Time-dependent CP violation in two-body charmless b-decays at LHCb

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Ghent, Belgium, EPS-HEP 2019

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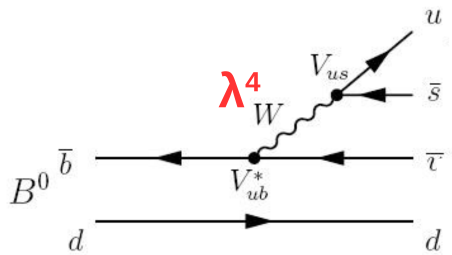
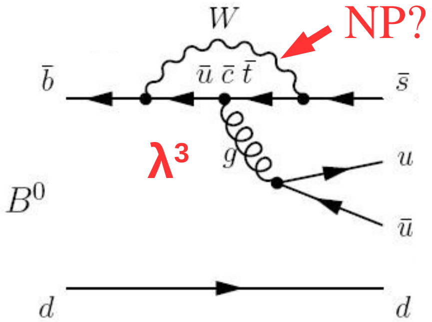
Charmless decays: what are we looking for?

- Charmless decays are suppressed at the tree level → penguin amplitudes are relevant compared to trees:



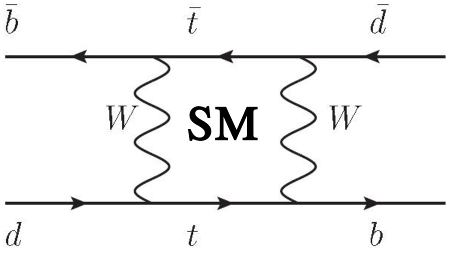
b→u tree



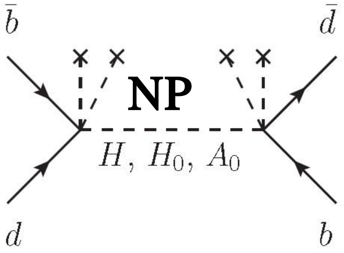
b→d,s penguin

can interfere→CP violation (CPV)

- Additionally, neutral B mesons can oscillate (mix), adding another weak phase → possibility for a time-dependent CP violation (TDCPV).



or



?

- CPV in charmless decays is sensitive to loops → can be compared to CPV in tree decays and probe virtual contributions beyond the Standard Model (SM).

Experimentally, what do we expect?

- Hadronic final states (except for $\pi^0 \to \gamma\gamma$).

- Small ($<10^{-4}$) branching fractions.

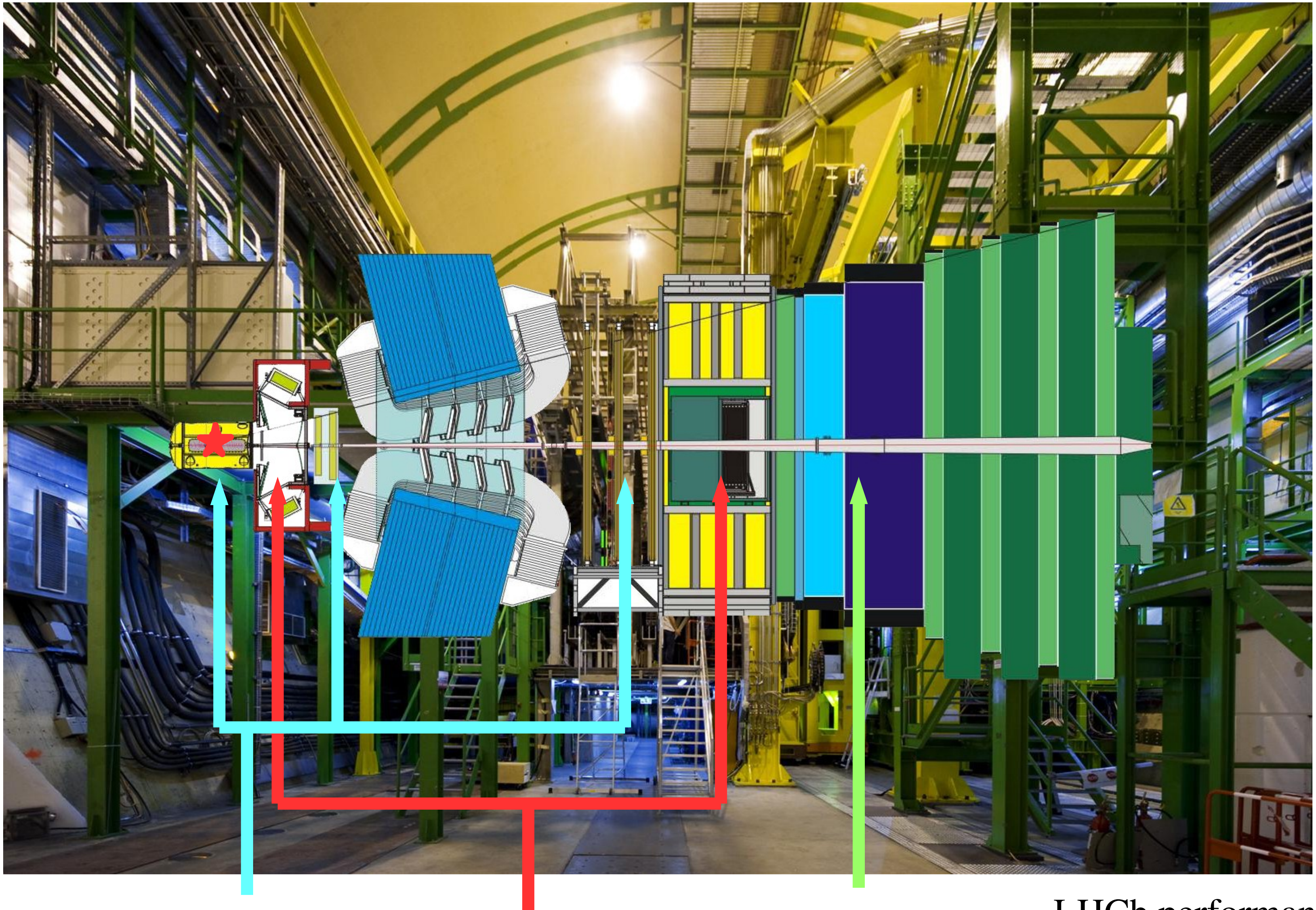
- For most neutral channels, CPV accessible only through **time-dependent (TD), flavour-tagged analyses**.
  - Tagging power at LHCb: ~5%.

- Due to this, for most decays, programme in two steps:

  1. Observe modes for the first time and extract branching fractions.

  2. Perform time-dependent angular, amplitude analyses to access physics observables , e.g. **phases, CPV observables**.

The LHCb detector



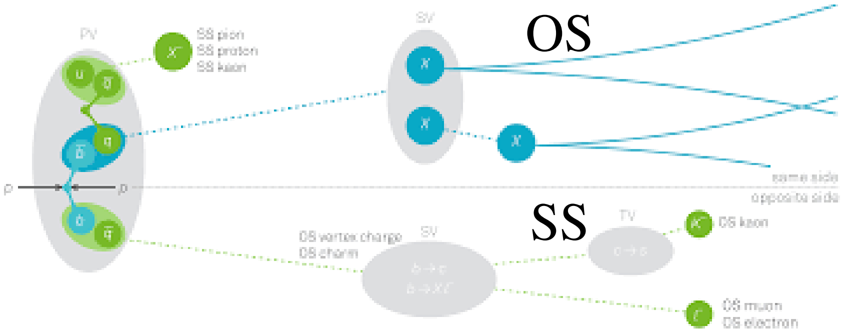
Tracking
$\Delta p/p = 0.5\text{-}1\%$

PID
95% K eff
For 5% $\pi \to K$ misID

Calorimetry
ECAL resolution:
$1\ \% + 10\ \%/\sqrt{E[\text{GeV}]}$

LHCb performance paper
Int. J. Mod. Phys. A 30, 1530022 (2015)

A question of time (and flavour)



- Flavour tagging at LHCb is the prediction of the produced meson flavour.
  - Combines same-side (SS) and opposing-side (OS)
- Relevant information: tagging power (tagging efficiency + mistag rate)
- Calibrated on **control samples reweighted for kinematics**.

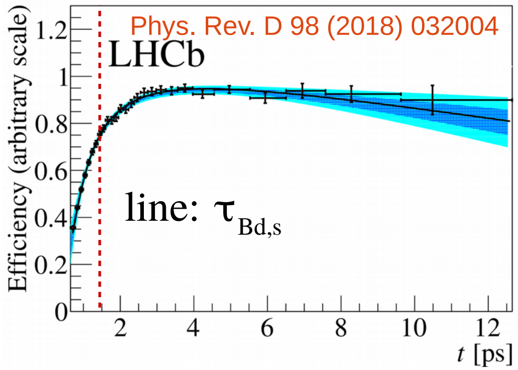
Typical tagging power ~ 5%

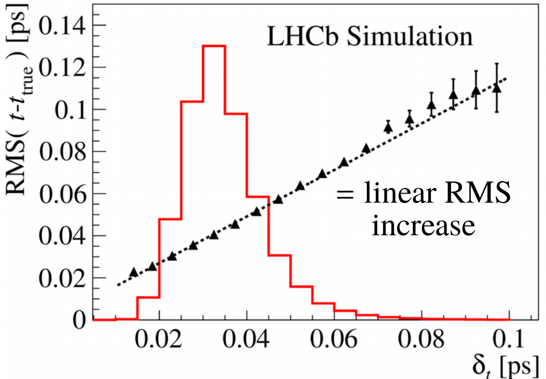
- Efficiency heavily depends on vertex displacement ≡ time. Need to be modelled, using for instance control modes.
  - Example: difference with pure exponential with $\Gamma = 1/\tau_B$.
- Resolution effects also not negligible: typical error is **0.03 ps**, scales with event-by-event quantity δ_t.
- Example of $B \to (K\pi)(K\pi)$:

$$\sigma_t(\delta_t) = \underline{p_0^{\sigma_t}} + \underline{p_1^{\sigma_t}}(\delta_t - \langle\delta_t\rangle)$$

→ used to convolve TD PDFs

from fit to MC





$B_{d,s} \rightarrow h^+h^{(')-}$: motivation and event selection

Phys. Rev. D 98 (2018) 032004

- First observation of CPV in B_s decays was on $B_s \rightarrow \pi^+K^-$!

- $B^0 \rightarrow \pi\pi$ and $B_s \rightarrow KK$ are U-spin partners (equivalent under d ↔ s).
  - Possible to **determine γ and $-2\beta_s$** following, e.g. Phys. Lett. B741 (2015) 1.
  - Using γ as external input + $B_s \rightarrow Kl\upsilon$ and $B \rightarrow \pi l\upsilon$: reduce uncertainty on ϕ_s due to U-spin symmetry to 0.5° from 5° in the LHCb Upgrade era [Phys. Rev. D 94, 113014 (2016)].

- $B \rightarrow \pi\pi$ is important to measure the $\boldsymbol{\alpha}$ angle.

- Experimentally in LHCb, pions and kaons are quite close one from another, basically only differ by RICH information.

  → **It often makes sense to study all related channels to have a better handle.**

Goal is to measure **time-dependent CPV in $B \rightarrow \pi\pi$ and $B_s \rightarrow KK$**, and **time-integrated CPV in $B_{(s)} \rightarrow K\pi$** with **Run 1 data.**

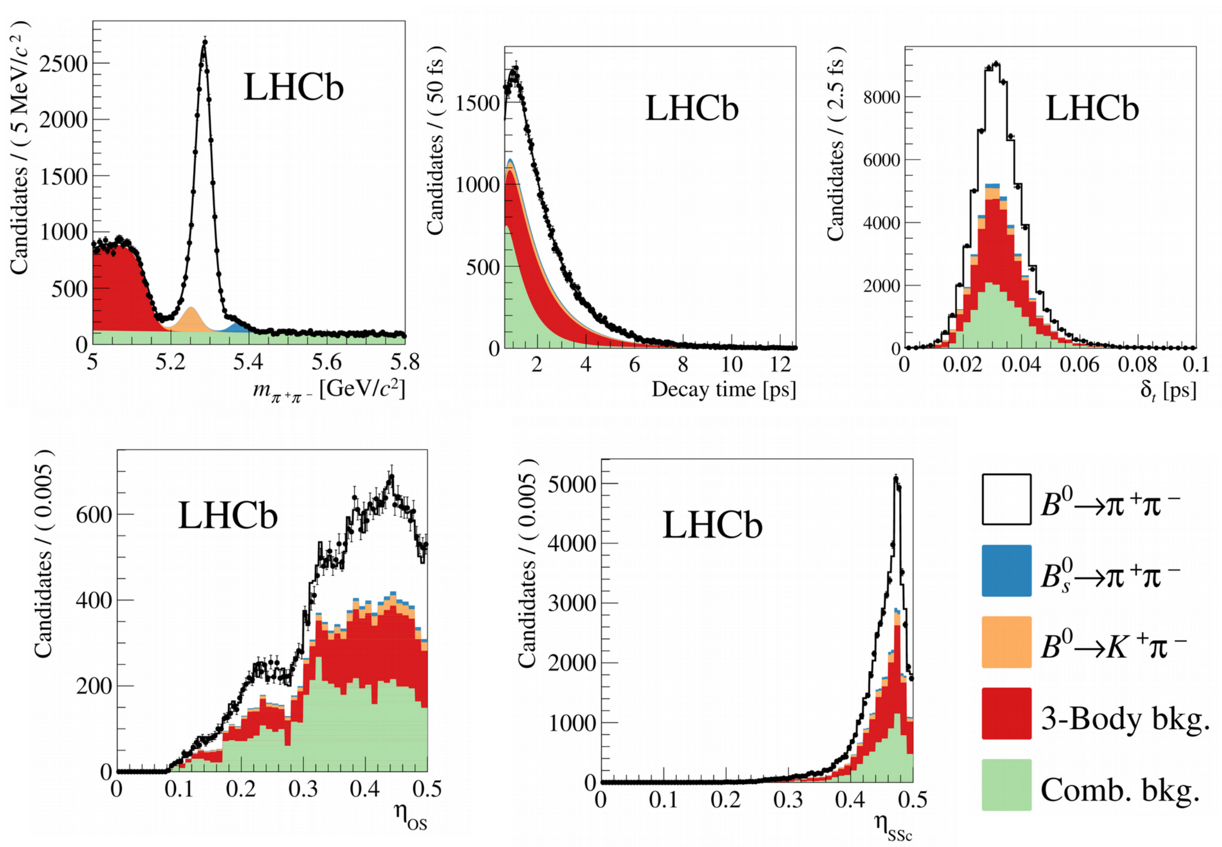
$B_{d,s} \to h^+h^{(')-}$: modelling all distributions

Phys. Rev. D 98 (2018) 032004

- Discriminating variables between event species are the invariant mass, the decay time (and its uncertainty), tagging decision and mistag probability.

Mode	Status
$\pi\pi$ reconstruction mode	
$B_d \to \pi^+\pi^-$	**Signal**
$B_s \to \pi^+\pi^-$	Considered in the fit
$B_d \to K^+\pi^-$	Crossfeed background
$K\pi$ reconstruction mode	
$B_d \to K^+\pi^-$	**Signal**
$B_s \to K^+\pi^-$	**Signal**
$B_d \to \pi^+\pi^-$	Crossfeed background
$B_s \to K^+K^-$	Crossfeed background
KK reconstruction mode	
$B_d \to K^+K^-$	Considered in the fit
$B_s \to K^+K^-$	**Signal**
$B_d \to K^+\pi^-$	Crossfeed background
$\Lambda_b \to pK^-$	Crossfeed background

+ combinatorial background
+ partially reconstructed background ($B_{u,d,s} \to hh' + X$)



$B_{d,s} \to h^+h^{(\prime)-}$: results and conclusion

Phys. Rev. D 98 (2018) 032004

TDCPV (KK and ππ modes)

$$A_{CP}(t) = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right)}, \quad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2},$$

Time-integrated CPV (Kπ modes)

$$A_{CP} = \frac{\left|\bar{A}_{\bar{f}}\right|^2 - \left|A_f\right|^2}{\left|\bar{A}_{\bar{f}}\right|^2 + \left|A_f\right|^2},$$

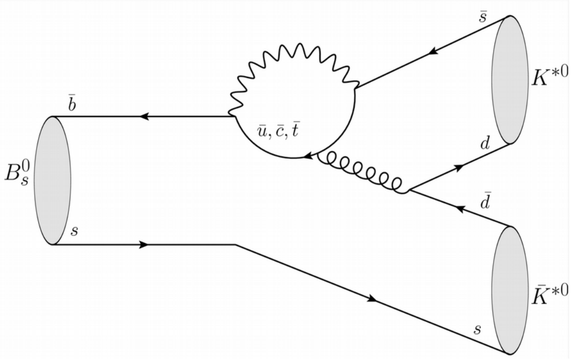
	Current result	Former LHCb-only stat.	Former PDG stat. (*: LHCb-only)
$C_{\pi\pi}$	$= -0.34 \pm 0.06 \pm 0.01$	0.15	0.05
$S_{\pi\pi}$	$= -0.63 \pm 0.05 \pm 0.01$	0.13	0.06
C_{KK}	$= 0.20 \pm 0.06 \pm 0.02$	0.11	*
S_{KK}	$= 0.18 \pm 0.06 \pm 0.02$	0.12	*
$A^{\Delta\Gamma}(KK)$	$= -0.79 \pm 0.07 \pm 0.10$	/	/
$A_{CP}(B)$	$= -0.084 \pm 0.004 \pm 0.003$	0.007	0.006
$A_{CP}(B_s)$	$= 0.213 \pm 0.015 \pm 0.007$	0.04	0.04

LHCb-only uncertainty gets divided by 2-3 depending on the observable
Statistical uncertainties competitive or better than PDG ones!

$(C_{KK}, S_{KK}, A^{\Delta\Gamma}(KK)) \neq (0,0,-1)$ by $> 4\sigma$ → strongest evidence for time-dependent CPV in B_s sector to date.

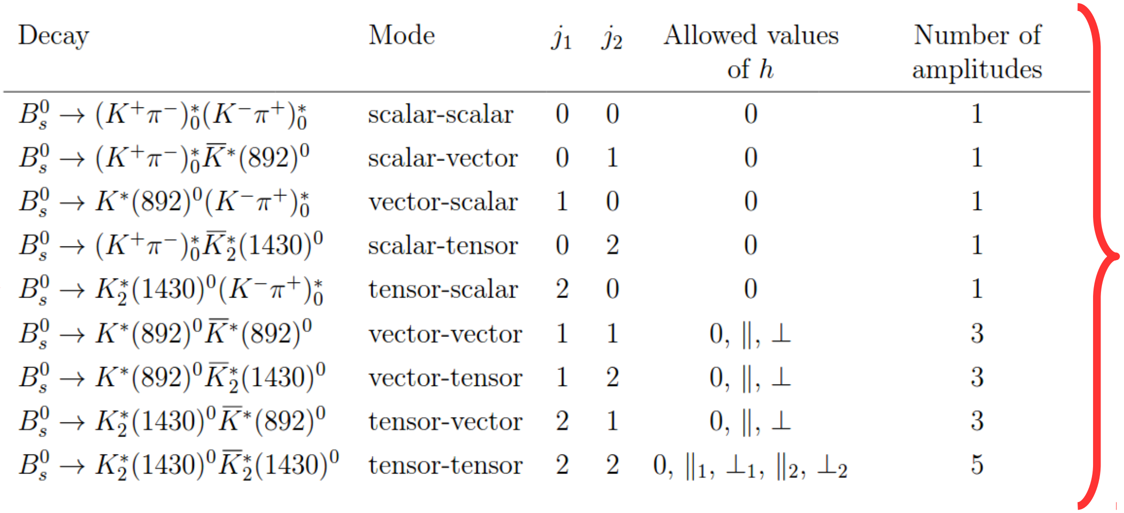
Measurement of $\phi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$

JHEP 03 (2018) 140



- Decay dominated by a gluonic penguin diagram
  - Complementary to measurements in EW penguins.
- Powerful check of the SM.
  - $\Phi_s^{c\bar{c}} = -0.021 \pm 0.031$ rad, measured in for instance $B_s \to J/\Psi K^+K^-$.
  - $\Phi_s^{d\bar{d}}$ is the **weak phase** measured in loop-dominated **$b \to d\bar{d}s$** transitions.
- Decay first observed in 2011 by LHCb [PLB 709 (2012) 50], updated in 2012 [JHEP 07 (2015) 166].
- Still analysis on **Run 1** dataset but (Kπ) invariant-mass windows have been enlarged → need a full amplitude analysis.

First time for tensor components !



Decay	Mode	j_1	j_2	Allowed values of h	Number of amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	scalar-scalar	0	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	scalar-vector	0	1	0	1
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	vector-scalar	1	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	scalar-tensor	0	2	0	1
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	tensor-scalar	2	0	0	1
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	vector-vector	1	1	$0, \Vert, \perp$	3
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	vector-tensor	1	2	$0, \Vert, \perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	tensor-vector	2	1	$0, \Vert, \perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	tensor-tensor	2	2	$0, \Vert_1, \perp_1, \Vert_2, \perp_2$	5

19 amplitudes

Measurement of $\phi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$

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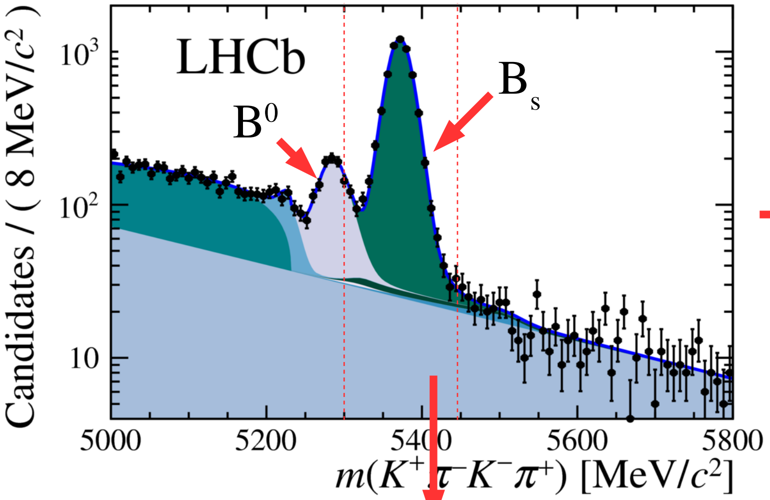
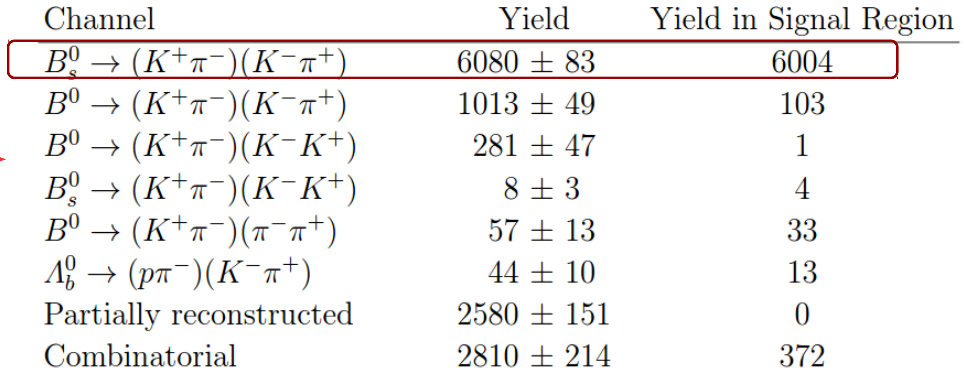
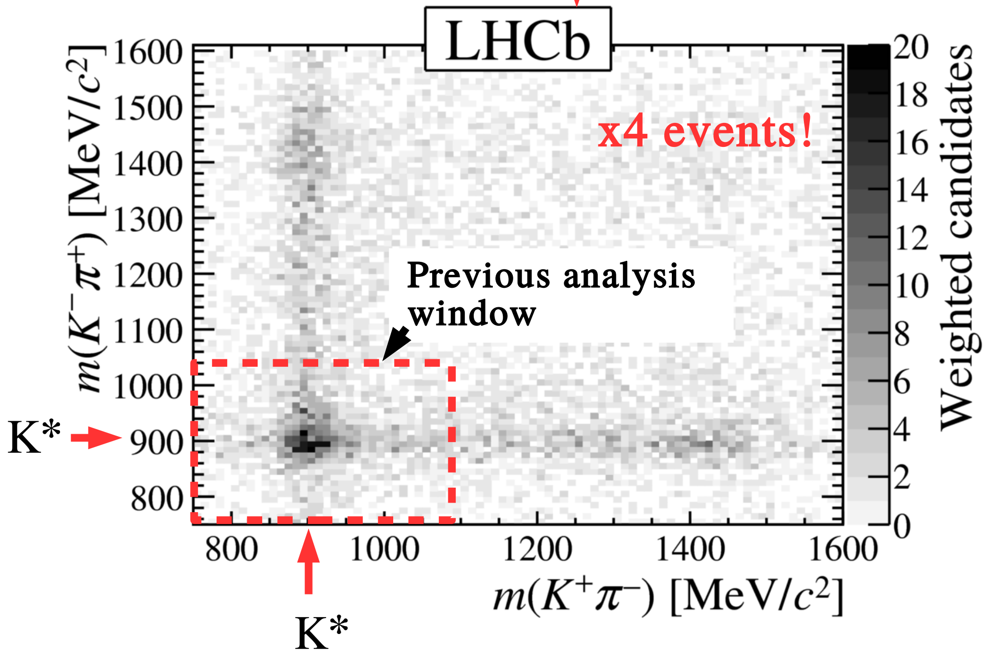
- First things first: yield extraction

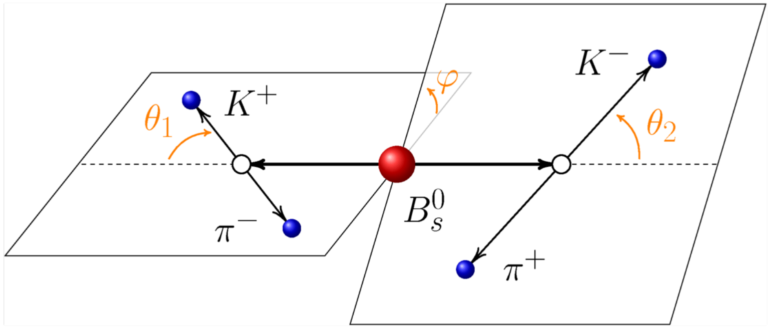




Channel	Yield	Yield in Signal Region
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$	6080 ± 83	6004
$B^0 \to (K^+\pi^-)(K^-\pi^+)$	1013 ± 49	103
$B^0 \to (K^+\pi^-)(K^-K^+)$	281 ± 47	1
$B_s^0 \to (K^+\pi^-)(K^-K^+)$	8 ± 3	4
$B^0 \to (K^+\pi^-)(\pi^-\pi^+)$	57 ± 13	33
$\Lambda_b^0 \to (p\pi^-)(K^-\pi^+)$	44 ± 10	13
Partially reconstructed	2580 ± 151	0
Combinatorial	2810 ± 214	372



- Amplitudes depend on masses and angles.



Measurement of $\phi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$

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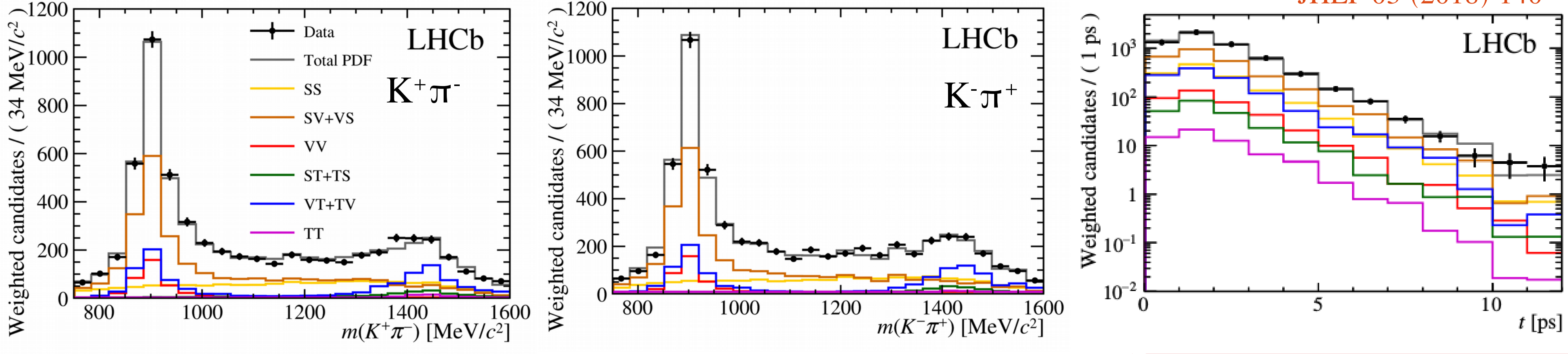
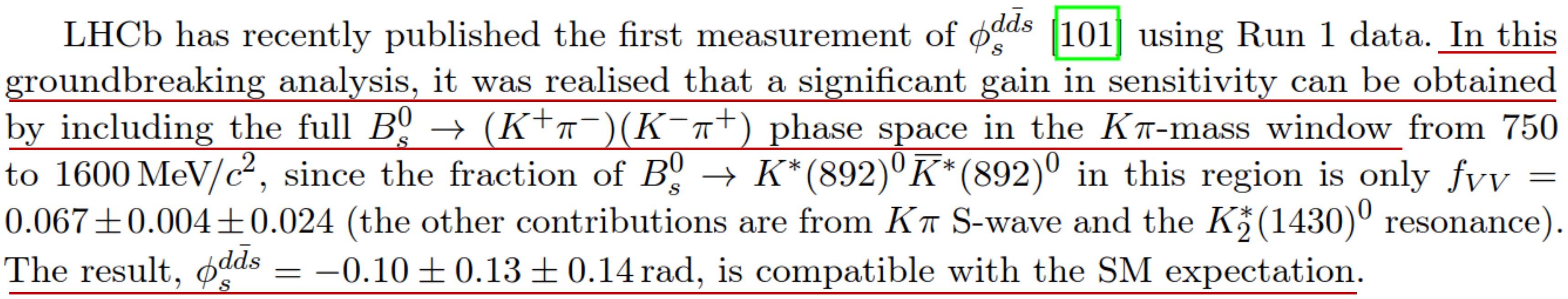


- Dominant systematic: size of simulated samples.
- First measurement of **$\Phi_s^{d\bar{d}}$ = -0.10 ± 0.13 ±0.14 rad**!
- **$|\lambda|$= 1.035±0.034±0.089** → both compatible with SM.

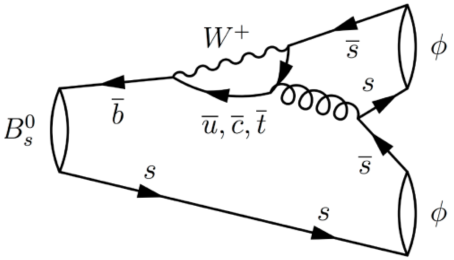
Reminder: LHCb measurements of:
$\Phi_s^{c\bar{c}}$ = -0.010 ± 0.039 rad
Φ_s^{ss} = 0.17 ± 0.15 rad


LHCb has recently published the first measurement of $\phi_s^{d\bar{d}s}$ [101] using Run 1 data. In this groundbreaking analysis, it was realised that a significant gain in sensitivity can be obtained by including the full $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ phase space in the $K\pi$-mass window from 750 to 1600 MeV/c^2, since the fraction of $B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$ in this region is only $f_{VV} = 0.067 \pm 0.004 \pm 0.024$ (the other contributions are from $K\pi$ S-wave and the $K_2^*(1430)^0$ resonance). The result, $\phi_s^{d\bar{d}s} = -0.10 \pm 0.13 \pm 0.14$ rad, is compatible with the SM expectation.

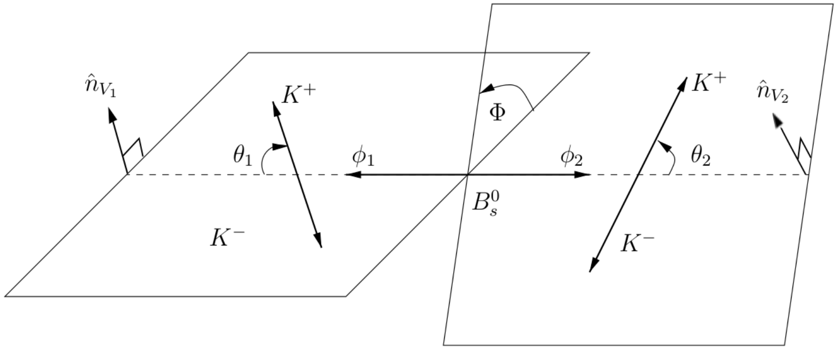
From “Physics case for an LHCb Upgrade II” [CERN-LHCC-2018-027(1808.08865)]

Measuring $\phi_s^{s\bar{s}s}$ using $B_s \to \phi\phi$: motivation

- Decay forbidden at loop-level, dominated by (gluonic) $b \to s\bar{s}s$.
- Mixing with B_s oscillations could give rise to time-dependent CPV.
  - CPV phase $\phi_s^{s\bar{s}s}$ predicted < 0.02 rad [Phys.Rev.D80:114026,2009].
  - Previous LHCb result ($3fb^{-1}$): $\phi_s^{s\bar{s}s} = -0.17 \pm 0.15 \pm 0.03$ rad.
  - **We detect kaons not ϕ**'s: TD angular analysis to disentangle CP eigenstates SS, SV, VV, where S = scalar, V = vector.



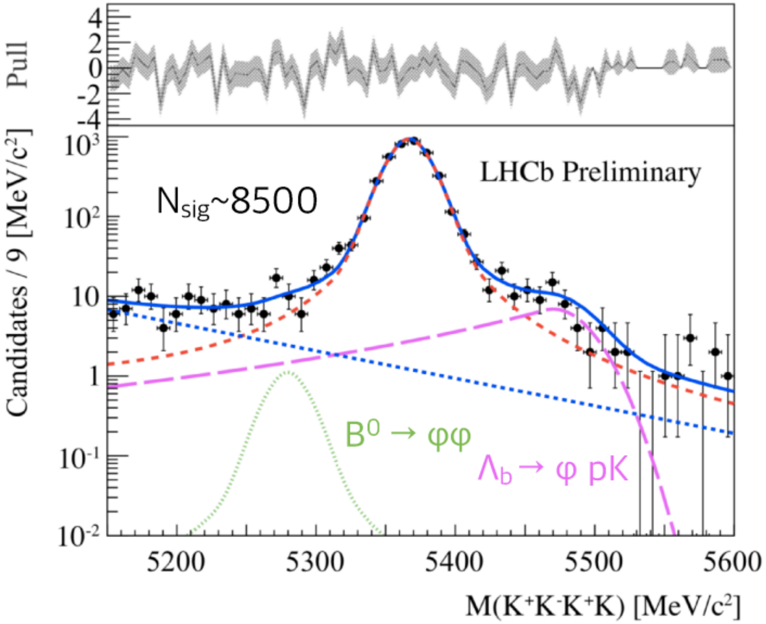
- Possible to measure time-integrated CPV with triple products.



- P→ VV decay → possible to measure longitudinal polarisation.
  - Predicted $f_L = 0.36^{+0.23}_{-0.18}$
- Additional search for $B^0 \to \phi\phi$ decay.
  - Suppressed by OZI rule in SM → predicted BF ~ 10^{-8}.
  - Supersymmetric models with R-parity violation could show BF ~ 10^{-7}.
- Analysis performed on **Run 1 + 2015 + 2016**.

Measuring $\phi_s^{s\bar{s}s}$ using $B_s \to \phi\phi$: how to do it

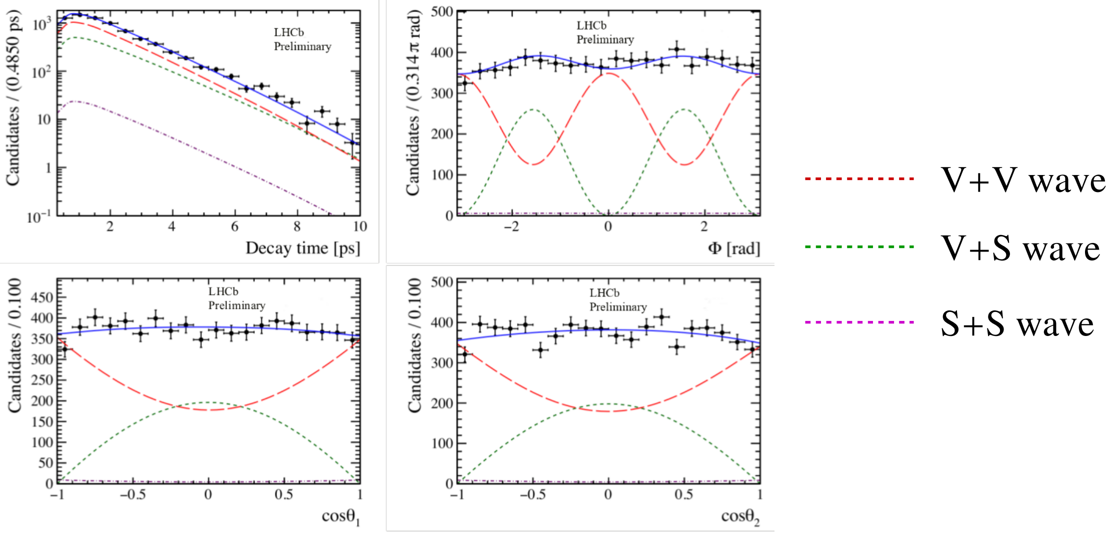
- Events selected using cuts + neural network
  - Required to have $m(K^+K^-)$ within 25 MeV of PDG mass.
- Only one peaking background left: $\Lambda_b \to pK\phi$.
- Found **4.9 ± 9.2 B^0 events** with dedicated selection.



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

Best limit available, compatible with SM.

- Angular analysis performed on weighted data events to disentangle partial waves.
  - Scalar+Scalar wave negligible.



Measuring $\phi_s^{s\bar{s}s}$ using $B_s \to \phi\phi$: results on CPV

- Angular amplitude of the $\phi\phi$ final state sum of three terms, denoted with the 0, ⊥ and || subscripts

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

In good agreement with previous measurements

- Triple-product asymmetries are found compatible with previous measurements and are averaged with them.

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

- Time-dependent CPV extracted both in a polarisation-dependent and -independent way. Results agree well.

$$\begin{aligned}
\phi_{s,\parallel} &= 0.014 \pm 0.055\,(\text{stat}) \pm 0.011\,(\text{syst}) \;\; \text{rad}, \\
\phi_{s,\perp} &= 0.044 \pm 0.059\,(\text{stat}) \pm 0.019\,(\text{syst}) \;\; \text{rad}.
\end{aligned}$$

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

No significative CPV found, compatible with SM

Summary of presented results

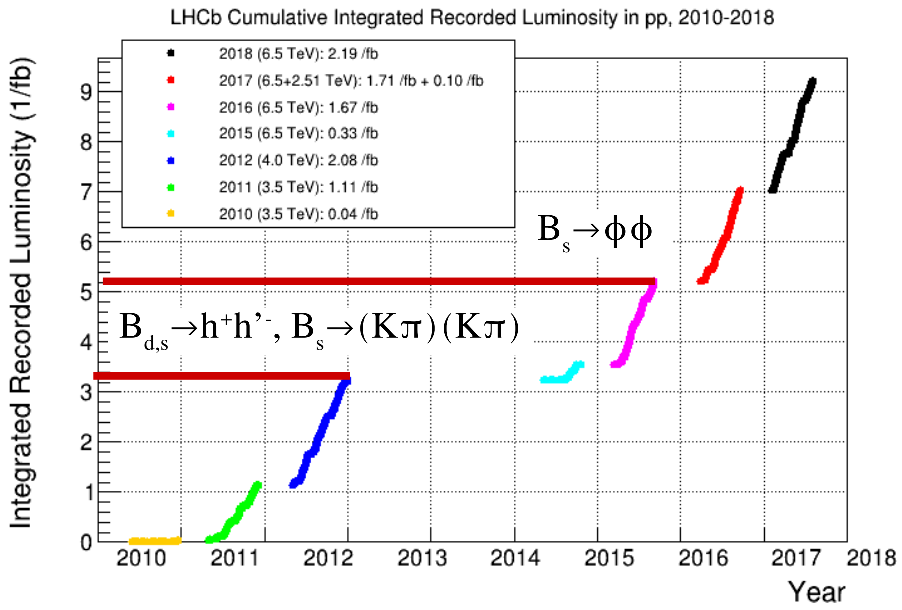
- $B_{d,s} \rightarrow h^+h^{(')-}$:
  - best single-experiment results on $B\rightarrow\pi\pi$
  - dominates the world average on $B_{d,s}\rightarrow K\pi$
  - only ones to measure $B_s\rightarrow KK$: **strongest evidence to date of TDCPV in B_s sector**.

- Measurement of $\phi_s^{d\bar{d}}$ in $B_s \rightarrow (K^+\pi^-)(K^-\pi^+)$
  - **first measurement of $\phi_s^{d\bar{d}}$.**

- Measuring $\phi_s^{s\bar{s}s}$ using $B_s\rightarrow\phi\phi$: results on CPV
  - best limits on $B_d\rightarrow\phi\phi$.
  - **time-dependent & time-independent CPV measured**

Conclusion

- Charmless results on Run 1 are being finished → need to include entire Run 2.



- Systematic uncertainties start to be comparable to statistical uncertainties.
  - No one single culprit: e.g. size of simulated samples ($\phi_s^{d\bar{d}}$) or crossfeed model ($C_{\pi\pi}$, $S_{\pi\pi}$).

- A closer look at systematic reveal that most large ones are statistical in nature

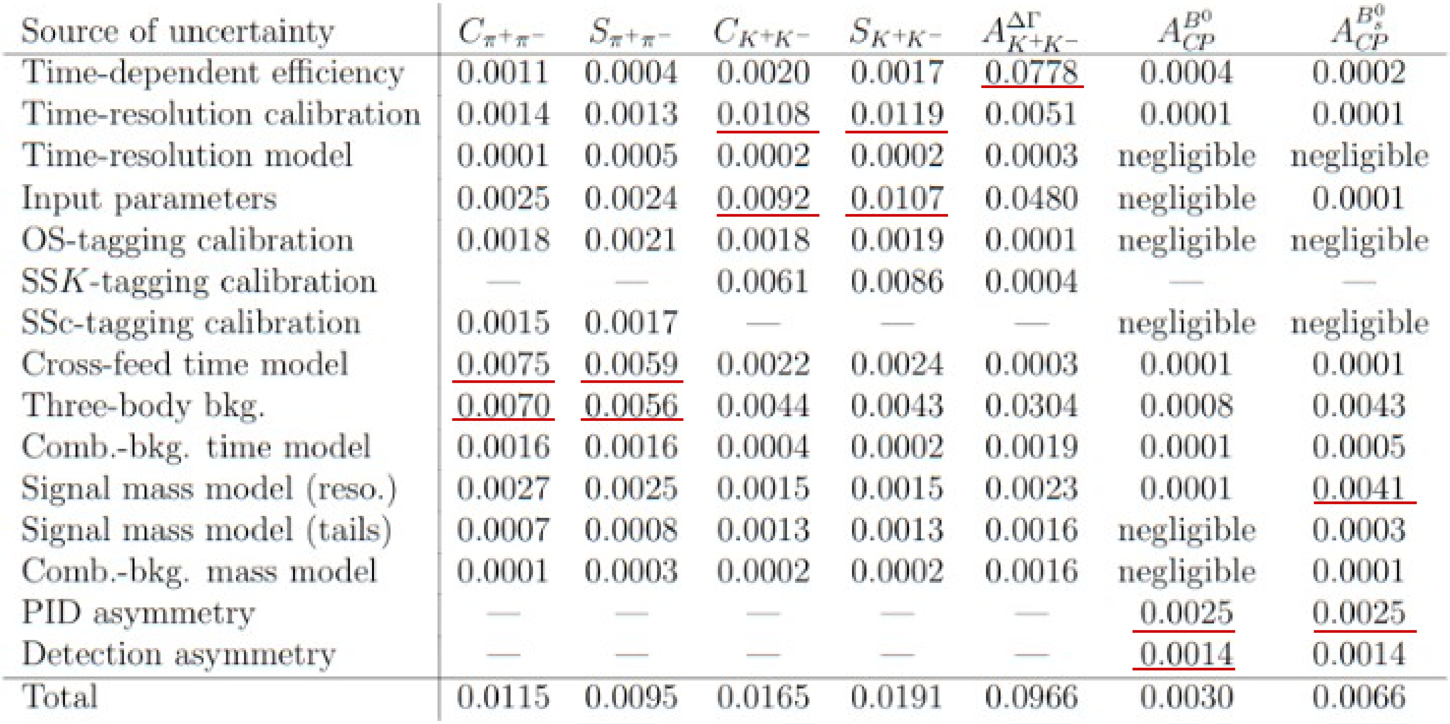
  → not a show stopper.

- Addition of more data will allow to perform these full-fledged analyses on even more different modes, for instance $B \to \phi K_S$.

Analyses of charmless decays in LHCb are already getting many world-best measurement on few modes, but full potential will start to unfold with addition of more statistics.

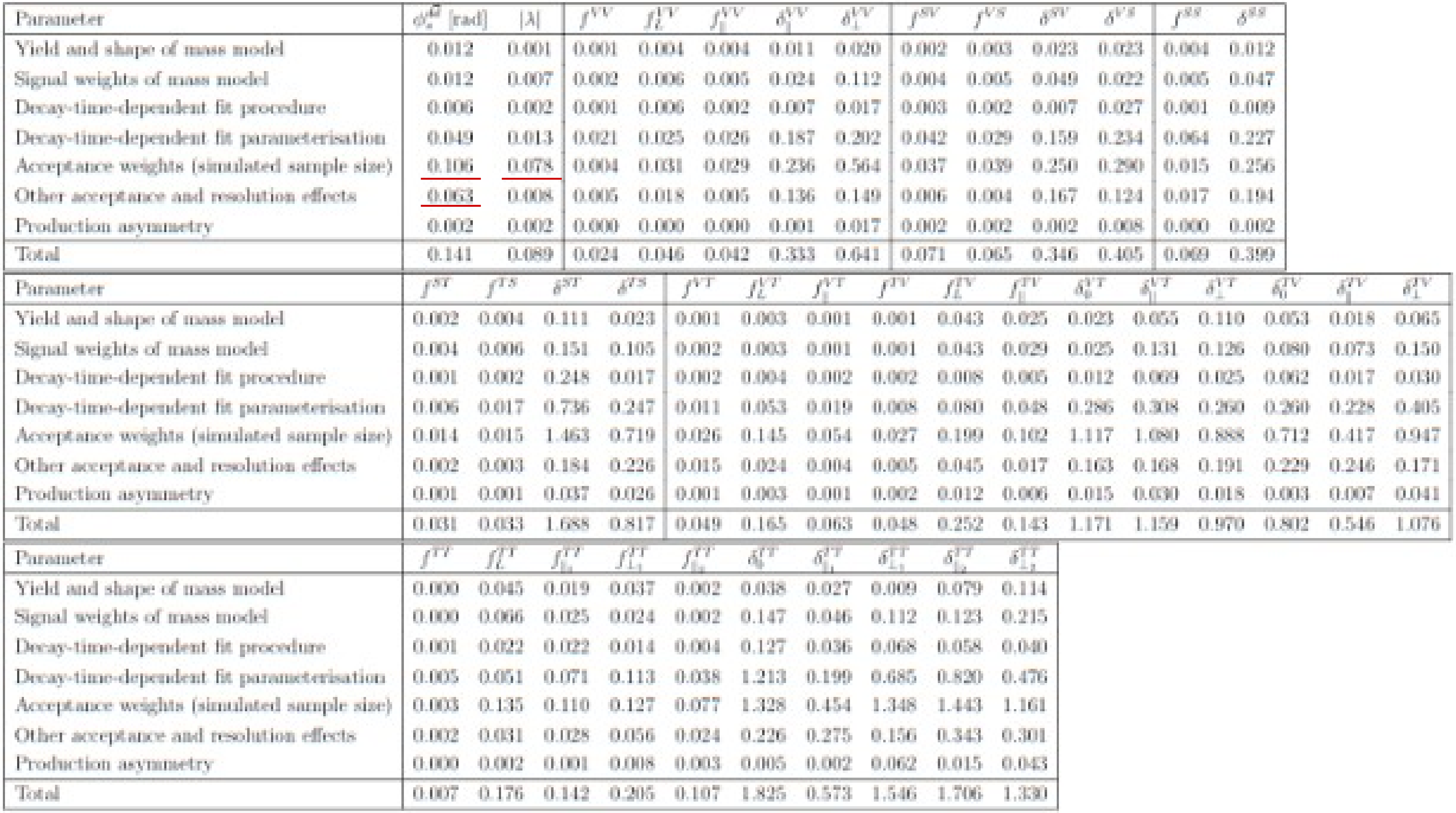
Thank you!

Systematics: B→hh



Source of uncertainty	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A_{CP}^{B^0}$	$A_{CP}^{B^0_s}$
Time-dependent efficiency	0.0011	0.0004	0.0020	0.0017	0.0778	0.0004	0.0002
Time-resolution calibration	0.0014	0.0013	0.0108	0.0119	0.0051	0.0001	0.0001
Time-resolution model	0.0001	0.0005	0.0002	0.0002	0.0003	negligible	negligible
Input parameters	0.0025	0.0024	0.0092	0.0107	0.0480	negligible	0.0001
OS-tagging calibration	0.0018	0.0021	0.0018	0.0019	0.0001	negligible	negligible
SSK-tagging calibration	—	—	0.0061	0.0086	0.0004	—	—
SSc-tagging calibration	0.0015	0.0017	—	—	—	negligible	negligible
Cross-feed time model	0.0075	0.0059	0.0022	0.0024	0.0003	0.0001	0.0001
Three-body bkg.	0.0070	0.0056	0.0044	0.0043	0.0304	0.0008	0.0043
Comb.-bkg. time model	0.0016	0.0016	0.0004	0.0002	0.0019	0.0001	0.0005
Signal mass model (reso.)	0.0027	0.0025	0.0015	0.0015	0.0023	0.0001	0.0041
Signal mass model (tails)	0.0007	0.0008	0.0013	0.0013	0.0016	negligible	0.0003
Comb.-bkg. mass model	0.0001	0.0003	0.0002	0.0002	0.0016	negligible	0.0001
PID asymmetry	—	—	—	—	—	0.0025	0.0025
Detection asymmetry	—	—	—	—	—	0.0014	0.0014
Total	0.0115	0.0095	0.0165	0.0191	0.0966	0.0030	0.0066

Systematics: B→(Kπ)(Kπ)

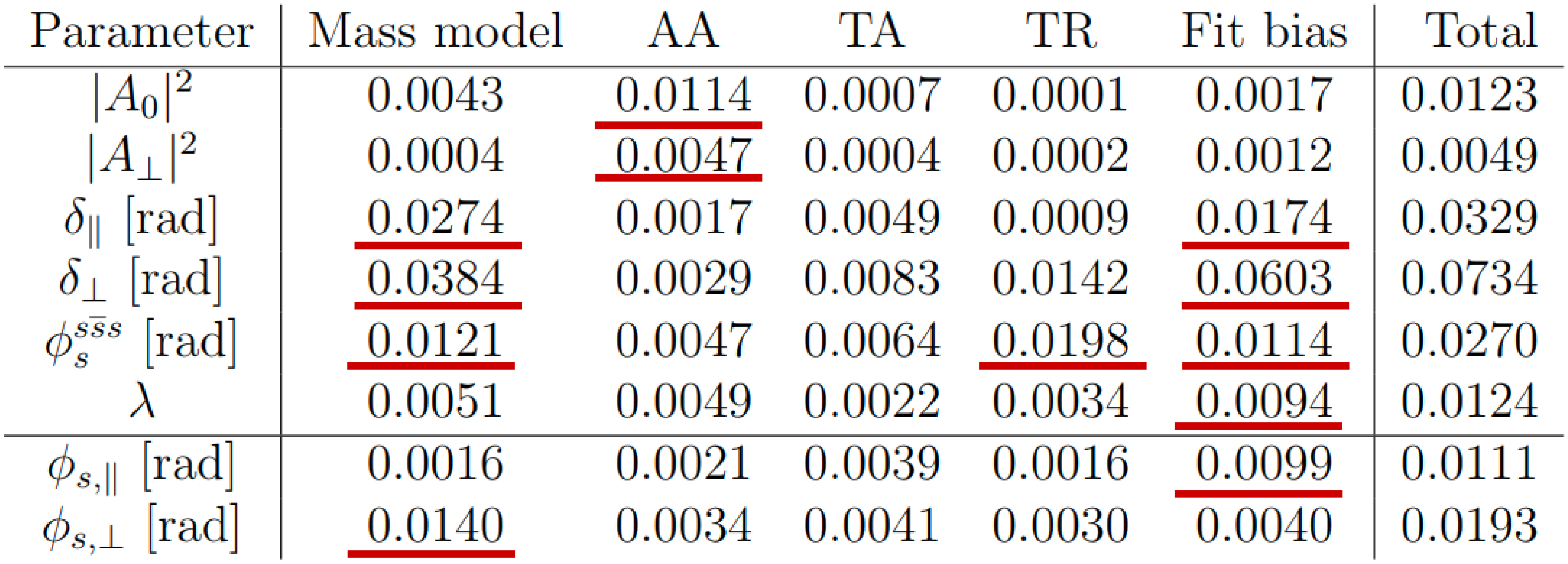


Parameter	$\phi_s^{d\bar{d}}$ [rad]	$\lvert\lambda\rvert$	f^{VV}	f_L^{VV}	$f_\parallel^{VV}$	$\delta_\parallel^{VV}$	$\delta_\perp^{VV}$	f^{SV}	f^{VS}	δ^{SV}	δ^{VS}	f^{SS}	δ^{SS}
Yield and shape of mass model	0.012	0.001	0.001	0.004	0.004	0.011	0.020	0.002	0.003	0.023	0.023	0.004	0.012
Signal weights of mass model	0.012	0.007	0.002	0.006	0.005	0.024	0.112	0.004	0.005	0.049	0.022	0.005	0.047
Decay-time-dependent fit procedure	0.006	0.002	0.001	0.006	0.002	0.007	0.017	0.003	0.002	0.007	0.027	0.001	0.009
Decay-time-dependent fit parameterisation	0.049	0.013	0.021	0.025	0.026	0.187	0.202	0.042	0.029	0.159	0.234	0.064	0.227
Acceptance weights (simulated sample size)	0.106	0.078	0.004	0.031	0.029	0.236	0.564	0.037	0.039	0.250	0.290	0.015	0.256
Other acceptance and resolution effects	0.063	0.008	0.005	0.018	0.005	0.136	0.149	0.006	0.004	0.167	0.124	0.017	0.194
Production asymmetry	0.002	0.002	0.000	0.000	0.000	0.001	0.017	0.002	0.002	0.002	0.008	0.000	0.002
Total	0.141	0.089	0.024	0.046	0.042	0.333	0.641	0.071	0.065	0.346	0.405	0.069	0.399

Parameter	f^{ST}	f^{TS}	δ^{ST}	δ^{TS}	f^{VT}	f_L^{VT}	$f_\parallel^{VT}$	f^{TV}	f_L^{TV}	$f_\parallel^{TV}$	δ_0^{VT}	$\delta_\parallel^{VT}$	$\delta_\perp^{VT}$	δ_0^{TV}	$\delta_\parallel^{TV}$	$\delta_\perp^{TV}$
Yield and shape of mass model	0.002	0.004	0.111	0.023	0.001	0.003	0.001	0.001	0.043	0.025	0.023	0.055	0.110	0.053	0.018	0.065
Signal weights of mass model	0.004	0.006	0.151	0.105	0.002	0.003	0.001	0.001	0.043	0.029	0.025	0.131	0.126	0.080	0.073	0.150
Decay-time-dependent fit procedure	0.001	0.002	0.248	0.017	0.002	0.004	0.002	0.002	0.008	0.005	0.012	0.069	0.025	0.062	0.017	0.030
Decay-time-dependent fit parameterisation	0.006	0.017	0.736	0.247	0.011	0.053	0.019	0.008	0.080	0.048	0.286	0.308	0.260	0.260	0.228	0.405
Acceptance weights (simulated sample size)	0.014	0.015	1.463	0.719	0.026	0.145	0.054	0.027	0.199	0.102	1.117	1.080	0.888	0.712	0.417	0.947
Other acceptance and resolution effects	0.002	0.003	0.184	0.226	0.015	0.024	0.004	0.005	0.045	0.017	0.163	0.168	0.191	0.229	0.246	0.171
Production asymmetry	0.001	0.001	0.037	0.026	0.001	0.003	0.001	0.002	0.012	0.006	0.015	0.030	0.018	0.003	0.007	0.041
Total	0.031	0.033	1.688	0.817	0.049	0.165	0.063	0.048	0.252	0.143	1.171	1.159	0.970	0.802	0.546	1.076

Parameter	f^{TT}	f_L^{TT}	$f_{\parallel_1}^{TT}$	$f_{\perp_1}^{TT}$	$f_{\parallel_2}^{TT}$	δ_0^{TT}	$\delta_{\parallel_1}^{TT}$	$\delta_{\perp_1}^{TT}$	$\delta_{\parallel_2}^{TT}$	$\delta_{\perp_2}^{TT}$
Yield and shape of mass model	0.000	0.045	0.019	0.037	0.002	0.038	0.027	0.009	0.079	0.114
Signal weights of mass model	0.000	0.066	0.025	0.024	0.002	0.147	0.046	0.112	0.123	0.215
Decay-time-dependent fit procedure	0.001	0.022	0.022	0.014	0.004	0.127	0.036	0.068	0.058	0.040
Decay-time-dependent fit parameterisation	0.005	0.051	0.071	0.113	0.038	1.213	0.199	0.685	0.820	0.476
Acceptance weights (simulated sample size)	0.003	0.135	0.110	0.127	0.077	1.328	0.454	1.348	1.443	1.161
Other acceptance and resolution effects	0.002	0.031	0.028	0.056	0.024	0.226	0.275	0.156	0.343	0.301
Production asymmetry	0.000	0.002	0.001	0.008	0.003	0.005	0.002	0.062	0.015	0.043
Total	0.007	0.176	0.142	0.205	0.107	1.825	0.573	1.546	1.706	1.330

Systematics: $B_s \to \phi\phi$

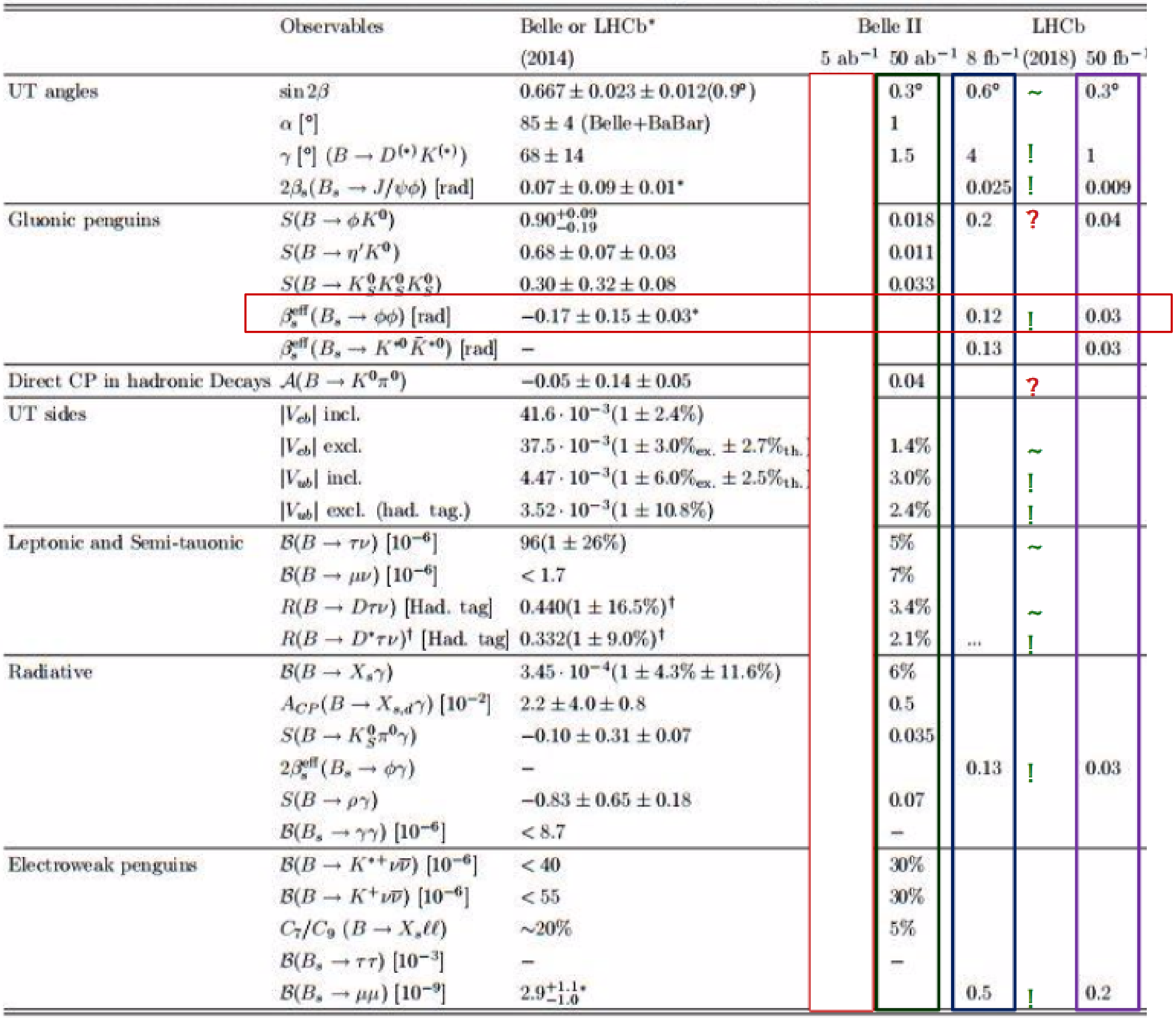


Parameter	Mass model	AA	TA	TR	Fit bias	Total
$\lvert A_0\rvert^2$	0.0043	0.0114	0.0007	0.0001	0.0017	0.0123
$\lvert A_\perp\rvert^2$	0.0004	0.0047	0.0004	0.0002	0.0012	0.0049
$\delta_\parallel$ [rad]	0.0274	0.0017	0.0049	0.0009	0.0174	0.0329
$\delta_\perp$ [rad]	0.0384	0.0029	0.0083	0.0142	0.0603	0.0734
$\phi_s^{s\bar{s}s}$ [rad]	0.0121	0.0047	0.0064	0.0198	0.0114	0.0270
λ	0.0051	0.0049	0.0022	0.0034	0.0094	0.0124
$\phi_{s,\parallel}$ [rad]	0.0016	0.0021	0.0039	0.0016	0.0099	0.0111
$\phi_{s,\perp}$ [rad]	0.0140	0.0034	0.0041	0.0030	0.0040	0.0193

AA: angular acceptance
TA: decay time acceptance
TR: decay time resolution

Backup: … and a few more

- From B. Golob @ Manchester 2016



	Observables	Belle or LHCb*	Belle II		LHCb		
		(2014)	$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$	$8\ \mathrm{fb}^{-1}$	(2018)	$50\ \mathrm{fb}^{-1}$
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (0.9^{\circ})$		0.3°	0.6°	~	0.3°
	$\alpha\ [^{\circ}]$	85 ± 4 (Belle+BaBar)		1			
	$\gamma\ [^{\circ}]\ (B \to D^{(*)} K^{(*)})$	68 ± 14		1.5	4	!	1
	$2\beta_s (B_s \to J/\psi\phi)$ [rad]	$0.07 \pm 0.09 \pm 0.01^{*}$			0.025	!	0.009
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$		0.018	0.2	?	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$		0.011			
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$		0.033			
	$\beta_s^{\mathrm{eff}} (B_s \to \phi\phi)$ [rad]	$-0.17 \pm 0.15 \pm 0.03^{*}$			0.12	!	0.03
	$\beta_s^{\mathrm{eff}} (B_s \to K^{*0} \bar{K}^{*0})$ [rad]	–			0.13		0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$		0.04		?	
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3} (1 \pm 2.4\%)$					
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3} (1 \pm 3.0\%_{\mathrm{ex.}} \pm 2.7\%_{\mathrm{th.}})$		1.4%		~	
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3} (1 \pm 6.0\%_{\mathrm{ex.}} \pm 2.5\%_{\mathrm{th.}})$		3.0%		!	
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3} (1 \pm 10.8\%)$		2.4%		!	
Leptonic and Semi-tauonic	$\mathcal{B}(B \to \tau\nu)\ [10^{-6}]$	$96 (1 \pm 26\%)$		5%		~	
	$\mathcal{B}(B \to \mu\nu)\ [10^{-6}]$	< 1.7		7%			
	$R(B \to D\tau\nu)$ [Had. tag]	$0.440 (1 \pm 16.5\%)^{\dagger}$		3.4%		~	
	$R(B \to D^{*}\tau\nu)^{\dagger}$ [Had. tag]	$0.332 (1 \pm 9.0\%)^{\dagger}$		2.1%	...	!	
Radiative	$\mathcal{B}(B \to X_s \gamma)$	$3.45 \cdot 10^{-4} (1 \pm 4.3\% \pm 11.6\%)$		6%			
	$A_{CP}(B \to X_{s,d} \gamma)\ [10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$		0.5			
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$		0.035			
	$2\beta_s^{\mathrm{eff}} (B_s \to \phi\gamma)$	–			0.13	!	0.03
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$		0.07			
	$\mathcal{B}(B_s \to \gamma\gamma)\ [10^{-6}]$	< 8.7		–			
Electroweak penguins	$\mathcal{B}(B \to K^{*+} \nu\bar{\nu})\ [10^{-6}]$	< 40		30%			
	$\mathcal{B}(B \to K^{+} \nu\bar{\nu})\ [10^{-6}]$	< 55		30%			
	$C_7/C_9\ (B \to X_s \ell\ell)$	~20%		5%			
	$\mathcal{B}(B_s \to \tau\tau)\ [10^{-3}]$	–		–			
	$\mathcal{B}(B_s \to \mu\mu)\ [10^{-9}]$	$2.9^{+1.1 *}_{-1.0}$			0.5	!	0.2

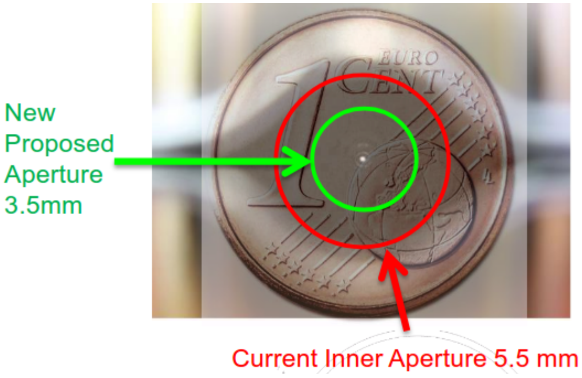
Backup: my LHCb cheat sheet

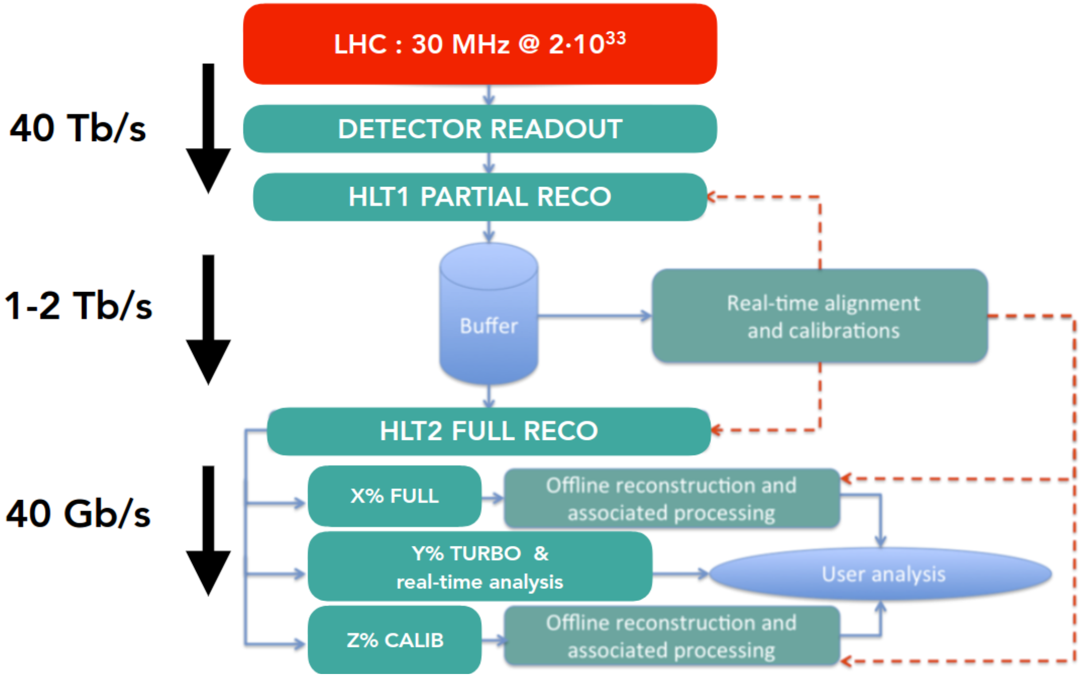
- **Luminosity**: fb^{-1}.
- **Acceptance**: 0.01-0.4 rad, ~25% of producted bb pairs.
- **$b\bar{b}$ cross-section** in acceptance: **72 – 154 μb** (7-13 TeV).
  - So ~ 200 billions of pairs in acceptance for Run 1.
- **B-daughter energy:** 10-100 GeV, max. ~20 GeV transverse energy: ~10% of that.
- **Decay-time resolution: 0.02-0.05 ps, linear with delta(t).**
- **Charmless branching fraction**: 10^{-4}–10^{-6}.
  - Typical ε(rec) ~ 10^{-3} → number of events from hundreds to tens of thousands.
- **Tagging power**: ~5%.
- (Visible) **interactions per crossing**:
  - Run 2: (1.5)
  - Upgrade: 7.6 (5.2)

Final-state particles	
μ	The stuff golden modes are made of.
p, $K^{\pm}$, $\pi^{\pm}$	Bread and butter, however possible mis-ID.
$e^{\pm}$	Challenging (brehmstrahlung).
γ, n	Challenging (only in calorimeter).
π^0 (as 2γ) K^0_S (as $2\pi^{\pm}$) Λ^0 (as pπ) Ξ^- (as Λπ)	Difficult: either displaced or made of γ.
K^0_L	(Nigh?)impossible.
υ	Indirect constraints, but initial state is not known.

Backup: my Upgrade cheat sheet

- **Peak luminosity**: $4\text{x}10^{32}$ cm^{-2}s^{-1} → $2\text{x}10^{33}$ cm^{-2}s^{-1}. Upgrade 2: $2\text{x}10^{34}$.
- **VeLo**: from silicon strips to pixel detector, smaller aperture.
- **TT, IT, OT**: from silicon + straw tubes to silicon strips/fibers.
- **Rich**: replace HPDs and electronics.
- **Calorimeters**: reduce PMT gain and new electronics.
- **Muon**: new electronics.





LHC : 30 MHz @ $2{\cdot}10^{33}$

DETECTOR READOUT

HLT1 PARTIAL RECO

Buffer

Real-time alignment and calibrations

HLT2 FULL RECO

X% FULL

Offline reconstruction and associated processing

Y% TURBO & real-time analysis

User analysis

Z% CALIB

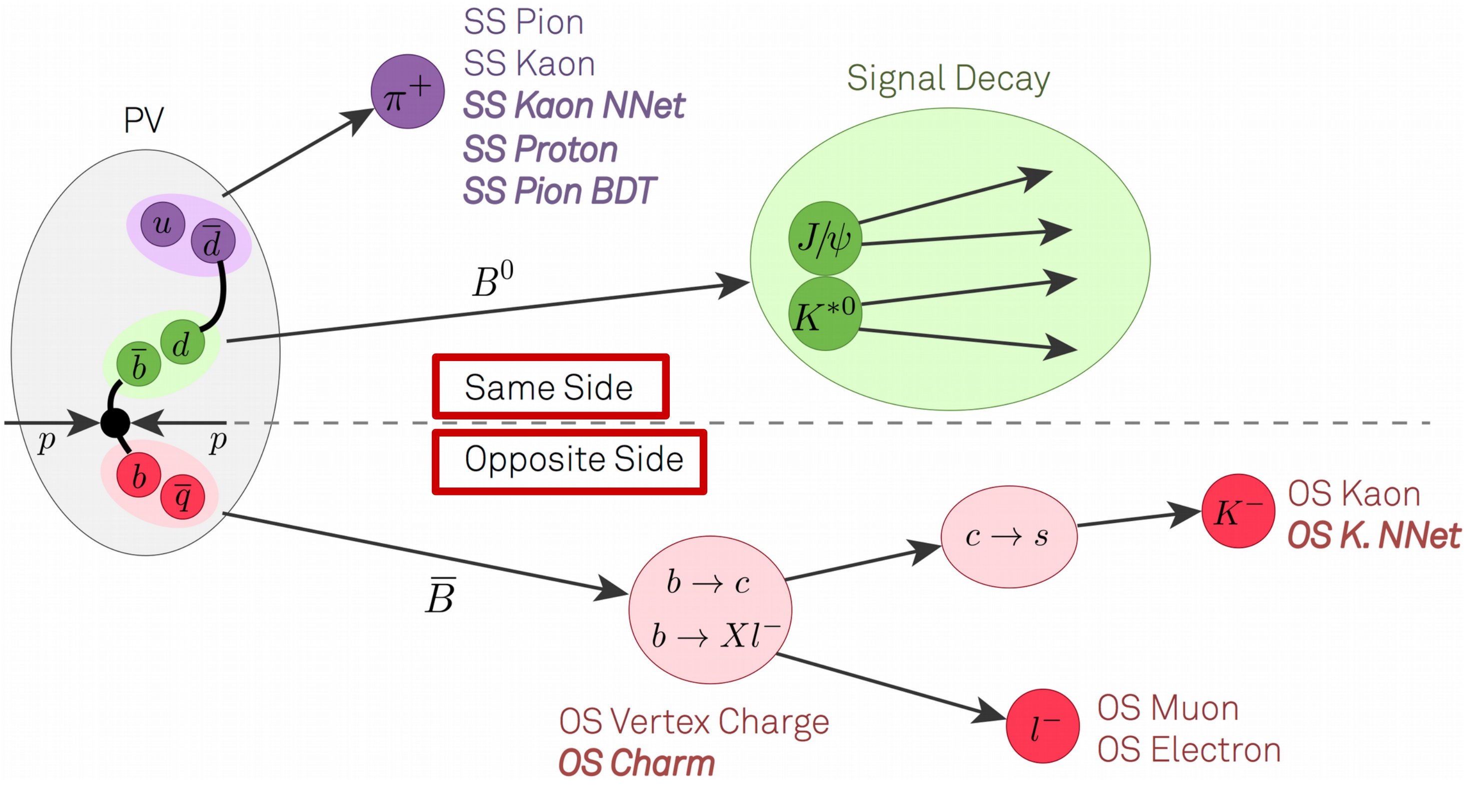
Offline reconstruction and associated processing

40 Tb/s

1-2 Tb/s

40 Gb/s

Backup: flavour tagging at LHCb



Combined tagging power: 3-8%