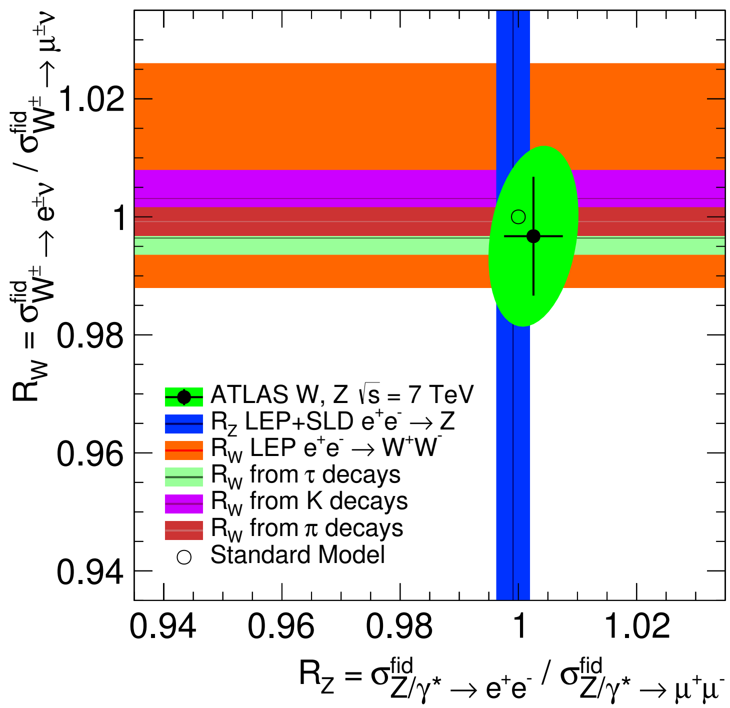
Prospects for tests of LFU and LFV at Belle II.

S. Glazov on behalf of Belle II collaboration

Mainz, 30 Jan 2019.

Experimental data on LFU and LFV



ATLAS EPJC 77 (2017) 367;

LEP+SLD, PR 427 (2006) 257;

HFAG arXiv:1412.7515;

KTEV PRD70 (2004) 092007;

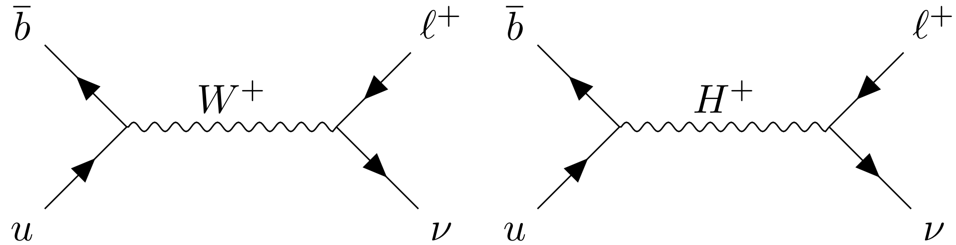
NA62 PLB 719 (2013) 326;

PIENU PRL 115 (2015) 071801.

- Lepton flavour violation probed to 10^{-12} level in μ decays.
- Lepton universality for $Z \to \ell\ell$ probed to per mille accuracy at LEP, including $\Gamma_{Z\to\tau\tau}/\Gamma_{Z\to\ell\ell} = 1.0019 \pm 0.0032$.
- Lepton universality for $W \to e\nu$ and $W \to \mu\nu$ decays measured directly, controlled with high precision using π, K and τ decays. Some tension for $W \to \tau\nu$ from LEP: ($\Gamma(\tau\nu)/\Gamma(e\nu) = 1.063 \pm 0.027$, $\Gamma(\tau\nu)/\Gamma(\mu\nu) = 1.070 \pm 0.026$).

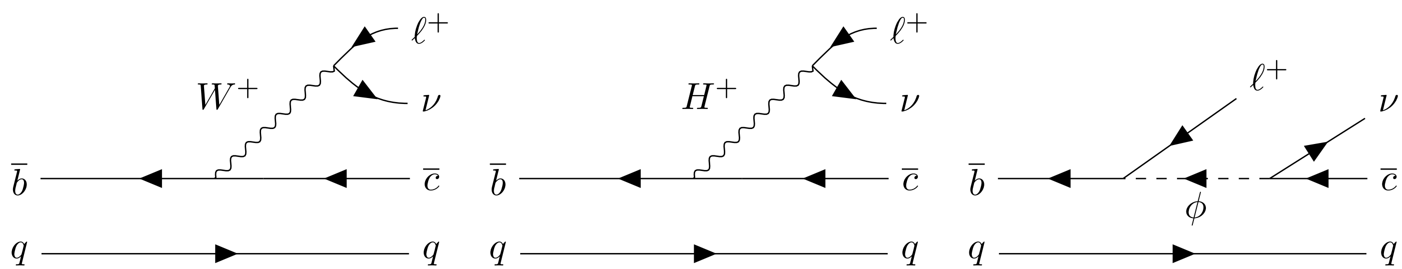
B decays and LFV/LFU

- Leptonic decays $B^{\pm} \to \ell^{\pm}\nu$, $B^0 \to \ell\ell'$.

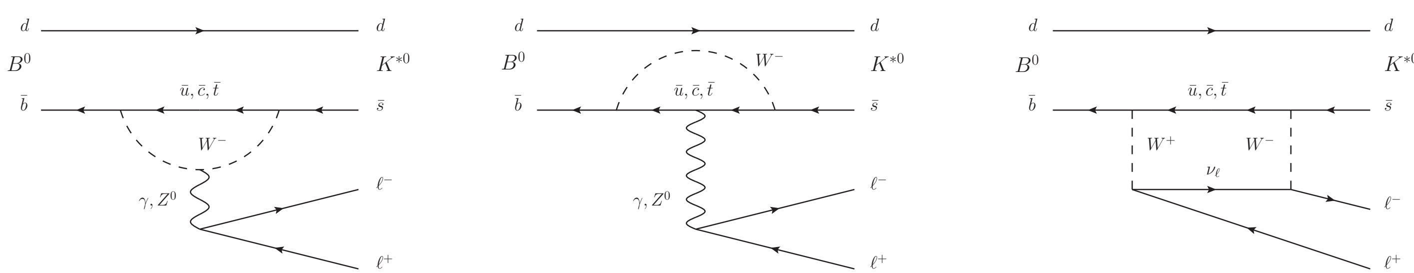


See talk of Lu Cao tomorrow.

- Semileptonic decays $B \to X\ell\nu$



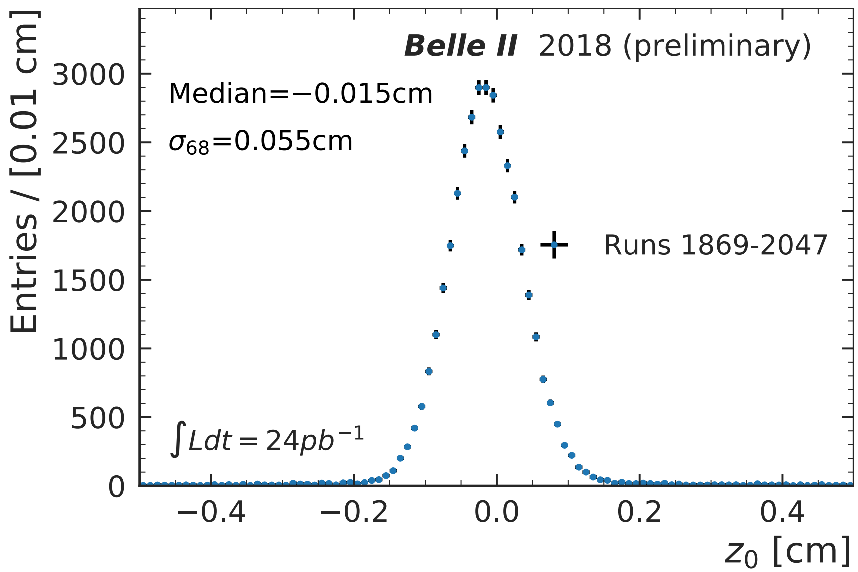
- FCNC processes $B \to X_{s(d)}\ell^+\ell^-$.

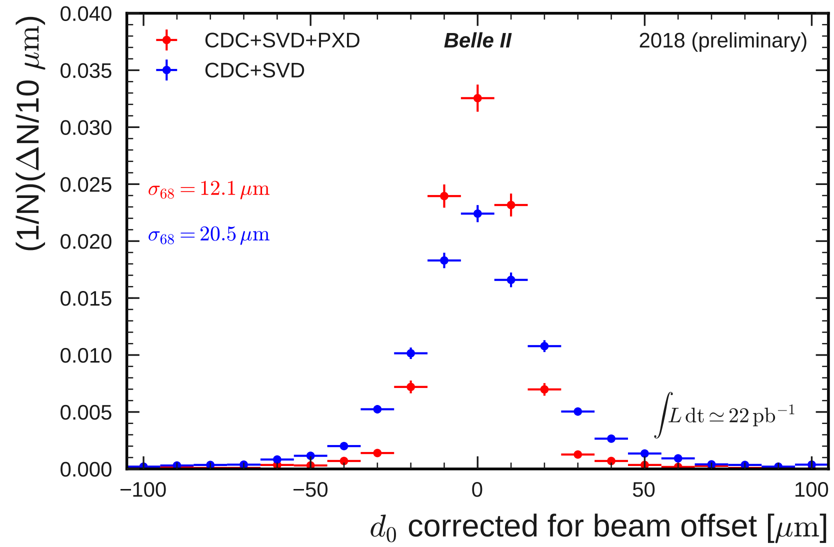


B-factories vs pp

- Pros:
  - Nearly 4π reconstruction (however, not so good for K_L)
  - Hadronic/semileptonic tagging, full event interpretation (FEI), reliable reconstruction of missing energy
  - Excellent reconstruction of both muons and electrons.
- Cons:
  - Lower rates
  - Lower energies, larger multiple scattering effects, reduced tracking efficiency.
  - Stronger dependence of final state topologies on Q^2

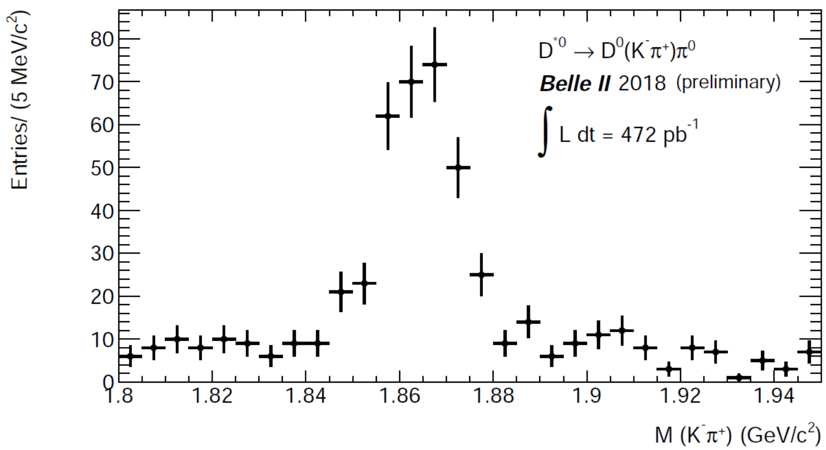
Status of Belle-II in phase-II

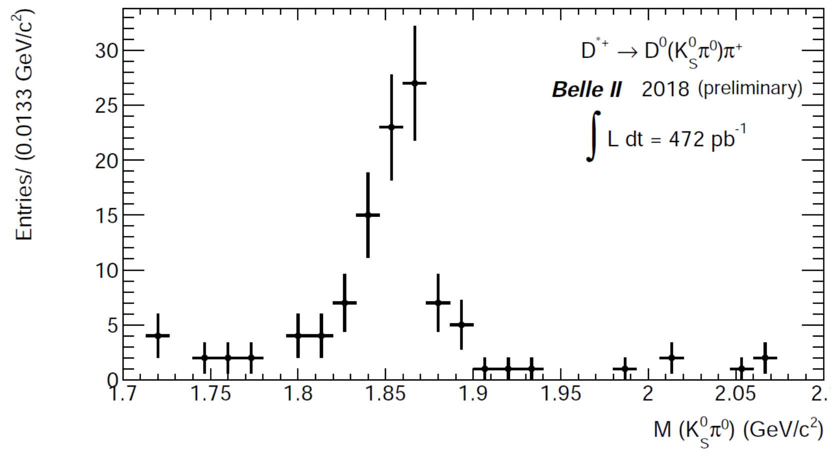




- z-vertex spread at 0.5 mm level (vs 1 cm at Belle-I): strong focusing, large crossing angle, towards nano-beam scheme.
- Transverse impact parameter resolution of 12 μm (vs 10 μm expected) thanks to PXD, about twice better vs Belle-I.
- However many challenges remain, including high background, requiring further machine and detector tuning.

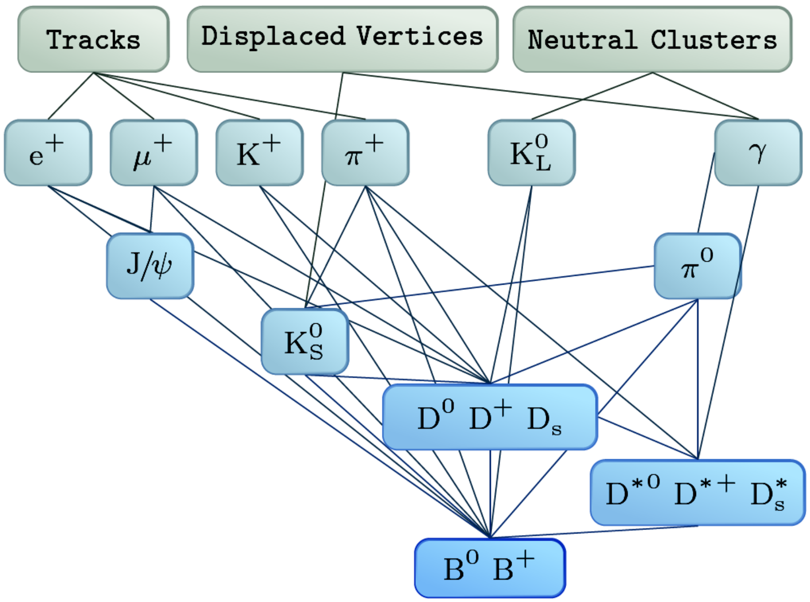
D-meson reconstruction

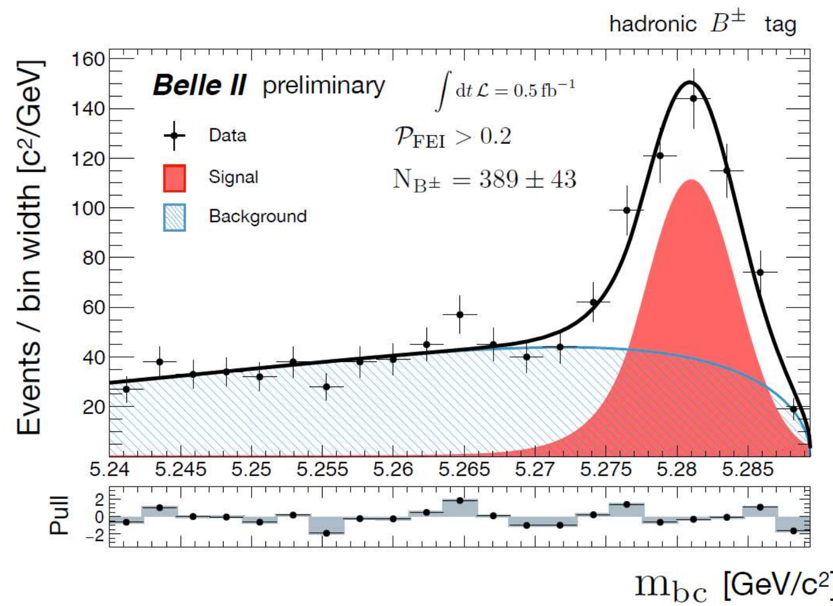




- D^* mesons are reconstructed from $D^{*0} \to D^0\gamma, D^0\pi^0$ and $D^{*+} \to D^+\pi^0, D^0\pi^+$ while D are from $D^0 \to K_S^0\pi^0$, $\pi^+\pi^-, K^-\pi^+, K^+K^-, K^-\pi^+\pi^0, K_S^0\pi^+\pi^-, K_S^0\pi^+\pi^-\pi^0, K^-\pi^+\pi^+\pi^-$, $D^+ \to K_S^0\pi^+, K_S^0K^+, K_S^0\pi^+\pi^0, K^-\pi^+\pi^+, K^+K^-\pi^+, K^-\pi^+\pi^+\pi^0$, $K_S^0\pi^+\pi^+\pi^-$
- Many of the channels are "rediscovered" at Belle II.
- With increased statistics, different channels provide important systematic check.

B-tagging: full event interpretation





- Hierarchical approach using several stages to construct full decay chains of B^0, B^+ mesons.
- Heavy use of ML methods (BDT) leads to improvement vs previous methods.
- Can used for hadronic as well as semileptonic tagging. For $B^{\pm}$ Hadronic / semileptonic tag efficiency is 0.61% / 1.45%, about twice better vs Belle.
- Tested on early Belle-II data.

arXiv:1807.0868

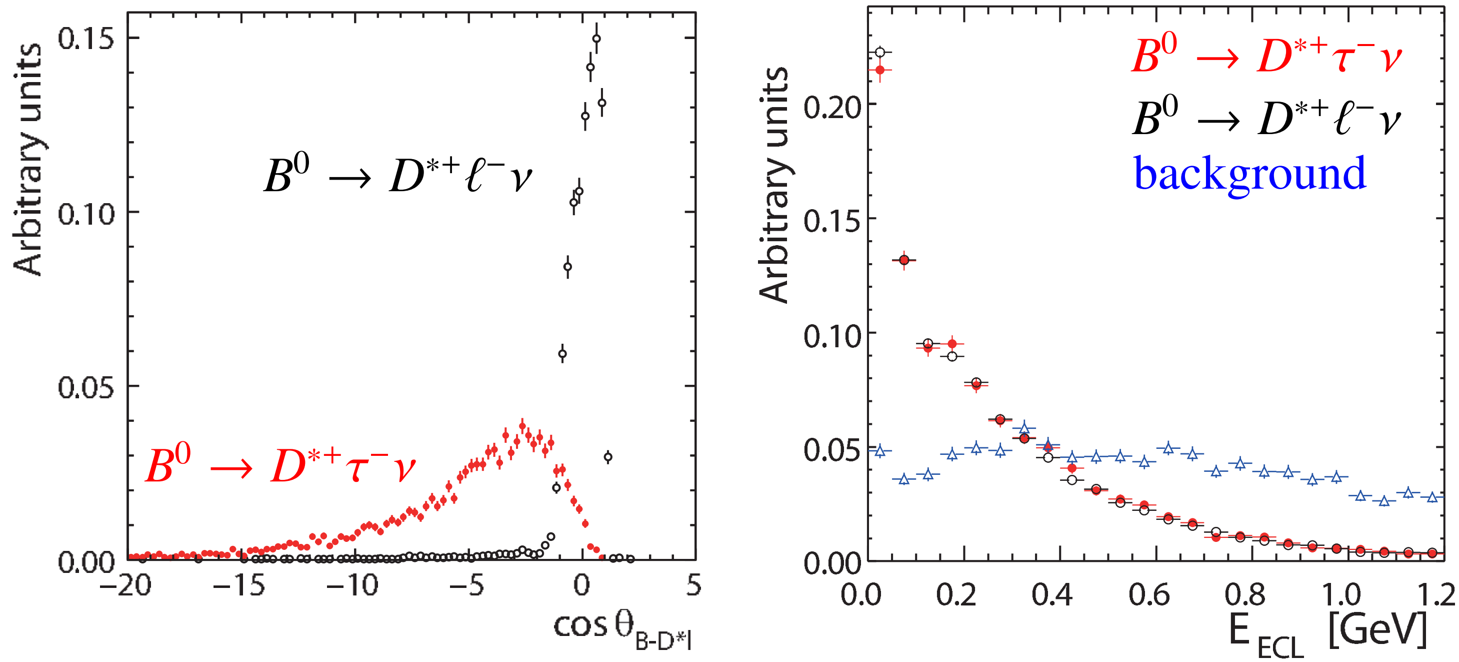
Semileptonic decays: R_D and R_{D^*}

Exp.	Tag method	τ^- decays	Observables	Fit variables
Belle PRL 99, 191807 (2007)	Untagged	$e^-\nu_\tau\bar{\nu}_e, \pi\nu_\tau$	$\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)$	$M_{\rm bc}^{\rm comp}$
Belle PRD 82, 072005 (2010)	Untagged	$\ell^-\nu_\tau\bar{\nu}_\ell, \pi\nu_\tau$	$\mathcal{B}(B^- \to D^{(*)0}\tau^-\bar{\nu}_\tau)$	$M_{\rm bc}^{\rm comp}$ and p_{D^0}
Belle PRD 92, 072014 (2015)	Hadronic	$\ell^-\nu_\tau\bar{\nu}_\ell$	$R_D, R_{D^*}, q^2, \lvert p_\ell^*\rvert$	$M_{\rm miss}^2$ and O_{NB}†
Belle PRD 94, 072007 (2016)	Semileptonic	$\ell^-\nu_\tau\bar{\nu}_\ell$	$R_{D^*}, \lvert p_\ell^*\rvert\, \lvert p_{D^*}^*\rvert$	$E_{\rm ECL}$ and O'_{NB}‡
Belle PRL 118, 211801 (2017)	Hadronic	$h^-\nu_\tau$	$R_{D^*}, P_\tau(D^*)$	$E_{\rm ECL}$ and $\cos\theta_{\rm hel}$

Several methods to reconstruct $B \to D^{(*)}\tau\ell\nu$:

- Untagged early measurements used for observation of the decay
- Hadronically tagged for simultaneous fit of R_D, R_{D^*} and determination of differential distributions (semileptonic τ decays).
- Semileptonically tagged, with semileptonic τ decays for R_{D^*}
- Hadronically tagged with hadronic τ decays, for τ polarisation measurements.

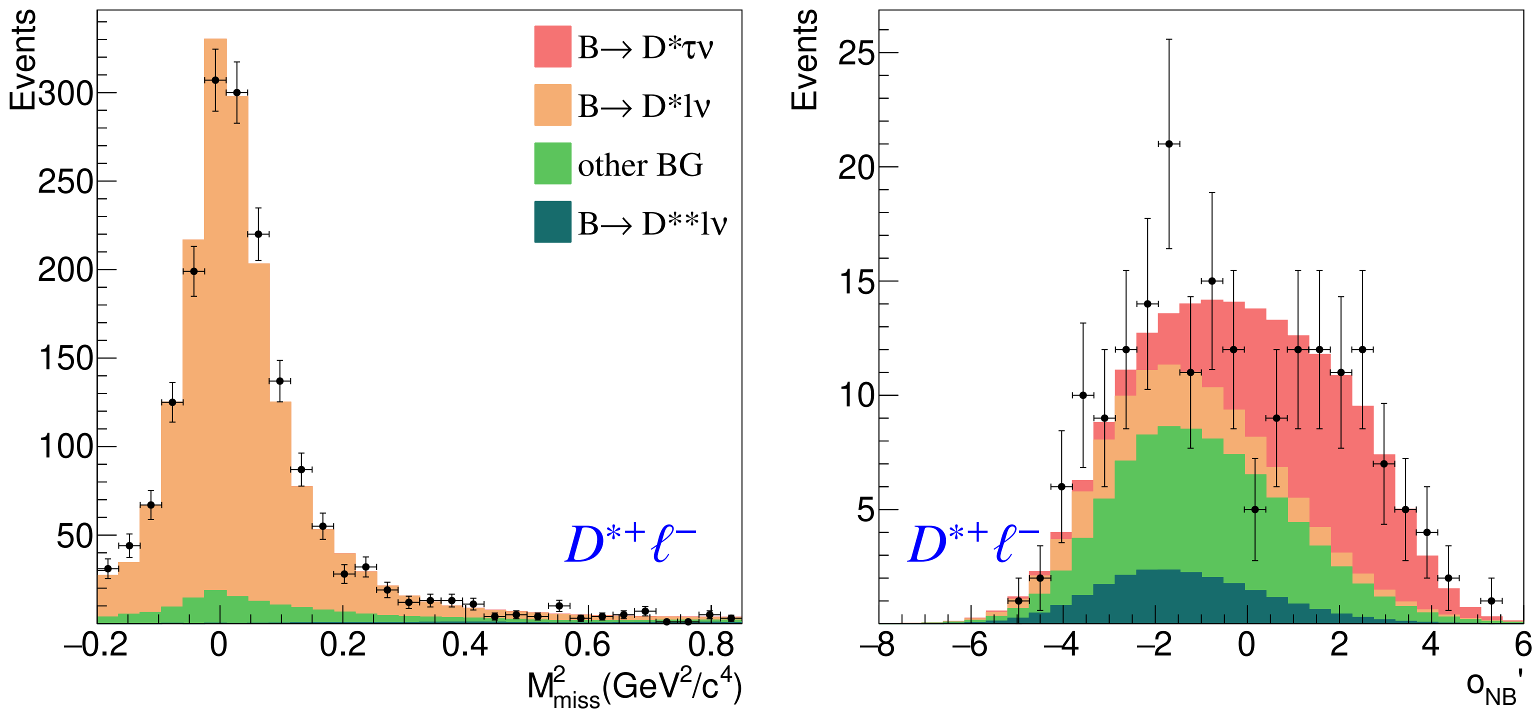
Measurement of $R_{D^{*+}}$ with semileptonic tag at Belle



$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\text{beam}}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|},$$

- Use leptonic $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ decays to reconstruct τ; require two leptons of opposite charge, missing energy and D^{*+}.
- Combine lepton of opposite charge with D^{*+}, compute $\cos\theta_{B\text{-}D^*\ell}$.
- E_{ECL} — sum of energies of extra neutrals in calorimeter — useful to separate background

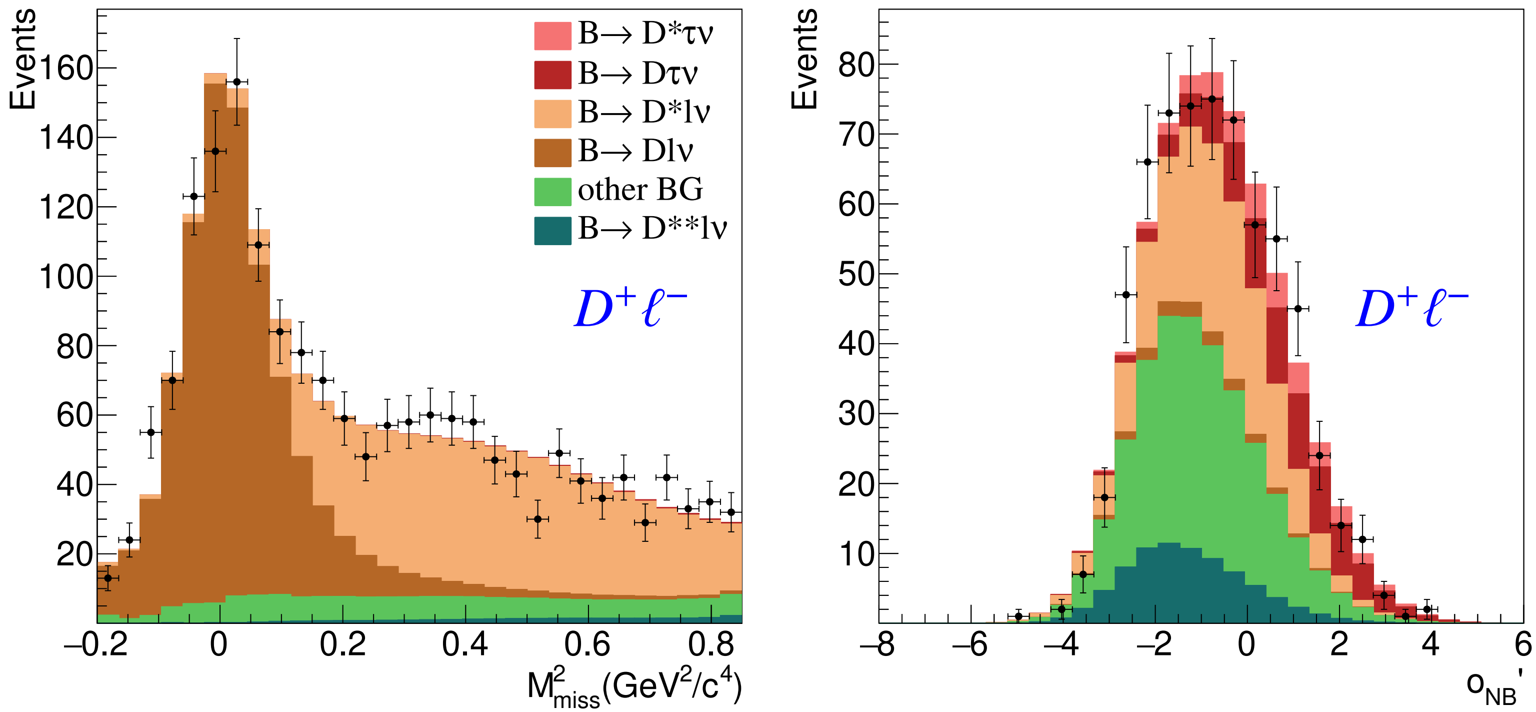
Measurement of R_{D^*} with hadronic tag at Belle



$$M^2_{\text{miss}} = (p_{e^+e^-} - p_{\text{tag}} - p_{D^{(*)}} - p_\ell)^2 .$$

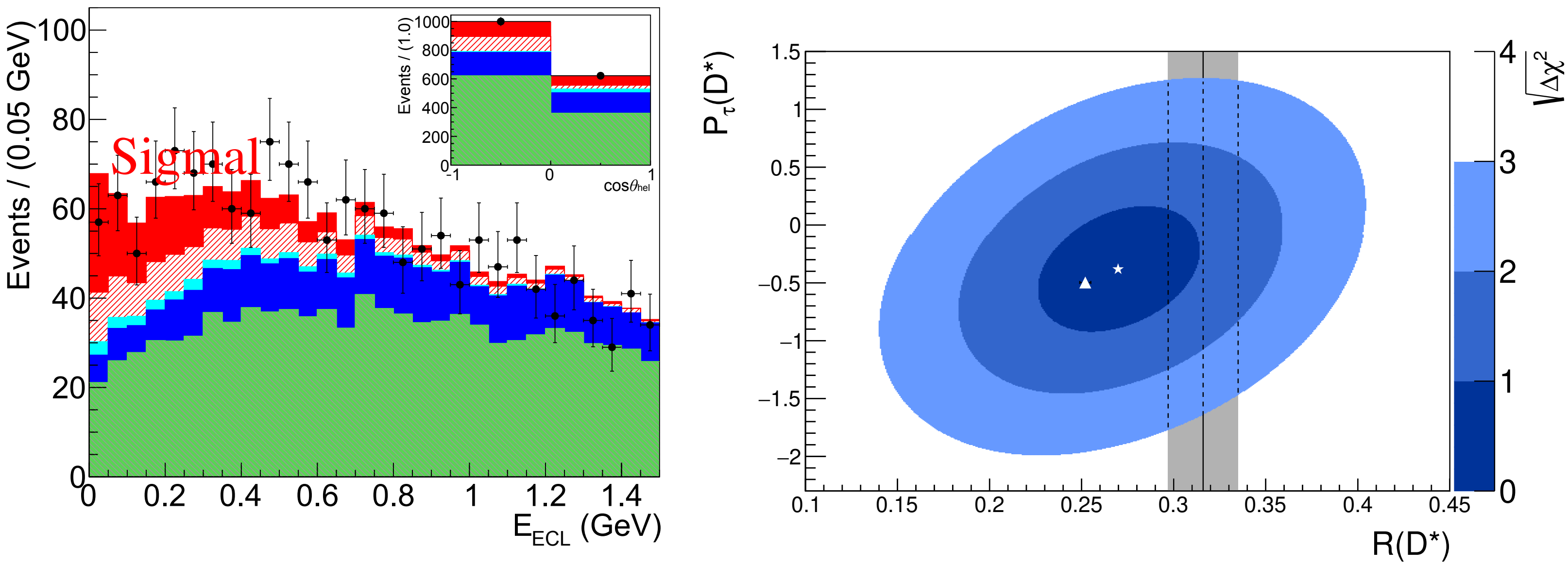
- Use reconstructed hadronically tagged B and $D^{(*)} + \ell$ with $\ell = \mu, e$ to determine M^2_{miss}.
- Low $M^2_{\text{miss}} < 0.85$ GeV is used to determine normalization $B \to D^{(*)}\ell\nu$, high $M^2_{\text{miss}} > 0.85$ GeV — to fit NN output to determine $B \to D^{(*)}\tau\nu$. For NN, E_{ECL} is the main discriminating variable.

Measurement of R_D with hadronic tag at Belle



- Simultaneous fit of ℓ normalization, τ signal for D and D^* samples together with some of background sources while others are fixed to MC expectations.
- Significant backgrounds are $D^{**}\ell$ (fitted) and for $D\ell$ cross-feed from $D^*\ell$ (fitted).

R_{D^*} and τ polarisation measurements



- SM predictions for τ polarisation are very accurate: $P_\tau(D^*) = -0.497 \pm 0.013$, while BSM allows for larger variations.
- Polarisation is measured in two-body hadronic $\tau^- \to \pi^- \nu$ and $\tau^- \to \rho^- \nu$ ($\rho^- \to \pi^- \pi^0$) decays.
- Significant backgrounds from misreconstructed D^* candidates, hadronic B decays.

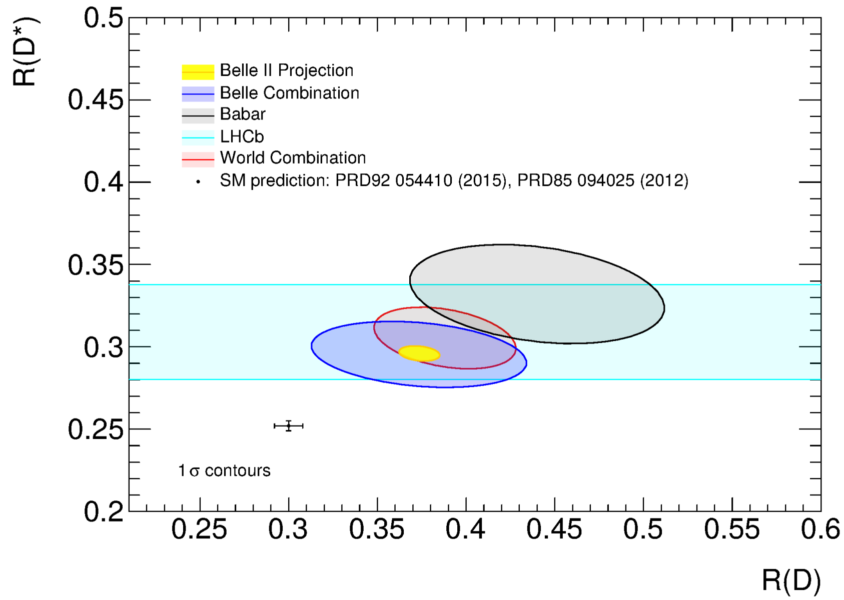
$R_{D^{(*)}}$ measurements: systematic uncertainties

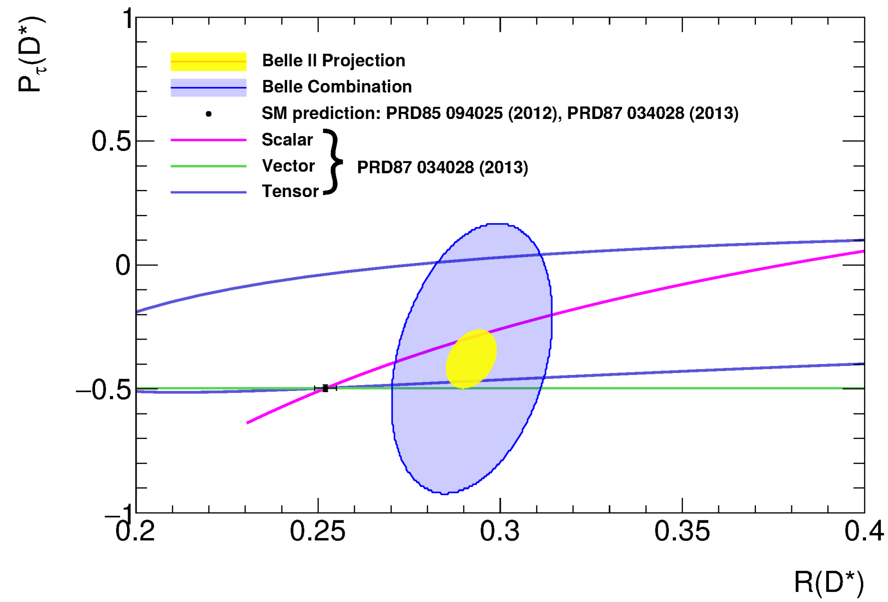
Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

- Leading systematic sources:
  - $B \to D^{**}\ell\nu$ for analyses with leptonic τ decays;
  - Hadronic B decays for $\tau \to h\nu_\tau$ analysis
- Other significant sources are form factors of $B \to D^{(*)}\ell/\tau\nu$ decays, background from $B \to X_c D^{(*)}$ and cross-feed from $B \to D^*\ell/\tau\nu$ to $B \to \ell/\tau\nu$.

$\to$ dedicated measurements of $B \to D^{**}\ell\nu$; direct constrain on $B \to D^{**}\tau\nu_\tau$.

$R_{D^{(*)}}$ and polarisation measurement projections for Belle II



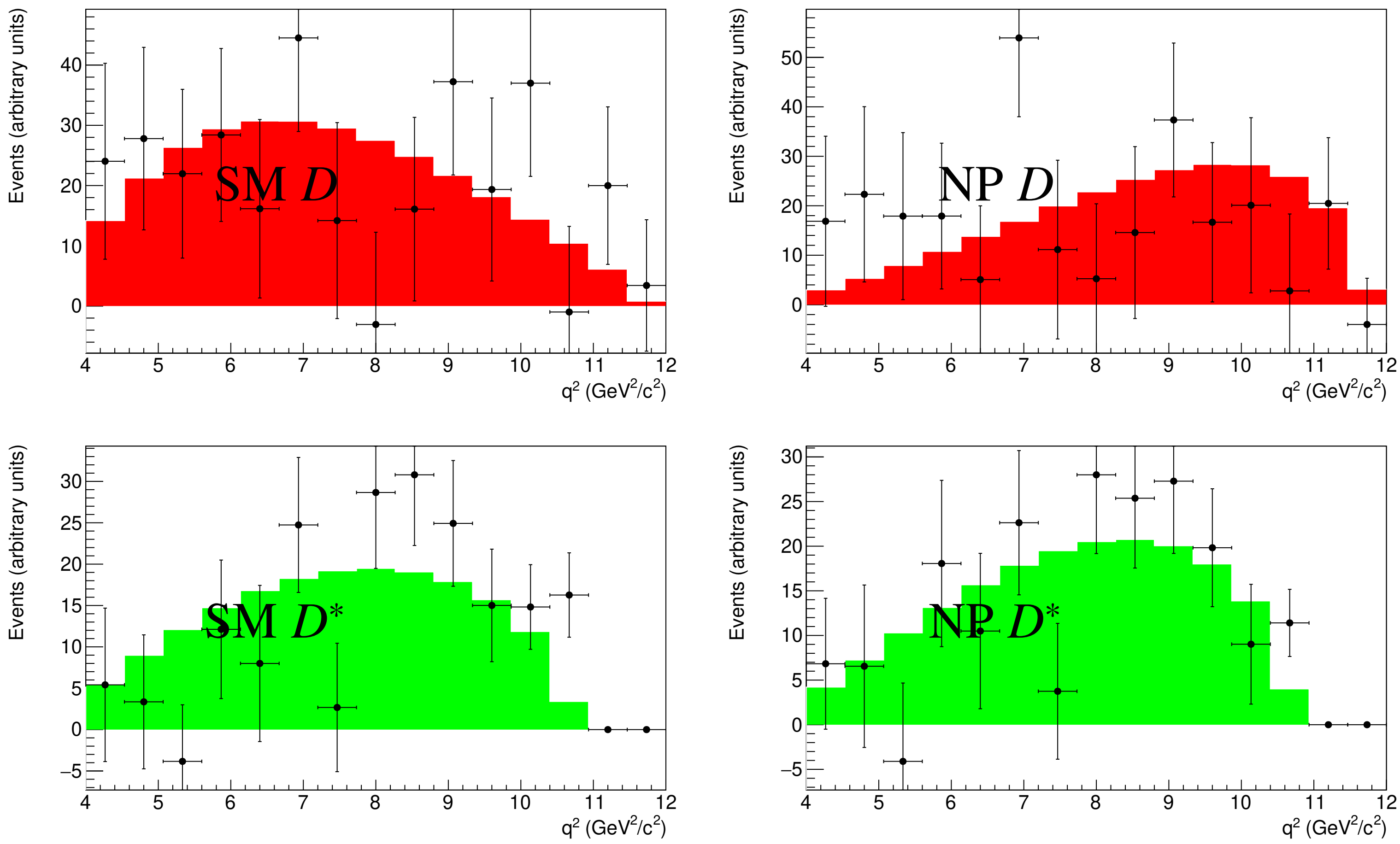


	$5\ \text{ab}^{-1}$	$50\ \text{ab}^{-1}$
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

- Projections for 5 and 50 ab^{-1}. For 50 ab^{-1} systematics start to play important role.
- $P_\tau(D^*)$ as well as the double ratio of R_{D^*}/R_D provide extra information on the nature of NP (if deviation remains).

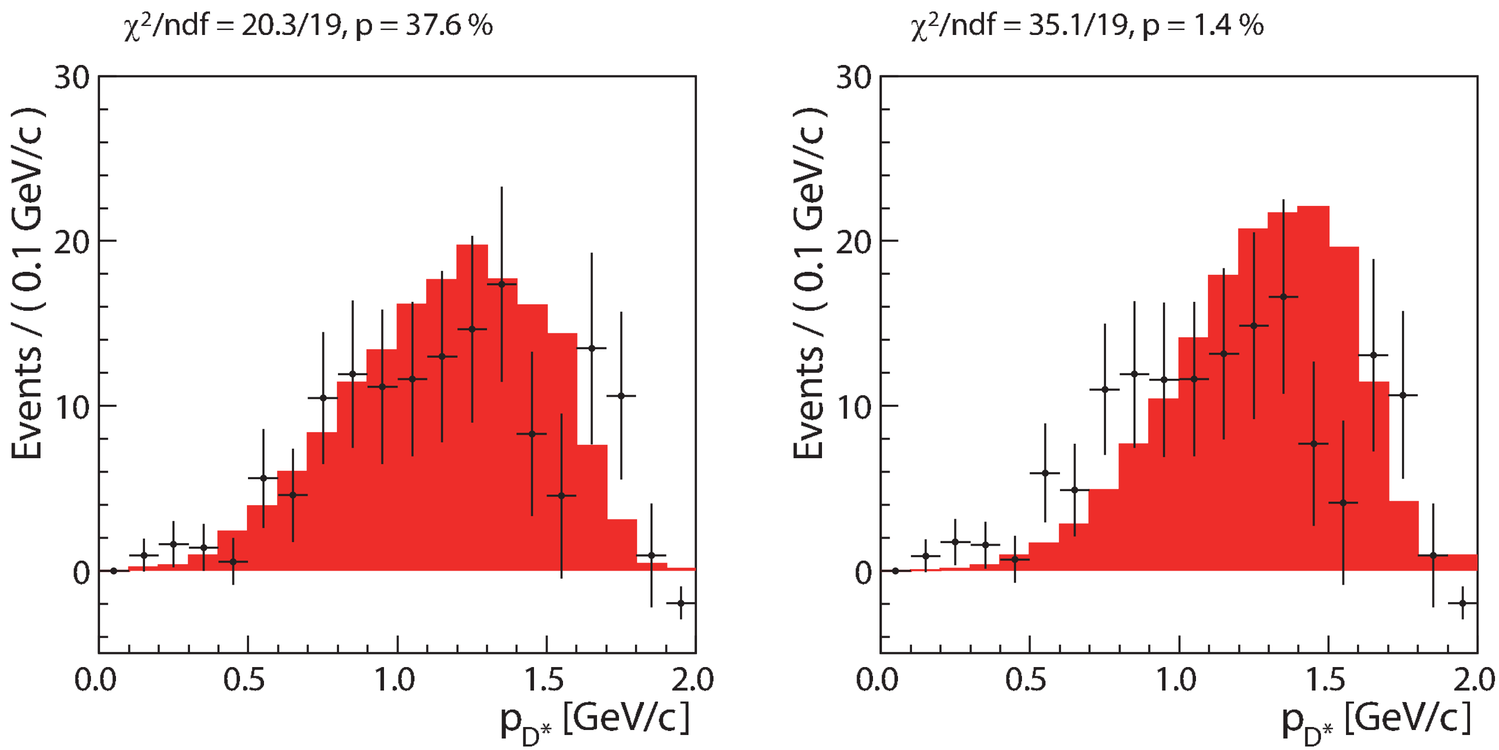
arXiv:1808.10567

Differential $R_{D^{(*)}}$ measurements (hadronic tag)



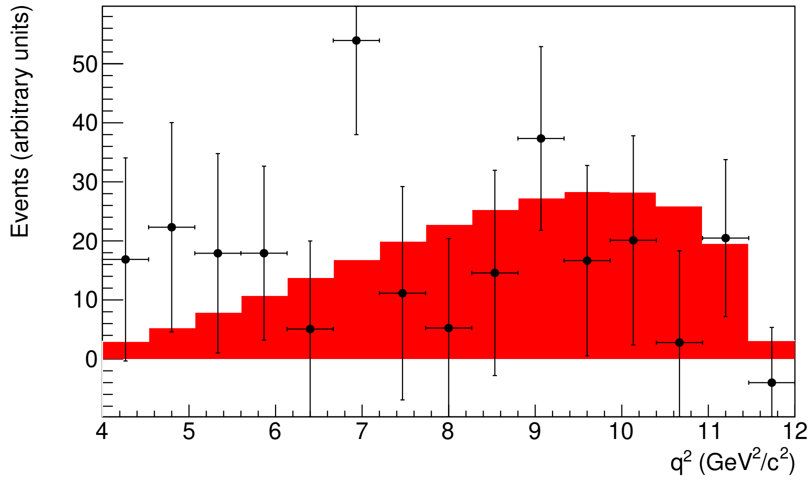
- Compare $q^2 = (P_B - p_{D^{(*)}})^2$ distributions vs SM and NP scenarios.
- Significant discriminating power in the q^2 distribution, different for $B \to D^*\tau\nu$ vs $B \to D\tau\nu$.

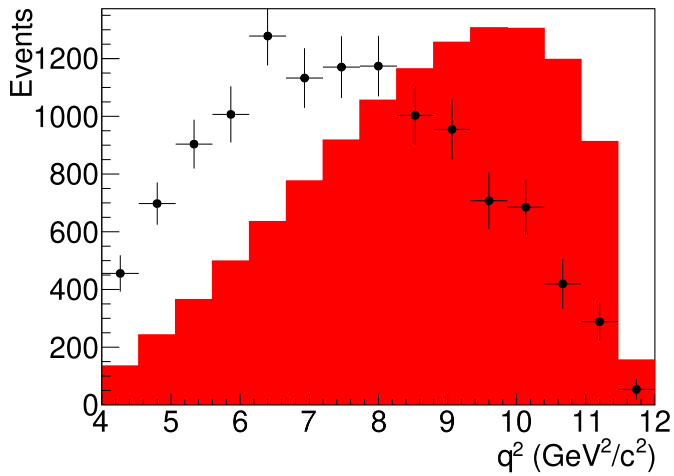
Differential $R_{D^{(*)}}$ measurements (semileptonic tag)



- For semileptonic tag, q^2 can not be determined directly, use P_{D^*} instead.
- Some additional discrimination between SM and R_2-type leptoquark model.

Differential measurements: Belle-II projections





$$M_{\rm NP} \sim (2\sqrt{2} G_F V_{cb} C_X)^{-1/2} \sim 5 - 10 \text{ TeV}$$

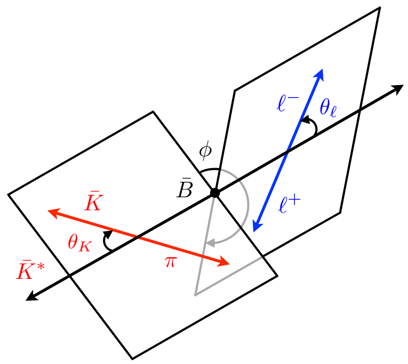
- Hadron-tag based analysis for published Belle vs Belle II estimated using 50 ab^{-1}.
- Strong discriminating power vs 2HDM of type II model.
- Discrimination vs other models with scalar or tensor mediators.

arXiv:1808.10567

FCNC: $B \to K^* \ell\ell$ differential rate

Angular decomposition for the differential rate:

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



$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$

$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

Redefinition of parameters: $P'_{i=4,5,6,8} = \dfrac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$

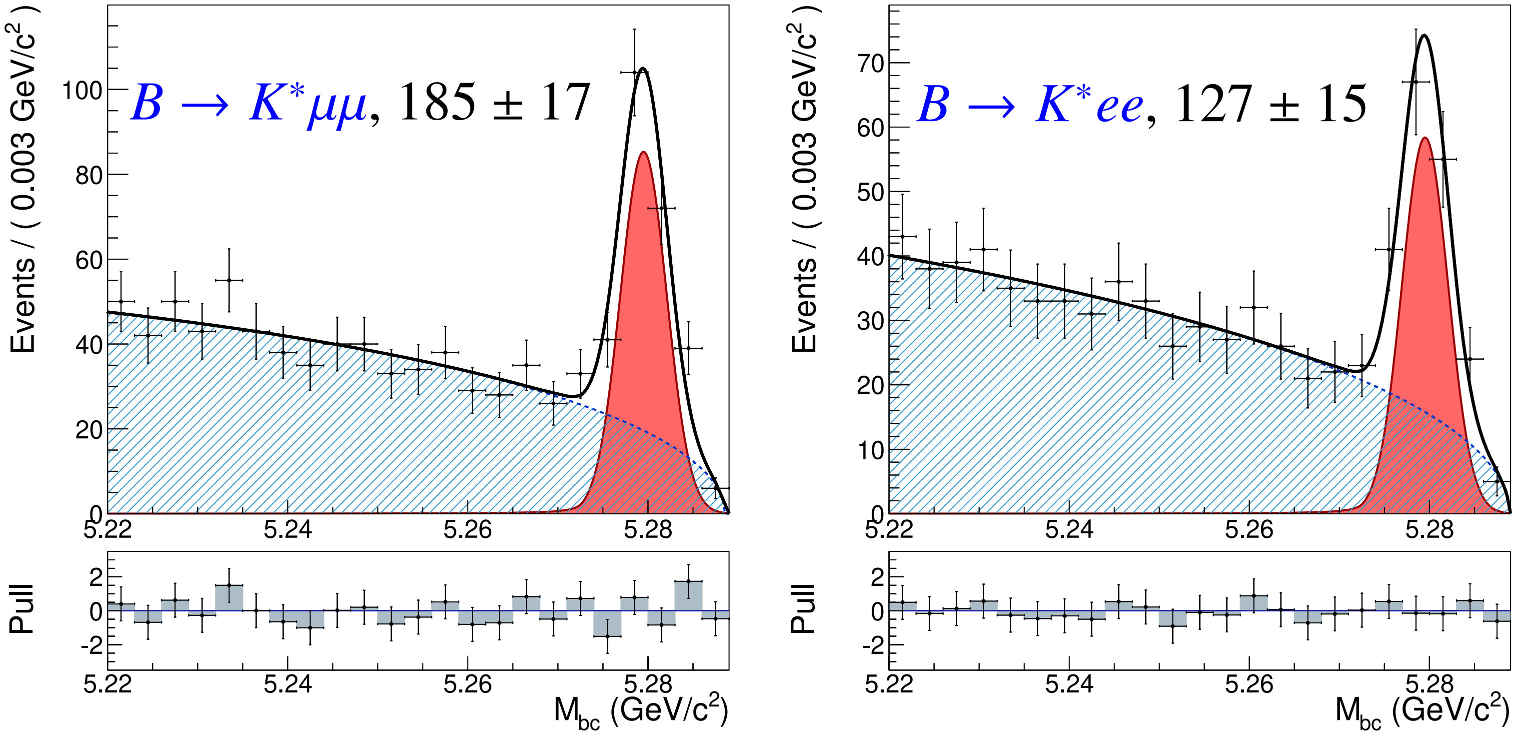
Folding of variables:

$$P'_4, S_4 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases} \qquad P'_5, S_5 : \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$$

For small q^2, P'_5 is connected to semi-leptonic operators Q_9 and Q_{10}.

$$P'_5 \simeq \frac{\mathrm{Re}\left(C^*_{10}C_{9,\perp} + C^*_{9,\parallel}C_{10}\right)}{\sqrt{\left(|C_{9,\perp}|^2 + |C_{10}|^2\right)\left(|C_{9,\parallel}|^2 + |C_{10}|^2\right)}},$$

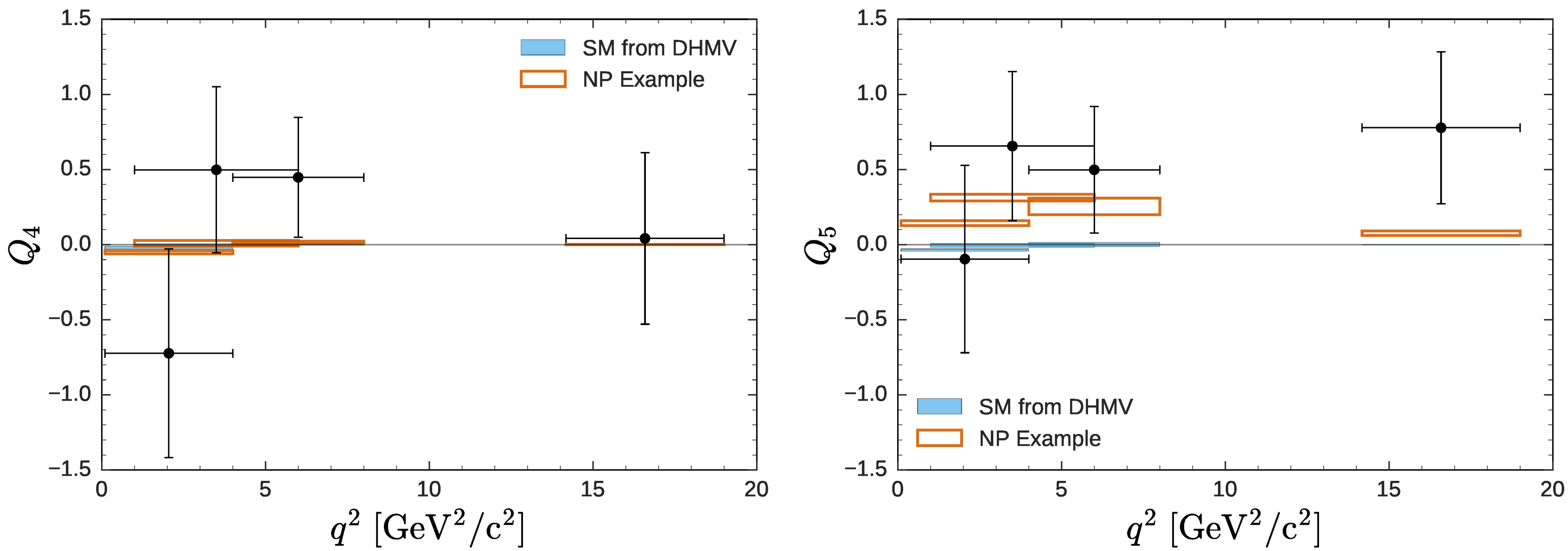
$B \to K^{(*)}\mu\mu$ and $B \to K^{(*)}ee$ at Belle



- Fit to beam constrained mass distribution, $M_{bc} = \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$.
- Similar quality for $K^*\mu\mu$ and K^*ee reconstruction: reduced systematics for R_{K^*}.

PRL118, 111801 (2017).

Differential LFU tests for $B \to K^{(*)}\ell\ell$

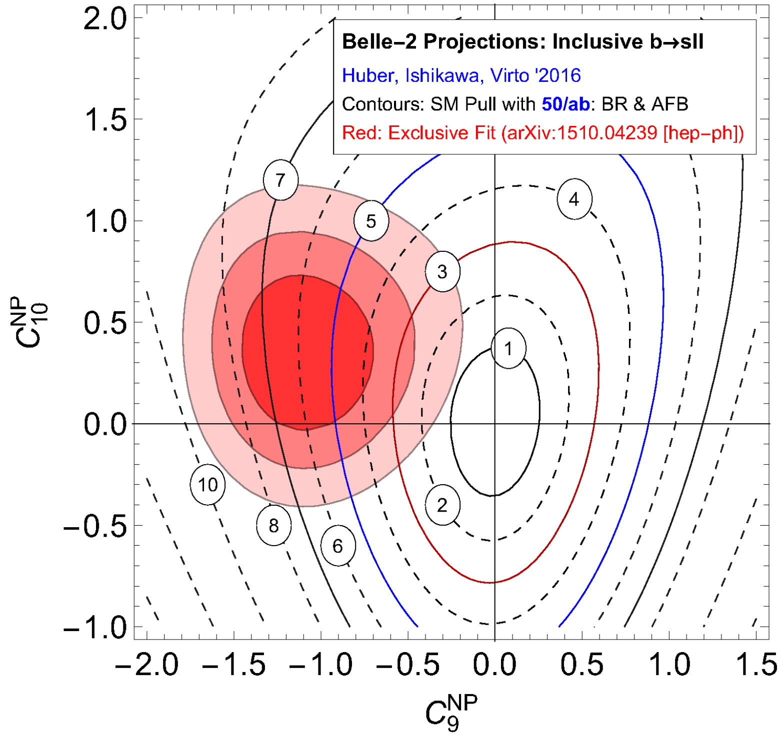


- Determine flavour dependent angular coefficient difference: $Q_i = P'_{i,\mu} - P'_{i,e}$.
- Sensitivity to NP in Q_5, errors dominated by statistics.
- Modeling of QED radiation / bin-to-bin migrations may start play a role with improved stats.

(Note that the measurement is presented for two different binning schemes, the measurement for the $1 < q^2 < 6\ \mathrm{GeV}^2$ bin is correlated with measurements in the overlaping bins.)

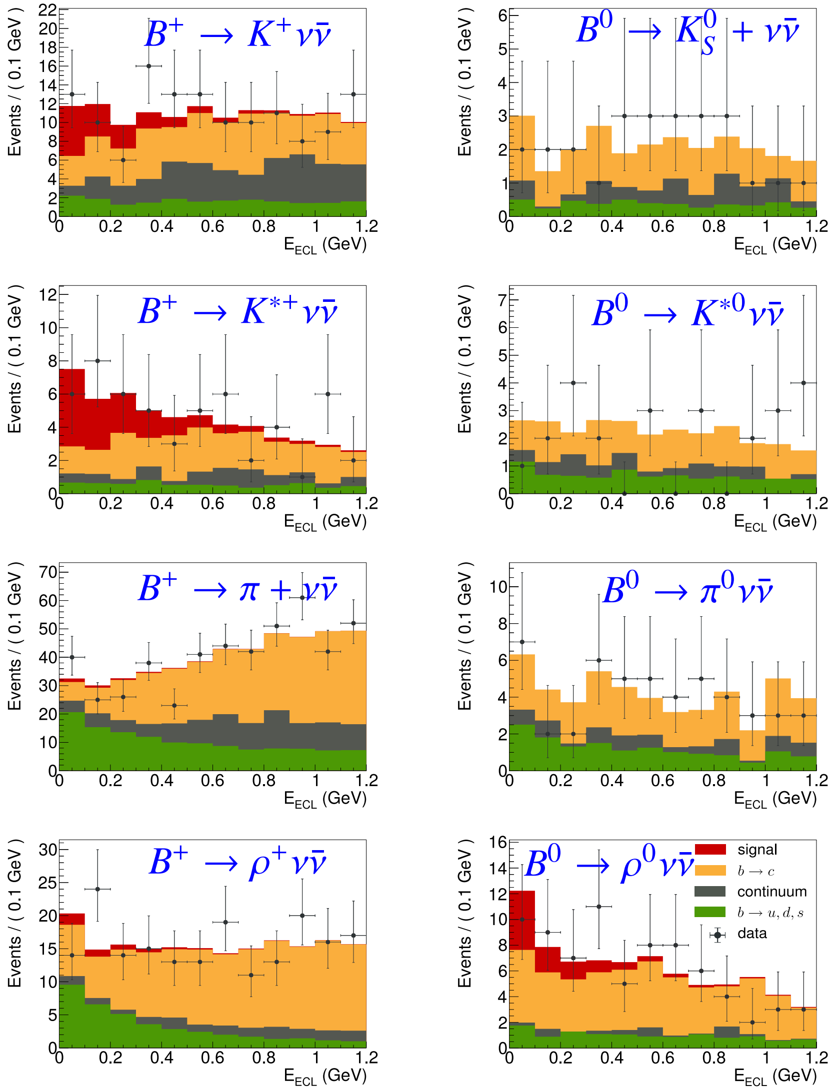
PRL118, 111801 (2017).

Inclusive $B \to X_s \ell\ell$ decays



- Initial measurements sum over exclusive method with $M_{X_s} \lesssim 1.8\,\mathrm{GeV}$, eventually: fully inclusive recoil method.
- Theoretical uncertainties from M_{X_s} cut, resolved photon contribution, charmonium resonances.
- Can be performed for $X_s ee$ and $X_s \mu\mu$ separately.

$B \to h\nu\bar{\nu}$ study from Belle (semileptonic tag)

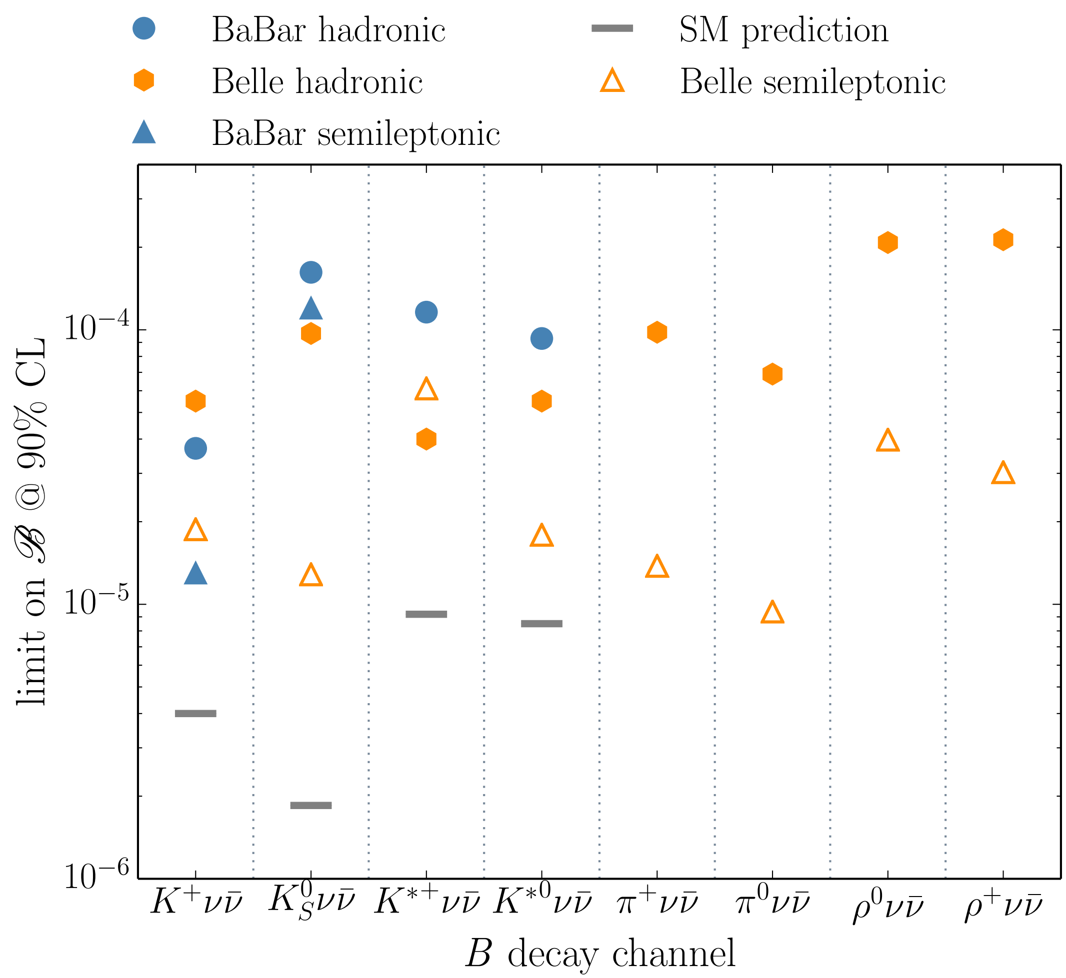


PRD 96, 091101 (2017)

- Simultaneous analysis of $B \to s, d\nu\bar{\nu}$ transition in several modes
- Presence of LFV may affect these modes
- Relative background fractions are fixed to MC expectations
- No significant signal yield:

Channel	Expected limit	Observed limit
$K^+\nu\bar{\nu}$	0.8×10^{-5}	1.9×10^{-5}
$K_S^0\nu\bar{\nu}$	1.2×10^{-5}	1.3×10^{-5}
$K^{*+}\nu\bar{\nu}$	2.4×10^{-5}	6.1×10^{-5}
$K^{*0}\nu\bar{\nu}$	2.4×10^{-5}	1.8×10^{-5}
$\pi^+\nu\bar{\nu}$	1.3×10^{-5}	1.4×10^{-5}
$\pi^0\nu\bar{\nu}$	1.0×10^{-5}	0.9×10^{-5}
$\rho^+\nu\bar{\nu}$	2.5×10^{-5}	3.0×10^{-5}
$\rho^0\nu\bar{\nu}$	2.2×10^{-5}	4.0×10^{-5}

$B \to h\nu\bar{\nu}$ limits from Belle

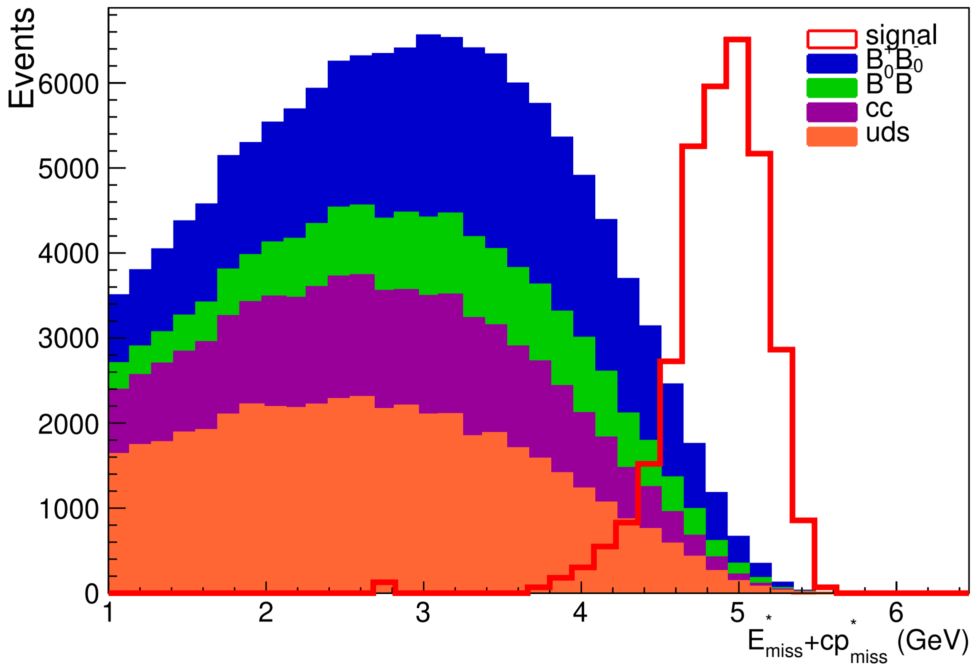


- Best upper limits at the time
- Golden channel for Belle-II

PRD 96, 091101 (2017)

Perspectives for $B \to K^* \nu\bar{\nu}$ at Belle II

$K^{*+} \to K^+\pi^0$ channel



- Study based on hadronic tag, using FEI.
- Good discrimination vs background using $E_{\rm miss} + p_{\rm miss}$ variable with low correlation to $m_{\nu\bar{\nu}}$
- Expected observation with 4 ab^{-1}, 10% accuracy with 50 ab^{-1}.
- Measurement of K^* longitudinal polarisation fraction to 0.08 (SM accuracy 0.03).

arXiv:1808.10567

Perspectives for $B \to K^*\tau\tau$

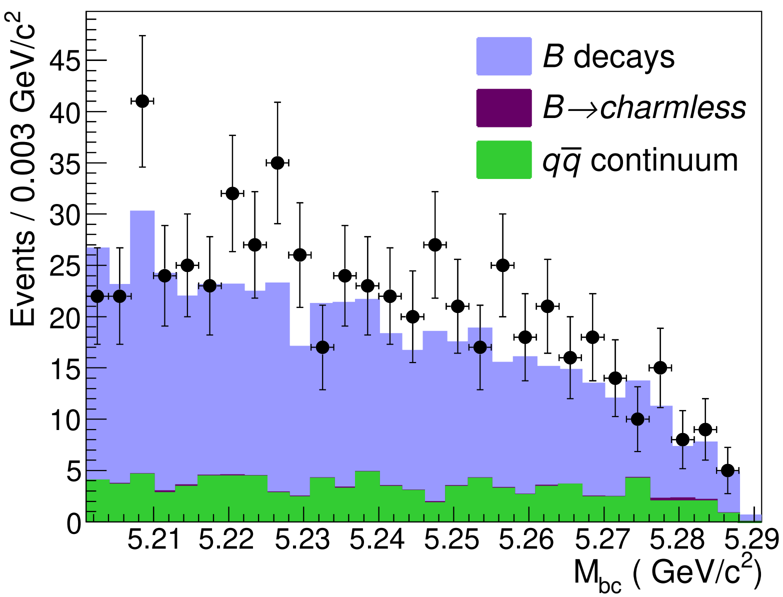
Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 8.1	–
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	< 2.1
$\mathrm{Br}(B^+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

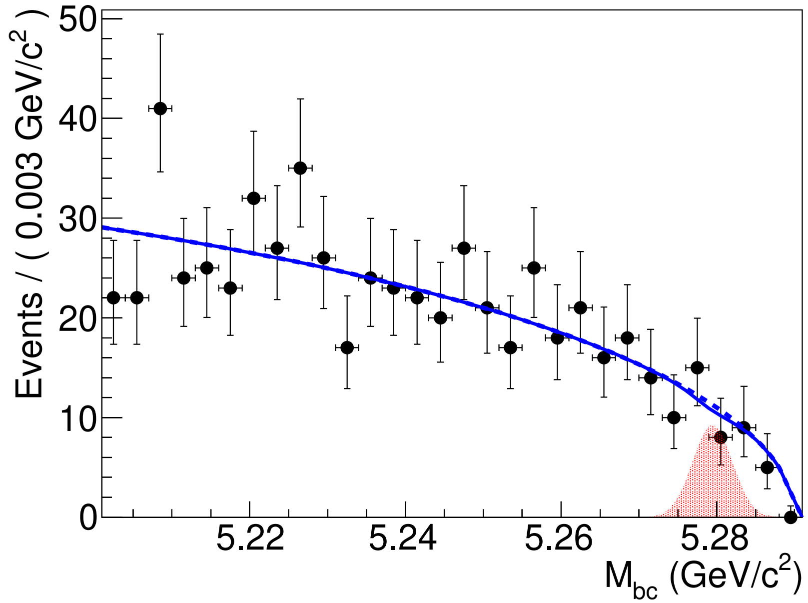
- Standard Model $B \to K\tau\tau$ is difficult at Belle II even with full luminosity.
- Lepton flavour violating processes, such a $B \to K\tau\mu$, are easier to get to better limits.

$\to$ perhaps some room for CepC/FCCee to do flavour physics.

arXiv:1808.10567

Belle search for $B \to K^{*0}\mu e$





- Selection on beam-constrained mass M_{bc} and the energy difference $\Delta E = E_B - E_{\text{beam}}$, continuum suppression using NN (kinematics, flavour tagging).
- Main remaining background from (a) both B decay semileptonically, (b) $B \to \bar{D}^{(*)} X \ell^+ \nu$, $\bar{D}^* \to X \ell^- \bar{\nu}$, (c) lepton mis-ID. Suppressed by NN using vertex, ECL information.
- $B(B^0 \to K^{*0}\mu^+ e^-) < 1.2 \times 10^{-7}$, $B(B^0 \to K^{*0}\mu^- e^+) < 1.6 \times 10^{-7}$, $B(B^0 \to K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$

PRD 98, 071101 (2018)

Summary

- Belle-II is an excellent detector for lepton universality studies, especially for the channels involving missing energy, but also for ee vs $\mu\mu$ channels, due to similar reconstruction efficiency.
- Most of the channels at Belle-II are statistics limited, however for $R_{D(*)}$ better modeling of $B \to D^{**}\ell\nu$ and hadronic B decays is needed.
- ML-based full event iterpretation tagging method improves B-meson tagging compared to Belle-I. Further improvements are possible, with better modelling of B decays used for the training.