Experimental Vision

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Mainz Institute for Theoretical Physics

Future Challenges in Non-Leptonic B Decays: Theory and Experiment

Guidelines

(thanks Javier & Keri)

1. What are the physics motivations for experimentalists at LHCb (and Belle 2) to spend their valuable time on experimental studies of non-leptonic B decays?

2. What do you hope to achieve? And how does this relate to the objectives of the theorists?

3. Very important point: What do you expect will be the "legacy" of LHCb (and Belle 2) concerning non-leptonic B decay studies? (for example we all know what the legacy of the B factories was in this context, so this might be a reference point, but of course we should look forward and not back).

4. Given the motivation, the objectives and the expected future impact (the "legacy") of the experiments:

    4.1. What is the status and the progress? (broadly speaking, of course)

    4.2. What are the main obstacles and difficulties that we face?

    4.3. Any exciting turnouts? New and smart ideas? (we know LHCb is full of brilliant fellows so this section might be very long).

5. Requests and questions to theorists. How can we improve the process by collaborating?

What are the physics motivations for experimentalists at LHCb (and Belle 2) to spend their valuable time on experimental studies of non-leptonic B decays?

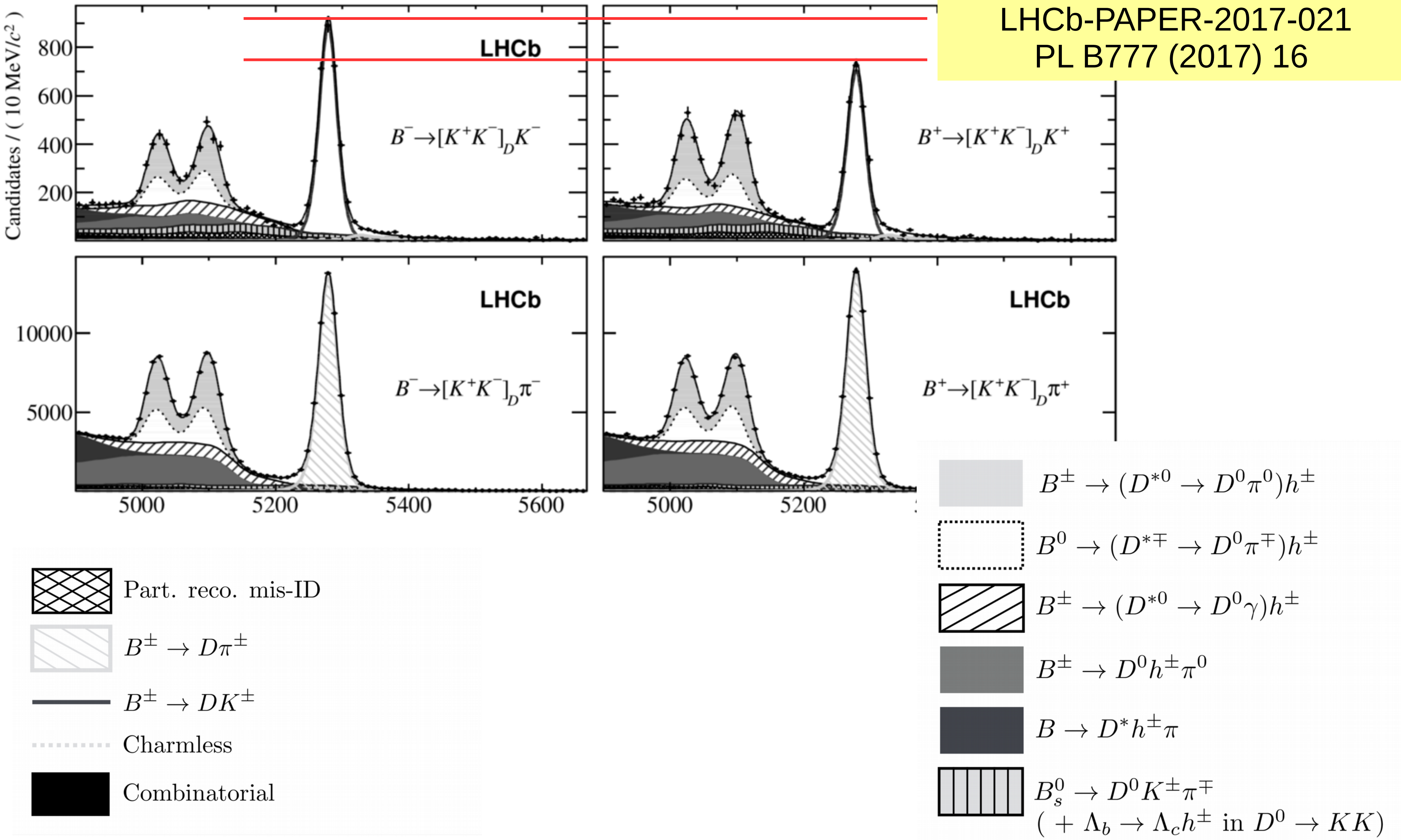
Motivation (I)

Non-leptonic B decays provide:

- multiple ways of studying CP violation
  - trees vs. loops
  - SM benchmarks vs. NP sensitive
  - CPV in mixing/decay/mixing-decay interference

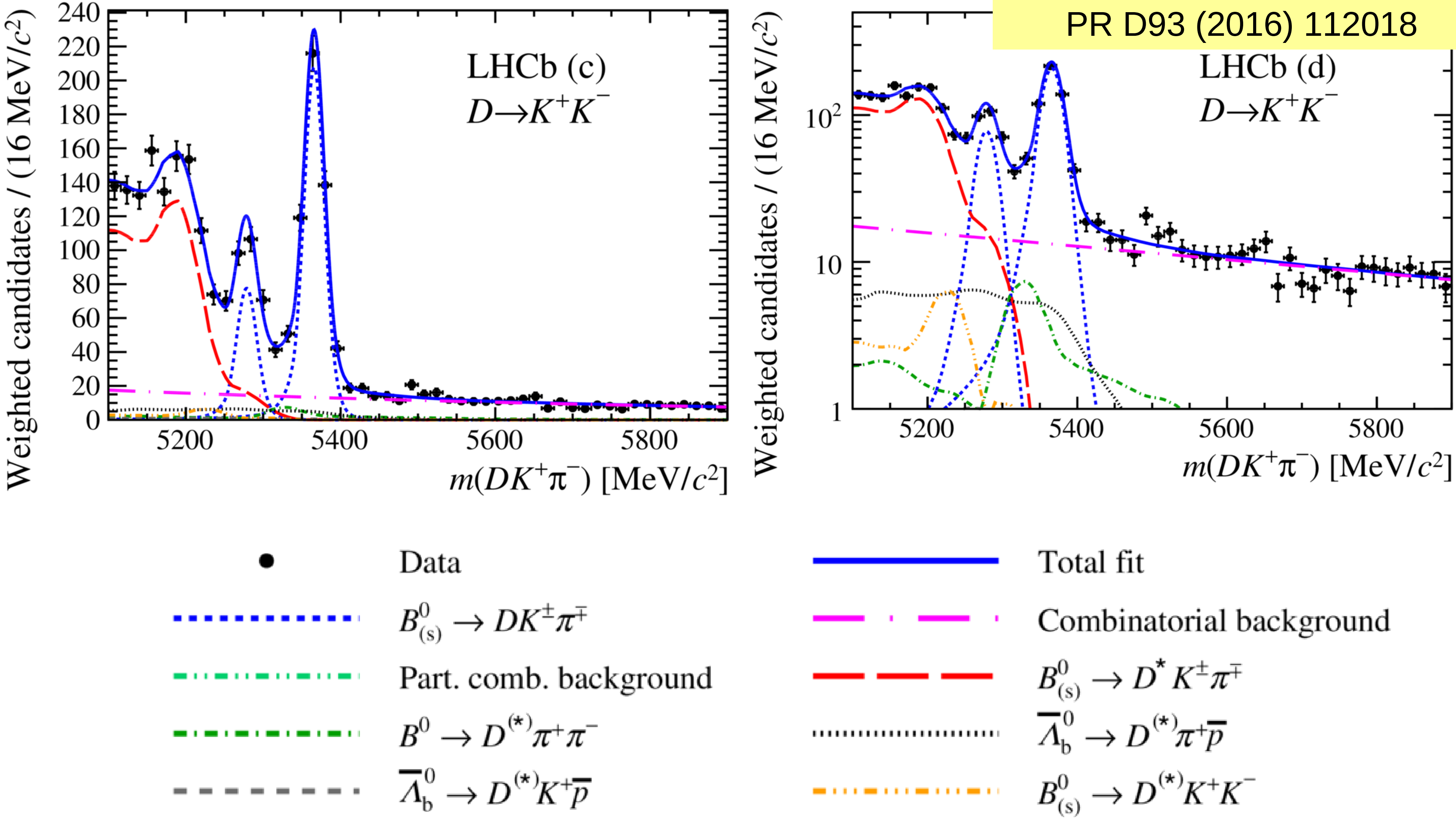
Measurement of CP observables in $B^{\pm} \to D^{(*)}K^{\pm}$ and $B^{\pm} \to D^{(*)}\pi^{\pm}$ decays

LHCb-PAPER-2017-021
PL B777 (2017) 16

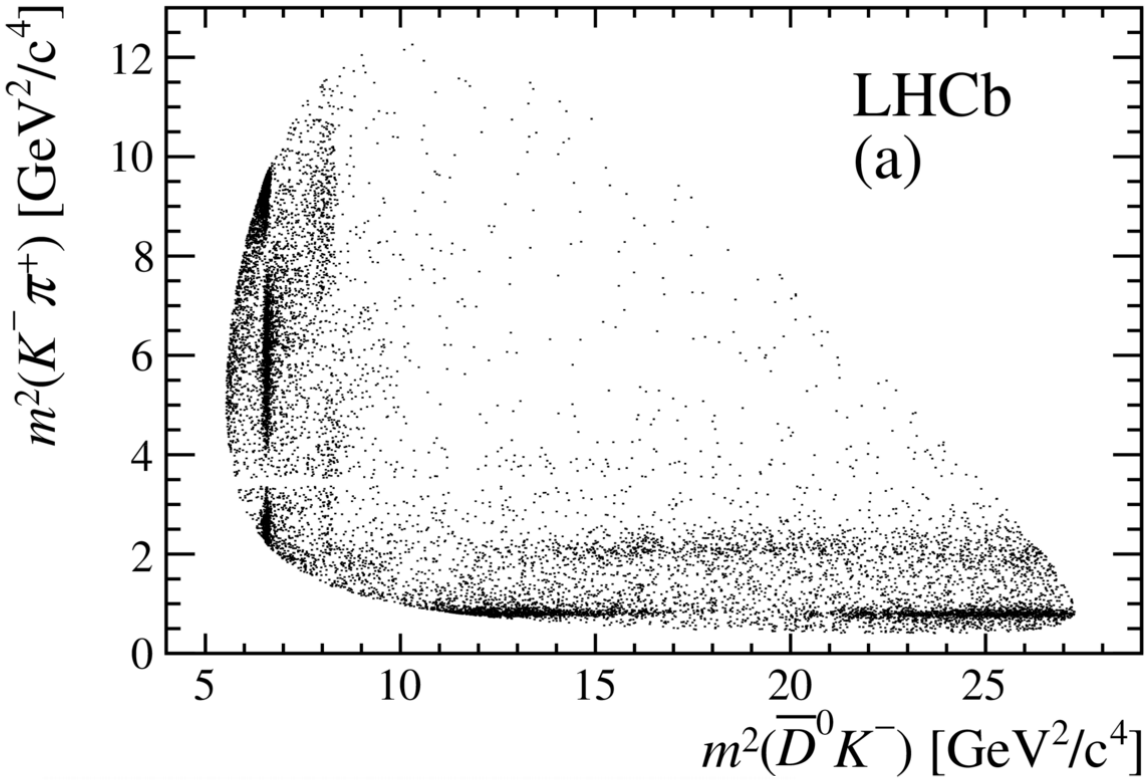


Constraints on the unitarity triangle angle γ from Dalitz plot analysis of $B^0 \to DK^+\pi^-$ decays

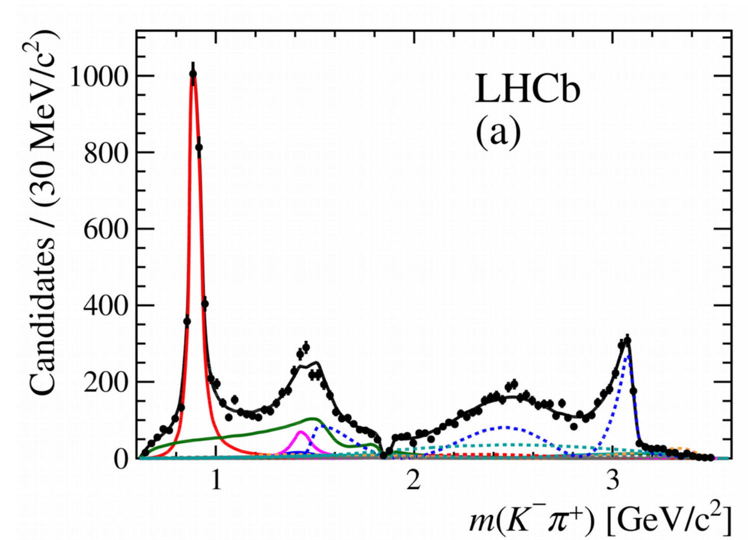
LHCb-PAPER-2015-059
PR D93 (2016) 112018

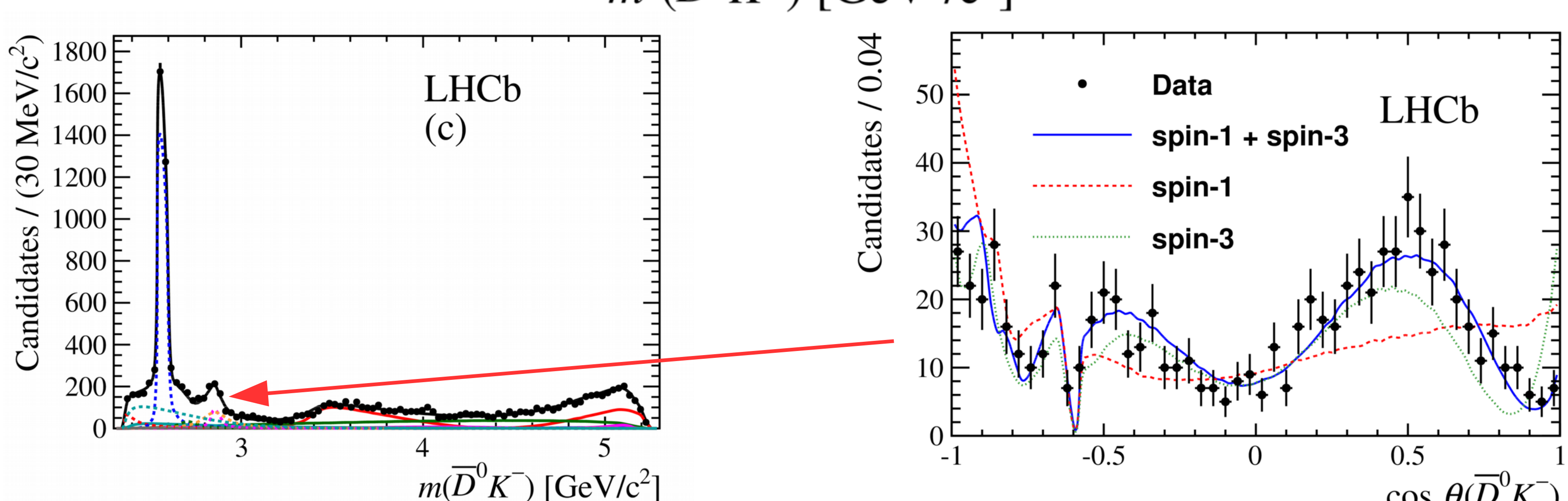


Dalitz plot analysis of $B^0_s \to \overline{D}^0 K^- \pi^+$ decays



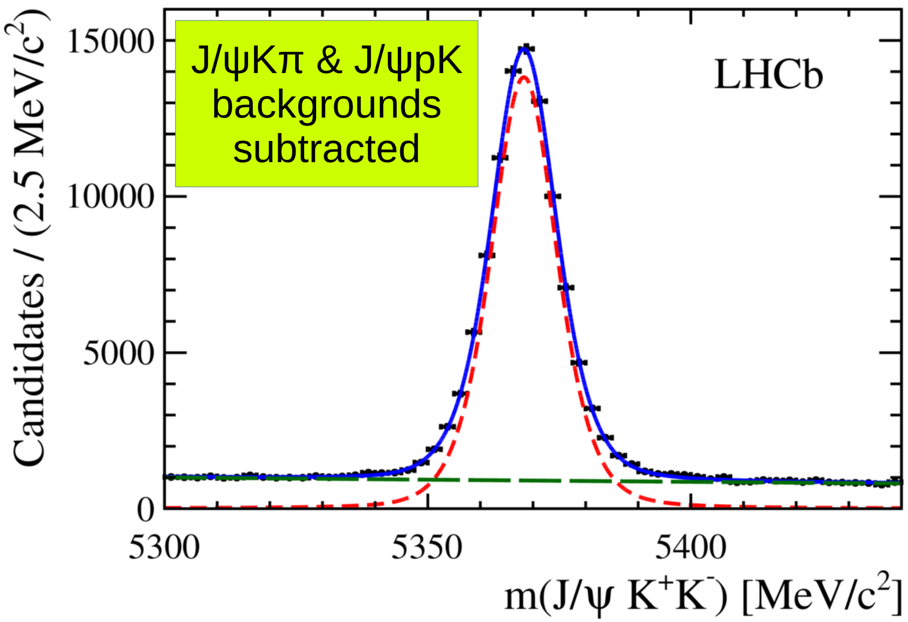
LHCb-PAPER-2014-036
PR D93 (2016) 112018

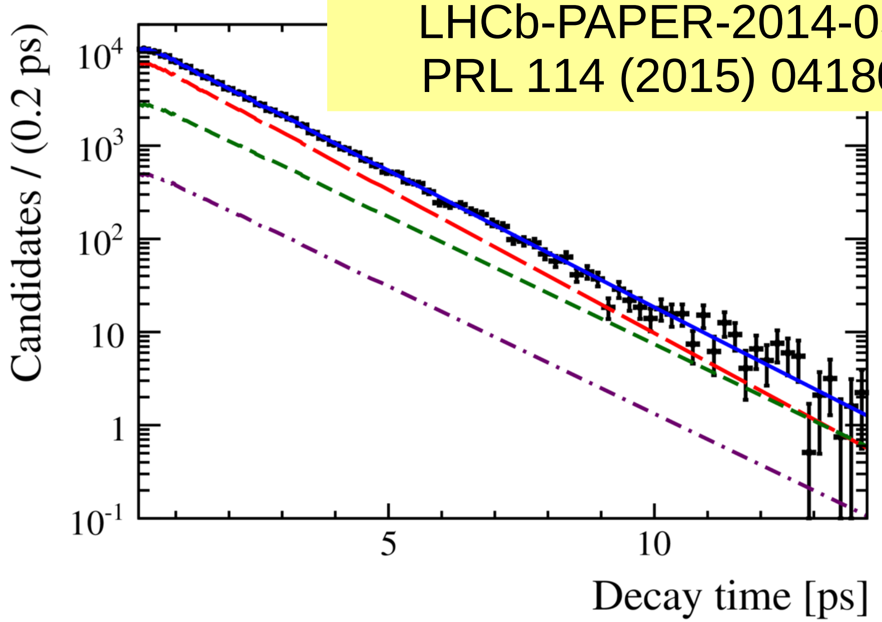


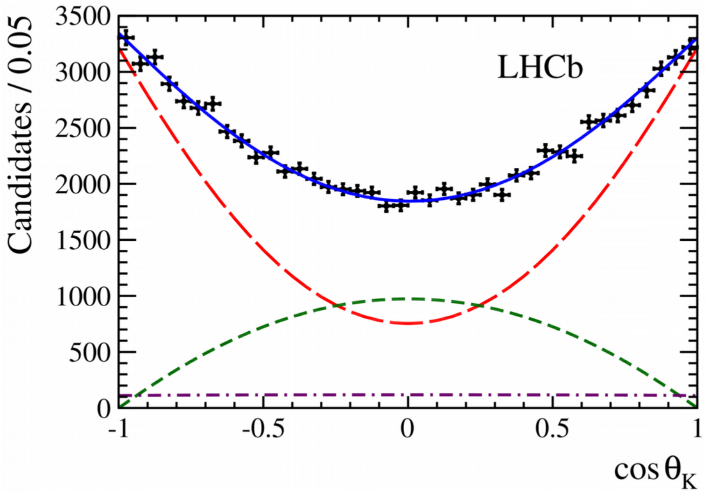


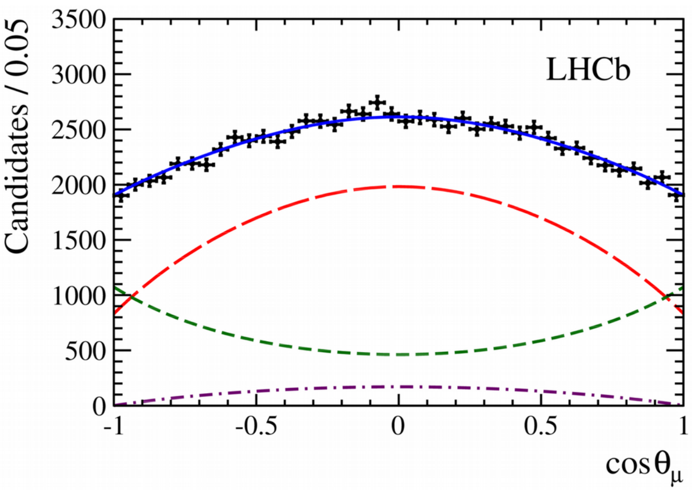
Precision measurement of CP violation in $B^0_s \to J/\psi K^+K^-$ decays

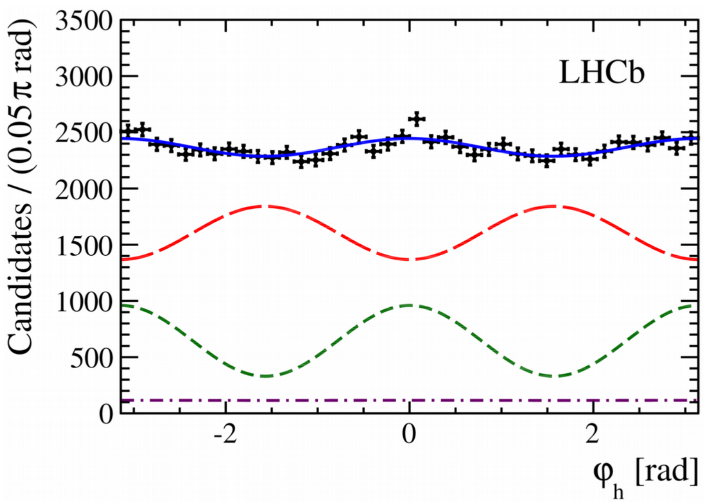
LHCb-PAPER-2014-059
PRL 114 (2015) 041801





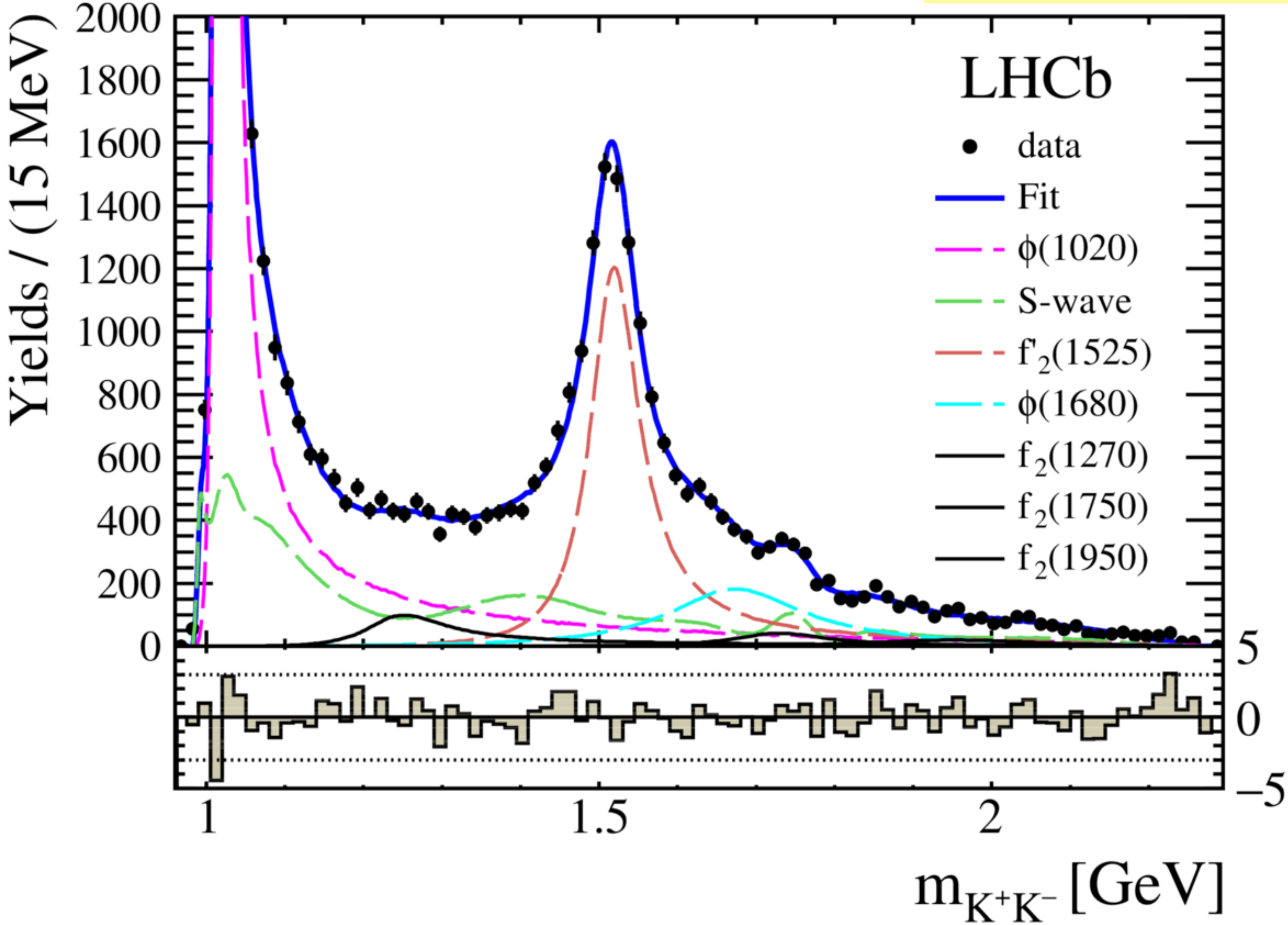






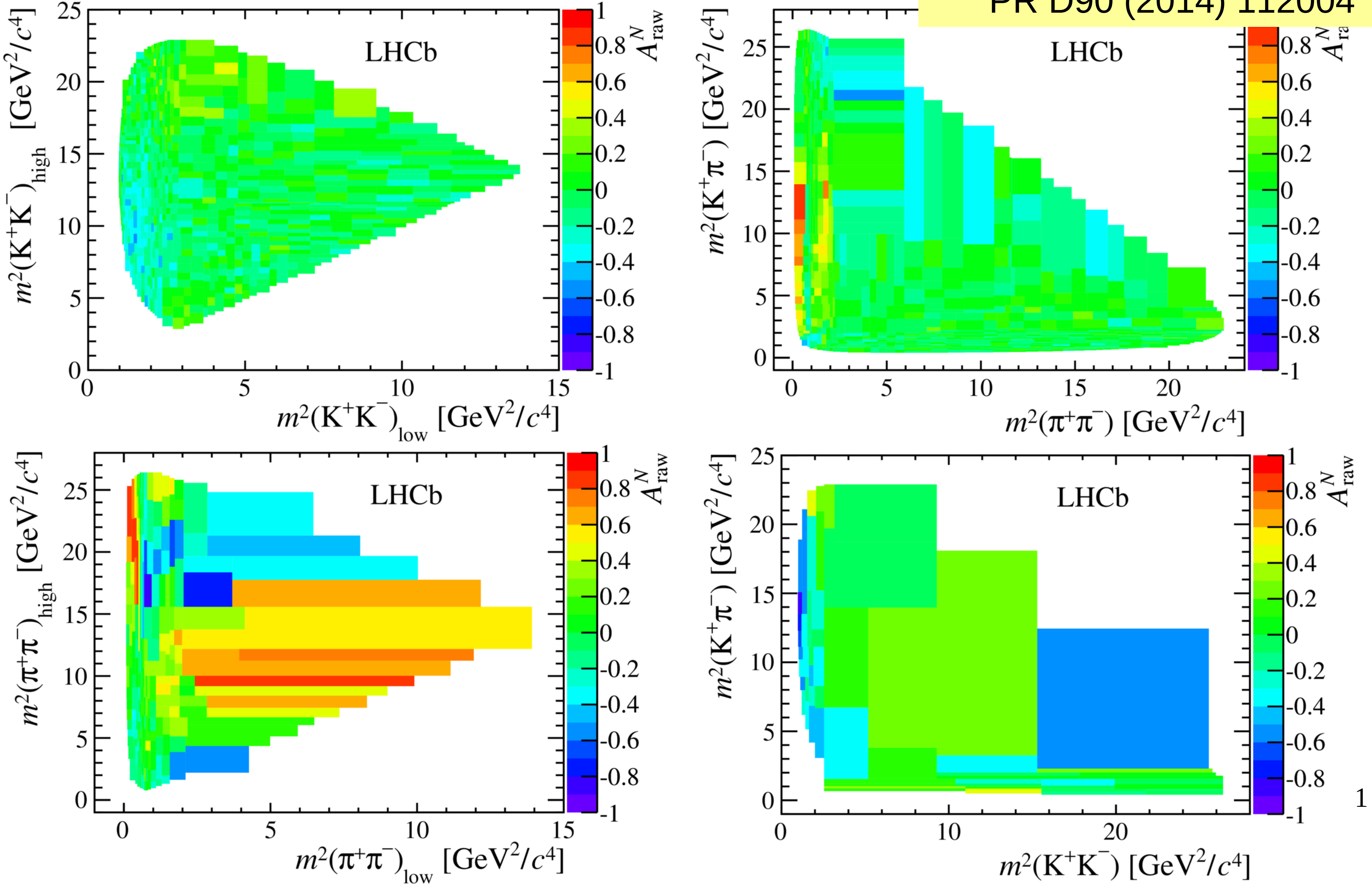
Resonances and CP violation in B^0_s and $\overline{B}^0_s \to J/\psi K^+K^-$ decays in the mass region above the $\phi(1020)$

LHCb-PAPER-2017-008
JHEP 08 (2017) 037



Measurements of CP violation in the three-body phase space of charmless $B^{\pm}$ decays

LHCb-PAPER-2014-044
PR D90 (2014) 112004



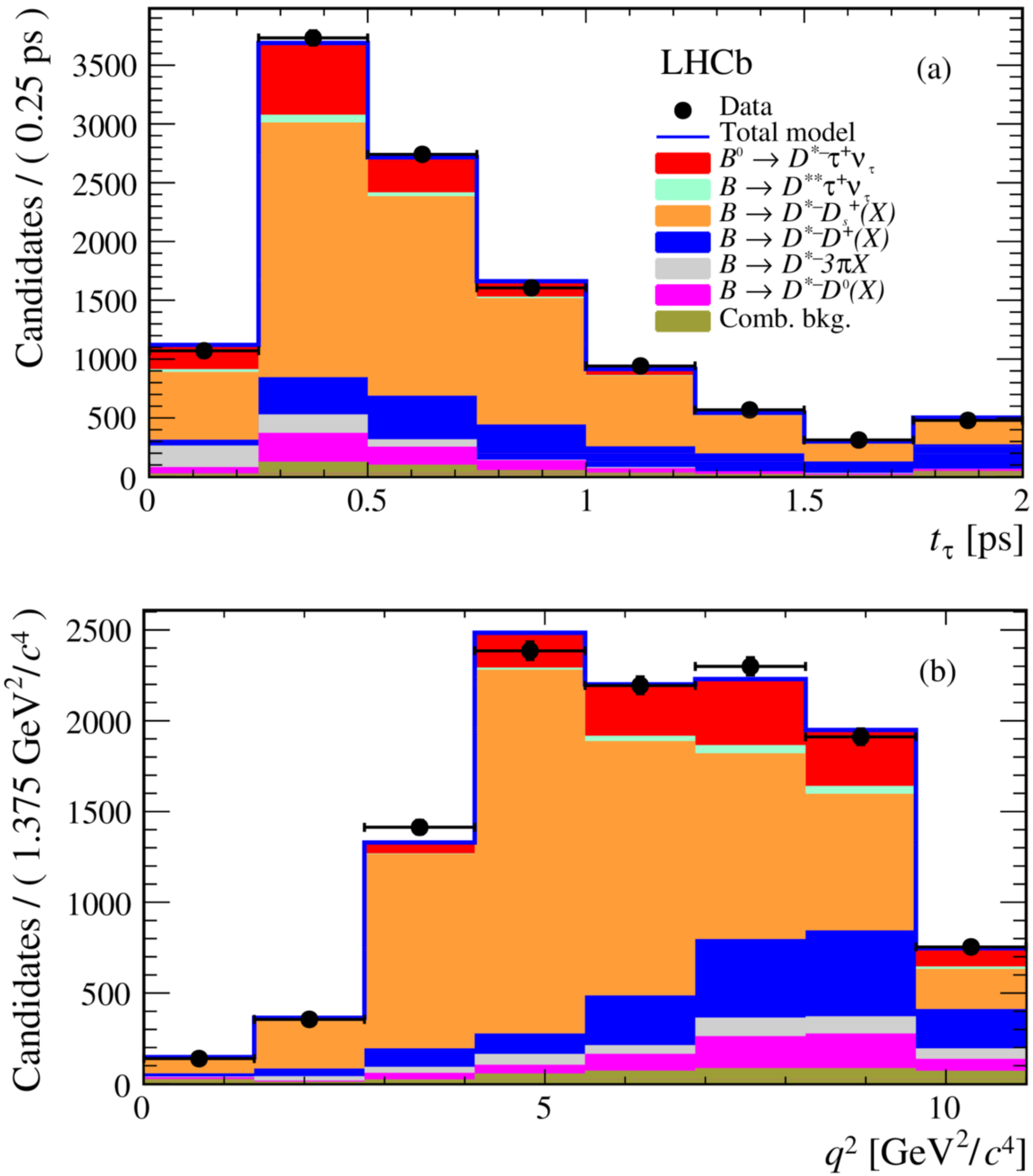
Motivation (II)

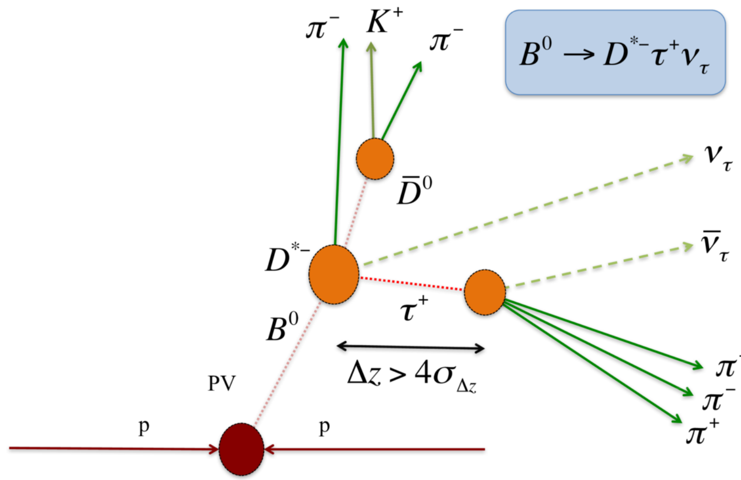
Non-leptonic B decays provide:

- only way of understanding phenomenology of B hadrons
  - account for ~2/3 of decays
  - constitute backgrounds to essentially all channels of interest

Measurement of the $B^0 \to D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays

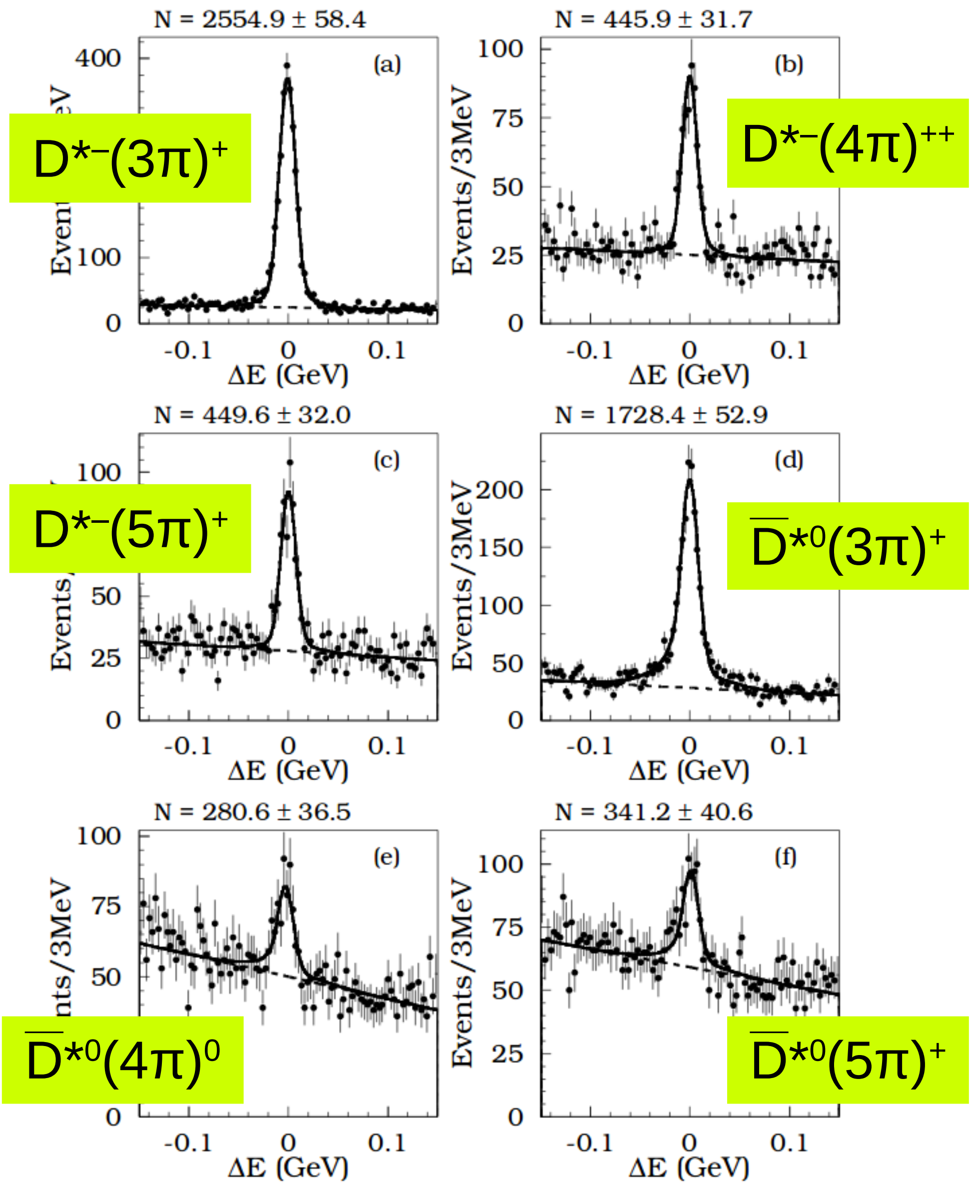
LHCb-PAPER-2017-027
PR D97 (2018) 072013

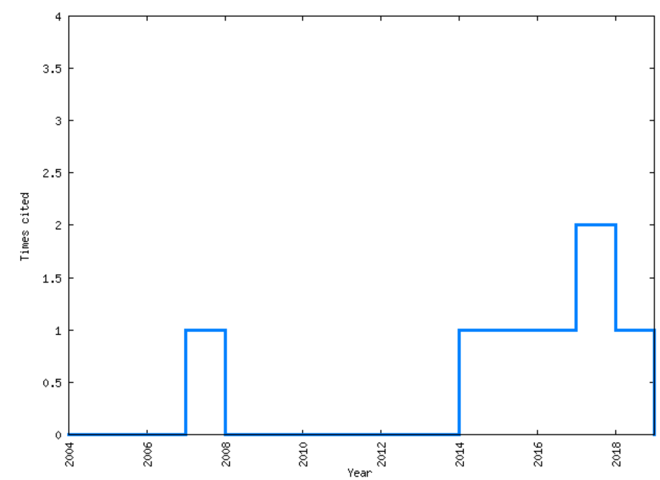




Observation of $B^0 \to D^{*-}(5\pi)^+$, $B^+ \to D^{*-}(4\pi)^{++}$ and $B^+ \to \overline{D}^{*0}(5\pi)^+$

BELLE-PREPRINT-2004-25
PR D70 (2004) 111103





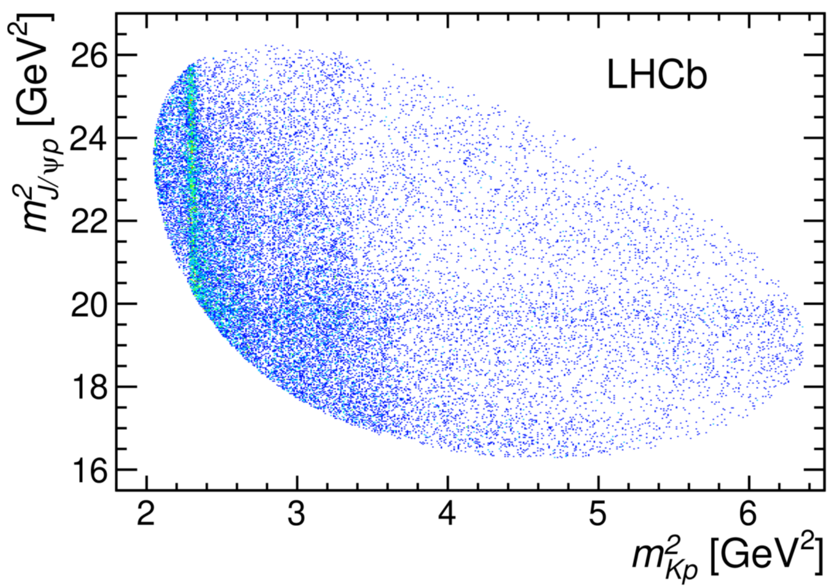
Motivation (III)

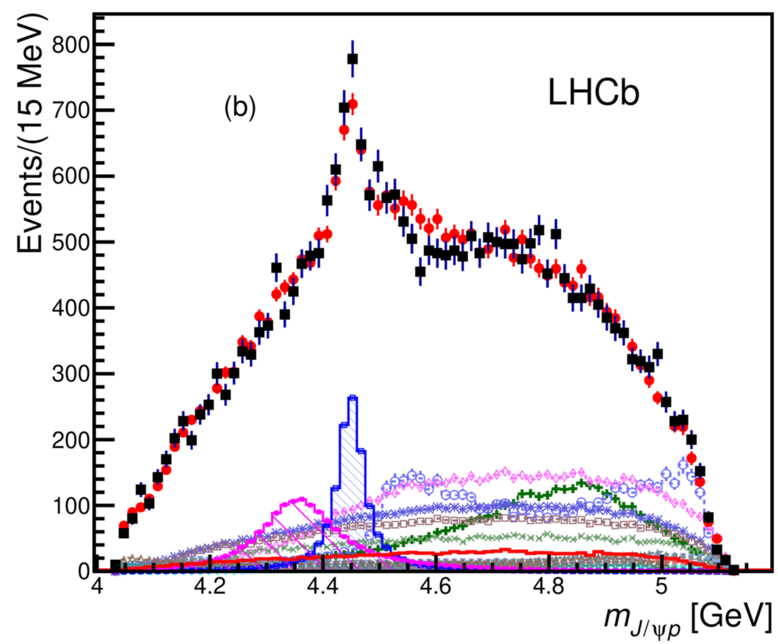
Non-leptonic B decays provide:

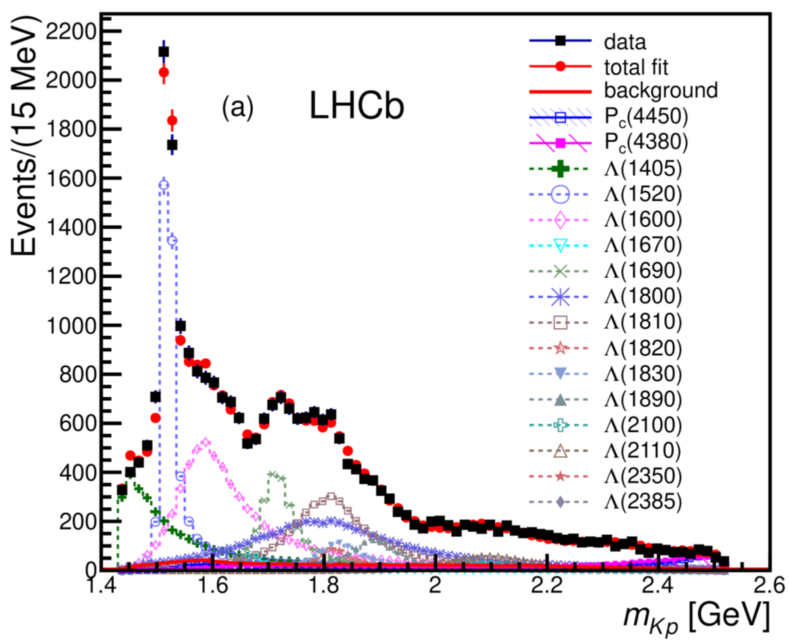
- unique possibilities to understand QCD
  - test models that can be used to predict branching fractions, CP asymmetries, polarisations, etc.
  - study resonant and nonresonant structures in multibody decays
  - measurements of the properties of hadrons, including new discoveries (QCD exotics & conventional states)
  - provide input for studies of (semi-)leptonic B decays
    - e.g. discussions on $K\pi$ S-wave and charm loop effects in $B \to K\pi\mu\mu$

Observation of J/ψp resonances consistent with pentaquark states in $\Lambda^0_b \rightarrow J/\psi K^- p$ decays

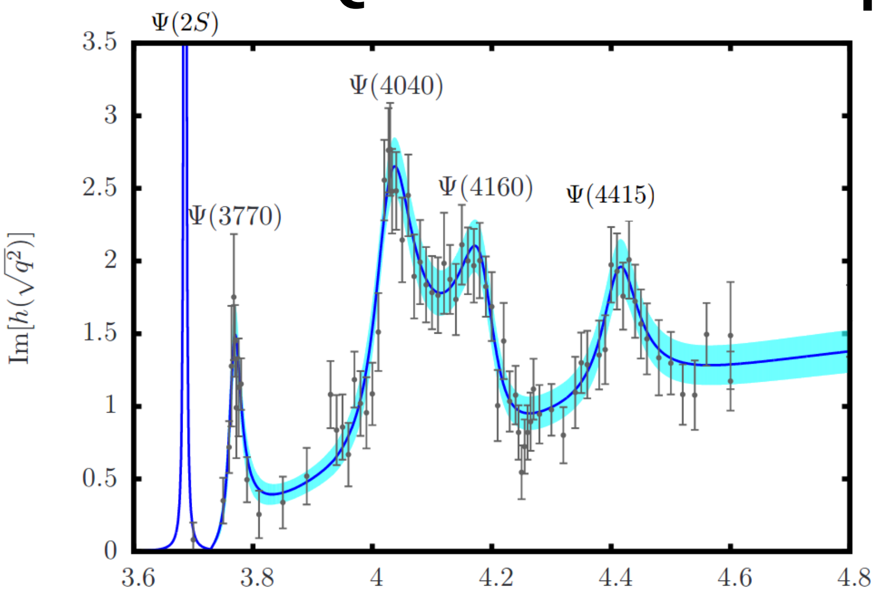
LHCb-PAPER-2015-029
PRL 115 (2015) 072001

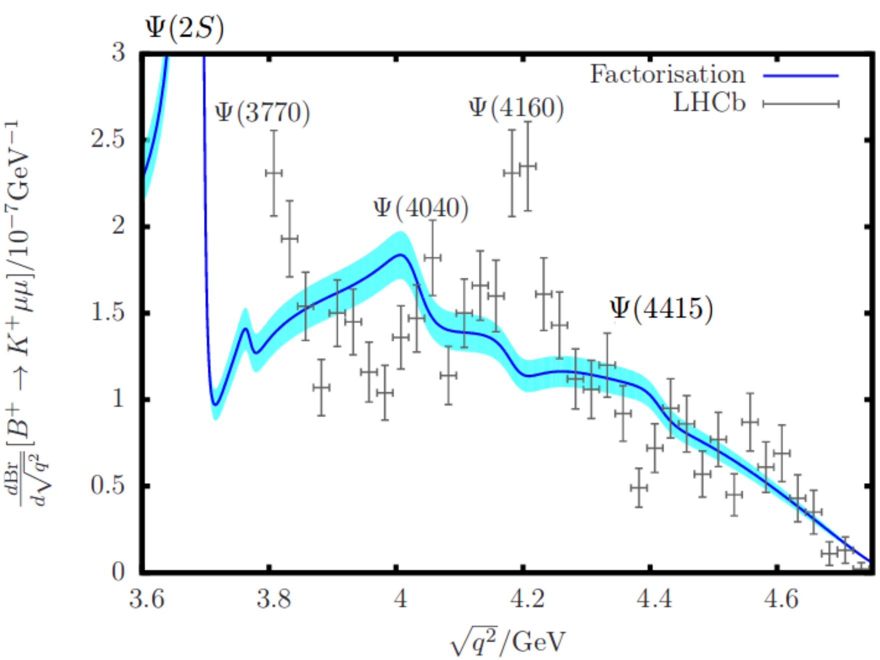






Resonances gone topsy turvy - the charm of QCD or new physics in $b \to s\ell^+\ell^-$?

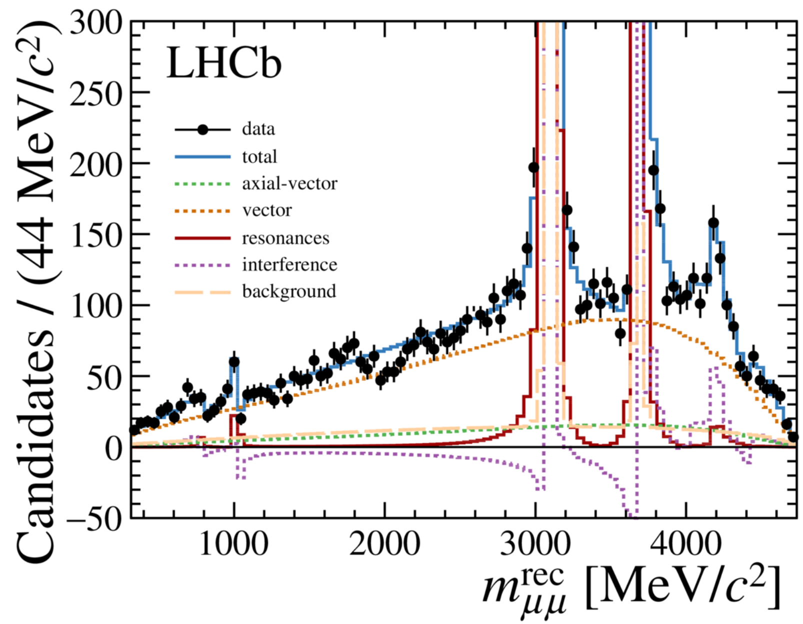




Zwicky & Lyon
arXiv:1406.0566

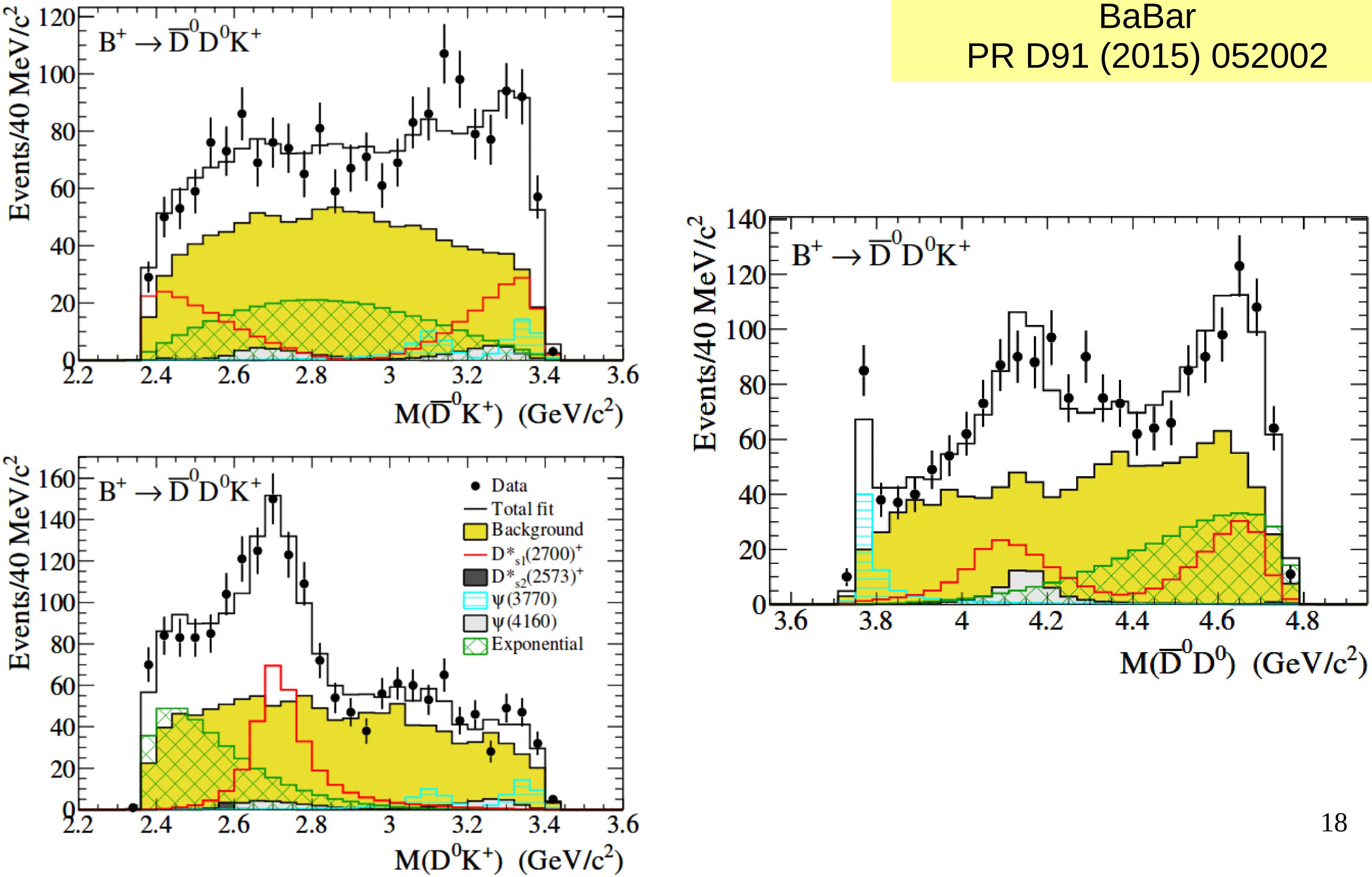
BESIII data from
PL B660 (2008) 315

LHCb-PAPER-2016-045
EPJ C77 (2017) 161



Dalitz plot analyses of $B^0 \to D^- D^0 K^+$ and $B^+ \to \overline{D}^0 D^0 K^+$ decays

BaBar
PR D91 (2015) 052002



Experimentalists' valuable time

- All "B physics experiments" have broad physics programmes
  - BaBar/Belle/BelleII, LHCb, CDF/D0/ATLAS/CMS
- In BaBar, non-leptonic B decays covered in 6 out of 12 top level working groups (*)
  - producing ~270 out of ~580 publications
- In LHCb, corresponding number is 4 out of 9 WGs
  - and ~270 out of ~460 publications
    - includes "b hadrons and quarkonia" WG (production as well as decays)
    - there are more b hadron species to study compared to BaBar/Belle
    - charmless hadronic B decays: BaBar 127 & LHCb 56 papers

- (*) Have counted photons as leptons, i.e. not including $b \to s\gamma$, etc.

Experimentalists’ valuable time

- How do experimentalists choose which topics to work on?
  - Personal interests
  - Encouragement from theorists
  - Follow the money (funding) – hot topics
  - Desire for career progression – citation hunting

What do you hope to achieve? And how does this relate to the objectives of the theorists?

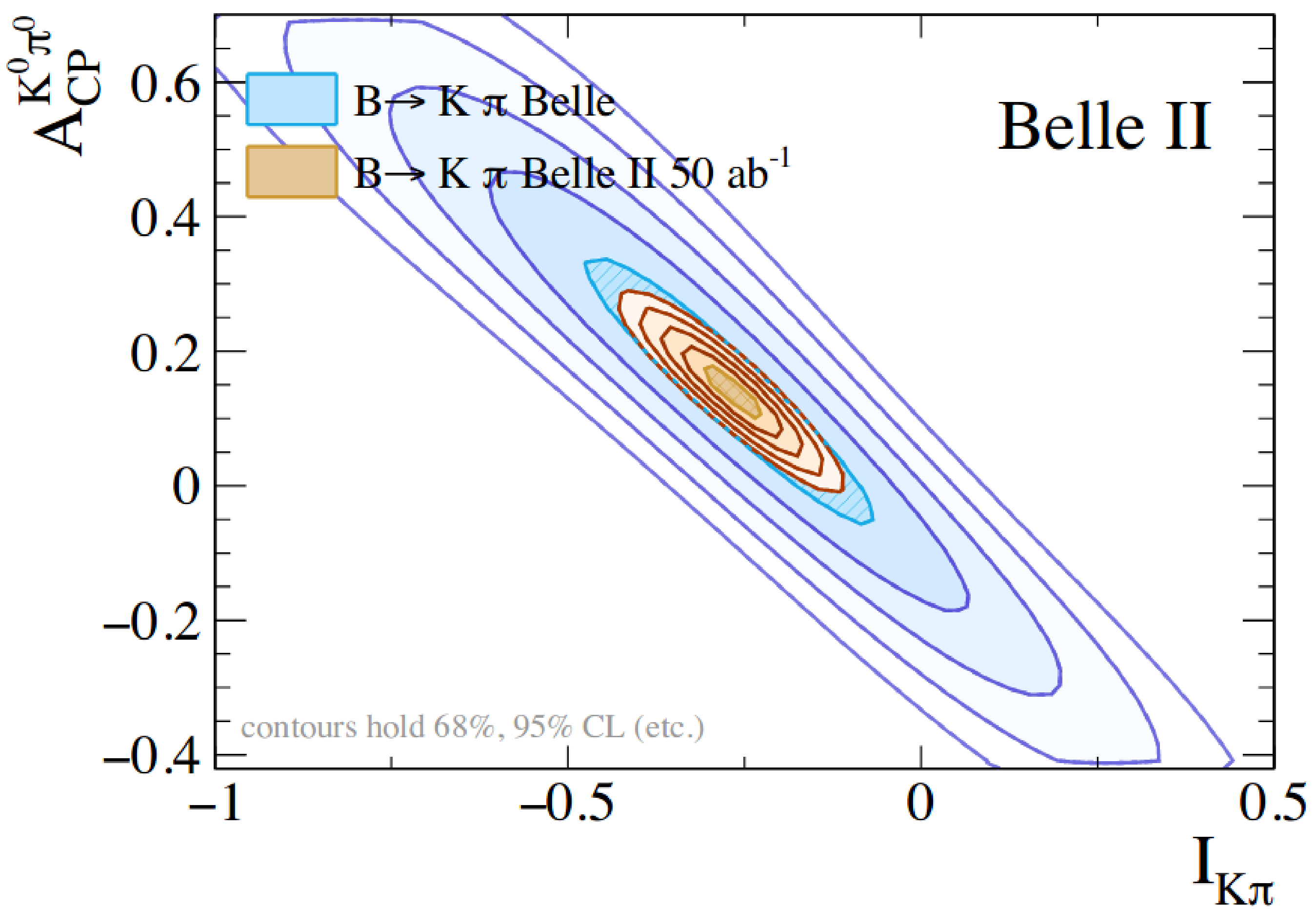
Two-body decays

- Hope that we can measure all experimentally accessible two-body (PP) decays
  - Mostly done for $B_{(s)} \rightarrow h^+h'^-$ ($h = \pi, K, D, D_s$)
    - Rare B_s modes ($D\pi$, DK) not yet searched for
  - More challenging with light neutral particles
    - Especially π^0,η,η' ← opportunities for Belle II
    - But also K_S

Isospin asymmetry sum rule

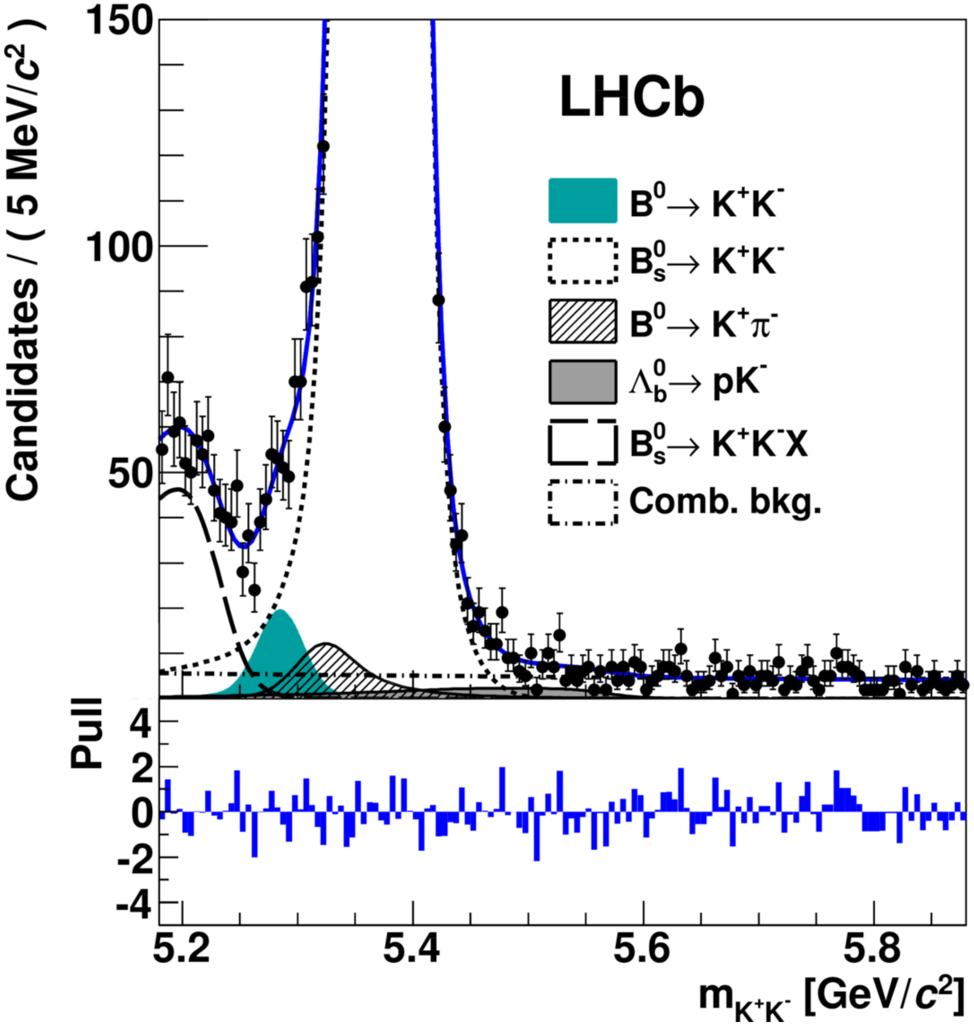
Belle II Physics Book
arXiv:1808.10567

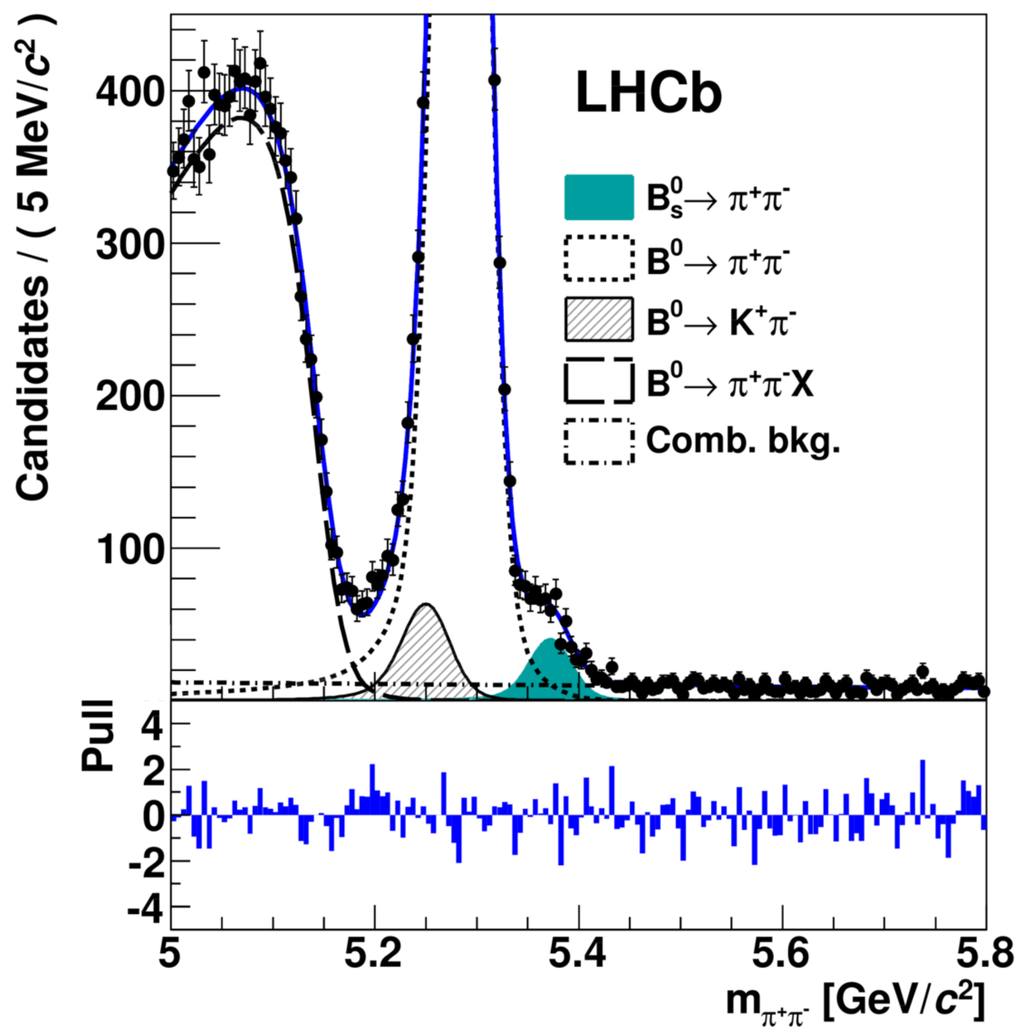
$$I_{K\pi} = A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



Observation of the annihilation decay mode $B^0 \to K^+K^-$

LHCb-PAPER-2016-036
PRL 118 (2017) 081801

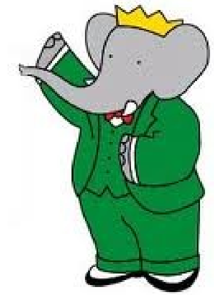




Three- & more-body decays

- Huge progress at LHCb in
  - $B \to Dhh$ ($h = \pi, K$), work in progress on D^*hh
  - $B \to J/\psi hh$, some progress also for $\eta_c hh$ and $\chi_{c1} hh$
  - $B \to VV$, where both $V \to h^+h^-$
- Work in progress on
  - $B \to hhh$
  - $B \to K_s hh$ (but no decay-time-dependent CPV yet)
- Still many more interesting modes to cover
  - $B \to DDh$ (also interesting with one or two D^*s)
  - … modes with π^0s
    - needed to complete sum rule relations also for PV, VP & VV modes

B factory
Dalitz plot analyses



$K^+K^+K^-$	PR D85 (2012) 112010	PR D71 (2005) 092003
$K^+K^+K_S$	PR D85 (2012) 112010	PR D82 (2010) 073011
$K^+K_SK_S$	PR D85 (2012) 112010	No amplitude analysis
$K_SK_SK_S$	PR D85 (2012) 054023	No amplitude analysis
$K^+\pi^+\pi^-$	PR D78 (2008) 012004	PRL 96 (2006) 251803
$K_S\pi^+\pi^-$	PR D80 (2009) 112001	PR D79 (2009) 072004
$K^+\pi^-\pi^0$	PR D83 (2011) 112010	No amplitude analysis
$K_S\pi^+\pi^0$	PR D96 (2017) 072001	No amplitude analysis
$\pi^+\pi^+\pi^-$	PR D79 (2009) 072006	No amplitude analysis
$\pi^+\pi^+\pi^0$	PR D88 (2013) 012003	PR D77 (2008) 072001

All modes with 0, 1 or 3 kaons ($K^\pm$ or K_S) & 0 or 1 π^0

What do you expect will be the "legacy" of LHCb (and Belle 2) concerning non-leptonic B decay studies?

LHCb & upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\ K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Will not reach limiting theory uncertainty!

Given the motivation, the objectives and the expected future impact of the experiments:

- What is the status and the progress?
- What are the main obstacles and difficulties that we face?
- Any exciting turnouts? New and smart ideas?

Requests and questions to theorists.
How can we improve the process by collaborating?