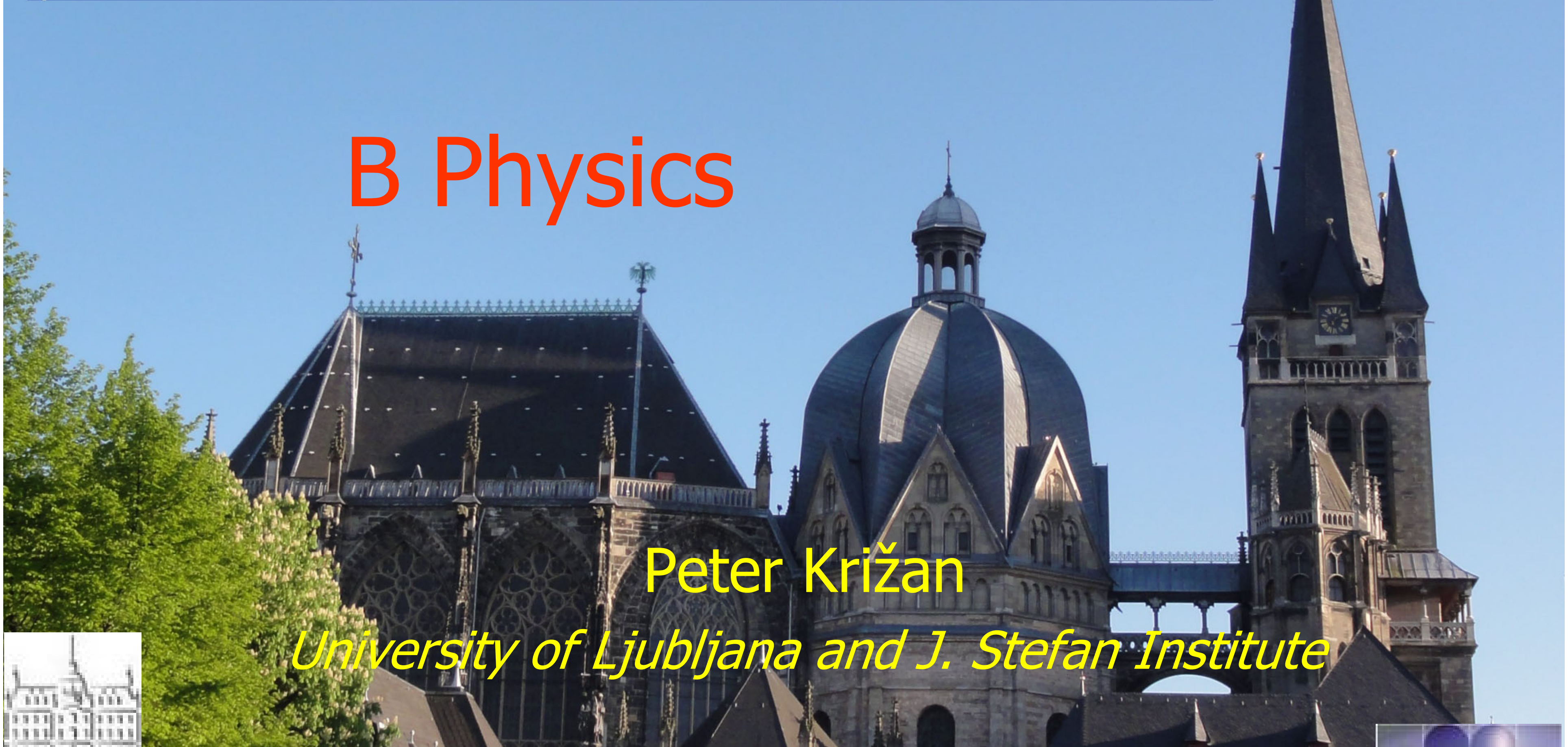
Physics in Collision

40th International Symposium on Physics in Collision

RWTH Aachen University, Aachen, Germany | September 14-17, 2021

B Physics



Peter Križan

University of Ljubljana and J. Stefan Institute

for the Belle II and Belle Collaborations,

with material from the ATLAS, CMS, and LHCb collaborations

Contents of the talk

Introduction

Facilities

Cabibbo-Kobayashi-Maskawa matrix studies

CP violation studies

Searches for new physics in rare decays

QCD dynamics in B decays

Outlook

Studies of lepton flavour universality, anomalies → talk by Marcello Rotondo

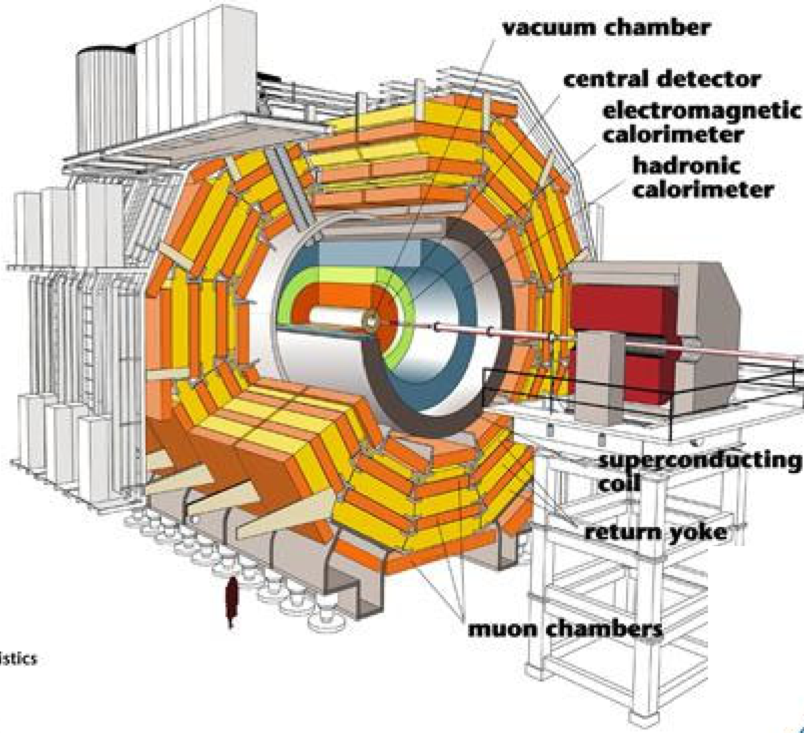
Motivation

B decays have been and continue being a very hot topic in searches for new physics.

Physics of B mesons has contributed substantially to our present understanding of elementary particles and their interactions.

Intriguing phenomena that have been seen in the recent years make this research area one of the most interesting in particle physics.

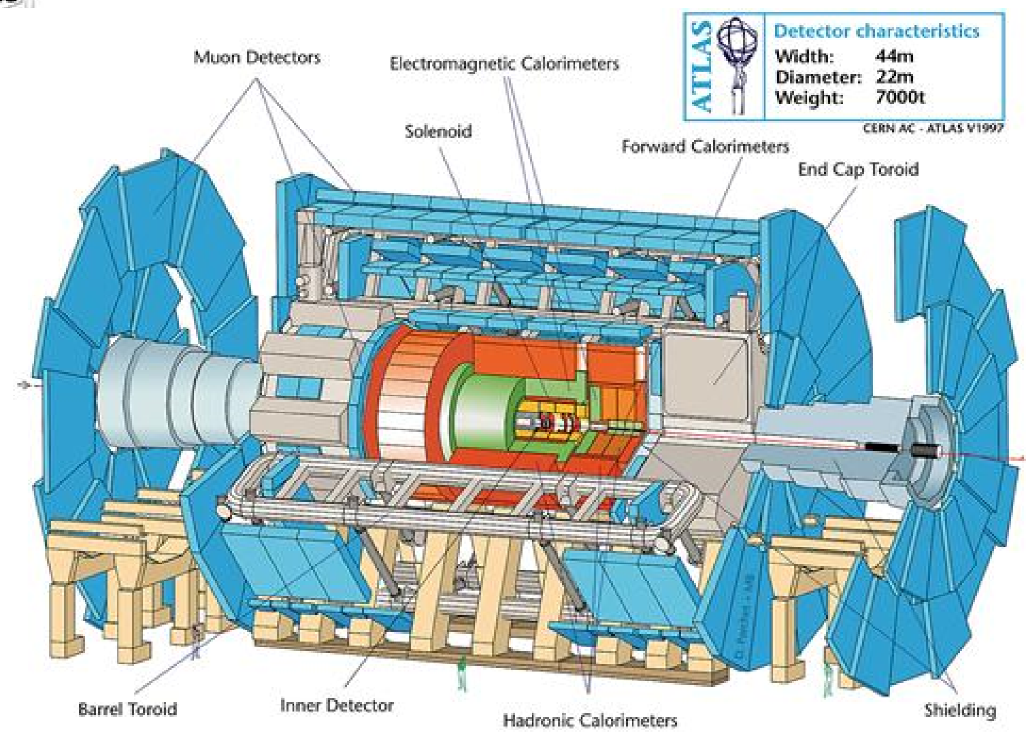
Facilities: ATLAS, CMS



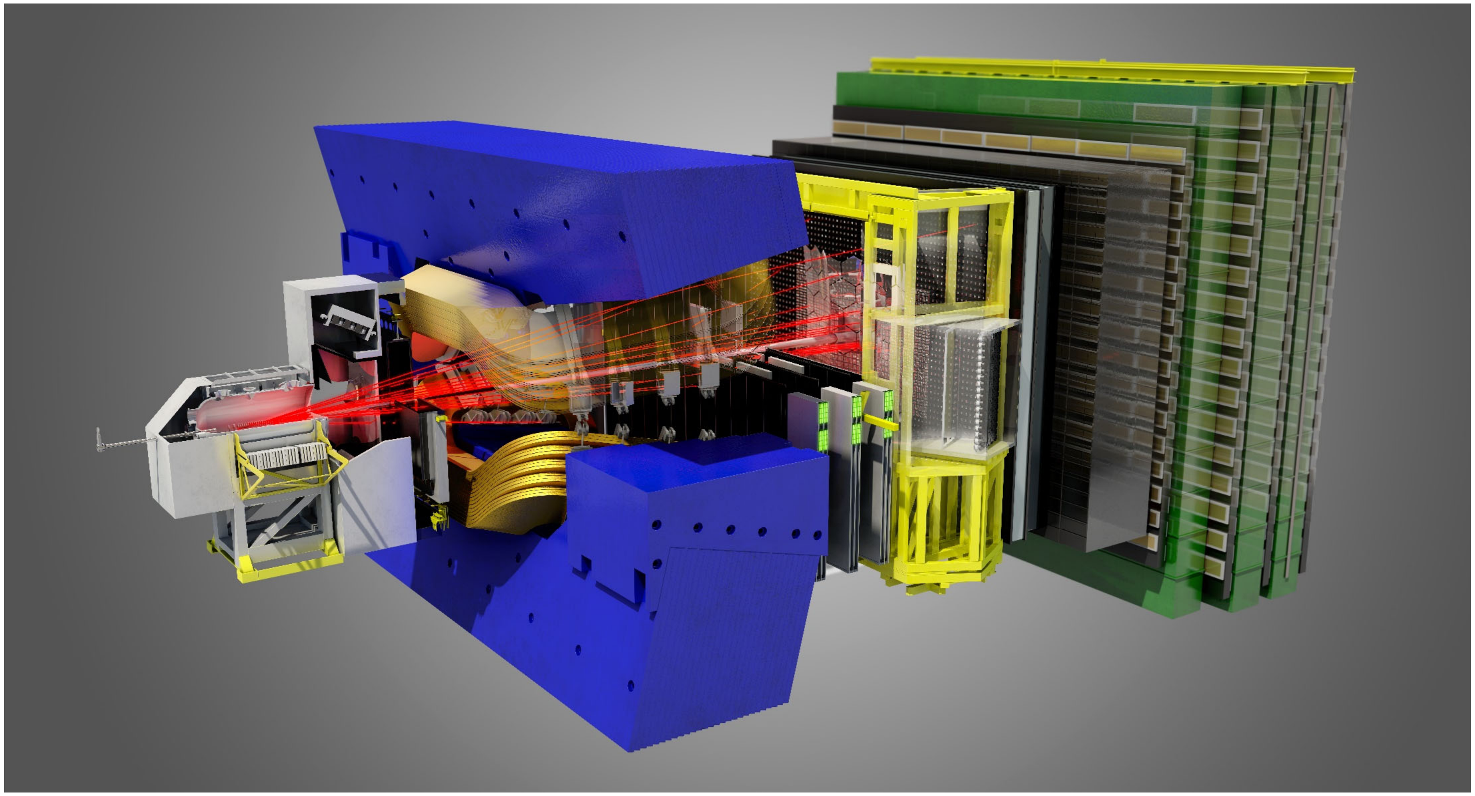
Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

General purpose detectors at LHC with features relevant to flavour physics: excellent vertexing, tracking, muon and electron identification, dedicated triggers



Facilities: LHCb @ LHC



pp collsions in forward region: huge production rates of b hadrons.

Large boost + excellent vtx resolution: background rejection and decay-length resolution.

Excellent momentum and mass resolution.

Outstanding PID (K-π) and μ reconstruction.

Dedicated trigger system for beauty and charmed hadrons.

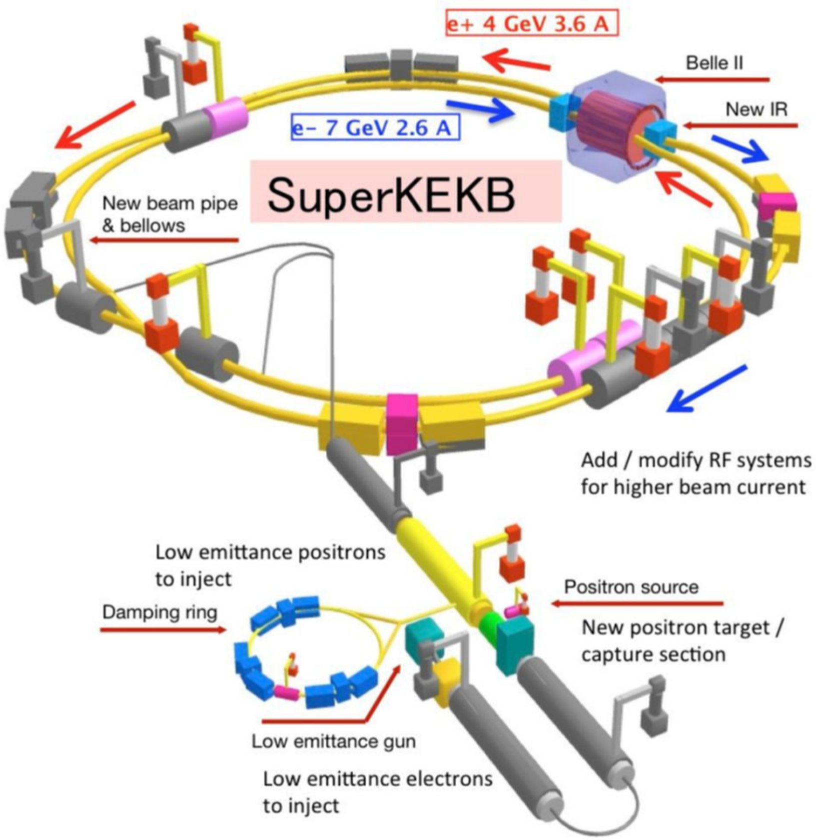
Facilities: Belle II @ SuperKEKB

beam current x1.5

beam-beam param. x1

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{R_L}{R_\xi}\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}$$

vertical beta function x 1/20

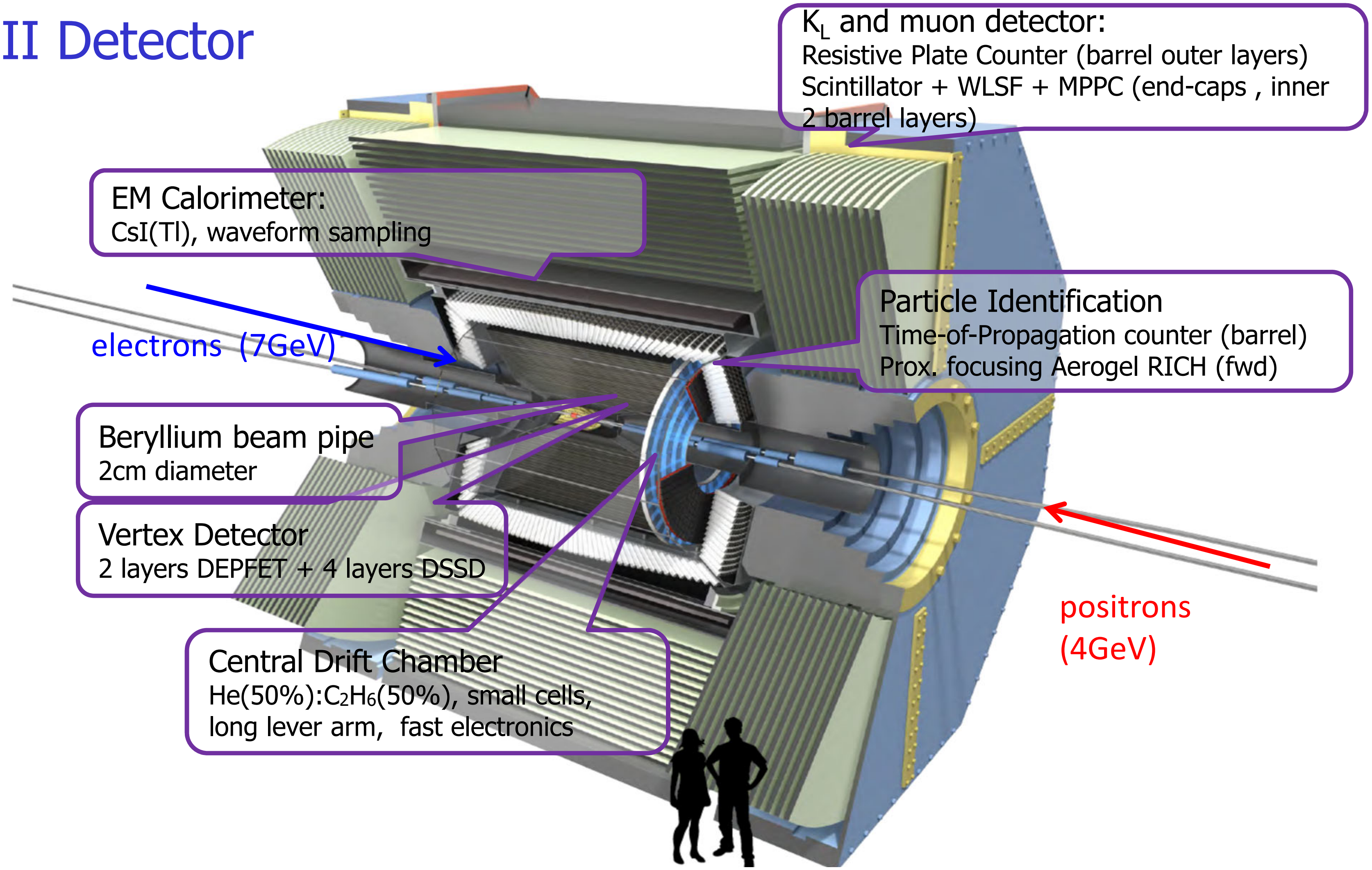


Idea: to increase the luminosity of KEKB by a factor of 30, employ Nano-Beam scheme (P. Raimondi): squeeze beta function at the IP (βx*,βy*) and minimize longitudinal size of overlap region

- Modestly increase the beam currents from 1.64A + 1.19A to 2.8A+2.0A (e-,e+)
- Dramatically decrease the beam cross section: β_y^* from 5.9mm/5.9mm to 0.27mm/0.30mm
- Increase the crossing angle to 83mrad

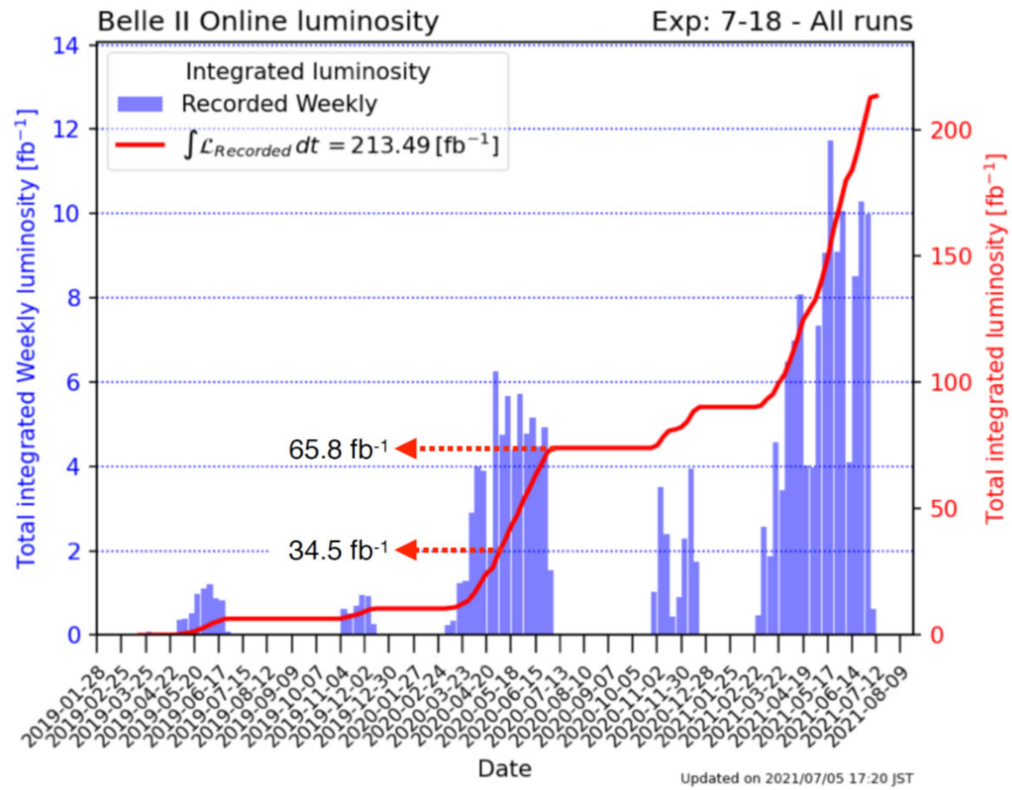
Strong focusing of beams down to vertical beam size of ~50 nm requires very low emittance beams and a powerful sophisticated final focus

Belle II Detector



- Exactly two B mesons produced (at Υ(4S))
- Hermetic detector
- High flavour tagging efficiency (~30%)
- Detection of gammas, π^0s, K_Ls
- Very clean detector environment (can observe decays with several neutrinos in the final state!)

Facilities: Belle II



Very successful data taking throughout the pandemic

-overall data taking efficiency of 89.5%

-reached world record instantaneous luminosity of 3.12×10^{34} cm^{-2} s^{-1}, collected up to 12 fb^{-1} per week: Super-B factory mode

This talk: results with ~70 fb^{-1}, on tape 213 fb^{-1}

Ultimate goal: reach 50 ab^{-1} by operating at the instantaneous luminosity of 6×10^{35} cm^{-2} s^{-1}

Contents of the talk

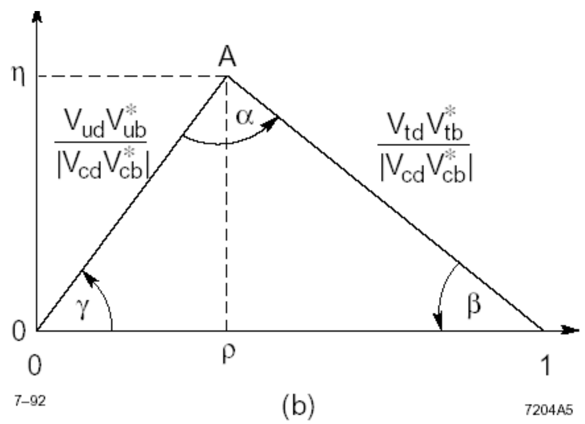
- Introduction
- Facilities
- CKM studies
- CPV studies
- Searches for new physics in rare decays
- QCD dynamics in B decays
- Outlook

CKM studies

Cabibbo-Kobayashi-Maskawa (CKM) quark transition matrix

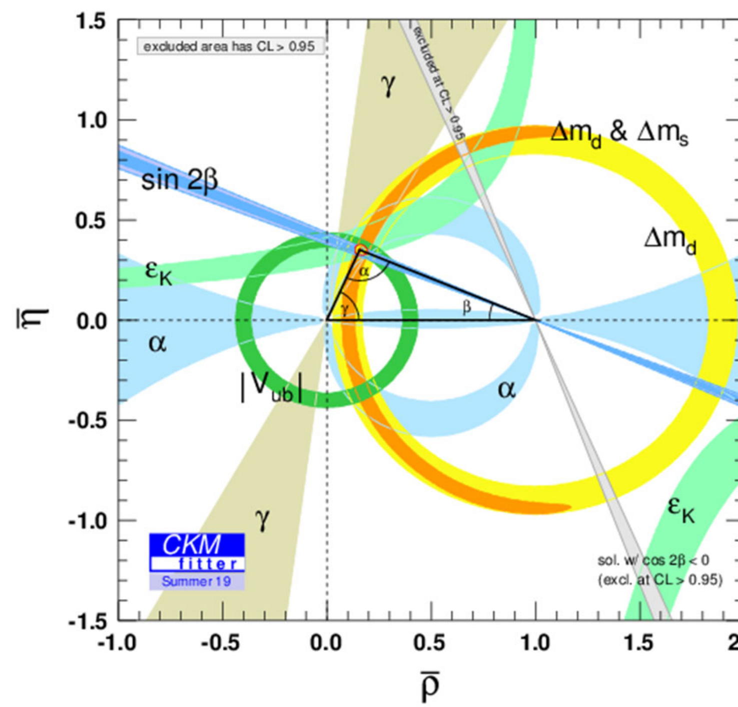
Unitarity triangle: geometrical interpretation of the unitarity of the matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



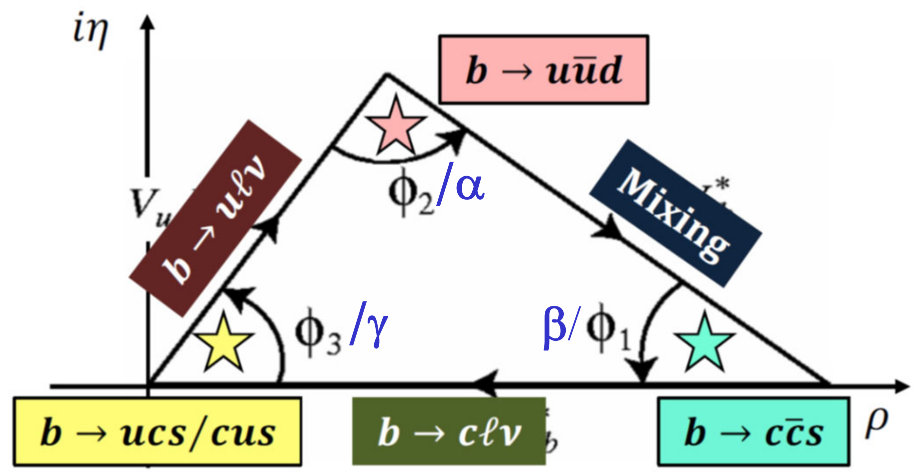
Constraints from measurements of angles and sides of the unitarity triangle → Remarkable agreement, but still ~10% NP allowed

Also: searches for NP in comparison of angles as determined in processes dominated by tree and loop diagrams



CKM studies

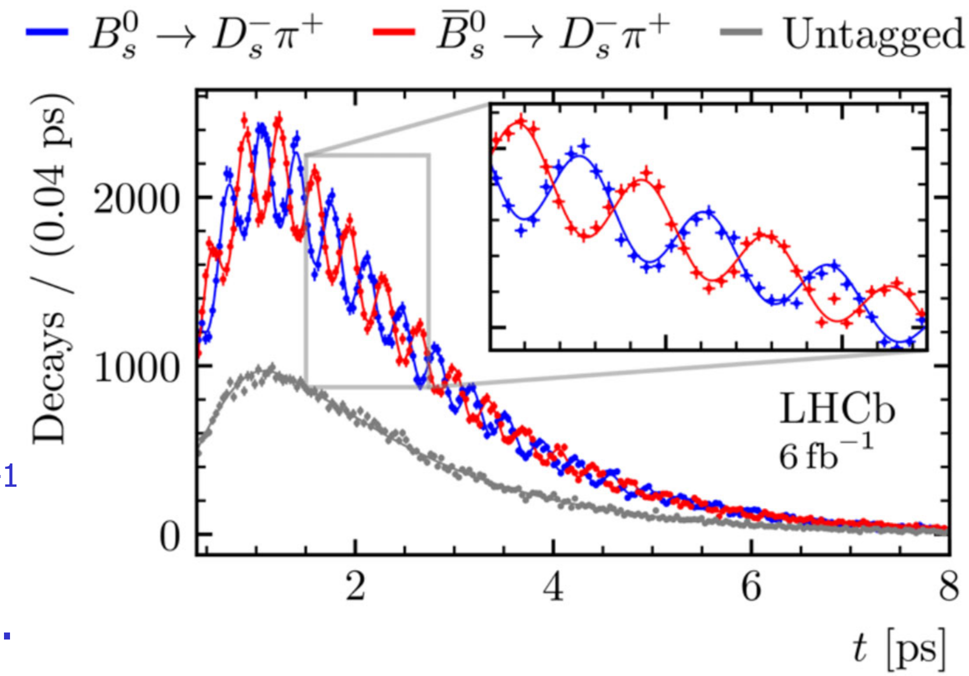
- B_s mixing - LHCb
- ϕ_s - ATLAS, CMS, LHCb
- γ / ϕ_3 - LHCb, Belle II
- $|V_{ub}|$ and $|V_{cb}|$ - Belle, Belle II
- $|V_{ub}|/|V_{cb}|$ - LHCb

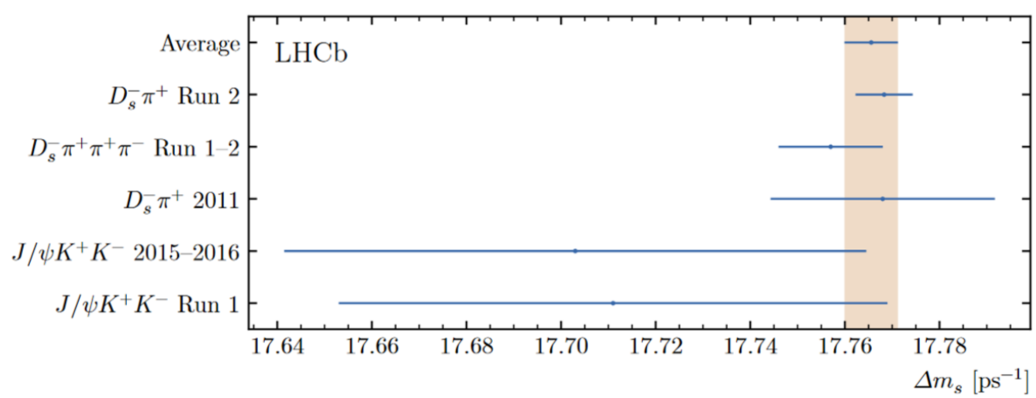


B_s mixing

B_s^0 mass difference Δm_s
– Measured by oscillation frequency with $B_s^0 \rightarrow D^{\mp}\pi^{\pm}$ decays
– Flavour tagging identifies B_s^0 / anti B_s^0 at production

Data sample 6 fb^{-1}
– Δm_s = 17.7683 ± 0.0051 ± 0.0032 ps^{-1}
– Precision 3 x 10^{-4}
– Including $B_s^0 \rightarrow D^{\mp}h^{\pm}\pi^{\pm}\pi^{\mp}$ decays et al.
– Δm_s = 17.7656 ± 0.0057 ps^{-1}





LHCb-PAPER-2021-005, arXiv:2104.04421
LHCb-PAPER-2020-030, JHEP 03 (2021) 137

ϕ_s with $B_s^0 \to J/\psi\ \varphi$ decays

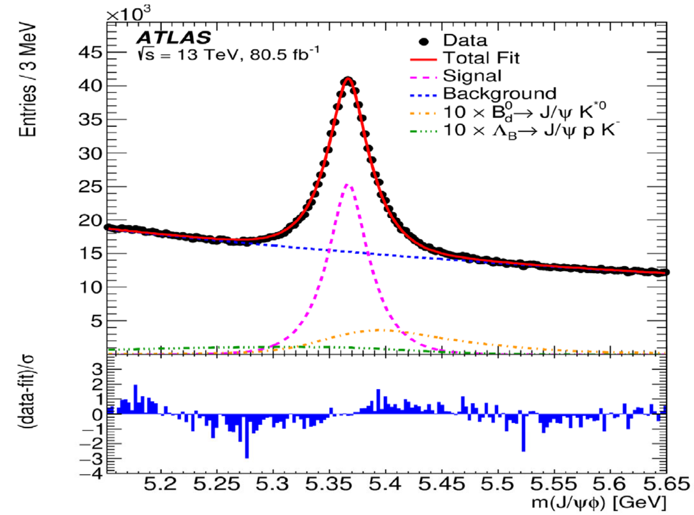
Eur. Phys. J. C 81 (2021) 342

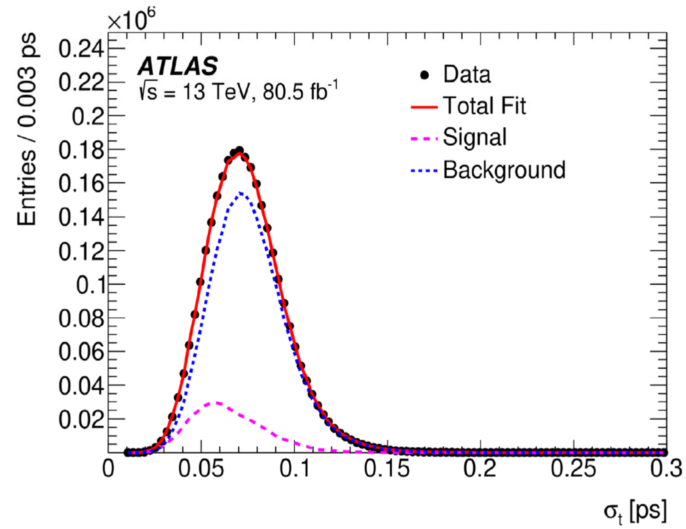
ϕ_s is the parameter of CP violation in $B_s^0 \to J/\psi\ \varphi$ decays.

In SM, this parameter is given by the CKM matrix elements, $\phi_s = -2\arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb})$
CKMfitter: $\phi_s = -0.03696^{+0.00072}_{-0.00082}$

Measurement:

- 2015 – 2017 ATLAS data: 80.5 fb^{-1}@ 13TeV
- Trigger: two μ candidates consistent with J/ψ mass ($\Delta m \sim 50$ MeV)
- "Low" p_T cut, no decay time/impact parameter cuts
- High signal yield (~ 45k)
- Flavour tagging using Opposite-side leptons (μ, e) or b-jet-charge tagging
- Calibrated Tagging power: (1.75 ± 0.01)%
- Silicon pixels and strips tracker: $\sigma_t \sim 65$ fs





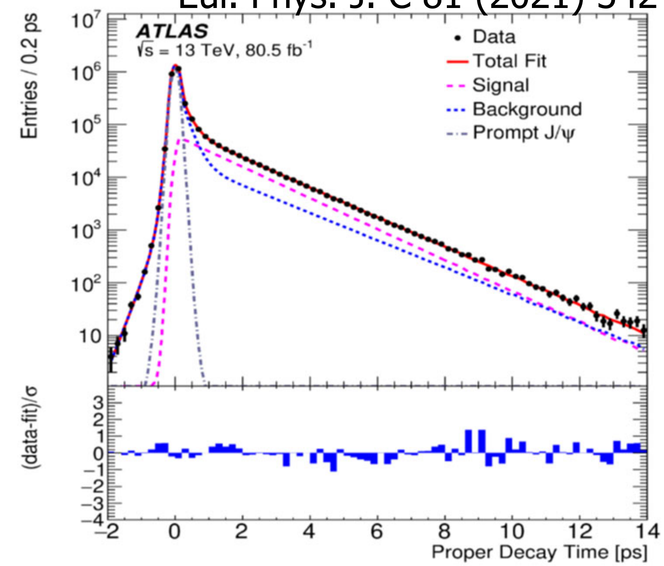
ϕ_s with $B_s^0 \rightarrow J/\psi\ \varphi$ decays

ATLAS EXPERIMENT

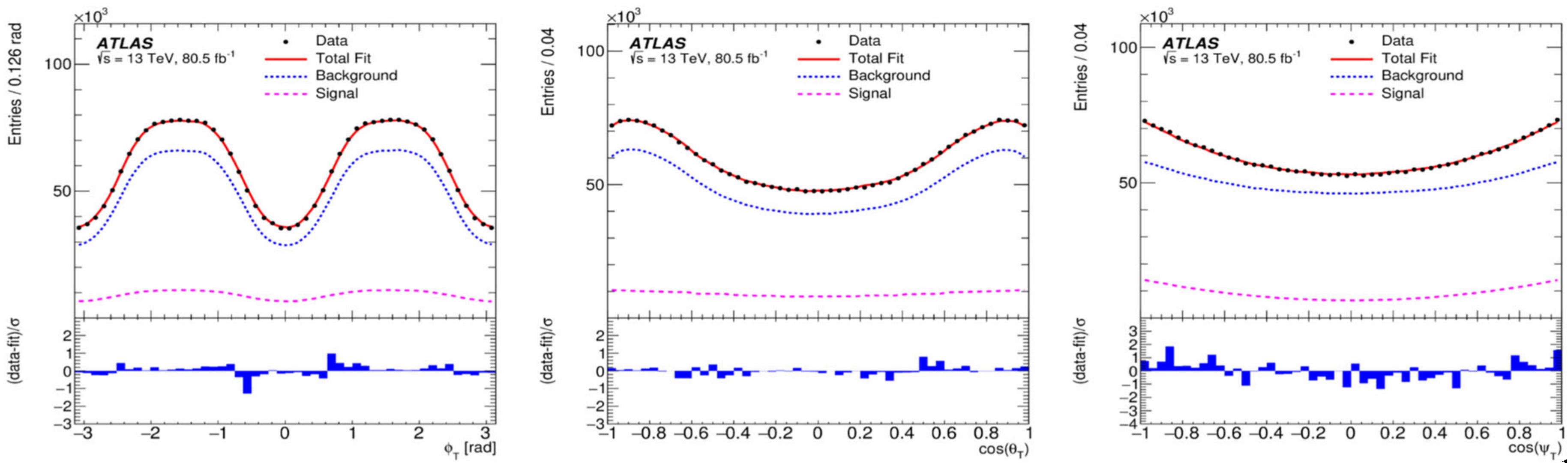
Eur. Phys. J. C 81 (2021) 342

6-D (3 angles, decay time, mass, mistag probability and decay time error) likelihood fit to extract ϕ_s

- ϕ_s = -0.081 ± 0.041(stat.) ± 0.022(sys.)
- Systematics dominated by flavour tagging, modeling of background angular distribution, fit bias.
- Consistent with Run 1 result
- Combined: ϕ_s = -0.087 ± 0.042, $\Delta\Gamma$ = 0.0657 ± 0.0057ps^{-1}



Full Run 2 analysis under way – additional 60 fb^{-1}



ϕ_s with $B_s^0 \rightarrow J/\psi\ \varphi$ decays

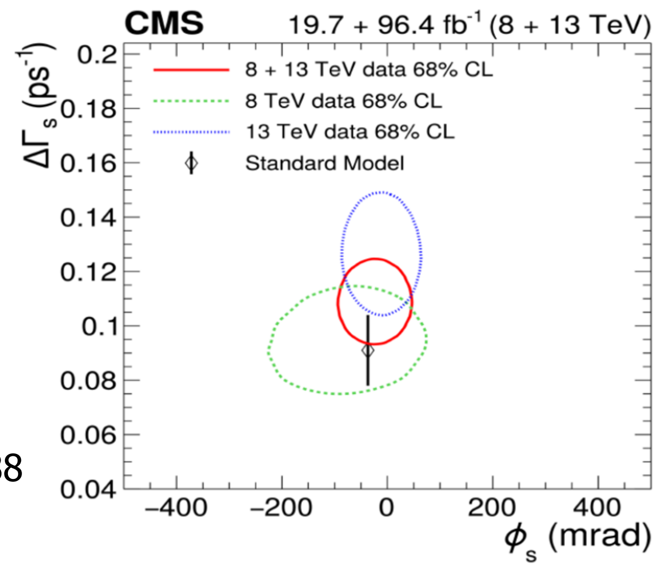
CMS

Similar analysis, on 96.4 fb^{-1}

- ϕ_s = -0.011 ± 0.050(stat.) ± 0.010(sys.)
- Systematic dominated by angular efficiency and model bias
- Combined with Run 1

ϕ_s = -0.021 ± 0.045, $\Delta\Gamma$ = 0.1032 ± 0.0106 ps^{-1}

Phys. Lett. B 816 (2021) 136188



LHCb

2015-2016 data, 4.9 fb^{-1}

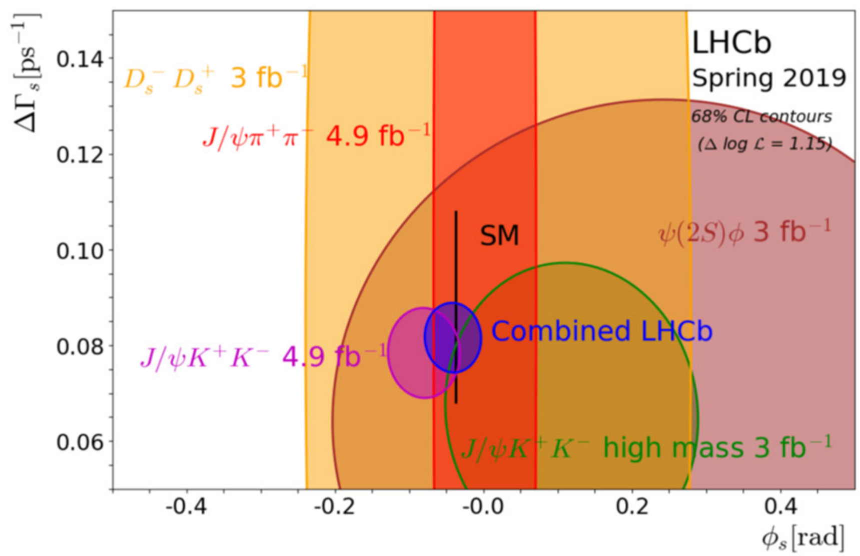
- ϕ_s = -0.083 ± 0.041(stat.) ± 0.006(sys.)
- Combined with Run 1

ϕ_s = -0.080 ± 0.032, $\Delta\Gamma$ = 0.1032 ± 0.0048 ps^{-1}

Combined with all other measurements by LHCb

ϕ_s = -0.041 ± 0.025, $\Delta\Gamma$ = 0.0813 ± 0.0106 ps^{-1}

Eur. Phys. J. C 79 (2019) 706, Eur. Phys. J. C 80 (2020) 601

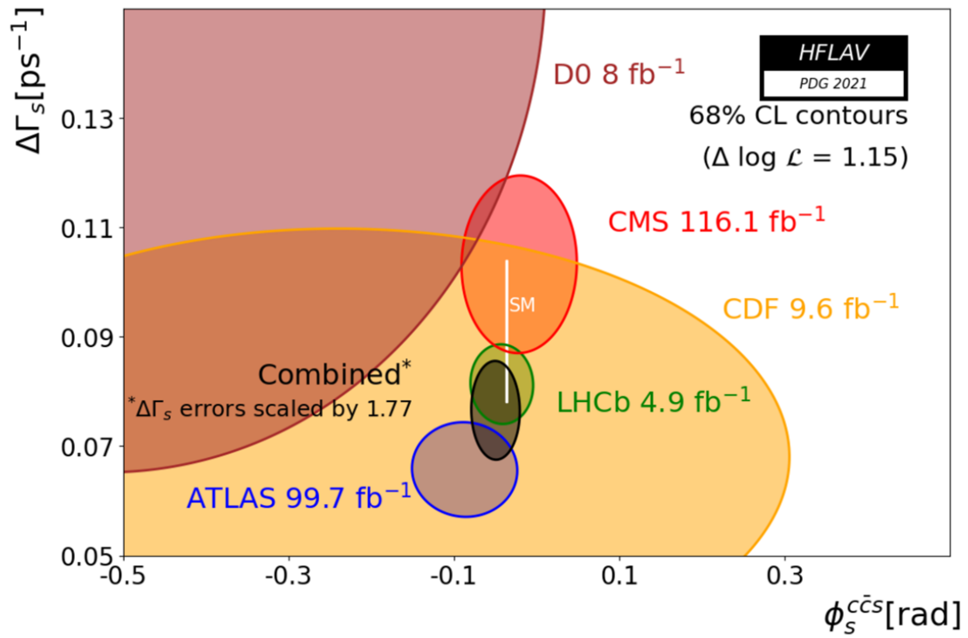


ϕ_s world average - HFLAV

World average HFLAV

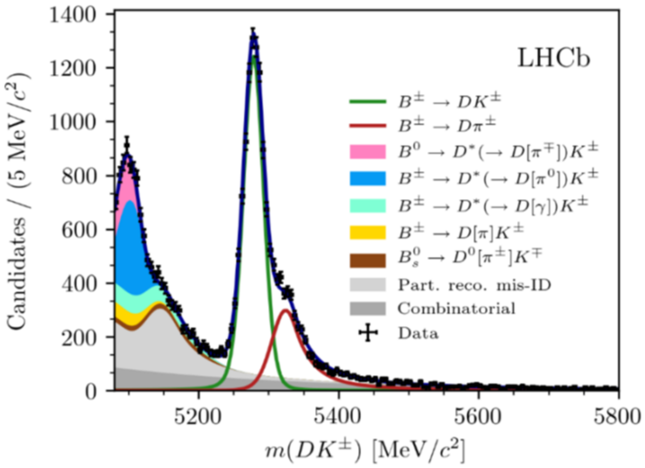
$\phi_s = -0.041 \pm 0.025$ rad ,

$\Delta\Gamma_s = 0.082 \pm 0.005$ ps^{-1}



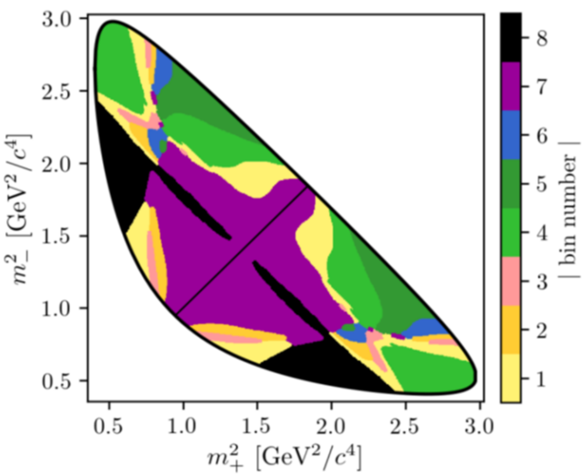
- Measurements are statistically dominated
- Consistent with SM and consistent with no CP violation in the interference
- Several "full Run 2" analyses are ongoing → expect soon to improve ϕ_s precision

CKM angle γ from time integrated measurements

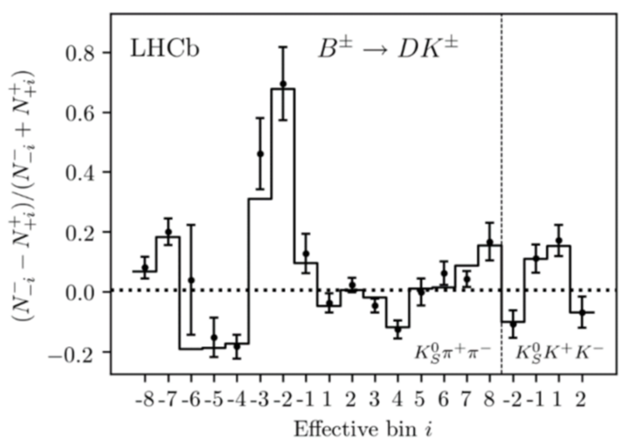


From interference between two amplitudes leading to the same final state

$$B^- \to D^0(\to K^0_S h^+ h^-)K^- \propto V_{cb}$$
$$B^- \to \overline{D}^0(\to K^0_S h^+ h^-)K^- \propto V_{ub}$$
$$m^2_\pm = m(K^0_S, h^\pm)$$



- external input: strong-phase difference between the D decay amplitudes at any given point of the Dalitz plot from CLEO and BES III combined data
- CPV parameters from the distribution of events in the Dalitz plot: very large asymmetries in population of bins
- full Run 1+2 statistic (9/fb)



Most precise γ measurement from a single analysis

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$
$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$
$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$
$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$
$$\delta_B^{D\pi^\pm} = (291^{+24}_{-26})^\circ.$$

arXiv:2010.08483
JHEP 02 (2021) 169

Towards Belle II Measurement of ϕ_3 /γ with $B \rightarrow D^{(*)}K/\pi$ Transitions

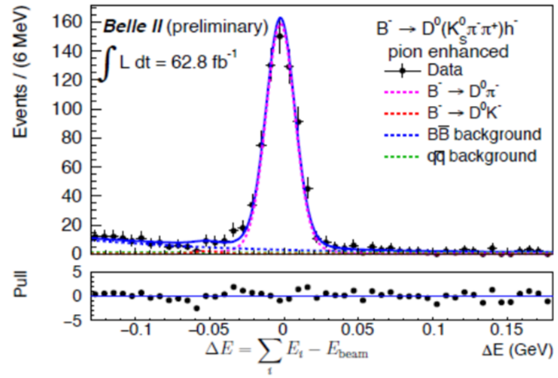
https://arxiv.org/abs/2104.03628

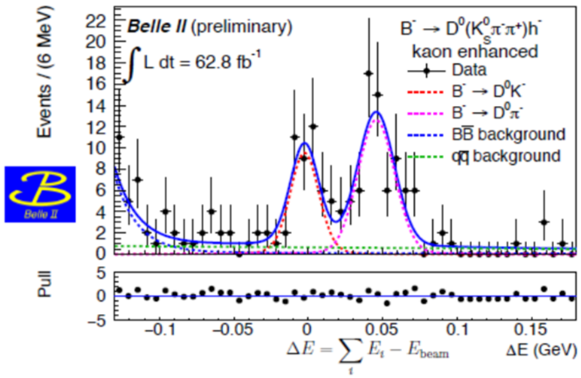
$B^- \rightarrow D^{(*)0}\pi^-$ and $B^0 \rightarrow D^{(*)+}\pi^-$ are the most abundant hadronic B decays

$B^- \rightarrow D^{(*)0}K^-$ sensitive to CKM unitarity triangle angle ϕ_3 (or γ)

"golden" mode: $B^- \rightarrow D^{(*)}(K^0_S\pi^+\pi^-)K^-$

Many systematic uncertainties cancel in the ratio of decay rates





$$R^{(*)0} = \frac{\Gamma(B^- \rightarrow D^{(*)0}K^-)}{\Gamma(B^- \rightarrow D^{(*)0}\pi^-)} \qquad R^{(*)+} = \frac{\Gamma(\bar{B}^0 \rightarrow D^{(*)+}K^-)}{\Gamma(\bar{B}^0 \rightarrow D^{(*)+}\pi^-)}$$

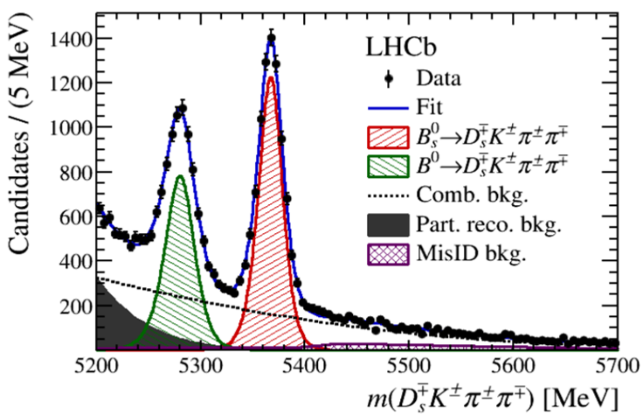
	$B^- \rightarrow D^0(K^-\pi^+)h^-$	$B^- \rightarrow D^0(K^0_S\pi^+\pi^-)h^-$	$\bar{B}^0 \rightarrow D^+h^-$
Belle II $R^{+/0}$ $(\times 10^{-2})$	$7.66 \pm 0.55 \,^{+0.11}_{-0.08}$	$6.32 \pm 0.81 \,^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$
LHCb $R^{+/0}$ $(\times 10^{-2})$	$7.77 \pm 0.04 \pm 0.07$ [24]	$7.77 \pm 0.04 \pm 0.07$ [24]	$8.22 \pm 0.11 \pm 0.25$ [25]

Re-optimization of Belle ϕ_3-analysis ongoing

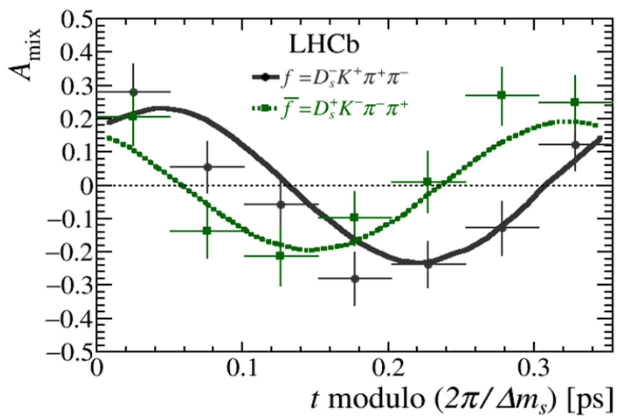
- precision of favoured BPGGSZ method strongly depends on recent BES III results on strong phases between D^0 and $\bar{D}^0$ decays to $K^0_S\pi^+\pi^-$
- aiming for first Belle+Belle II combined result soon

Angle γ from a time dependent measurement

arXiv:2011.12041
JHEP 03 (2021) 137



- $B_s^0 \to D^{\mp}K^{\pm}\pi^{\pm}\pi^{\mp}$
- CPV due to interference between mixing and decay to the same final state
- several contributing final states: amplitude analysis
- full Run 1+2 statistic (9 fb^{-1})



- model-dependent approach:
  describe resonance contributions with an amplitude model
- model independent approach: integrate over phase space

Parameter	Model-independent	Model-dependent	
r	$0.47^{+0.08}_{-0.08}{}^{+0.02}_{-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$	ratio of the decay amplit. to the same final state
κ	$0.88^{+0.12}_{-0.19}{}^{+0.04}_{-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$	coherence factor
δ [°]	$-6\ ^{+10}_{-12}\ ^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$	strong phase difference
$\gamma - 2\beta_s$ [°]	$42\ ^{+19}_{-13}\ ^{+6}_{-2}$	$42 \pm 10 \pm 4 \pm 5$	weak phase difference

uncertainty from amplitude modeling

Angle γ and charm mixing

CONF-2021-001

- New method

– First simultaneous determination of CKM angle γ and charm mixing parameters

– 151 observables, 52 parameters

- CKM angle γ

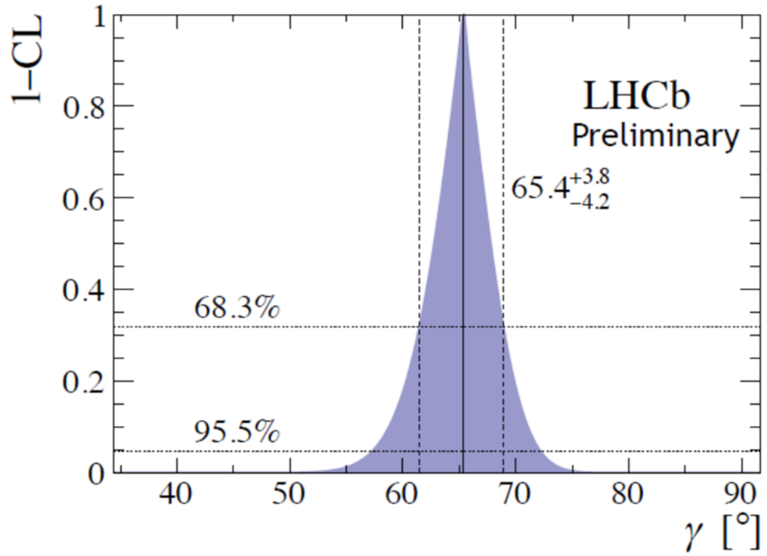
$$\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$$

– Most precise measurement

- Comparison

– Excellent agreement with indirect global CKM fits – Utfit

$$\gamma = (65.8 \pm 2.2)^{\circ}$$

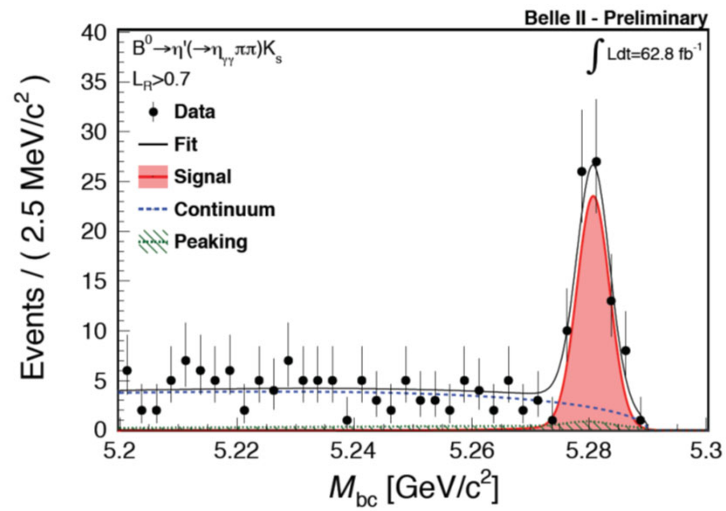


Angle ϕ_1/β – first Belle II measurements of $B \to \eta' K$ and $B^0 \to J/\psi K^0_L$

$B \to \eta' K$ is a rare charmless hadronic penguin diagram mediated decay, CP violation in SM given by of $\sin(2\phi_1)$
- particularly sensitive to new physics in the hadronic loop.

First Belle II measurement of branching ratios in good agreement with the world average

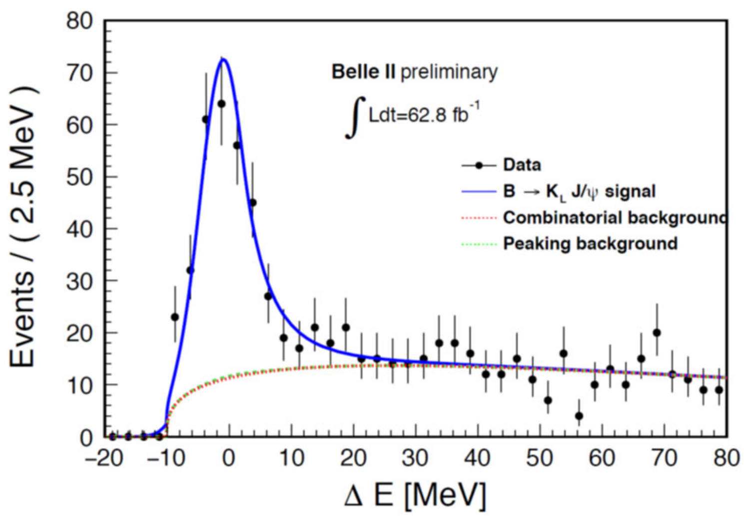
Channel	This analysis $\mathcal{B}$ $(\times 10^6)$	World average [9]
$B^\pm \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}(\text{stat}) \pm 3.4(\text{syst})$	70.4 ± 2.5
$B^0 \to \eta' K^0$	$59.9\ ^{+5.8}_{-5.5}(\text{stat}) \pm 2.7(\text{syst})$	66 ± 4



$$M_{bc} = \sqrt{E^{*2}_{beam}c^4 - p^{*2}_B c^2}$$

The measurement of $\sin(2\phi_1)$ using $B^0 \to J/\psi K^0_L$ complements the one from $B^0 \to J/\psi K^0_S$
- signal yield compatible with Belle result (no syst. yet)

$$N_{\text{sig}}\ (\mu^+\mu^-) = 267 \pm 21(\text{stat}) \pm 28(\text{peaking})$$
$$N_{\text{sig}}\ (e^+e^-) = 226 \pm 20(\text{stat}) \pm 31(\text{peaking})$$



$$\Delta E = E^*_B - E_{beam}$$

Next to come: precise measurement of B^0 lifetime and mixing frequency

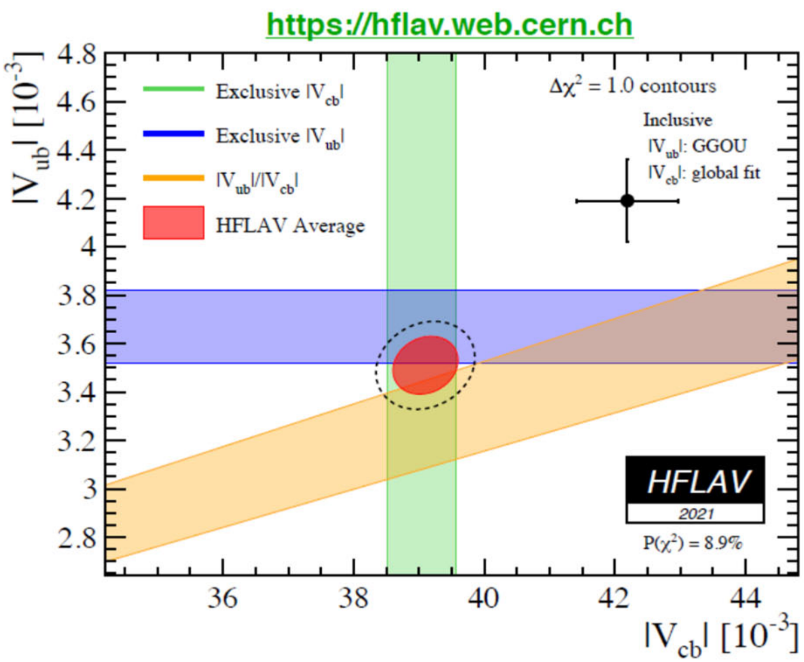
Ultimately at Belle II expect a x5 improvement in precision in ϕ_1/β – measurement still limited by statistics

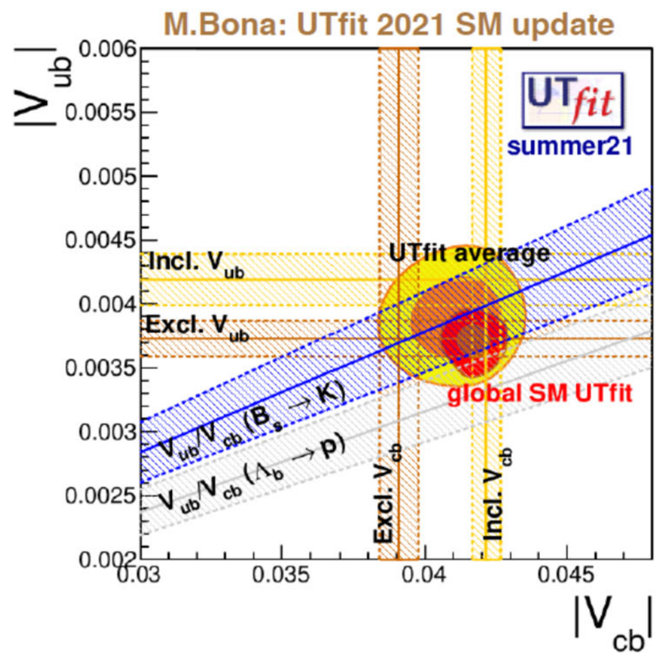
Measuring of the sides $|V_{ub}|$ and $|V_{cb}|$

Inclusive and exclusive semi-leptonic B decays

- $|V_{ub}|$: $B \to X_u l \nu$, $B \to \pi (\rho, \eta) l \nu$ ($l = e, \mu$)
- $|V_{cb}|$: $B \to X_c l \nu$, $B \to D(*) l \nu$ ($l = e, \mu$)

Long-standing discrepancy between inclusive and exclusive determinations of CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$



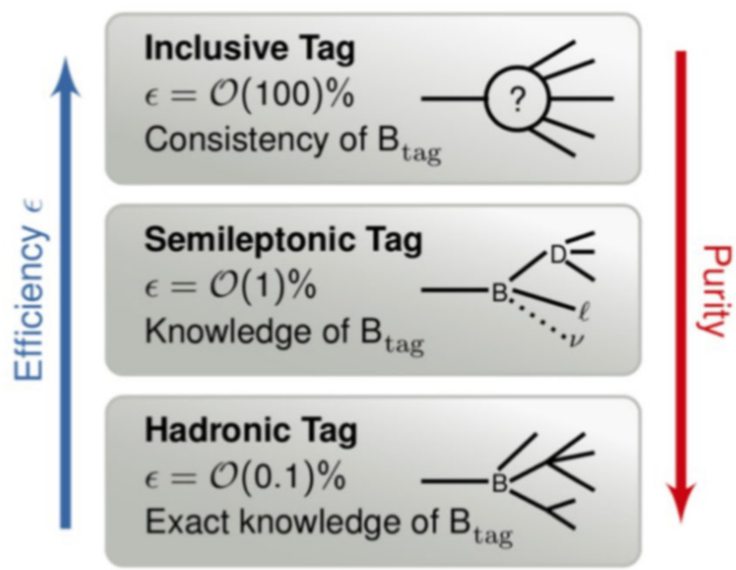


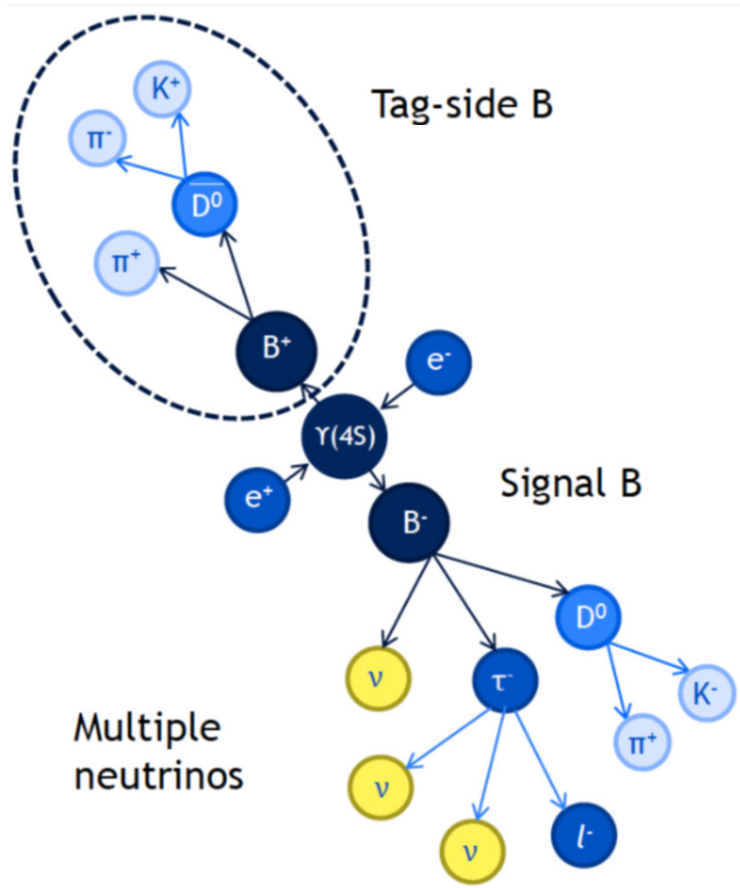
Measuring of the sides V_{ub} and V_{cb} in inclusive measurements at Belle and Belle II

Profit from the fact that exactly two B mesons are produced in e^+e^- collisions

→ Full Event Interpretation

- hierarchical multivariate technique (>200 BDTs) to reconstruct the B-tag side (semi-leptonic or hadronic) through $O(10^3)$ different decay modes
- results in a significantly increased tagging efficiency compared to Belle
- reconstruction of tag-side B → flavour/charge, momentum of the signal B, exclude tag side particles

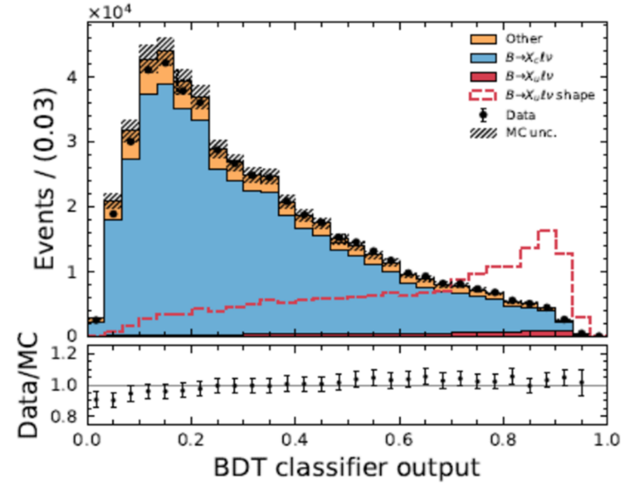


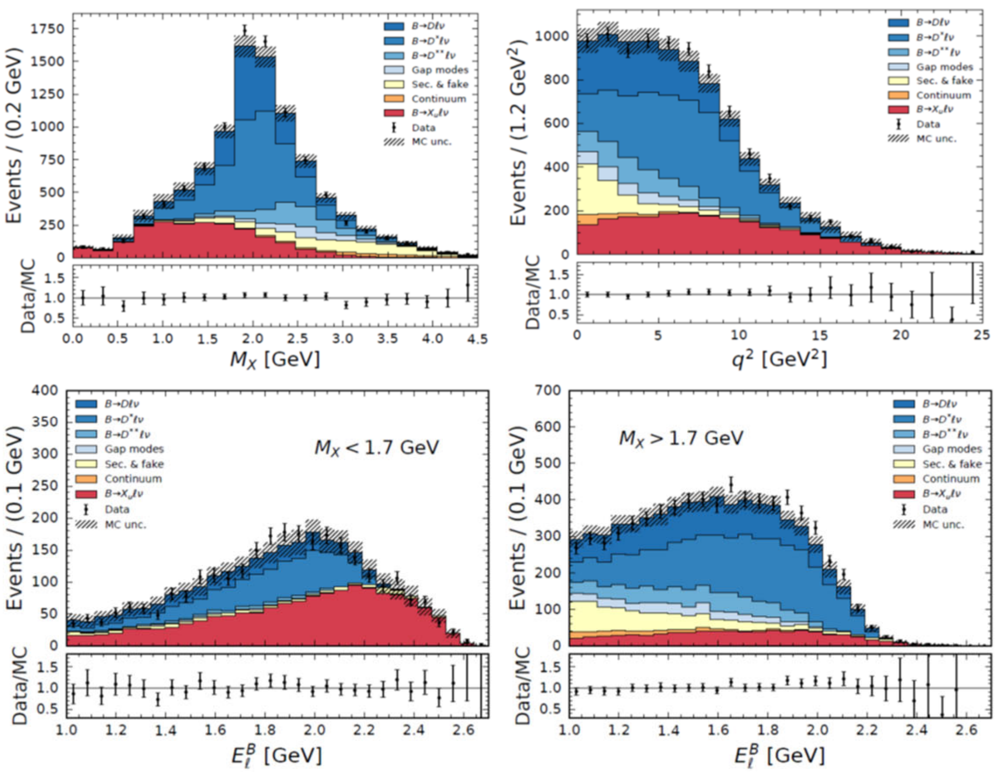


$|V_{ub}|$ from inclusive $B \to X_u l \nu$ with Hadronic Tagging

PRD 104 (2021) 012008

- Full reconstruction of hadronic B_{tag} - NIM A 654, 432-440 (2011)
- Inclusive measurement
- Challenging due to $B \to X_c l \nu$ contamination
- Background supression by a BDT





Measure partial decay rate - extrapolation to full phase space → model dependent

$$|V_{ub}|\ (\mathrm{BLNP}) = \left(4.05 \pm 0.09^{+0.20}_{-0.21}{}^{+0.18}_{-0.20}\right) \times 10^{-3},$$

$$|V_{ub}|\ (\mathrm{DGE}) = \left(4.16 \pm 0.09^{+0.21}_{-0.22}{}^{+0.11}_{-0.12}\right) \times 10^{-3},$$

$$|V_{ub}|\ (\mathrm{GGOU}) = \left(4.15 \pm 0.09^{+0.21}_{-0.22}{}^{+0.08}_{-0.09}\right) \times 10^{-3},$$

$$|V_{ub}|\ (\mathrm{ADFR}) = \left(4.05 \pm 0.09^{+0.20}_{-0.21} \pm 0.18\right) \times 10^{-3}.$$

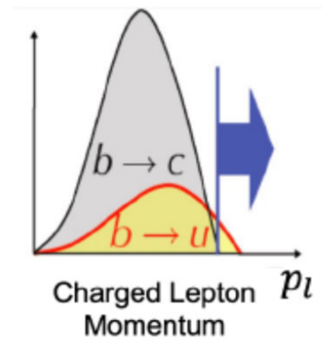
Final result

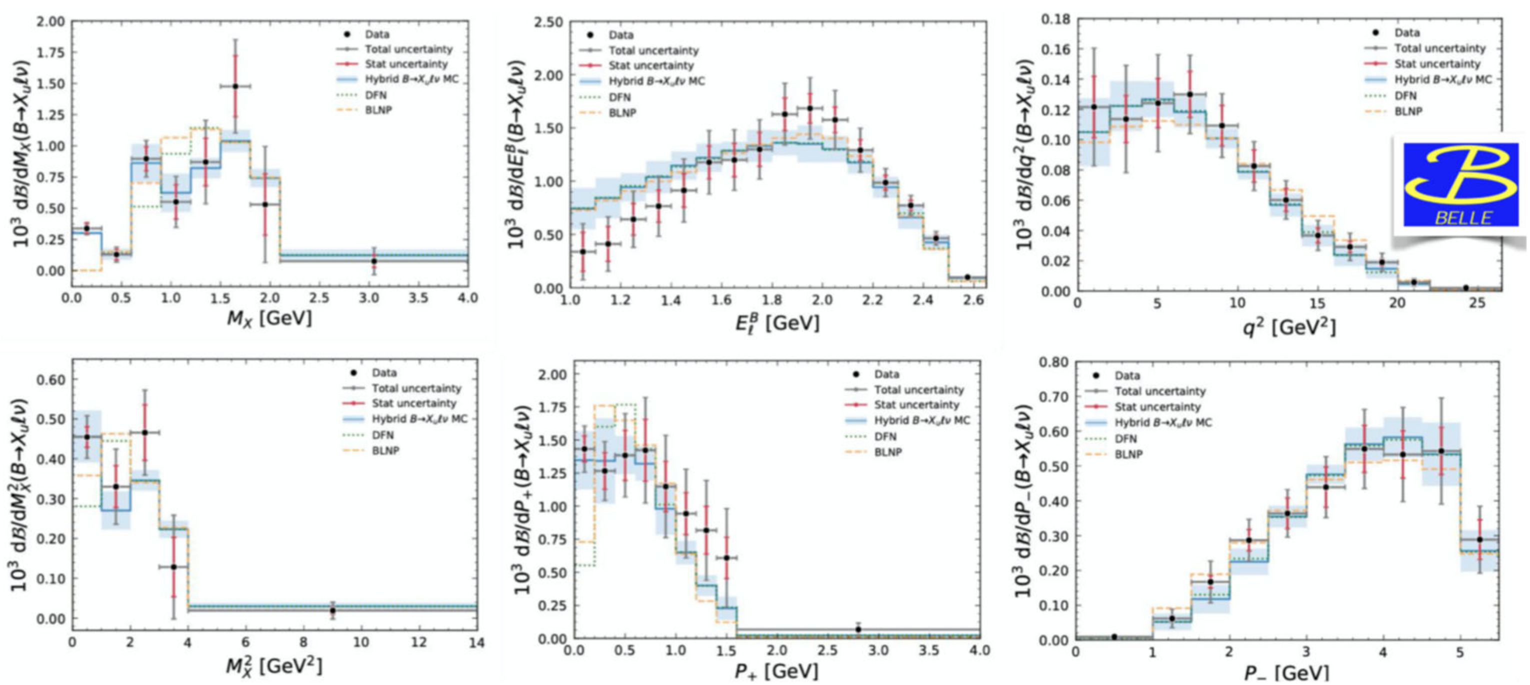
$$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}.$$

$b \to u\, l\, \nu$ - differential decay rate

arXiv:2107.13855

- Challenging due to $B \to X_c\, l\, \nu$ contamination: clear separation through kinematic variables, e.g. lepton momentum endpoint or low M_X
- Full reconstruction of hadronic B_{tag}
- Inclusive measurement: measure the differencial decay rate in 6 kinematic variables q^2, E_l^B, M_X, M_X^2, P_+, P_- (light cone momenta $P_\pm = E_X \pm p_X$)



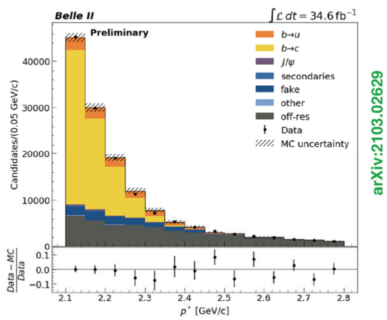


Necessary input for future model-independent determinations of $|V_{ub}|$

Inclusive and exclusive b→(c,u) l ν branching fractions with Belle II

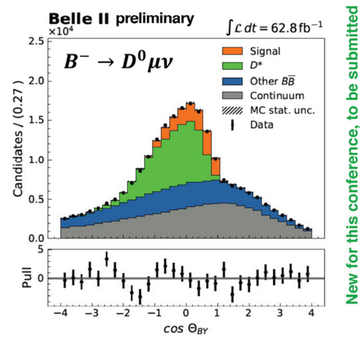
A large variety of different analysis strategies will help to resolve the remaining discrepancies

Untagged inclusive $X_u \ell \nu$



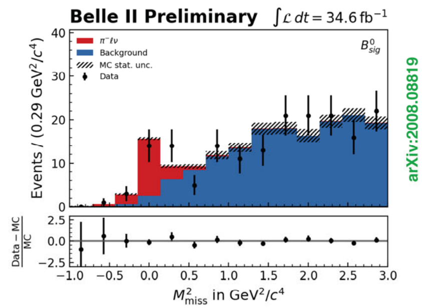
3σ significance for b-u

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



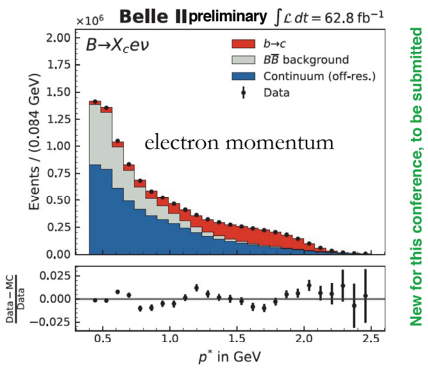
$\mathcal{B}(B^- \to D^0 \ell^- \overline{\nu}_l) = (2.293 \pm 0.053_{\rm stat} \pm 0.084_{\rm syst})\%$

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



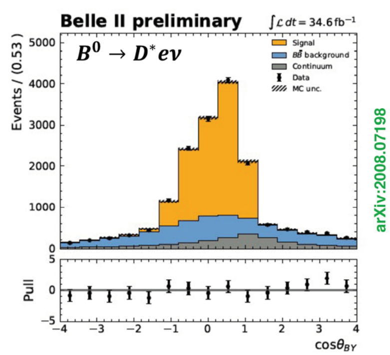
$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell)$ $(1.58 \pm 0.43_{\rm stat} \pm 0.07_{\rm sys}) \times 10^{-4}$

Untagged inclusive $X_c \ell \nu$



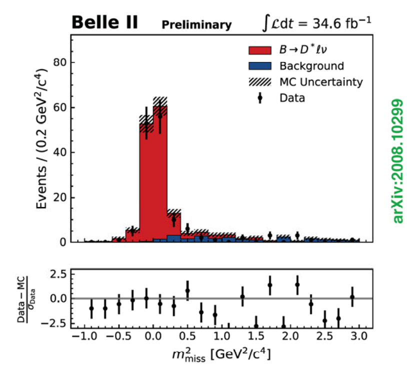
$\mathcal{B}(B \to X_c \ell \nu) = (9.75 \pm 0.03(stat) \pm 0.47(syst))\%$

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



$\mathcal{B}(\overline{B}^0 \to D^{*+} \ell^- \overline{\nu}_l) = (4.60 \pm 0.05_{\rm stat} \pm 0.17_{\rm syst} \pm 0.45_{\pi_s})\%$

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



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

Lepton momentum p* in the CMS

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

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

Alternative approaches, such as the recently proposed use of inclusive q^2-moments, are expected to further enhance sensitivity to V_{cb}

$|V_{ub}|/|V_{cb}|$ with $B_s^0 \to K^- \mu^+ \nu_\mu$ at LHCb

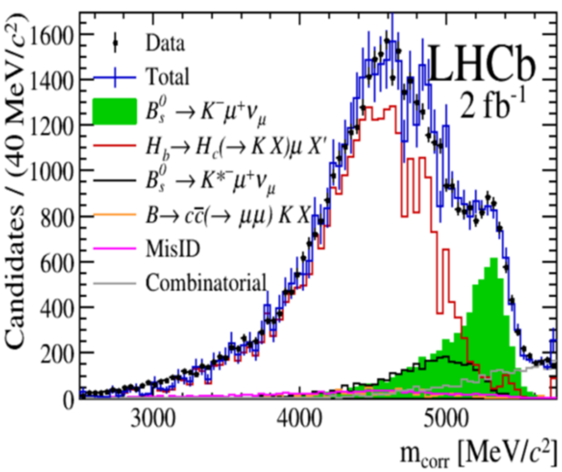
Measure ratio of BRs of $B_s^0 \to K^- \mu^+ \nu_\mu$ and $B_s^0 \to D_s^- \mu^+ \nu_\mu$ decays: PRL 126 (2021) 081804

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\textbf{experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{d\Gamma(B_s^0 \to K^- \mu^+ \nu_\mu)/dq^2}{d\Gamma(B_s^0 \to D_s^- \mu^+ \nu_\mu)/dq^2}}_{\textbf{theory input}}$$

Use LCSR for low q^2 (<7 GeV$^2/c^4$), LQCD for high q^2 (>7 GeV$^2/c^4$).

Data sample: 2 fb^{-1} ; N($B_s^0 \to K^- \mu^+ \nu_\mu$;low q^2) ~ 13k; N($B_s^0 \to D_s^- \mu^+ \nu_\mu$) ~ 200k

$$\begin{aligned}
\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu) &= (1.06 \pm 0.05(\text{stat}) \pm 0.04(\text{syst}) \pm 0.06(\text{ext}) \pm 0.04(\text{FF})) \times 10^{-4} \\
|V_{ub}|/|V_{cb}|(\text{low}) &= 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF}) \\
|V_{ub}|/|V_{cb}|(\text{high}) &= 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(\text{FF})
\end{aligned}$$



- First observation of $B_s^0 \to K^- \mu^+ \nu_\mu$
- Discrepancy between low and high q^2 regions (LCSR for low q^2, LQCD for high q^2).

CP violation studies

- CPV in 2-body B^0 and B_s decays - LHCb
- $K\pi$ puzzle - Belle II

CPV in the $B_s^0 \to K^+K^-$ decay

Time dependent CP asymmetries in $B_s^0 \to K^+K^-$ decay

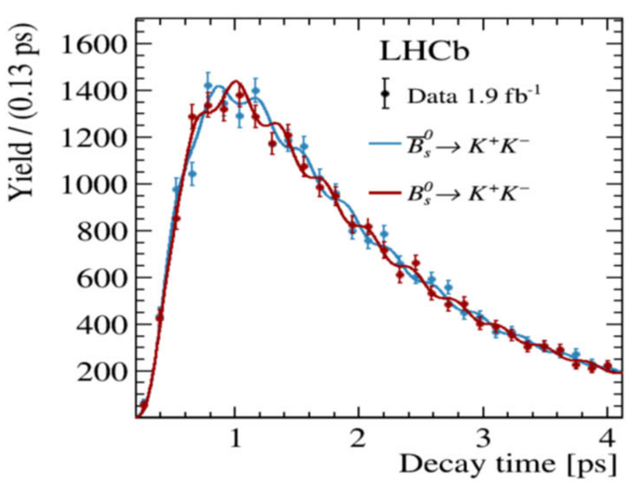
JHEP 03 (2021) 075

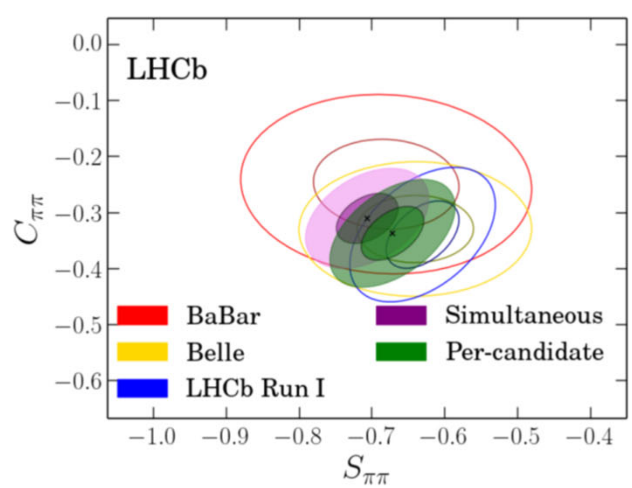
- Requires: Flavour tagging(4.5% – 5.1%) and excellent decay time resolution (~44 fs)
- Data: 1.9 fb^{-1} of Run 2

→ CP violation parameter $S_{KK} = 0.123 \pm 0.034(stat.) \pm 0.015(sys.)$

First observation of time-dependent CP violation in B_s^0 decays

Another way to measure CKM angle α





From a related analysis: direct CP violation parameters in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays:

$$A_{CP}^{B^0 \to K^+\pi^-} = -0.082 \pm 0.003 \pm 0.003, A_{CP}^{B_s^0 \to K^-\pi^+} = +0.236 \pm 0.013 \pm 0.011$$

Expected impact of Belle II on the longstanding Kπ puzzle

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

An Isospin sum rule has been proposed as a sensitive null-test: PLB 627, 82 (2005)

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

- a violation of the sum rule would be evidence for New Physics
- precision on $A_{CP}^{K^0\pi^0}$ is the most limiting input for the test of the sum rule

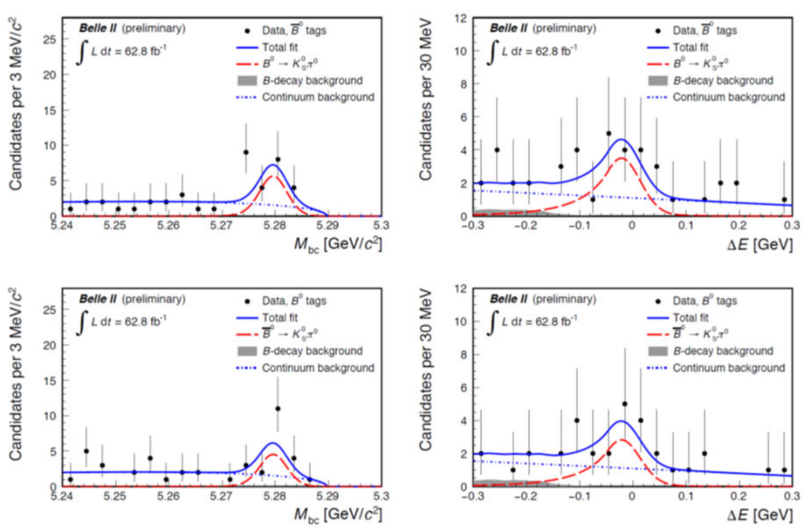
arXiv:2104.14871

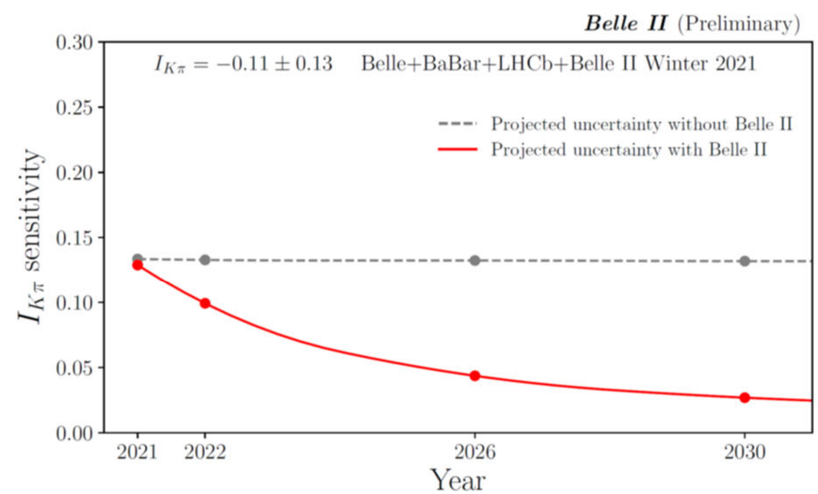
$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst}), \text{ and}$$

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

$\overline{B}^0$ tag

B^0 tag

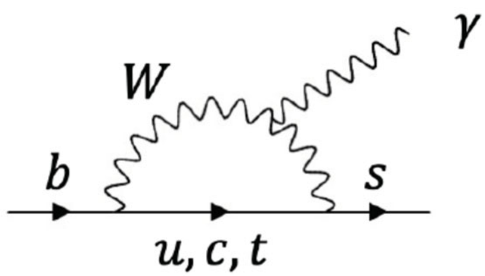


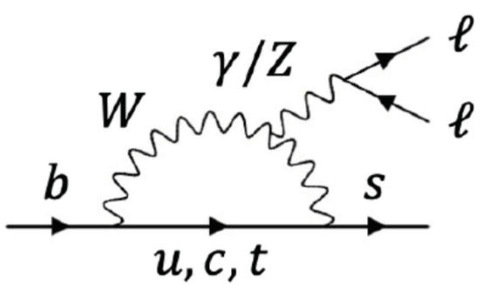


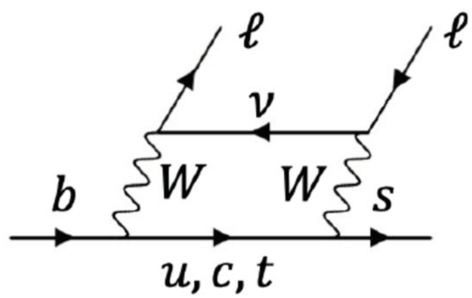
Searches for new physics in rare decays

- $b \to s\gamma$ - Belle II
- $B \to K^{*}\mu^{+}\mu^{-}$ and $B_s^0 \to \phi\mu^{+}\mu^{-}$ differential decay rates – LHCb
- $B^{\pm} \to K^{\pm}\nu\nu$ – Belle II with inclusive tag
- $B_{(s)}^0 \to \mu^{+}\mu^{-}(\gamma)$ - LHCb

New physics could be, e.g., leptoquarks, new particles in loops/boxes, new particles in the final state instead of neutrino pairs

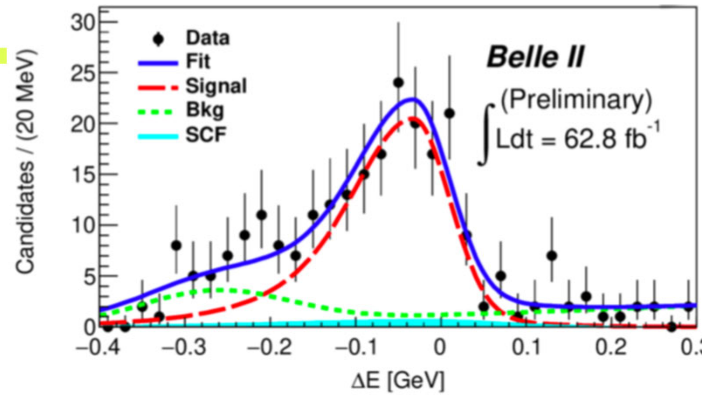






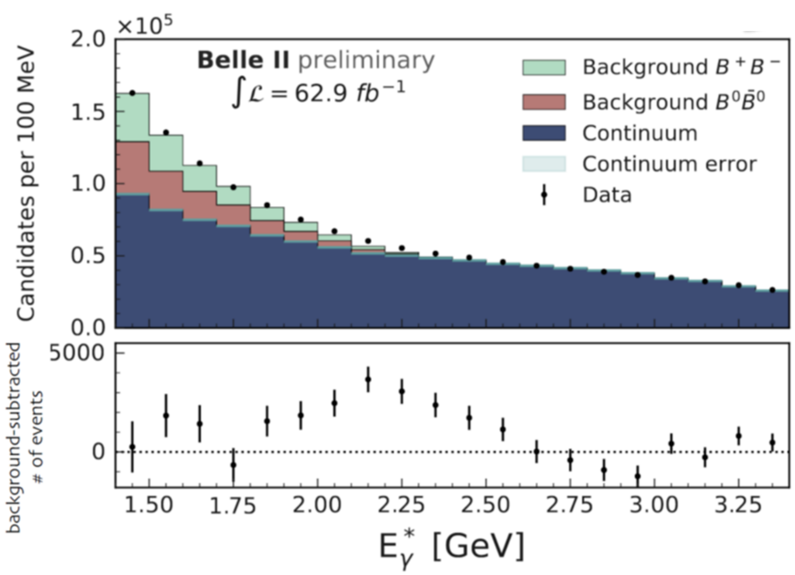
b→sγ: first results at Belle II

- $B \to K^{*}\gamma$ branching fraction measurement, with 63 fb^{-1}
- full reconstruction of the decay chain: charged and neutral K^* + high energy photon
- Measured BR consistent with world average values at 1-2 σ
- CP and isospin asymmetry measurement foreseen in the next iterations of the analysis



(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$

Mode	Br (fit) x10^{-5}
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.5 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})$
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	$4.4 \pm 0.9(\text{stat}) \pm 0.6(\text{syst})$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.0 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$5.4 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})$



- $B \to X_s\gamma$ with untagged method, 63 fb^{-1}
- Reconstruct only high energy γ from signal side
- Extract signal from photon energy spectrum
- Excess visible in the expected signal region

$b \to s \ell^+\ell^-$ branching fractions

Differential branching fractions

– Decay rate of $b \to s \ell^+\ell^-$ sensitive to BSM

– Branching fractions low for muons (B^+, B^0, B_s^0 and Λ_b^0)

$B_s^0 \to \varphi \mu^+ \mu^-$ arXiv:2105.14007

$dB/dq^2 = (2.88 \pm 0.22) \times 10^{-8}/(\mathrm{GeV}^2/c^4)$

for $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$

– In agreement with Run 1 result

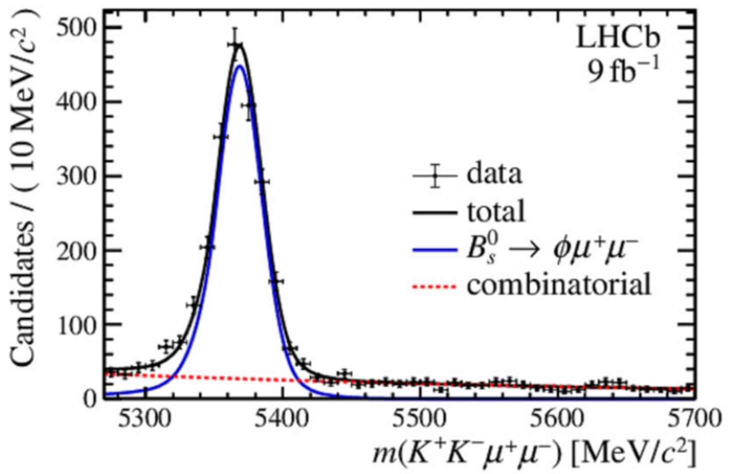
– 3.6σ deviation tension with SM

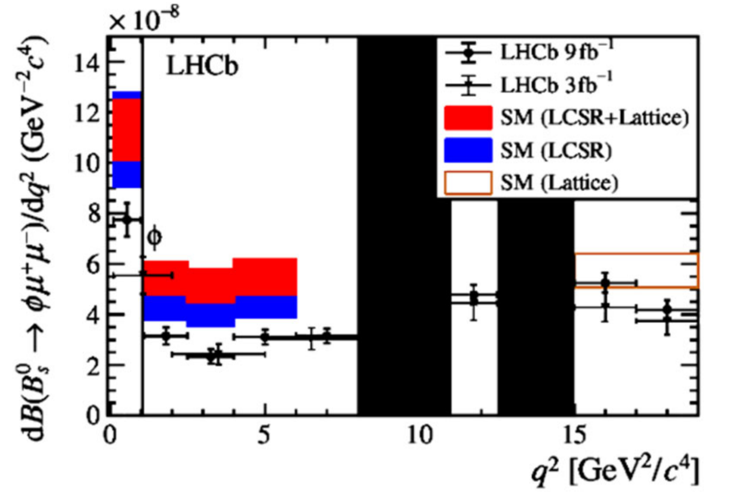
$B_s^0 \to \varphi\mu^+\mu^-$

– Observables F_L, ACPi asymmetries, coefficients Si

– Compatible with SM, tension in F_L

arXiv:2107.13428





b → s ℓ⁺ℓ⁻ angular analysis

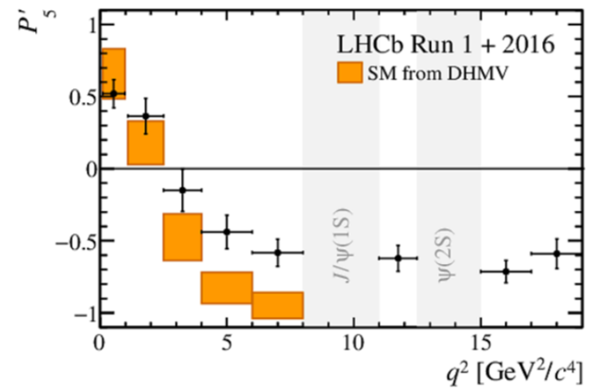
Angular observables: polarisation, asymmetries vs q^2

$B^0 \to K^{*0}\mu^+\mu^-$ PRL 125 (2020) 011802

– Local tension 2.5σ and 2.9σ in asymmetry P_5' with SM in q^2 bins [4,6] and [6,8] GeV^2/c^4

– Global analysis finds a tension of 3.3σ

– Consistent with ATLAS, Belle, CMS results

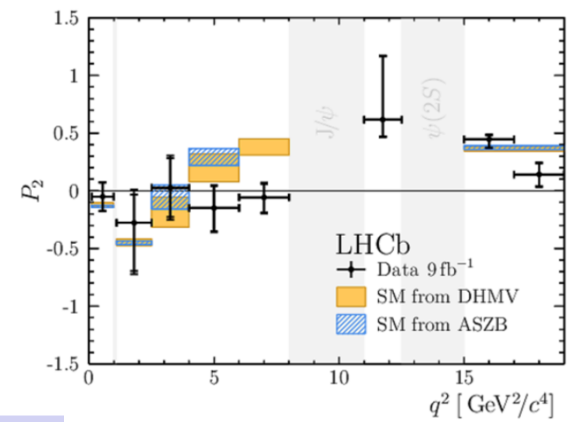


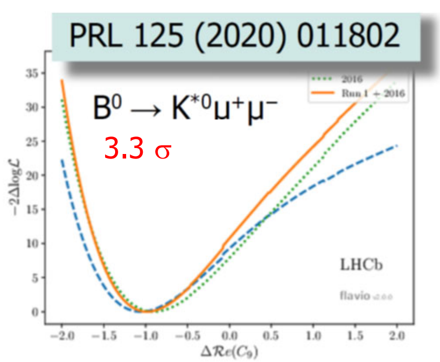
$B^+ \to K^{*+}\mu^+\mu^-$ PRL 126 (2021) 161802

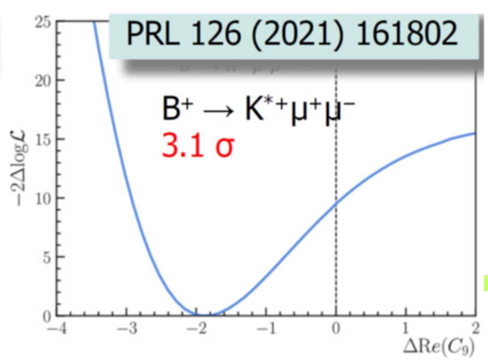
– First LHCb measurement

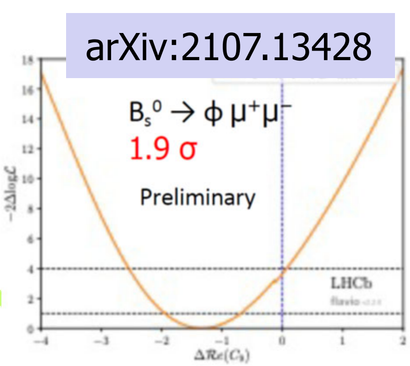
– Local tension with SM up to 3.0σ in $P_2(\sim A_{FB})$ in q^2 bin [6,8] GeV^2/c^4

– Global tension 3.1σ determined in a fit to the effective field theory Wilson coefficient Re(C9)





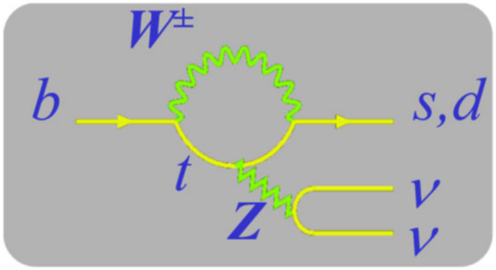


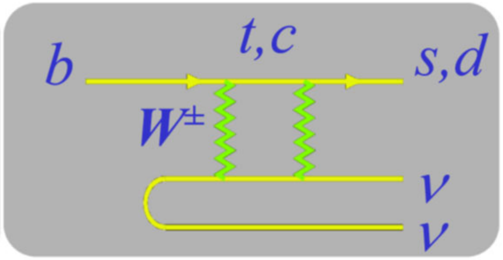


Negative shift of ΔRe(C9) from SM preferred value by a 2 to 3σ level

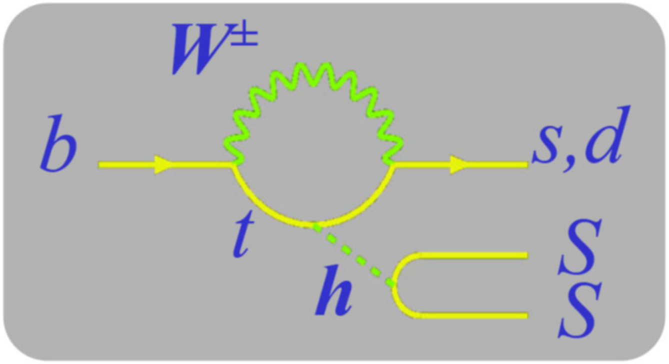
Search for $B^{\pm} \to K^{\pm}\nu\bar{\nu}$

SM: penguin + box diagrams





Look for deviations from the expected values → information on anomalous couplings C^{ν}_{L} and C^{ν}_{R} compared to the SM value $(C^{\nu}_{L})^{SM}$, coming from the loop or from processes like



Flavour-Changing Neutral Current process that has not yetcbeen observed

-no photon contribution/much cleaner theoretical prediction

$\mathcal{B}(B^{\pm} \to K^{\pm}\nu\nu) = (4.6 \pm 0.5) \times 10^{-6}$

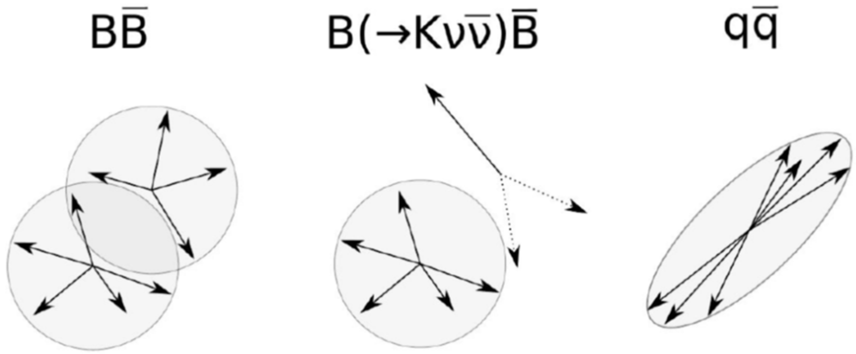
Previous searches based on tagged analyses

-semi-leptonic tag: $\varepsilon_{sig} \sim 0.2\%$ (Belle)

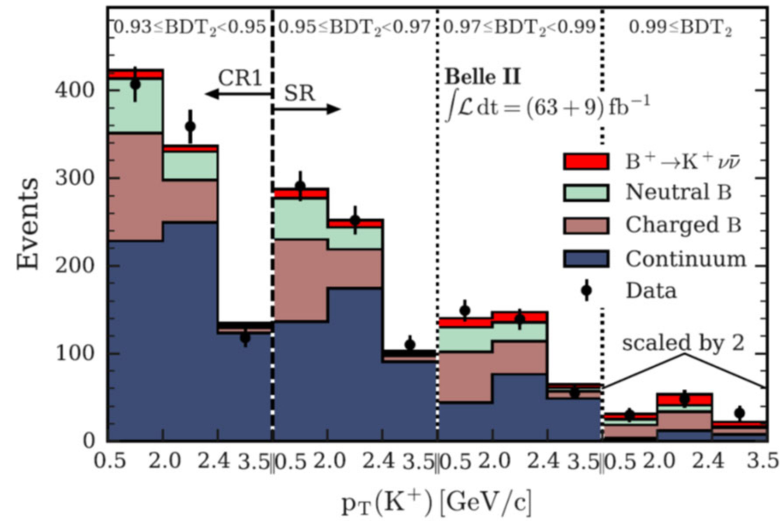
-hadronic tag: $\varepsilon_{sig} \sim 0.04\%$ (BaBar)

New approach by Belle II based on an inclusive tag

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



PRL (accepted) arXiv:2108.03216

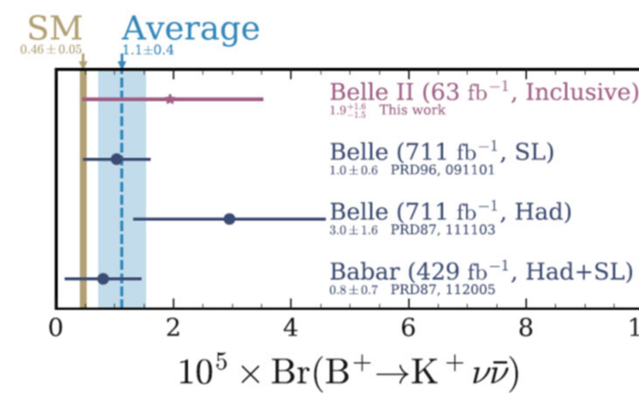


New approach by Belle II based on an inclusive tag

-no explicit reconstruction of the second B-meson

-use BDTs to exploit distinctive topological features of $B^{\pm} \to K^{\pm}\nu\bar{\nu}$

-much higher efficiency of ε_{sig} ~ 4.3% resulting in increased sensitivity per luminosity



Further improvements are underway

- more data (already have 3x more on tape)
- additional channels ($B^0 \to K^{*0}\nu\bar{\nu}$, $B^0 \to K_S^0\nu\bar{\nu}$...)
- improved/extended classifiers (neural networks)

Events of different tagging methods are to a large degree statistically independent and can be combined, details are under study.

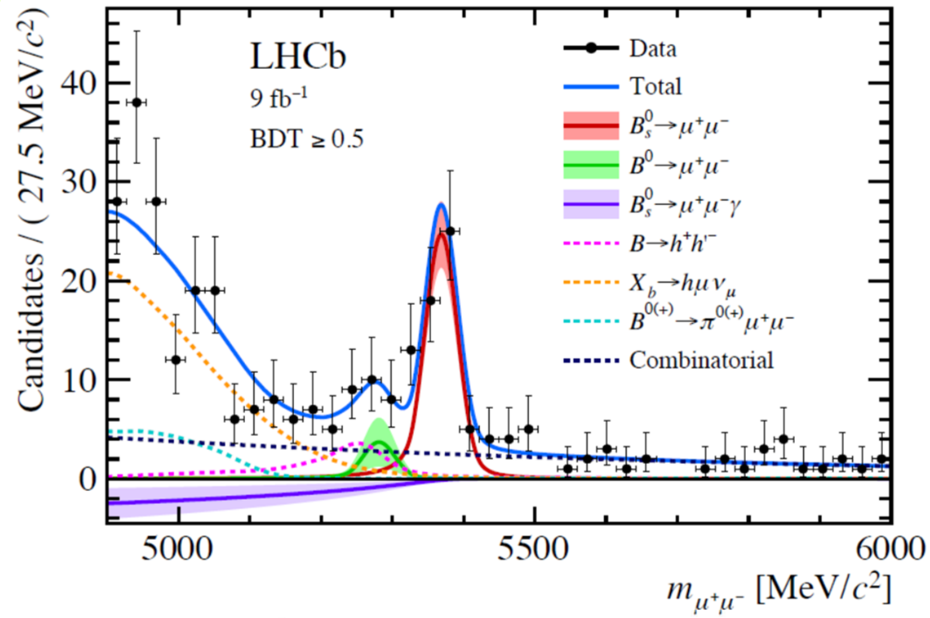
$B_{(s)}^0 \to \mu^+ \mu^- (\gamma)$

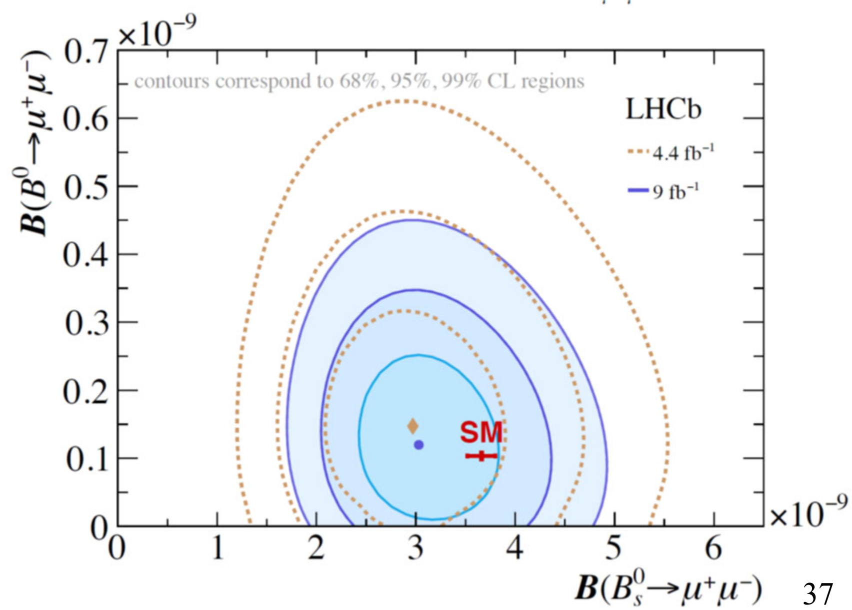
- Very rare leptonic decay
- – Helicity and CKM suppressed
- – Sensitive to New Physics

- $B_s \to \mu^+ \mu^-$
- – $\mathcal{B}(B_s \to \mu^+ \mu^-) = 3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11} \times 10^{-9}$
- – Significance > 10 σ
- – in agreement with SM

- $B^0 \to \mu^+ \mu^-$
- – $\mathcal{B}(B^0 \to \mu^+ \mu^-) < 2.6 \times 10^{-10}$ at 95% CL

- First search for $B_s \to \mu^+ \mu^- \gamma$
- – $\mathcal{B}(B_s \to \mu^+ \mu^- \gamma) < 2.0 \times 10^{-9}$ at 95% CL for $m_{\mu\mu} > 4.9$ GeV/c^2





arXiv:2108.09283
arXiv:2108.09284

QCD dynamics in B decays – important for the interpretation of measurements

- $B \rightarrow X_u\, l\, \nu$ differential cross section (see above) – Belle
- $B^+ \rightarrow D^0\, \pi^+$, $B^0 \rightarrow D^0\, \pi^0$ decays – Belle
- $B^0 \rightarrow D^-\, \pi^+$, $D^-\, K^+$ decays - Belle

$B^0 \to D^- \pi^+$, $D^- K^+$ decays

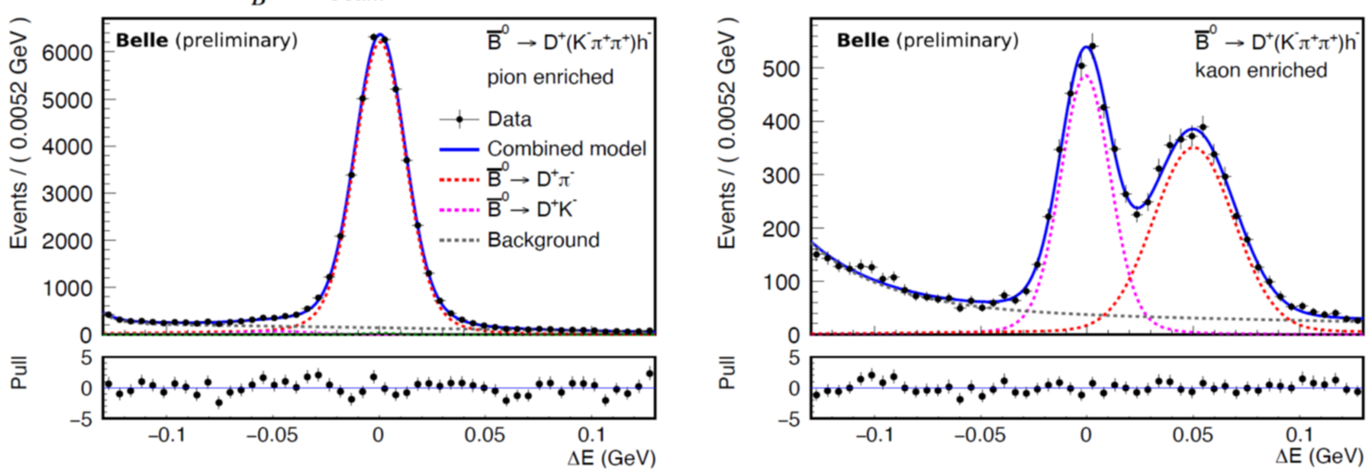
$B^0 \to D^- \pi^+$, $D^- K^+$ decays: both modes are important as signal or control channels for measurements of angle ϕ_3 / γ.

Significant background from $B^0 \to D^- \pi^+$ in $D^- K^+$ decays due to the misidentification of pion as a kaon.

A **simultaneous fit** is performed to samples enhanced in prompt tracks that are either **pions** [$\mathcal{L}(K/\pi) < 0.6$] or **kaons** [$\mathcal{L}(K/\pi) > 0.6$].

Cross-feed from both decay modes is also determined from the simultaneous fit. The corresponding pion→kaon misidentification probability which is also determined in the fit, is found to be consistent with the standard Belle value from an independent study.

$$\Delta E = E_B^* - E_{beam}$$



https://arxiv.org/abs/2104.03628

$B^0 \to D^- \pi^+$, $D^- K^+$ decays

- The ratio of $B^0 \to D^-K^+$ and $B^0 \to D^-\pi^+$ branching fraction

$$R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+K^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} = (8.20 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})) \times 10^{-2}$$

LHCb: J. High Energ. Phys. 2013, 1 (2013)
Ratio = $8.22 \pm 0.11(\text{stat}) \pm 0.25(\text{syst})$

- Measurement of branching fraction for $B^0 \to D^-\pi^+$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = \frac{N^{\text{total}}_{D\pi}}{2 \times f_{00} \times N_{B\bar{B}} \times \epsilon_{D\pi} \times \mathcal{B}(D^- \to K^+\pi^-\pi^-)}$$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = [2.50 \pm 0.01_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.04_{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-3}$$

BaBar: Phys.Rev.D 75 (2007) 031101
$\mathcal{B}[B^0 \to D^-\pi^+] = [2.55 \pm 0.05_{\text{stat}} \pm 0.16_{\text{syst}}] \times 10^{-3}$

CLEO2: Phys.Rev.D 66 (2002) 031101
$\mathcal{B}[B^0 \to D^-\pi^+] = [2.68 \pm 0.12_{\text{stat}} \pm 0.24_{\text{syst}}] \times 10^{-3}$

- Measurement of branching fraction for $B^0 \to D^-K^+$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = \mathcal{B}(B^0 \to D^-\pi^+) \times R^D$$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = [2.05 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.04_{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-4}$$

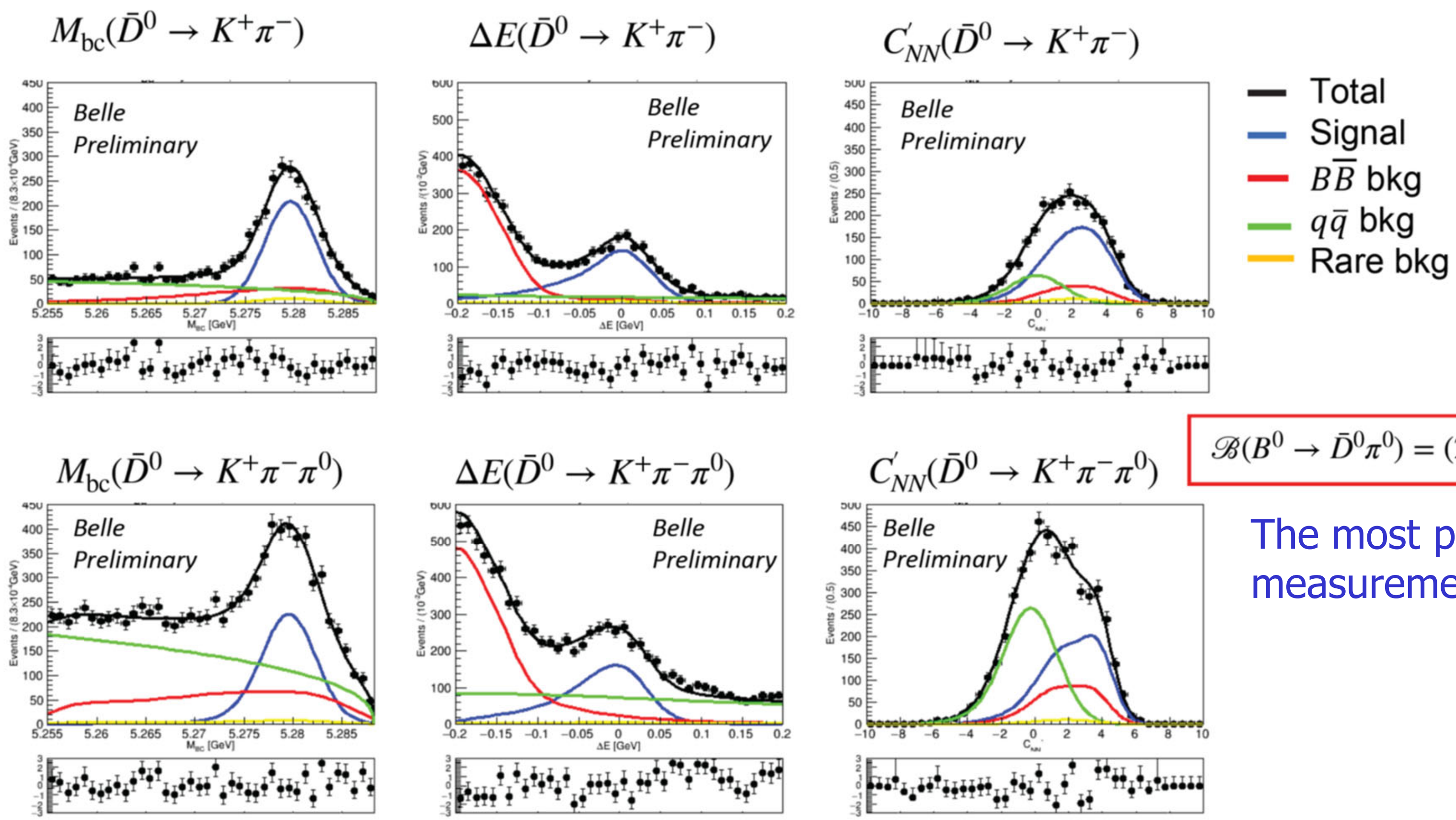
LHCb: Phys.Rev.Lett. 107 (2011) 211801
$\mathcal{B}[B^0 \to D^-K^+] = [1.89 \pm 0.19_{\text{stat}} \pm 0.10_{\text{syst}}] \times 10^{-4}$

Belle: Phys.Rev.Lett. 87 (2001) 111801
$\mathcal{B}[B^0 \to D^-K^+] = [1.7 \pm 0.4_{\text{stat}} \pm 0.1_{\text{syst}}] \times 10^{-4}$

https://arxiv.org/abs/2104.03628

$B^0 \to D^0 \pi^+$, $D^0 \pi^0$ decays

Preliminary



$D^0 \pi^0$

$$\mathcal{B}(B^0 \to \bar{D}^0\pi^0) = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}$$

The most precise measurement in this channel

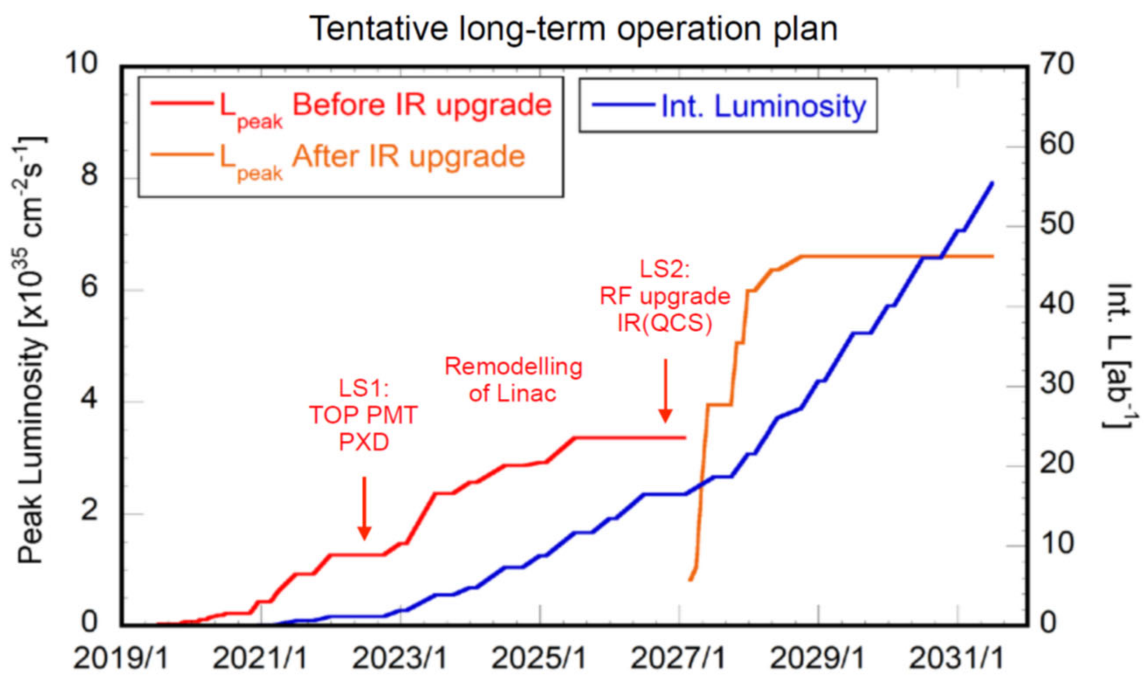
$$\mathcal{B}(B^+ \to \bar{D}^0\pi^+) = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$

$D^0 \pi^+$

The most precise measurement in this channel

Outlook

Outlook: Belle II



Ultimate goal: reach 50/ab by operating at the design luminosity of 6 x 10^{35} cm^{-2} s^{-1}

Current working plan follows the KEK Roadmap2020

- LS1 in 2022 for pixel vertex detector (PXD) & partial replacement of MCP-PMT in TOP
- options for a possible IR upgrade (LS2) ≳2026 under study

Outlook: LHCb

Upgrade I: Major project being installed currently for operation in Run 3

- All sub-detectors read out at 40 MHz for a fully software trigger with the new data centre
- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

Upgrade II

- Fully exploit LHC facility for flavour physics & beyond, for LS4
  - Expression of interest (2017), Physics Case (2018)
  - Strong support in European Strategy (2020)
- Framework Technical Design Report
  - Options to achieve physics programme
  - Drafting in progress, for delivery later this year

Summary

- Physics of B mesons has contributed substantially to our present understanding of elementary particles and their interactions
- B decays have been and continue being a very hot topic in searches for new physics. Intriguing phenomena that have been seen in recent years make this research area one of the most interesting in particle physics.
- LHCb is finalizing its Upgrade I, and Belle II has entered the super-B-factory regime.
- Expect a new, exciting era of discoveries, and a friendly competition and complementarity of LHCb and Belle II, as well ATLAS and CMS