LHCb Highlights

EPS-HEP Conference 2021

European Physical Society conference on high energy physics 2021

Online conference, July 26-30, 2021

Franz Muheim

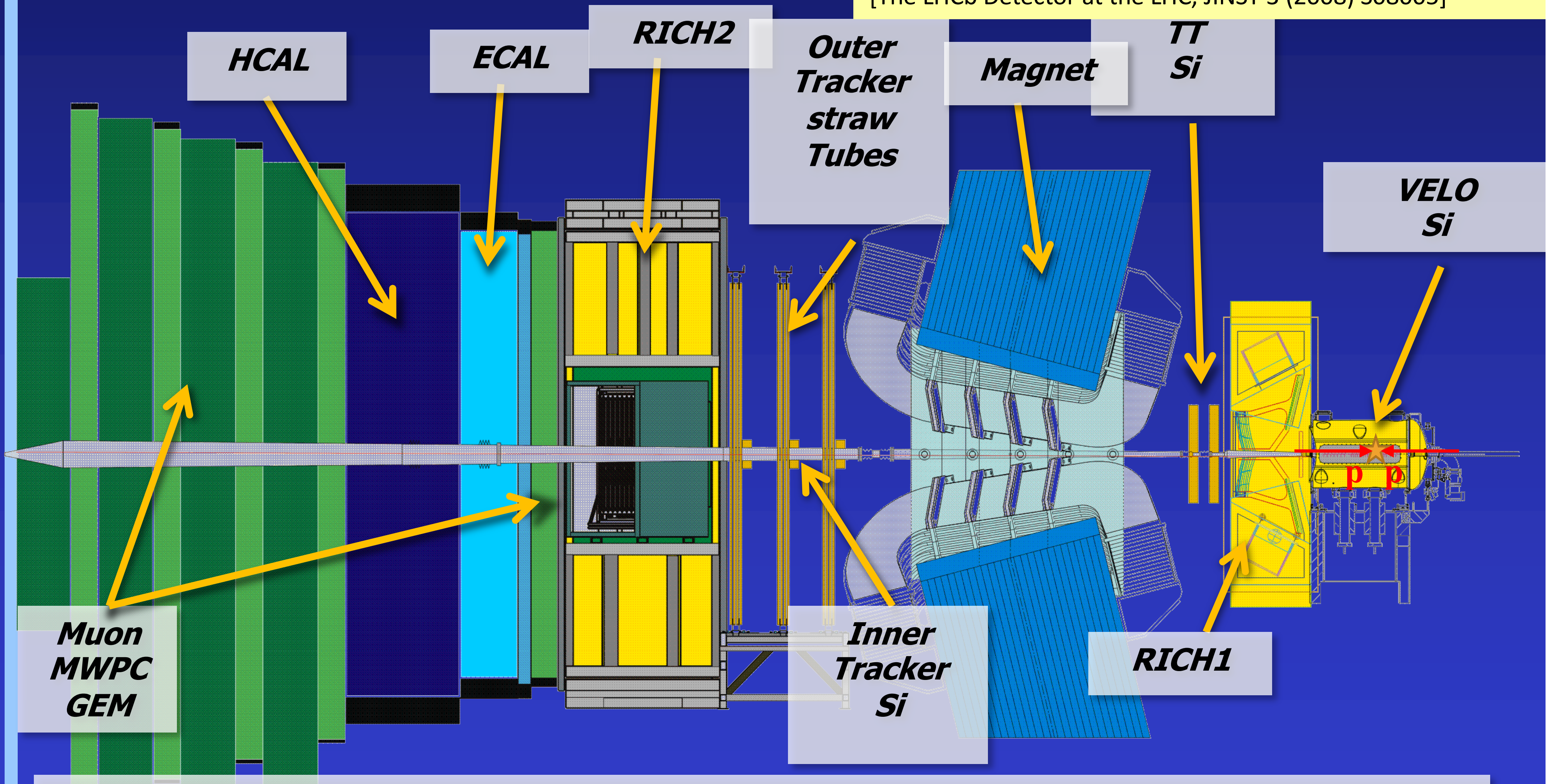
University of Edinburgh and CERN

on behalf of the LHCb collaboration

- **Introduction**
- **Selected physics highlights**
- **LHCb upgrade**
- **Conclusions**

LHCb detector

[The LHCb Detector at the LHC, JINST 3 (2008) S08005]

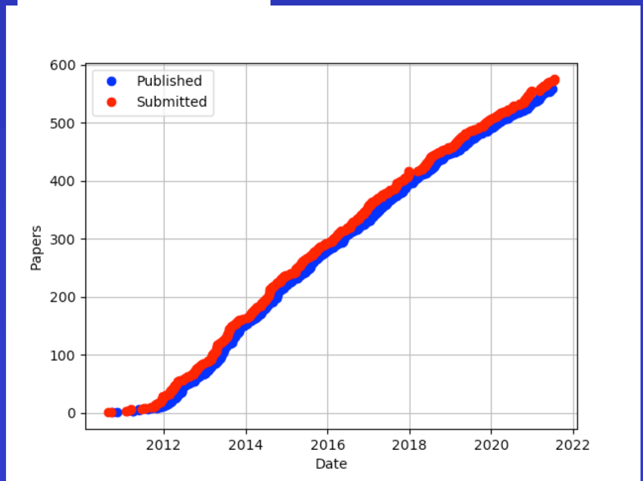


- Great Vertex Resolution! Primary/secondary separation, proper time resolution.
- Excellent momentum and mass resolution.
- Outstanding PID (K-π) and μ reconstruction.
- Dedicated Trigger system for beauty and charmed hadrons

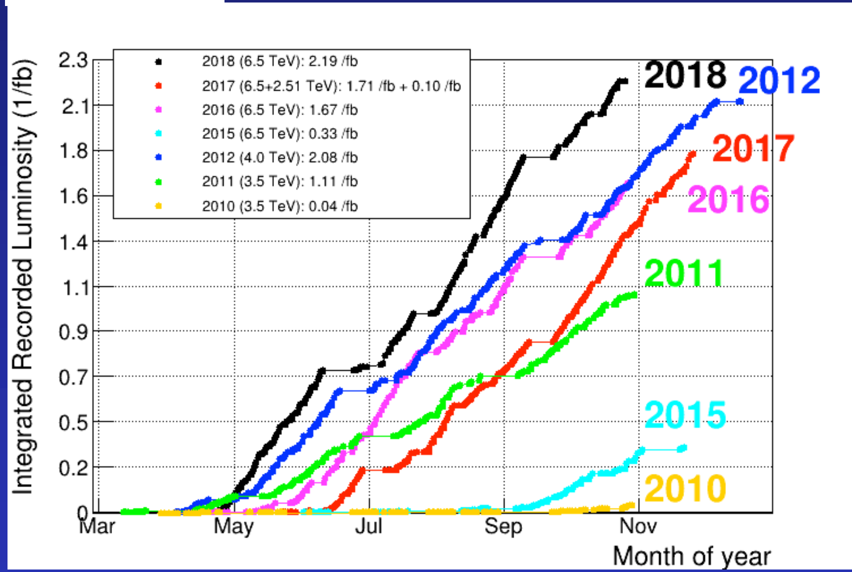
LHCb experiment

- **LHCb collaboration**
  - 1500 members and > 1000 authors
  - 86 institutes, 19 Countries
- **Data samples**
  - Run 1 and 2 with 3 fb^{-1} and 6 fb^{-1}
- **Physics output**
  - 575 papers submitted, 558 published
  - ~20 new papers for this summer

Publications



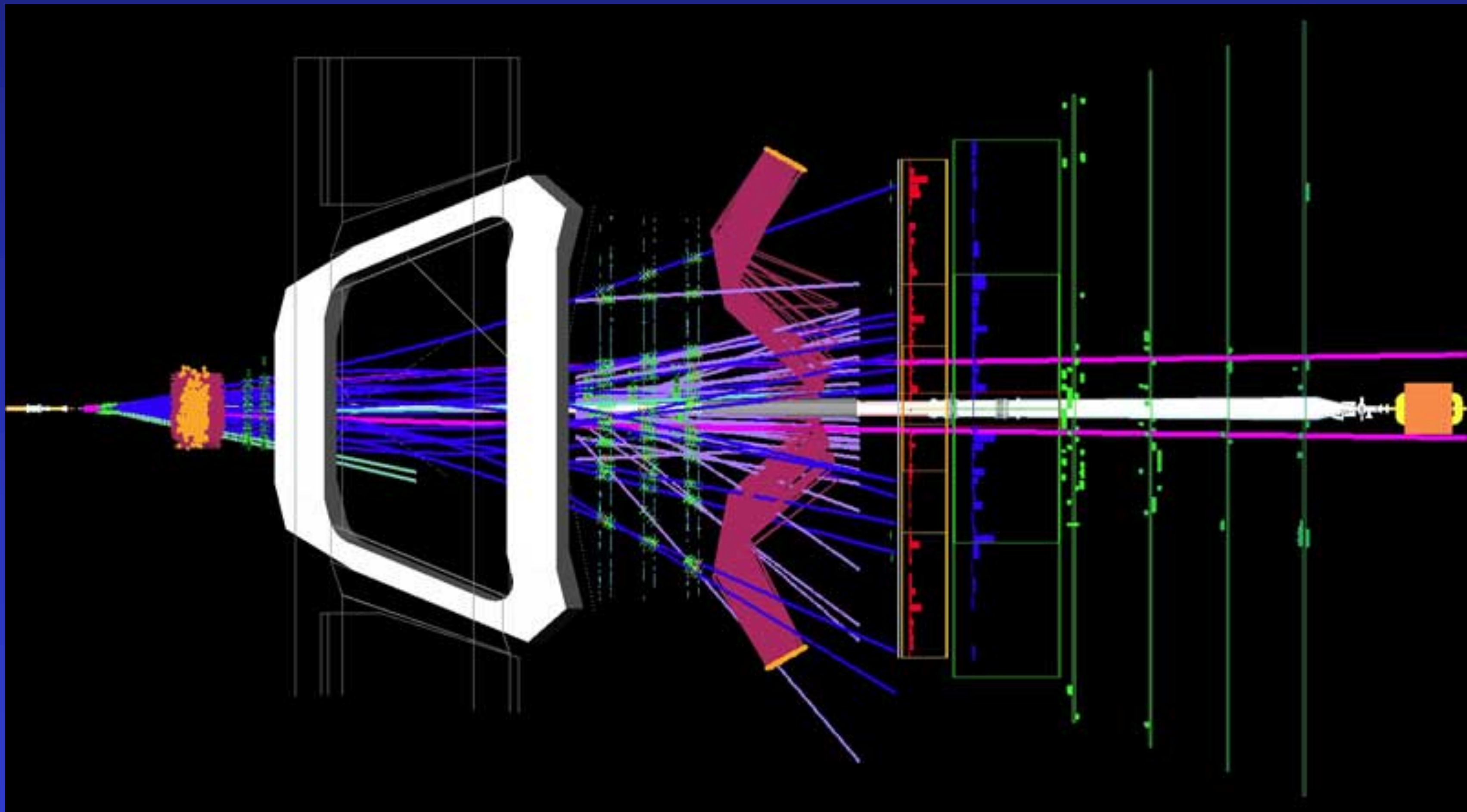
Luminosity



- **LHCb talks at EPS**
  - Rare decays and CP violation
    Paula Alvarez, Thu 29/7 15:15
  -

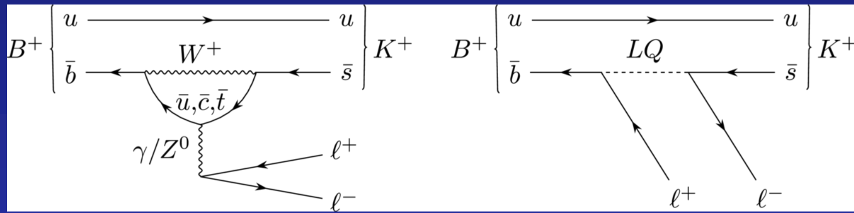
Monday	Tuesday	Wednesday	Thursday	Friday
			9:30 $T_{cc}^+ \to D^*D$ I. Polyakov	9:30 R_K M. McCann
10:30 W-mass R. Hunter	10:00 $B \to DDK$ & X(3872) Q. Xu	10:45 Charged hadrons O. Boente	10:15 P_c^+ in $B^0_s \to J/\psi pp$ J. Fu	10:00 $B^0_s \to \phi\mu\mu$ Ch. Langenbruch
10:45 Charm in pPb Ch. Gu	10:45 R(D*) B. Mitreska	11:00 SMOG S. Mariani		10:30 DM T. Mombacher
	11:00 Λ^0_b prod asym L. Dufour	11:00 Charm baryons A. Xu		
11:35 CKM γ M. Whitehead	11:15 V_{ub} A. Lupato	11:15 Charm mixing F. Betti	11:15 $\Lambda^0_b \to \Lambda^0 \gamma$ P. Gironella	11:15 $B^0_s \to \mu\mu$ M.Ramos
		12:30 Highlights **F. Muheim**		
14:15 $B^0_s \to KK$ Th. Grammatico				
14:15 PbPb G. Manca				
14:45 $B^+_c \to DD$ F. Bishop	16:00 Intrinsic charm L. Sestini		**15:15 Rare decays and CPV** **P. Alvarez**	
15:45 $B \to hhh$ L. Soares	16:30 LLP A. Usachov	17:30 ϕ_s V. Lukhasenko	17:30 New b hadrons H.Mu	

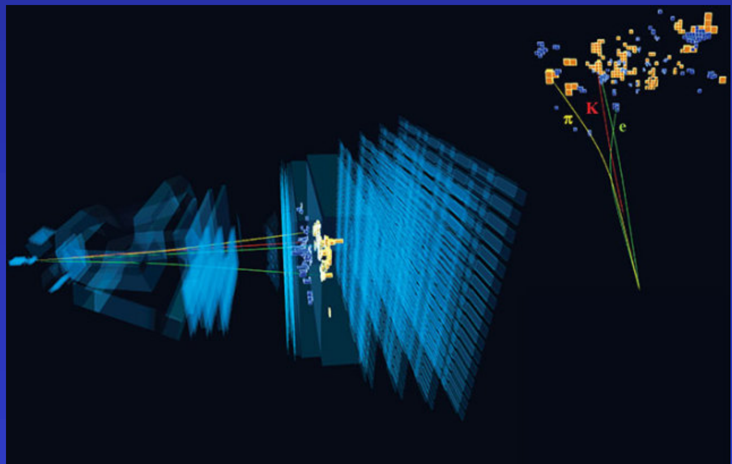
Rare decays



Electroweak penguin decays

- **Flavour changing neutral currents**
  - $b \rightarrow s\, \ell^+\ell^-$
  - Forbidden at tree level in SM
  - Branching fractions at 10^{-6} to 10^{-10}
  - Powerful probe of New Physics





Report	Title	Observ.	Comment
	2020		
2003.04352	Search for the lepton flavour violating decay $B^+\to K^+\mu^-\tau^+$ using B^{*0}_{s2} decays	Limit	Lepton Flavour Viol.
2003.03999	Search for the rare decays $B^0_s\to e^+e^-$ and $B^0\to e^+e^-$	Limit	Rare decay
2003.04831	Measurement of *CP*-averaged observables in the $B^0\to K^{*0}\mu^+\mu^-$ decay	P_5'	Angular asymmetry
2010.06011	Strong constraints on the $b\to s\gamma$ photon polarisation from $B^0\to K^{*0}e^+e^-$ decays	C_7'	Wilson coefficient
2012.13241	Angular analysis of the $B^+\to K^{*+}\mu^+\mu^-$ decay	P_5'	Angular asymmetry
	2021		
2103.11769	Test of lepton universality in beauty quark decays	R_K	Lepton Flavour Non-Univ.
2105.14007	Differential branching fraction of $B^0_s\to\phi\,\mu^+\mu^-$ and search for $B^0_s\to f'_2\mu^+\mu^-$	$d\Gamma/dq^2$	Decay rate
PAPER-2021-007	Improved measurement of $B^0_{(s,d)}\to\mu^+\mu^-$ decays	BR	Rare decay
PAPER-2021-008	Measurement of $B^0_s\to\mu^+\mu^-$ and search for $B^0\to\mu^+\mu^-$ and $B^0_s\to\mu^+\mu^-\gamma$ decays	BR	Rare decay
PAPER-2021-017	Search for the $\Xi_b\to\Xi\gamma$ radiative decay	Limit	Rare decay
PAPER-2021-022	Updated angular analysis of the rare decay $B^0_s\to\phi\,\mu^+\mu^-$	F_L, A_{FB}	Angular asymmetry
PAPER-2021-030	Measurement of the photon polarization in $\Lambda^0_b\to\Lambda\gamma$ decays	C_7'	Polarization

- **Significant part of physics programme**
  - 7 papers already in 2021
  - Branching fractions, angular analysis, Lepton flavour universality or violation

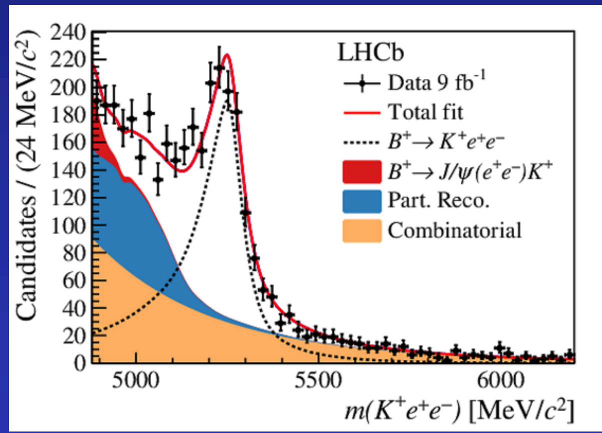
Test of lepton flavour universality

LHCb-PAPER-2021-004, arXiv:2103.11769
99 citations

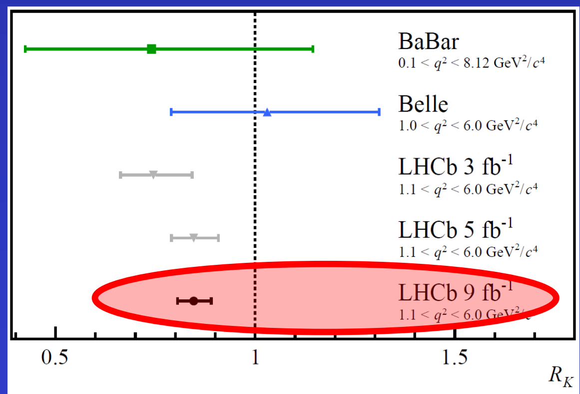
- **Lepton flavour universality**
  - $B^+ \to K^+\mu^+\mu^-$ vs $B^+ \to K^+e^+e^-$ decays
  - Clean theoretical prediction

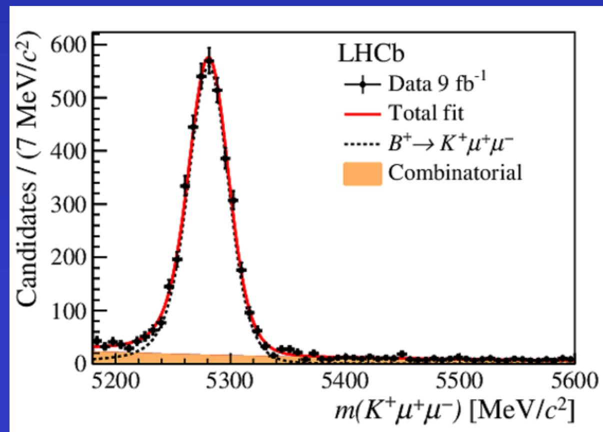
$$R_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}\Big|_{[q^2_{min}, q^2_{max}]}$$
$$= 1 \pm \mathcal{O}(10^{-4})^{[\mathrm{QCD}]} \pm \mathcal{O}(10^{-2})^{[QED]}$$

  - Measuring double ratio with J/ψ modes reduces systematic uncertainties

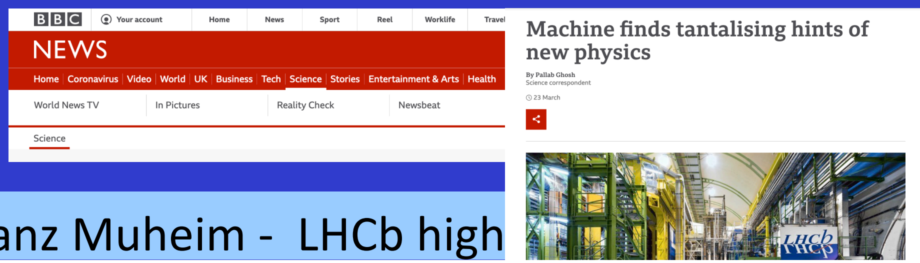


- **Result**
  - $R_K = 0.846^{+0.044}_{-0.041}$
  - 3.1σ evidence for LFU
  - More measurements and more data needed





  - #CautiouslyExcited



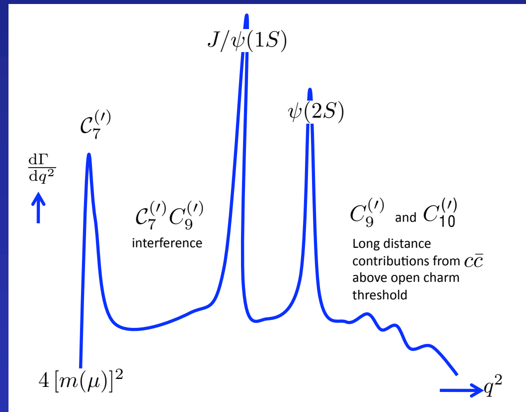
Lepton flavour universality tests at LHCb
Michael McCann

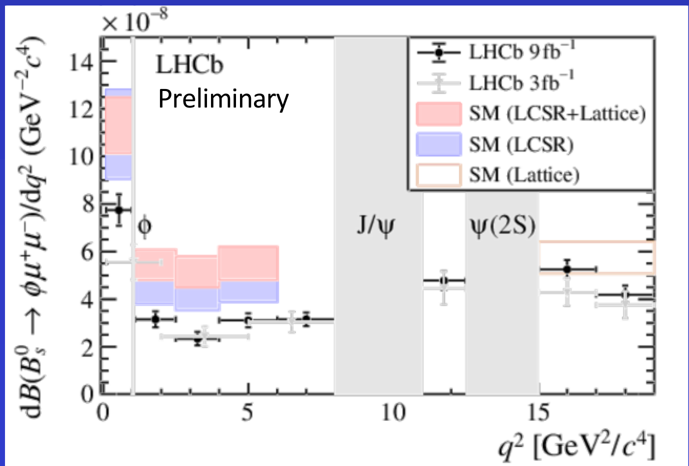
$b \to s \ell^+\ell^-$ branching fractions

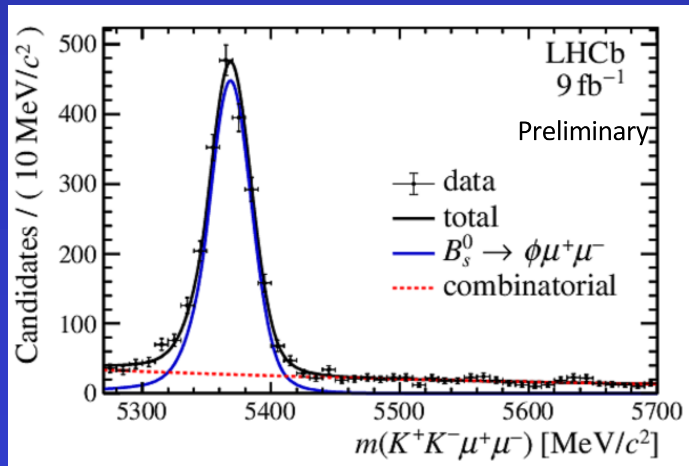
NEW

LHCb-PAPER-2021-014
arXiv:2105.14007

- **Differential branching fractions**
  - Decay rate of $b \to s \ell^+\ell^-$ sensitive to BSM
  - Branching fractions low for muons (B^+, B^0, B_s^0 and Λ_b^0)
- **$B_s^0 \to \phi\mu^+\mu^-$**
  - $dB(B_s^0 \to \phi\mu^+\mu^-)/dq^2 = (2.88 \pm 0.21) \times 10^{-8}/(\mathrm{GeV}^2/c^4)$ for $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$
  - In agreement with Run 1 result
  - 3.6σ deviation tension with SM



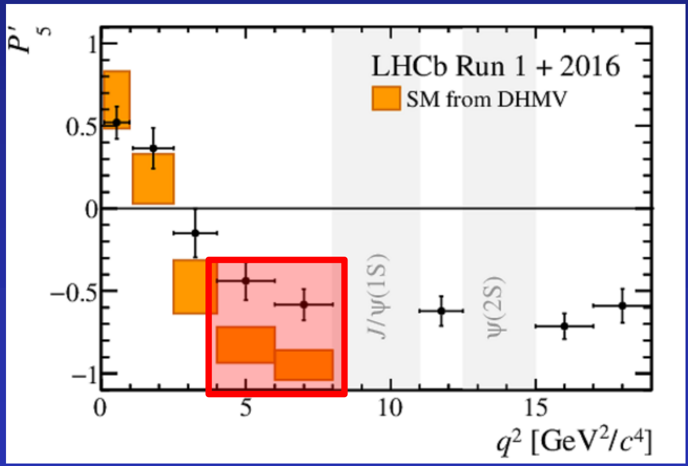




$b \to s\, \ell^+\ell^-$ angular analysis

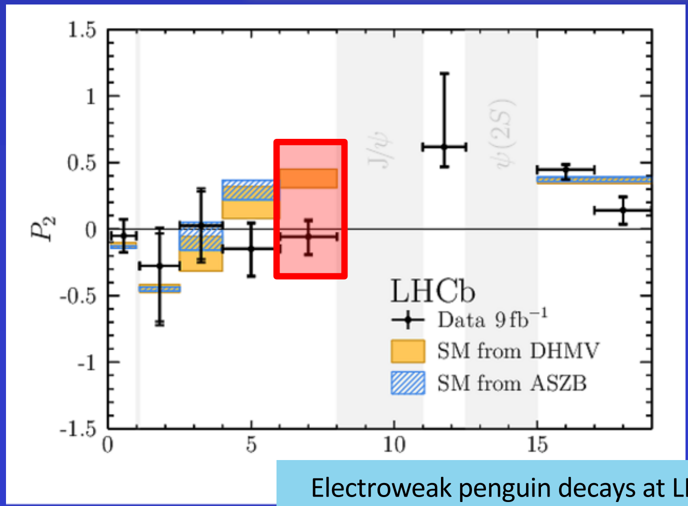
- **Angular observables**
  - Polarisation, asymmetries vs q^2
- $B^0 \to K^{*0}\mu^+\mu^-$
  - Local tension 2.5σ and 2.9σ in asymmetry P_5' with SM in q^2 bins [4,6] and [6,8] GeV^2/c^4
  - Global analysis finds tension 3.3σ
  - Consistent with ATLAS, Belle, CMS results

PRL 125 (2020) 011802



- $B^+ \to K^{*+}\mu^+\mu^-$
  - First LHCb measurement
  - Local tension with SM up to 3.0σ in P_2(~ A_{FB}) in q^2 bin [6,8] GeV^2/c^4
  - Global tension 3.1σ determined in fit to effective field theory Wilson coefficient Re(C_9)

PRL 126 (2021) 161802



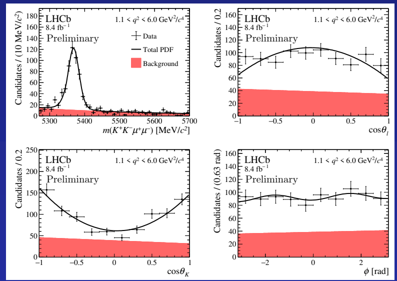
Electroweak penguin decays at LHCb
Christoph Langenbruch

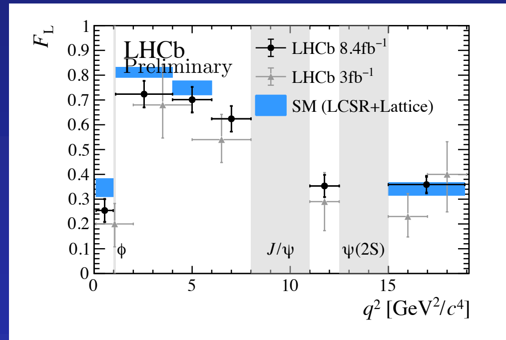
$b \to s\, \ell^+\ell^-$ angular analysis

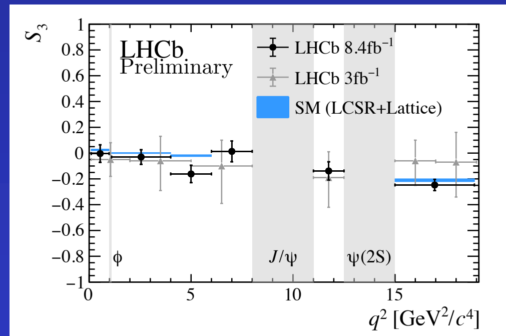
NEW

LHCb-PAPER-2021-022

- $B_s^0 \to \phi\mu^+\mu^-$
  - First angular analysis in this mode
  - Observables F_L and coefficients S_i
  - Compatible with SM, tension in F_L
  - Compatibility 1.9σ using "Flavio" package to fit for shift of EFT coefficient $\Delta Re(C_9)$ i.e. vector coupling from SM

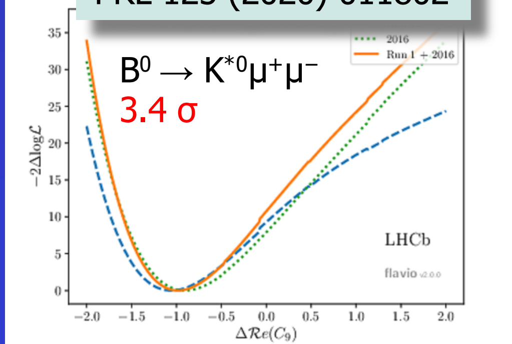




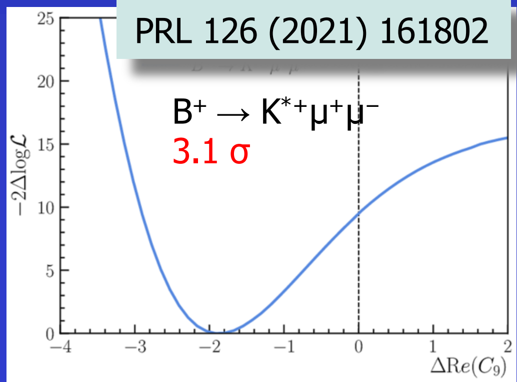


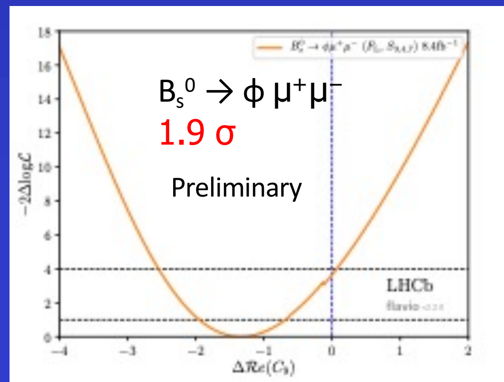
- **Summary**
  - Internally consistent trends observed for $\Delta Re(C_9)$ in $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$
  - Negative shift of $\Delta Re(C_9)$ from SM preferred 2 to 3σ level

PRL 125 (2020) 011802



PRL 126 (2021) 161802



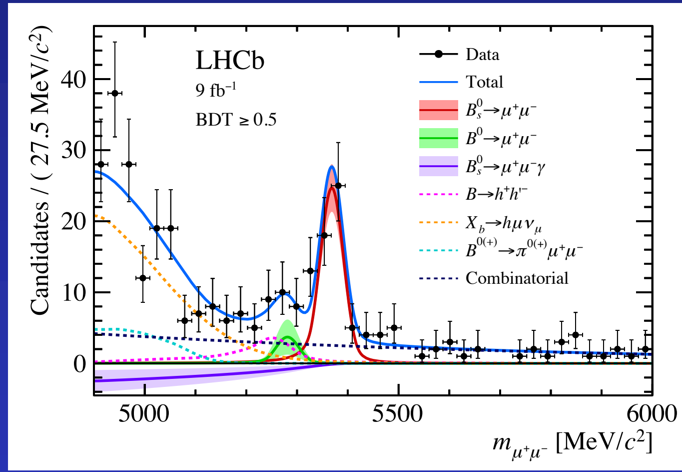


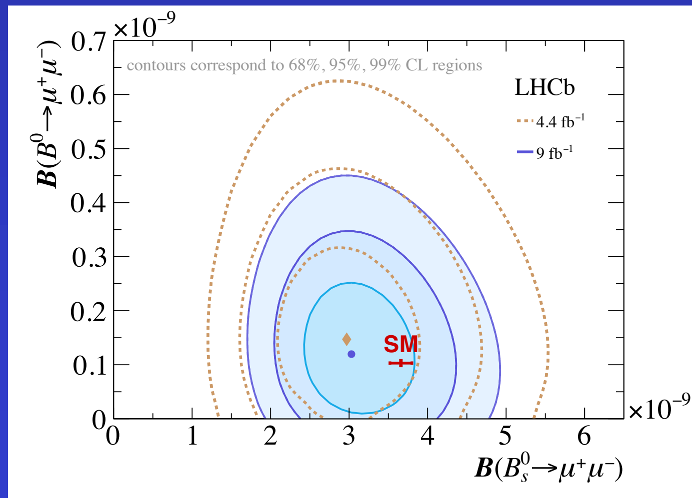
Electroweak penguin decays at LHCb
Christoph Langenbruch

$B_{(s)}^0 \to \mu^+\mu^-(\gamma)$

LHCb-PAPER-2021-007
LHCb-PAPER-2021-008

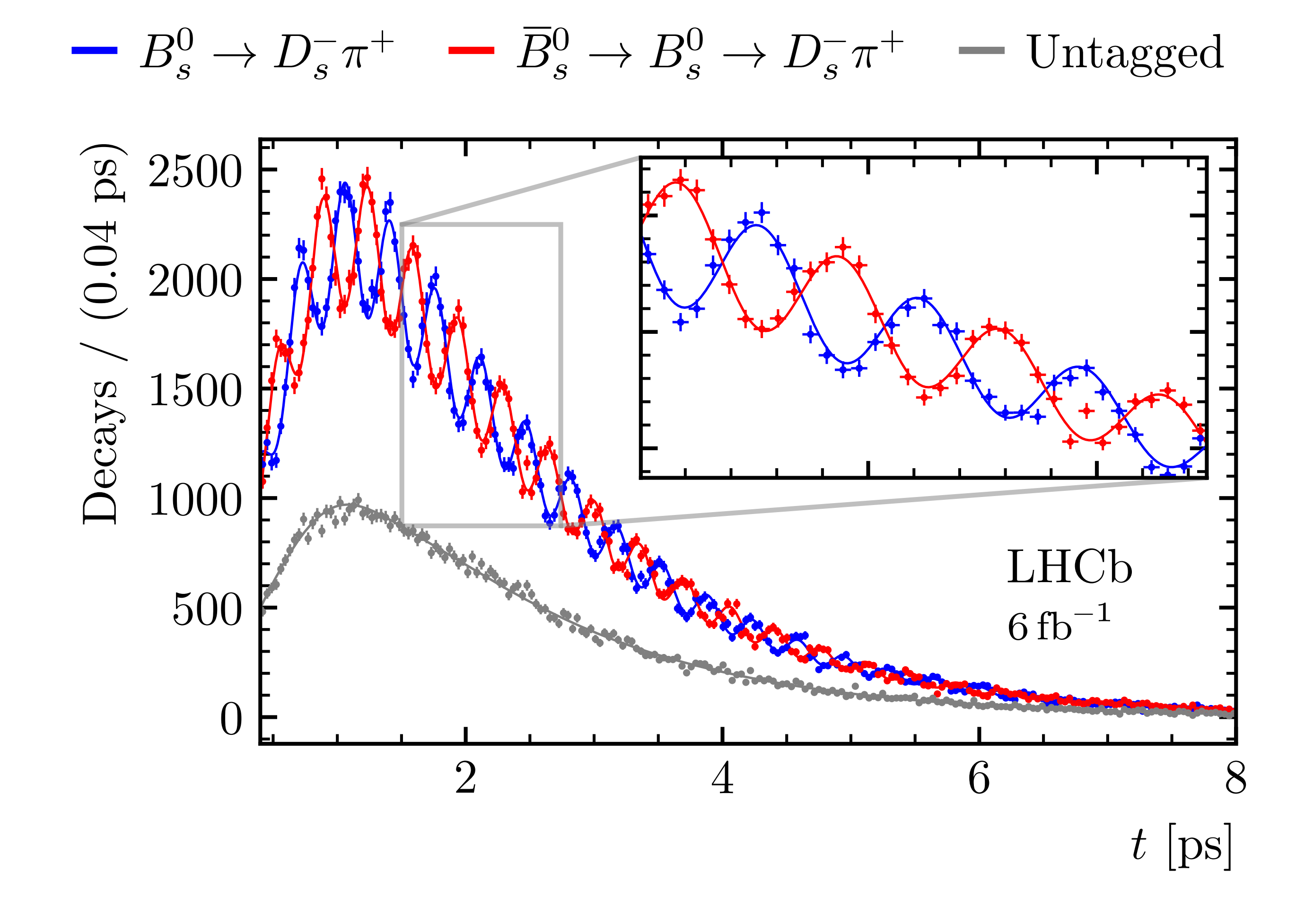
- **Very rare leptonic decay**
  - Helicity and CKM suppressed
  - Sensitive to New Physics
- **$B_s^0 \to \mu^+\mu^-$**
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46}_{-0.43}\,^{+0.15}_{-0.11} \times 10^{-9}$
  - Significance > 10 σ
  - in agreement with SM
- **$B^0 \to \mu^+\mu^-$**
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL
- **First search for $B_s^0 \to \mu^+\mu^-\gamma$**
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ at 95% CL for $m_{\mu\mu} > 4.9$ GeV/c^2





Very rare decays at LHCb
Miguel Ramos Pernas

Oscillations, ~~CP~~ and charm

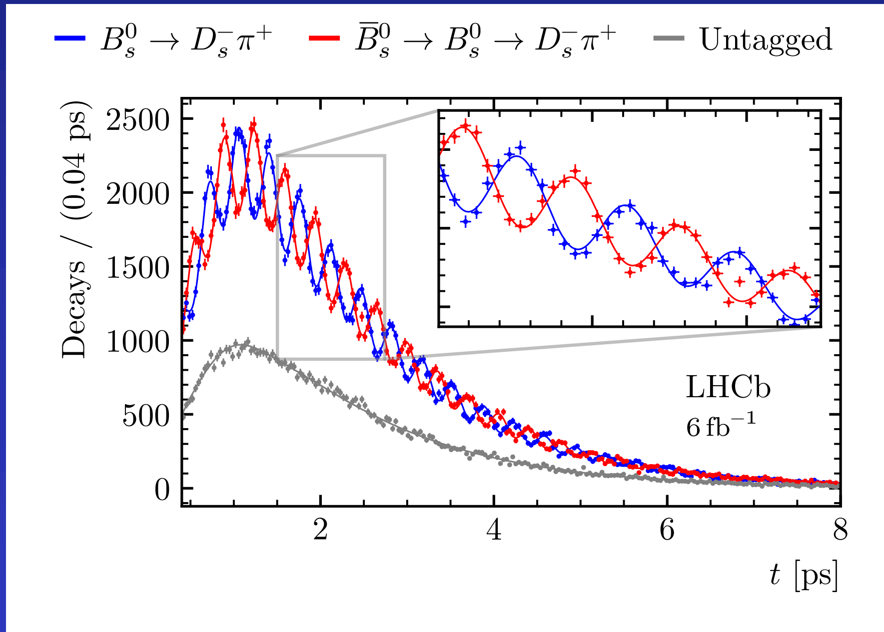


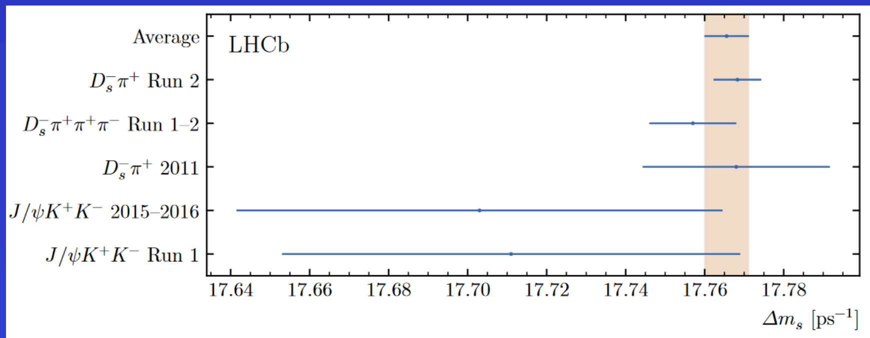
B_s Oscillations

- **B_s^0 mass difference Δm_s**
  - Measured by oscillation frequency with $B_s^0 \rightarrow D_s^{\mp}\pi^{\pm}$ decays
  - Flavour tagging identifies B_s^0 / anti-B_s^0 at production

- **Legacy measurement**
  - $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ ps^{-1}$
  - Precision 3×10^{-4}
  - Including $B_s^0 \rightarrow D_s^{\mp}h^{\pm}\pi^{\pm}\pi^{\mp}$ et al.
  - $\Delta m_s = 17.7656 \pm 0.0057\ ps^{-1}$

LHCb-PAPER-2021-005, arXiv:2104.04421
LHCb-PAPER-2020-030, JHEP 03 (2021) 137





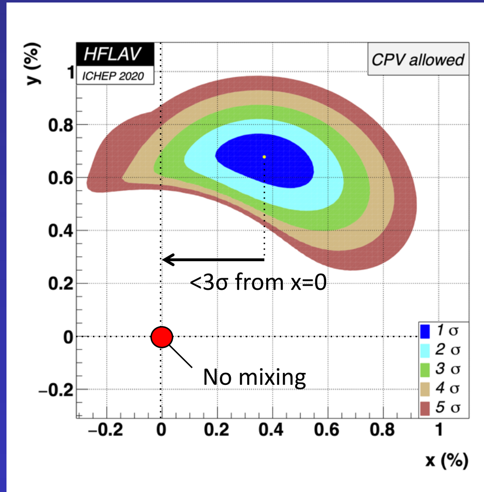
Measurement of the CKM angle gamma at LHCb
Mark Whitehead

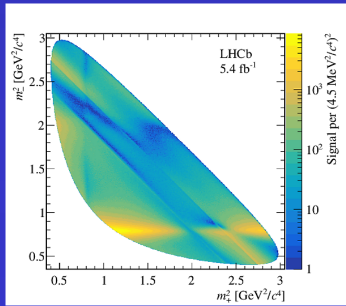
Charm mixing

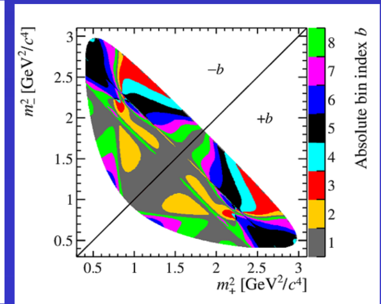
NEW

LHCb-PAPER-2021-009
arXiv:2106.03744

- **Charm D^0 Mixing**
  - Unique: up-type quarks
  - Small mixing, sensitive to $\cancel{CP}$
  - $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$ $\quad x \equiv (m_1 - m_2)c^2/\Gamma$ $\quad y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$
  - No measurement of $x \neq 0$ until this summer
- **Charm at LHCb**
  - Large cross section - σ_{cc} ~ 5 mb, charm rate ~2 MHz
  - Run 2 - dedicated Turbo trigger - 15 kHz to tape
- **$D^0 \rightarrow K_S^0 \pi^+\pi^-$**
  - 30.6M decays & very small background
- **Bin-flip method**
  - Measure asymmetry between D^0 and anti-D^0 in binned Dalitz plot $m^2(K_S^0\pi^-)$ vs $m^2(K_S^0\pi^+)$
  - In each bin approx. constant strong-phase difference between D^0 and anti-D^0 amplitude







Mixing and time-dependent CPV in charm decays at LHCb Federico Betti

Observation of mass difference

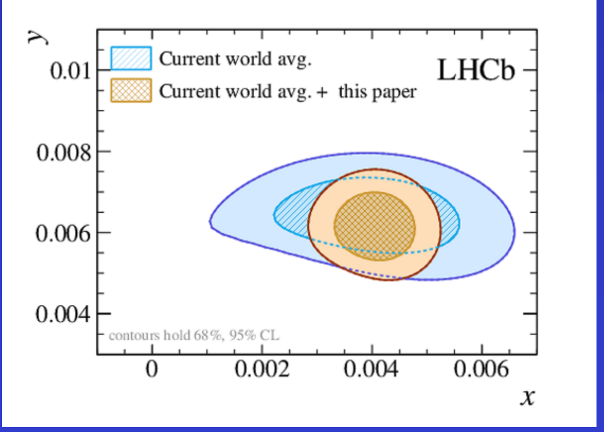
NEW

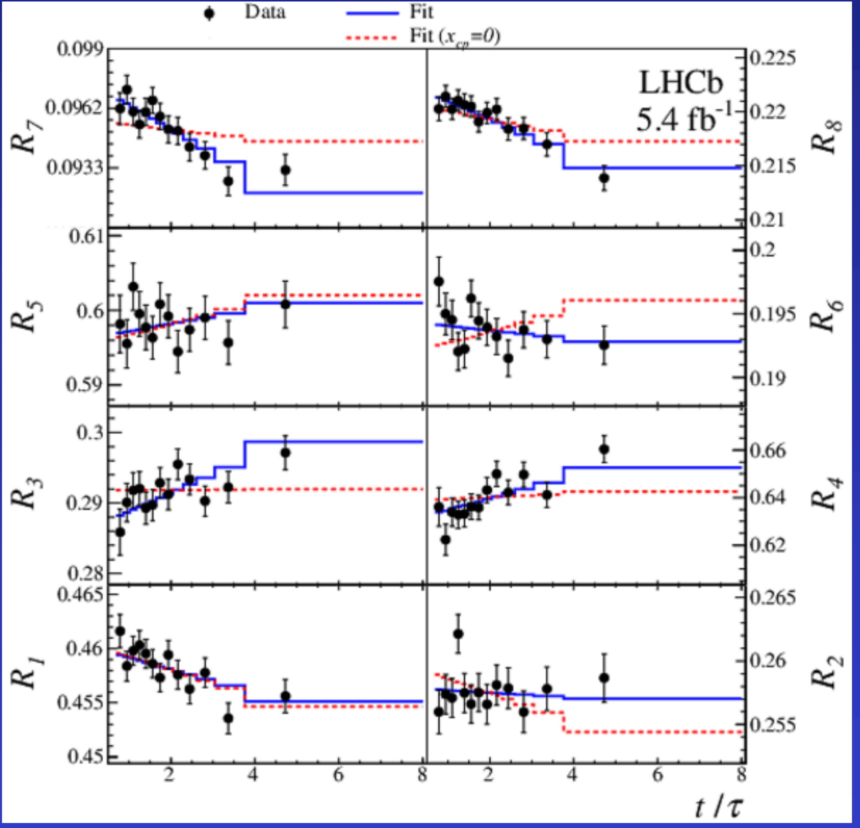
LHCb-PAPER-2021-009
arXiv:2106.03744

- **Observation**
  - of small mass difference
    in neutral charm meson eigenstates

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

  - $m_1 - m_2 = 6.4 \times 10^{-6}$ eV = 1×10^{-38} g
  - Significance > 7 σ
  -





No evidence for $\cancel{CP}$ at 2 x 10^{-4}

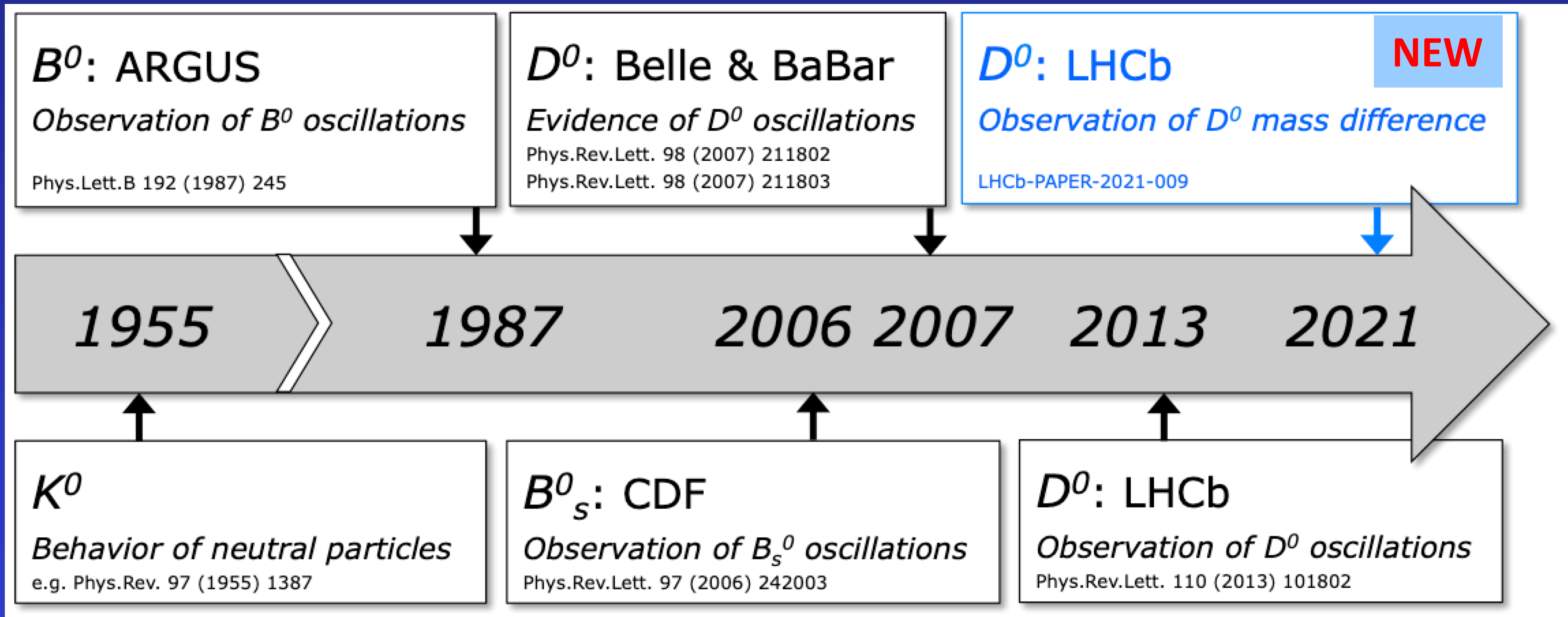
Mixing and time-dependent CPV in charm decays at LHCb Federico Betti

Neutral particle oscillations

- **Timeline**

NEW

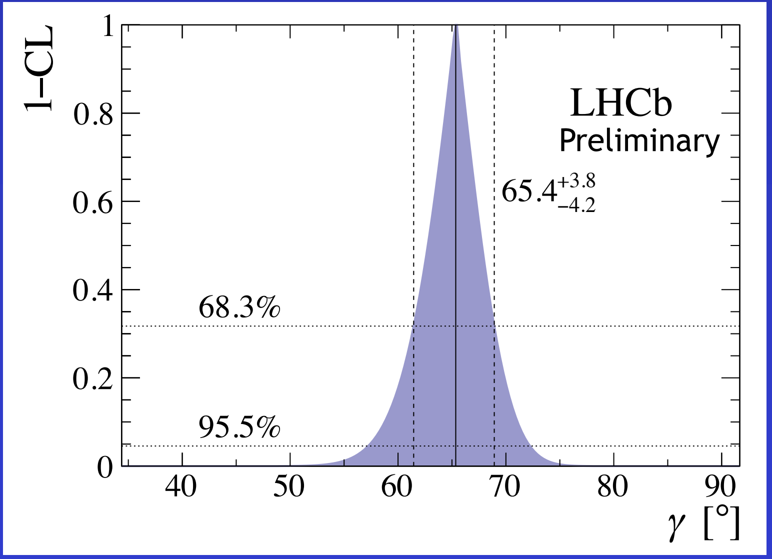
LHCb-PAPER-2021-009
arXiv:2106.03744



CKM angle γ and charm mixing

LHCb-CONF-2021-001

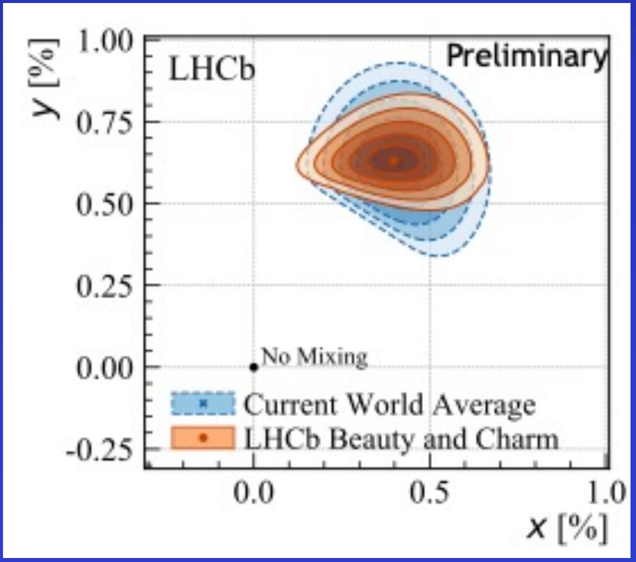
- **New method**
  - First simultaneous determination of CKM angle γ and charm mixing parameters
  - 151 observables, 52 parameters
- **CKM angle γ**
  - $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
  - Most precise measurement



- **Comparison**

NEW

  - Excellent agreement with indirect global CKM fits
  - $\gamma = (65.8 \pm 2.2)^\circ$ UTfit
- **Charm mixing**
  - $y = (0.630^{+0.033}_{-0.030})\%$,
  - $x = (0.400^{+0.052}_{-0.053})\%$
  - Precision on y improved by factor 2



Measurement of the CKM angle gamma at LHCb
Mark Whitehead

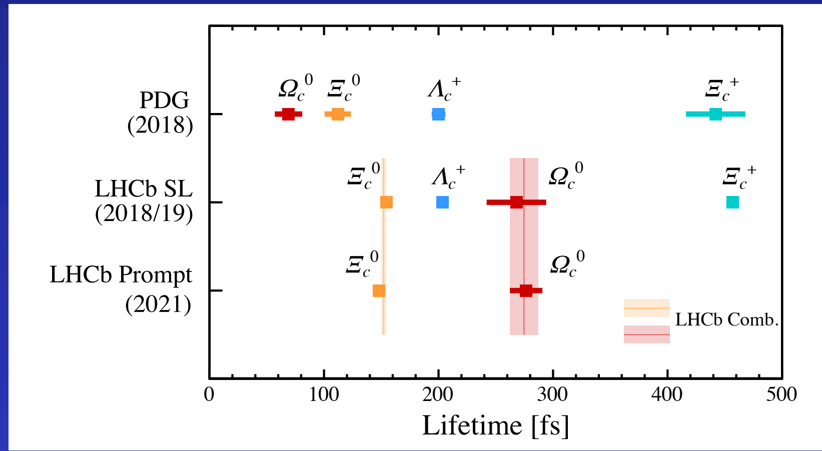
Charmed Ω_c^0 baryon lifetime

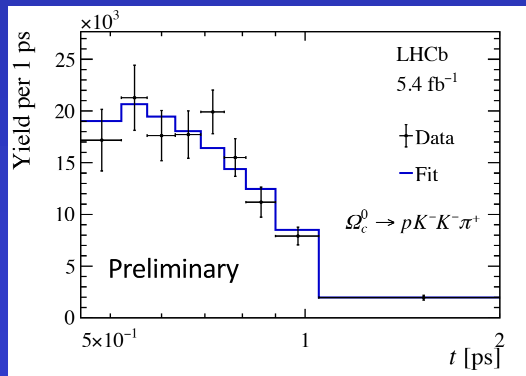
NEW

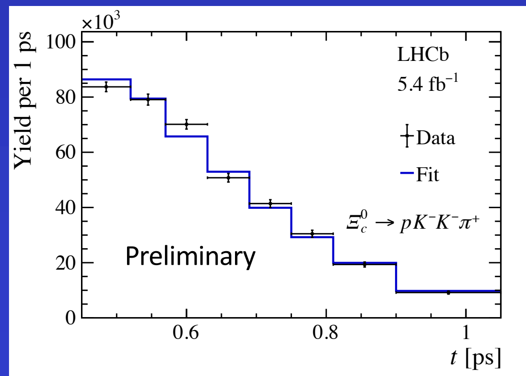
LHCb-PAPER-2021-021

PRL 121 (2018) 092003

- **Charmed baryon lifetimes**
  - Λ_c^+ (udc), Ξ_c^+ (usc), Ξ_c^0 (dsc), Ω_c^0 (ssc)
  - Hierarchy (PDG 2018)
    $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$
  - 2018 - LHCb measures longer $\tau(\Omega_c^0)$ in semileptonic b-baryon decays
- **Promptly produced c-baryons**
  - $\Omega_c^0 \rightarrow p K^- K^- \pi^-$
  - $\Xi_c^0 \rightarrow p K^- K^- \pi^-$
  - $\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7\,\text{fs},$
  - $\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2\,\text{fs},$
  - Confirms $\tau(\Omega_c^0)$ is 4x longer
- **New lifetime hierarchy**
  - $\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$

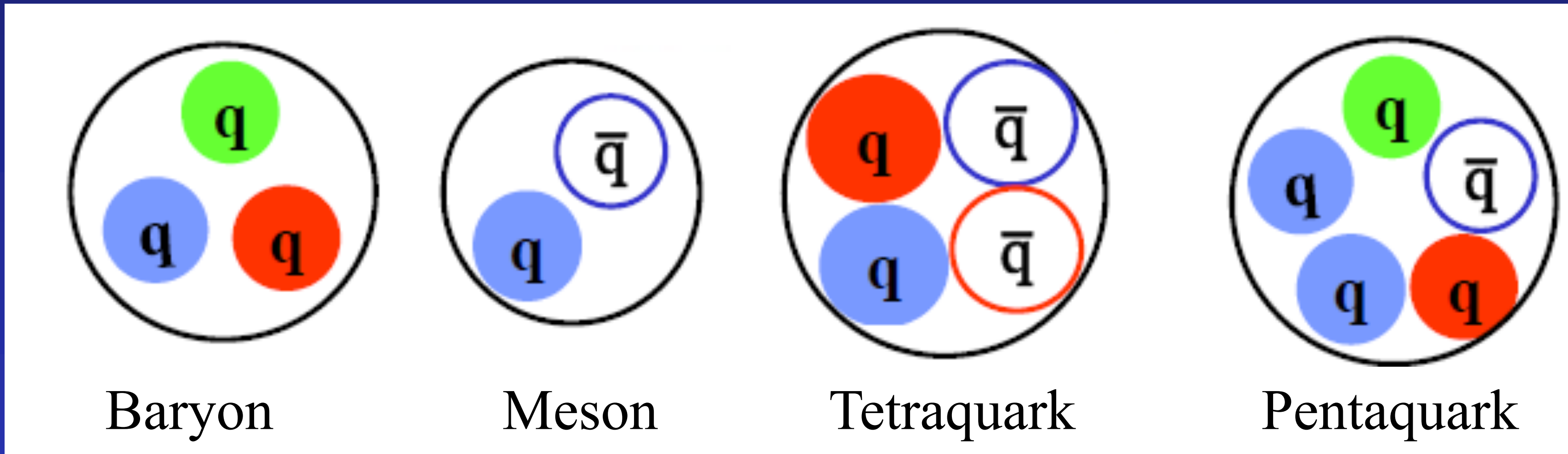


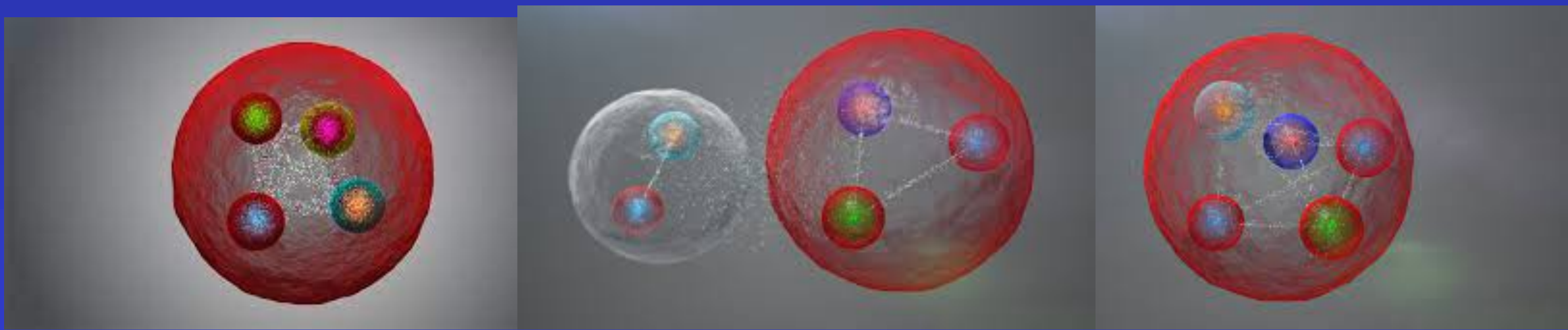




LHCb results in charm baryons
Ao Xu

Exotic Spectroscopy

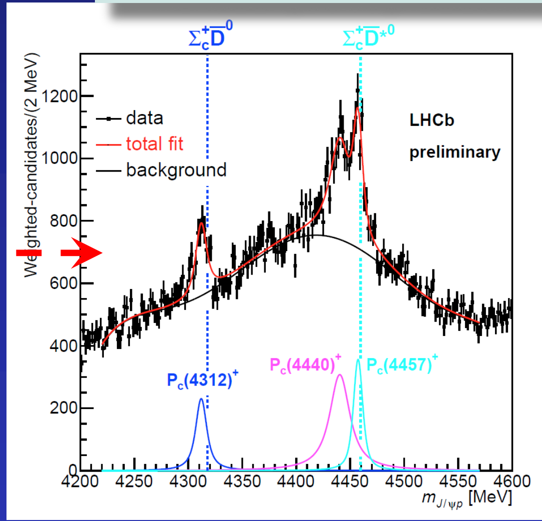




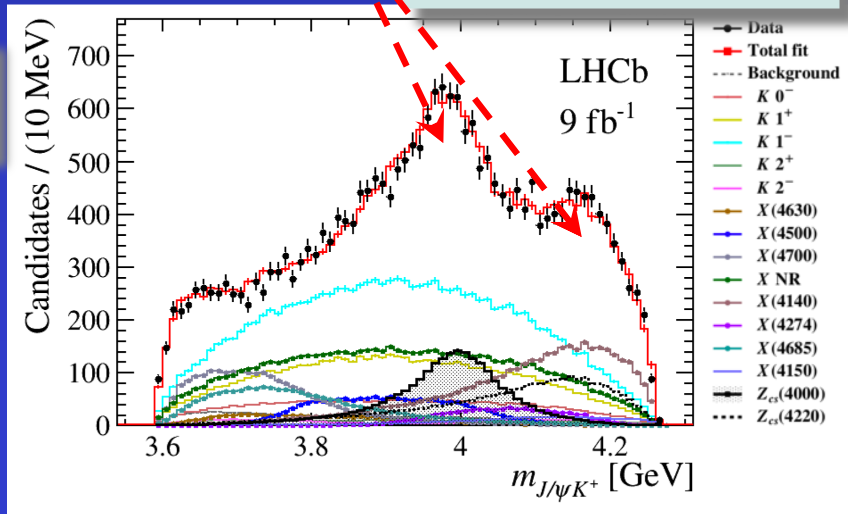
Exotic Spectroscopy

- **Overview**
  - Discovery of X(3872) - now $\chi_{c1}(3872)$ - by Belle in 2003 started new era in exotic spectroscopy
  - Observation of $c\bar{c}uud$ pentaquarks $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$
  - Observation of two $\bar{c}cu\bar{s}$ tetraquarks $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$
  - Evidence for two $\bar{c}du\bar{s}$ tetraquarks $X_0(2900)$ and $X_1(2900)$

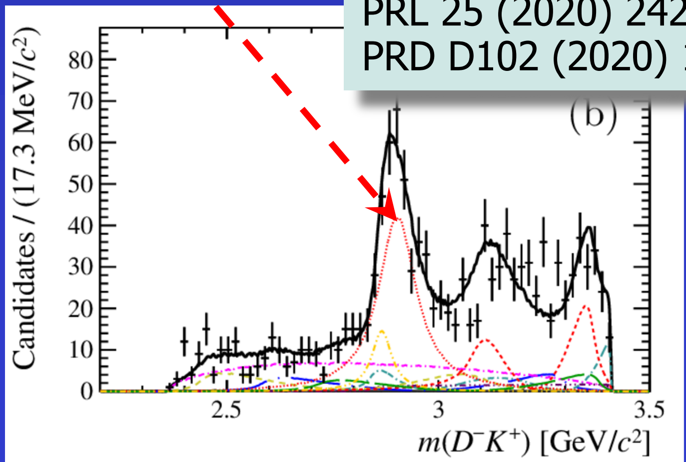
PRL 122 (2019) 222001



LHCb-PAPER-2020-044
arXiv:2106.03744



PRL 25 (2020) 242001
PRD D102 (2020) 112003



Observation of excited Ξ_b^0 baryons

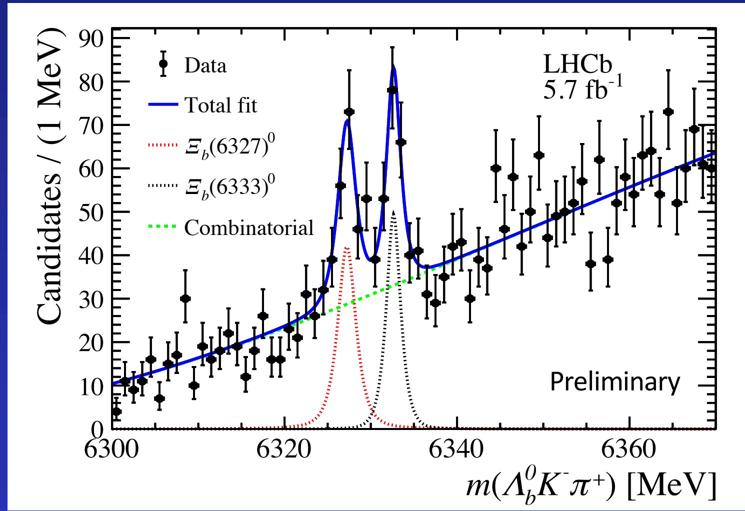
NEW

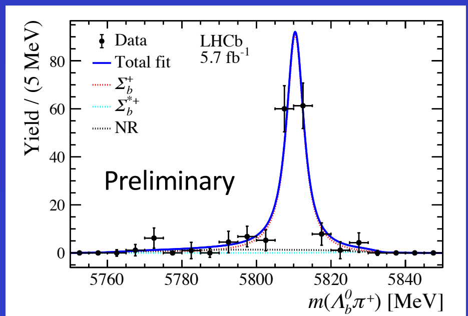
LHCb-PAPER-2021-025

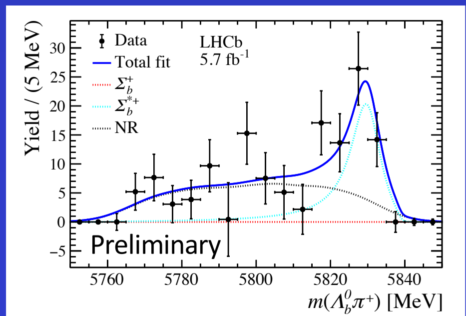
- $\Xi_b^0 \to \Lambda_b^0 K^- \pi^+$ **spectrum**
  - Using 1.6 M $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ and $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ decays
- **Observation**
  - Two new excited Ξ_b^0 states

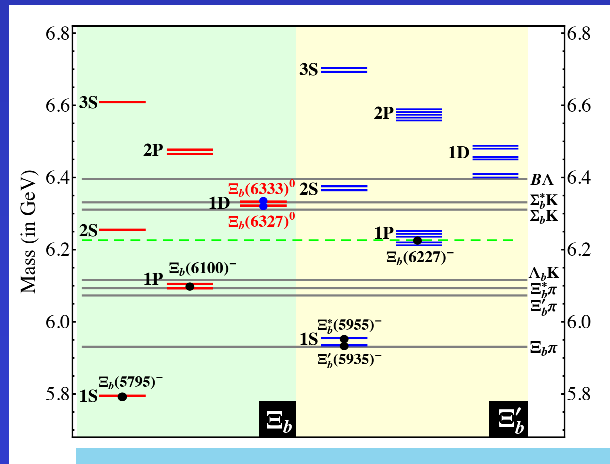
$$
\begin{aligned}
m_{\Xi_b(6327)^0} &= 6327.28^{+0.23}_{-0.21} \pm 0.08 \pm 0.24\,\text{MeV},\\
m_{\Xi_b(6333)^0} &= 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22\,\text{MeV},\\
\Gamma_{\Xi_b(6327)^0} &< 2.20\ (2.56)\,\text{MeV at } 90\%\ (95\%)\ \text{CL},\\
\Gamma_{\Xi_b(6333)^0} &< 1.55\ (1.85)\,\text{MeV at } 90\%\ (95\%)\ \text{CL},
\end{aligned}
$$

  - Intermediate structures
  - Ξ_b^0 **(6327)** $\quad \Sigma_b^+ \to \Lambda_b^0 \pi^+ \quad$ Ξ_b^0 **(6333)**









Beauty-hadron spectroscopy at LHCb
Hongjie Mu

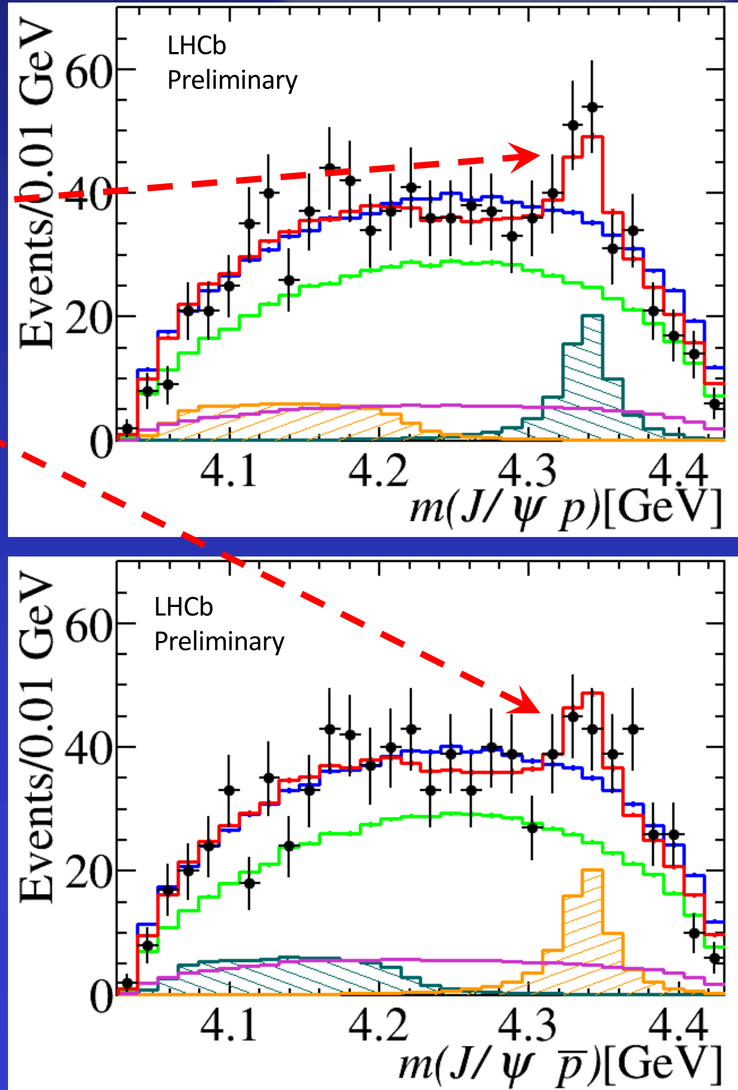
Evidence for structure in J/ψp

NEW

LHCb-PAPER-2021-018

- **Amplitude analysis**
  - using 800 $B_s^0 \rightarrow J/\psi p\bar{p}$ decays
  - Observe structure in $J/\psi p$ and $J/\psi\bar{p}$ spectrum
  - Significance of 3.1σ to 3.7σ depending on J^P assignment
- **Evidence**
  - For $P_c(4337)^+$ state
  - Consistent with a $(c\bar{c}uud)$ pentaquark
  - Mass and width

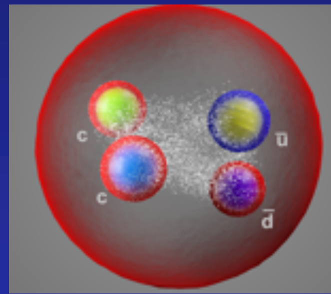
$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV},$$

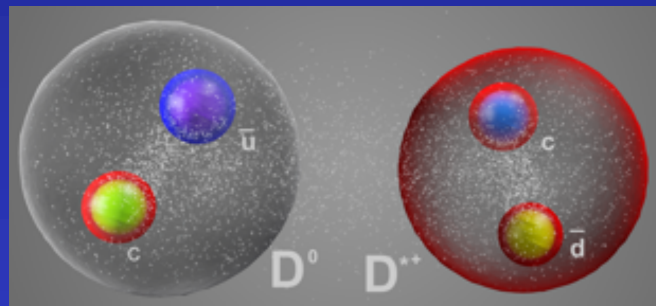


Recent LHCb results on pentaquark candidates
Jinlin Fu

Exotic Spectroscopy

- **Categories of observed resonance states**
  - Excited states: $b\bar{q}$, $c\bar{q}$, bqq, cqq
  - Exotic states: $c\bar{c}(q\bar{q})$, $c\bar{c}c\bar{c}$, $c\bar{q}q\bar{q}$, $c\bar{c}qqq$
  - Evidence for two $\bar{c}d u\bar{s}$ tetraquarks
  - Natural width varies from O(1) to O(100) MeV





- **Heavy quark symmetry**
  - Predicts doubly heavy tetraquark hadron $cc\bar{q}\bar{q}$ or $bb\bar{q}\bar{q}$ to be long-lived with respect to strong interaction
- **Doubly charmed tetraquark T_{cc}^{+}**
  - Ground state T_{cc}^{+} with $J^P = 1^+$
  - Many models predict T_{cc}^{+} mass close to the D*D threshold
- **Observation strategy**
  - Search for narrow exotic state in same sign doubly charmed mass spectrum

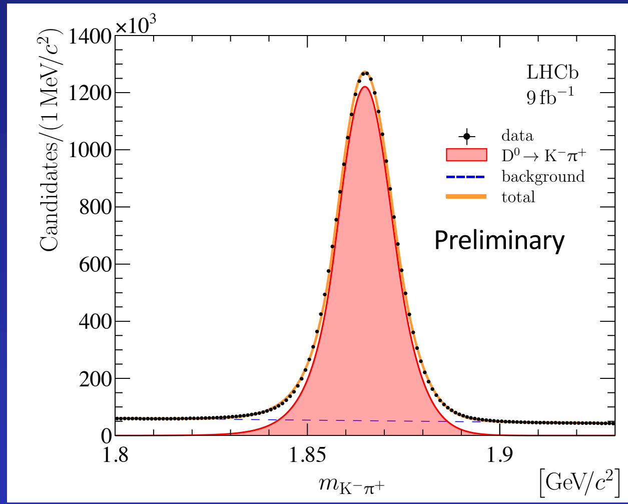
Search for T_{cc}^{+} state

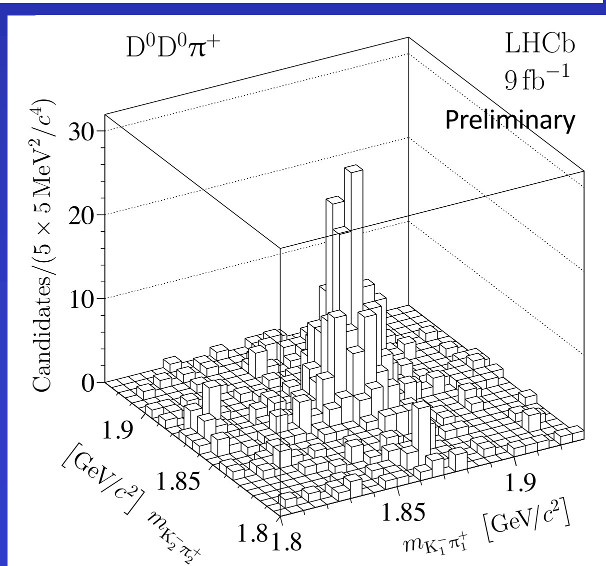
NEW

LHCb-PAPER-2021-031

- T_{cc}^{+} search
  - Expected to decay to $D^0 D^0 \pi^+$ with $D^0 \to K^- \pi^+$
  - Study $D^0 D^0 \pi^+$ mass spectrum
  - Mass near $D^{*+}D^0$ and $D^{*0}D^+$ thresholds
  - mass difference

$$\delta m \equiv m_{T_{cc}^{+}} - (m_{D^{*+}} + m_{D^0})$$





- Method
  - Unbinned log-likelihood fit to 2 dimensional D^0 mass combinations of $D^0 D^0 \pi^+$ candidates
  - to subtract background from combinatorial $K^- \pi^+$ pairs

Recent LHCb results on exotic meson candidates
Ivan Polyakov

Observation of T_{cc}^+ state

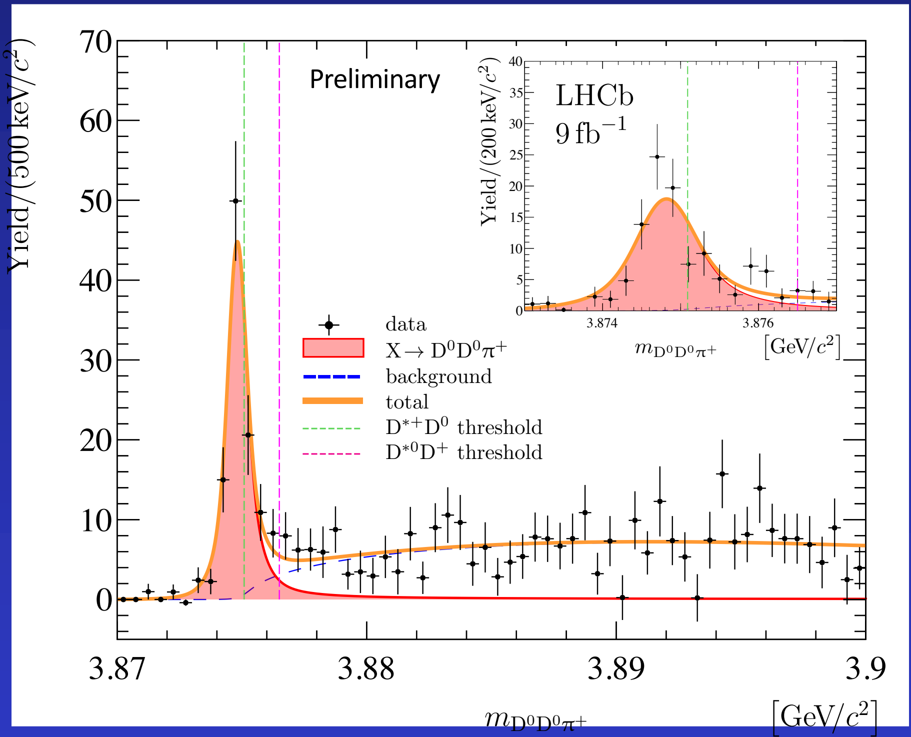
NEW

LHCb-PAPER-2021-031

- **First observation of a same-sign doubly charmed tetraquark T_{cc}^+**
  - Very narrow state in $D^0 D^0 \pi^+$ mass spectrum
  - Consistent with $cc\bar{u}\bar{d}$ tetraquark
  - Mass very close to $D^{*+}D^0$ mass thresholds
  - Manifestly exotic
- **Parameters of T_{cc}^+**
  - Fit structure with P-wave relativistic Breit-Wigner

$$\begin{aligned} \delta m_{\mathrm{BW}} &= -273 \pm 61 \pm 5 \,^{+11}_{-14}\, \mathrm{keV}/c^2\,, \\ \Gamma_{\mathrm{BW}} &= 410 \pm 165 \pm 43 \,^{+18}_{-38}\, \mathrm{keV}\,, \end{aligned}$$

  - Uncertainties stat, syst and due $J^P = 1^+$ assumption
  - Significance for signal > 10 σ
  - Significance for $\delta m_{BW} < 0$ 4.3 σ

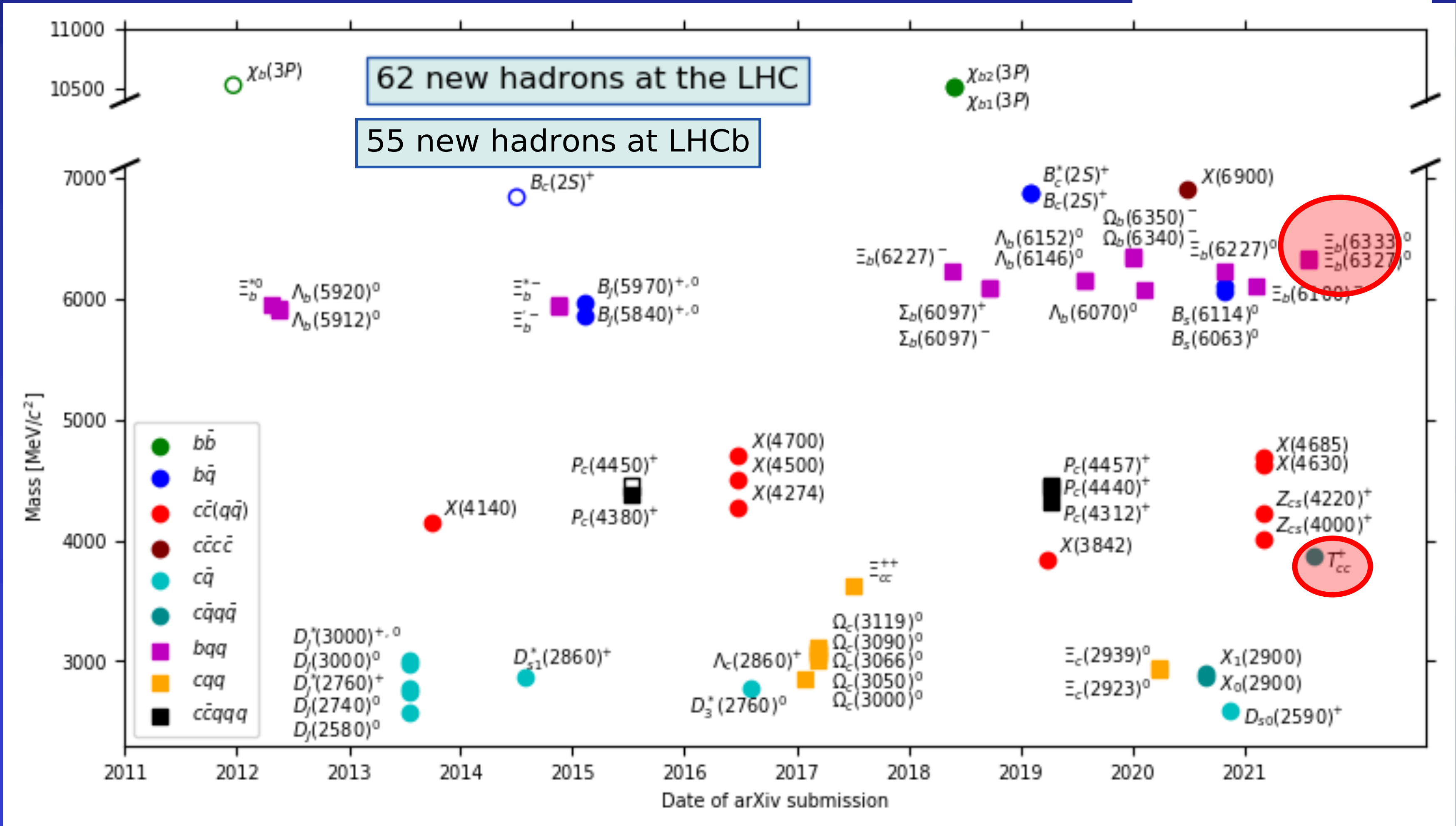


Recent LHCb results on exotic meson candidates
Ivan Polyakov

Spectroscopy at the LHC

- **Status 28 July 2021**

from
Patrick Koppenburg



Electroweak, QCD, Heavy Ions

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

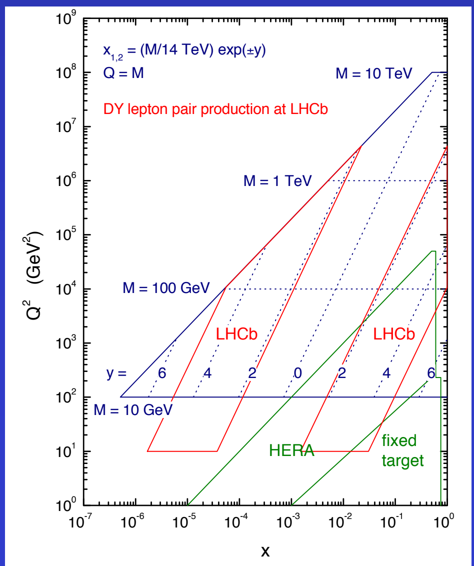
The largest group that leaves invariant the kinematic terms $-\overline{L}\gamma^\mu\partial_\mu L - \overline{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \frac{1}{2}N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken sym-

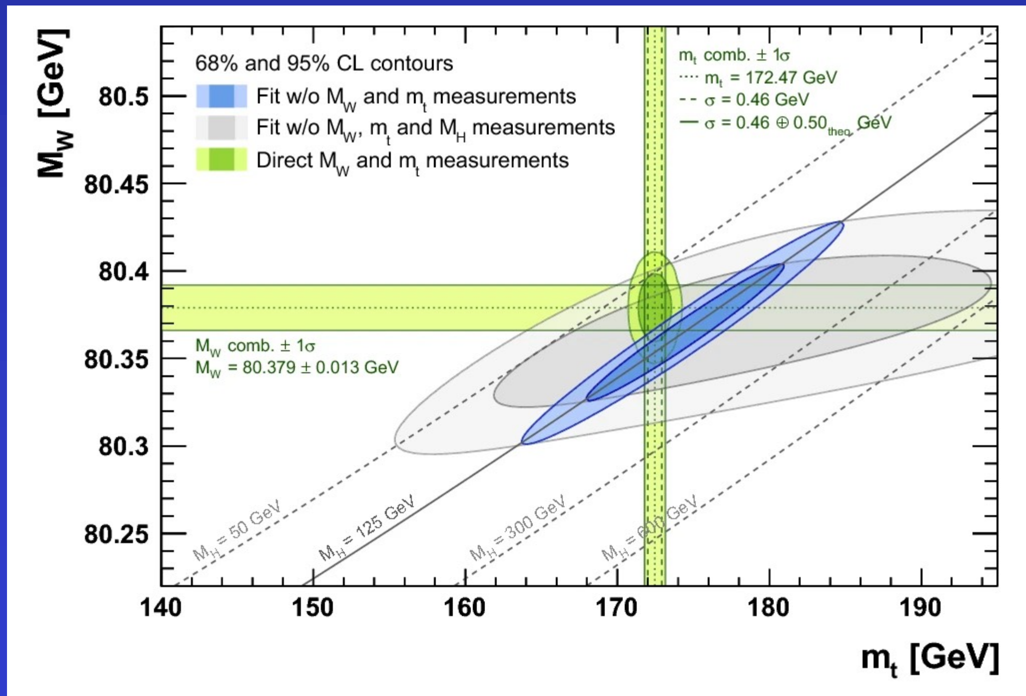
W mass measurement

- **W boson mass**
  - Fundamental parameter of Standard Model
  - Sensitivity to new physics limited by direct m_W measurements
  - Most precise results from ATLAS, CDF and D0

Global electroweak fit
EPJC 78, 675 (2018) GFitter

- **LHCb parton distributions**





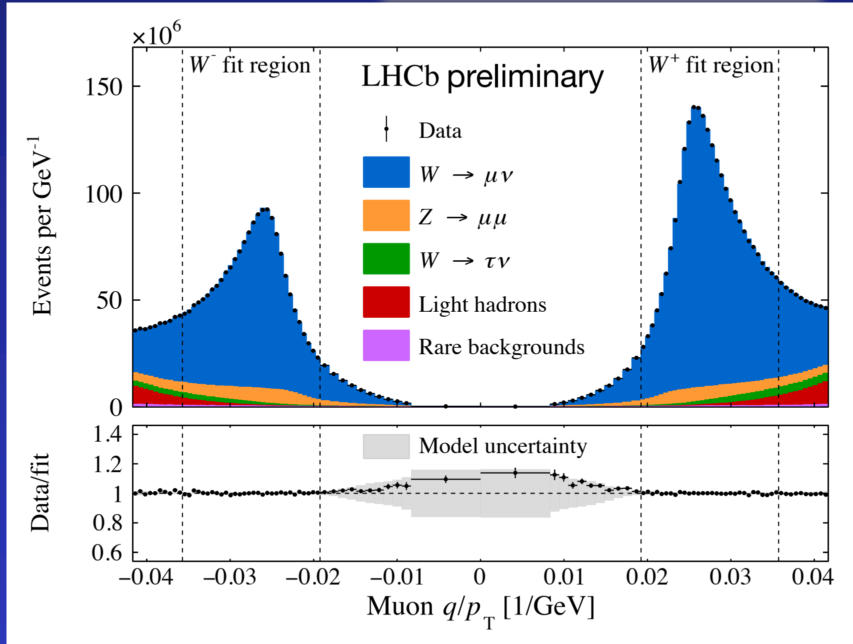
W mass measurement

NEW

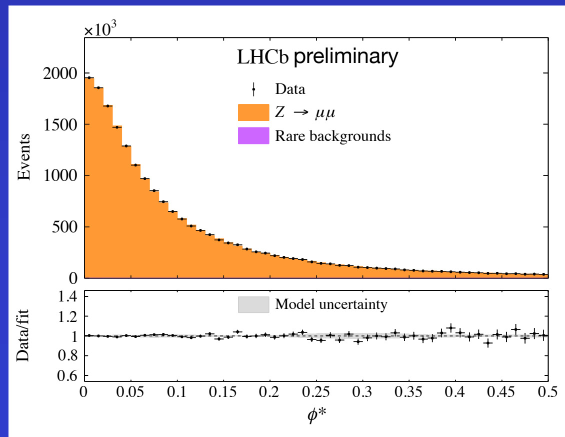
LHCb-PAPER-2021-024

- **Method**
  - $W^+ \to \mu^+ \nu_\mu$ decay mode
  - Transverse momentum p_T of muon with charge q peaks at ~$m_W/2$
  - Shift in m_W distorts q/p_T spectrum
  - Muon p_T depends on transverse momentum p_T^W of W boson
  - $Z \to \mu^+\mu^-$ decays measured simultaneously

$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M},$$



- **m_W determination**
  - Simultaneous fit to q/p_T and ϕ^* of W and Z
  - Precision: 23 MeV stat. uncertainty
  - Systematic uncertainties from PDF, theory and experiment



Measurement of the W boson mass with the LHCb detector
Ross Hunter

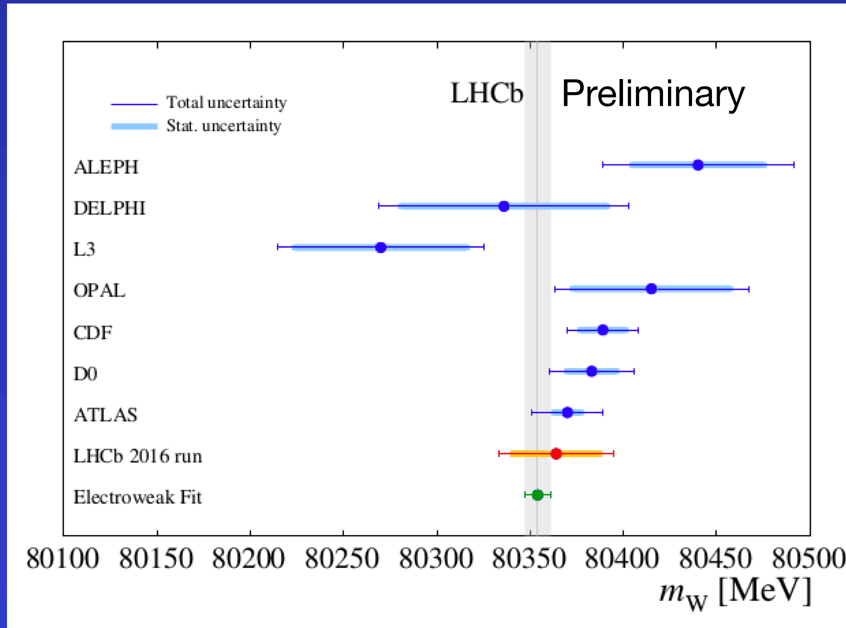
W mass measurement

NEW

LHCb-PAPER-2021-024

- **W boson mass**
  - Using 2016 data sample 1.6 fb^{-1}
  - $$m_W = 80364 \pm 23_{\mathrm{stat}} \pm 11_{\mathrm{exp}} \pm 17_{\mathrm{theory}} \pm 9_{\mathrm{PDF}}\ \mathrm{MeV}$$

- **Discussion and outlook**
  - First LHCb measurement of W boson mass m_W
  - Pathfinder analysis: 32 MeV precision using ~1/3 of Run 2 data sample
  - Expect LHCb precision < 20 MeV with full Run 1&2 data set
  - Average LHCb with ATLAS could profit from –ve PDF correlations



EPJC 75 12, 601 (2015)

Measurement of the W boson mass with the LHCb detector
Ross Hunter

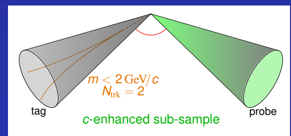
Intrinsic charm of proton

NEW

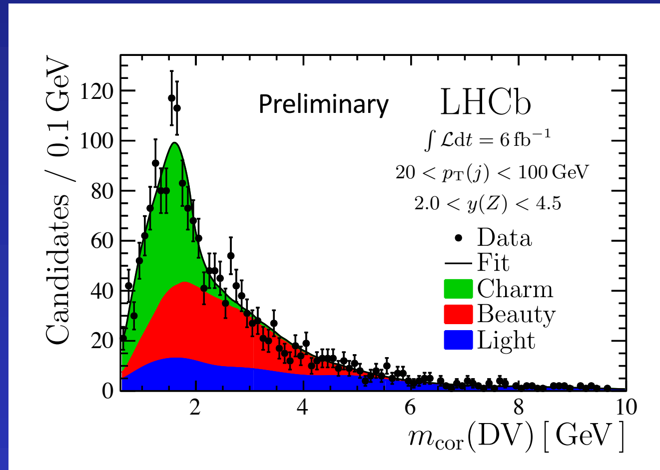
LHCb-PAPER-2021-029

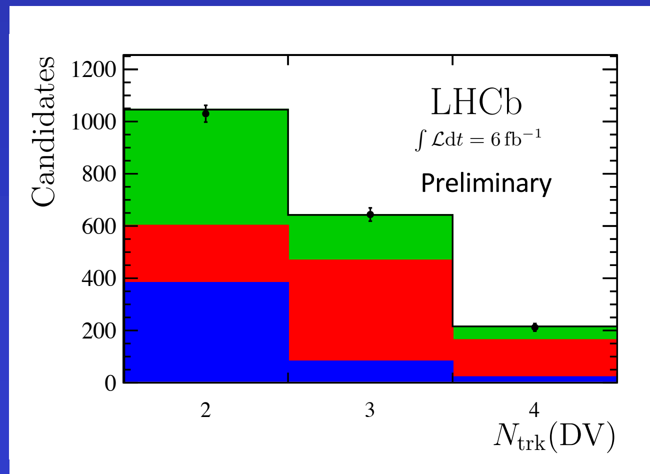
PRD 93 (2016) 074008

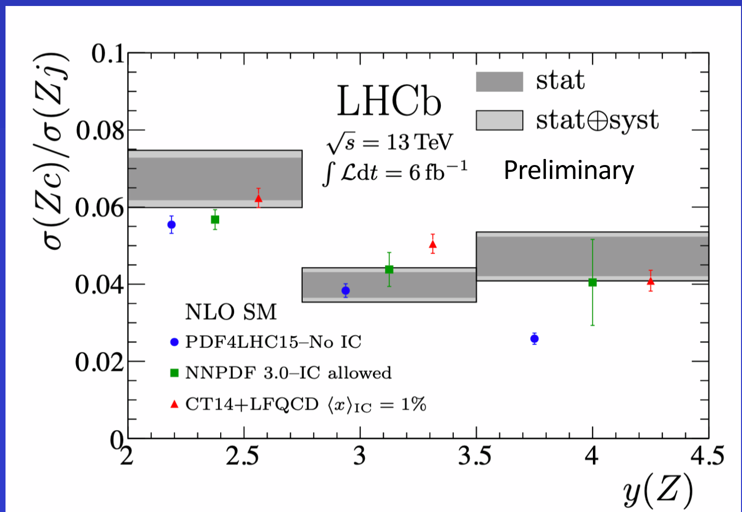
- **Z boson and charm jets**
  - σ(Zc)/σ(Zj) fraction of Z+jet events where jet originates from a charm quark
- **Charm-jet**
  - Displaced vertex DV, corrected mass m_{cor}
  - Calibrated with tag and probe



- **Result**
  - Sizable enhancement of c-jets at high Z rapidity
  - Consistent with 1% intrinsic charm in proton





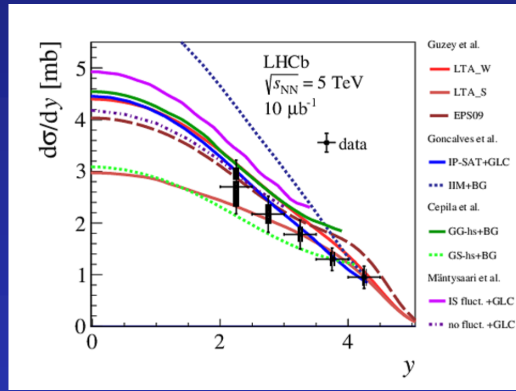


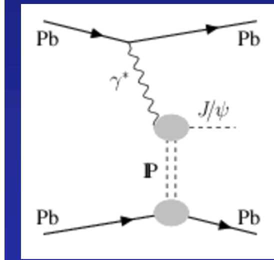
QCD physics measurements at the LHCb experiment
Lorenzo Sestini

Heavy Ion Physics

LHCb-PAPER-2021-013
arXiv:2107.03223

- **PbPb collisions at √s = 5 TeV**
  - Coherent production of J/ψ ultraperipheral lead-lead collisions
  - J/ψ → $\mu^+\mu^-$ rapidity 2.0<y<4.5
  - Cross-section σ = 4.45±0.24±0.18±0.58 mb
  - Comparison to phenomenological models





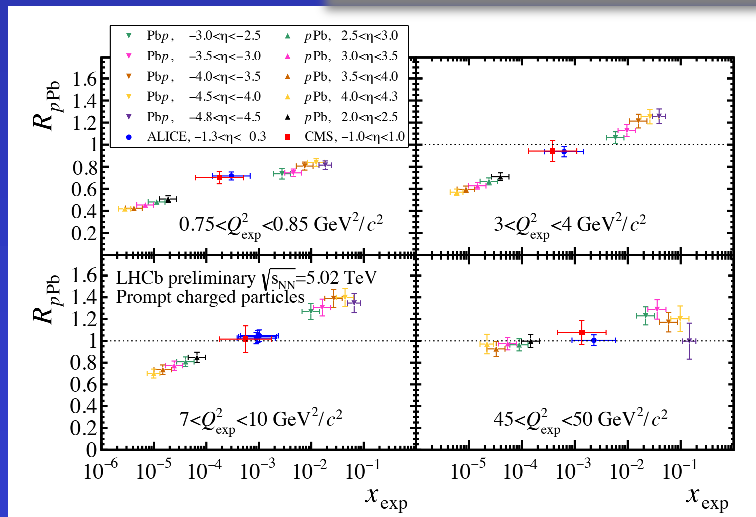
NEW

LHCb-PAPER-2021-015

- **Charged particle production at √s = 5 TeV**
  - Comparison of pPb and pp data samples
  - Nuclear modification factor

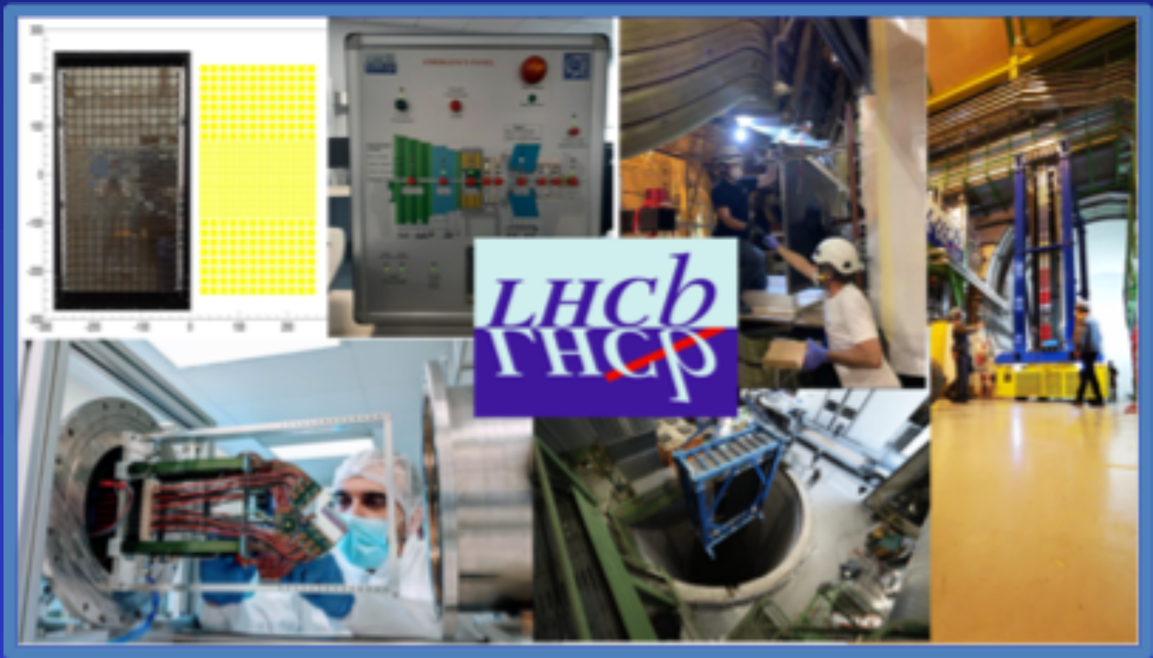
$$R_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}}) = \frac{1}{A}\frac{d^2\sigma_{p\mathrm{Pb}}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}{d^2\sigma_{pp}(\eta, p_{\mathrm{T}})/dp_{\mathrm{T}}d\eta}$$

  - Continuous evolution of R_{pPb} vs x_{exp} between forward, central and backward η



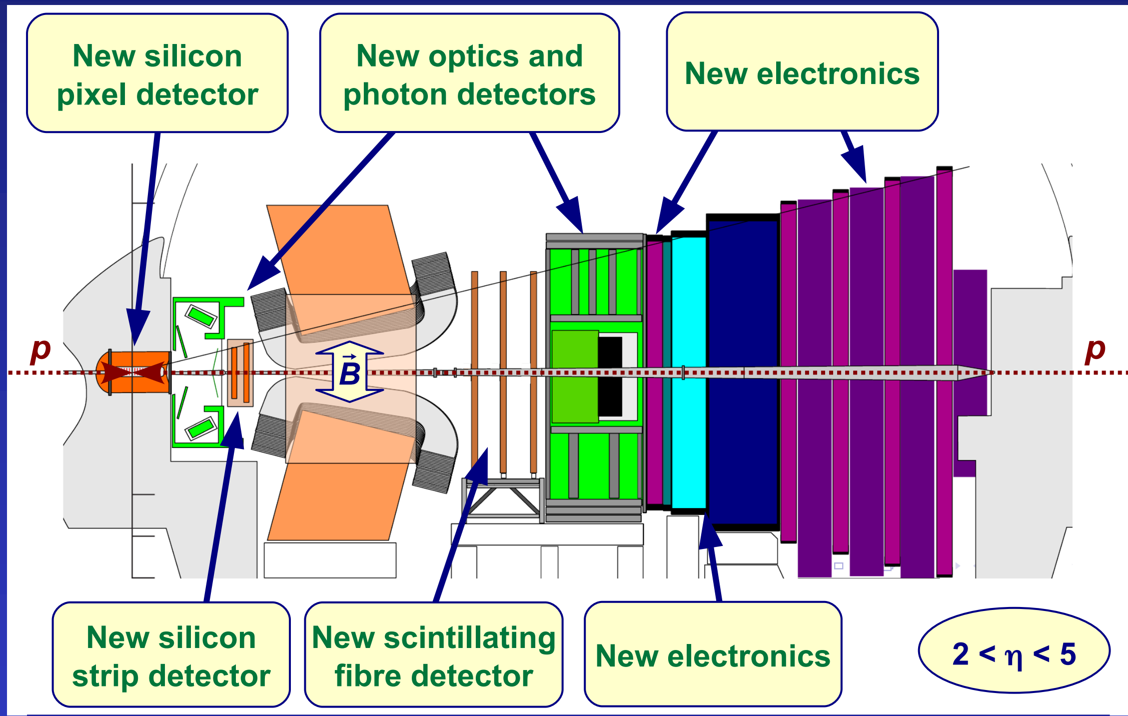
Charged hadron production at LHCb
Oscar Boente

Upgrades present and future

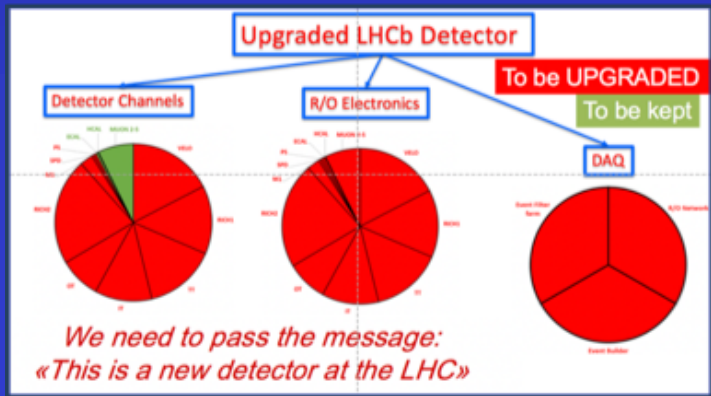


LHCb upgrade I

- **LHCb upgrade**
  - = new detector
  - Installation ongoing
  - Huge challenge
  - intensified due to Covid

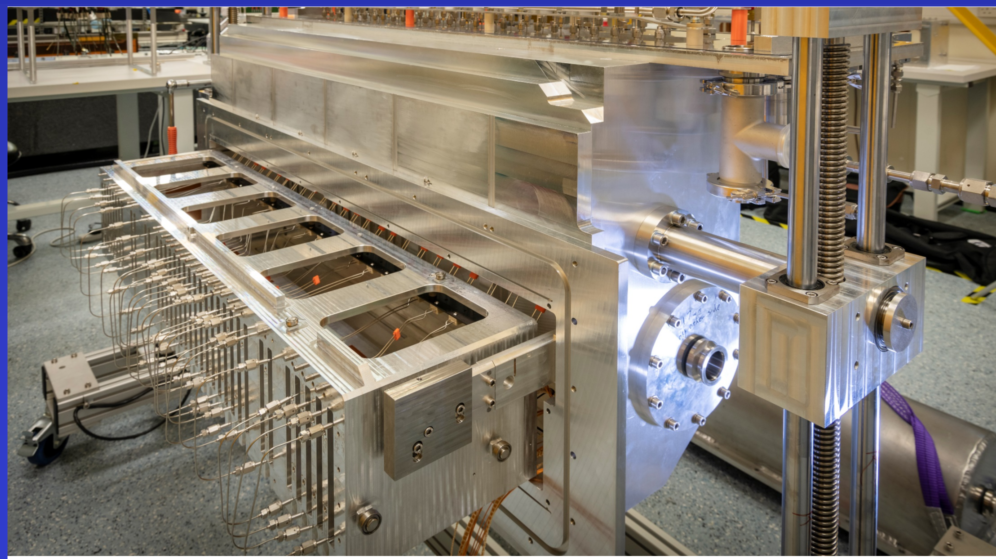


- **Status of Installaton**
  - Significant progress under difficult circumstances
  - Travel restrictions are still a concern
  - Commissioning has started RICH, CALO, Muons



VELO and UT

- **VELO modules**
  - 40 of 52 modules produced
  - Assembly of half-VELO starting
- **UT modules**
  - production nearly complete
  - Module mounting next

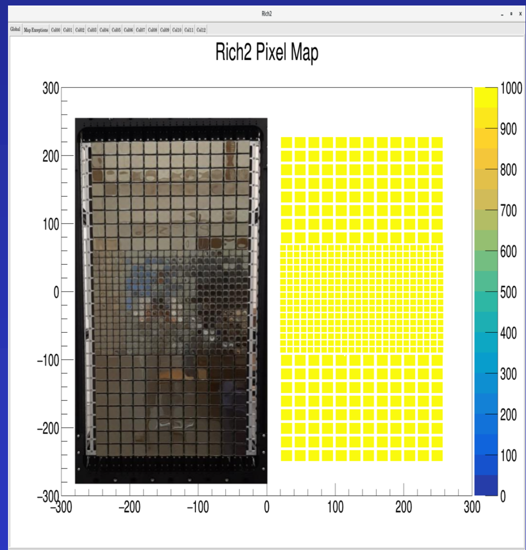


SciFi tracker

- **SciFi half detector installed**
  - Happened 10 days ago – a major milestone
  - 6/12 C-frames installed

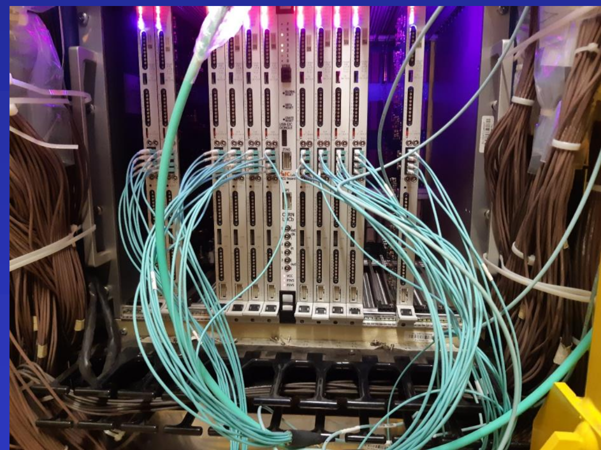
RICH, CALO, Muons Commissioning

- **RICH 2 installed**
  – 1st detector in commissioning



  – A side switched on
  – DCS and DAQ

- **CALO**
  – Front-end board installation progressing well

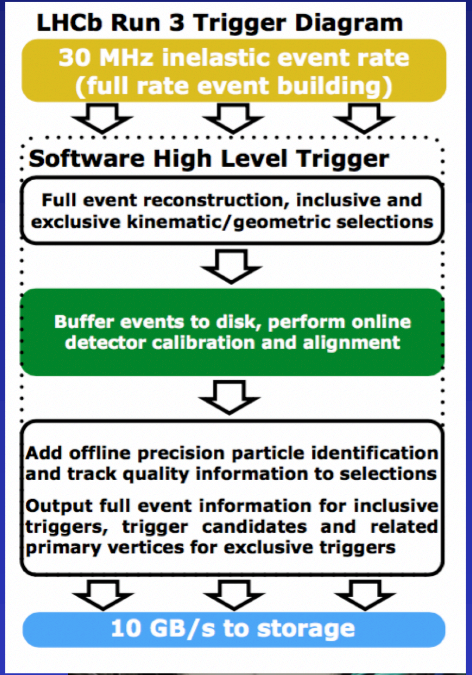


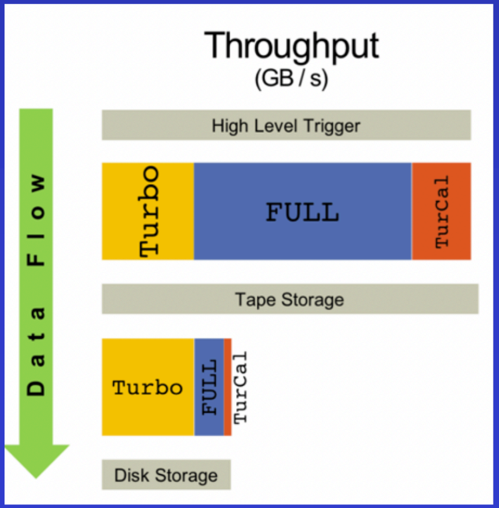
- **Muons**
  – Electronics installed

  – Commissioning ongoing

LHCb Upgrade I – Online & Trigger

- **Software High Level Trigger**
  - 30 MHz event rate
  - 10 GB/s to Storage
- **Online installation**
  - Event builder PC servers & FPGA DAQ cards completed
  - Event builder network > 100 Tb/s achieved (200 *x* Run2, 32 Tb/s required)
  - Commissioning of Muon, RICH, CALO underway
- **GPU HLT1 trigger**
  - Event reconstruction In trigger achieved in single GPU card
  - Full reconstruction in trigger achieved required CPU event rate



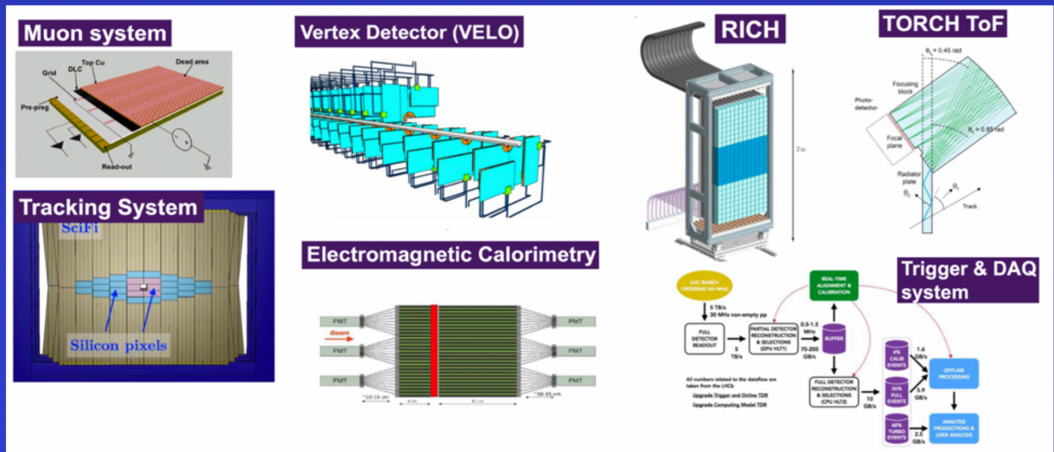


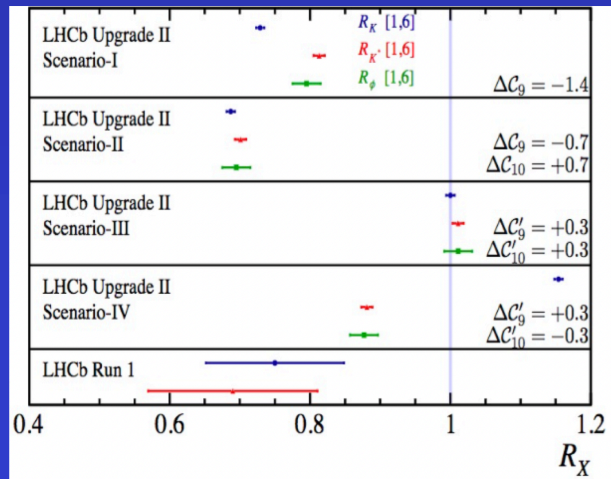
LHCb Upgrade II

- **LHC flavour physics facility**
  - Fully exploit HL-LHC luminosity for flavour physics & beyond
  - Expression of interest (2017)
  - Physics Case (2018)
  - Strong support in European Strategy (2020)

2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031 2032	2033 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz UPGRADE I	$L = 2 x 10^{33}$	LHCb Consolidate: UPGRADE Ib	$L = 2 x 10^{33}$ $50 fb^{-1}$	LHCb UPGRADE II	$L=1\text{-}2x\ 10^{34}$ $300 fb^{-1}$
ATLAS Phase I Upgr	$L = 2 x 10^{34}$	ATLAS Phase II UPGRADE	HL-LHC $L = 5 x 10^{34}$		HL-LHC $L = 5 x 10^{34}$
CMS Phase I Upgr	$300 fb^{-1}$	CMS Phase II UPGRADE			$3000 fb^{-1}$
Belle II	$5 ab^{-1}$	$L = 6 x 10^{35}$	$50 ab^{-1}$		

- **Framework TDR**
  - Drafting in progress, delivery later this year





Conclusions

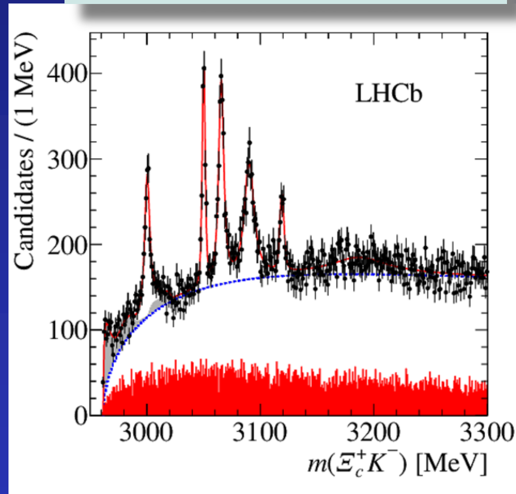
- LHCb is producing lots of exciting physics results
  - in many areas - rare decays, CP violation, charm, spectroscopy, electroweak, QCD, exclusive production, heavy ion, fixed target, > 30 papers in 2021
- Flavour anomalies
  - Cautious excitement
  - More results on lepton flavour universality, and under way
- Highlights of highlights this week
  - First observation of a doubly charmed same-sign tetraquark T_{cc}^{+}
  - Measurement of W mass
  - Indication of intrinsic charm in proton
- LHCb upgrade
  - Huge progress during last year despite difficult circumstances
  - RICH, CALO and Muon in commissioning
  - Planning for future upgrade in ~2030 is gaining momentum

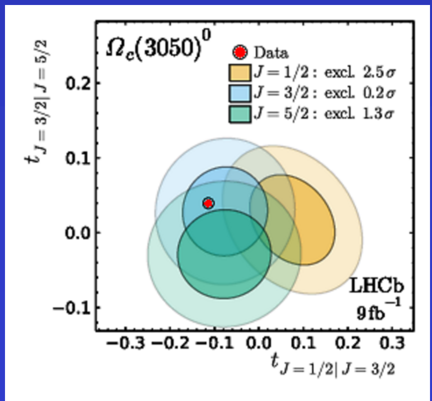
Backup

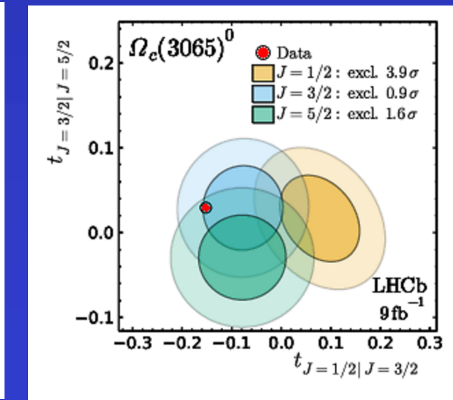
Excited Ω_c^0 baryons

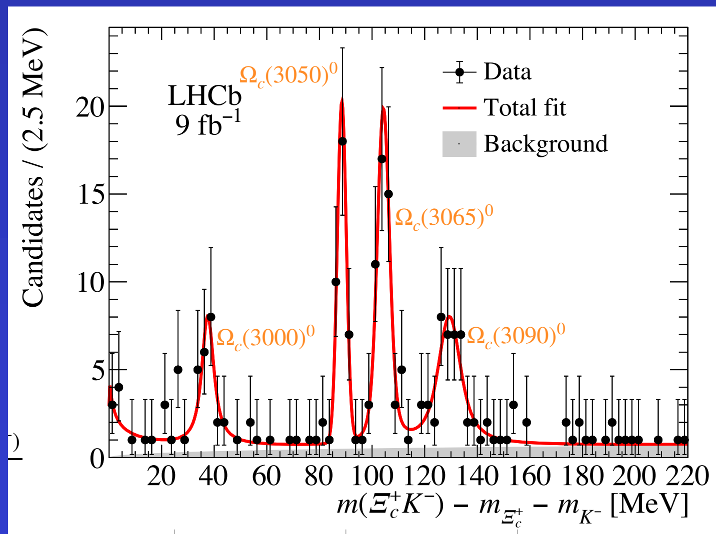
LHCb-PAPER-2021-012
arXiv:2107.03419

- **Discovery of 5 excited Ω_c^0 states**
  - In prompt $\Xi_c^+ K^-$ production
- **Observation in b-baryon production**
  - $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$
  - Observe 4 of 5 states
    and a structure at threshold
  - Measure quantum numbers
  - Spin ½ excluded at 2.5σ and 3.9σ
    for $\Omega_c^0(3050)$ and $\Omega_c^0(3065)$





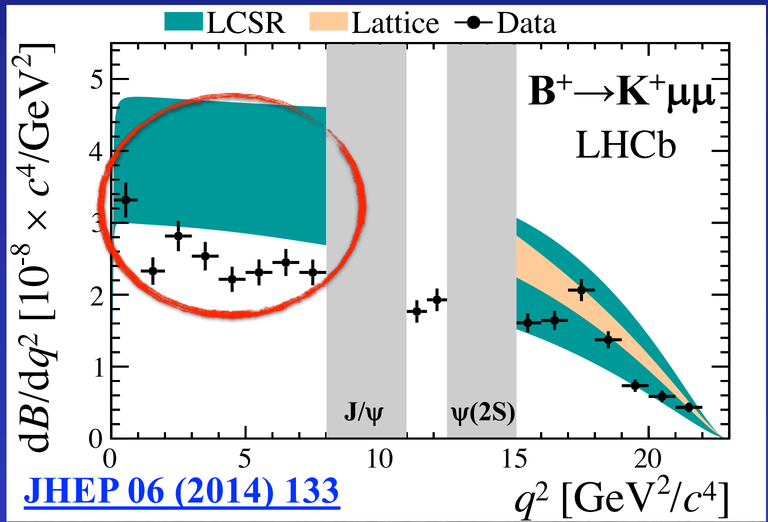


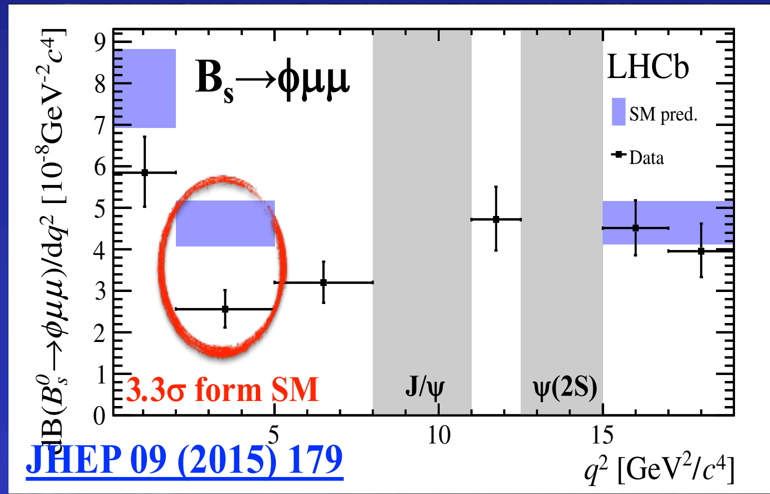


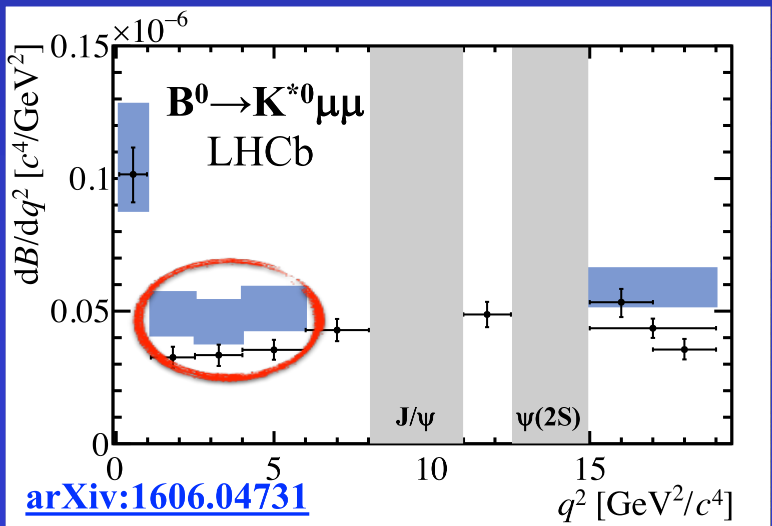
LHCb results in charm baryons
Ao Xu

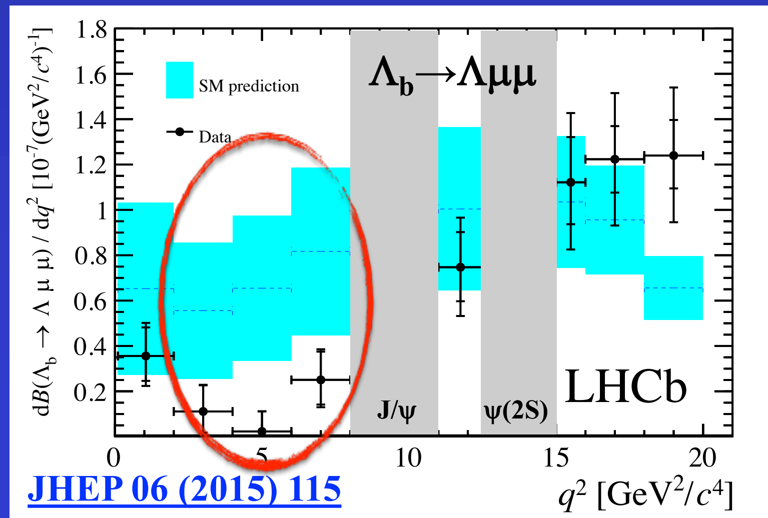
$B_{(s)}^{0(+)} \to K^{*0(+)}\mu^+\mu^-$ & $\Lambda_b \to \Lambda\mu^+\mu^-$

- **Branching fraction measurements**
  - consistently below Standard Model predictions





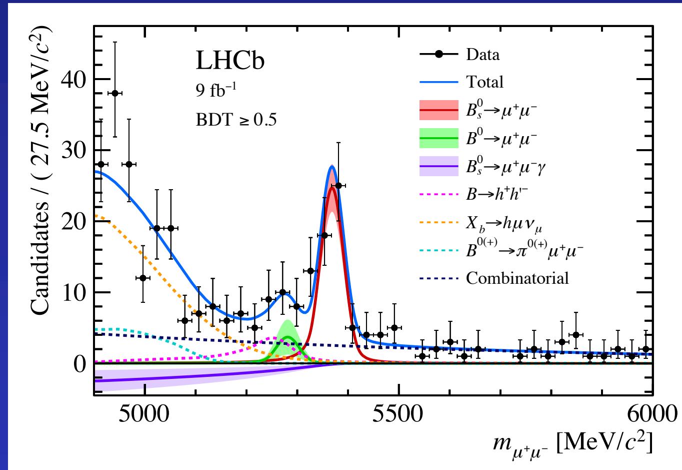


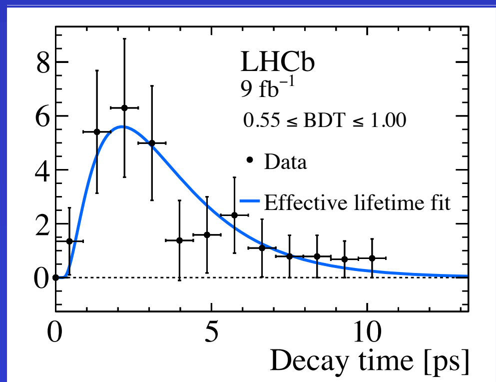


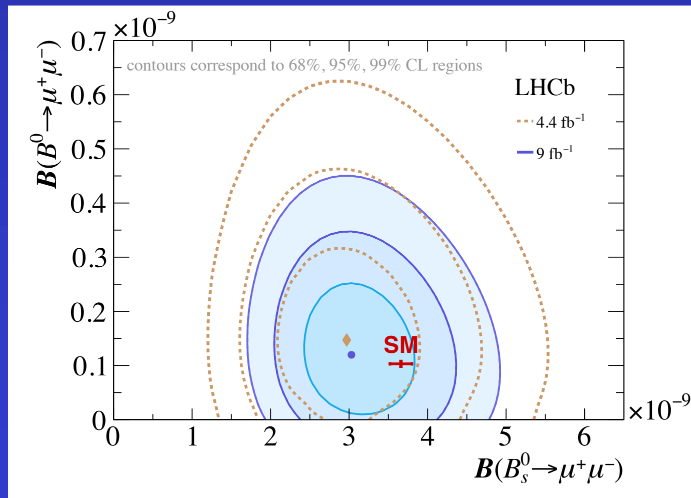
$B_{(s)}^0 \rightarrow \mu^+\mu^-(\gamma)$

LHCb-PAPER-2021-007
LHCb-PAPER-2021-008

- **Very rare leptonic decay**
  - Helicity and CKM suppressed
  - Sensitive to New Physics
- **$B_s^0 \rightarrow \mu^+\mu^-$**
  - $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 3.09^{+0.46}_{-0.43}\,^{+0.15}_{-0.11} \times 10^{-9}$
  - Significance > 10 σ, in agreement with SM
- **$B^0 \rightarrow \mu^+\mu^-$**
  - $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL
- **First search for $B_s^0 \rightarrow \mu^+\mu^-\gamma$**
  - $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$ at 95% CL for $m_{\mu\mu} > 4.9\ \mathrm{GeV}/c^2$
- **Effective lifetime**
  - $\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03$ ps







Very rare decays at LHCb
Miguel Ramos Pernas

The end