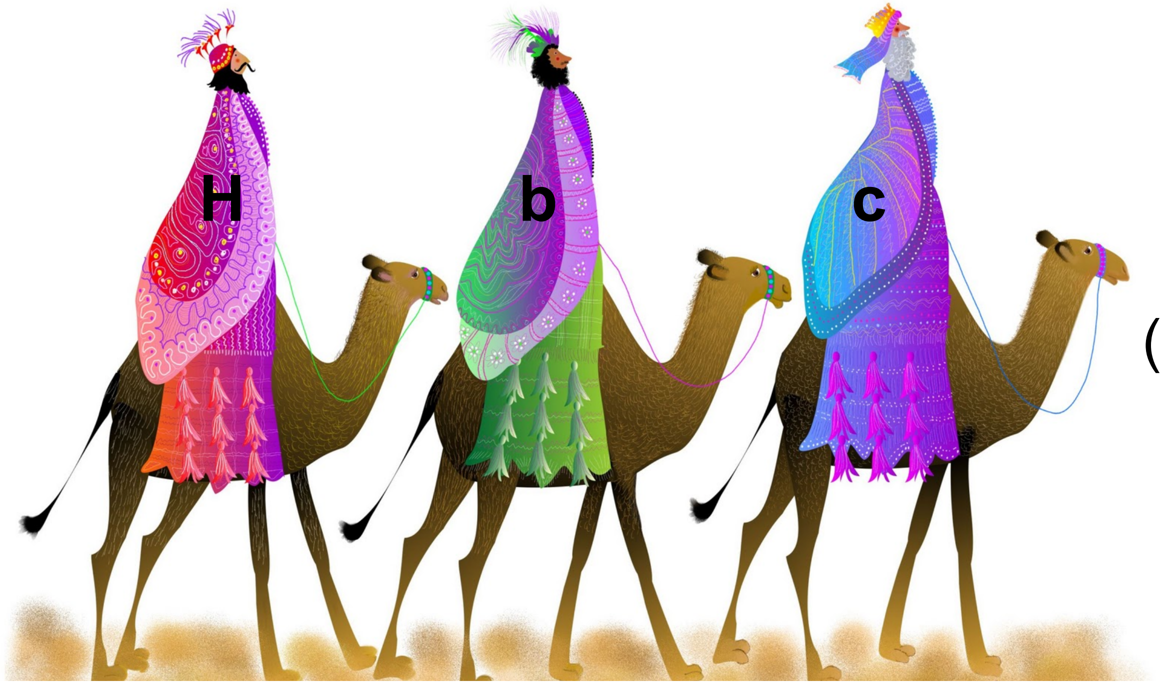
Highlights of LHCb measurement in rare decays and discovery of first pentaquark states with Run1 data



Cracow Epiphany Conference
8 January 2015

Artur Ukleja
(National Centre for Nuclear Research)
on behalf of the LHCb Collaboration

Outline

- **Introduction**
  - ✧ Why are we interested in flavour physics?

- **The selected measurements in the LHCb**
  - ✧ Exotic spectroscopy of X(3872), Z(4430) and pentaquark states $P_c(4380)$, $P_c(4450)$
  - ✧ Very rare and rare decays:
    $B^0 \to \mu^+\mu^-$, $B^0 \to K^{*0} \mu^+\mu^-$, $B^+ \to K^+ \mu^+\mu^-$, $B^0_s \to \phi \mu^+\mu^-$, $\Lambda_b \to \Lambda \mu^+\mu^-$
  - ✧ Probes of lepton universality – ratios of branching fractions:
    $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$, $B^0 \to D^{(*)}\tau\nu / B^0 \to D^{(*)}\mu\nu$

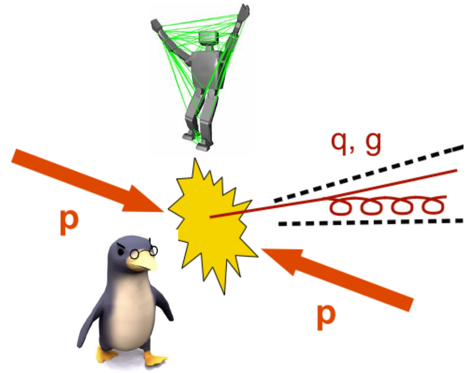
- **Summary**

Why are we interested in flavour physics?

- The Standard Model (SM) is a theory which describes well existed data, but there are many phenomena which are not understood:
    - known value of CPV in the SM is too small to explain the observed size of matter domination over antimatter in the Universe

- The main goal of particle physics is to search for physics beyond the SM

There are two ways of searches for New Physics:



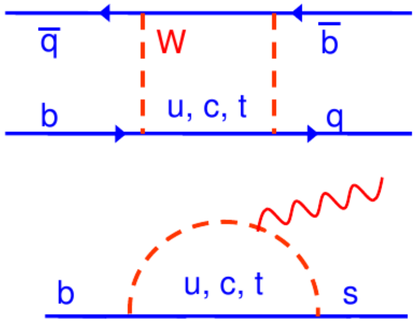
- direct searches for produced new objects (Atlas and CMS)

- indirect searches via testing the SM in precise measurements of known processes, finding disagreement will be indirect indication of new phenomena existence (BaBar, Belle, LHCb,…)

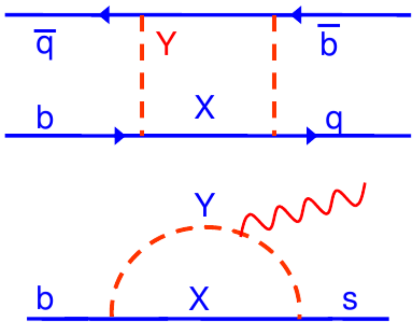
Why are we interested in flavour physics?

- The new particles can be exchanged in the loops

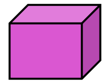
Standard Model



New Physics



box diagrams



penguin diagrams

In particular, we are interested in:

- CP symmetry violation in B and D sectors (see A. Obłąkowska-Mucha's talk)
  - ➢ so far, there is no observation of CPV in charm sector, the SM predictions are very small
- very rare decays of B (this talk)
  - ➢ predicted highly supressed in SM
- as well as test of QCD models (quarkonia spectroscopy is an area where these tests can be performed)

LHCb – precision detector

The single-arm forward spectrometer (a new concept for HEP experiments)

$\sigma(b\bar{b}) = 284 \pm 53\mu\text{b}$ [PLB 694 (2010) 209]

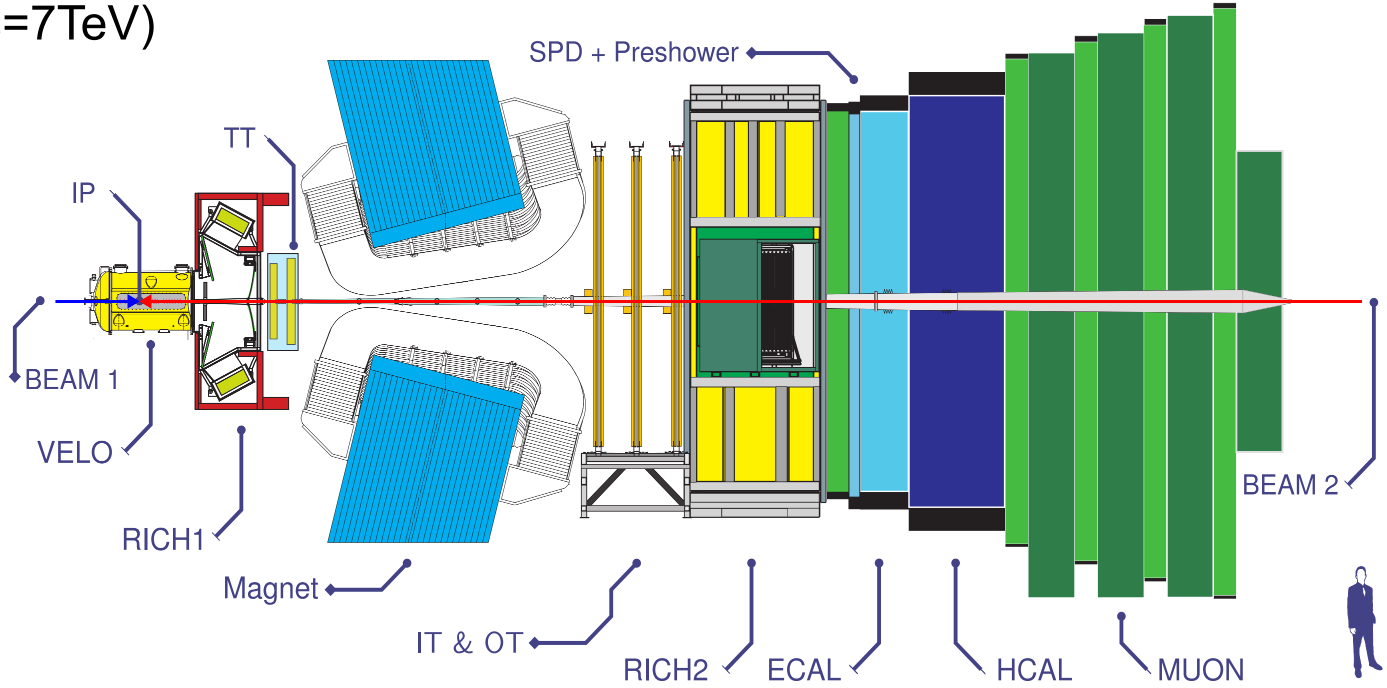
$10 < \theta < 300$ mrad ($2<\eta<5$)

$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$ [LHCb-CONF-2010-013]

(at $\sqrt{s}$=7TeV)

Run 1:
1/fb (2011), 2/fb (2012)

For each 1/fb:
~28k $B^0_s \to J/\psi(\mu\mu)\,\phi(K^+K^-)$
~2M $D^{*\pm} \to D^0(\to K^-K^+)\pi^\pm$



- VELO – precision primary and secondary vertex measurements,
  resolution of IP: 20 μm, decay lifetime resolution ~ 45 fs: 0.1 $\tau(D^0)$
- Excellent tracking resolution: $\Delta p/p = 0.4\%$ at 5 GeV to 0.6% at 100 GeV
- RICH – very good particle identification for π and K

Exotic spectroscopy at LHCb

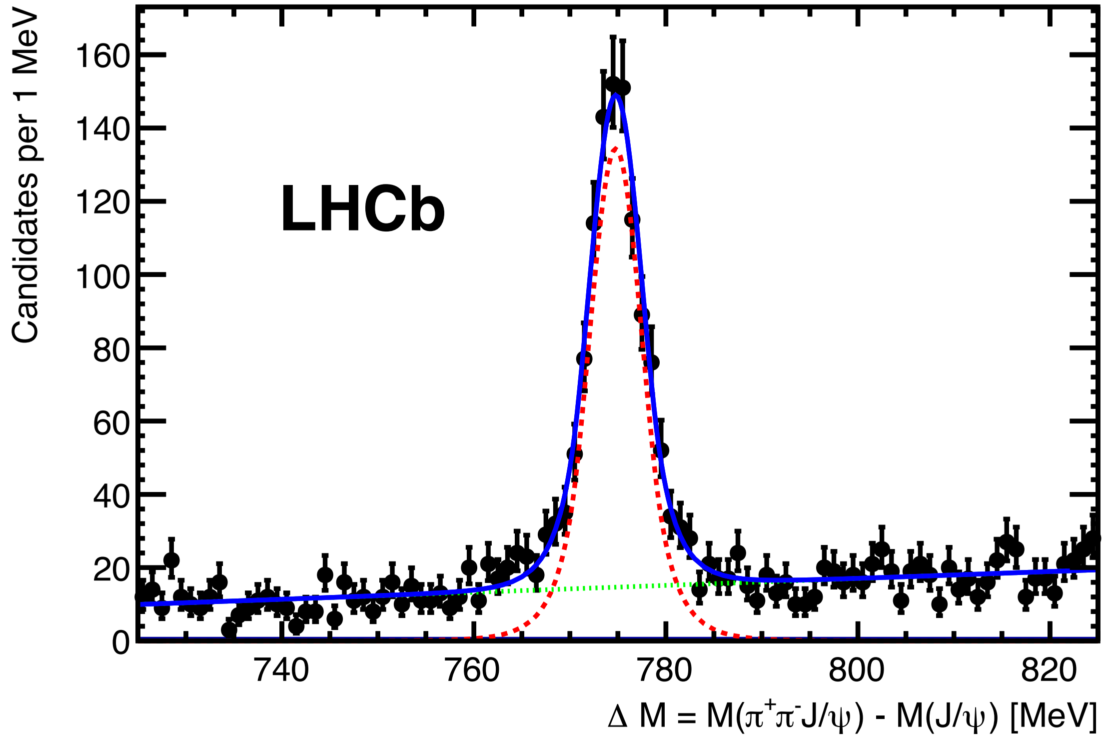
Heavy flavour spectroscopy is an important test of QCD models (masses, lifetimes, decay properties, quantum numbers, etc.)

Observation of the X(3872) resonance:

- First observed by Belle (2003)
  Phys.Rev.Lett.91(2003)262001
- It has now been seen by 6 experiments (Belle, BaBar, CDF, D0, LHCb, CMS) in B decays and prompt production
- LHCb determined quantum numbers $J^{PC} = 1^{++}$ via angular analysis of $B \to X(J/\psi\pi\pi)K$
  Phys.Rev.Lett.110(2013)222001
  Phys.Rev.D92(2015)011102(R))
- Nature is still unclear; compatible with tetraquark, molecule or $\chi_{c1}(2^3P_1)$ hypotheses (possibly mixed); it excludes any other charmonium state

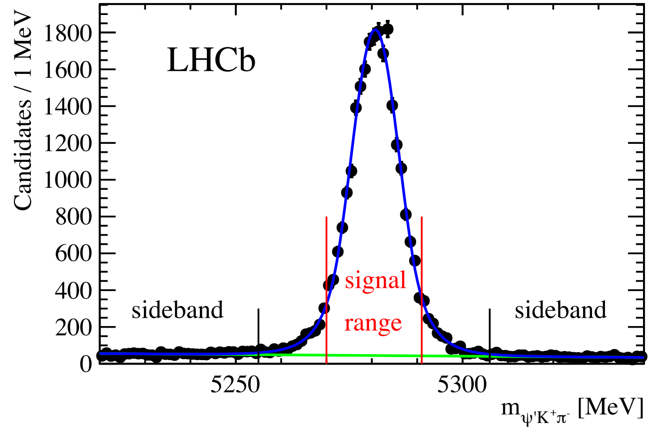
LHCb 3/fb; 1011±38 $B^+ \to XK^+$, $X \to \rho^0(\pi^+\pi^-)J/\psi$ decays

Phys.Rev.D92(2015)011102(R)

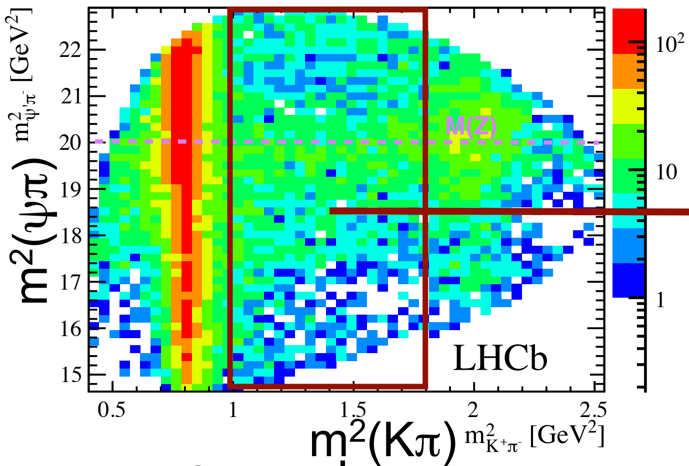


Exotic spectroscopy at LHCb

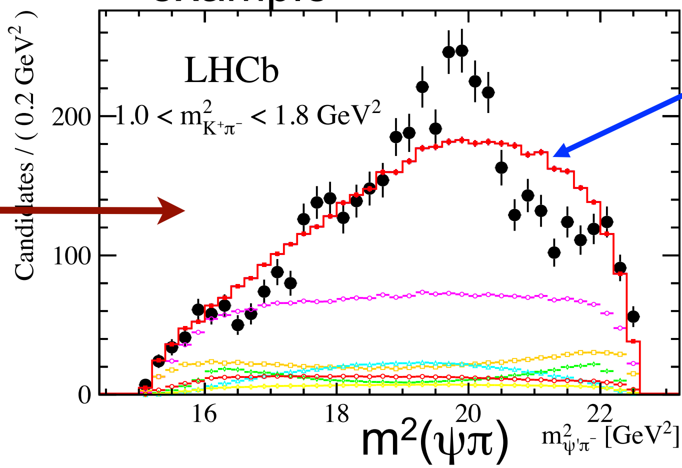
Observation of the Z(4430)$^{\pm}$:
- First seen by Belle (2008)
- Among all tetraquark candidates the Z(4430)$^{-}$ is special; being charged it cannot be a c anti-c state
- LHCb sees 125k B→ψ(2S)Kπ decays

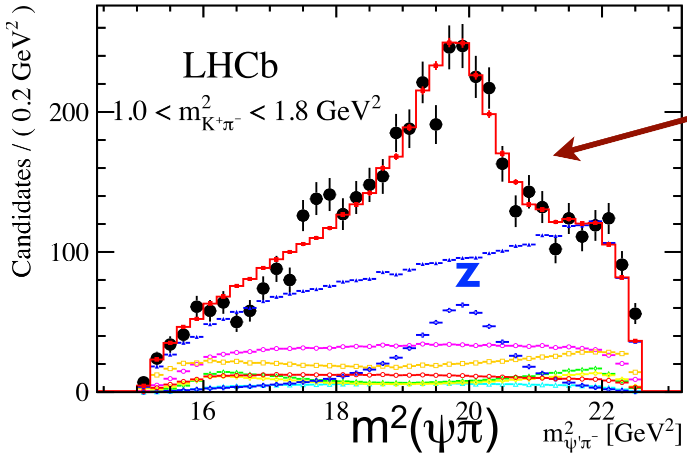


LHCb-PAPER-2014-014



example



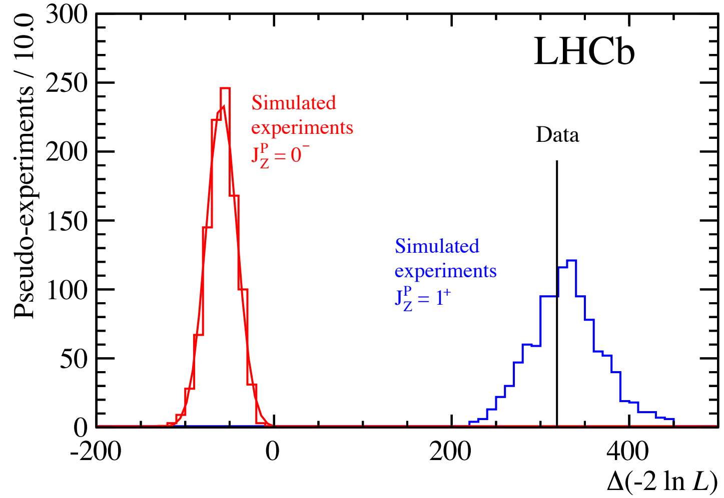


- data
- total fit
- Z(4430)$^{-}$ excluded
- K*(892)
- K* S-wave
- Z(4430)$^{-}$
- background
- K*(1410)
- K*(1680)
- K$^*_2$(1430)

No Z(4430) p-value ~10^{-6}

Fit with Z(4430) p-value ~12%

The spin is confirmed to be 1$^+$



Pentaquarks

- Predicted by Gell-Mann (64), Zweig (64), other later in context of specific QCD models: Jafee (76), Högaasen & Sorba (78), Strottman (79)

M.Gell-Mann (Phys.Lett.8(1964)214-215):
"Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q anti-q), etc. , while mesons are made out of (q anti-q), (q q anti-q anti-q), etc."

Volume 8, number 3 PHYSICS LETTERS

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

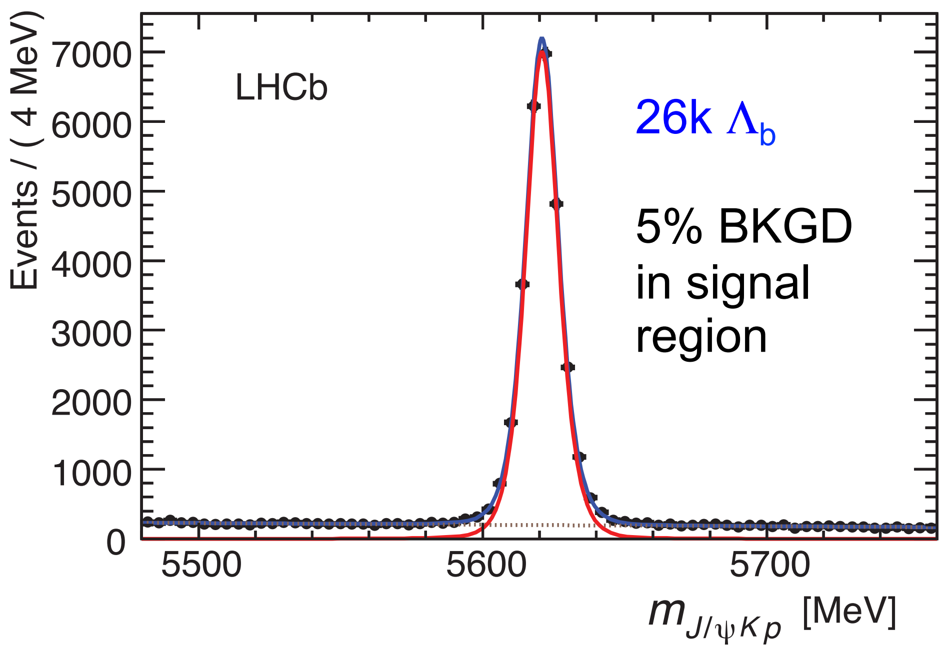
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

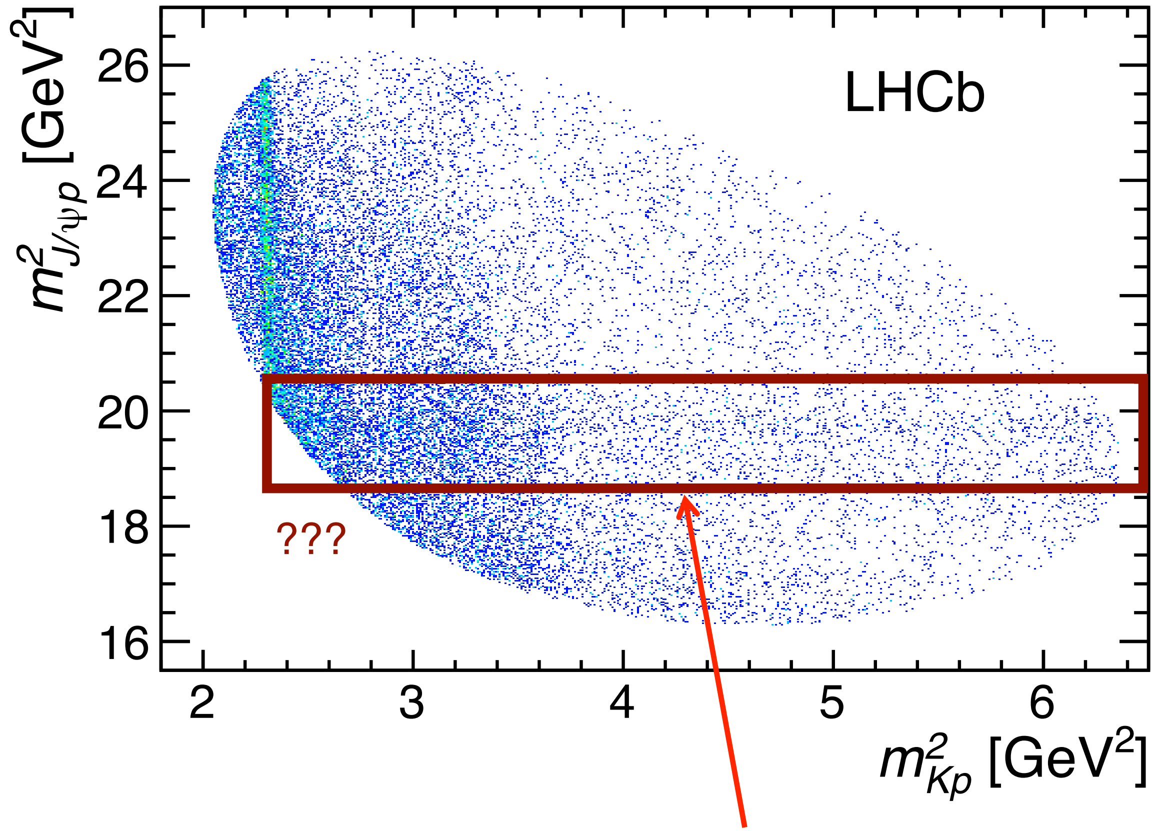
- No convincing states for 51 years
- Previous observations have been refuted

The $\Lambda_b \to J/\psi p K$ decays

- The decay $\Lambda_b \to J/\psi pK$ was first used by LHCb to make a precision measurements of the Λ_b lifetime
- Results shown here use the full Run 1 data set, 3/fb

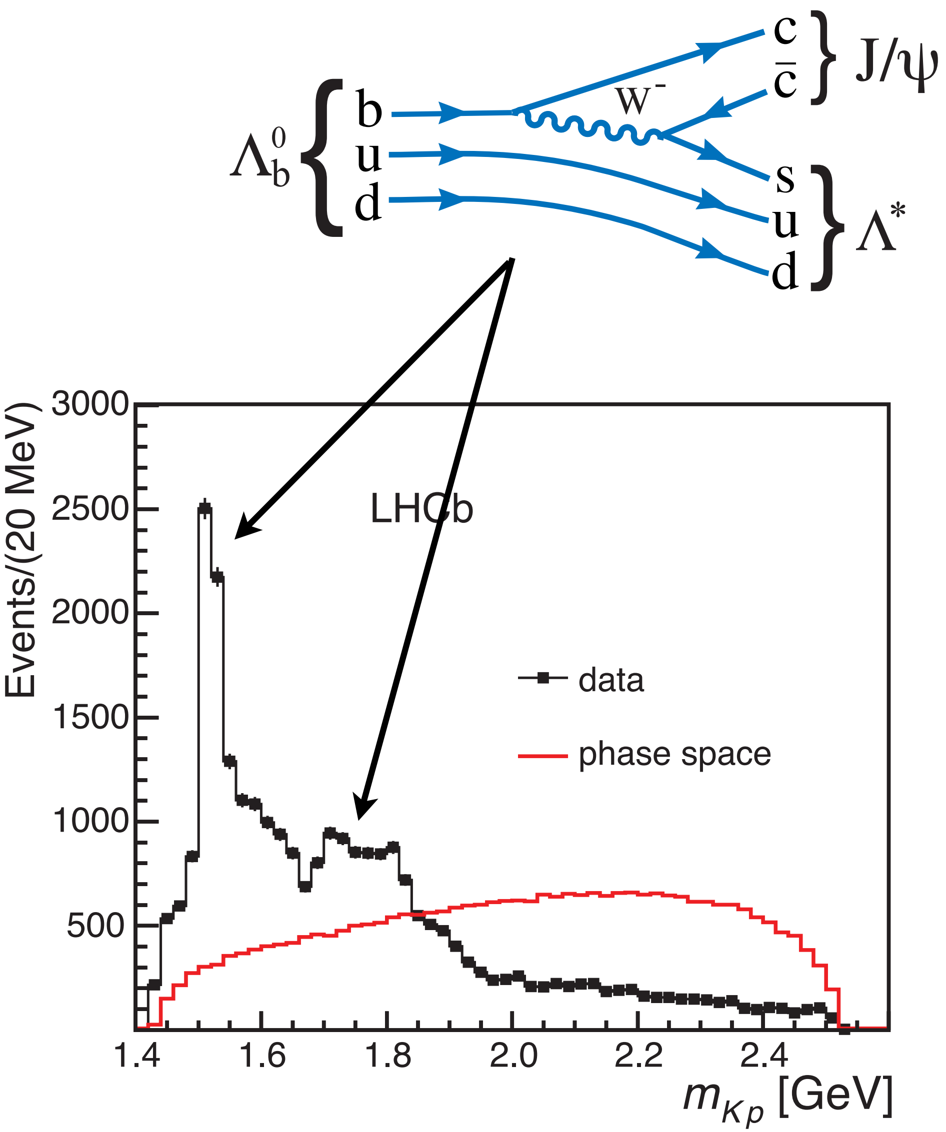
Phys.Rev.Lett.115(2015)072001

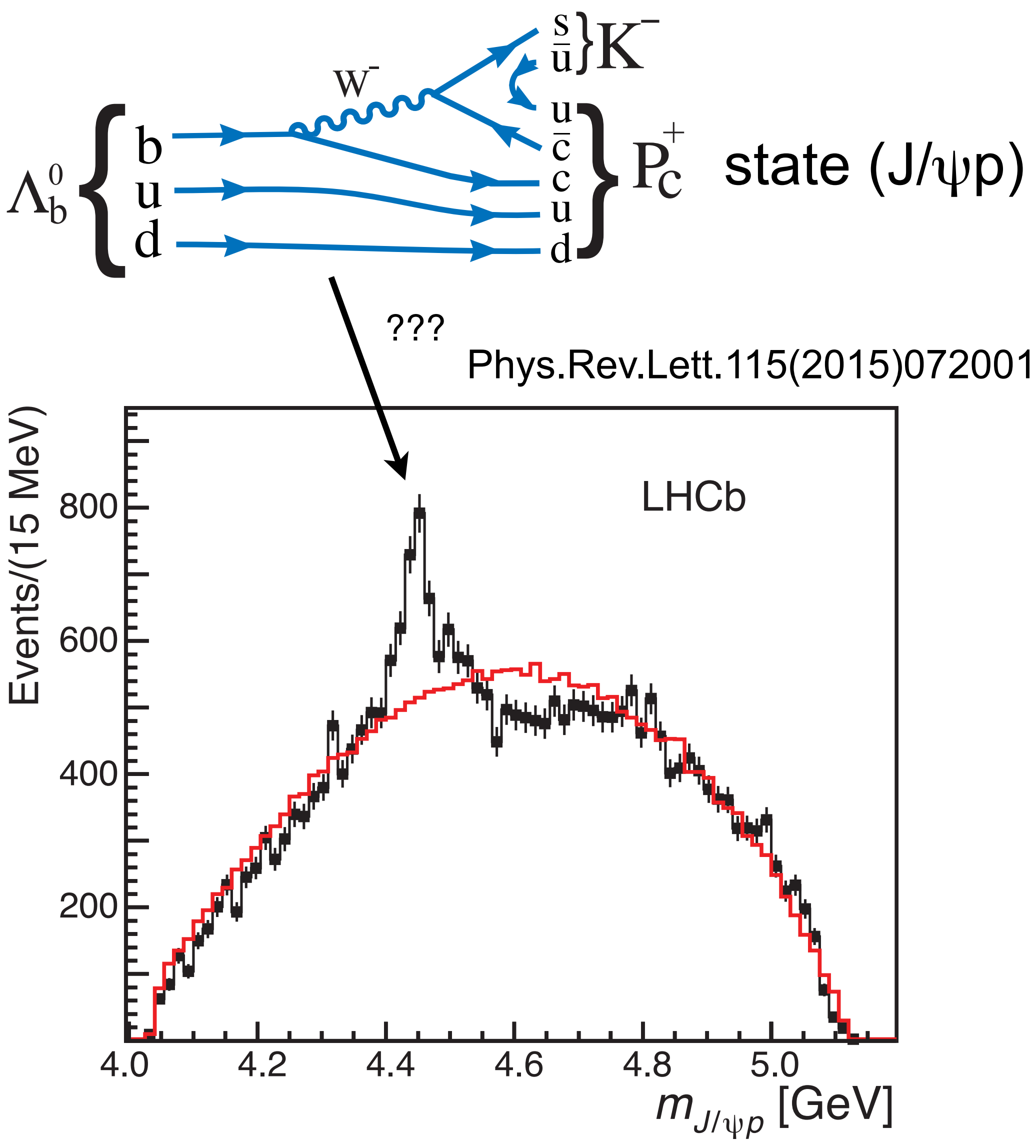




The three-body decay make a Dalitz plot, which showed an unusual feature

Mass projections of $\Lambda_b \to J/\psi p K$



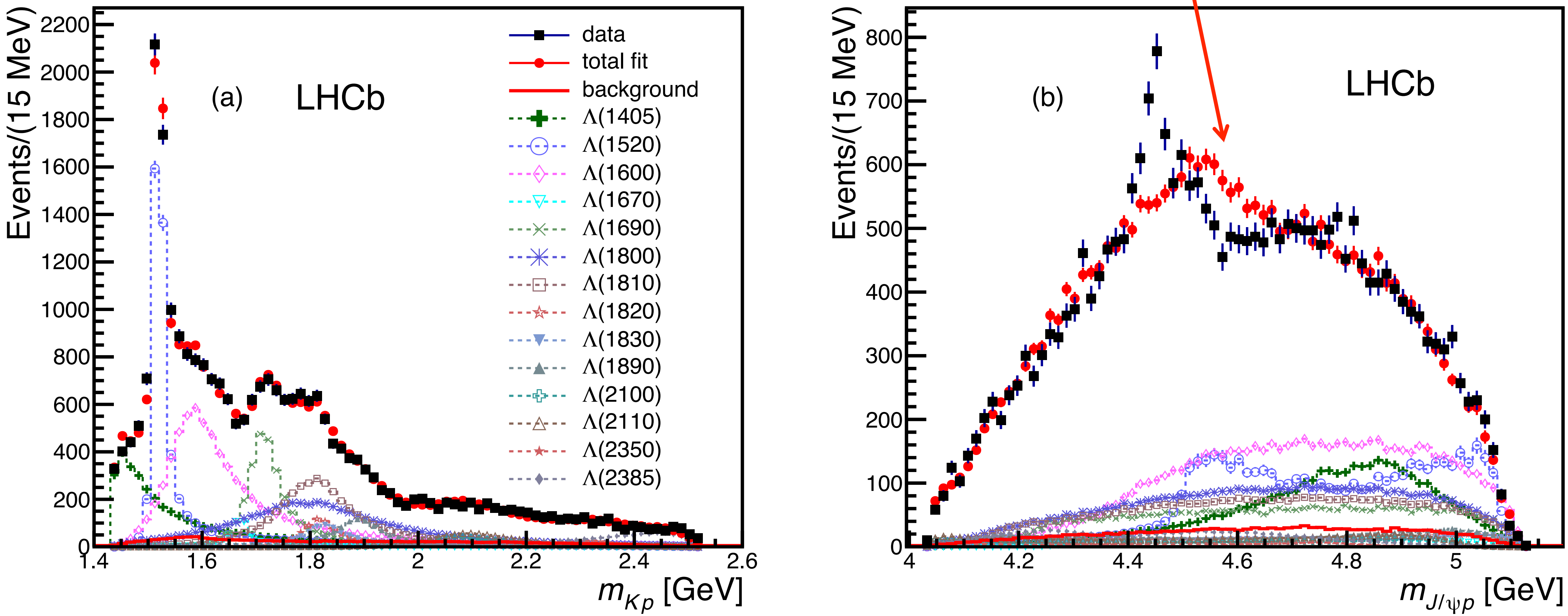


An unexpected peaking structure was observed in the $J/\psi p$ system

No pentaquark

The amplitude analysis is performed. Fits with all known Λ^* resonances but no pentaquark amplitudes fail to describe the data.

Phys.Rev.Lett.115(2015)072001

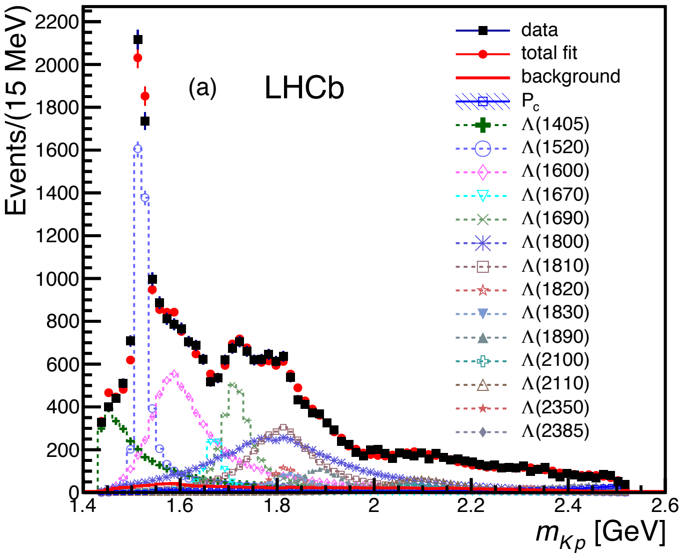


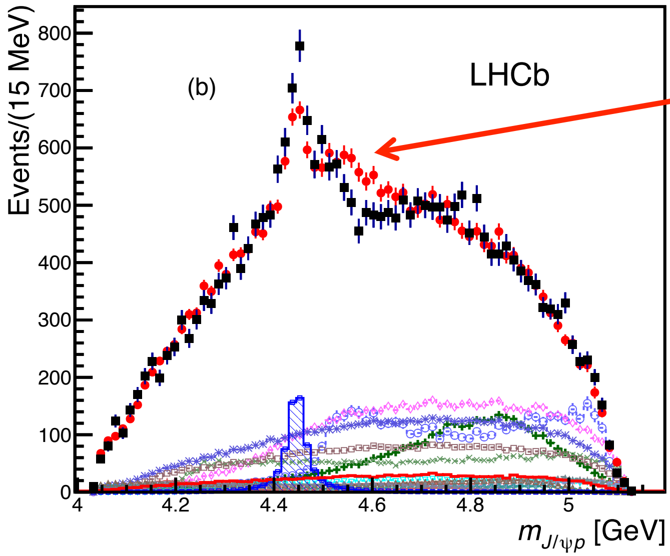
Also tried adding: all Σ^* (isospin-violating) decays; two new Λ^* resonances with free M, Γ; 4 non-resonant Λ^* amplitudes. All fail to describe the data.

With pentaquark

Phys.Rev.Lett.115(2015)072001

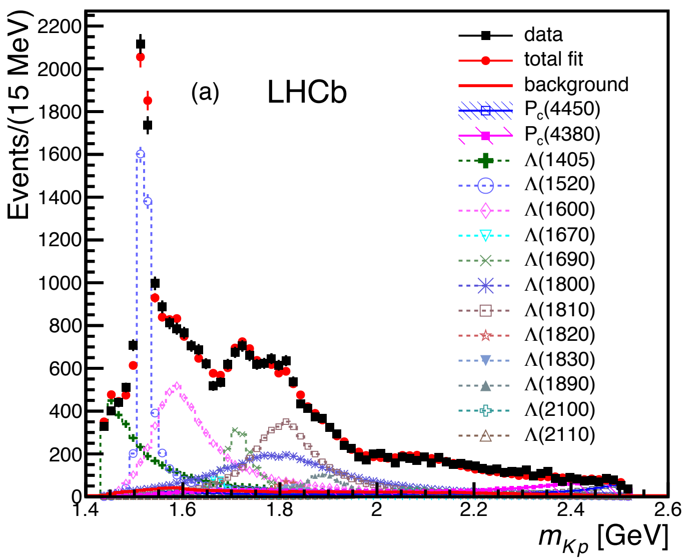
One pentaquark

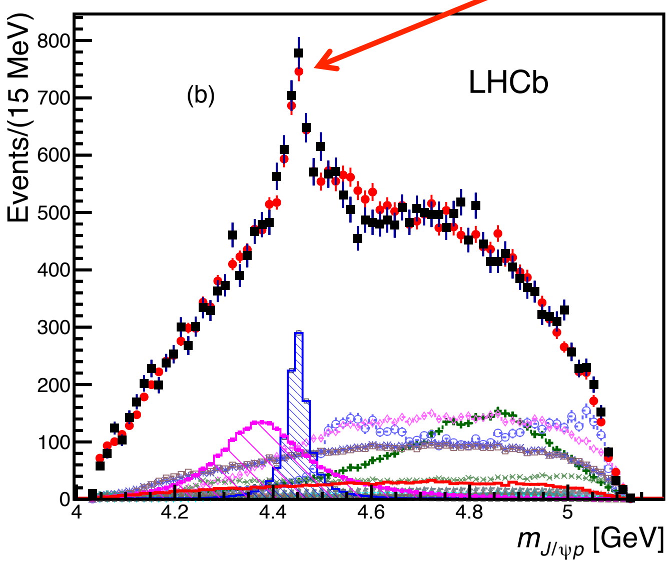




Adding one pentaquark state improves the description but still fails to fully describe the data

Two pentaquarks





Two pentaquarks (P_c= 4380MeV, 4450MeV) describe data

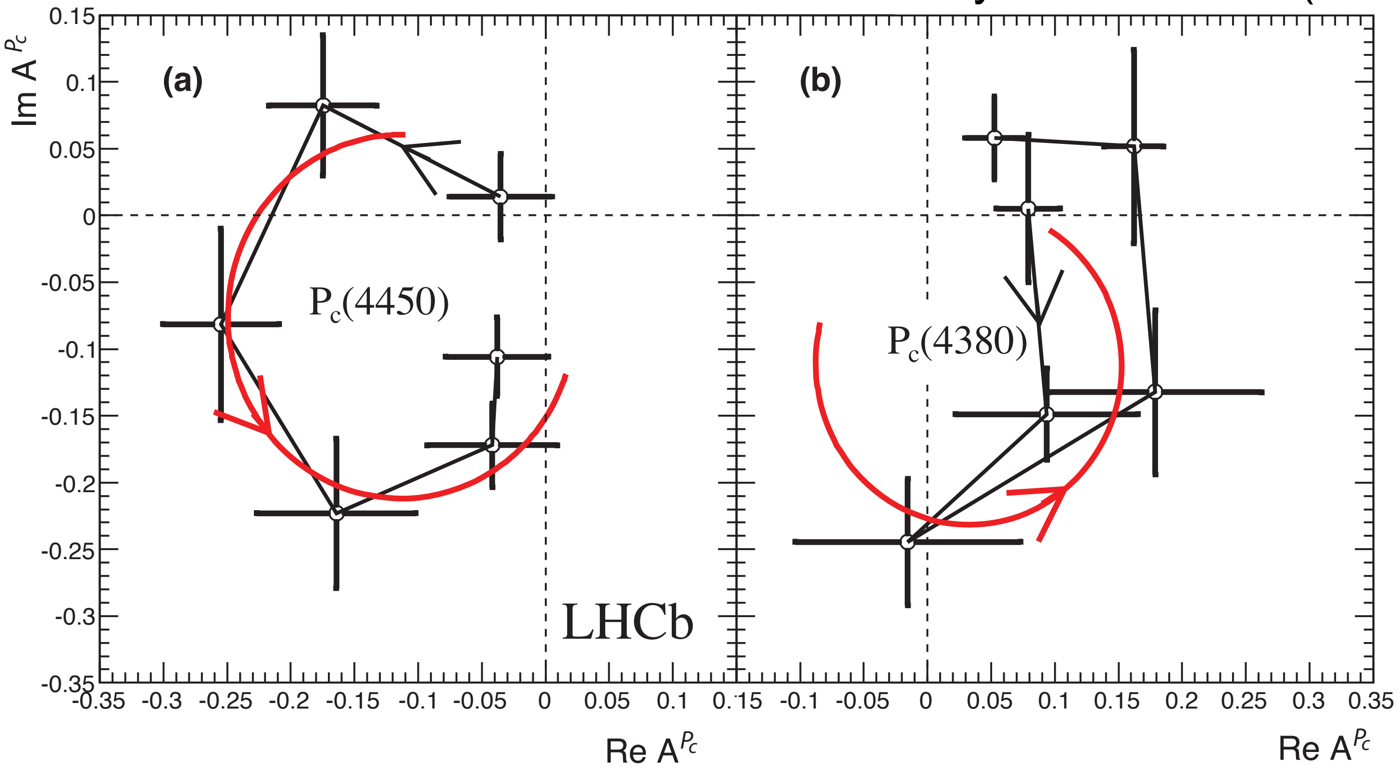
Best fit has $J^P = 3/2^-$ (lower mass) and $5/2^+$ (higher mass), also $(3/2^+,5/2^-)$ & $(5/2^+,3/2^-)$ are preferred

They have spin 3/2 & 5/2 & opposite parity

Are there resonances?

- The Argand diagram shows the typical phase motion of a resonance.
- Clear resonant-like behavior of the $P_c(4450)$; uncertainties too large to make conclusive statement about $P_c(4380)$.

Phys.Rev.Lett.115(2015)072001



LHCb has observed two states decaying into J/ψp consistent with pentaquark content of (c anti-c u u d)

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

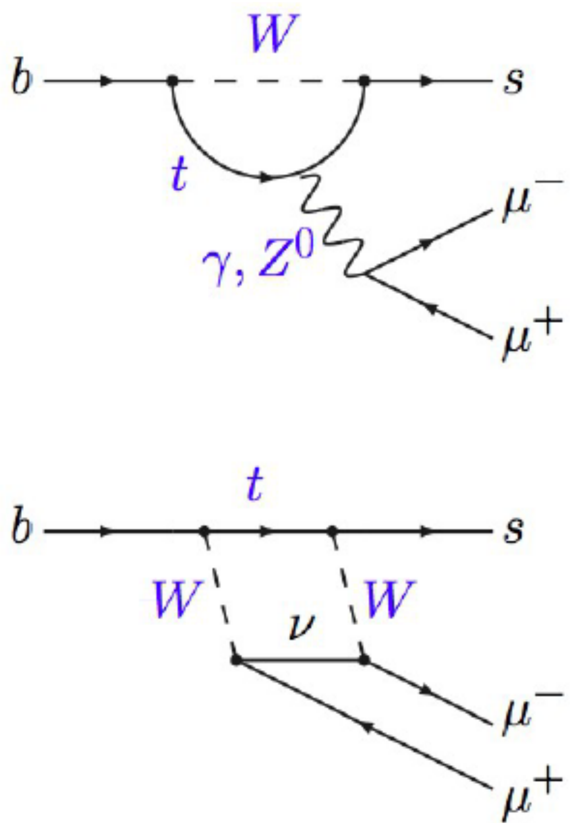
Rare decays as indirect probes for BSM physics

- Rare flavour changing neutral current (FCNC) decays (proceeds via a b- to s-quark) are forbidden at tree level in the SM
- It only occurs via electroweak penguin and box processes
- New heavy particles in SM extensions can enter in competing processes and can significantly change the branching fraction of the decay

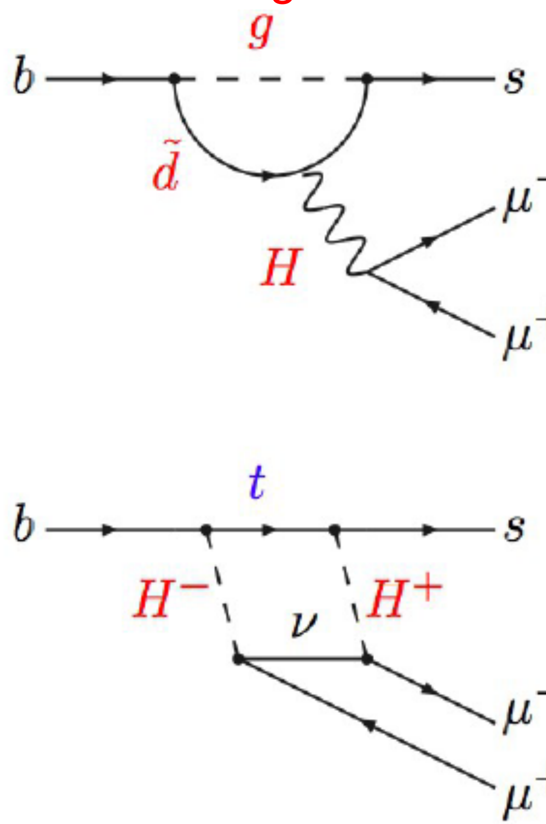
Today:

- $B^0_{(s)} \to \mu^+\mu^-$
- $B^0 \to K^*\mu^+\mu^-$
- $B^{0,+} \to K^{0,+,*+}\,\mu^+\mu^-$
- $B^0_s \to \phi\,\mu^+\mu^-$
- $\Lambda_b \to \Lambda\,\mu^+\mu^-$

SM diagrams



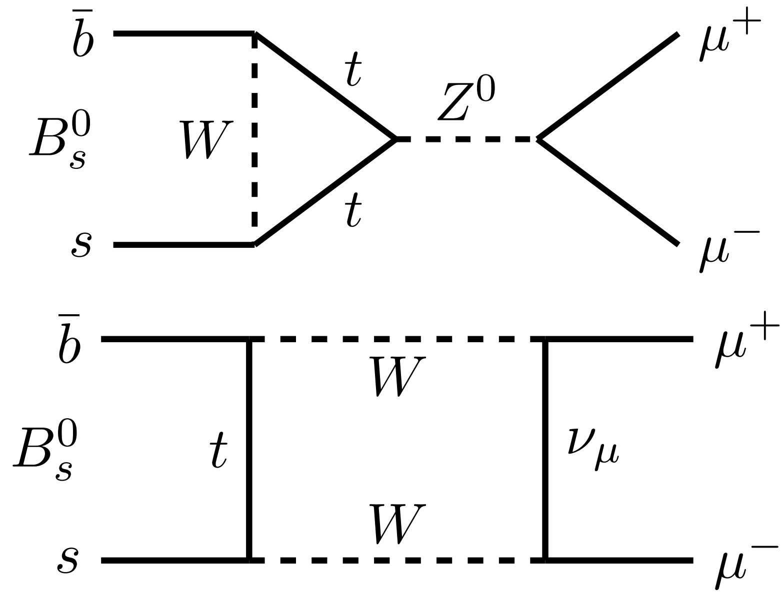
NP diagrams



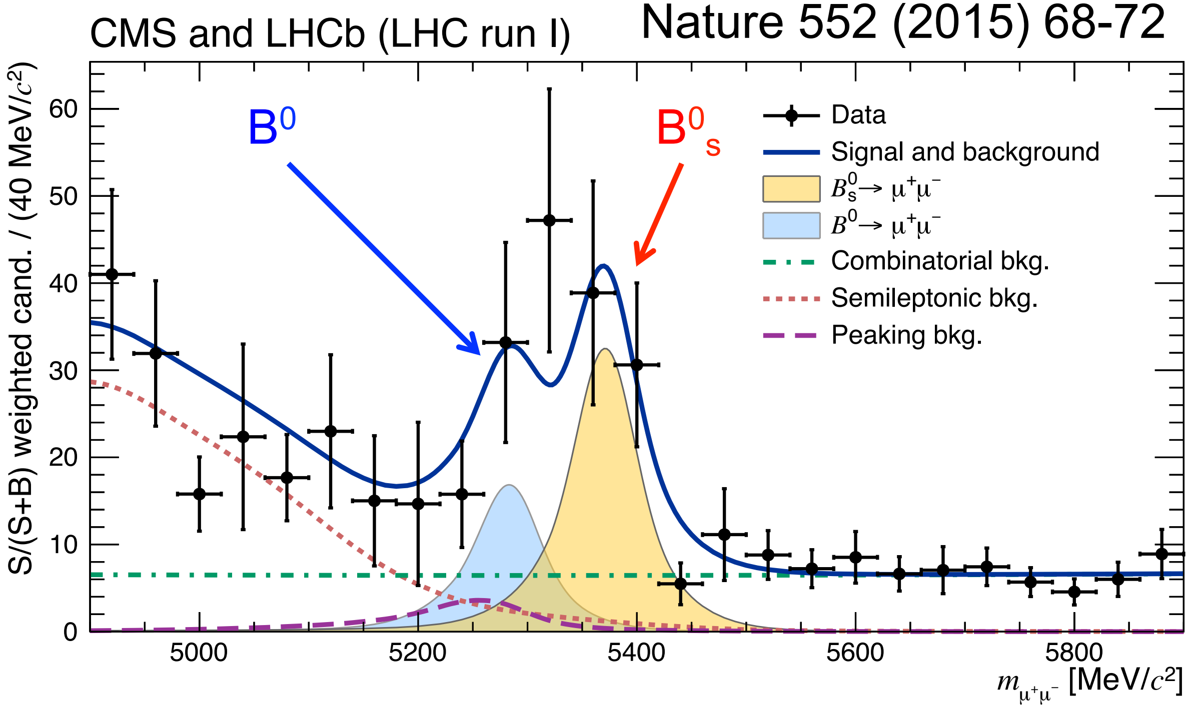
Very rare $B^0_{(s)} \to \mu^+\mu^-$ decays

- Purely leptonic final state: theoretically and experimentally very clean
- Very sensitive to NP
- SM predictions (accounting for $\Delta\Gamma_s \neq 0$):

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$



Nature 552 (2015) 68-72



- First observation of $B^0_s \to \mu^+\mu^-$ with 6.2σ significance:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

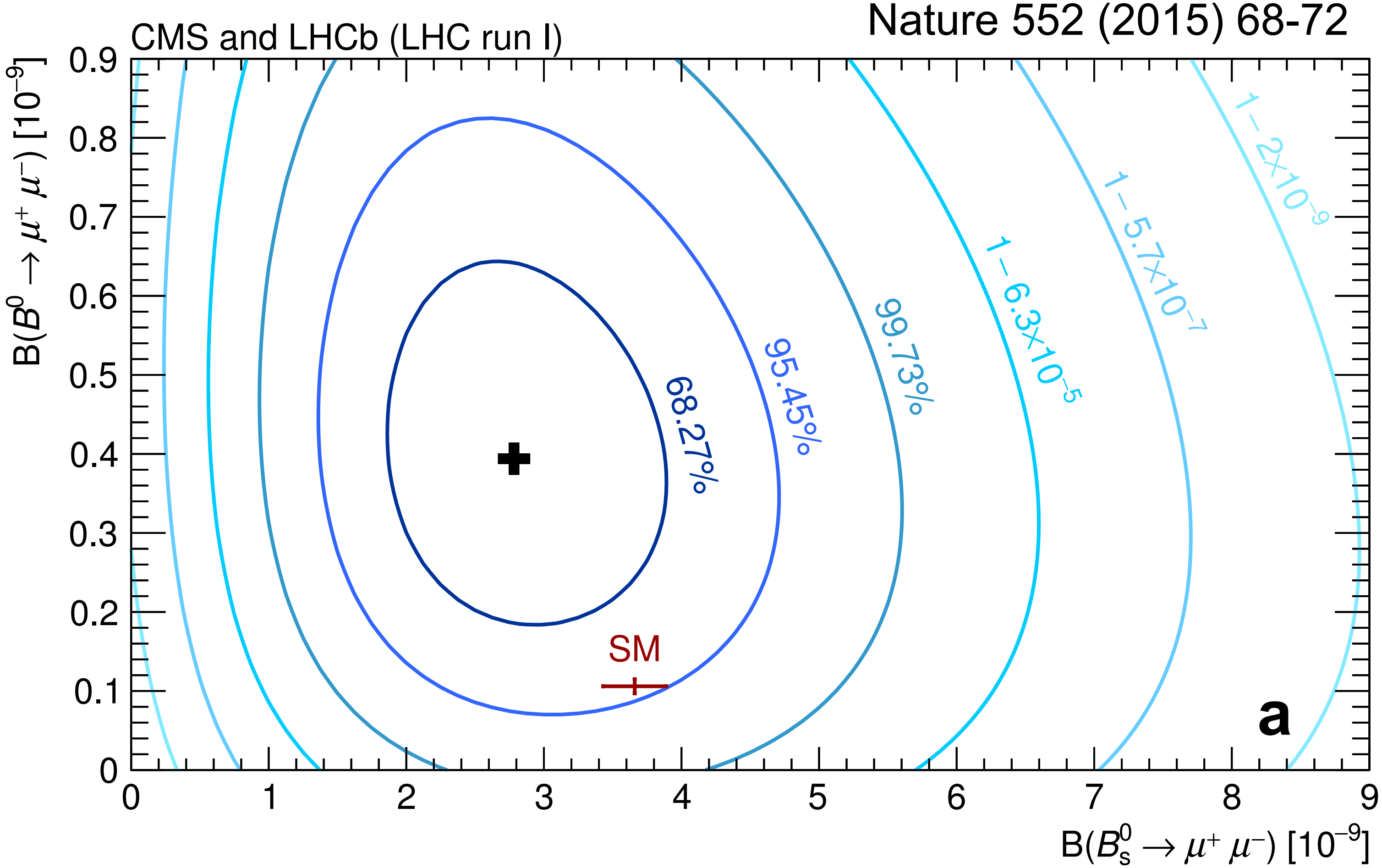
- First evidence of $B^0 \to \mu^+\mu^-$ with 3.0σ significance:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

- Both compatible with SM

The ratio R = BF($B^0 \to \mu\mu$) / BF($B^0_s \to \mu\mu$)

Nature 552 (2015) 68-72



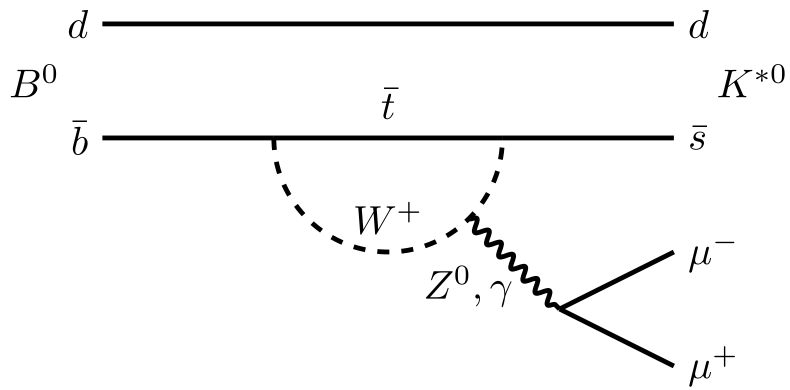
$$\mathcal{R}_{\rm SM} = 0.0295^{+0.0028}_{-0.0025}$$

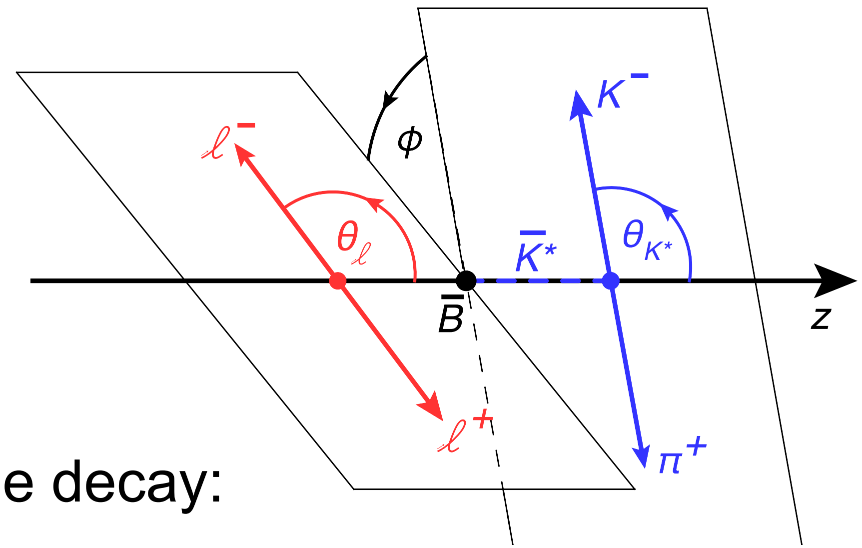
$$\mathcal{R} = 0.14^{+0.08}_{-0.06}$$ compatible at $2.3\,\sigma$

More details (including future plans): Hannah Mary Evans

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

The final state of the decay can be fully described by three angles and $q^2 = m^2_{\mu\mu}$





The CP-averaged angular distribution of the decay:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

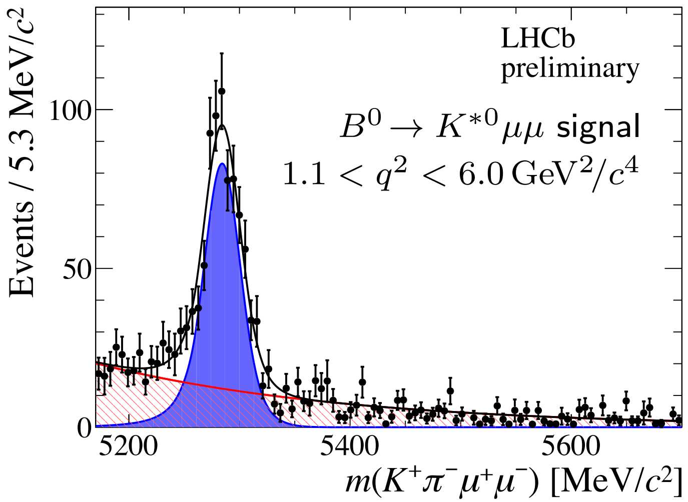
S_j – CP-averaged observables (relationships reduce the number of observable)
F_L ($= S_1$) – the longitudinal polarisation fraction of the K^{*0}
A_{FB} ($= 3/4\ S_6$) – the forward-backward asymmetry of the dimuon system

Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\,\mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012, 2398 ± 57 events

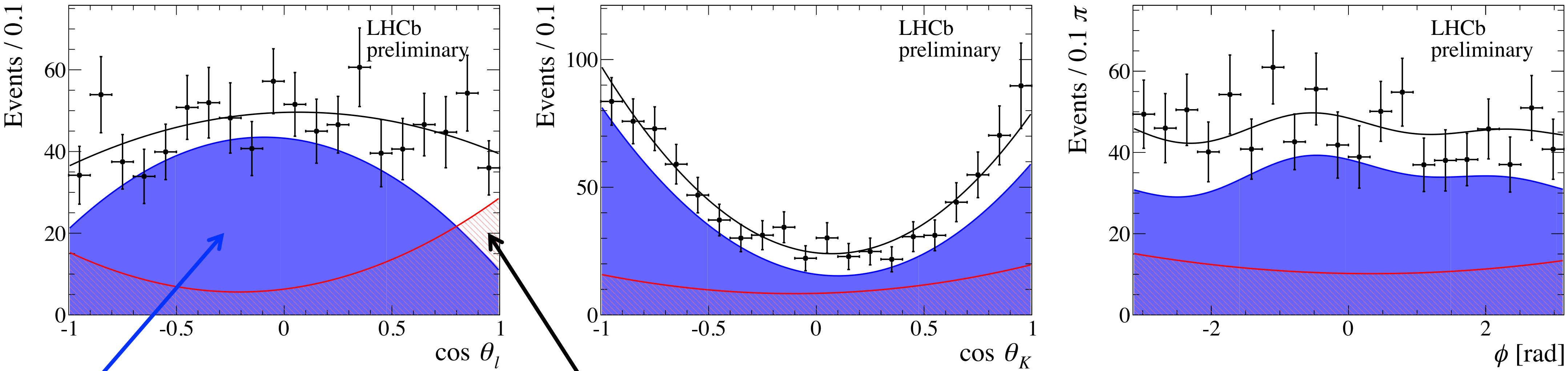
LHCb-PAPER-2015-051

Example in one q^2 bin



The CP-averaged observables F_L, A_{FB} and S_j are determined from a simultaneous unbinned maximum likelihood fit to three angles and invariant mass distributions in q^2 bins

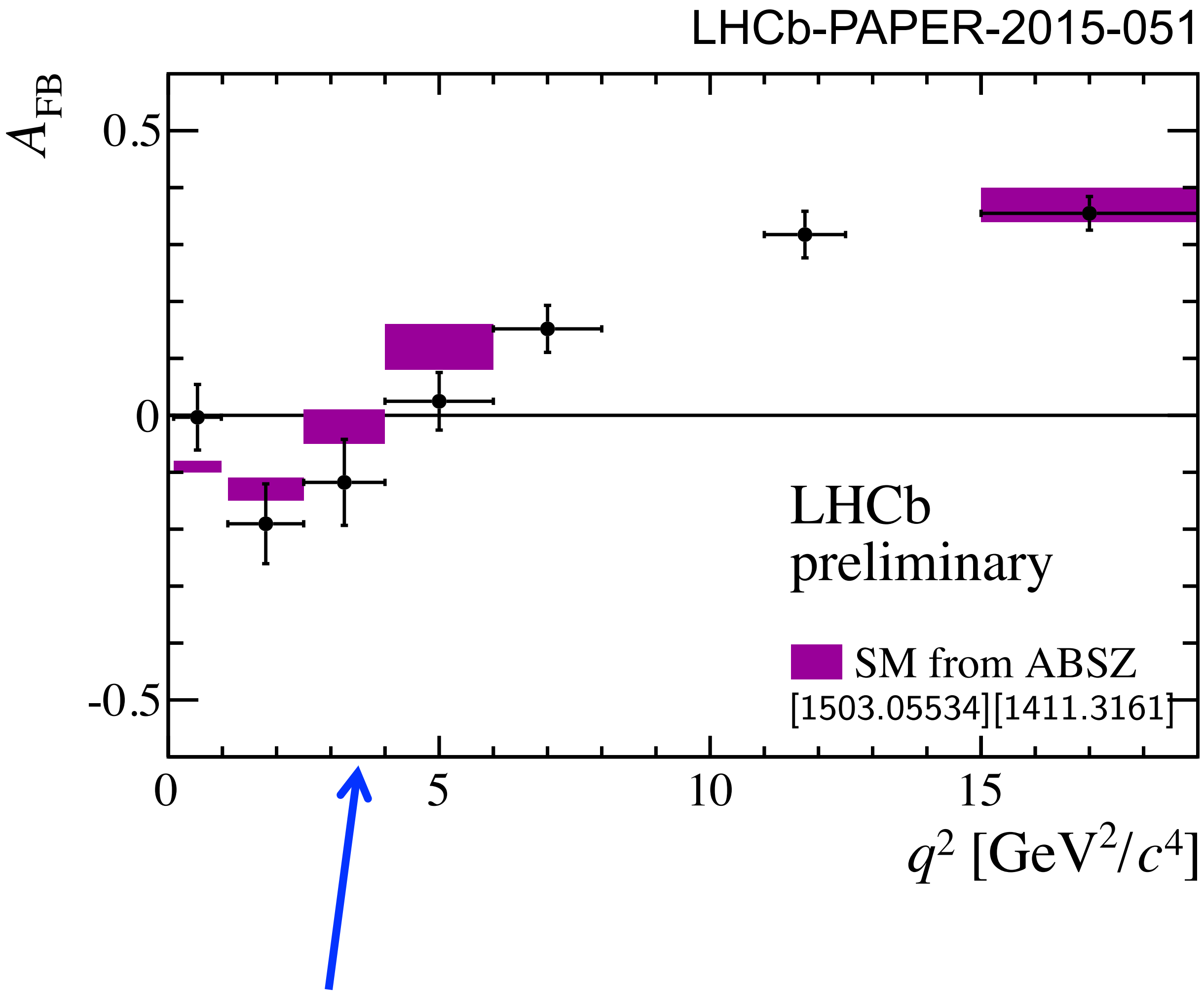
Good agreement of the fitted function with the data is observed

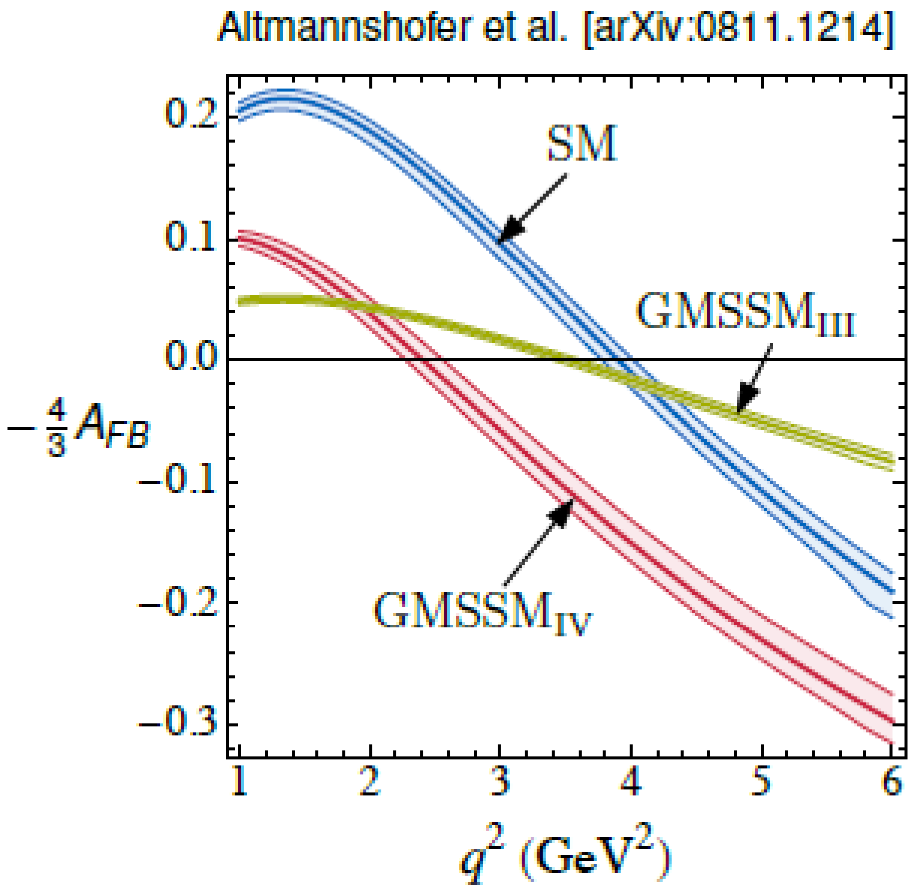


signal component

background component

Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

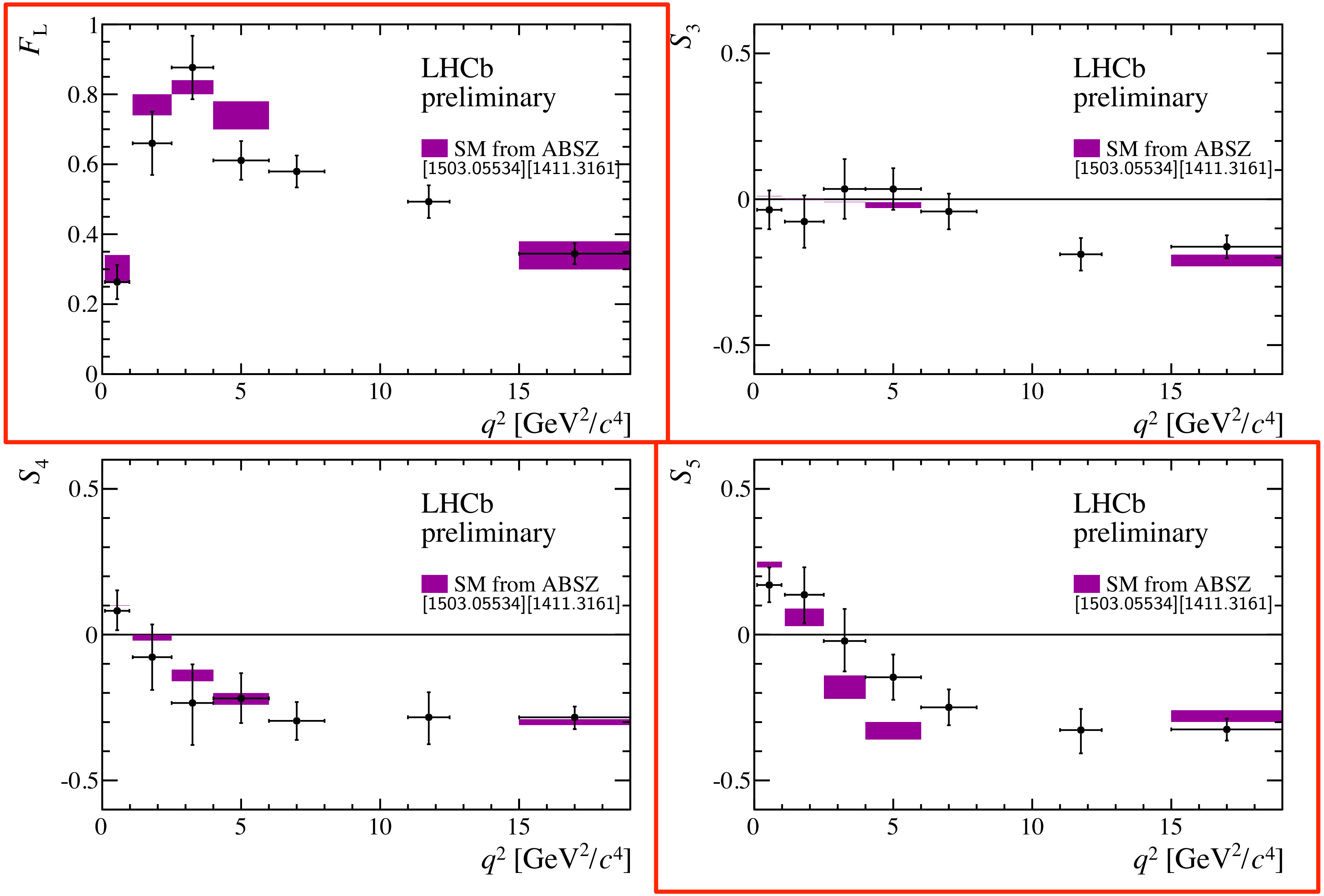




- The q^2 at zero of A_{FB} is a good probe of New Physics.
- The zero-crossing point of A_{FB} is determined to be $3.7^{+0.8}_{-1.1}$ GeV^2, which is in good agreement with the SM prediction

Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\,\mu^+\mu^-$ decays

The measured CP-averaged observables F_L, S_3, S_4, S_5 (LHCb-PAPER-2015-051)

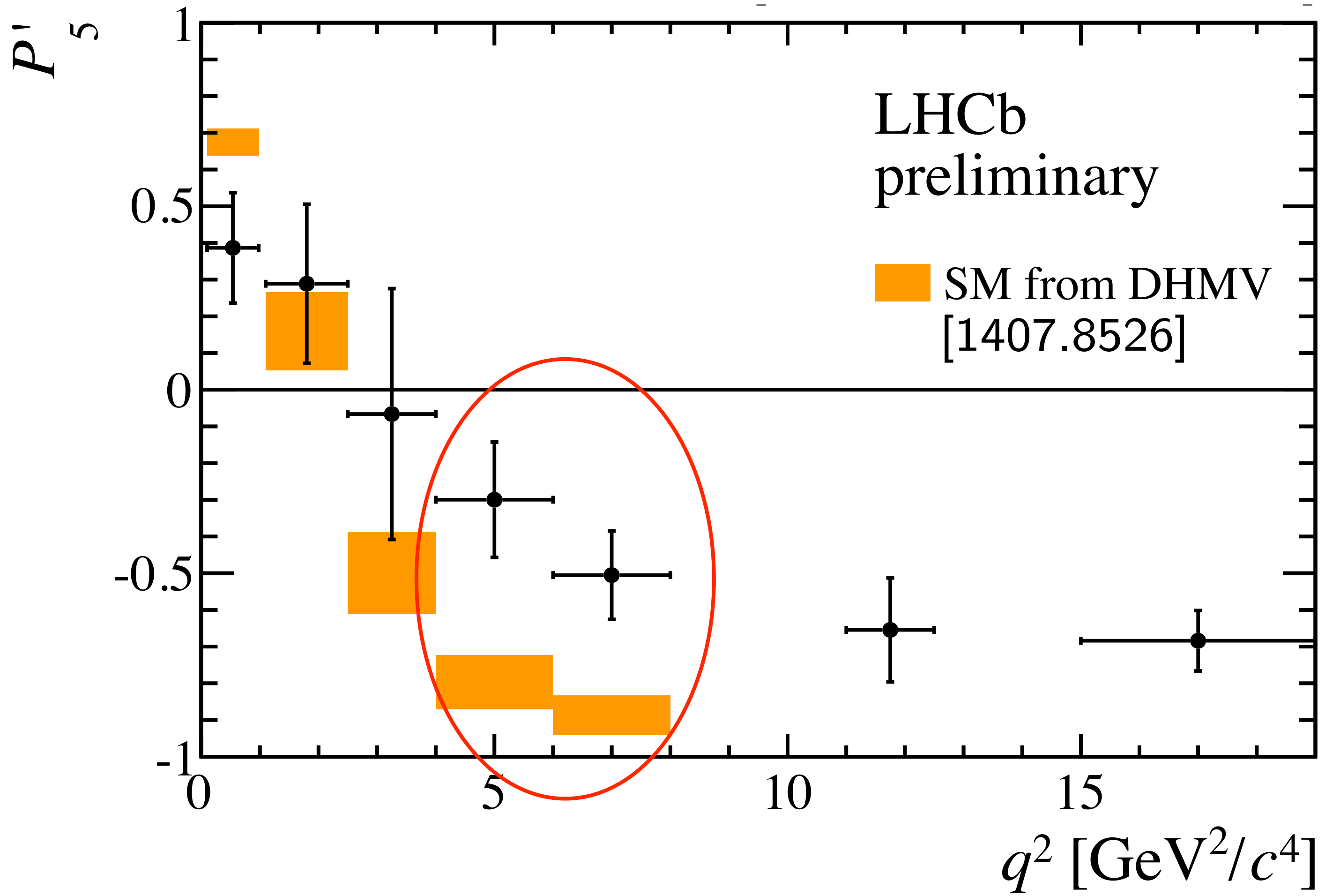


Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

Perform ratios of angular observables where form factors cancel at leading order

$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

LHCb-PAPER-2015-051

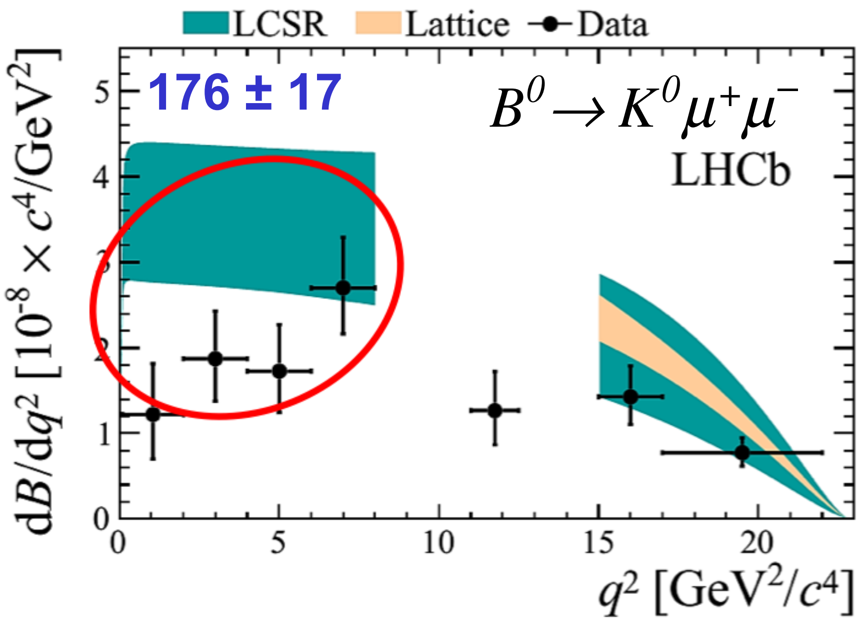


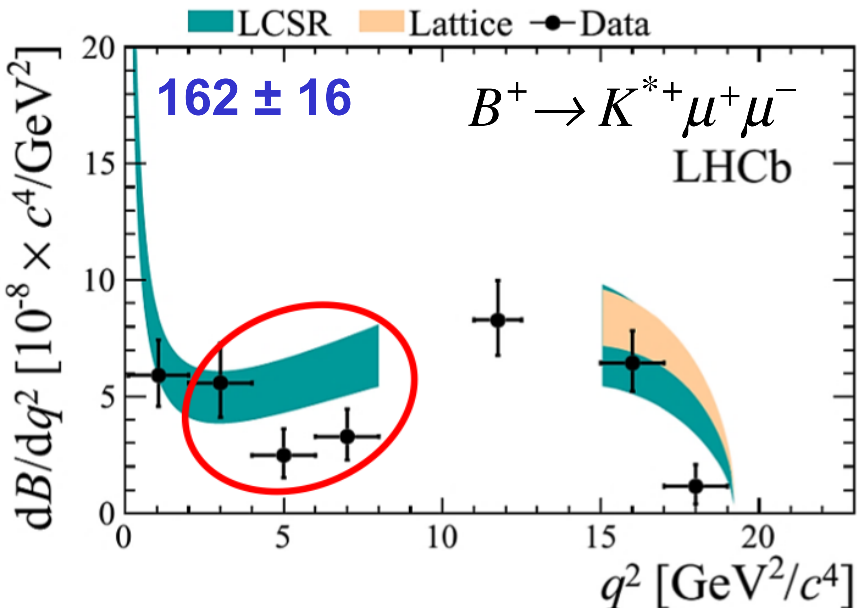
A naïve combination of the deviations in two bins of P'_5: $4 < q^2 < 8$ GeV^2 give a significance of 3.7σ agreement with the SM prediction

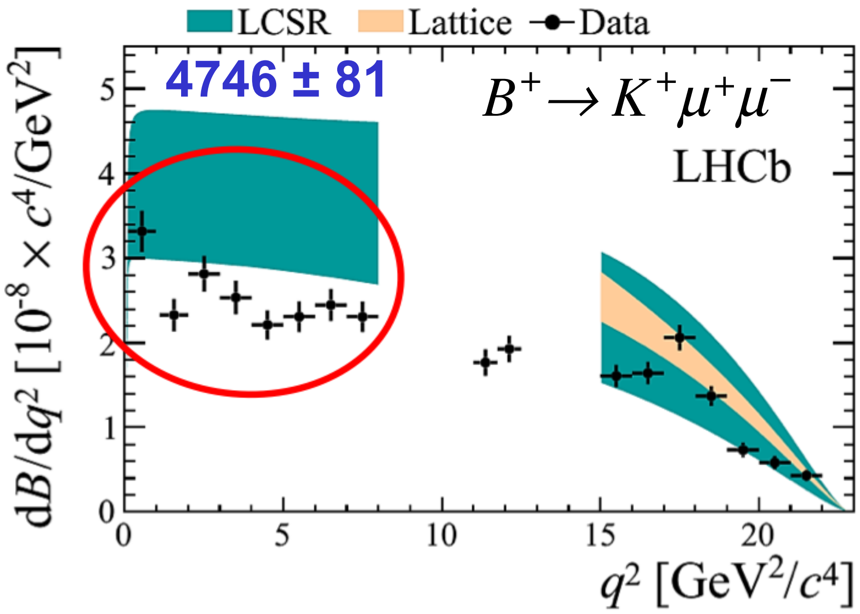
The decays: $B^{0,+} \to K^{0,+,*+} \mu^+\mu^-$

We measure also the differential branching fractions

JHEP06(2014)133





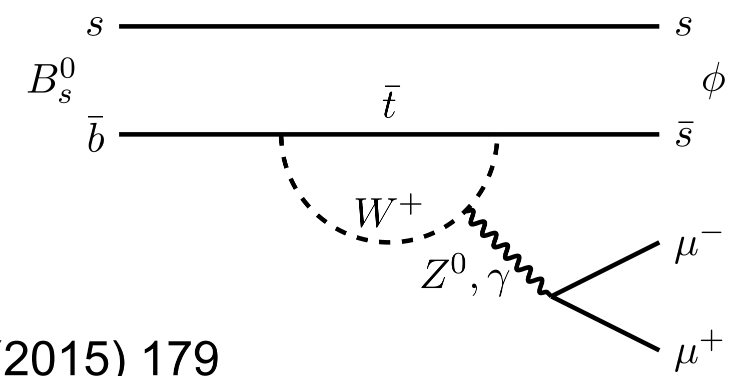


Trend to be below SM prediction at low q^2?

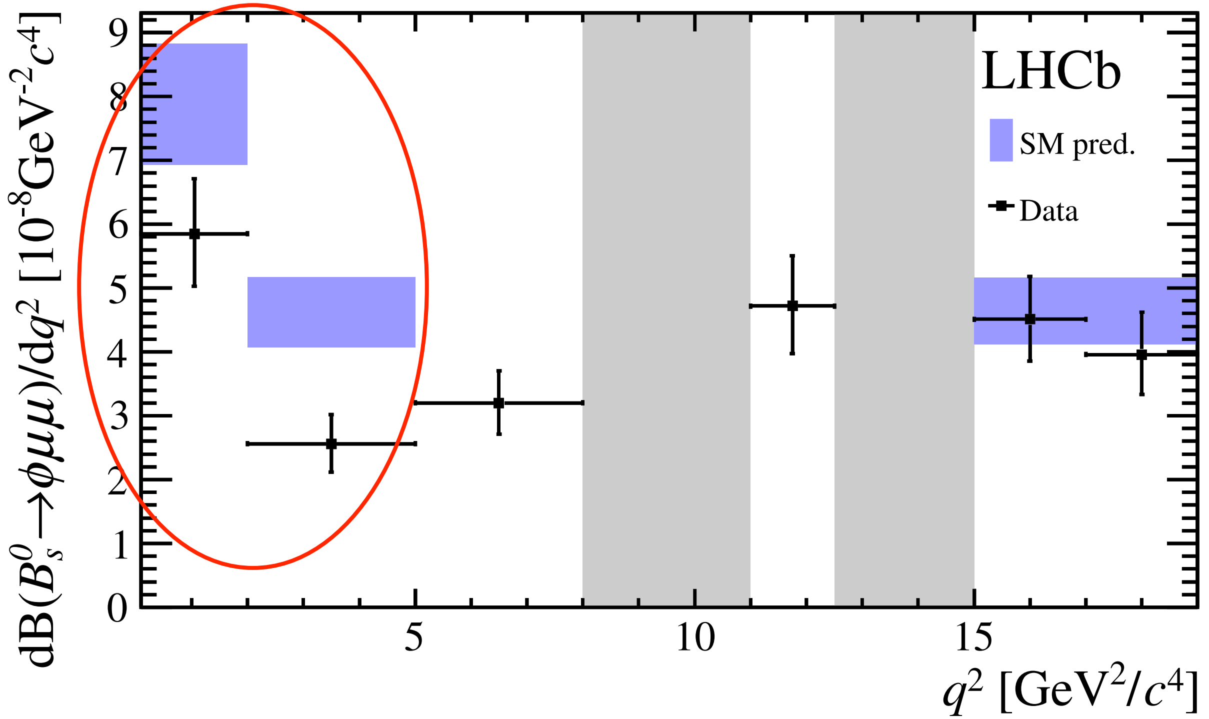
Rare $B^0_s \to \phi(\to K^+K^-)\,\mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012, 432 ± 24 events

- Dominant $b \to s\mu^+\mu^-$ decay for B^0_s, analogous to the decay $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$
- Full angular analysis performed, measure also differential branching fraction



JHEP09 (2015) 179



SM predictions from arXiv:1411.3161, arXiv:1503.05534

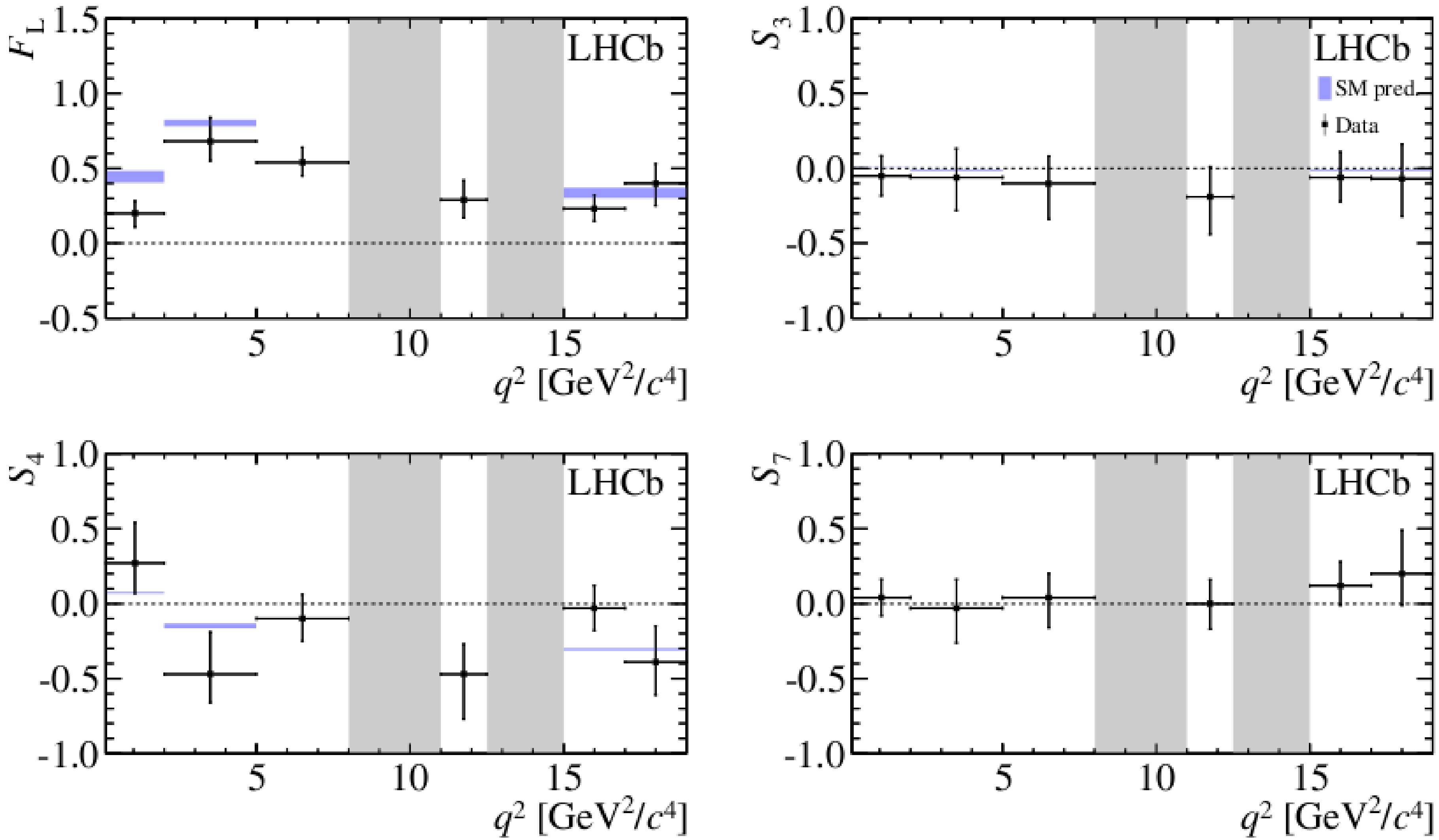
For the q^2 region $1<q^2<6\ \mathrm{GeV}^2$ the differential branching fraction of

$$(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8}\ \mathrm{GeV}^{-2}$$

is 3.3σ below the SM prediction of (4.81 ± 0.56) x 10-8 GeV^{-2}

Rare $B^0_s \to \phi(\to K^+K^-)\, \mu^+\mu^-$ decays

JHEP09 (2015) 179



All angular observables consistent with the Standard Model

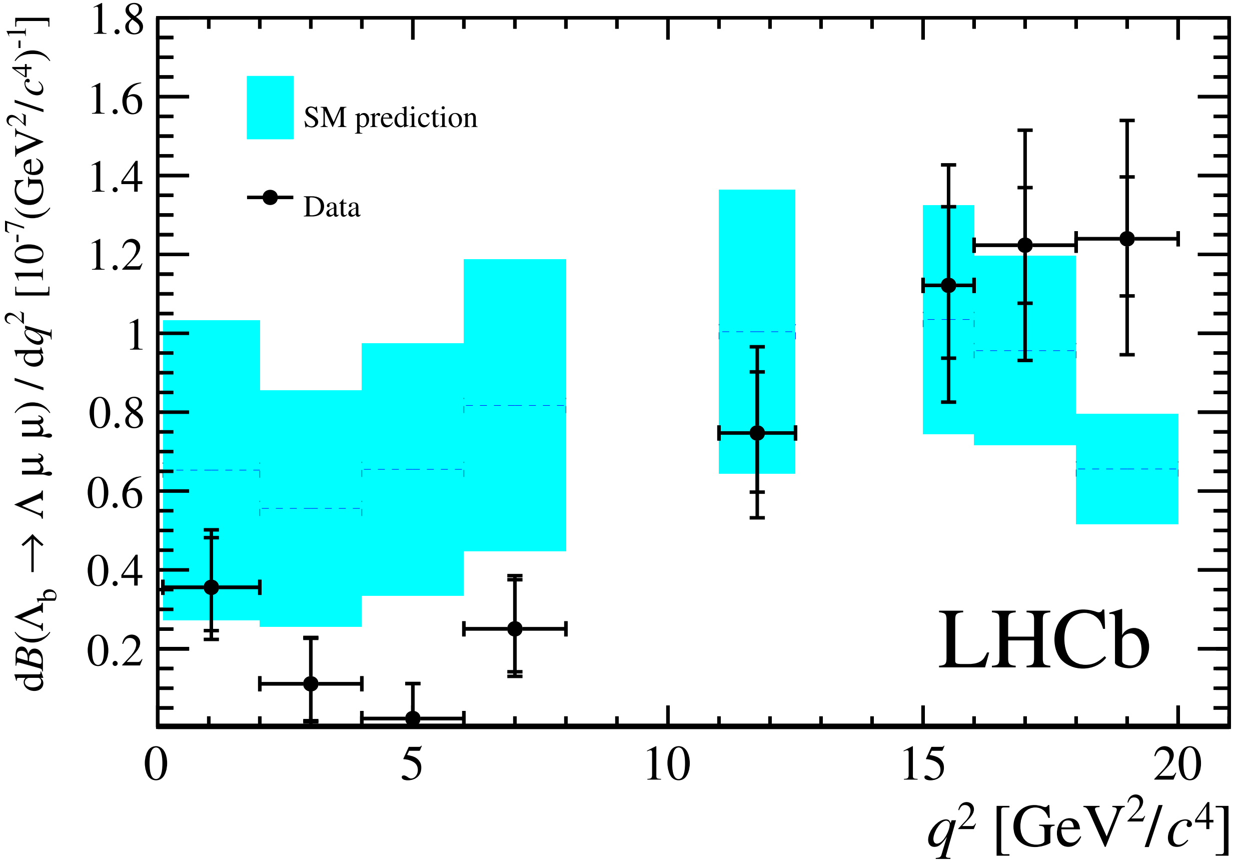
Rare $\Lambda_b \to \Lambda \mu^+\mu^-$ decays

JHEP06 (2015) 115

LHCb 3/fb, 2011+2012:

$1.1<q^2<6$ GeV^2: 9.4 ± 6.3 candidates (1.7 significance)

$15<q^2<20$ GeV^2: 276 ± 20 candidates (21 significance)



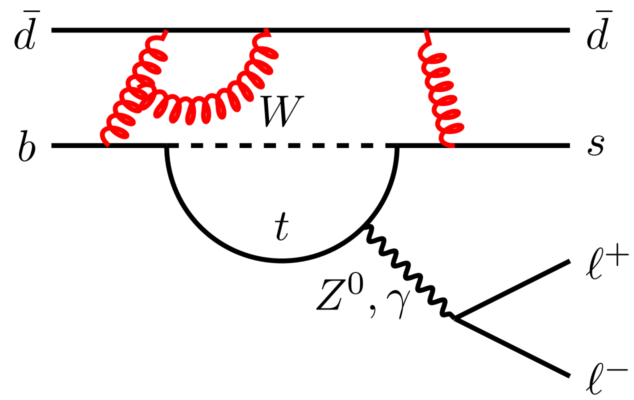
SM predictions from arXiv:1212.4827

Similar tension with SM prediction for branching fraction at low q^2

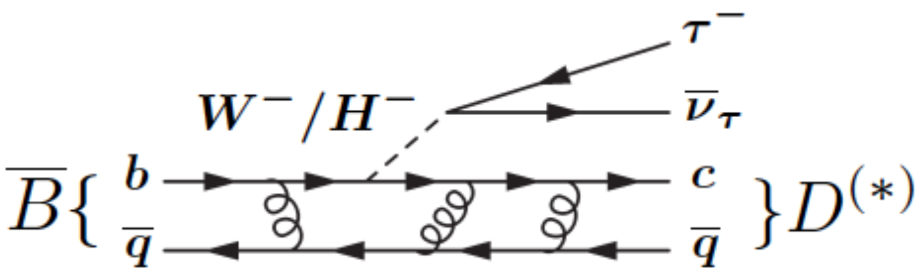
Statistics still low for angular analysis

Probes of lepton universality

- Lepton flavour universality and conservation are accidental in the Standard Model.
- Any evidence of lepton flavour violation will point directly to new physics.
- Despite countless searches in many experiments no evidence of lepton flavour violation (apart from neutrinos...).
- Today:
  - $B^+ \to K^+\mu^+\mu^-$ / $B^+ \to K^+e^+e^-$



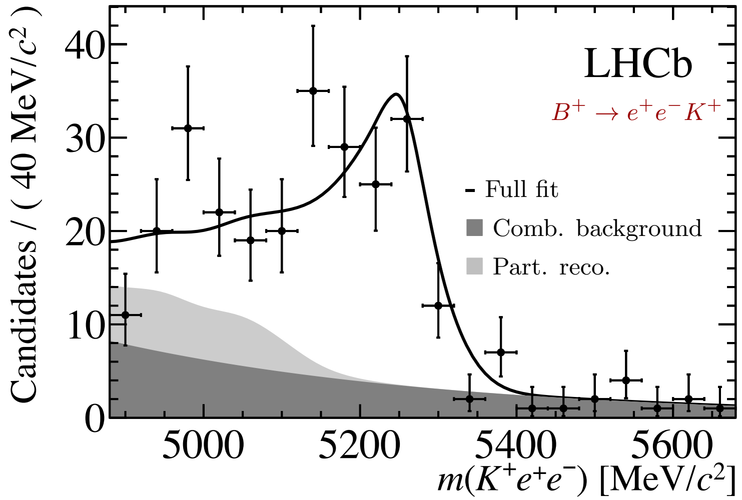
  - $B^0 \to D^{(*)}\tau\nu$ / $B^0 \to D^{(*)}\mu\nu$

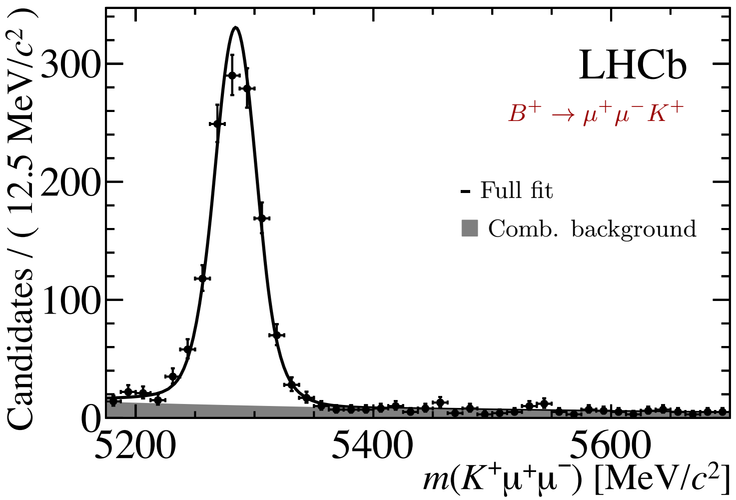


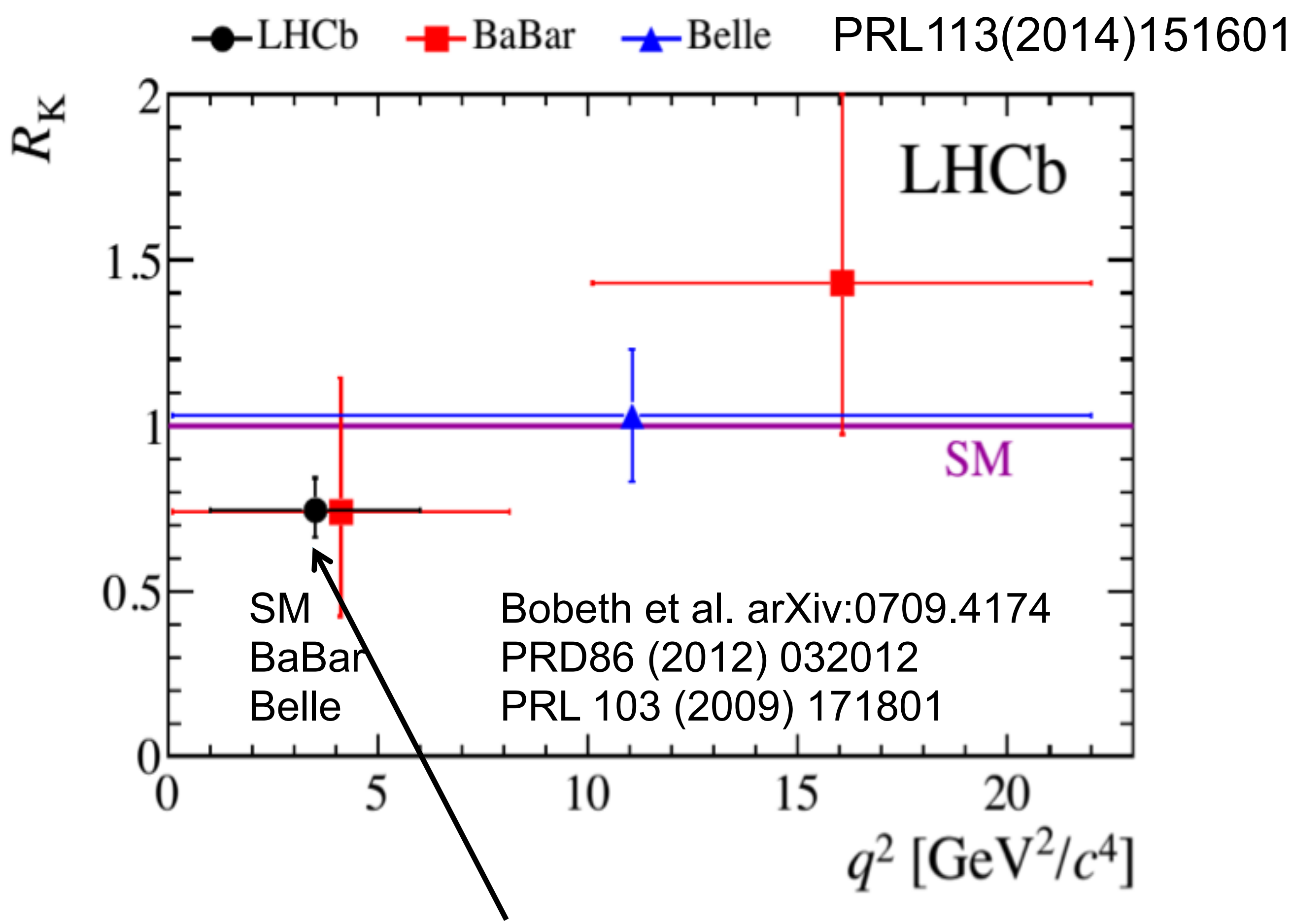
Lepton universality using $B^+ \rightarrow K^+l^+l^-$

- The deficit of $B^+\rightarrow K^+\mu^+\mu^-$ compared to expectation in the differential branching fraction at low q^2 could be seen in $K^+\mu^+\mu^-/K^+e^+e^-$ ratio (R_K)
- SM prediction is R_K = 1 with an uncertainty of $O(10^{-3})$

Example mass fit for Ke^+e^-
note huge tail due to energy loss







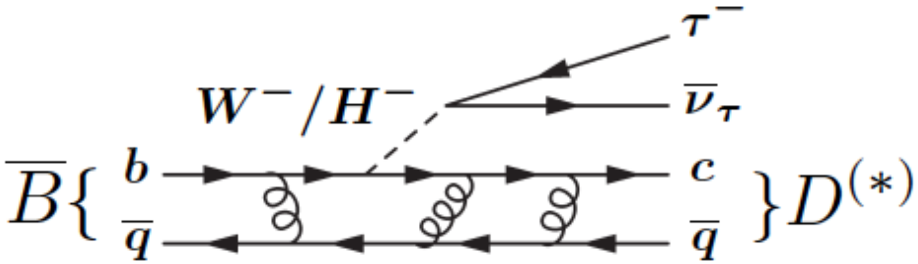
$R_K(1<q^2<6\ \text{GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$

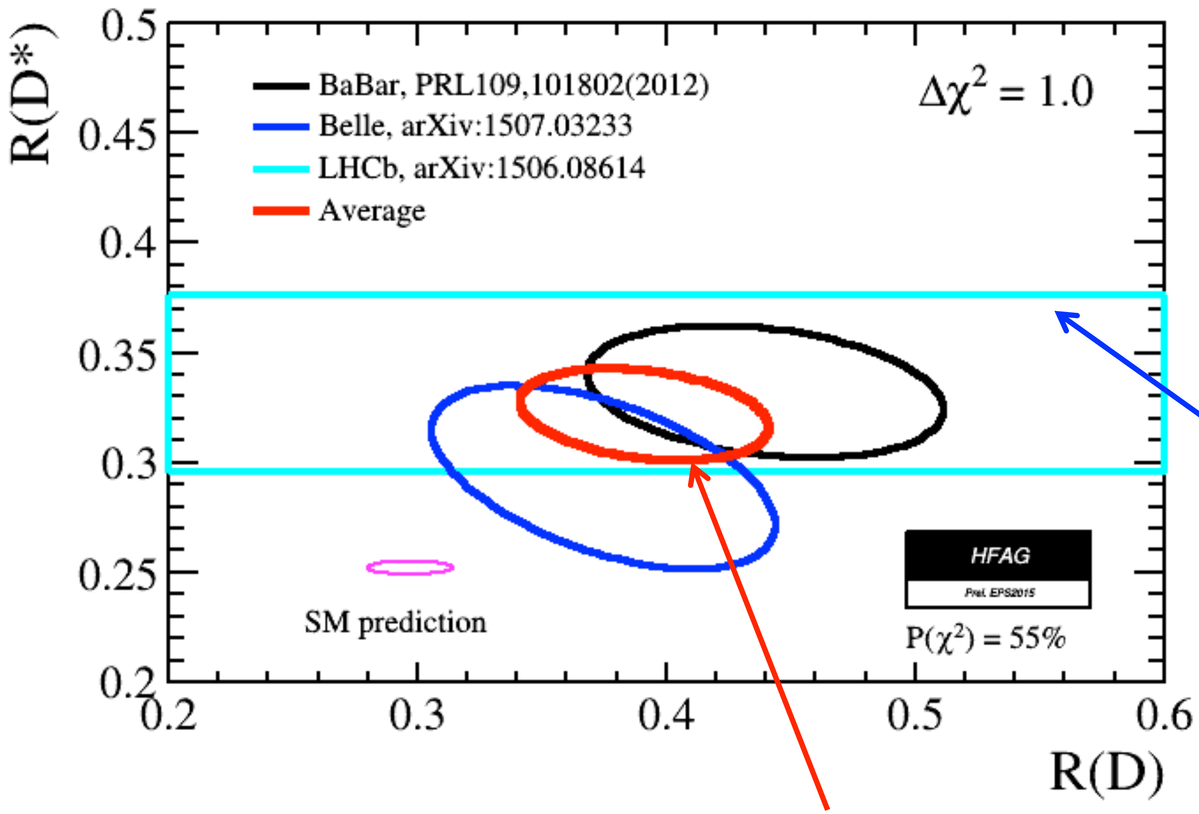
Only 2.6σ from SM but suggestive

The decays $B^0 \to D^{(*)} \tau \nu$, $B^0 \to D^{(*)} \mu \nu$

We count decays with B, once in the final state there is heavy lepton (τ) and once light (μ)

$$R(D^*) \equiv \frac{B\left(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu \nu_\tau)\bar{\nu}_\tau\right)}{B\left(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu\right)}$$





- Powerful channel to test lepton universality
- Sensitive to New Physics
- Measurements form BaBar and Belle hint of lepton universality violation

LHCb (PRL115(2015)112001):

- Agree with other measurements
- 2.1σ above SM: $R(D^*)^{SM} = 0.252 \pm 0.003$

Combined result from all measurements: 3.9σ above Standard Model

Summary

- The LHCb has performed spectacularly well in Run 1 (2011+2012, 3/fb) confirming so far the robustness of the Standard Model

- For the first time, LHCb has observed two resonant states in $J/\psi p$ consistent with pentaquarks: $P_c(4380MeV)$, $P_c(4450MeV)$

- Rare decays are an excellent laboratory to search for BSM effects

- Several potential ~3σ hints of BSM effects to be explored further:
  - ✧ in rare $B^0 \to K^{*0}\mu^+\mu^-$ decays observable P'_5 in $4 < q^2 < 8$ GeV^2 give a significance of 3.7σ agreement with the SM
  - ✧ in rare $B^0_s \to \phi\mu^+\mu^-$ decays in $1<q^2<6$ GeV^2 the differential branching fraction is 3.3σ below the SM and this trend is seen in other decays
  - ✧ $\mathcal{B}(D^*\tau\nu)/\mathcal{B}(D^*\mu\nu) = 0.336 \pm 0.027 \pm 0.030$ agree with SM (2.1σ), but combined result from all measurements is 3.9σ above SM


BACK UP!

Prospects

Future:

- Data are being recorded, 2015-18 > 8/fb at $\sqrt{s}$=13 TeV (Run 2)

- Move towards precision era for $B_{(s)} \rightarrow X \mu^+\mu^-$ decays

- Expand physics programme to more modes with electrons and taus:
  - ✧ not only R_k ($B \rightarrow Ke^+e^-/B \rightarrow K\mu^+\mu^-$) but similar ratios with different hadronic systems (K^*, ϕ, Λ, etc.)
  - ✧ not only $D^*\tau\nu$, but also $D\tau\nu$, $D_s\tau\nu$, $\Lambda_c\tau\nu$, etc.

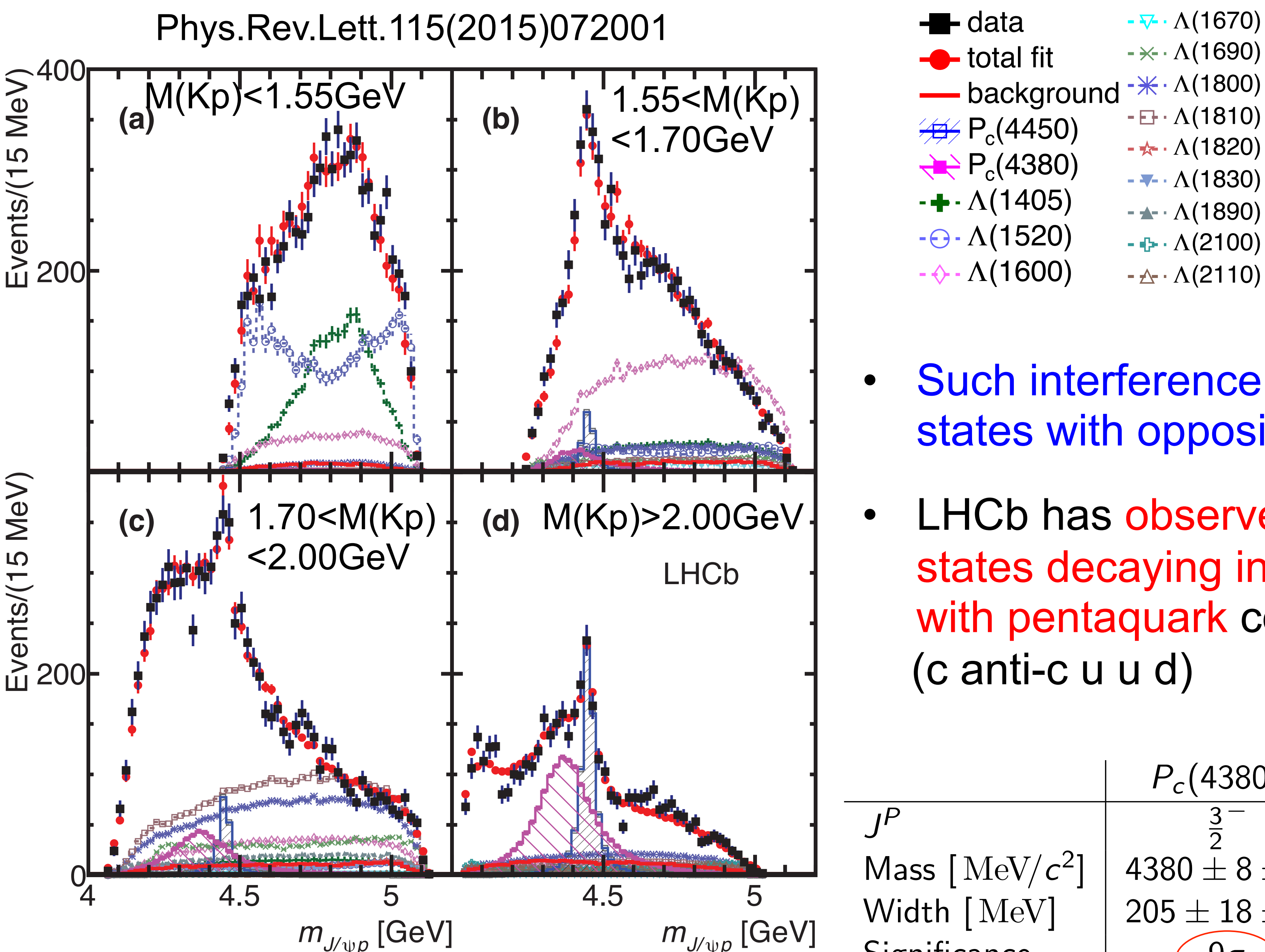
- LHCb upgrade (starting 2019) plans to collect ~50/fb data in 2022 and reach sensitivity which are comparable or better than theoretical uncertainties

LHCb upgrade

EPJ C73(2013)2373

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	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
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2%
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	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°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	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	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

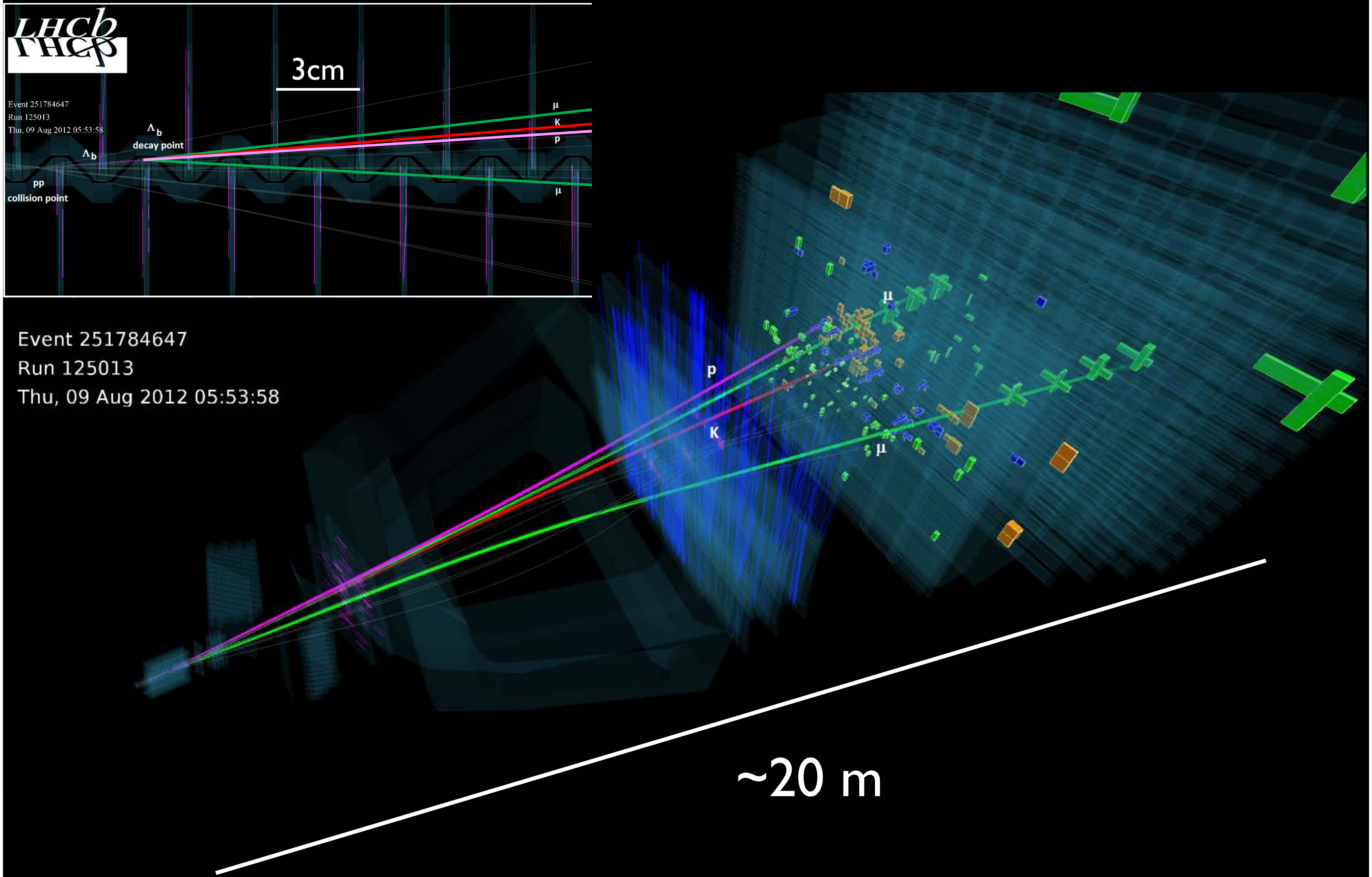
Pentaquarks interference



- Such interference requires two states with opposite parity
- LHCb has observed two resonant states decaying into J/ψp consistent with pentaquark content of (c anti-c u u d)

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

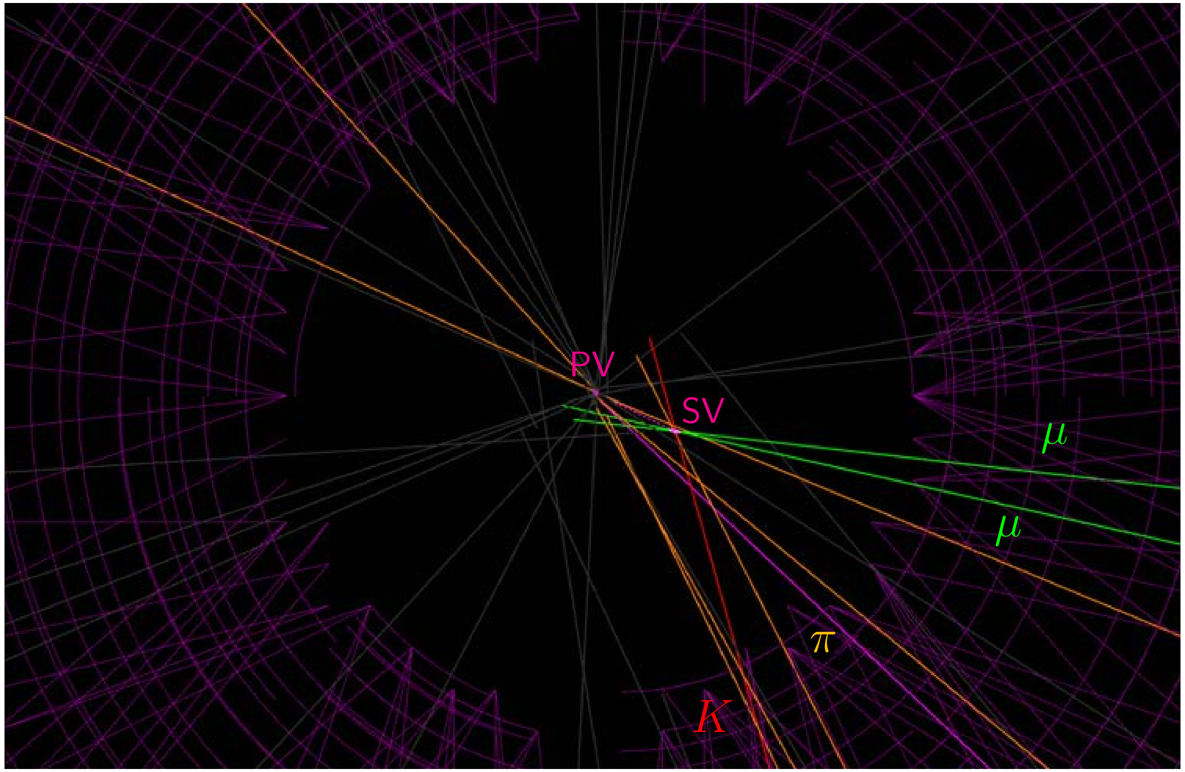
$\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$ candidate

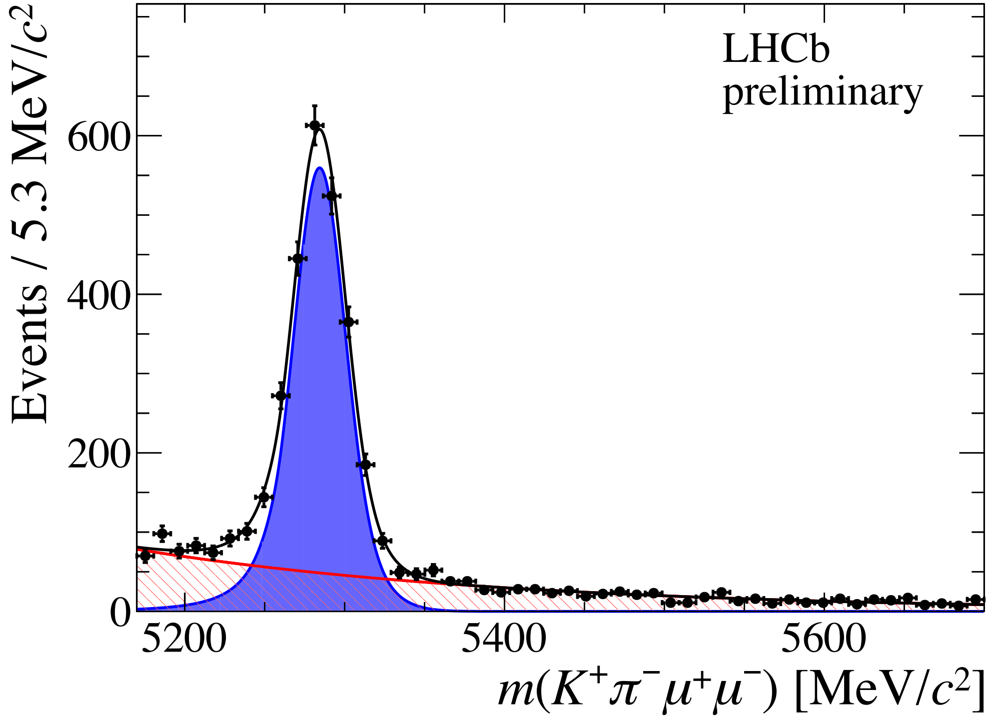


Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\,\mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012

LHCb-CONF-2015-002

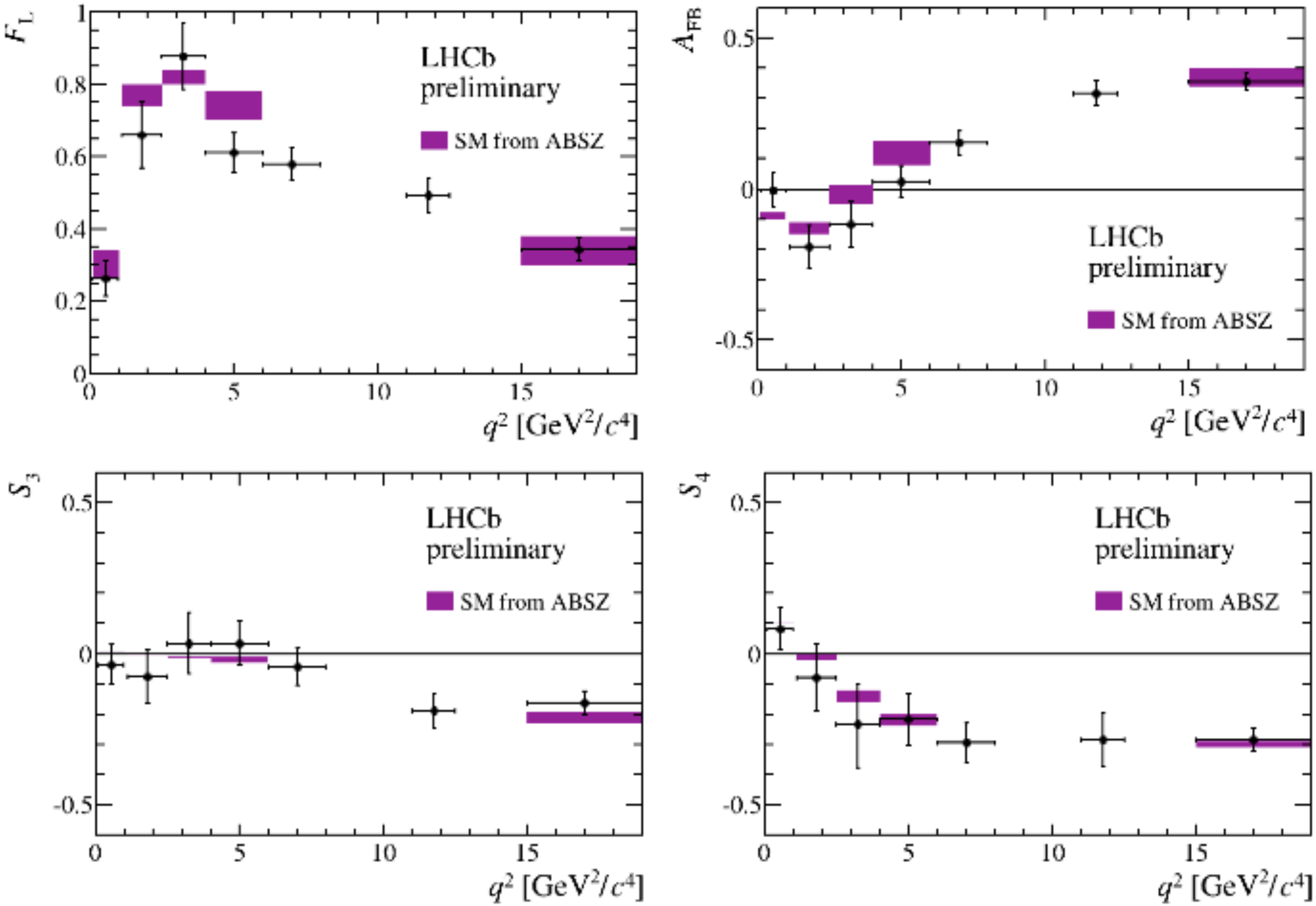




Full q^2 range: 2398 ± 57 events

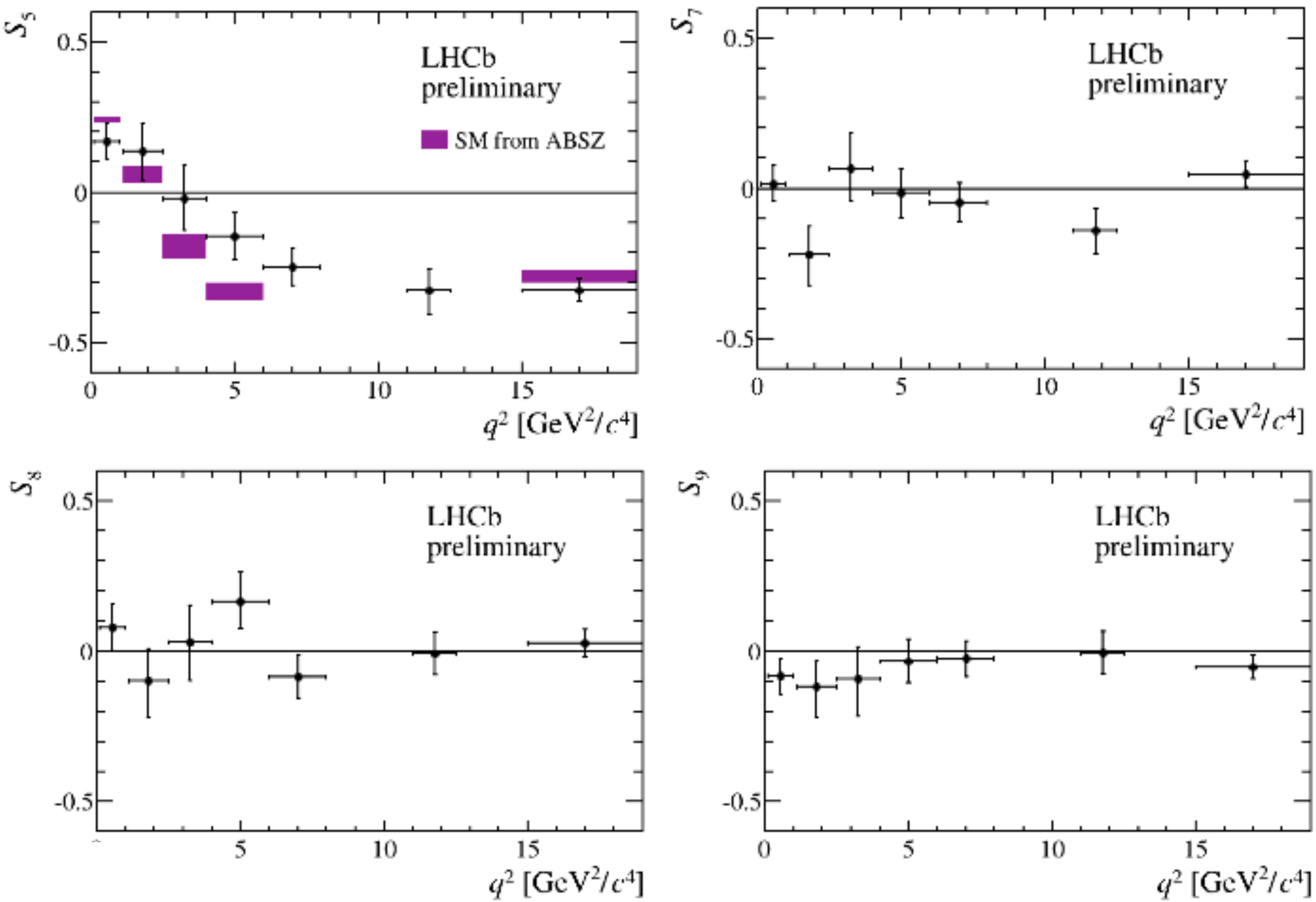
Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

LHCb-CONF-2015-002



Rare $B^0 \to K^{*0}(\to K^+\pi^-)\,\mu^+\mu^-$ decays

LHCb-CONF-2015-002



Rare $B^0_s \to \phi(\to K^+K^-)\,\mu^+\mu^-$ decays

JHEP09 (2015) 179