RECENT RESULTS ON B- PHYSICS AND MULTIQUARK STATES FROM LHCb

Helmholtz International Summer School
"Physics of Heavy Quarks and Hadrons":
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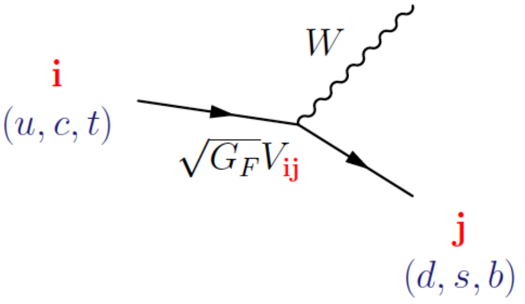
on behalf of the LHCb Collaboration

Quark flavour mixing



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

V_{CKM} originates from MISALIGNMENT between UP and DOWN quark couplings to the Higgs boson

$$-\mathcal{L}_Y^q = Y^D \bar{Q}_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_R + Y^U \bar{Q}_L \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix} U_R + H.C. \qquad Y^U \neq Y^D \qquad V_{CKM} = U_L^{U+} U_L^D$$

- The Kobayashi-Maskawa (KM) mechanism introduces CP violation in the SM
  - it is the only source of CP violation in the SM, in absence of neutrino masses or θ_{QCD}
- CKM matrix has minimal flavour violation
  - extended theories do not replicate in general such flavour structure
- KM theory is highly predictive
  - huge range of phenomena, over many orders of magnitude in energy with only 4 independent parameters (not including quark masses)

The Kobayashi-Maskawa theory

- The CKM matrix must be UNITARY for a *fixed number of quark generations* (e.g. 3) : $V_{CKM}^{+} = V_{CKM}$
- Which provides many relationships, such as TRIANGLES :

$$\overset{1\cdot\lambda^3}{V_{ud}V_{ub}^*} + \overset{\lambda\cdot\lambda^2}{V_{cd}V_{cb}^*} + \overset{\lambda^3\cdot 1}{V_{td}V_{tb}^*} = 0 \quad \overset{\lambda\cdot\lambda^3}{V_{us}V_{ub}^*} + \overset{1\cdot\lambda^2}{V_{cs}V_{cb}^*} + \overset{\lambda^2\cdot 1}{V_{ts}V_{tb}^*} = 0 \quad \overset{1\cdot\lambda}{V_{ud}V_{us}^*} + \overset{\lambda\cdot 1}{V_{cd}V_{cs}^*} + \overset{\lambda^3\cdot\lambda^2}{V_{td}V_{ts}^*} = 0$$

- Consistency of measurements in various triangles *are* tests of the Standard Model providing MODEL-INDEPENDENT CONSTRAINTS on new physics.

  Only one independent phase , but 4 measurable combinations can be formed of the type $V_{\alpha i}V_{\alpha j}{}^{*}V_{\beta j}V_{\beta i}{}^{*}$

  (the 6 individual quark phases are not measurable)

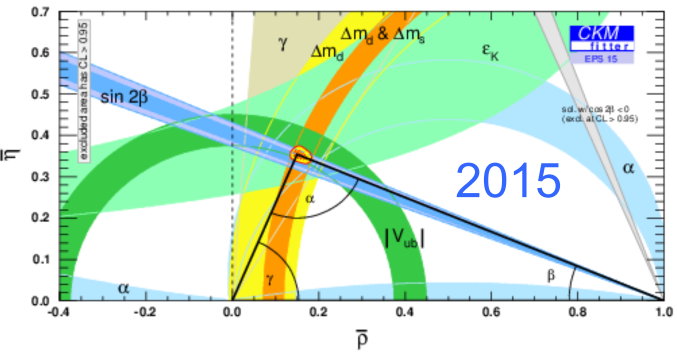
- Two phases characterize the first triangle:

  $\beta \equiv \arg\left[-V_{cd}V_{cb}^*/(V_{td}V_{tb}^*)\right]$ (this talk)

  $\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)\right]$ (backup slides)

  LHCb has performed a new measurement:

  $\gamma = (70.9\,^{+7.1}_{-8.5})^{\circ}$ of unique importance for SM tests LHCb-CONF-2016-001



- The triangles with very short sides later in this talk ($\beta_s \equiv \arg\left[-V_{ts}V_{tb}^*/(V_{cs}V_{cb}^*)\right]$)

Two roads to travel the new physics path

NEW HEAVY PARTICLES
remain in the vacuum
and produce visible effects
through quantum fluctuations

RARE DECAYS
do they conform loop
corrections within the SM?

CP VIOLATION
Baryogenesis in the
early universe requires
new cources of CPV
(not necessarily in quark sector)
Is KM theory perturbed?

NEUTRINOS
SM already broken in this sector
CPV now realistic with sizable θ_{13}

NP
territory

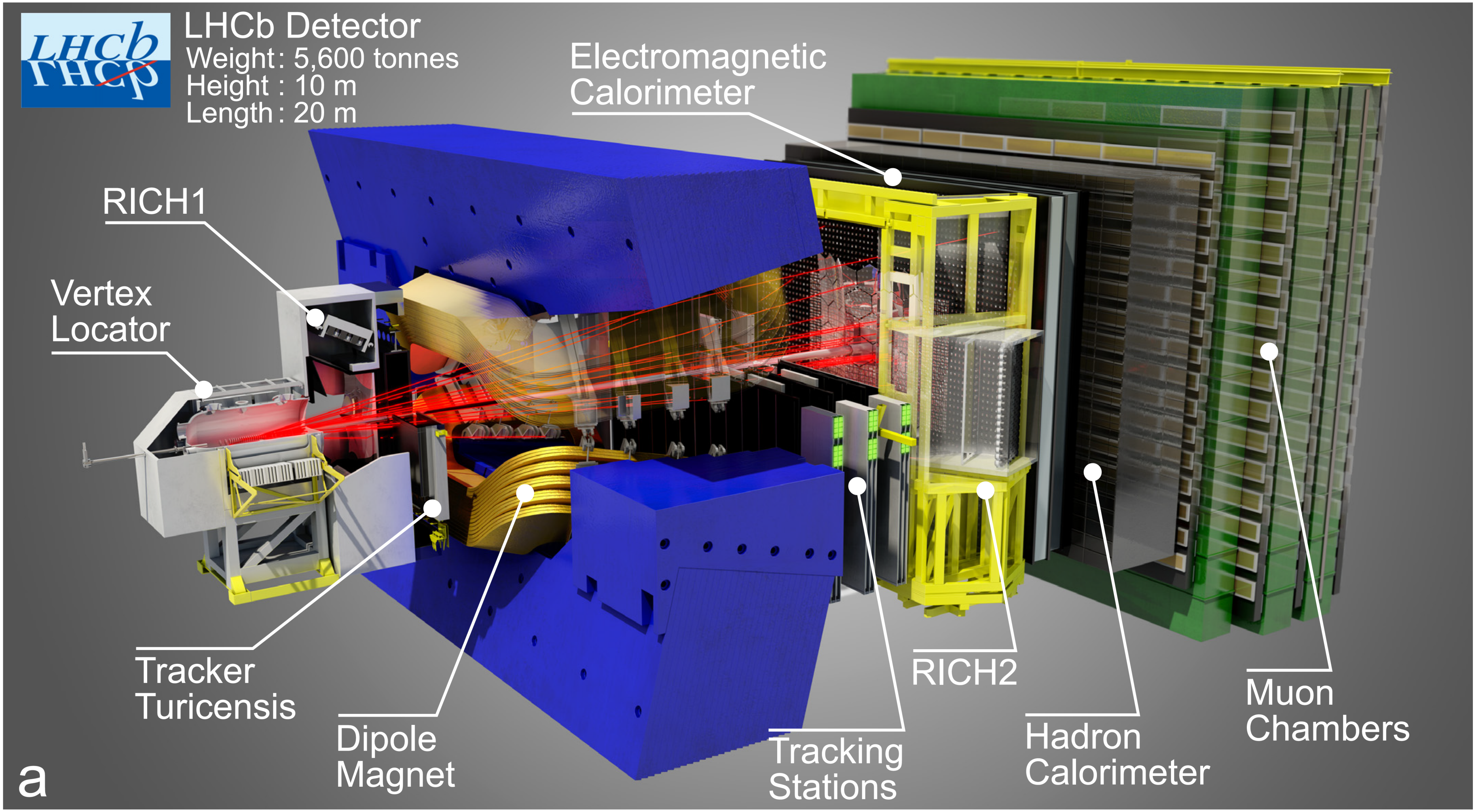
leaky
SM

NEW HEAVY PARTICLES
extracted from the vacuum
into the laboratory on
their mass shell

Measure masses
and couplings of
SUSY particles,
LEPTOQUARKS,
new HIGGSES,
heavy NEUTRINOS
vector-like quarks, etc

If within reach, ATLAS and CMS will determine the spectrum of the new particles

The LHCb apparatus



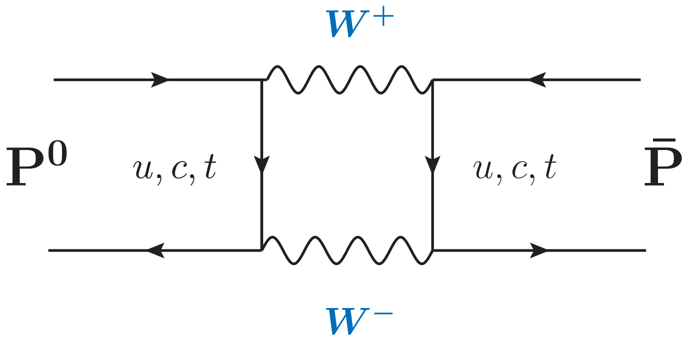
The LHCb detector at the LHC, JINST 3 (2008) S08005

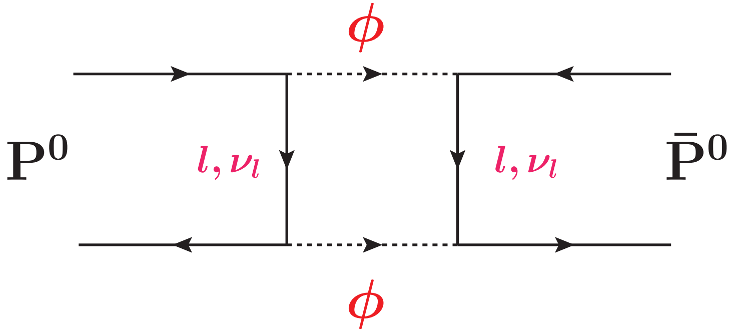
PART I

NEUTRAL MESON MIXING AND CP VIOLATION

The neutral mesons

- Only 4 long-lived neutral mesons exist in Nature: **K^0, D^0, B^0** and **B^0_s**, since the t-quark does not live long enough.
- They all undergo particle (P^0) / antiparticle ($\bar{P}^0$) oscillation. In the SM, it is dominated by *loop diagrams with $W^\pm$ and t-quark* (*b-quark for D^0*). Beyond the SM, new heavy particles may enter the loop. e.g. leptoquarks *Φ*, or other:





- *Oscillation parameters can be accurately measured*, they PROBE HIGH MASSES IN VACUUM, are important assets to constrain new physics models.
- Forward production at the LHC is an extremely powerful factory for these mesons, in addition to e^+e^- $\Upsilon(4s)$ machines. CP-violation was discovered on the K^0 (1963), and the B^0 provided essential ground for Kobayashi-Maskawa theory (2001). LHCb can add precision, specially with new sources, as B^0_s and D^0.

The mixing matrix

- So quantum loops create the high (*H*) and low (*L*) mass eigenstates ($p, q \in \mathbb{C}$) :

$$|P_{H,L}\rangle \equiv p|P^0\rangle + q|\bar{P}^0\rangle \qquad |P_{H,L}(t)\rangle = e^{-im_{H,L}t}e^{-\Gamma_{H,L}t/2}|P_{H,L}(0)\rangle$$

- Which generate oscillation of the flavor states:

$$|\psi(t)\rangle = \psi_1(t)|P^0\rangle + \psi_2(t)|\bar{P}^0\rangle \quad \text{with} \quad i\frac{d}{dx}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \left(\mathcal{M} - \frac{i}{2}\mathit{\Gamma}\right)\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

- Under CPT invariance , the mixing matrix $\mathcal{R} = \left(\mathcal{M} - \frac{i}{2}\mathit{\Gamma}\right)$ has 5 real observables: $m_H, m_L, \Gamma_H, \Gamma_L$, and ϕ with $\Delta m \equiv m_H - m_L \quad \Delta\Gamma \equiv \Gamma_L - \Gamma_H$:

$$\mathcal{M} = \begin{pmatrix} m_H & M_{12} \\ M_{12}^* & m_L \end{pmatrix} \qquad \mathit{\Gamma} = \begin{pmatrix} \Gamma_H & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_L \end{pmatrix} \qquad \phi = \arg\left(M_{12}^*\Gamma_{12}\right) \quad \text{CP} - \text{violating}$$

- The oscillation is a **QUANTUM CLOCK** , generic to the $\mathrm{P}^0 - \bar{\mathrm{P}}^0$ system, that needs to be stopped with the observation of the meson decay at a given time t.
- Theory (EW + QCD) and experiment should independently determine the mixing matrix observables. Technically, the experiment requires to choose a particular final state.

The CP-violation observables

- If the chosen mode is SELF-TAGGING (only accesible from $P^0\,(+)$ or $\bar{P}^0\,(-)$), and we perform flavor tagging at t=0, time evolution for mixed flavor is:

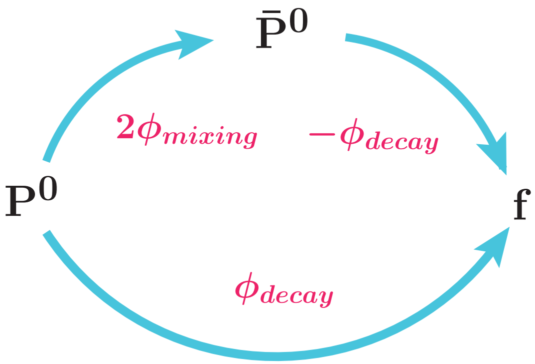
$$\Gamma_{\text{mixed}}(t) = |\overset{(-)}{A}|^2 \left|\frac{q}{p}\right|^{\pm 1} \frac{e^{-\Gamma t}}{2}\left[\cosh(\Delta\Gamma t/2) \pm \cos(\Delta m t)\right]$$

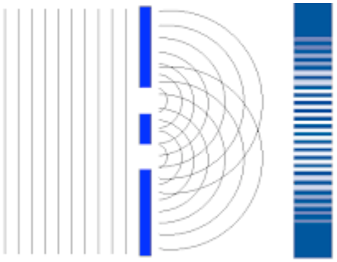
- If a CP-EIGENSTATE is chosen, then **INTERFERENCE** between the mixing and the decay amplitudes: $A_f\ (P^0 \to f)$ and $\bar{A}_f\ (\bar{P}^0 \to f)$ happens, governed by the complex number:

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

CP conservation $\Leftrightarrow |\lambda_f| = 1$

$$\text{phase}(\lambda_f) = 2\left(\phi_{decay} - \phi_{mixing}\right)$$





antiparticle goes backward in time

- The corresponding time evolution, with t=0 tagging, is then:

$$\Gamma_{\pm}(t) = |A|^2 \left|\frac{p}{q}\right|^{0,1} \frac{e^{-\Gamma t}}{2}(H \pm I)$$

$$H = \left(1 + |\lambda_f|^2\right)\cosh\left(\Delta\Gamma t/2\right) - 2\text{Re}(\lambda_f)\sinh\left(\Delta\Gamma t/2\right)$$

$$I = \left(1 - |\lambda_f|^2\right)\cos\left(\Delta m t\right) + 2\text{Im}(\lambda_f)\sin\left(\Delta m t\right)$$

Measurement of Δm_d for B^0 meson

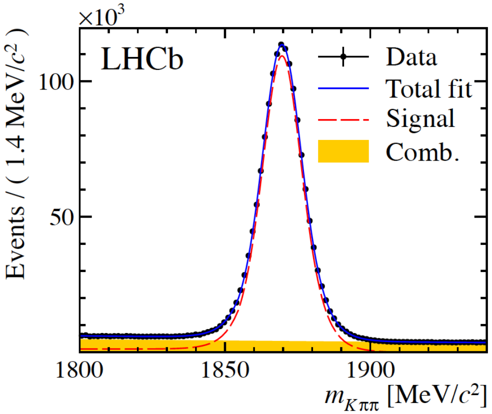
- The decays $B^0 \to D^- \mu^+ \nu_\mu X \quad D^- \to K^+\pi^-\pi^-$ and $B^0 \to D^{*-} \mu^+ \nu_\mu X \quad D^{*-} \to \bar{D}^0 (K^+\pi^-)\pi^-$ are chosen at LHCb for their high branching fraction (b → c) and efficient μ-ID
- Huge statistical samples ($\sim 2 \times 10^6$ D^0) were collected with 3 fb^{-1}, with excellent mass resolution
- The proper decay time of the B^0 meson is calculated as:

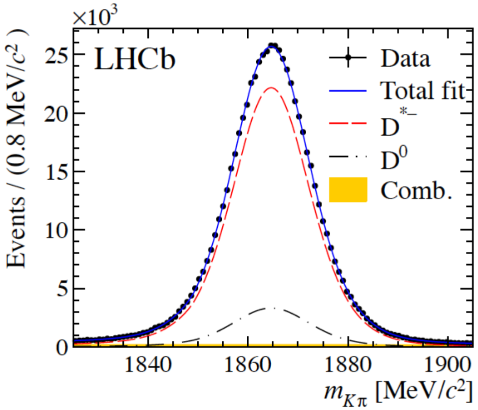
$$t = \frac{M_{B^0} \cdot L \cdot k}{p_{\rm rec}}$$

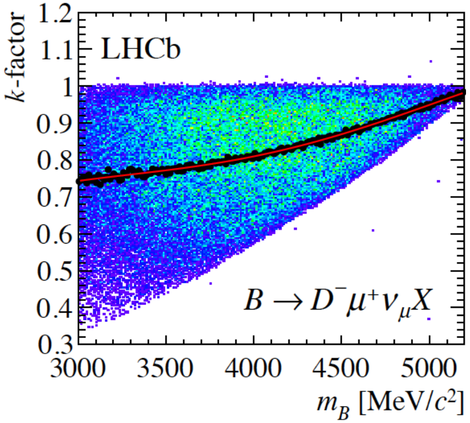
L = decay path (at the vertex detector)
$p_{\rm rec}$ = visible momentum (missing neutrino)

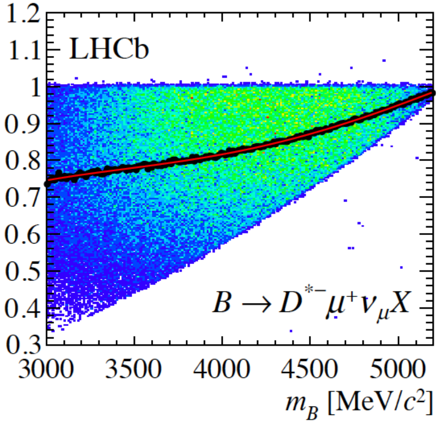
- The correction factor $k = \langle p_{\rm rec} / p_{\rm true} \rangle$ originates from the undetected neutrino, and it is accurately described by the simulation. It degrades time resolution only slightly (75 fs)

LHCb collaboration, R. Aaij et al. arXiv:1604.03475 (2016)









Measurement of Δm_d for B^0 meson

- The flavor (B^0 or $\bar{B}^0$) is identified both at production time (t = 0) and at decay time (self-tagging modes), so that:

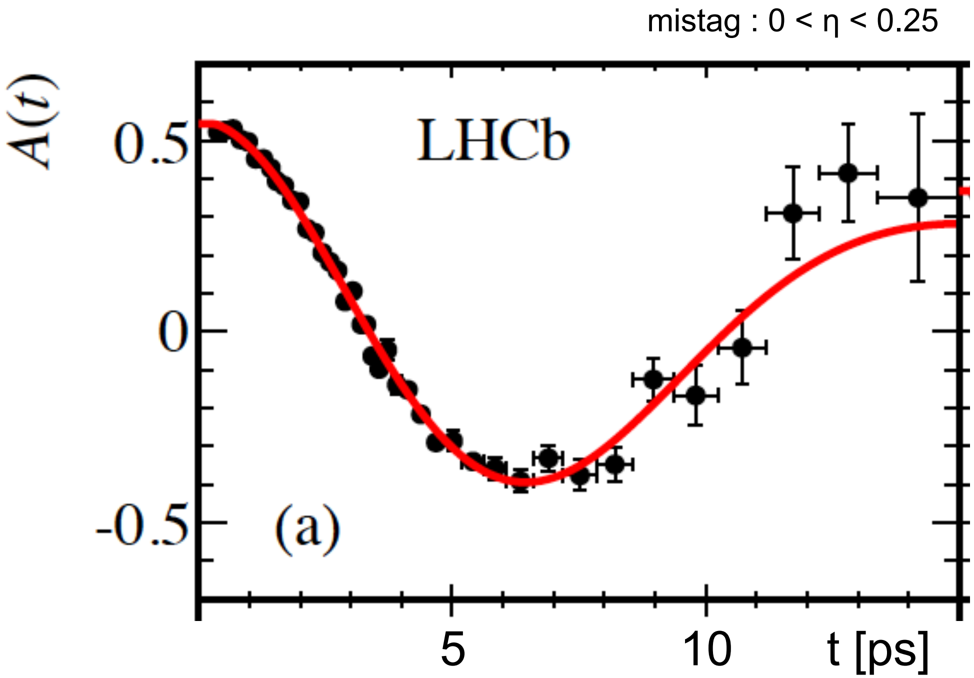
$$N^{\text{unmix}}(t) = N\left(B^0 \to D^{(*)-}\mu^+\nu_\mu X\right)(t) \propto e^{-\Gamma_d t}\left[1+\cos(\Delta m_d t)\right]$$

$$N^{\text{mix}}(t) = N\left(B^0 \to \bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu X\right)(t) \propto e^{-\Gamma_d t}\left[1+\cos(\Delta m_d t)\right]$$

$$A(t) = \frac{N^{\text{unmix}} - N^{\text{mix}}}{N^{\text{unmix}} + N^{\text{mix}}} = \cos(\Delta m_d t)$$

- Flavor tagging at t = 0 is decided using information from the other b hadron present in the event (charge of leptons, kaons, detached vertex)
- Overall tagging power is 2.46 ± 0.04 % in 2012 for D^-, and similarly for other samples
- World's most precise, in agreement with previous measurements, and very constraining for NP models

LHCb collaboration, R. Aaij et al. arXiv:1604.03475 (2016)



$$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\,\text{ps}^{-1}$$

Measurement of Δm_s for B^0_s meson

$$B^0_s - \bar{B}^0_s$$

- The B^0_s shows the HIGHEST OSCILLATION FREQUENCY of all neutral mesons. Governed by tree-level diagrams with t-quark, Δm_s is a crucial ingredient in searches for physics beyond the SM

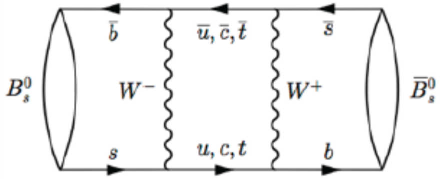
- Measurement requires SUB-PICOSECOND decay time resolution σ_t , which at LHCb ($\sigma_t = 44$ fs) is provided by a powerful vertex detector, and the strong forward Lorentz boost at the LHC.

$$\Gamma(t) \propto \Gamma_s e^{-\Gamma_s t} \tfrac{1}{2} \left[\cosh\left(\Delta\Gamma_s t/2\right) + \cos\left(\Delta m_s t\right)\right]$$

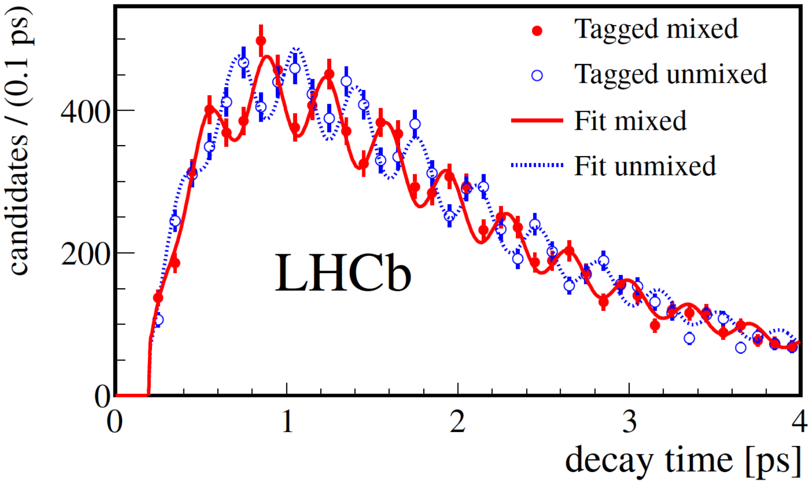
- As for B^0 meson, t = 0 flavor tagging comes from opposite-side charged particles, improved with same-side particles (total power ≈ 3.5 %)

$B^0_s \to D^-_s \pi^+$ $\quad D_s \to \phi(K^+K^-)\pi^-, K^{*0}(K^+\pi^-)K^-, K^-\pi^+\pi^-$

Difference between the two mass eigenstates:
$\Delta m_s = m_H - m_L$



LHCb collaboration, R. Aaij et al. N. J. Phys. 15 (2013) 053021



$$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$$

Only $1\,\mathrm{fb}^{-1}$, still the most precise measurement to date

CP violation in B^0 and B^0_s mixing

- In B^0 (q=d) and B^0_s (q=s) oscillation, the 3 real observable quantities of the mixing matrix

$$q = d, s \quad |\mathrm{M}^q_{12}| \;, |\Gamma^q_{12}| \;, \phi_q \equiv \arg\left(-\frac{\mathrm{M}^q_{12}}{\Gamma^q_{12}}\right)$$

can be obtained univocally from:

$$\mathcal{M} = \begin{pmatrix} m_H & M_{12} \\ M^*_{12} & m_L \end{pmatrix} \qquad \mathit{\Gamma} = \begin{pmatrix} \Gamma_H & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_L \end{pmatrix}$$

a) the mass difference $\Delta \mathrm{M}_q \approx 2|\mathrm{M}^q_{12}|$

b) the width difference $\Delta\Gamma_q \approx 2|\Gamma^q_{12}|\cos\phi_q$

c) the SEMILEPTONIC ASSYMMETRY

$$\frac{N(\bar{B}) - N(B)}{N(\bar{B}) + N(B)} \approx a^q_{SL} = \frac{|\Gamma^q_{12}|}{|\mathrm{M}^q_{12}|}\sin\phi_q = \frac{\Delta\Gamma_q}{\Delta \mathrm{M}_q}\tan\phi_q$$

- Any new physics (NP) deviations from the SM are described by a complex number:

$$\mathrm{M}^q_{12} \equiv \mathrm{M}^{q,SM}_{12}\Delta^{NP}_q \quad \text{with} \quad \Delta^{NP}_q = |\Delta^{NP}_q|\, e^{i\phi^{NP}_q}$$

- Such "new physics situation" happened in 2010 after the precision measurement by the D0 detector at Fermilab of $a_{SL} = (-9.75 \pm 2.51 \pm 1.41) \times 10^{-3}$ from the asymmetry of the SAME SIGN dimuons:

$$a_{SL} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

D0 collaboration, V. M. Abazov et al., PRL 105 (2010) 081801

Note the measurement exploits, in $p\bar{p}$ collisions, a CP-symmetric INITIAL state

CP violation in B^0 and B^0_s mixing

- What can we say *today* about this NP situation? Both LHC experiments (pp collider) and B-factories (e^+e^-) tried to reproduce this (challenging) measurement
- LHCb has been able to disentangle the components related to B^0_s (q=s) and B^0 (q=d) mesons, using semileptonic decays

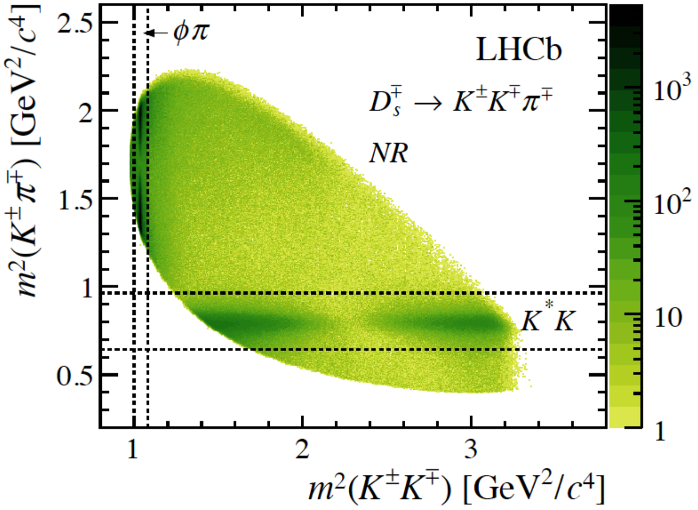
LHCb collaboration, arXiv: 1605.09768 (2016), submitted to PRL
LHCb collaboration, Phys. Rev. Lett. 114, 041601 (2015)

- The chosen modes were:

$$B^0_s \to D^-_s \mu^+ \nu_\mu X \quad D^-_s \to K^+ K^- \pi^-$$

$$B^0 \to D^- \mu^+ \nu_\mu X \quad D^- \to K^+ \pi^- \pi^-$$

$$B^0 \to D^{*-} \mu^+ \nu_\mu X \quad D^{*-} \to \bar{D}^0 (K^+ \pi^-) \pi^-$$



- In both cases the *SL* asymmetry was defined:

$$a_{SL} = \frac{\Gamma(\bar{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\bar{B} \to f) + \Gamma(B \to \bar{f})}$$

- The untagged time-integrated asymmetry is: $a_{SL} = 2A_{raw}$ (mixed + unmixed)
- In B^0_s the high oscillation frequency Δm_s reduces the effect of the small production asymmetry by factor 10^{-3}. Detection and background asymmetries are fully assessed.

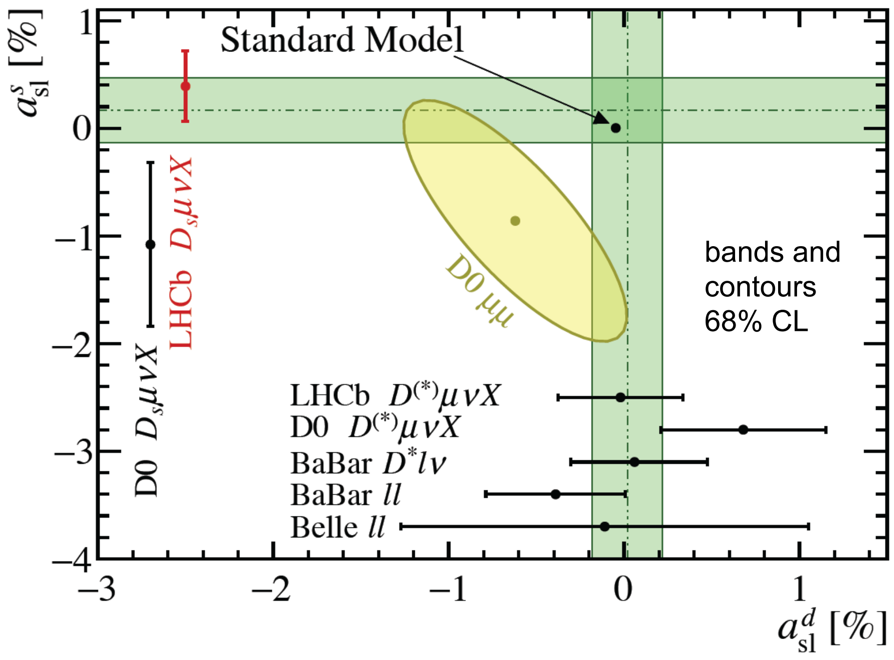
Summary CPV in B^0 and B^0_s mixing

- Final LHCb values are the most precise to date, compatible with other measurements:

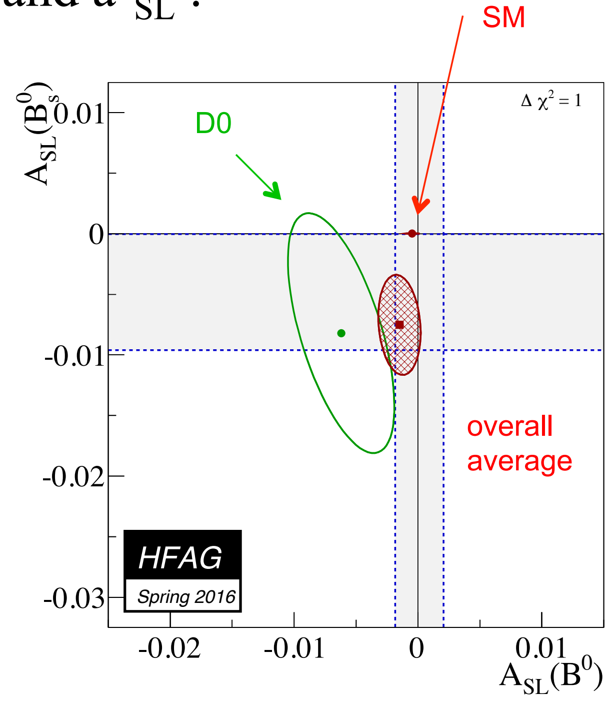
  $a^s_{SL} = (0.39 \pm 0.26\ (\mathrm{stat}) \pm 0.20\ (\mathrm{syst}))\ \%$ LHCb collaboration, arXiv: 1605.09768 (2016), submitted to PRL

  $a^d_{SL} = (-0.02 \pm 0.19\ (\mathrm{stat}) \pm 0.30\ (\mathrm{syst}))\%$ LHCb collaboration, Phys. Rev. Lett. 114 041601 (2015)

- Summary of existing measurements of a^s_{SL} and a^d_{SL} :



bands and contours 68% CL



SM

D0

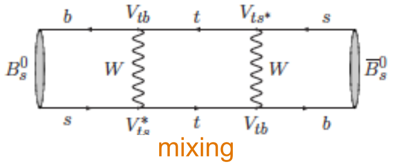
overall average

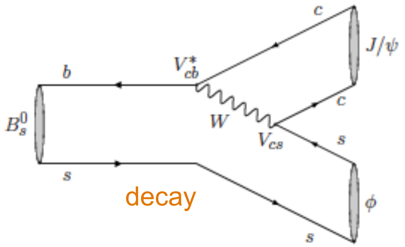
D0 μμ included in average

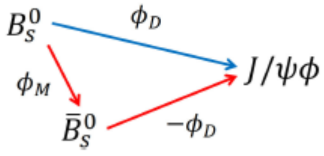
- There is consistency with the SM prediction, and among the measurements (the puzzle has virtually disappeared)

The CP-violating phase β_s

- Essential test of CKM unitarity on the triangle: $\overset{\approx 0}{V_{us}V_{ub}^*} + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ of a very short side, only accesible to hadron colliders. The tree-level decay: $B^0_s \rightarrow J/\psi\phi$ provides normalization for the SM, while new particles may still contribute to the mixing







- Mixing/decay interference with CP-eigenstates, key complex number: $\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$

$$\phi_s = -\arg(\lambda_f) = \phi_M - 2\phi_D = -2\beta_s = -2\arg\left(\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right)$$

$$A_{CP}(t) = \frac{\Gamma_{B_s^0} - \Gamma_{\bar{B}_s^0}}{\Gamma_{B_s^0} + \Gamma_{\bar{B}_s^0}} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

$$\left(C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \quad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \quad A_{\Delta\Gamma} \equiv \frac{-2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2} \right)$$

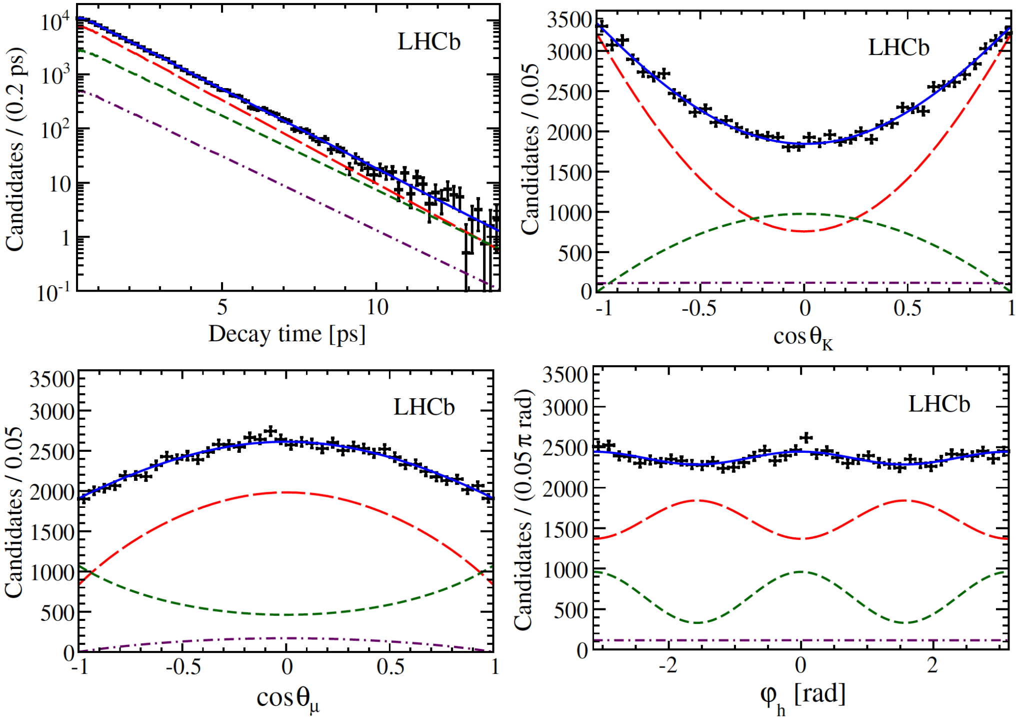
- The $J/\psi\phi$ is the main goal for β_s by LHCb, complemented with several other B^0_s CP-eigenstates sensitive to β_s from mixing/decay interference with *loop* decays:

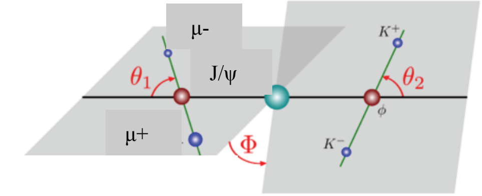
$$B_s^0 \to D_s^+ D_s^- \quad B_s^0 \to \phi\phi \quad B_s^0 \to K^{*0}\bar{K}^{*0}$$

- SM error really small: $\phi_s^{c\bar{c}s} = -2\beta_s = -37.6^{+0.8}_{-0.7}$ mrad CKMfitter PRD 84 (2011) 033005

β_s measurement by LHCb

LHCb collaboration, R. Aaij et al. PRL 114 (2015) 041801





$$\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$$

$$\Delta m_s = 17.711\,^{+0.055}_{-0.057} \pm 0.011 \text{ ps}^{-1}$$

$$\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1}$$

$$\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1}$$

$$|\lambda| = 0.964 \pm 0.019 \pm 0.007$$

CP – even

CP – odd

S – wave$(K\pi)$

- Fit decay time and helicity angles, result *consistent with SM* (no direct CPV |λ|=1)
- LHCb tagging power: (3.73 ± 0.019 ± 0.007) % Decay time resolution ≈ 46 fs
- Most precise $\phi_s^{c\bar{c}s}$ to date. Additional measurement from $B_s^0 \to J/\psi\,\pi^+\pi^-$ gives:

  $\phi_s^{c\bar{c}s} = 50 \pm 69 \pm 8$ mrad , combination: $\phi_s^{c\bar{c}s} = -10 \pm 39$ mrad

Current status of β_s

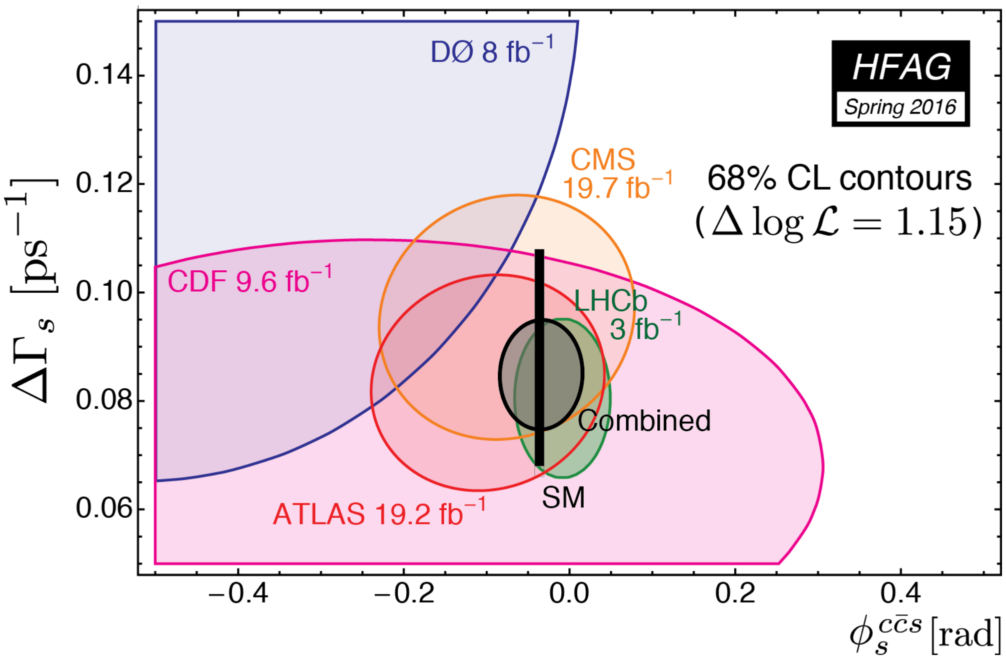
- A significant effort on ϕ_s and $\Delta\Gamma_s$ for the B^0_s meson has been focused by LHCb, in a major test of the Kobayashi-Maskawa theory of the SM

- World averaged values are:

$\phi_s^{ccs} = -33 \pm 33$ mrad

$\Delta\Gamma_s = 83 \pm 6\ \text{ns}^{-1}$

SM $\left\{ \begin{array}{l} \phi_s^{ccs} = -37.6 \pm 0.8 \text{ mrad} \\ \Delta\Gamma_s = 88 \pm 20\ \text{ns}^{-1} \end{array} \right.$



see also M. Artuso, G. Borisov, A. Lenz, arXiv: 1511.09466, CKMfitter PRD 84 (2011) 033005

Further improvement will require assessment of higher order corrections, related to penguin diagrams. Some estimates on ϕ_s^{ccs} pollution have been made by relating mirror channels under SU(3) rotations, yielding < 21 mrad.

LHCb collaboration, JHEP 11 (2015) 082, K. De Bruyn R. Fleischer, JHEP 03 (2015) 145

sin(2β) from B⁰→J/ψK⁰ₛ

- LHCb has newly measured the phase

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

that, TOGETHER WITH γ, completes the standard CKM unitarity triangle:

$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^*$$

- The β-phase had great historical importance, since it provided the first evidence of CPV in the b-quark sector (BaBar-Belle, 2001), in the golden CP-eigenstate:

$$B^0 \to J/\psi K_s^0$$

- LHCb has analysed the time evolution of the asymmetry:

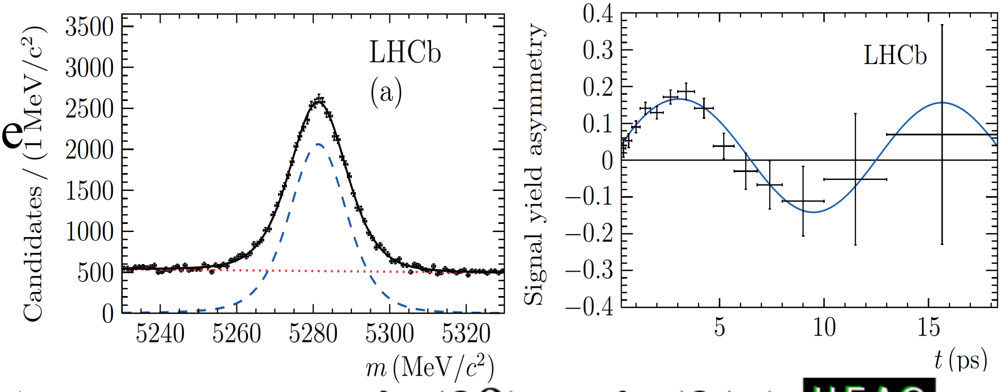
$$A(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} = S\sin(\Delta m t) - C\cos(\Delta m t)$$

with 41500 $B^0 \to J/\psi K_s^0$ decays:

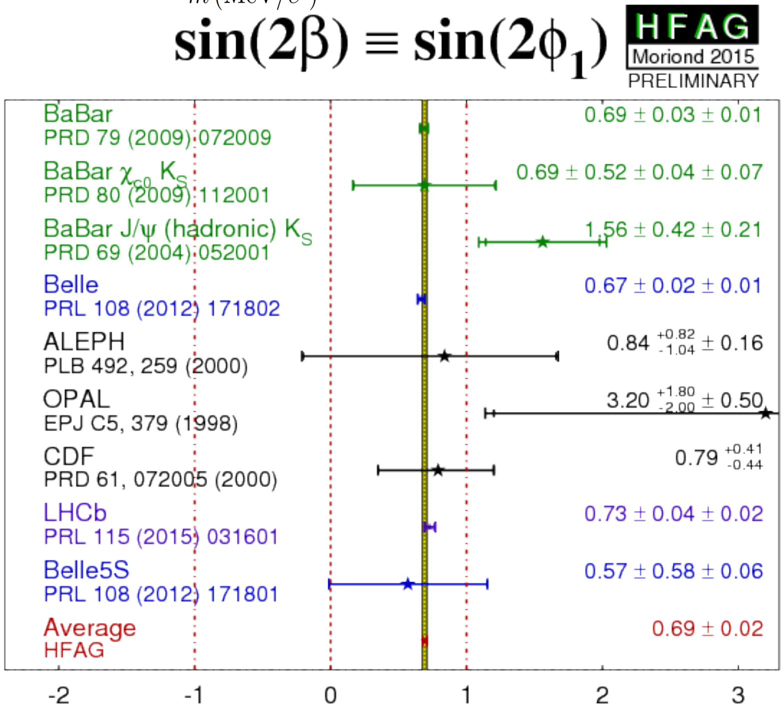
$$S = \sin(2\beta) = 0.731 \pm 0.035(\mathrm{stat}) \pm 0.020(\mathrm{syst})$$

$$C = -0.038 \pm 0.032(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

LHCb collaboration, PRL 115, 031601 (2015)



$\sin(2\beta) \equiv \sin(2\phi_1)$



CPT non conservation

- Is CPT violated? This would imply Lorentz non invariance

  (see O. Greenberg, Phys. Rev. Lett. 89 (2002) 231602)

- The SU(3)×SU(2)×U(1) SM of gauge interactions is believed to be the low-energy limit of a more fundamental theory with *gravity*. String theories involve interactions that could destabilize the vacuum, and spontaneously generate a VEV≠0 of Lorentz tensors. This is the so-called Standard Model Extension : SME

  D. Colladay and V. A. Kostelecky, Phys. Rev. D58 (1998) 116002

- The natural scale for a gravity theory is the Planck mass $M_P = 1.22 \times 10^{19}\ GeV/c^2$ so at collider experiments we should aim at effects $m_W/M_P \simeq 10^{-17}$
  Is this feasible at all?

- In neutral meson oscillation, the quantum frequencies are accurately measured. Could the masses and lifetimes of the B^0 and $\bar{B}^0$ mesons NOT be equal ? In other words : is the *complex number* $\delta m + i\delta\Gamma/2$ non zero?

$\delta m \equiv (M_{11} - M_{22})/2 \quad \delta\Gamma \equiv (\Gamma_{11} - \Gamma_{22})/2$ DIAGONAL elements of the mixing matrix $\mathcal{M} - \frac{i}{2}\Gamma$

CPT non conservation at LHCb

- The eigenstates: $p, q \in \mathbb{C}$
$$\begin{cases} |B_L\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle \\ |B_H\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle \end{cases}$$
will generate an observable phase angle shift in the B/ $\overline{\mathrm{B}}^0$ asymmetry oscillation, for $z \neq 0$. Our sensitivity relies on the ratio $z = \dfrac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2}$. The denominator is quite small as compared to $M_{B^0_{(s)}}$, and the real figure of merit is $r = \Delta m \,/\, M_{B^0_{(s)}}$.
Note: $\Delta m \lesssim 2.1 \times 10^{-3}\ eV/c^2$ $\Delta\Gamma \lesssim 0.4 \times 10^{-3}\ eV$ $M_{B^0{}_{(s)}} \approx 5.3\ GeV/c^2$

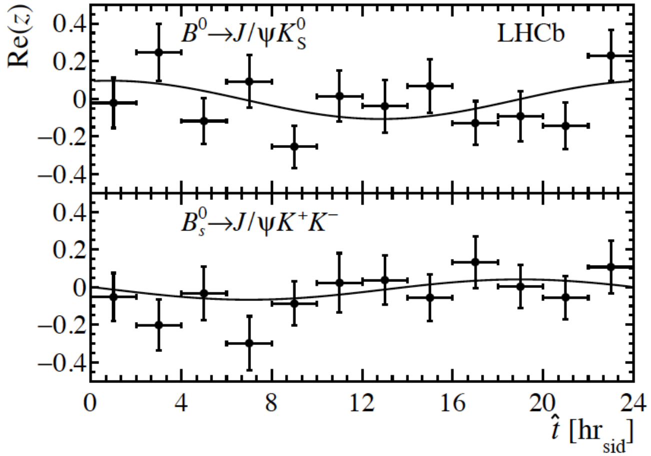
- In the SME Lagrangian, Lorentz-violating terms are introduced for the fermions with coefficients a_μ ($-\,a_\mu$ for antifermions). For a $(q_1, \bar{q}_2)$ meson the coefficient is $\Delta a_\mu = a_\mu^{q_1} - a_\mu^{q_2}$, and *z* depends on the 4-velocity $\beta^\mu = \gamma(1, \vec{\beta})$ of the meson, as
$$z \simeq \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

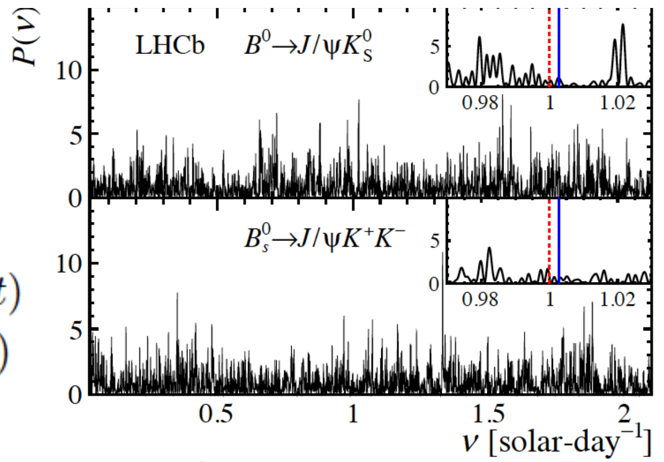
- So at LHCb there is a further ×20 enhancement in sensitivity to Δa_μ ,with $\langle\gamma\beta\rangle \approx 20$
In the SME Δa_μ is *real* , so that : $\mathrm{Im}(z)/\mathrm{Re}(z) = (1/2)\Delta\Gamma/\Delta m$

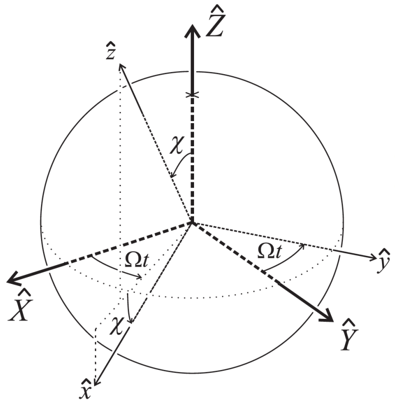
LHCb result on CPT non conservation

R. Aaij et al. , LHCb Collaboration, Phys. Rev. Lett. 116 (2016) 241601

- CP-eigenstates were chosen for B^0 and B^0_s mesons : $B^0 \to J/\psi K^0_s$ $\quad B^0_s \to J/\psi K^+K^-$. Corrections to $\frac{d\Gamma_f}{dt}$ for $z\neq 0$ are *known*, and deviations from $z=0$ fitted.
- Sidereal coordinates (fixed stars) were used, with LHCb beam location on Earth's rotating frame. The $B^0/\bar{B}^0$ mass difference should depend periodically on sidereal time. A wide frequency search was performed, referred to day/night correlations.
- No significant periodicities found, and Δa_μ was determined, for B^0 and B^0_s , with precisions $\mathcal{O}\left(10^{-15}\right) GeV$ and $\mathcal{O}\left(10^{-14}\right) GeV$ respectively.







For B^0_s :

$$\mathrm{Re}(z) = -0.022 \pm 0.033(stat) \pm 0.005(syst)$$
$$\mathrm{Im}(z) = 0.004 \pm 0.011(stat) \pm 0.002(syst)$$

10^3 improvement on B^0 existing measurements by BaBar and × 10 improvement on B^0_s measurements by D0

PART II

PROBING THE FLAVOUR STRUCTURE OF THE SM :

New operators in b→ s μμ ?

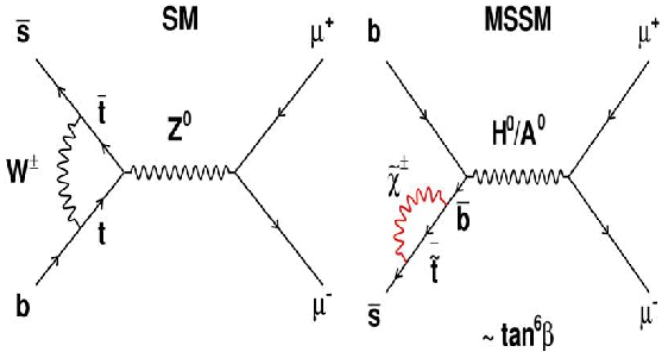
Lepton universality, or LFV?

Minimal Flavor Violation MFV?

$B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

- $B \rightarrow \mu^+\mu^-$ decays are an extremely sensitive field to New Physics models

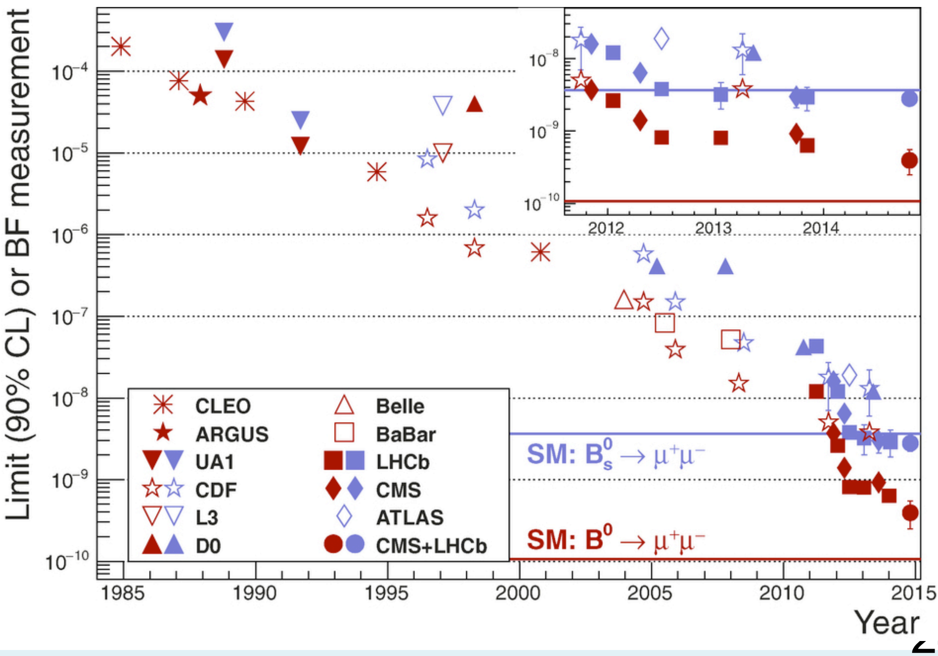
  Very suppressed (10^{-9}-10^{-10}) in SM due to:
  - ❑ GIM mechanism / CKM unitarity
  - ❑ Helicity suppression (left-handed $W^\pm$)
  - ❑ Smallness off-diagonal CKM elements (minimal flavor violation)
  - + dominated by short-distance interactions



Features not generally respected by generic extensions !

Painstakingly searched for over 30 years ...

Nature Letter 522 (2015) 68



- Predictions are sharp:

  $B(B_s \rightarrow \mu^+\mu^-)_{SM} = (3.66 \pm 0.23)\times 10^{-9}$

  $B(B^0 \rightarrow \mu^+\mu^-)_{SM} = (1.06 \pm 0.09)\times 10^{-10}$

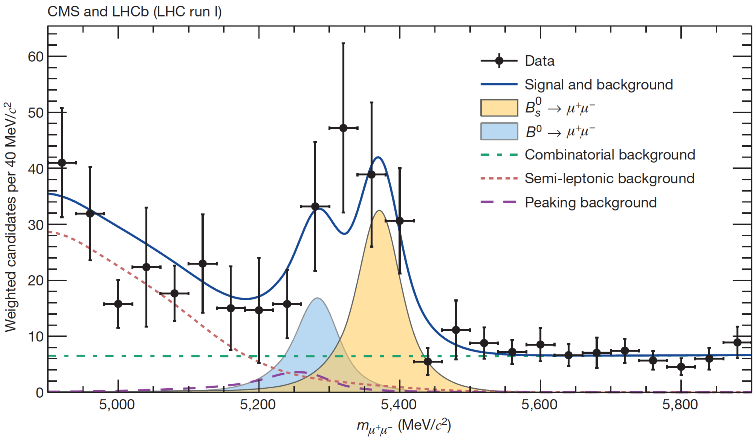
- Exemplary sensitivity for SUSY:

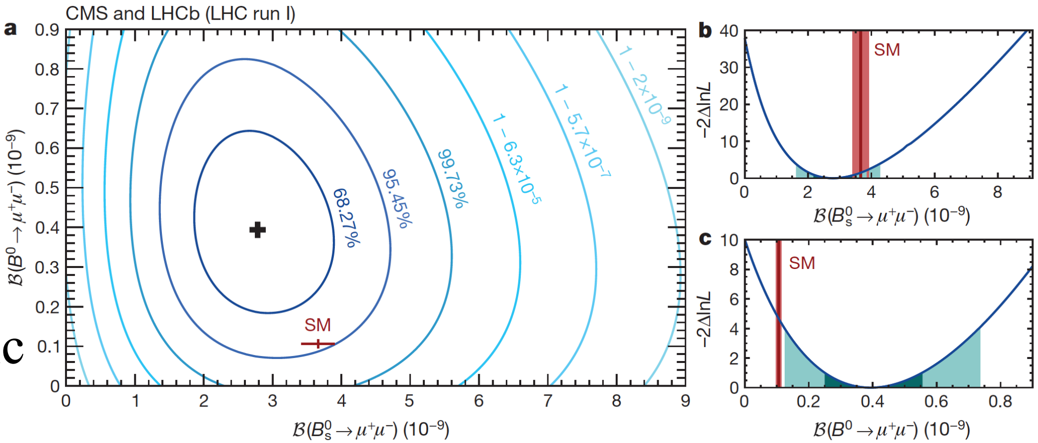
  $B(B_s \rightarrow \mu^+\mu^-) \approx (\tan\beta)^6/M_{A0}$

$B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

- LHCb / CMS collaborative effort
  - completely different geometrical coverage with respect to LHC beams
  - experiments designed for different purposes: higher instantaneous $\mathcal{L}$ at CMS compensates for lower low-mass dimuon efficiency and resolution
- Combination of CMS and LHCb data results in the discovery of $B_s \rightarrow \mu^+\mu^-$, and in a 3σ effect for $B^0 \rightarrow \mu^+\mu^-$
- Results consistent with SM at −1.2σ and +2.2σ level
- Global analyses of Wilson coefficients, including other leptonic and semileptonic observables, are needed to pin down new physics operators

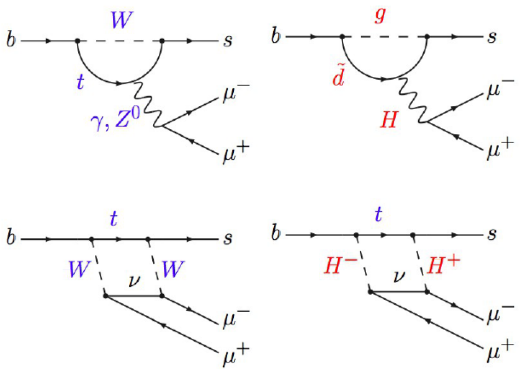
Nature Letter 522 (2015) 68





A NEW PHASE OF PRECISION MEASUREMENTS IS INITIATED

Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$



- Rare $b \rightarrow s \mu^+\mu^-$ FCNC only allowed in the SM by calculable electroweak penguin and box diagrams, open to new heavy particles (Z', extra H...)
- Angular observables in $K^{*0}(K^+\pi^-)\mu^+\mu^-$ are characterized by 6 amplitudes: $A^{L,R}_{0,\parallel,\perp}$
  3 K^{*0} helicities and 2 $\mu^+\mu^-$ chiralities (L,R)
- The full set of 9 (CP-averaged) observables was analized by LHCb in 2013 arXiv:1304.6325 (1 fb^{-1}), as function of $q^2(\mu^+\mu^-)$, showing statistical agreement with the SM predictions in all of them, except in the particular observable:

$$P_5{}' = \sqrt{2}Re\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right) / \sqrt{F_L(1-F_L)} = S_5/\sqrt{F_L(1-F_L)} \qquad F_L = |A_0^L|^2 + |A_0^R|^2$$

or simply S_5 , which showed a significant discrepancy (3.7σ)

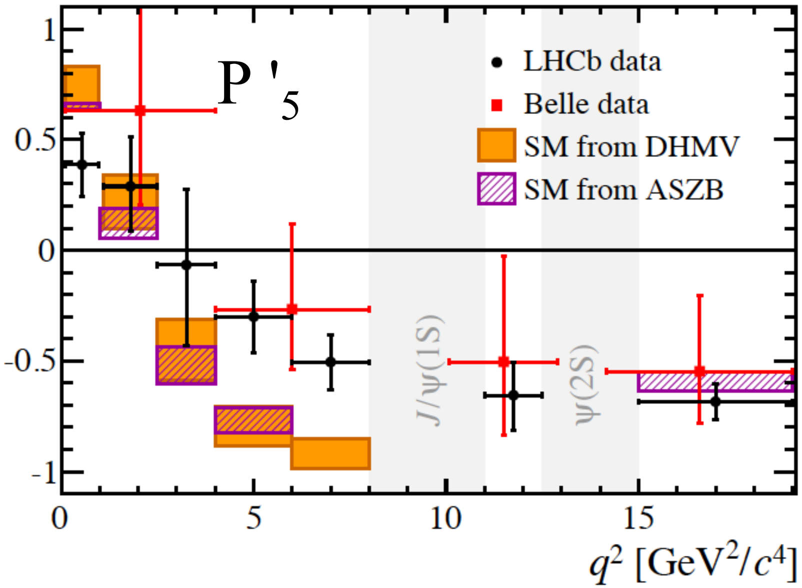
- Possible interpretations of this discrepancy and consistency of all $b \rightarrow s\mu\mu$ transitions has been widely discussed in the literature (~ 20 papers in 2014/2015). LHCb has updated the result with the full 3 fb^{-1} data sample and performed a *global fit to all observables*, to assess the difference with respect to SM predictions

$B^0 \rightarrow K^{*0} \mu^+\mu^-$ & tension in P'_5

- The discrepancy in P'_5 was *confirmed* with 3 fb^{-1} in $2<q^2<6$ GeV^2/c^4 . Also seen by Belle arXiv: 1604.04042 in K^*ll. SM given by two calculations: DHMV and ASZB.
- Various theoretical analyses showed that the difference can consistently be accounted for by modifying the real part of the coefficients C_9 and C_{10} associated with the (V, A) Wilson operators in $b \rightarrow s\, \mu^+\mu^-$ transitions:

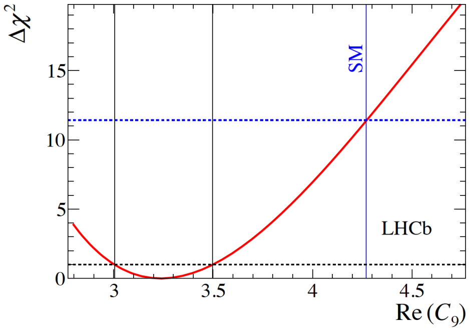
$$\mathcal{O}_9 \equiv (\bar{s}_L \gamma_\mu b_L)\,(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}_{10} \equiv (\bar{s}_L \gamma_\mu b_L)\,(\bar{\mu}\gamma^\mu \gamma^5 \mu)$$

LHCb collaboration, R. Aaij et al., JHEP 02 (2016) 104.



DHMV: S. Descotes-Genon et al., JHEP 12 (2014) 125.
ASZB: W. Altmannshofer S. Straub, Eur. Phys. J C75 (2015) 382.
see recent discusion at T. Blake et al. arXiv:1606.00916 (2016)

- C_{10} being constrained by the BF $B_s \rightarrow \mu^+\mu^-$, LHCb has performed a global χ^2 −fit to all angular observables and determined the best-fit value to be shifted: $\Delta Re(C_9) = -1.04 \pm 0.25$ from the SM value of 4.27, with 3.4σ significance.



- Shift could be caused by *new vector particle* or by *unexpectedly high hadronic effect*

Lepton universality

- Gauge interactions in the SM are flavor-universal at tree level, and all flavor-dependent interactions originate from the Yukawa couplings to the Higgs boson.
- It is the smallness of neutrino masses that makes lepton interactions universal (e, μ, τ). The only theoretical uncertainty in ratios of semileptonic decays comes from different lepton masses.
- Z^0 decays at LEP tested lepton universality to 10^{-3} level. Heavy quark decays tested e-μ in $B \rightarrow K l^+ \nu$ to 5% level, and constraints on μ-τ are poorer (10% in charm: $D_s^+ \rightarrow l^+ \nu$).
- The ratios below are particularly sensitive to physics beyond the SM:

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \left[d\Gamma\left(B^+ \to K^+ \mu^+ \mu^-\right)/dq^2\right]\, dq^2}{\int_{q^2_{min}}^{q^2_{max}} \left[d\Gamma\left(B^+ \to K^+ e^+ e^-\right)/dq^2\right]\, dq^2} \qquad R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)} \tau \nu_\tau\right)}{\Gamma\left(B \to D^{(*)} \mu \nu_\mu\right)}$$

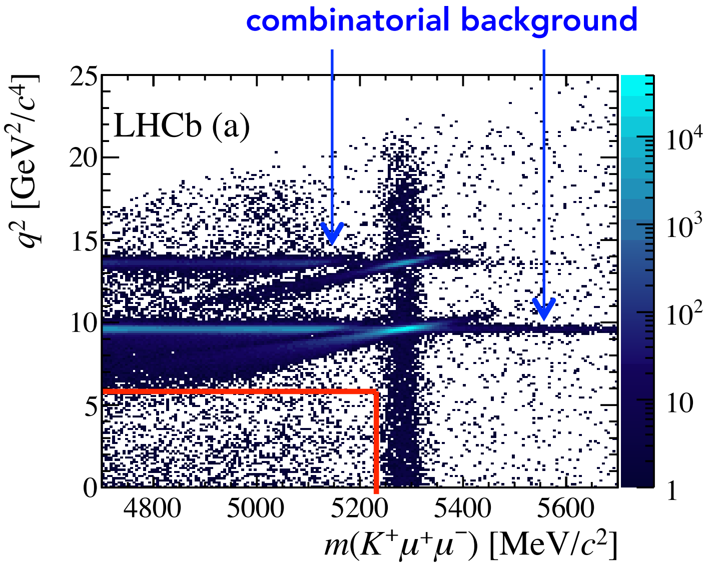
and have been recently addressed by experiments, including LHCb.

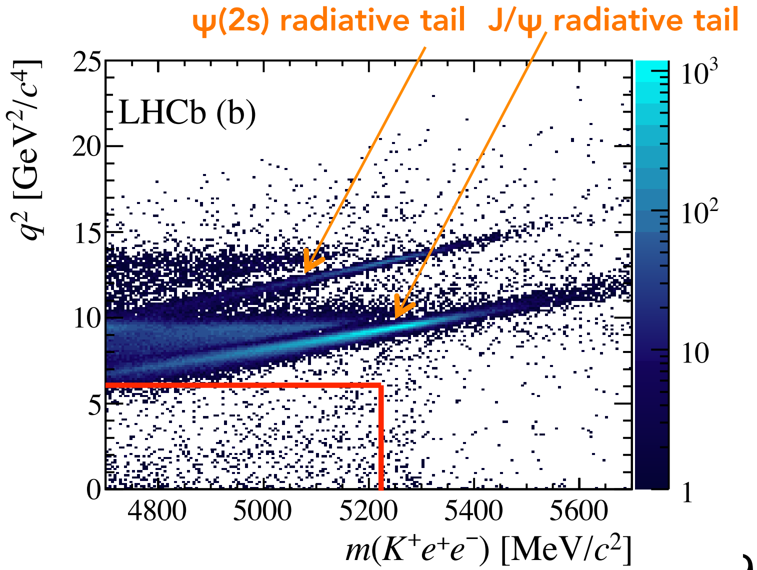
R_K observable at LHCb

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \left[d\Gamma\left(B^+ \to K^+\mu^+\mu^-\right)/dq^2\right]\ dq^2}{\int_{q^2_{min}}^{q^2_{max}} \left[d\Gamma\left(B^+ \to K^+e^+e^-\right)/dq^2\right]\ dq^2}$$

LHCb collaboration, PRL 113 (2014) 151601

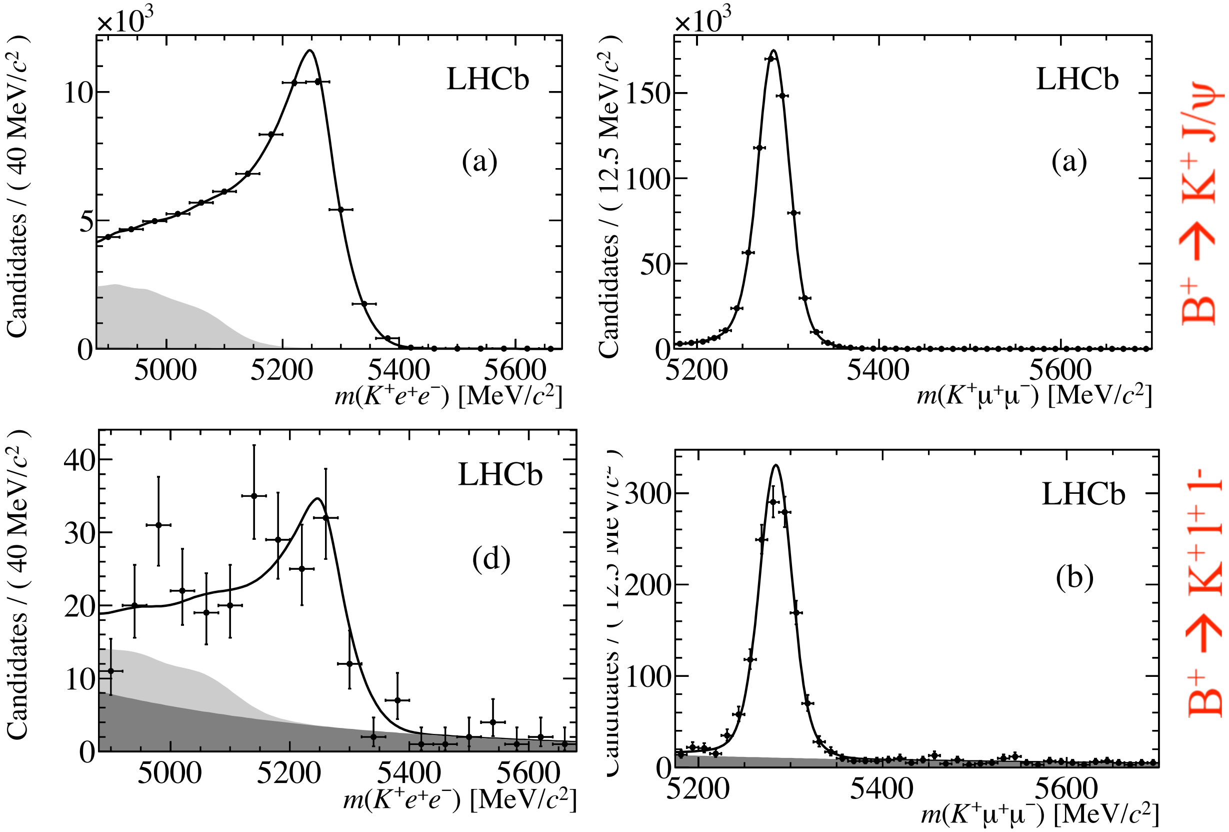
- Ratio free of all hadronic uncertainties, notably form factors
- 1< q^2 < 6 GeV^2 excludes J/ψ and region above ψ(2s) affected by broad charmonium resonances
- Strong advantage is taken from the copious control channel B^+ → J/ψ (l^+l^-) K^+ to cancel potencial sources of systematics (assuming universality in J/ψ → l^+l^-)


combinatorial background


ψ(2s) radiative tail J/ψ radiative tail

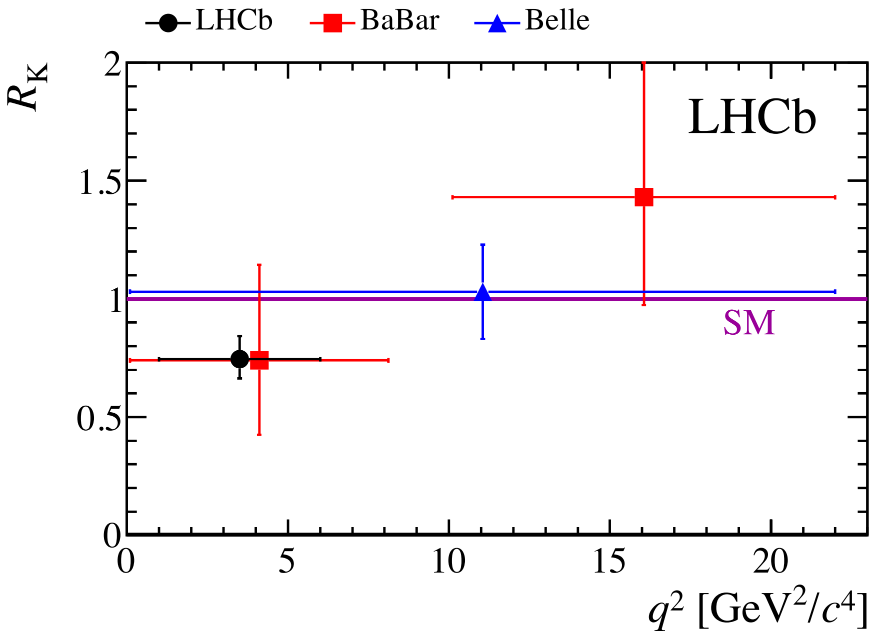
R_K measurement

- Ratio of partially reconstructed background to signal for $B^+ \rightarrow K^+ e^+e^-$ is determined from ratio in $B^+ \rightarrow J/\psi\,(e^+e^-)\,K^+$ with correcting factors
- Resolution properties for electron pairs are evaluated using the J/ψ signal, incorporating a small resolution effect from MC



- Analysis was performed independently for 3 different trigger types (e, K, other). Dominant systematics is parametrization of $B^+ \rightarrow J/\psi\,(e^+e^-)\,K^+$ mass distribution and estimate of trigger efficiencies (3% each)

Summary of R_K results



LHCb : PRL 113 (2014) 151601
BaBar : PRD 86 (2012) 032012
Belle : PRL 103 (2009) 171801

$$R_K = 0.745\,^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

- R_K is compatible with earlier, but less precise measurements. Only **2.6σ** from SM expectation (O(10^{-3})), but suggestive.
- Deficit of muons consistently seen by LHCb also in other b → s $\mu^+\mu^-$ channels

B → $D^{(*)}\tau\nu$ introduction

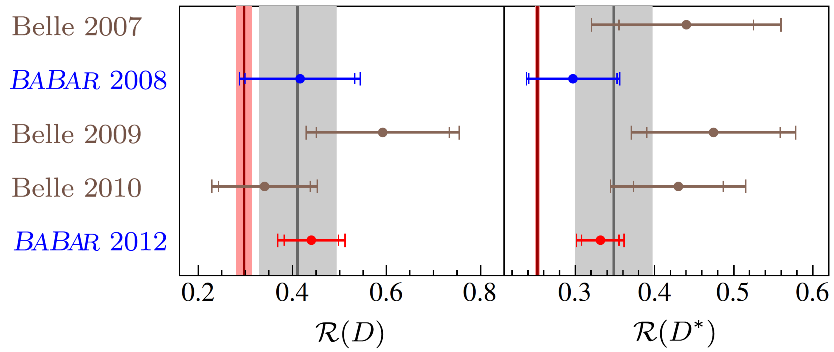
- Lepton universality can be broken by new physics with τ lepton, and ratios like $R(D^*)=\mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ are sensitive to it
  - in two Higgs doblet models (2HDM), the D/D* helicity amplitudes H_s become:

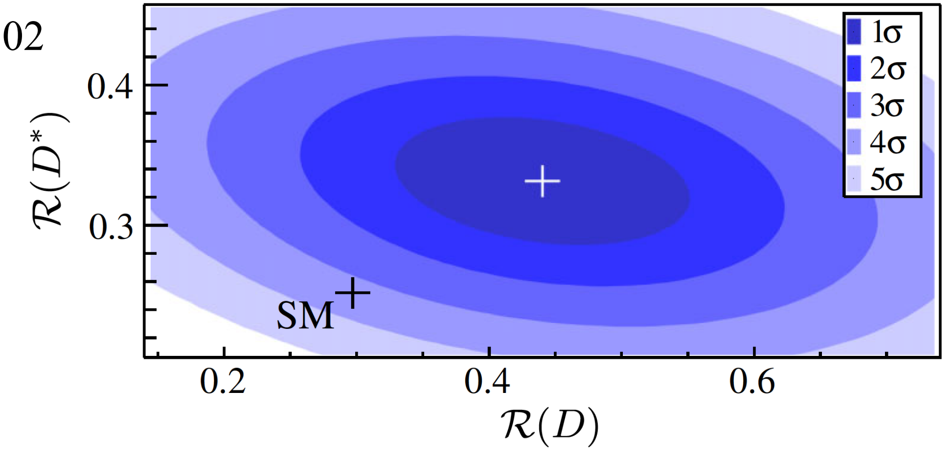
$$H_s^{2HDM} \approx H_s^{SM}\left(1+(S_R \pm S_L)\frac{q^2}{m_\tau(m_b \mp m_c)}\right)$$

with scalar NP contributions $S_{L,R}$ proportional to $(\bar{c}P_{L,R}b)\,(\bar{\tau}P_L\nu_\tau)$ $P_{L,R}=(1\mp\gamma_5)/2$

- BaBar reported *anomalously high values* of both $R(D^*)$ and R(D), by > 3σ :

PRD 88 (2013) 072012, also PRL 109 101802

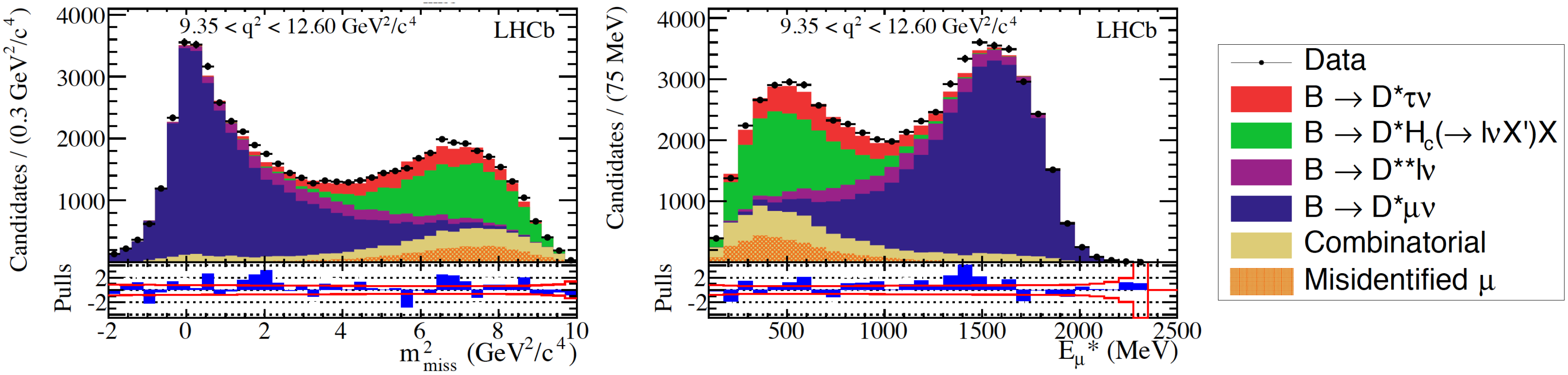




- Those exclude 2HDM where $S_L= 0$ (type II, minimal SUSY) in the full tanβ-$m_{H\pm}$ plane, but are compatible with more general 2HDM having $|S_R+S_L|<1.4$

B → D*τν at LHCb

- First b → τ reconstruction at a hadron collider: $R(D^*) = \dfrac{\Gamma\left(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau\right)}{\Gamma\left(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu\right)}$
  Challenging at the LHC, both decays produce identical final-state topologies, with no kinematic constraint $D^{*+} \to D^0(K^-\pi^+)\pi^+$

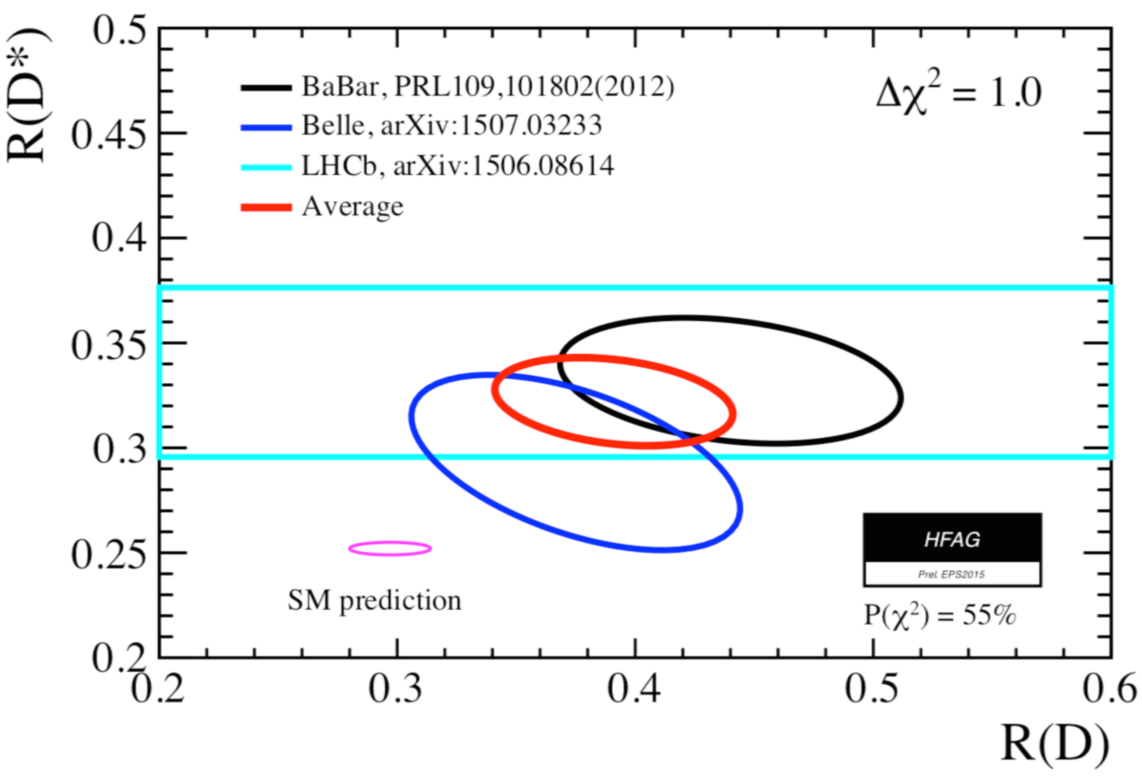


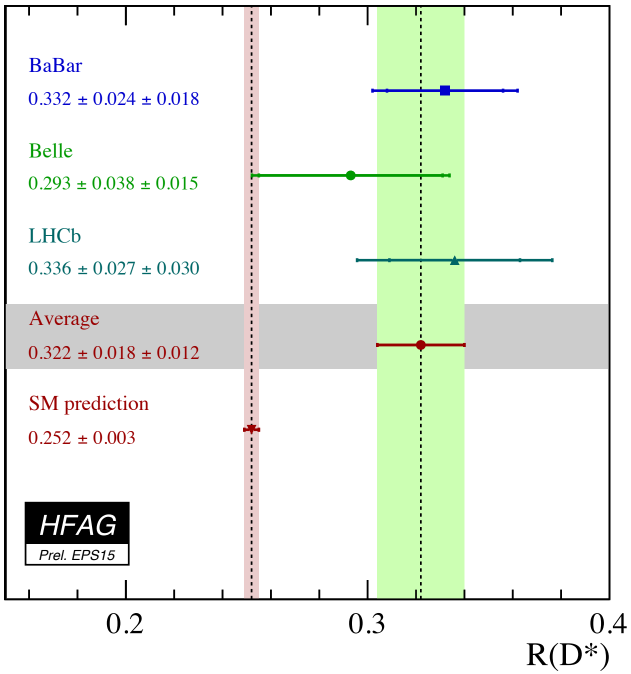
$$\boxed{R(D^*) = 0.336 \pm 0.027 \pm 0.030}$$

R. Aaij et al. PRL 115, 111803 (2015)

- LHCb result *confirms* the excess to the SM value 0.252±0.003. Fit also extracts form factor parameters, which appear to agree with world averages.
  - ❑ B^0 rest-frame variables (m_{miss}^2, E_μ^*, $q^2 = (p_B - p_D)^2$) are measured with (15-20)% resolution thanks to $\vec{p}_B$ estimation with charged particles
  - ❑ Control samples of the different backgrounds allow precise corrections

$B \to D^{(*)}\tau\nu$ combination





Average: $R(D^*) = 0.322 \pm 0.018 \pm 0.012 \quad R(D) = 0.391 \pm 0.041 \pm 0.028$

- Combination still **3.9σ** above the SM expectation:

$$R(D^*) = 0.252 \pm 0.003 \quad R(D) = 0.297 \pm 0.017$$

Including the new independent $R(D^*)$ from Belle arXiv:1603.06711, with semileptonic decays, makes SM deviation go to even higher significance

Hidden-Sector bosons

- Dark matter (DM) may arise from quasi-stable particles in the Supersymmetry breaking sector at 1-10 TeV scale, that interact feebly with all known particles.
- Spontaneous breaking of the Peccei-Quinn symmetry (U(1) rotation of R-handed u,d-type quarks) leads to a light pseudo Nambu-Goldstone boson, the axion (χ). Its observation would provide fundamental understanding of why CP-violation is not seen in strong interactions.
- The axion has been postulated to explain the e^+ excess observed in cosmic ray experiments (PAMELA and AMS-2) : TeV-scale DM would decay into axions and get very long lived. These should then be light (GeV scale) in order to couple mainly to e and μ .

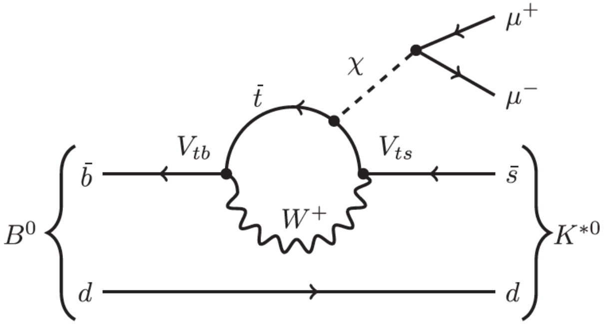
Y. Nomura and J. Thaler Phys. Rev. D 79, 075008 (2009)

O. Adriani et al. PAMELA Collaboration, Phys. Rev. Lett. 111, 081102 (2013)

M. Aguilar-Benítez et al. , AMS Collaboration, Phys. Rev. Lett. 113, 121102 (2014)

Higgs portal to Hidden-Sector

- The axion can be detected at accelerators through its mixing with a CP-odd Higgs boson A^0 (either in SUSY or in 2HDM's with VEV : $\langle H_{1,2} \rangle_0 = v_{1,2}$). The top-quark can host this portal through FCNC loop decays $b \to s\chi$, with amplitude:



$$\mathcal{M}(b \to s\chi) = -\sin\theta\, \mathcal{M}(b \to sA^0) \qquad \tan\theta = n\frac{v_{EW}}{f_\chi \tan\beta}$$

where $\tan\beta \equiv \frac{v_1}{v_2}$ and $v_{EW} = \sqrt{v_1^2 + v_2^2}$

$n = 1$ (DFSZ axion) $n = 2$ (NMSSM) $\qquad f_\chi$ is the axion decay constant

M. Freytsis, Z. Ligeti, and J. Thaler Phys. Rev. D 81, 034001 (2010).

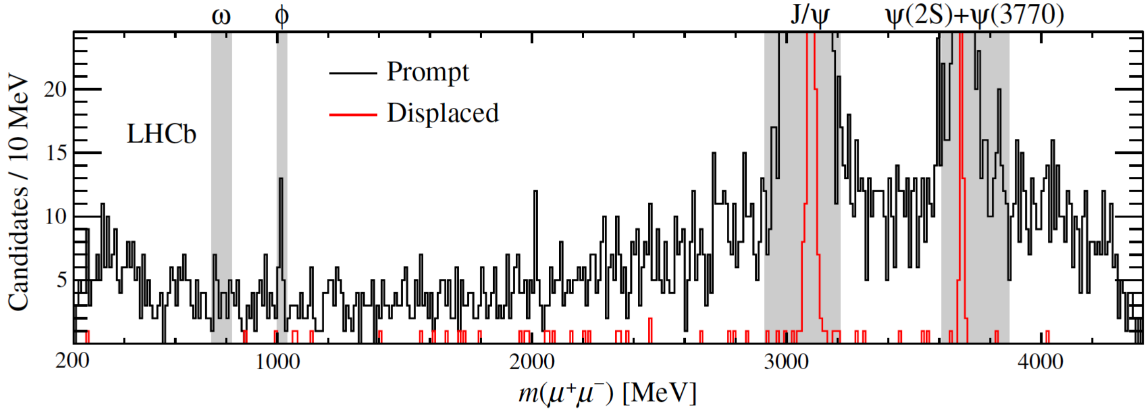
- For $f_\chi \gtrsim 10\,\mathrm{TeV}$ the axion does not decay at the primary vertex, so detection involves VERTEXING and high $\mu^+\mu^-$ MASS RESOLUTION to search for narrow states in $b \to s\mu\mu$ ($B^0 \to K^{*0}\mu^+\mu^-$ was chosen by LHCb).
- Similar principles, but with the SM Higgs boson as portal, allow searching for a χ scalar field responsible for inflation at the early universe, the inflaton.

F. Bezrukov, and D. Gorbunov, J. High Energy Phys. 05 010 (2010).

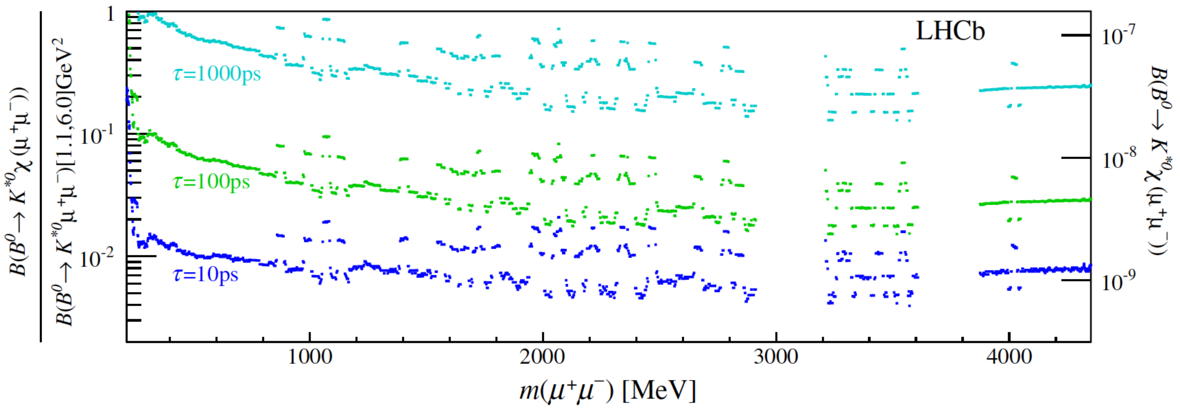
Dimuon spectrum $B^0 \rightarrow K^{*0}\chi(\mu^+\mu^-)$

- The BF product $\mathcal{B}(B^0 \to K^{*0}\chi(\mu^+\mu^-)) \equiv \mathcal{B}(B^0 \to K^{*0}\chi) \times \mathcal{B}(\chi \to \mu^+\mu^-)$ is measured relative to $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$, with normalization restricted to $1.1 < m^2(\mu^+\mu^-) < 6.0\ \mathrm{GeV}^2$

R. Aaij et al. , LHCb collaboration, PRL 115, 161802 (2015)

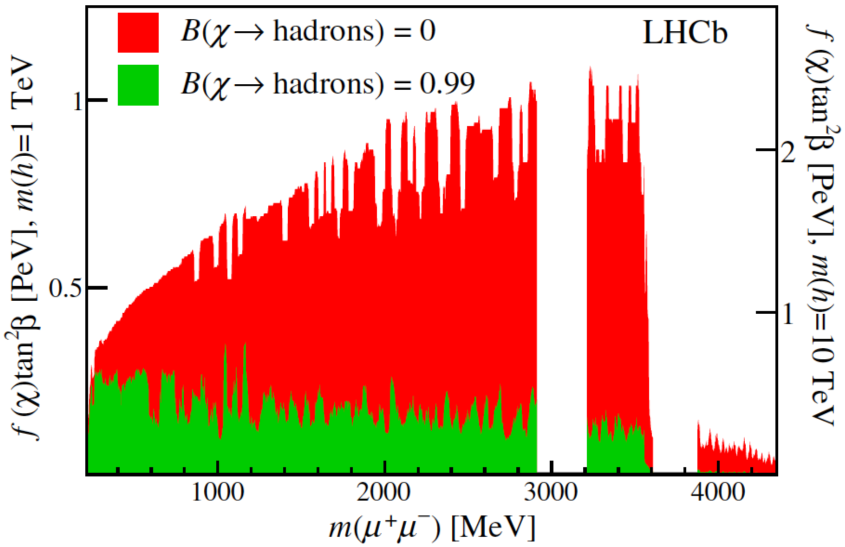


- Many uncertainties cancel for signal and normalization sharing the same final state. Hidden theory parameters are also safer from the ratio.

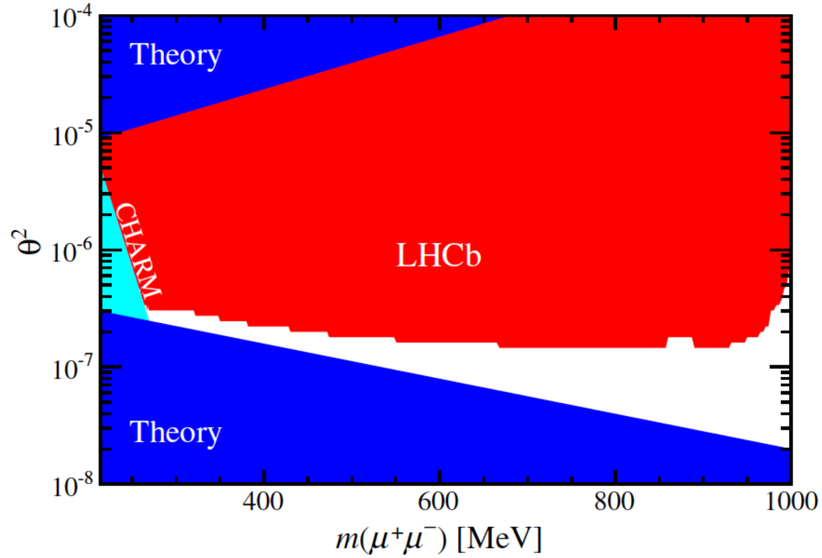


Exclusion regions hidden sector

Axion decay constant × tanβ² (PeV)



Inflaton mixing angle θ²



- No evidence for a signal is observed. Constraints exclude most of previously allowed region

R. Aaij et al. , LHCb collaboration, PRL 115, 161802 (2015)

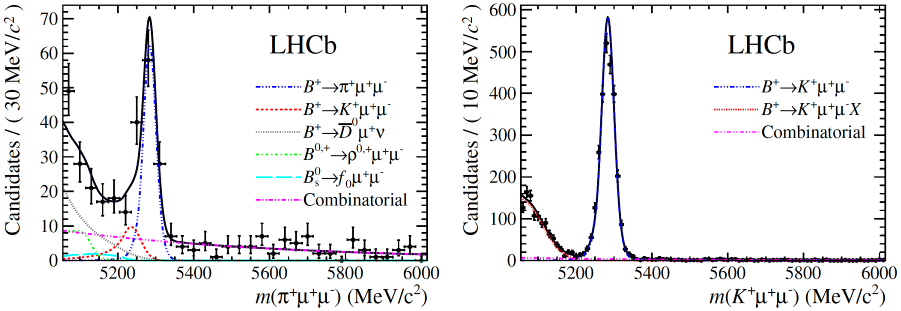
- First dedicated search over a large mass range for a hidden sector boson in a decay mediated by a b → s transition, and most sensitive search over the entire accesible mass range

Stringent constraints are placed for theories that predict the existence of additional scalar or axial-vector fields

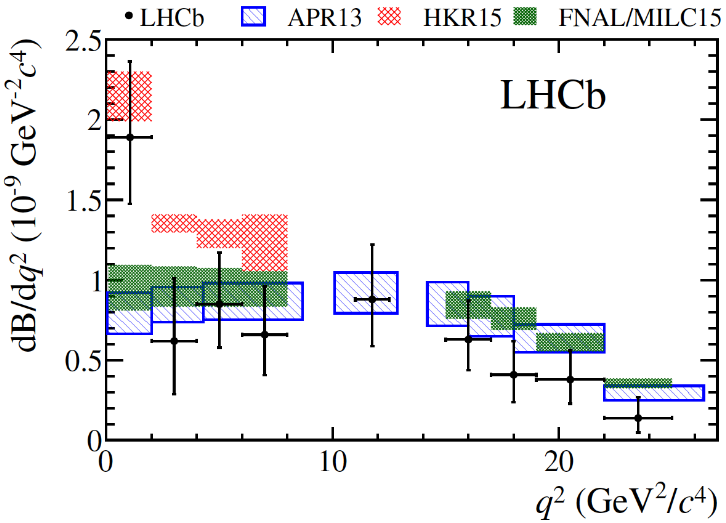
$B^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ and $B^{\pm} \rightarrow K^{\pm}\mu^{+}\mu^{-}$

The LHCb collaboration, R. Aaij et al. JHEP (2015) 034

- Rare decays sensitive to new particles in a extended flavor structure. The LHCb measurement of $\frac{d\mathcal{B}}{dq^2}(B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-})$ is in agreement with the SM prediction APR and with lattice QCD calculations FNAL/MILC.



APR: A. Ali, A. Parkhomenko, A. Rusov, Phys. Rev. D89 (2014)
FNAL/MILC: arXiv:1507.01618
HKR: C. Hambrock, A. Khodajmirian, A. Rusov arXiv:1506.07760



- Further measurement of the ratio

$$\frac{\mathcal{B}(B^{+} \to \pi^{+}\mu^{+}\mu^{-})}{\mathcal{B}(B^{+} \to K^{+}\mu^{+}\mu^{-})} = 0.038 \pm 0.009\,(\text{stat}) \pm 0.001\,(\text{syst})$$

allows a precision determination of $|V_{td}/V_{ts}|$.

Form-factors uncertainties now reduced greatly

- The normalization channels: $B^{+} \to J/\psi\,(\mu^{+}\mu^{-})\,K^{+}$ play an essential role to ensure cancellation of many systematic sources of uncertainty

Testing MFV

$|V_{td}/V_{ts}|$

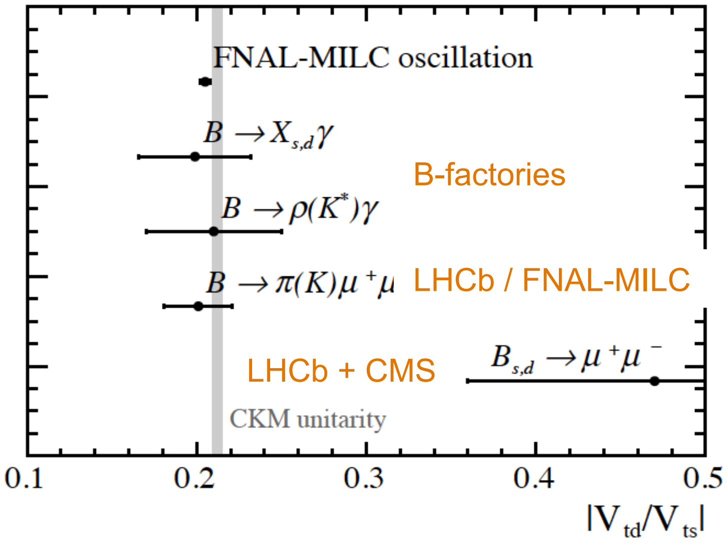
T. Blake, G. Lanfranchi, D.M. Straub, arXiv:1606.0091 (2016)

- A sensitive test of the SM and possible extensions to it comes from *comparing this ratio as extracted from different sources*:

Rare B decays

Oscillation frequencies (B^0,B^0_s) with lattice QCD

CKM unitarity



- The extractions agree and are so far consistent with the SM, and also with models sharing the Minimal Flavor Violation hypothesis (MFV)
- The largest deviation is currently seen from the ratio:

$$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)}$$

in two channels that provide the *theoretically cleanest* extraction among all rare decays, ultimately comparable in precision to that from meson oscillation

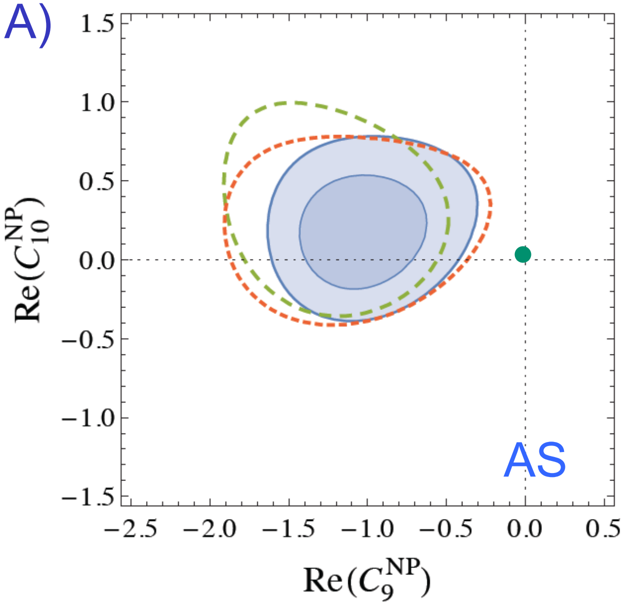
MFV : G. D'ambrosio et al. arXiv:hep-ph/0207036 /A. J. Buras et al., arXiv:hep-ph/0007085

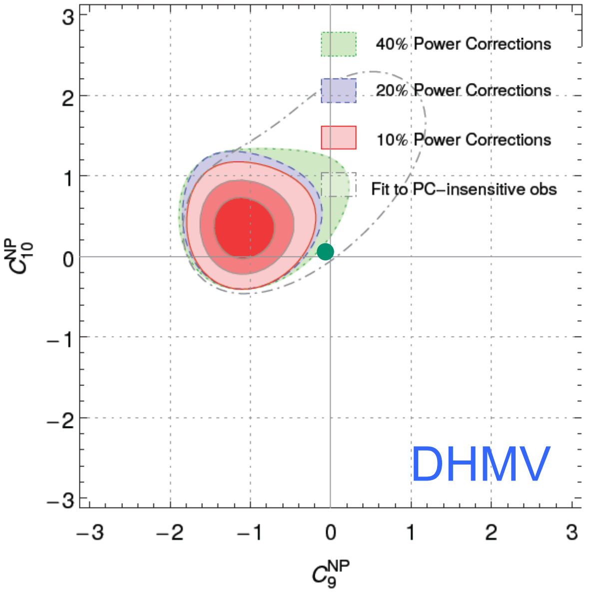
FNAL-MILC oscillation : A. Bazavov et al., arXiv:1602.03560 (2016)

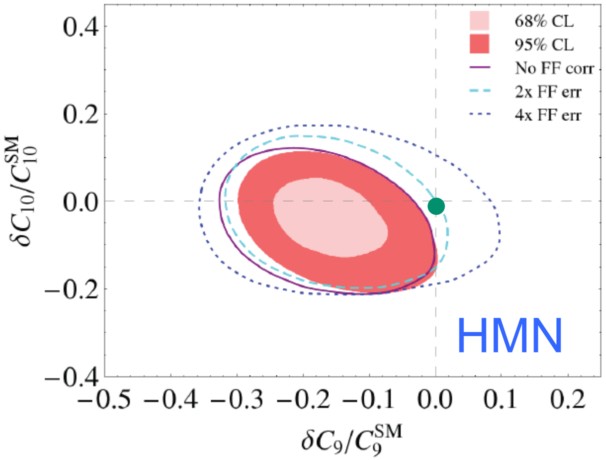
FNAL-MILC: Daping Du et al., arXiv:1510.02349 (2016)

Global analyses on Wilson coefficients

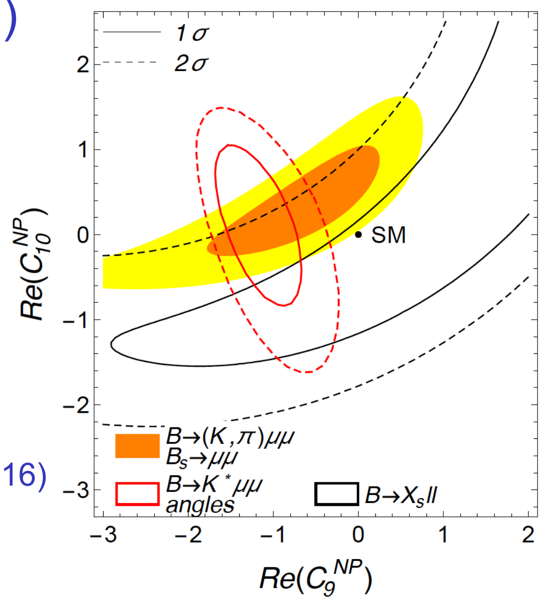
A)







B)



- Global fits have been published on the consistency of the Wilson coefficients C_9 and C_{10} in b → s ($\gamma,\mu^+\mu^-$) observables from flavor experiments (LHCb en particular)

$$\mathcal{O}_9 \equiv (\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu) \quad \mathcal{O}_{10} \equiv (\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma^5\mu)$$

A) T. Blake, G. Lanfranchi, and D. M. Straub, arXiv:1606.00916 (2016)

B) Fermilab Lattice and MILC Collaboration, Daping Du et al., arXiv:1510.02349 (2016)

Summary on flavour physics

- Flavour physics in the quark sector has florished over the last two years, with a large number of precision tests of the Standard Model of particle physics. LHC experiments have been succesful on this.
- Sensitivity to $B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ has reached the 10^{-10} level and will continue to improve
- No evidence of new physics has been found in the first precision measurements of the CKM phases β_s and γ, providing further support for the Kobayashi-Maskawa theory of CP violation.
- A few interesting "tensions" with the SM to follow up very closely:
  - hints on lepton non-universality in R_K, $R(D^*)$ and $R(D)$
  - S_5 observable in $B \rightarrow K^{*0}\,\mu\mu$ appears to deviate from SM. Possible explanations can be new physics or unexpectedly high hadronic effects.

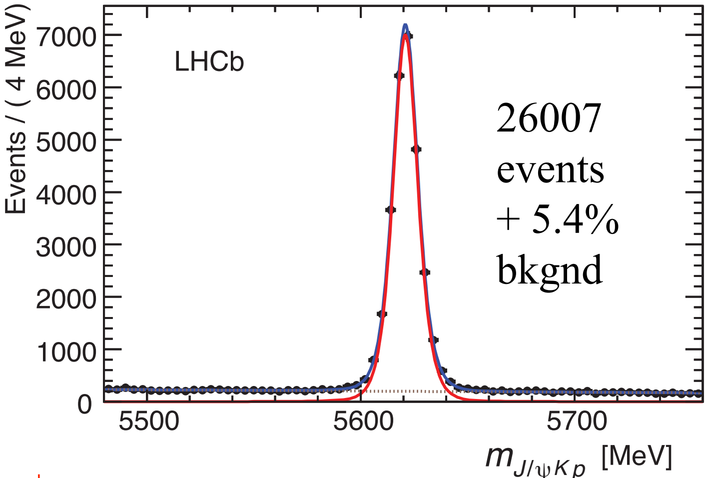
PART III
MULTIQUARK
STATES

Some history about pentaquarks

- Five-quark states of matter, beyond the simple quark model picture, have been an inspiring case of QCD
- No reason why they should not exist
  - predicted by Gell-mann (64) and Zweig (64), specific QCD models Jaffe (76), Strottman (79), Hogaasen & Sorba (78), Lipkin (87)
- But no convincing findings 50 years after Gell-mann paper proposing qqq and $qqqq\bar{q}$ states
  - Various enhancements observed in mass spectra, including $\theta^+ \rightarrow K^+ n$, $D^{*-}p$, and $\Xi^{--} \rightarrow \Xi^- \pi^-$ mostly "demystified", see review K. H. Hicks Eur. Phys. J. H37 (2012).

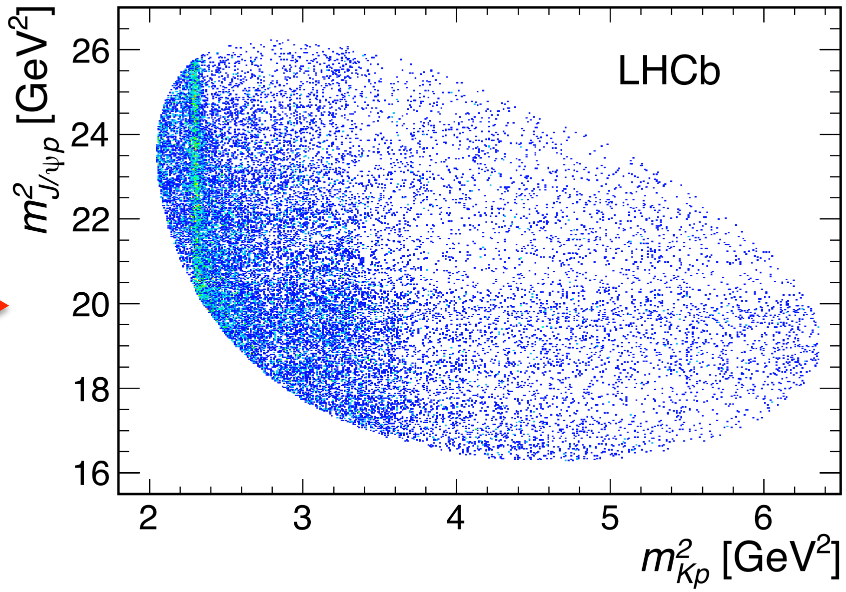
$\Lambda_b \rightarrow J/\psi K^- p$ signal

- Great Λ_b [udb] → $J/\psi K^- p$ signal at LHCb: $pp \rightarrow b\bar{b} + X \quad \sqrt{s} = 8\,TeV$, with very small background, due to trigger on displaced vertices, large acceptance for low p_T $J/\psi \rightarrow \mu^+\mu^-$, and excellent mass resolution
- Dalitz plot shows resonant Λ^* structures in $K^- p$ mass and unexpected feature in $J/\psi\, p$ mass



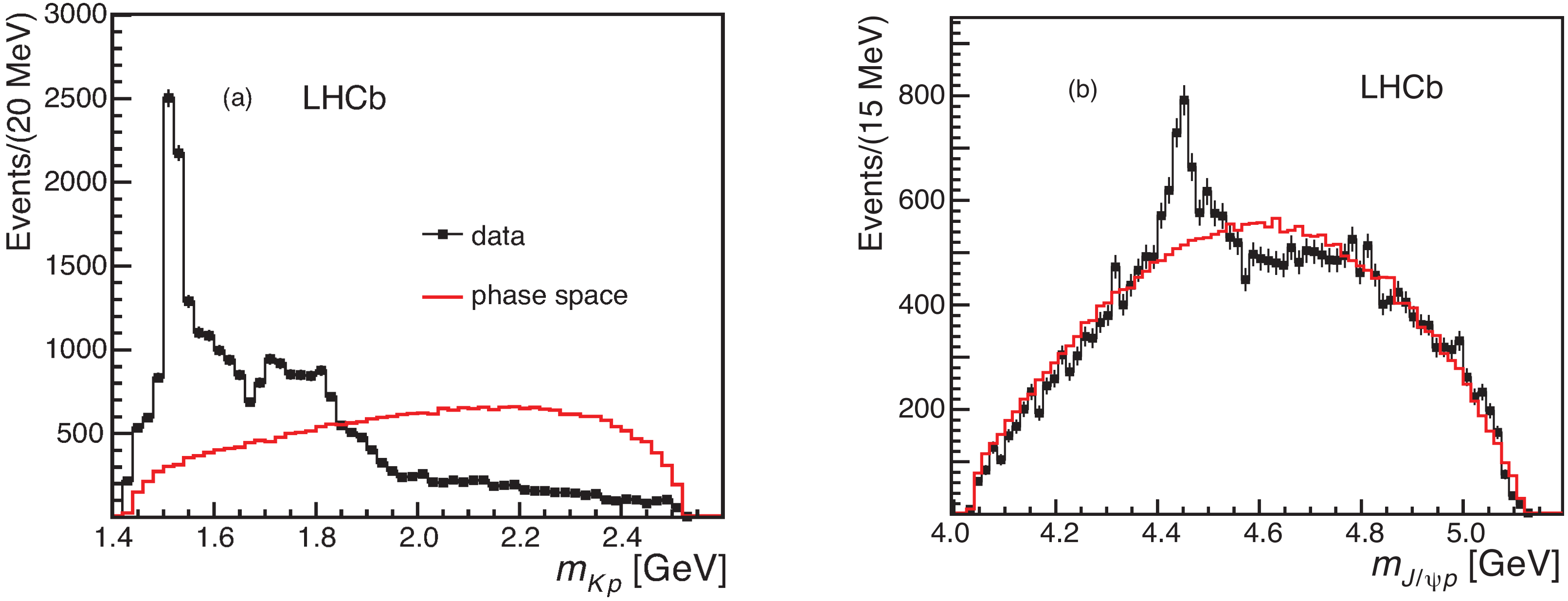
26007 events + 5.4% bkgnd

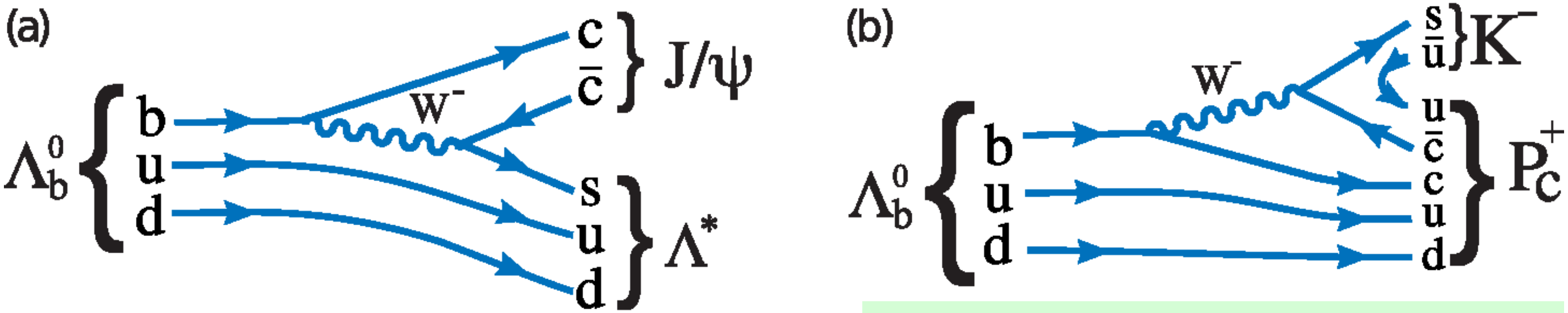
↓ ↓ ↓ ... Λ^*'s



Dalitz plot Projections

LHCb collaboration, R. Aaij et al., Phys. Rev. Lett. 115, 072001 (2015)





minimal quark content: uudc$\bar{c}$

Is this diagram real ?

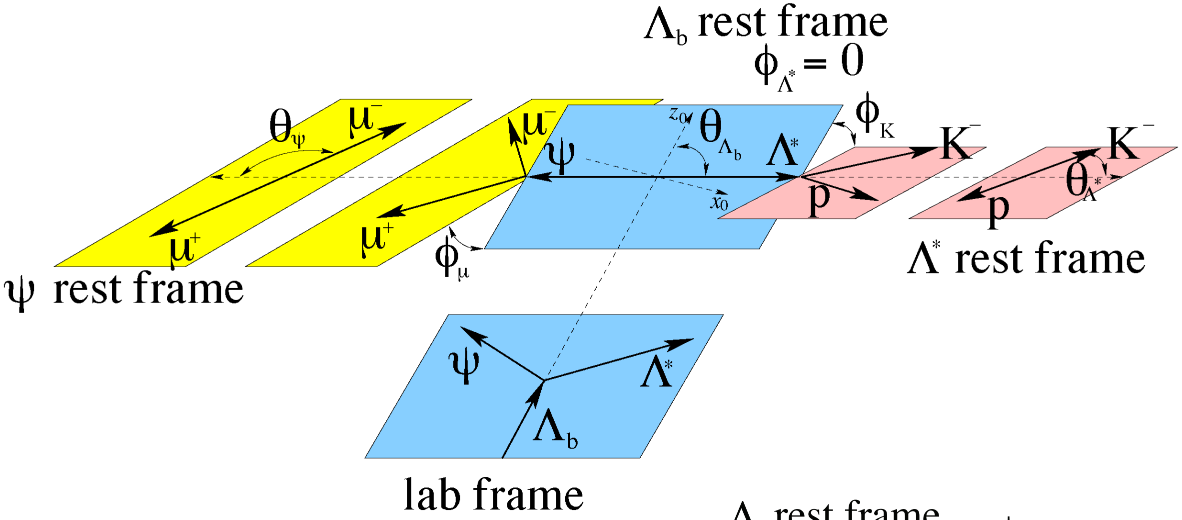
Amplitude analysis

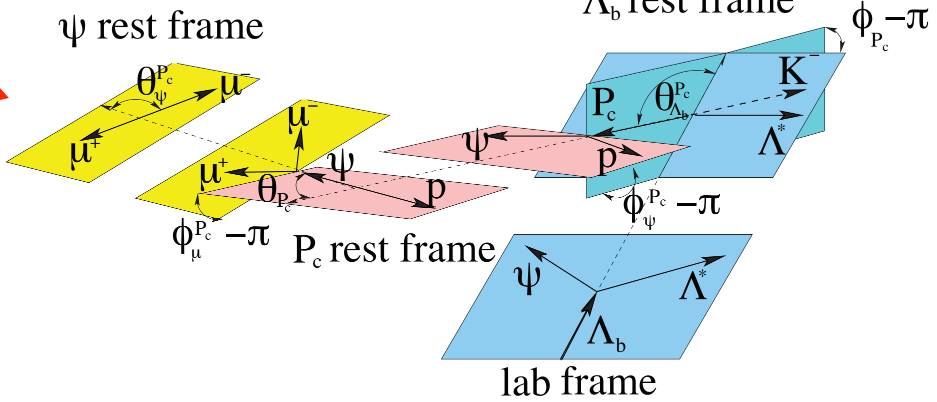
- *Interference between two channels*:

  $\Lambda_b \rightarrow J/\psi \Lambda^*$,
  $\Lambda^* \rightarrow K^- p$

  and

  $\Lambda_b \rightarrow \mathbf{P_c}^+ K^-$,
  $\mathbf{P_c}^+ \rightarrow J/\psi\, p$





- m(K^-p) & 5 decay angles are independent phase space dimensions
- Sequential *weak/strong decay helicity amplitudes*
- Parity conservation assumed in strong decays and in Λ_b production

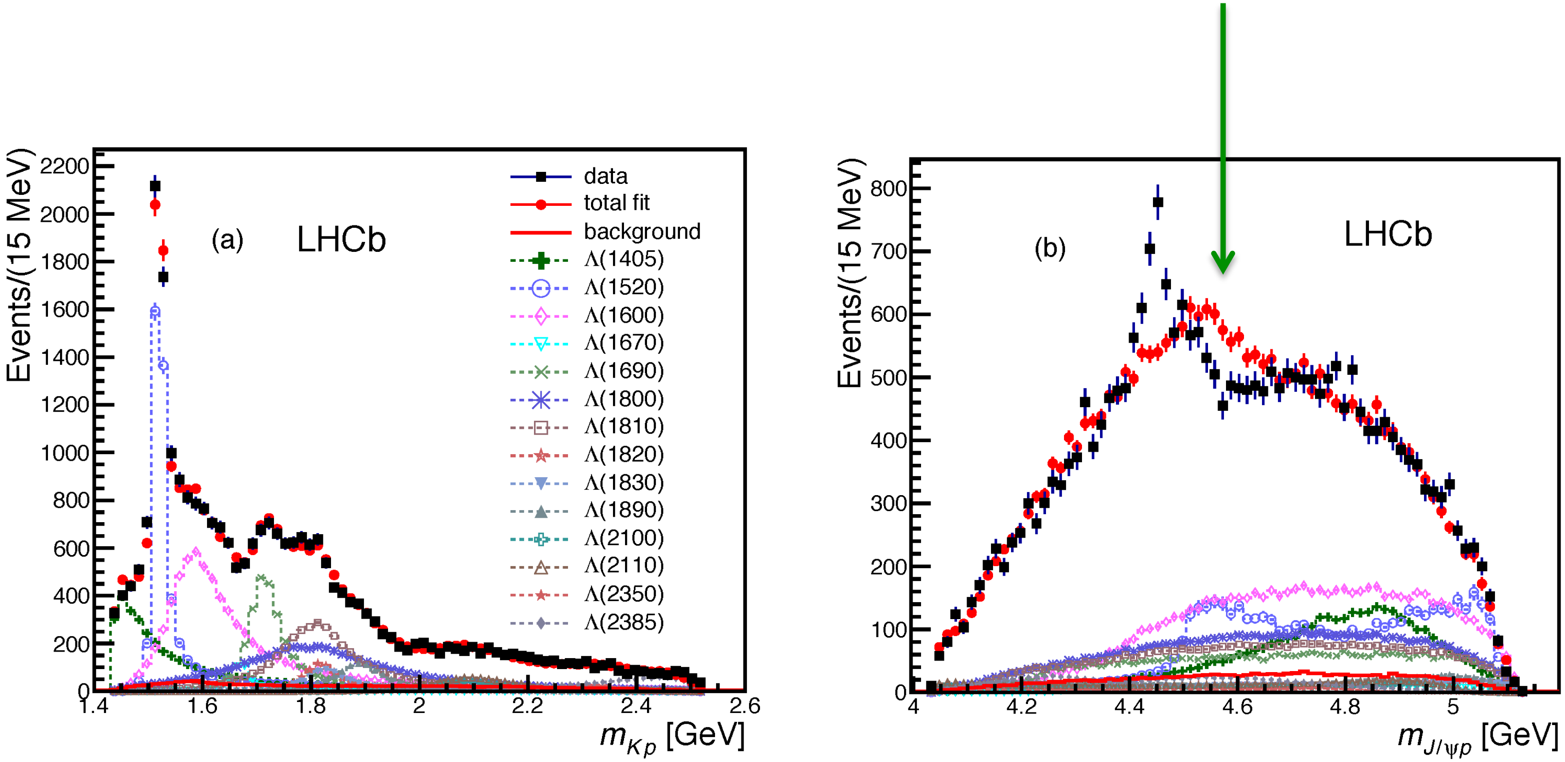
Models: extended & reduced

- Consider up to 13 Λ^* states & allowed L values

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6
			# parameters	64	146

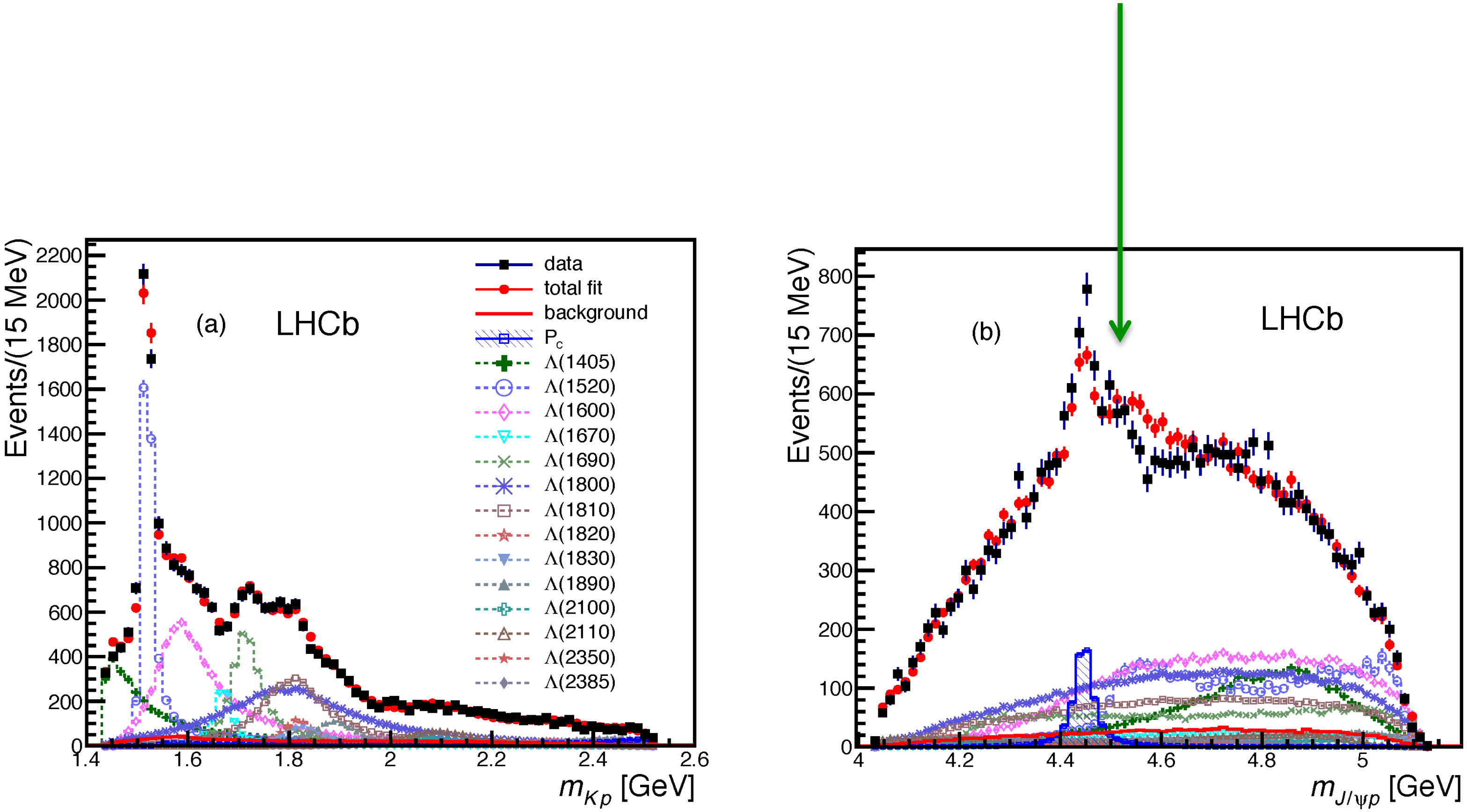
Results without P_c states

- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine but not $m_{J/\Psi p}$
- Additions of non-resonant, or extra Λ^*'s do not help



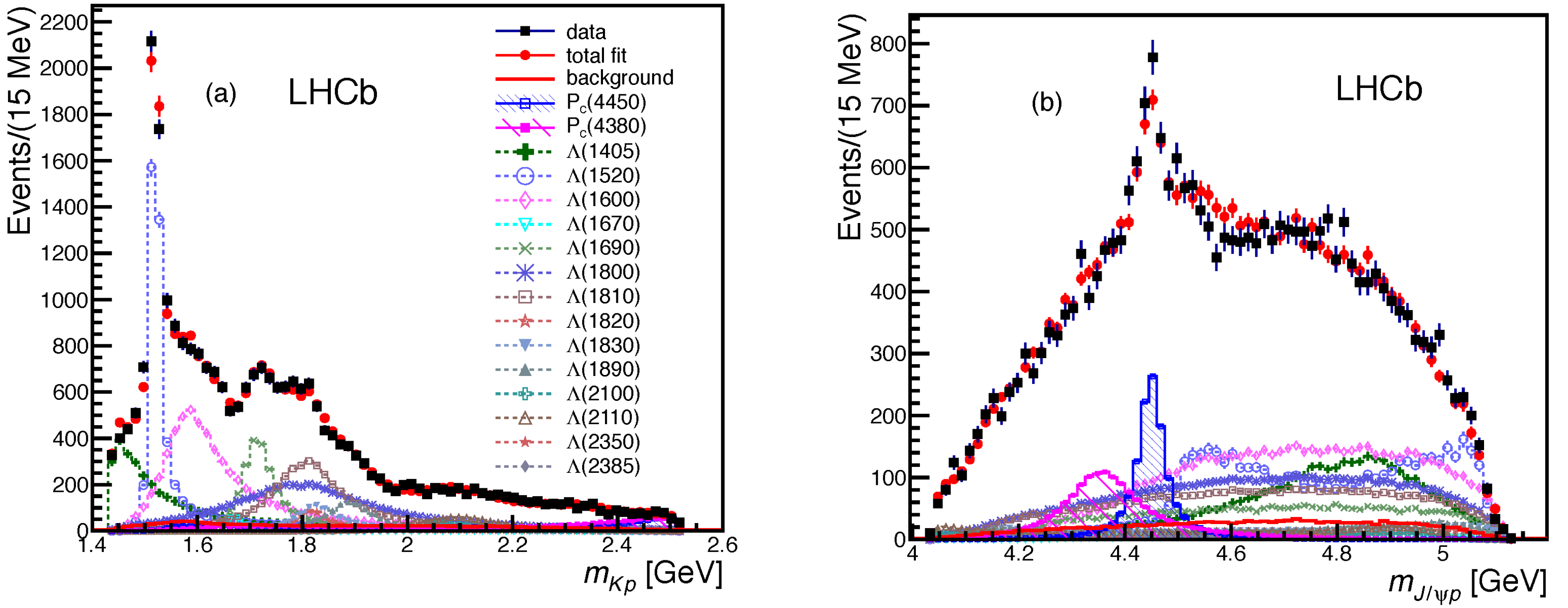
Extended model with one P_c

- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

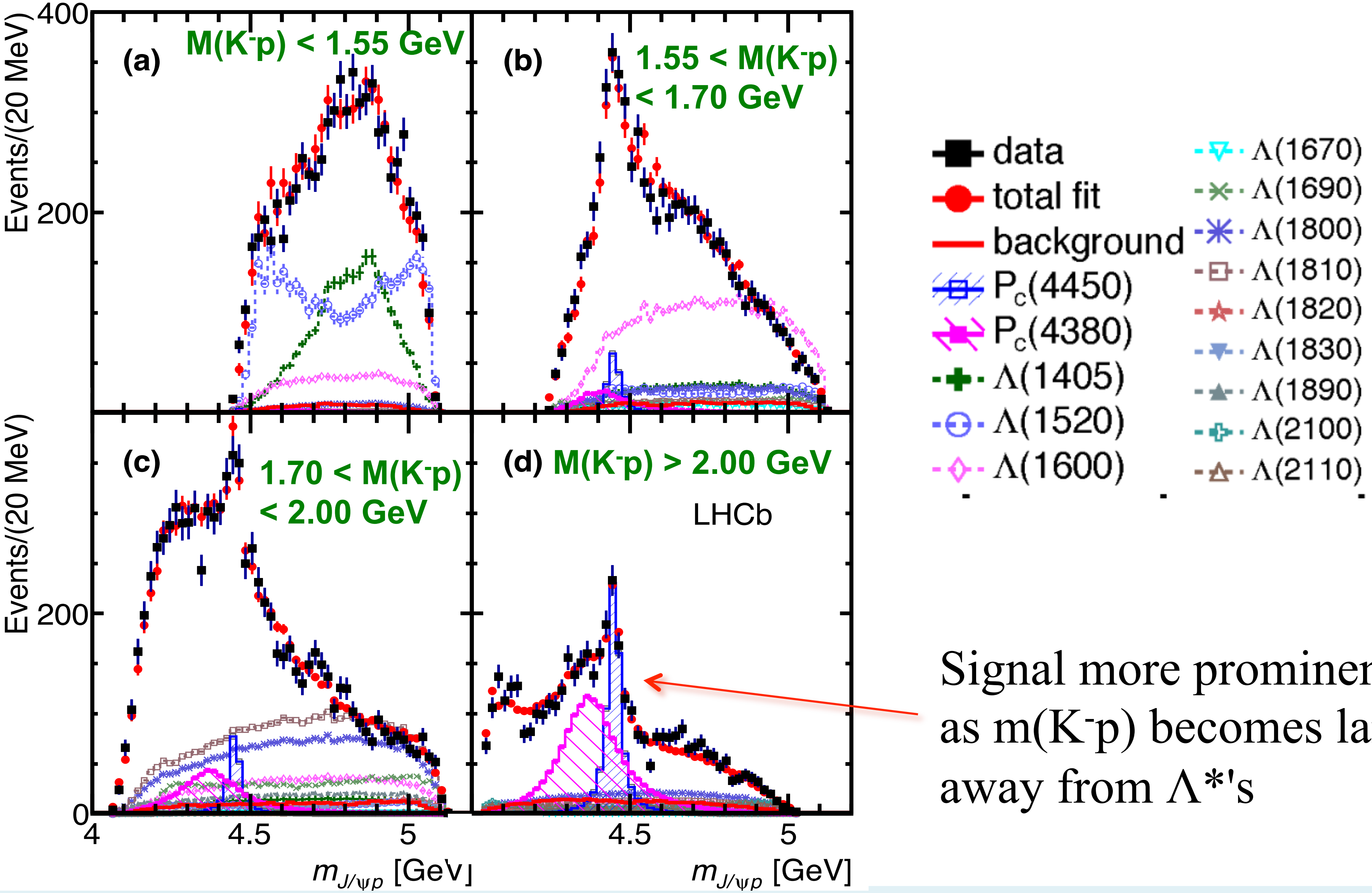


Reduced model with two P_c's

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



Intervals of m(K^-p)



Signal more prominent as m(K^-p) becomes large, away from Λ*'s

Results and significance

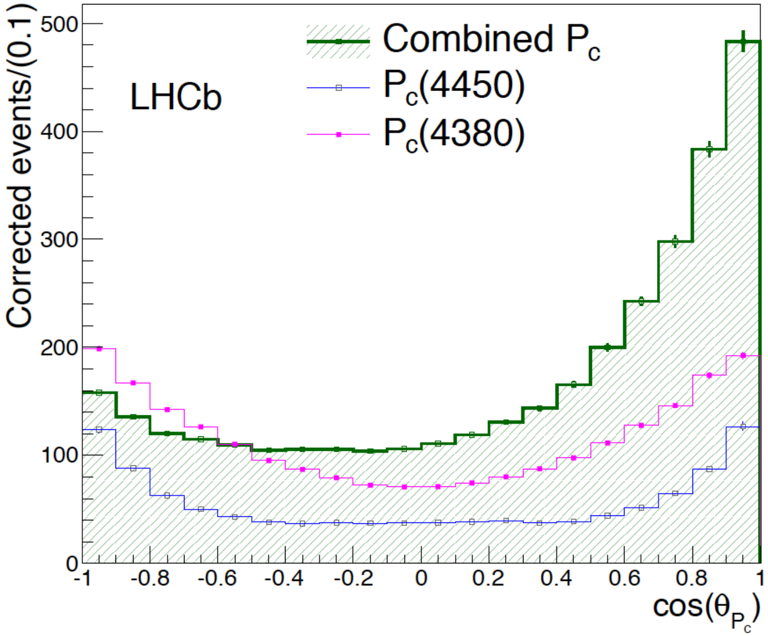
	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c^+(4380)$	4380 ± 8 ± 29	205 ± 18 ± 86	8.4 ± 0.7 ± 4.2
$P_c^+(4450)$	4449.8 ± 1.7 ± 2.5	39 ± 5 ± 19	4.1 ± 0.5 ± 1.1
	Λ(1405)		15 ± 1 ± 6
	Λ(1520)		19 ± 1 ± 4

- Fit improves after adding 1 P_c by $\Delta(-2\ln\mathcal{L})=14.7^2$, then adding the 2nd P_c by 11.6^2, and adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Similar significance expected from toy simulations: 1st state has 9σ and 2nd state 12σ, including systematic uncertainties
- The analysis is confirmed by a model independent approach (MI) on the same data (R. Aaij et al., arXiv:1604.05708 (2016))

Data demands two states

- Interference between *opposite parity* P_c^+ states needed to explain decay angular distribution
- θ_{Pc} is the J/ψ angle in P_c^+ rest frame
- Fit projections are shown

NEGATIVE INTERFERENCE (LARGE M_{KP})



POSITIVE INTERFERENCE (SMALL M_{KP})

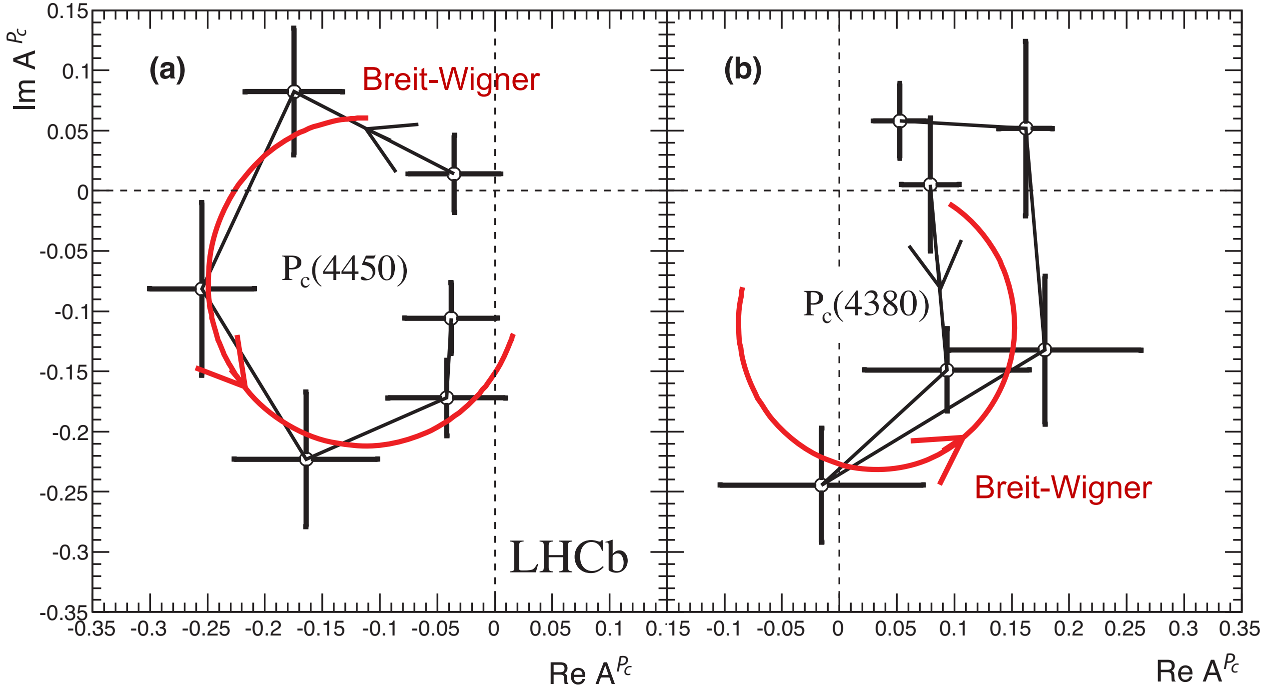
INDIVIDUALLY SYMMETRIC RATES

Phase behaviour

- Breit-Wigner amplitudes determined for 6 bins in (M_X-Γ, M_X+Γ)

$$\frac{1}{M_X^2 - m^2 - iM_X\Gamma(m)}$$

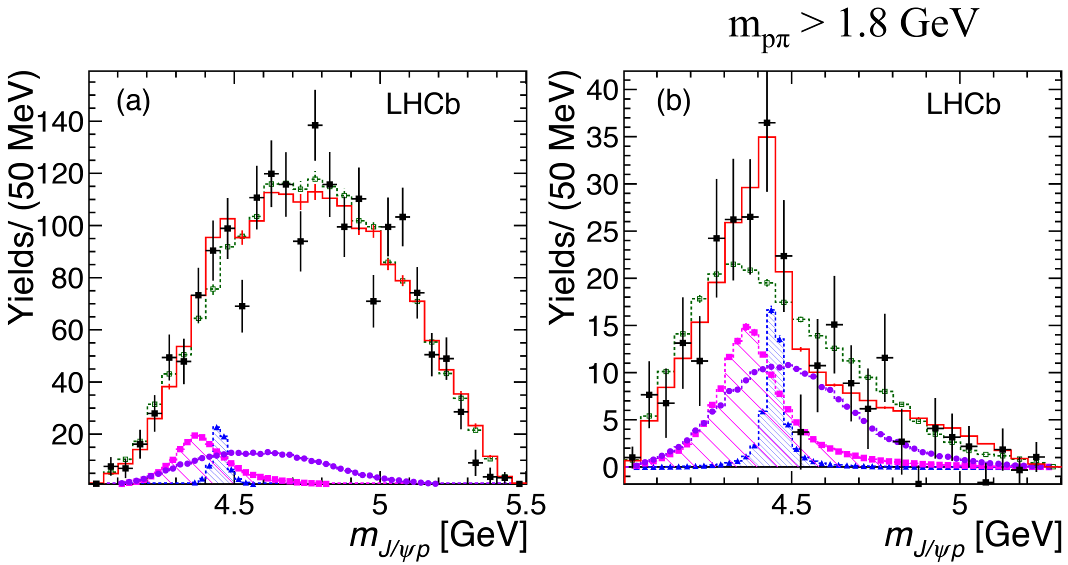
Canonical resonance unitary amplitude.
The phase should run counter-clockwise.



Pentaquark also in $\Lambda_b \rightarrow J/\psi p \pi^-$

R. Aaij et al., the LHCb collaboration arXiv:1606.06999 (2016)

- The pentaquark signals in $J/\psi p$ *should also be seen* in the Cabibbo suppressed channel $\Lambda_b \rightarrow J/\psi p \pi^-$, given sufficient statistics
- With measured relative BF 8.2%, LHCb has carried out such analysis, following the lines of the previous one, with a full amplitude model.



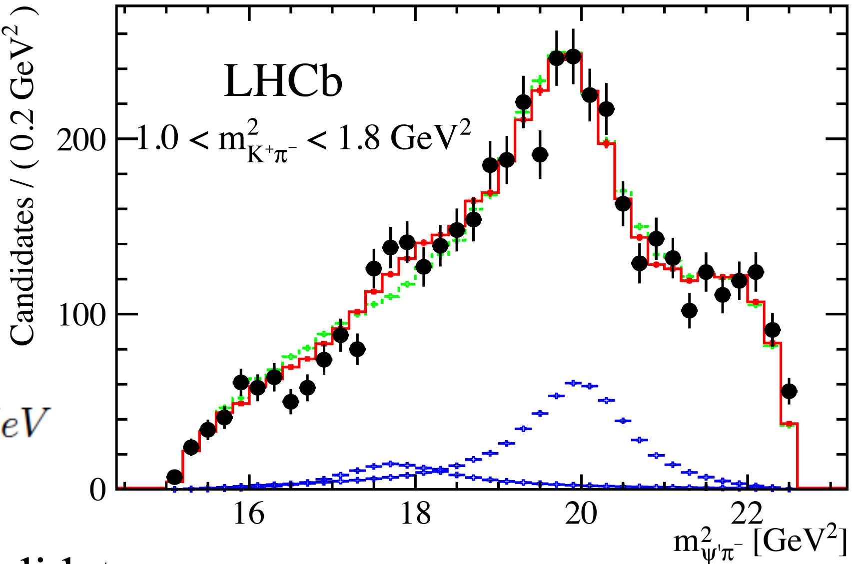
- A *significantly better description of the data* is achieved by either including the two P_c^+ states observed in $\Lambda_b \rightarrow J/\psi p K^-$, or the $Z_c(4200)^-$ reported by Belle and LHCb. The total significance is 3.1σ when both types of exotics are included
- Within the statistical and systematic errors, the data are *consistent with the $P_c(4380)^+$ and $P_c(4450)^+$ production rates expected from the previous observation*. Assuming $Z_c(4200)^-$ is negligible, there is 3.3σ significance for both P_c together.

The tetraquark Z(4430)$^-$

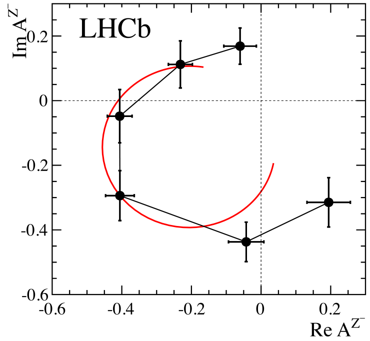
R. Aaij et al., the LHCb collaboration PRL 112, 222022 (2014)

- This charged charmonium-like state $Z^-(4430) \to \psi'\pi^-$ with $c\bar{c}d\bar{u}$ quark content was discovered by Belle PRL 100 (2008) 142001 .
- LHCb has confirmed Z(4430)$^-$ as a resonance and *established its spin-parity to be 1*$^+$ (both with very high significance):

$$M_{Z_1^-} = 4475 \pm 7^{+15}_{-25}\ MeV/c^2 \quad \Gamma_{Z_1^-} = 172 \pm 13^{+37}_{-34}\ MeV$$



- The amplitude model of the $B^0 \to \psi'\ K^+\pi^-$ $\psi' \to \mu^+\mu^-$ Dalitz plot with 25176 ± 174 candidates followed the same lines as that of $\Lambda_b^0 \to J/\psi p K^-$ $J/\psi \to \mu^+\mu^-$. Results were also confirmed by a MI approach.
- A lower mass signal Z^-_0 , with preferred J^P = 0$^-$, is also found: $M_{Z_0^-} = 4239 \pm 18^{+45}_{-10}\ MeV/c^2$ $\Gamma_{Z_0^-} = 220 \pm 47^{+108}_{-74}\ MeV$, with large significance (6σ). This state is not showing up in the MI approach, and its full characterization as a resonance will need confirmation with larger samples.

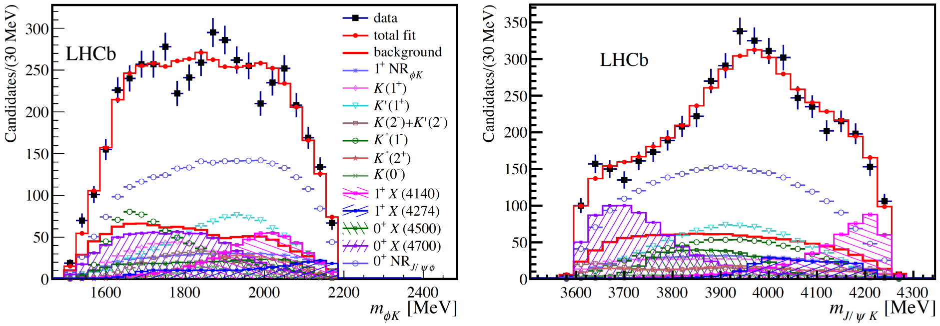


Argand plot for the Z(4430)$^-$ state

New exotic states in J/ψϕ mass

R. Aaij et al. LHCb collaboration, arXiv:1606.07895
submitted to PRL, 25 Jun 2016

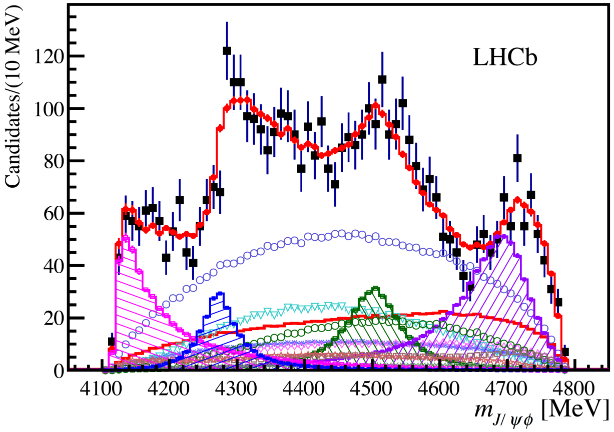
- LHCb has performed an amplitude analysis of 4289 ± 151 $B^+ \rightarrow J/\psi \phi K^+$ decays, with $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$. *The data cannot be described with a model with only excited kaon states* decaying into ϕK^+ .
- Four J/ψϕ *tetraquark* states are observed, with quantum numbers:



	Mass (MeV)	Width (MeV)	J^{PC}	S / QN (nσ)
X(4140)	$4146.5 \pm 4.5\,^{+4.6}_{-2.8}$	$83 \pm 21\,^{+21}_{-14}$	1^{++}	8.4 / 5.7
X(4274)	$4273.3 \pm 8.3\,^{+17.2}_{-3.6}$	$56 \pm 11\,^{+8}_{-11}$	1^{++}	6.0 / 5.8
X(4500)	$4506.0 \pm 11\,^{+12}_{-15}$	$92 \pm 21\,^{+21}_{-20}$	0^{++}	6.1 / 4.0
X(4700)	$4704.0 \pm 10\,^{+14}_{-24}$	$120 \pm 31\,^{+42}_{-33}$	0^{++}	5.6 / 4.5

Signals seen before, now established

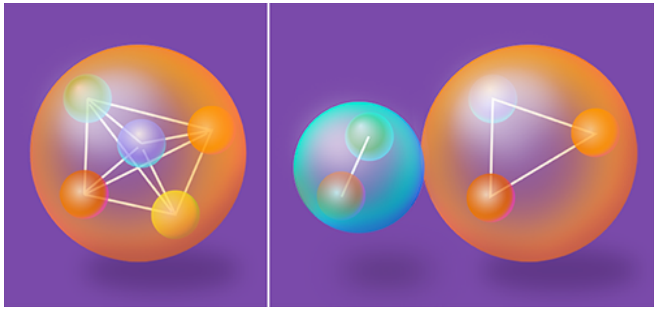
NEW !



- The first two show consistency with previous measurements (CDF,Belle,CMS,D0, BaBar) X(4140) can also be described by a 0^{-+} cusp model for $D_s^+ D^*_{s0}(2317)^-$ scattering, but the likelihood is substantially worse than that of the resonance model

Summary on multiquarks

- LHCb has found two resonant quantum states coupled to J/ψ p with pentaquark content $uudc\bar{c}$ (PRL 115, 072001 (2015)). Their preferred spin-parities J^P are: ($3/2^-$, $5/2^+$), ($3/2^+$,$5/2^-$) or ($5/2^+$,$3/2^-$). Opposite parity is highly significant.



- Determination of their binding mechanism will require more study. *Different* QCD-inspired approaches have been proposed.
- Charmonium-related tetraquark states have been reported by several experiments, of the $c\bar{c}d\bar{u}$ type : Z(4430) (resonant character 1^+ shown by LHCb) and Z(4239), and of the $J/\psi\phi$ type: X(4140), X(4274), X(4500), X(4700).
- Lattice QCD calculations would be *most welcome* to provide masses

A new field of spectroscopy seems to have emerged

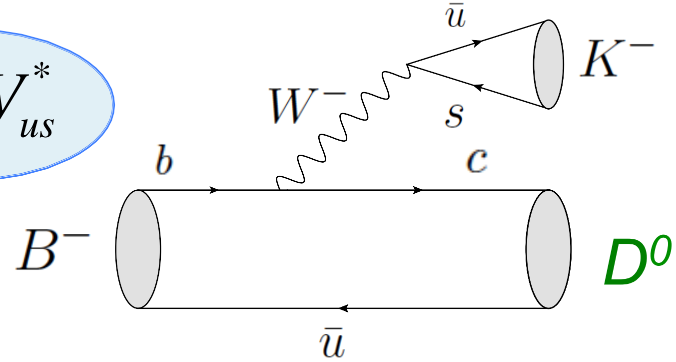
BACKUP SLIDES

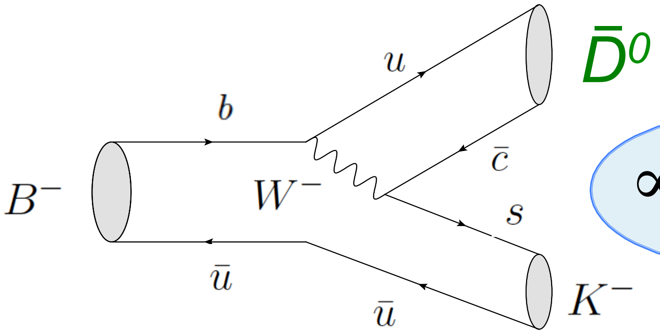
MEASUREMENT OF THE CP-VIOLATING PHASE γ FROM TREE DIAGRAMS

Why γ from B → DK is important

- γ plays a unique role in CKM physics $\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/(V_{cd}V_{cb}^{*})\right]$
  - it can be measured from direct CP violation in tree diagrams alone (since top quark is not involved in the couplings)
- Therefore a reference point for the Standard Model
  - particularly important after New Physics is discovered

$\propto V_{cb}V_{us}^{*}$



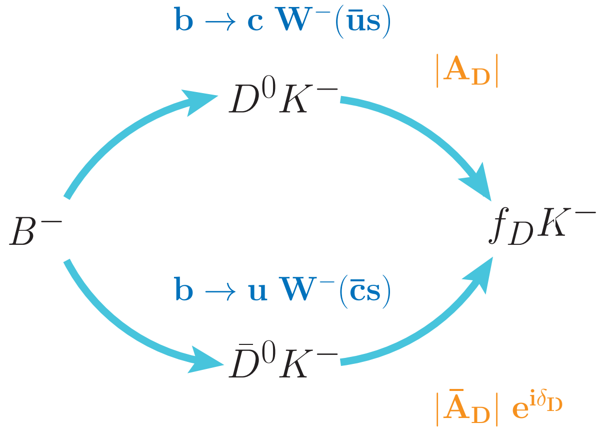


$\propto V_{ub}V_{cs}^{*}$

- A final state COMMON to D^0 and $\bar{D}^0$ is required. Different possibilities are characterized in the literature (GLW,ADS,GGSZ)

GLW: *Gronau-London-Wyler PL B253 (1991) 483. , PLB 265 (1991) 172.*
ADS: *Atwood-Dunietz-Soni PRL 78 (1997) 3257. , PRD 63 (2001) 036005.*
GGSZ: *Giri-Grossman-Soffer-Zupan PRD 68 (2003) 054018*

γ MEASUREMENTS (GLW-ADS)



$\mathbf{b \to c\ W^-(\bar{u}s)}$

$|A_D|$

D^0K^-

B^-

f_DK^-

$\mathbf{b \to u\ W^-(\bar{c}s)}$

$\bar{D}^0K^-$

$|\bar{A}_D|\ e^{i\delta_D}$

- Interference between (balanced) $b \to u$ and $b \to c$ amplitudes. Common element:

$$\frac{A(B^- \to \bar{D}^0K^-)}{A(B^+ \to D^0K^+)} \equiv r_B e^{i(\delta_B - \gamma)}$$

- Different modalities for various $D^0/\bar{D}^0$ final states f_D ($B^\pm \to f_D K^\pm$). Also neutral $\overset{(-)}{B^0}$ decays ($\overset{(-)}{B^0} \to f_D \overset{(-)}{K^{*0}}$), with $K^{*0} \to K^+\pi^-$. Main cases are:

- $f_D = K^+K^-, \pi^+\pi^-$, CP-eigenstates (GLW). CP-violation rates:

$$\Gamma(B^\pm \to f_D K^\pm) = 1 + r_B + 2r_B\cos(\delta_B \pm \gamma)$$

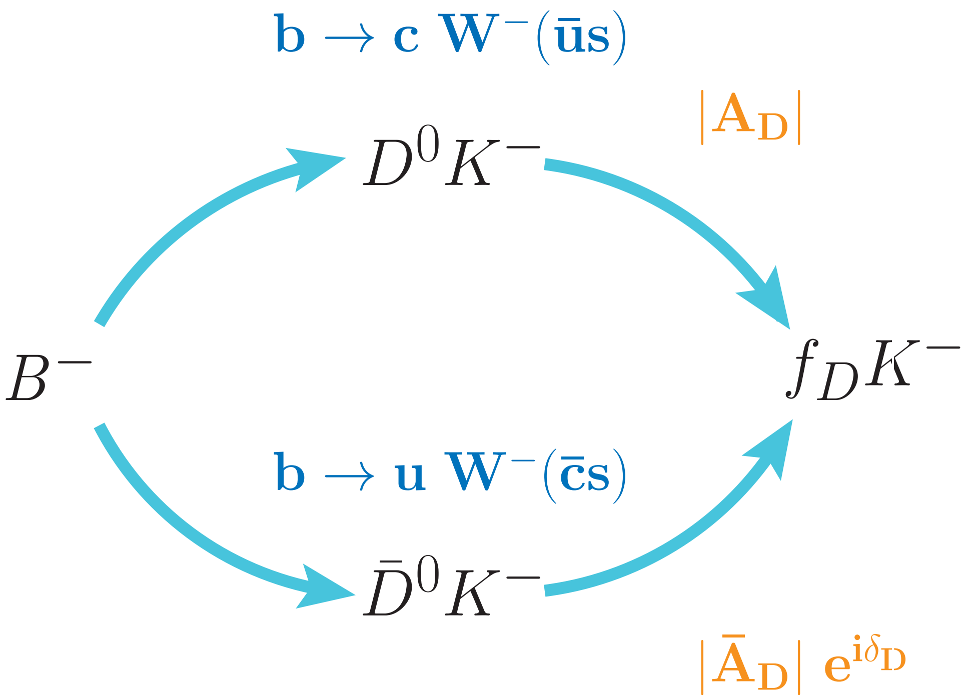
- $f_D = \pi^-K^+, K^-\pi^+$ (Cabibbo suppressed/favored , ADS)

Ratio of D^0-decay amplitudes then comes into play : $\dfrac{A_D(\pi^-K^+)}{\bar{A}_D(K^-\pi^+)} \equiv r_D e^{i\delta_D}$

With the CP-violating rates contributing as:

$$\Gamma(B^\pm \to f_D K^\pm) = r_D^2 + r_B^2 + 2r_Dr_B\cos(\delta_B + \delta_D \pm \gamma)$$

γ MEASUREMENTS (qGLW-qADS)



- Extensions of both of the above to higher multiplicities, have also been used by LHCb:

$$f_D = \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^0, \pi^+\pi^-\pi^0 \quad \text{(quasi GLW)}$$

$$f_D = \pi^-K^+\pi^+\pi^-, \pi^-K^+\pi^0, K^0_S\pi^-K^+ \quad \text{(quasi ADS)}$$

Which require :

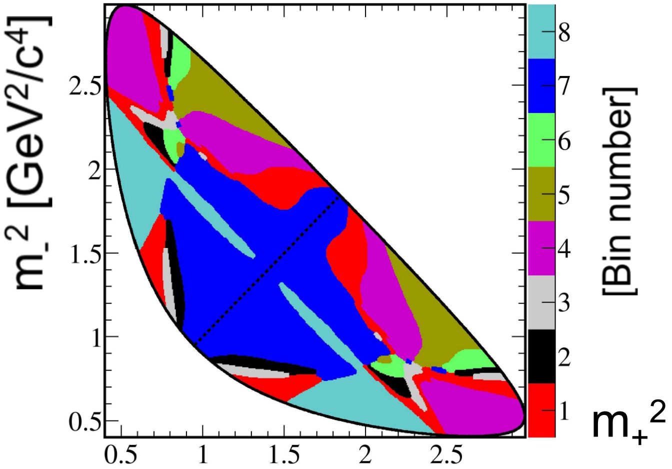
a) Fraction of CP = +1 eigenstate F_+ for self-conjugate modes f_D ($k_D = 2F_+ - 1$)

b) And coherence factors k_D^f :

$$k_D^f e^{i\delta_D^f} \equiv \frac{\int A_f(x)\bar{A}_f(x)dx}{A_f\bar{A}_f}$$

$D^0 \rightarrow K^0_S\pi^+\pi^-$ and $D^0 \rightarrow K^0_S K^+K^-$ modes

- These modes (GGSZ) played an important role in recent (2016) LHCb γ measurements
- The D^0-decay amplitude A_D is distributed over the $K^0_S\pi^+\pi^-$ Dalitz plot $m_\pm = m(K^0_S\pi^\pm)$
  Assume $A_D(m^2_-, m^2_+) = \bar{A}_D(m^2_+, m^2_-)$, since CP violation in D^0-decay is very small.



- Complication: a hadron phase $\delta_D(m^2_-, m^2_+)$ shows up in the Dalitz plot, generating an interference pattern which needs to be handled.
- The distribution within the phase space can be analysed as:

$$\mathcal{P}_\pm = |A_D|^2 + |z_\pm|^2|\bar{A}_D|^2 + 2k_D\mathrm{Re}[z_\pm A^*_D\bar{A}_D]$$

with

$$z_\pm \equiv r_B e^{i(\delta_B \pm \gamma)}$$

k_D : coherence factor

- Two methods have been established to determine de cartesian coordinates:

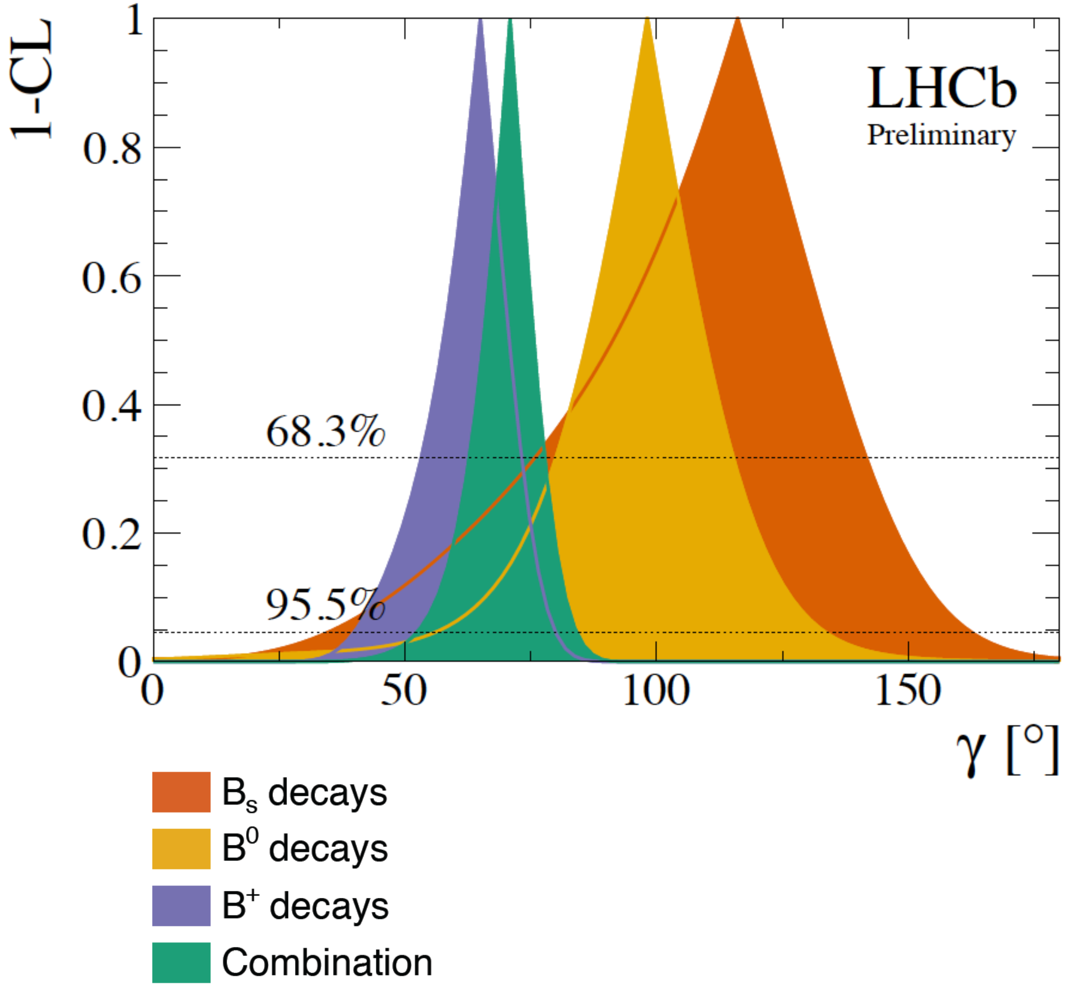
$$x_\pm \equiv r_B\cos(\delta_B \pm \gamma) = \mathrm{Re}(z_\pm) \qquad y_\pm \equiv r_B\sin(\delta_B \pm \gamma) = \mathrm{Im}(z_\pm)$$

both valid for $B^\pm \to f_D K^\pm$ and $\overset{(-)}{B^0} \to f_D \overset{(-)}{K^{*0}}$

a) Model-independent : use external data from CLEO-c coherent $D^0/\bar{D}^0$ production to determine the binned averages over the Dalitz plot: $c_i \equiv \langle\cos\delta_D\rangle$ $s_i \equiv \langle\sin\delta_D\rangle$

b) Model-dependent : perform amplitude analysis with explicit resonance model that will take care of the hadron phase

Full combination for γ measurement



Quantity	Value
γ (°)	70.9
68% CL (°)	[62.4,78.0]
r_B^{DK}	0.1006
68% CL	[0.095, 0.106]
δ_B^{DK} (°)	141.1
68% CL (°)	[133.4, 147.2]
$r_B^{DK^{*0}}$	0.217
68% CL	[0.169, 0.261]
$\delta_B^{DK^{*0}}$ (°)	189.0
68% CL (°)	[169.0, 213.0]

Summary of γ measurement

- A world-leading measurement of γ is made from a combination of LHCb analysis:

$$\gamma = \left(70.9\,^{+7.1}_{-8.5}\right)^{\circ}$$

- The result is inline with analogous B-factory single-experiment conclusions:

BaBar: $\gamma = (70 \pm 18)^{\circ}$

Belle: $\gamma = \left(73\,^{+13}_{-15}\right)^{\circ}$

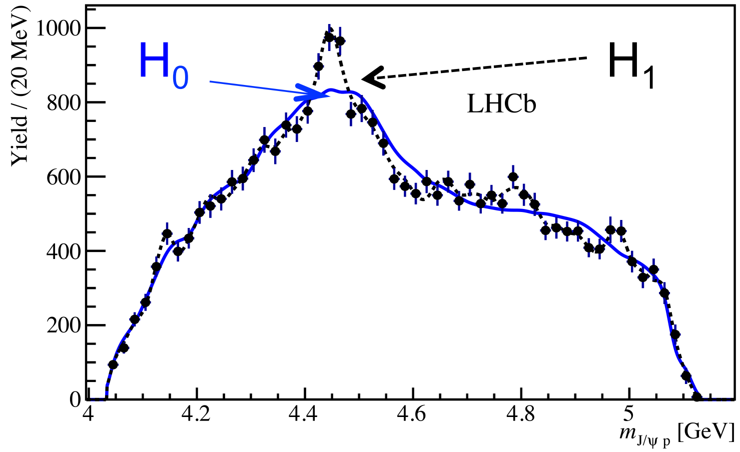
- It is ≈ 1σ high when compared with expectation from other measurements with Constrained Minimal Flavour Violation for $\sin 2\beta = 0.691 \pm 0.017$ and new lattice determinations of hadronic matrix elements in B-mixing (Fermilab-MILC arXiv:1602.03560) :

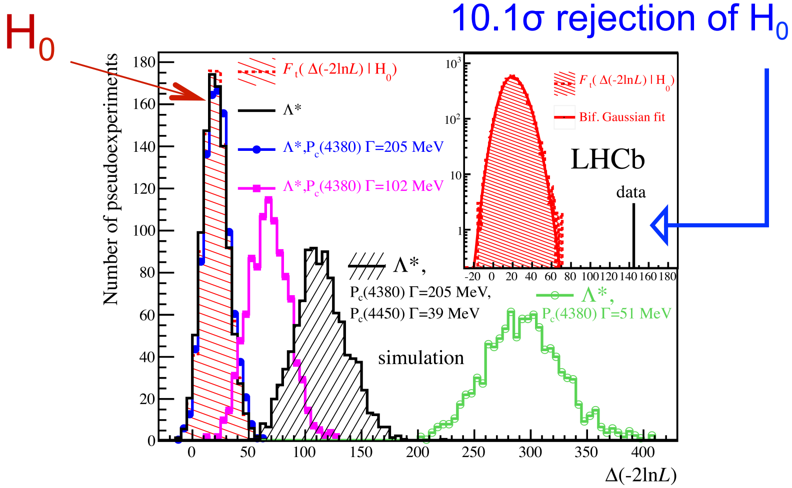
UUT (CMFV): $\gamma = (62.7 \pm 2.1)^{\circ}$ (Blanke-Buras arXiv: 1602.04020)

$\Lambda_b \rightarrow J/\psi K^- p$ model-independent analysis

A different analysis of the same data: The LHCb collaboration arXiv:1604.05708 (2016)

- *Minimal assumptions* on the mass and spin of m_{Kp} structures in the Dalitz plot, no assumptions on their number, resonant structure nature, or line shapes.
- The null-hypothesis (H_0) is characterized by a maximum $L_{max}(m_{Kp})$ in a Legendre polynomial expansion P_L of the efficiency corrected $\cos\theta_{\Lambda*}$ angular distribution.
- An alternative hypothesis (H_1) is defined as $L \leq L_{large}$ where L_{large} is *large enough to reproduce* the structures induced by J/ψp pentaquark resonances P_c .
- The result *supports the amplitude model-dependent observation* of the J/ψp resonances previously reported.





10.1σ rejection of H_0

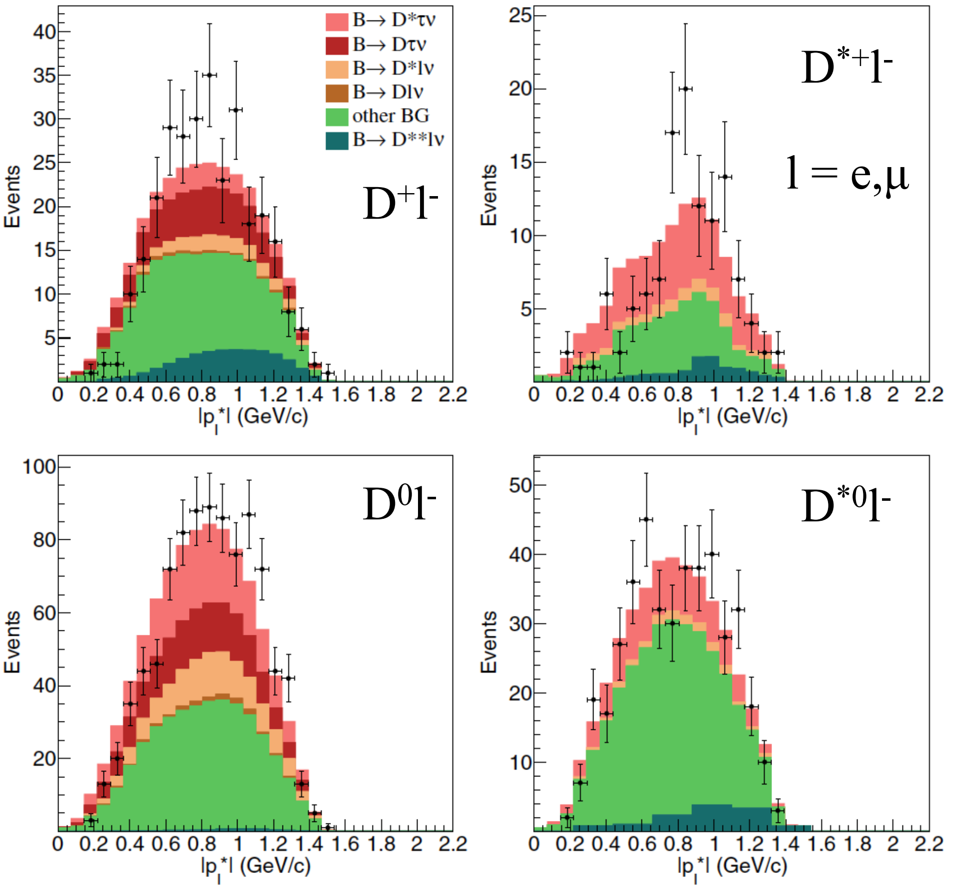
Simulations of specific pseudoexperiments generated from the previous amplitude models

R(D) and R(D*) from Belle

M. Huschle et al. PRD 92, 072014 (2015)

- New result from Belle 2015 using the full Belle $\Upsilon \rightarrow BB$ data set of 711 fb^{-1}
- Tau is reconstructed in both electron and muon modes
- Both low M_{miss}^2 and high M_{miss}^2 are used in the fit to constrain the lepton normalization
- At B-factories one can profit from the beam energy constraint. Dominant systematics is understanding of D^{**} background

$$R(D^*) = 0.293 \pm 0.038\ (\text{stat}) \pm 0.015\ (\text{syst})$$
$$R(D) = 0.375 \pm 0.064\ (\text{stat}) \pm 0.026\ (\text{syst})$$



p_l^* : lepton momentum in the signal-B frame

$M_{miss}^2 > 2.0\ GeV^2/c^4$ in plots

Summary on lepton universality

Are we beginning to see cracks in the SM?

- LHCb is expanding its physics programme to more modes, with electrons and taus:
  - similar to R_K but with different hadrons : K^{*0}, Φ, Λ, etc
  - do also $D^*\tau(\rightarrow 3\pi\nu)\nu$, and $D\tau\nu$, $\Lambda_c\tau\nu$, etc
- And search in addition for lepton number violation in channels like $B \rightarrow \tau\mu$, $K\tau\mu$, $Ke\mu$ ...
- The results on R_K (consistently with R_{D*}) have motivated interpretations beyond the SM, as possible scalar leptoquark states on the TeV mass scale, see:

M. Bauer and M. Neubert, arXiv: 1511.01900,
also G. Hiller and M. Schmaltz arXiv:1408.1627