LHCb Searches for New Physics in Heavy Flavour

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On behalf of the LHCb collaboration

Outline

- **Introduction**
  - Motivation
  - LHCb experiment
- **Rare Decays**
  - Observation of $B_s \to \mu^+\mu^-$
  - Angular analysis in $B^0 \to K^{*0}\mu^+\mu^-$
- **Lepton Flavour Universality**
  - $B^+ \to K^+\mu^+\mu^-$ vs $B^+ \to K^+e^+e^-$
  - $B \to D^{*+}\tau^-\nu$
- **CP violation**
  - ϕ_s in $B_s \to J/\psi\phi(KK)$
  - ϕ_s in $B_s \to \phi\phi$
  - A_{sl} – CPV in mixing
  - B_s lifetimes
- **Unitarity Triangle**
  - CKM angle gamma
  - V_{ub}
- **Exotic Spectroscopy**
  - Pentaquarks
  - Tetraquarks
  - X(5568)?
  - X(4140)
- **Conclusion**

- See also Umberto Marconi
  - LHCb upgrade plans and physics potential

Heavy Flavour & New Physics

- **How to search for New Physics in Heavy Flavour?**
  - Sensitive to NP appearing as virtual particles in loop processes
  - Observable deviations from SM expectations in CP violation (~~CP~~) and rare decays
- **CKM mechanism**
  - Based on only 4 parameters - makes many precise SM predictions
  - Only source of ~~CP~~ in Standard Model

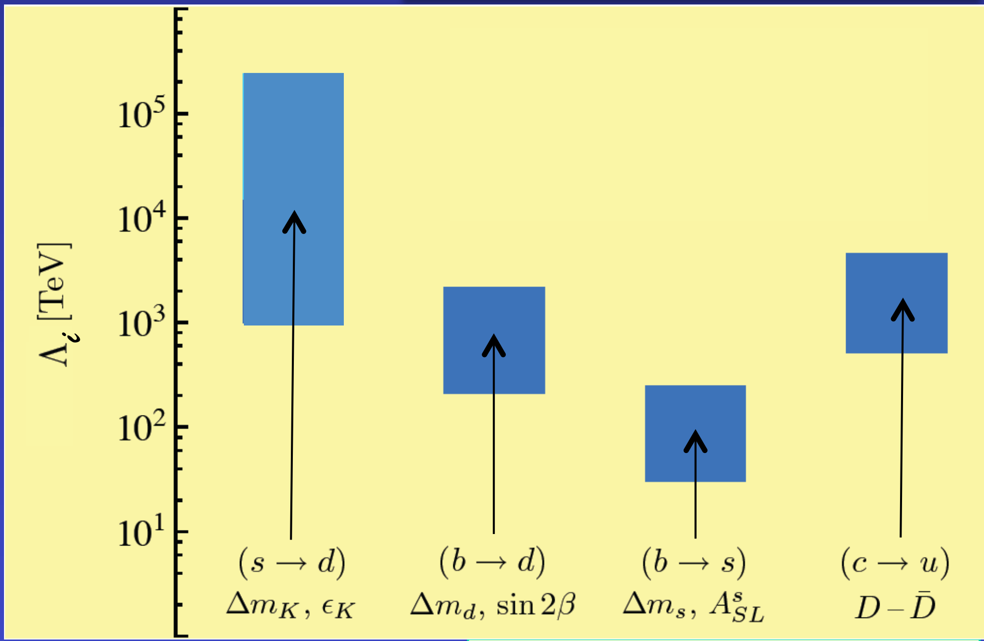
$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - \boxed{i\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-\boxed{i\eta}) & -A\lambda^2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

  - Flavour changing neutral currents (FCNC) suppressed in SM
  - *When you have eliminated the impossible, whatever remains, however improbable, must be the truth?* Sherlock Holmes

New Physics Flavour Problem

- **Add new physics to SM Lagrangian**
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$
- **Flavour transitions**
  - probe high mass scales
  - parameterised in terms of operators, couplings and mass scales
- **NP flavour problem**
  - If couplings c_i ~1 NP should have been seen
  - particles have large masses >> 1 TeV or couplings are small c_i << 1 & same as in SM

New physics ruled out from Λ_i=0 to somewhere in the blue boxes

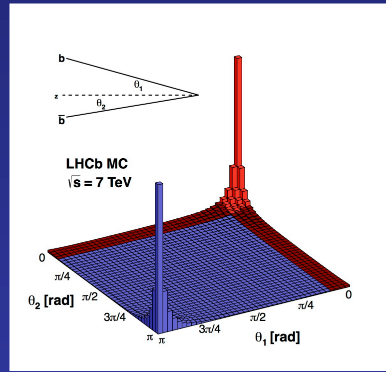


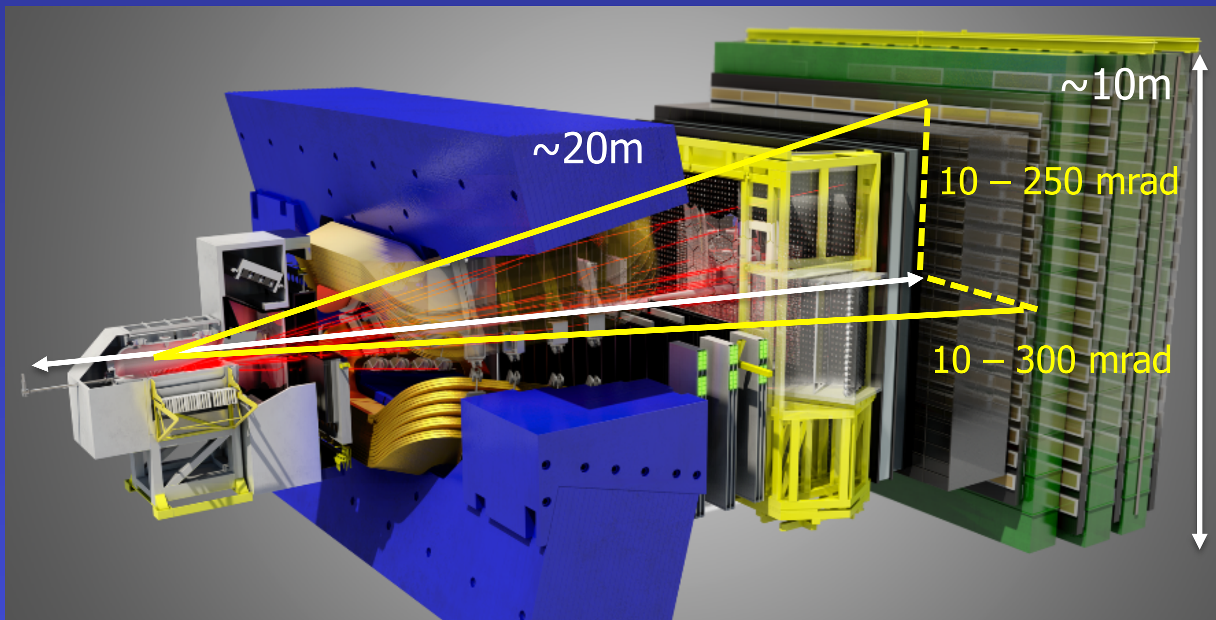
See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

LHC and experiments

LHCb Experiment

- **LHC is a flavour factory**
  - beauty quark cross section
    $\sigma_{bb} \sim 300\ (500)\ \mu b$ at $\sqrt{s} = 7\ (13)$ TeV,
  - Very large charm cross section $\sigma_{cc} \sim 20\ \sigma_{bb}$
- **LHCb**
  - dedicated experiment for heavy flavour physics

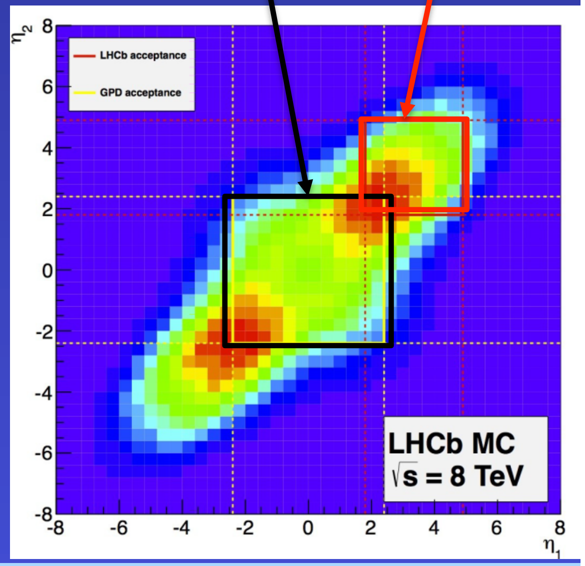




JINST 3 (2008) S08005

ATLAS & CMS region | η | < 2.5

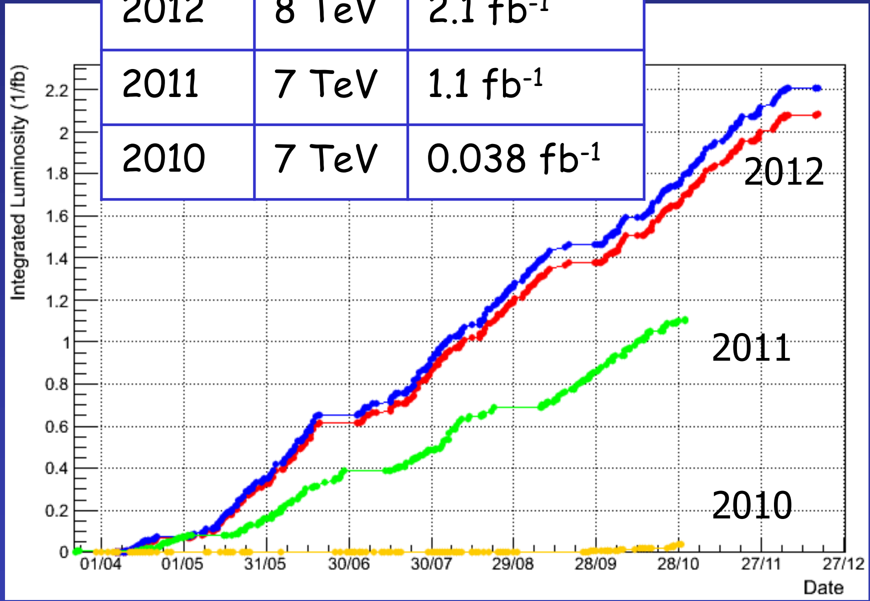
LHCb region 2 < η < 5



LHCb Performance

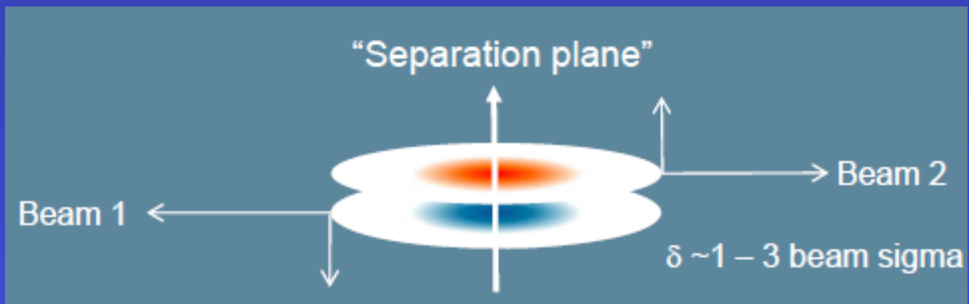
Int. J. Mod. Phys. A **30**, 1530022 (2015)

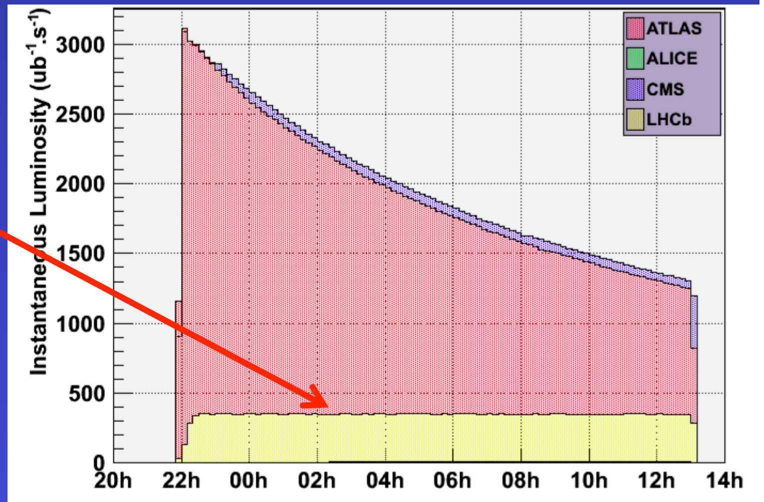
2012	8 TeV	2.1 fb^{-1}
2011	7 TeV	1.1 fb^{-1}
2010	7 TeV	0.038 fb^{-1}



- **Very successful Run-1**
  - LHCb operated at luminosities up to $L = 4\times10^{32}\ cm^{-2}\ s^{-1}$ 2x design luminosity
  - Average # of visible interactions/ crossing $\mu = 1.4$ (nominal 0.4)
  - Integrated $\int L dt \sim 3\ fb^{-1}$ on tape
  - 91% data taking efficiency
  - ~ 5 kHz of physics data to tape

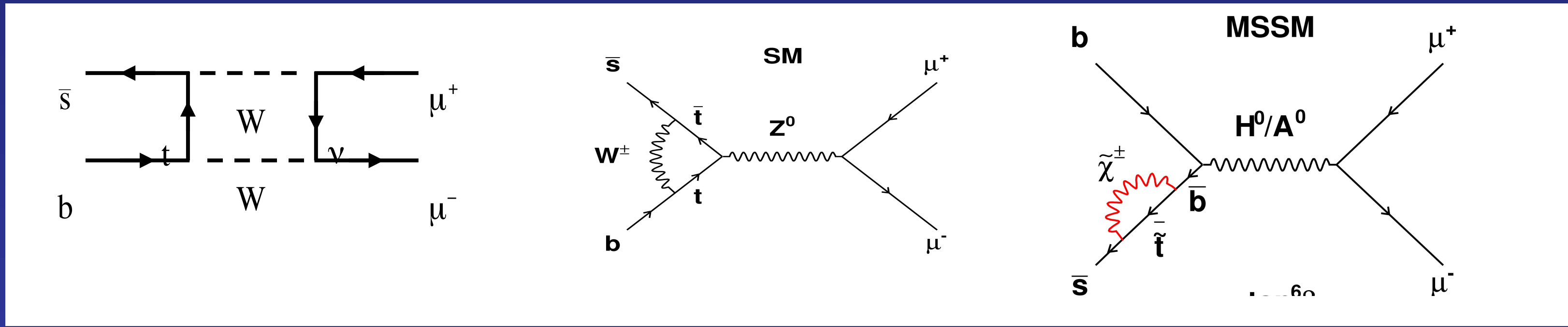
Luminosity levelling





Rare Decays

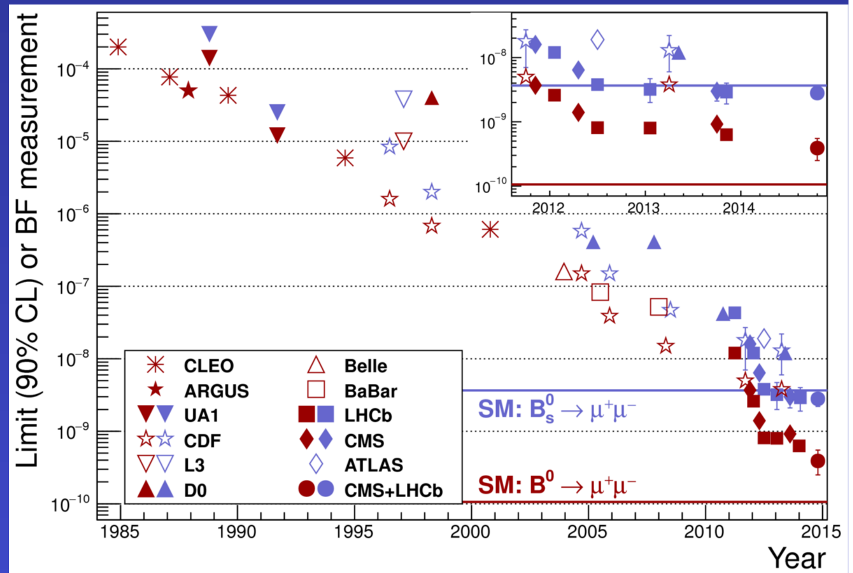
Rare decay $B_s \to \mu^+\mu^-$



- **Decay highly suppressed in SM**
  - CKM and helicity suppressed
  - Predicted SM branching ratio
  - BR ($B_s \to \mu^+\mu^-$) = $(3.66 \pm 0.23) \times 10^{-9}$
  - BR ($B^0 \to \mu^+\mu^-$) = $(1.06 \pm 0.09) \times 10^{-10}$

C. Bobeth et al., PRL 112, 101801 (2014)

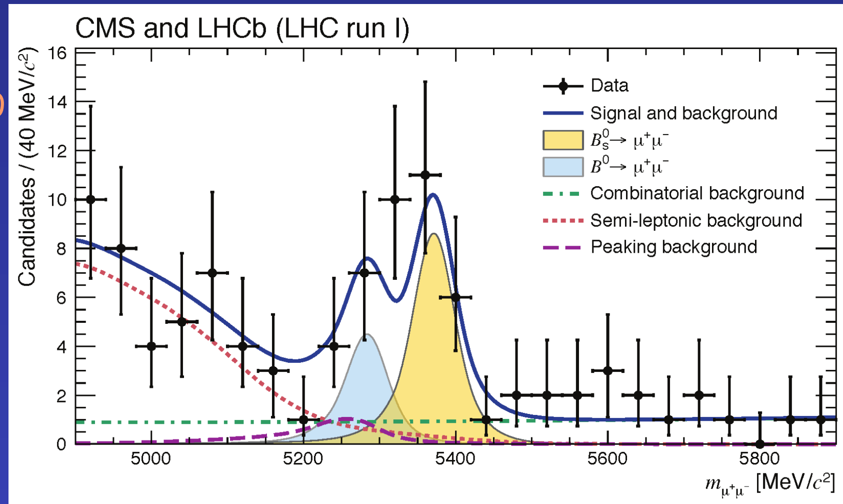
- **Very sensitive to new physics**
  - Strongly enhanced in MSSM models
  - Rate $\propto \tan^6\beta / M_H$

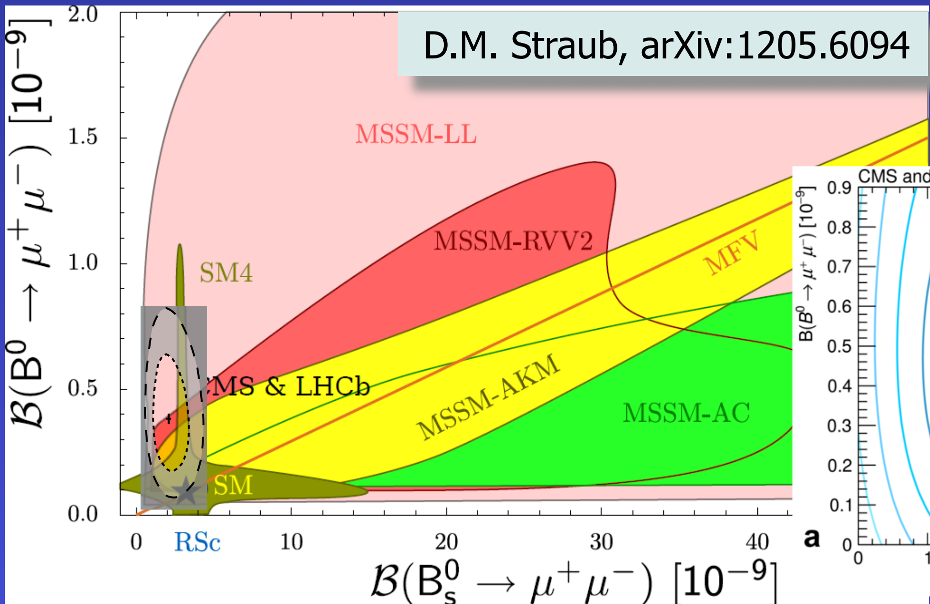


Observation of $B_s \to \mu^+\mu^-$

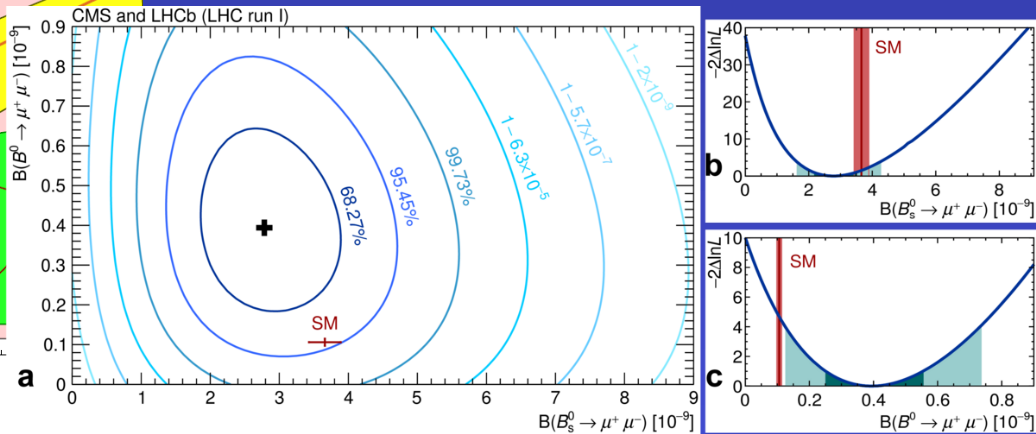
LHCb: Phys. Rev. Lett. 111 (2013) 101805
CMS: Phys. Rev. Lett. 111 (2013) 101804
Nature (2015) 522, 68–72

- **LHCb and CMS joint paper**
  - Observe $B_s \to \mu^+\mu^-$ at 6.2σ significance
  - $BR(B_s \to \mu^+\mu^-) = (2.8 +0.7 -0.6) \times 10^{-9}$
  - 3σ evidence for $B_d \to \mu^+\mu^-$
  - $BR(B_d \to \mu^+\mu^-) = (3.9 +1.6 -1.4) \times 10^{-10}$
- **Implications**
  - NP SUSY models with large tan β ruled out





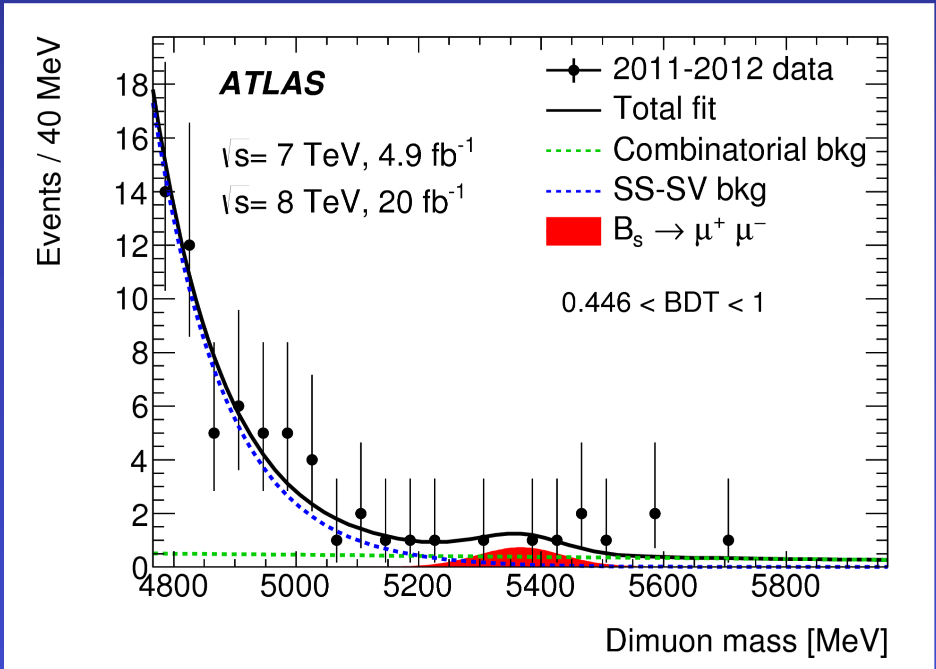
D.M. Straub, arXiv:1205.6094

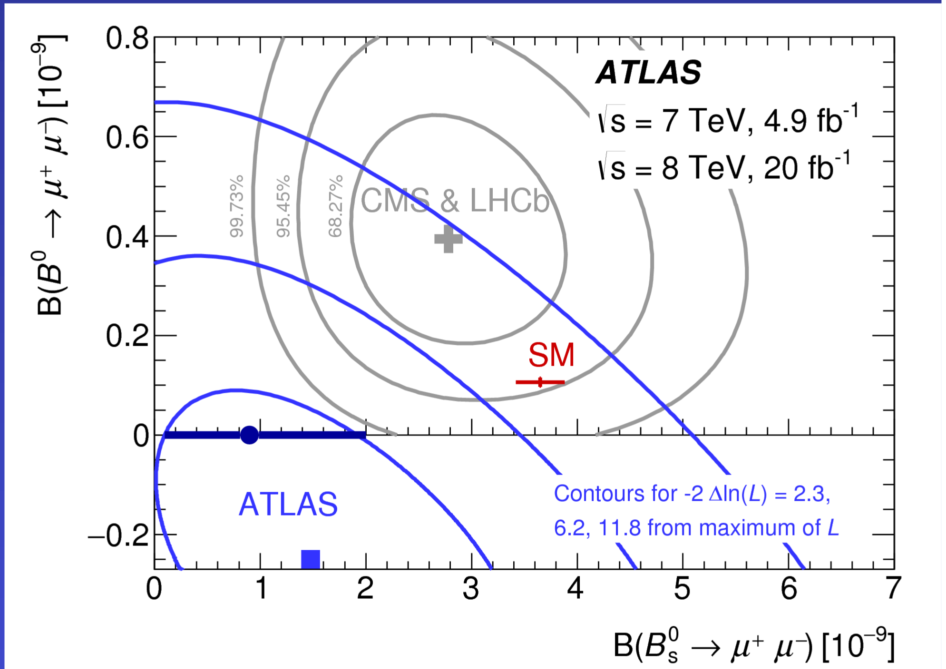


Observation of $B_s \to \mu^+\mu^-$

ATLAS: arXiv:1604.04263
Submitted to EPJC

- **ATLAS measurement**
  - $BR(B_s \to \mu^+\mu^-) = (0.9 +1.1-0.8) \times 10^{-9}$
  - $BR(B_d \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ @ 95% C.L.
  - Consistent with SM prediction at 2σ

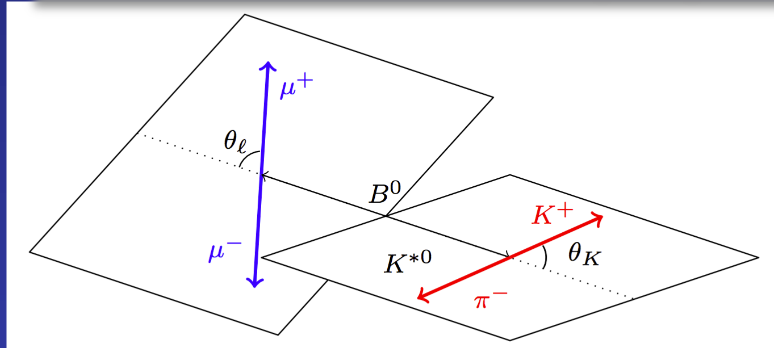




Angular Analysis in $B^0 \to K^{*0}\mu^+\mu^-$

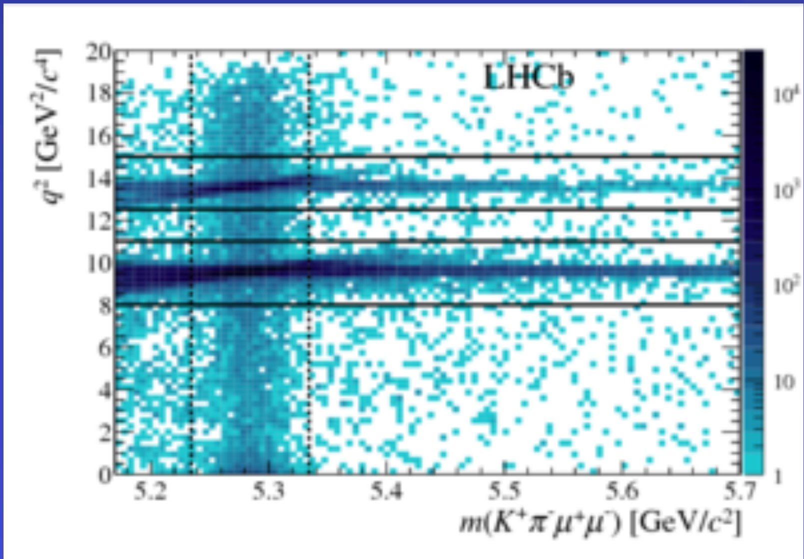
LHCb-PAPER-2015-051, arXiv: 1512.04442
JHEP 02 (2016) 104

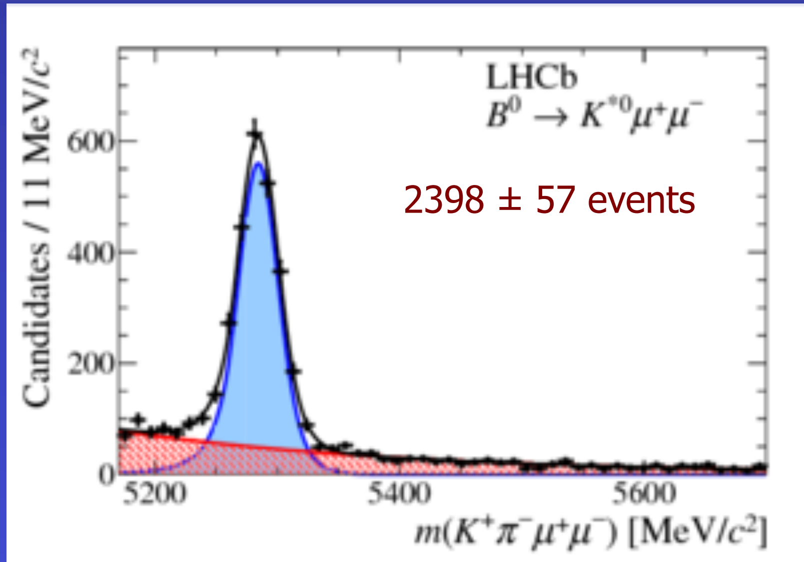
- $B^0 \to K^{*0}\mu^+\mu^-$
  - Clean SM predictions
  - sensitive to NP
  - Clean signature
  - Low branching ratio $O(10^{-6})$



$$\mathcal{B}(B^0 \to K^*(892)^0\mu^+\mu^-) = (1.036\,^{+0.018}_{-0.017} \pm 0.012 \pm 0.007 \pm 0.070) \times 10^{-6},$$

New: LHCb-PAPER-2016-012, To be submitted to JHEP





Angular Analysis in $B^0 \to K^{*0}\mu^+\mu^-$

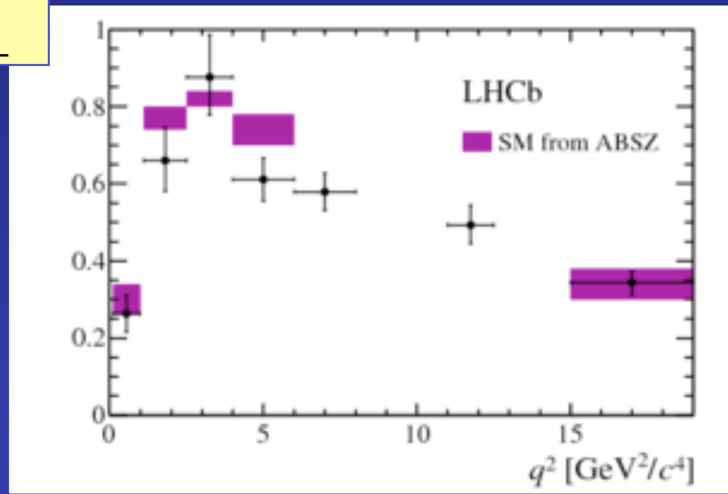
LHCb-PAPER-2015-051, arXiv: 1512.04442
JHEP 02 (2016) 104

- **Many angular observables**
  - P→ VV' decay described by $q^2 = m^2(\mu\mu)$ invariant mass and 3 helicity angles
  - Forward Backward Asymmetry A_{FB}
  - K^{*0} longitudinal polarisation F_L
  - Asymmetries S_i
  - Differential decay rate

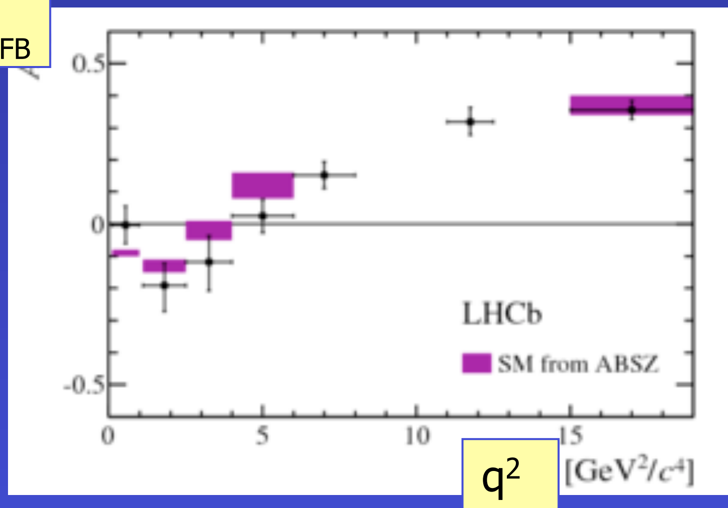
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

- **LHCb measurements**
  - of all independent observables
  - Shown are A_{FB} and F_L

F_L



A_{FB}



Angular Analysis in $B^0 \to K^{*0}\mu^+\mu^-$

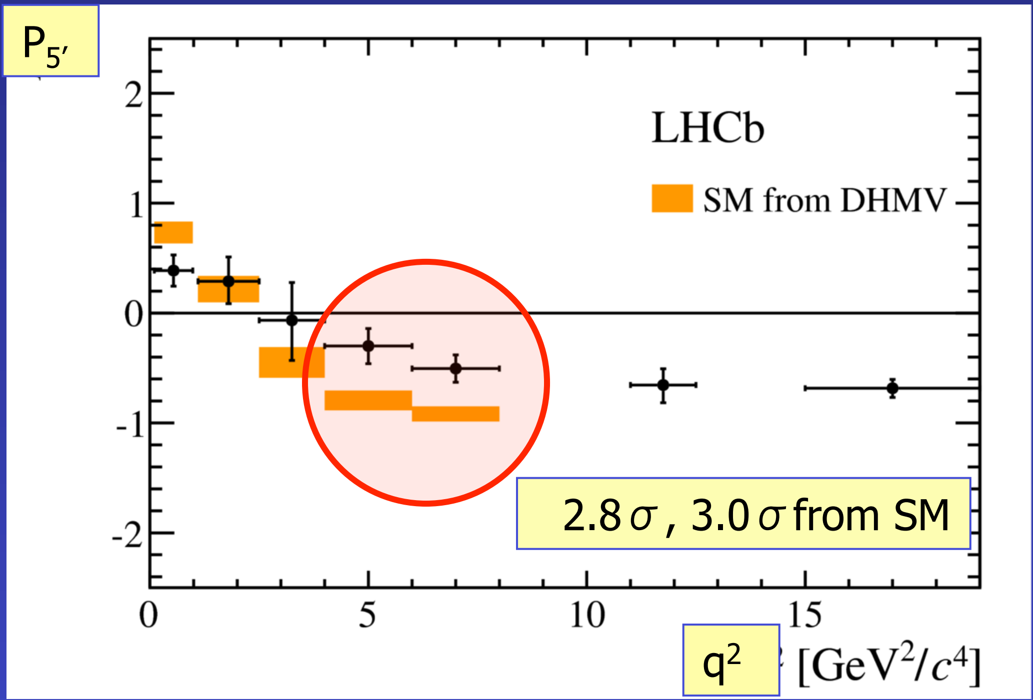
LHCb-PAPER-2015-051, arXiv: 1512.04442
JHEP 02 (2016) 104

- New observable basis

$$P'_{i=4,5,6,8} = \frac{S_{i=4,5,6,8}}{\sqrt{F_L(1-F_L)}}$$

  - form factor independent

Descotes et al, arXiv:1307.5683



- LHCb anomaly
  - Tension in P_5' first seen in 1 fb^{-1} remains in 3 fb^{-1}
  - Fit to all observables has 3.5 σ discrepancy to SM
  - New Physics contribution to Wilson coeff. C_9 or QCD?

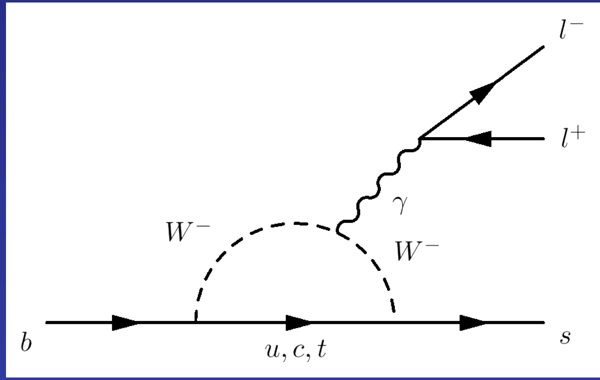
Lepton Flavour Universality

$B^+ \rightarrow K^+l^+l^-$

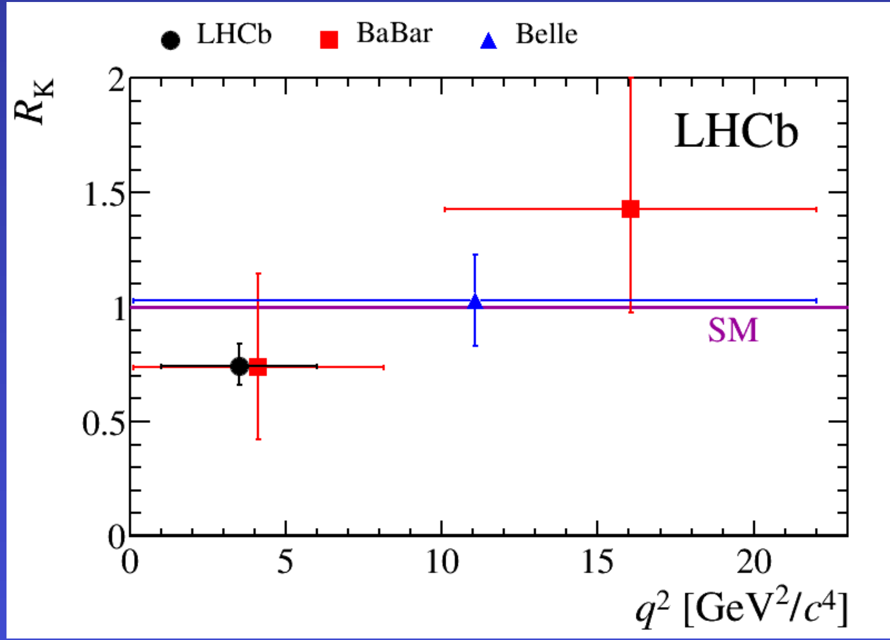
LHCb-PAPER-2014-024, PRL 113,151601 (2014)

- **Lepton universality in SM**
  - Couplings identical for $b \rightarrow s\, l^+l^-$
  - Expect unity for branching ratio R(K)

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-2}$$



- **LHCb measusrement**
  - R(K) = 0.745 ± 0.090 ± 0.036
  - 2.6σ deviation
- **Interpretation**
  - Statistical fluctuation or new physics in $b \rightarrow s\mu^+\mu^-$?
  - Related to 2.4σ excess in $H \rightarrow \tau\mu$ at CMS ?
- **Future plans**
  - Measure R(K*), R(ϕ), R(Λ)



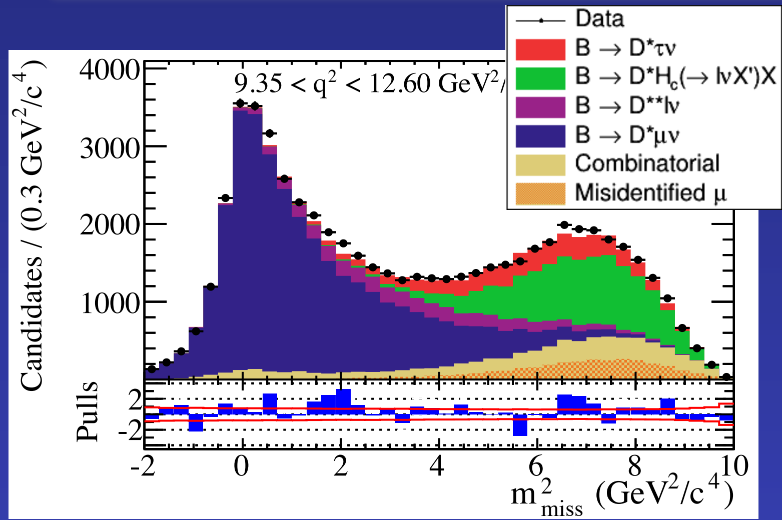
$B^0 \rightarrow D^{*+}\tau^-\nu$

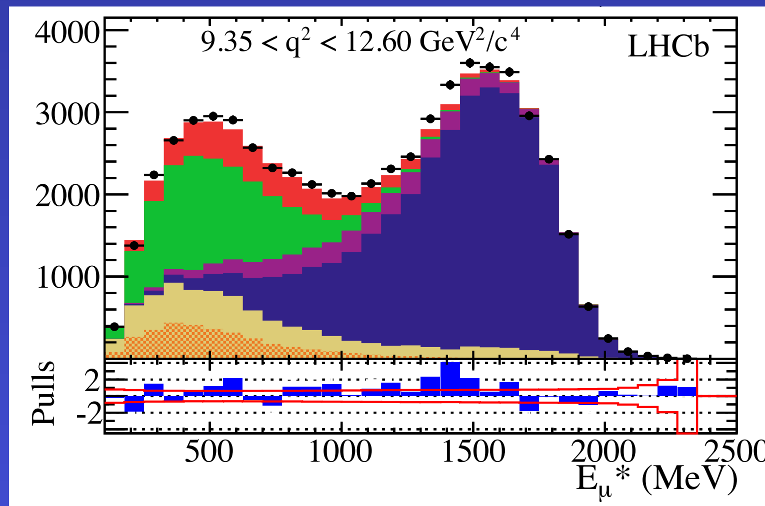
LHCb-PAPER-2015-025, arXiv:1506.08614
Phys. Rev. Lett. 115 (2015) 111803

- **Challenge at hadron collider**
  - No mass peak and large background
  - Use $\tau^- \rightarrow \mu^-\nu_\mu\nu_\tau$ final state
  - Missing mass squared and muon energy in B rest frame
  - Use superb LHCb tracking to remove backgrounds
  - Same final state for signal and normalisation

$$R_{D^*} = \frac{\mathcal{B}(\overline{B^0} \rightarrow D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B^0} \rightarrow D^{*+}\mu^-\overline{\nu}_\mu)}$$

- **LHCb Measurement**
  - R(D*) = 0.336 ± 0.027 ± 0.030
  - 2.1 σ deviation from SM





$B^{0+} \to D^{*+}\tau^-\nu, D^0\tau^-\nu$

- **Excess by Belle and Babar**
  - Cannot be explained by Higgs doublet model
- **Current Status**
  - Measurement by LHCb in 2015
  - Update by Belle in 2016
  - Average is 4.0 σ deviation from SM
- **Plans**
  - LHCb is also measuring hadronic tau final states
  - Belle-II

BaBar

$\mathbf{R(D) = 0.440 \pm 0.058 \pm 0.042}$
$\mathbf{R(D^*) = 0.332 \pm 0.024 \pm 0.018}$

Belle

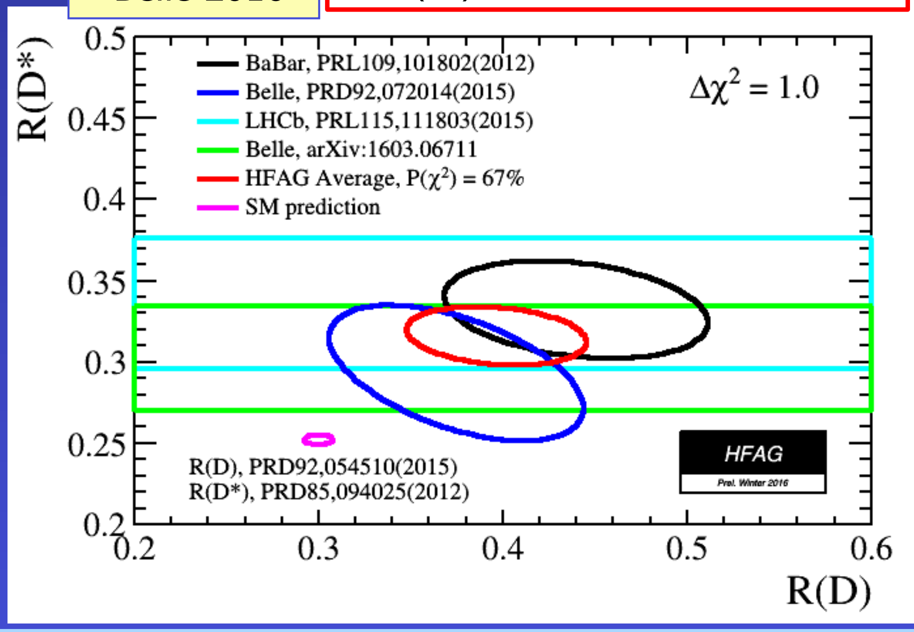
$\mathbf{R(D) = 0.375 \pm 0.064 \pm 0.026}$
$\mathbf{R(D^*) = 0.293 \pm 0.038 \pm 0.015}$

LHCb

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

Belle 2016

R(D*) = 0.302 ± 0.030 ± 0.011



CP Violation

CP Violation in $B_s \to J/\psi\phi$

3 fb^{-1}, LHCb-PAPER-2014-059 PRL 114, 041801 (2015)

1 fb^{-1}, PRD 87, 112010 (2013)

0.37 fb^{-1}, PRL 108, 101803 (2012)

J. Charles et al., PRD 84 (2011) 033005

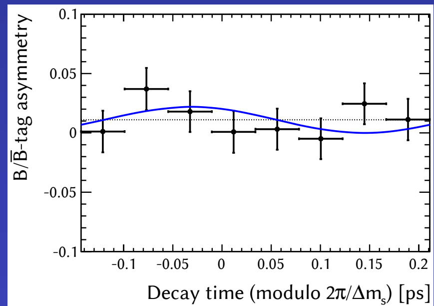
- **Weak phase ϕ_s**
  - Small SM prediction $\phi_s = -36.3 \pm 1.3$ mrad
  - Sensitive to NP in B_s mixing and decay
- **LHCb golden mode $B_s \to J/\psi\phi(KK)$**
  - fit to B_s mass, decay time and angular distributions

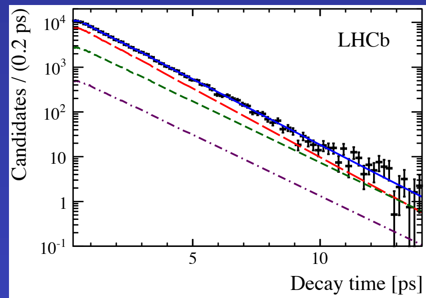
$\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad

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

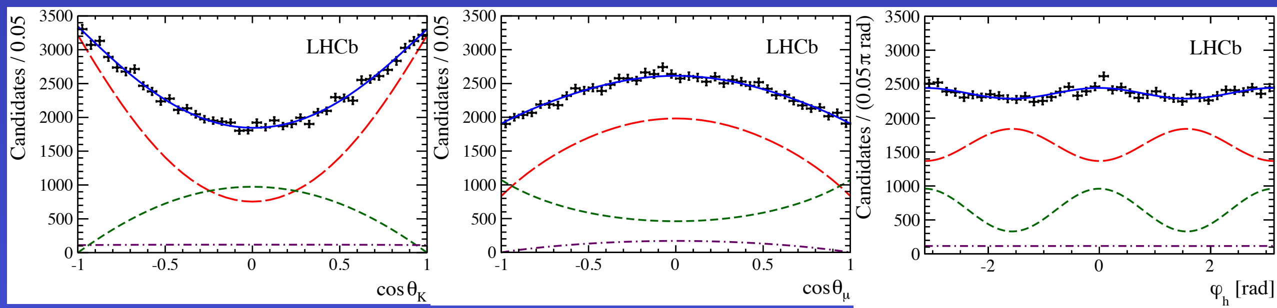
$\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0015\ ps^{-1}$

$\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0033\ ps^{-1}$



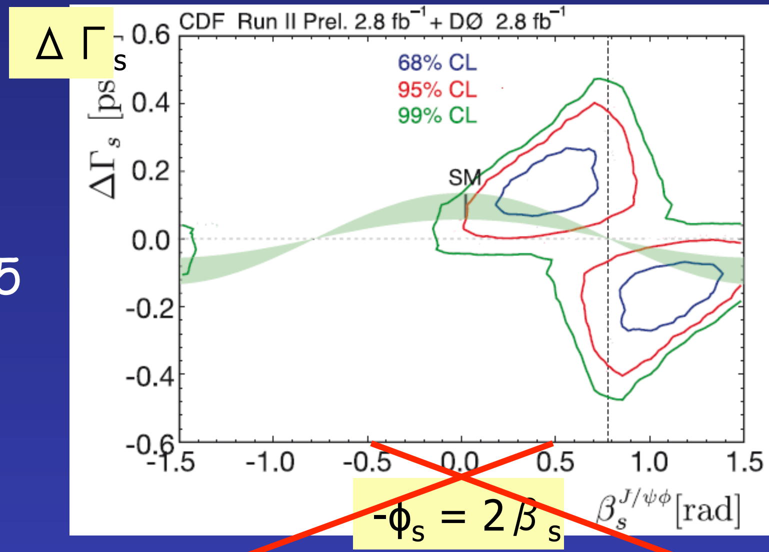


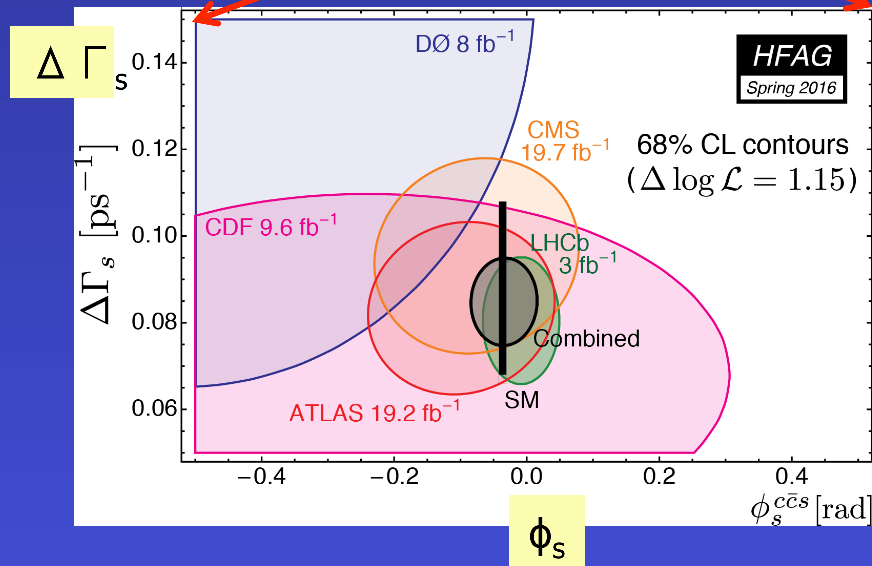
- Additional LHCb modes
  $B_s \to J/\psi\pi^+\pi^-$
  $B_s \to D_s^+D_s^-$



CP Violation in $B_s \to J/\psi\phi$

- **Weak phase ϕ_s status**
  - Early measurements by CDF & D0 (in 2009) 2.3σ discrepancy with SM
  - ATLAS, CMS and LHCb results in 2015
  - LHCb dominates world average
  - $\phi_s = -0.034 \pm 0.033$ rad
    $\Delta\Gamma_s = 0.082 \pm 0.006$ ps^{-1}
  - No New Physics >> SM





- **LHCb Plans**
  - Quadruple data set in run 2
  - LHCb upgrade after 2020

CP Violation in B_s Mixing

- **Semileptonic asymmetry**
  - measures CPV in mixing
  - very small in SM
- **a_{sl} at LHCb**
  - Time-integrated asymmetry in $B_s \to D_s^- \mu^+ \nu$, new 3/fb

$$A = \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)}$$
$$= \frac{a_{sl}^s}{2} + \left(a_p - \frac{a_{sl}^s}{2}\right) \frac{\int \exp(-\Gamma_s t)\cos(\Delta m_s t)\varepsilon(t)\,dt}{\int \exp(-\Gamma_s t)\cos(\Delta\Gamma_s/2 \cdot t)\varepsilon(t)\,dt}$$

  - a^s_{sl} = (0.39±0.26±0.20)%
  - Time-dependent asymmetry in $B_d \to D^{(*)-} \mu^+ \nu$
  - a^d_{sl} = (−0.02 ± 0.19 ± 0.30)%
  - ~3.0 σ deviation by D0

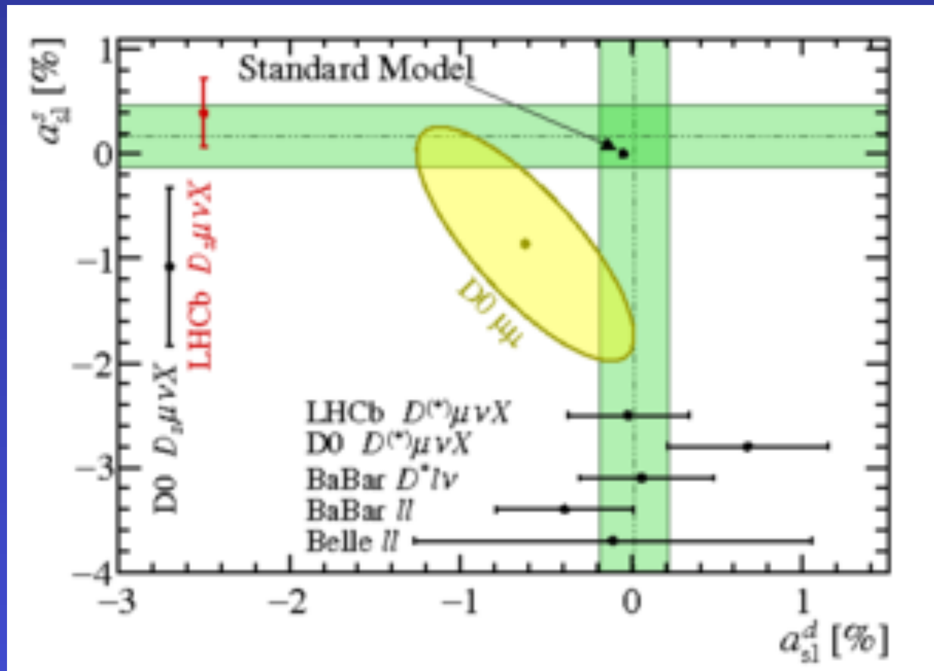
Lenz, Nierste, arXiv:1205.1444

$$a_{sl} = 1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi_{12}$$

$$a_{sl}^d = (-4.1 \pm 0.6) \cdot 10^{-4}$$
$$a_{sl}^s = (+1.9 \pm 0.3) \cdot 10^{-5}$$

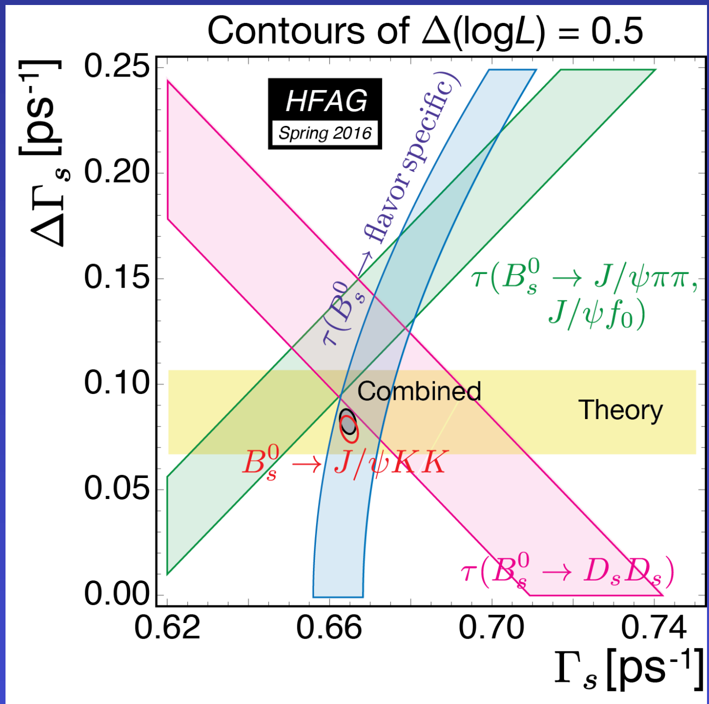
New: LHCb-PAPER-2016-013, arXiv:1605.09768

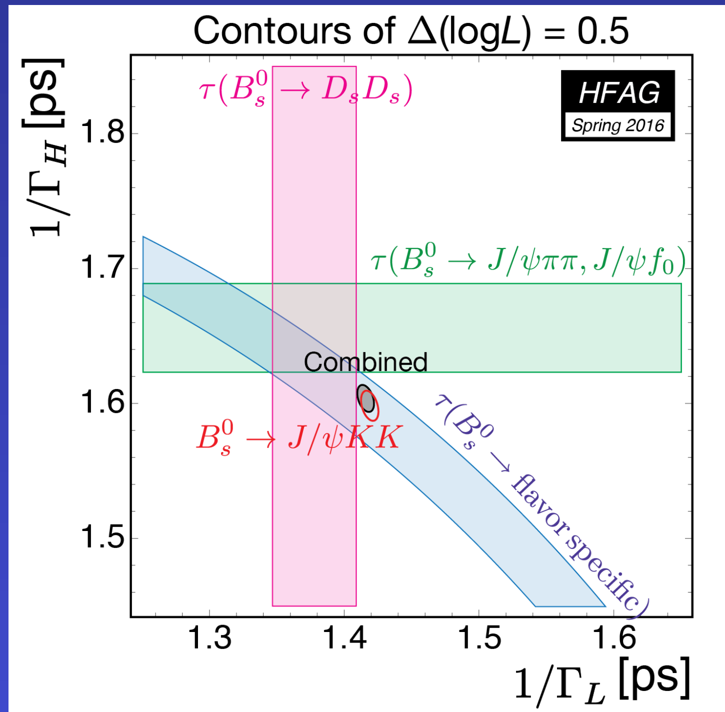
LHCb-PAPER-2014-053, PRL 114 (2015) 041601



B_s Lifetimes

- **Measurements of B_s lifetimes consistent with SM prediction**
  - $B_s \to J/\psi\phi(KK)$ most precise
  - Flavour specific decays, $B_s \to D_s^- \mu^+ \nu X$
  - Pure CP even or CP odd eigenstates

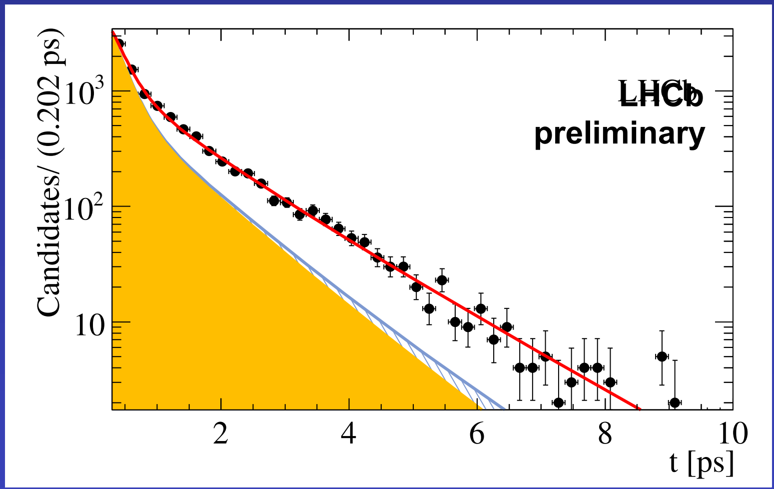


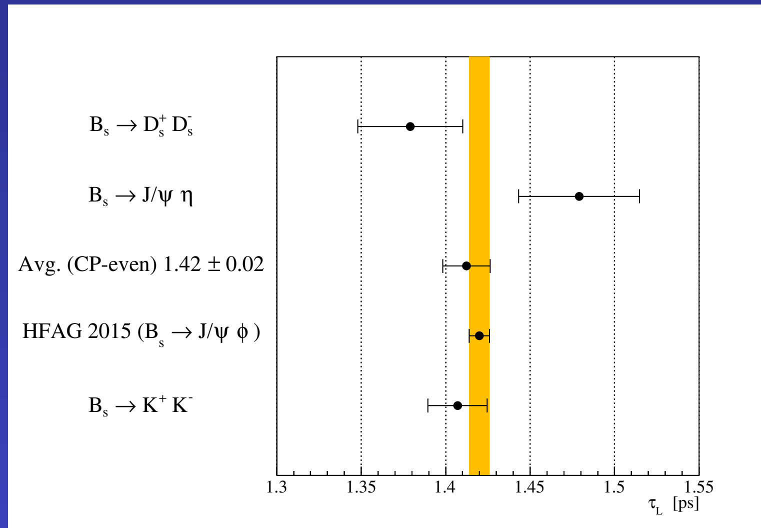


B_s Lifetimes

- $B_s \to J/\psi\eta(\to\gamma\gamma)$
  - CP odd eigenstate
  - Measure lifetime τ_L of $B_{s,light}$

New: LHCb-PAPER-2016-017, to be submitted



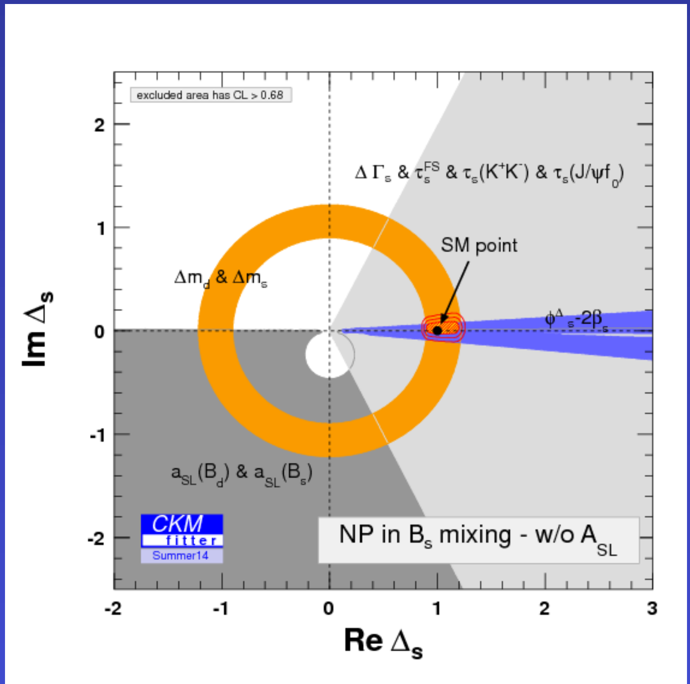


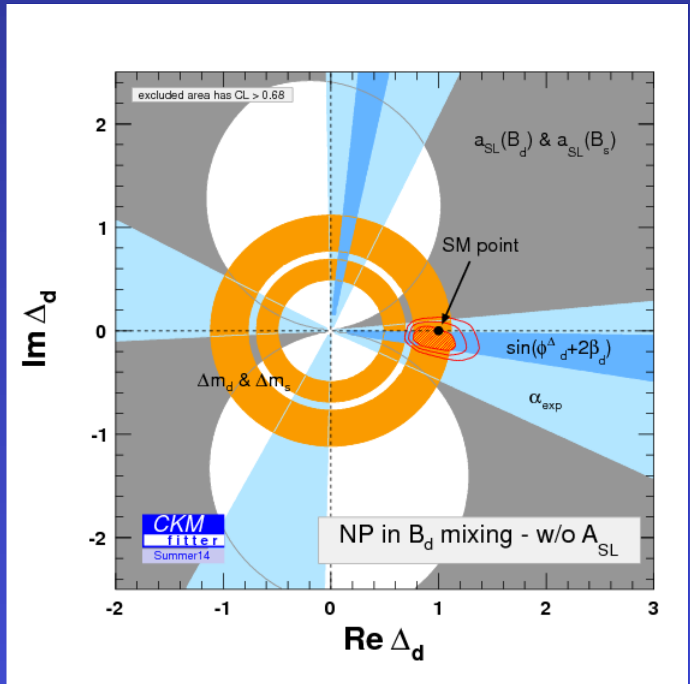
$$\tau_{\rm eff} = 1.479 \pm 0.034\ ({\rm stat}) \pm 0.011\ ({\rm syst})\ {\rm ps}.$$

  - In agreement with SM precition

New Physics in B_s Mixing

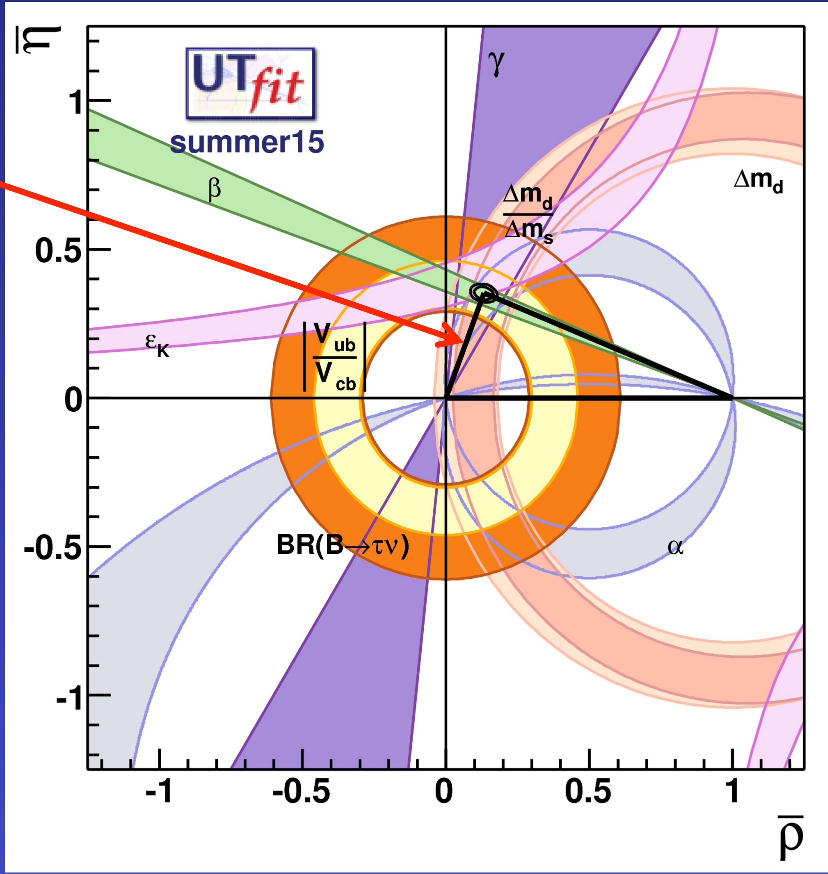
- **Implications**
  - Use parameterisation $M_{12} = M_{12}^{SM}\,\Delta_s$
  - ϕ_s and ϕ_d (aka ϕ_1 or $\sin 2\beta$) limit NP (to ~30% at 3σ for ϕ_s)
  - Need to control hadronic uncertainties (penguin pollutions)
  - More data required





Unitarity Triangle

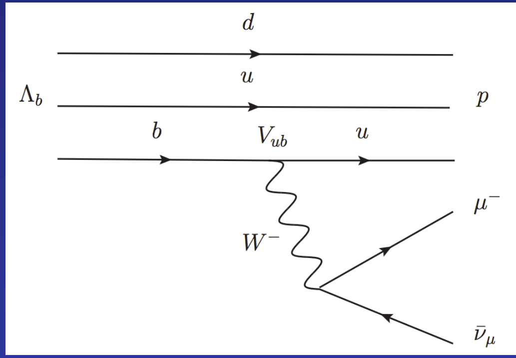
$|V_{ub}/V_{cb}|$

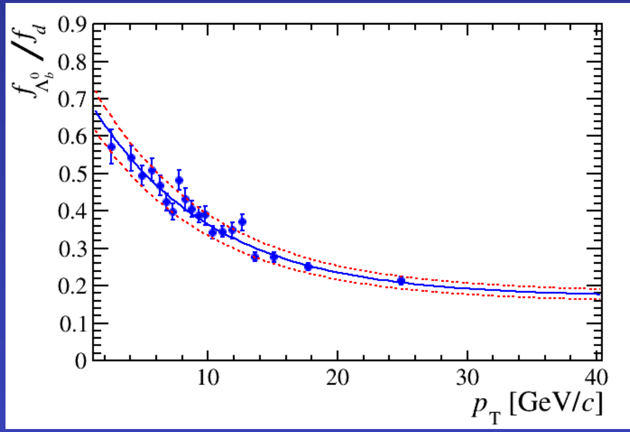


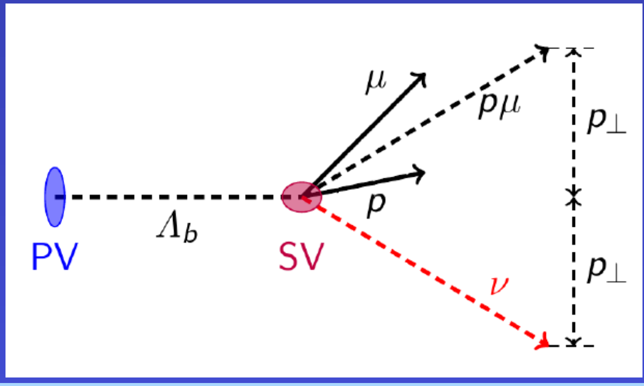
$|V_{ub}|$ with $\Lambda_b \to p\mu\nu$

- **LHC is a Λ_b factory**
  - B^0:B_s^0:Λ_b ~ 4:1:2 in LHCb acceptance
  - Large Λ_b production cross section
- **LHCb method**
  - $\Lambda_b \to p\mu\nu$ is cleaner than $B^0 \to \pi\mu\nu$
  - Challenge ist to separate $b \to u\mu\nu$ from $b \to c\mu\nu$ with isolation BDT
- **Corrected mass**
  - Minimum mass consistent compatible with B-hadron flight direction

$$m_{\rm corr} = \sqrt{m^2 + p_\perp^2} + p_\perp$$





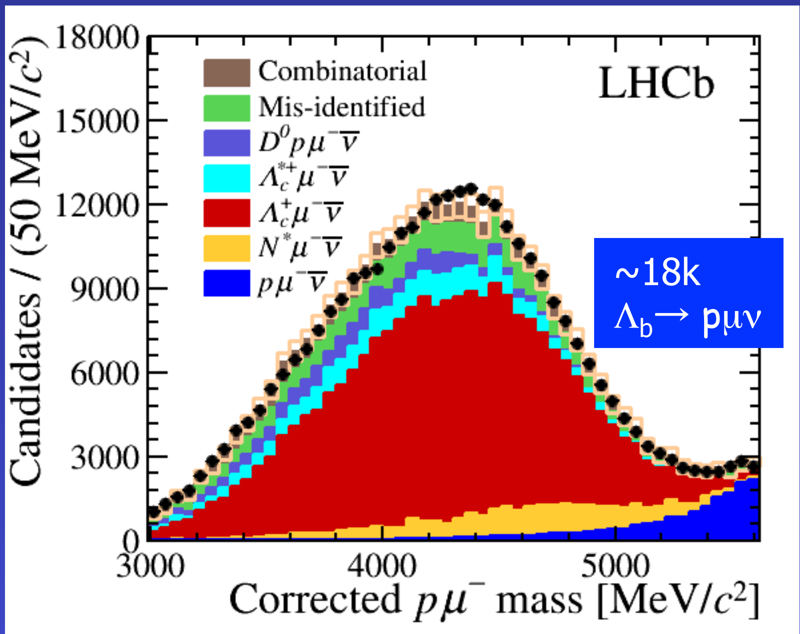


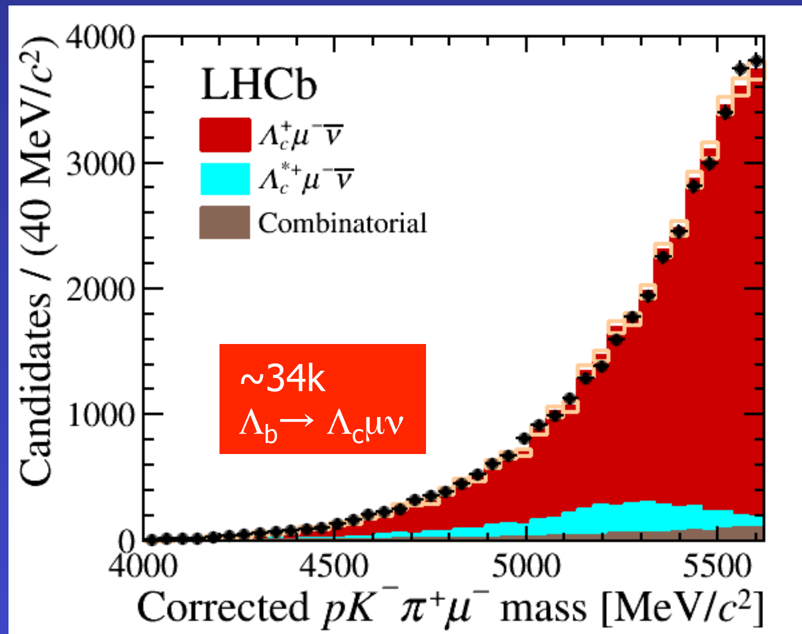
$|V_{ub}|$ with $\Lambda_b \to p\mu\nu$

Nature Physics 10 (2015) 1038

Meinel, Wingate, arXiv:1503.01421]

- **LHCb measurement**
  - Measure ratio $|V_{ub}|^2 / |V_{cb}|^2$
  - Many systematic uncertainties cancel
  - Need Lattice calculation for form factor

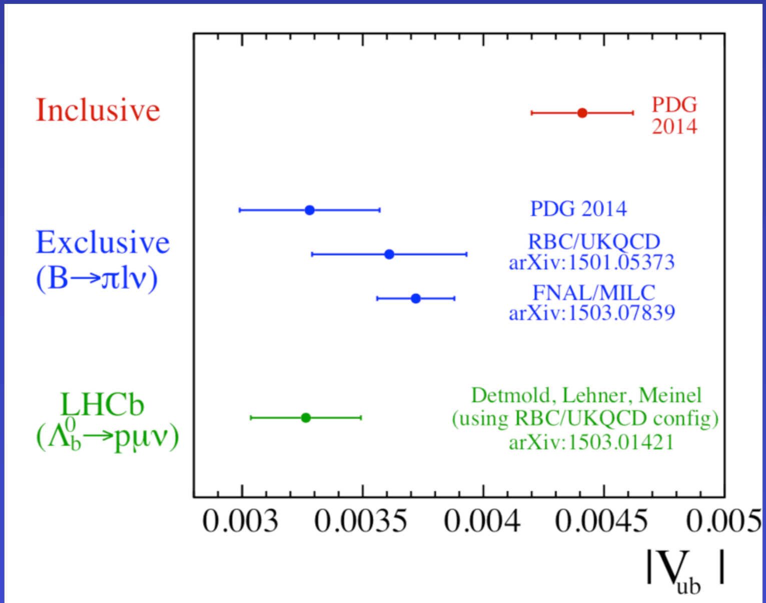


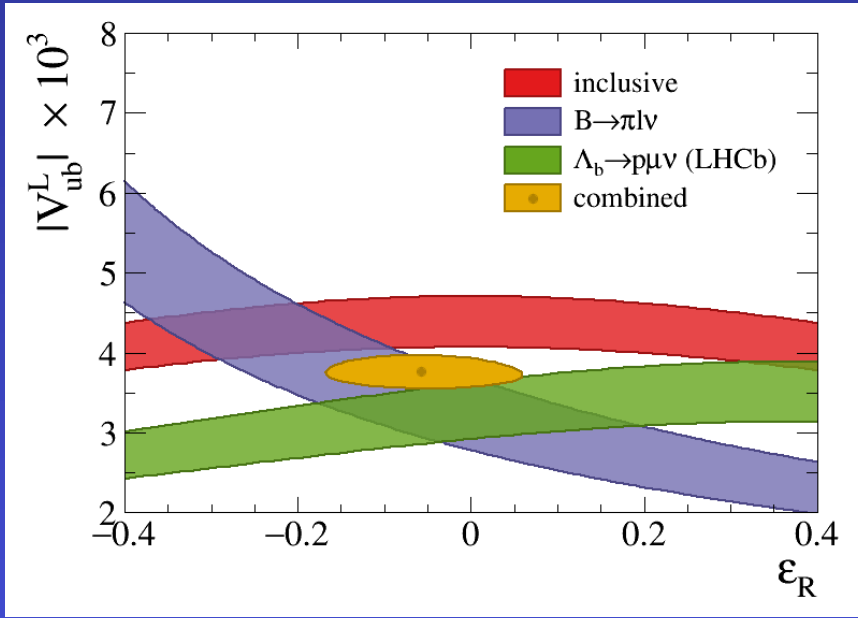


$$|V_{ub}| = (3.27 \pm 0.15(stat) \pm 0.17(syst) \pm 0.06(theory)) \times 10^{-3}$$

$|V_{ub}|$ Status

- **$|V_{ub}|$ discrepancy remains**
  - Exclusive LHCb measurement is 3.5σ from inclusive
  - Systematic uncertainty limited by lattice calculation
  - $\Lambda_b \rightarrow p\mu\nu$ has different sensitivities on right handed currents than $B \rightarrow \pi\mu\nu$
  - Right-handed currents disfavoured by combination





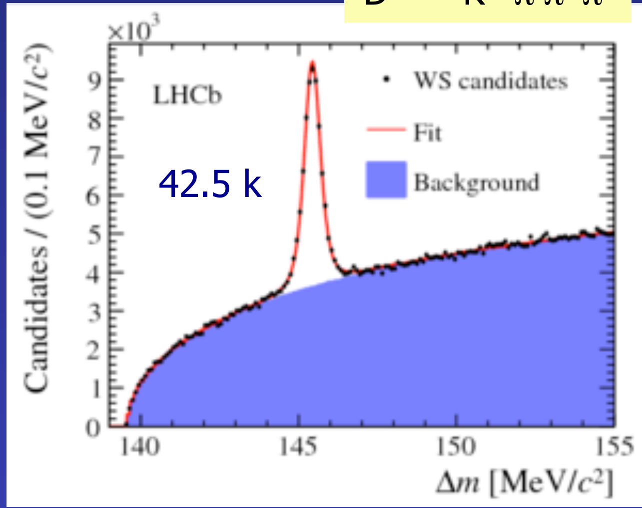
Charm

Mixing in $D^0 \to K^-\pi^+\pi^-\pi^+$

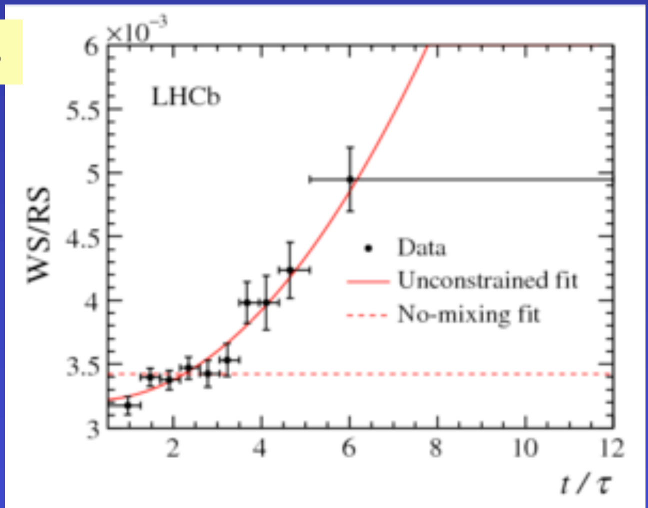
New: LHCb-PAPER-2015-057, arXiv:1602.07224

- LHCb result
  - First observation of D^0-$\bar{D}^0$ Mixing in $D^0 \to K^- \pi^+\pi^-\pi^+$ decays
  - $R_D^{K3\pi} = (5.67 \pm 0.12) \times 10^{-2}$
  - $R_D^{K3\pi}\, y' = (0.3 \pm 1.8) \times 10^{-3}$
  - useful input for γ measurement

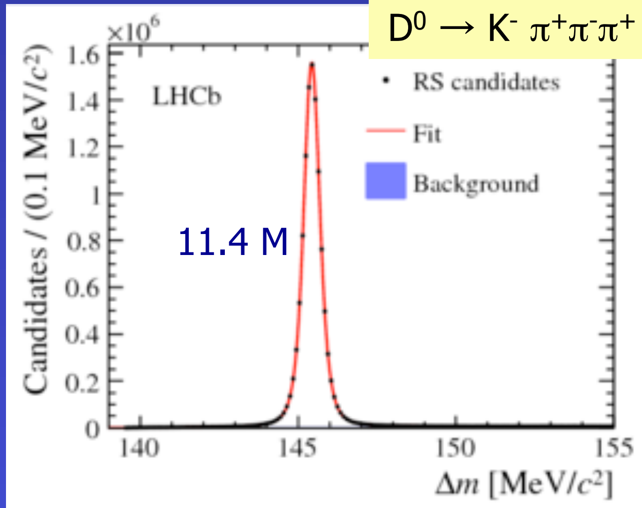
$D^0 \to K^+ \pi^-\pi^+\pi^-$



WS/RS



$D^0 \to K^- \pi^+\pi^-\pi^+$



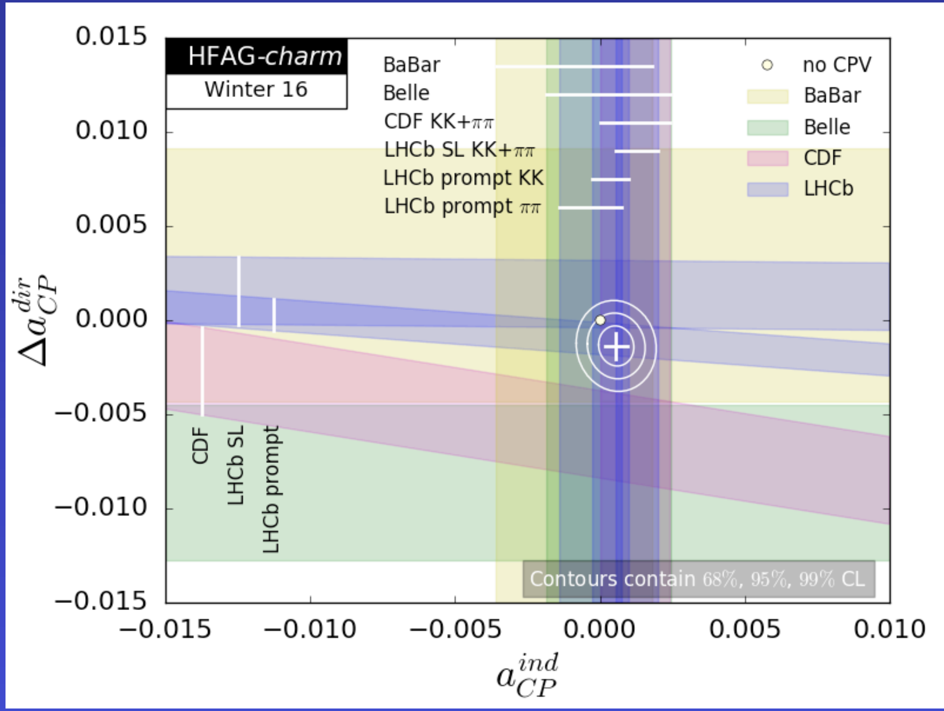
CP violation in $D^0 \rightarrow K^-K^+, \pi^-\pi^+$

New: LHCb-PAPER_2015-055, PRL 116 (2016) 191601

LHCb-PAPER_2014-069, JHEP 04 (2015) 043

- **No evidence for CP violation**
  - In charm system- whether in mixing, decay or mixing-decay interference
  - New: ΔA_{CP} = (−0.10 ±0.08 (stat.) ±0.03 (syst.))% — prompt D*
  - ΔA_{CP} = (0.14 ±0.16 (stat.) ±0.08 (syst.))% — $B \rightarrow D^0\mu^{\pm}X$
  - Both full run-1 data $3fb^{-1}$

- **HFAG average**
  - Agreement with no CP violation at CL = 6.5×10^{-2}

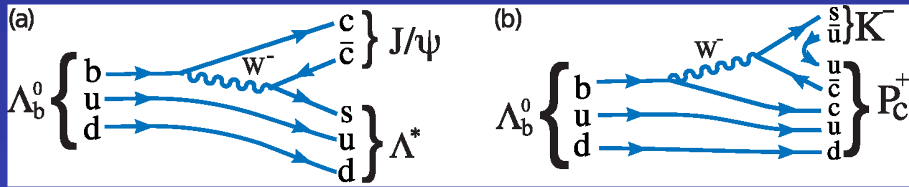


Exotic Spectroscopy

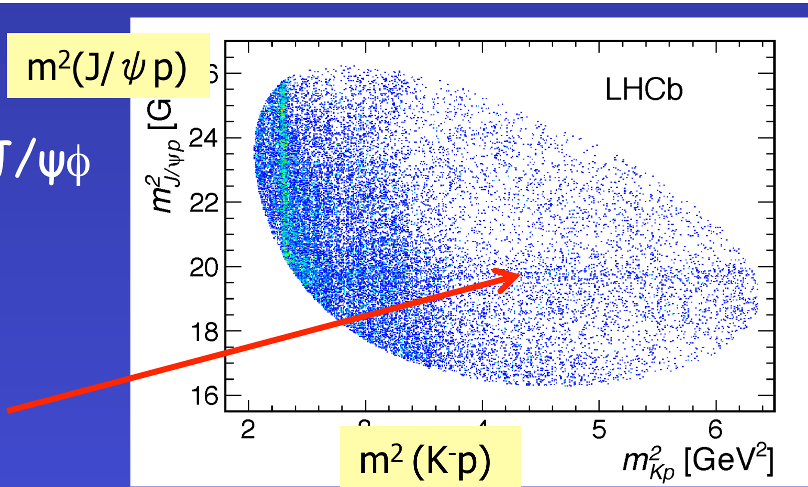
Pentaquarks

LHCb-PAPER-2015-029, arXiv:1507.03414
Phys. Rev. Lett. 115 (2015) 072001

- **Pentaquarks**
  - First suggested by Gell-Mann in seminal quark paper (1964)
  - QCD allows existence of Pentaquarks
- **Status 2014**
  - ~2004 several previous "observations" of pentaquark states
  - All claims refuted
  - Could Pentaquark be produced in B-baryon decays?



- **$\Lambda_b \rightarrow J/\psi K^- p$ decay**
  - First looked for as backgrnd in $B_s \rightarrow J/\psi\phi$
  - Large signal found
  - Used to measure Λ_b lifetime
  - Dalitz plot shows unusual feature

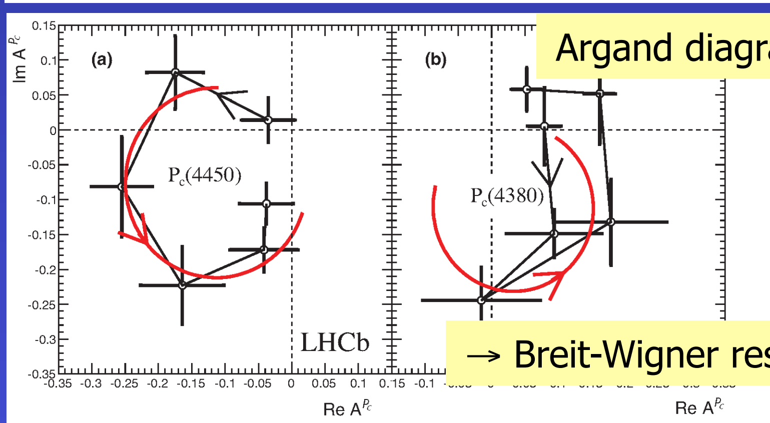


Pentaquarks

LHCb-PAPER-2015-029, arXiv:1507.03414
Phys. Rev. Lett. 115 (2015) 072001

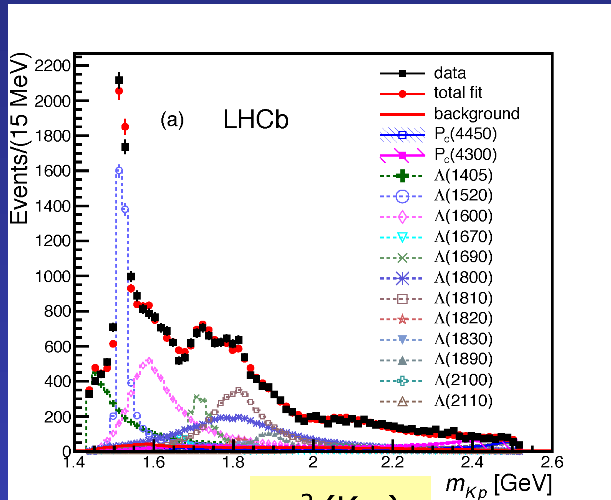
- **Two Pentaquark states observed in $\Lambda_b \to J/\psi K^- p$ decay**
  - 6-dim Fit to sum of amplitudes
  - Fit to $\Lambda^* \to K^- p$ resonances only not sufficient to describe data
  - Two P_c states (c cbar u u d) required

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

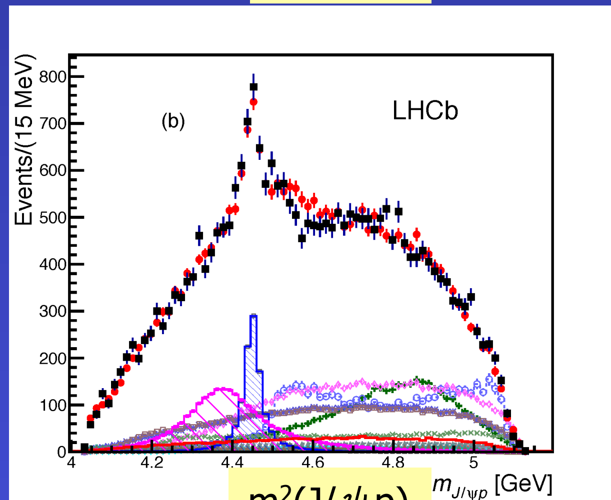


Argand diagrams

→ Breit-Wigner resonances



m^2 ($K^- p$)

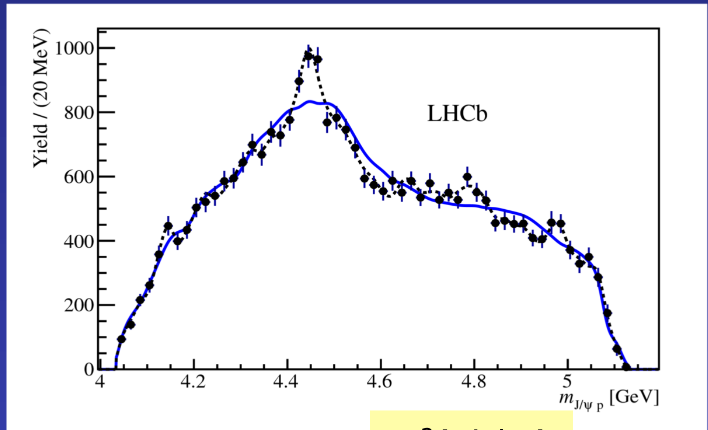


$m^2(J/\psi\, p)$

Pentaquarks

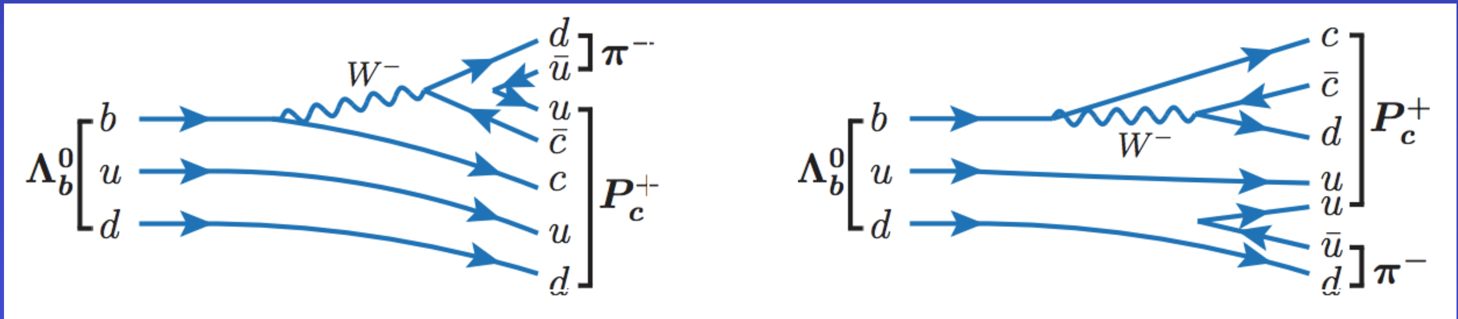
New: LHCb-PAPER-2016-009, arXiv:1604.05708
Submitted to PRL

- **Two Pentaquark states observed in $\Lambda_b \rightarrow J/\psi K^- p$ decay**
  - confirmed by model independent analysis
  - no assumption on Λ^* resonances
  - Λ^* not sufficient to describe data



$m^2(J/\psi\, p)$

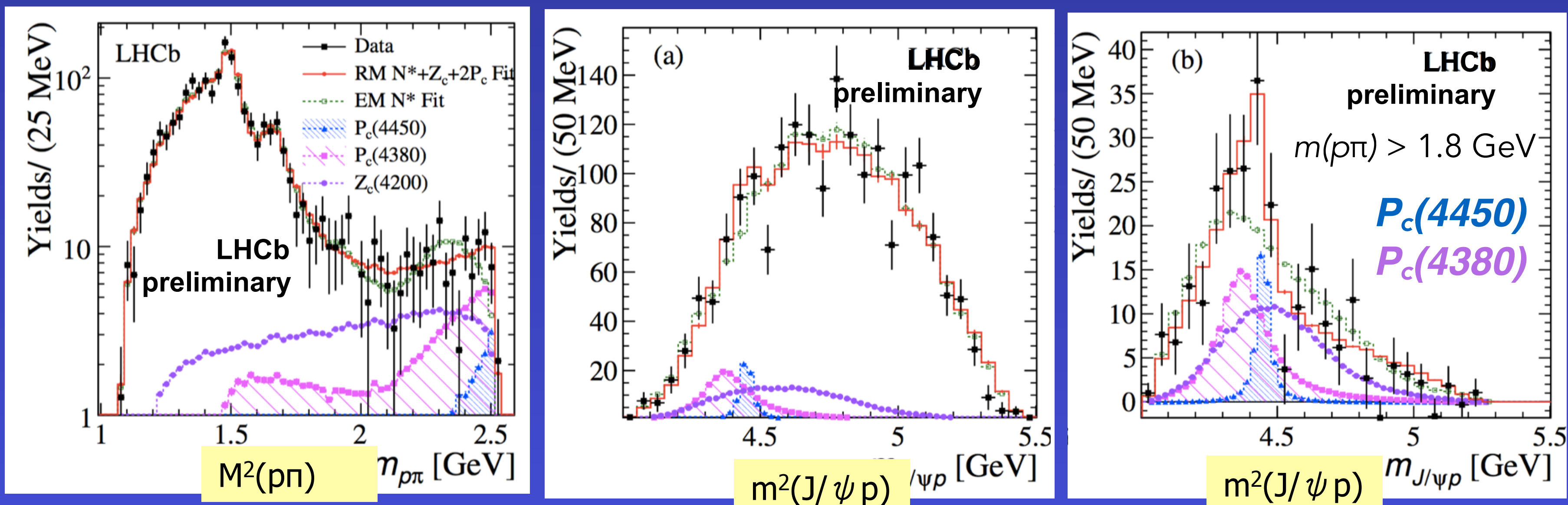
- **Search for Pentaquark states in $\Lambda_b \rightarrow J/\psi p \pi^-$ decays**
  - Observation of same two P_c states would confirm exotic nature
  - Two decay diagrams will interfere



Pentaquarks

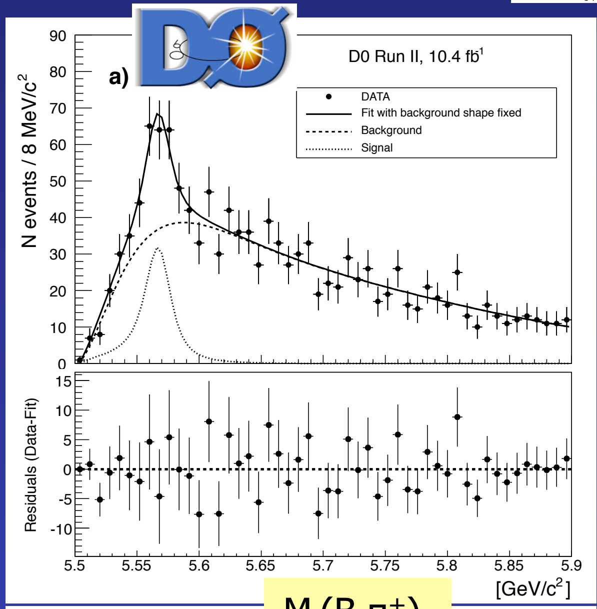
New: LHCb-PAPER-2016-015,
To be submitted to PRL

- **Evidence for Pentaquark states in $\Lambda_b \to J/\psi p \pi^-$ decays**
  - Fit to $N^* \to \pi^- p$ resonances only not sufficient to describe data
  - Model with two P_c states gives good fit
  - 3.3σ evidence for both P_c states
  - Possible Z_c (4200) tetraquark → Combined evidence for two P_c states and Zc(4200) reduces to 3.1σ → more data required

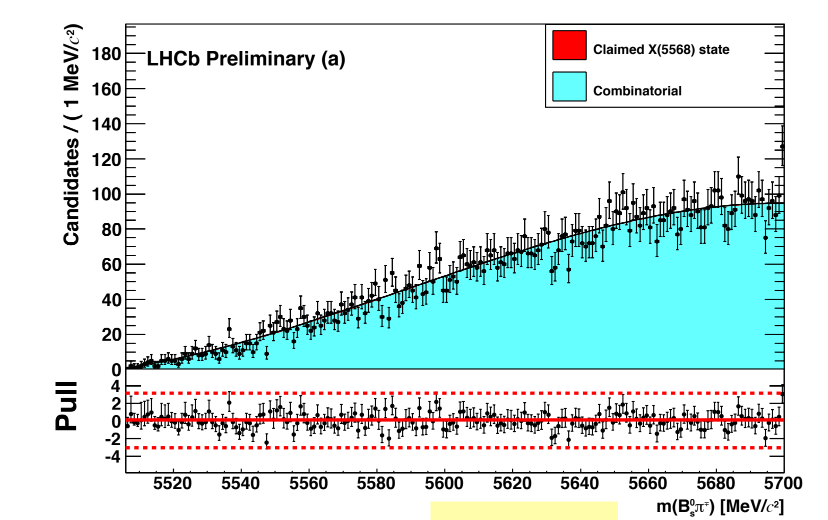


X(5568)?

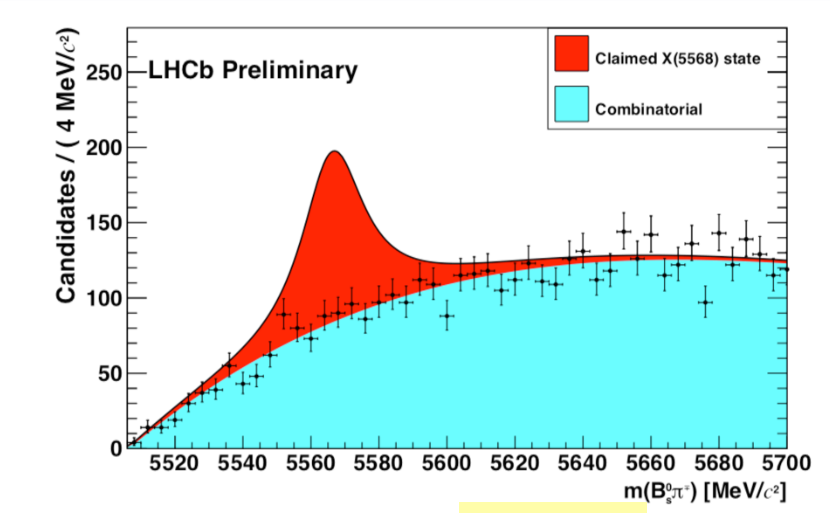
- **Tetraquark candidate X(5568)**
  - D0@Tevatron claims 5.1σ evidence for $X(5568)^+ \rightarrow B_s\,\pi^+$
  - Rate R = (8.6±1.9±1.4)% of B_s production
- **LHCb** **New:** LHCb-CONF-2016-004, arXiv:1507.03414
  - 20 times larger data set
  - Sees nothing, R < 0.01 @ 95% C.L.



M ($B_s\pi^+$)



M ($B_s\pi^+$)

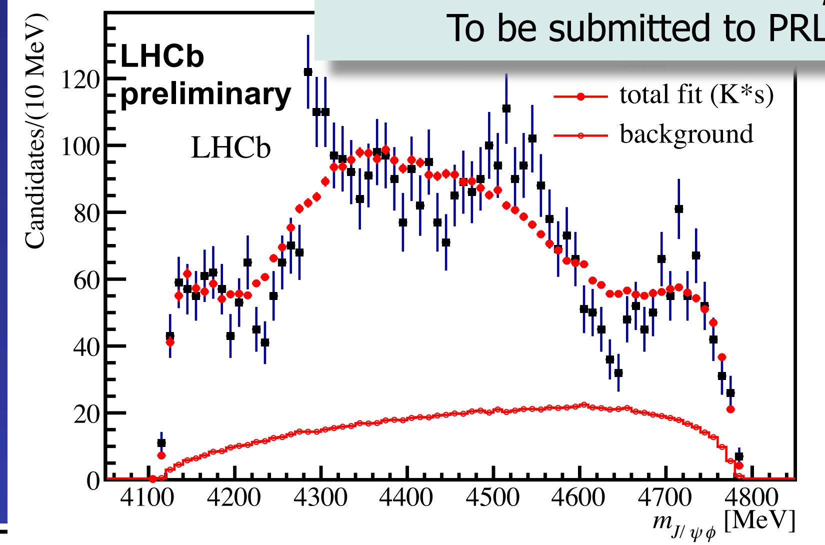


M ($B_s\pi^+$)

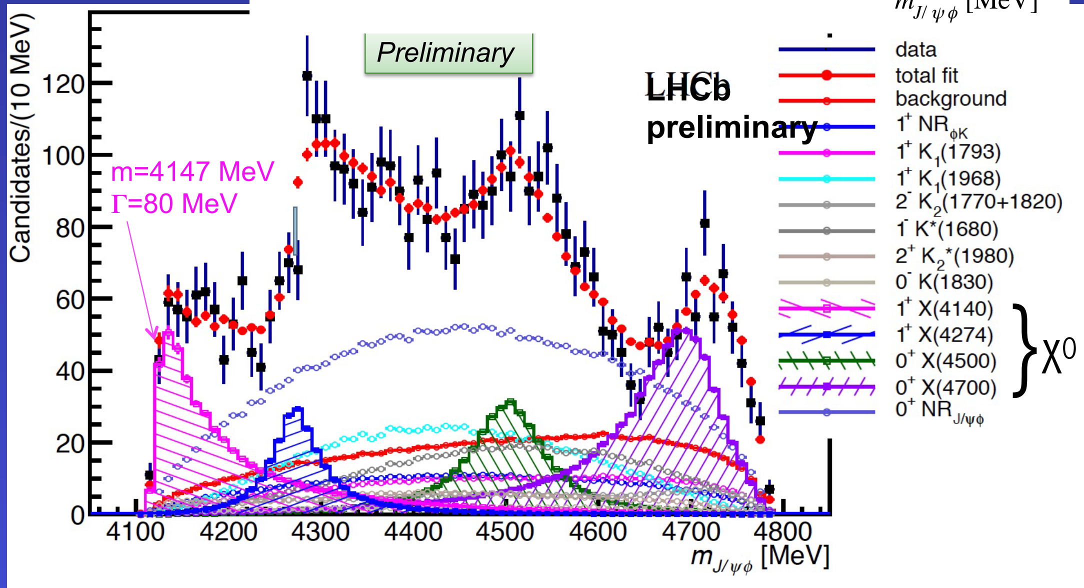
X(4140)

New: LHCb-PAPER-2016-018,
To be submitted to PRL

- X(4140)
  - $J/\psi\phi$ structure in $B^- \to J/\psi\phi K^-$ decays
  - Seen (first by CDF) or not seen by several experiments



- New LHCb measurement
  - 4 visible Breit-Wigner structures required
  - Lowest state fits best with $D_s D_s^*$ cusp
  - Also consistent with wide X(4140)



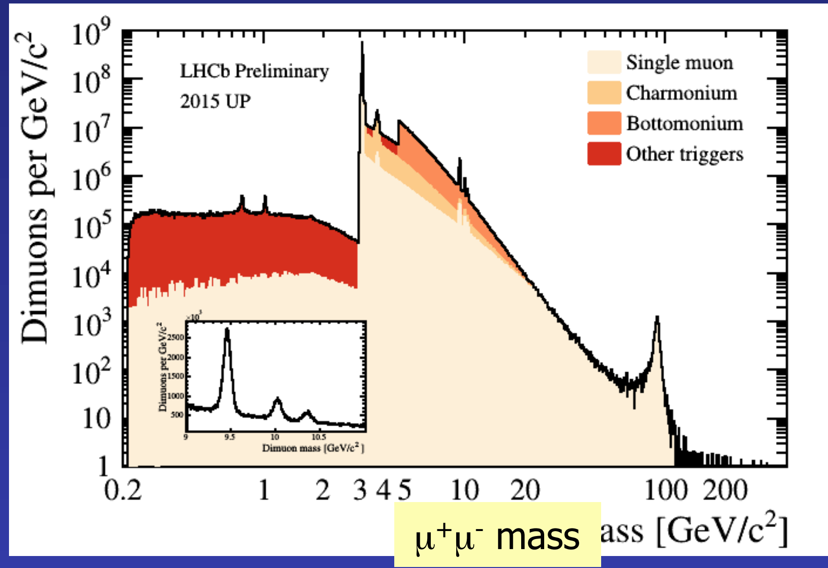
LHC & LHCb - Run 2

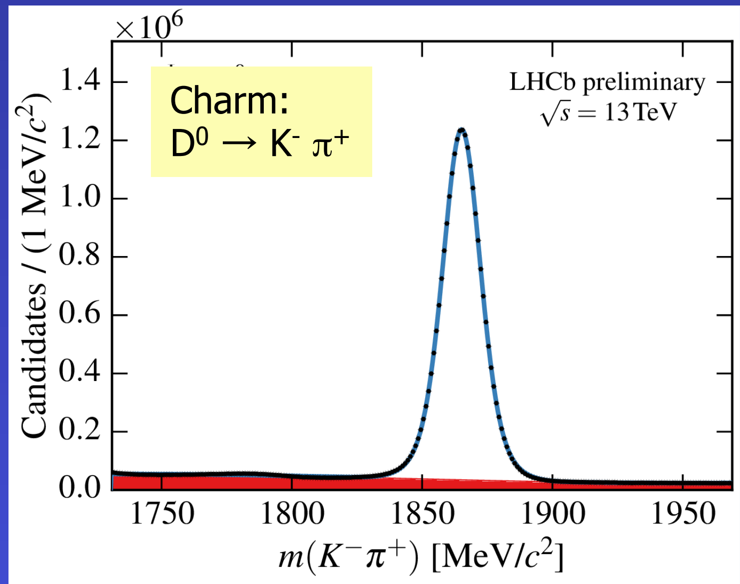
LHCb Run 2

- **LHC restarted in 2015**
  - Operated successfully at $\sqrt{s}$ = 13 TeV
  - 2016 plan is collect data
- **LHCb restarted in 2015**
  - All detectors fully operational
  - Deployed new trigger scheme
  - 2016 plan is collect data
- **2015 data**
  - Dimuon mass spectrum
  - b and charm quark production published

LHCb-PAPER-2015-037, JHEP 10 (2015) 172
LHCb-PAPER-2015-041, JHEP 03 (2016) 159

- **2016 data**
  - $D^0 \to K^- \pi^+$ with turbo trigger





Conclusions

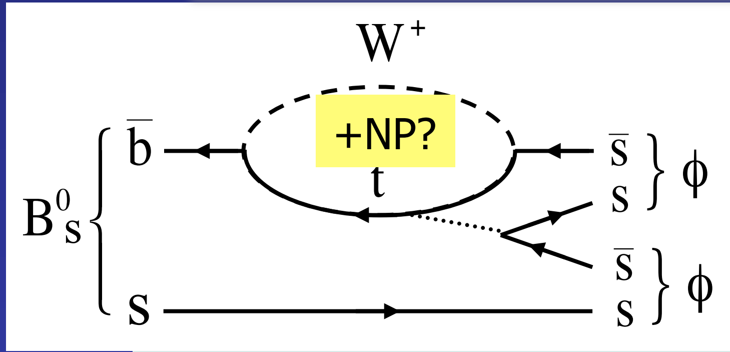
- **LHCb and Flavour physics at the LHC are a huge success**
  - Unprecented data samples allow measurements in new areas, e.g. B_s and baryon
  - Precision measurements of CP violation and rare decays
  - Large NP ruled out in many flavour physics observables
  - A few deviations to SM at 2σ to 3σ (4σ when including B factories)
  - NP or statistical fluctuations? → more data is required
- **LHCb Highlights include**
  - Observation of $B_s \to \mu\mu$
  - 3σ discrepancy in angular analysis of $B^0 \to K^{*0}\mu\mu$ ($B^+ \to Kll$)
  - Measurement of V_{ub} in $\Lambda_b \to p\mu\nu$
  - Most precise measurement of ϕ_s in $B_s \to J/\psi\phi$
  - ~2.4σ and 2.1σ evidence for LFU Violation in $B^+ \to Kll$ and $B \to D^{*+}\tau^-\nu$
  - Observation of pentaquark states

Backup

CP Violation in $B_s \to \phi\phi$

Phys. Rev. D 90 (2014) 052011

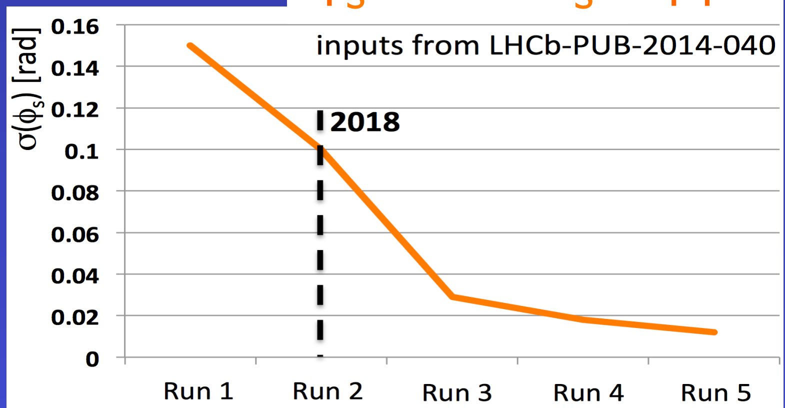
- $B_s \to \phi\phi$ is golden mode for upgrade
  - probe CP violating weak phase ϕ_s in hadronic B_s penguin decays
  - Sensitive to new physics in decay amplitude
  - Prediction for ϕ_s very close to zero



M. Raidal, arXiv:hep-ph/0209091
M. Bartsch et al., arXiv:0810.0249

- LHCb results on $B_s \to \phi\phi$
  - $\phi_s = -170 \pm 150 \pm 30$ mrad
- LHCb upgrade
  - Sensitivity $\sigma(\phi_s) \sim 0.02$
  - Comp. to $\sigma(\phi_s, \text{theory}) \leq 0.02$
  - Non zero ϕ_s result → New Physics

ϕ_s from $B_s \to \phi\phi$



Z(4430)$^-$ Resonance

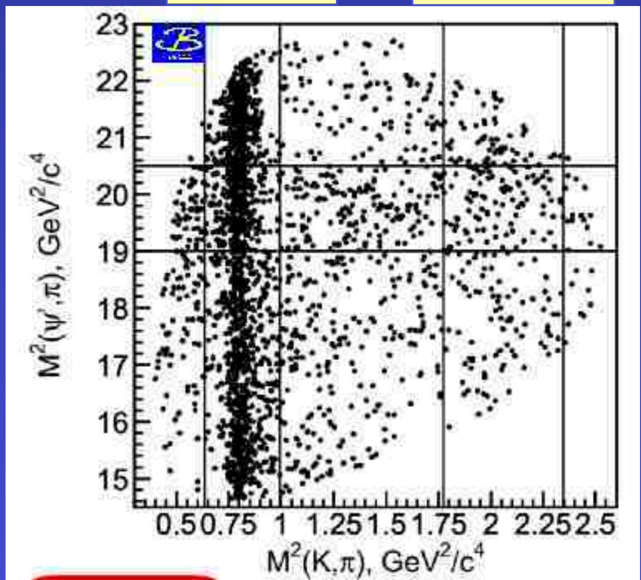
- **Status**
  - $Z(4430)^- \to \psi(2S)\pi^-$ observed by Belle in $B^0 \to \psi(2S)\, K^+\pi^-$ decays
  - not seen by BaBar
  - charged state, not described by quarkonia model
  - quark content $c\bar{c}u\bar{d}$?

PRD88 (2013) 074026

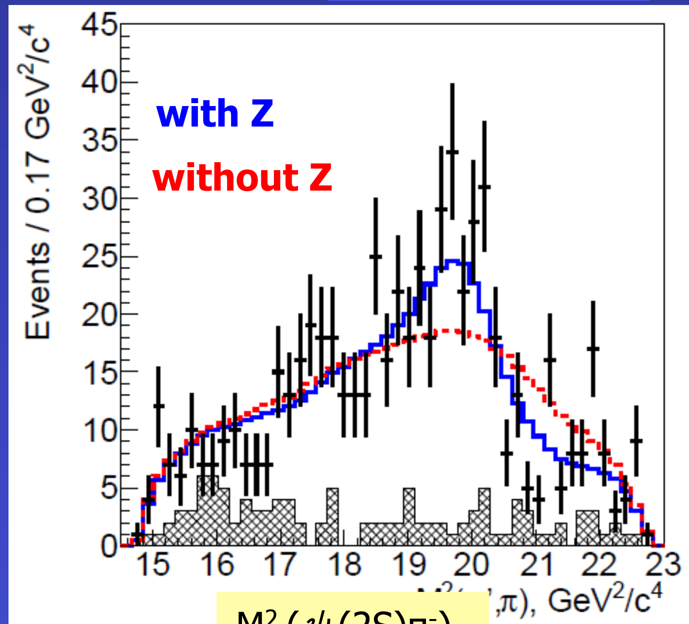
PRD79 (2009) 112001

K*(892)

$K_2(1430)$



K* veto region

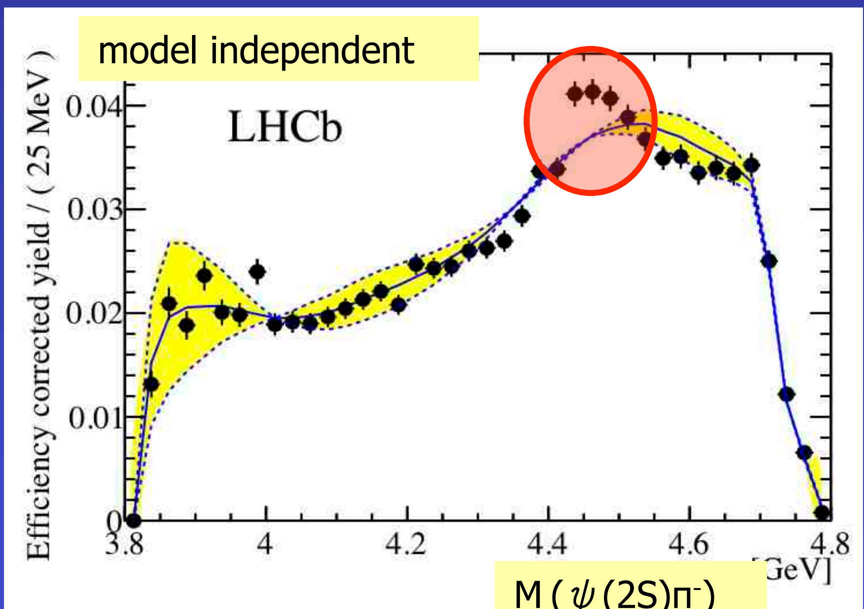


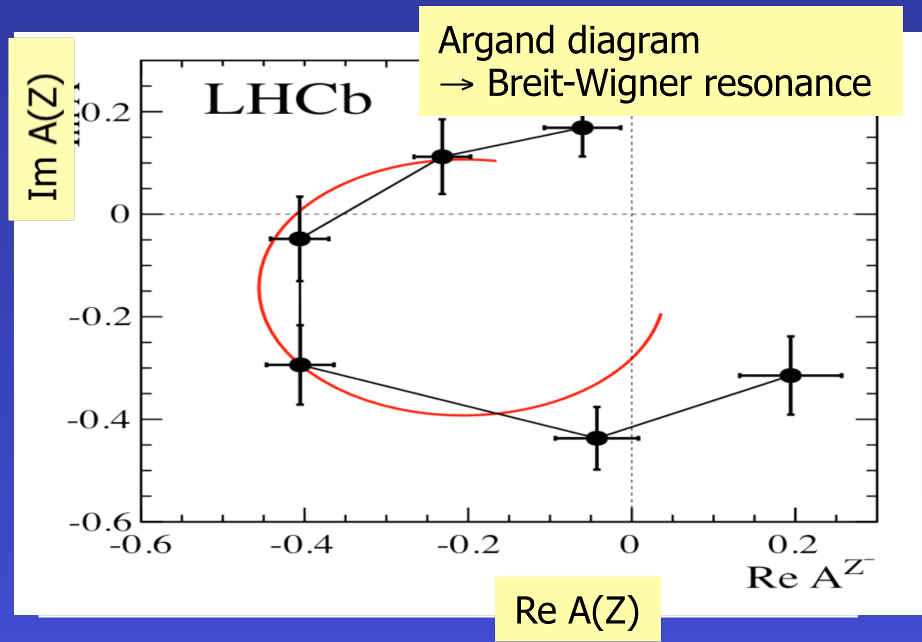
$M^2(\psi(2S)\pi^-)$

Z(4430)⁻ Resonance

LHCb-PAPER-2014-014, arXiv:1404.1903
Phys. Rev. Lett. 112 (2014) 222002

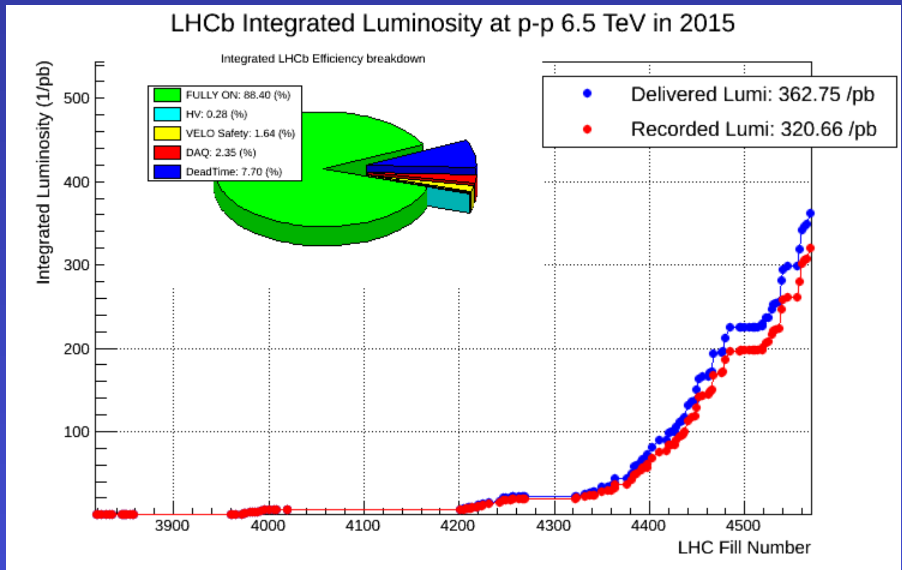
- **LHCb confirms Z(4430)⁻**
  - Observation of the resonant character of the Z(4430)⁻ state
- **Measurement based on 4-dim amplitude fit**
  - highly significant Z(4430)⁻ state is required
  - spin-parity is unambiguosly 1^+
  - Consistent with a **tetraquark** state

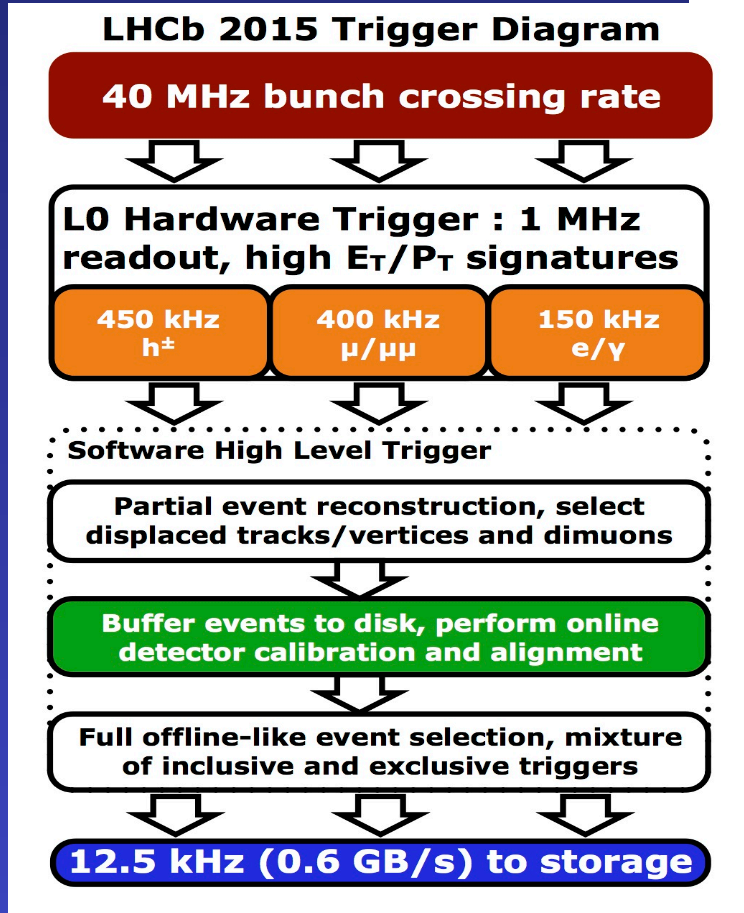




LHC & LHCb - Run 2

- **LHC restarted in 2015**
  - Operated successfully at $\sqrt{s}$ = 13 TeV
  - 25 ns bunch crossing,
  - 2244 bunches
- **LHCb restarted in 2015**
  - All detectors fully operational
  - Deployed new trigger scheme





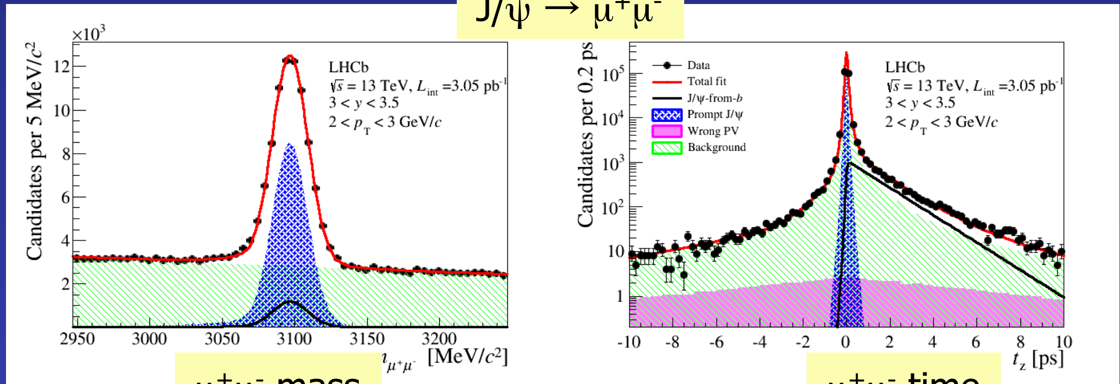
- Online calibration and alignment
- Offline reconstruction in High Level Trigger!

Results at √s = 13 TeV

- b quark and charm production

LHCb-PAPER-2015-037, JHEP 10 (2015) 172
LHCb-PAPER-2015-041, JHEP 03 (2016) 159

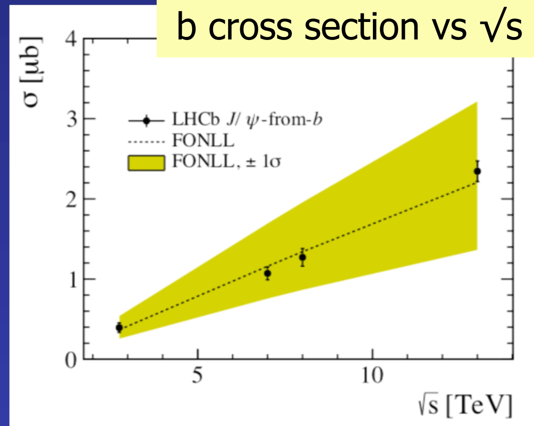
$J/\psi \rightarrow \mu^+\mu^-$

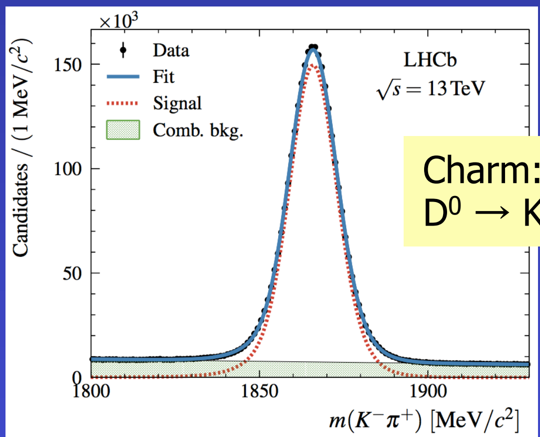


$\mu^+\mu^-$ mass

$\mu^+\mu^-$ time

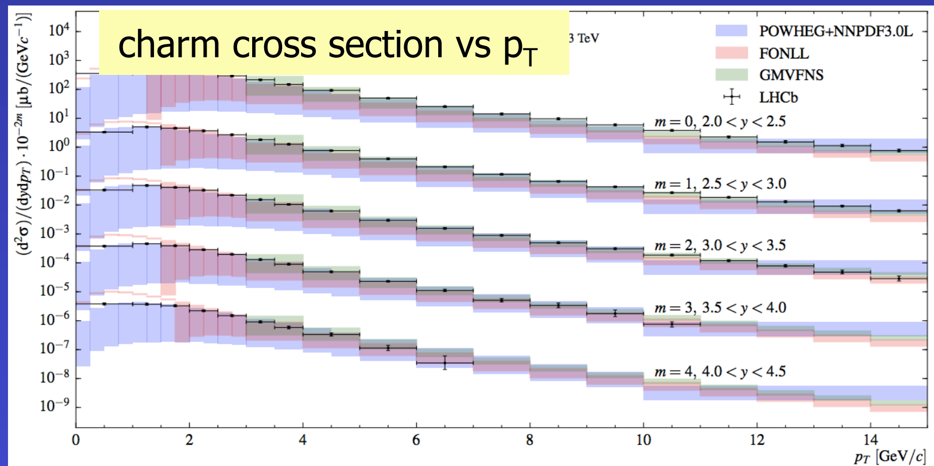
b cross section vs √s





Charm:
$D^0 \rightarrow K^- \pi^+$

charm cross section vs p_T



- Cross sections agree with expectations

The End