Search for dark boson in the decay $B^+ \to K^+\chi(\to \mu^+\mu^-)$ at LHCb

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Motivation

- There is a long list of theoretical models that predict the existence of new particles that couple to the SM sector by mixing with the Higgs

$$\begin{pmatrix} H \\ \chi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} H' \\ \chi' \end{pmatrix}$$

- Inflaton[1], axion-like[2], dark matter mediator[3] models also predict the new boson to be light.

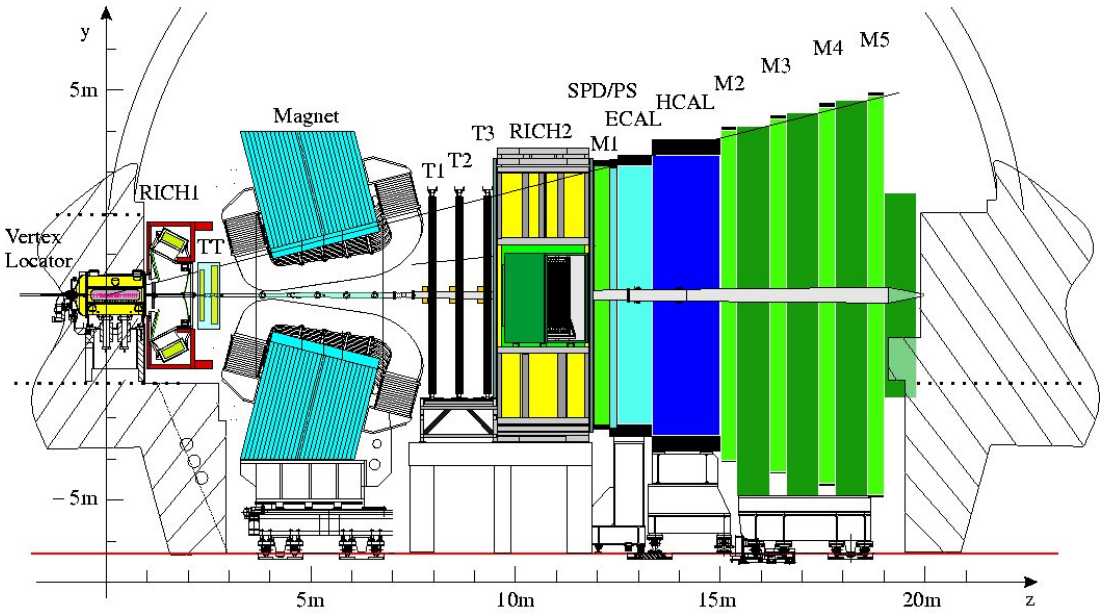
[1] JHEP 1005:010,2010

[2] Phys.Rev.D81:034001,2010

[3] Phys. Lett. B727 (2013) 506-510

The LHCb detector

1. LHCb is a forward spectrometer placed at LHC
   - Pseudorapidity range: $2 < \eta < 5$
   - focused on the study of b and c decays
   - 3 fb^{-1} of data collected in 2011 and 2012

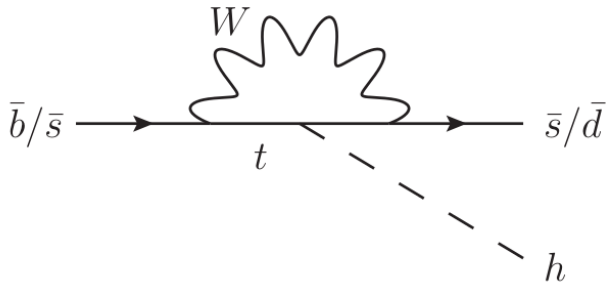


Why at LHCb?

Main production via B meson:

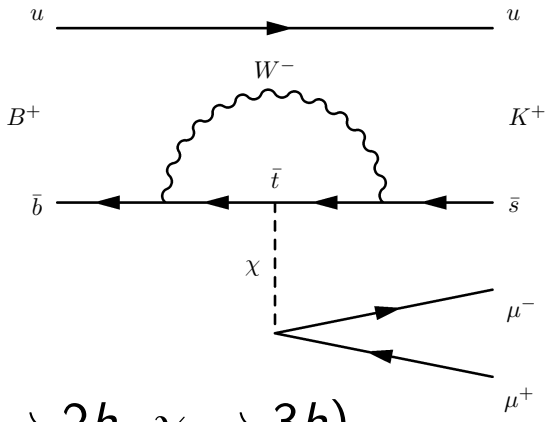
If χ mixes with the Higgs and it is light enough

$$\Gamma(K \to \pi\chi) \propto (m_t^2 \mid V_{ts}^* V_{td} \mid)^2 \propto m_t^4 \lambda^5$$
$$\Gamma(D \to \pi\chi) \propto (m_b^2 \mid V_{cb}^* V_{ub} \mid)^2 \propto m_b^4 \lambda^5$$
$$\Gamma(B \to K\chi) \propto (m_t^2 \mid V_{ts}^* V_{tb} \mid)^2 \propto m_t^4 \lambda^2$$



- Looking for dark boson decaying into muons

$$B^+ \to K^+\chi(\to \mu^+\mu^-)$$



- $\mathcal{B}(\chi \to \mu^+\mu^-)$:
  - dominant till the hadronic threshold ($\chi \to 2h$, $\chi \to 3h$)
  - always significant $\mathcal{O}(10^{-2})$ in the full mass range

Signal properties

Depending on the coupling to the SM/hidden sector, we can identify two **lifetime** regimes:

$$\left[\begin{array}{c}\text{detector resolution}\\ \sigma_\tau \sim 0.2\ \text{ps}\end{array}\right]$$

Long lifetime:

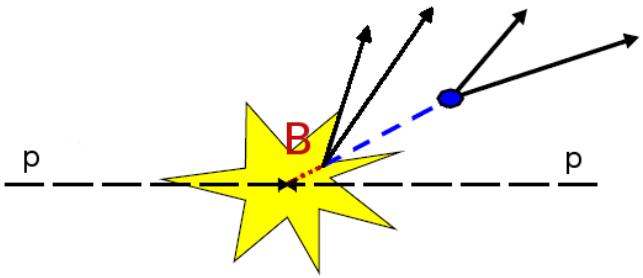
- Inflaton [JHEP1005(2010)010]

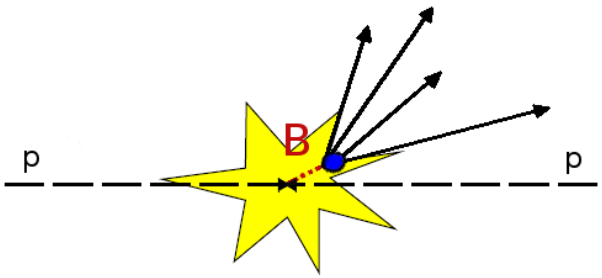
- Displaced vertex
- Almost background free
- Lower reconstruction efficiency

Short lifetime:

- Dark matter mediator [Phys.Lett.B727(2013)]
- Axion(like) [Phys.Rev.D81(2010)034001]

- Prompt decay
- Contamination from SM background



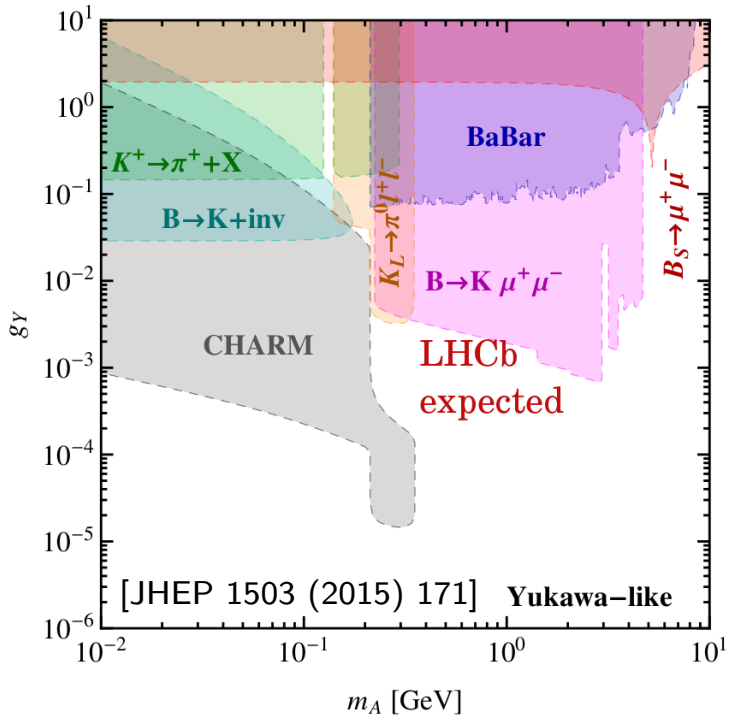


$B^+ \to K^+(\chi \to \mu^+\mu^-)$: motivation

- Benchmark model: *Inflaton* [1]
  - $\tau_\chi = 10^{-8} \div 10^{-10}$ s,
  - $m_\chi < \mathcal{O}(1\ \text{GeV})$,
  - $\mathcal{B}(B \to K\chi) \sim 10^{-6}$
  - natural width $\ll$ detector resolution
  - effective coupling to SM particles:
    - $g_Y \frac{m_f}{v_{EW}}$, $g_Y \equiv \sin\theta$

Interesting parameter values,
in the range we can test!

Existing experimental limit



Similar analysis in BaBar [1] and Belle [2] with $B \to K\mu\mu$ decay

- All models predict dark boson with width ~ 0.

[1] Phys.Rev.D86(2012)032012
[2] Phys.Rev.Lett.103(2009)171801

The experimental search ...

Status of the analysis

1. The analysis is still blind
2. Several MC simulations are used
3. Background has been studied intensively
4. Sensitivity study currently underway to define the final selection.

Selection

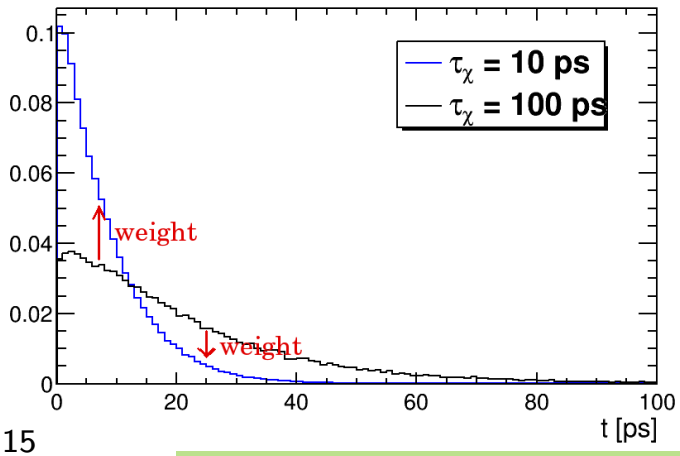
1. Triggered on muons
2. Multivariate selection:
   - input variables include:
     - tracks quality reconstruction,
     - primary, B and di-muon quality vertex reconstruction,
     - B transverse momentum,
     - di-muon distance of closest approach,
     - muon and χ candidate isolation
3. Optimized maximizing Punzi figure-of-merit $P = \frac{S}{\frac{5}{2}+\sqrt{B}}$
4. Factorize lifetime into two components: $\mathcal{L} = \mathcal{L}^{prompt} \cdot \mathcal{L}^{displaced}$
   - *prompt*
     - irreducible SM background $B^+ \to K^+\mu^+\mu^-$
   - *displaced*
     - (almost) background free

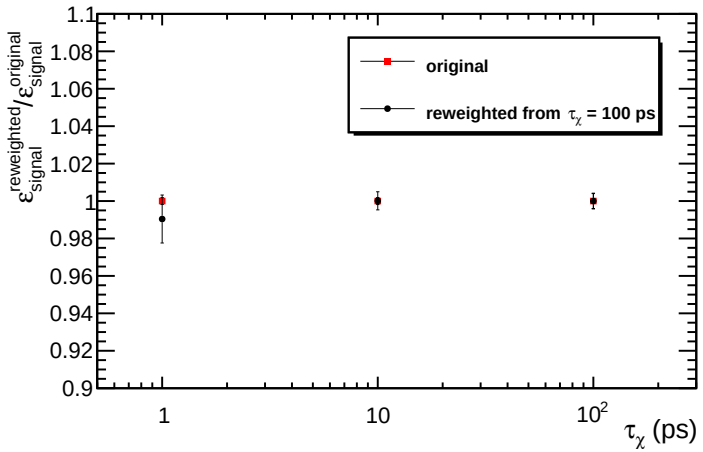
Signal simulation

- Unknown mass and lifetime
  - We tried to cover the mass & lifetime plane in a smart way

τ_χ (ps)	m_χ (MeV)										
1							2500				
10							2500				
100	250	500	800	1000	1500	2000	2500	3000	3500	4000	4500
1000							2500				

- For each mass different lifetimes can be reweighted analytically
  - the procedure is tested on the $m_\chi = 2500$ MeV samples.

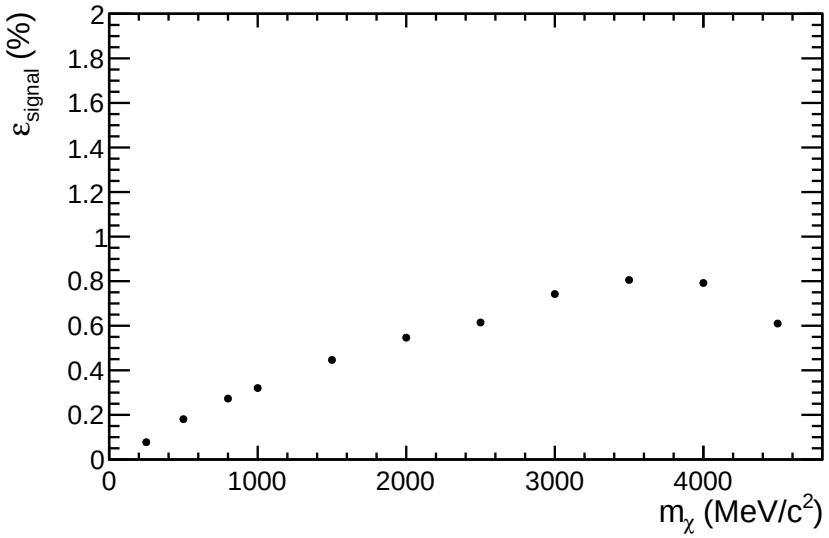




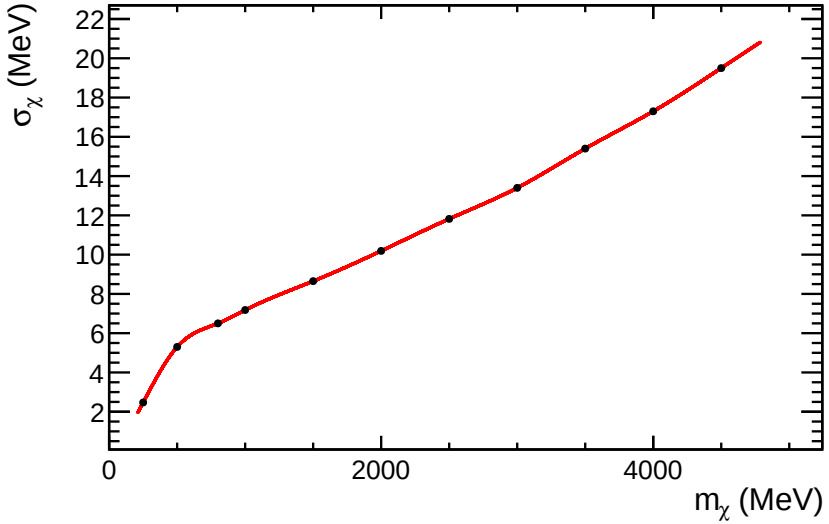
Signal simulation: resolution & efficiency

- Total efficiency:

$$\varepsilon_{signal} = \varepsilon_{acc} \times \varepsilon_{trigger} \times \varepsilon_{reco} \times \varepsilon_{PID}$$



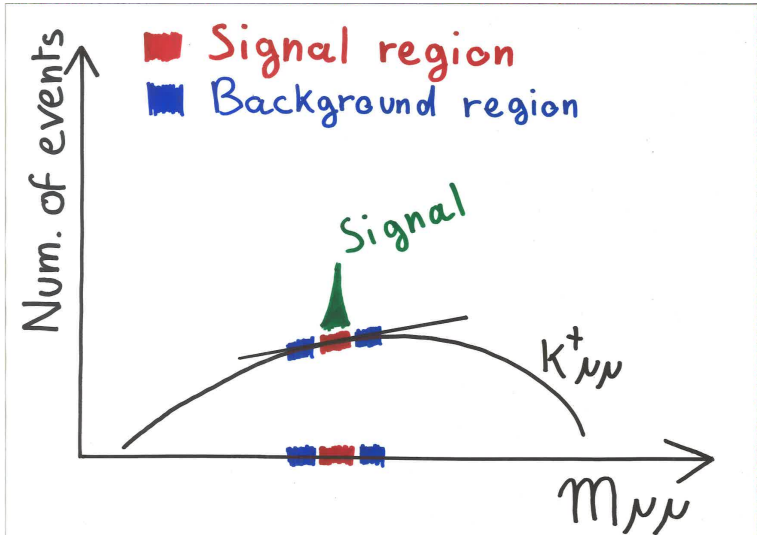
- Di-muon mass resolution



Strategy of the search: prompt bin

Looking for di-muon resonance:

- Total invariant mass $K^+\mu^+\mu^-$ required to fall into the B window
  - $m_B \in [5230, 5330]$ MeV
- B^+ mass is constrained to improved the di-muon resolution
- Scan m_{test} in steps of $1/2\ \sigma_\chi$
  - $2m_\mu < m_{test} < m_B - m_K$



Background

Background from B decays:

1. SM $B^+ \to K^+\mu^+\mu^-$: **irreducible!**
   - main background in the prompt bin
2. SM di-muon resonances: ϕ, J/ψ, ψ(2S), ψ(3770): **vetoed**
   - $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$
3. mis-identified B decays:
   - $B^+ \to K^+ D^0(\to K\pi)$
   - $B^+ \to \pi^+ D^0(\to K\pi)$

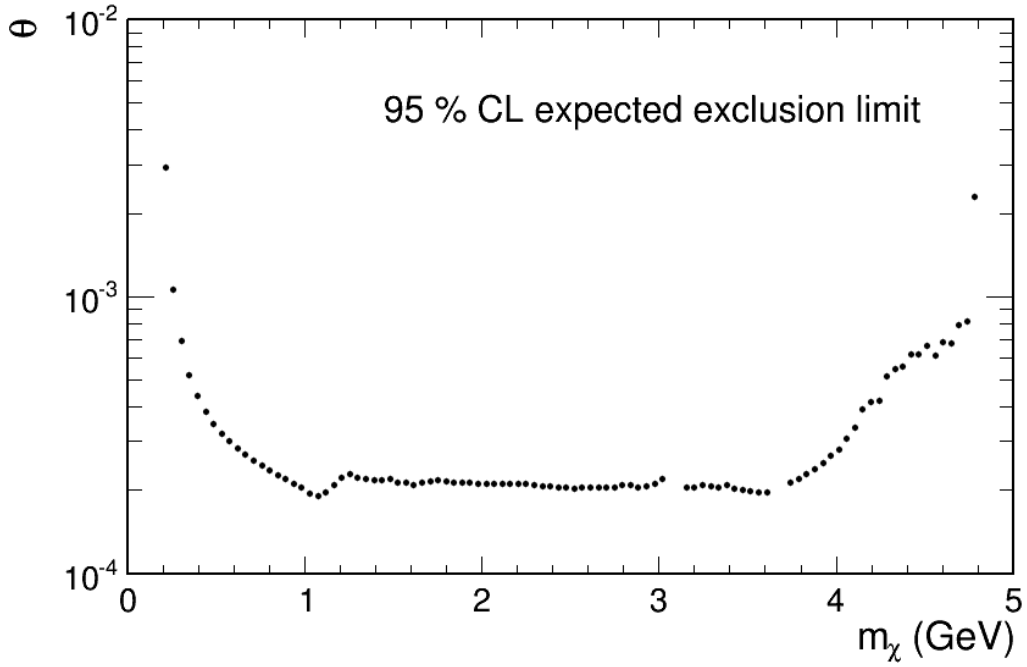
   } **rejected** by more stringent PID cuts
   - $B^+ \to 3h$ $(KKK, KK\pi, K\pi\pi, \pi\pi\pi)$: **negligible**
   - $B^0 \to K^*(\to K\pi)\mu^+\mu^-$,one missed track: **negligible**

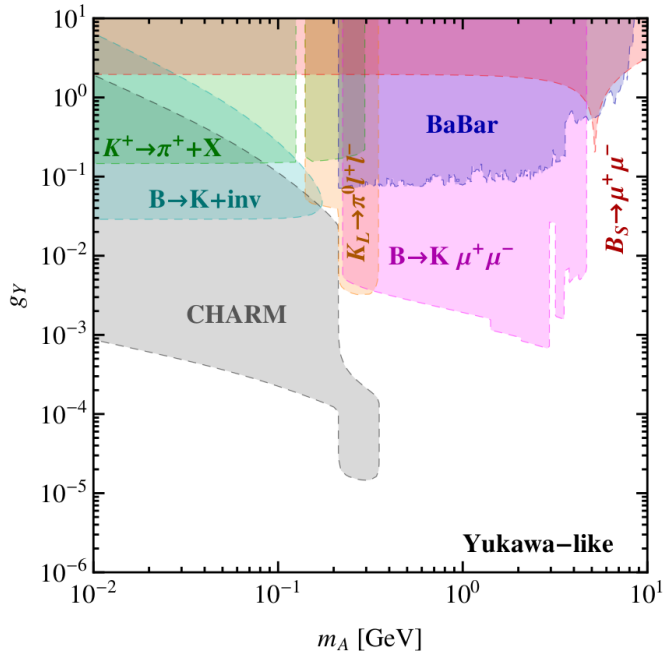
Combinatorial background:

- does not peak in the signal region (B window [5230, 5330] MeV)
- strongly **reduced** by the BDT selection
- can affect the displaced region

Sensitivity

Expected sensitivity of the search for a selection with $\tau^{displaced} > 1$ ps*





Note: different y-axis range.

* The choise of the threshold at 1 ps is a pure example, the factorization in prompt/displaced bins still has to be optimized.

Conclusion

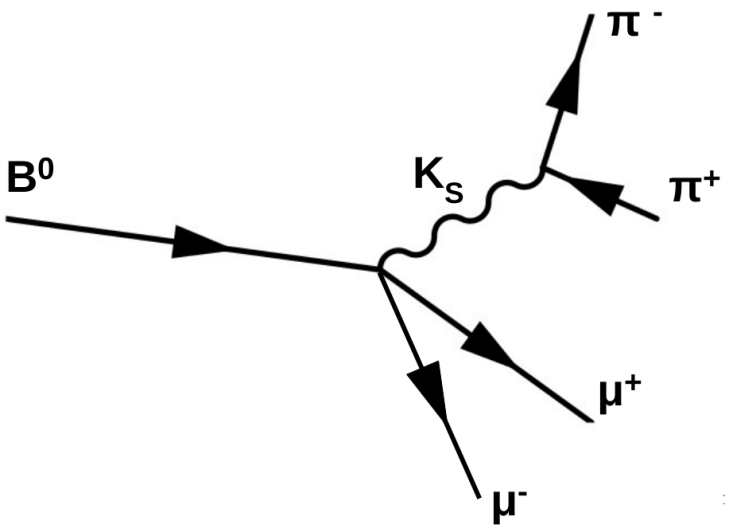
1. A search for a dark boson in the decay channel $B^+ \to K^+(\chi \to \mu^+\mu^-)$ is studied
   - resolution, efficiency and background contamination are well understood
2. LHCb is expected to improve (up to one order of magnitude) the limit of the B factories in the allowed mass range.
3. Looking forward to completing the selection and to looking at events in the (blinded) signal region.

Backup

Control channel: $B^0 \to J/\psi K_S$

As usual in LHCb analysis, we require a control channel to correct and validate the MC simulation of the signal:

- Same topology (displaced vertex) except for the final number of tracks
- well known branching ratio: $\mathrm{BR}(B^0 \to (J/\psi \to \mu\mu)(K_S^0 \to \pi\pi)) = 1.8 \cdot 10^{-5}$
- $\sim 28.5 \cdot 10^3$ events observed at LHCb

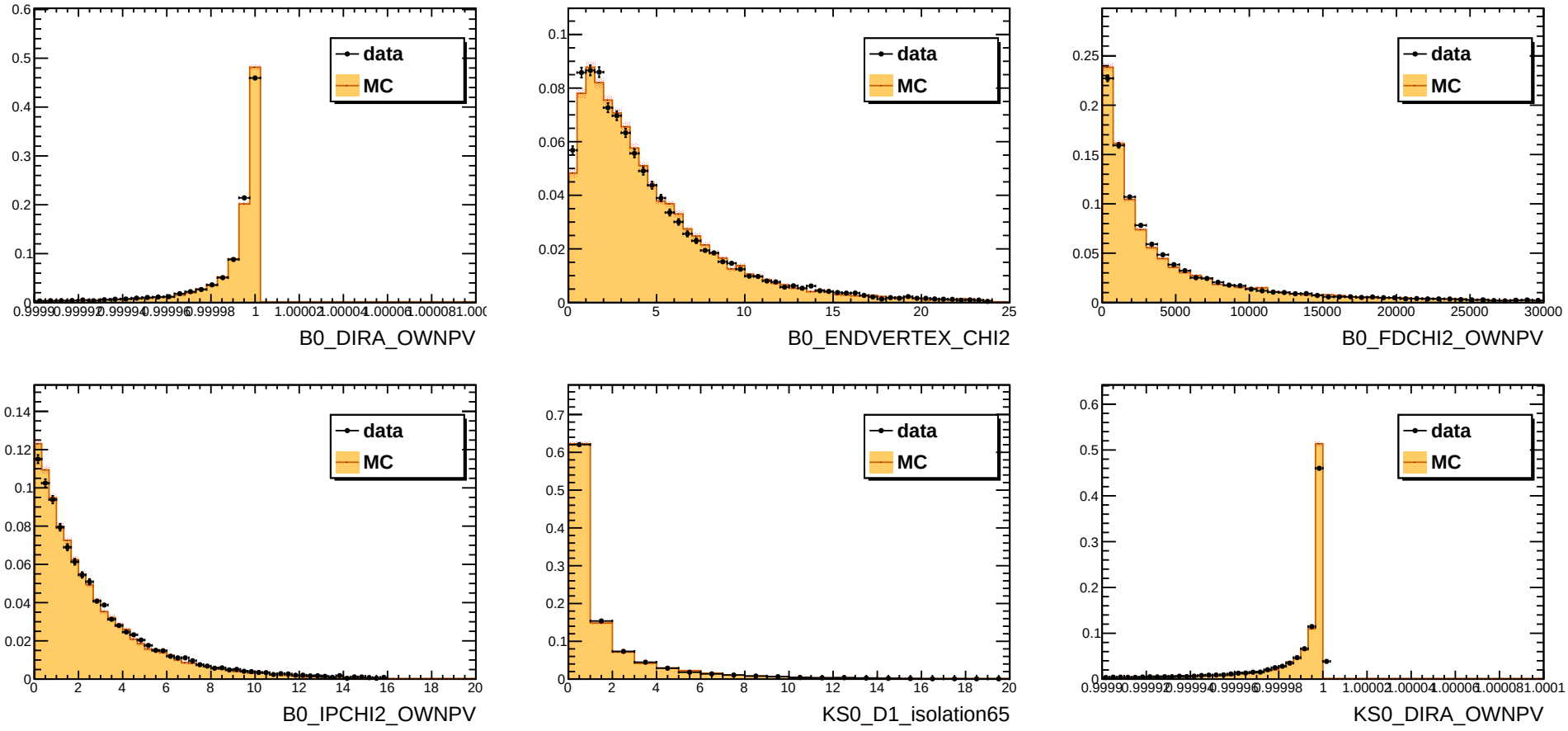


Data-driven correction of the MC efficiency:

$$\varepsilon^{sig} = \varepsilon^{sig}_{MC} \frac{\varepsilon^{norm}_{DATA}}{\varepsilon^{norm}_{MC}}$$

Control channel: $B^0 \to J/\psi K_S$

Data/MC comparison



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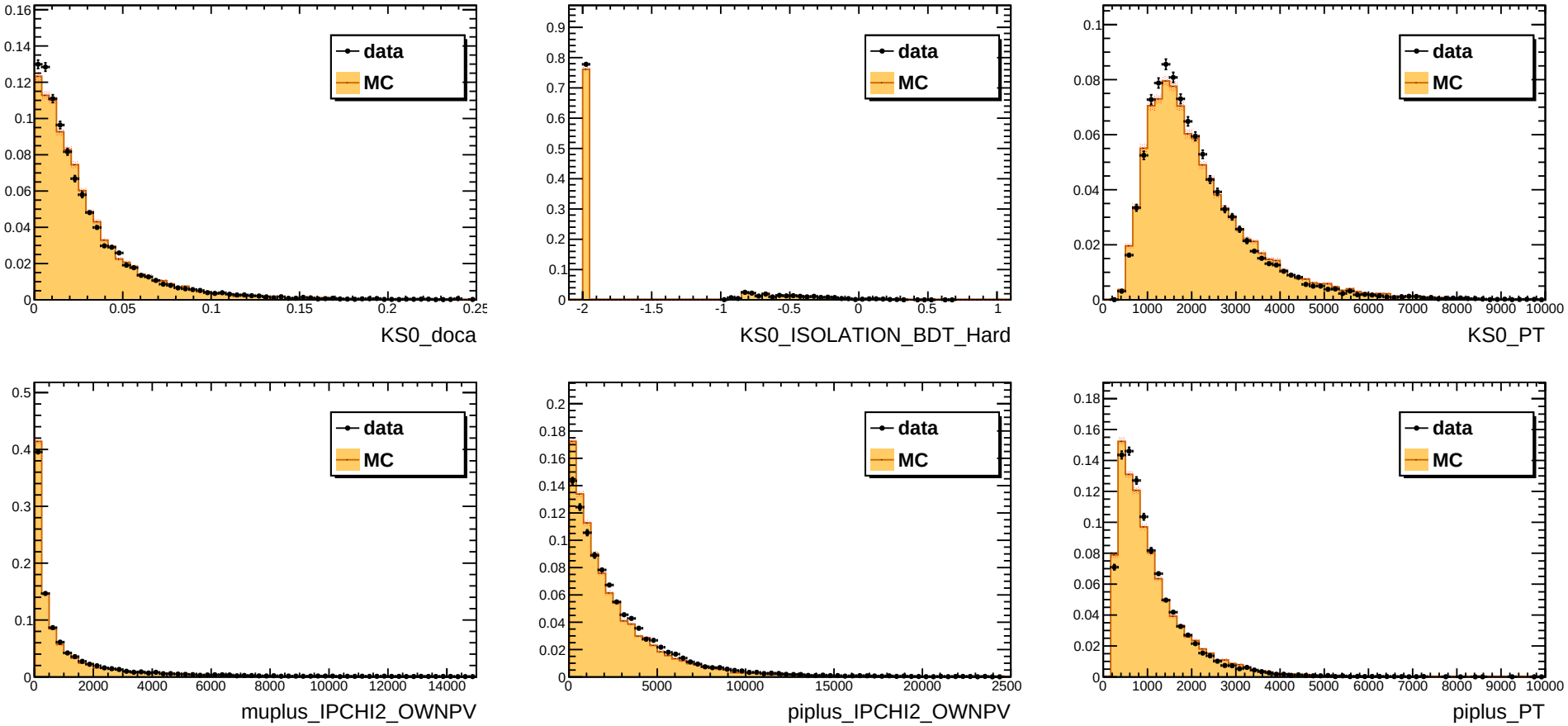

Very good agreement!!