



Physics in Collision

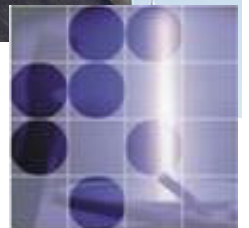
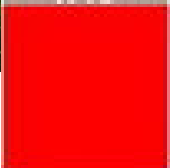
40th International Symposium on Physics in Collision
RWTH Aachen University, Aachen, Germany | September 14-17, 2021

B Physics

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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

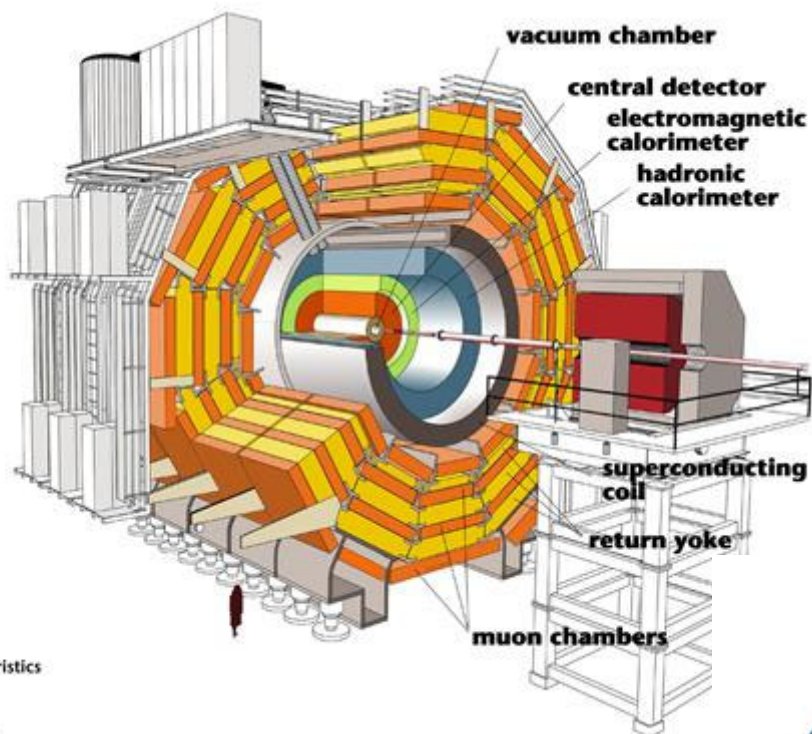
Motivation

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.

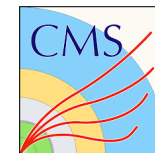
Intriguing phenomena that have been seen in the recent years make this research area one of the most interesting in particle physics.

Facilities: ATLAS, CMS

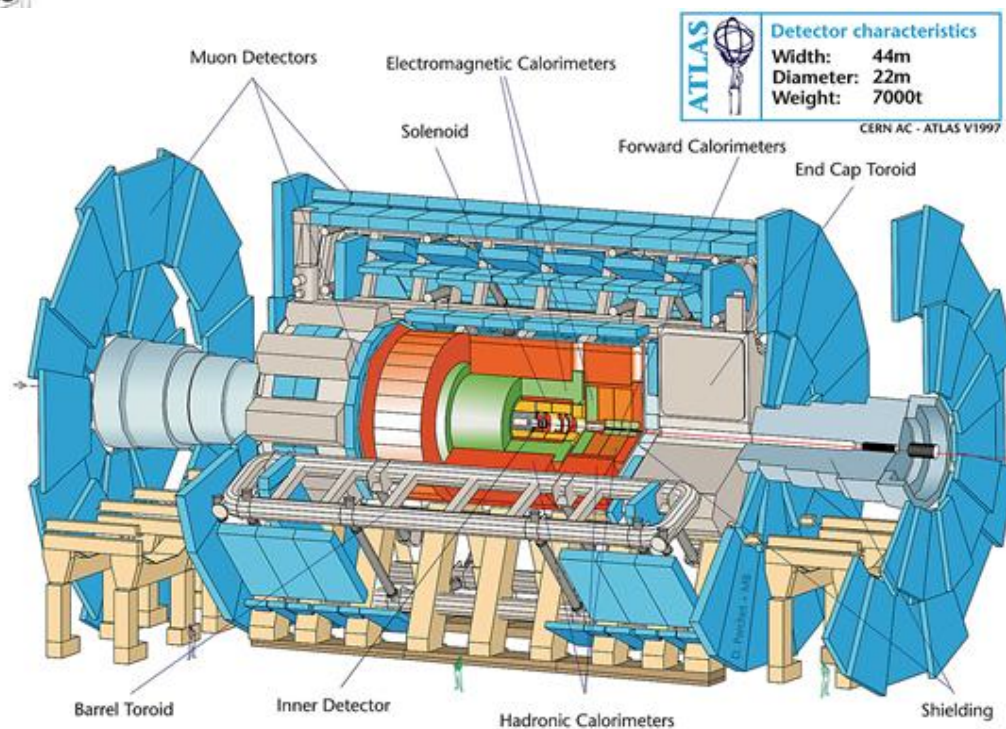


Detector characteristics

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



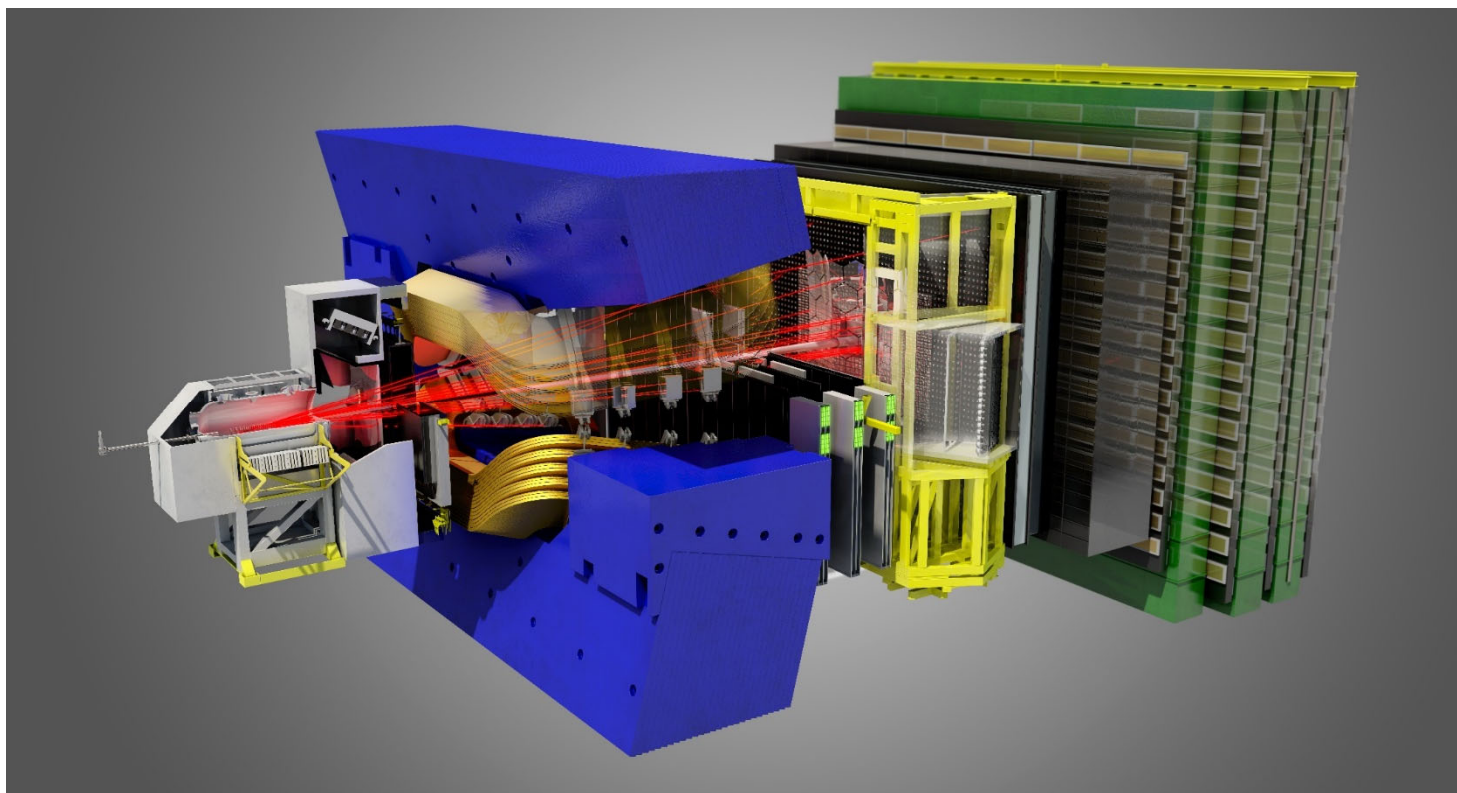
General purpose detectors at LHC with features relevant to flavour physics: excellent vertexing, tracking, muon and electron identification, dedicated triggers



Detector characteristics	
Width:	44m
Diameter:	22m
Weight:	7000t

CERN AC - ATLAS V1997

Facilities: LHCb @ LHC



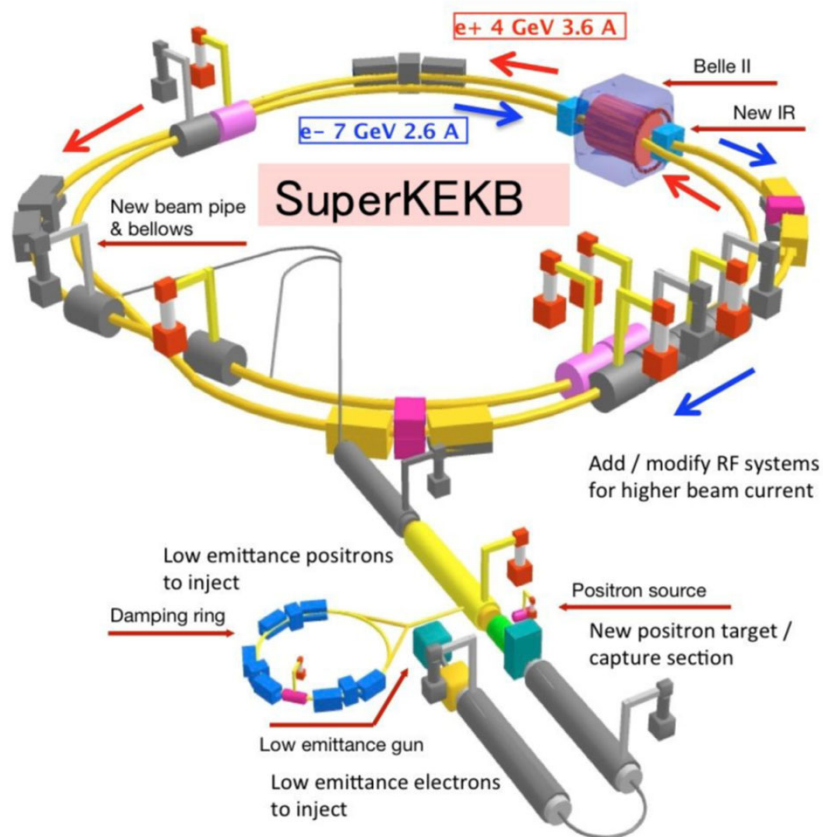
pp collisions in forward region: huge production rates of b hadrons.
 Large boost + excellent vtx resolution: background rejection and decay-length resolution.
 Excellent momentum and mass resolution.
 Outstanding PID ($K-\pi$) and μ reconstruction.
 Dedicated trigger system for beauty and charmed hadrons.

Facilities: Belle II @ SuperKEKB

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

beam current $\times 1.5$ beam-beam param. $\times 1$

vertical beta function $\times 1/20$



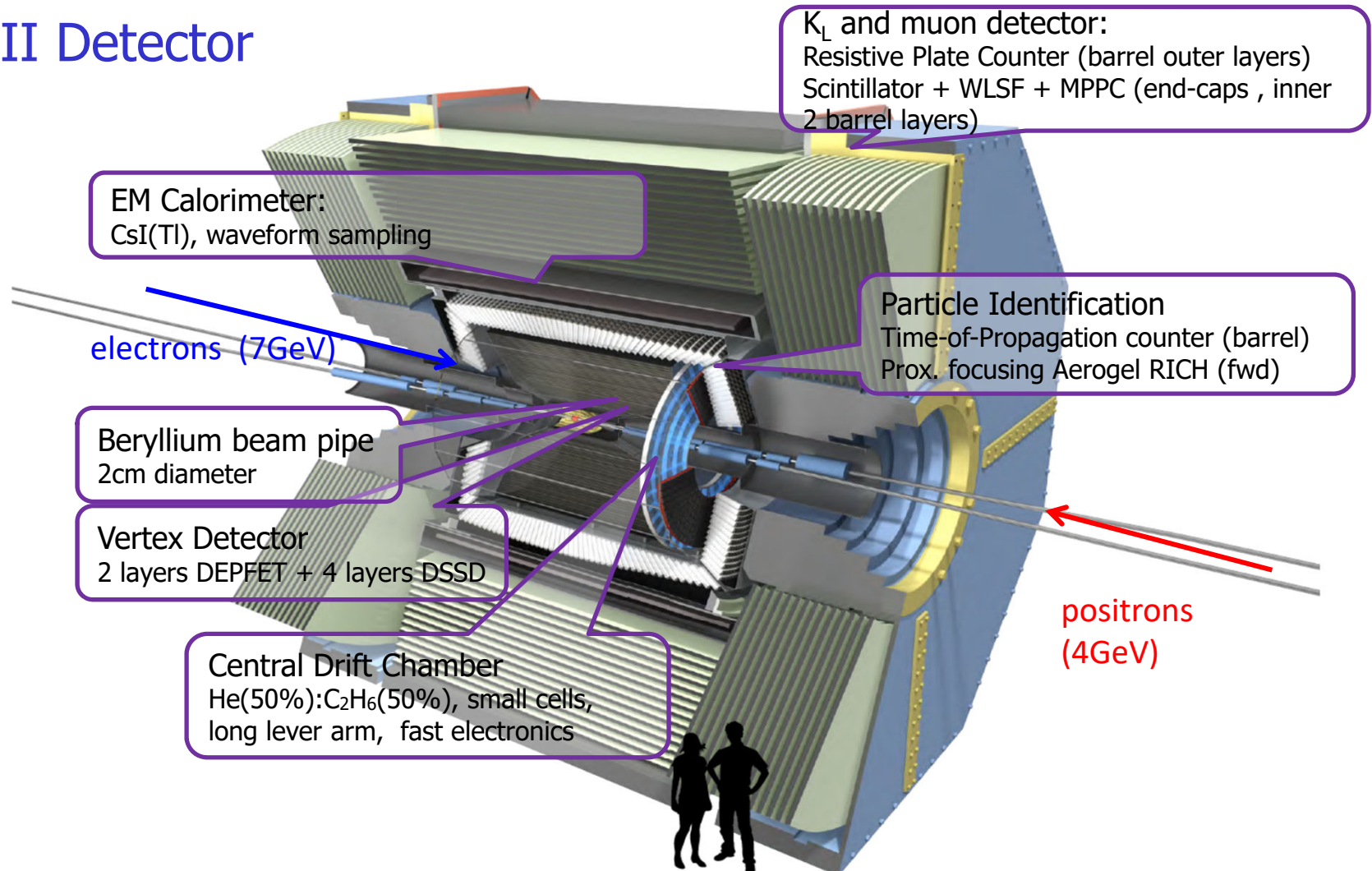
Idea: to increase the luminosity of KEKB by a factor of 30, employ **Nano-Beam scheme** (P. Raimondi): squeeze beta function at the IP (β_x^*, β_y^*) and minimize longitudinal size of overlap region

- 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

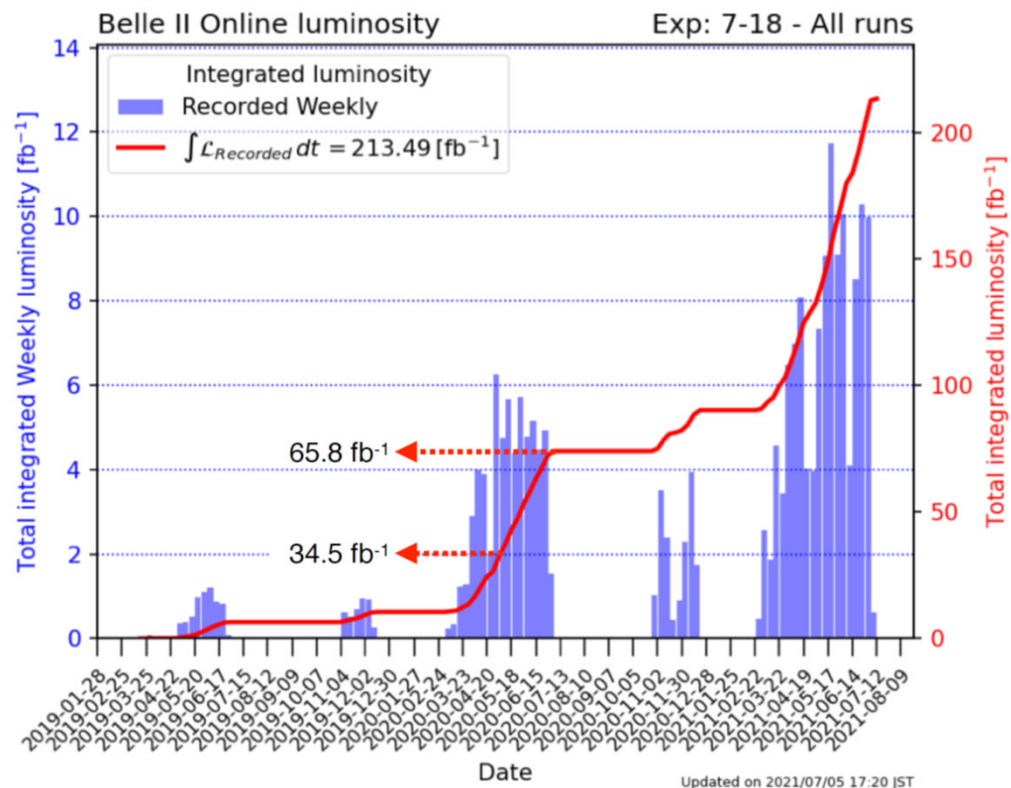


Belle II Detector



- Exactly two B mesons produced (at $\Upsilon(4S)$)
- Hermetic detector
- High flavour tagging efficiency ($\sim 30\%$)
- Detection of gammas, π^0 s, K_L s
- 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 $3.12 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, collected up to 12 fb^{-1} per week: Super-B factory mode

This talk: results with $\sim 70 \text{ fb}^{-1}$, on tape 213 fb^{-1}

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

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CKM studies

CPV studies

Searches for new physics in rare decays

QCD dynamics in B decays

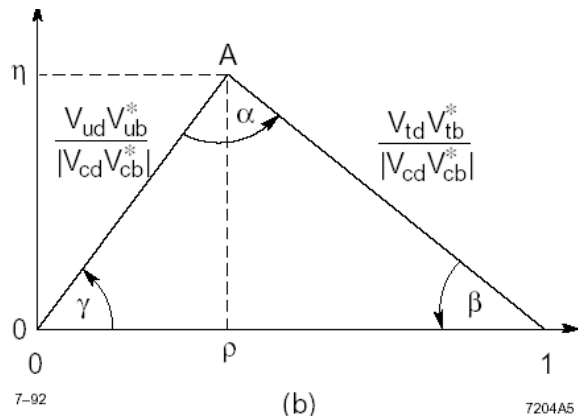
Outlook

CKM studies

Cabibbo-Kobayashi-Maskawa (CKM) quark transition matrix

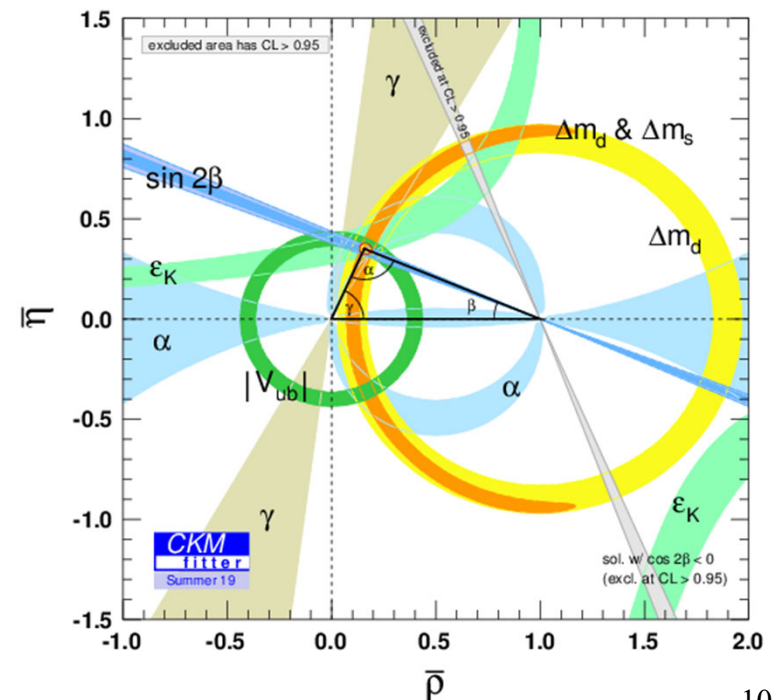
Unitarity triangle: geometrical interpretation of the unitarity of the matrix

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



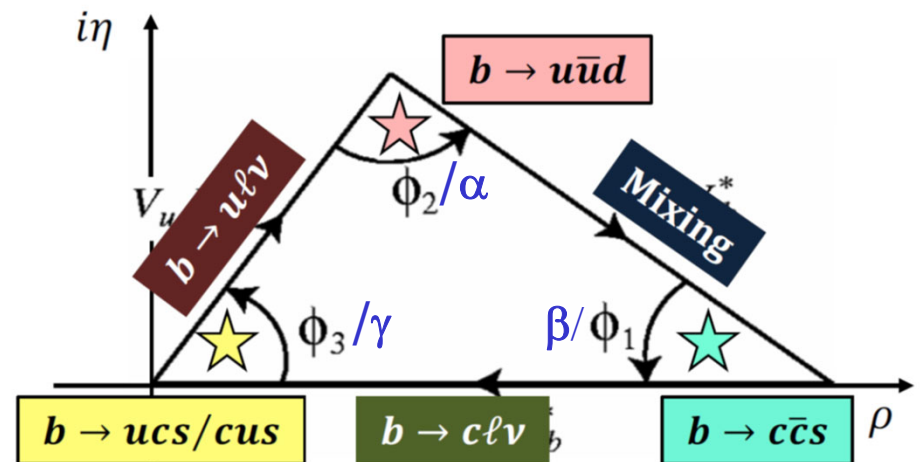
Constraints from measurements of angles and sides of the unitarity triangle \rightarrow Remarkable agreement, but still $\sim 10\%$ NP allowed

Also: searches for NP in comparisons 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



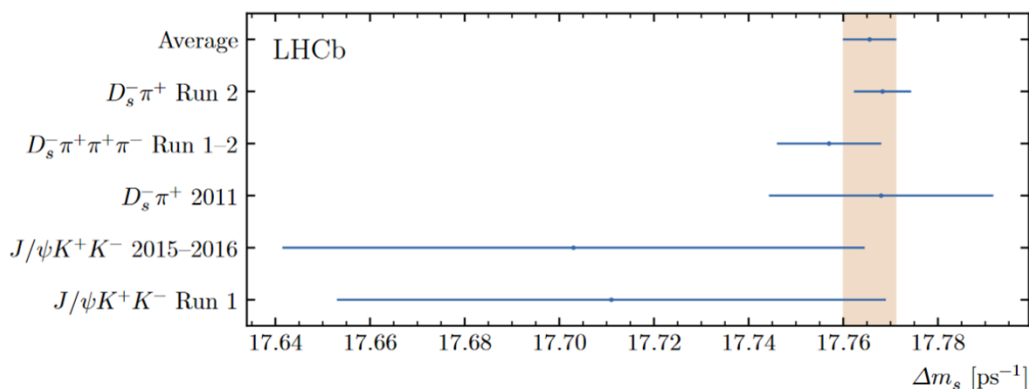
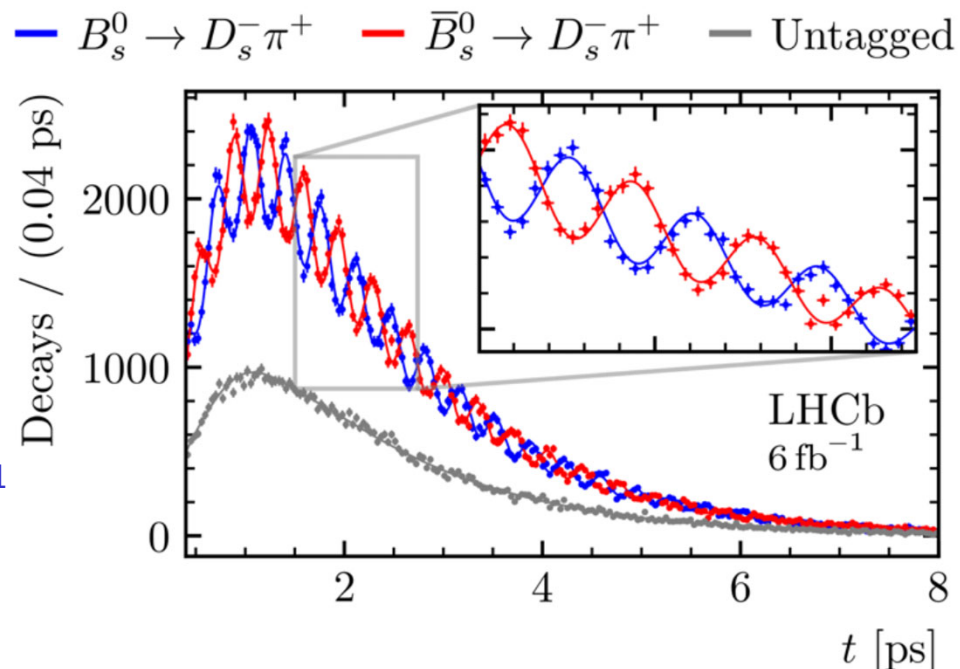
B_s mixing

B_s⁰ mass difference Δm_s

- Measured by oscillation frequency with B_s⁰ → D[∓]π[±] decays
- Flavour tagging identifies B_s⁰ / anti B_s⁰ at production

Data sample 6 fb⁻¹

- $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \text{ ps}^{-1}$
- Precision 3×10^{-4}
- Including B_s⁰ → D[∓]h[±]π[±]π[∓] decays et al.
- $\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}$



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



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

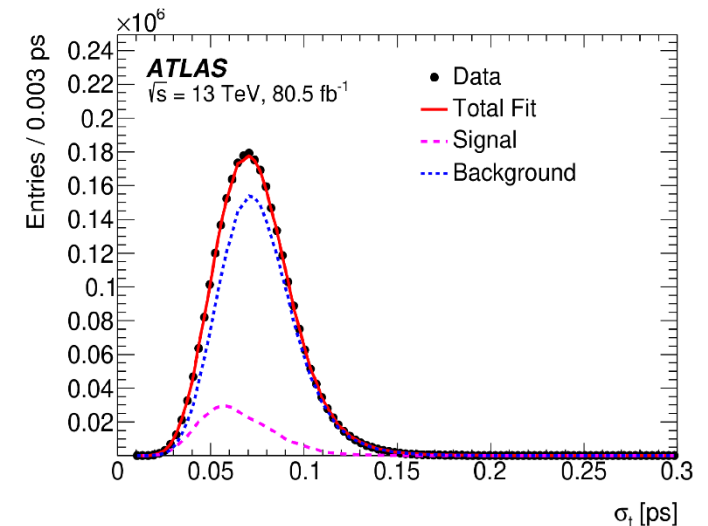
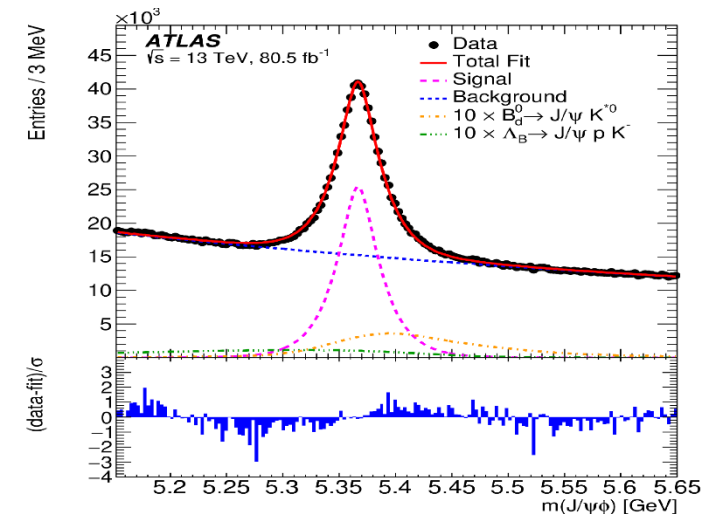
ϕ_s is the parameter of CP violation in $B_s^0 \rightarrow J/\psi \phi$ decays.

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

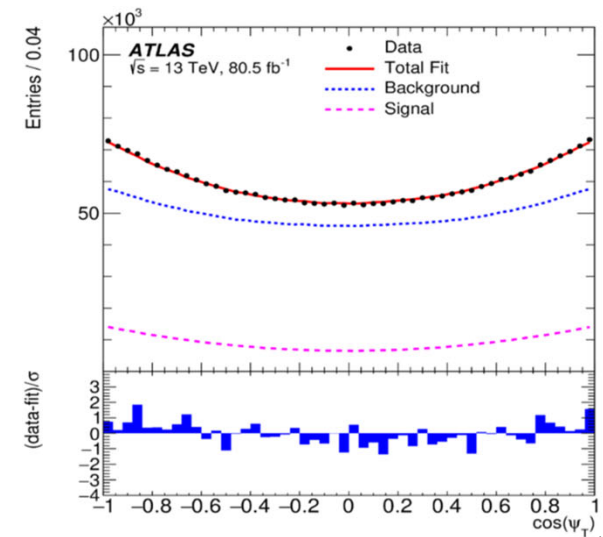
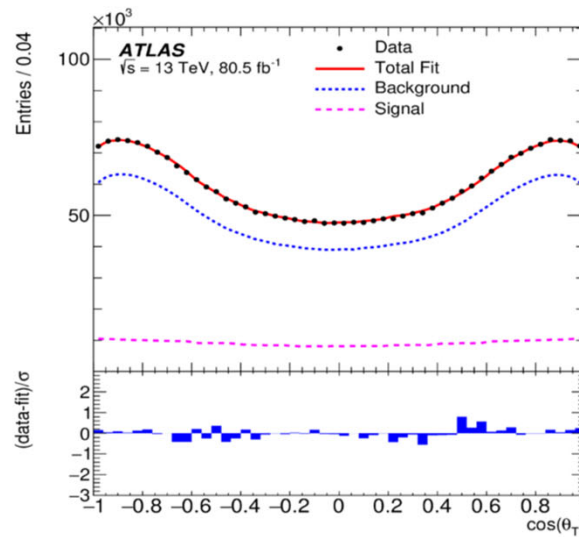
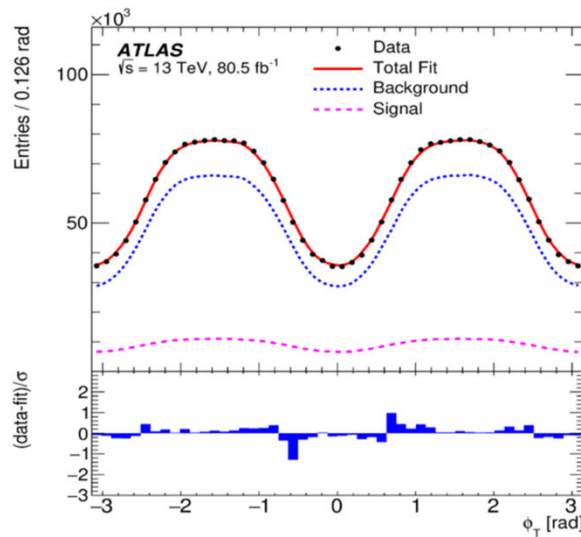
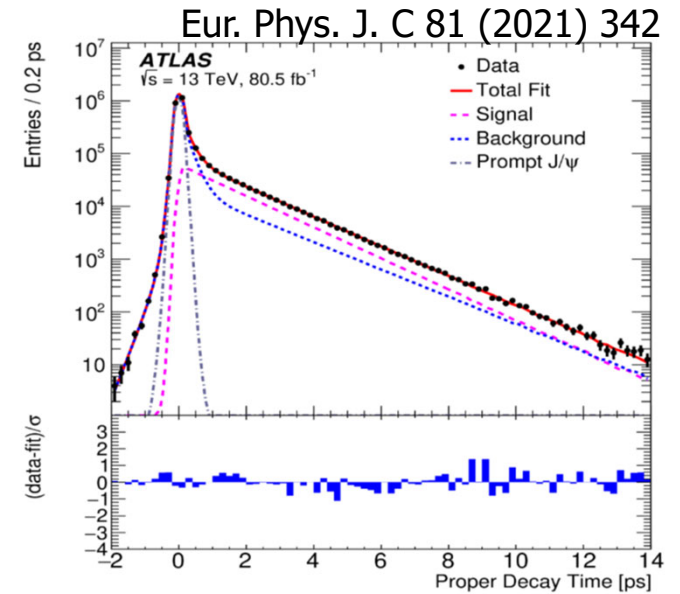


ϕ_s with $B_s^0 \rightarrow J/\psi \phi$ decays

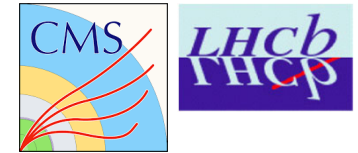
Unbinned max. likelihood fit (3 angles, decay time, mass, mistag probability and decay time error) to extract ϕ_s

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

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



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



CMS

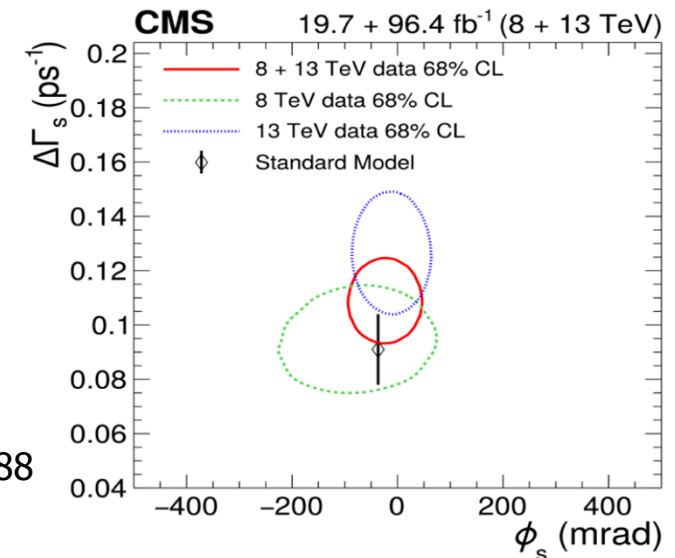
Similar analysis, on 96.4 fb^{-1}

- $\phi_s = -0.011 \pm 0.050(\text{stat.}) \pm 0.010(\text{sys.})$
- Systematic dominated by angular efficiency and model bias

- Combined with Run 1

$$\phi_s = -0.021 \pm 0.045, \Delta\Gamma = 0.1032 \pm 0.0106 \text{ ps}^{-1}$$

Phys. Lett. B 816 (2021) 136188



LHCb

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

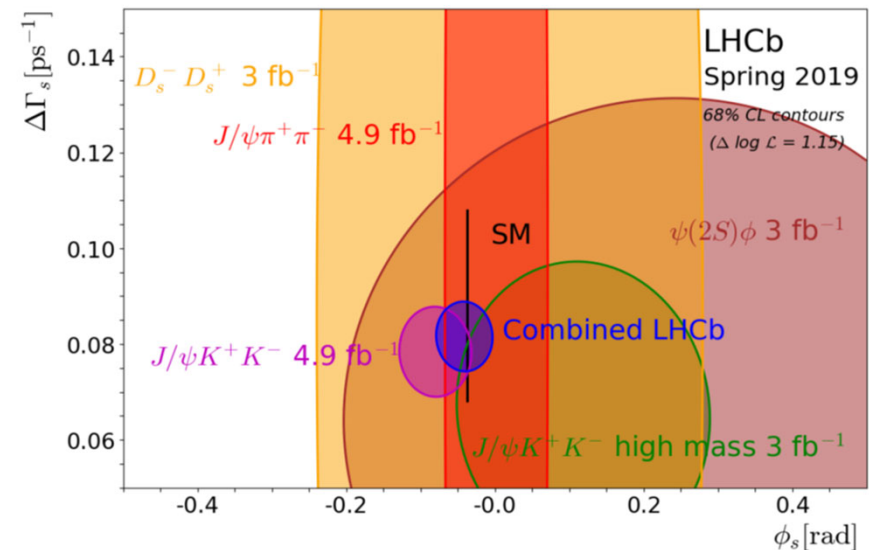
- $\phi_s = -0.083 \pm 0.041(\text{stat.}) \pm 0.006(\text{sys.})$

- Combined with Run 1

$$\phi_s = -0.080 \pm 0.032, \Delta\Gamma = 0.1032 \pm 0.0048 \text{ ps}^{-1}$$

Combined with all other measurements by LHCb

$$\phi_s = -0.041 \pm 0.025, \Delta\Gamma = 0.0813 \pm 0.0106 \text{ ps}^{-1}$$



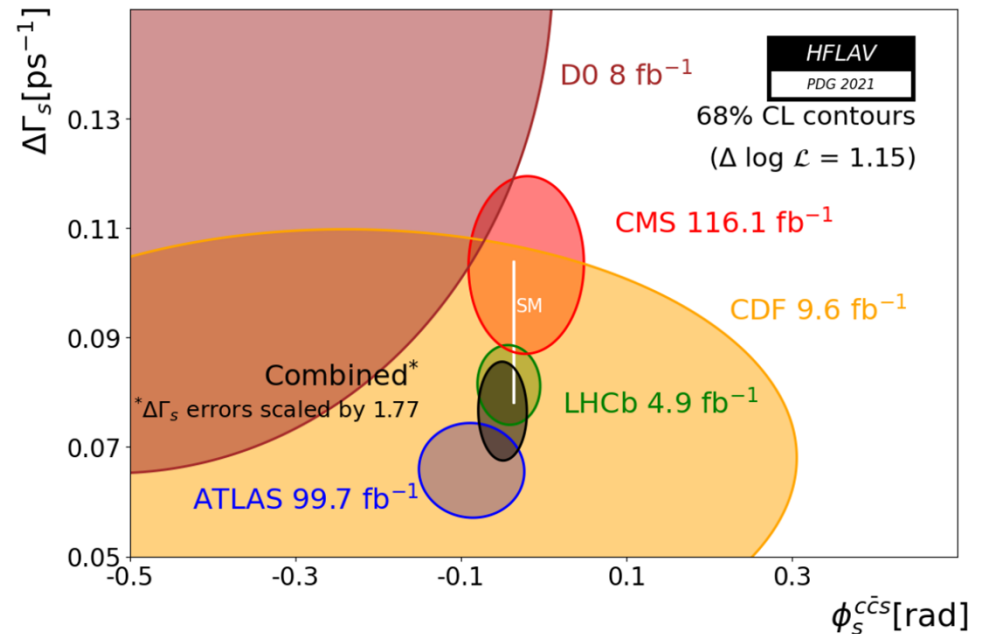
Eur. Phys. J. C 79 (2019) 706, Eur. Phys. J. C 80 (2020) 601

Peter Križan, Ljubljana

ϕ_s world average - HFLAV

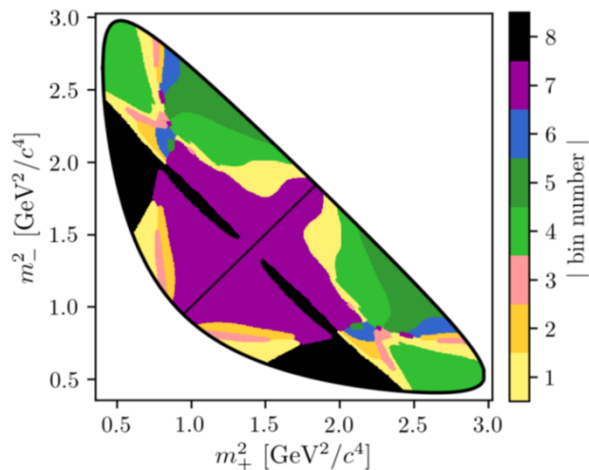
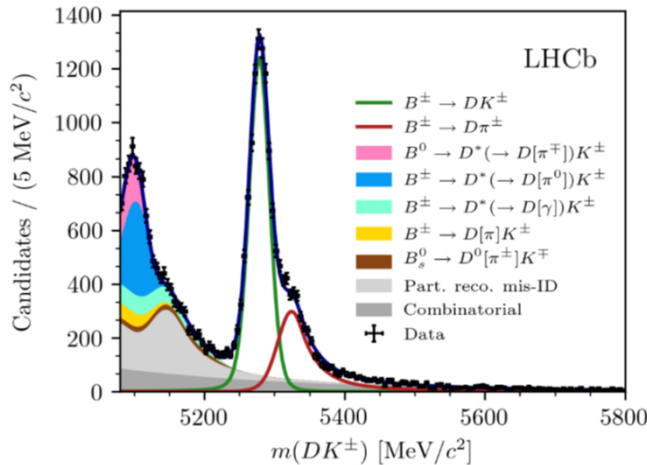
World average HFLAV

$$\phi_s = -0.041 \pm 0.025 \text{ rad},$$
$$\Delta\Gamma_s = 0.082 \pm 0.005 \text{ ps}^{-1}$$



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

CKM angle γ from time integrated measurements



arXiv:2010.08483
JHEP 02 (2021) 169

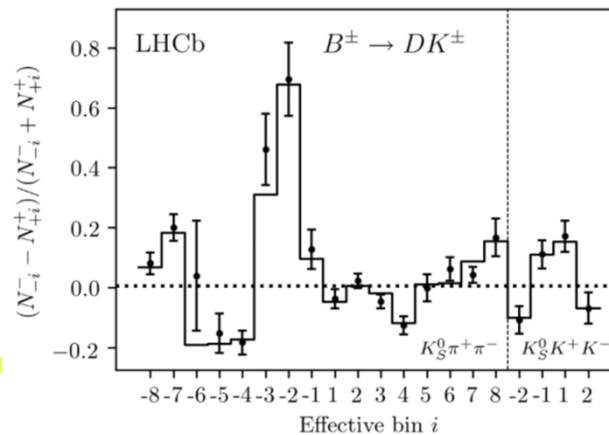
From interference between two amplitudes leading to the same final state

$$B^- \rightarrow D^0(\rightarrow K_S^0 h^+ h^-) K^- \propto V_{cb}$$

$$B^- \rightarrow \bar{D}^0(\rightarrow K_S^0 h^+ h^-) K^- \propto V_{ub}$$

$$m_{\pm}^2 = m(K_S^0, h^{\pm})$$

- 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

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ,$$

$$r_B^{DK^\pm} = 0.0904^{+0.0077}_{-0.0075},$$

$$\delta_B^{DK^\pm} = (118.3^{+5.5}_{-5.6})^\circ,$$

$$r_B^{D\pi^\pm} = 0.0050 \pm 0.0017,$$

$$\delta_B^{D\pi^\pm} = (291^{+24}_{-26})^\circ.$$

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



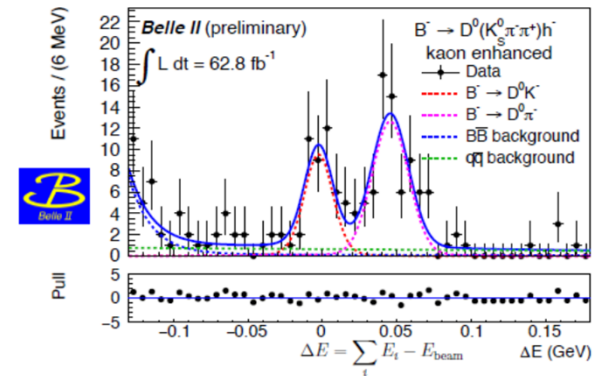
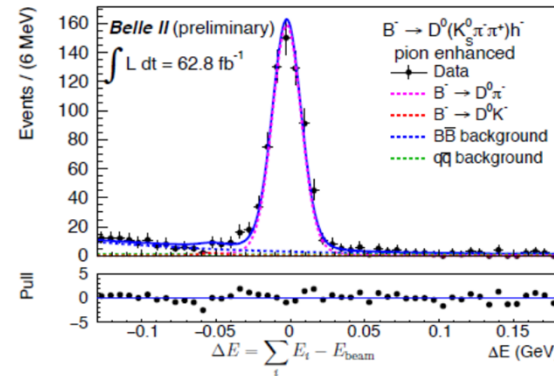
<https://arxiv.org/abs/2104.03628>

$B^- \rightarrow D^{(*)0} \pi^-$ 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: $B^- \rightarrow D^{(*)}(K_S^0 \pi^+ \pi^-) K^-$

Many systematic uncertainties cancel in the ratio of decay rates



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

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

	$B^- \rightarrow D^0(K^- \pi^+) h^-$	$B^- \rightarrow D^0(K_S^0 \pi^+ \pi^-) h^-$	$\bar{B}^0 \rightarrow D^+ h^-$
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]

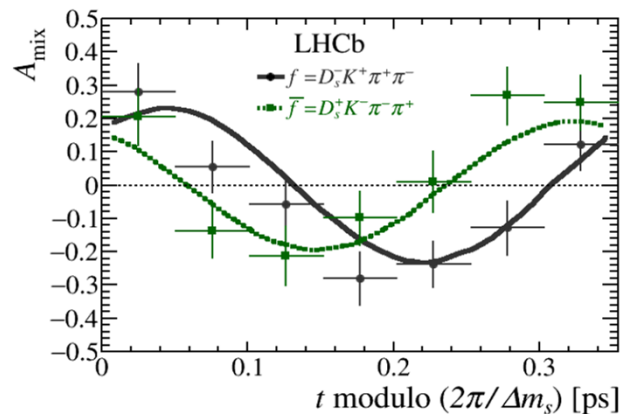
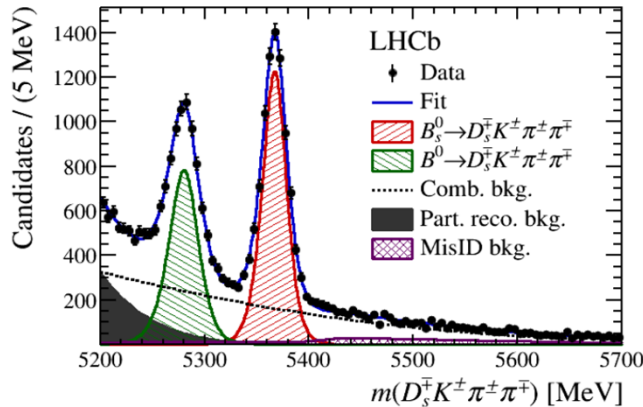
Re-optimization of Belle ϕ_3 -analysis ongoing

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

Angle γ from a time dependent measurement

arXiv:2011.12041

JHEP 03 (2021) 137



- $B_s^0 \rightarrow D_s^+ K^\pm \pi^\pm \pi^\mp$
- 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	$0.47^{+0.08}_{-0.08}^{+0.02}_{-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.88^{+0.12}_{-0.19}^{+0.04}_{-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
δ [°]	$-6^{+10}_{-12}^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$ [°]	$42^{+19}_{-13}^{+6}_{-2}$	$42 \pm 10 \pm 4 \pm 5$

ratio of the decay ampl. to the same final state
coherence factor
strong phase difference
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

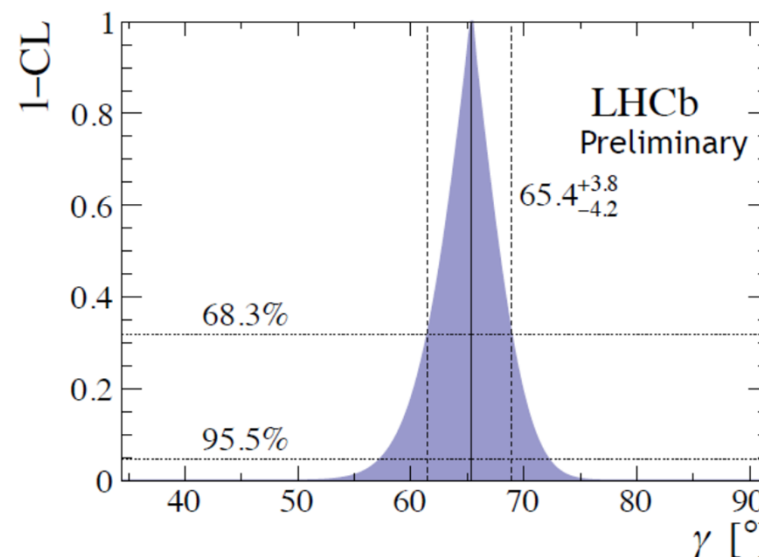
$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

- Most precise measurement

- Comparison

- Excellent agreement with indirect global CKM fits – Ufit

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



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



$B \rightarrow \eta' K$ is a rare charmless hadronic penguin diagram mediated decay, CP violation in SM given by $\sin(2\phi_1)$
- 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]
$B^\pm \rightarrow \eta' K$	$63.4^{+3.4}_{-3.3}(\text{stat}) \pm 3.4(\text{syst})$	70.4 ± 2.5
$B^0 \rightarrow \eta' K^0$	$59.9^{+5.8}_{-5.5}(\text{stat}) \pm 2.7(\text{syst})$	66 ± 4

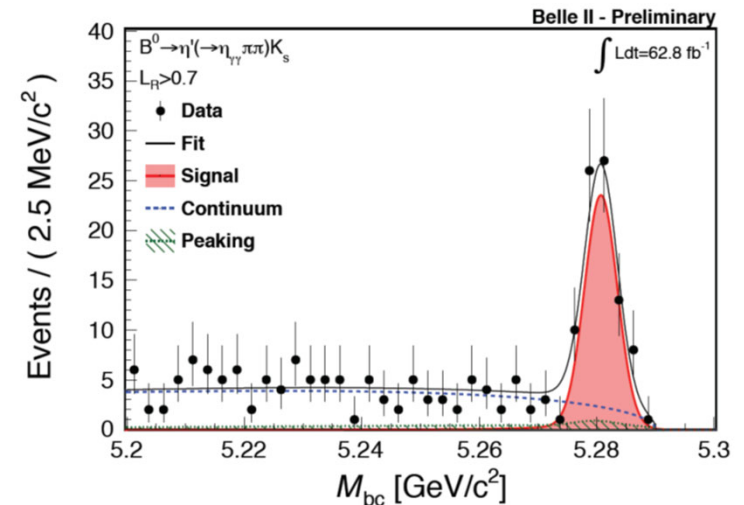
The measurement of $\sin(2\phi_1)$ using $B^0 \rightarrow J/\psi K_L^0$ complements the one from $B^0 \rightarrow J/\psi K_S^0$
- signal yield compatible with Belle result (no syst. yet)

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

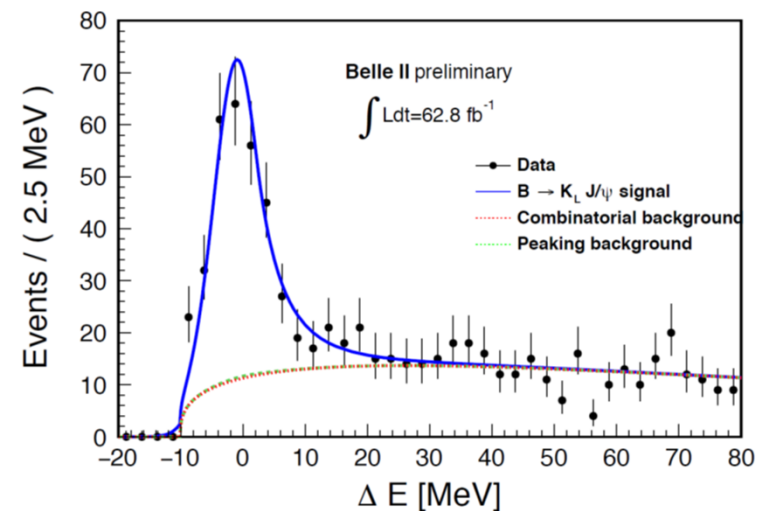
$$N_{\text{sig}} (e^+ e^-) = 226 \pm 20(\text{stat}) \pm 31(\text{peaking})$$

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



$$M_{bc} = \sqrt{E_{beam}^{*2} c^4 - p_B^{*2} c^2}$$



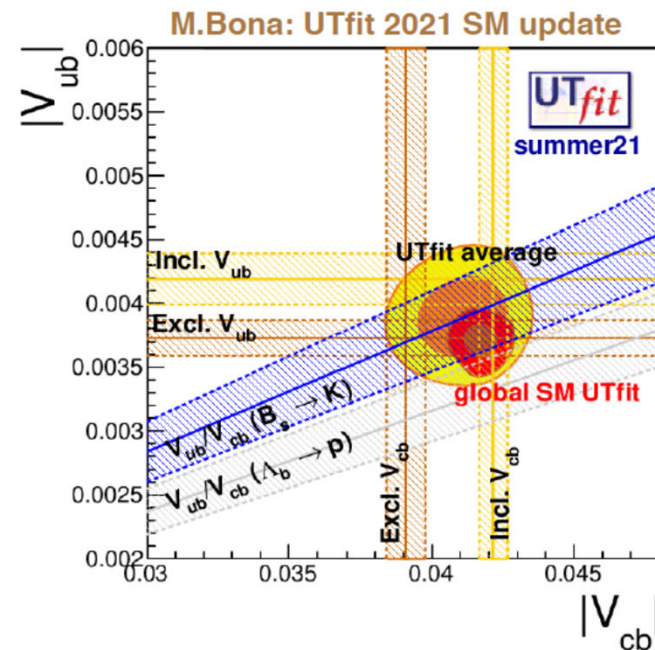
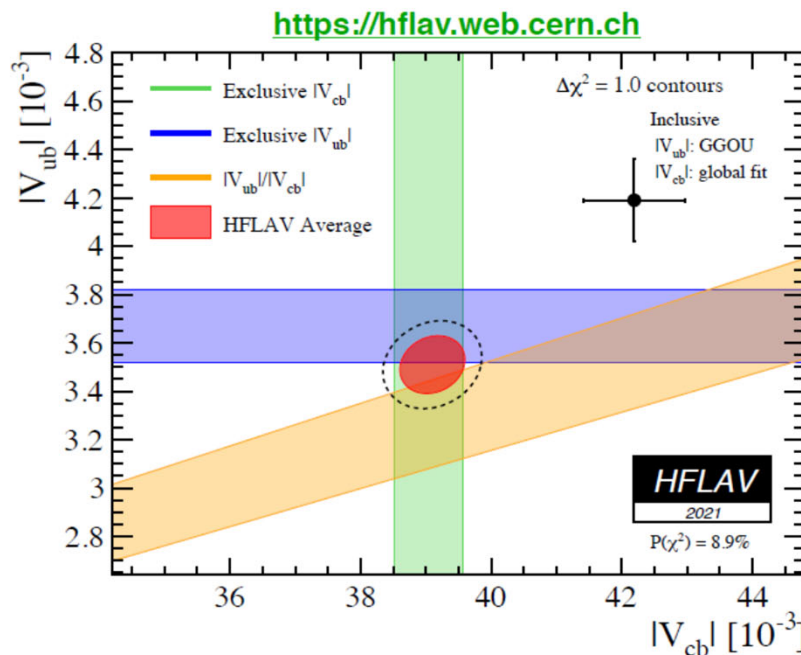
$$\Delta E = E_B^* - E_{beam}$$

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

Inclusive and exclusive semi-leptonic B decays

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

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

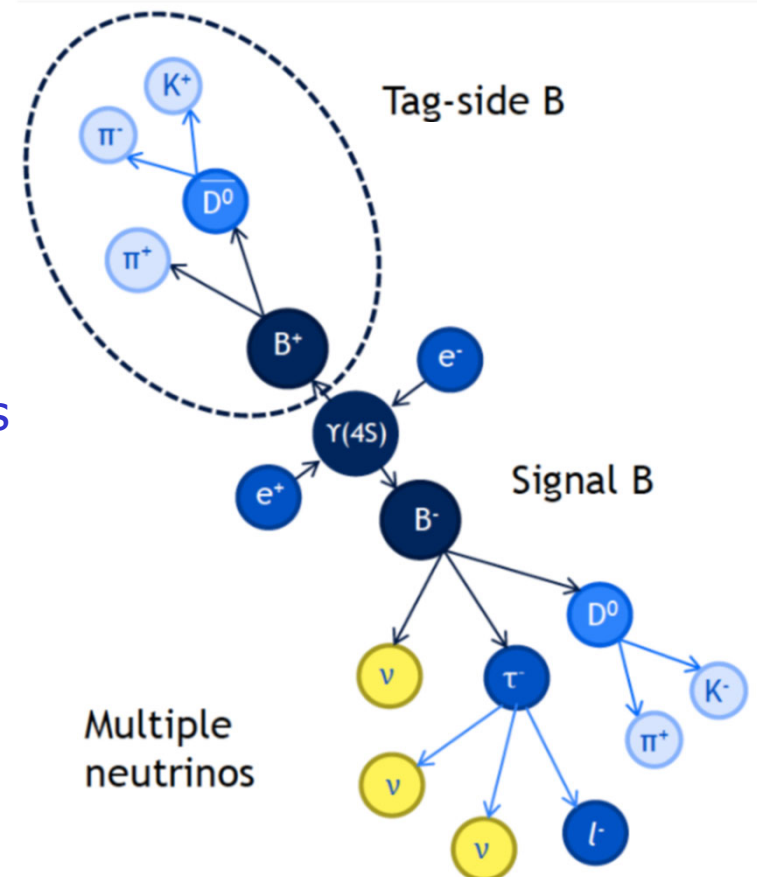
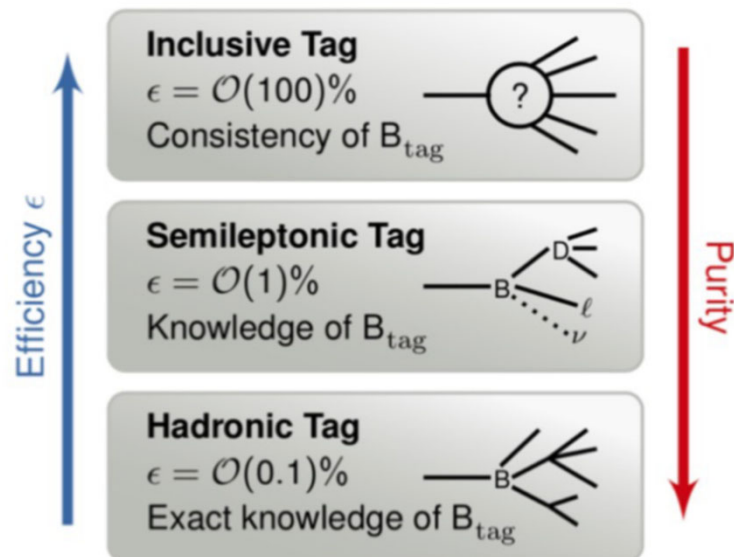
→ Full Event Interpretation

- 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

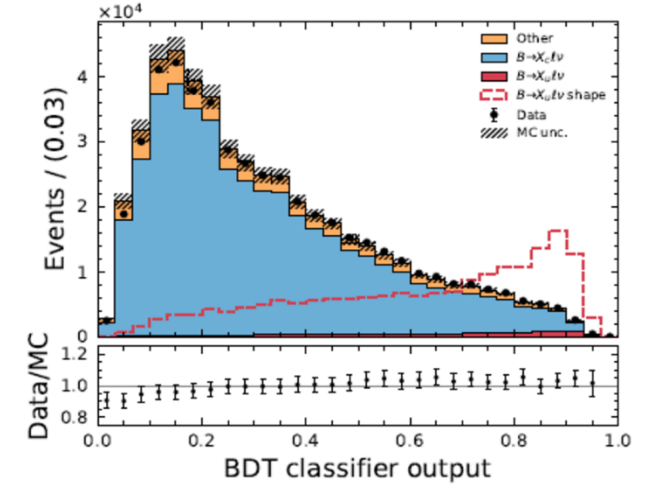
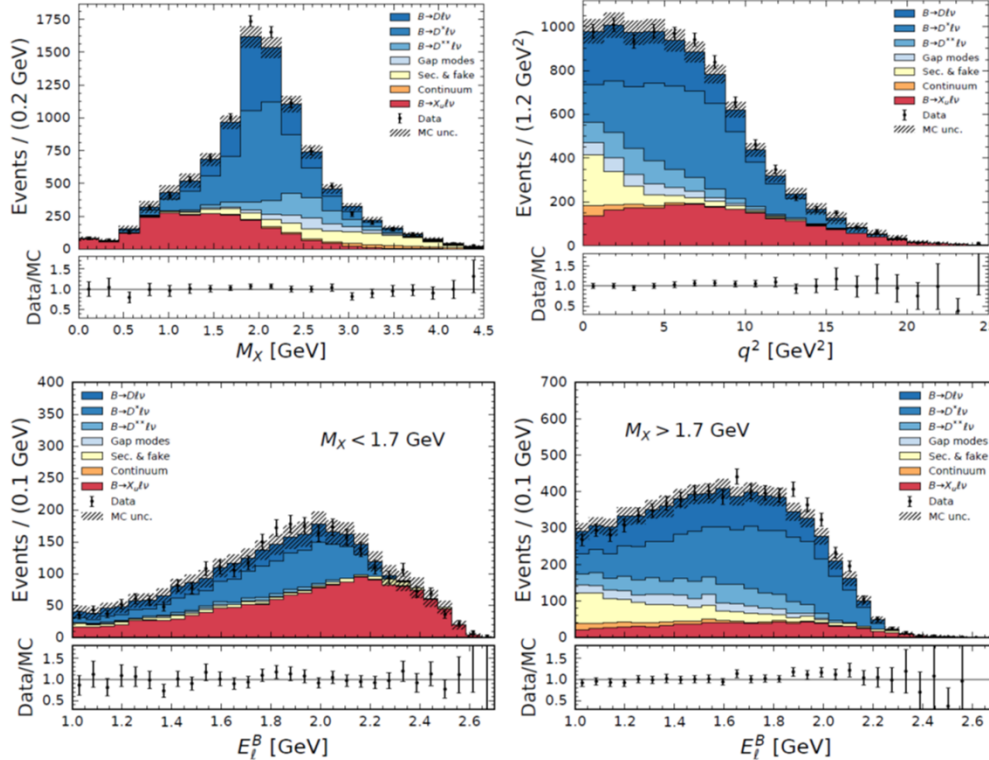


$|V_{ub}|$ from inclusive $B \rightarrow X_u \ell \nu$ with Hadronic Tagging



PRD 104 (2021) 012008

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



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

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

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

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

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

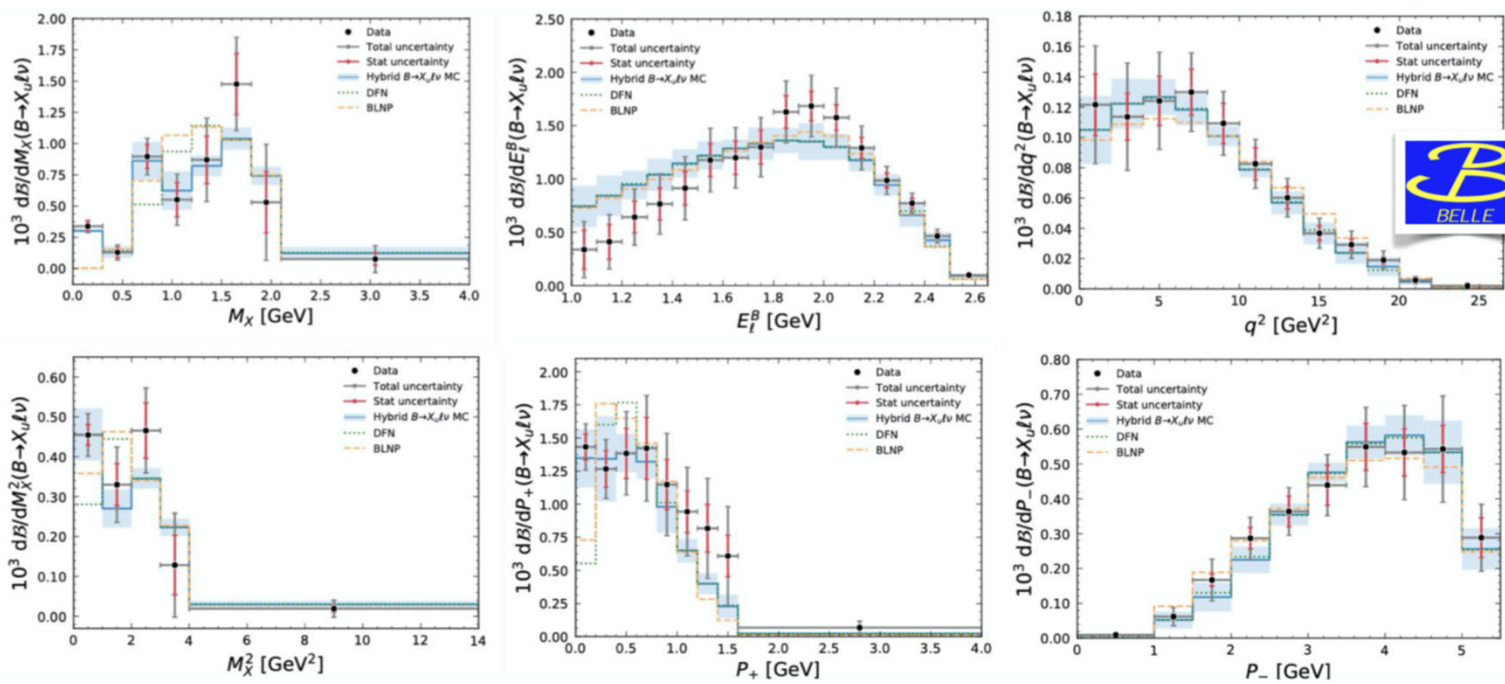
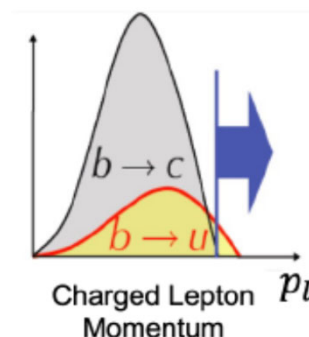
Final result

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

$b \rightarrow u \ell \nu$ - differential decay rate

arXiv:2107.13855

- Challenging due to $B \rightarrow X_c \ell \nu$ 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 differential decay rate in 6 kinematic variables q^2 , E_ℓ^B , M_X , M_X^2 , P_+ , P_- (light cone momenta $P_\pm = E_X \pm p_X$)



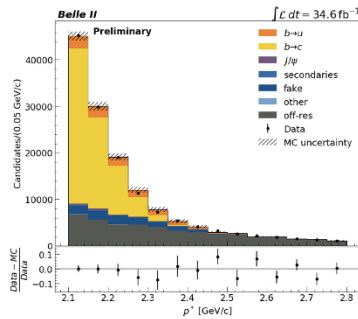
Necessary input for future model-independent determinations of $|V_{ub}|$

Inclusive and exclusive $b \rightarrow (c,u) \ell \nu$ branching fractions with Belle II



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

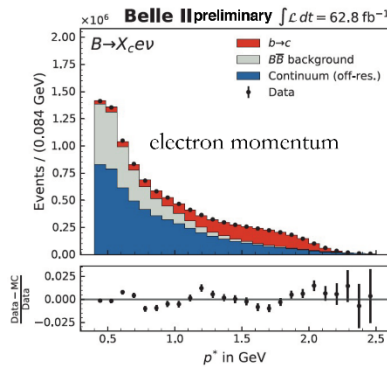
Untagged inclusive $X_u \ell \nu$



3σ significance for b-u

arXiv:2103.02629

Untagged inclusive $X_c \ell \nu$

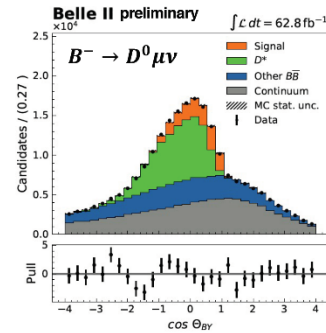


$$\mathcal{B}(B \rightarrow X_c \ell \nu) = (9.75 \pm 0.03(\text{stat}) \pm 0.47(\text{syst}))\%$$

Lepton momentum p^* in the CMS

New for this conference, to be submitted

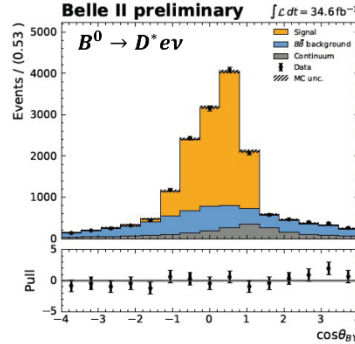
Untagged exclusive $B \rightarrow D^0 \ell \nu$



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

New for this conference, to be submitted

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

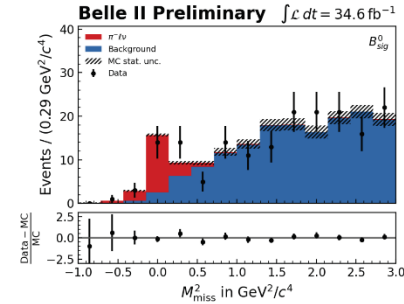


$$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell) = (4.60 \pm 0.05_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.45_{\pi_\pi})\%$$

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

arXiv:2008.07198

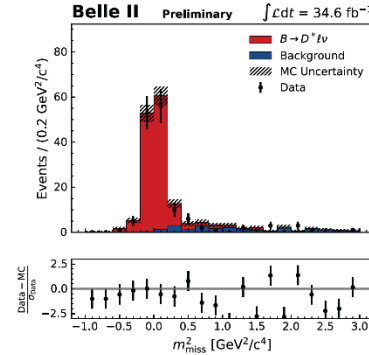
FEI hadronic tag excl. $B^0 \rightarrow \pi \ell \nu$



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

arXiv:2008.08819

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



$$\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell) = (4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_\pi})\%$$

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

arXiv:2008.10299

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 $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$ at LHCb

Measure ratio of BRs of $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$ and $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ decays:

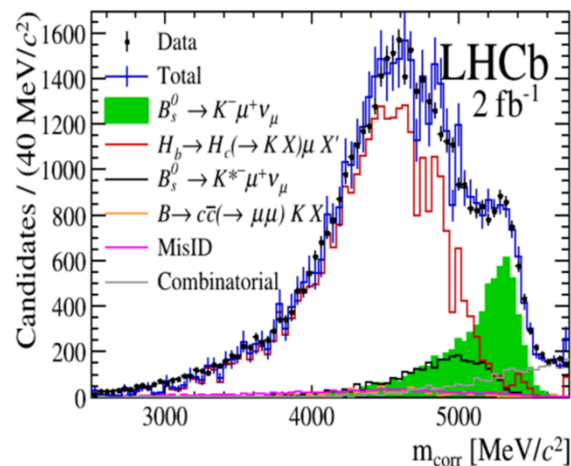
PRL 126 (2021) 081804

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

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

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

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



- First observation of $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$
- 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 $B_s^0 \rightarrow K^+K^-$ decay

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

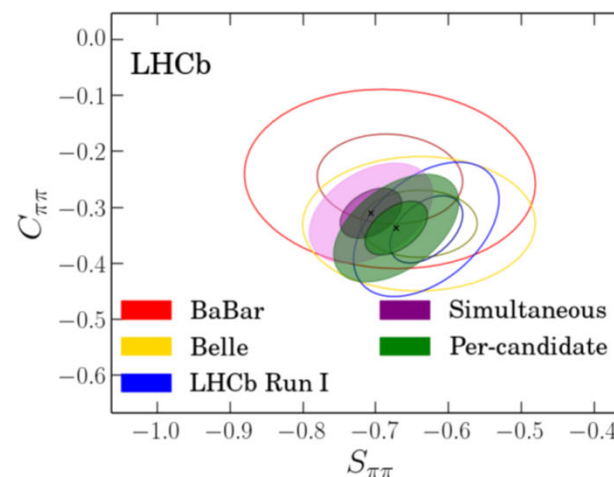
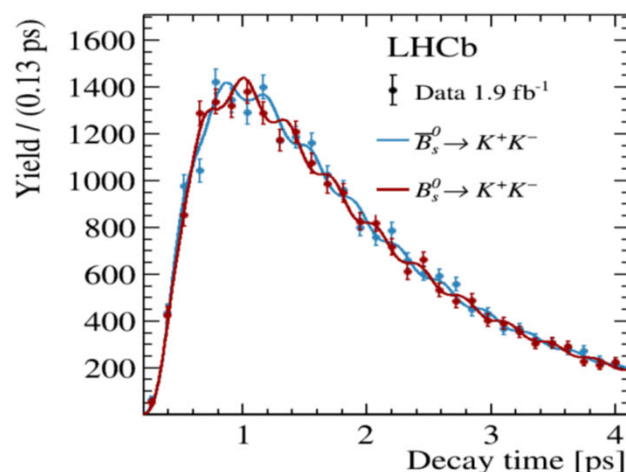
JHEP 03 (2021) 075

- 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 $S_{KK} = 0.123 \pm 0.034(\text{stat.}) \pm 0.015(\text{sys.})$

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 $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow K^-\pi^+$ decays:

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

Expected impact of Belle II on the longstanding $K\pi$ puzzle



A significant difference is seen between direct CP asymmetry in $B^0 \rightarrow K^+ \pi^-$ and $B^+ \rightarrow K^+ \pi^0$ 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)

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

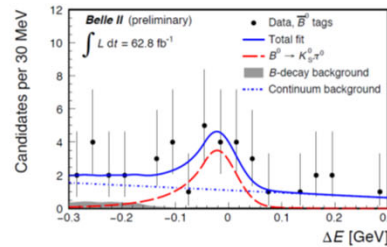
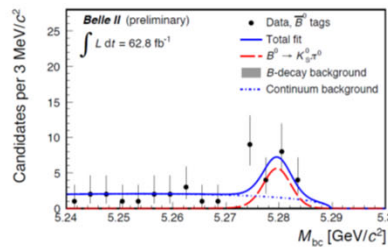
- a violation of the sum rule would be evidence for New Physics
- precision on $\mathcal{A}_{CP}^{K^0 \pi^0}$ is the most limiting input for the test of the sum rule

arXiv:2104.14871

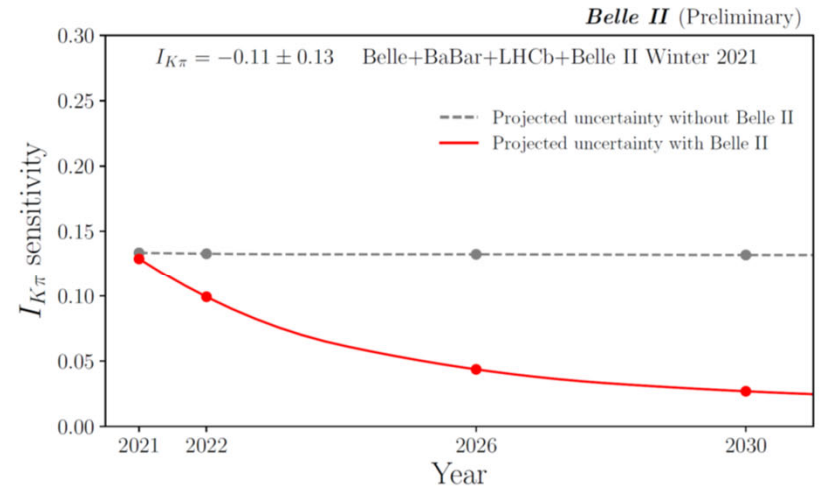
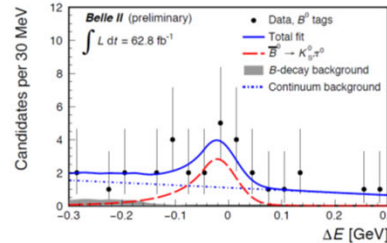
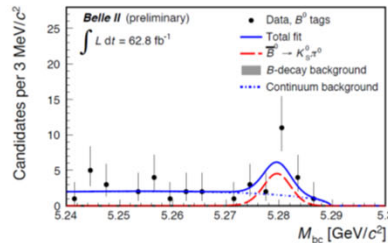
$$\mathcal{A}_{K^0 \pi^0} = -0.40_{-0.44}^{+0.46}(\text{stat}) \pm 0.04(\text{syst}), \text{ and}$$

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

\bar{B}^0 tag



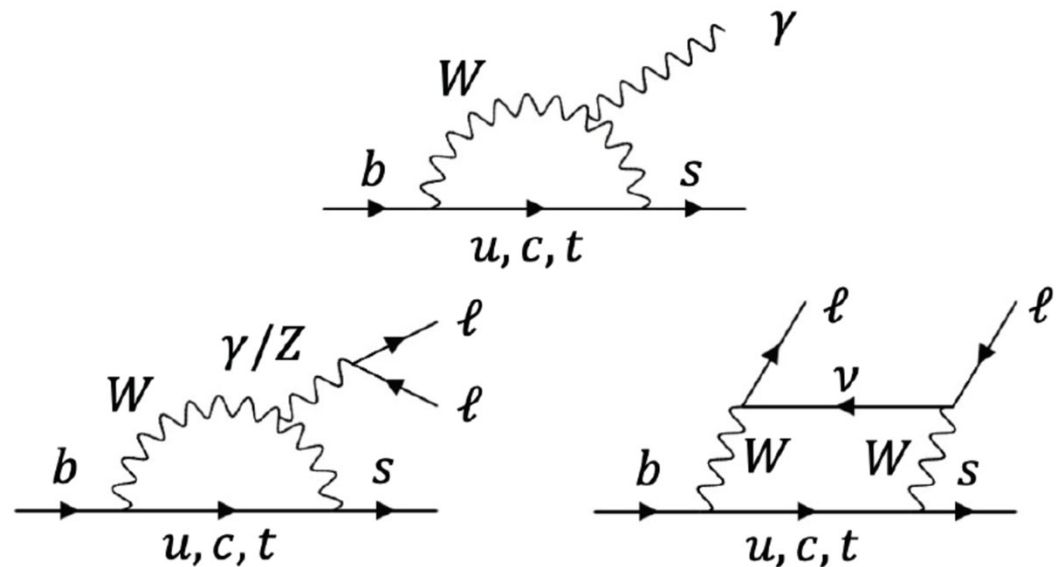
B^0 tag



Searches for new physics in rare decays

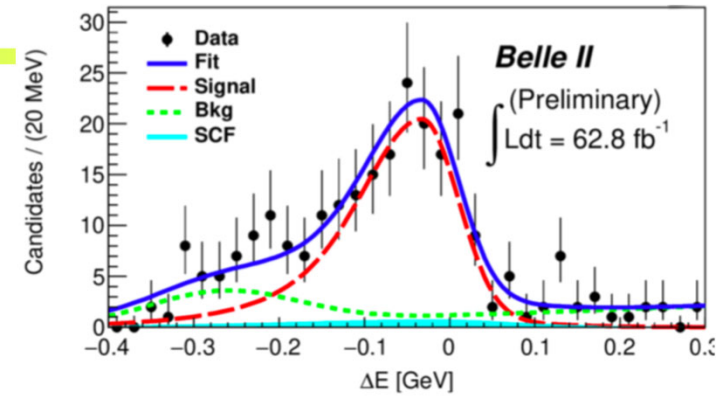
- $b \rightarrow s\gamma$ - Belle II
- $B \rightarrow K^*\mu^+\mu^-$ and $B_s^0 \rightarrow \phi\mu^+\mu^-$ differential decay rates – LHCb
- $B^\pm \rightarrow K^\pm\nu\nu$ – Belle II with inclusive tag
- $B_{(s)}^0 \rightarrow \mu^+\mu^-(\gamma)$ - LHCb

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



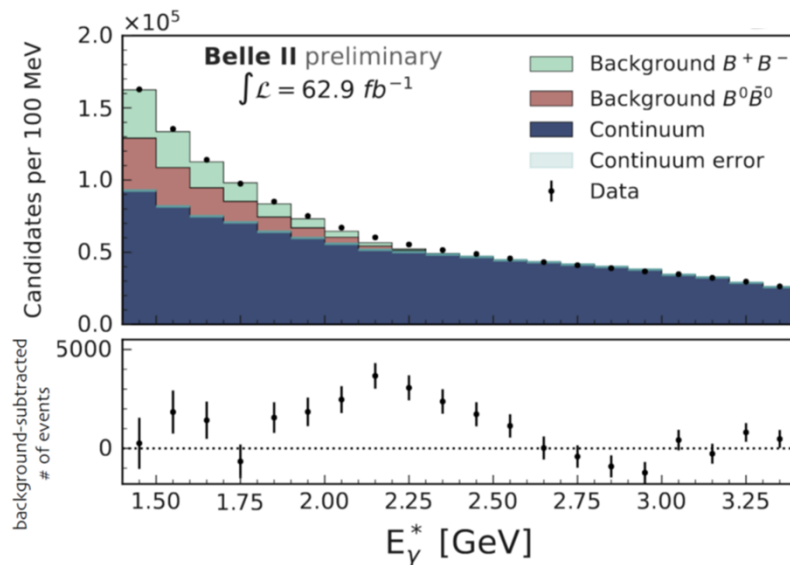
$b \rightarrow s \gamma$: first results at Belle II

- $B \rightarrow K^* \gamma$ 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 $1\text{-}2 \sigma$
- CP and isospin asymmetry measurement foreseen in the next iterations of the analysis



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

Mode	Br (fit) $\times 10^{-5}$
$B^0 \rightarrow K^{*0} [K^+ \pi^-] \gamma$	$4.5 \pm 0.3(\text{stat}) \pm 0.2(\text{syst})$
$B^0 \rightarrow K^{*0} [K_S^0 \pi^0] \gamma$	$4.4 \pm 0.9(\text{stat}) \pm 0.6(\text{syst})$
$B^+ \rightarrow K^{*+} [K^+ \pi^0] \gamma$	$5.0 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$
$B^+ \rightarrow K^{*+} [K_S^0 \pi^+] \gamma$	$5.4 \pm 0.6(\text{stat}) \pm 0.4(\text{syst})$



- $B \rightarrow X_s \gamma$ 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

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

Differential branching fractions

- Decay rate of $b \rightarrow s \ell^+ \ell^-$ sensitive to BSM
- Branching fractions low for muons (B^+ , B^0 , B_s^0 and Λ_b^0)

$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$

arXiv:2105.14007

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

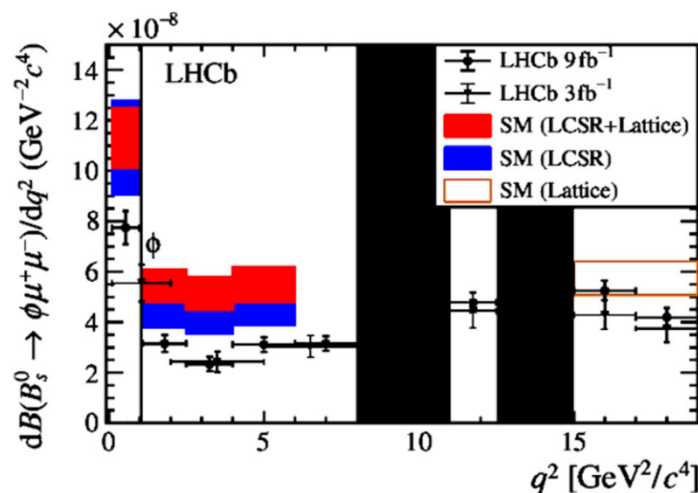
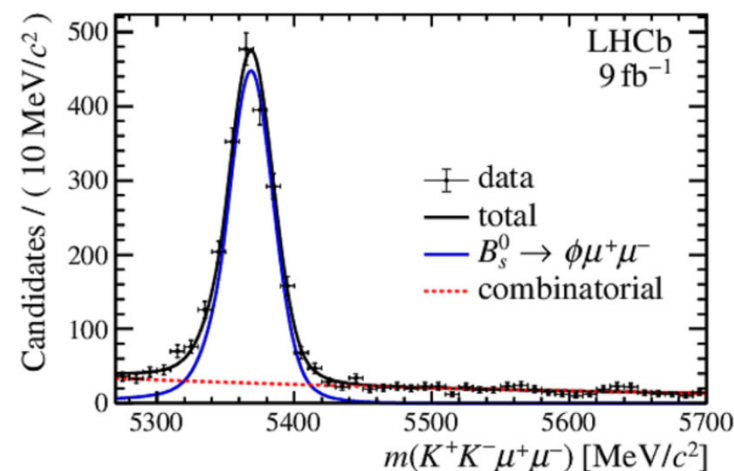
for $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$

- In agreement with Run 1 result
- 3.6σ deviation tension with SM

$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$

- Observables F_L , ACPi asymmetries, coefficients S_i
- Compatible with SM, tension in F_L

arXiv:2107.13428



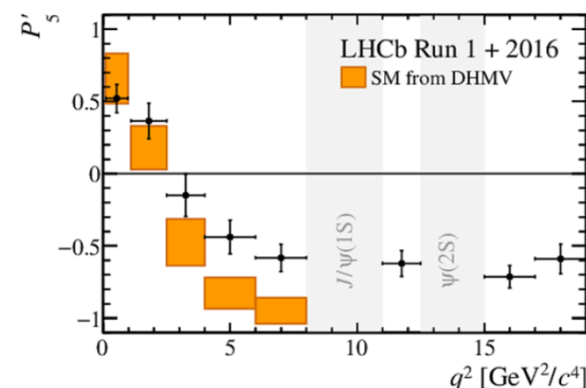
$b \rightarrow s \ell^+ \ell^-$ angular analysis

Angular observables: polarisation, asymmetries vs q^2

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

PRL 125 (2020) 011802

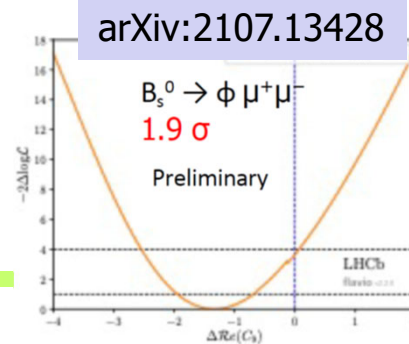
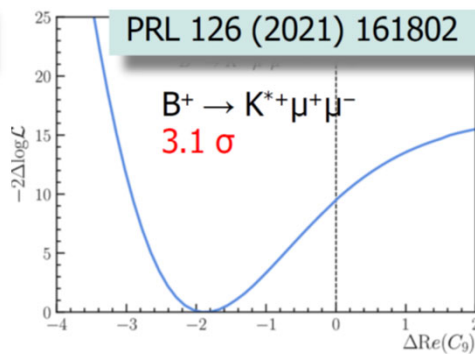
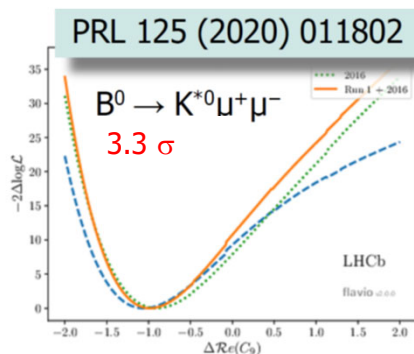
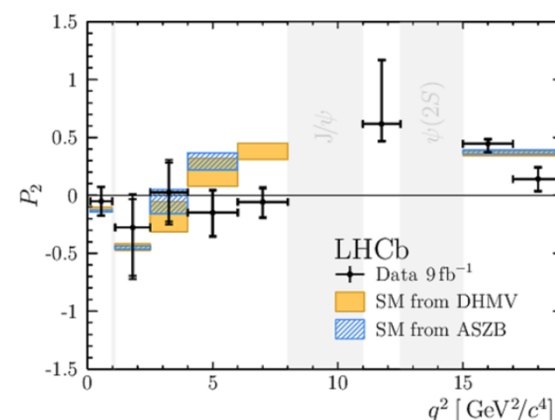
- Local tension 2.5σ and 2.9σ in asymmetry P_5' with SM in q^2 bins $[4,6]$ and $[6,8]$ GeV^2/c^4
- Global analysis finds a tension of 3.3σ
- Consistent with ATLAS, Belle, CMS results



$B^+ \rightarrow K^{*+} \mu^+ \mu^-$

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 $\text{Re}(C_9)$

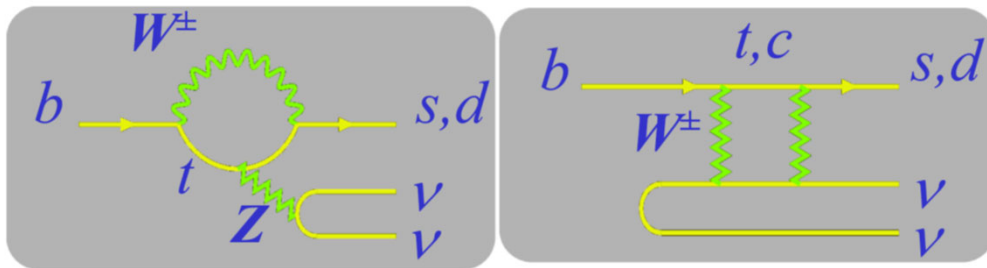


Negative shift of $\Delta\text{Re}(C_9)$ from SM preferred value by a 2 to 3σ level

Peter Križan, Ljubljana

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

SM: penguin + box diagrams



Look for deviations from the expected values \rightarrow information on anomalous couplings C_L^{ν} and C_R^{ν} compared to the SM value $(C_L^{\nu})^{\text{SM}}$, coming from the loop or from processes like

Flavour-Changing Neutral Current process that has not yet been observed

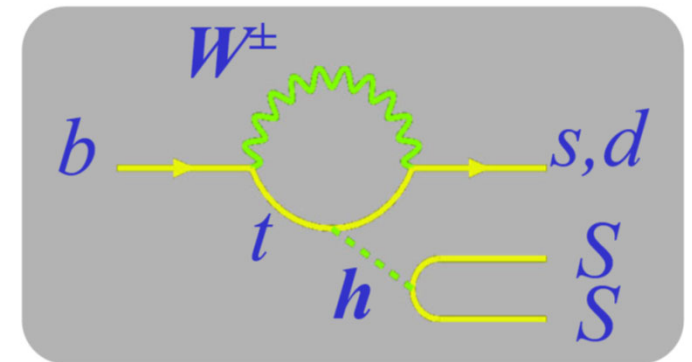
-no photon contribution/much cleaner theoretical prediction

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

Previous searches based on tagged analyses

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

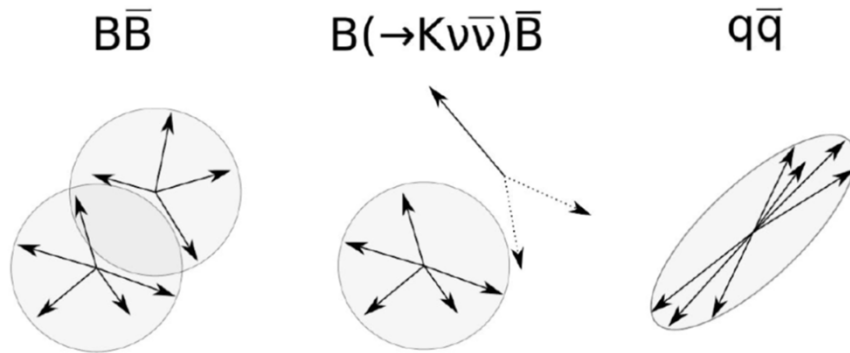
-hadronic tag: $\epsilon_{\text{sig}} \sim 0.04\%$ (BaBar)



New approach by Belle II based on an inclusive tag

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

PRL (accepted) arXiv:2108.03216

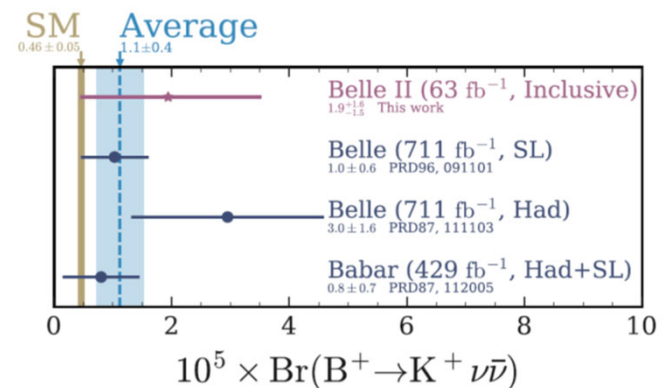
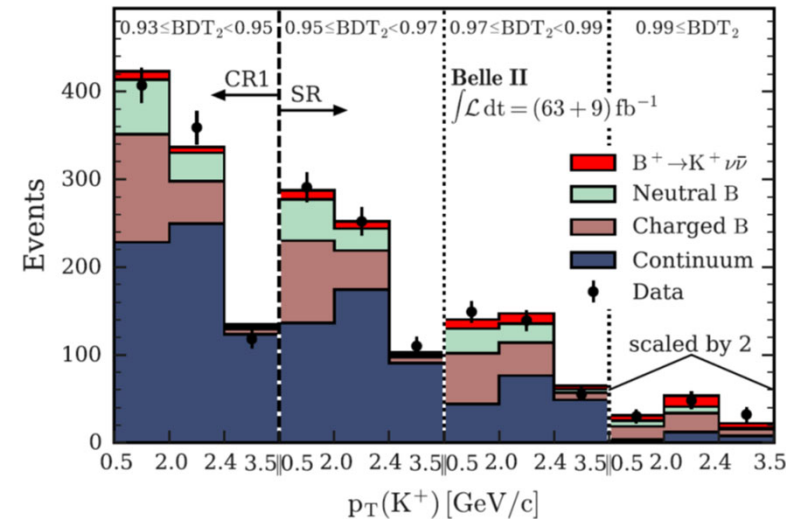


New approach by Belle II based on an **inclusive tag**
 -no explicit reconstruction of the second B-meson
 -use BDTs to exploit distinctive topological features of $B^\pm \rightarrow K^\pm \nu \bar{\nu}$

-much higher efficiency of $\epsilon_{\text{sig}} \sim 4.3\%$ resulting in increased sensitivity per luminosity

Further improvements are underway

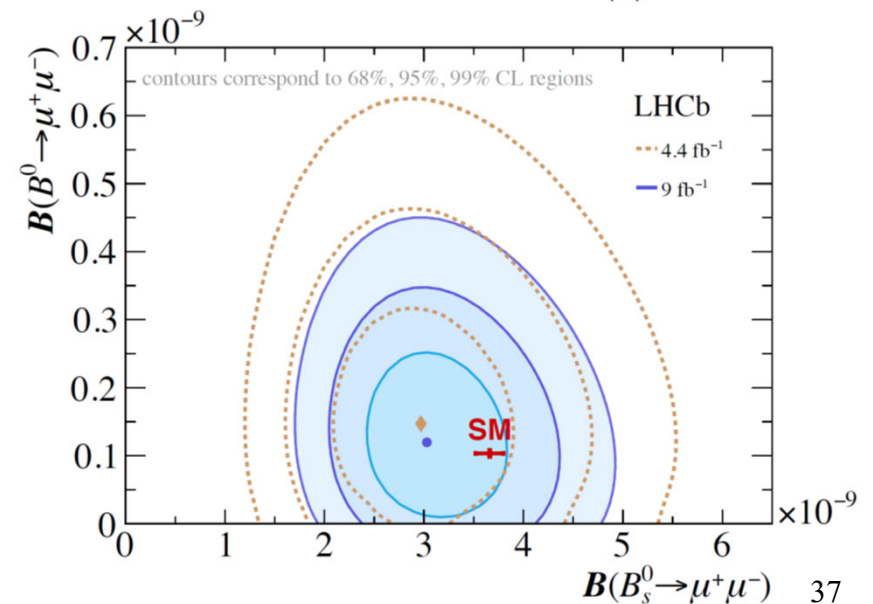
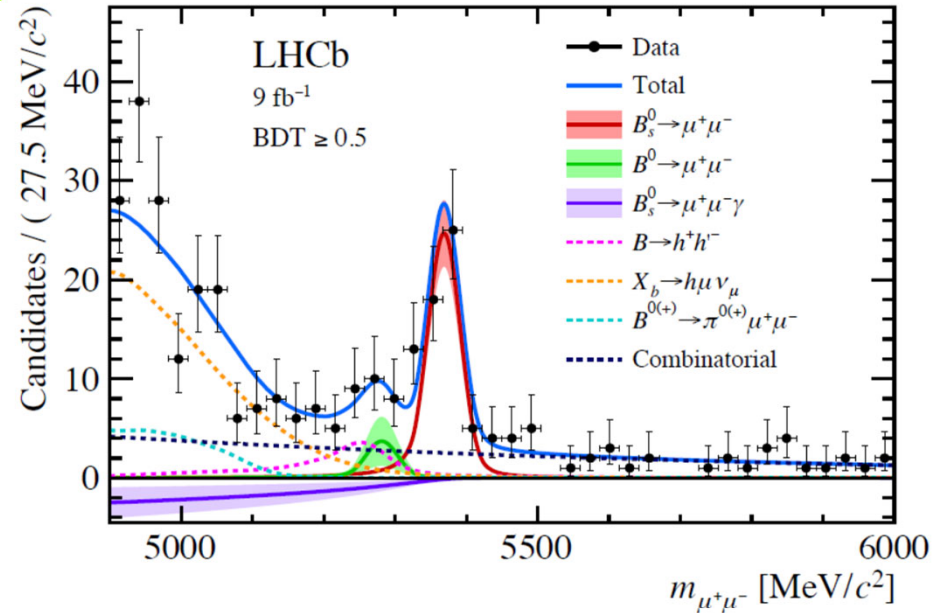
- more data (already have 3x more on tape)
- additional channels ($B^0 \rightarrow K^{*0} \nu \bar{\nu}$, $B^0 \rightarrow K_S^0 \nu \bar{\nu}$...)
- improved/extended classifiers (neural networks)



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

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

- Very rare leptonic decay
 - Helicity and CKM suppressed
 - Sensitive to New Physics
- $B_s \rightarrow \mu^+ \mu^-$
 - $B(B_s \rightarrow \mu^+ \mu^-) = 3.09^{+0.46}_{-0.43} {}^{+0.15}_{-0.11} \times 10^{-9}$
 - Significance $> 10 \sigma$
 - in agreement with SM
- $B^0 \rightarrow \mu^+ \mu^-$
 - $B(B^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-10}$ at 95% CL
- First search for $B_s \rightarrow \mu^+ \mu^- \gamma$
 - $B(B_s \rightarrow \mu^+ \mu^- \gamma) < 2.0 \times 10^{-9}$ at 95% CL for $m_{\mu\mu} > 4.9 \text{ GeV}/c^2$



arXiv:2108.09283

arXiv:2108.09284

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

- $B \rightarrow X_u \ell \nu$ 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

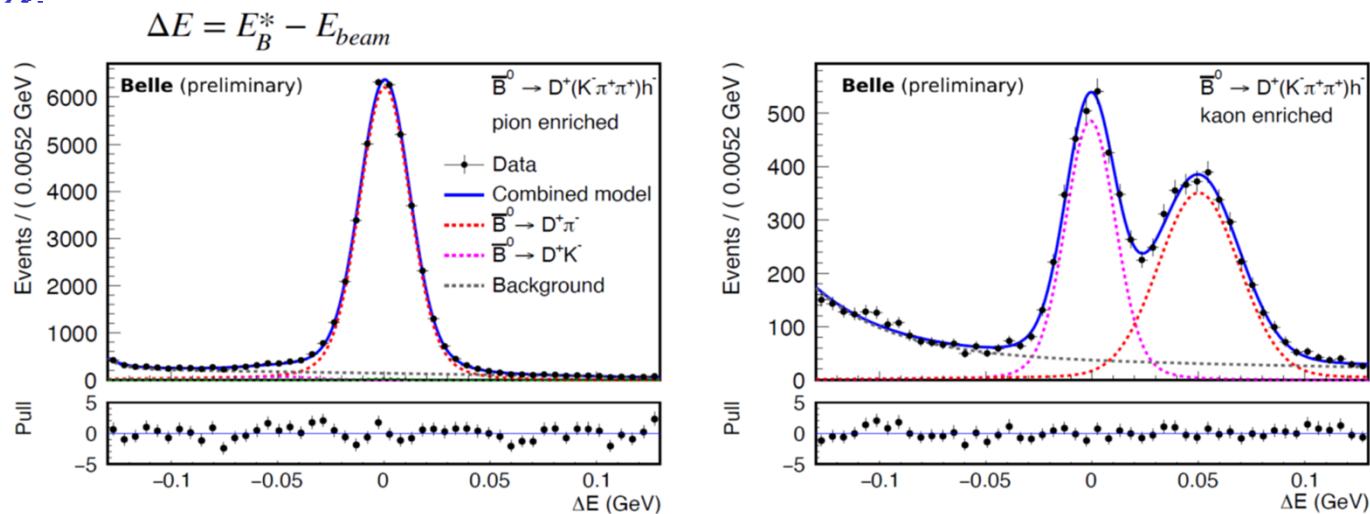
$B^0 \rightarrow D^- \pi^+, D^- K^+$ decays

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

Significant background from $B^0 \rightarrow D^- \pi^+$ 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 \rightarrow kaon misidentification probability which is also determined in the fit, is found to be consistent with the standard Belle value from an independent study.



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



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

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

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 $B^0 \rightarrow D^- \pi^+$

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

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

BaBar: Phys.Rev.D 75 (2007) 031101

$$\mathcal{B}[B^0 \rightarrow D^- \pi^+] = [2.55 \pm 0.05_{\text{stat}} \pm 0.16_{\text{syst}}] \times 10^{-3}$$

CLEO2: Phys.Rev.D 66 (2002) 031101

$$\mathcal{B}[B^0 \rightarrow D^- \pi^+] = [2.68 \pm 0.12_{\text{stat}} \pm 0.24_{\text{syst}}] \times 10^{-3}$$

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

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

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

LHCb: Phys.Rev.Lett. 107 (2011) 211801

$$\mathcal{B}[B^0 \rightarrow D^- K^+] = [1.89 \pm 0.19_{\text{stat}} \pm 0.10_{\text{syst}}] \times 10^{-4}$$

Belle: Phys.Rev.Lett. 87 (2001) 111801

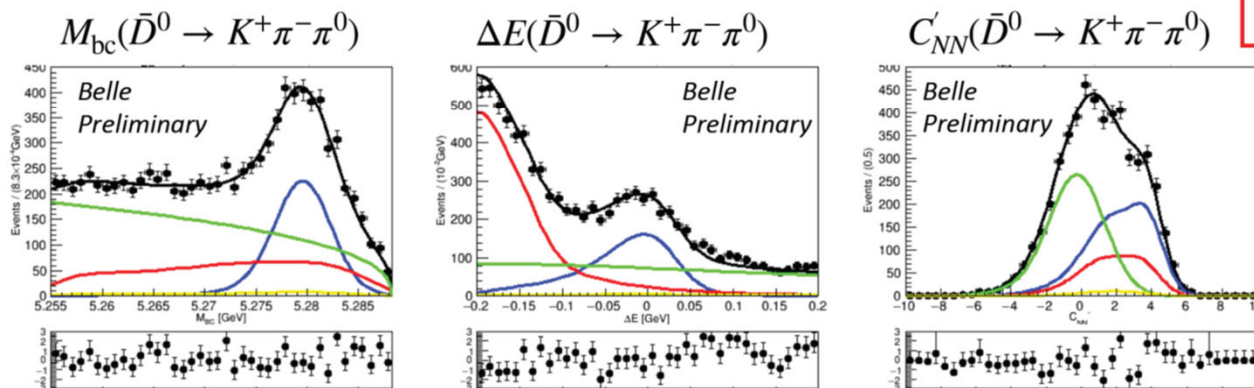
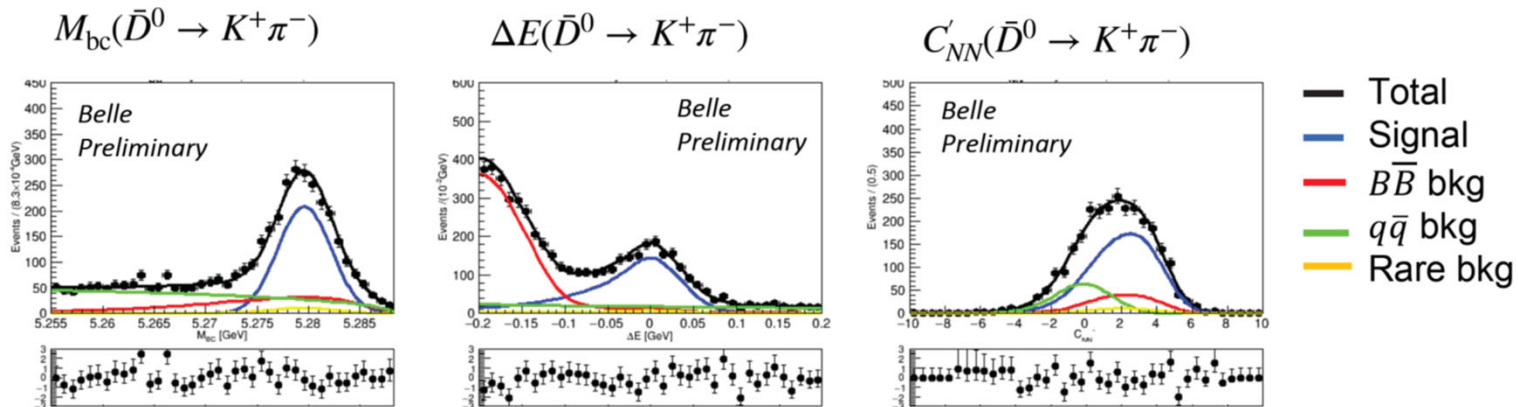
$$\mathcal{B}[B^0 \rightarrow D^- K^+] = [1.7 \pm 0.4_{\text{stat}} \pm 0.1_{\text{syst}}] \times 10^{-4}$$

<https://arxiv.org/abs/2104.03628>

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

Preliminary

$D^0 \pi^0$



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

The most precise measurement in this channel

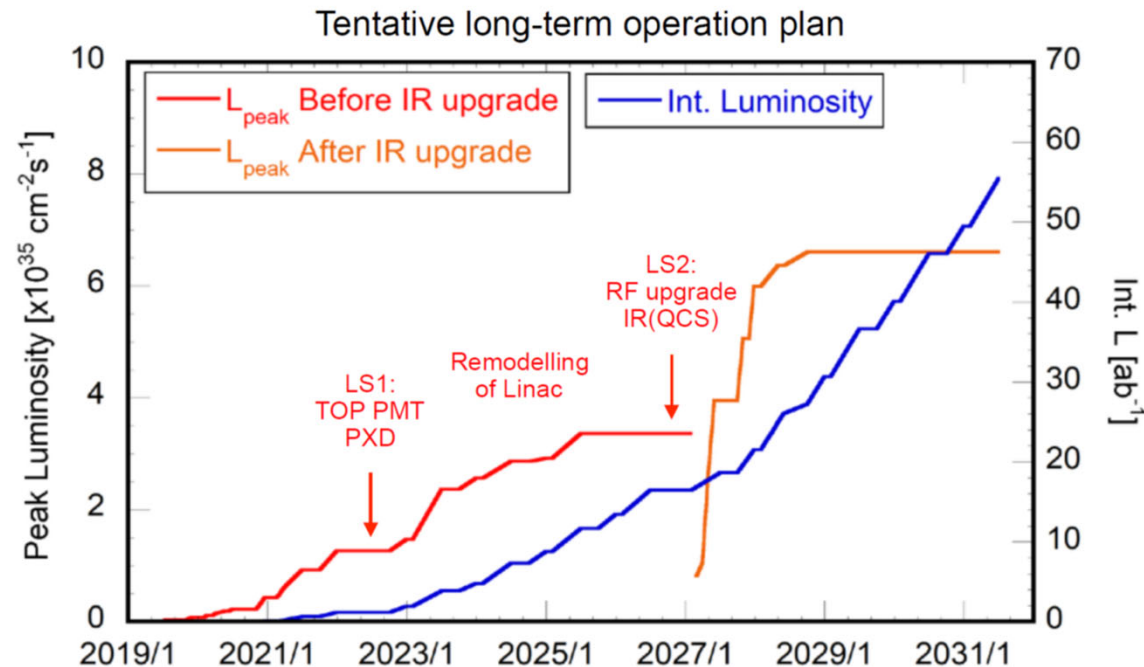
$$\mathcal{B}(B^+ \rightarrow \bar{D}^0 \pi^+) = (4.53 \pm 0.02 \pm 0.14) \times 10^{-3}$$

$D^0 \pi^+$

The most precise measurement in this channel

Outlook

Outlook: Belle II



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

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) $\gtrsim 2026$ 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

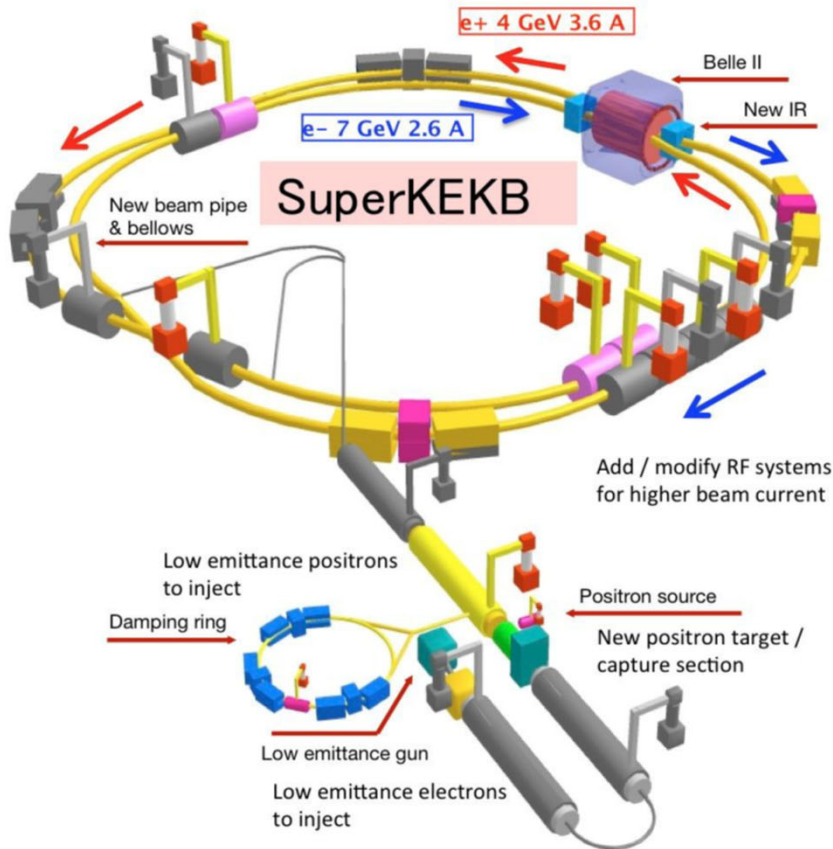
Additional slides

Facilities: Belle II @ SuperKEKB

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

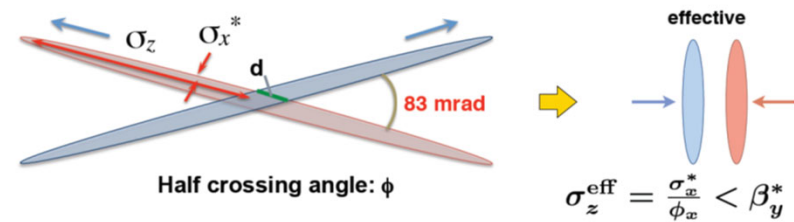
beam current **x1.5** beam-beam param. **x1**

vertical beta function **x 1/20**



LER / HER	KEKB	SuperKEKB	Effect
Energy [GeV]	3.5 / 8	4.0 / 7.0	boost x 2/3
Crossing angle $2\phi_x$ [mrad]	22	83	
β_y^* [mm]	5.9 / 5.9	0.27 / 0.30	L x 20
I_{\pm} [A]	1.64 / 1.19	2.8 / 2.0	L x ~1.5
$\epsilon_y = \sigma_y \times \sigma_{y'}$ [pm]	140 / 140	13 / 16	
$\xi_y \sim (\beta_y^* / \epsilon_y)^{1/2} / \sigma_x^*$	0.129 / 0.09	0.09 / 0.09	L x 1
Luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	2.1	60	L x 30

Nano-Beam scheme (P. Raimondi): squeeze beta function at the IP (β_x^*, β_y^*) and minimize longitudinal size of overlap region to avoid hourglass effect

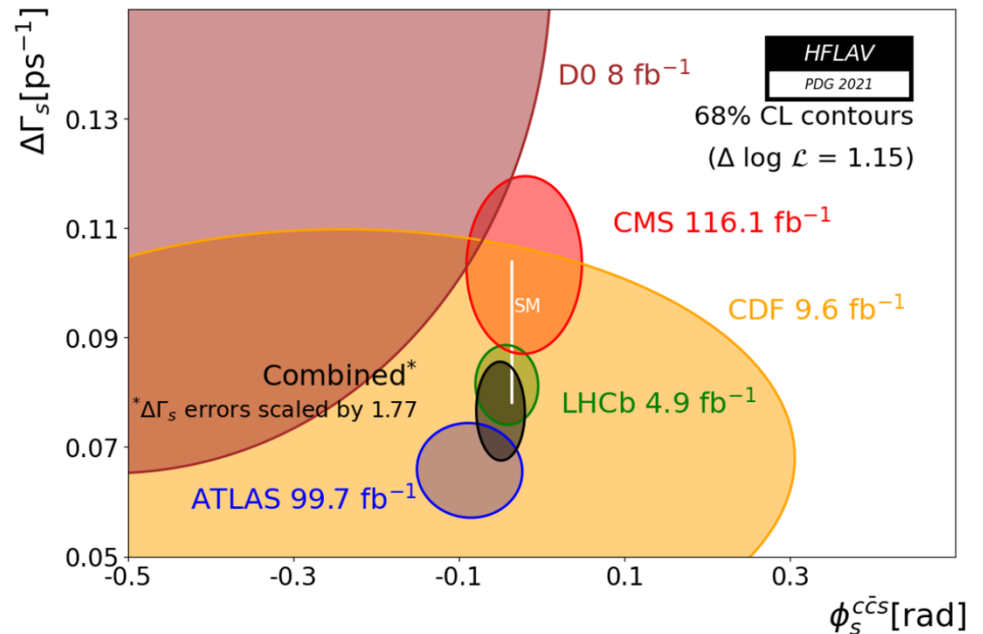


Strong focusing of beams down to vertical size of ~50 nm requires very low emittance beams and large crossing angle (83 mrad). Need powerful and sophisticated final focus system.

ϕ_s world average - HFLAV

World average HFLAV

$$\phi_s = -0.041 \pm 0.025 \text{ rad},$$
$$\Delta\Gamma_s = 0.082 \pm 0.005 \text{ ps}^{-1}$$

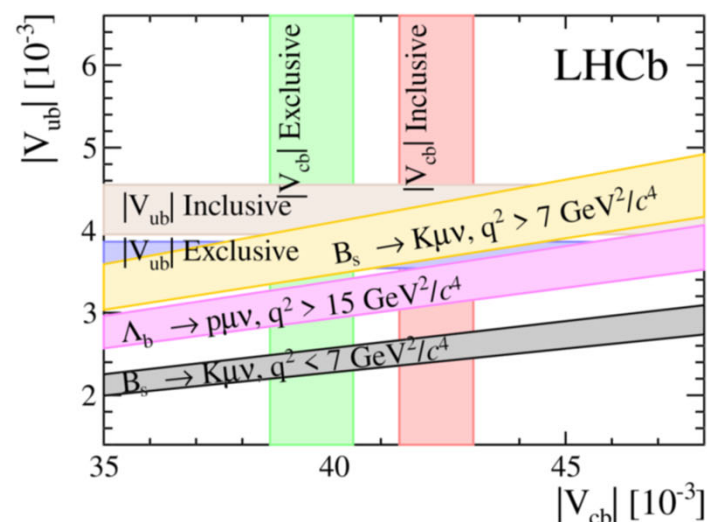
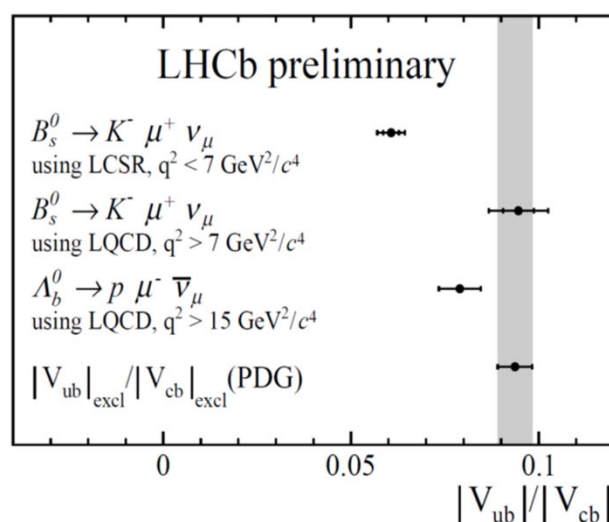


- Measurements are statistically dominated
- Consistent with SM and consistent with no CP violation in the interference
- Several "full Run 2" analyses are ongoing → expect soon to improve ϕ_s precision

* HFLAV comment: Due to tensions between analyses for some of the measured parameters, scale factors are applied on their errors. The scale factors are calculated per parameter, in one dimension, using the PDG prescription. For example the scale factors of the errors of Γ_s , $\Delta\Gamma_s$ and ϕ_{sccs} are 2.5, 1.77 and 1, respectively. The scale factors are applied in a way that preserves the total correlation matrix of each analysis.

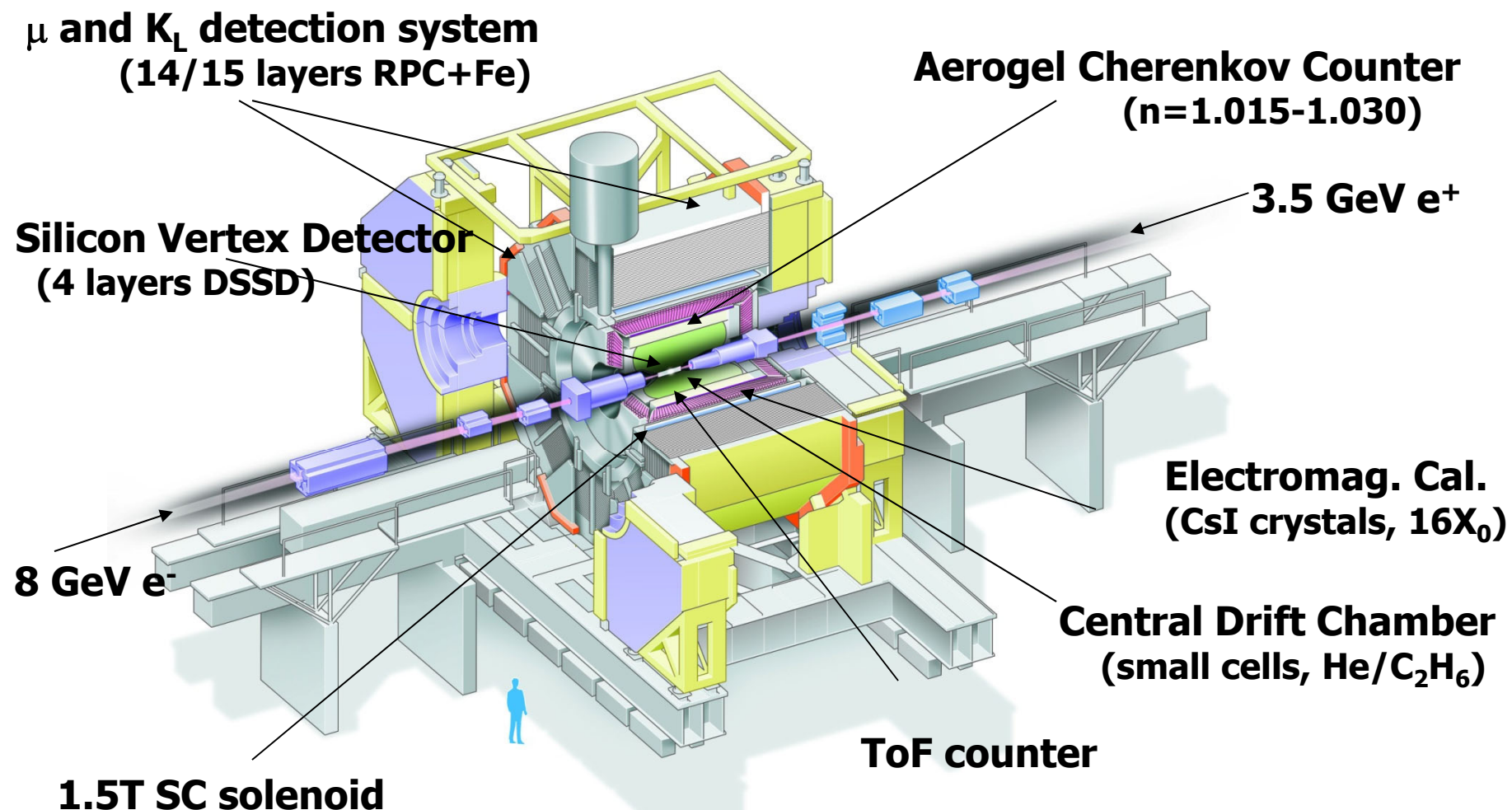
$|V_{ub}|/|V_{cb}|$ with $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$ at LHCb

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



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

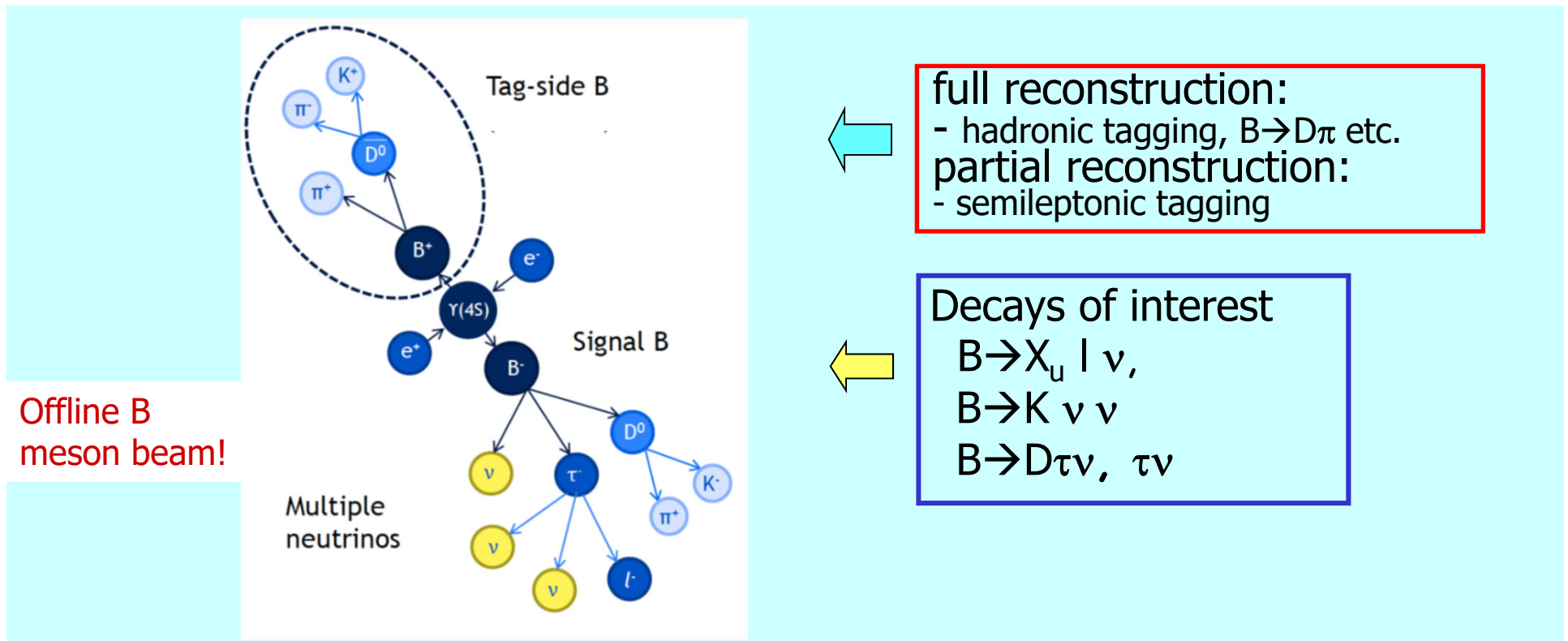
Belle spectrometer at KEK-B



Full Event Interpretation (FEI) - tagging of the B meson decay

At Belle II (just like previously at Belle and BaBar) exactly two B mesons are produced in the e^+e^- collision.

Idea: **fully (or partially) reconstruct** one of the B's to tag B flavor/charge, determine its momentum, and exclude decay products of this B from further analysis



Powerful tool for B decays with neutrinos → **unique feature at B factories**