Recent results on *charm* and *beauty* FCNC decays

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on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects (IW)
Geneva (CERN) - October 27, 2023

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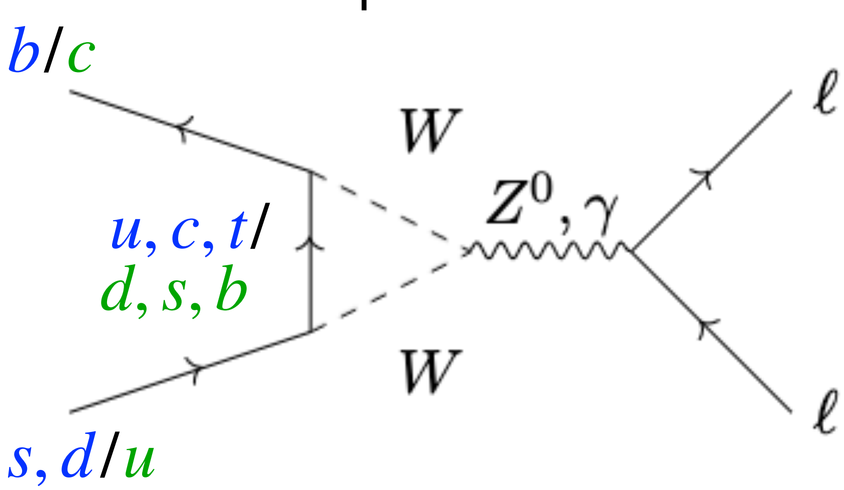
TU Dortmund and Emmy Noether program

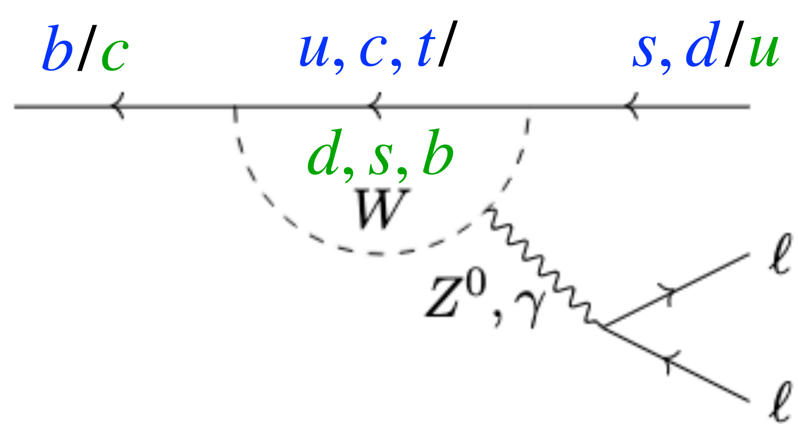
Flavour Changing Neutral Currents

- **FCNC** ($b \to s, d$ and $c \to u$ transitions) are *forbidden* at **tree** level
- In the SM, only *allowed* at **loop** level (penguin and box diagrams):

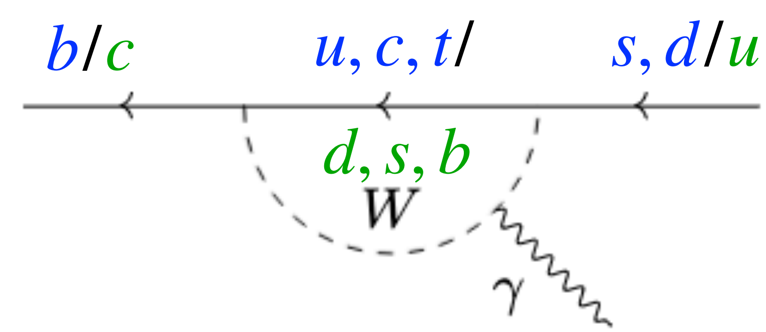
leptonic:



semileptonic:



radiative:



→ sensitive to **New Physics**!

(supersymmetry, leptoquarks, new gauge bosons, extended Higgs, …)

- **Charm** decays:
  - further *suppressed* (GIM mechanism)
  - *huge* production cross-section @LHC

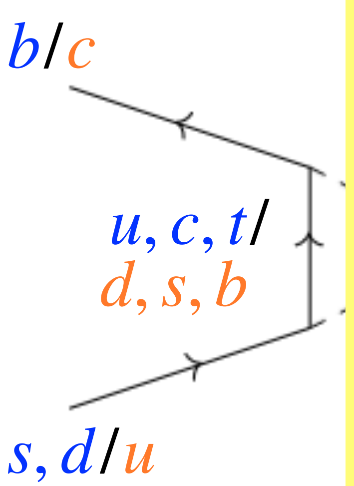
$\sigma(pp \to c\bar{c} X)_{\sqrt{s} = 13\,\mathrm{TeV}} \cong 2.4$ mb

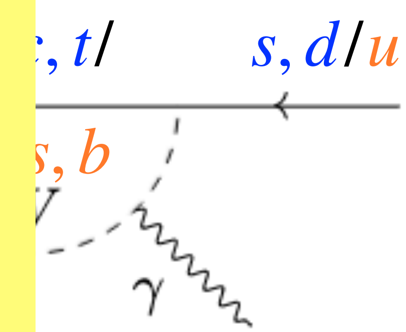
[JHEP 03 (2016) 159]

Flavour Changing Neutral Currents

- **FCN**… **tree** level
- In the … grams):

le… …ative:





…**ew Physics**!
…ptoquarks,
…ended Higgs, …)

- **Char**…
  - furth…
  - *hug*…

…≅ 2.4 mb
…59]

QCD challenges

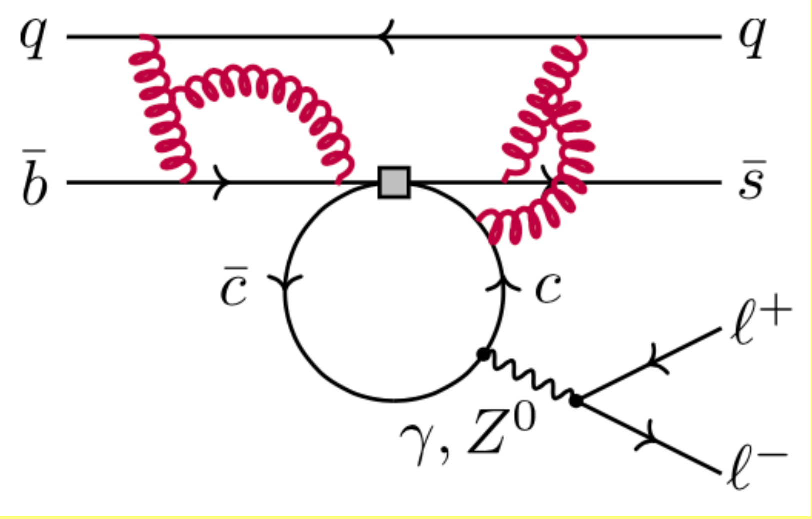
hadrons (*local* form-factors)

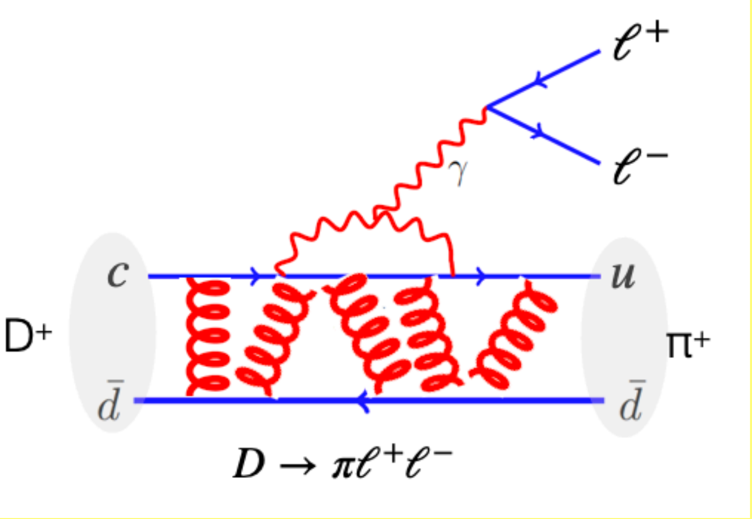
+

$q\bar{q}$ **loops** (*non-local* form-factor)

+

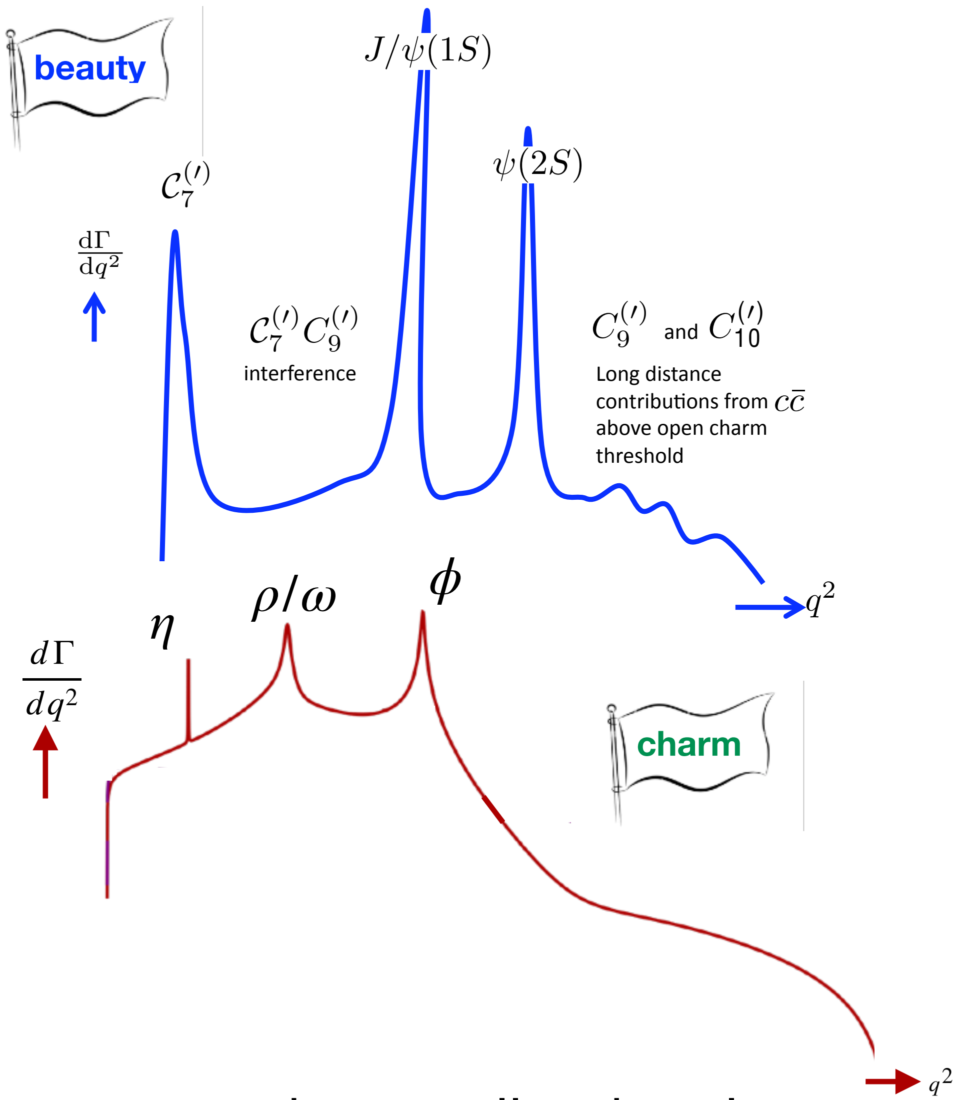
non-factorizable **soft-gluon** corrections





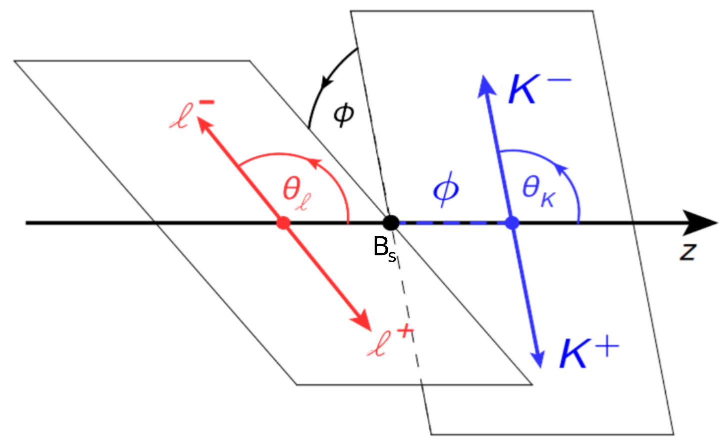
Observables

Branching fractions

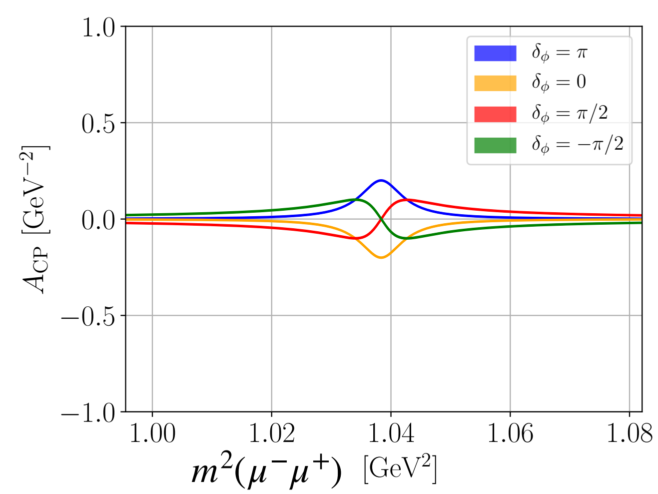


+ experimentally simple
- significant hadronic uncertainties

Angular analysis

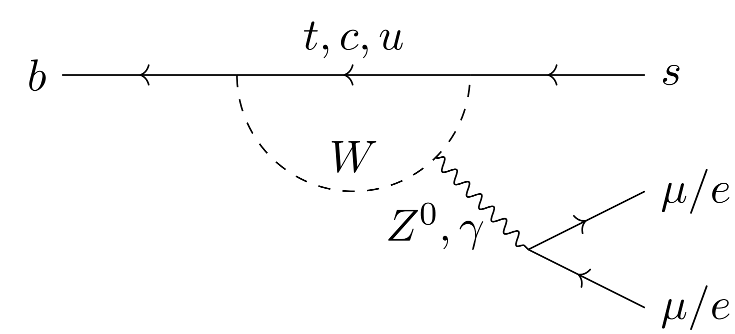


CP violation

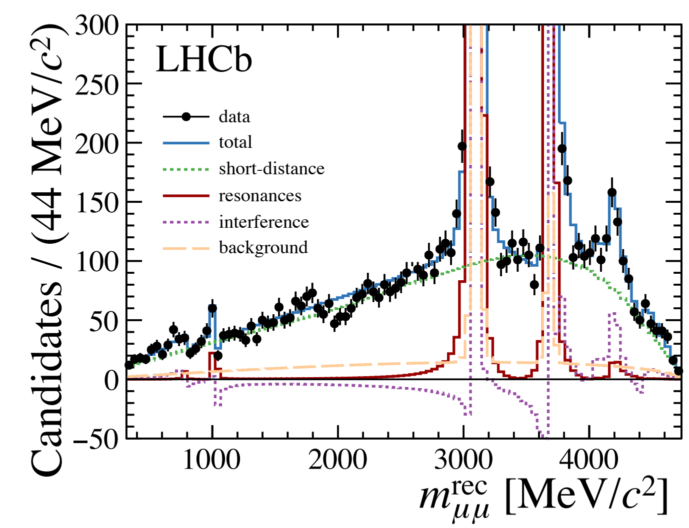


+ theoretically clean
+ probe structures of potential NP

LFU tests



Amplitude analysis

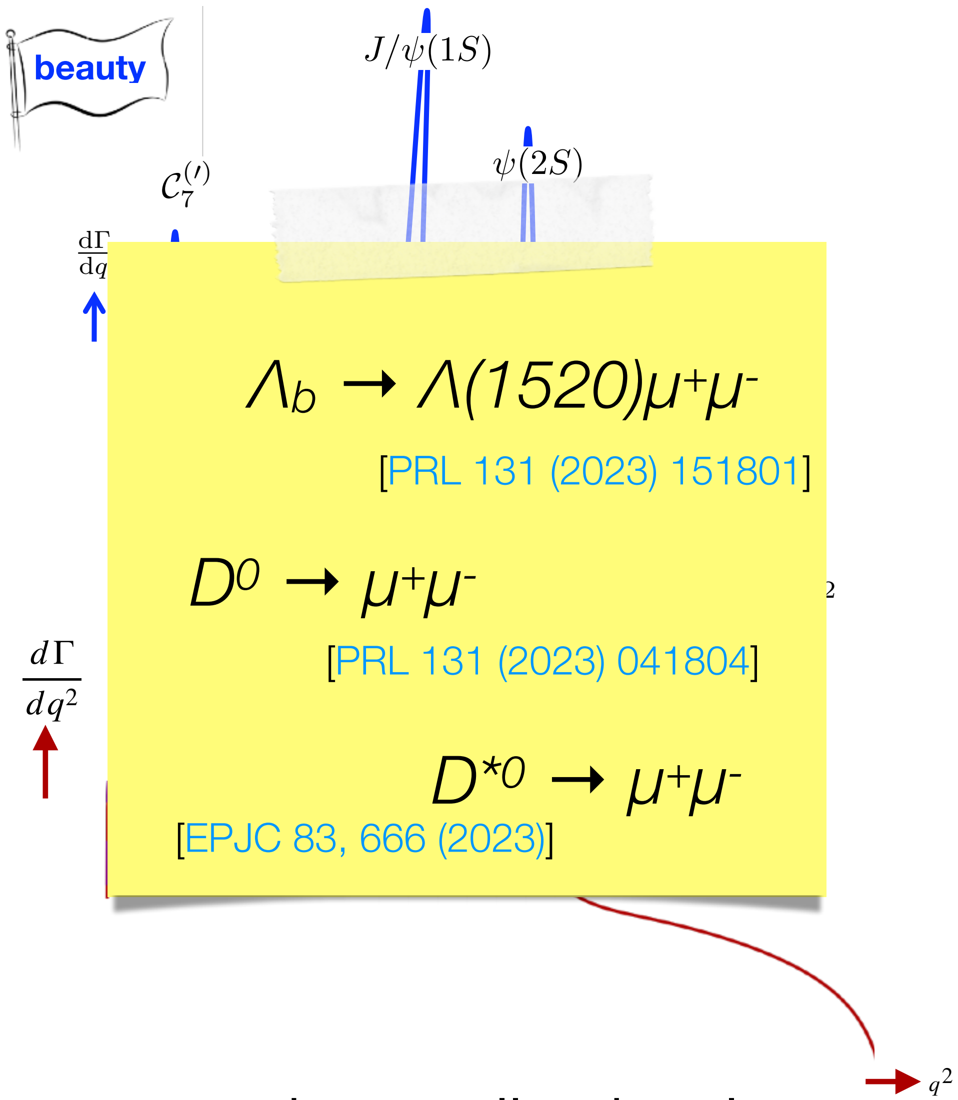


+ information about the composition of the decay

In this talk

The full LHCb dataset (Run1+Run2) is exploited

Branching fractions



$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ [PRL 131 (2023) 151801]

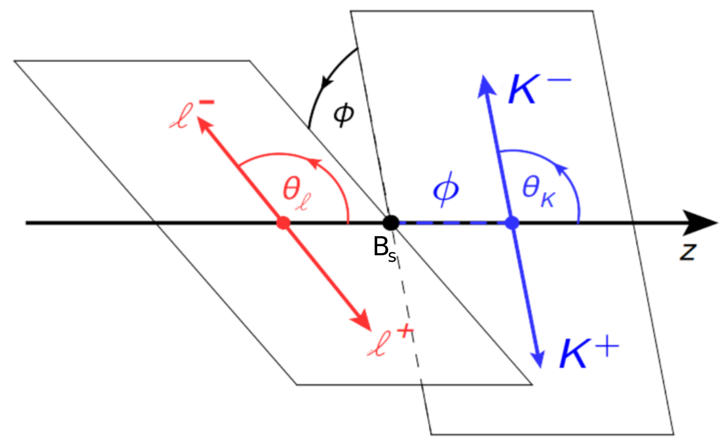
$D^0 \to \mu^+\mu^-$ [PRL 131 (2023) 041804]

$D^{*0} \to \mu^+\mu^-$ [EPJC 83, 666 (2023)]

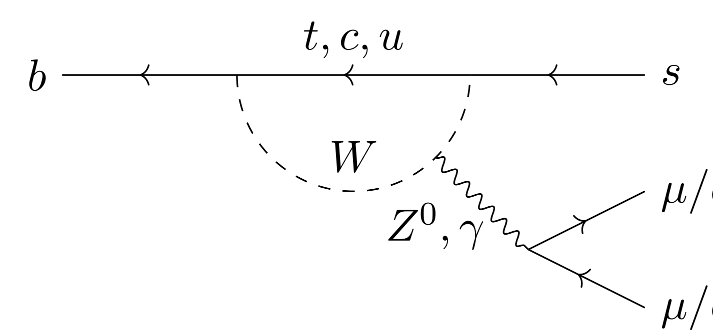
+ experimentally simple

- significant hadronic uncertainties

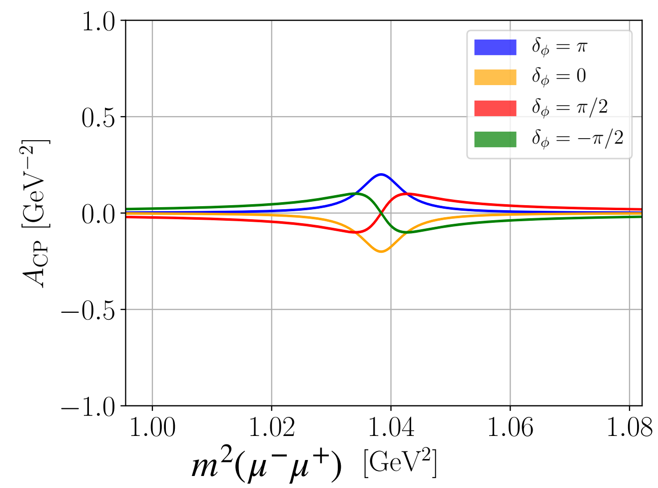
Angular analysis



LFU tests



CP violation



+ theoretically clean

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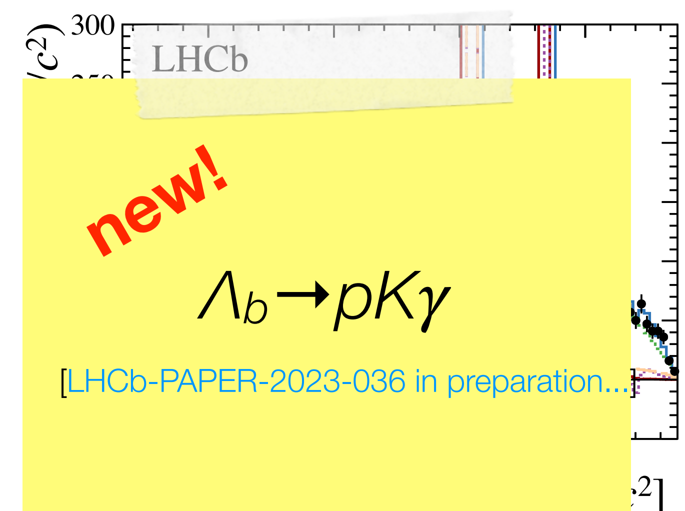
Amplitude analysis



new!

$\Lambda_b \to pK\gamma$

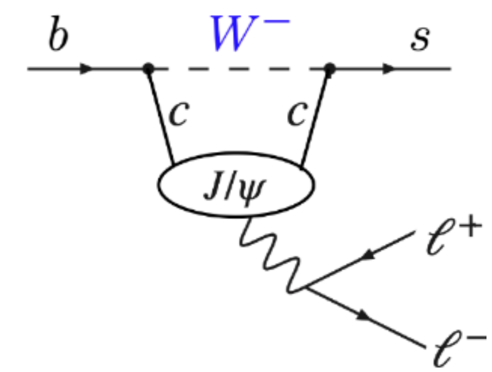
[LHCb-PAPER-2023-036 in preparation…]

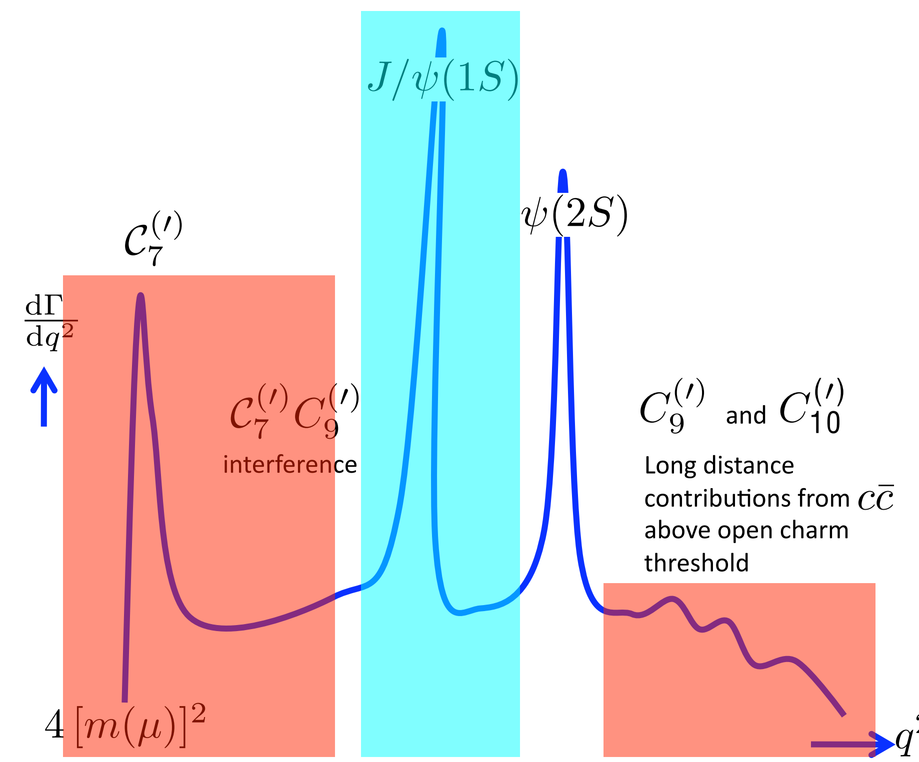
+ information about the composition of the decay

Branching fractions strategy

- Measurement in q^2 bins:

$$\frac{d\mathcal{B}}{dq^2} = \frac{\mathcal{B}(norm)}{q^2_{max} - q^2_{min}} \cdot \frac{N_{sig}}{N_{norm}} \cdot \frac{\epsilon_{norm}}{\epsilon_{sig}}$$



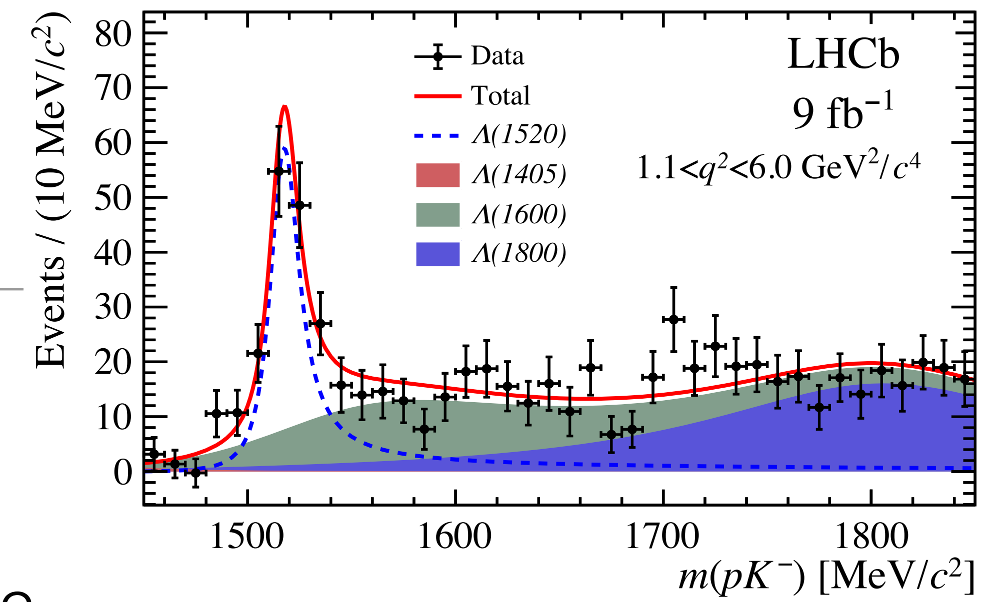


- Remove J/ψ q^2 region and use it as normalisation channel

- Relative to *normalisation* mode:
  – Cancellation of systematic uncertainties
  – Exploit $\psi(2S)$ as *control mode* to check procedure

similar approach also possible with *charm* decays exploiting the ϕ resonance beauty [PRL 131 (2023) 151801]

$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$

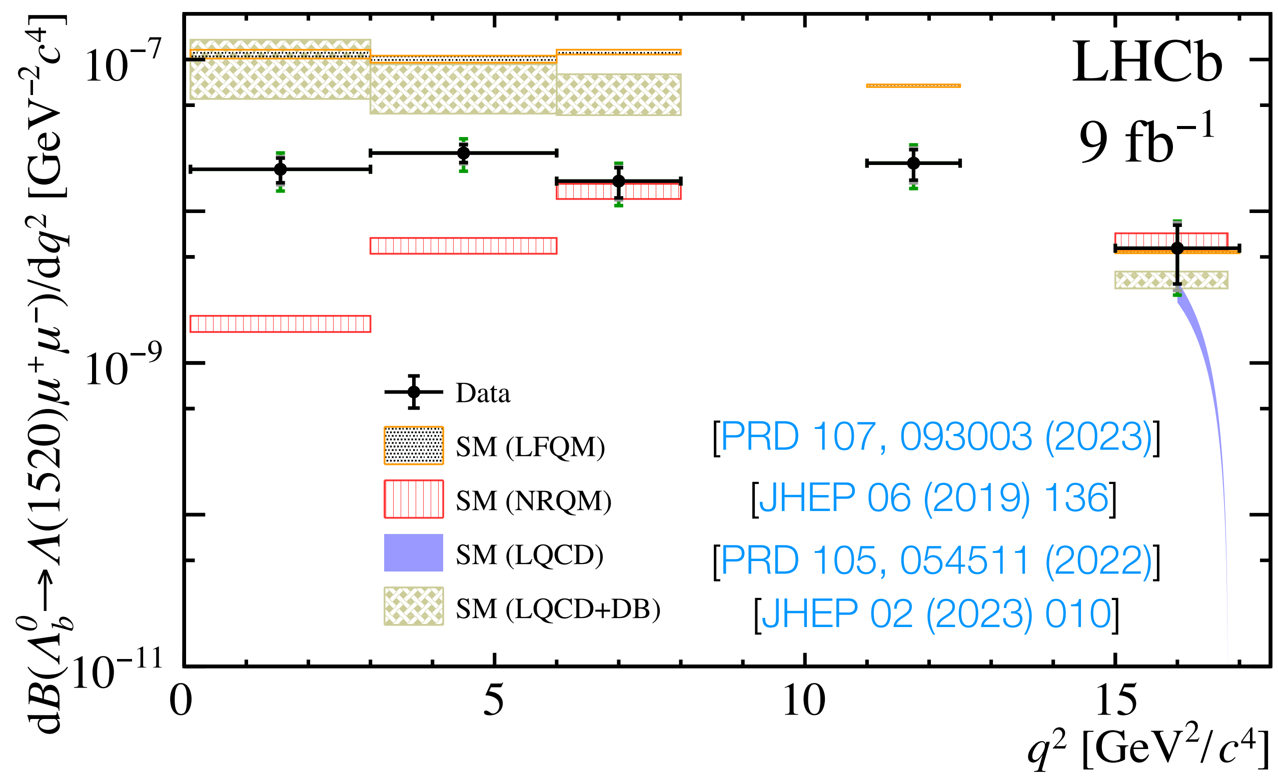


[JHEP 06 (2015) 115]

- Previously done with the ground state $\Lambda \to p\pi$ (challenging due to long Λ life-time)
- Can we isolate the excited *Λ(1520)* in the *pK* spectra?

stat. ± syst. ± $\Lambda_b \to pK^- J/\psi$ and $J/\psi \to \mu^+\mu^-$

q^2 interval [GeV$^2/c^4$]	$N_{\Lambda(1520)\mu^+\mu^-}$	$\frac{d\mathcal{B}(\Lambda_b^0\to\Lambda(1520)\mu^+\mu^-)}{dq^2}$ [10^{-8} GeV$^{-2}c^4$]
0.1–3.0	96 ± 18	1.89 ± 0.35 ± 0.19 ± 0.36
3.0–6.0	138 ± 18	2.42 ± 0.32 ± 0.17 ± 0.45
6.0–8.0	65 ± 14	1.58 ± 0.36 ± 0.16 ± 0.30
11.0–12.5	59 ± 14	2.07 ± 0.47 ± 0.26 ± 0.39
15.0–17.0	12 ± 5	0.57 ± 0.24 ± 0.13 ± 0.11
1.1–6.0	175 ± 21	1.95 ± 0.23 ± 0.16 ± 0.37



- Internal systematics uncertainty under control but *huge* impact of <u>external</u> inputs

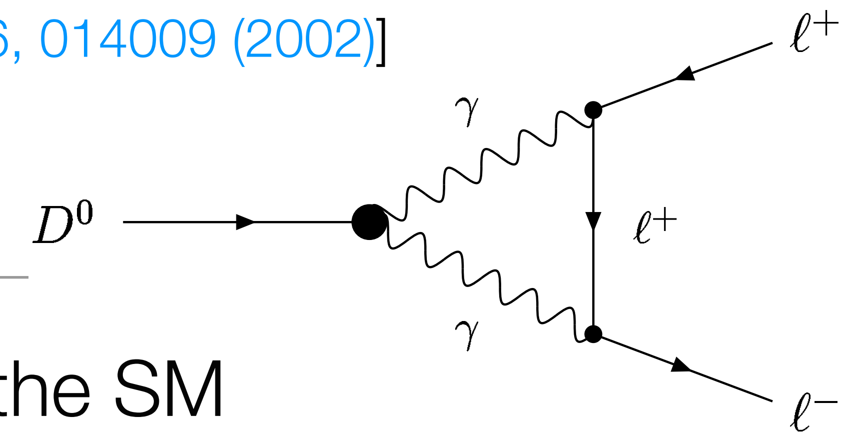
- High q^2: agreement with theory predictions
- Low q^2: significant variations, consolidation required

- LFQM: light-front quark model
- NRQM: non-relativistic quark model
- LQCD: lattice QCD
- LQCD+DM: lattice QCD + dispersive model

[PRL 131 (2023) 041804]

Search for $D^0 \to \mu^+\mu^-$

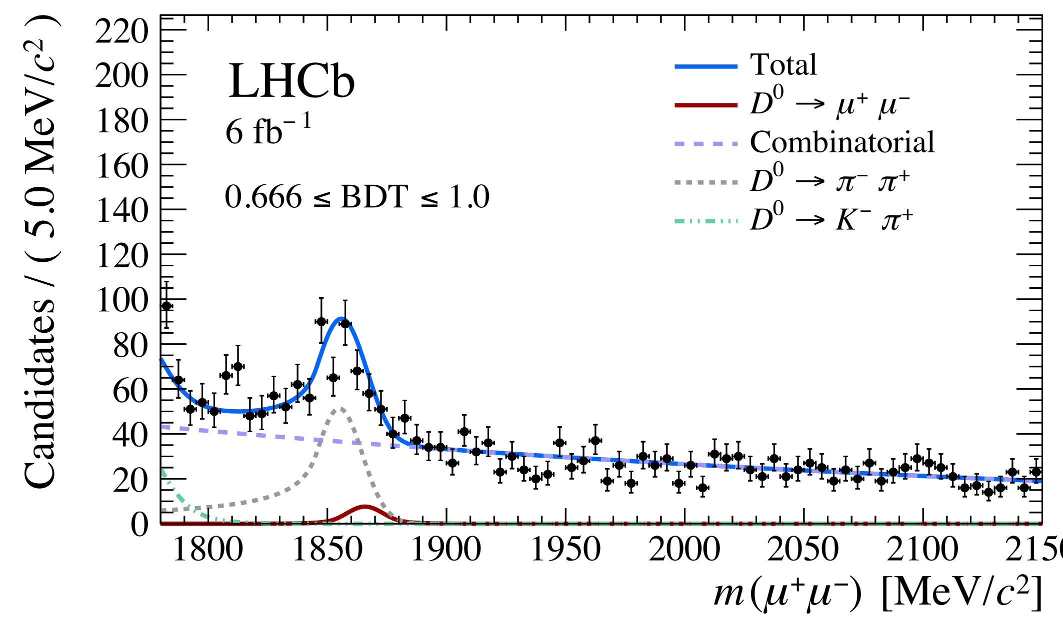
[PRD 66, 014009 (2002)]



- Intermediate two-photon state → *BF* ~ 10^{-13} in the SM
  BF < 10^{-11} (Belle constraint from $D^0 \to \gamma\gamma$) [PRD 93, 051102(R)]

- Using $\boldsymbol{D^{*+} \to D^0\pi^+}$ decays with $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ as normalisation channels

- *Backgrounds* and how to deal with them:
  - **combinatorial** (multivariate analysis)
    → three search windows
  - misidentified $\boldsymbol{\pi^+\pi^- \to \mu^+\mu^-}$
    → tight PID requirements



- No significant signal observed:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1\,(3.5) \times 10^{-9} \text{ at } 90\ (95)\%\ \text{CL}$$

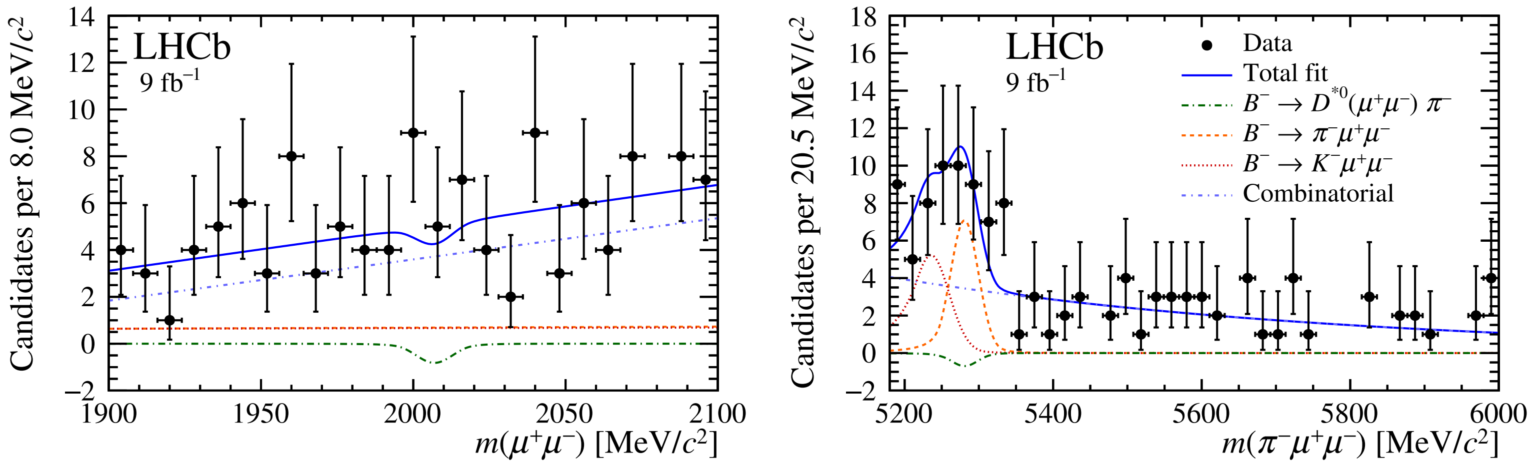
- Most stringent limit of FCNC in the charm sector

main source of systematics:
hardware (L0) trigger efficiency

[EPJC 83, 666 (2023)]

Search for $D^{*0}(2007) \to \mu^+\mu^-$

- SM predictions $BF \sim 10^{-19}$ [JHEP 11 (2015) 142]
- Look for $\boldsymbol{B^- \to D^{*0}\pi^-}$ decays (background reduction !) and use $B^- \to J/\psi K^-$ as normalisation channel
- Simultaneous fit to m($\mu^+\mu^-$) and m($\pi^-\mu^+\mu^-$)



- No excess with respect to the bkg-only hypothesis:

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\%\ \text{CL}$$

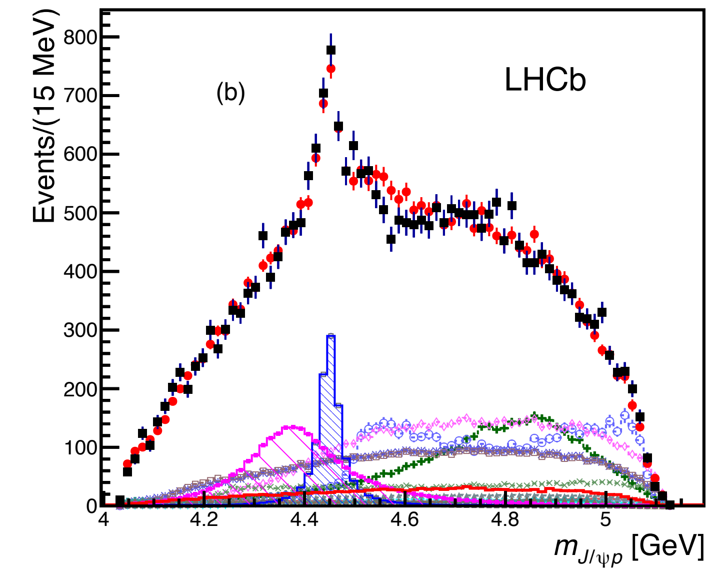
- Most stringent limit on leptonic D^{*0} decays

main source of systematics: external inputs (*BF*)

[LHCb-PAPER-2023-036 in preparation...]

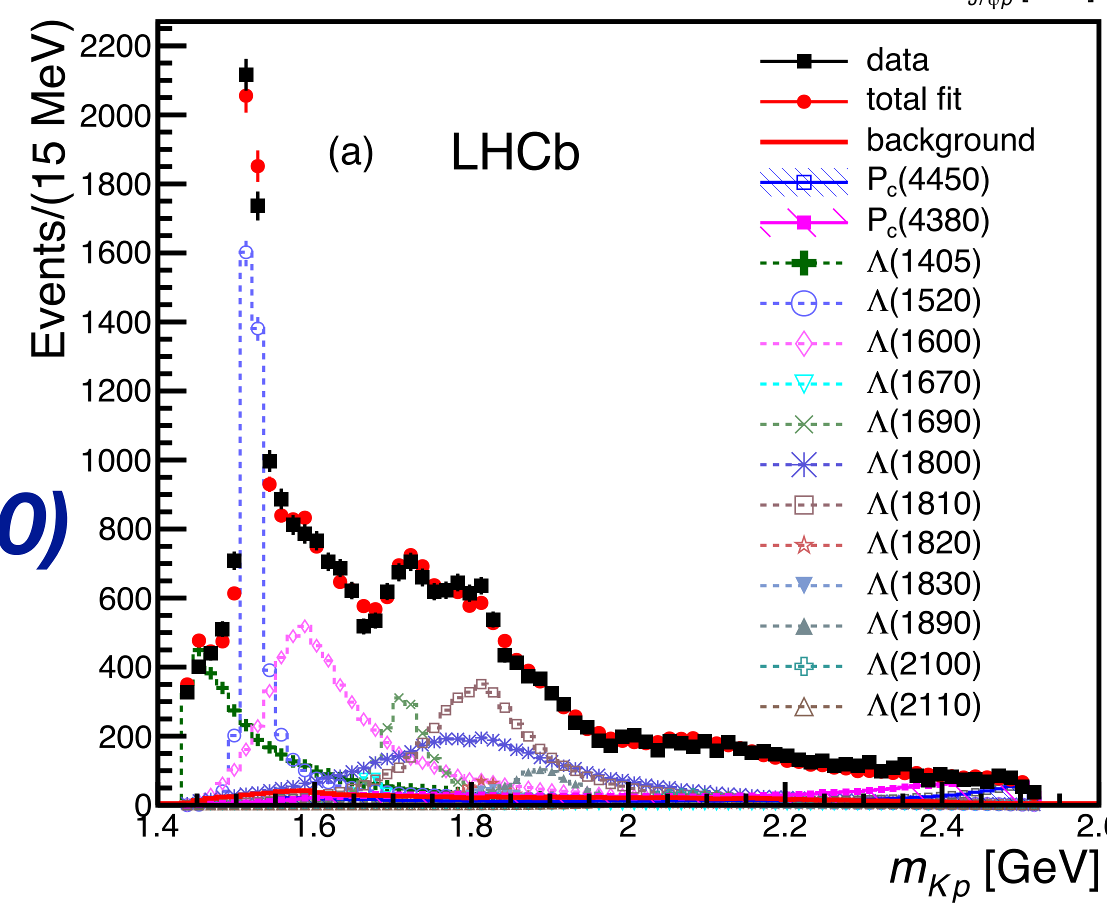
Amplitude analysis of $\Lambda_b \to pK\gamma$ why?

- $\boldsymbol{\Lambda_b \to pKll}$ deeply investigated @LHCb: [PRL 115, 072001 (2015)]
  - LFU measurement R_{pK} [JHEP 05 (2020) 040]
  - branching fractions [PRL 131 (2023), 151801]
  - CPV [JHEP 06 (2017) 108]



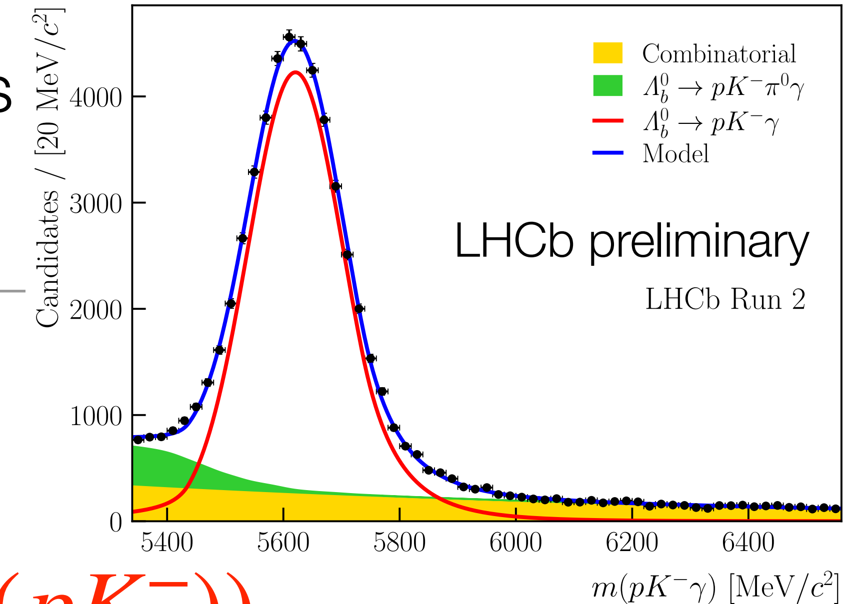
- Hard to interpret due to *little* knowledge of the *pK* spectrum (theoretically limited)

- How can we gain information in terms of resonance structure?
  - *Previous* attempt with $\boldsymbol{\Lambda_b \to pKJ/\psi}$: also discovery of a new state ***Pc(4450)***
  - $\boldsymbol{\Lambda_b \to pK\gamma}$**:** access to *heavier* states with $m(pK) > 2$ GeV/c^2



[LHCb-PAPER-2023-036 in preparation...]

50k signal candidates
in full LHCb dataset



Amplitude model

- Amplitude for a generic $\Lambda_b \to \Lambda\gamma$ decay is

$$\mathscr{A}^{\Lambda}_{\lambda_\Lambda,\lambda_p} = d^{J_\Lambda}_{\lambda_\Lambda,\lambda_p}(\theta_p)\, H^{\Lambda}_{\lambda_\Lambda,\lambda_\gamma}\, h^{\Lambda}_{\lambda_p}\, X_{J_\Lambda}(m(pK^-))$$

Wigner-D function
rotation of spin states
from the Λ helicity frame
into the p helicity frame

helicity couplings
for $\Lambda_b \to \Lambda\gamma$ and $\Lambda \to pK$
$(\lambda_K = 0)$

decay dynamics

- Possible resonance helicities are $\lambda_\Lambda = \pm 1/2$ for $J_\Lambda = 1/2$ and $\lambda_\Lambda = \pm 1/2, \pm 3/2$ for $J_\Lambda \geq 3/2$:
  → 2 (4) possible helicity couplings for spin $J_\Lambda = 1/2\,(\geq 3/2)$

- Final decay rate is the *sum* over all appearing Λ resonances and their possible helicities λ_Λ (coherent sum) as well as the initial and final state helicities $\lambda_{\Lambda_b^0}$, λ_p, λ_γ (incoherent sum)

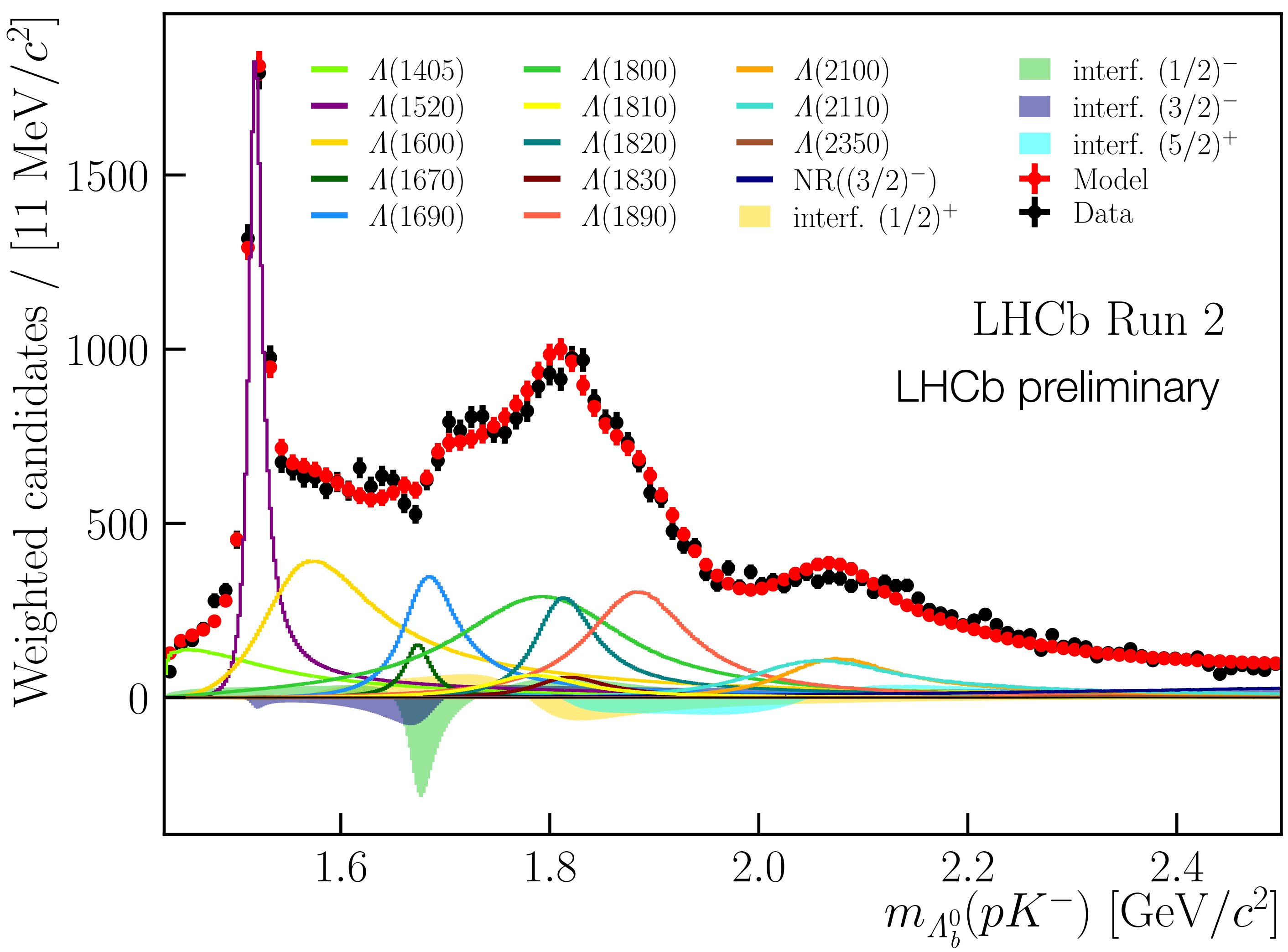
[LHCb-PAPER-2023-036 in preparation...]

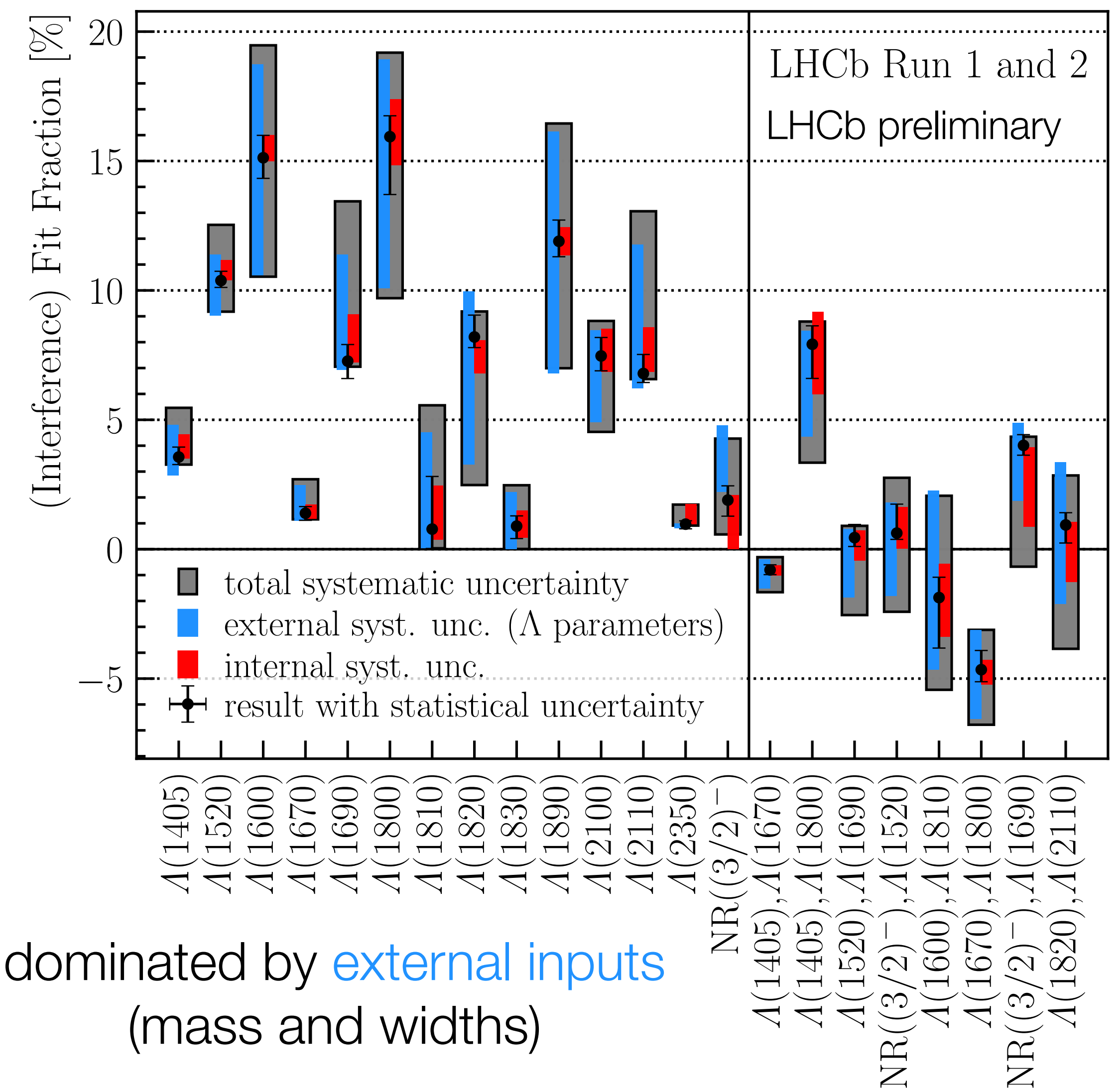
Results

- *Best model* containing all the Λ states with $L \leq 3$ (mass and width fixed to their nominal values) plus a non-resonant component with $J^P = 3/2^-$

(considered for syst. uncert.)

- *Second* best model: no non-resonant component and mass and width of the $\Lambda(2100)$ and $\Lambda(2110)$ floating using Gaussian constraints





dominated by external inputs (mass and widths)

Prospects for Run1+Run2 data
…and discussion

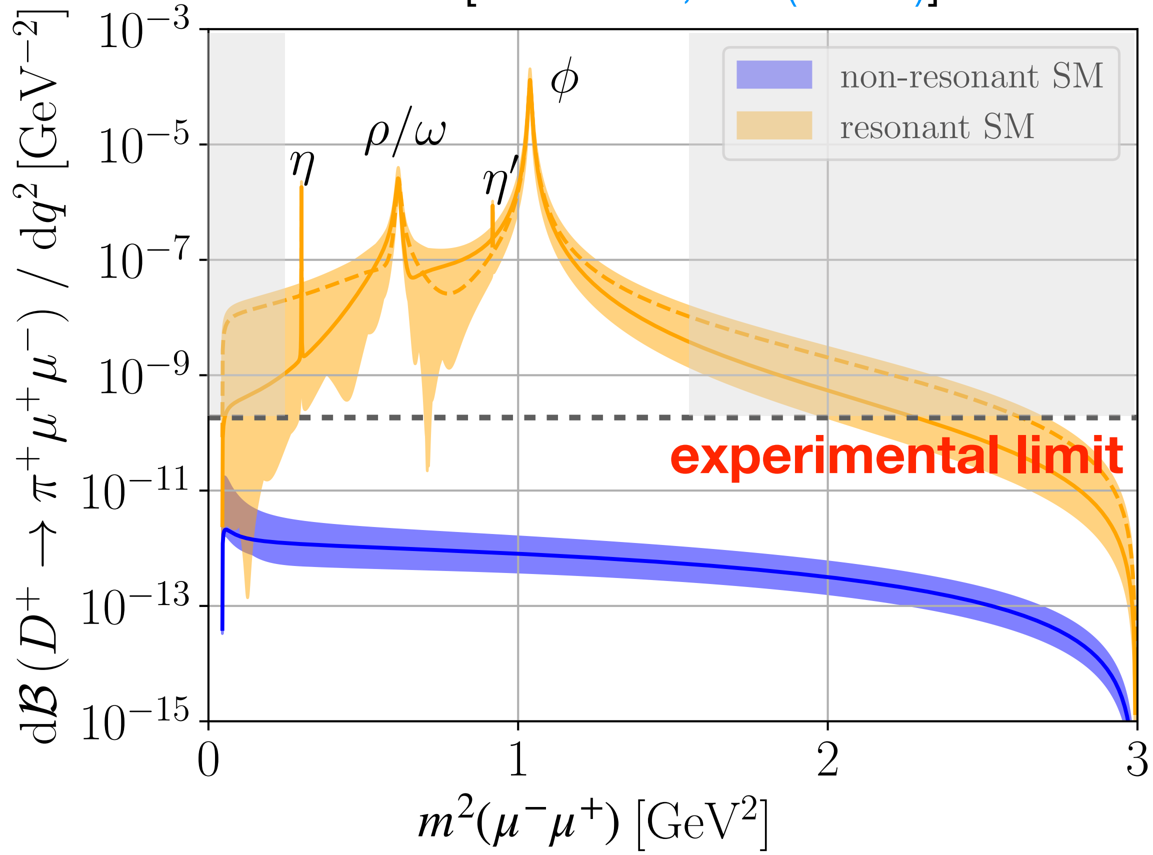
…feedbacks from *Charm* and *Beauty* rare-decays communities @***LHCb*** ongoing analyses in $D_{(s)}^+ \to h^+ll$ and $\Lambda_c^+ \to pll$

Alternative approaches in semi-leptonic decays

- **Method (A)** [PRD 97, 091101 (2018), JHEP 06 (2021) 044]

Measure *BF* in *non-resonant* region: signal events → NP (?)

[EPJC 80, 65 (2020)]



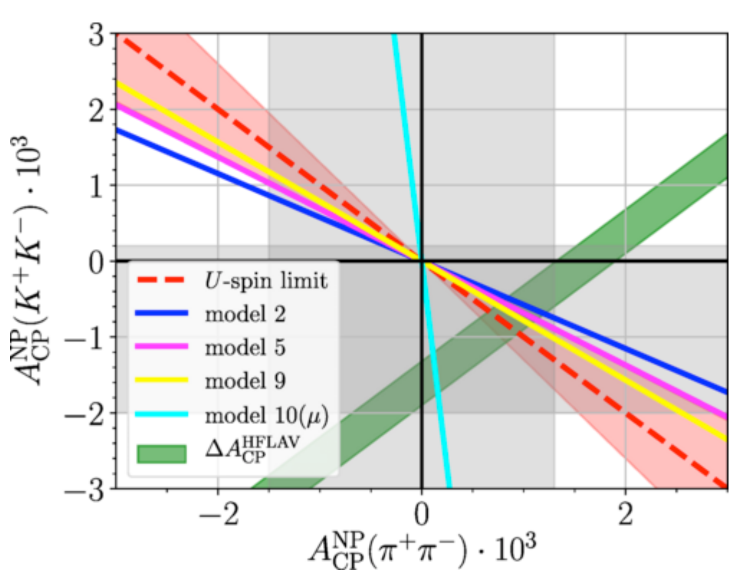
applied only in D^0 decays so far

- **Method (B)** [PRL 121, 091801 (2018), PRL 128, 221801 (2022)]

Study *resonant* region with clean null tests:

- *CP* asymmetry
- Angular observables

[PRD 101, 115006]



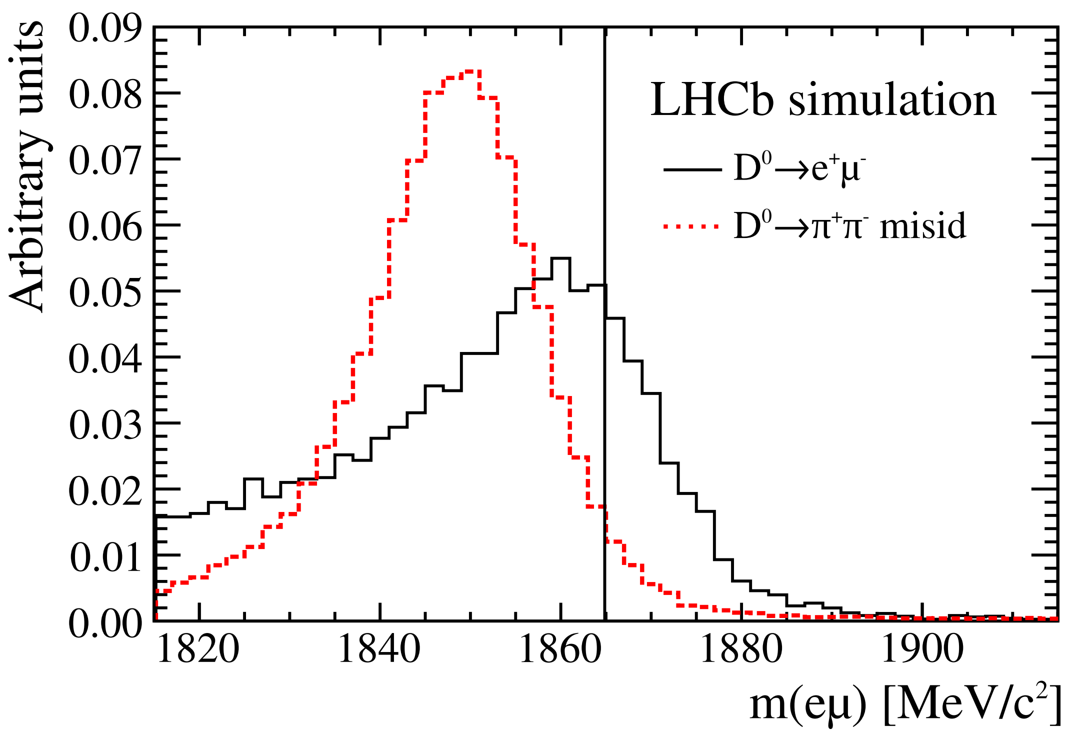
🎁: depending on the nature of possible NP, correlations with the observed *CP* violation in *hadronic* decays may exist charm

More challenges with photons and electrons

- Branching ratio and A_{CP} in ***radiative*** decays
  - study $\boldsymbol{D^0 \to V\gamma}$ ($V = \phi, \rho, K^*$)
  - complement *Belle* measurements [PRL 118, 051801 (2017)]
  - room for NP with A_{CP} up to 10% while BF SM-like

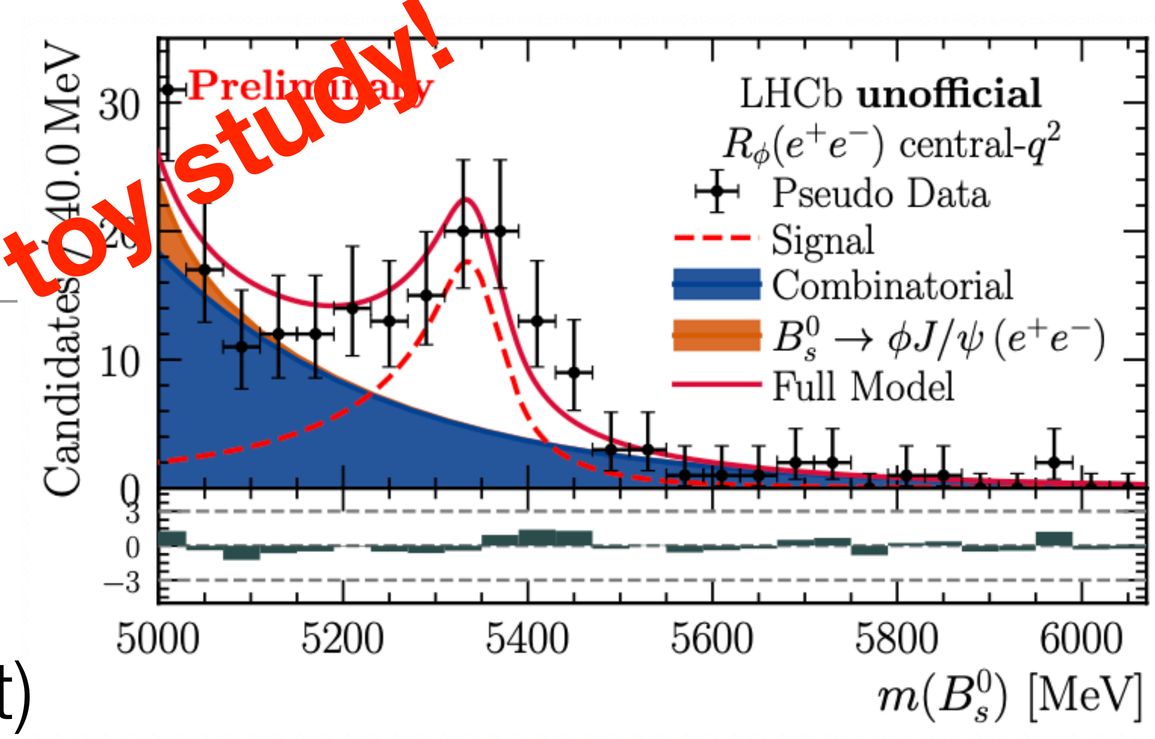
[JHEP 08 (2017) 091]

[Phys. Lett. B754 (2016) 167]



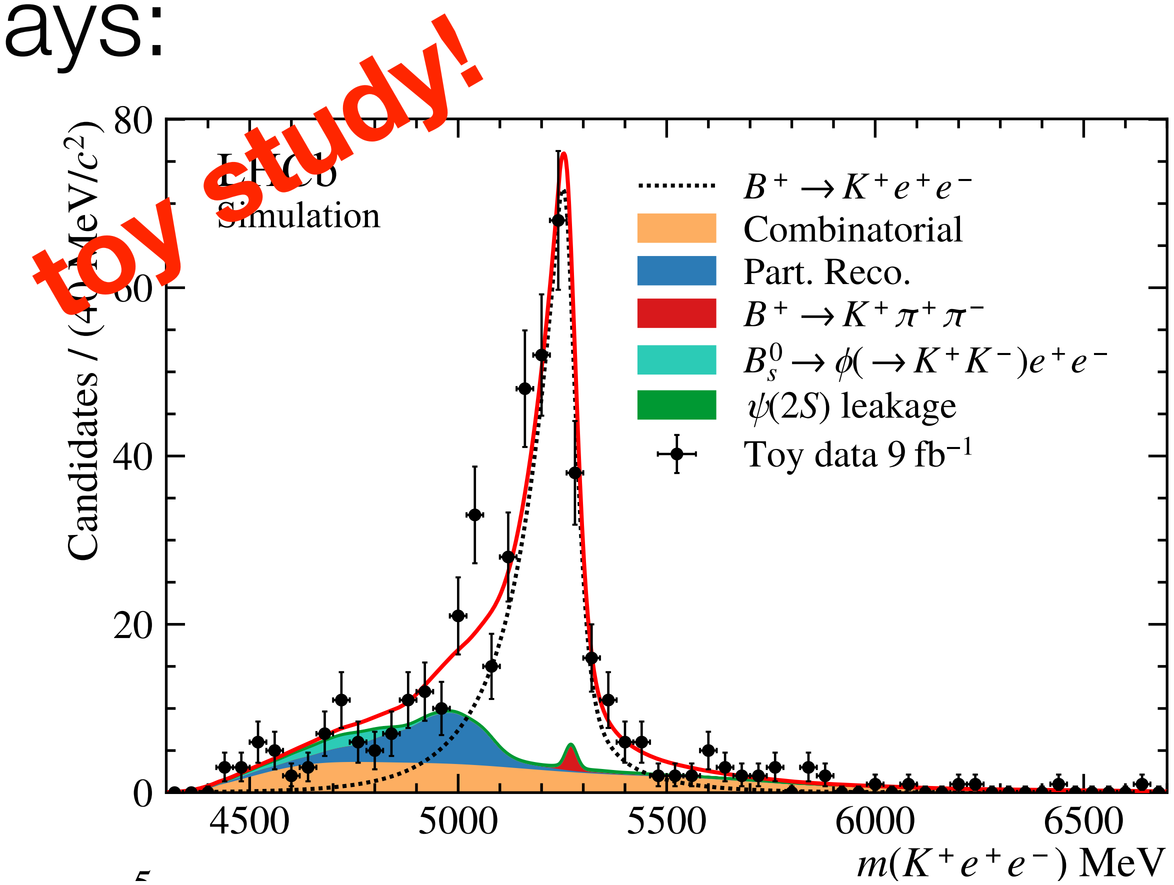
- Final states with ***electrons***
  - experimentally *challenging*
  - coming soon:
    first **LFU** test with $D_{(s)}^+ \to \phi(\to ll)\pi^+$
  - exploring also **BF** and **LNV+LFV**

Upcoming LFU tests



- **Exclusive**:
  - R_ϕ with $B_s \to \phi ll$,
  - R_Λ with $\Lambda_b \to \Lambda ll$ (first measurement)
  - R_{pK} with $\Lambda_b \to pKll$ (update with 2017+2018)

- **Non-exclusive** multi-body decays:
  - $B^+ \to K\pi\pi ll$
  - $B^0 \to K\pi ll$ (outside K^* resonance)

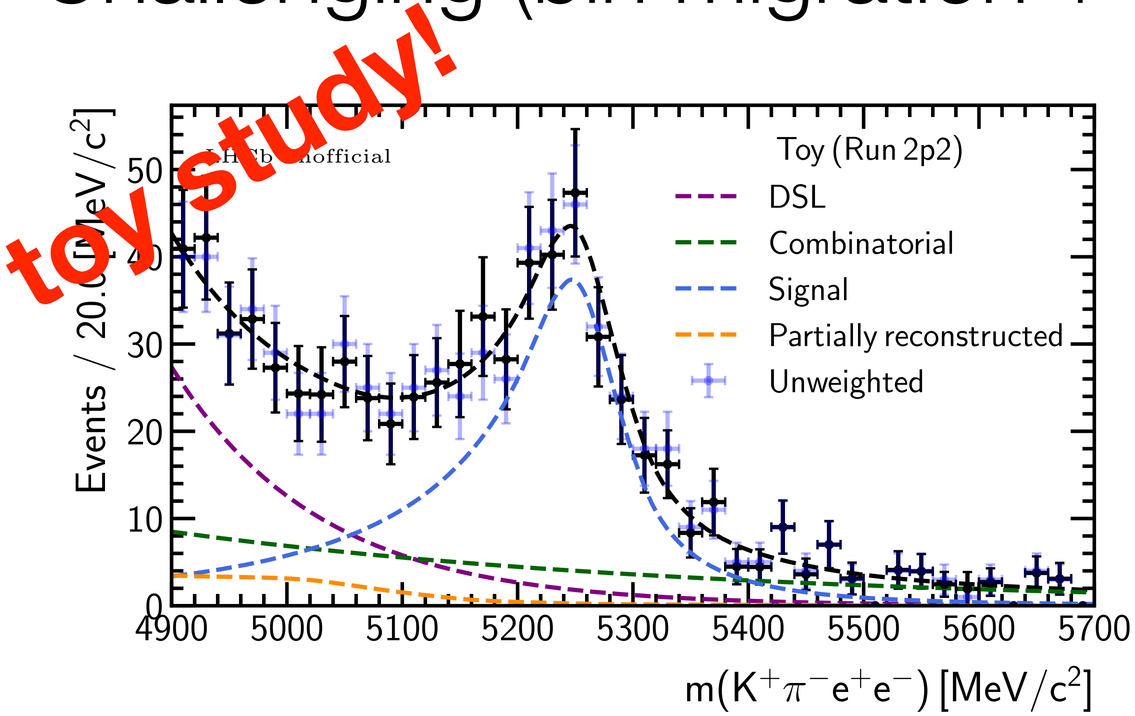


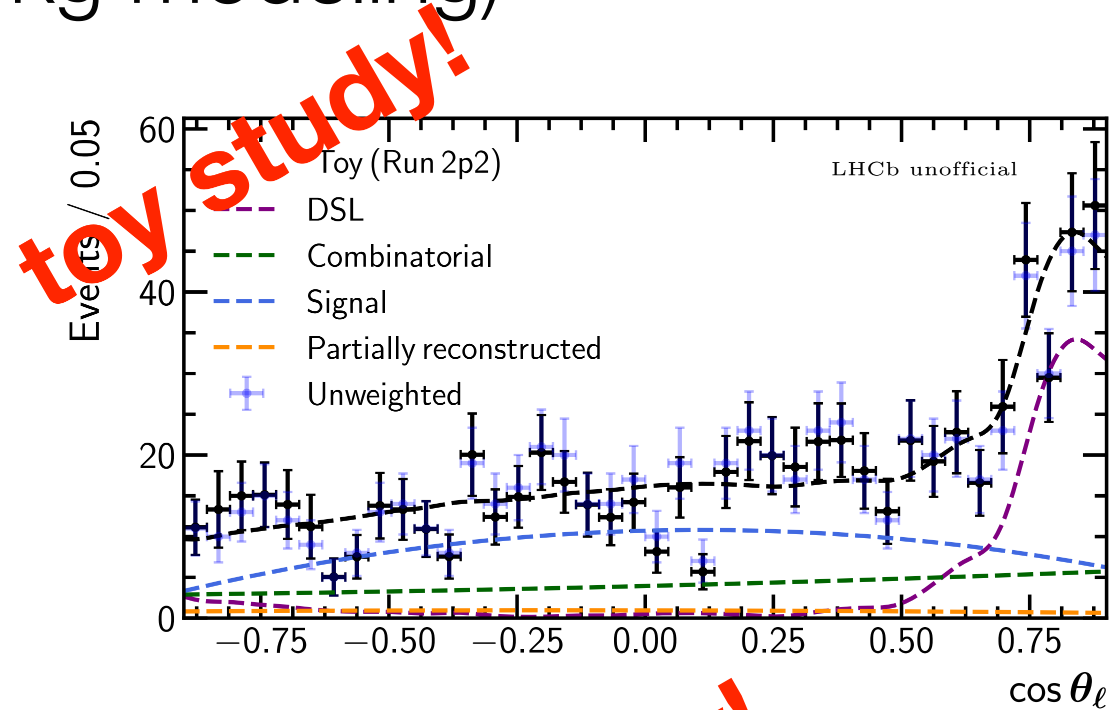
- **High q^2** region in $R_{K^{(*)}}$ and R_ϕ:
  - background contamination

    $\psi(2S)$ + part. reconstructed + misID beauty

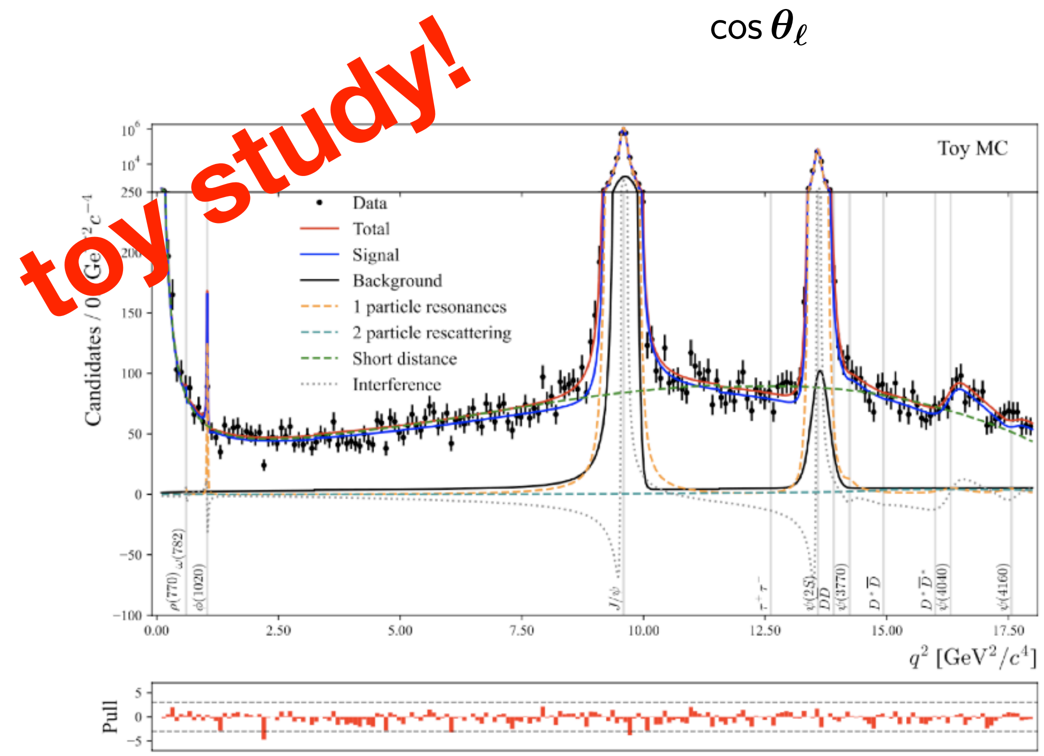
Angular observables

- Challenging (bin migration + bkg modeling)





- ***B→K*μμ***: extra fit parameters (massive leptons + scalar amplitudes)



- **Binned/Unbinned?**
  - *unbinned*: study different models
  - *binned*: more bins and full dataset

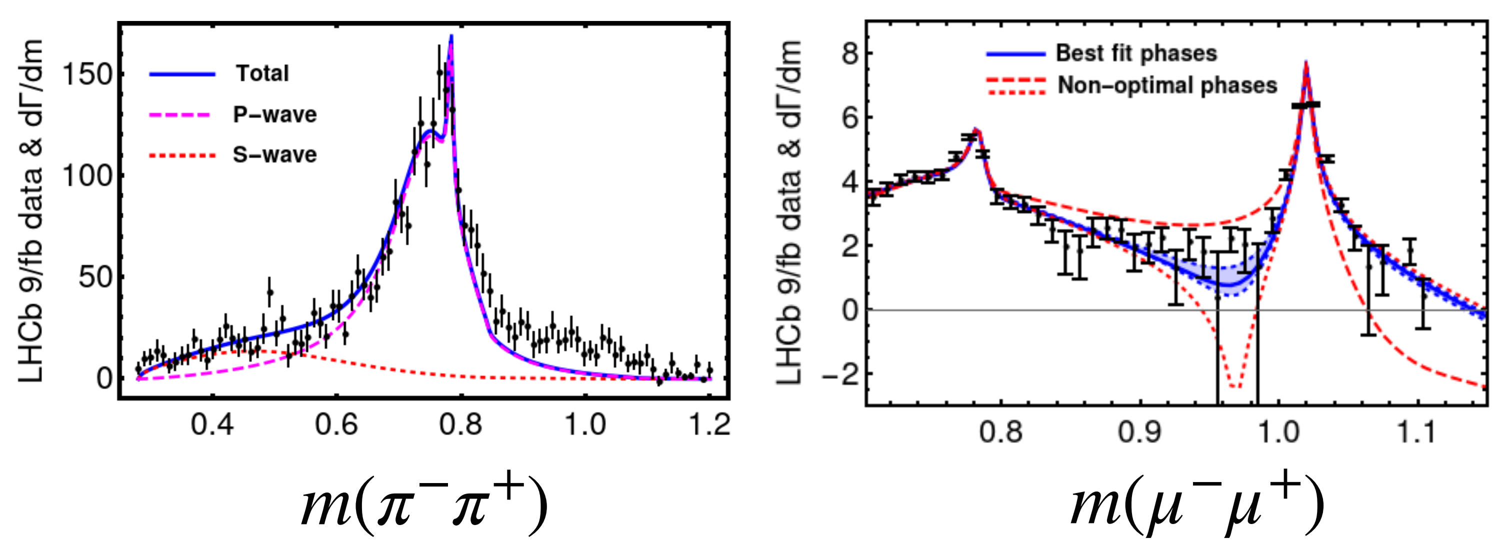
What can we do? (as experimentalists)

- **Hybrid** *approaches:* [Eur. Phys. J. C 77 (2017) 161]
  amplitude analysis for the extraction of observables (complementary to binned approach).
  Is this effort appreciated?

- **Communication**:
  should we share more information? what can be helpful?
  eg. invariant-mass spectra

S. Fajfer, L. Silva, E. Solomonidi @Charm2023

really appreciated
feedback about the effects of a
S-wave component in $D^0 \to \pi^+\pi^-\mu^+\mu^-$



beauty charm

Inputs from theory

- Need for theory **predictions** in beauty:
  - model dependent approaches requires solid inputs regarding QCD effects
  - $b \to d$ transitions not advanced such as $b \to s$
  - not accurate description of excited K^0 and Λ resonances

Global analyses of rare b→d and b→s decays - A. Smolkovic @IW2023

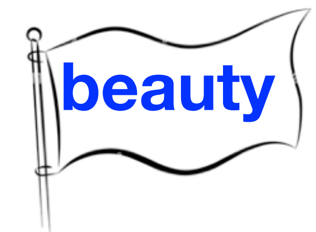
Theory of rare charm decays - L. Silva @IW2023

- **Guidance**: how can we improve theoretical interpretation?
  - theoretically clean observables (angular and A_{CP})
  - multi-lepton final states, so far only $B_{(s)}^0 \to 4\mu$
  - radiative decays
  - $b \to d$ transitions

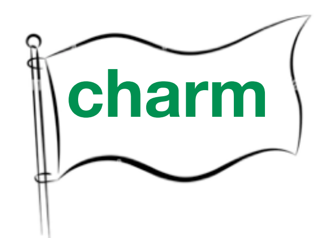
An unbinned amplitude analysis of B→πμμ decays - A. Marshall @IW2023

Conclusions

- Presented recent results for rare *charm* and *beauty* decays



- In **beauty** decays:
  - measurement limited by *external* inputs (still experimental)
  - theoretical effort is necessary to *converge* on the understanding of Λ resonances such as in $\boldsymbol{\Lambda_b \to \Lambda(1520)\mu^+\mu^-}$
  - better understanding of *pK* mass spectrum thanks to $\boldsymbol{\Lambda_b \to pK\gamma}$
  - complementary observables and update of existing measurements on their way



- In **charm** decays:
  - most stringent limits in $\boldsymbol{D^0 \to \mu^+\mu^-}$ and $\boldsymbol{D^{*0} \to \mu^+\mu^-}$
  - measurements *statistically* limited
  - theoretical predictions are hard, looking for *clean* observables

    (started measuring *CP* and angular observables, more input welcome!)

Thanks!