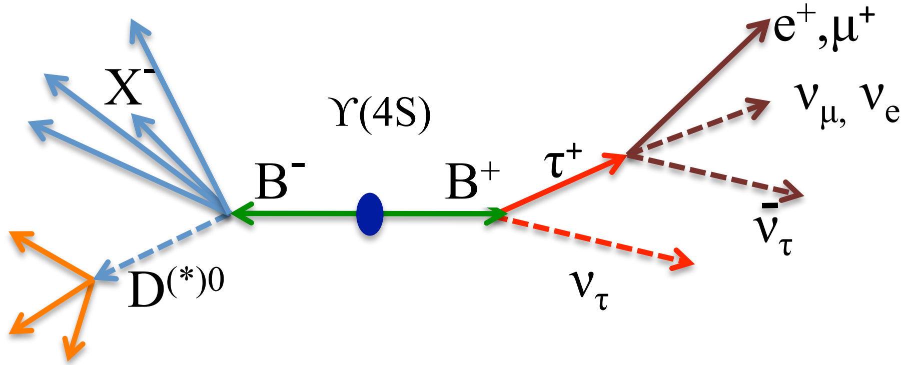
Full Event Interpretation

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

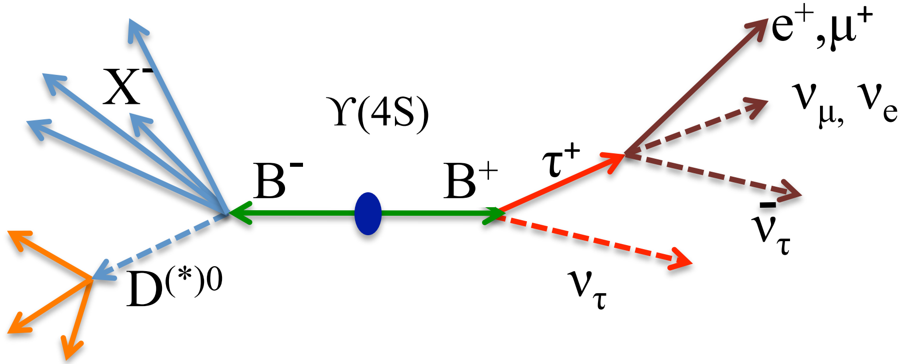
- Tag with semileptonic decays
  - PRO: Higher efficiency ε_{tag} >O(1%)
    CON: more backgrounds,
    B momentum unmeasured
- Tag with hadronic decays
  - PRO: much cleaner events,
    B momentum reconstructed
    CON: smaller efficiency ε_{tag} <O(1%)

Fully reco **Look for signal**





B reconstruction strategy



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

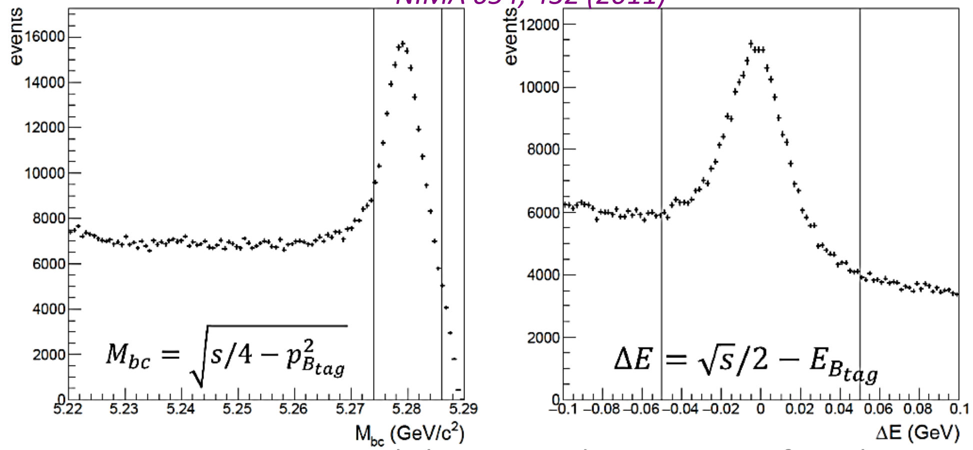
BaBar determined the purity on data to rank the decay modes

Belle pioneered a multilevel MV classifier further developed in Belle II

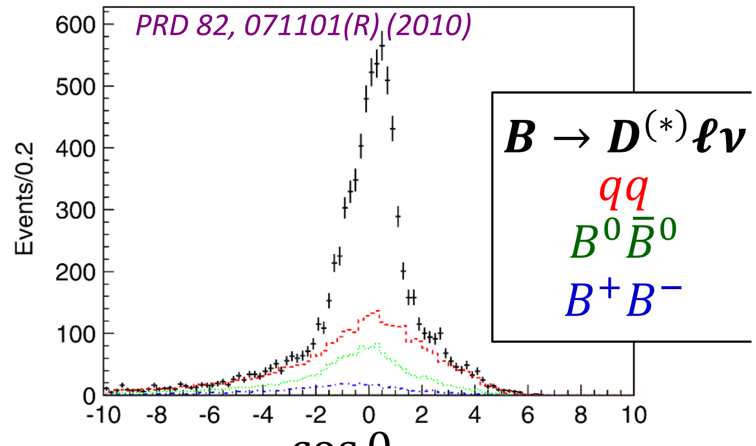
“Tagging” extended to B → D l ν decays

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

NIMA 654, 432 (2011)

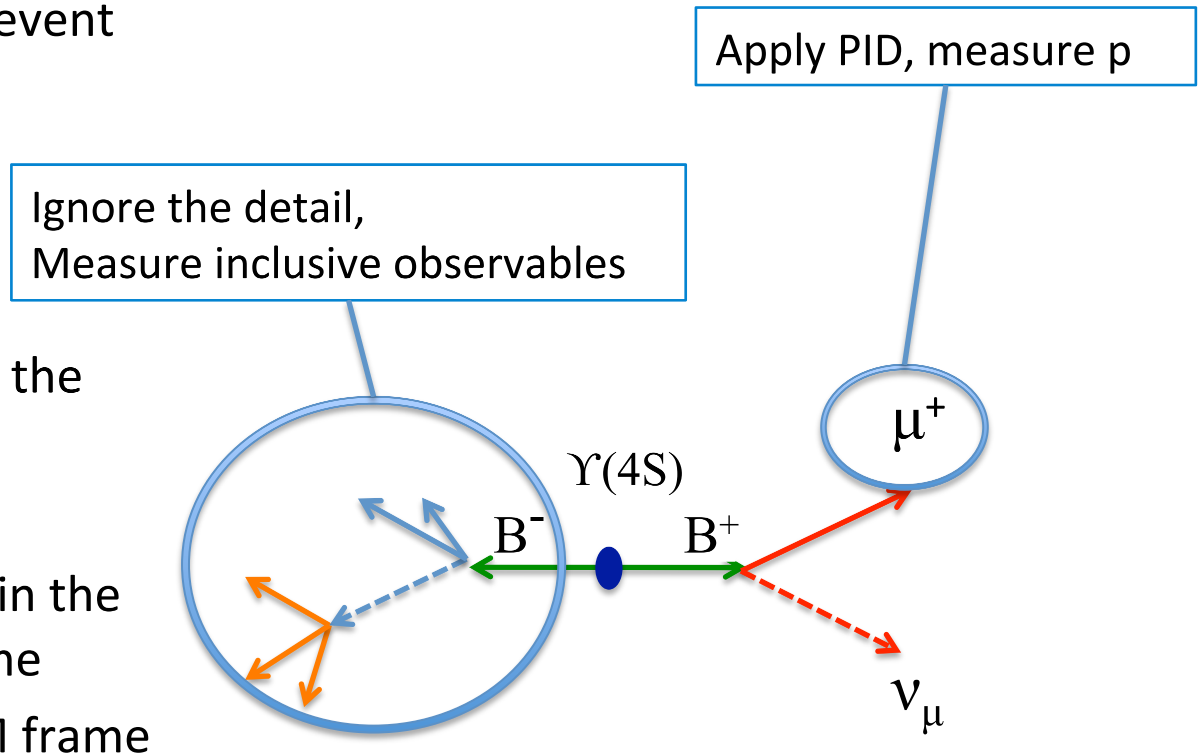


$$\cos\theta_{B-D^{(*)}l} = \frac{2E_{beam}E_{D^{(*)}l} - m_B^2 - m_{D^{(*)}l}^2}{2\,p_B\,p_{D^{(*)}l}}$$



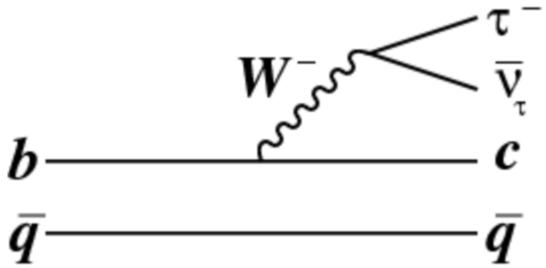
Untagged analyses: less constraints, more statistics

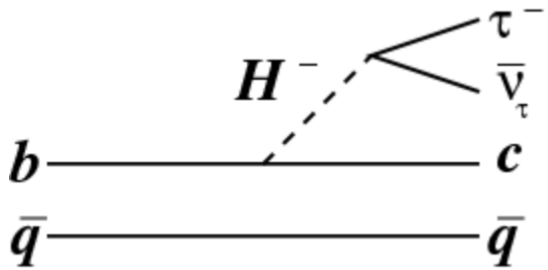
- Inclusive on the rest of the event when the signal signature strong enough
- B → π l ν
  - Loose requirements on the other B
- B → μ ν
  - Monochromatic muon in the final state in B rest frame
    - Smeared in the CM frame

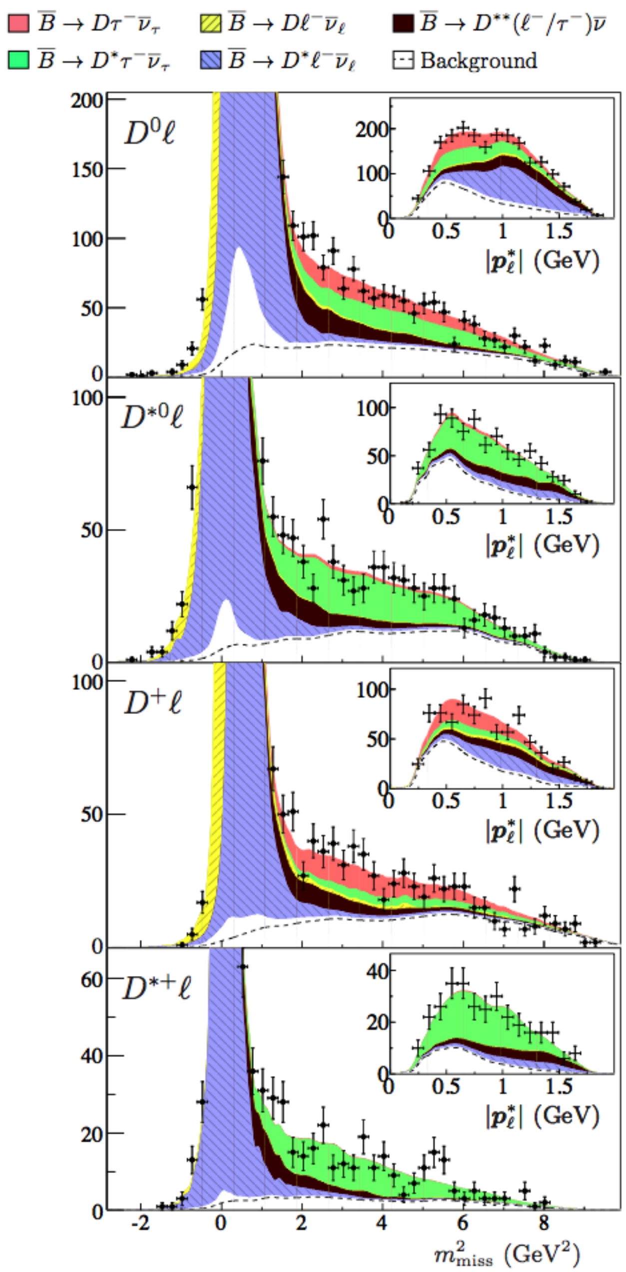


High efficiency but large backgrounds, too

B → $D^{(*)}$ τν







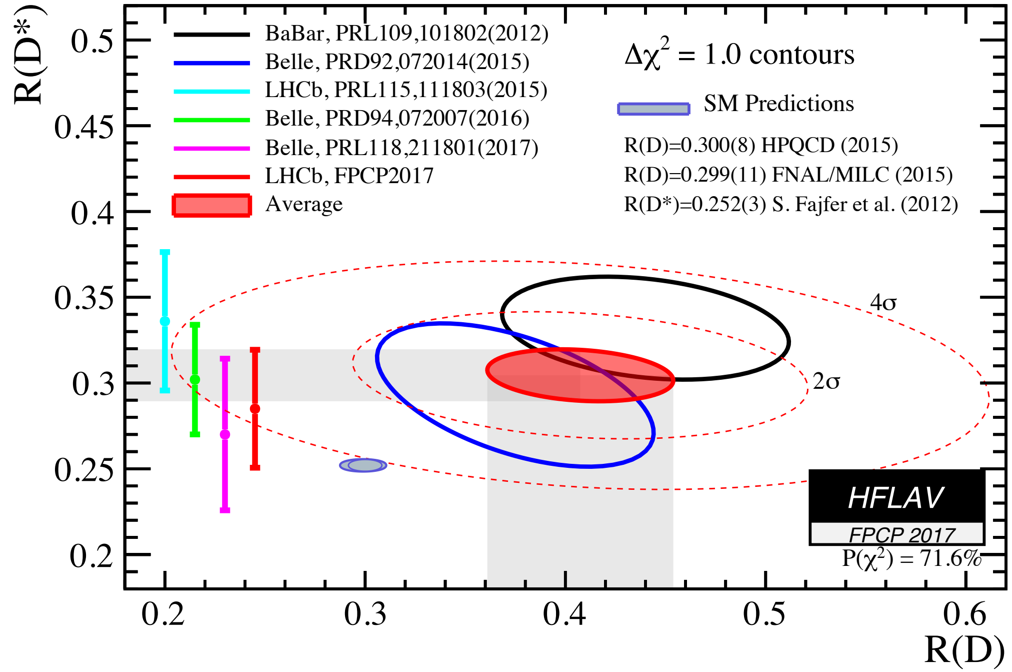
Standard Model prediction theoretically clean
Yield and q^2 distribution from a form factor

Simplest case of new Physics from Charged Higgs

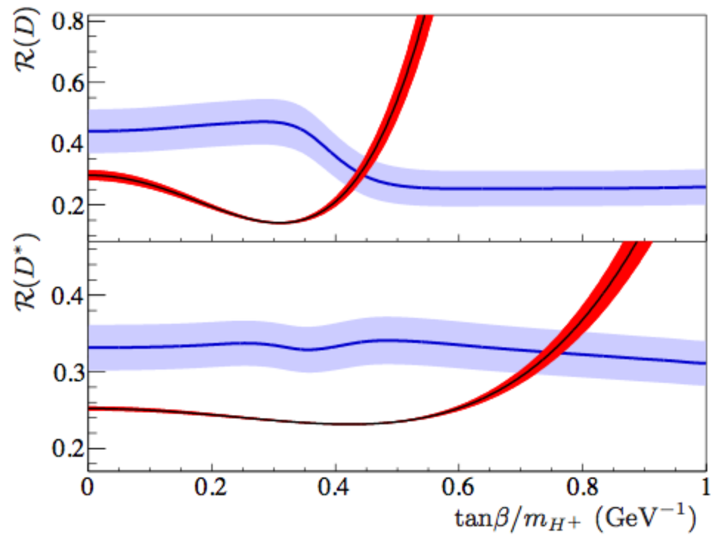
Measure a ratio R = B(B→ $D^{(*)}$ τ ν)/B(B→$D^{(*)}$lν)
Experimentally hard: signature is not a peak on a smooth background!

Data driven methods to control the backgrounds
(most dangerous D** background)

LFU violation?



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

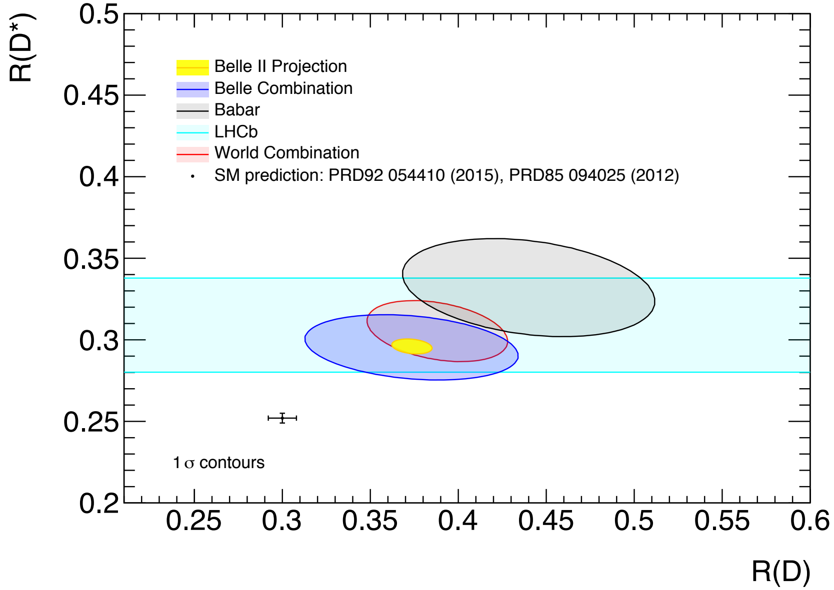


4σ away from SM prediction pointing to Lepton Flavour Universality violation
Simplest NP extensions like 2HDM type II not sufficient

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 (heard also at this conference)

Current measurement and impact of Belle II



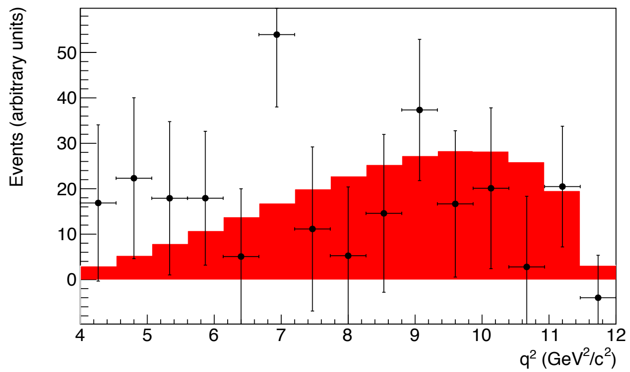
Belle II will greatly improve the statistical uncertainty on R(D) and R(D*)

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

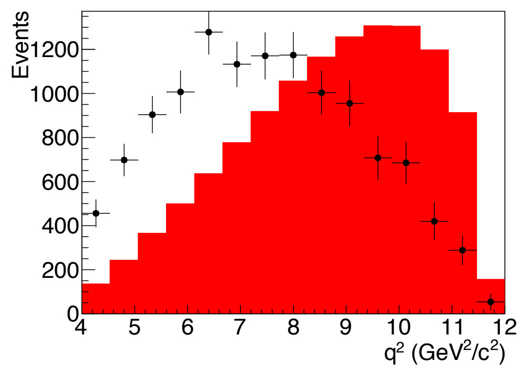
A simultaneous R(D), R(D*) and R(D**) determination may be feasible

Differential distribution can be measured to constrain NP contributions

Belle Data



Belle II pseudo-data



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

Block histograms is a 2HDM-type II benchmark

Belle II projections

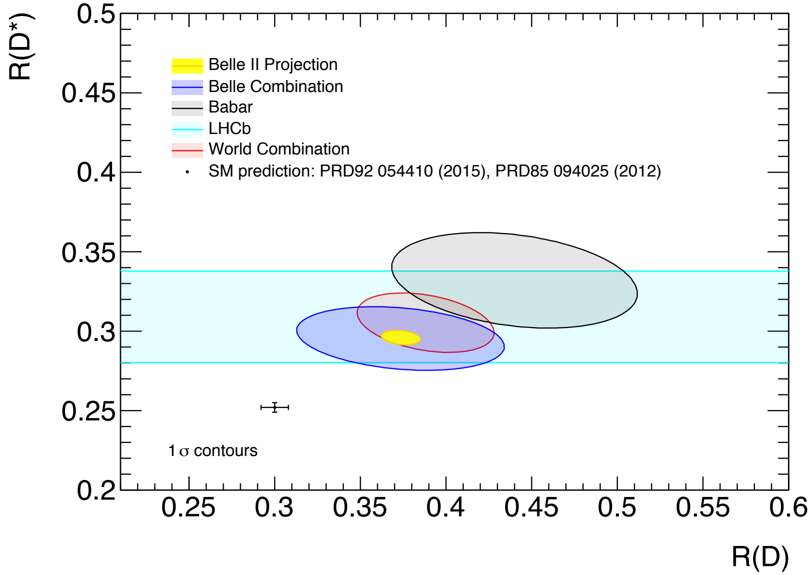
We will confirm the excess early.
After 10% of data taking we expect
4% uncertainty on R(D*) and
6% uncertainty on R(D).

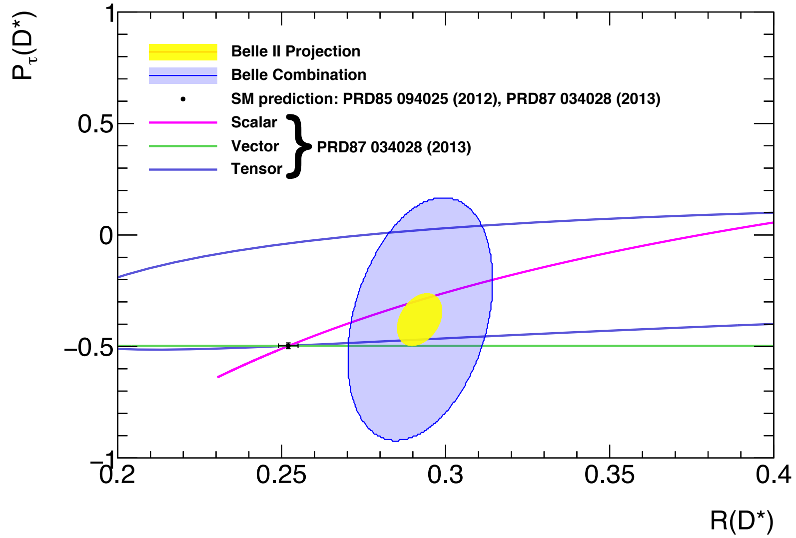
Ultimate precision 1-2% (limited by systematics)

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

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





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)

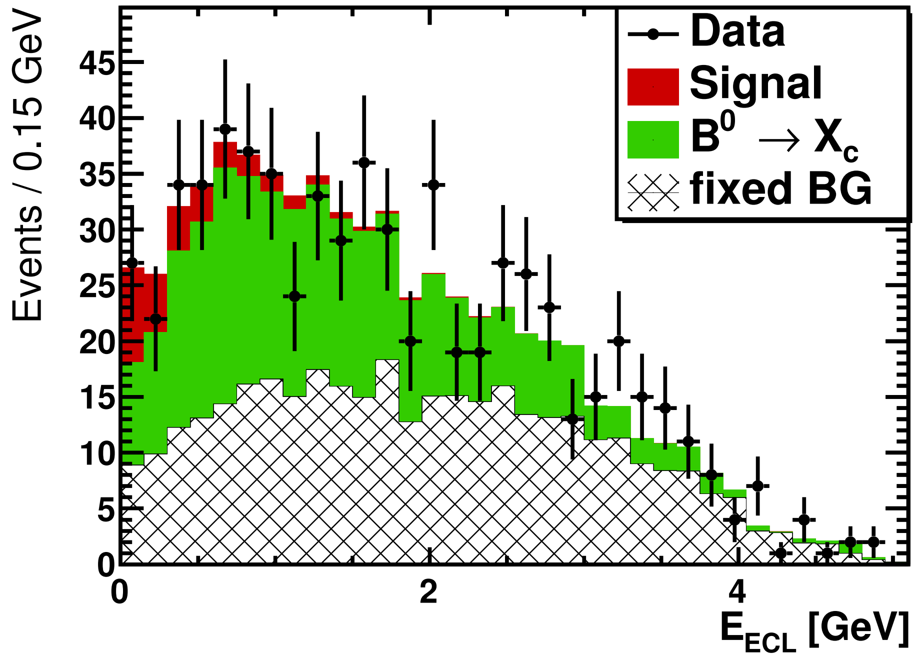
$$\mathcal{B}(B \to \pi\tau\bar{\nu}) < 2.5 \times 10^{-4}.$$

Corresponding central value:

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

Belle II extrapolation

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

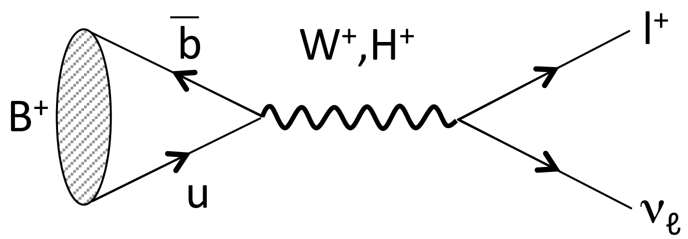


LFU with leptonic decays

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	-	-

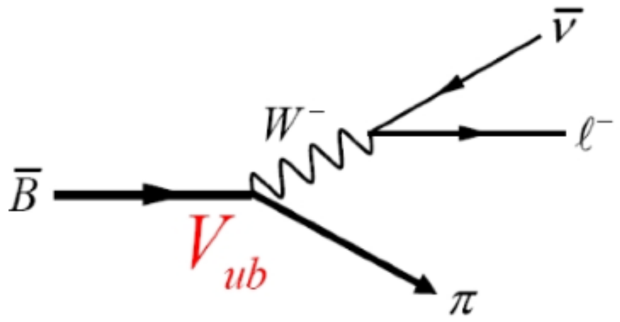
Belle II Full simulation with expected background conditions with hadronic tags only

Extrapolation of untagged Belle analysis

* arxiv:1712.04123 2.4σ excess [2.9,10.7]×10^{-7} at 90% C.L.

|Vub| extraction from b → u

Exclusive decays



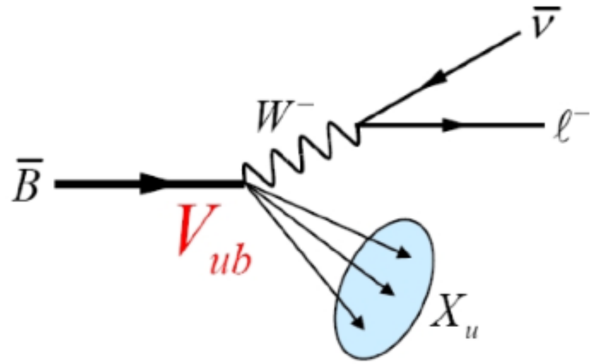
$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} p_\pi^3 |V_{ub}|^2 \times |f(q^2)|^2$$

Theory input: form factors
(Lattice and sum rules)

Experimentally more constrained

Both untagged & tagged analyses

Inclusive decays



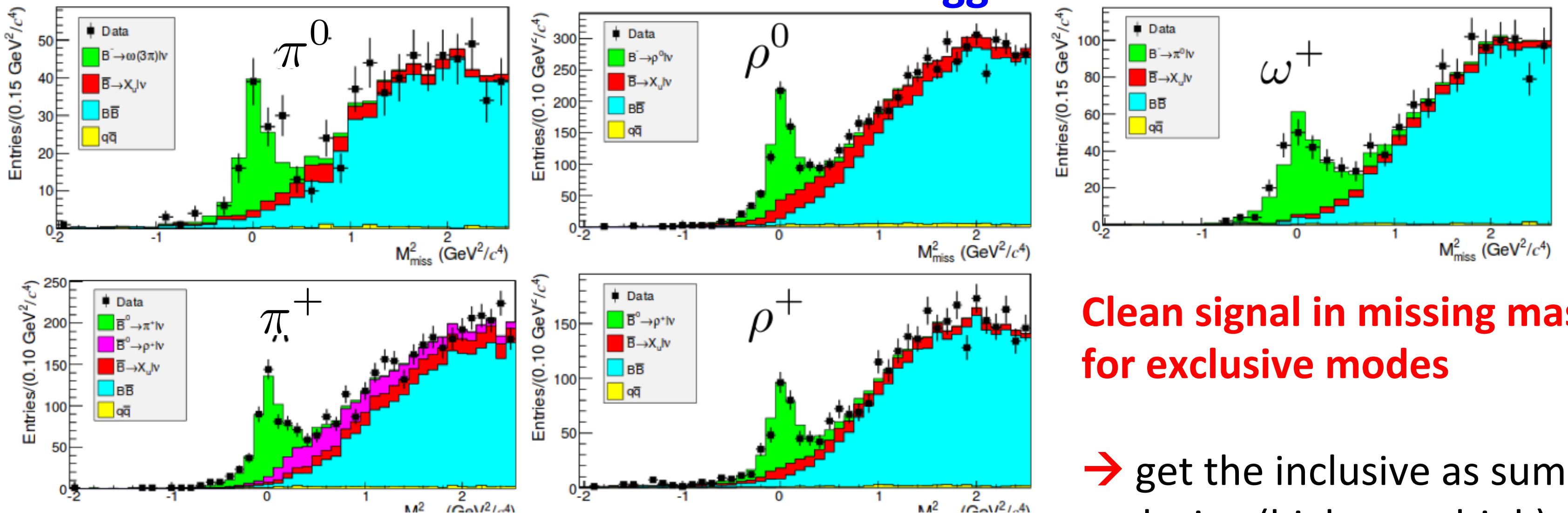
$$\Gamma_{SL} = |V_{ub}|^2 \frac{G_F^2 m_b^5}{192\pi^3} \times A_{pert} \times A_{non-pert}(1/m_b)$$

Theory input: OPE
Huge b→c l ν background
- Must select phase space region (M_X, q^2, p_l) to enhance B→ u signal

Need theory to extrapolate to full rate
- Risk: Tight selections jeopardize theory extrapolation

Current Measurements of Vub and implications for Belle II

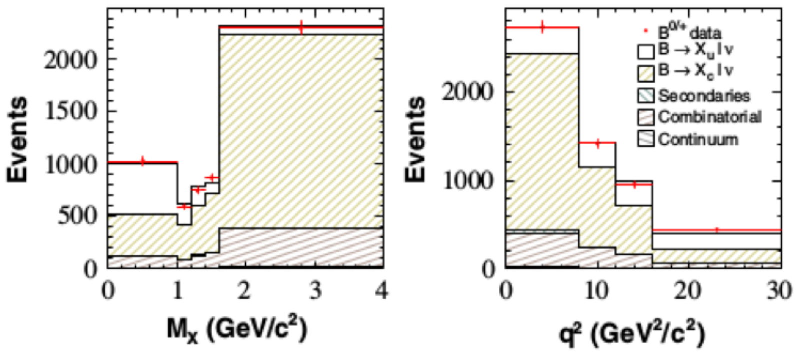
Belle exclusive tagged



Clean signal in missing mass for exclusive modes

→ get the inclusive as sum of exclusive (higher multipl.) modes?

Belle inclusive tagged

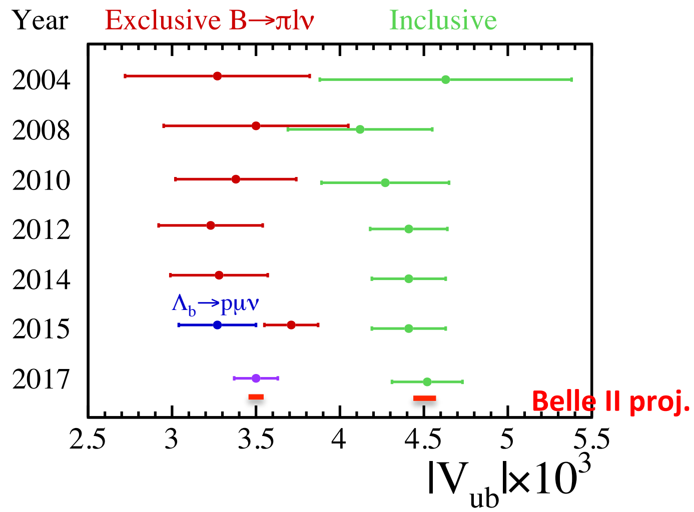


b → u l ν signal enhanced w.r.t. b → c backgrounds in low M_X and high q^2 but

systematics effects from charm background composition and u quark fragmentation
→ models can be improved with Belle II

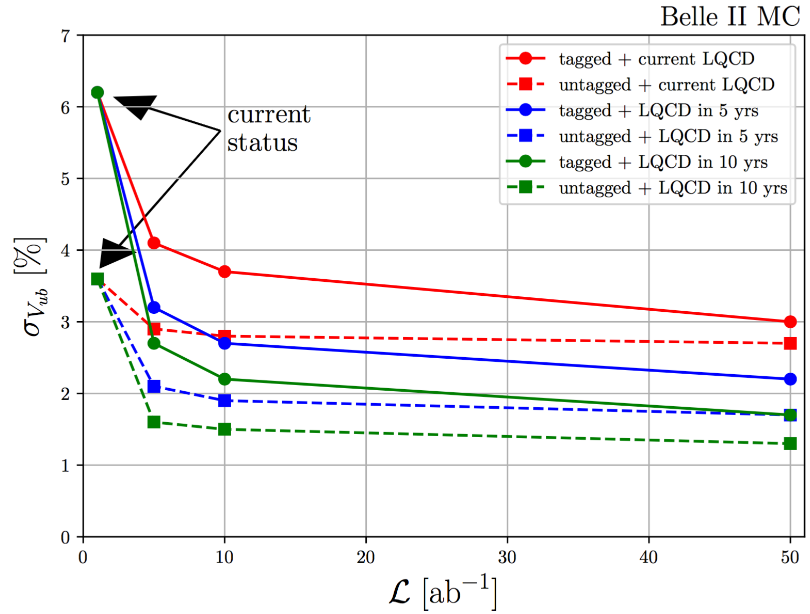
Extrapolation to Belle II

$|Vub|_{exc}$ vs $|Vub|_{inc}$ "tension" is still here after years of experimental and theoretical efforts.

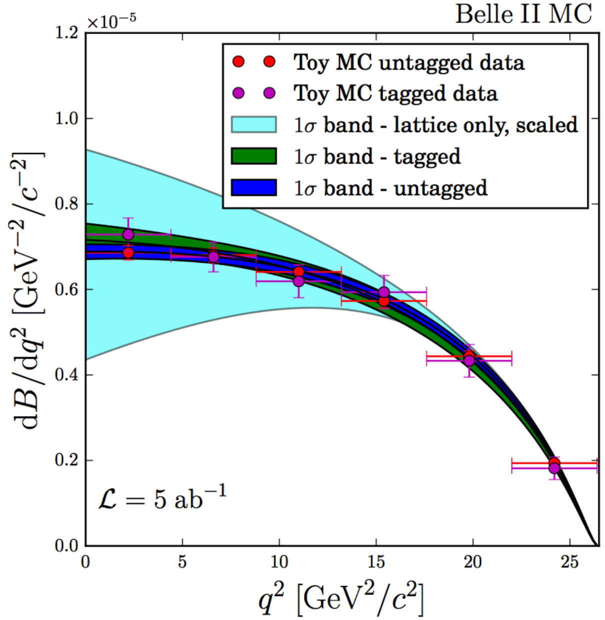


Tagged and untagged Belle II B → π l ν

Uncertainty projections

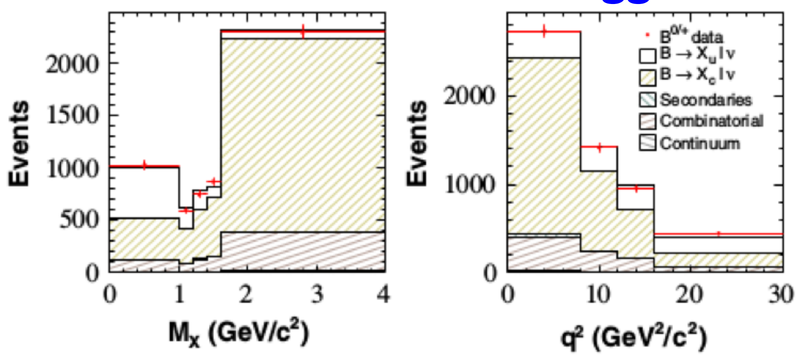


dB/dq²



Inclusive |Vub| in Belle II

Belle inclusive tagged

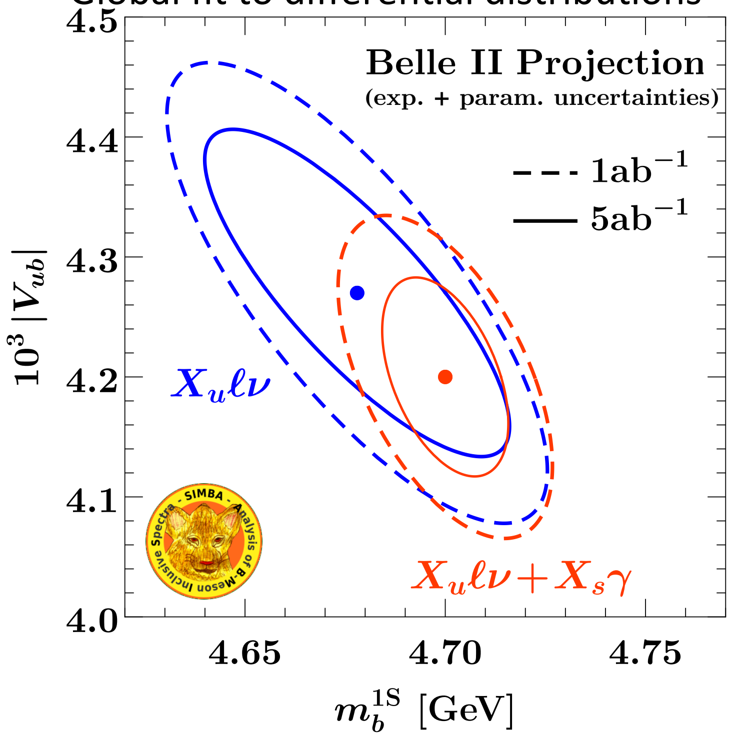


Source	Error on $\mathcal{B}$ (irreducible limit)
$\mathcal{B}(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors $(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors & $\mathcal{B}(D^{(**)}\ell\nu)$	0.2
$B \to X_u\ell\nu$(SF)	3.6 (1.8)
$B \to X_u\ell\nu(g \to s\bar{s})$	1.5
$\mathcal{B}(B \to \pi/\rho/\omega\ell\nu)$	2.3
$\mathcal{B}(B \to \eta^{(\prime)}\ell\nu)$	3.2
$\mathcal{B}(B \to X_u\ell\nu)$ unmeasured/fragmentation	2.9 (1.5)
Continuum & Combinatorial	1.8
Secondaries, Fakes & Fit	1.0
PID& Reconstruction	3.1
BDT/Normalisation	3.1 (2.0)
Total	8.1
(Total reducible)	7.4
(Total irreducible)	3.2

b → u l ν signal enhanced w.r.t. b → c backgrounds in low M_X and high q^2 but

systematics effects from charm background composition and u quark fragmentation
→ models can be improved with Belle II

Global fit to differential distributions



|Vub| extrapolation for Belle II (2)

Mode and dataset	Uncertainty (%) EXP. ONLY
|Vub| exclusive (tagged)	
Belle	3.8
Belle II 5 ab^{-1}	1.8
Belle II 50 ab^{-1}	1.2
|Vub| exclusive (untagged)	
Belle	2.7
Belle II 5 ab^{-1}	1.2
Belle II 50 ab^{-1}	0.9
|Vub| inclusive (tagged)	
Belle	6.0
Belle II 5 ab^{-1}	2.6
Belle II 50 ab^{-1}	1.7

Expect theory error to decrease to 1% for exclusive and 2-4% for inclusive

Most promising are exclusive analyses with hadronic tags → perform clean and detailed exploration of exclusive b→ u modes spectra.

Untagged analyses still competitive for |Vub| measurement with $B \rightarrow \pi l \nu$

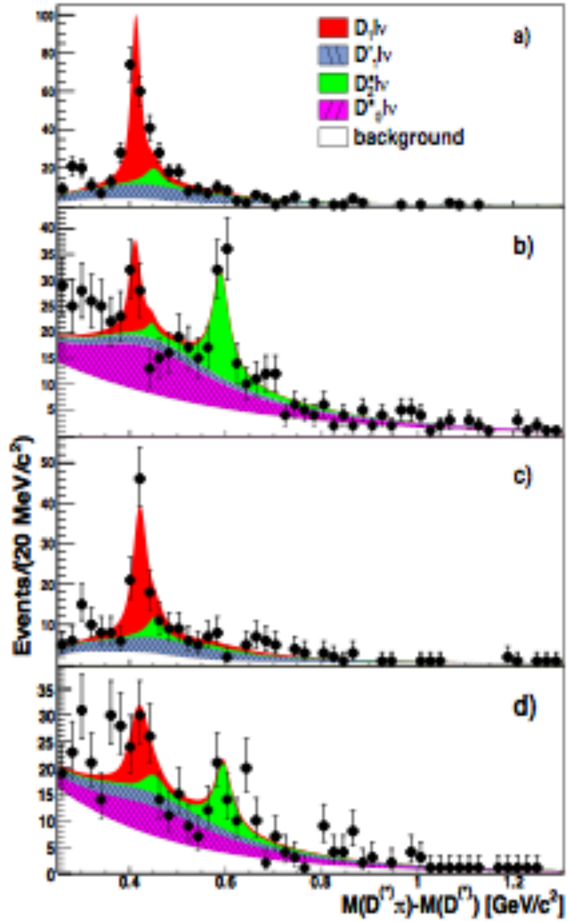
Exploit at maximum the differential distributions for a global Vub fit (inclusive meas.)

$B \to X_c\, l\, \nu$ at Belle II

(Modest) improvement of experimental uncertainties expected.

•Better determination of $B \to D^{**}\, l\, \nu$
•Improved control on the tag B normalization
•Reduce experimental systematics from PID and tracking

We assume theory uncertainty at 1% that will saturate the error budget



Fitted $D^{(*)}\pi$ mass spectrum of Phys.Rev.Lett. 101 (2008) 261802

Belle II goals:
Detailed exploration of $B \to D\, n\pi\, l\, \nu$. Isolate all resonant modes and measure form factors.

Assess the agreement between inclusive and exclusive Vcb

Check if exclusive modes saturate inclusive rate

Conclusions

Unique capabilities of e+ e- SuperKEKB and Belle II detector provide a big discovery potential with semileptonic decays

The physics program is competitive and largely complementary with LHC

We expect to confirm soon the excess seen in B →D(*) $\tau\ \nu$ decays using 10% of the data taking.

Detailed measurements of the differential spectra will help to discriminate among NP models. Additional observables sensitive to LFU violations will be measured.

We expect good improvement of Vub measurements both with inclusive and exclusive approaches.