11th International Workshop
on the *CKM* Unitary Triangle
24th November 2021

CP violation measurements in two-body charmless decays at LHCb

Daniele Manuzzi, on behalf of the LHCb collaboration

In this presentation

- Physics Motivations
- The LHCb detector

- *Measurement of CP violation in the decay $B^+ \to K^+\pi^0$*
  [Phys.Rev.Lett. 126 (2021) 9, 091802]

  ← 1st measurement at hadron collider, more precise than the previous world average

- *Observation of CP violation in two-body $B^0_{(s)}$-mesons decays to charged pions and kaons* [JHEP 03 (2021) 075]

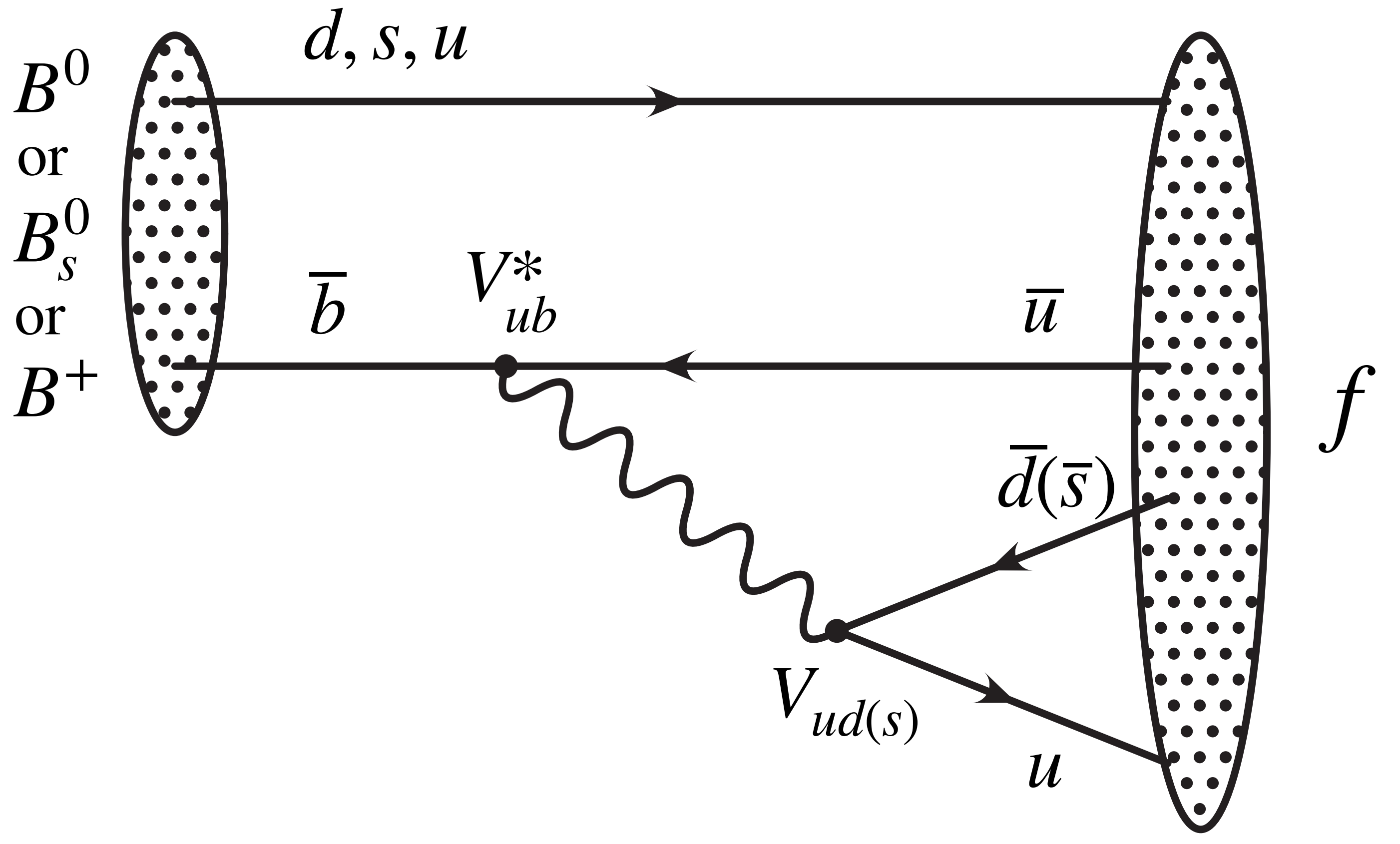
  ← 1st observation of time-dependent CP violation in the B_s sector

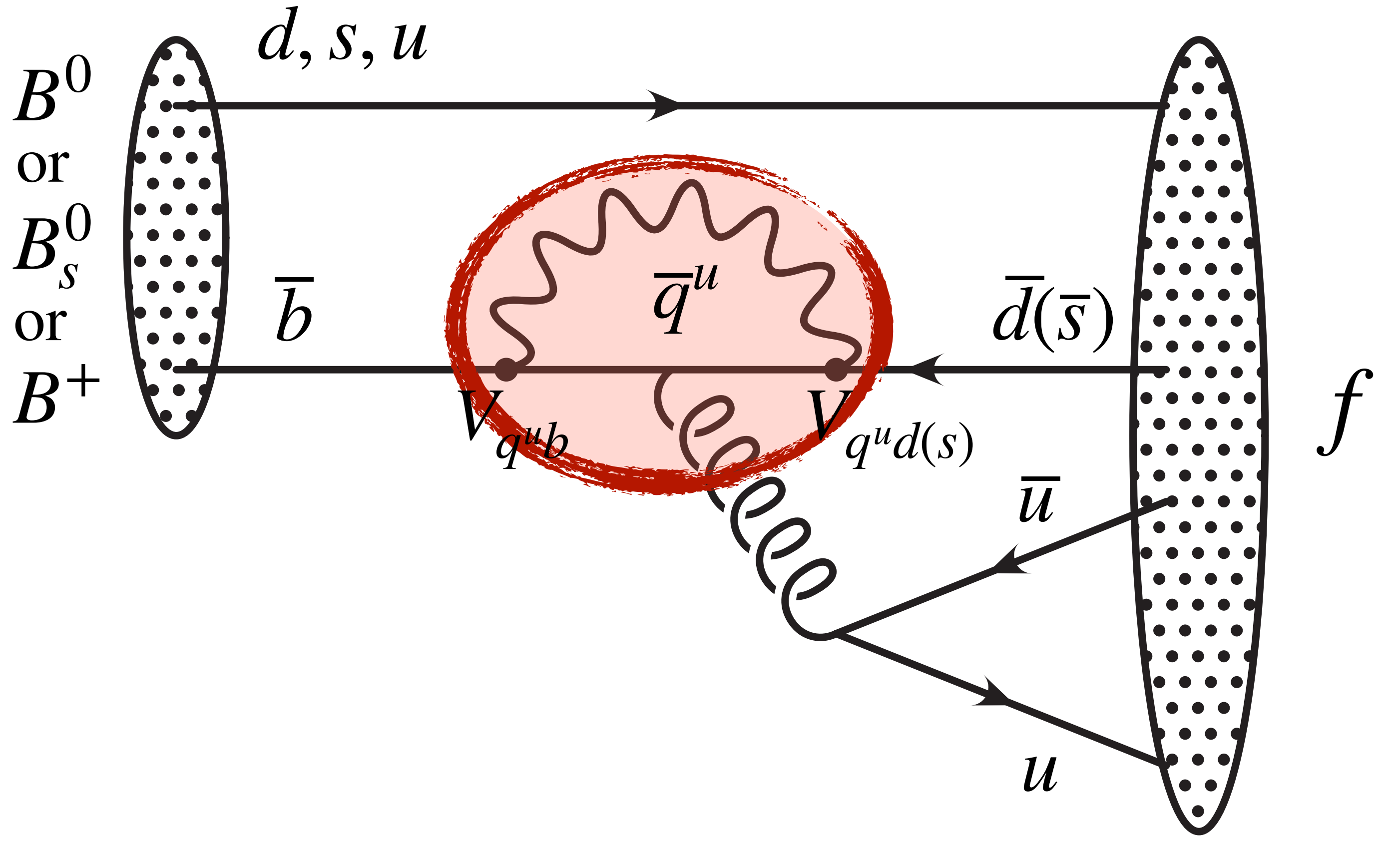
- Conclusions and outlook

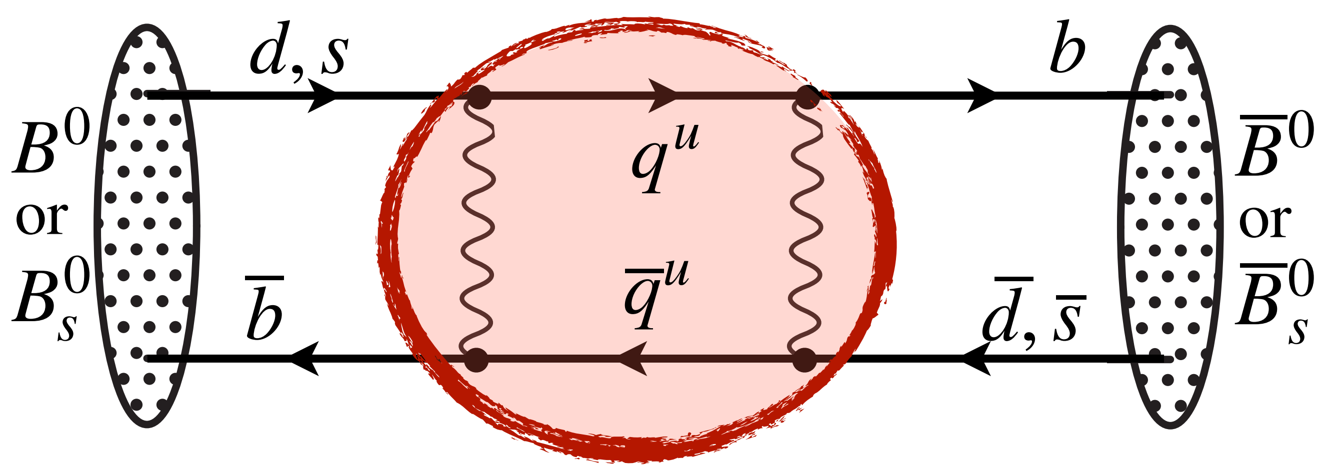
Generalities

- The $b \to u$ **tree-level** transitions and the $b \to s(d)$ **penguin** transitions dominate the charmless B-hadron decays
  - Similar magnitudes due to CKM suppression
  - Physics BSM in the loops may be revealed by comparison of measured quantities and SM predictions

- **Relevant quantities**: branching fractions, time-integrated and time-dependent CP asymmetries
  - Sensitive to UT angles and $B^0_{(s)}$ mixing phases,
  - but the combination of several measurements is necessary to extract the CKM parameters



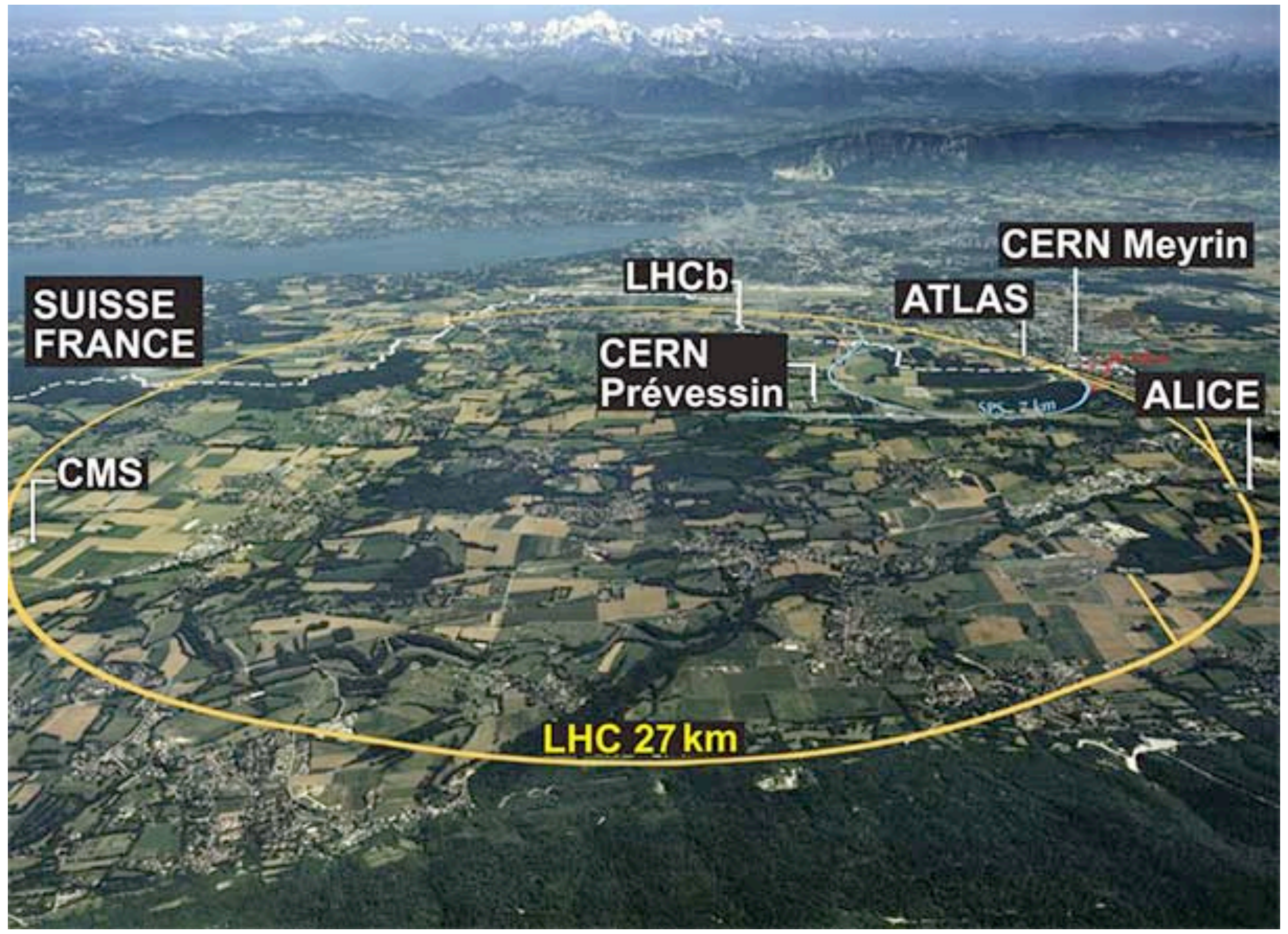


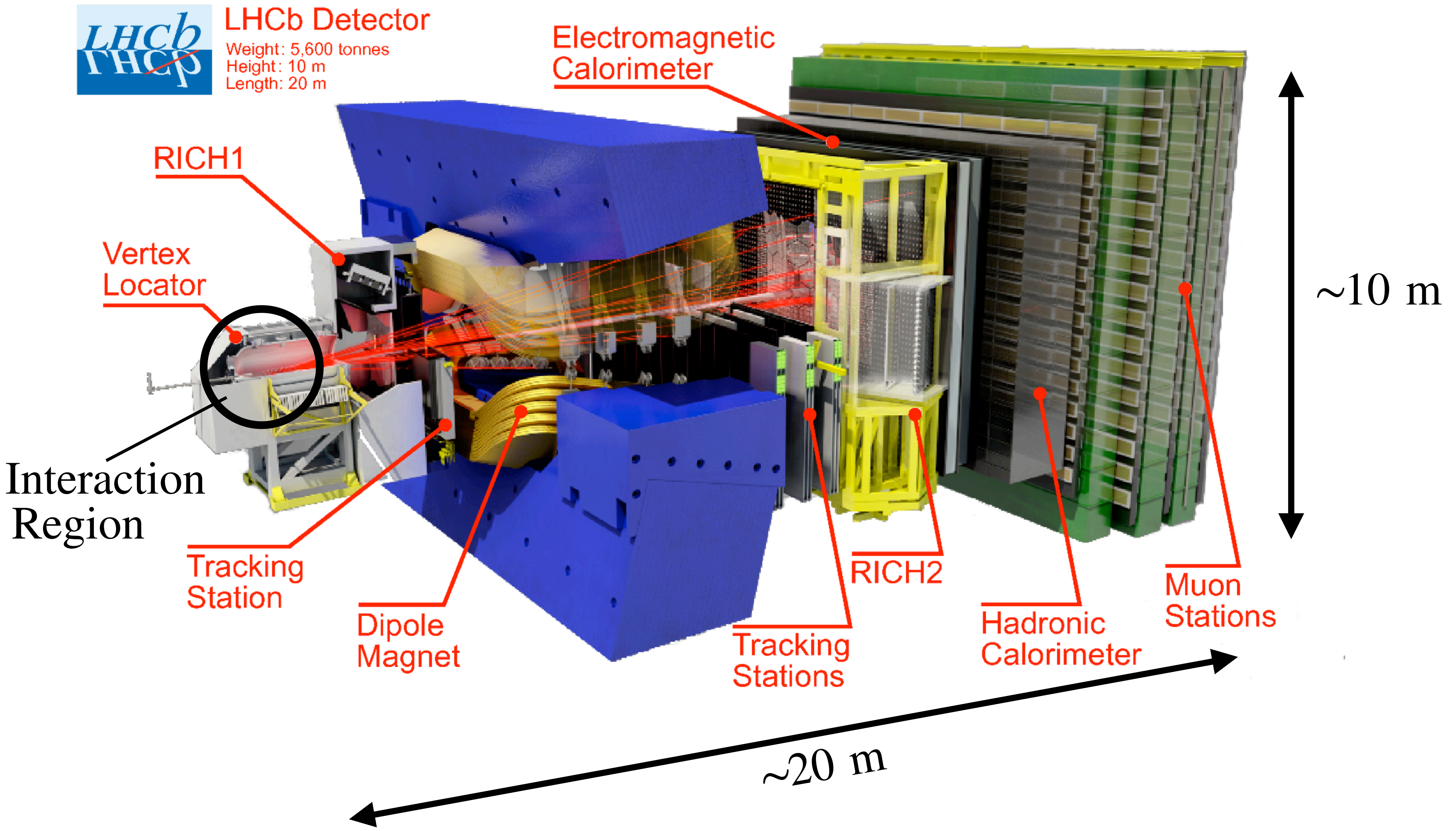


The LHCb detector

- LHCb is a forward spectrometer, operating at LHC $(\sqrt{s} = 13\ \text{TeV})$
  - High geometrical efficiency in collecting $b\bar{b}$ and $c\bar{c}$ quark pairs
  - Excellent time resolution, momentum resolution, PID performances

$\sigma_t \sim 45\ \text{fs}$ $\delta p/p \sim 0.4 - 0.6\,\%$ RICH





[JINST 3 S08005]
[Int. J. Mod. Phys. A 30 (2015)1530022]

Measurement of CP violation in the decay $B^+ \to K^+\pi^0$

[Phys.Rev.Lett. 126 (2021) 9, 091802 - arXiv:2012.12789]

Motivations

- **The long-standing $B \to K\pi$ puzzle:**

$$A_{CP}(B^+ \to K^+\pi) = \frac{\Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^- \to K^-\pi^0) + \Gamma(B^+ \to K^+\pi^0)}$$

  - Isospin relations ➡ $A_{CP}(B^+ \to K^+\pi^0) = A_{CP}(B^0 \to K^+\pi^-)$

  - The experimental state of the art was [HFLAV2019]:

$$A_{CP}^{WA}(B^+ \to K^+\pi^0) = (+4.0 \pm 2.1)\,\%$$
$$A_{CP}^{WA}(B^0 \to K^+\pi^-) = (-8.4 \pm 0.4)\,\%$$

→ Almost 6σ discrepancy!

$\Delta A_{CP}(K\pi) = (12.4 \pm 2.1)\,\%$

  - **Is it due to strong phases and amplitudes or is new physics emerging from the loops?**

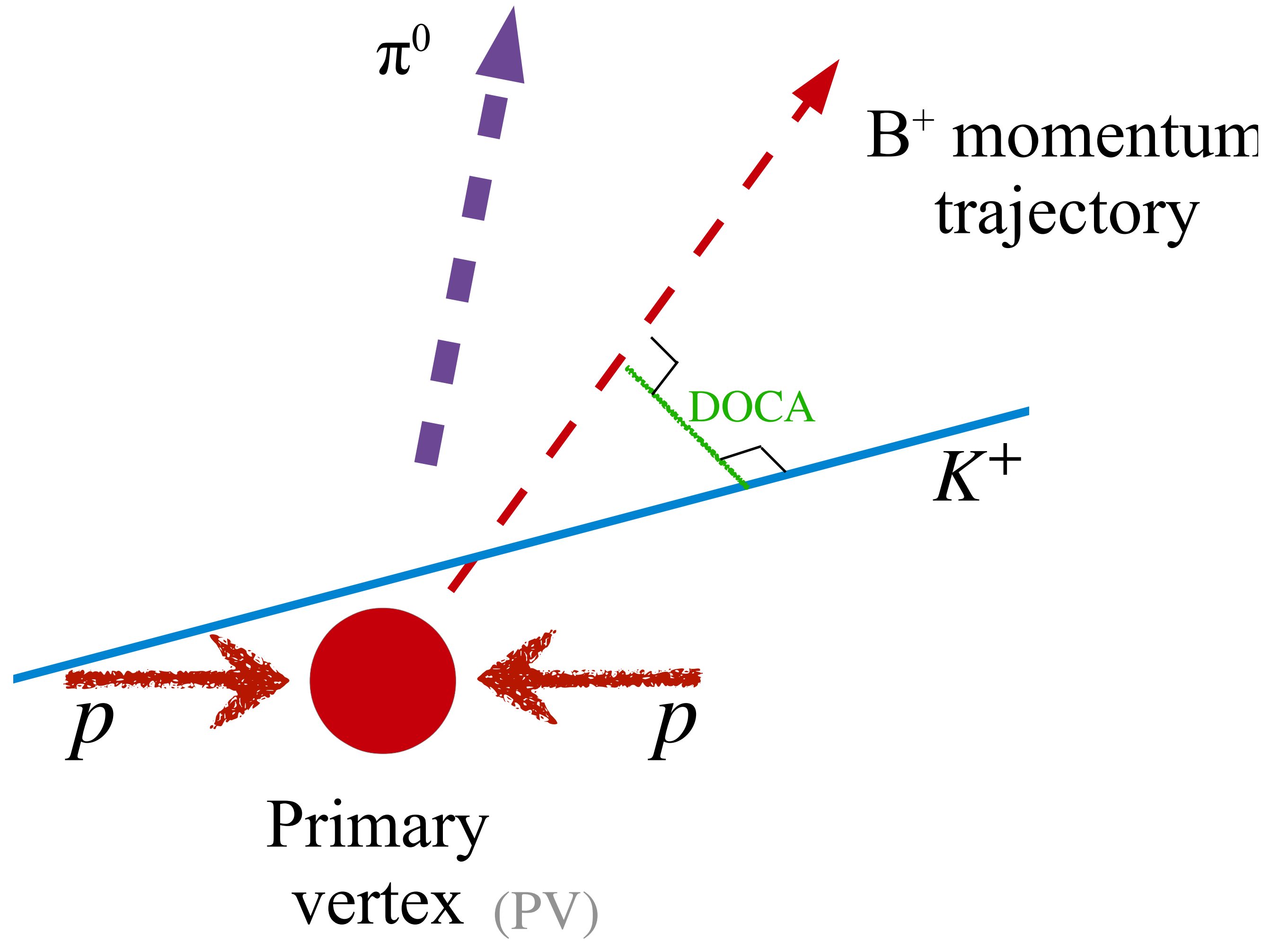
  - Full $B \to K\pi$ puzzle sum rule [PLB627(2005)82]: ← any deviation from this would be a sign of new physics

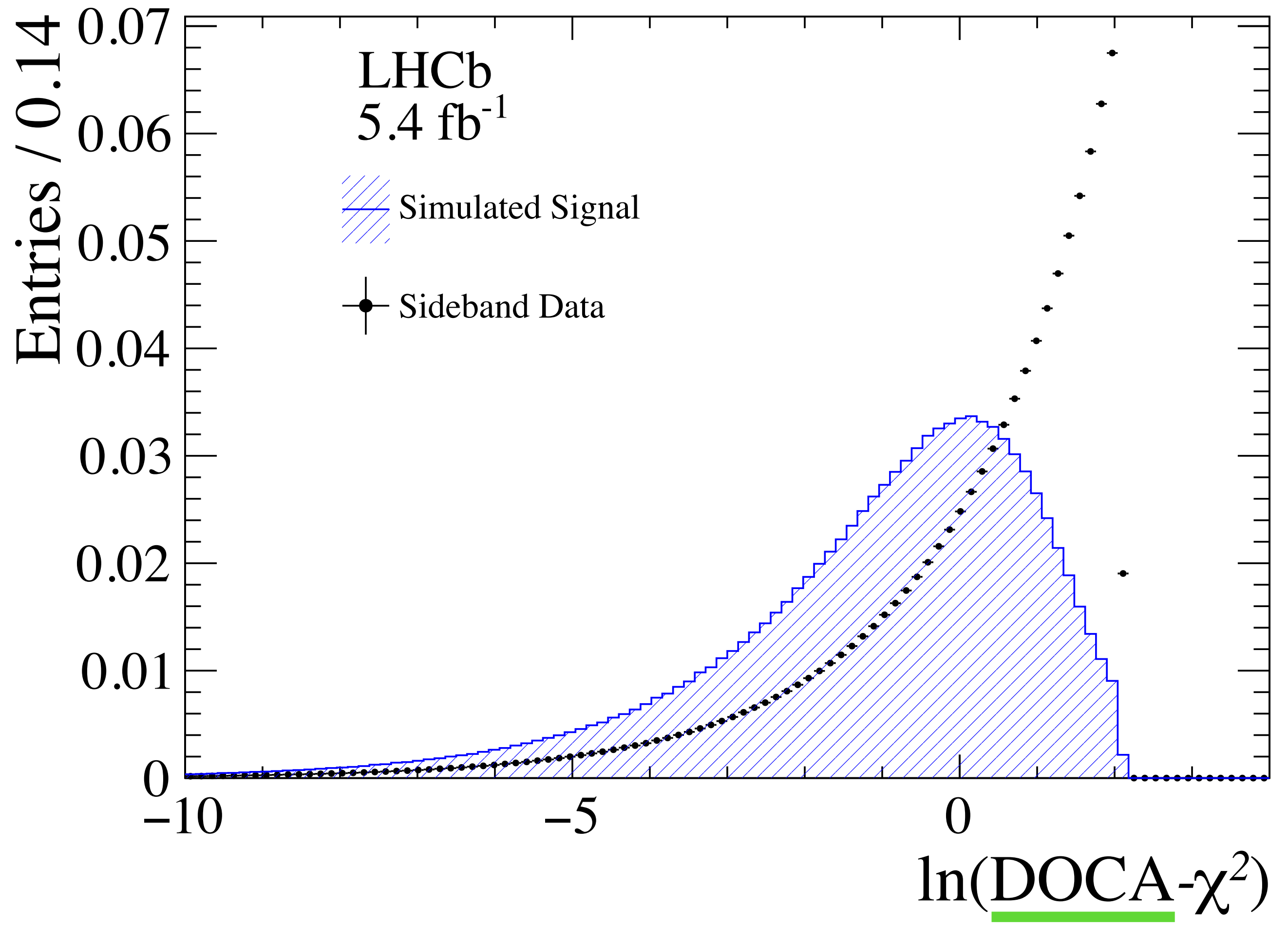
$$A_{CP}(B^0 \to K^+\pi^-) + A_{CP}(B^+ \to K^0\pi^+)\frac{\mathbf{B}(B^+ \to K^0\pi^+)}{\mathbf{B}(B^0 \to K^+\pi^-)}\frac{\tau^0}{\tau^+} = A_{CP}(B^+ \to K^+\pi^0)\frac{2\mathbf{B}(B^+ \to K^+\pi^0)}{\mathbf{B}(B^0 \to K^+\pi^-)}\frac{\tau^0}{\tau^+} + A_{CP}(B^0 \to K^0\pi^0)\frac{2\mathbf{B}(B^0 \to K^0\pi^0)}{\mathbf{B}(B^0 \to K^+\pi^-)}\frac{\tau^0}{\tau^+}$$

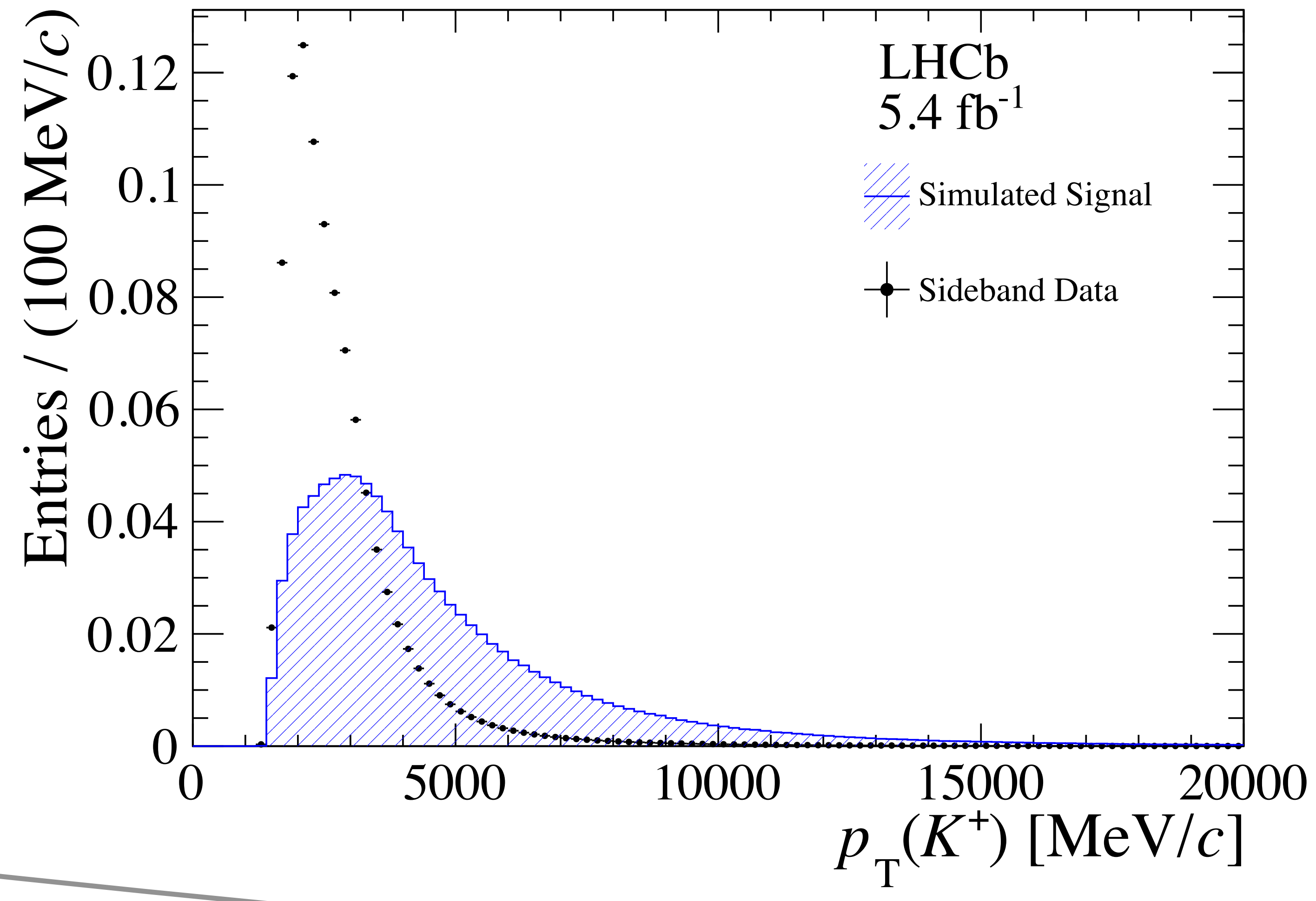
Candidates reconstruction and selection

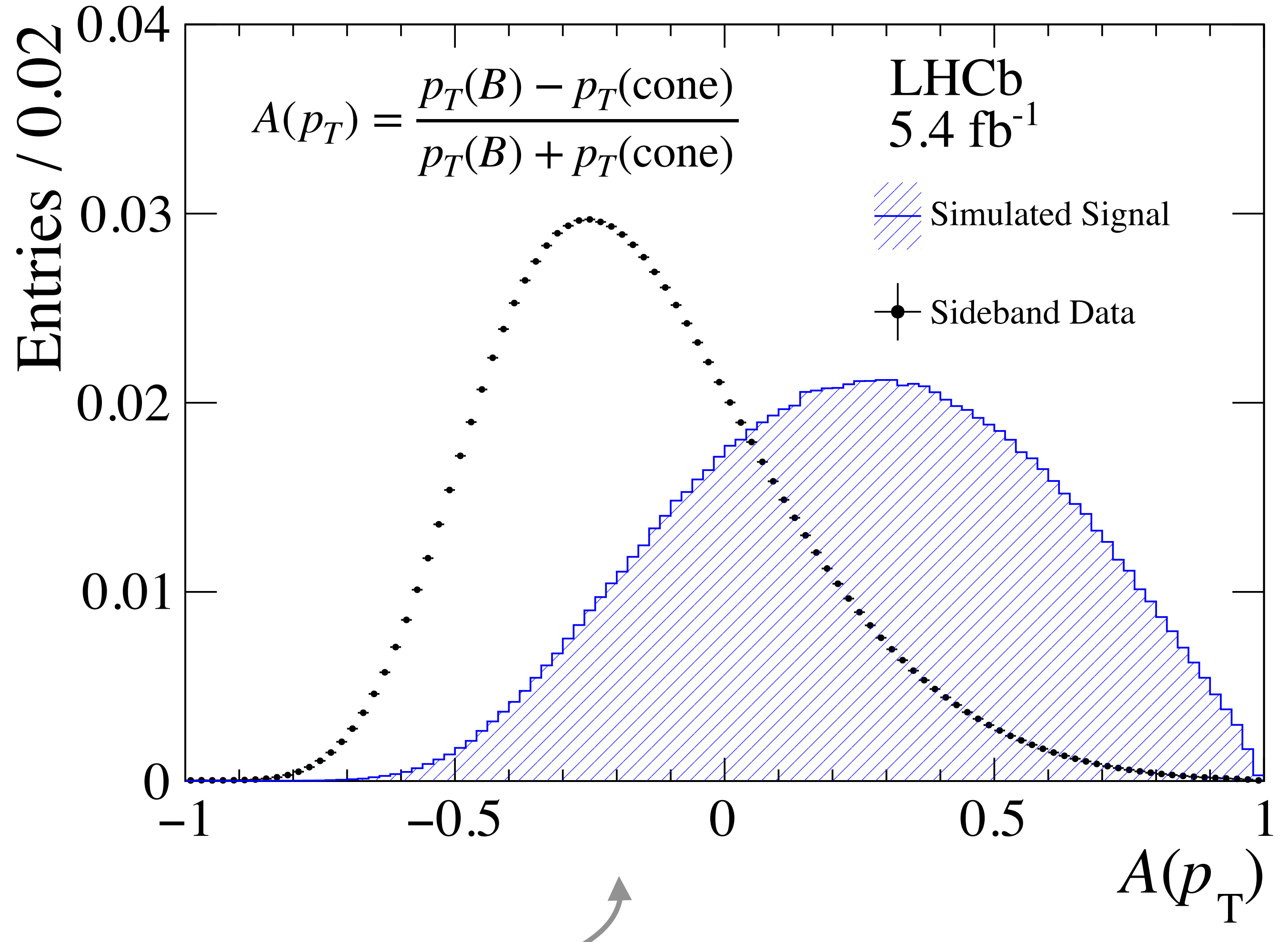
- Data collected during the Run2 of LHCb
  $(5.4\ \text{fb}^{-1} @ \sqrt{s} = 13\ \text{TeV})$
- Challenging signal reconstruction:
  - No displaced secondary vertex to identify B meson
  - Background due to π^0 reconstruction
- **Idea:** look for a K^+ inconsistent with PV, but consistent with B^+ trajectory
  - Momentum of B^+ candidate from K^+ and π^0 momenta
    (π^0 constrained to the closest PV to the K^+ track)
  - B candidate trajectory constrained to PV
  - **D**istance **o**f **c**losest **a**pproach between B^+ and K^+ candidates is required to be small
  - Candidate isolation criteria are applied
  - BDT trained to optimise the final selection

[LHCb-PAPER-2020-040 supplementary material]



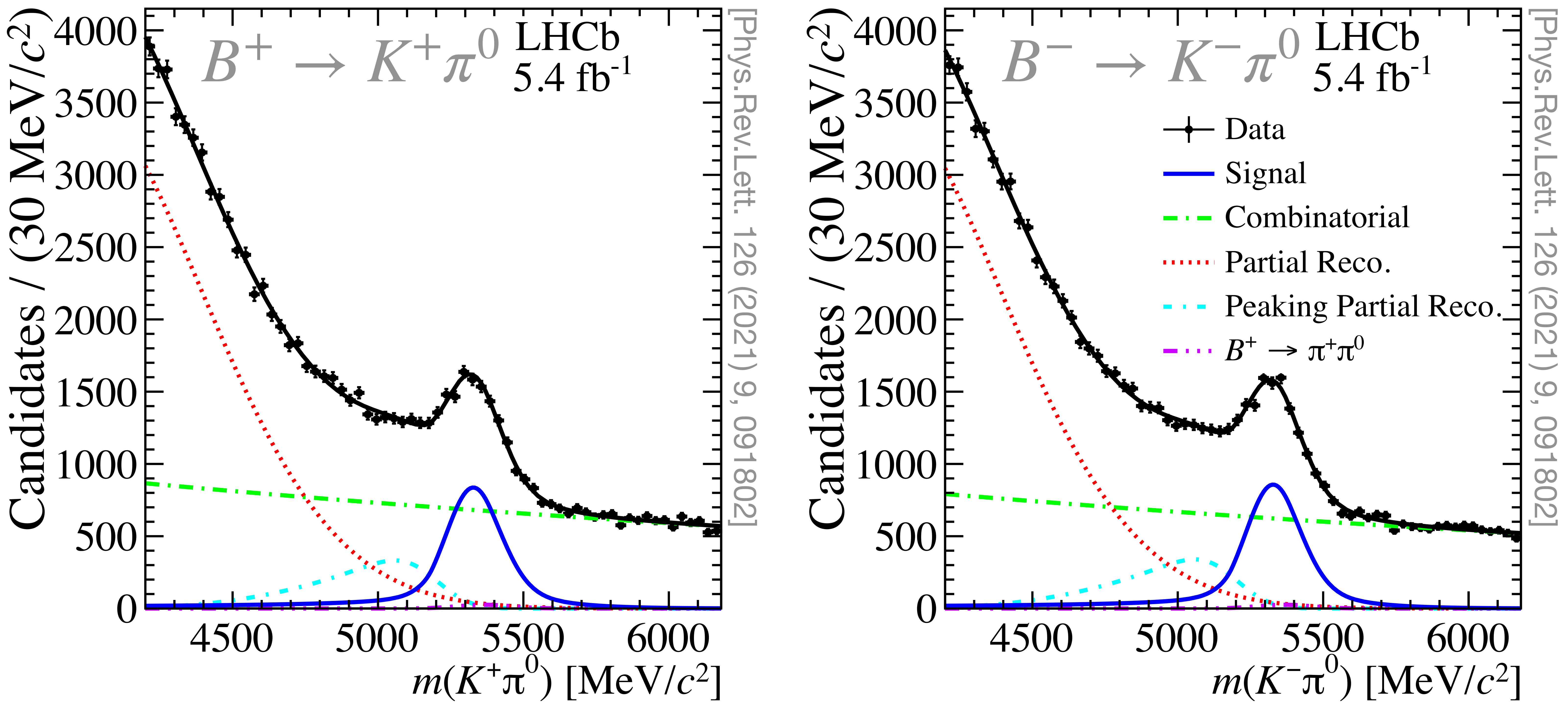






Extraction of the Raw Asymmetries

- Candidates separated by charge:
  - Independent yields and asymmetries
  - Common shape parameters



- Background sources:
  - Combinatorial
  - Partially Reconstructed
  - Peaking Partially Reconstructed ⟵ **due to resonance polarisation**
    $B^+ \to (K^{*+} \to K^+\pi^0)\pi^0$, $B^0 \to (K^{*0} \to K^+\pi^-)\pi^0$, $B^0 \to K^+(\rho^- \to \pi^-\pi^0)$
  - $B^+ \to \pi^+\pi^0$, i.e. $\pi^+ \to K^+$ mis-ID ⟵ **low rate, estimated with calib. sample** $(D^0 \to K^-\pi^+)$
  - **Total signal yield: ~16k** $(B^+ + B^-)$

$$A_{\rm raw}^{\rm MagUp}(B^+ \to K^+\pi^0) = (0.5 \pm 2.2)\,\%$$
$$A_{\rm raw}^{\rm MagDw}(B^+ \to K^+\pi^0) = (1.9 \pm 2.1)\,\%$$

[Phys.Rev.Lett. 126 (2021) 9, 091802]

Nuisance Asymmetries

- $A_{CP}(B^+ \to K^+\pi^0) = A_{\rm raw}(B^+ \to K^+\pi^0) - (A^B_{\rm prod.} + A^K_{\rm det.})$
- Total effect of nuisance asymmetries measured with $B^+ \to (J/\psi \to \mu^+\mu^-)K^+$ decays:
  - High statistics (~680k) and purity (>99%)
  - Momentum distributions of B^+ and K^+ reweighted to those of signal candidates
  - $A^B_{\rm prod.} + A^K_{\rm det.} = A_{\rm raw}(B^+ \to J/\psi K^+) - A_{CP}(B^+ \to J/\psi K^+)$

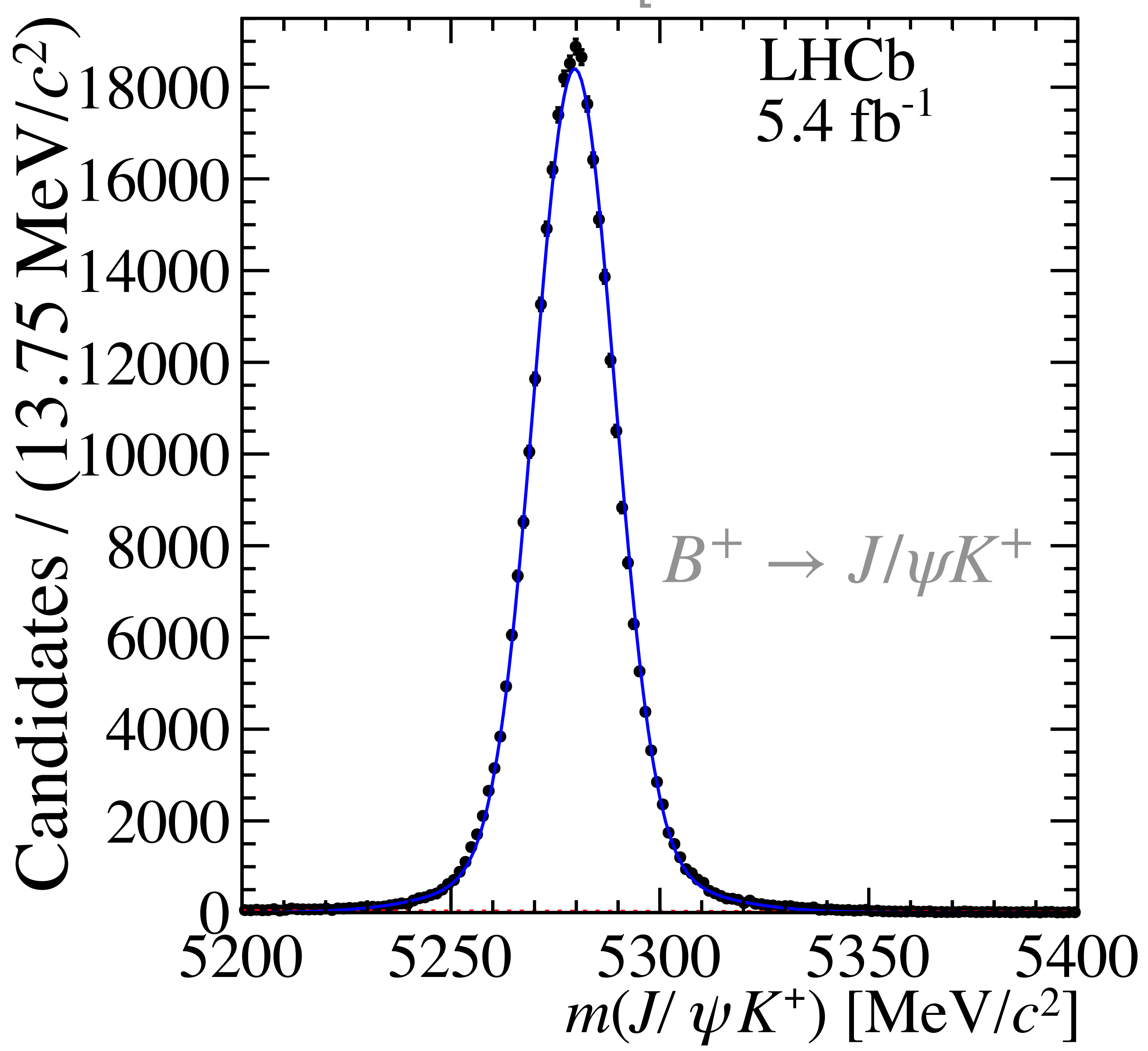
$A_{CP}(B^+ \to J/\psi K^+) = (0.2 \pm 0.3)\,\%$
from the world average

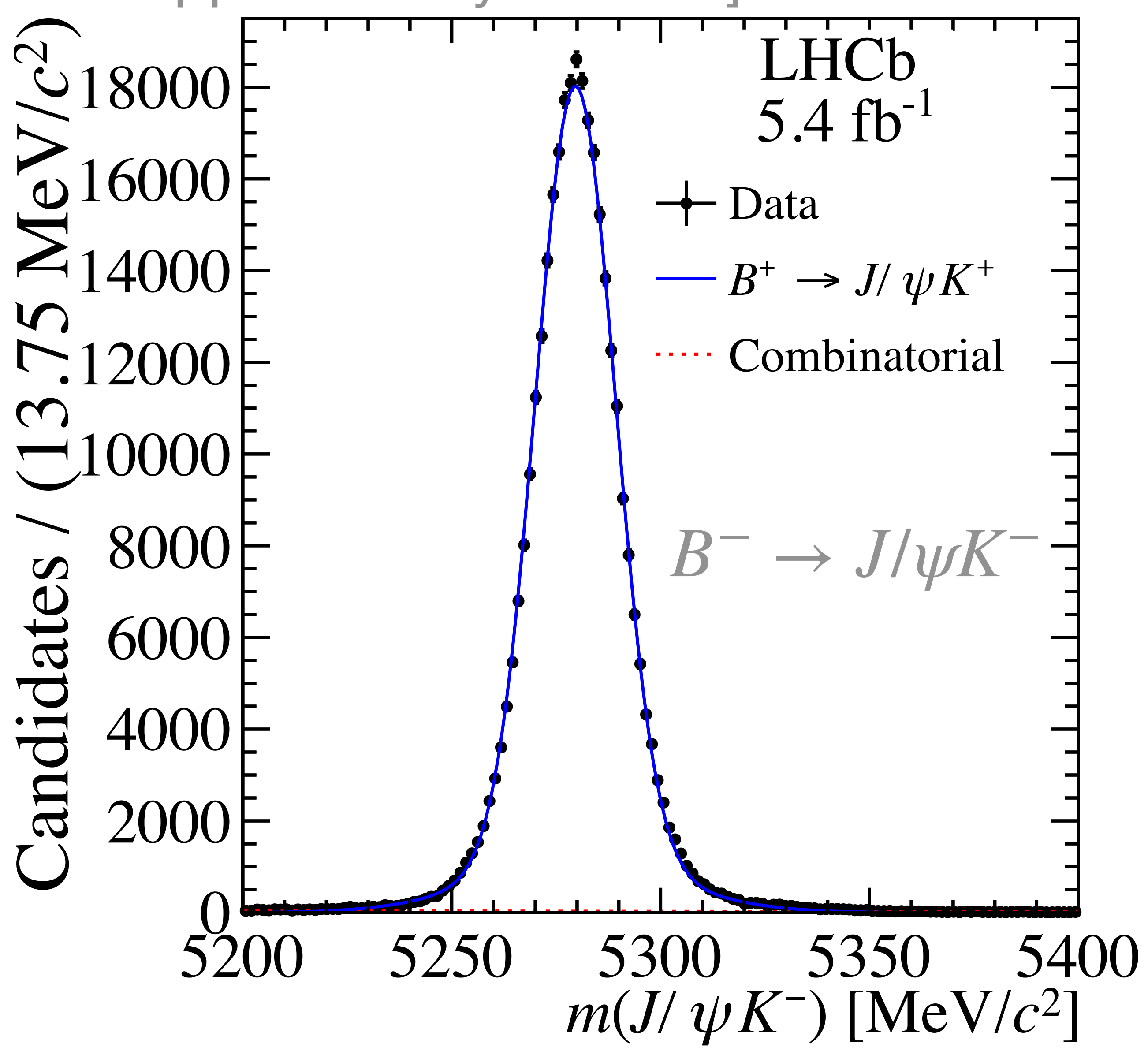
[LHCb-PAPER-2020-040 supplementary material]

$A^{\rm MagUp}_{\rm raw}(B^+ \to J/\psi K^+) = (-0.9 \pm 0.2)\,\%$

$A^{\rm MagDw}_{\rm raw}(B^+ \to J/\psi K^+) = (-1.2 \pm 0.2)\,\%$

[Phys.Rev.Lett. 126 (2021) 9, 091802]





Results

- The direct CP asymmetry has been measured to be:

$$A_{CP}^{\mathrm{LHCb}}(B^+ \to K^+\pi^0) = (2.5 \pm 1.5 \pm 0.6 \pm 0.3)\,\%$$

[Phys.Rev.Lett. 126 (2021) 9, 091802] stat. syst. ext.

Most precise determination to date

- New world average: $A_{CP}^{\mathrm{WA}}(B^+ \to K^+\pi^0) = (3.1 \pm 1.7)\,\%$, which implies:

$$A_{CP}^{\mathrm{WA}}(B^+ \to K^+\pi^0) - A_{CP}^{\mathrm{WA}}(B^0 \to K^+\pi^-) = (11.5 \pm 1.4)\,\%$$

[HFLAV2019]

nonzero at 8σ

- From full $K\pi$-puzzle sum rule:

$$A_{CP}^{\mathrm{SR}}(B^0 \to K^0\pi^0) = (-13.8 \pm 2.5)\,\%$$

while the experimental determination is:

$$A_{CP}^{\mathrm{WA}}(B^0 \to K^0\pi^0) = (1 \pm 10)\,\%$$

[HFLAV2019]

nonzero at 5.5σ

More insight needed to uncover new physics

[JHEP01(2018)074, PLB785(2018)525]

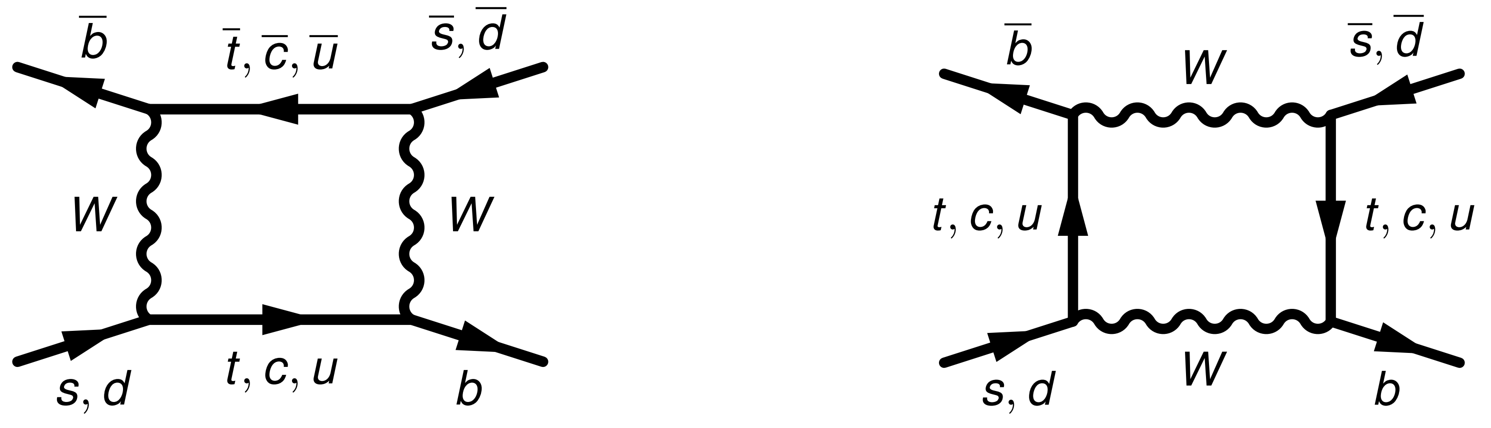
Observation of CP violation in two-body $B^0_{(s)}$-mesons decays to charged pions and kaons

[JHEP 03 (2021) 075]

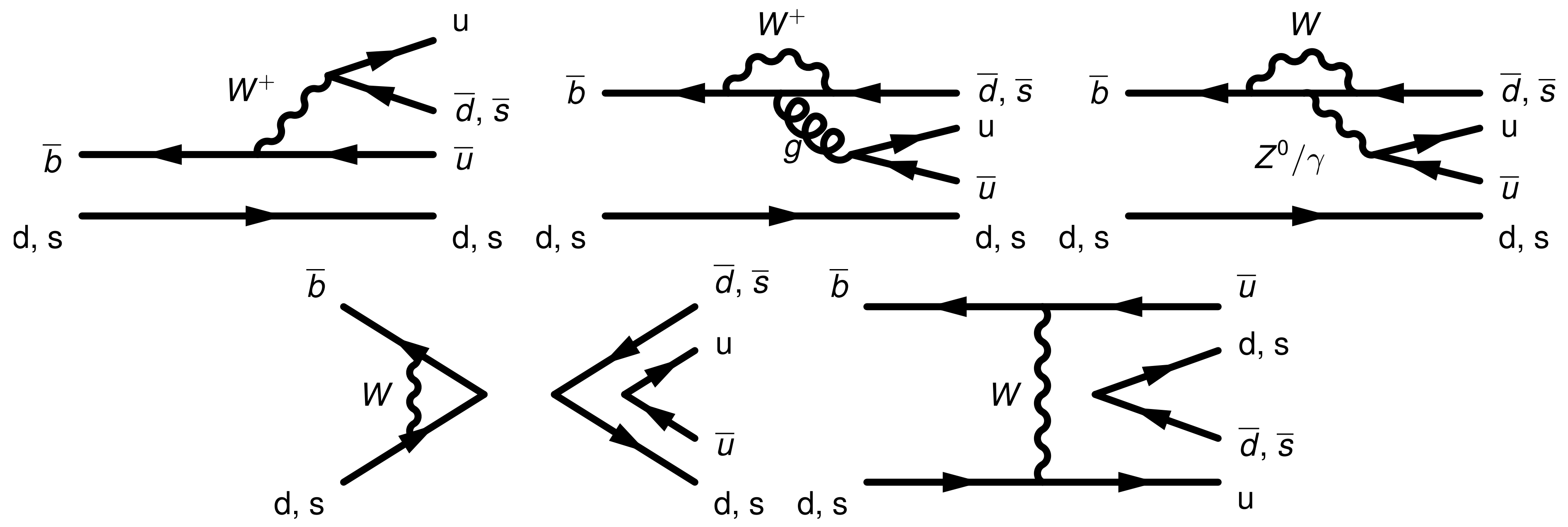
Motivations

- The CP violation observables in the $B^0_{(s)} \to h^+h^-$ decays carry information about the angles α and γ of the Unitary Triangle and the $B_{(s)}$ mixing phase, $\beta_{(s)}$ $(h = K, \pi)$

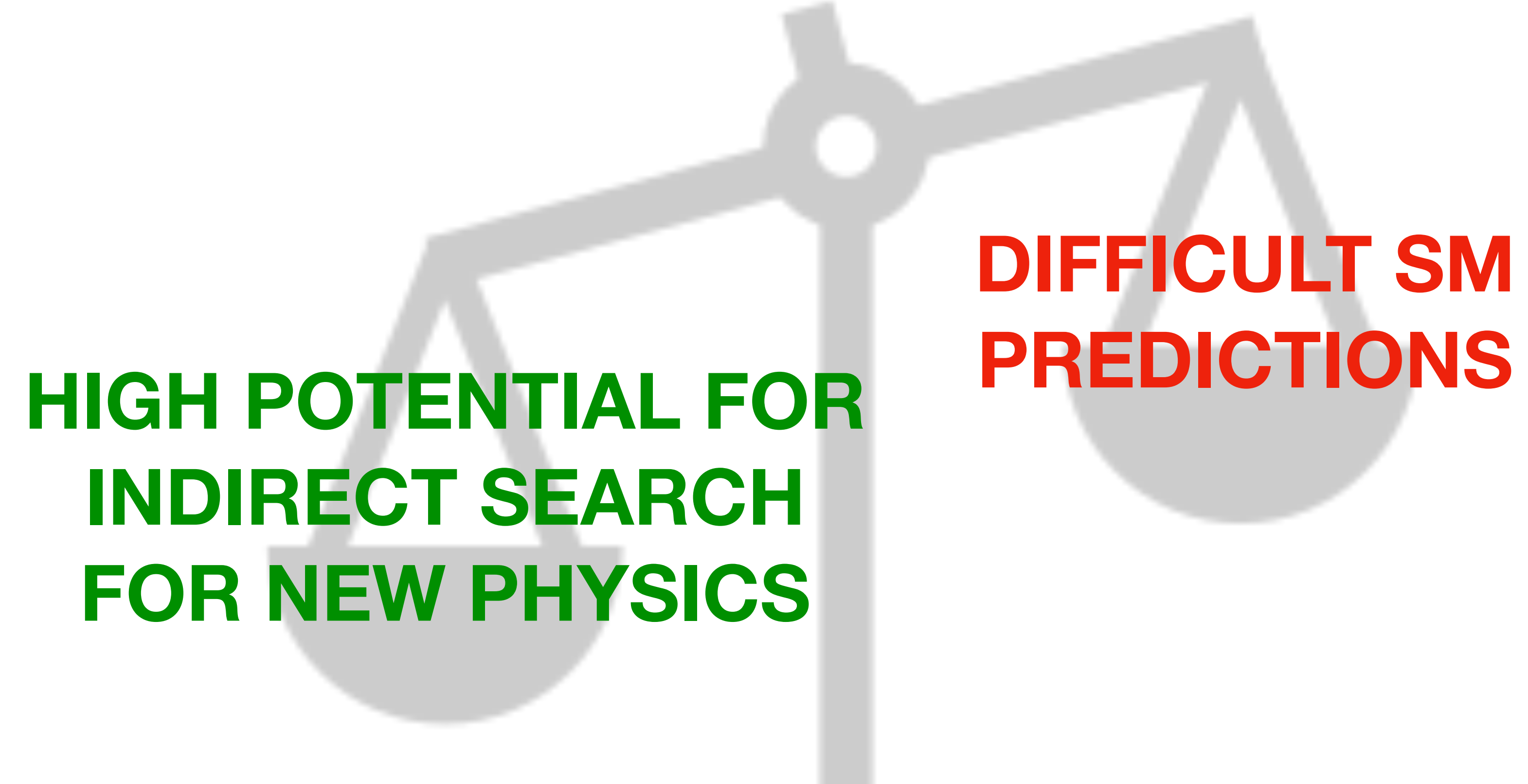
Mixing diagrams



Decay diagrams



- Several topologies of Feynman diagrams contribute:
  - New physics may emerge from the loops
  - Hadronic uncertainties make CKM parameter estimations highly non-trivial
  - Need to **combine several quantities** from different decays



[PLB459(1999)306, PJC71(2011)1532, JHEP10(2012)029, PRD94(2016)113014]

Goals

- **Time-integrated** CP asymmetries of $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays

$$A_{CP}^{B^0_{(s)}} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

$B^0_{(s)} \to f \equiv K^+\pi^-(K^-\pi^+)$
$\bar{B}^0_{(s)} \to \bar{f} \equiv K^-\pi^+(K^+\pi^-)$

- **Time-dependent** CP asymmetries of $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)}$$

CPT sim.

NO $\not{C}\not{P}$ in mixing

$$= \frac{S_f \sin(\Delta m_{d(s)} t) - C_f \cos(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

$\not{C}\not{P}$ in the decay

$\not{C}\not{P}$ in interference of mixing and decay

Unitarity bound: $\left(C_f\right)^2 + \left(S_f\right)^2 + \left(A_f^{\Delta\Gamma}\right)^2 = 1$ → **Control check** ***a posteriori***

Note: $\Delta\Gamma_d \approx 0$
[Eur. Phys. J. C77, 895 (2017)]

Dataset

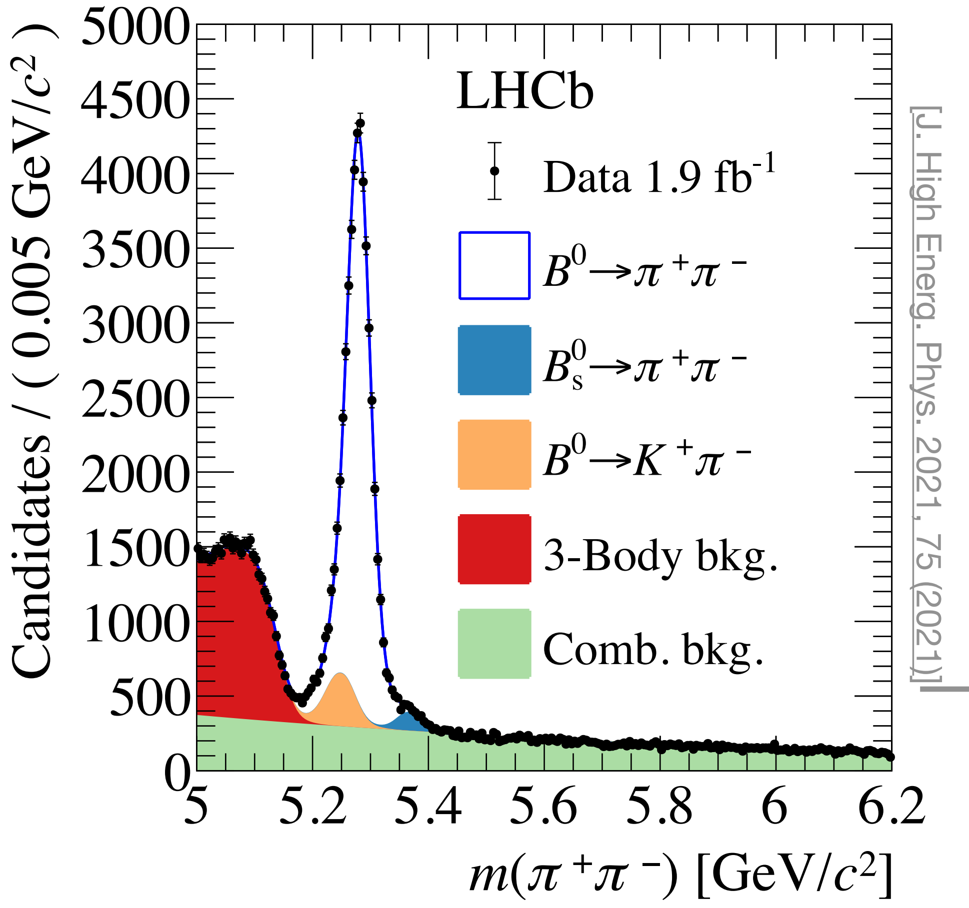
- Data collected during 2015 and 2016 $(1.9\ \mathrm{fb}^{-1} @ \sqrt{s} = 13\ \mathrm{TeV})$
  - Final results combined with the corresponding ones, from the analysis of LHCb Run1 data $(3.0\ \mathrm{fb}^{-1} @ \sqrt{s} = 7-8\ \mathrm{TeV})$ [PRD98(2018)032004]

- Background sources:
  - Cross-feed → Crucial PID performance to distinguish the spectra
  - Random tracks → BDT to suppress the combinatorial bkg.
  - Partially reconstructed 3-body decays

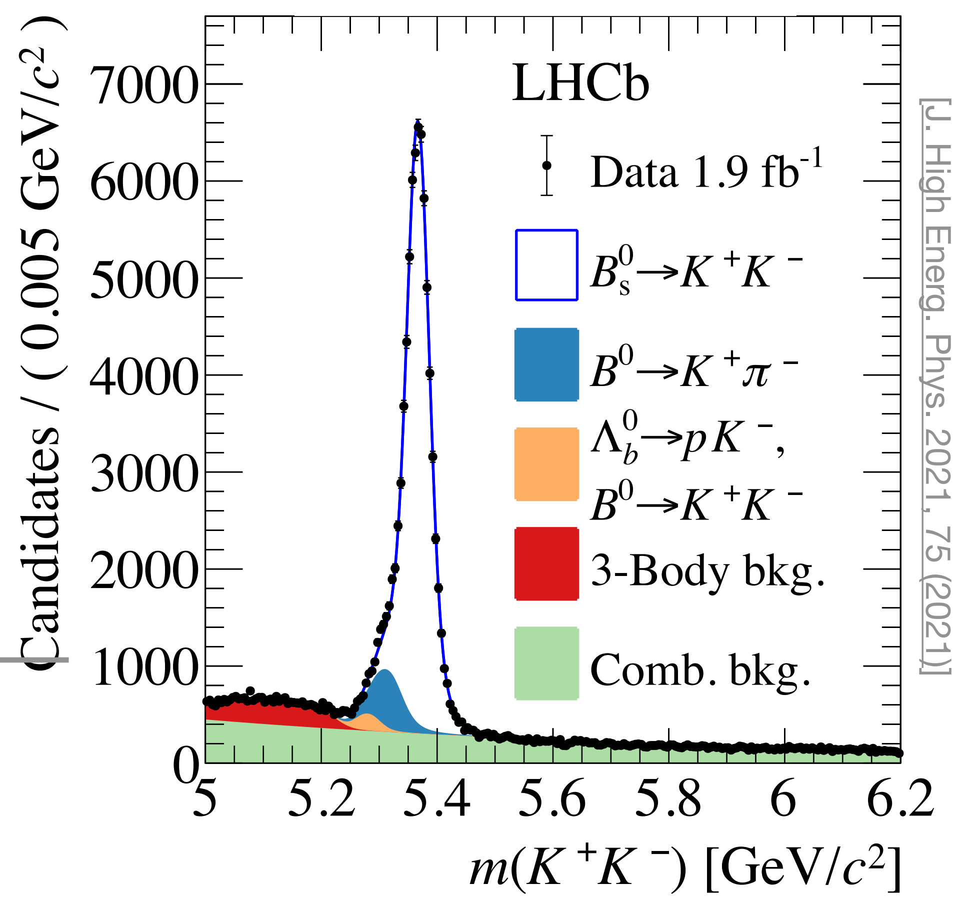
[J. High Energ. Phys. 2021, 75 (2021)]

FINAL SIGNAL YIELDS			
$B^0 \to \pi^+\pi^-$	$B^0 \to K^+\pi^-$	$B^0_s \to \pi^+K^-$	$B^0_s \to K^+K^-$
~46k	~140k	~11k	~70k

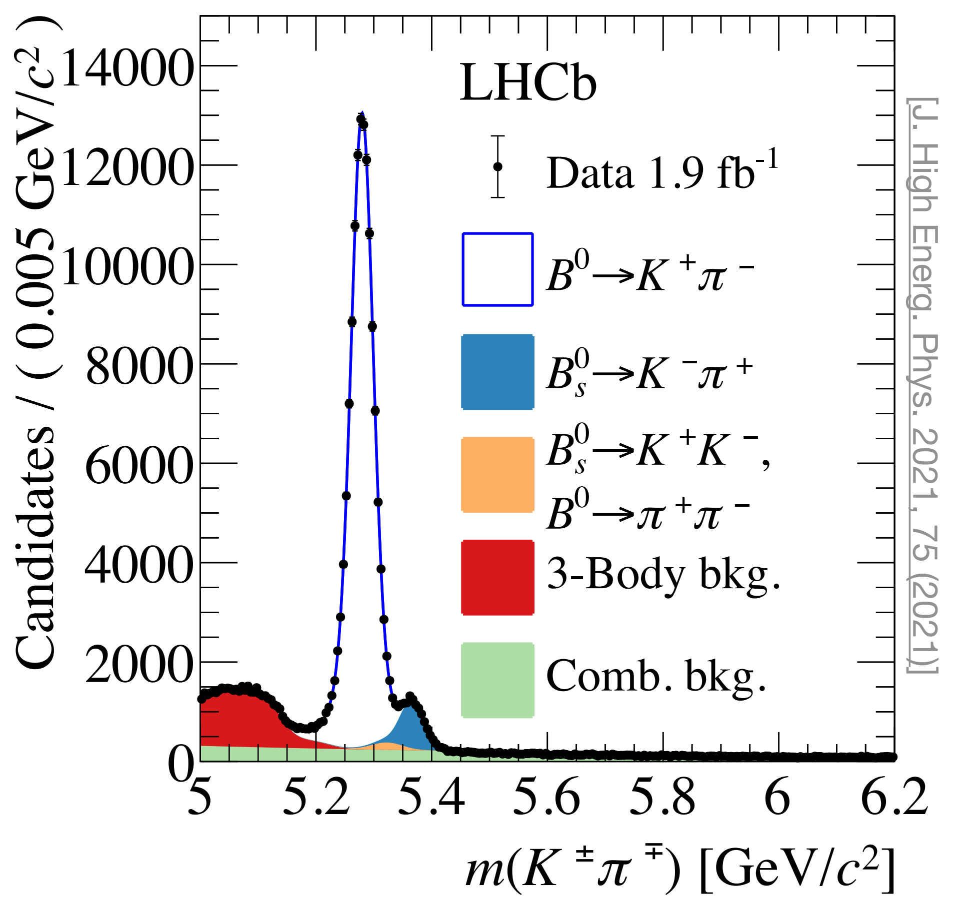
$\pi\pi$ SPECTRUM



KK SPECTRUM



$K\pi$ SPECTRUM



Experimental Effects

- Production Asymmetry → **Extracted from the final fit**
- Detection Asymmetries → **Studied on prompt $D^+ \to K^+\pi^+\pi^-$ and $D^+ \to K^0_S\pi^+$ decays** [JHEP 07 (2014) 041]
- Final state misidentification → **From calibration datasets**

- **Wrong flavour tagging**
- **Decay-time resolution**
- **Decay-time acceptance**

→ **Various methods,** crucial role for time-dependent $\not{C}\not{P}$ measurements (next slide)

Analysis Strategies

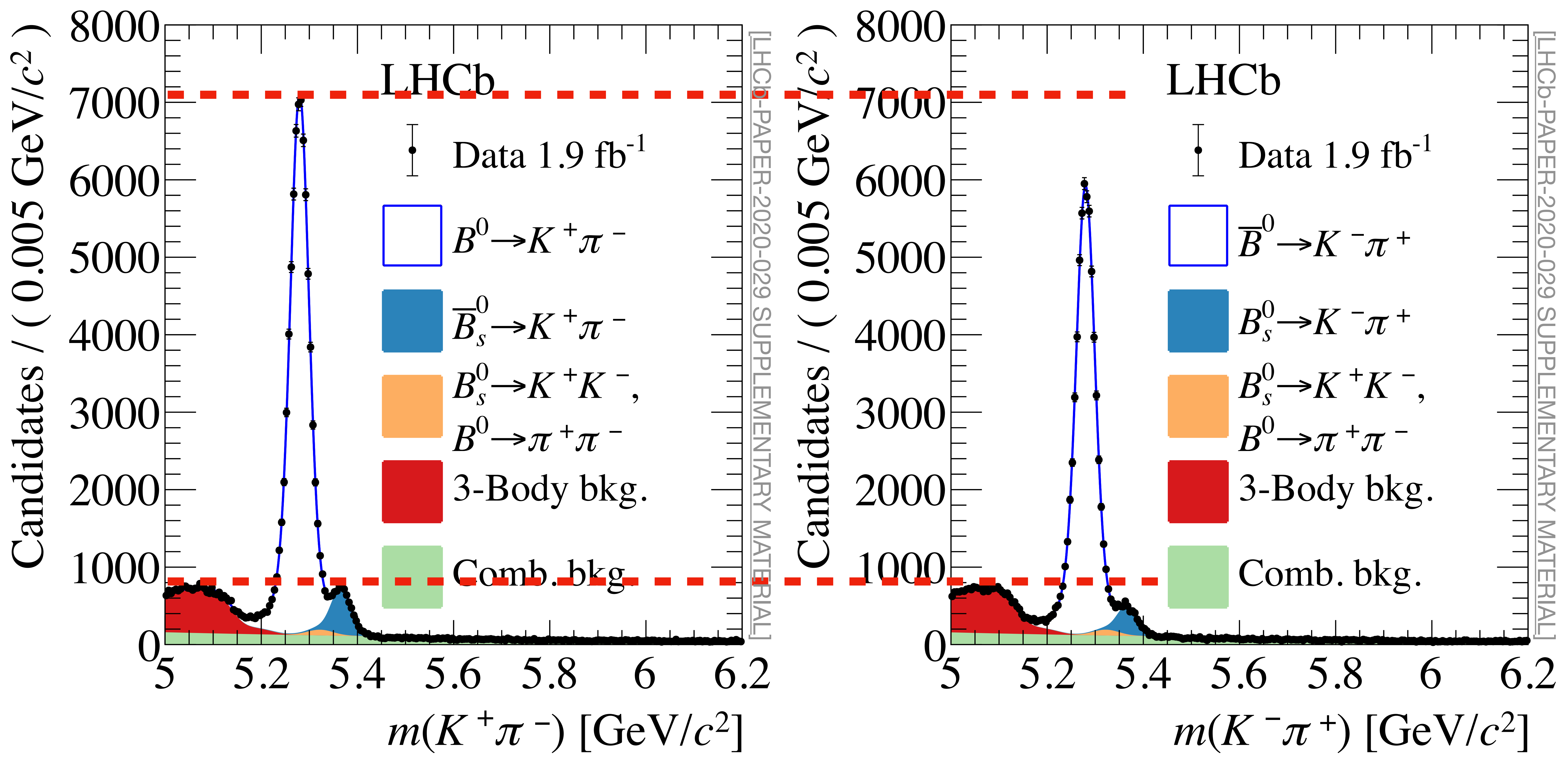
- **Two methods** are used to cross-check each other:

	"Simultaneous"*	"Per-event"
Fit	Simultaneous fit to all the spectra	Independent fit to bkg.-subtracted $\pi^+\pi^-$ and K^+K^- spectra
Decay Time Resolution	Averaged resolution for all events	Per-event resolution as a function of the decay time error
Flavour Tagging	Distinct OS and SS taggers, calibrated during the fit with $B^0 \to K^+\pi^-$candidates	Single combined tagger, calibrated before the fit
Acceptance correction	Calibrated using $B^0 \to K^+\pi^-$candidates	Per-event *swimming* method (see backup slides)

Calibrated with prompt $J/\psi \to \mu^+\mu^-$ and $\Upsilon(4S) \to \mu^+\mu^-$ decays

*: results from this method are used for combination with previous LHCb results.

Results for $B^0_{(s)} \to K^\pm \pi^\mp$



[Run1: PRD98(2018)032004]
[J. High Energ. Phys. 2021, 75 (2021)]

Final combinations with Run1 results:

$$A_{CP}^{B^0} = (-8.31 \pm 0.34)\,\%$$

$$A_{CP}^{B^0_s} = (+22.5 \pm 1.2)\,\%$$

stat.+syst. uncertainty

Most precise determination of these quantities to date

These results fulfil the SM consistency test proposed in [PLB 621 (2005) 126]

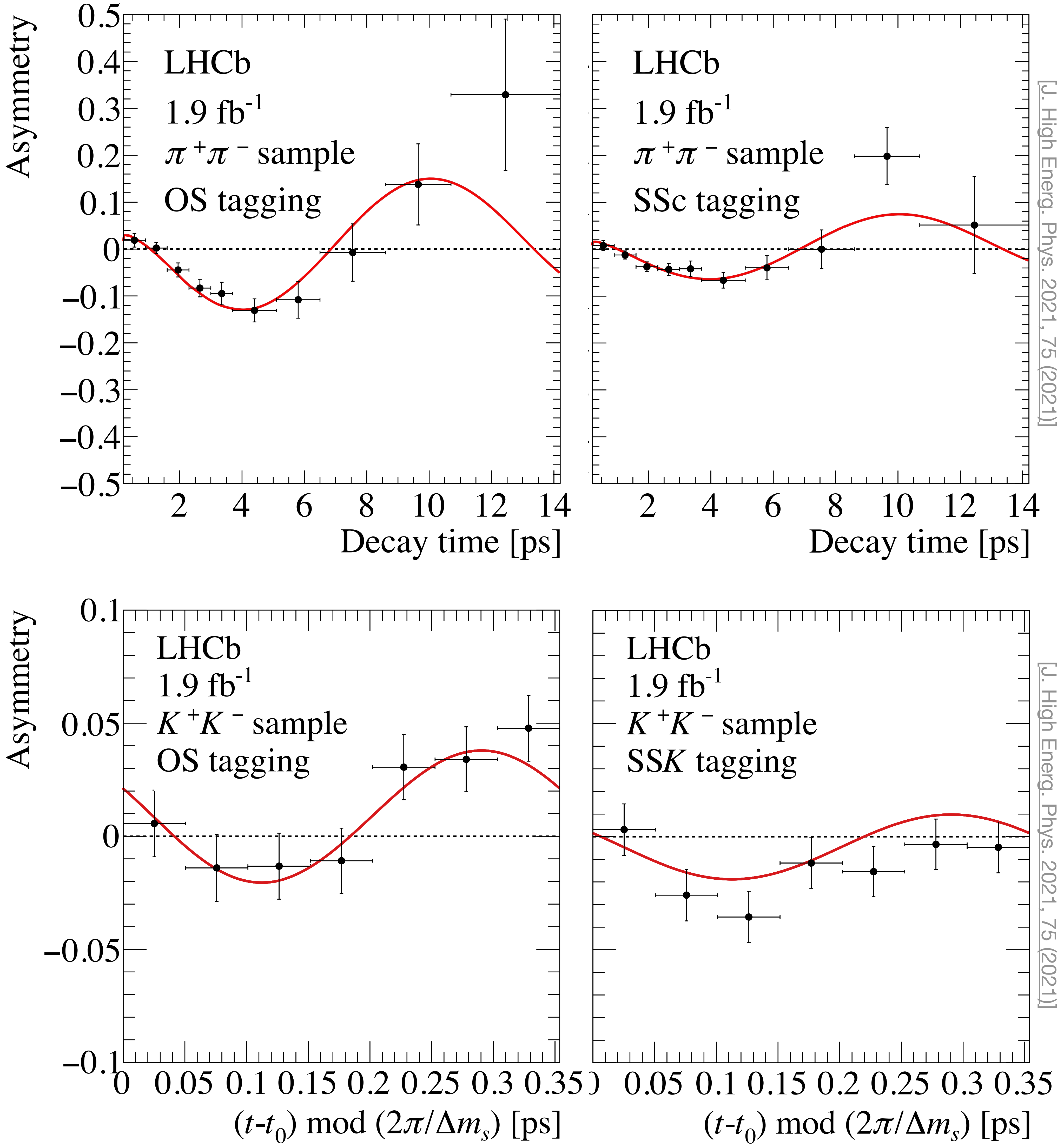
$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B^0_s}} + \frac{\mathbf{B}(B^0_s \to \pi^+K^-)\tau_d}{\mathbf{B}(B^0 \to K^+\pi^-)\tau_s} = -0.085 \pm 0.025 \pm 0.035$$

from A_{CP}

from external inputs

No evidence of new physics

Results for $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$



Decay time is folded into 1 oscillation period

[Run1: PRD98(2018)032004]
[J. High Energ. Phys. 2021, 75 (2021)]

Final combinations with Run1 results:

$C_{\pi\pi} = (-32.0 \pm 3.8)\,\%$

$S_{\pi\pi} = (-67.2 \pm 3.4)\,\%$

Most precise determination of these quantities to date

$C_{KK} = (17.2 \pm 3.1)\,\%$

$S_{KK} = (13.9 \pm 3.2)\,\%$

$A_{KK}^{\Delta\Gamma} = (-89.7 \pm 8.7)\,\%$

stat.+syst. uncertainty

1st OBSERVATION OF TIME-DEPENDENT CP VIOLATION IN THE B_s SECTOR!!!

$(C_{KK}, S_{KK}, A_{KK}^{\Delta\Gamma}) \neq (0,0,-1)$ at 6.5σ

$$\sqrt{(C_{KK})^2 + (S_{KK})^2 + (A_{KK}^{\Delta\Gamma})^2} = 0.93 \pm 0.08$$ ✓

Plots from the "per-event" method in the backup

Conclusions & Outlook

- The latest LHCb results about CP violation measurements in charmless two-body B-hadron decays have been presented
  - They are all consistent with the previous determinations

- CP violation in $B^+ \to K^+\pi^0$:
  - Very challenging analysis at hadronic collider
  - Measurement more precise than previous world average
  - Prospects are strongly dependent on performance at the higher occupancies expected in the upcoming Run3 and beyond (especially ECAL performance)

- CP violation in $B^0_{(s)} \to h^+h^-$ $(h \equiv K, \pi)$:
  - First observation ever of time-dependent CP violation in the B^0_s sector
  - Will benefit a lot from including data collected in 2017 and 2018 ← news expected soon
  - Explore time-dependent measurements of rarer modes like $B^0_s \to \pi^+\pi^-$

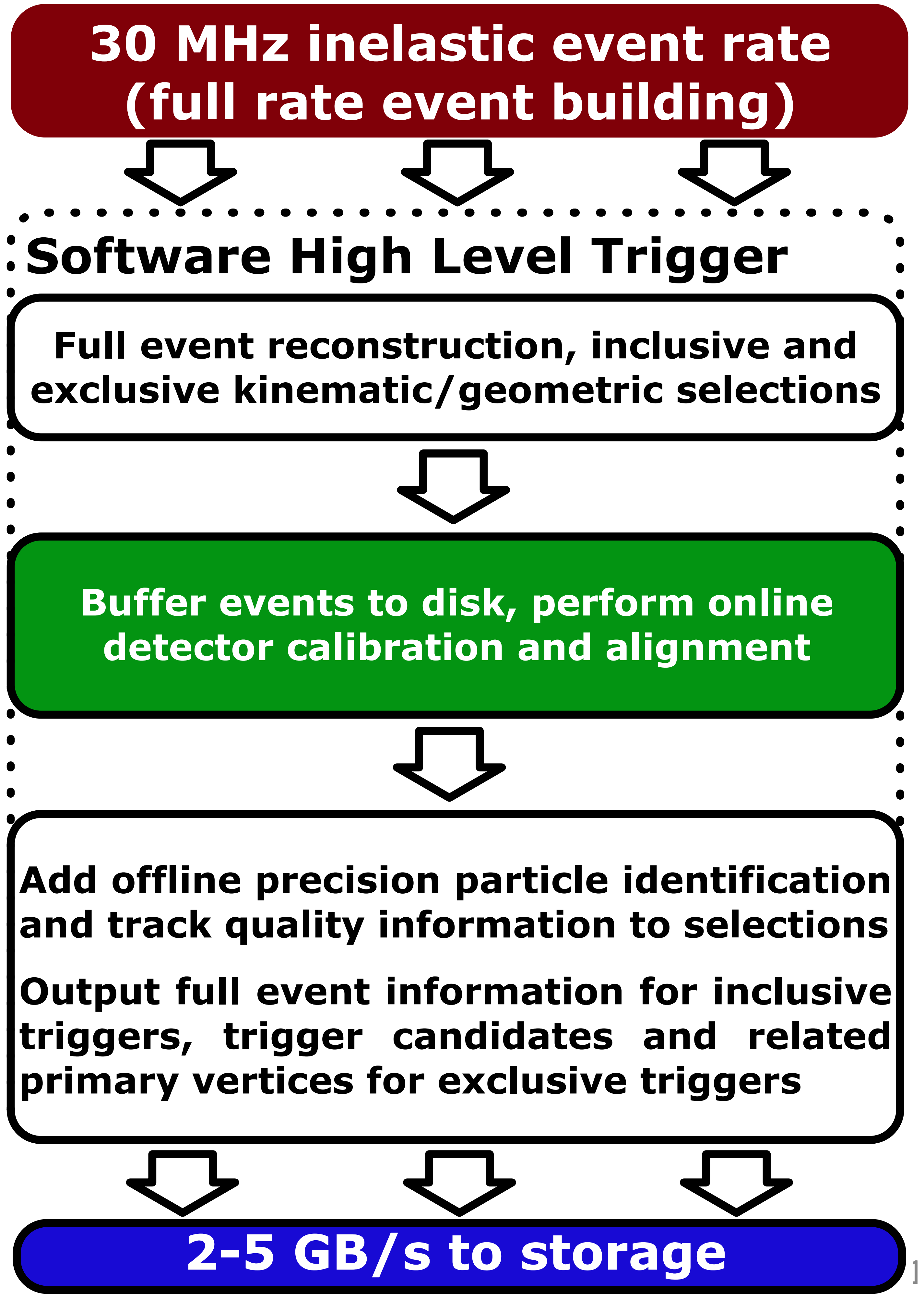
Backup slides

Plans for the near future

- LHCb Upgrade will start taking data soon
  - Plan to collect **x5 more data in the same time**, working with **x5 more populated events**
  - Almost completely redesigned detector and trigger

LHC era			HL-LHC era
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)
3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	46 fb^{-1}

LHCb Upgrade Trigger Diagram

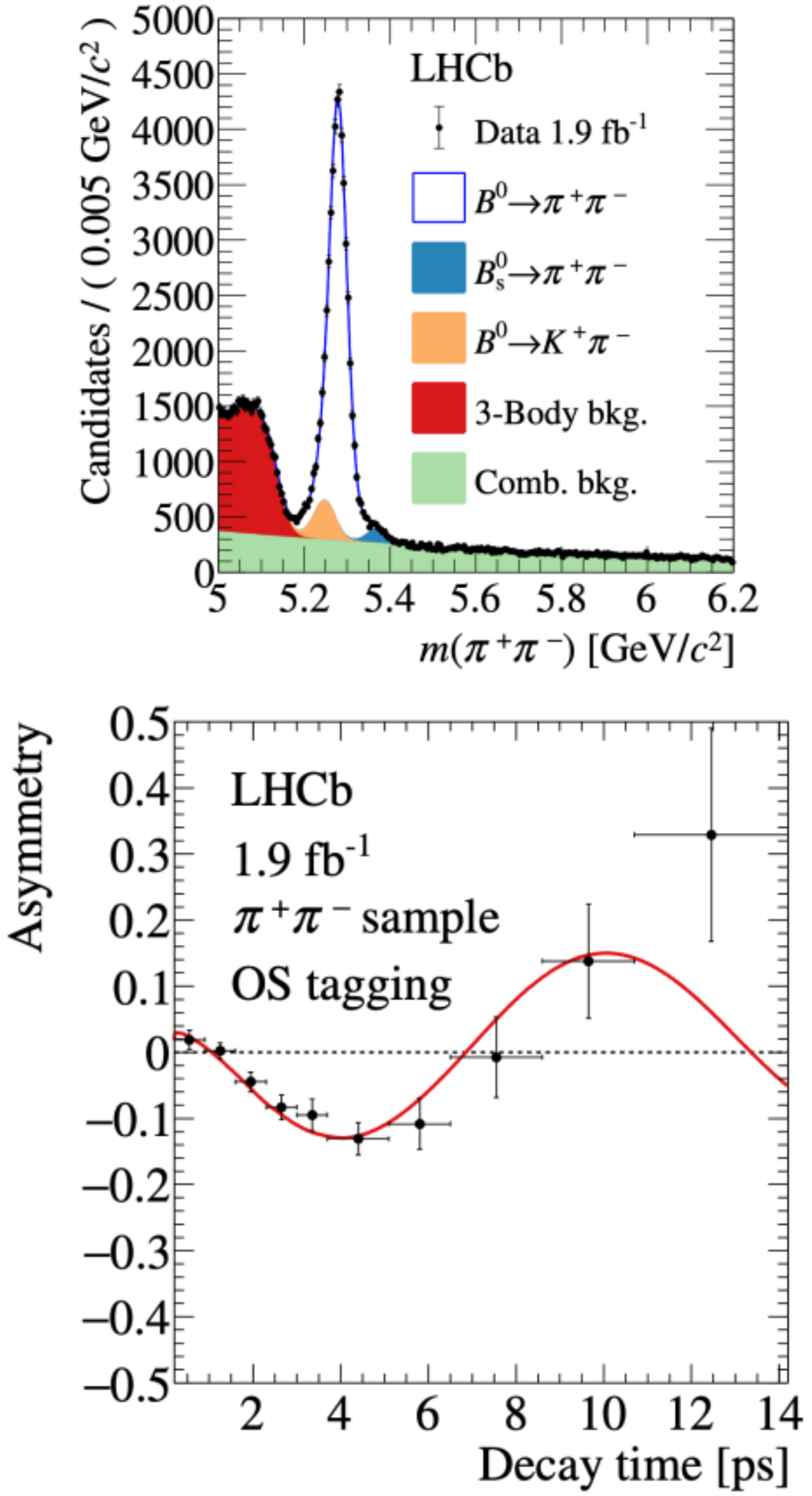


Systematics uncertainties on $A_{CP}^{\mathrm{LHCb}}(B^+ \to K^+\pi^0)$

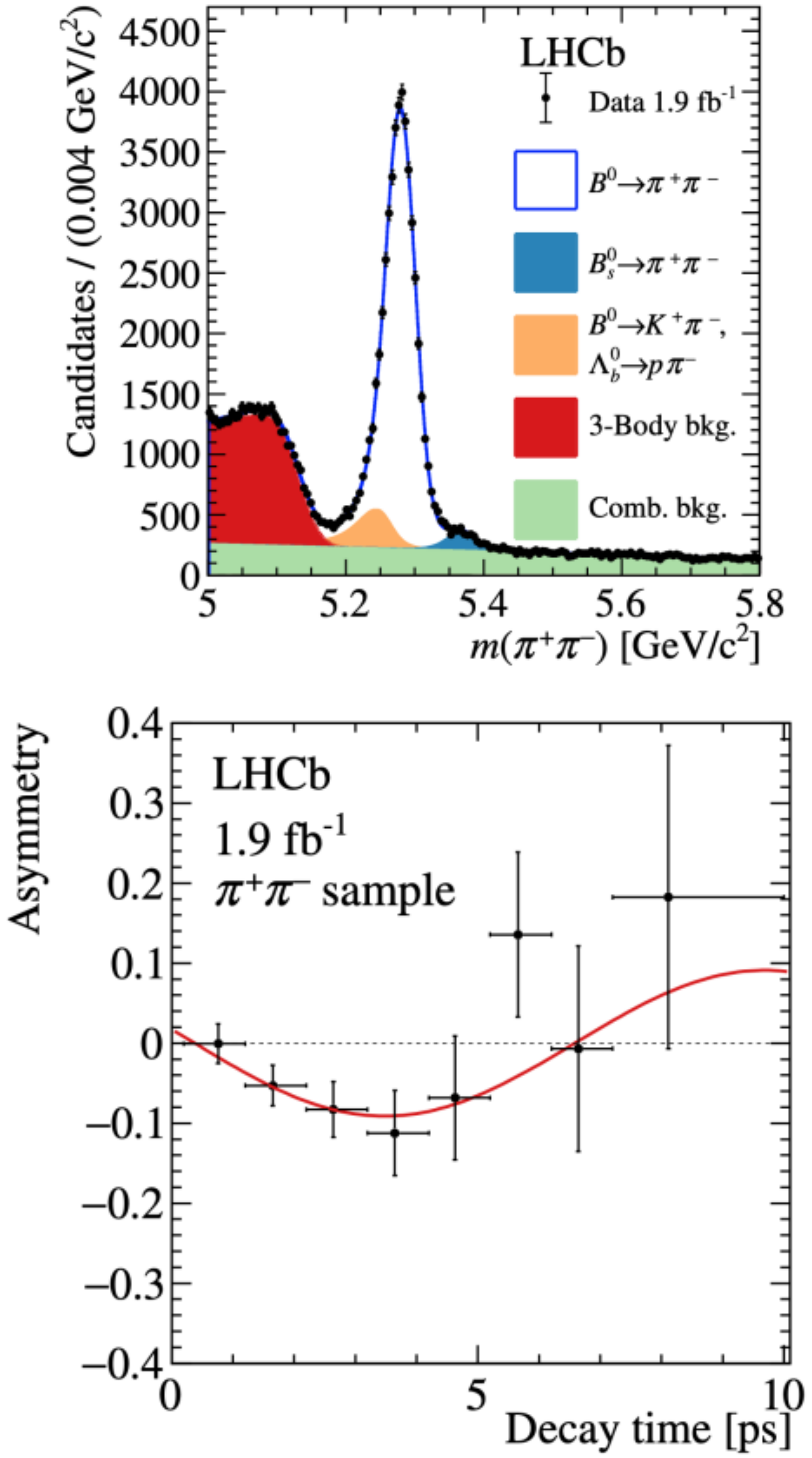
Systematic	Value ($\times 10^{-3}$)
Signal modeling shape	4.3
Combinatorial background shape	1.3
Partial reco. background shape	1.3
Peaking partial reco. background shape	1.2
Peaking partial reco. background offset	1.3
Peaking partial reco. background resolution	1.4
$B^+ \to \pi^+\pi^0$ yield	1.3
$B^+ \to \pi^+\pi^0$ CP asymmetry	1.5
Multiple candidates	1.3
Production/detection asymmetry stat.	2.1
Production/detection asymmetry weights	0.5
Sum in quadrature	6.1

CP-violation in $B^0 \to \pi^+\pi^-$ decays

Simultaneous method



Per-event method



JHEP 03 (2021) 075

JHEP 03 (2021) 075

Simultaneous method

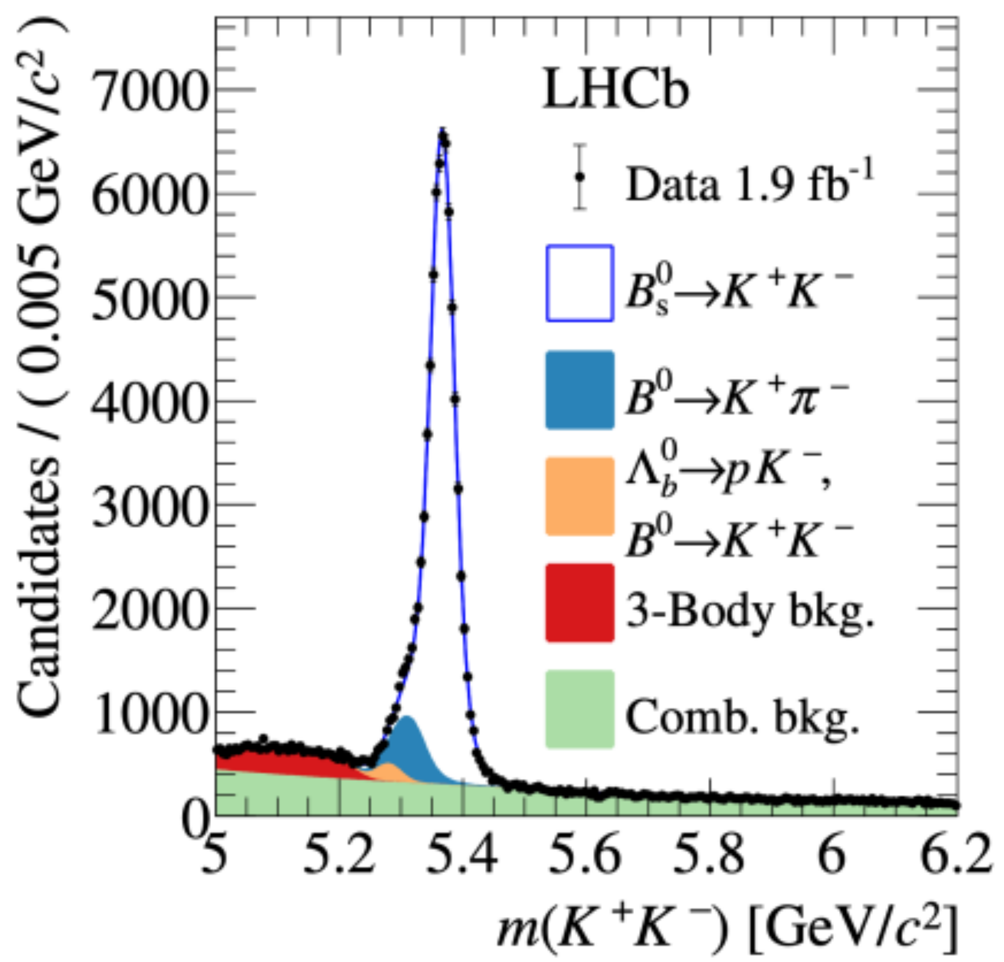
$$C_{\pi\pi} = -0.311 \pm 0.045,$$
$$S_{\pi\pi} = -0.706 \pm 0.042,$$

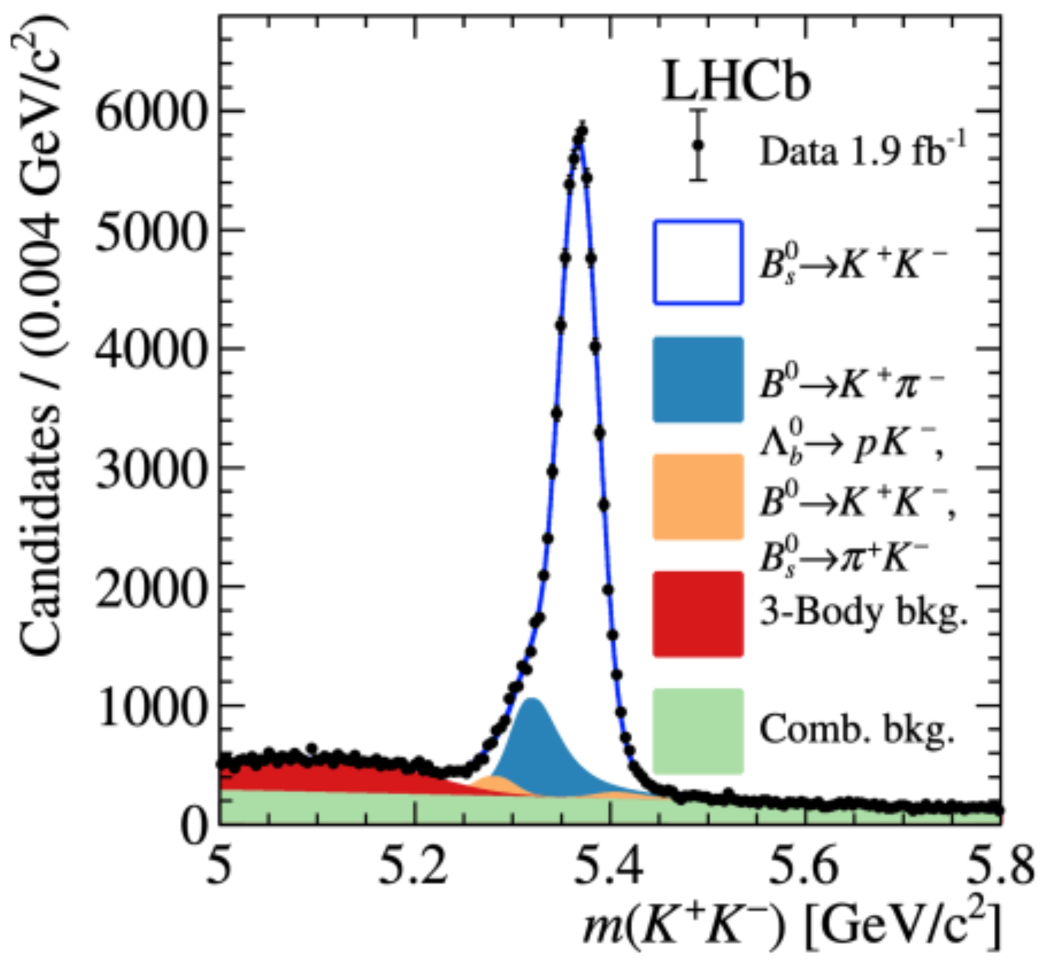
Per-event method

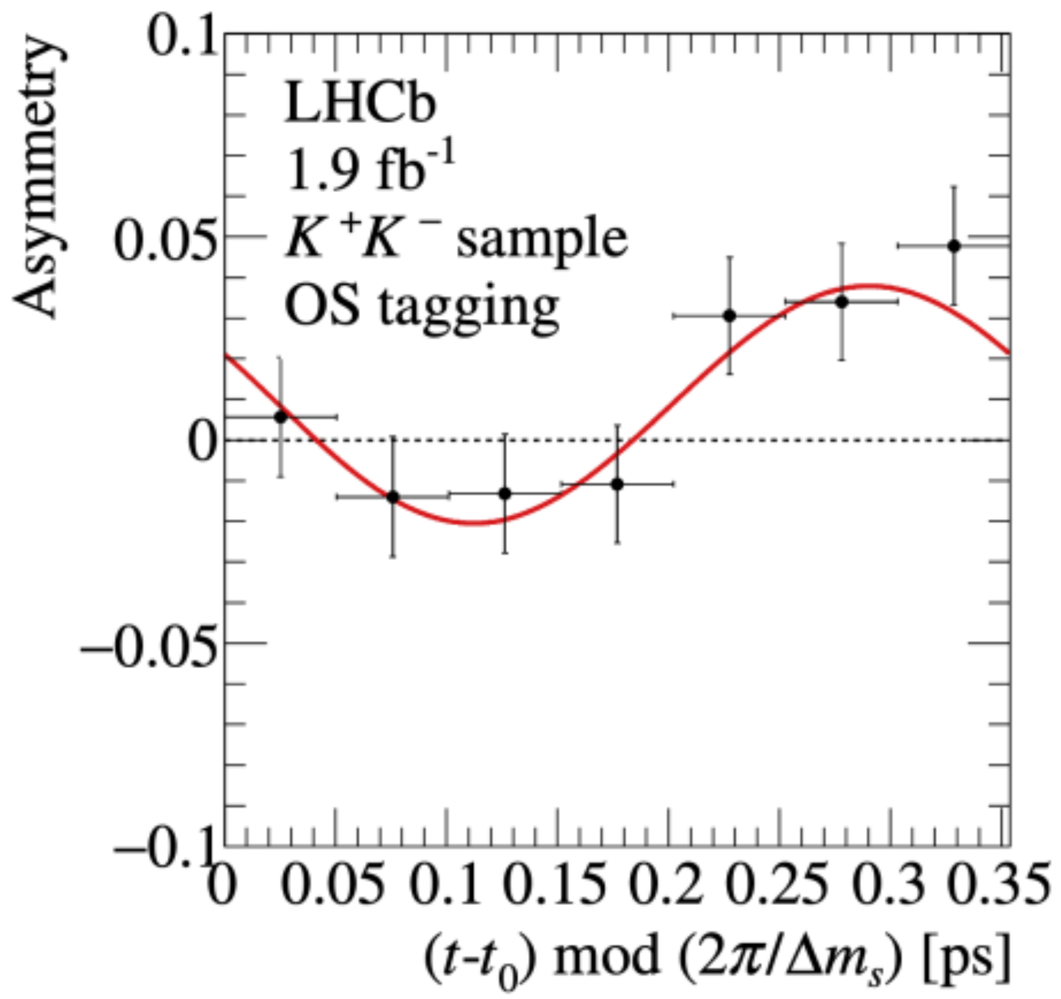
$$C_{\pi\pi} = -0.338 \pm 0.048,$$
$$S_{\pi\pi} = -0.673 \pm 0.043,$$

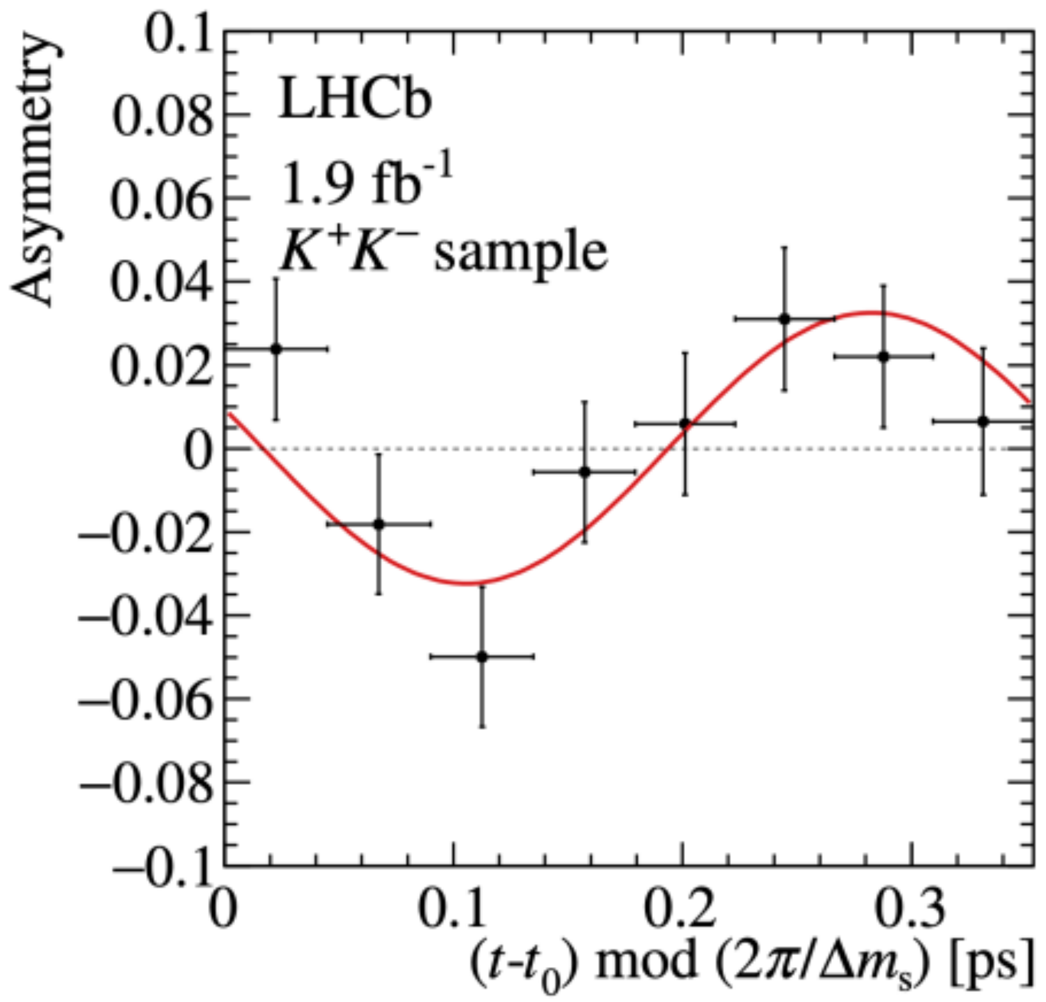
CP-violation in $B^0 \to K^+K^-$ decays

Simultaneous method | **Per-event method**









Decay time is folded into 1 oscillation period

JHEP 03 (2021) 075

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Simultaneous method

$$C_{KK} = 0.164 \pm 0.034,$$
$$S_{KK} = 0.123 \pm 0.034,$$
$$\mathcal{A}^{\Delta\Gamma}_{KK} = -0.833 \pm 0.054,$$

Per-event method

$$C_{KK} = 0.173 \pm 0.042,$$
$$S_{KK} = 0.166 \pm 0.042,$$
$$\mathcal{A}^{\Delta\Gamma}_{KK} = -0.973 \pm 0.071$$

CP-violation in $B^0_{(s)} \to h^+h^-$ decays: methods compatibility

- Compatibility between the two method is determined with pseudo experiments
  - Generate pseudo data with one fitting model and fit with both
  - Largest difference for $A^{\Delta\Gamma}_{KK}$ but large uncorrelated systematic uncertainties
  - Global compatibility at 1.5σ, dominated by difference in $A^{\Delta\Gamma}_{KK}$

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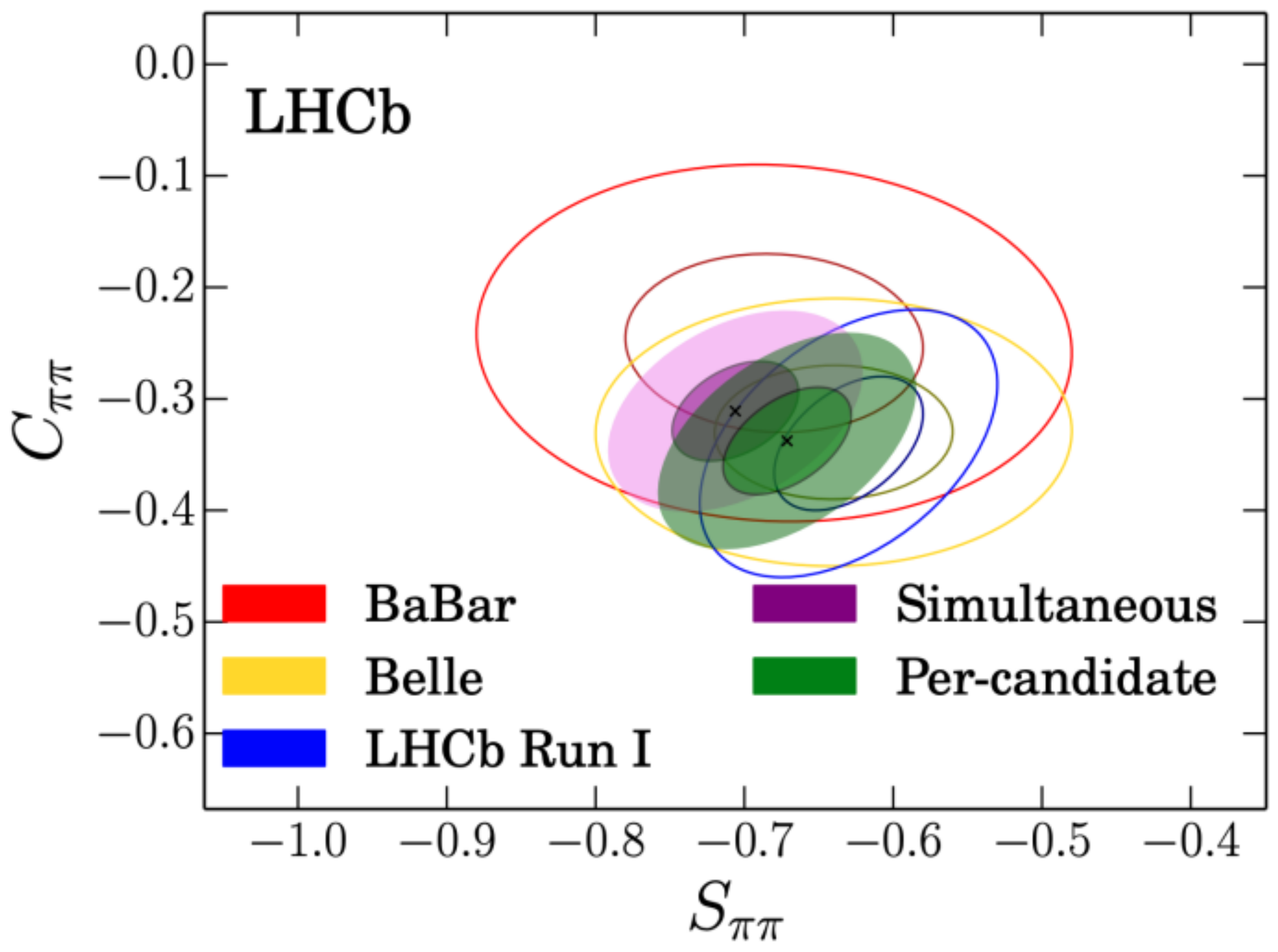

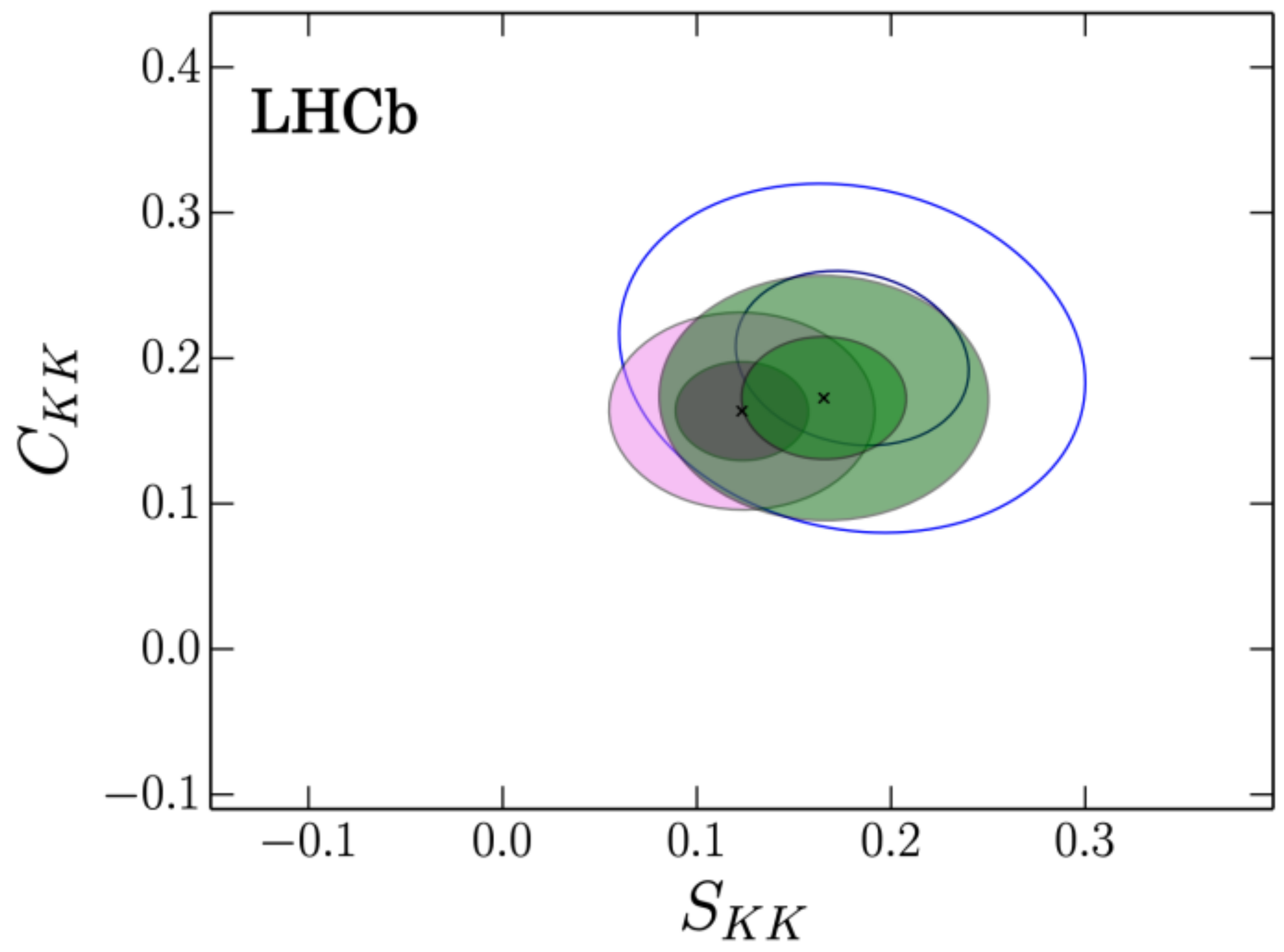

Systematics on $C\!\!\!/P$ in $B^0_{(s)} \to h^+h^-$ decays

Systematic uncertainties for simultaneous method

LHCb-PAPER-2020-029

Source	$C_{\pi\pi}$	$S_{\pi\pi}$	$A_{CP}^{B^0}$	$A_{CP}^{B^0_s}$	C_{KK}	S_{KK}	$\mathcal{A}_{KK}^{\Delta\Gamma}$
Time acceptance							
Model	0.0048	0.0027	0.0005	0.0005	0.0028	0.0029	0.0450
Calibration channel	0.0028	0.0013	0.0003	0.0057	0.0009	0.0009	0.0470
Transport between modes	0.0038	0.0019	0.0010	0.0001	0.0010	0.0007	0.0470
Time resolution							
Width	0.0015	0.0026	0.0001	0.0001	0.0087	0.0095	0.0000
Bias	0.0003	0.0003	0.0000	0.0000	0.0035	0.0034	0.0000
Average	0.0004	0.0007	0.0000	0.0000	0.0038	0.0038	0.0043
Input parameters	0.0029	0.0018	0.0001	0.0001	0.0055	0.0070	0.0471
B^0_s from B^+_c	–	–	–	–	0.0040	0.0032	0.0036
Flavour tagging							
SSK calibration	–	–	–	–	0.0033	0.0042	0.0001
Calibration model	0.0012	0.0013	0.0000	0.0000	0.0037	0.0034	0.0012
$H_b \to h^+h'^-$ mass model	0.0065	0.0078	0.0004	0.0074	0.0017	0.0018	0.0057
Cross-feed model	0.0075	0.0044	0.0001	0.0001	0.0011	0.0001	0.0015
Comb. bkg. model	0.0057	0.0030	0.0001	0.0015	0.0005	0.0005	0.0064
Part. reco. model	0.0043	0.0063	0.0005	0.0036	0.0012	0.0013	0.0113
PID in fit model	0.0020	0.0031	0.0002	0.0016	0.0004	0.0006	0.0013
PID asymmetry	–	–	0.0028	0.0028	–	–	–
Det. asymmetry	–	–	0.0012	0.0012	–	–	–
Total	0.0145	0.0128	0.0033	0.0108	0.0137	0.0149	0.0944

Per-event swimming method

- Acceptance corrected on per-event basis
- B-hadrons are moved along their momentum vector and decay time biasing selections are re-evaluated ("swimming method")
- Each hypothetical decay time is assigned a 0 (not accepted) or 1 (accepted). Transition times are called turning points
  - Acceptance is a step function within the "start" and "end" turning points of the event
- Biasing selections are:
  - Mother and daughter IP χ^2
  - DIRA
  - Flight distance χ^2
  - BDT
- Additional requirements on:
  - Radial flight distance
  - VELO acceptance
  - HLT1TrackMVA (it's an OR of the selected tracks)