CP violation

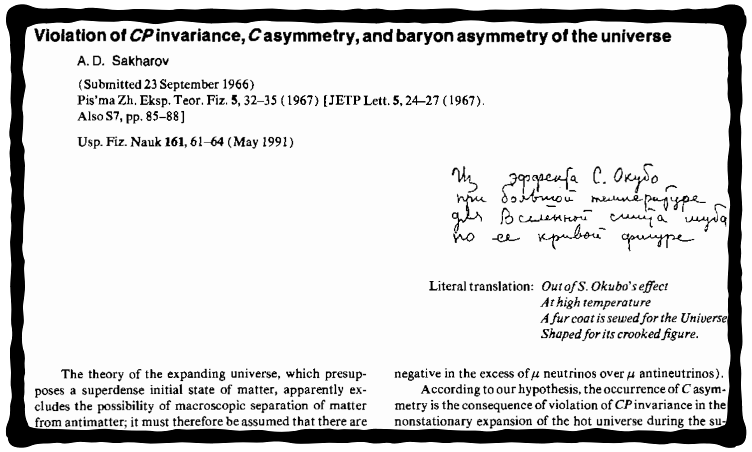
An experimental review

G. Finocchiaro INFN-LNF

32nd Rencontres de Blois, 20th October 2021

CP violation - introduction

- Non-invariance of fundamental interactions under the combined action of charge conjugation (*C*) and parity (*P*) transformations



Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are negative in the excess of μ neutrinos over μ antineutrinos).

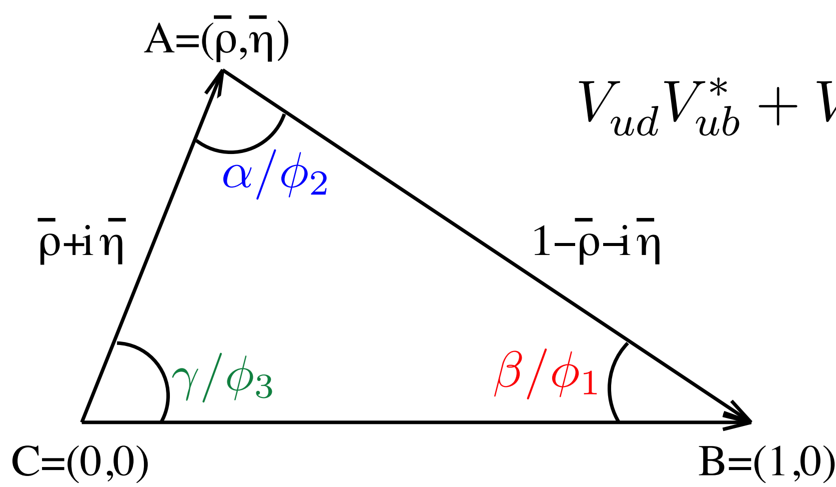
According to our hypothesis, the occurrence of *C* asymmetry is the consequence of violation of *CP* invariance in the nonstationary expansion of the hot universe during the su-

- (One of four) necessary condition for the dynamical generation of the baryon asymmetry in the Universe

- The Standard Model includes *CP* violation through (the single) irreducible phase of the unitary 3x3 CKM matrix

- Unitarity of the matrix can be expressed in terms of Unitarity Triangles (UTs)

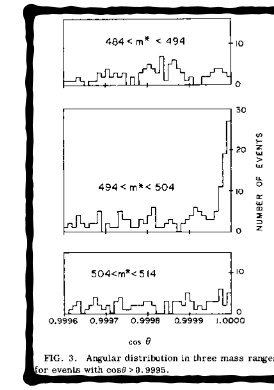
- All with equal area A_Δ, proportional to *CP* violation. In particular for the third generation:



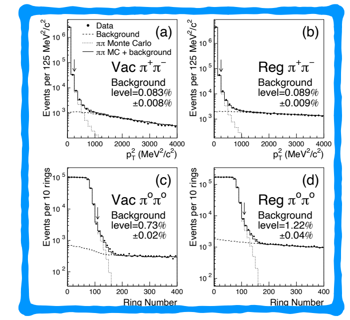
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- in the SM the UT must respect constraints so that all measurements of sides and angles converge in the same apex $(\bar{\rho},\ \bar{\eta})$

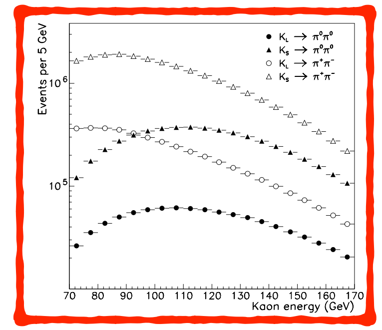
CP violation milestones



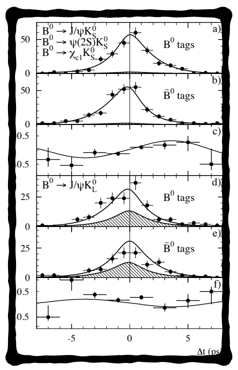
- 1964: J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay: Evidence for the 2π Decay of the K_2^0 Meson

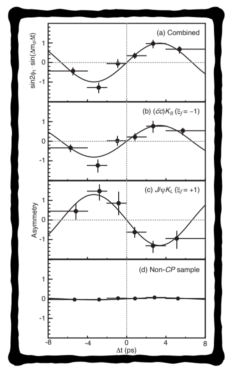


- 1999: KTeV Collaboration: Observation of Direct *CP* Violation in $K_{S;L} \rightarrow \pi\pi$ Decays

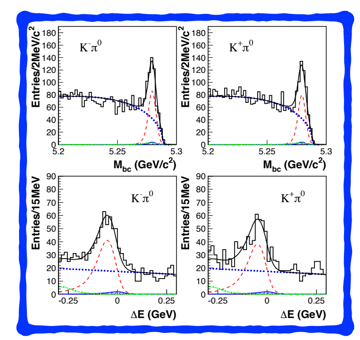


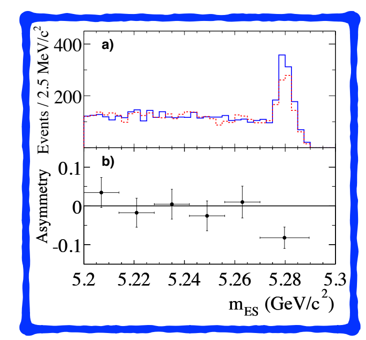
- 2001: NA48 Collaboration: A precise measurement of the direct *CP* violation parameter $Re(\varepsilon'/\varepsilon)$



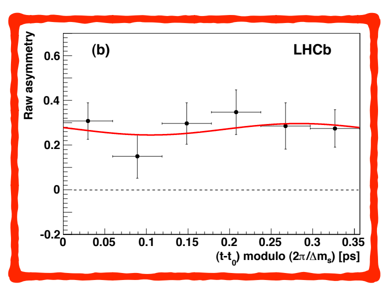


- 2001: BABAR Collaboration: Observation of *CP* Violation in the B^0 Meson System
- 2001: Belle Collaboration: Observation of Large *CP* Violation in the Neutral B Meson System

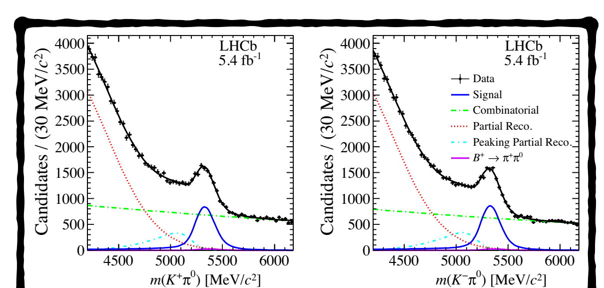




- 2004: BABAR Collaboration: Direct *CP* Violating Asymmetry in $B^0 \rightarrow K^+\pi^-$ decays
- 2004: Belle Collaboration: Evidence for Direct *CP* Violation in $B^0 \rightarrow K^+\pi^-$ Decays



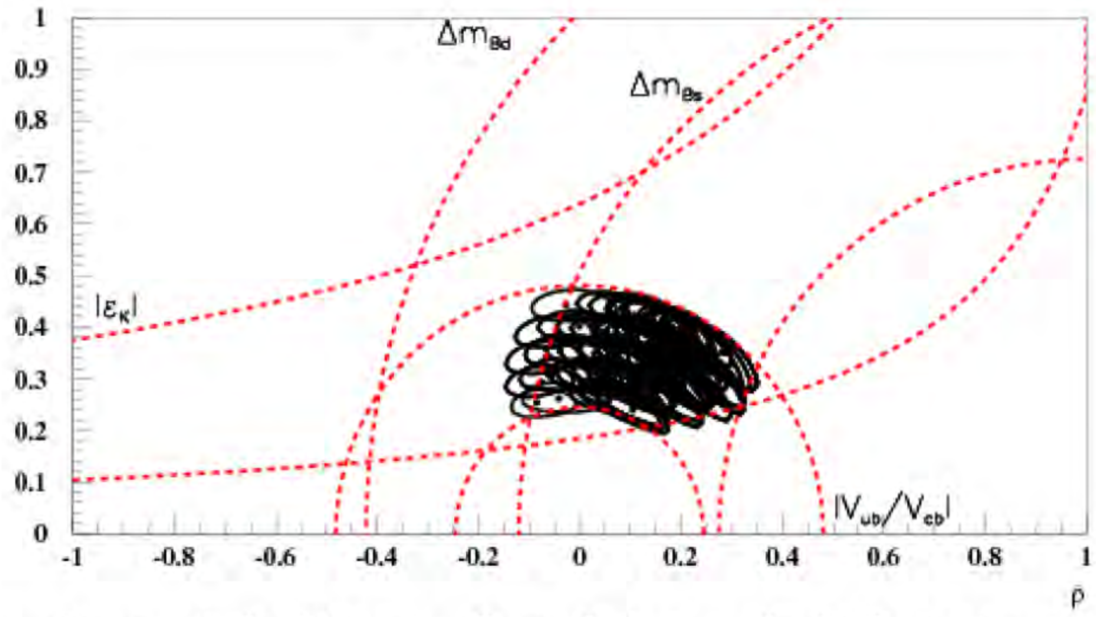
- 2013: LHCb Collaboration: First observation of *CP* violation in the Decays of B_s^0 Mesons



- 2019: LHCb Collaboration: Observation of *CP* violation in Charm Decays

Past, present, and future (of the UT)

BABAR PHYSICS BOOK, 1998



Past, present, and future (of the UT)

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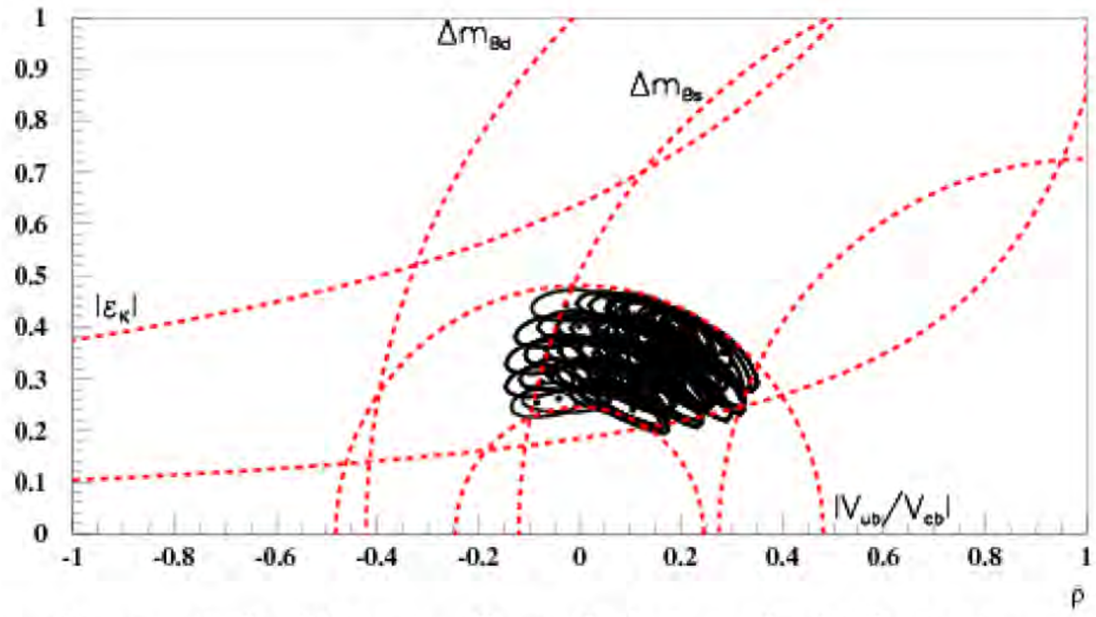
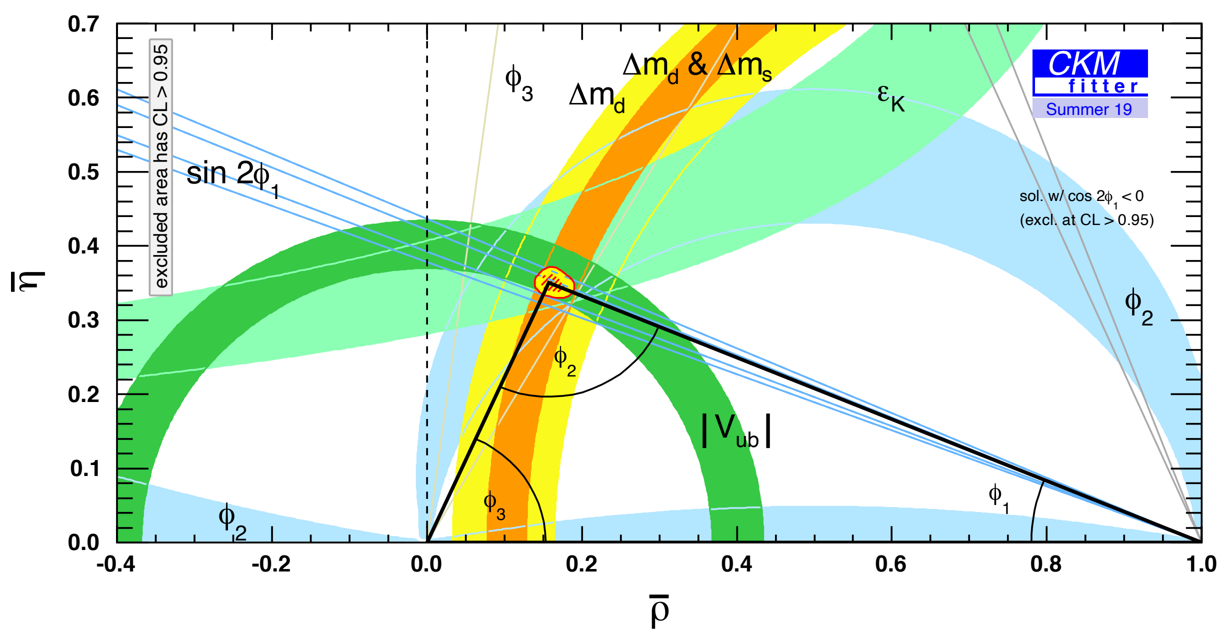
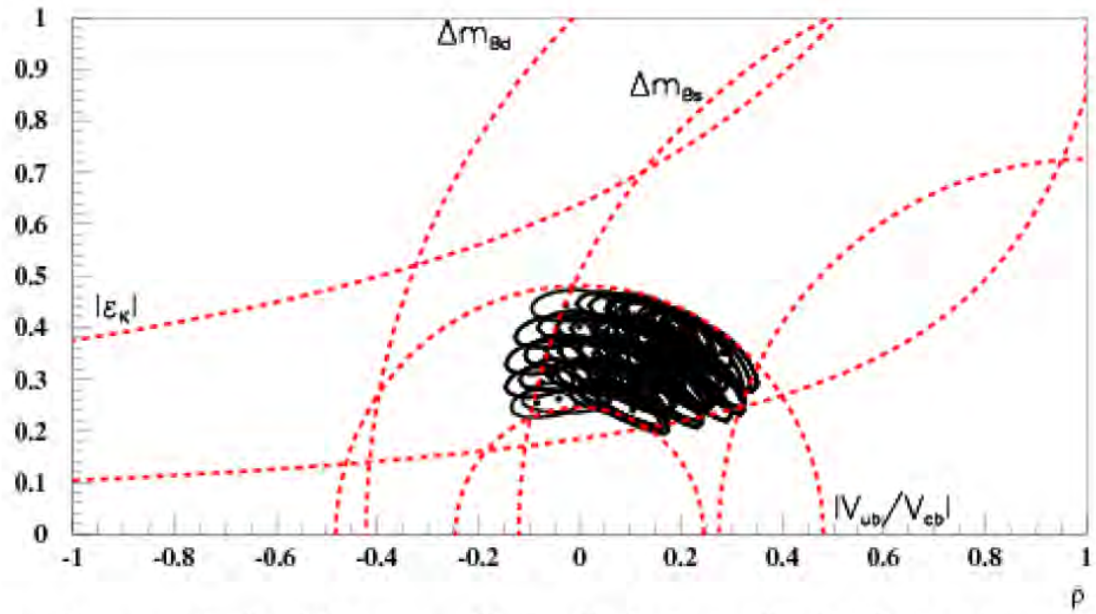


2019

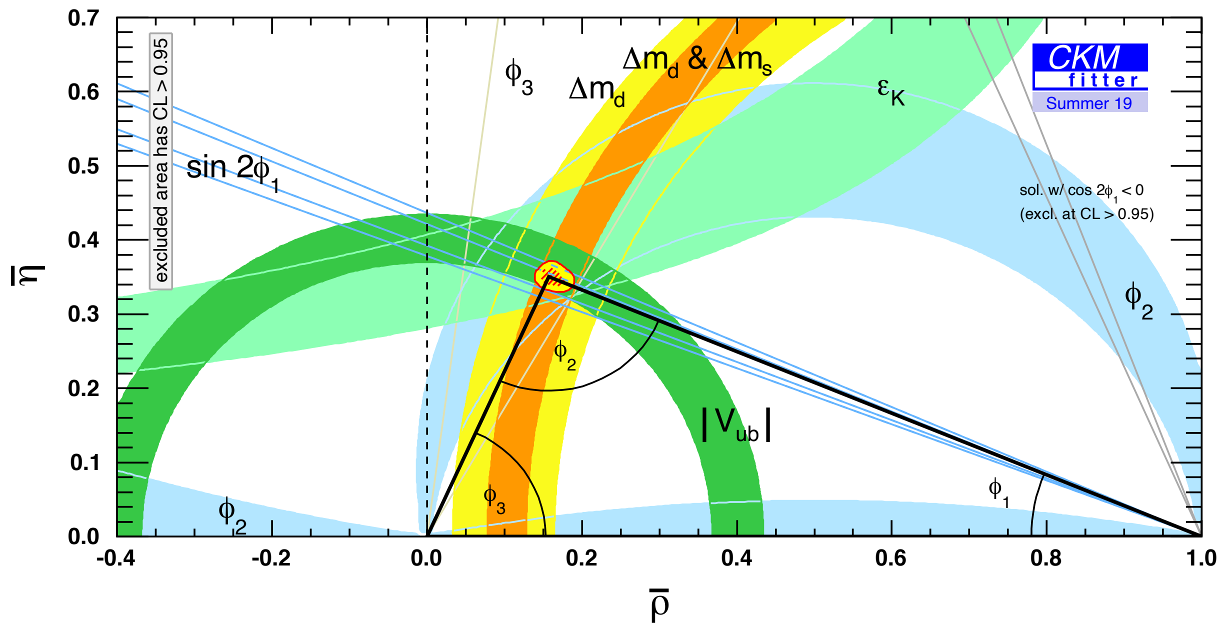


Past, present, and future (of the UT)

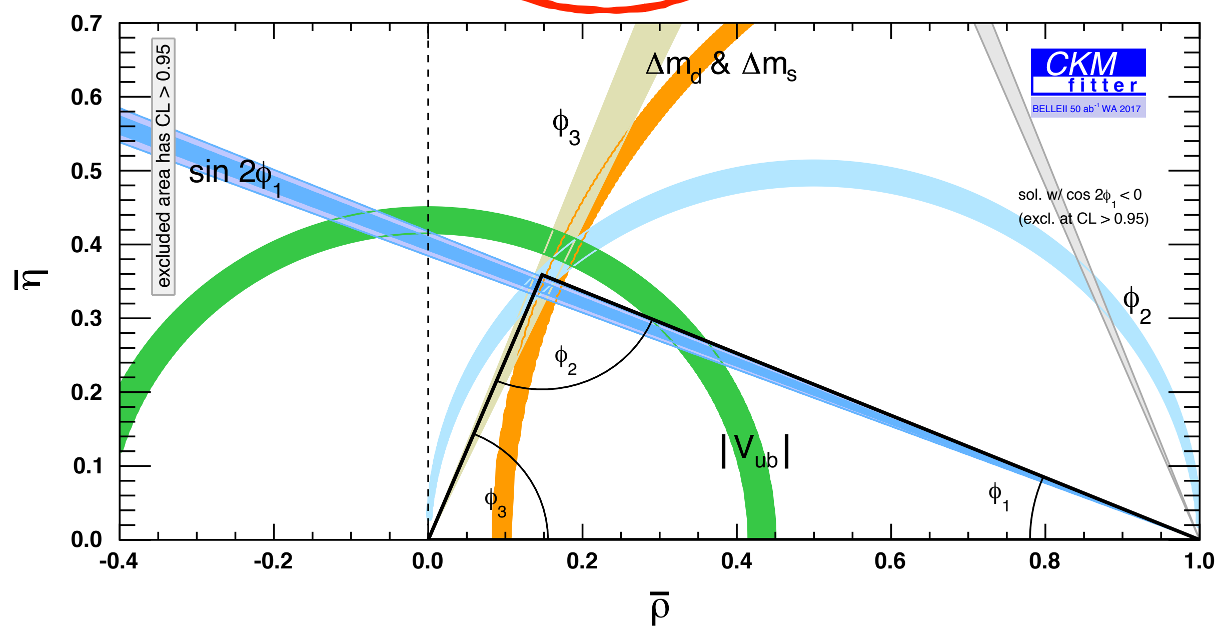
BABAR PHYSICS BOOK, 1998



2019



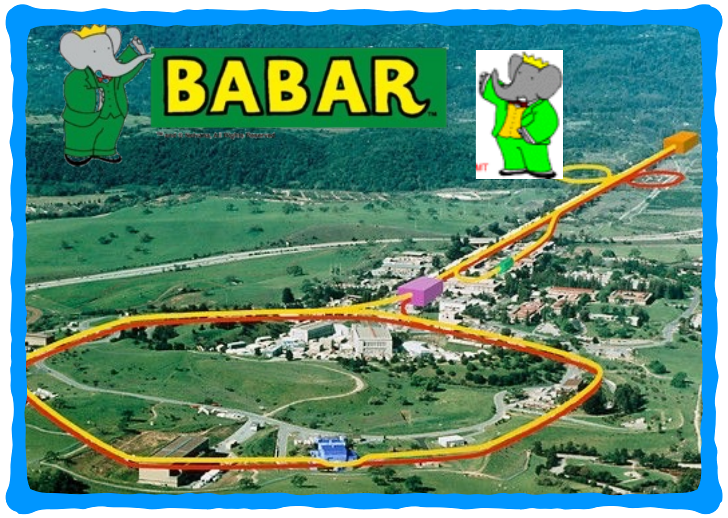
2030+



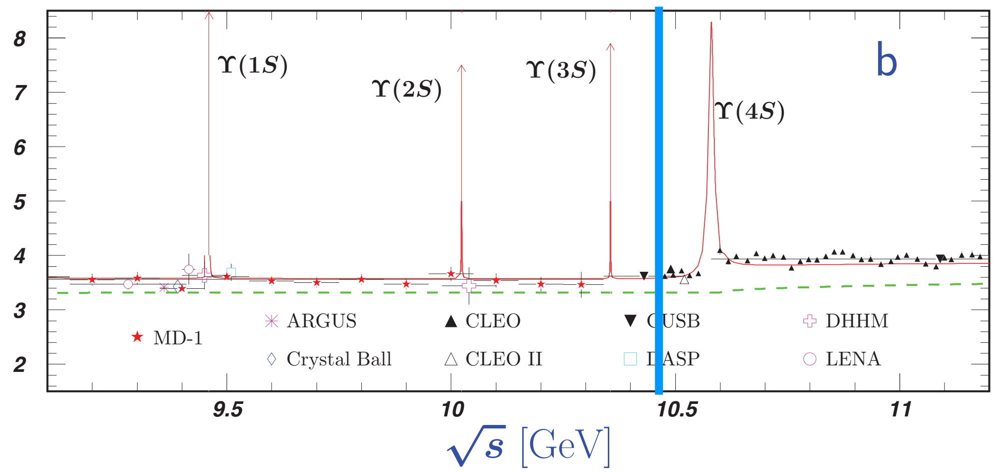
With central values as the present WA

Facilities for *CP* violation physics

The glorious past

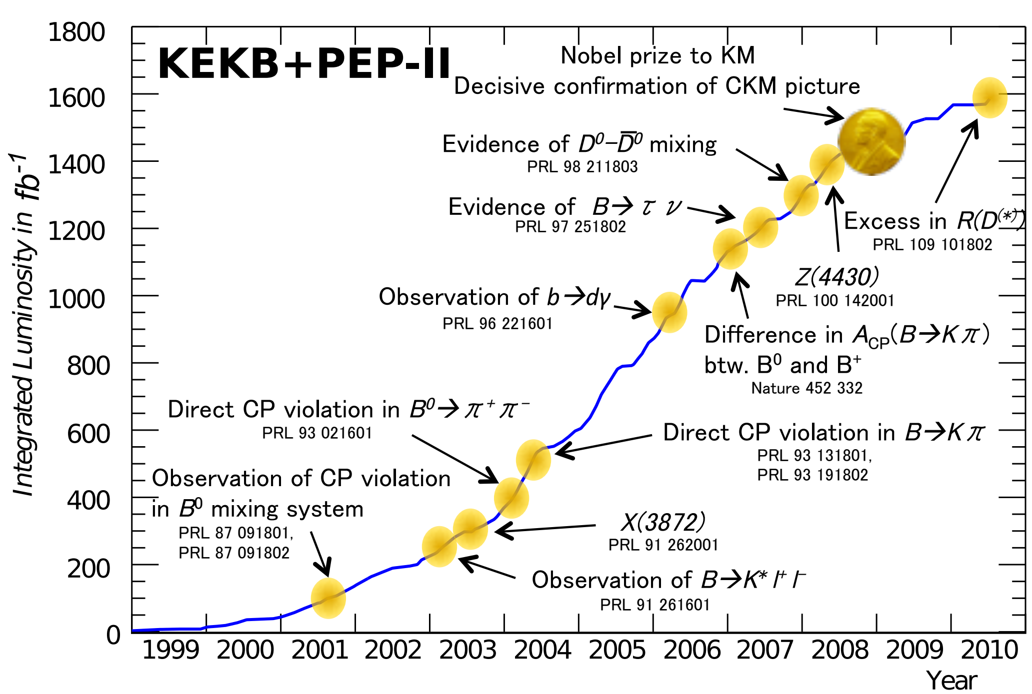


Total ~470fb-1

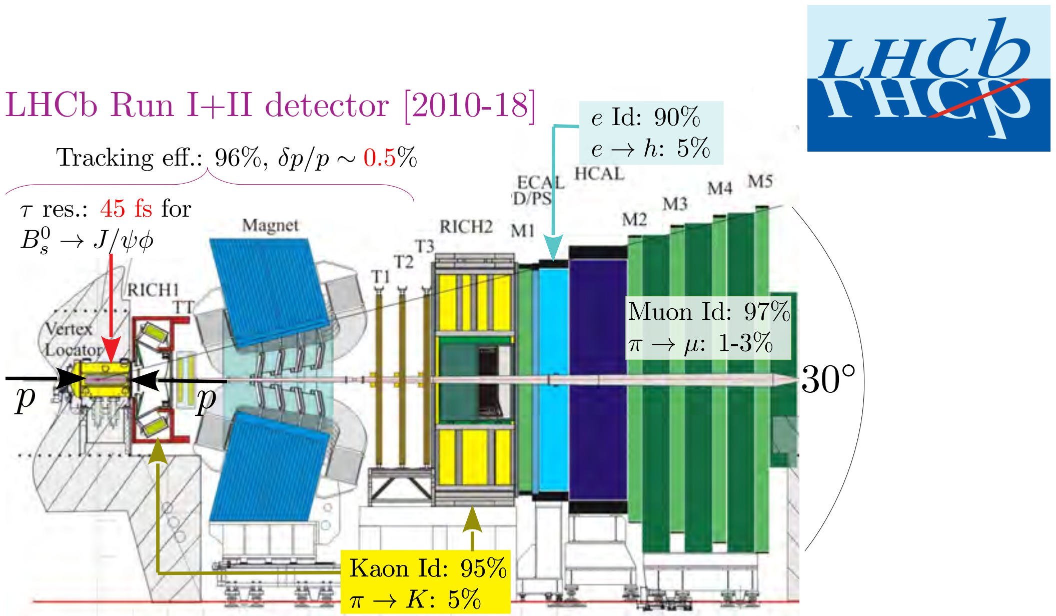


e^+e^- , asymmetric beam energies, (mainly) *Y(4S)*

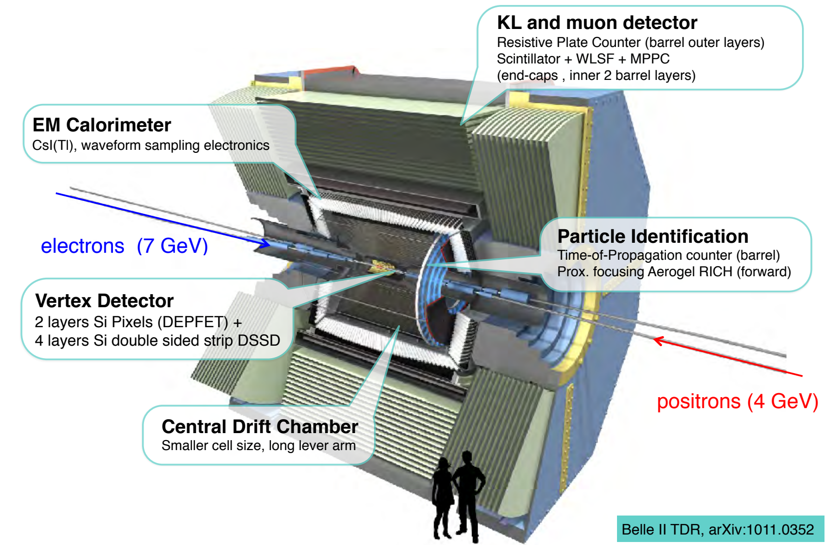
~870fb-1



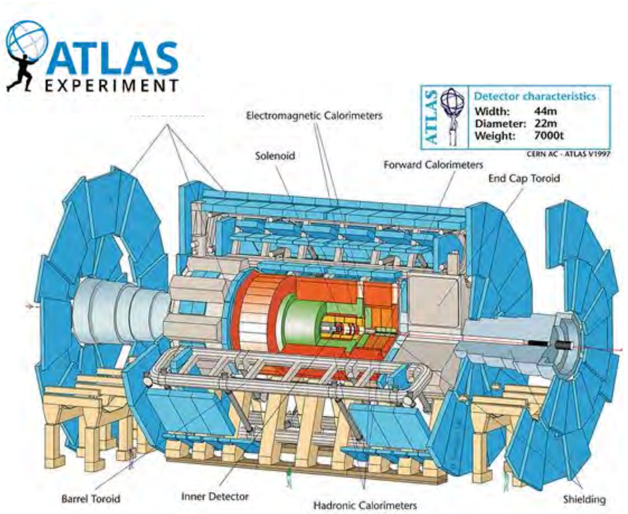
Present facilities for *CP* violation physics

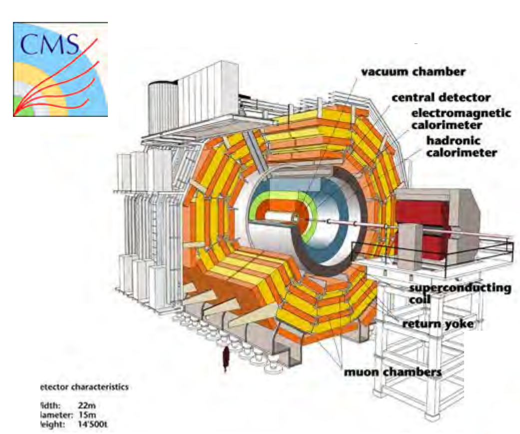


- pp collisions at LHC in forward region with large boost
- Excellent performance for *B* and *D* physics, can also measure baryons
- **σ(bb) = 250-500 μb** — ~9 fb^{-1} collected to date
- Restart data taking in 2022 with upgraded detector (x 5 data sample?)



- At SuperKEKB *B* (and charm, tau…) -factory, aiming at **factor 30** increase in specific luminosity
- simple trigger and event environment with B anti-B pairs produced in a coherent QM state with no additional particles.
- excellent *neutrals* and *electron* reconstruction, hermetic
- **σ(bb) = 1.1 nb** — ~200fb^{-1} collected to date

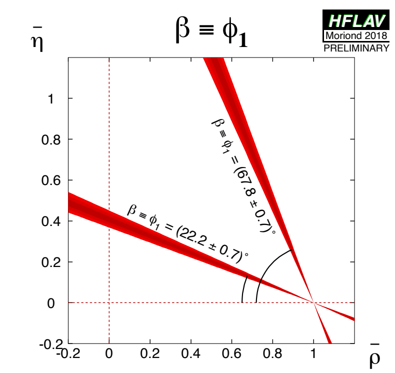




- General purpose detectors at LHC not designed for the intensity frontier
- Excellent performance
- **σ(bb) = 250-500 μb** — ~200fb^{-1} collected by each.

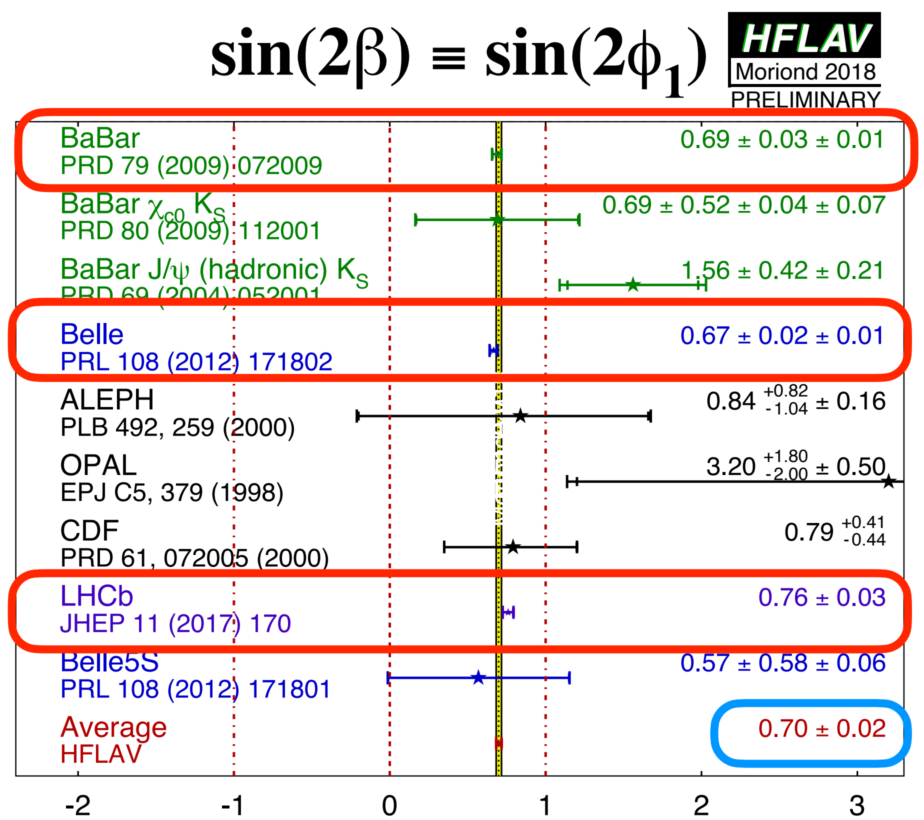
Measurements of β/ϕ1

$$\phi_1 = \beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$



- $B^0 \longrightarrow J/\psi K^0$ provides the most precise determination of sin($2\phi_1$)
  - theoretically clean(*) (tree-level), experimentally clear, first evidence of *CP* violation in the *B* system in the *B* factory era
  - reference to other determinations of sin($2\phi_1$) (or $\eta_f S_f$), dominated by loop diagrams and therefore sensitive to possible NP effects

Present status



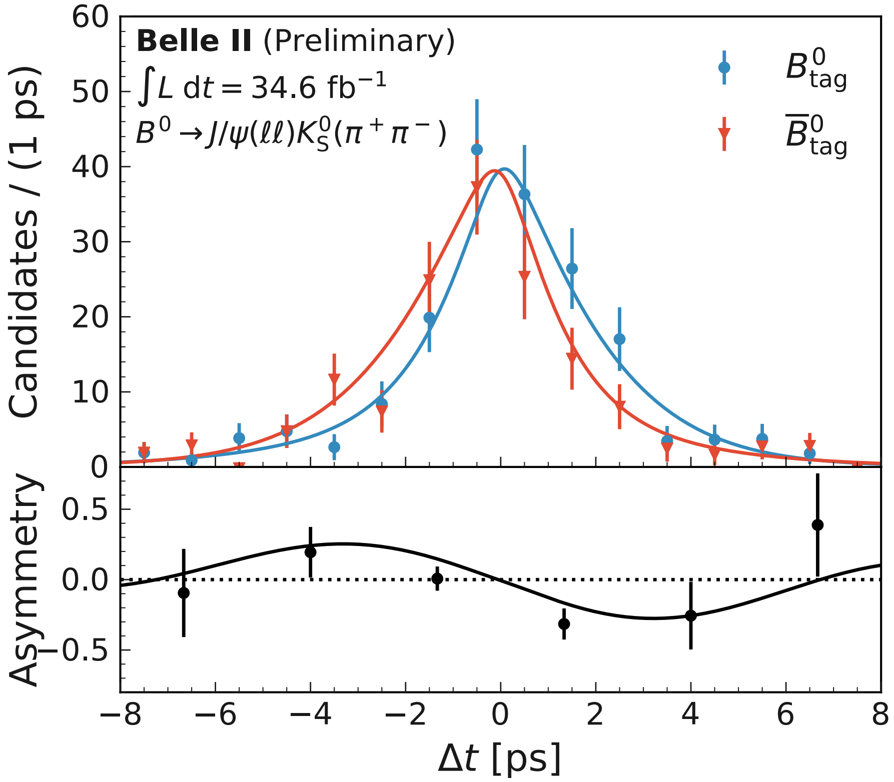
(*) long distance penguin effects can be disentangled eg with $J/\psi\pi^0$ and $J/\psi\pi^+$ decays

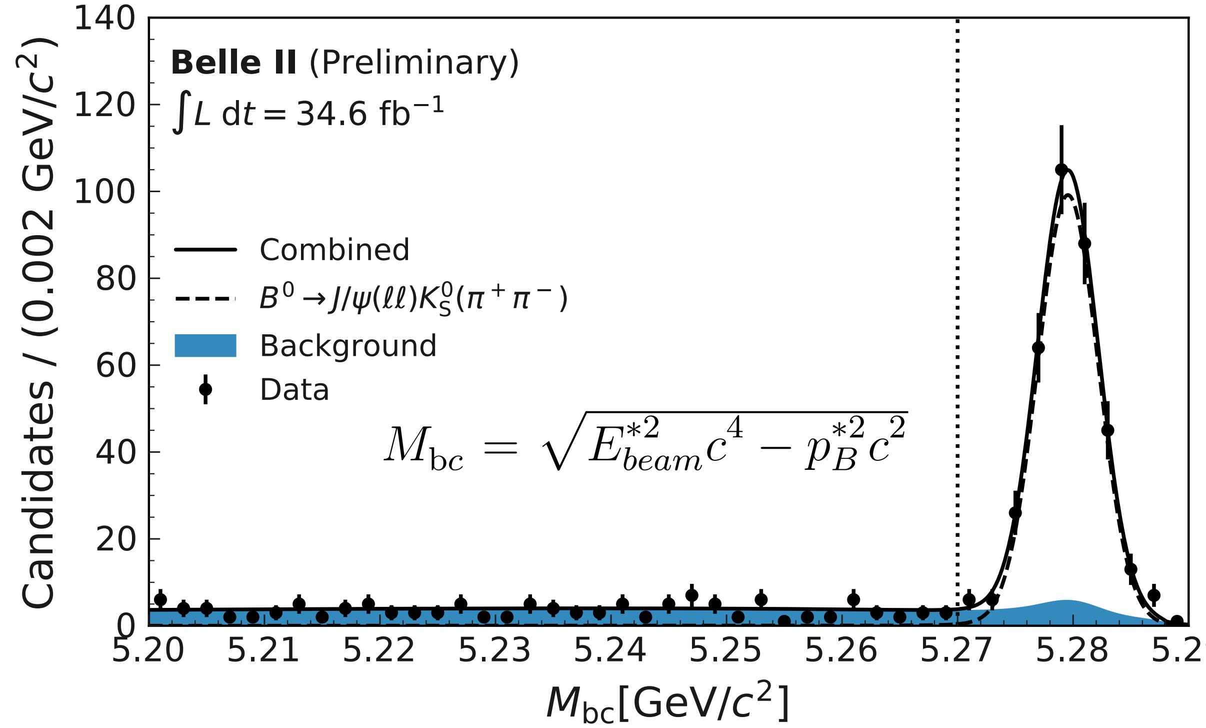
  - The $B^0 \longrightarrow J/\psi K^0$ analysis uses several key features (track and neutral reconstruction, vertexing, flavour tagging) of many analyses in the Belle II program: a good benchmark to gauge the performance.

Early TD measurements in $B^0 \to J/\psi K_S$

34.6 fb^{-1}

BELLE2-NOTE-PL-2020-011





$$A_{CP} = A^{\rm raw}_{CP}\,(1-2w)\otimes R(\Delta t)$$
$$= \sin(2\phi_1)\sin(\Delta m_d \Delta t)\,(1-2w)\otimes R(\Delta t)$$

$(1-2w)\otimes R(\Delta t)$ determined with high-statistics $B^0 \to D\pi$ sample

$$S_f = 0.55 \pm 0.21 \pm 0.04$$

- Presently no sensitivity on direct CPV
- Result consistent with WA

Paper on flavor tagging submitted to EPJC arXiv:2110.00790 [hep-ex]

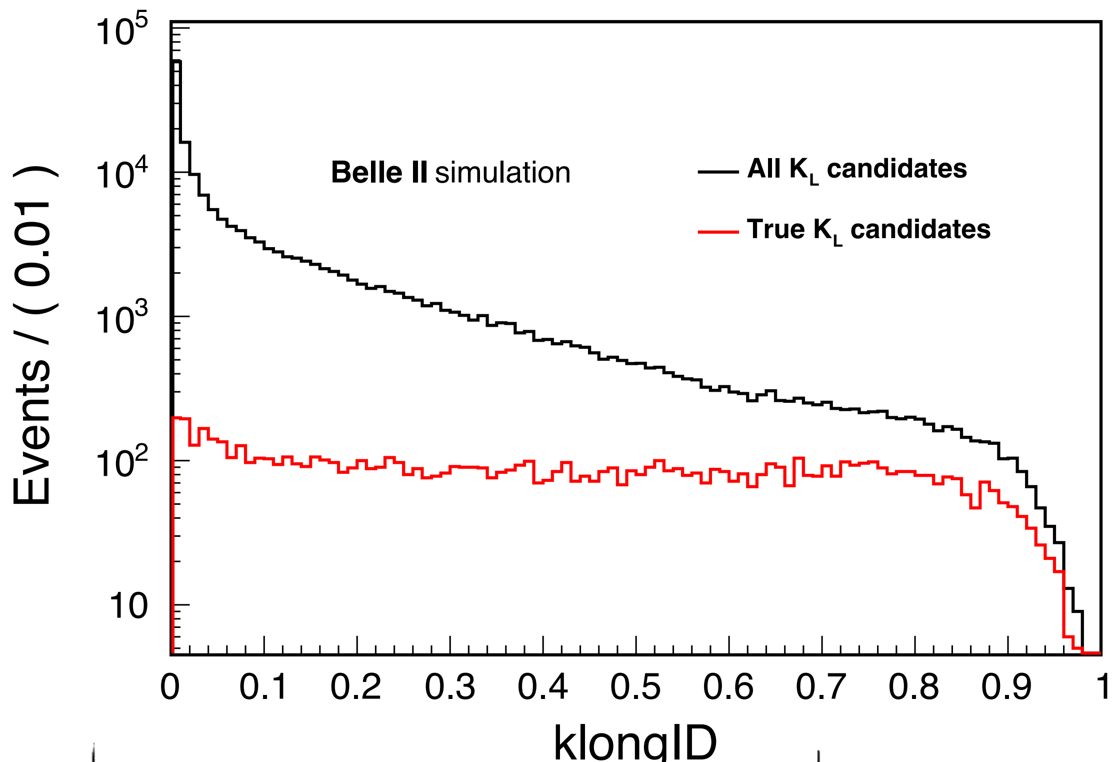
ε_{eff} = (30.0±1.2±0.4)%

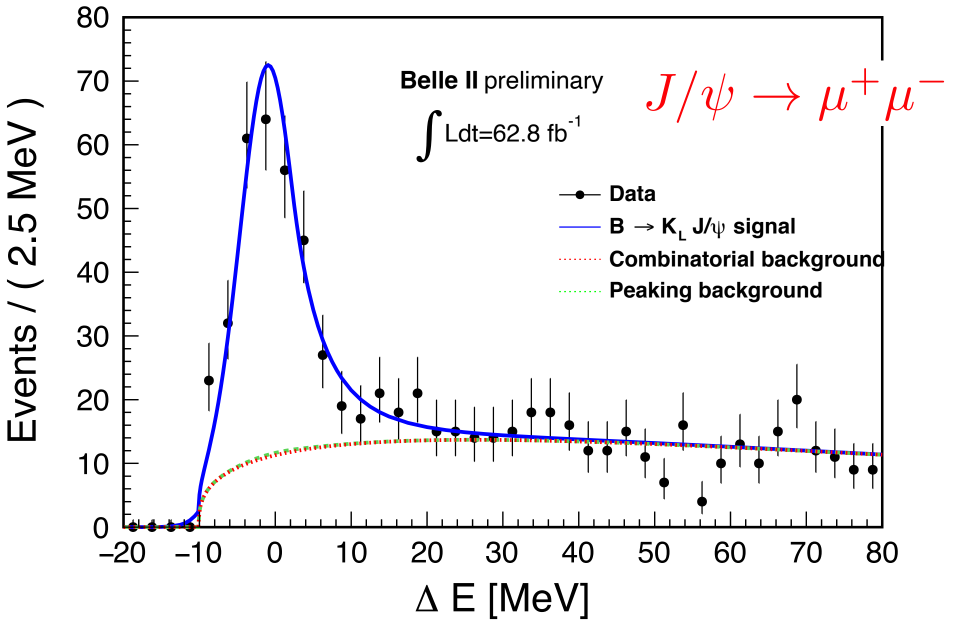
$B^0 \to J/\psi K^0_L$

62.8 fb^{-1}

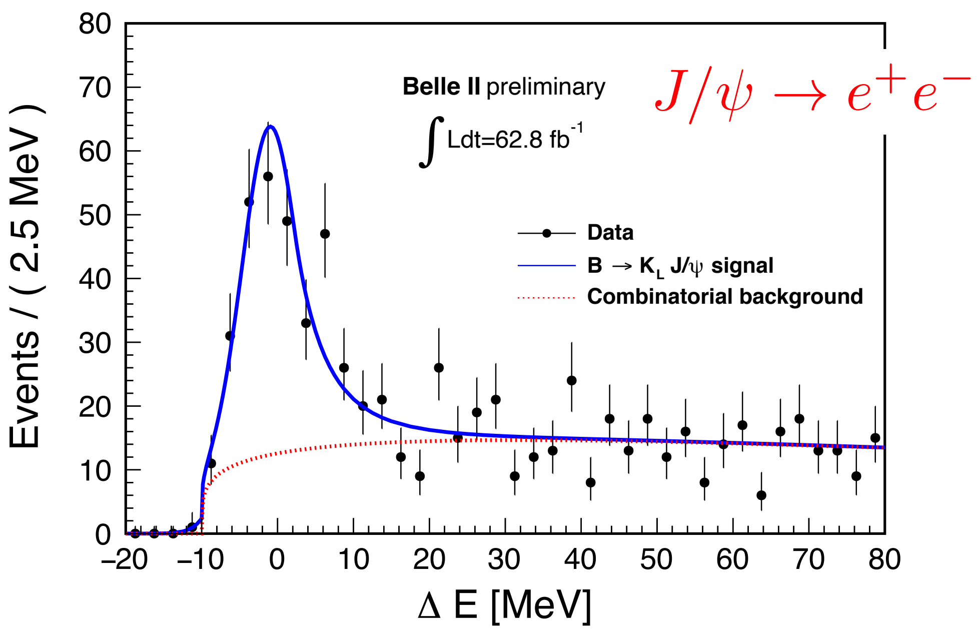
arXiv:2106.13547 [hep-ex]

- Belle II can reconstruct K^0_L mesons
- K^0_Ls reconstructed from neutral energy deposits in the KLM and ECL sub-detectors
- Multivariate selector to optimise efficiency and purity





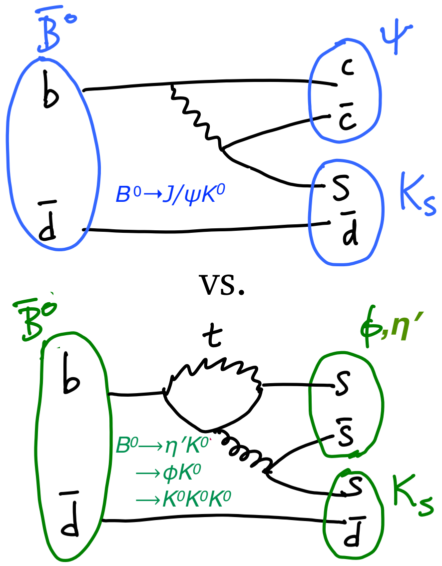
$$\Delta E = E^*_B - E_{beam}$$



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

- Efficiency and purity consistent with Belle

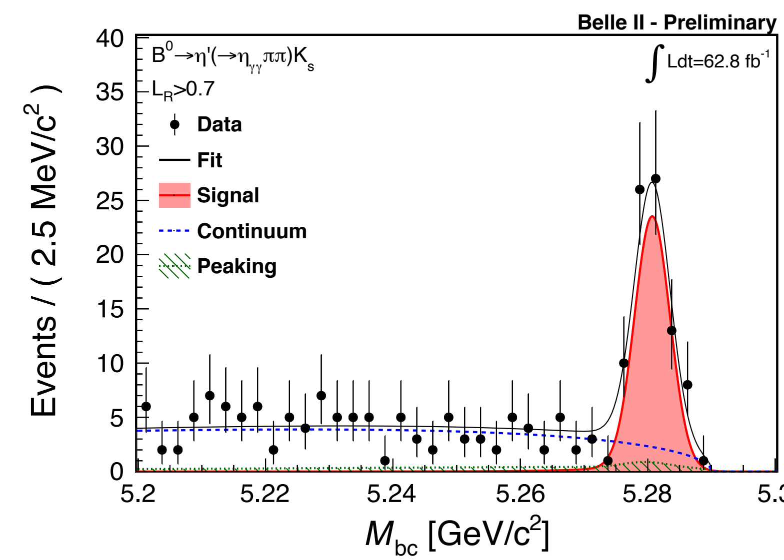
New *CPV* phases in $B \longrightarrow s$ penguin decays

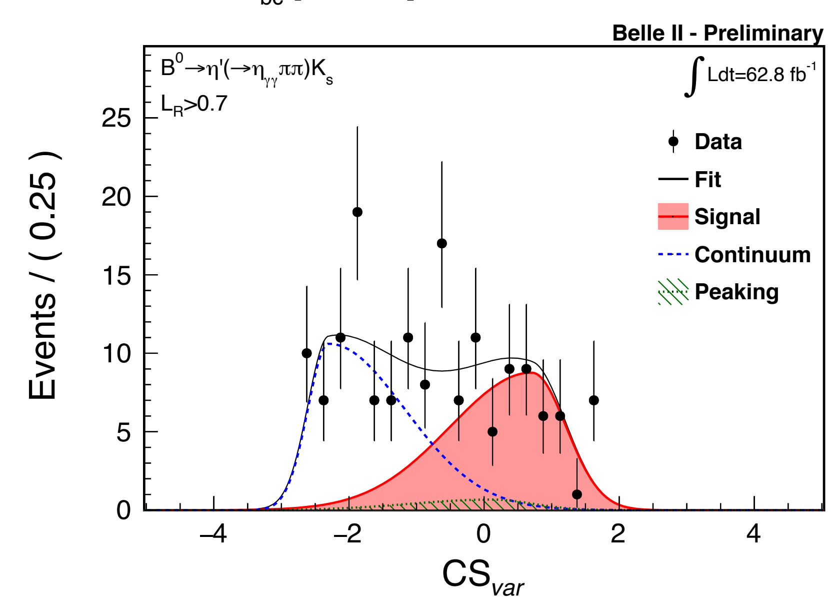


- In the SM the same value for "sin2β" is expected for the $b \to c\bar{c}s$, $b \to c\bar{c}d, b \to s\bar{s}s, b \to d\bar{d}s$ modes, but different BSM contributions can produce different asymmetries
- $b \to s\bar{s}s$ modes (with different degrees) show the best experimental and theoretical sensitivity
- Improvements of theoretical prediction also needed

- $B^0 \to \eta' K^0$ is the golden channel for the detection of NP in penguin-dominated decay modes
- Main challenge is the control of "continuum" background
- Dedicated multivariate signal/continuum discriminator, included in the final ML fit

Mode	B(10^{-6})
$B^\pm \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^\pm$	$63.9^{+4.6}_{-4.4} \pm 4.0$
$B^\pm \to \eta'(\to \eta(\to \pi^+\pi^-)\gamma)K^\pm$	$62.9^{+4.8}_{-4.8} \pm 5.5$
$B^0 \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^0_S$	$61.6^{+8.6}_{-8.0} \pm 3.9$
$B^0 \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^0_S$	$58.5^{+7.9}_{-7.4} \pm 4.4$





- Belle II competitive due to neutrals in the final state
- BF results consistent with the WA $S_f(\eta' K)$=0.63±0.06
- Event yield almost double than in Belle

Eventually, a factor ~5 improvement in β/ϕ_1 expected from Belle II

ϕ_s from $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$ at ATLAS and CMS

$$\phi_s \simeq -2\beta_s = -2arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

In the SM : $\phi_s = -37.9^{+0.7}_{-0.8}$ mrad

ATLAS: 80.5fb^{-1} @ 13 TeV — Eur. Phys. J C **81**, 342 (2021)

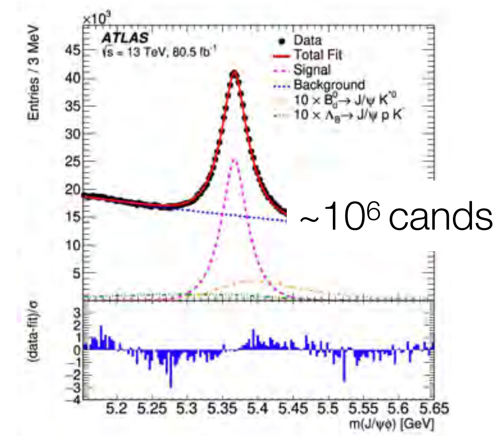
CMS: 96.4fb^{-1} @ 13 TeV — Phys. Lett. B **816** (2021) 136188

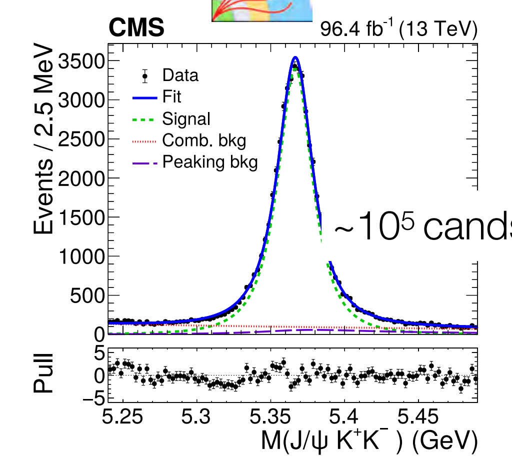
Event Selection

Trigger: J/ψ from 2 OS muon tracks (+ additional muon to tag the B_s flavour in CMS).

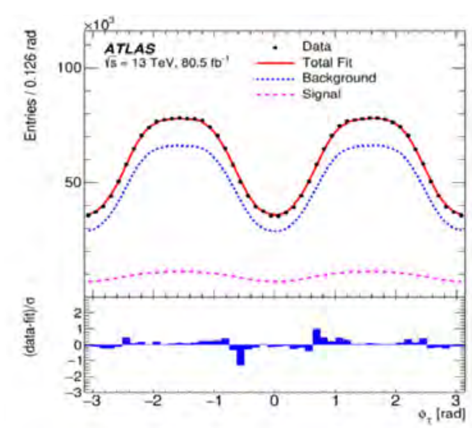
B_s flavour tag with OS semileptonic decays

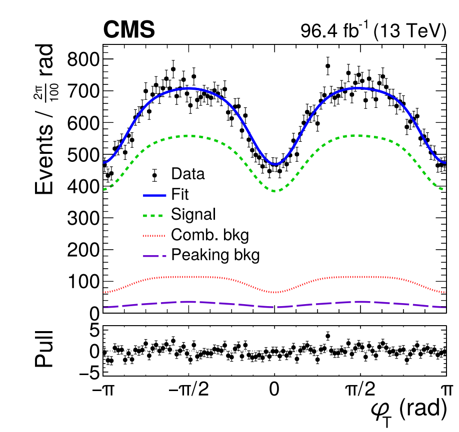
power$_{ATLAS}$=(1.75±0.01)% power$_{CMS}$=(10.5±0.1)%





- VV decay ==> complex angular analysis to disentangle the *CP*-even and *CP*-odd components
- 6-D (3 angles, decay time, ω_s, decay time error) maximum-likelihood fit to extract ϕ_s





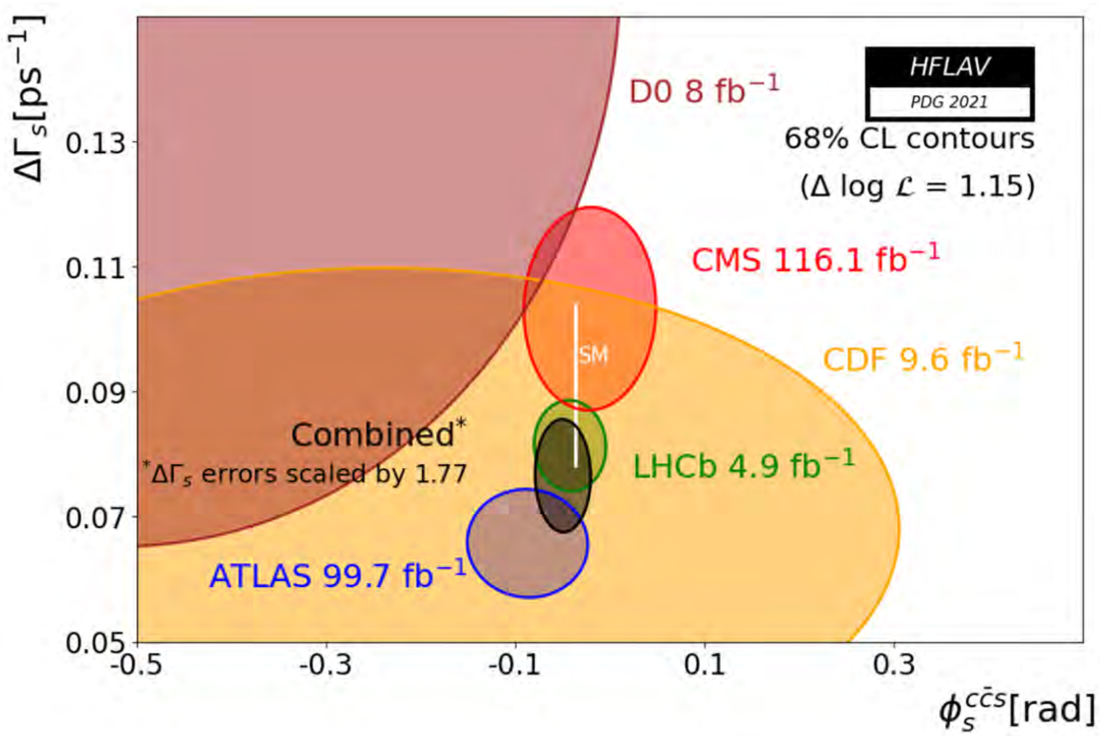
Status of ϕ_s measurements

ATLAS

$$\begin{aligned}\phi_s &= -0.087 \pm 0.036\ (\text{stat.}) \pm 0.021\ (\text{syst.})\ \text{rad} \\ \Delta\Gamma_s &= 0.0657 \pm 0.0043\ (\text{stat.}) \pm 0.0037\ (\text{syst.})\ \text{ps}^{-1} \\ \Gamma_s &= 0.6703 \pm 0.0014\ (\text{stat.}) \pm 0.0018\ (\text{syst.})\ \text{ps}^{-1}\end{aligned}$$

CMS

$$\begin{aligned}\phi_s &= -11 \pm 50\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad}, \\ \Delta\Gamma_s &= 0.114 \pm 0.014\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}\end{aligned}$$



HFLAV combined result $\phi_s = -0.050 \pm 0.019$

- Still statistically dominated
- Consistent with standard model and no *CPV*
- Several Run2 analyses ongoing ==> expect improvement of precision

2-body or quasi-2- body charmless B decays (and α/ϕ_2)

62.8 fb^{-1}

Towards α at Belle II

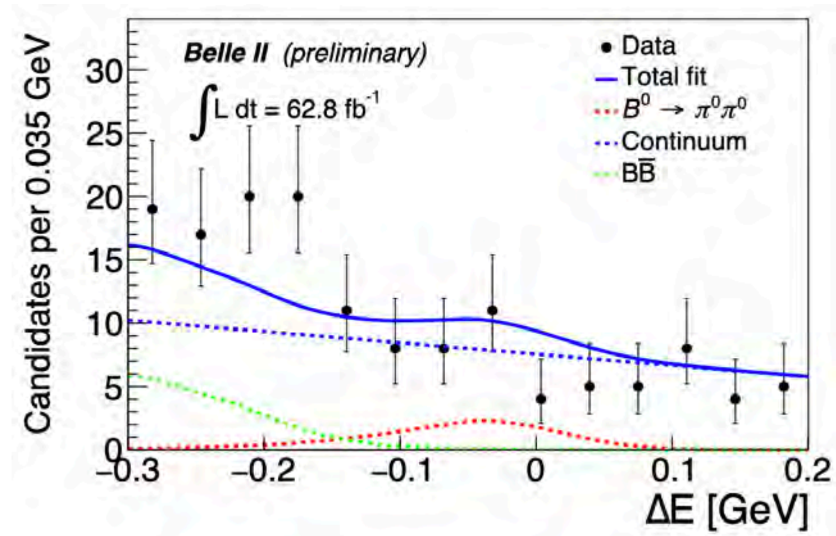
$$\phi_2 = \alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$

Unique Belle II capability to study all the $B \to \pi\pi, \rho\rho$ partner decays to determine α.

$B^0 \to \pi^0\pi^0$: very challenging because four γ's.
Train BDT to suppress background photons.
Then 3D fit of ΔE-M_{bc}-continuum suppression BDT.
Unique Belle II reach.

$$\mathscr{B}(B^0 \to \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$$

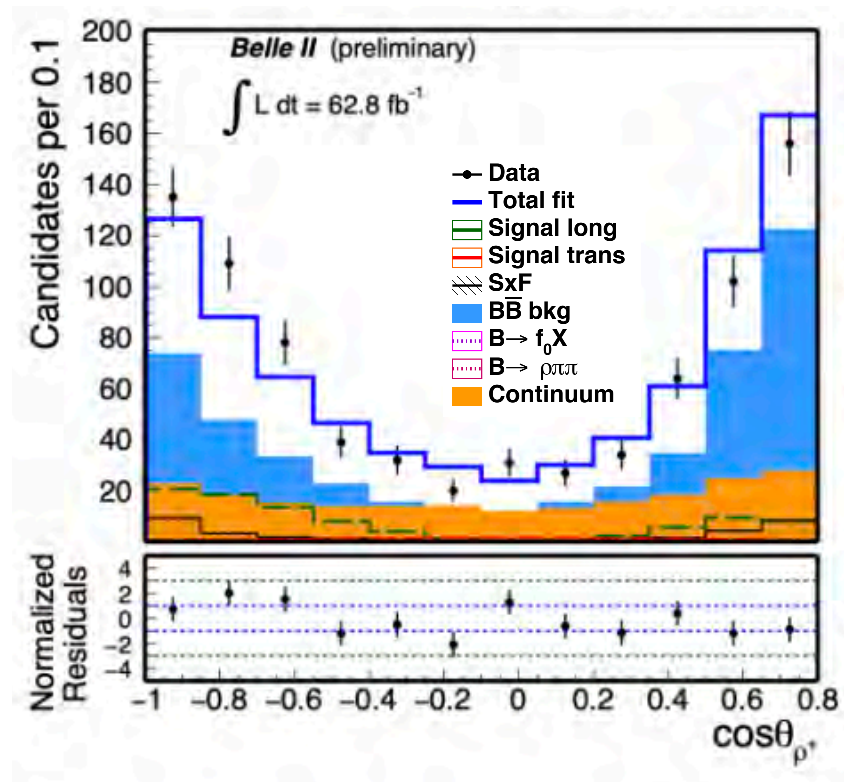
[arXiv:2107.02373]



$B^+ \to \rho^+\rho^0$: π-only final state, large background because of ρ mass width. Additional challenge of angular analysis → 6D fit including helicity angles.

$$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$$
$$\mathscr{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$$

[arXiv:2109.11456]



20% precision improvement wrt Belle on the same lumi!
Wrt BaBar's best (scaled): better on BF, same on f_L.

On track to measure the CKM angle *α* at Belle II

Charmless 2-body decays and the K-π puzzle

- Long-standing significant difference in the direct *CP* asymmetries in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays:

$$\Delta A_{CP} = 0.124 \pm 0.021$$

  - At tree level, only the spectator quark differs (but loop diagrams do contribute)
  - Large hadronic uncertainties
  - …which can be strongly reduced with suitable combinations of BF and CPV asymmetries

M. Gronau, Phys.Lett. B627 (2005) 82

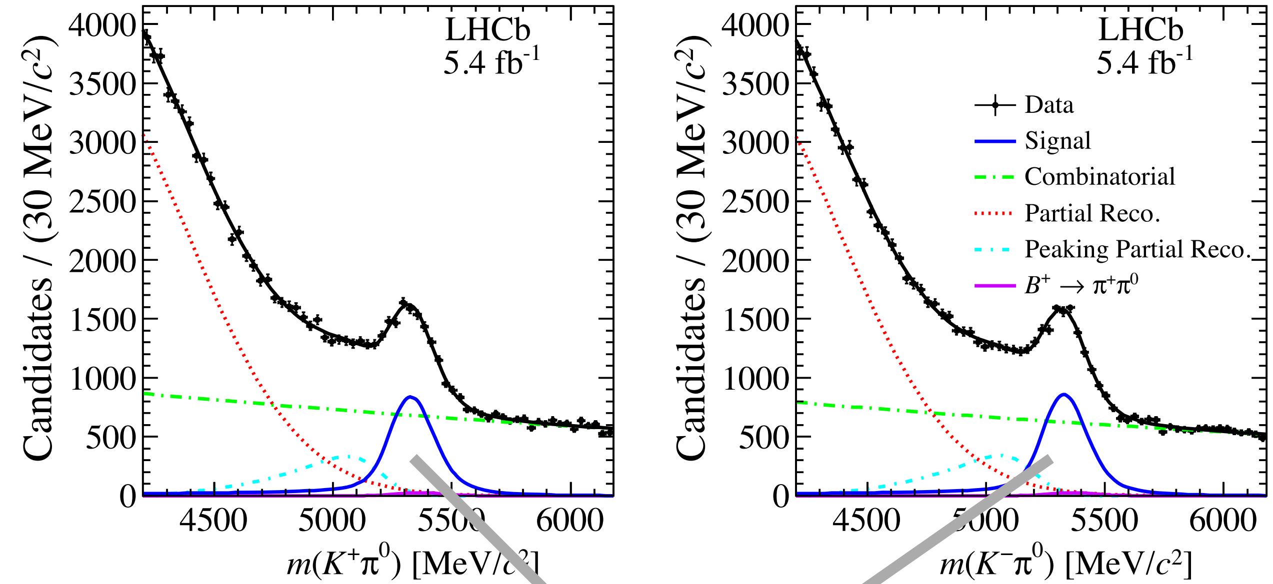
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- This isospin sum rule provides a stringent null test sensitive to potential NP effects.

Measurement of *CP* violation in $B^+ \to K^+\pi^0$ decays

6 fb^{-1} PRL 126 (2021) 091802

- Small CPV predicted by SM
- Effects of loop diagrams potentially larger
- Challenging measurement at a hadron collider



$$A_{CP}^{K^+\pi^0} = A_{\rm raw}^{K^+\pi^0} - A_{\rm prod}^{B} - A_{\rm det}^{K}$$

$$A_{\rm raw}^{K^+\pi^0}$$

$$A_{CP}^{J/\psi K^+} = A_{\rm raw}^{J/\psi K^+} - A_{\rm prod} - A_{\rm det}$$

From PDG

$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

Most precise measurement to date

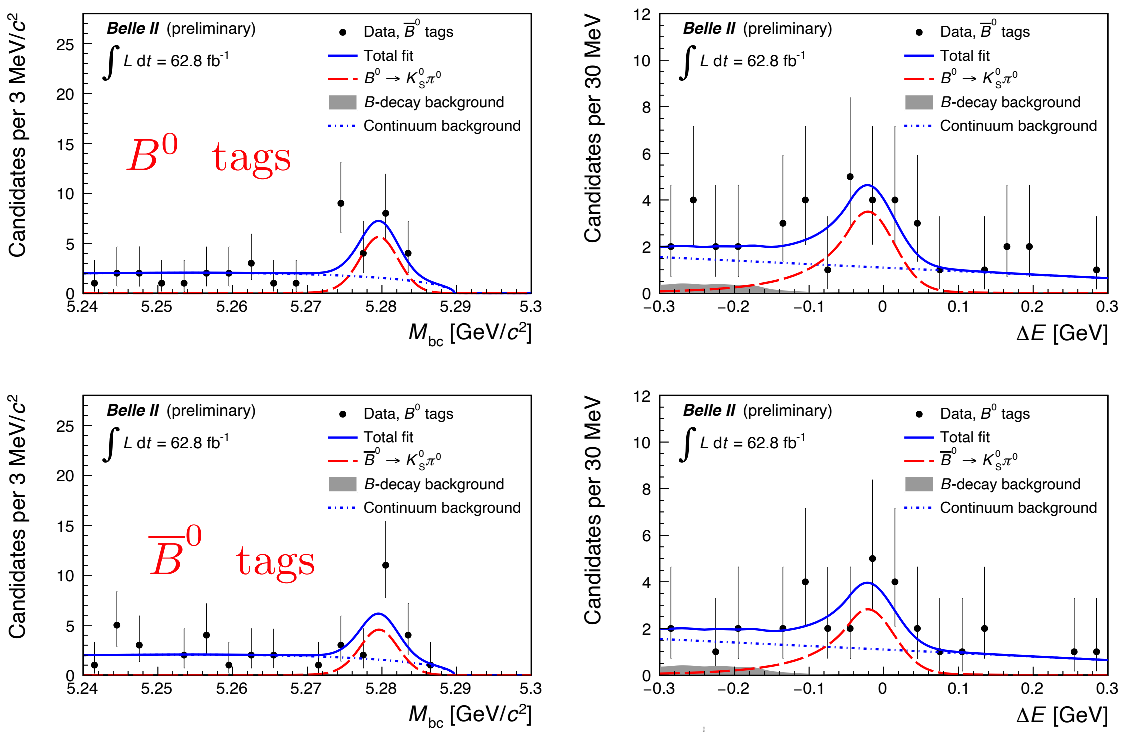
- Use $B \to J/\psi K^+$ control sample to determine other experimental asymmetries

$B^0 \to K^0\pi^0$ and the $K\pi$ puzzle

62.8 fb^{-1}

- Precision of the Isospin sum rule is limited by $\mathcal{A}_{K^0\pi^0}$
- Channel unique to Belle II

arXiv:2104.14871 [hep-ex]

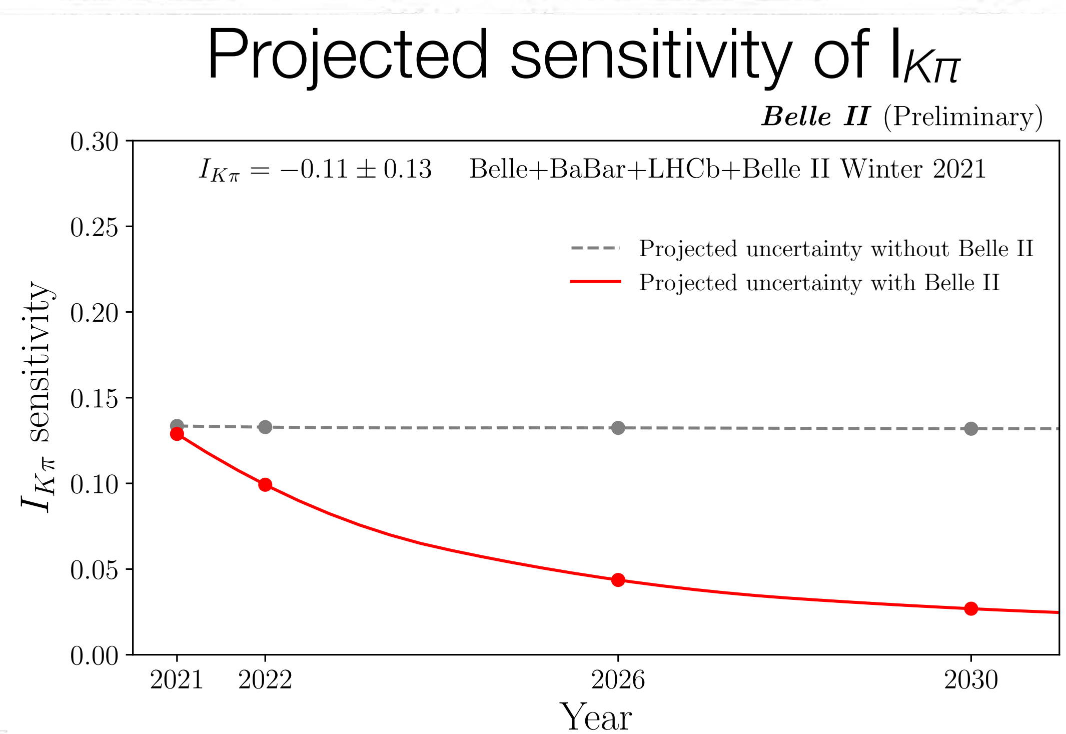


$$\mathcal{A}_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst}), \text{ and}$$

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

In agreement with previous measurements

Expect with more data to significantly contribute to the precision of the isospin sum rule determination

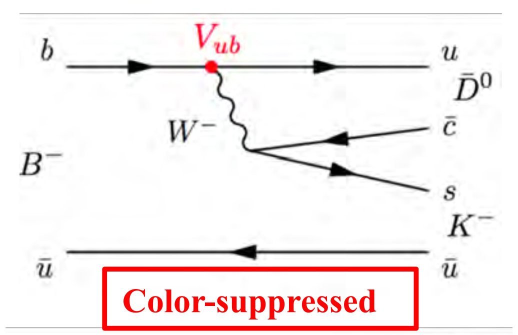


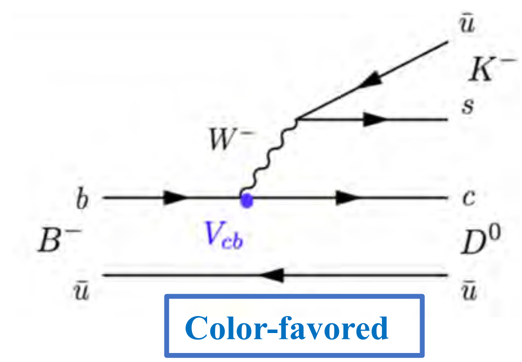
$$\gamma / \phi_3$$

Measurement of CKM angle γ/ϕ_3

$$\phi_3 = \gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$$

- Only CKM angle originated to very good extent by tree diagrams
  - Precisely calculable in the SM $\mathcal{O}(10^{-7})$ [J. Brod, J. Zupan, arxiv:1308.5663]
  - benchmark for NP searches
- Present status:





Direct measurement $\phi_3 = (66.4^{+3.4}_{-3.6})^\circ$ hflav.web.cern.ch

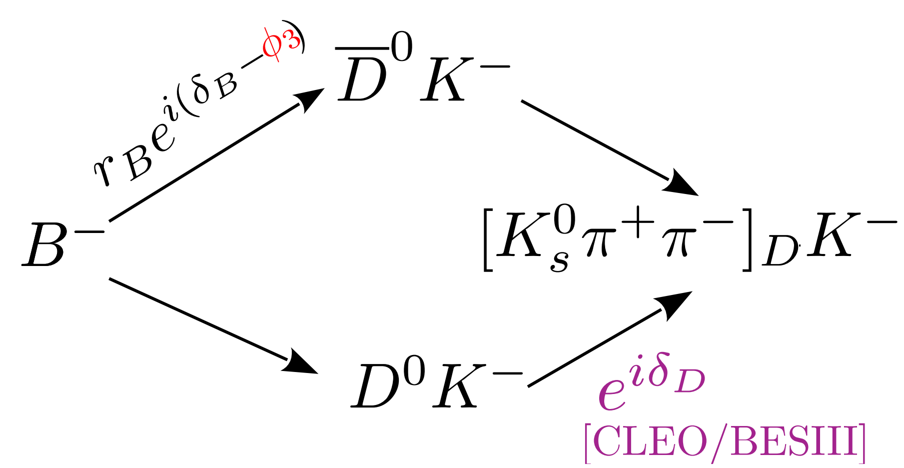
From UT constraints $\phi_3 = (65.7^{+0.9}_{-2.7})^\circ$ ckmfitter.in2p3.fr

Most precise ϕ_3 measurements obtained with Dalitz plot method

- Interference of self-conjugate multi-body final states: $D(K_S^0 h^- h^+)$ [Phys Rev D 68, 054018]
- Sensitivity to ϕ_3 from different Dalitz plot distributions of B^+ and B^-
- Dalitz structure contains strong phases of D decays

$$\frac{A^{suppr.}[B^- \to \overline{D^0} K^-]}{A^{favor.}[B^- \to D^0 K^-]} = r_B e^{i(\delta_B - \phi_3)}$$

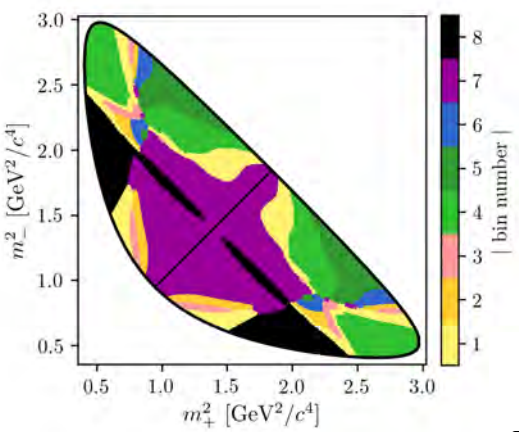
r_B amplitude ratio δ_B -strong-phase difference



Measurement of CKM angle γ/ϕ_3 with $B \to DK$ decays

9 fb^{-1} (7,8,13 TeV)

arXiv:2010.08483
JHEP 02 (2021) 169

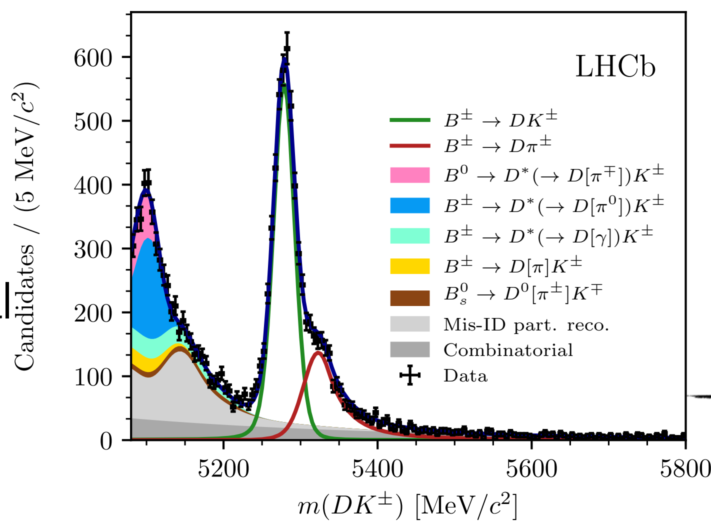


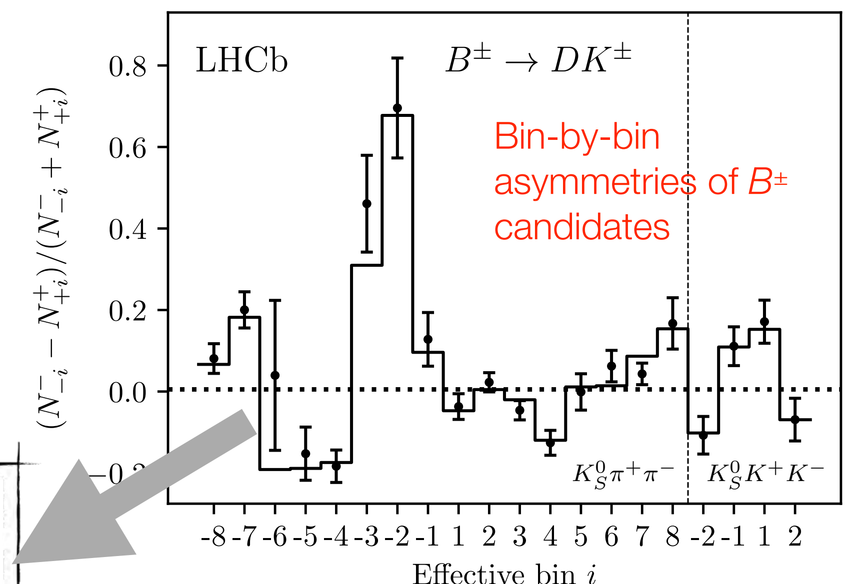
Model-independent analysis:

- Strong-phase difference between the D decay amplitudes in the Dalitz plot from CLEO and BES III combined data
- Use non uniform bins to optimise the sensitivity to γ.

New BES III measurement
[Phys. Rev. Lett. 124 (2020) 24, 241802]

"Global" fit to m_B to characterise the signal candidates

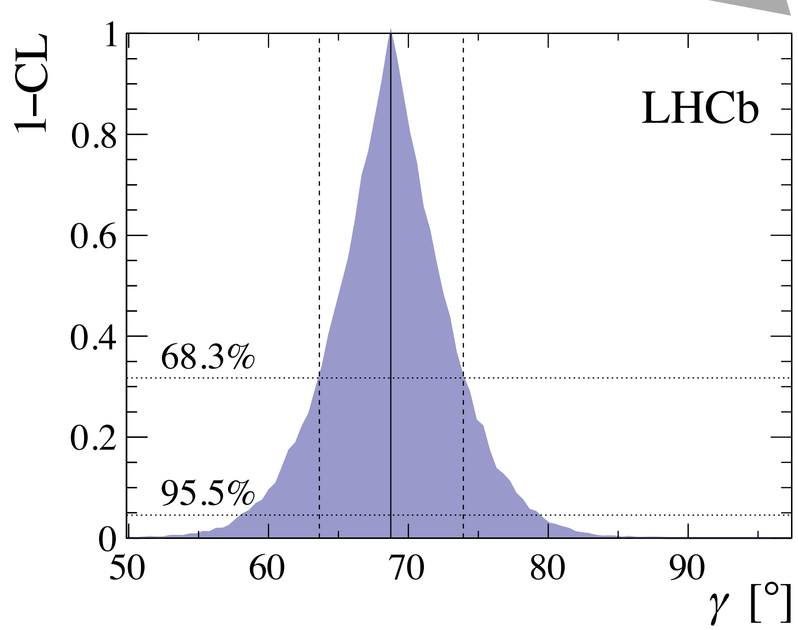




$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$

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

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



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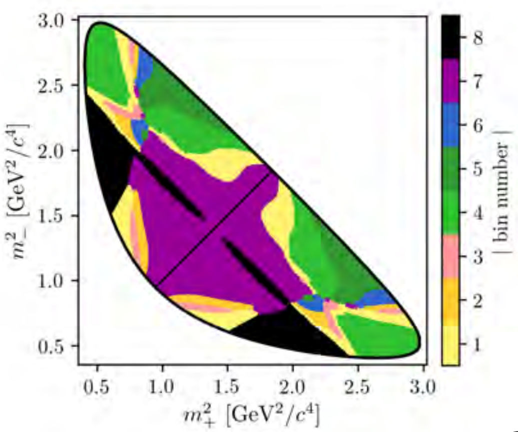
JHEP 02 (2021) 169



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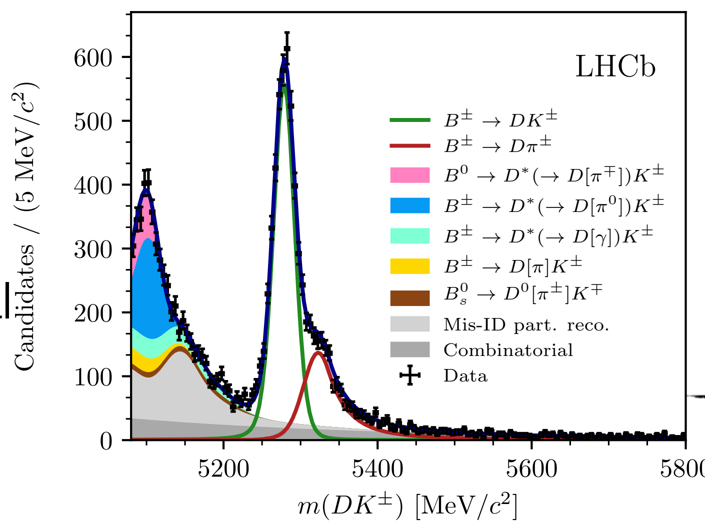

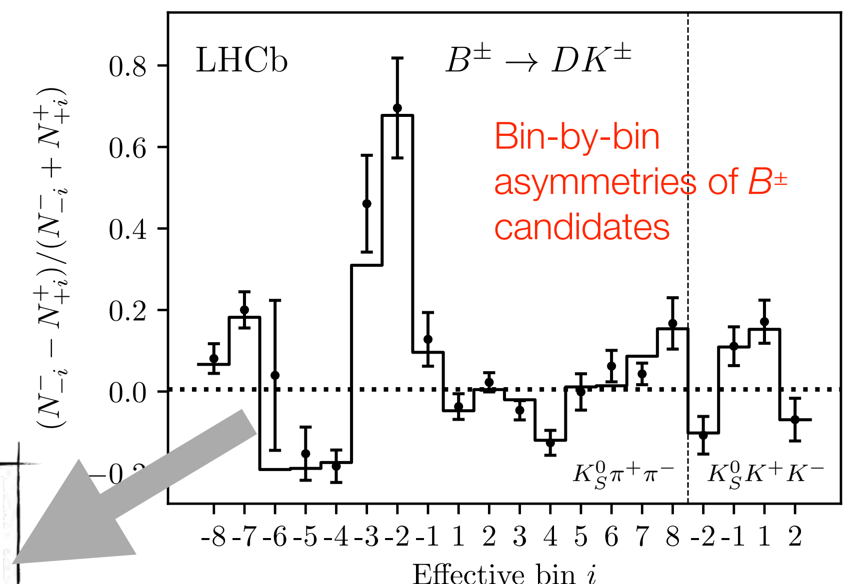

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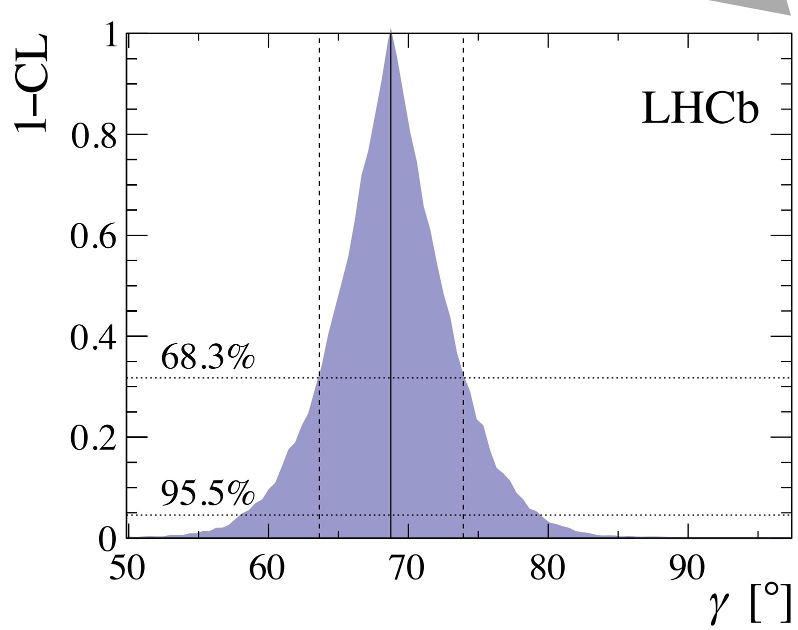
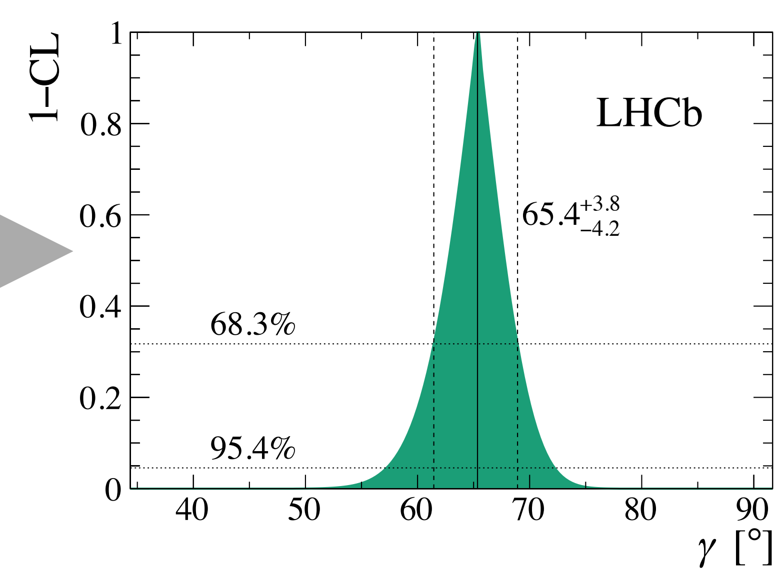




LHCb-CONF-2021-001

- New method to combine gamma and measurements of charm-mixing parameters (in LHCb)
- 151 observables, 52 parameters

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

- Most precise determination from a single experiment

Measurement of CKM angle γ/ϕ_3 with $B \to DK$ decays

Belle II + BELLE

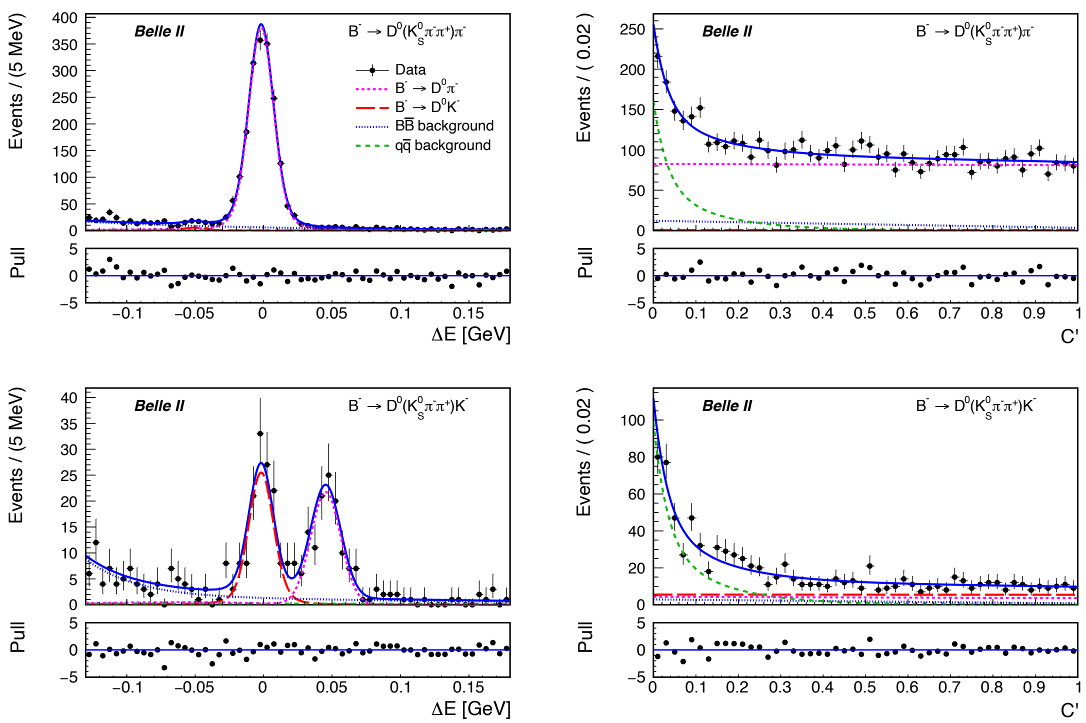
128 fb^{-1} (Belle II) + 711 fb^{-1} (Belle)

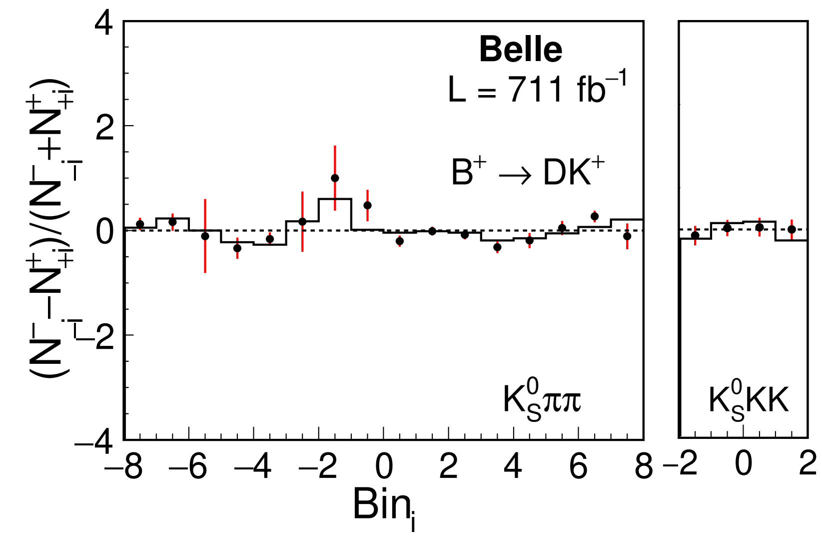
To be submitted to JHEP

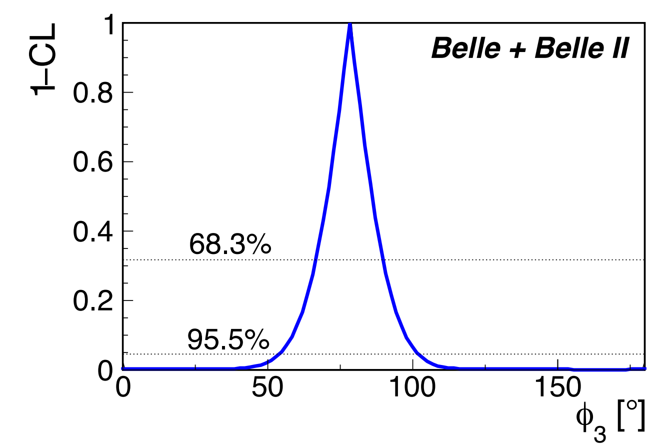
- LHCb dominates the scene, but Belle II can contribute, particularly in modes with neutrals in the final state
- Good K/π separation is important to suppress the dominant $B \to D\pi$ decays
- First analysis using the combined Belle and Belle II data sets
- Model-independent method

New BES III measurement os strong D0 phase differences [Phys. Rev. Lett. 124 (2020) 24, 241802

Belle II signal-enhanced projections in the $D[K_S^0\pi^+\pi^-]h^+$ final state







Combined results:

$\delta_B(^\circ)$	124.8 ± 12.9 (stat.) ± 0.5 (syst.) ± 1.7 (ext. input)
r_B^{DK}	0.129 ± 0.024 (stat.) ± 0.001 (syst.) ± 0.002 (ext. input)
$\phi_3(^\circ)$	78.4 ± 11.4 (stat.) ± 0.5 (syst.) ± 1.0 (ext. input)

$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$

$r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$

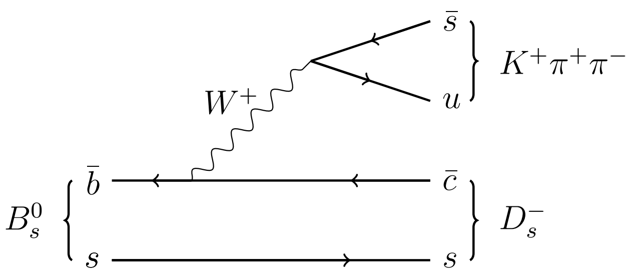
$\delta_B = (129.9 \pm 15.0 \pm 3.8 \pm 4.7)^\circ$

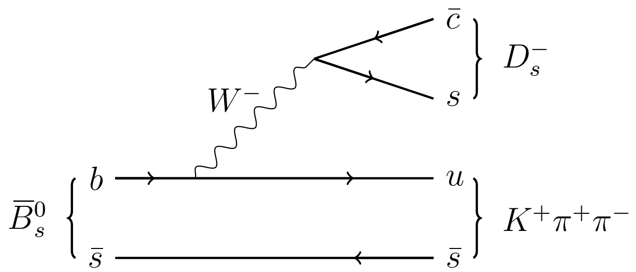
Significant improvement wrt the published Belle result [Phys. Rev. D 85 112014 (2012)] due to the analysis method, and more precise strong-phase inputs

γ from TD analysis of $B_s^0 \to D_s^{\mp} h^{\pm} \pi^{\pm} \pi^{\mp}$ decays

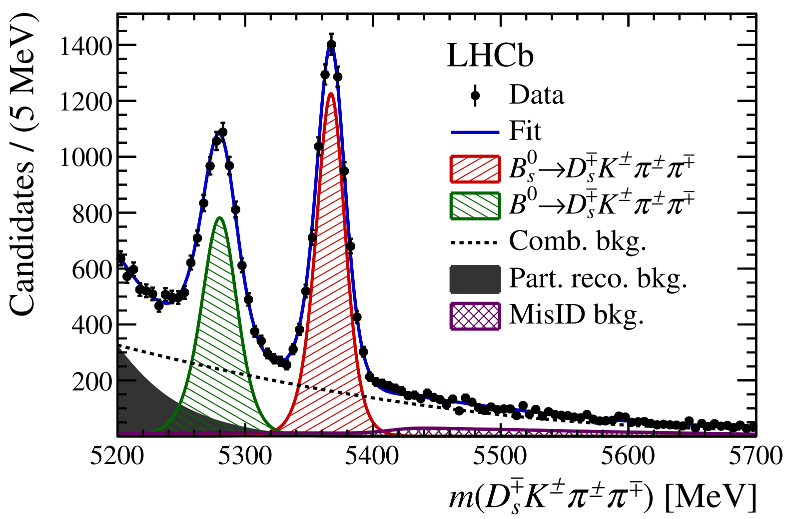
9 fb⁻¹ (7,8,13 TeV)

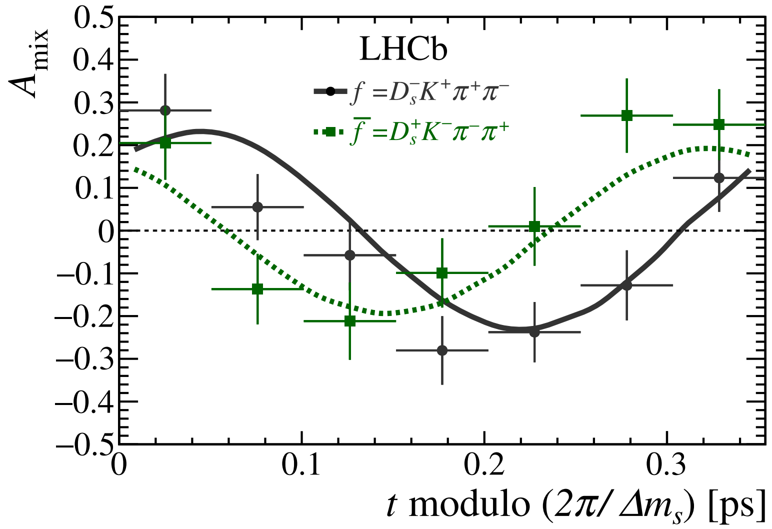
arXiv:2011.12041
JHEP 03 (2021) 137





- Interference of mixing and decay to the same final state
- Several final states contributing: complicated model-independent 5D amplitude analysis





- The fit measures $\gamma - 2\beta_s$; use LHCb measurement of β_s as external input to extract γ
- Alternative model-dependent analysis integrating over the 5D phase space. Results in excellent agreement
- 4.4/4.6 sigma evidence for mixing-induced CPV, and (dis)agree with the γ WA by 2.2/1.6 sigma.

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 [°]	$-6\,^{+10}_{-12}\,^{+2}_{-4}$	$-14 \pm 10 \pm 4 \pm 5$
$\gamma - 2\beta_s$ [°]	$42\,^{+19}_{-13}\,^{+6}_{-2}$	$42 \pm 10 \pm 4 \pm 5$

Observation of *CP* violation in D^0 decays

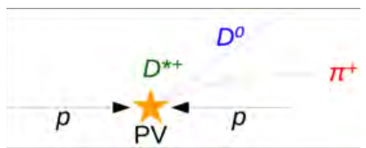
5.9 fb^{-1} (13 TeV)

Two possible flavour tags:

PRL 122, 211803 (**2019**)

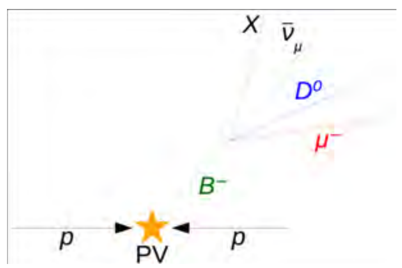
prompt

$D^{*\pm} \to D^0\pi^\pm$



semileptonic

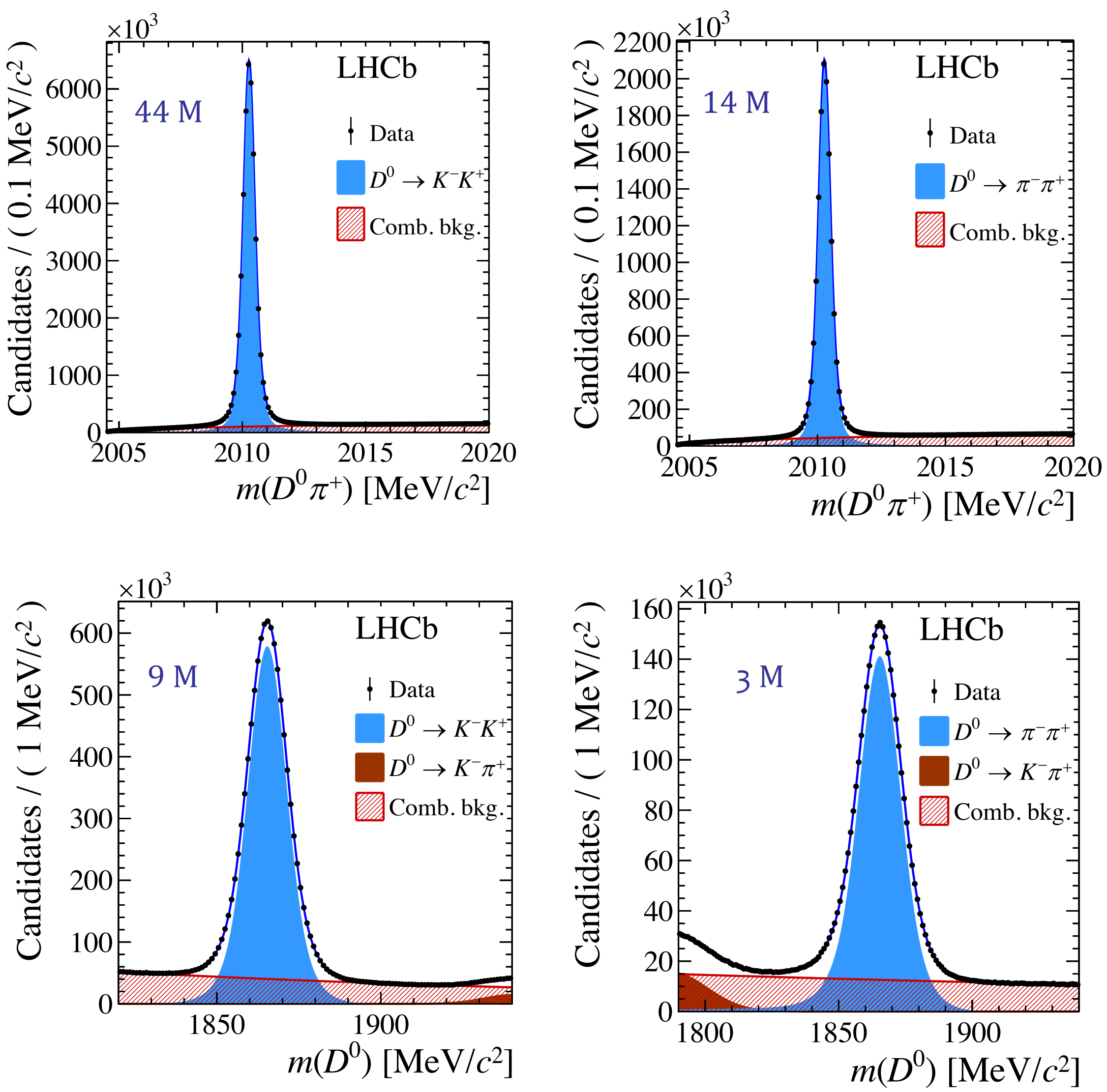
$B \to D^0\mu^\pm X$



$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \qquad A_{\rm raw}(f) = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

In ΔA_{CP} production and reconstruction asymmetries cancel out



$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

Compatible with previous LHCb results and the WA

Combination (including Run1+Run2) of prompt and semileptonic events:

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}}$$

$$\Delta a_{CP}^{\rm dir} \approx \Delta A_{CP} + \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma = (-15.7 \pm 2.9) \times 10^{-4}$$

5.3σ significance for direct CPV!

Measurement of *CP* violation in $D^0 \to K^0_S K^0_S$ decays

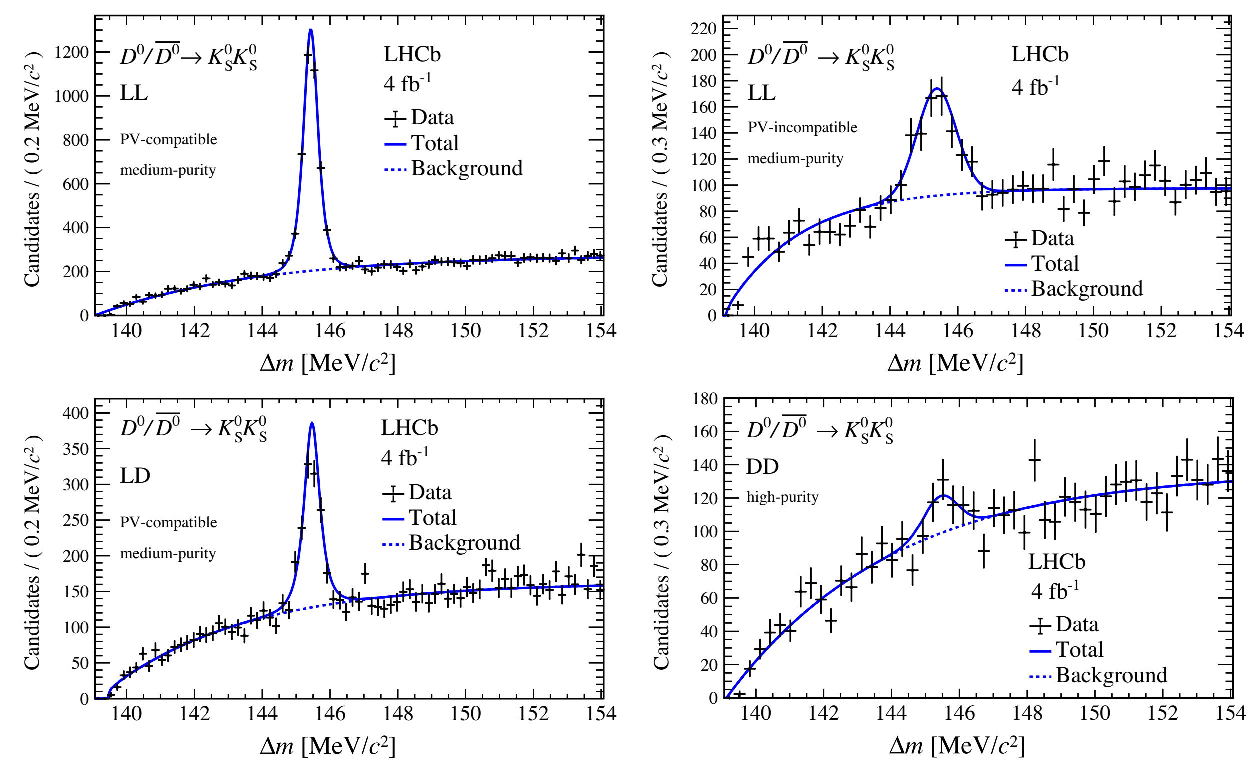
6 fb^{-1}

PR D 104, L031102 (2021)

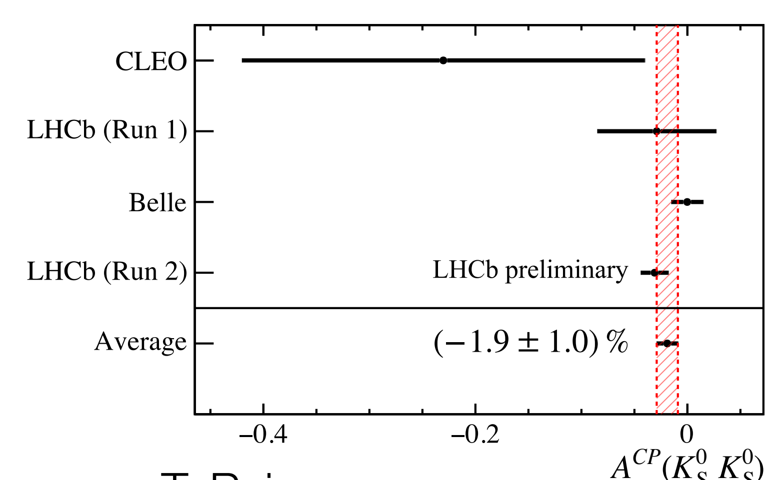
- Need to study CPV in additional D^0 decay channels
- No tree-level amplitude in SM (only annihilation & penguin)
- Effects of non-SM loop diagrams potentially large

$$\mathcal{A}^{CP}(K^0_S K^0_S) = \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\bar{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\bar{D}^0 \to K^0_S K^0_S)}$$

- Flavour tag from the soft pion charge in $D^{*\pm} \to D^0 \pi_s^\pm$ decays.



$$\mathcal{A}^{CP}(K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$



- Most precise measurement to date — an essential step to find CPV in the charm mixing
- Belle II will have also a good handle on this decay

T. Pajero
http://cds.cern.ch/record/2752245

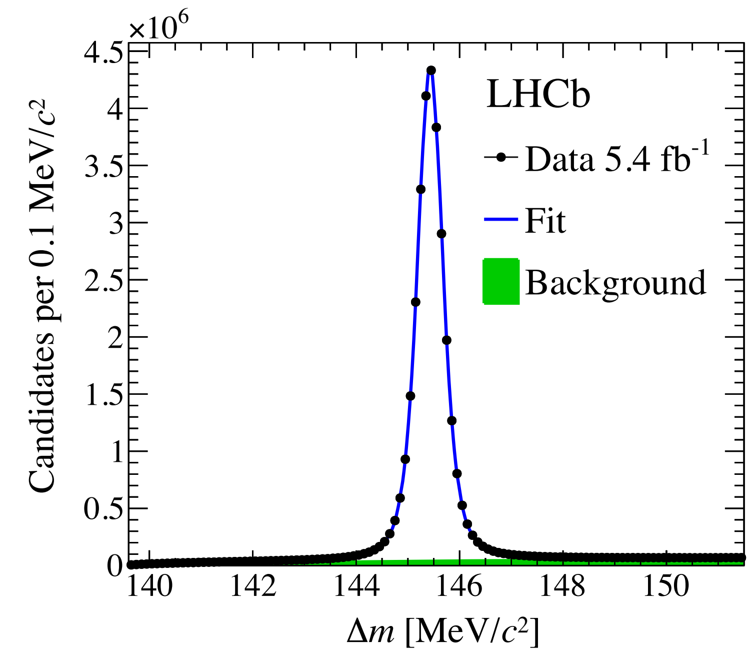
Observation of mass difference in $D^0 \to K^0_S \pi^+ \pi^-$ decays

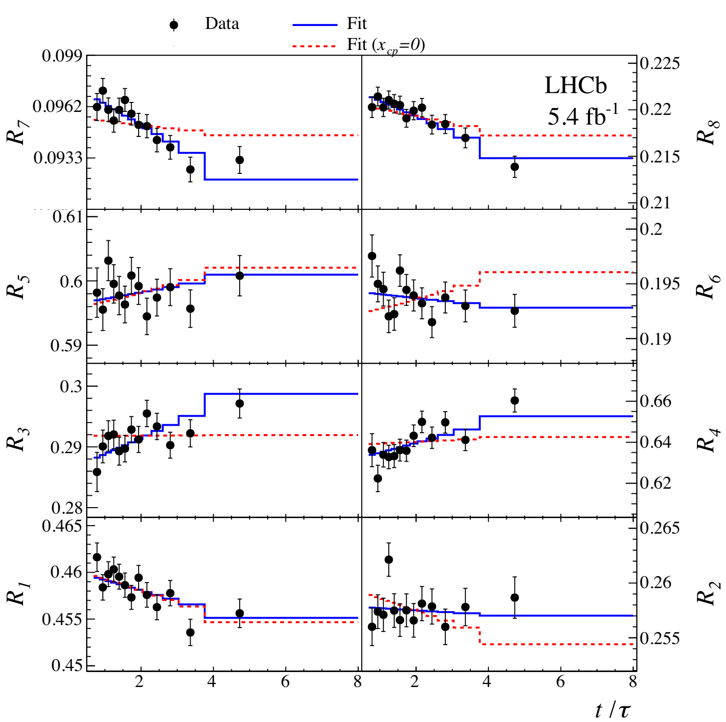
5.4 fb^{-1}

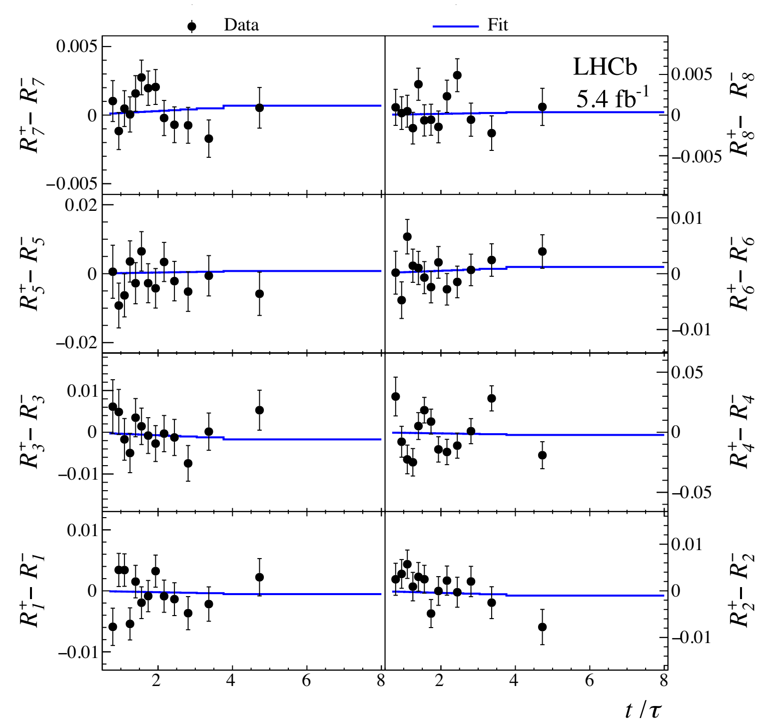
PRL 127, 111801 (2021)

- Flavour tag is given by the soft pion charge of $D^{*\pm} \to D^0 \pi_s^\pm$
- Bin flip technique used in the Dalitz plot
- Simultaneous decay-time and Dalitz plot analysis
- Key point in the analysis is control of detector acceptance and efficiency

Phys. Rev. D **99**, 012007







Results:

Mixing

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (4.6^{+1.5}_{-1.4}) \times 10^{-3},$$

CPV in Mixing

$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

Errors on x, y ϕ improved a factor 2 wrt previous HFLAV World Average!

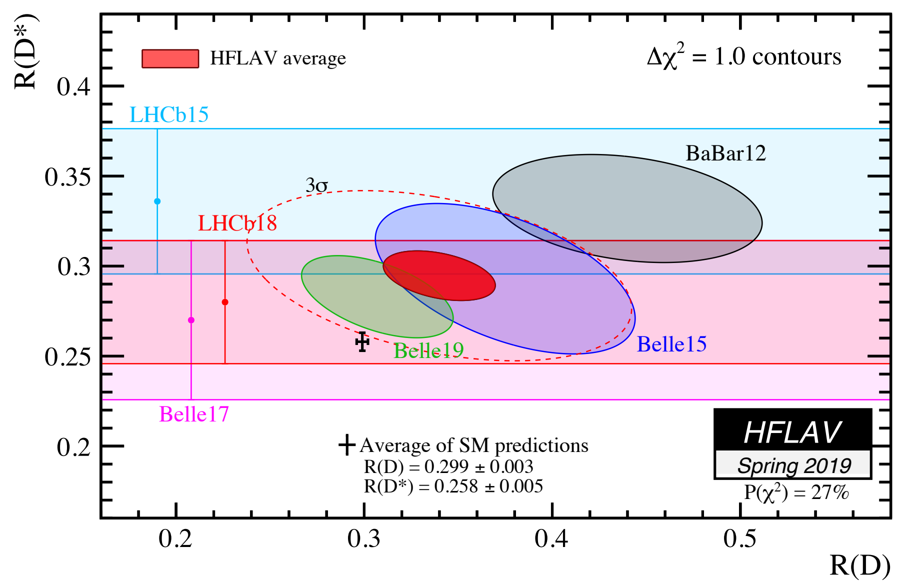
Summary and outlook

- A plethora of interesting new CPV results published recently
- LHCb plays the leading role now with its excellent performance
- ATLAS and CMS are contributing as well. More will come with the increased Run3 luminosity
- SuperKEKB and Belle II are picking up pace, with the unique features of an e+e- collider
- Expect a new exciting era of new discoveries in a friendly competition and complementarity among ATLAS, Belle II, CMS, and LHCb

Additional material

What we know, what we don't know

- SM supported by all experimental evidence at the current level of precision and energies
  – although discrepancies, or "tensions" do exist



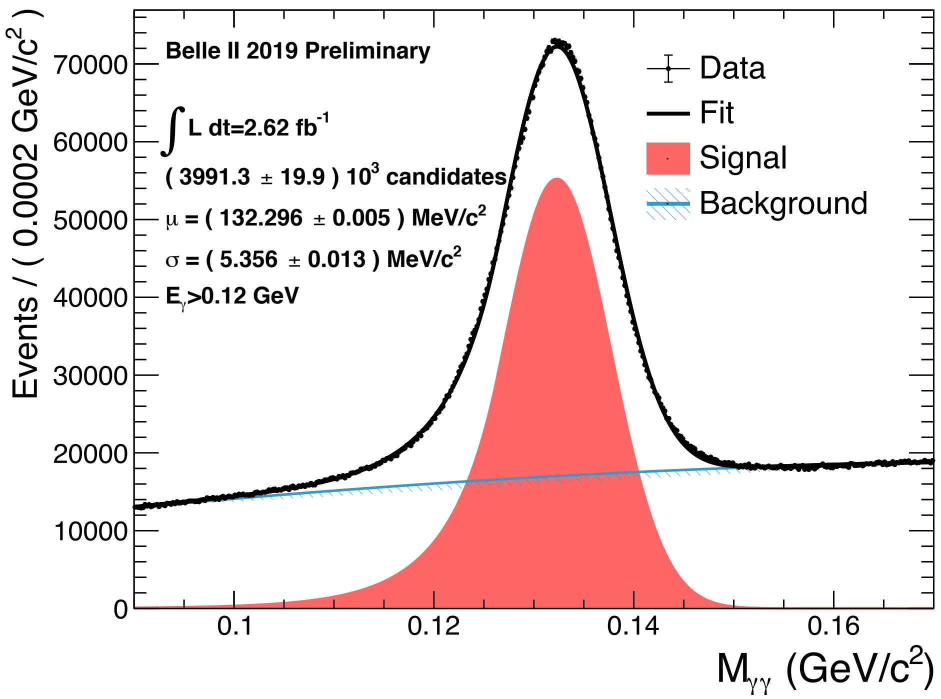
- However, the SM does not explain several fundamental questions
  – hierarchy of fermion masses, n. of generations, neutrino masses, matter-antimatter asymmetry, hierarchy of CKM matrix elements

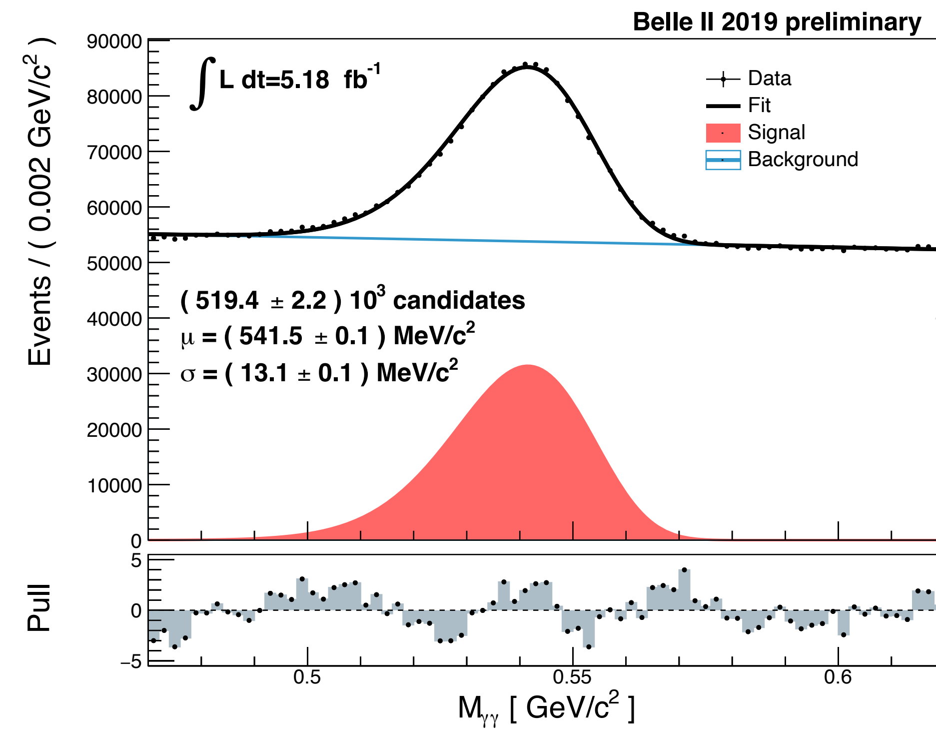
Several (NP) scenarios, with new particles and interactions, which can be investigated at the "energy" or at the "intensity" frontier.

Complementarity with LHCb

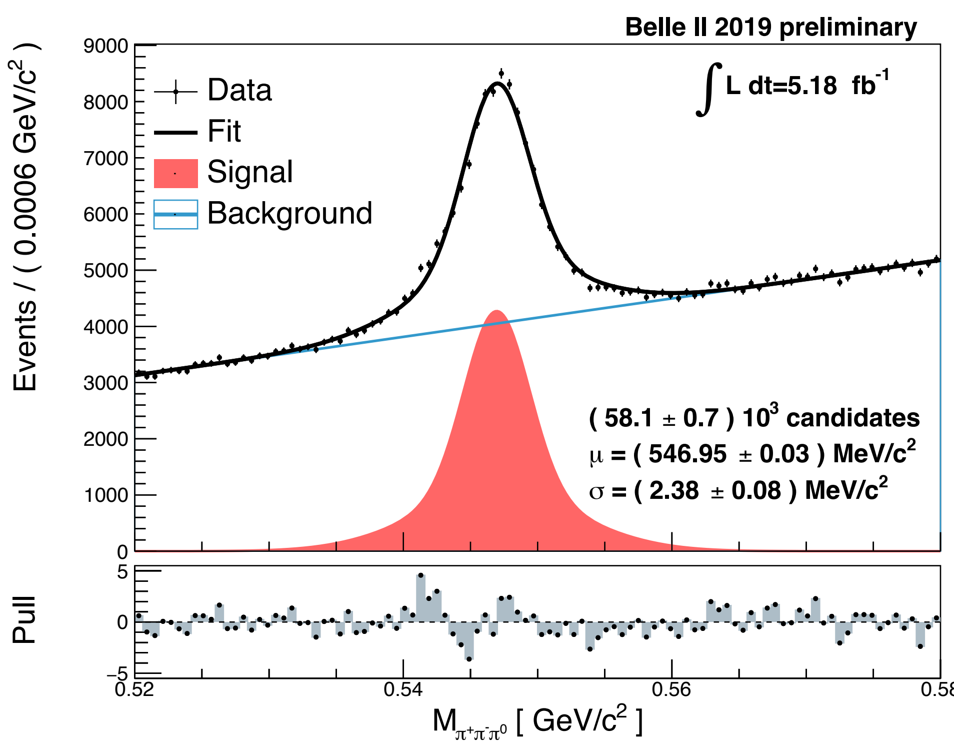
Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1}) goal	~50 (phase I)	~50,000
Background level	High	Low
Typical efficiency	Low	High
π^0, K_S efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	30%

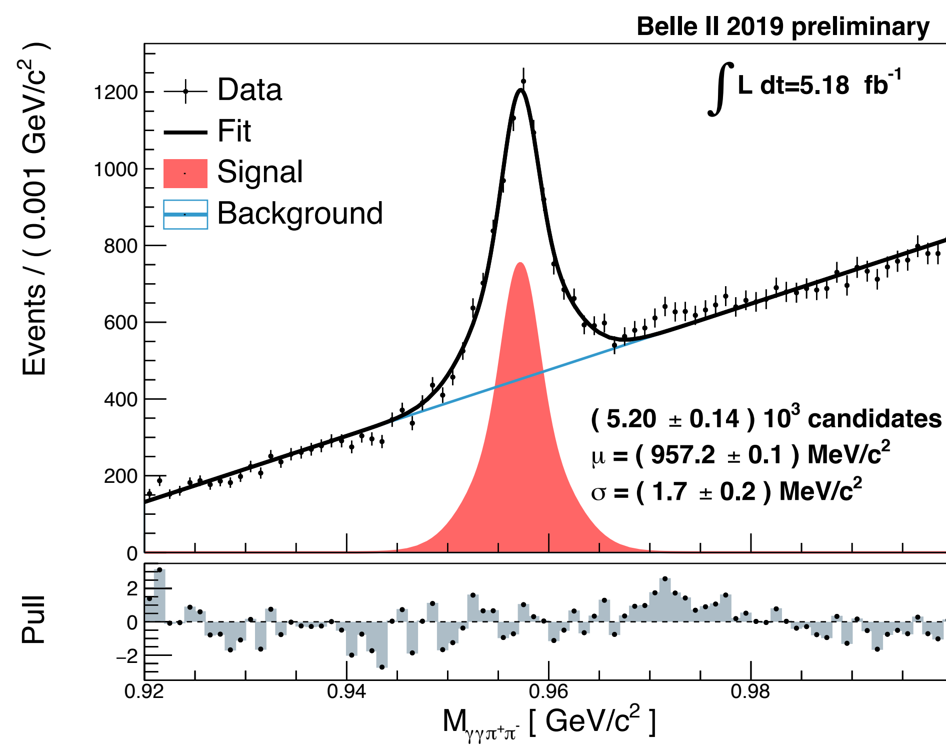
Belle II performance: neutral reconstruction





BELLE2-NOTE-PL-2019-019

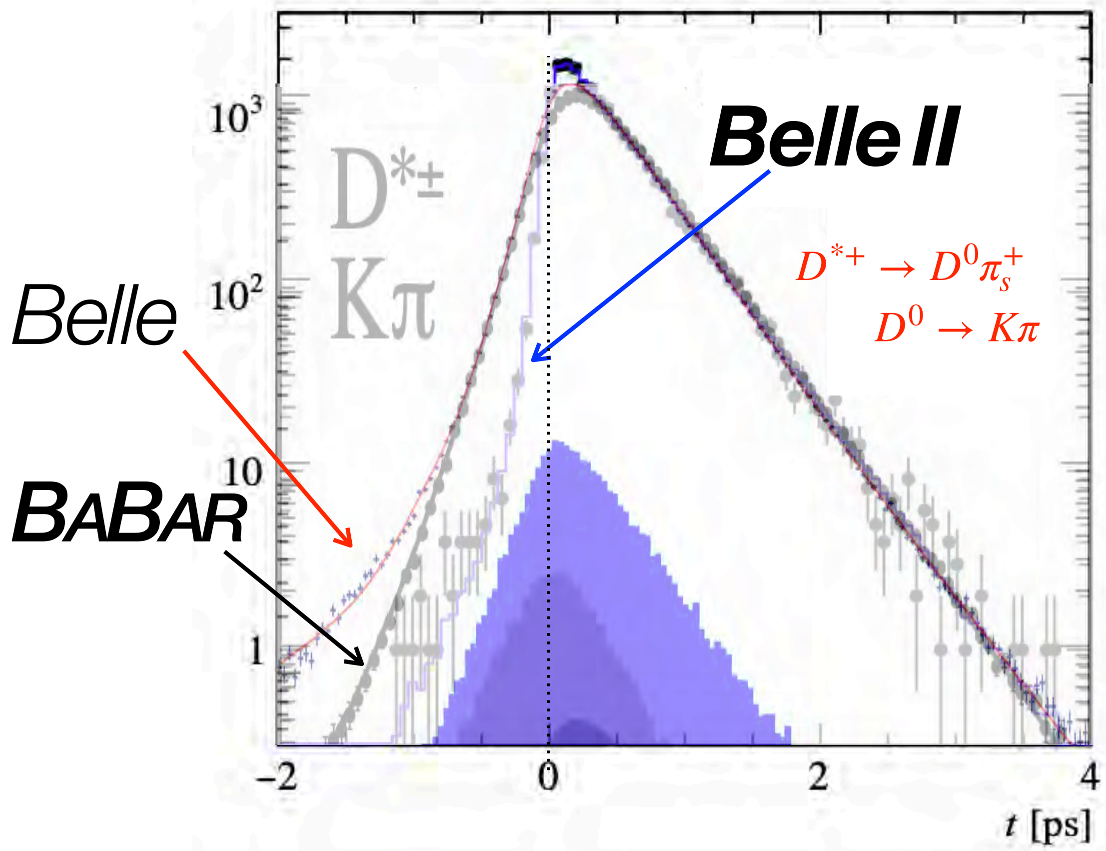




BELLE2-NOTE-PL-2020-003

Belle II performance: vertex reconstruction

- resolution improvement visible at $t < 0$:



$D^0 \to K^- \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$

G. Casarosa @ ICHEP 2020

In spite of the reduced boost, resolution is better than Belle and *BABAR*

- Incidentally, the best determination of the D^0 and D^+ lifetimes, consistent with the previous WA

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

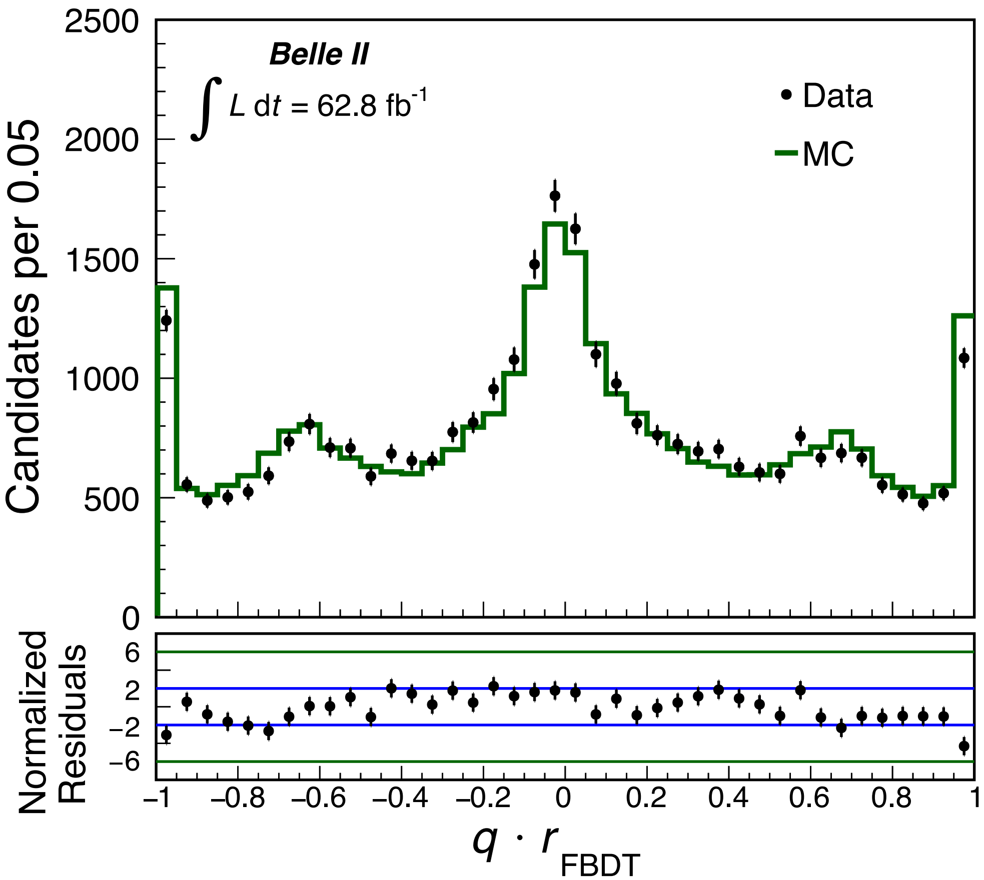
- A demonstration of the vertex capabilities and understanding of systematics, key ingredients toward future time-dependent measurements

Belle II performance: tagging

arXiv:2110.00790[hep-ex], submitted to EPJC

- Key ingredient to time-dependent CPV analyses
- One of the two B mesons is fully reconstructed, the other ("tag") is built with the remaining tracks/neutral objects. Two multivariate algorithms are used to determine the event flavour, combining information from charged leptons, charged kaons/pions, KS, Λ…
  - Category-based FBDT
  - Deep-learning Neural Network
  - 7 categories, with different efficiencies (ε) and purities (ω).
- Calibrated with $B \to D^{(*)}h^+$ events

$$B^0 \to D^{(*)-}h^+$$



$$\varepsilon_{\rm eff} = \sum_i \varepsilon_{{\rm eff},i} = \sum_i \varepsilon_i \cdot (1-2w_i)^2$$

	$\varepsilon_{{\rm eff},i} \pm \delta\varepsilon_{{\rm eff},i}$		
r- Interval	FBDT	DNN	Belle
Total	30.0 ± 1.3	28.8 ± 1.3	30.1 ± 0.4