Latest results from Belle II

Tadeáš Bilka[1*]

for the Belle II Collaboration

[1]Charles University, Prague

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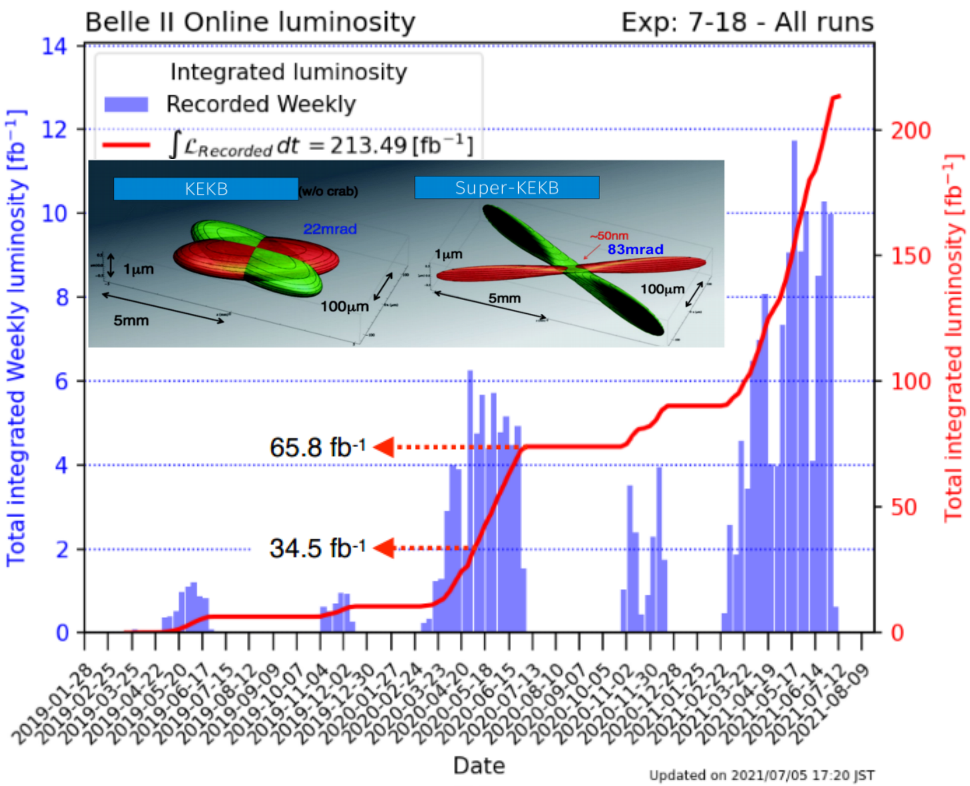
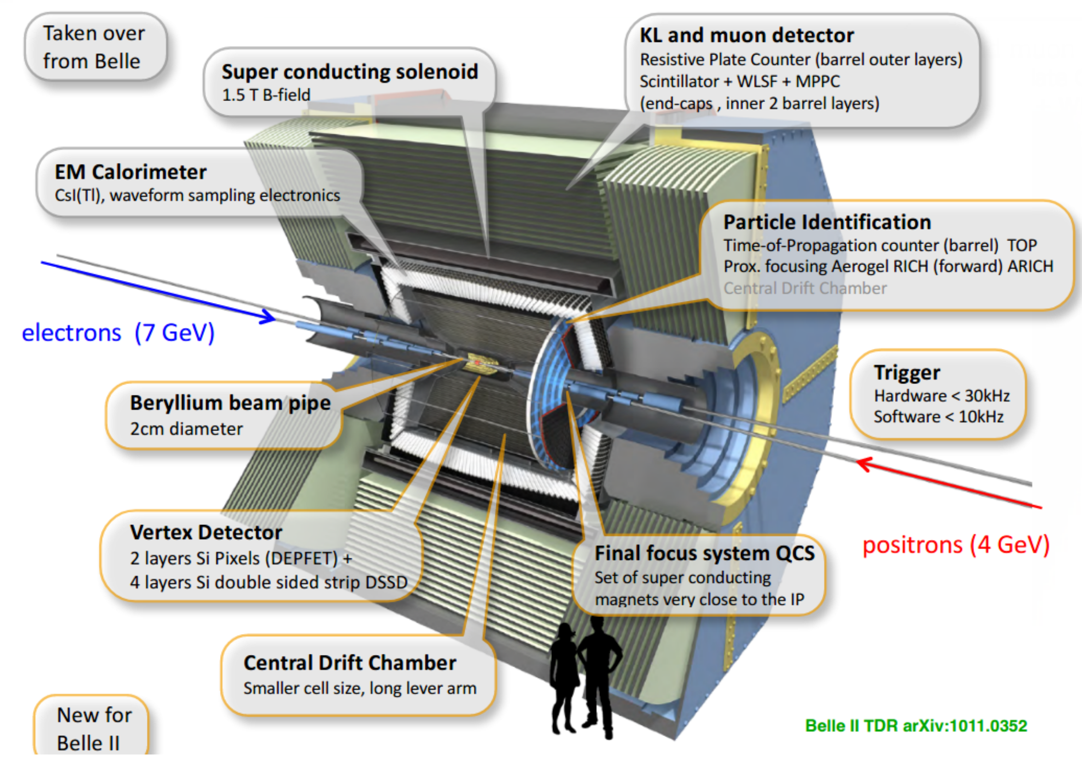
Blois, France

* bilka@ipnp.mff.cuni.cz

Super-B-Factory, Belle II Detector and Current Dataset





Luminosity record re-claimed, currently **3.12 x 10^{34}cm^{-2}s^{-1}** on June 22nd

Known initial state → unique precision for decays with π^0's or neutrinos in final state

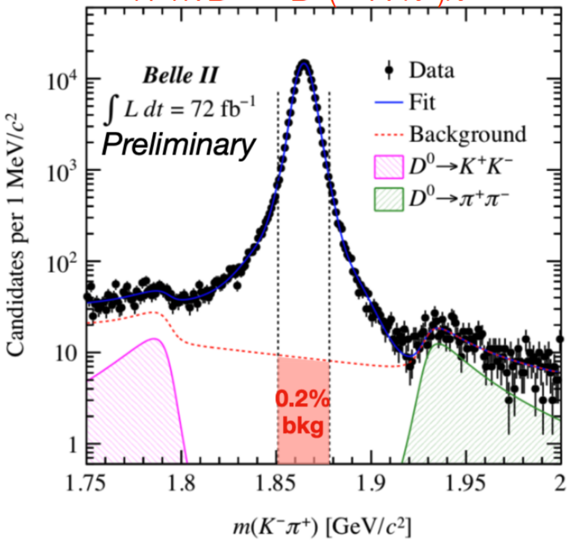
Despite machine tuning more challenging than expected… delivering first precision measurements!

Charm Lifetimes

- Measured for the first time with sub-percent precision by FOCUS – 20 years ago
- No measurement from Belle/BaBar/LHCb
- Test of non-pertubative QCD

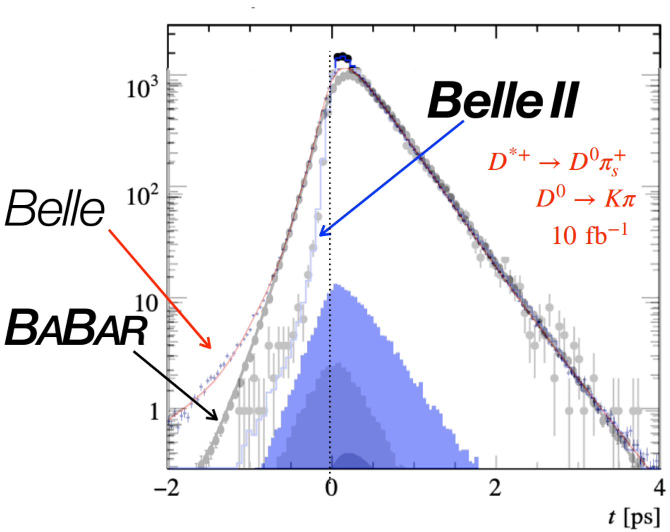
High purity signal candidates are selected from D*-tagged D decays. D's from B decays removed.

~171k $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

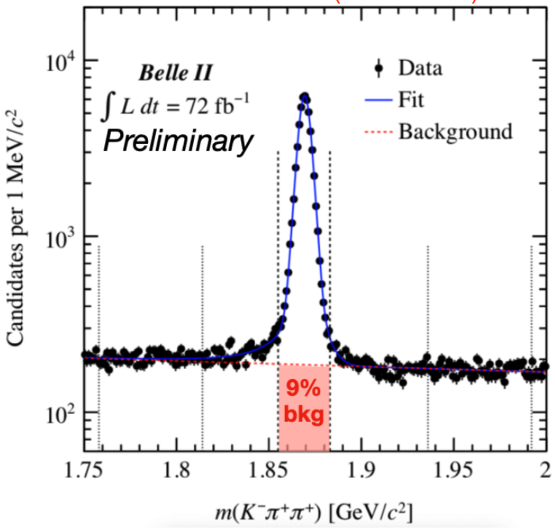


Excellent test of vertexing performance and understanding of systematics for CP-V measurements

- Alignment
- Interaction region description

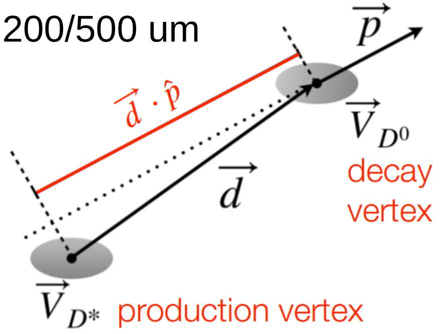


~59k $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$



D^0/D^+ Lifetime Measurement: Lifetime fit

200/500 um



$$t = \frac{m_D}{p}\left(\vec{d}\cdot\hat{p}\right)$$

Lifetime extracted by 2D UML fit to decay time and its uncertainty. All parameters extracted directly from the data.

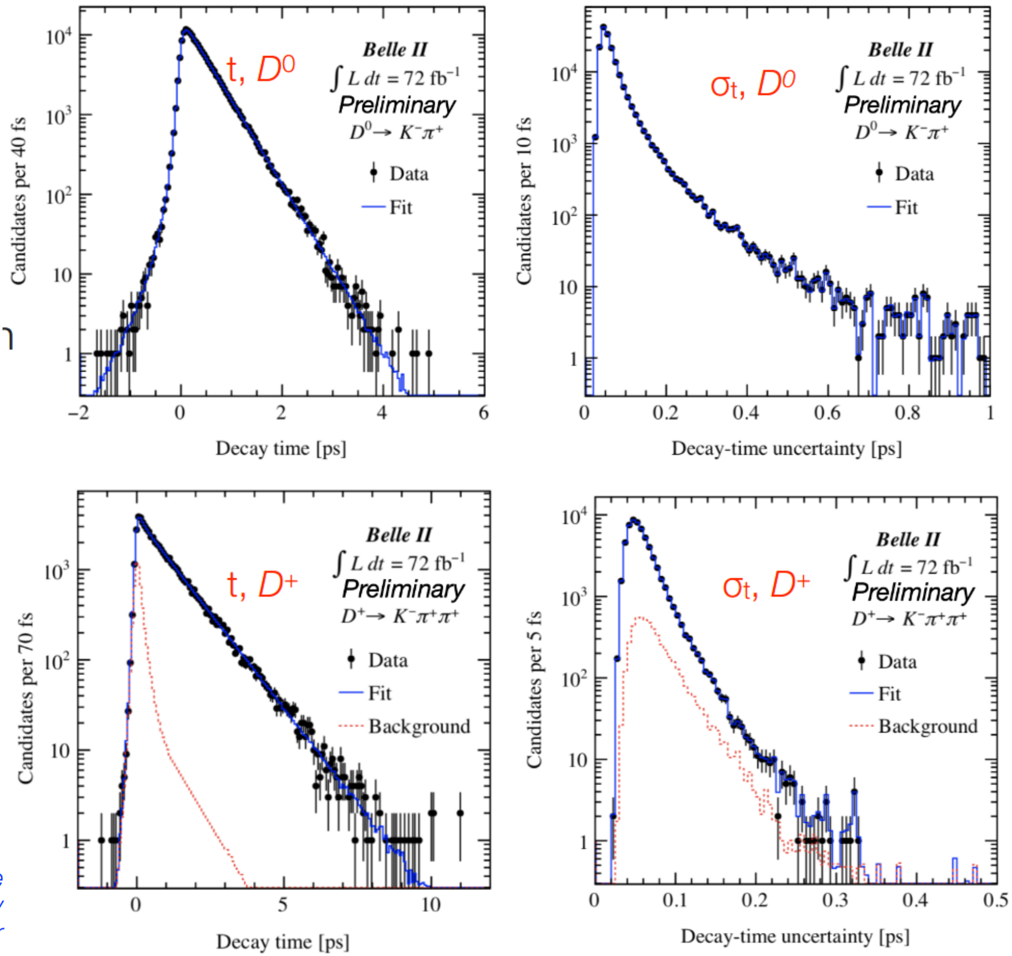
resolution function — fixed from data (binned template)

$$\mathrm{pdf}(t,\sigma_t\,|\,\tau,b,s) \propto \int_0^{\mathrm{inf}} e^{-t_{\mathrm{true}}/\tau} R(t-t_{\mathrm{true}}\,|\,\sigma_t,b,s)\,dt_{\mathrm{true}}\ \ pdf(\sigma_t)$$

resolution function

$$R(t-t_{\mathrm{true}}\,|\,\sigma_t,b,s) = G(t-t_{\mathrm{true}}\,|\,b,s\sigma_t)$$

b = bias
s = proper time uncertainty scaling factor



D^0/D^+ Lifetime Measurement

Results:

$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8\,\text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\text{fs}$$

$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015$$

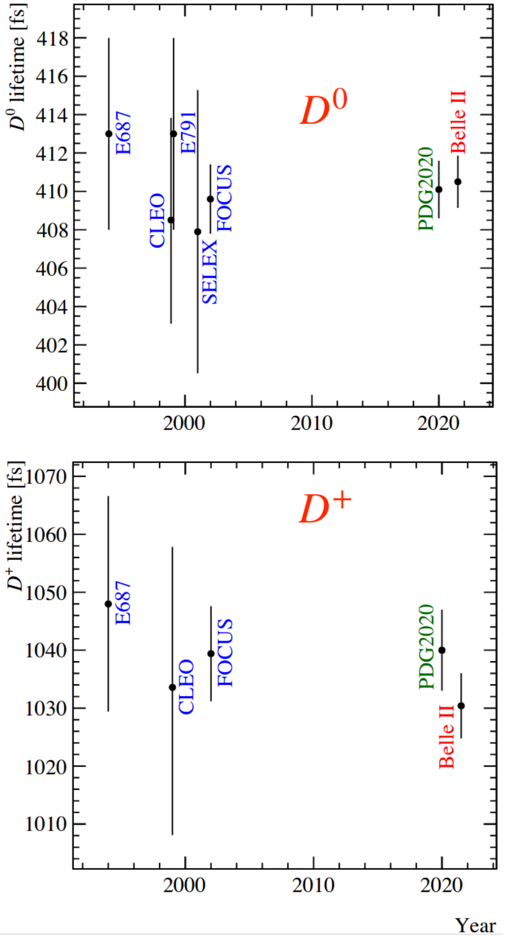
arXiv:2108.03216

Systematic uncertainties:

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Total systematic	0.8	3.1

Still dominated by statistics

Systematic uncertainty on alignment will be reduced an improved calibration



World leading result demonstrates excellent Belle II vertex resolution!

Charmless B decays: Further insights on Kπ puzzle

Belle II

A significant difference is seen between direct CP asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays:
$\Delta A_{CP} = 0.124 \pm 0.021$

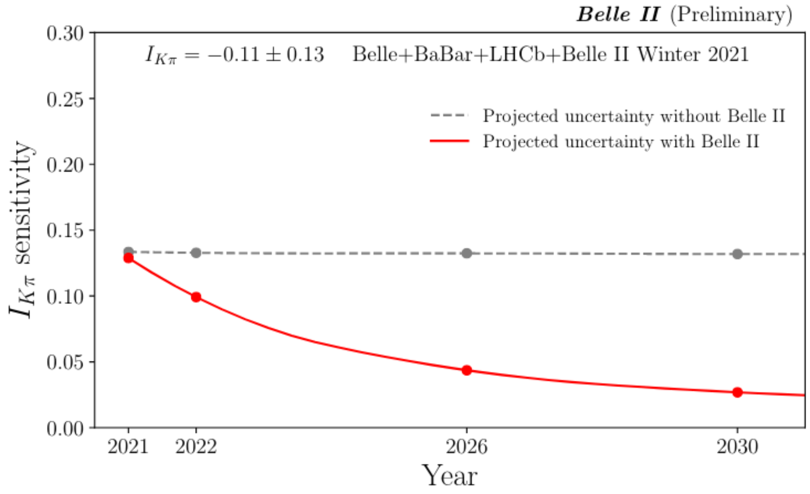
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

Null test with isospin sum rule

Limiting is precision of $A(K^0\pi^0)$ – only accessible at Belle II

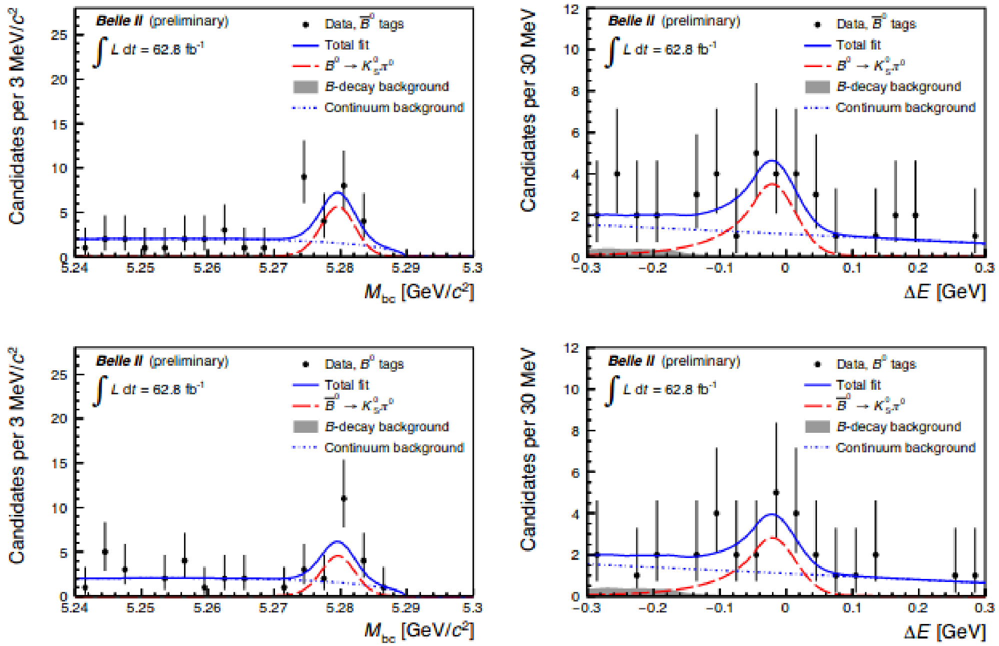
arXiv:2104.14871

$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst}), \text{ and}$$
$$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$$



$\overline{B}^0$ tag

B^0 tag



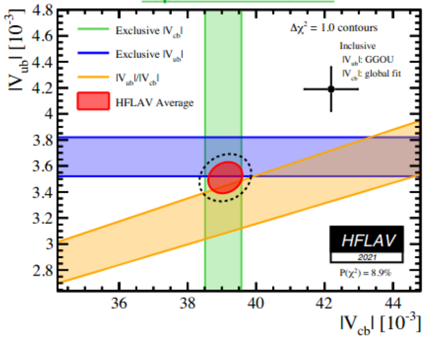
Semi-leptonic B-decays

- SM reference from tree-dominated processes
- Long-standing discrepancy between inclusive and exclusive measurements of
  $|V_{ub}|$ and $|V_{cb}|$
- Analyses using untagged + tagged (B) approach

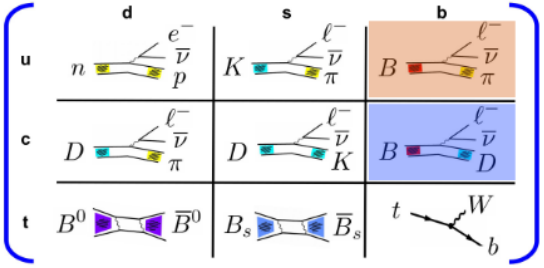
$|V_{ub}|$: $B \to X_u \ell \nu$, $B \to \pi(\rho,\eta)\ell\nu$ $(\ell = e, \mu)$

$|V_{cb}|$: $B \to X_c \ell \nu$, $B \to D^{(*)}\ell\nu$ $(\ell = e, \mu)$

https://hflav.web.cern.ch

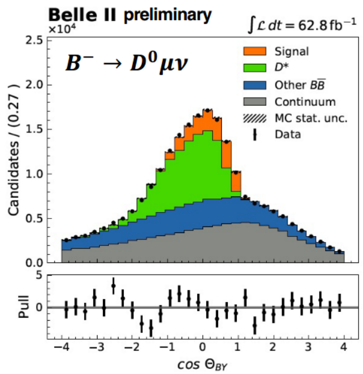


V =



Lepton momentum p* in the CMS

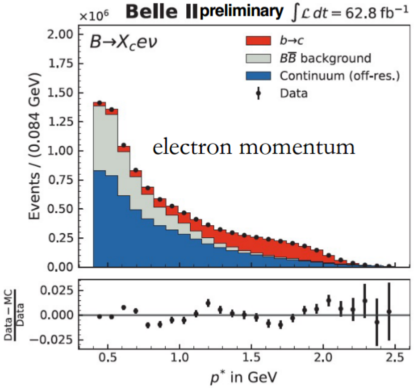
Untagged exclusive $B \to D^0 \ell \nu$



$\mathcal{B}(B^- \to D^0 \ell^- \overline{\nu}_l) = (2.293 \pm 0.053_{\text{stat}} \pm 0.084_{\text{syst}})\%$

θ_{BY} angle between B and $D\ell$ system

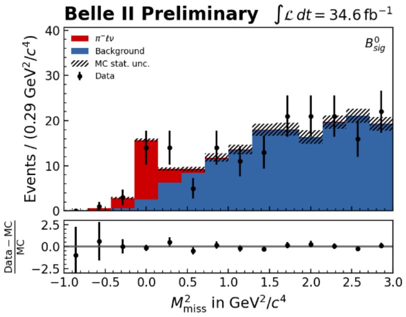
Untagged inclusive $X_c \ell \nu$



$\mathcal{B}(B \to X_c \ell \nu) = (9.75 \pm 0.03(stat) \pm 0.47(syst))\%$

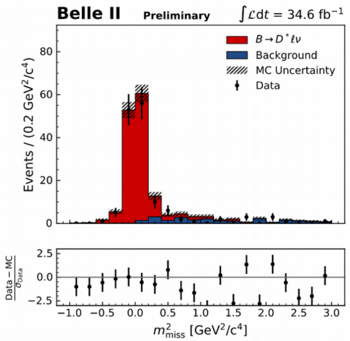
$$m^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$

FEI hadronic tag excl. $B^0 \to \pi^- \ell \nu$



$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell)$ | $(1.58 \pm 0.43_{\text{stat}} \pm 0.07_{\text{sys}}) \times 10^{-4}$

FEI hadronic tag excl. $B^0 \to D^* \ell \nu$



$\mathcal{B}(\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_l) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s})\%$

...

arXiv:2110.02648

https://docs.belle2

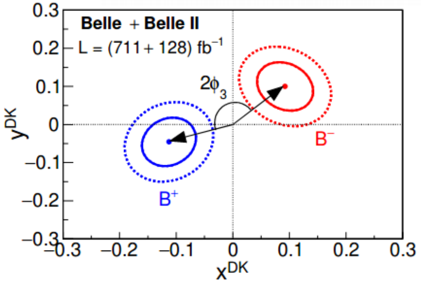
arXiv:2008.08819

arXiv:2008.10299

Towards precision CP-V: γ

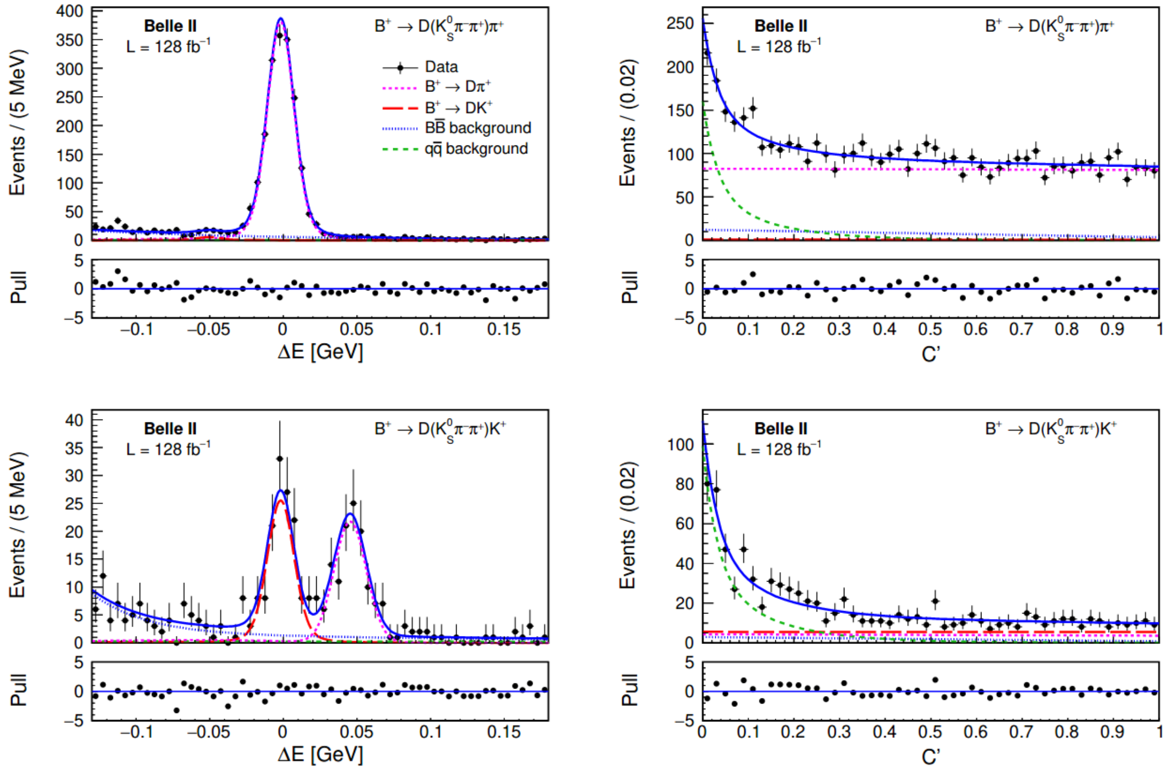
- Constraint BSM physics by comparing direct (tree … 3° error) and indirect (loops … 0.9° error) determination of γ
- First physics paper combining Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) data
- Simultaneous fit of energy-difference and background-suppression variable distributions of B+ and B- decays into $D(K_S hh)\pi$ and $D(K_S hh)K$ decays determines simultaneously CP-violating yield asymmetries across Dalitz plot and PID efficiencies/fake rates

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,.$$



External strong phase inputs (CLEO + BESIII)

The two interfering decays sensitive to ϕ_3 are $B^+ \to \bar{D}^0 K^+$ and $B^+ \to D^0 K^+$



Difference between observed and expected B energy

Transformed FastBDT output

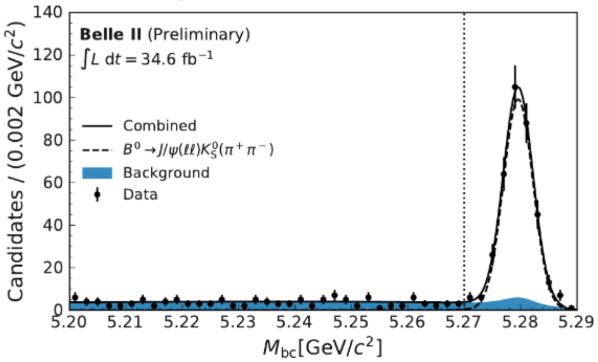
Towards precision CP-V: beta

BELLE2-NOTE-PL-2020-11

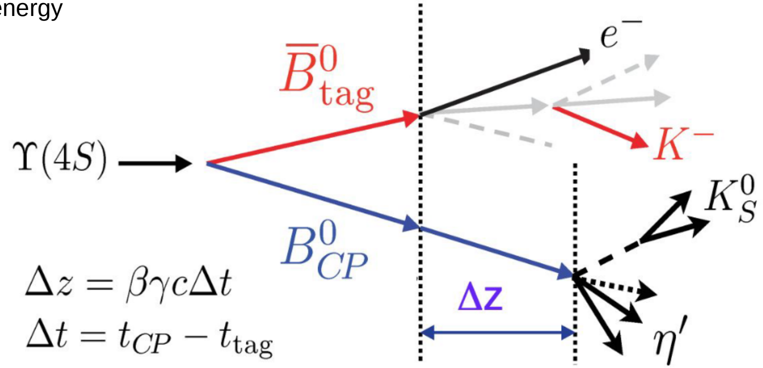
$B^0 \to J/\psi(e^-e^+/\mu^-\mu^+)K_S$

Flagship of B-Factory measurements:

$B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$



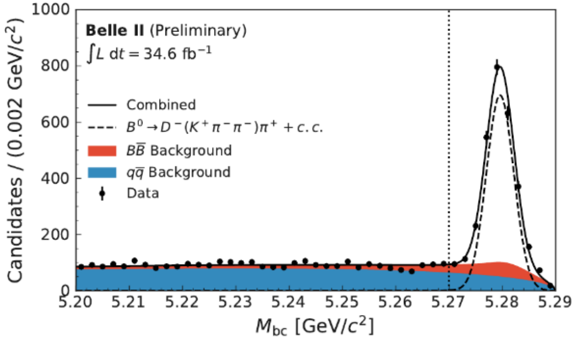
M_{bc} = Invariant B candidate mass where B energy is replaced by half of collision energy

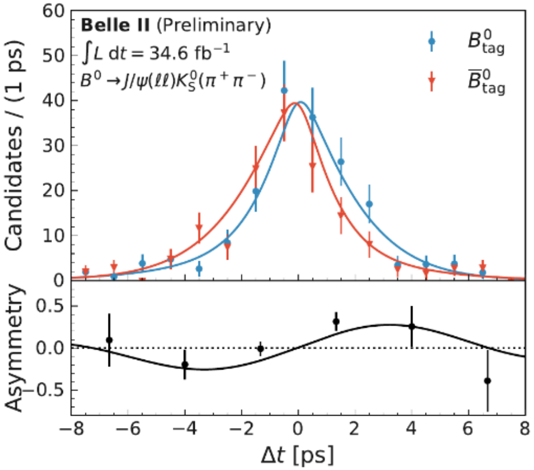


$\Delta z = \beta\gamma c\Delta t$

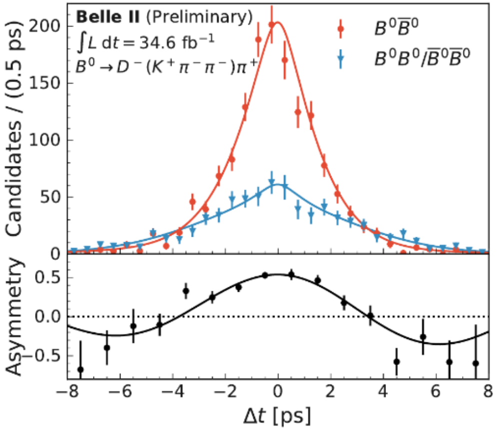
$\Delta t = t_{CP} - t_{\mathrm{tag}}$

<Δz> ~ 130 μm at Belle II





$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to \eta' K_S^0) - \Gamma(B^0(\Delta t) \to \eta' K_S^0)}{\Gamma(\overline{B}^0(\Delta t) \to \eta' K_S^0) + \Gamma(B^0(\Delta t) \to \eta' K_S^0)} = S_f \sin(\Delta m_B \Delta t) + \mathcal{A}_f \cos(\Delta m_B \Delta t)$$



TDCPV (assuming no direct CP-V)

Direct CP-V and mixing frequency

S = 0.55 ± 0.21 ± 0.04

Δm = (0.531 ± 0.046 ± 0.013) ps^{-1}

Towards precision CP-V: alpha

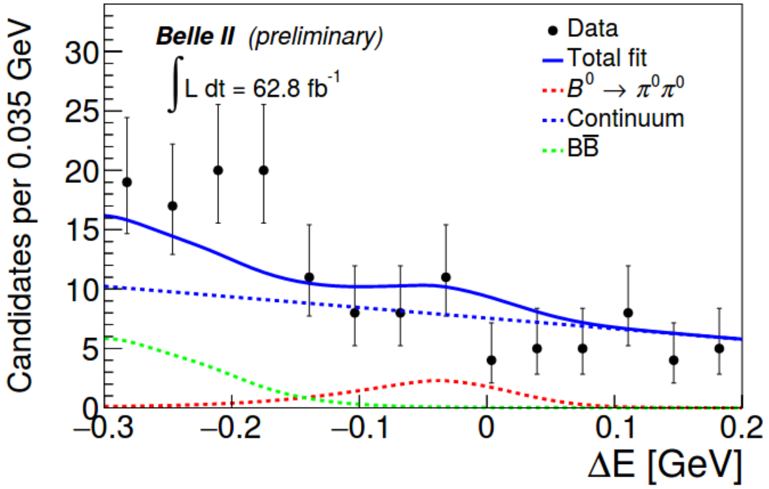
- Belle II has unique access to alpha through B → ππ, ρρ
- $B^0 \to \pi^0\pi^0$

Penguin and tree contributions disentagled by isospin relations

  - 4 gammas in final state ← suppress large photons background with a dedicated BDT
  - 3D fit in ΔE, M_{bc}, BDT

arXiv:2107.02373

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.98^{+0.48}_{-0.39} \pm 0.27) \times 10^{-6}$$



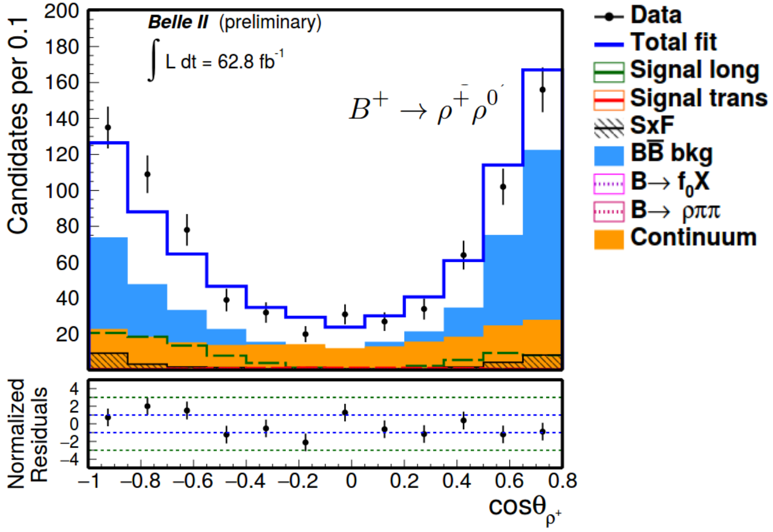
- $B^+ \to \rho^+\rho^0$
  - Final states with pions with large bkg due to wide ρ
  - 6D fit with helicity angles

arXiv:2109.11456

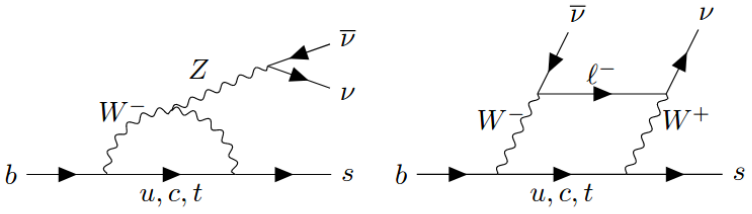
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$$

$$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst}).$$

  - Precision improved by 20% w.r.t. Belle



Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$

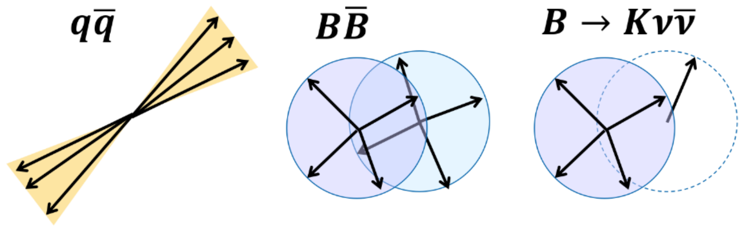


Motivation: Complementary BSM probe to explain anomalies in $b \to sl^+l^-$ (R_K) or constrain dark matter, leptoquarks

Flavour-changing neutral current process – not yet observed (UL ~ 10^{-5}), but with clean **SM prediction** $(4.6 \pm 0.5) \times 10^{-6}$

T. Blake, G. Lanfranchi, and D. M. Straub, Prog. Part. Nucl. Phys. **92**, 50 (2017).

Previous analyses: tagged approach with limited signal efficiency:
- semi-leptonic tag (0.2% @ Belle)
- hadronic tag (0.04% @ BaBar)



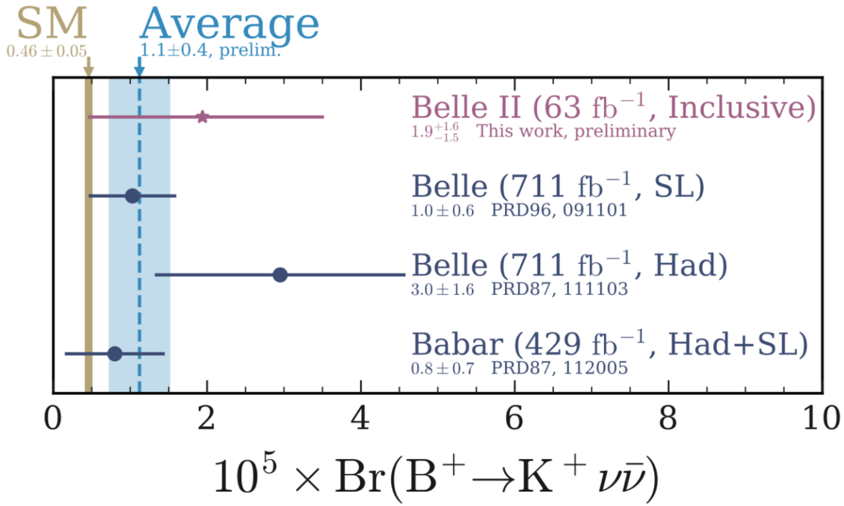
Belle II approach: **novel inclusive tagging** technique employing event shape, vertexing and kinematical variables

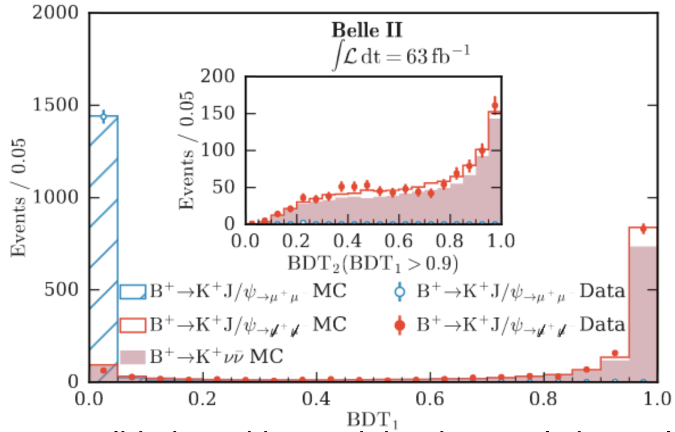
- signal efficiency 4.3% – higher sensitivity at given luminosity

Belle II Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$: Results

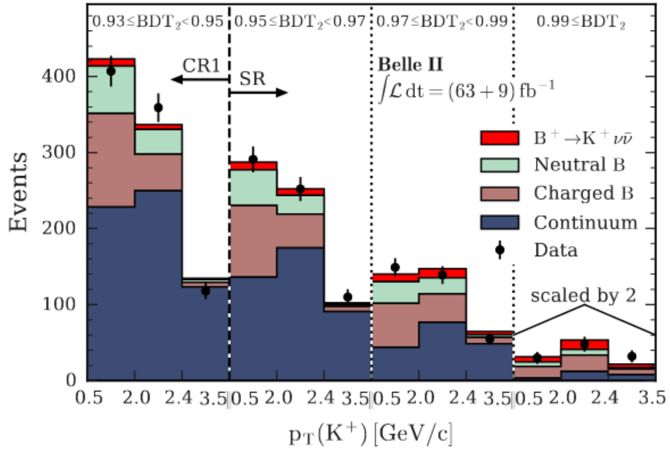
Competitive limit *with 63 fb^{-1} thanks to novel analysis approach*

- Track with highest p_T used as signal Kaon candidate
- Nested statistical-learning discriminators BDT_1 & BDT_2 (topology, rest-of-event, missing energy, vertex separation)
- Signal strength from binned ML fit to 2D histogram ($p_T(K^+)$, BDT_2 output)





Validation with reweighted control channel



arXiv:2104.12624, accepted to PRL!

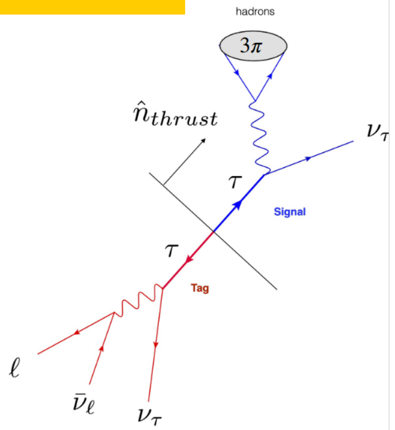
First Belle II B-Physics paper!

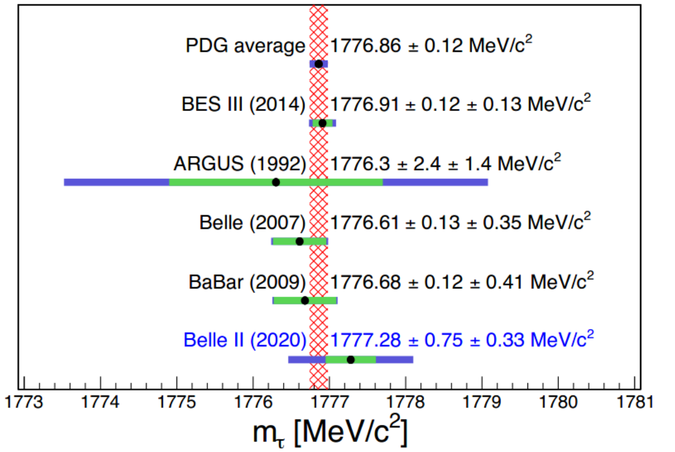
Towards Precision tau physics: Tau Mass Measurement

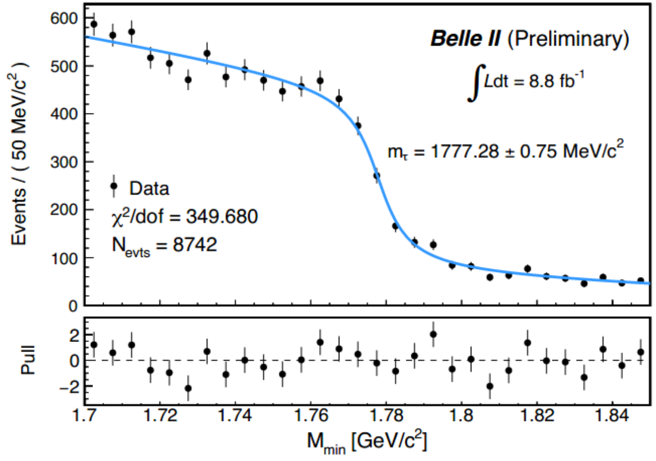
SuperKEKB as Tau-Factory

- Lepton masses and lifetimes are fundamental parameters of the SM → inputs to tests of lepton universality
- Mass cannot be measured directly → pseudo-mass technique

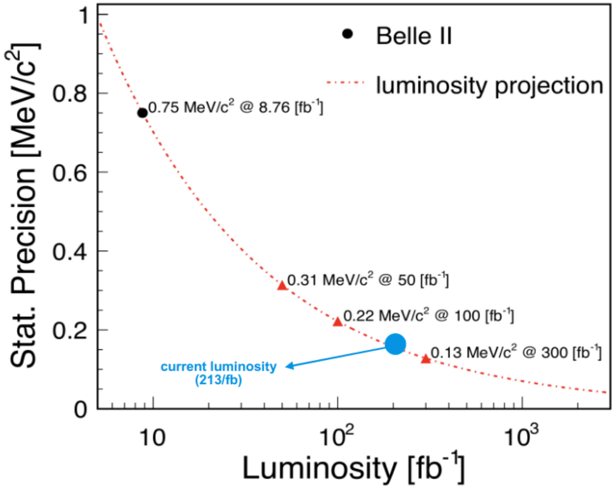
$$m_{\min} = \sqrt{m_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - p_{3\pi})} \leq m_\tau$$







arXiv:2008.04665



Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

To be reduced ...

Summary

- After many preliminary measurements, first world leading physics results from Belle II
  - Note that I skipped Dark sector studies with very early data and low lumi
    - → *Talk by Sascha Dreyer talk on DM searches (paralell session)*
  - Many interesting analyses not mentioned – mostly still preparatory for final measurement with more data
- Possible thanks to novel methods, data combination (with Belle) or **improved detector performance**
  - Vertex resolution almost twice better than Belle
- Already have 3x more data on tape ready for coming analyses

Thank you for your attention!

BACKUP

Towards precision CP-V: alpha

Belle II

- Belle II has unique access to alpha through $B \to \pi\pi$, $\rho\rho$

Penguin and tree contributions disentagled by isospin relations

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  - 4 gammas in final state ← suppress large photons background with a dedicated BDT
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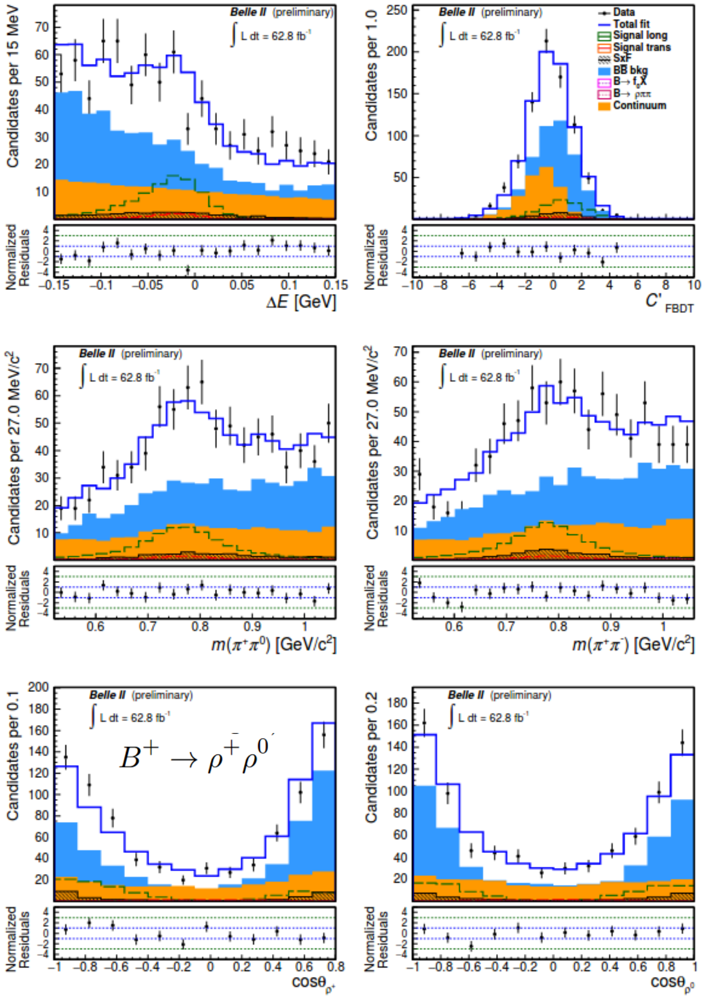
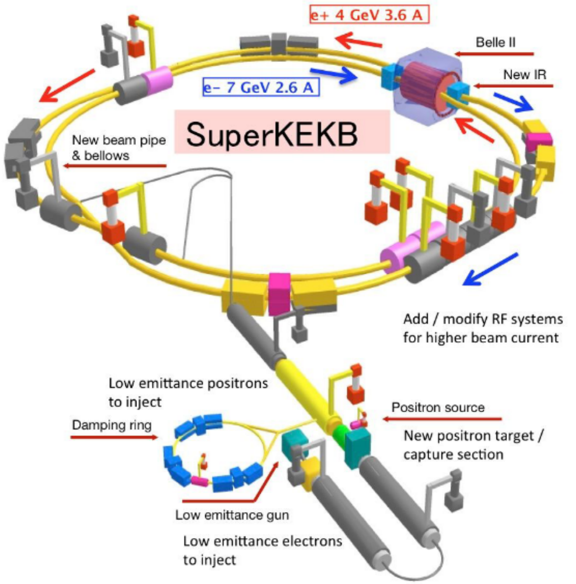
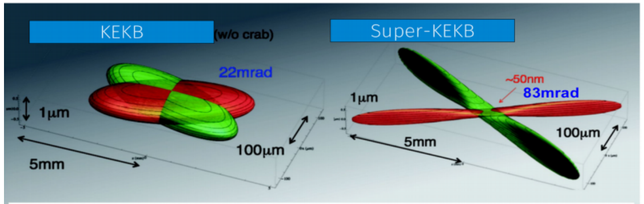


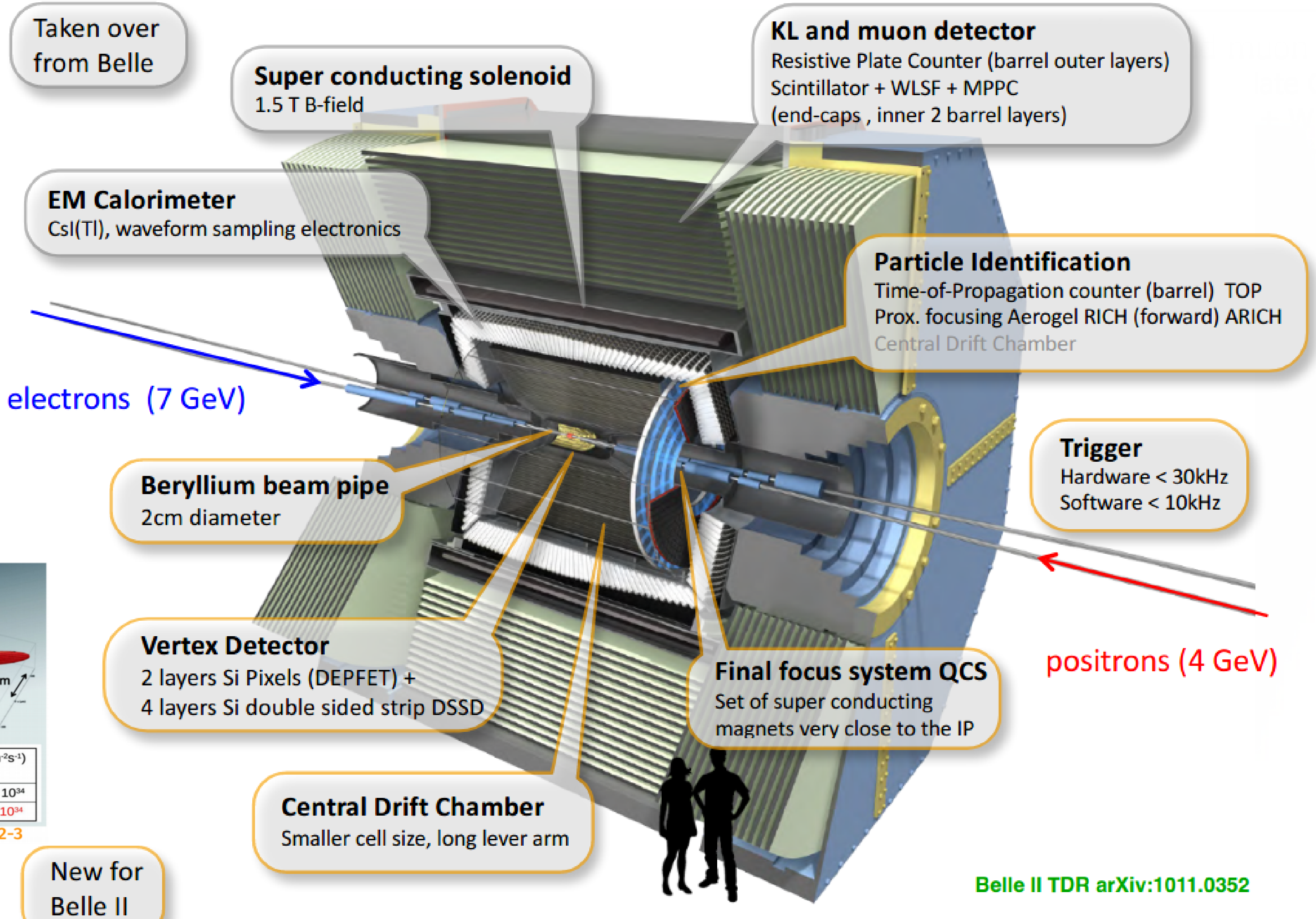
Belle II @ SuperKEKB





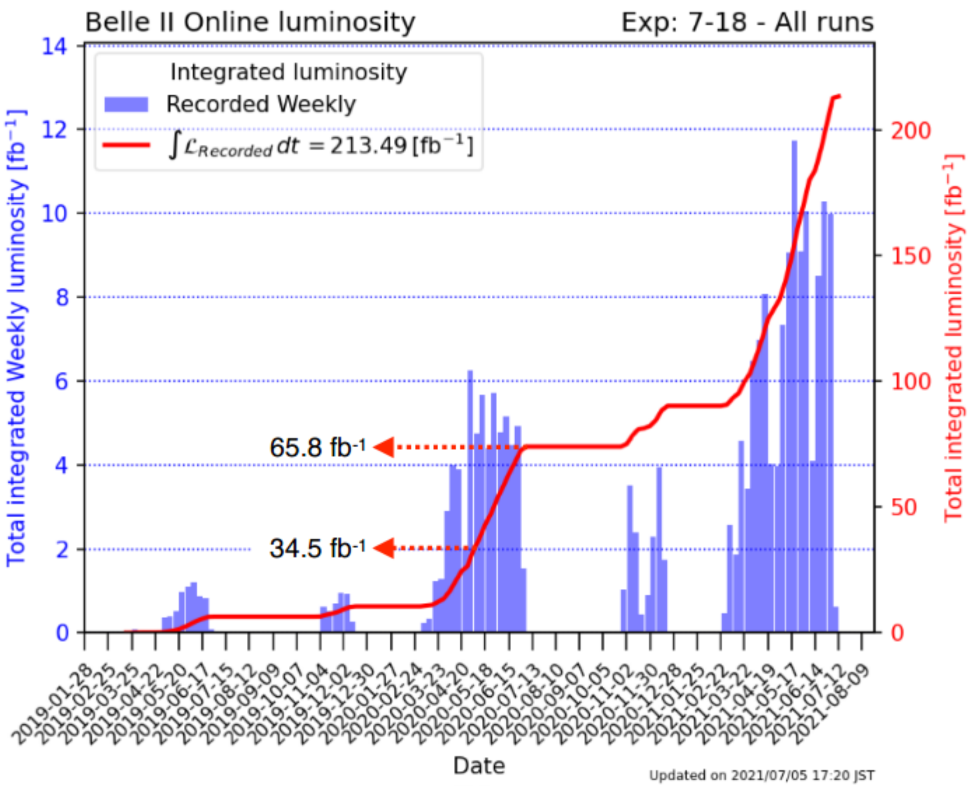
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

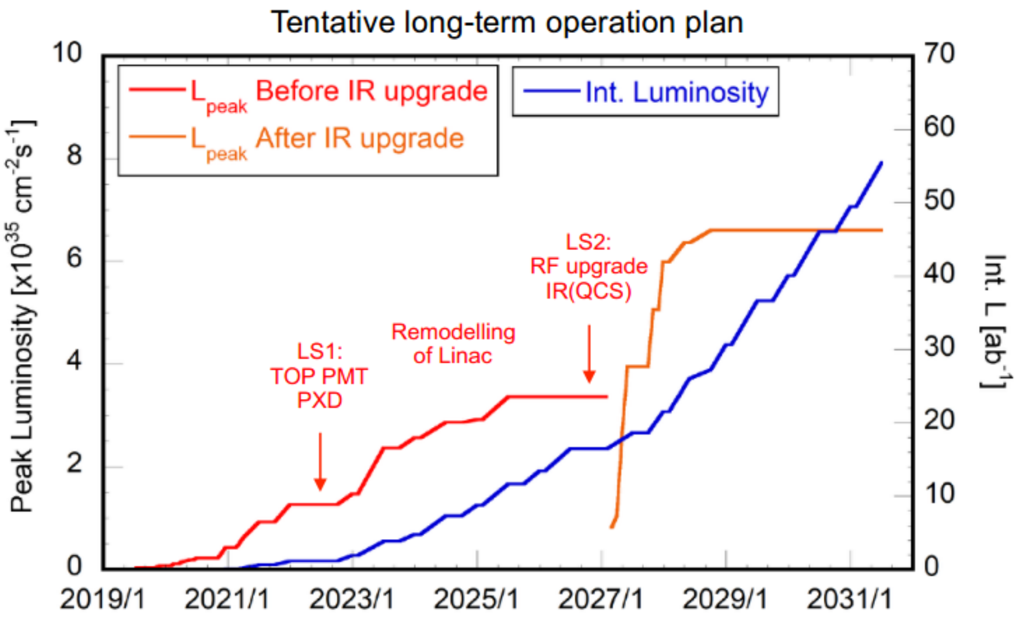
factor 20 factor 2-3



Belle II TDR arXiv:1011.0352

Integrated luminosity and long-term plan





Much more data to come in future ...

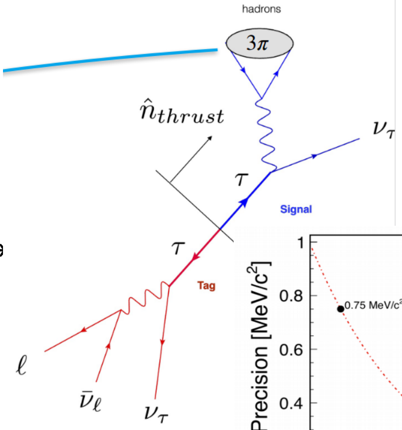
Luminosity record re-claimed, currently **$3.12 \times 10^{34} cm^{-2}s^{-1}$** on June 22nd

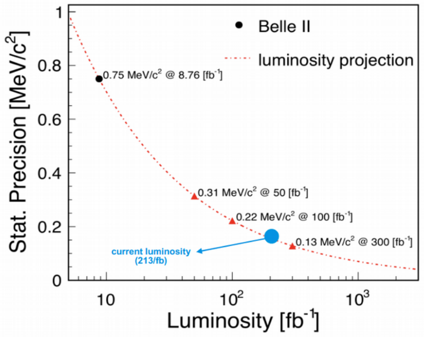
Collected up to 12/fb per week. 89.5% data-taking efficiency through the pandemic

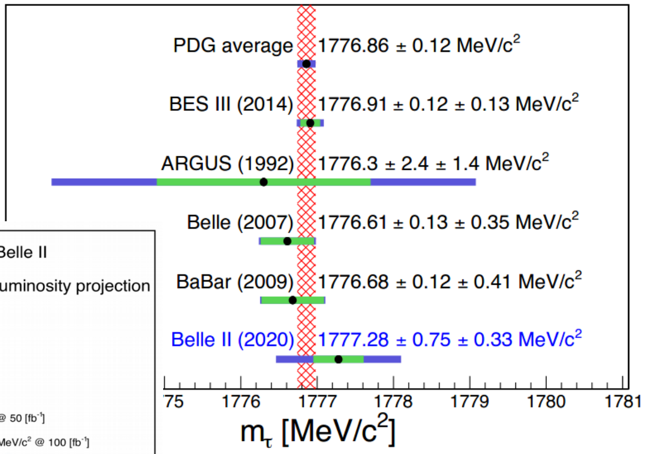
But machine tuning more challenging than expected... despite that – world leading physics results thanks to better methods and detector performance

Towards Precision tau physics: Tau Mass Measurement

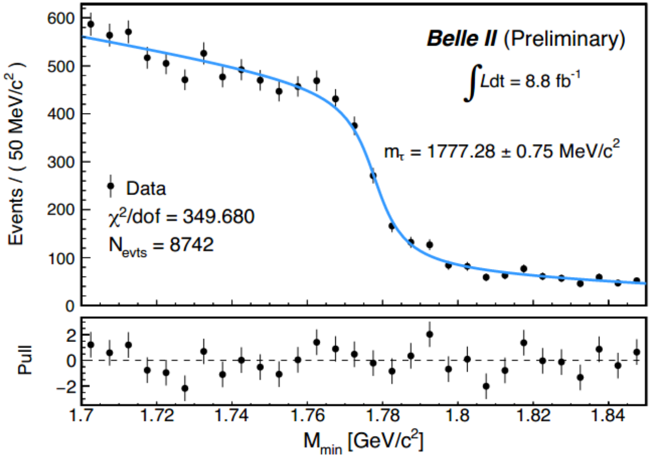
- Lepton masses and lifetimes are fundamental parameters of the SM inputs to tests of lepton universality
- Mass cannot be mesured directly → pseudo-mass technique







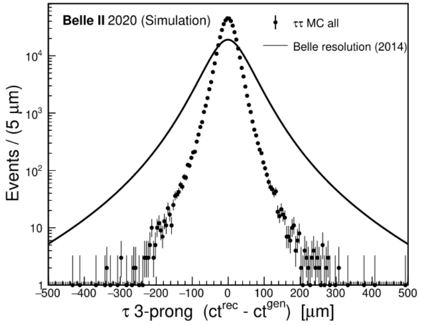
$$m_{\min} = \sqrt{m_{3\pi}^2 + 2(E_{\rm beam} - E_{3\pi})(E_{3\pi} - p_{3\pi})} \leq m_\tau$$



Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

To be reduced ...

Lifetime measurement in preparation – twice better vertex resolution

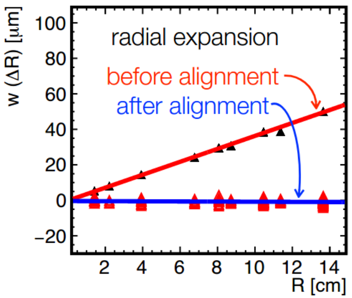


Systematics & Alignment

total uncertainties are 1.4 fs (D^0) and 5.6 fs (D^+)

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Input charm masses	0.01	0.03
Total systematic	0.8	3.1

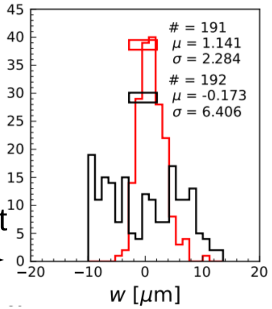
Alignment systematics evaluated conservatively – still using preliminary (prompt) calibration



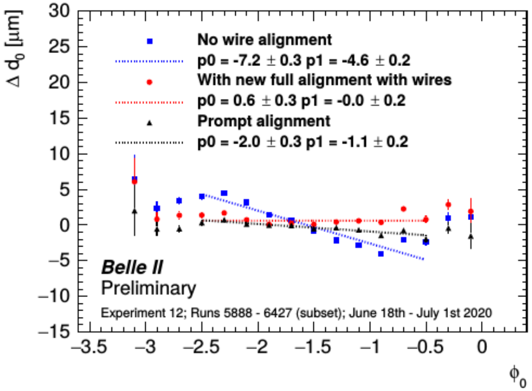
Systematic

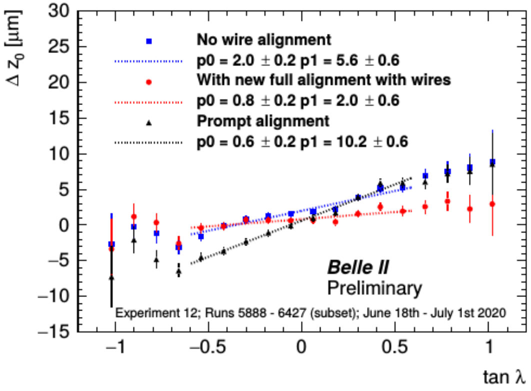
vs.

Random misalignment

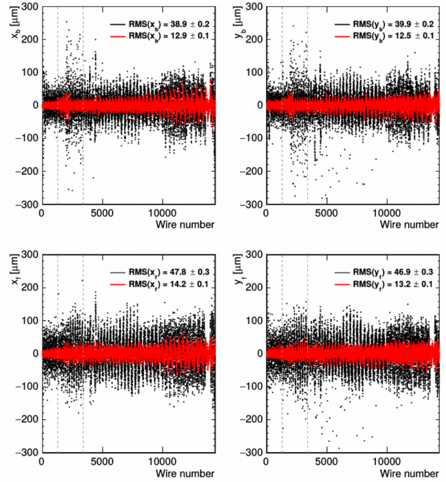


Alignment further improves after full reprocessing





Full simultaneous re-alignment with up to 55k parameters of VXD and drift chamber + run-dependent alignment of large structures and pixel sensors



Background systematics (mainly) for D^+ reducible with better modelling and more data

Belle II

Lifetime fit

Lifetime extracted by 2D UML fit to decay time and its uncertainty. All parameters extracted directly from the data.

resolution function — fixed from data (binned template)

$$\mathrm{pdf}(t, \sigma_t \,|\, \tau, b, s) \propto \int_0^{\mathrm{inf}} e^{-t_{\mathrm{true}}/\tau} R(t - t_{\mathrm{true}} \,|\, \sigma_t, b, s) dt_{\mathrm{true}} \; pdf(\sigma_t)$$

resolution function

$$R(t - t_{\mathrm{true}} \,|\, \sigma_t, b, s) = G(t - t_{\mathrm{true}} \,|\, b, s\sigma_t)$$

b = bias

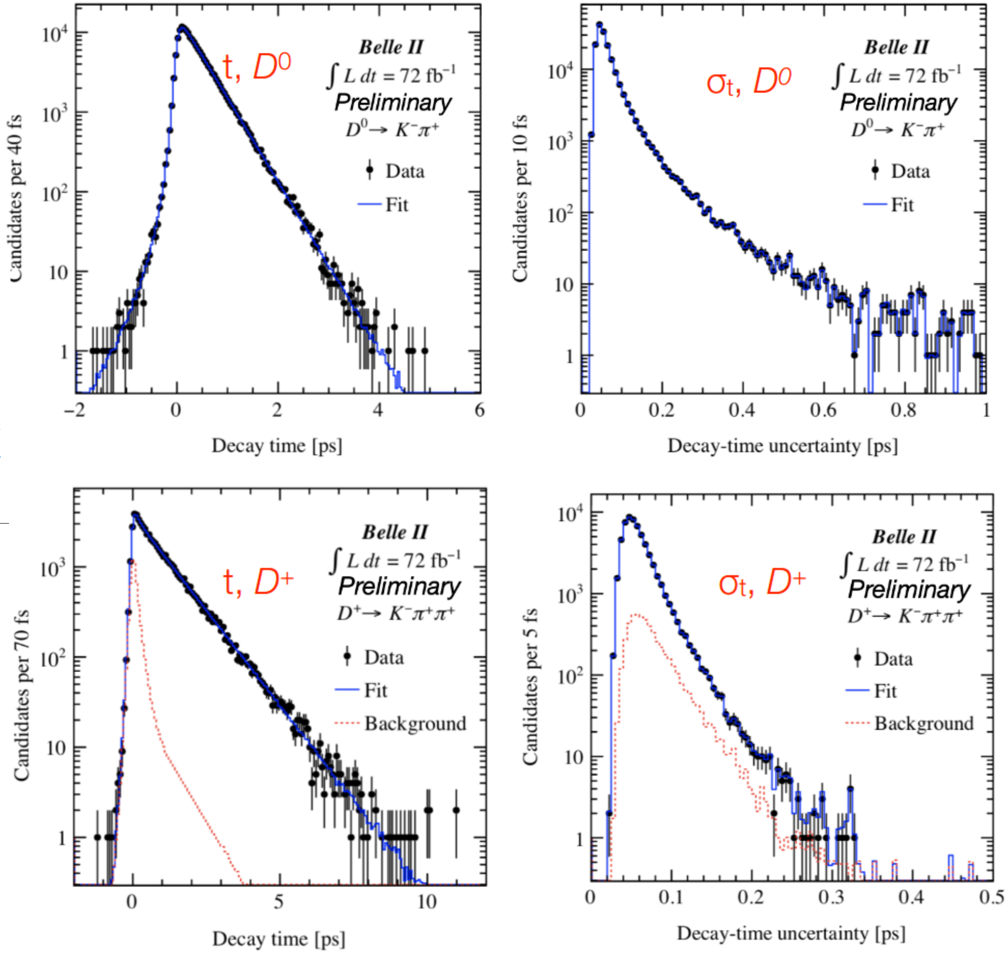
s = proper time uncertainty scaling factor

Empirical model for background from data side-bands. Fitted simultaneously with signal region. Bkg fraction fixed to result of mass fit

$$\mathrm{pdf}_{\mathrm{bkg}}(t, \sigma_t) = \mathrm{pdf}_{\mathrm{bkg}}(t \,|\, \sigma_t)\; \mathrm{pdf}_{\mathrm{bkg}}(\sigma_t)$$

zero-lifetime component — lifetime#1 component — lifetime#2 component

$$\mathrm{pdf}_{\mathrm{bkg}}(t|\sigma_t) = (1 - f_{bl})R(t\,|\,b + b_{\mathrm{bkg}}, s\sigma_t) + f_{bl}\big[f_{bl1}\mathrm{pdf}_{bl1}(t\,|\,\sigma_t, \tau_{b1}, b + b_{\mathrm{bkg}}, s) + (1 - f_{bl1})\mathrm{pdf}_{bl2}(t\,|\,\sigma_t, \tau_{b2}, b + b_{\mathrm{bkg}}, s)\big]$$



Belle II

LHCb-Belle II Comparison

Observable	Current Belle/ Babar	2019 LHCb	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})	LHCb (23 fb^{-1})	Belle II Upgrade (250 ab^{-1})	LHCb upgrade II (300 fb^{-1})
CKM precision, new physics in CP Violation							
$\sin 2\beta/\varphi_1$ ($B \to J/\psi K_S$)	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/φ_3	13°	5.4°	4.7°	1.5°	1.5°	0.4°	0.4°
α/φ_2	4°	–	2	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	2%	1%	3%	<1%	1%
φ_s	–	49 mrad	–	–	14 mrad	–	4 mrad
S_{CP}($B \to \eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015	○	0.007	○
A_{CP}($B \to K_S \pi^0$)	0.15	–	0.07	0.04	–	0.02	–
New physics in radiative & EW Penguins, LFUV							
S_{CP}($B_d \to K^* \gamma$)	0.32	○	0.11	0.035	○	0.015	○
R($B \to K^* l^+ l^-$) ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.09	0.03	0.03	0.01	0.01
R($B \to D^* \tau\nu$)	6%	10%	3%	1.5%	3%	<1%	1%
Br($B \to \tau\nu$), Br($B \to K^* \nu\nu$)	24%, –	–	9%, 25%	4%, 9%	–	1.7%, 4%	–
Br($B_d \to \mu\mu$)	–	90%	–	–	34%	–	10%
Charm and τ							
ΔA_{CP}(KK-$\pi\pi$)	–	8.5×10^{-4}	–	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
A_{CP}($D \to \pi^+ \pi^0$)	1.2%	–	0.5%	0.2%	–	0.1%	–
Br($\tau \to e \gamma$)	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
Br($\tau \to \mu\mu\mu$)	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

arXiv: 1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)