18th FPCP 2020

Online

Experimental status of CPV in B → 4h

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On behalf of the LHCb collaboration

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Setting the stage

- The Standard Model (SM) fails to explain matter anti-matter differences in our universe.
  - Charge-Parity (CP) violation allows to introduce differences in the decays of particles and antiparticles
- In the SM, flavour transitions in the quark sector are parametrised by the CKM matrix
  - CKM parameters are over constrained in the SM → great scenario to search for incompatibilities and small deviations due to New Physics (NP) effects
- New sources of CP-violating asymmetries are therefore expected in any satisfactory SM extension!

Minimal introduction to CPV

- Interference process: requires **at least two contributing amplitudes** in a decay
  - Non-vanishing strong and weak phase-difference
    - (T-odd choice of observables might overcome the strong-phase difference requirement)
  - Some SM predictions available with errors on/below the per cent level

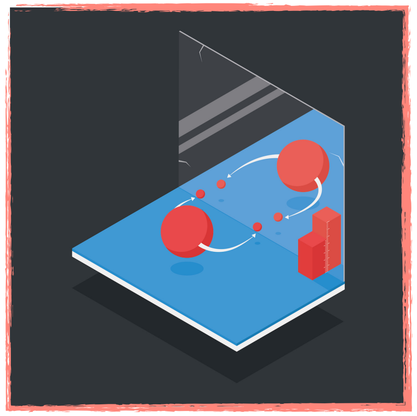
$$\phi_s^{SM} = -2\beta_s = -0.03686^{+0.00096}_{-0.00068}\ \text{rad}$$

CKM-fitter

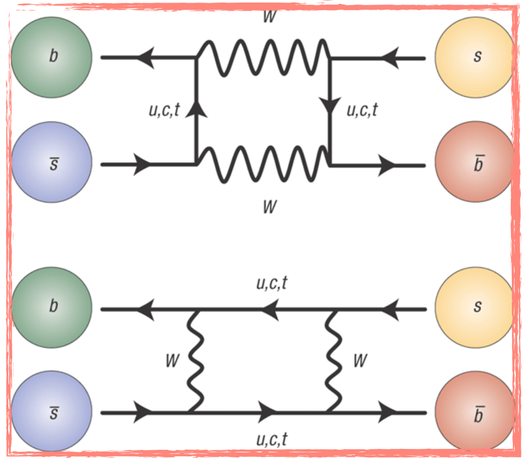
✦Triple-products asymmetries in charmless decays ~<5%

Nucl.Phys.B774:64-101,2007

Decay

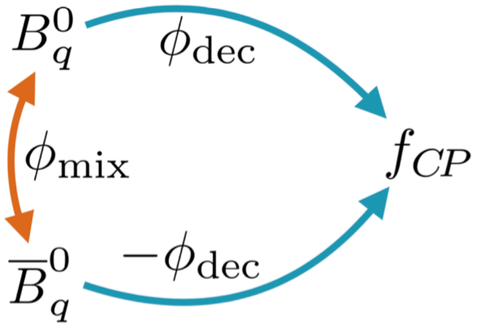


Mixing



Interference Mix/Dec

$$\beta_s \equiv \arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



$$\phi_s \equiv \phi_{\rm mix} - 2\phi_{\rm dec}$$

Known penguins?

Rare penguins?

No penguins?

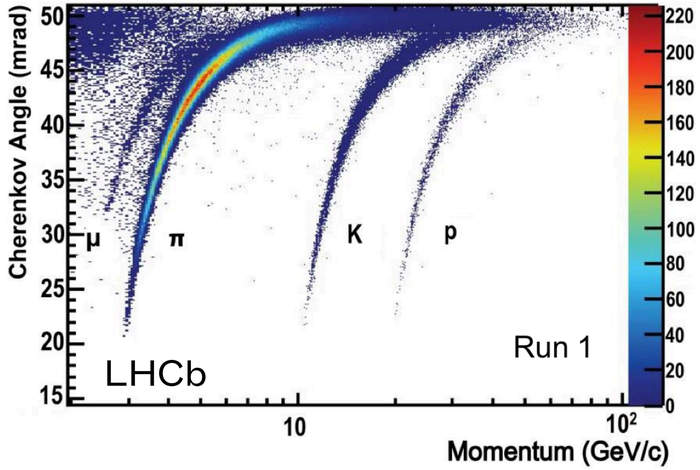
Analyses covered in this talk

- Amplitude analyses of charmless B decays
  - $B^0 \to (K^+\pi^-)(\pi^+\pi^-)$
  - $B^0_{(s,d)} \to (K^+\pi^-)(K^-\pi^+)$
  - $B^0_s \to \phi\phi$

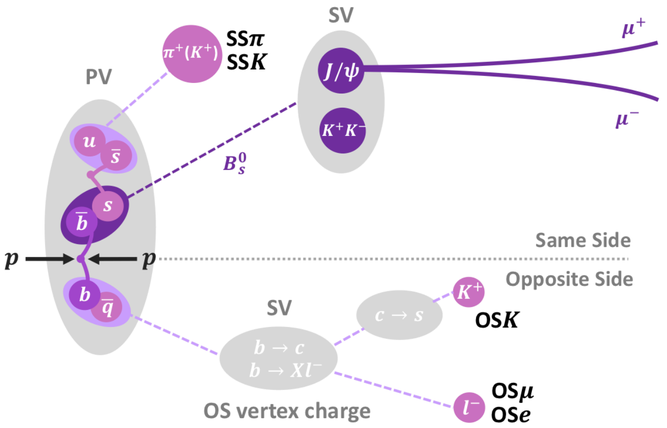
✺ Summary/Spoiler: Need to know the penguins!

Experimental requirements when measuring CPV

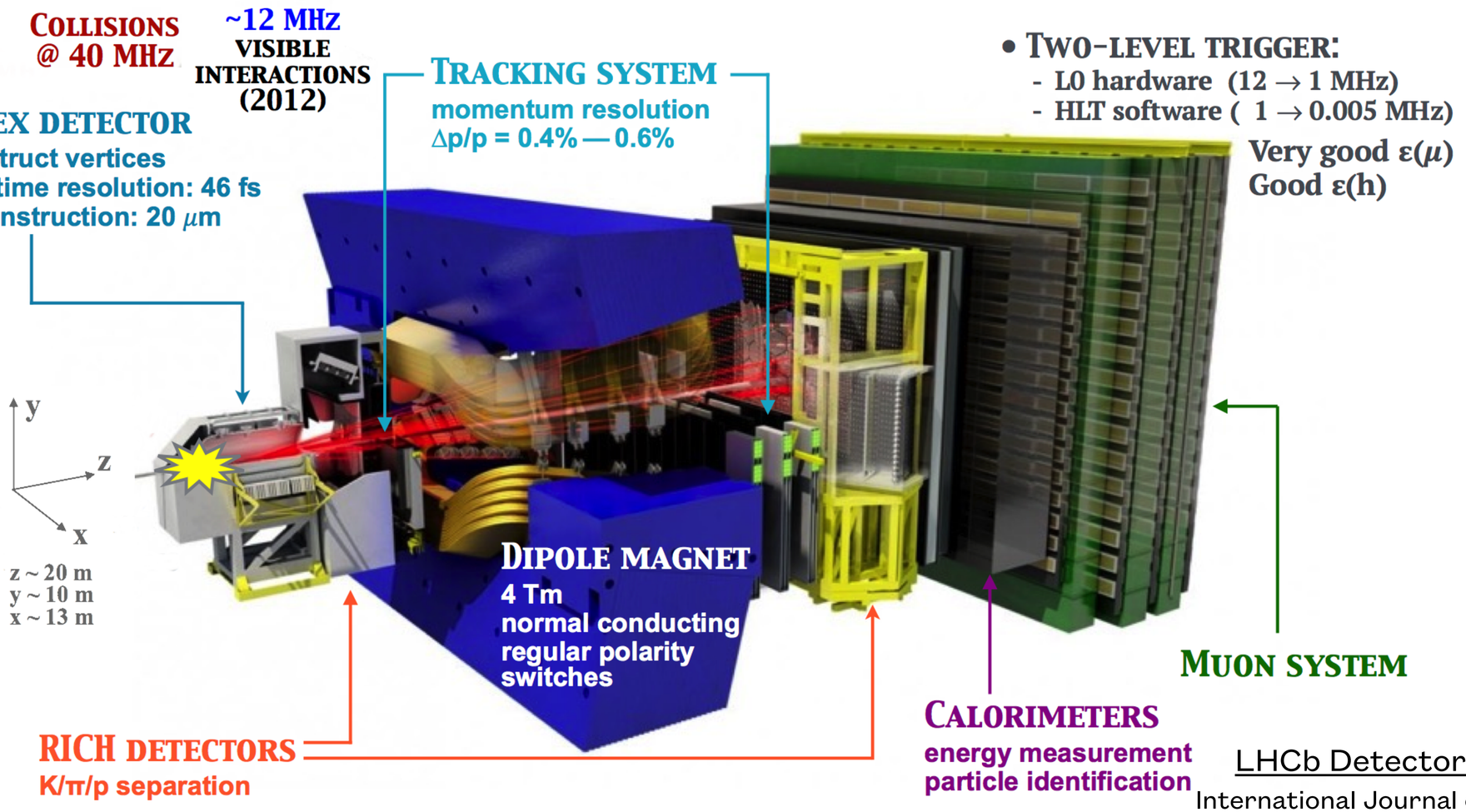
- Excellent **vertexing**
  - to separate primary form secondary vertices
  - to resolve fast oscillations
- Very good **Particle Identification** capabilities
  - to distinguish between topologically identical events
  - to tag the initial flavour content (~5% tag power)
- Sizeable data samples (precision!)
- Good control over known CP asymmetries/effects



RICH performance



LHCb detector

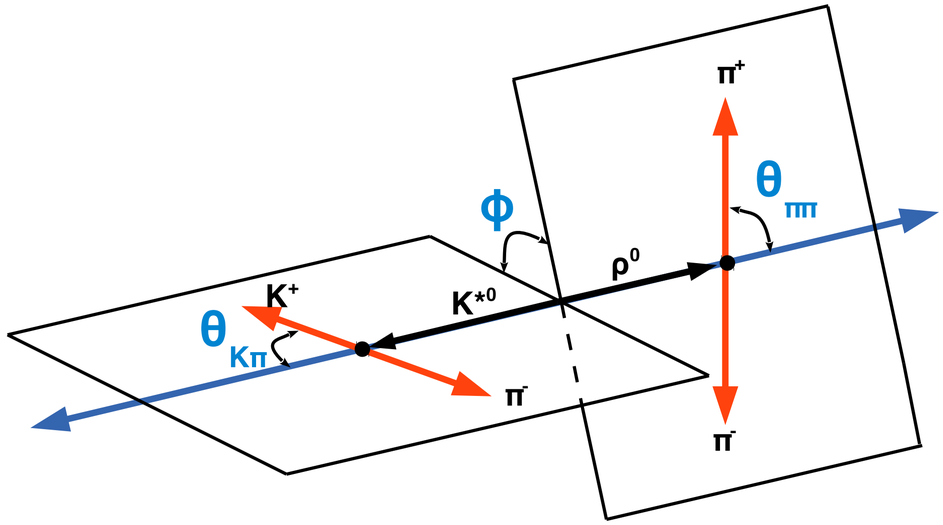


LHCb Detector Performance
International Journal of Modern Physics A
Vol. 30, No. 7 (2015) 1530022

Amplitude analyses

- Describe the decay rate in a multidimensional space
- Different choice of parameterisations depending on the analysis/formalism/goals
- For the analyses presented today
  - **3 helicity angles** (variables of D-Wigner functions)
  - **2 invariant masses** (different mass propagators, Breit-Wigner, Flattè, Gounaris-Sakurai…)
  - Decay time (gives access to ϕ_s)
- Total decay rate (*N* amplitudes) built following the **Isobar formalism**: coherent sum of contributions, where the relative phases and strengths of the amplitudes are the fit parameters:

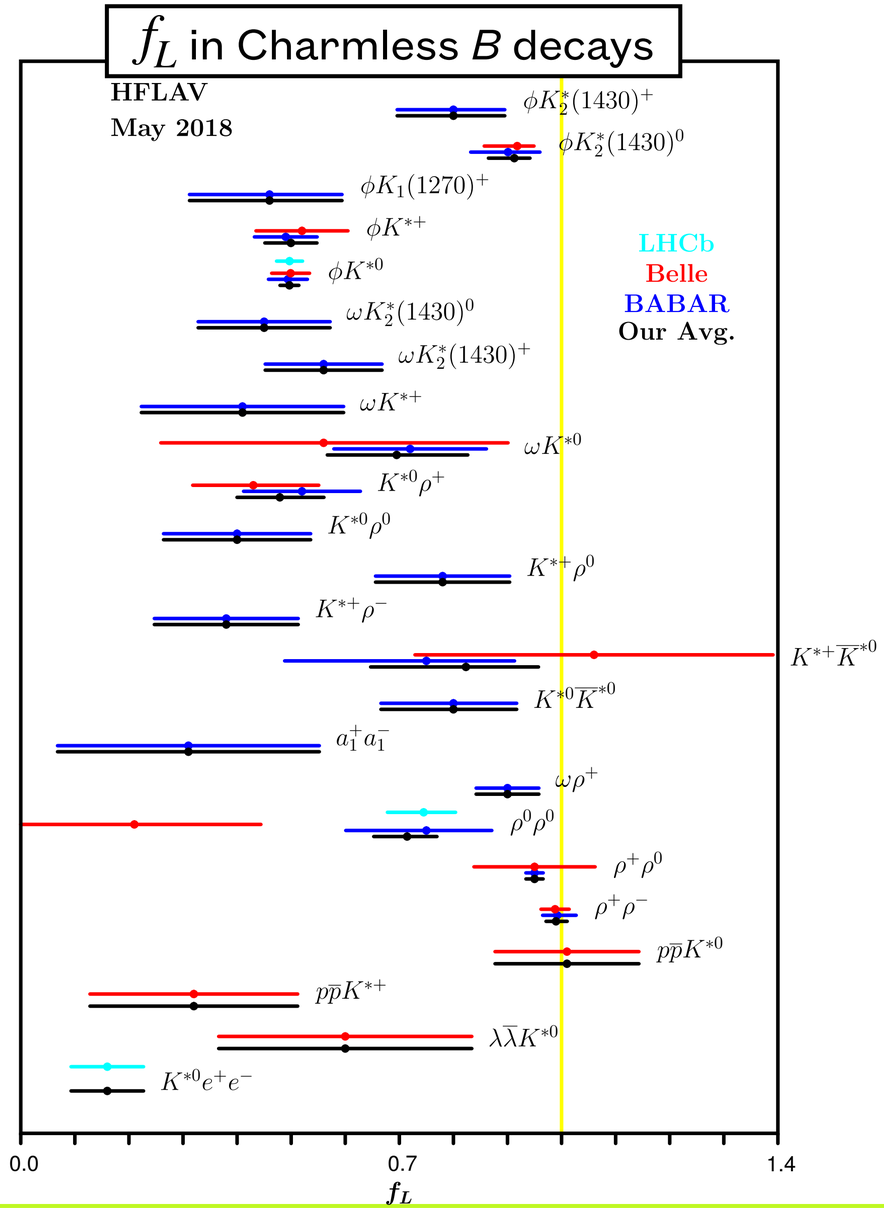
$$d^5\Gamma \propto \left| \sum_{i=1}^{N} A_i \cdot g_i(\cos\theta_{12}, \cos\theta_{34}, \phi) \cdot M_i(m_{12}, m_{34}) \right|^2$$



Convenient re-parameterisation of the amplitudes (spin1 resonances):

$$f^\lambda = \frac{|A^\lambda|^2}{|A^L|^2 + |A^{||}|^2 + |A^\perp|^2}$$

Polarisation fractions



Longitudinal polarisations

- Large values for **tree dominated** decays

$$A_L \gg A_- \gg A_+$$

- **Penguin dominated** modes spawn wider ranges, unclear pattern

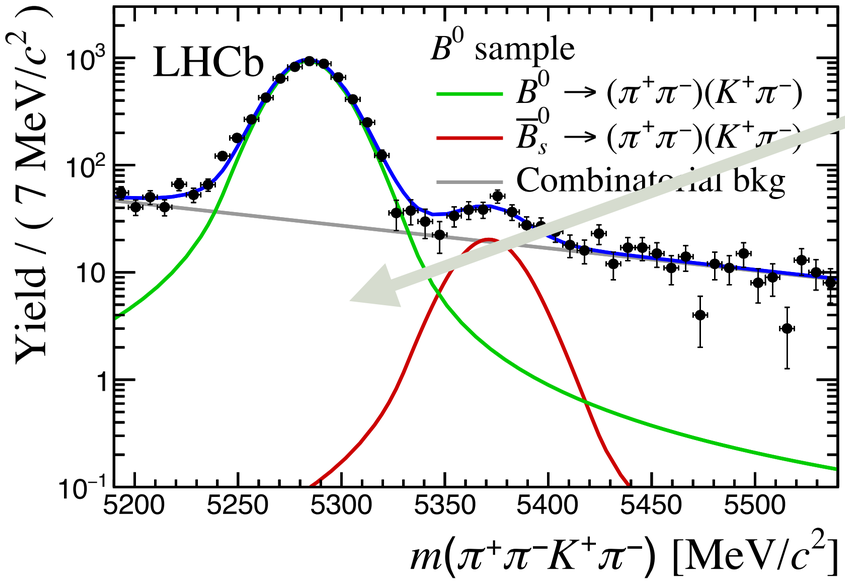
$$A_L \sim A_- \gg A_+$$

- All reported measurements are CP-averaged
- Precise predictions unavailable, **general dynamics not fully understood** → factorisation and expansion terms in perpendicular amplitudes complicated to deal with
- Non uniform theory predictions depending on the used approach (pQCD/QCDF)

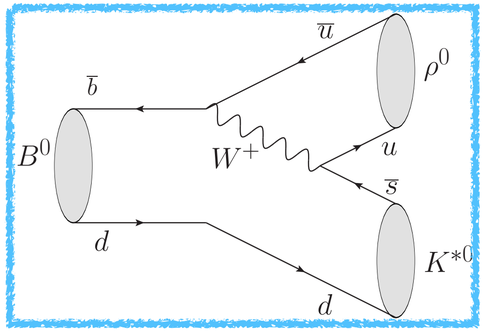
$B^0 \to (K^+\pi^-)(\pi^+\pi^-)$

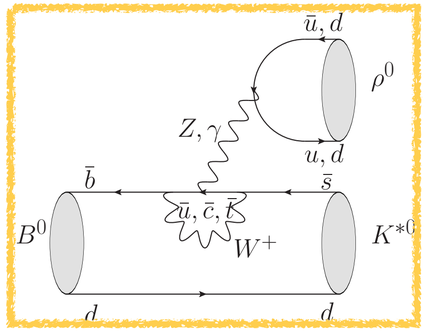
JHEP 05 (2019) 026

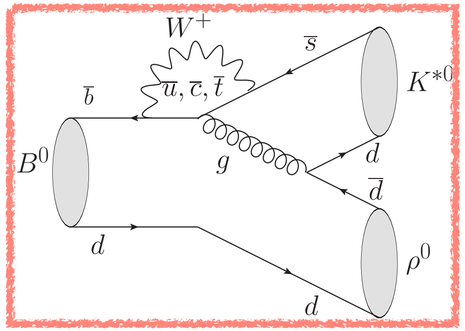
- Analysis performed on LHCb **Run I data** sample
- Charmless, **self-tagged** decay, with three competing amplitudes from: a doubly-Cabibbo suppressed tree, a colour allowed EW penguin and a colour suppressed gluonic penguin.
- **Sensitivity to CPV** by fitting both B and $\overline{B}$ samples.



~11k signal candidates!

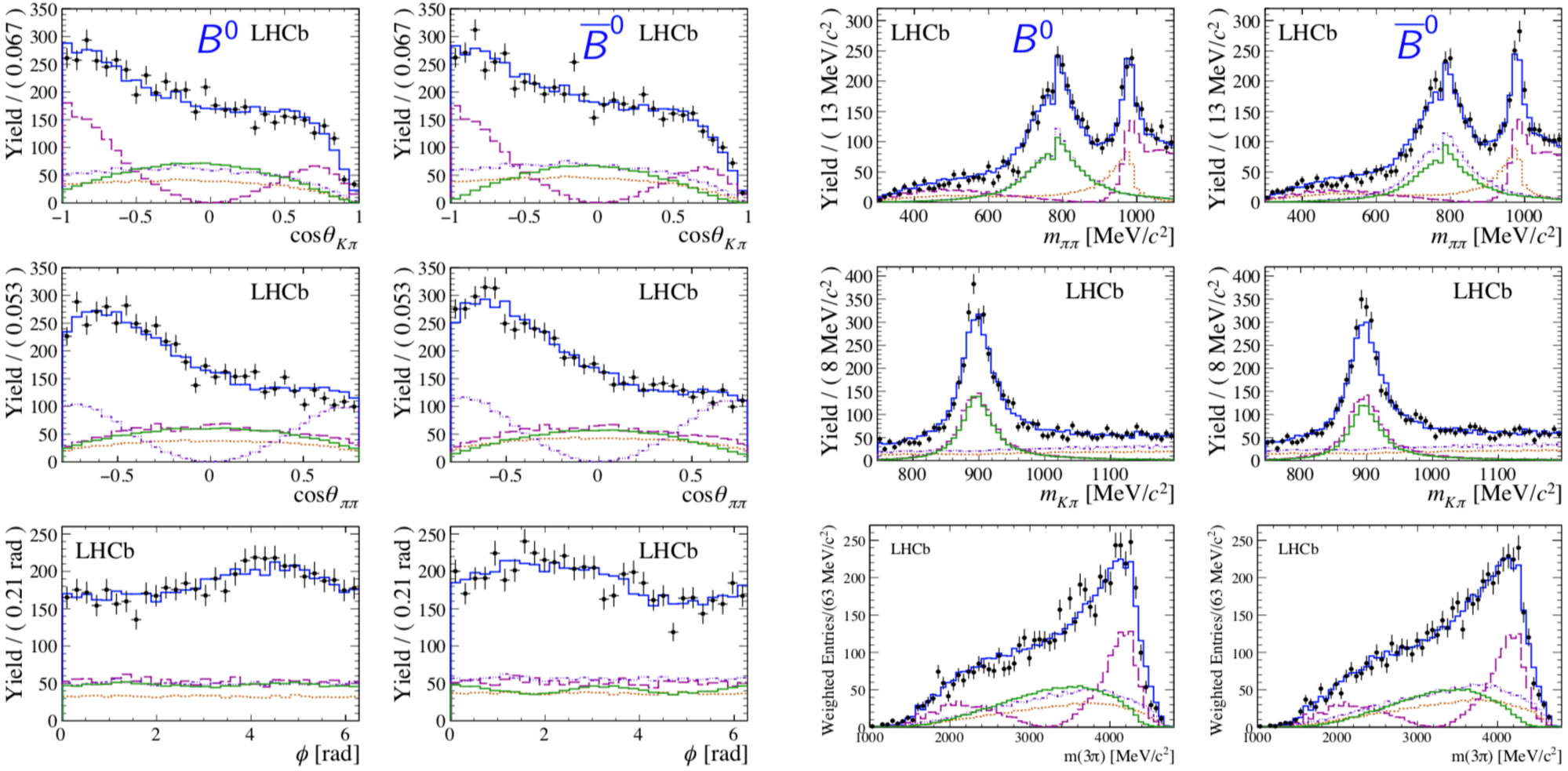






Fit projections

JHEP 05 (2019) 026



VV: $\rho K^*, \omega K^*$, **VS**: $\rho(K\pi), \omega(K\pi)$,

SV: $[f_0(500), f_0(980), f_0(1370)]K^*$,

SS: $[f_0(500), f_0(980), f_0(1370)](K\pi)$

Selected results

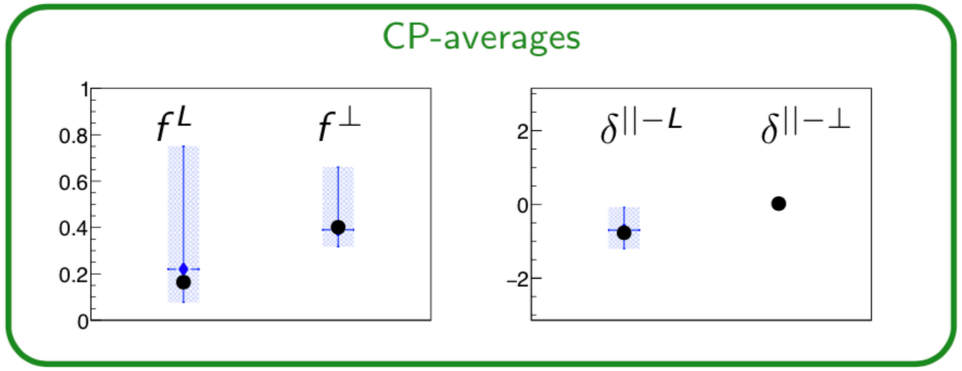
JHEP 05 (2019) 026

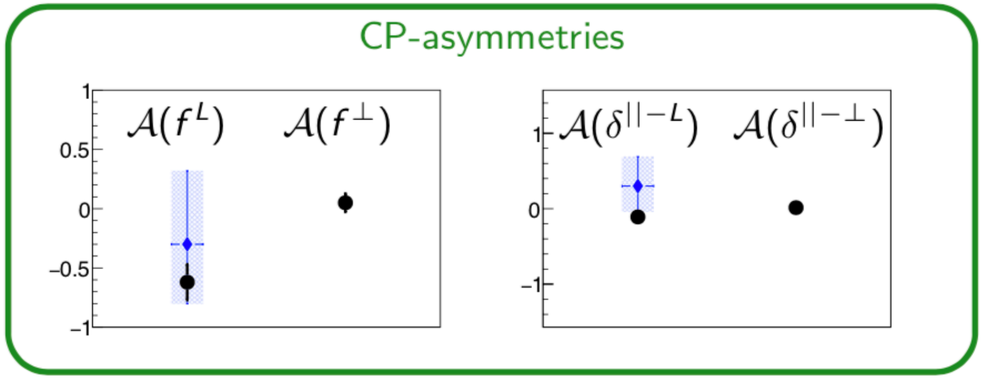
NUCL.PHYS.B774:64-101,2007

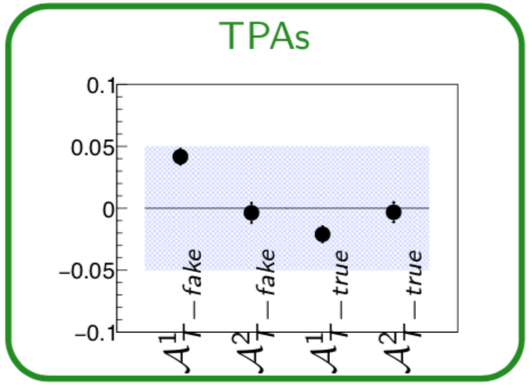
- **First amplitude analysis of this mode**, describing 13 amplitudes in the VV, SV, VS and SS configurations
- **First observation of CPV in angular distributions of VV decays**
- Hinting at EWP contribution more relevant than initially considered
- Most relevant uncertainties due to statistics, second relevant, due to the treatment of background events
- New (Dec'19) theoretical predictions on A_{CP} and $\mathscr{B}$, but only considering the interplay between the two channels $B^0 \to K_0^*(700)^0\rho(770)^0$ and $B^0 \to K^*(892)^0 f_0(500)$ (arXiv:1912.11874)

Fit results (stats. and syst. uncertainties included)

Theoretical predictions (QCDF) with uncertainties

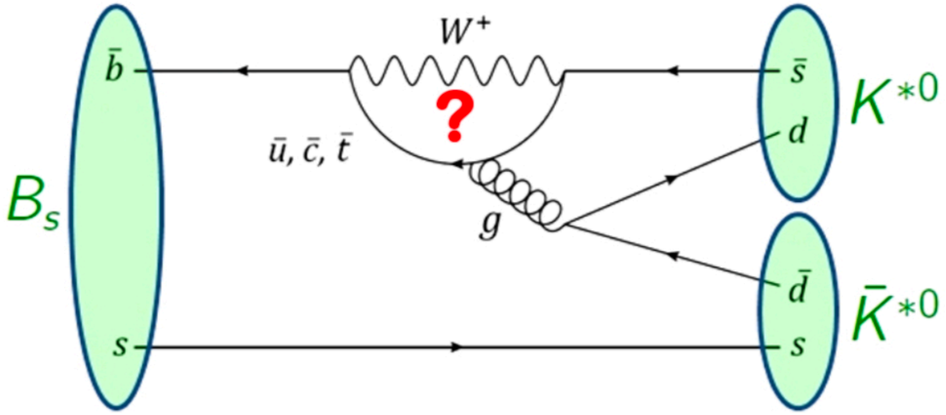






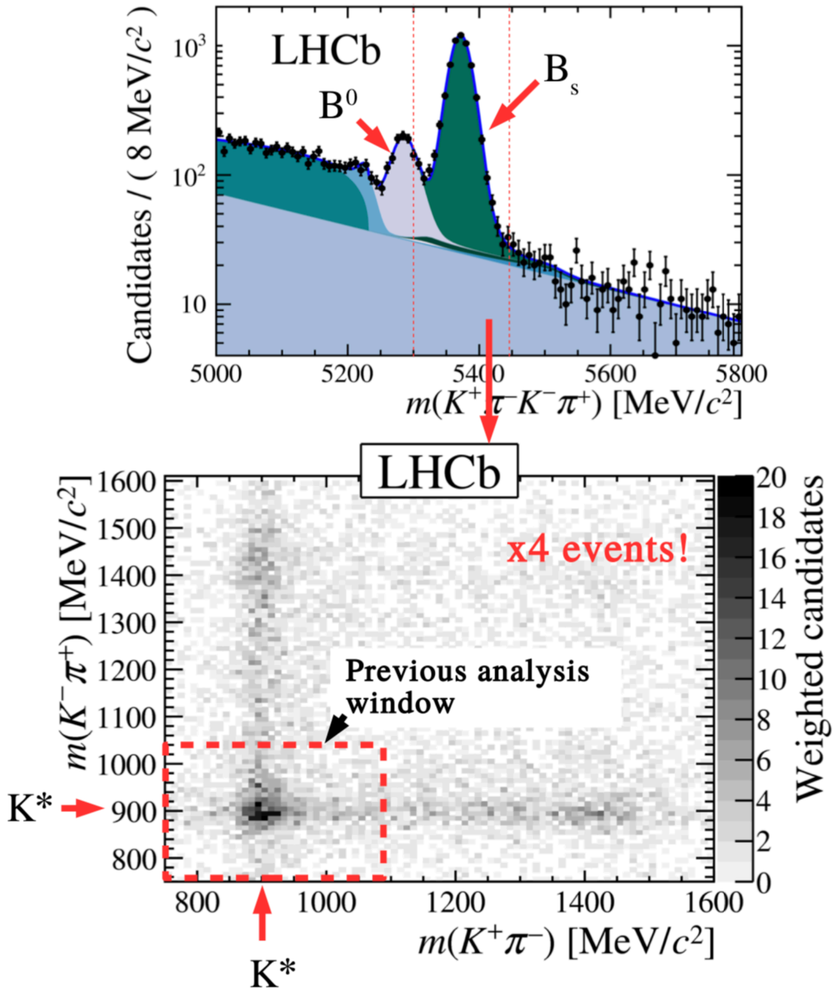
$B^0_{(s,d)} \to (K^+\pi^-)(K^-\pi^+)$

- Combination of CP eigenstates in the final state.
- Forbidden at tree-level: **pure gluonic penguin decay**, good sensitivity to new contributions!
- Long history in LHCb: 4 publications using up to full Run I data set
  (PLB 709 (2012) 50-58, JHEP 07 (2015) 166, JHEP 03 (2018) 140, JHEP 07 (2019) 032)
- Latest results (using full LHCb **Run I** data):
  - **JHEP 03 (2018) 140**: Time-dependent, tagged, amplitude analysis, Bs mode, measurement of $\phi_s^{d\bar{d}}$
  - **JHEP 07 (2019) 032**: First amplitude analysis of the Bd mode, untagged, time-integrated analysis



$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

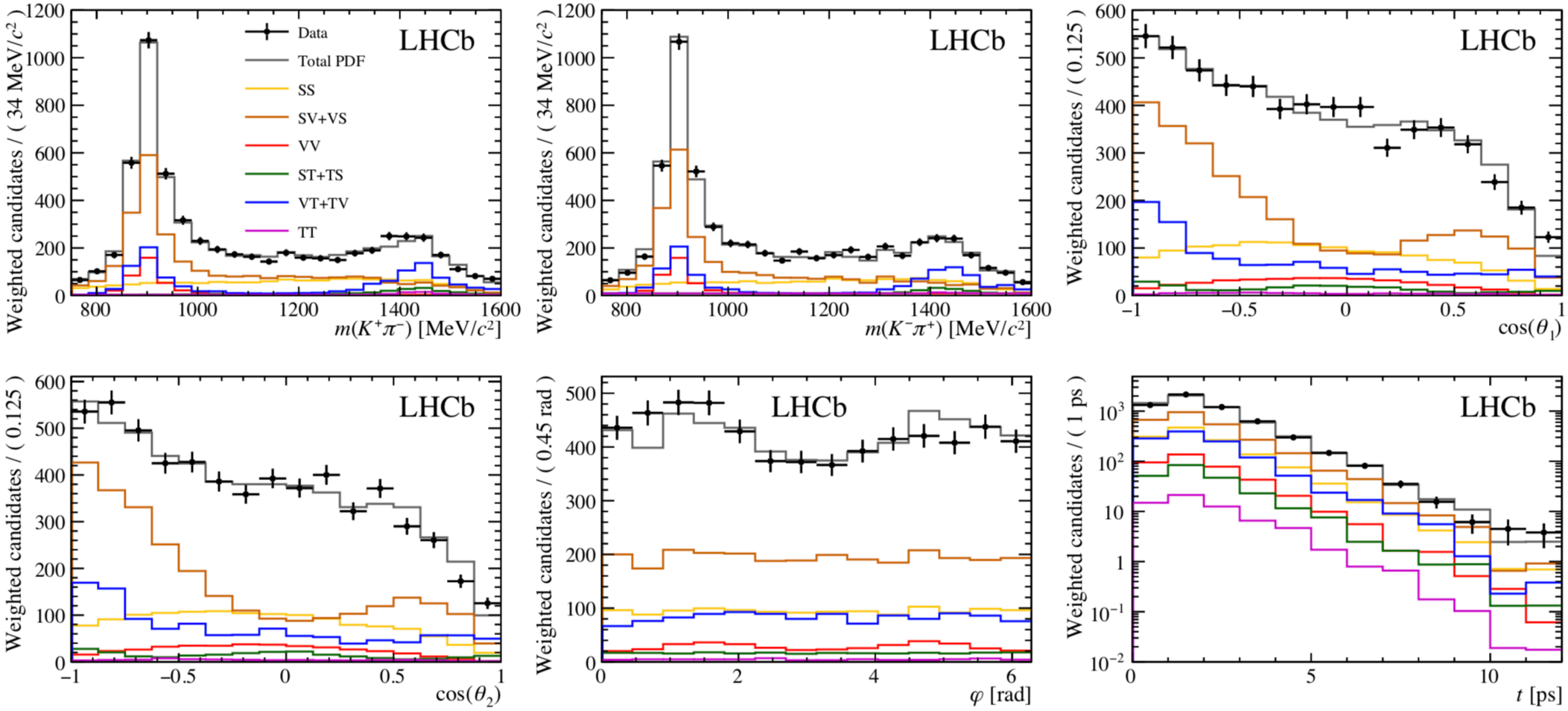
JHEP 03 (2018) 140



- **Time-dependent, tagged analysis**
- Analysis region extended way beyond the K* resonance region (accounts for spin-0, 1 and 2 components)
  - 9 decay channels, **19 contributing amplitudes**
  - Weak phase $\phi_s^{d\bar{d}}$ shared among all amplitudes
  - S-wave parameterisation:
    - Phase evolution taken from scattering phenomenology, Phys. Rev. D 93, 074025 (2016)
    - Modulus described with a form factor with floated parameters in the fit
- **~6k signal events**

Fit projections

JHEP 03 (2018) 140



Selected results

JHEP 03 (2018) 140

- (Using full LHCb Run I data)
- Measured 19 CP-averaged polarisation amplitudes. Highlighting the VV mode:

$$f_L = 0.208 \pm 0.032 \pm 0.046$$

- Measured 2 CP-violating observables:

$$\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14 \text{ rad} \qquad |\lambda| = 1.035 \pm 0.034 \pm 0.089$$

- All results compatible with SM expectations $\phi_s \sim 0,\ |\lambda| = 1$
- Systematic uncertainties dominated by the treatment of the multi-dimensional acceptance. Also relevant, the presence of the neglected extra vector resonances.

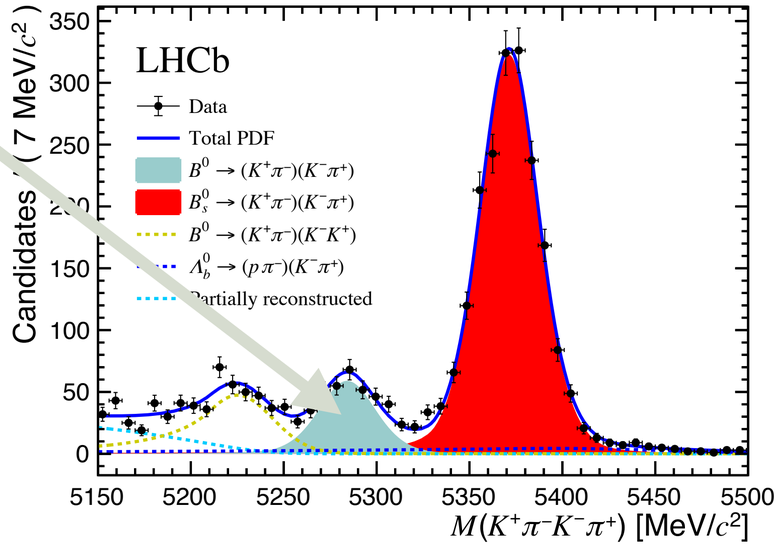
$B^0_d \to (K^+\pi^-)(K^-\pi^+)$

JHEP 07 (2019) 032

- Optimised selection for the rare mode ~ 350 signal events
- 6 amplitudes (spin-0 and 1) are described
- Large discrepancy found in its polarisation fractions with respect to its U-spin partner:

$$f_L^d = 0.724 \pm 0.051 \pm 0.016$$

$$f_L^s = 0.240 \pm 0.031 \pm 0.025$$



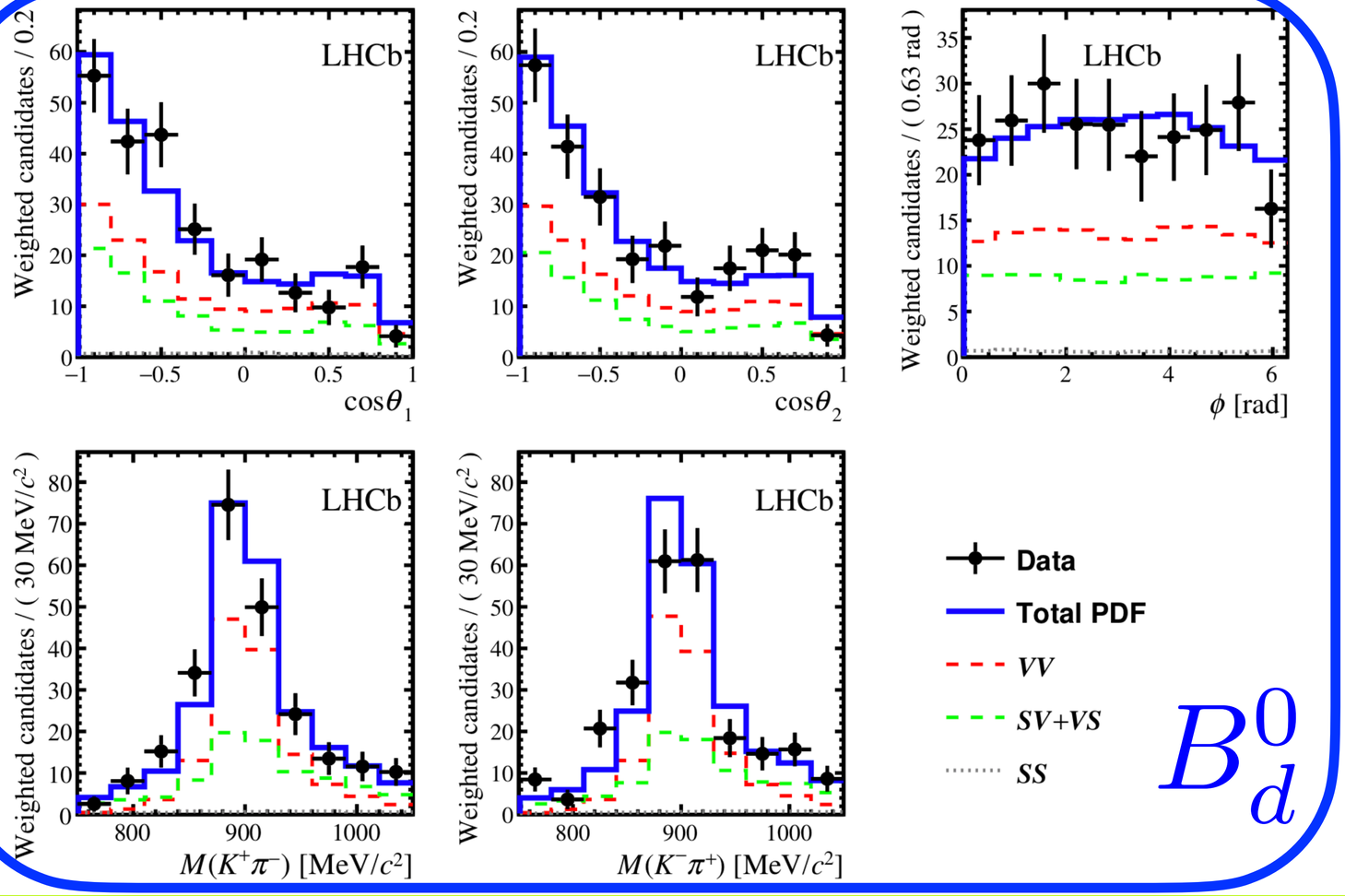
- Relative branching ratio also measured and found compatible with QCDF prediction. Known discrepancy with BaBar result due to their omission of the S-wave amplitude

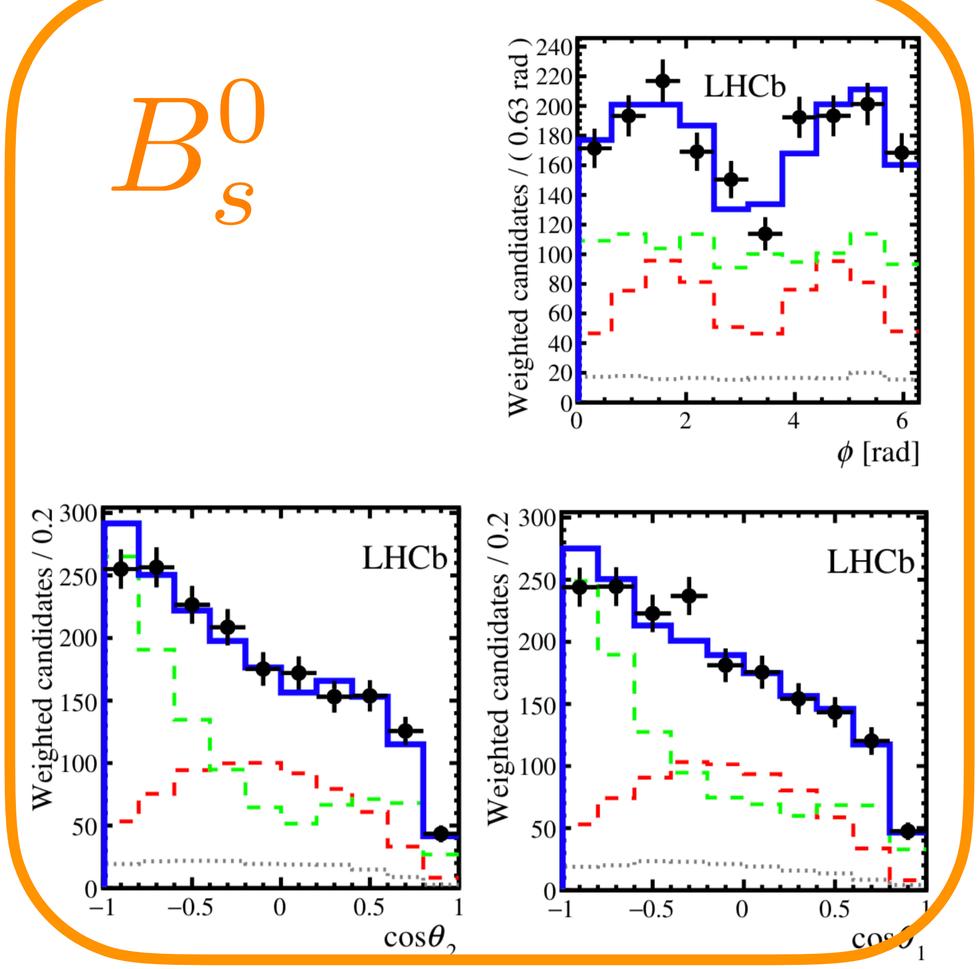
$$\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0}) = (8.0 \pm 0.9\,(\text{stat}) \pm 0.4\,(\text{syst})) \times 10^{-7}$$

QCDF prediction: Nucl.Phys.B774 (2007) 64 BaBar result: Phys.Rev.Lett.100 (2008) 081801

Fit projections

JHEP 07 (2019) 032

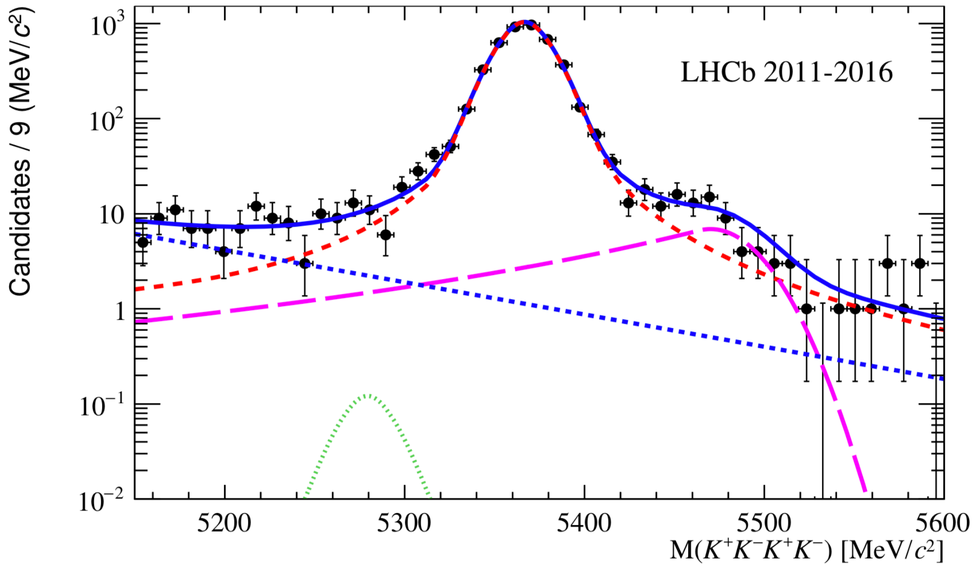




$B_s^0 \to \phi\phi$

JHEP 12 (2019) 155

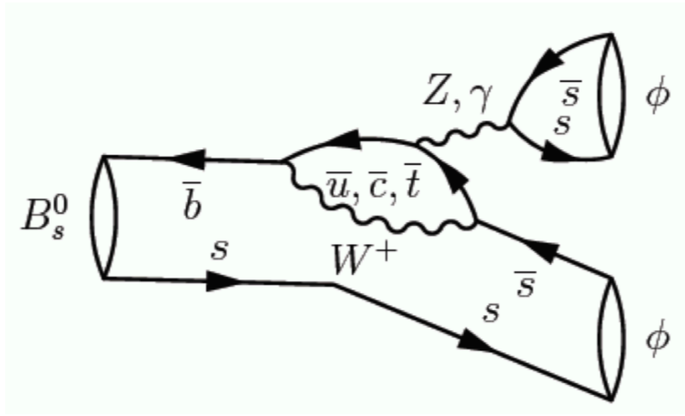
- **Time-dependent, tagged**, amplitude analysis of data corresponding to **LHCb Run I + 2015 + 2016**
- **Penguin** diagrams dominate the decay
- First time measuring one $\phi_s^{s\bar{s}}$ value per polarisation

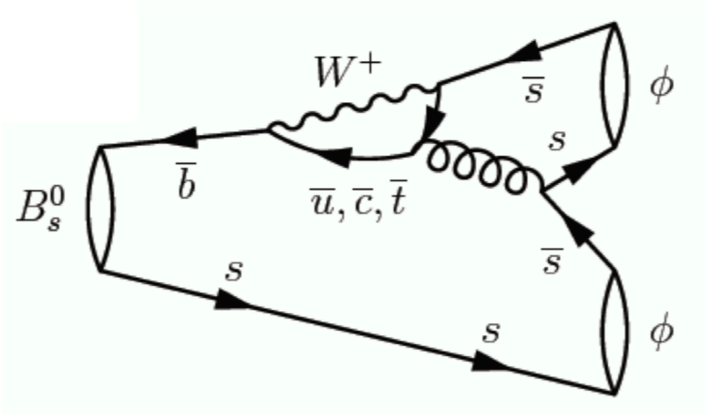


~8.5k signal events

Dedicated analyses to

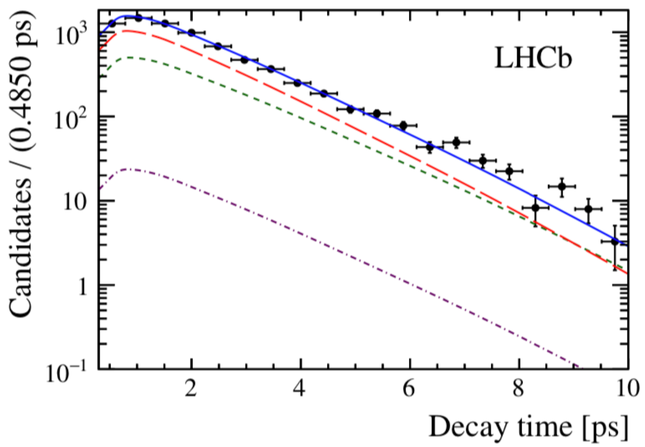
- Search for the rare mode B_d^0
- Measure Triple-Products

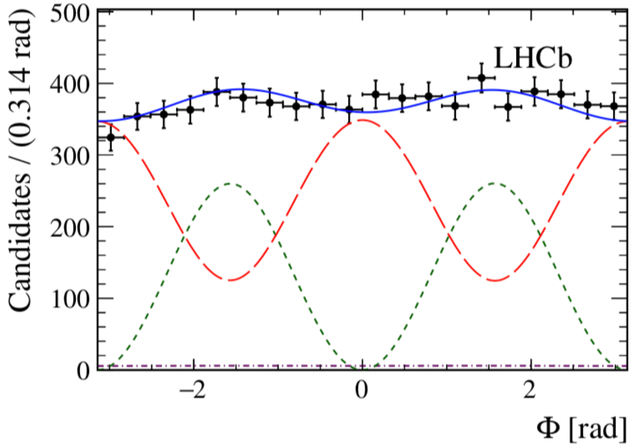


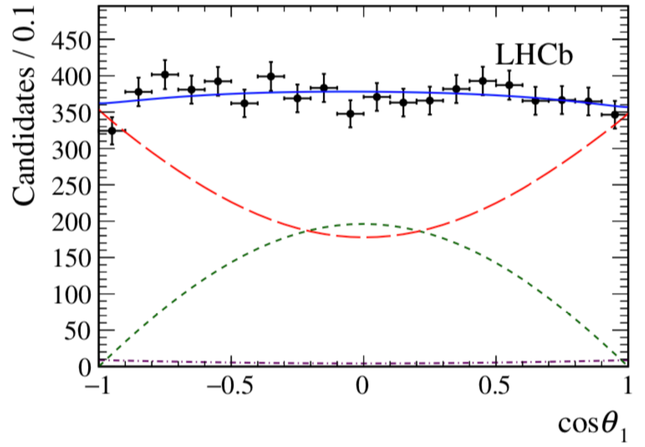


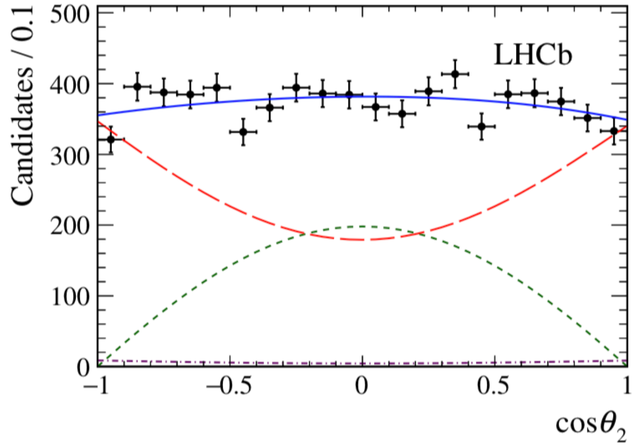
Fit projections

JHEP 12 (2019) 155









2 set-ups for the fit:

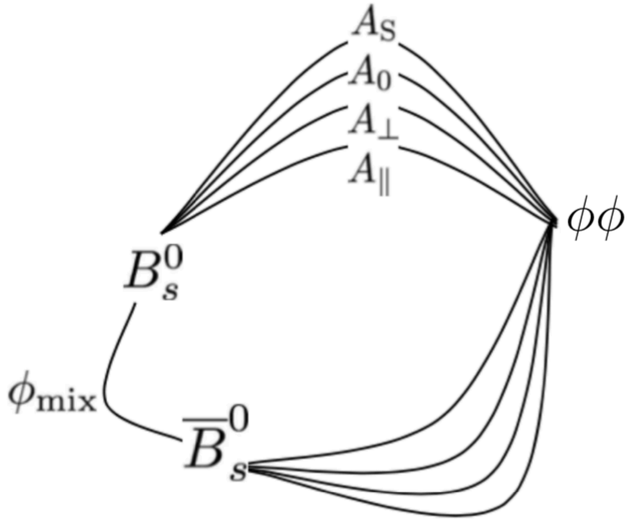
- One shared $\phi_s^{s\bar{s}}$ among polarisations
- One $\phi_s^{s\bar{s}}$ per polarisation (assuming no DCPV and $\phi_{s,0}^{s\bar{s}} = 0$)

Total fit

CP-even P-wave

CP-odd P-wave

S-wave combined with double S-wave



Selected results

JHEP 12 (2019) 155

From the polarisation independent fit

$$\phi_s^{s\bar{s}s} = -0.073 \pm 0.115\,(\text{stat}) \pm 0.027\,(\text{syst})\ \text{rad}$$
$$|\lambda| = 0.99 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

$$|A_0|^2 = 0.381 \pm 0.007\,(\text{stat}) \pm 0.012\,(\text{syst}),$$
$$|A_\perp|^2 = 0.290 \pm 0.008\,(\text{stat}) \pm 0.007\,(\text{syst}),$$
$$\delta_\perp = 2.818 \pm 0.178\,(\text{stat}) \pm 0.073\,(\text{syst})\ \text{rad},$$
$$\delta_\parallel = 2.559 \pm 0.045\,(\text{stat}) \pm 0.033\,(\text{syst})\ \text{rad}.$$

From the polarisation dependent fit

$$\phi_{s,\parallel} = 0.014 \pm 0.055\,(\text{stat}) \pm 0.011\,(\text{syst})\ \text{rad}$$
$$\phi_{s,\perp} = 0.044 \pm 0.059\,(\text{stat}) \pm 0.019\,(\text{syst})\ \text{rad}$$

From the time-integrated fit

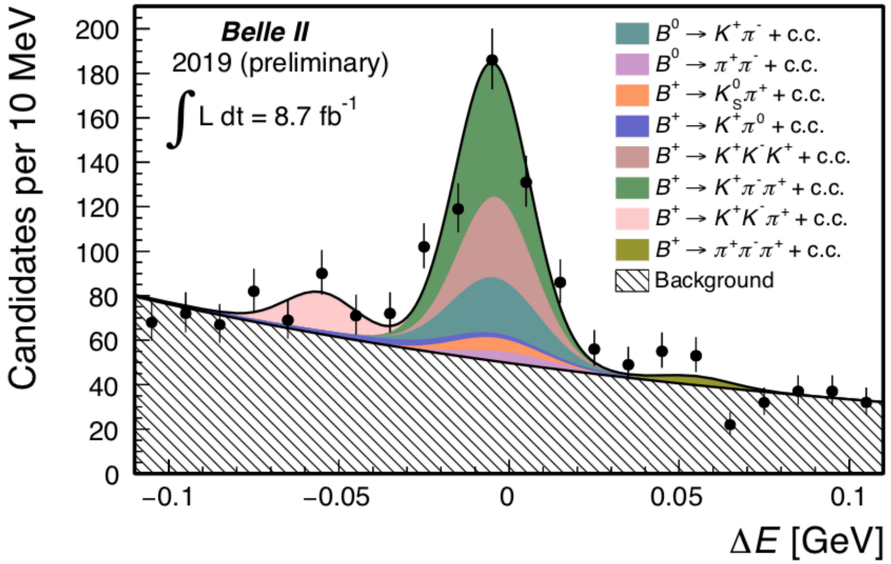
$$A_U = -0.003 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst})$$
$$A_V = -0.014 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst})$$

From the rare mode search

$$\mathcal{B}(B^0 \to \phi\phi) < 2.7 \times 10^{-8}\,(90\,\%\,\text{CL})$$

All results are compatible with SM expectations.

Any news from Belle II?



Based on preliminary results with 2 and 3 body decays:

The current Belle II performance in charmless B decay reconstruction is comparable to the Belle performance.

Belle II

BELLE2-CONF-PH-2020-001
May 29, 2020

Charmless B decay reconstruction in 2019 Belle II data

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Looking forward to the amplitude fits!

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Summary and conclusions

- Presented 4 amplitude analyses

$$B^0 \to (K^+\pi^-)(\pi^+\pi^-),\ B^0_{(s,d)} \to (K^+\pi^-)(K^-\pi^+),\ B^0_s \to \phi\phi$$

- Several new inputs from penguin dominated decays to the polarisation puzzle
- First $\phi_s^{d\bar{d}}$ measurement in the $B^0_s \to (K^+\pi^-)(K^-\pi^+)$ channel and most precise to date (with partial Run II data sample) in the $B^0_s \to \phi\phi$ decay mode.

Known penguin

Emperor

Rare penguin

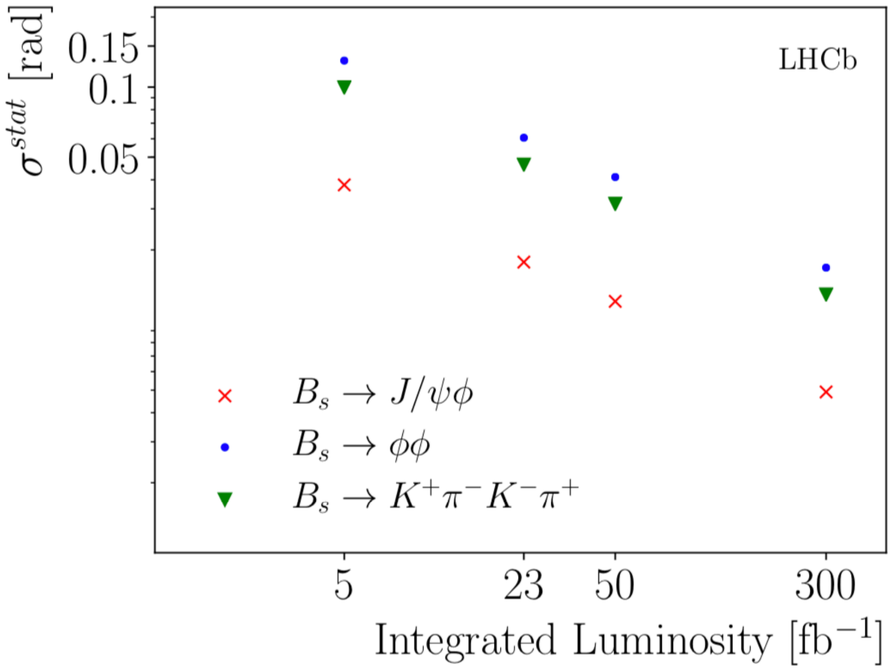
Little/Blue

No penguin

Blue-footed booby

✺ Summary/Spoiler: Need to know the penguins!

Amplitude analyses take long, but results with Run II data are underway! Very good prospects in terms of statistical uncertainties:



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Thanks for your attention!