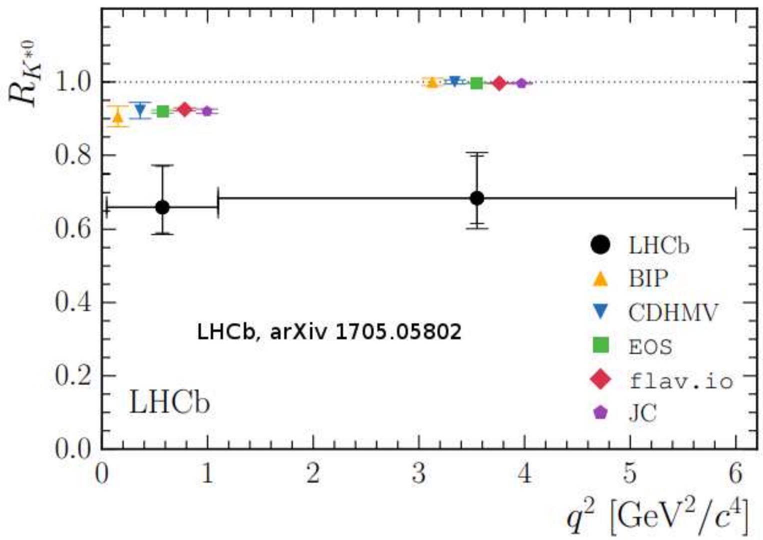
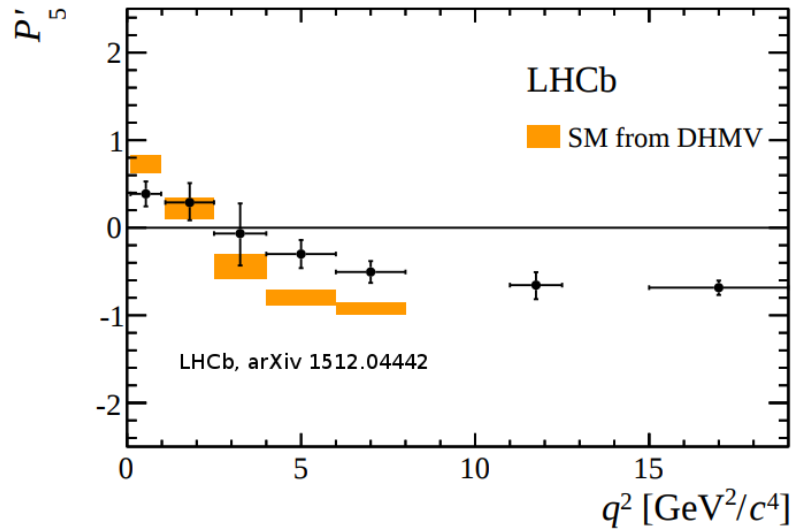
Anomalies in B (semi)leptonic decays at B factories

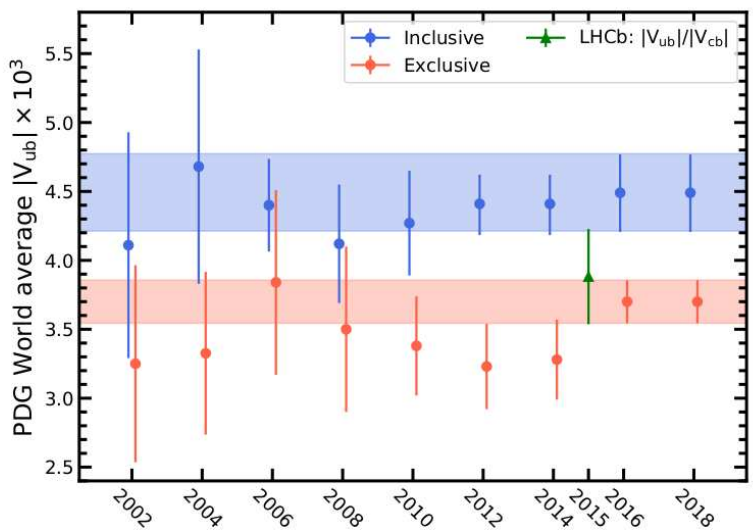
S. Glazov on behalf of Belle II collaboration

KAON2019, Perugia, 11 September 2019.

Signatures of B anomalies

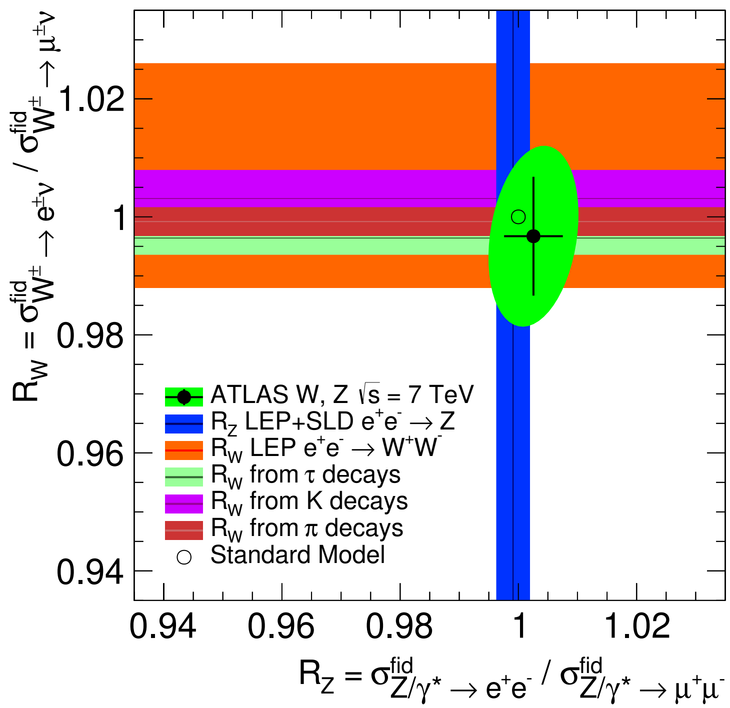






- Deviation from expected branching fractions
- Lepton flavour universality violation: $R_D, R_{D^*}, R_K, R_{K^*}$
- Anomalies in angular distributions
- Inconsistencies in $|V_{cb}|, |V_{ub}|$ determination for inclusive vs exclusive methods.

Experimental data on LFU



ATLAS EPJC 77 (2017) 367;

LEP+SLD, PR 427 (2006) 257;

HFAG arXiv:1412.7515;

KTEV PRD70 (2004) 092007;

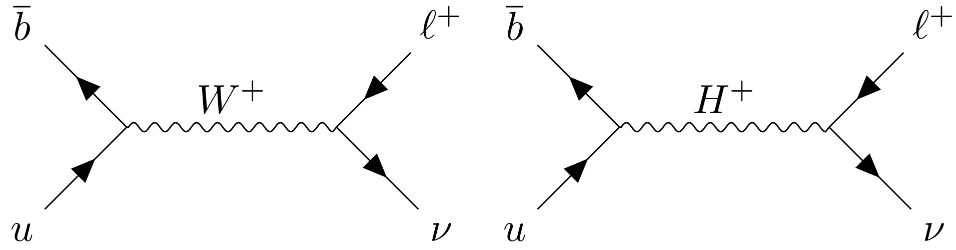
NA62 PLB 719 (2013) 326;

PIENU PRL 115 (2015) 071801.

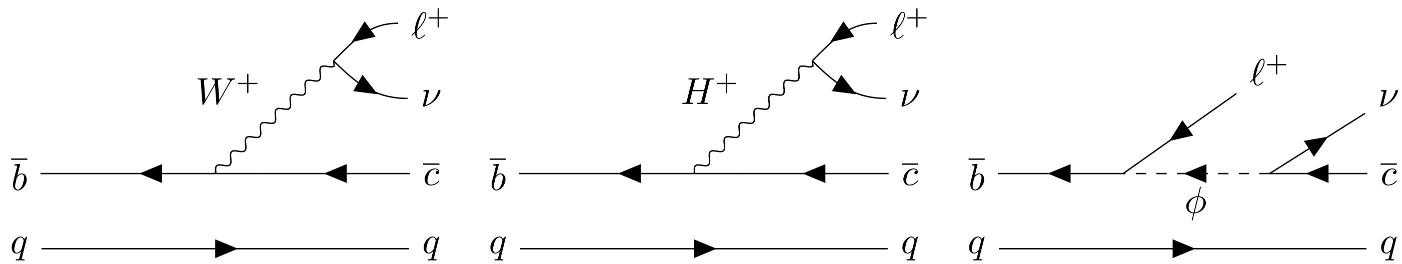
- Lepton flavour violation probed to 10^{-12} level in μ decays.
- Lepton universality for $Z \to \ell\ell$ probed to per mille accuracy at LEP, including $\Gamma_{Z\to\tau\tau}/\Gamma_{Z\to\ell\ell} = 1.0019 \pm 0.0032$.
- Lepton universality for $W \to e\nu$ and $W \to \mu\nu$ decays measured directly, 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

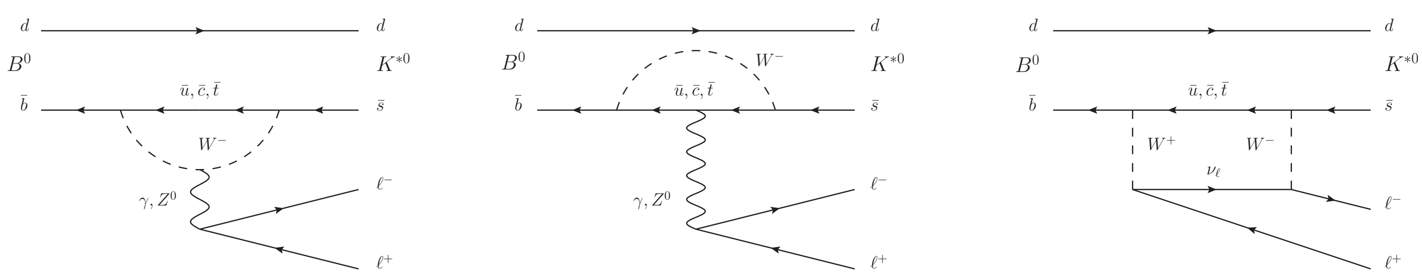
- Leptonic decays $B^{\pm} \to \ell^{\pm}\nu$, $B^0 \to \ell\ell'$.



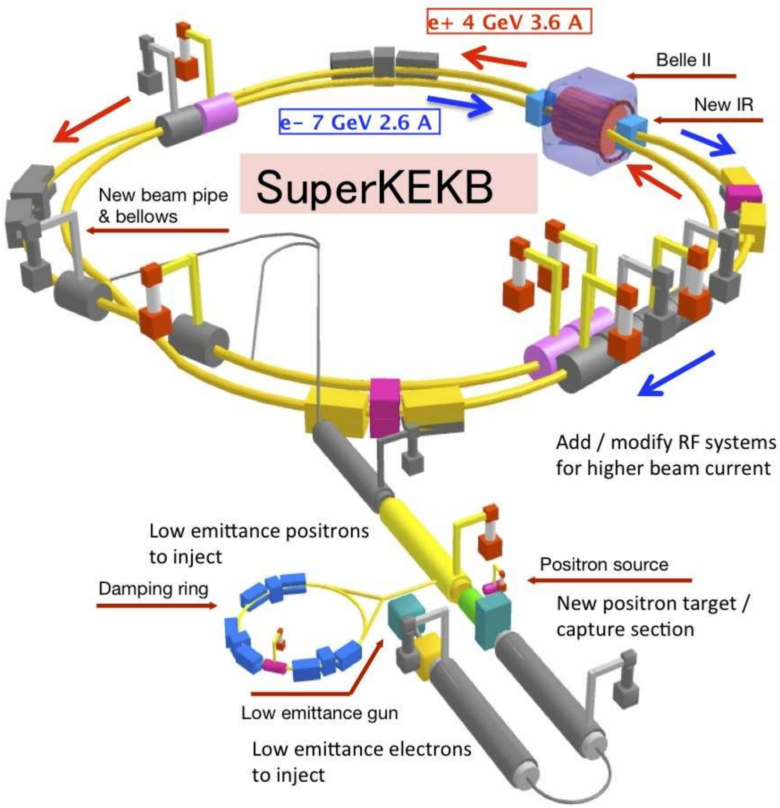
- Semileptonic decays $B \to X\ell\nu$

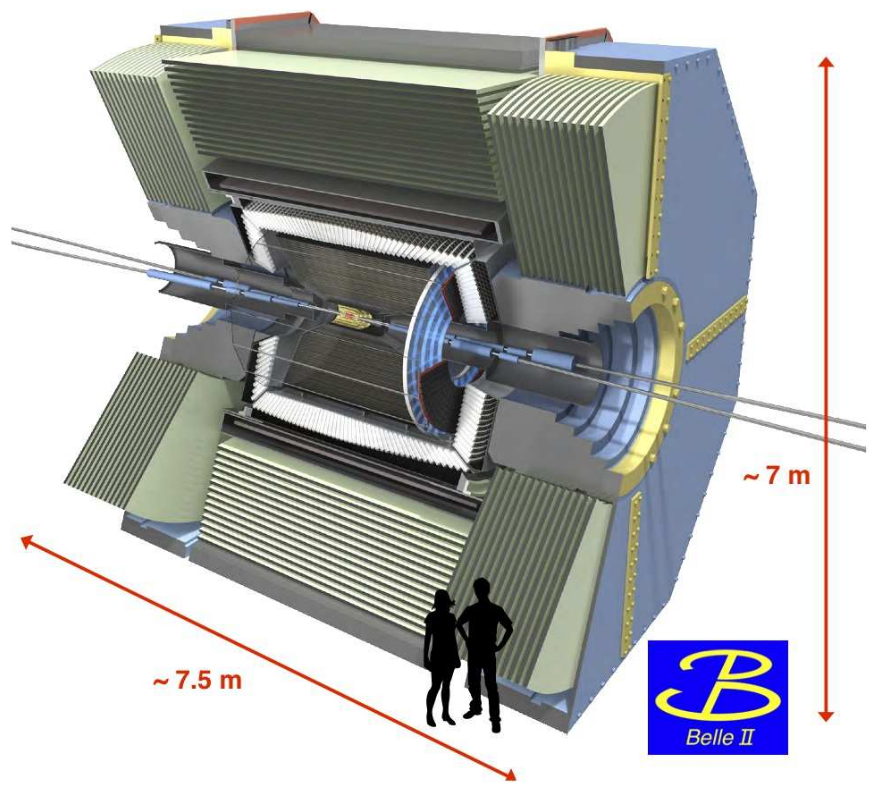


- FCNC processes $B \to X_{s(d)}\ell^+\ell^-$.



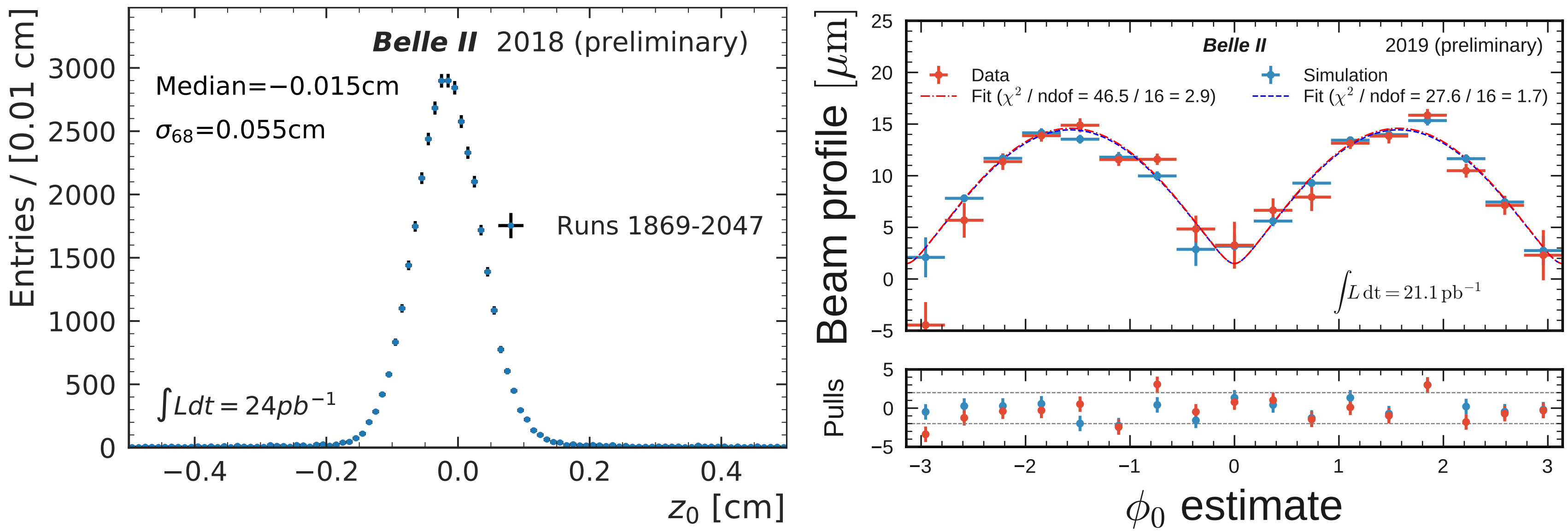
SuperKEKB and Belle II





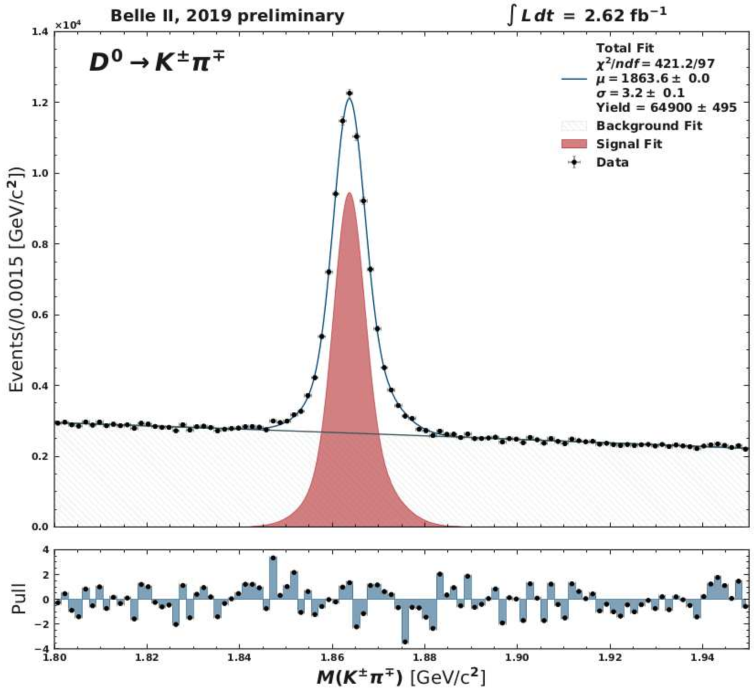
→ First physics data in 2018, 2019 runs.

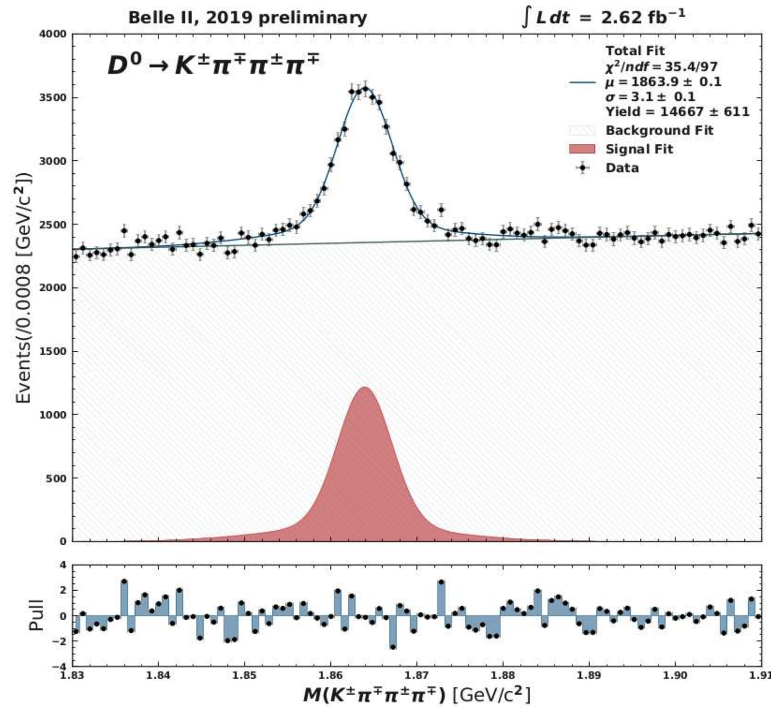
Status of Belle II



- 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.

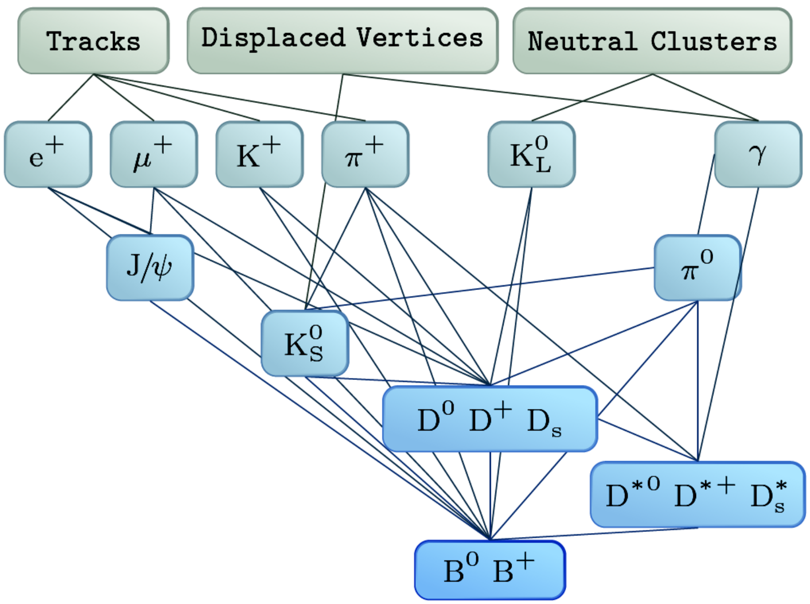
D-meson reconstruction

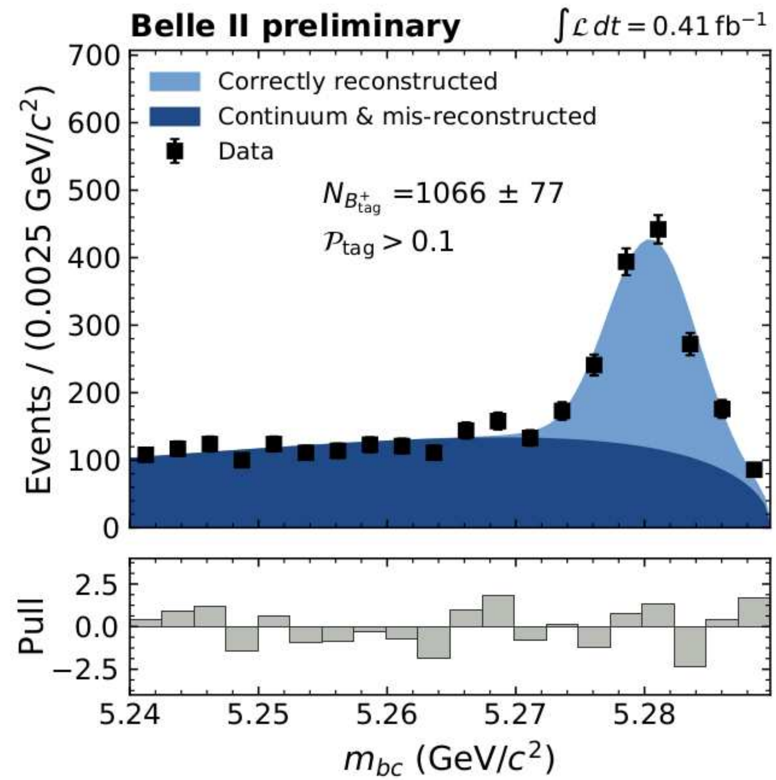




- D^* mesons are reconstructed from $D^{*0} \to D^0\gamma, D^0\pi^0$ and $D^{*+} \to D^+\pi^0, D^0\pi^+$ while D are from $D^0 \to K_S^0\pi^0$, $\pi^+\pi^-, K^-\pi^+, K^+K^-, K^-\pi^+\pi^0, K_S^0\pi^+\pi^-, K_S^0\pi^+\pi^-\pi^0, K^-\pi^+\pi^+\pi^-$, $D^+ \to K_S^0\pi^+, K_S^0K^+, K_S^0\pi^+\pi^0, K^-\pi^+\pi^+, K^+K^-\pi^+, K^-\pi^+\pi^+\pi^0, K_S^0\pi^+\pi^+\pi^-$
- 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.

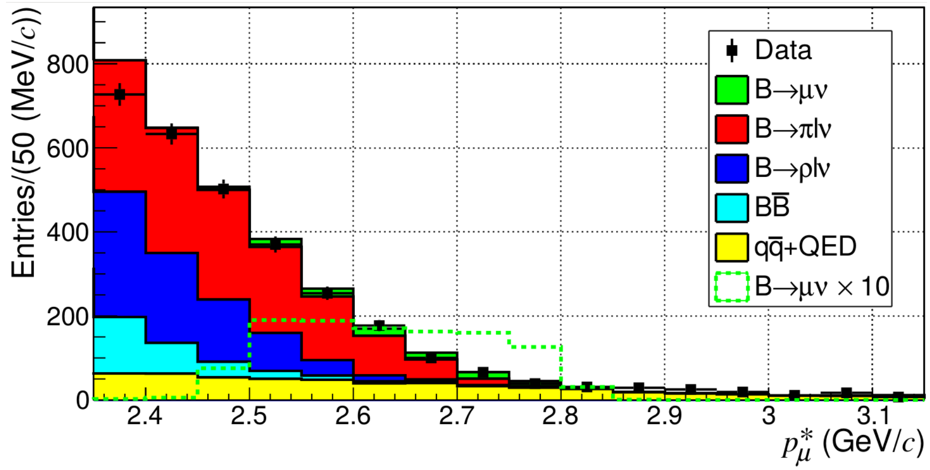
arXiv:1807.0868

Leptonic decays

Expected branching fraction and yield at Belle:

ℓ	$\mathcal{B}_{SM}$	N_{SM}^{Belle}
τ	$(8.45 \pm 0.70) \times 10^{-5}$	$(670 \pm 57) \times 10^{2}$
μ	$(3.80 \pm 0.31) \times 10^{-7}$	301 ± 25
e	$(8.89 \pm 0.73) \times 10^{-12}$	0.0071 ± 0.0006

PRL 121, 031801 (2018)



$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B,$$

- With decay constant from FLAG $f_B = 0.186 \pm 0.004$, interesting alternative for $|V_{ub}|$ determination.
- Analysis using 2D fit to p_μ^* and NN estimator.
- Signal branching fraction is determined using $R = N_{B\to\mu\bar{\nu}_\mu}/N_{N\to\pi\mu\bar{\nu}_\mu}$ to be $\mathcal{B}(B \to \mu\bar{\nu}_\mu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$, consistent with SM expectations.

PRL 121, 031801 (2018)

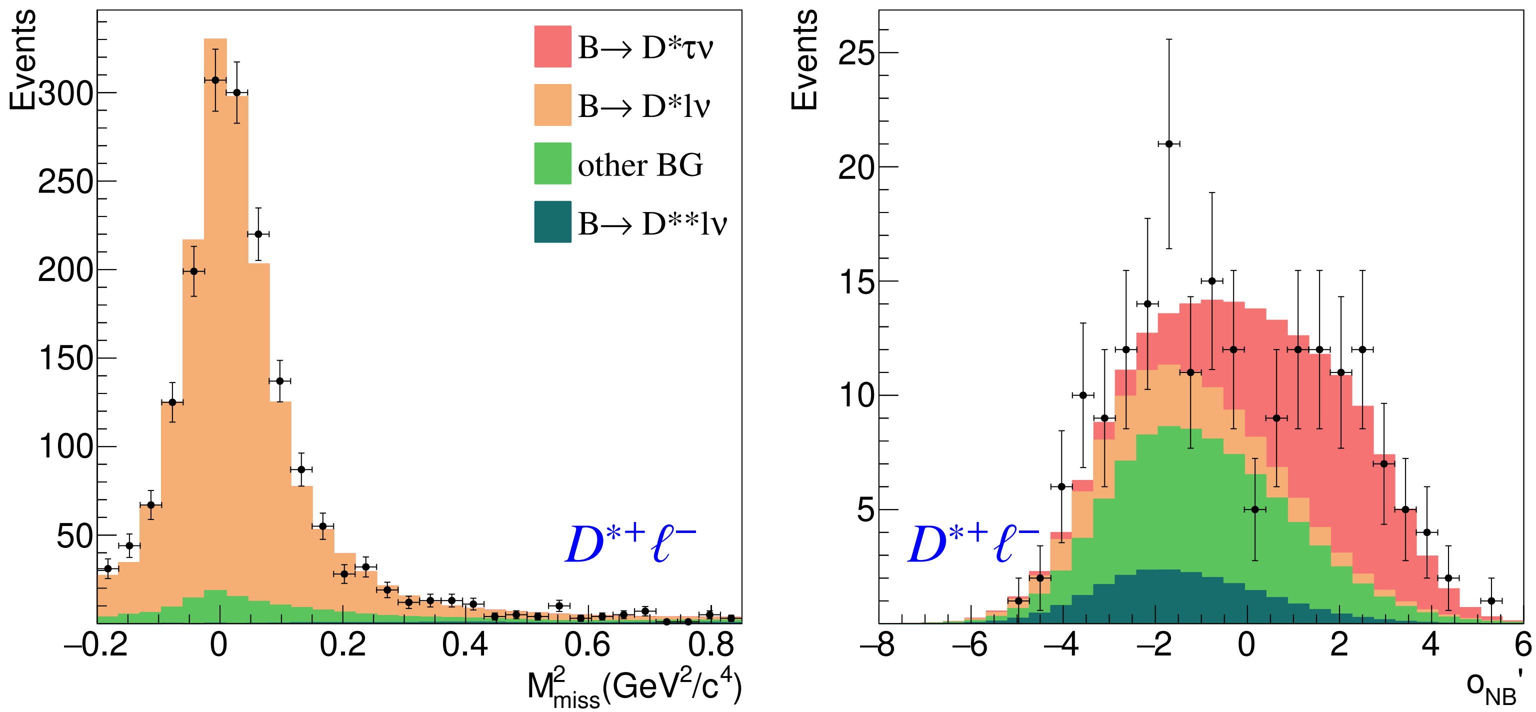
Semileptonic decays: R_D and R_{D^*}

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 PRL 118, 211801 (2017)	Hadronic	$h^- \nu_\tau$	R_{D^*}, $P_\tau(D^*)$	$E_{\rm ECL}$ and $\cos\theta_{\rm hel}$
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 preliminary conf-1902	Semileptonic FEI	$\ell^- \nu_\tau \bar{\nu}_\ell$	R_D, R_{D^*}	$E_{\rm ECL}$ and O_{BDT}

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).
- Hadronically tagged with hadronic τ decays, for τ polarisation measurements.
- Semileptonically tagged, with semileptonic τ decays for R_{D^*}, R_D

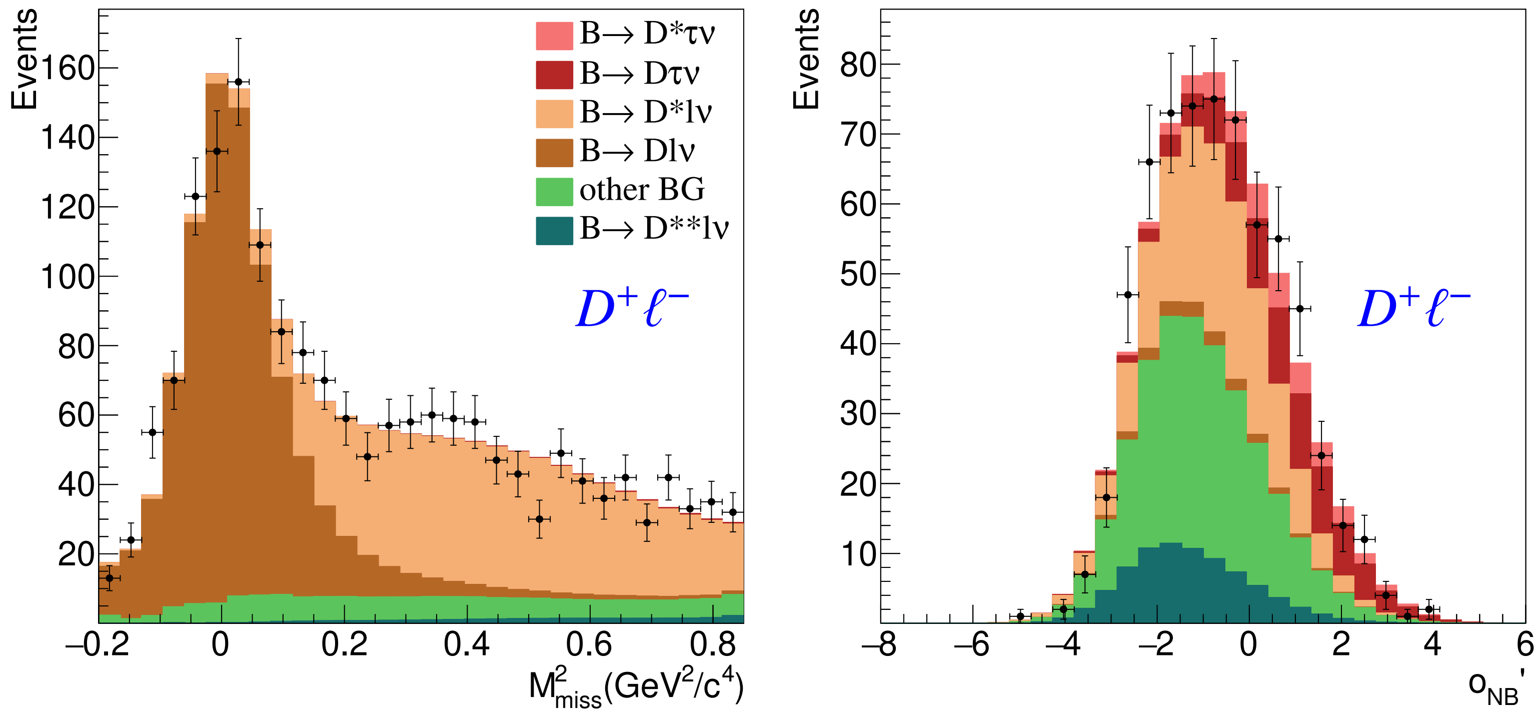
Measurement of R_{D^*} with hadronic tag at Belle



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

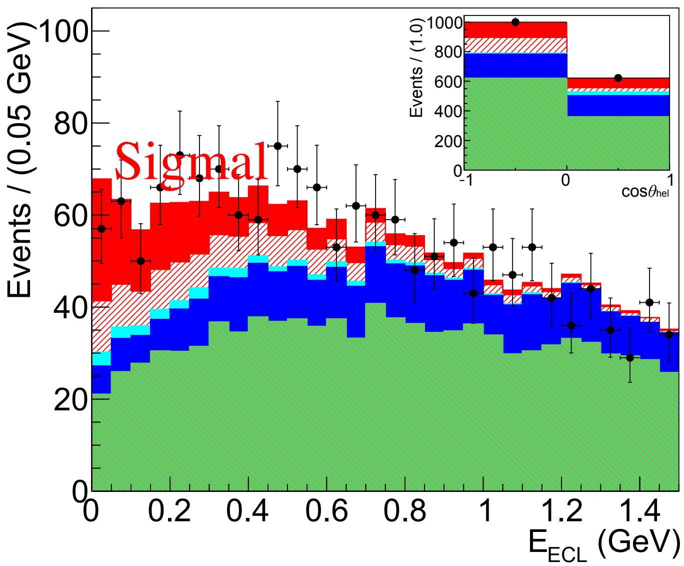
- Use reconstructed hadronically tagged B and $D^{(*)} + \ell$ with $\ell = \mu, e$ to determine M^2_{miss}.
- Low $M^2_{\text{miss}} < 0.85$ GeV is used to determine normalization $B \to D^{(*)}\ell\nu$, high $M^2_{\text{miss}} > 0.85$ GeV — to fit NN output to determine $B \to D^{(*)}\tau\nu$. For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

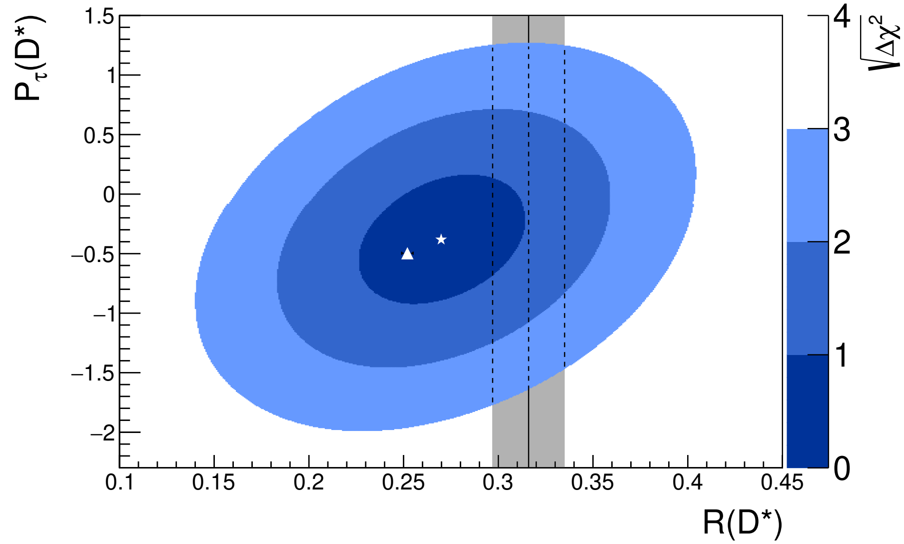
Measurement of R_D with hadronic tag at Belle



- 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).

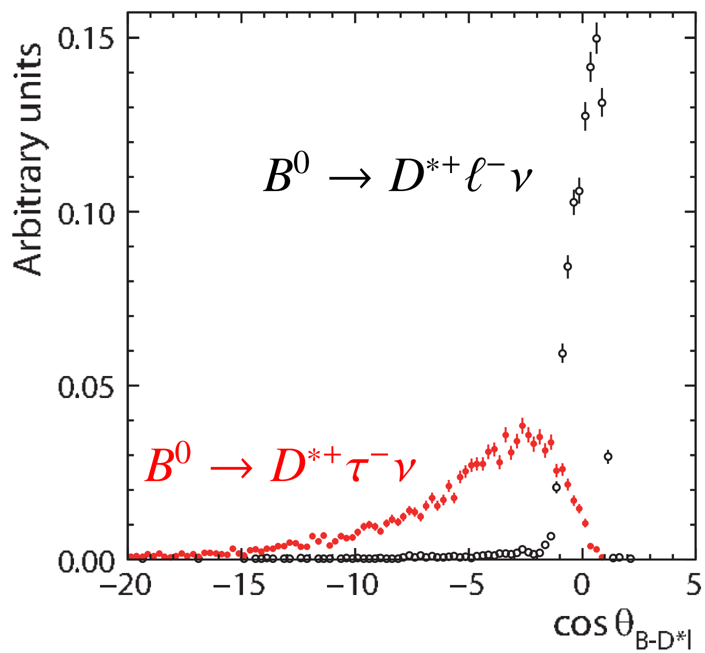
R_{D^*} and τ polarisation measurements

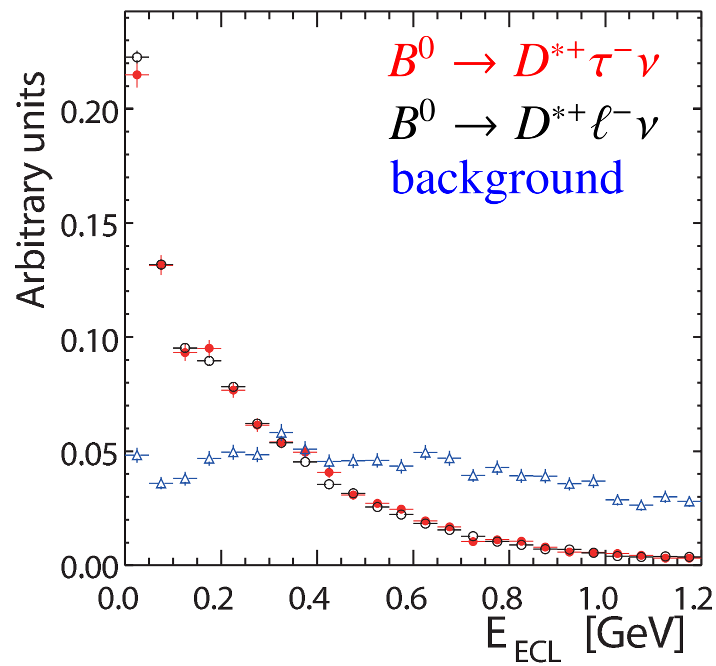




- SM predictions for τ polarisation are very accurate: $P_\tau(D^*) = -0.497 \pm 0.013$, while BSM allows for larger variations.
- Polarisation is measured in two-body hadronic $\tau^- \to \pi^- \nu$ and $\tau^- \to \rho^- \nu$ ($\rho^- \to \pi^- \pi^0$) decays.
- Significant backgrounds from misreconstructed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

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

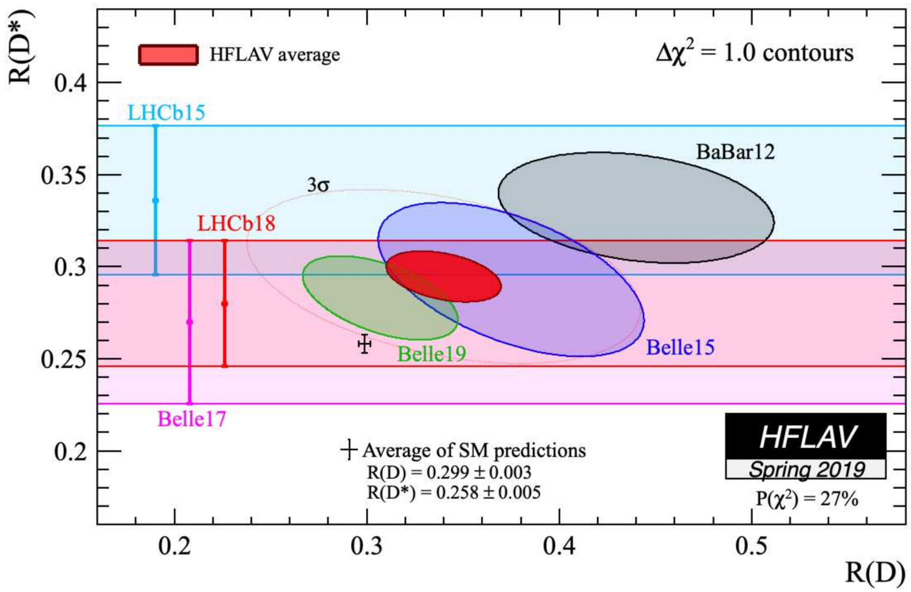


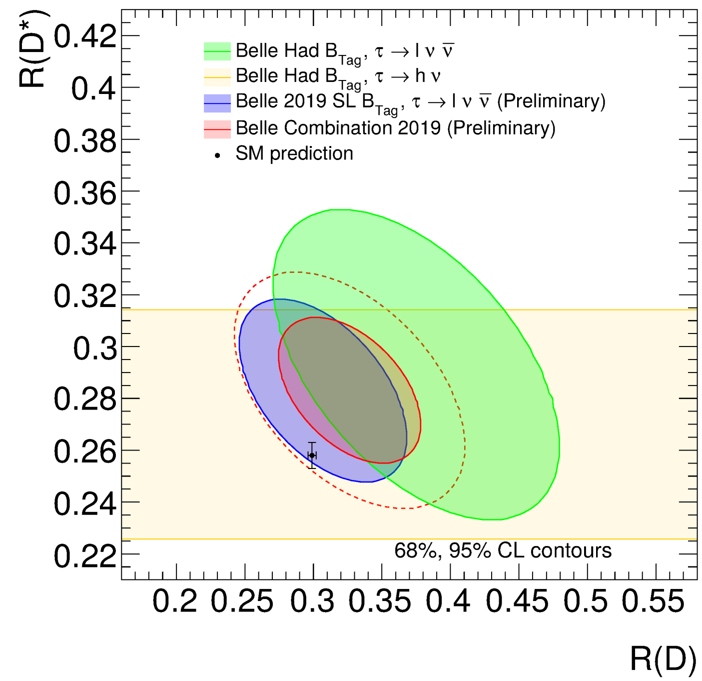


$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\rm beam}E_{D^*\ell} - m_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|},$$

- Use leptonic $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ decays to reconstruct τ; require two leptons of opposite charge, missing energy and D/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

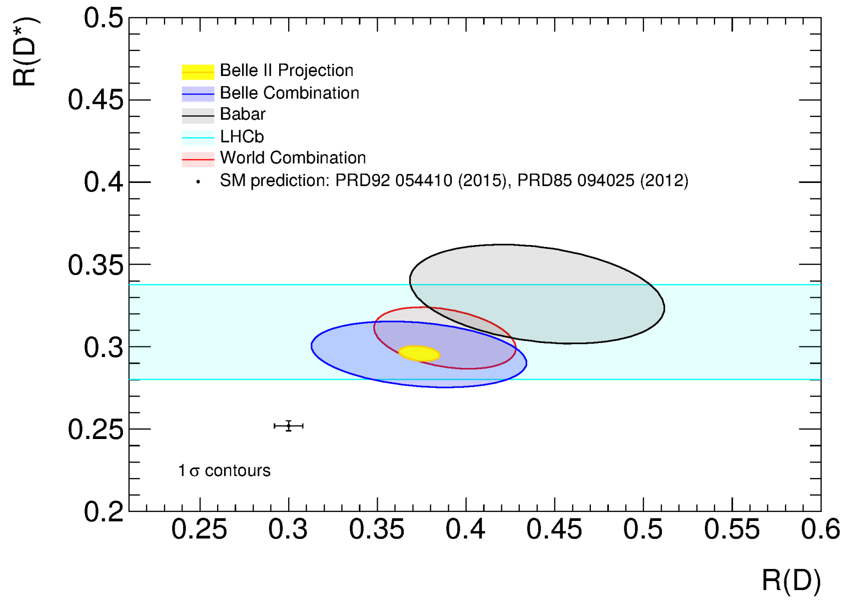
Summary of R_D, R_{D^*} measurements

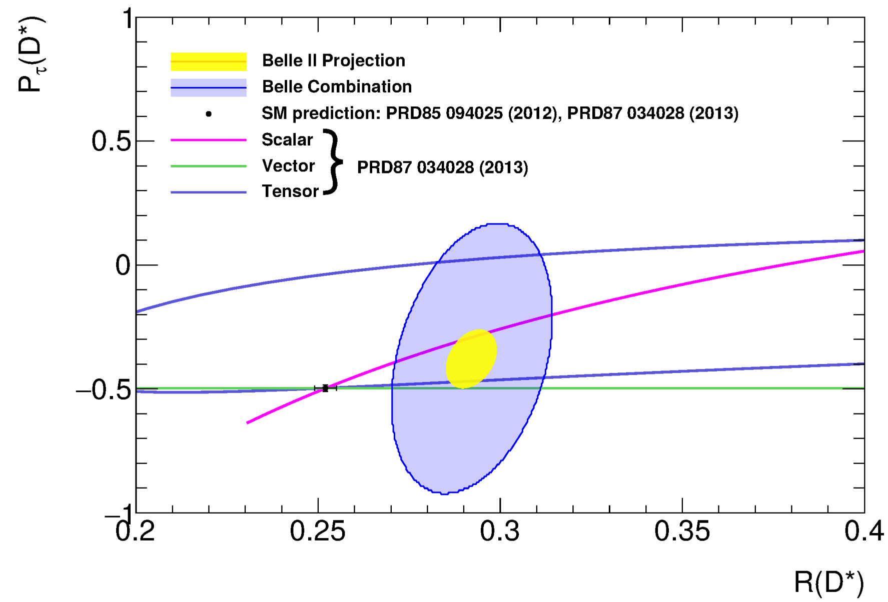




- New perliminary semileptonic tag based measurement of R_D, R_D^* is consistent with the old result, more precise.
- Recent measurements from Belle and LHCb reduce tensions with SM
- Combined Belle result is consistent with SM at 2σ level

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





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

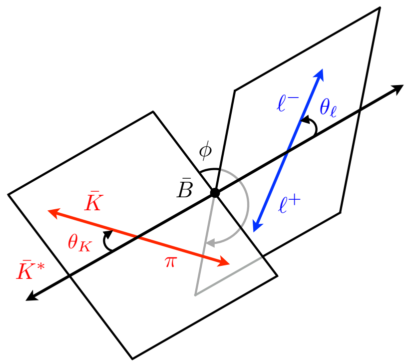
- Projections for 5 and 50 ab^{-1}. For 50 ab^{-1} systematics start to play important role.
- $P_\tau(D^*)$ as well as the double ratio of R_{D^*}/R_D provide extra information on the nature of NP (if deviation remains).

arXiv:1808.10567

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

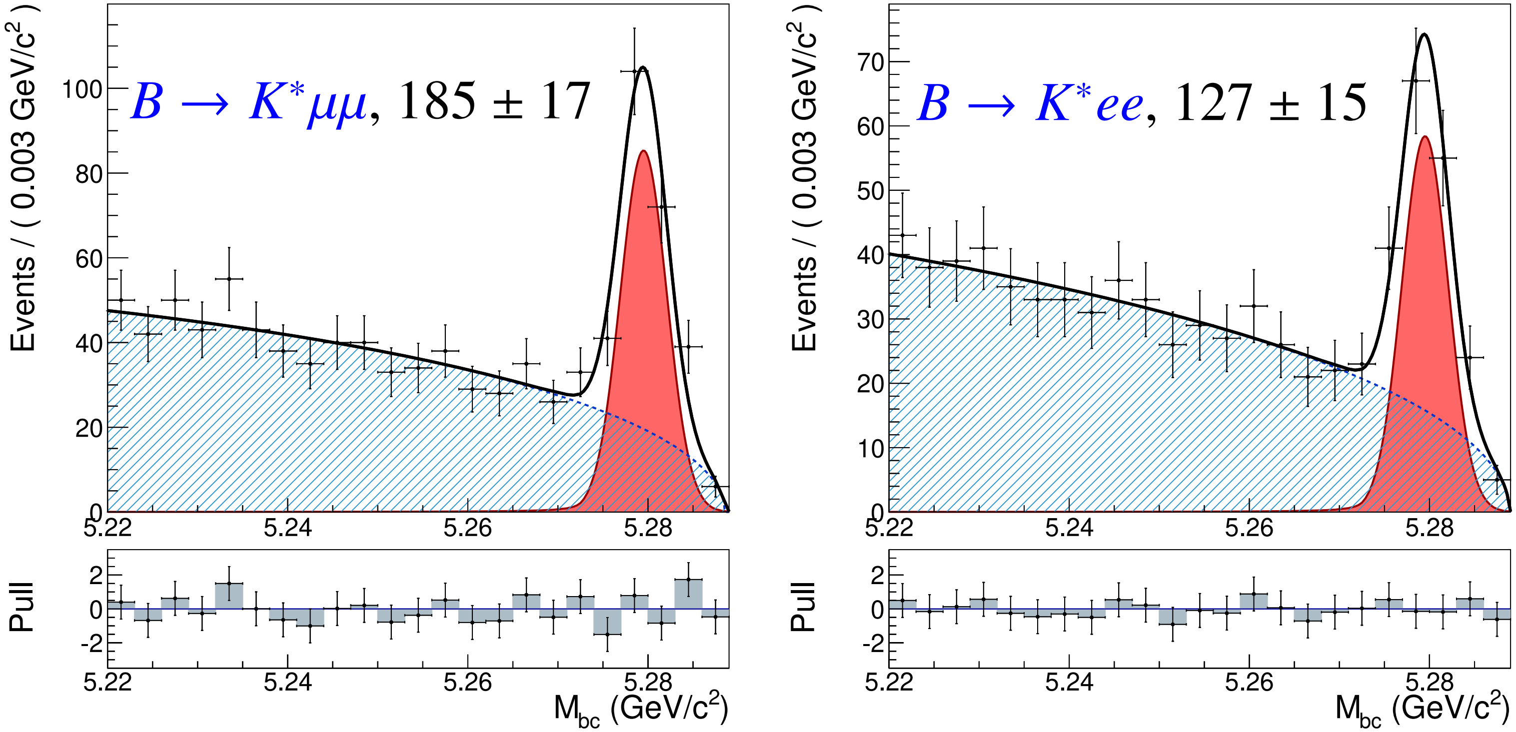
Folding of variables:

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

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

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

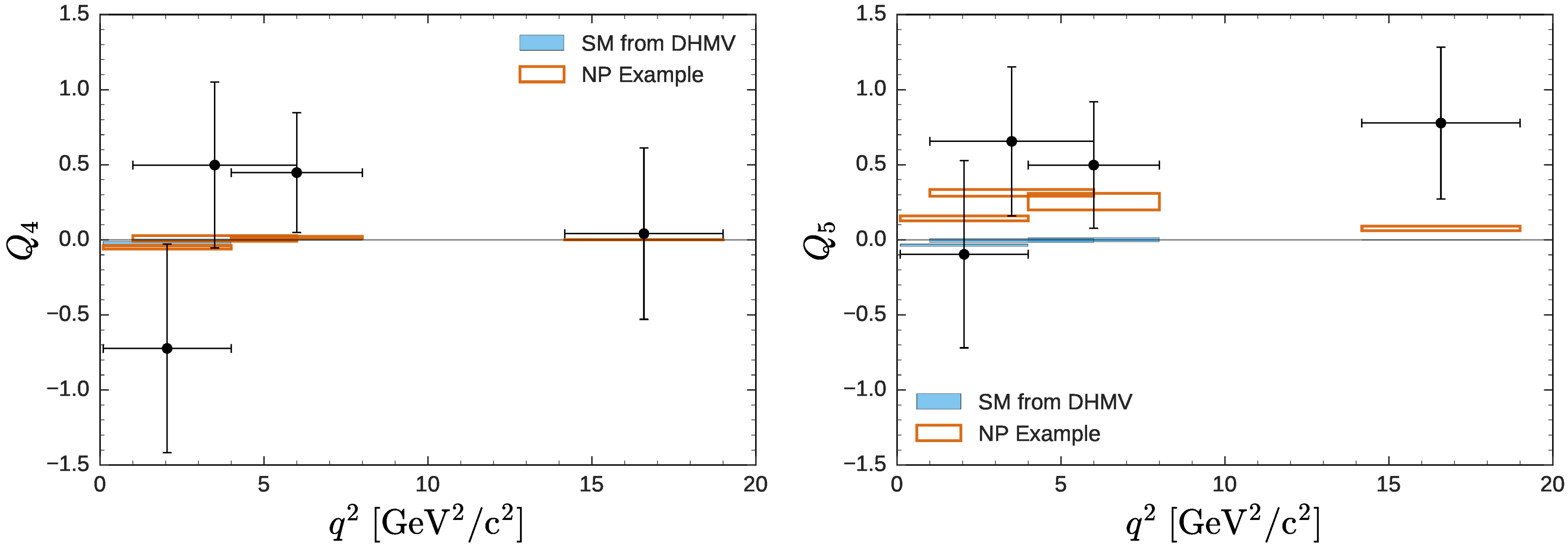
$B \to K^{(*)}\mu\mu$ and $B \to K^{(*)}ee$ at Belle



- 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 $B \to K^{(*)}\ell\ell$

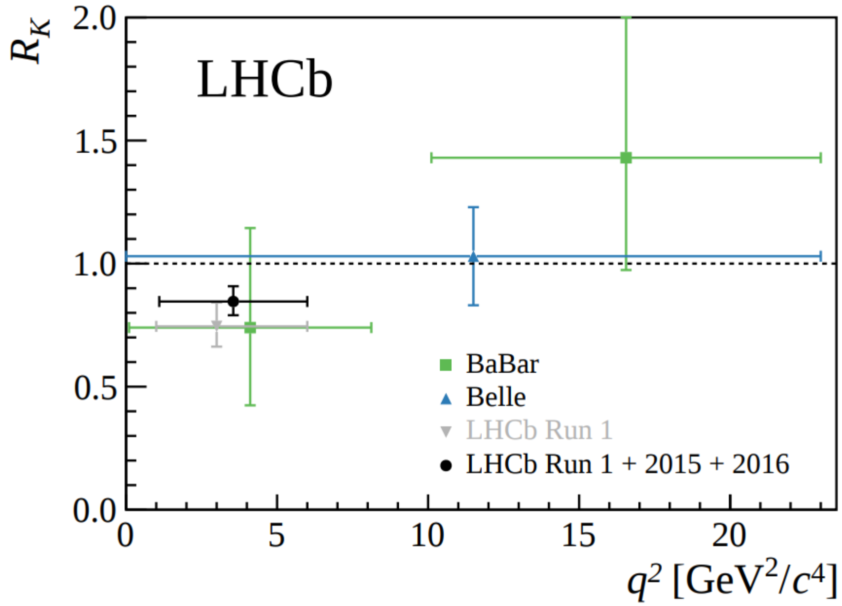


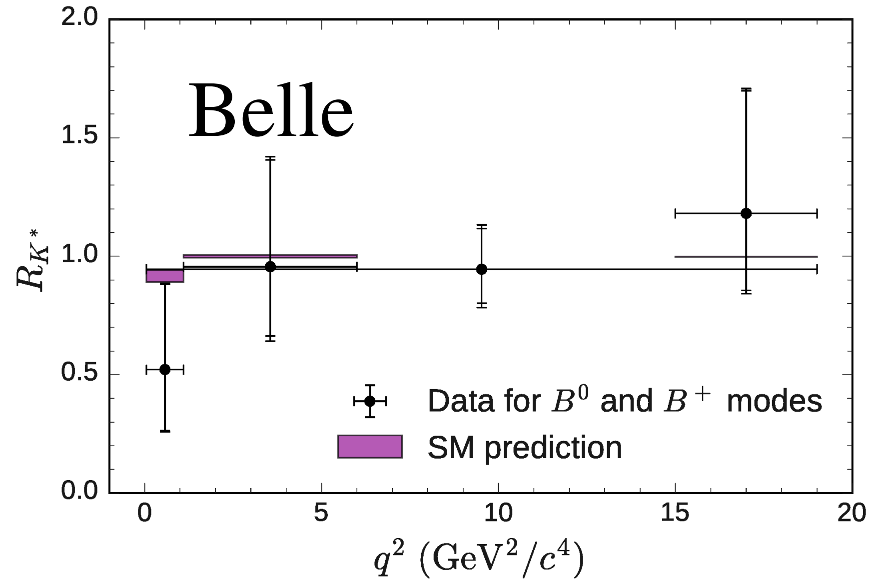
- Determine flavour dependent angular coefficient difference: $Q_i = P'_{i,\mu} - P'_{i,e}$.
- Sensitivity to NP in Q_5, errors dominated by statistics.
- Modeling of QED radiation / bin-to-bin migrations may start play a role with improved stats.

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

PRL118, 111801 (2017).

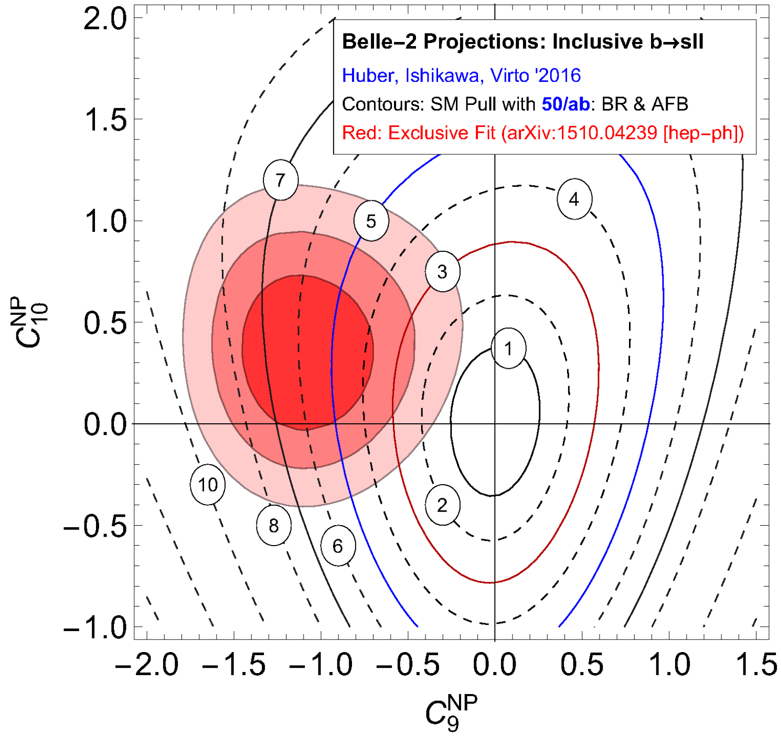
Recent R_K and R_{K^*} results





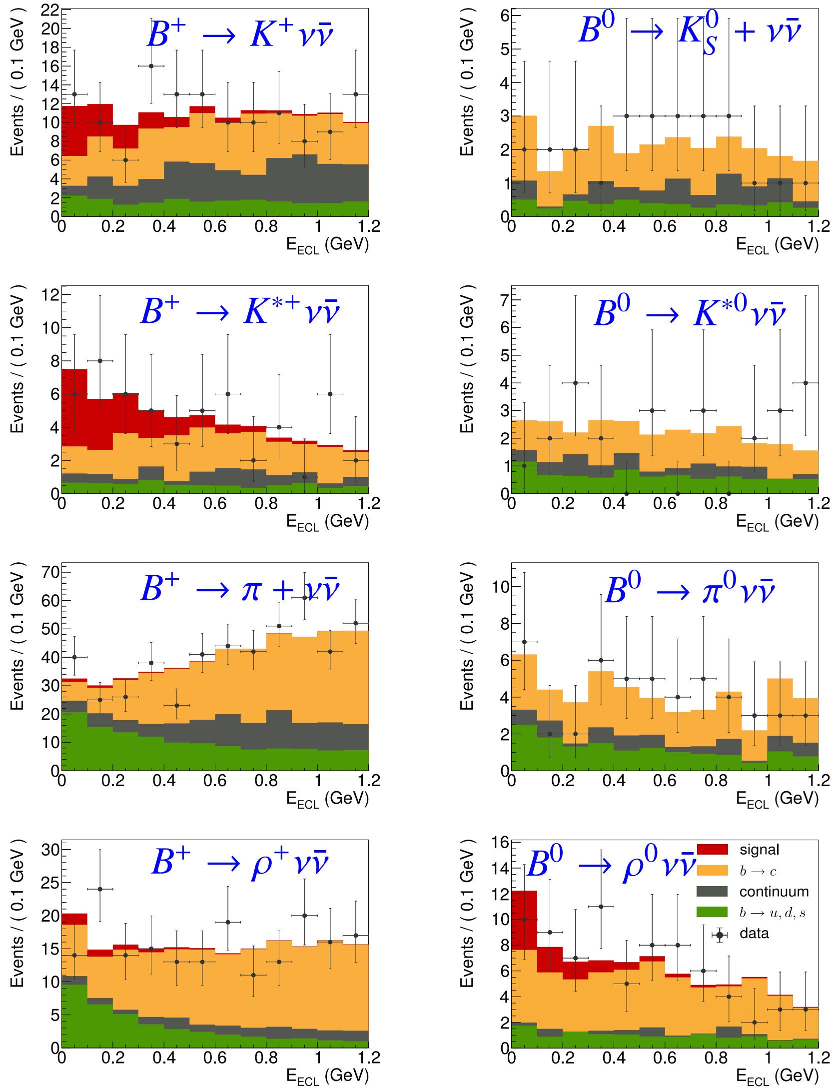
- Recent update on R_K from LHCb (PRL 122 (2019) 191801) and preliminary result from Belle on R_{K^*}.
- New measurements are closer to the SM predictions.

Perspective for inclusive $B \to X_s \ell\ell$ decays at Belle-II



- Initial measurements sum over exclusive method with $M_{X_s} \lesssim 1.8\,\text{GeV}$, 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)

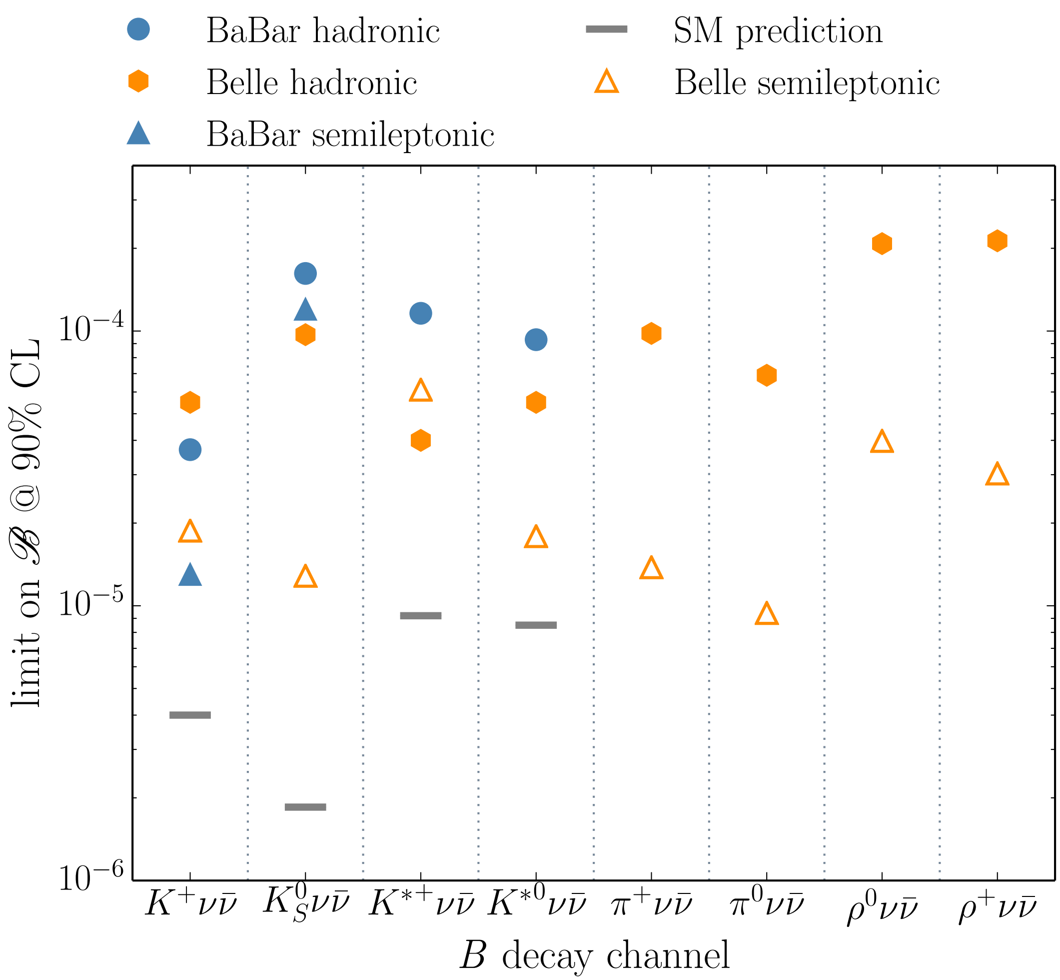


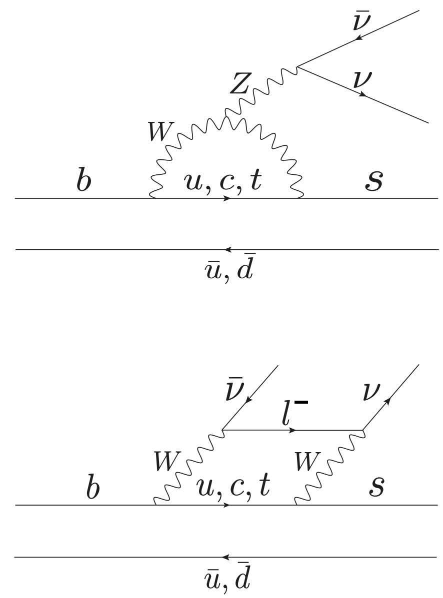
PRD 96, 091101 (2017)

- 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



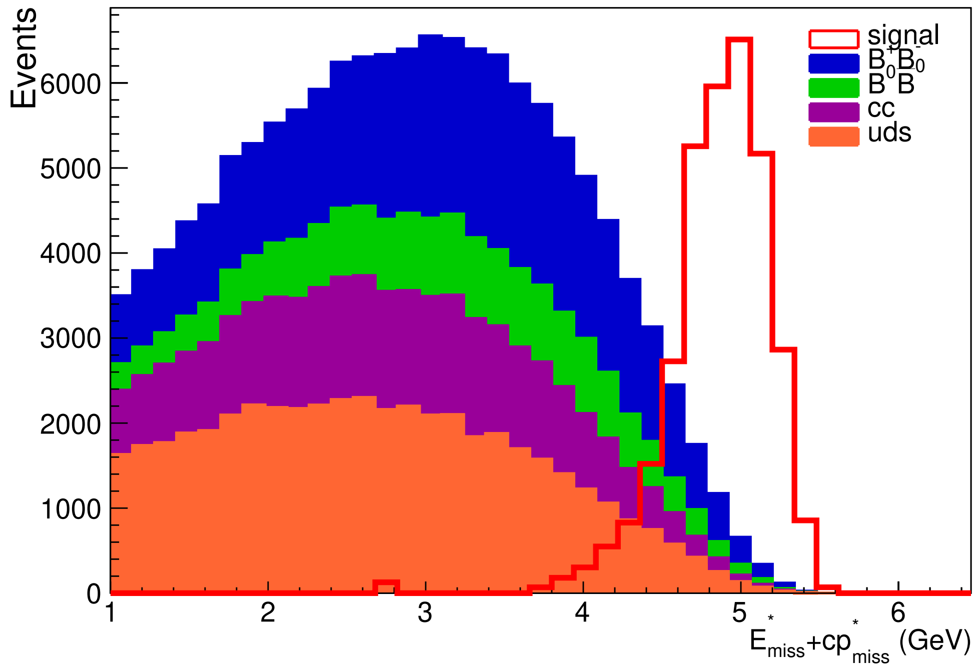


- Best upper limits at the time
- Golden channel for Belle-II

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 $E_{\text{miss}} + p_{\text{miss}}$ 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 $B \to K^*\tau\tau$

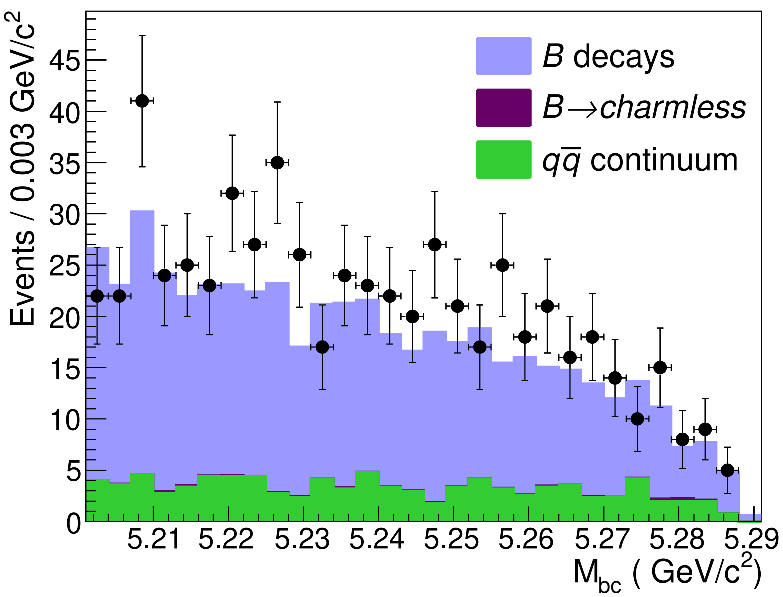
Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 6.5	< 2.0
$Br(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 30	< 9.6
$Br(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 8.1	–
$Br(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	< 2.1
$Br(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	–	<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

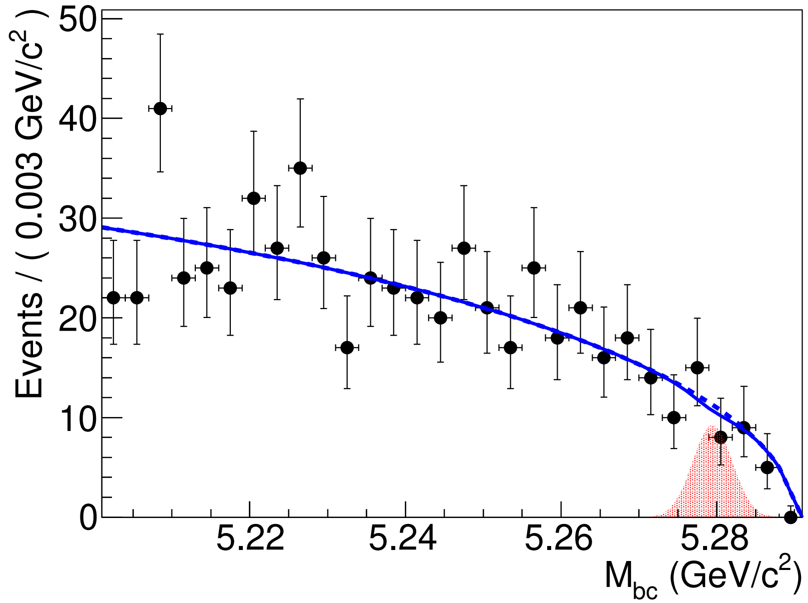
- Standard Model $B \to K\tau\tau$ is difficult at Belle II even with full luminosity.
- Lepton flavour violating processes, such a $B \to K\tau\mu$, are easier to get to better limits.

$\to$ 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.
- $\mathcal{B}(B^0 \to K^{*0}\mu^+ e^-) < 1.2 \times 10^{-7}$, $\mathcal{B}(B^0 \to K^{*0}\mu^- e^+) < 1.6 \times 10^{-7}$, $\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 1.8 \times 10^{-7}$

PRD 98, 071101 (2018)

Summary

- Anomalies in leptonic B decays are reduced with the recent data, however remain significant.
- 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.

The Belle II Physics Book: arXiv:1808.10567

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

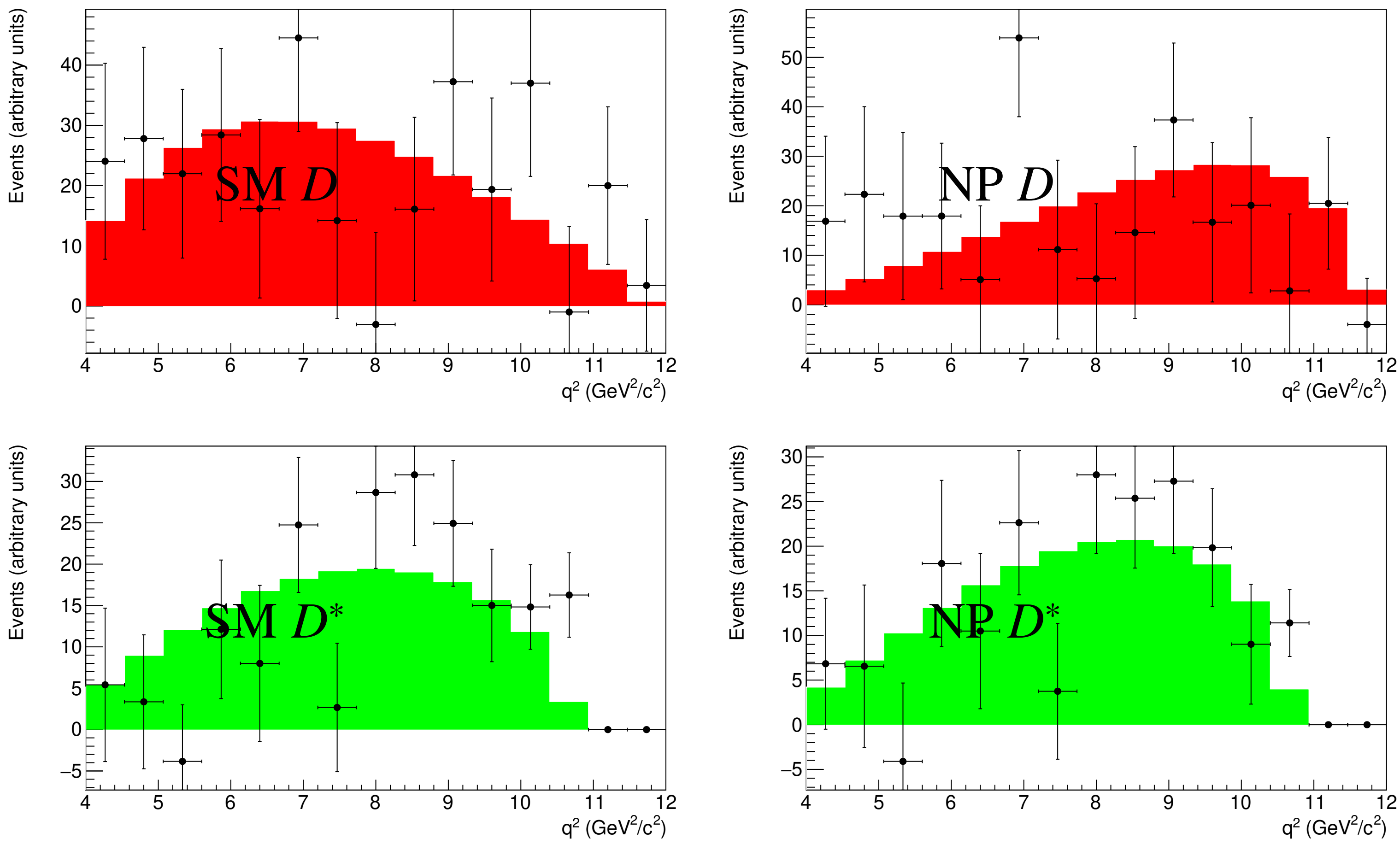
$R_{D^{(*)}}$ measurements: systematic uncertainties

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 $B \to \ell/\tau\nu$.

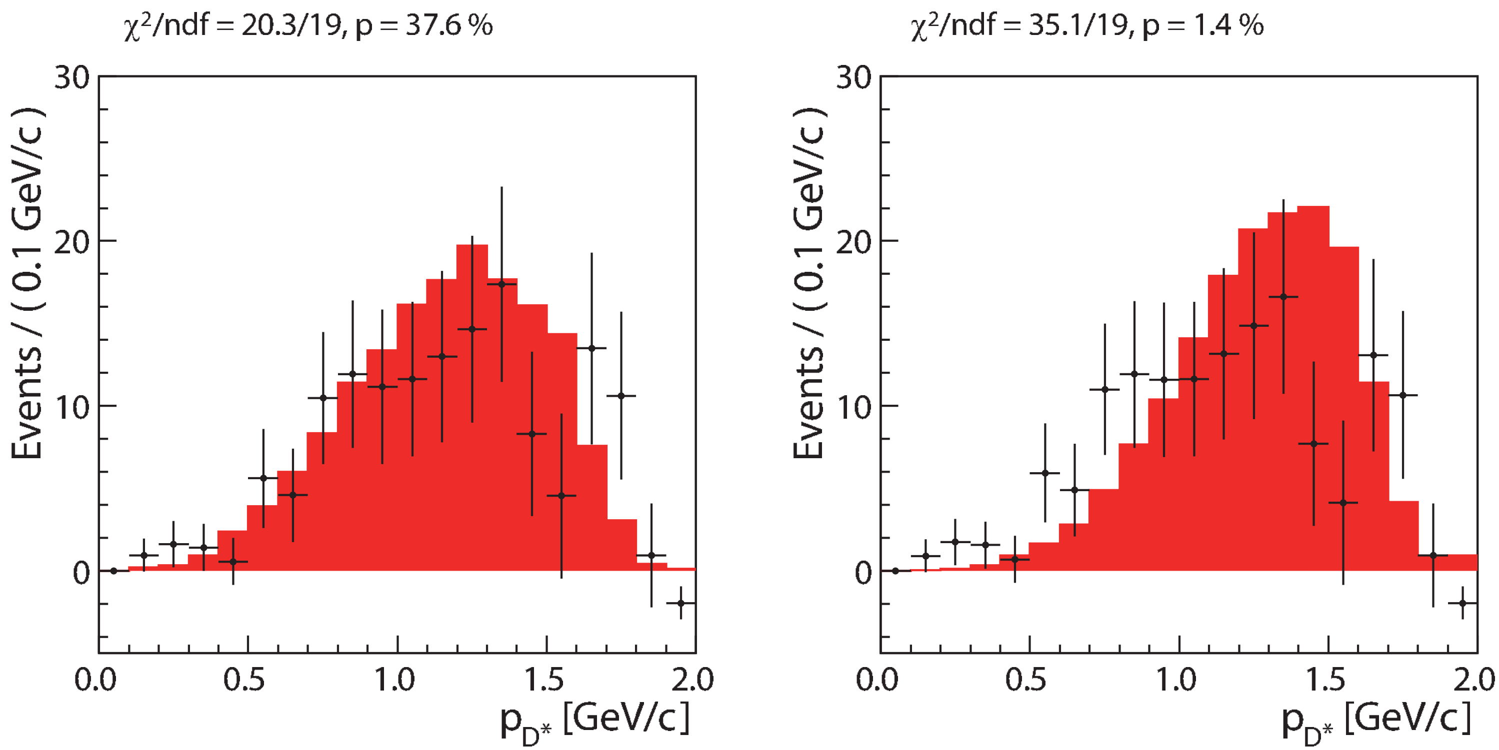
$\to$ dedicated measurements of $B \to D^{**}\ell\nu$; direct constrain on $B \to D^{**}\tau\nu_\tau$.

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



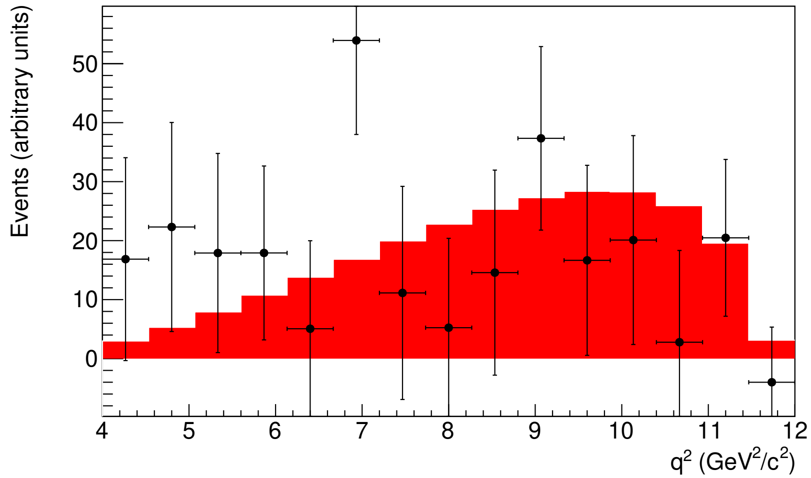
- Compare $q^2 = (P_B - p_{D^{(*)}})^2$ distributions vs SM and NP scenarios.
- Significant discriminating power in the q^2 distribution, different for $B \to D^* \tau \nu$ vs $B \to D \tau \nu$.

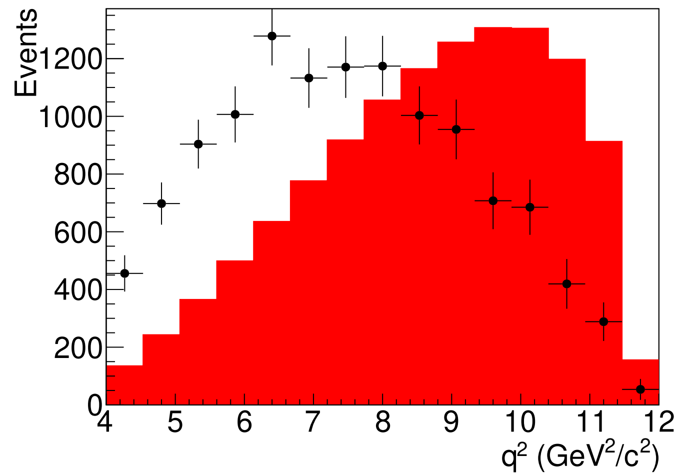
Differential $R_{D^{(*)}}$ measurements (semileptonic tag)



- 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





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

- 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