Highlights from the LHCb experiment

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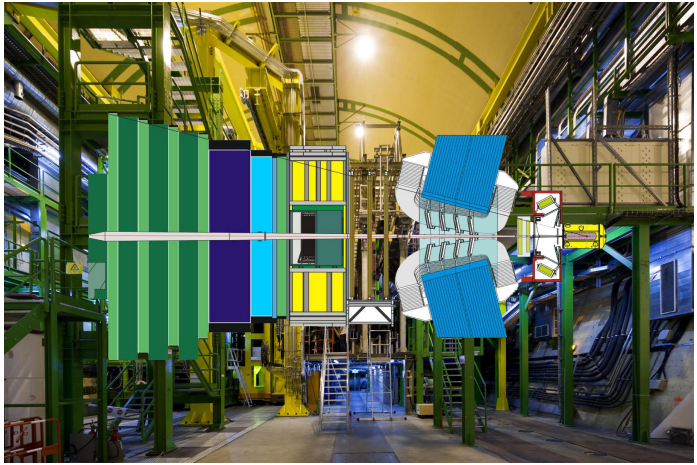
LHCb

The LHCb experiment

- forward-arm detector dedicated to the study of heavy-flavoured hadrons at the LHC
- great vertex and decay time resolution, PID

The LHCb detector in Run I+II



- forward-arm detector dedicated to the study of heavy-flavoured hadrons at the LHC
- great vertex and decay time resolution, PID

Today's highlights

LHCb is a multi-purpose experiment!

This talk:

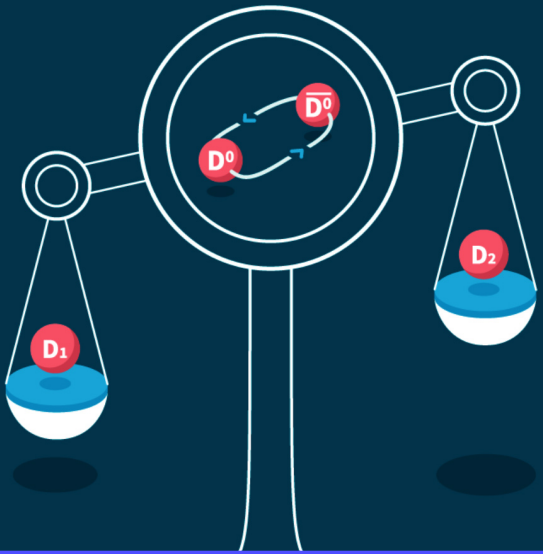
- selected physics results from past year
- a short intro to the LHCb upgrade

See these talks for more details:

- P. Gandini, *Spectroscopy at LHCb*, 19/08 16:00
- J. Cerasoli, *Rare decays at LHCb*, 22/08 18:15
- S. Ek-In, *Charm physics at LHCb*, 25/08 09:50

- Oscillations, CPV and charm
  - B_s^0 mass difference Δm_s
  - charm mixing and D^0 mass difference
  - CKM angle γ
  - Ω_c^0 lifetime
- Spectroscopy and exotic hadrons
  - evidence for $c\bar{c}uud$ pentaquark
  - first observation of doubly charmed T_{cc}^+ tetraquark
- W mass measurement
- Rare electroweak penguin decays
  - $B_{(s)}^0 \to \mu^+\mu^-(\gamma)$
  - $B_s^0 \to \phi\mu^+\mu^-$ branching fraction
  - $b \to s\ell\ell$ angular observables
  - LFU test with $B^+ \to K^+\ell^+\ell^-$
- LHCb upgrades

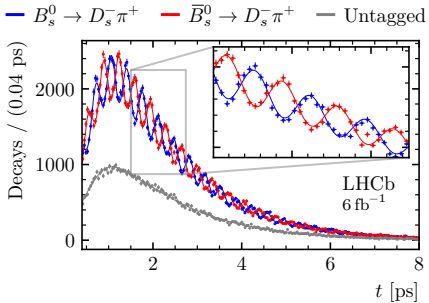
Oscillations, CPV and charm

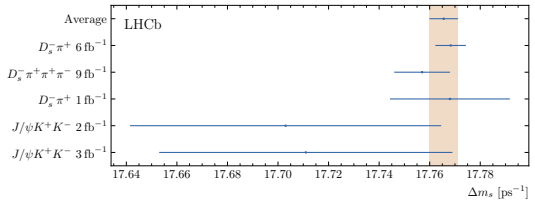


B_s^0 oscillations

[hep-ex:2104.04421] [JHEP 03 (2021) 137]

- Unique to LHCb; tag B_s^0 / $\bar{B}_s^0$ at production
- measure oscillation frequency with $B_s^0 \to D_s^{\mp}\pi^{\pm}$ decays collected in LHC Run 2
  $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \text{ps}^{-1}$
- combine with previous measurements such as $B_s^0 \to D_s^{\mp}h^{\pm}\pi^{\pm}\pi^{\mp}$ (full dataset)
  $\Delta m_s = 17.7656 \pm 0.0057\ \text{ps}^{-1}$

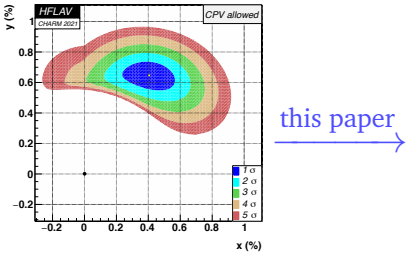




Charm mixing

[hep-ex:2106.03744]

- first observation of $\neq 0$ mass difference in D^0 system
  - $x \equiv (m_1 - m_2)/\Gamma, \qquad y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$
- 30.6M $D^0 \to K^0_S\pi^+\pi^-$ decays, very small BG
- **bin-flip** method: in each bin of $m^2(K^0_S\pi^-)$ vs $m^2(K^0_S\pi^+)$ Dalitz plot [Phys. Rev. D 99, 012007]
  - approx. constant strong phase difference
  - measure difference between D^0 and $\bar{D}^0$



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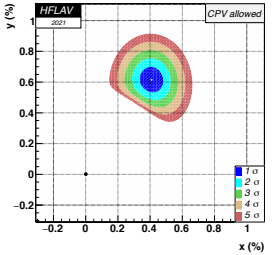
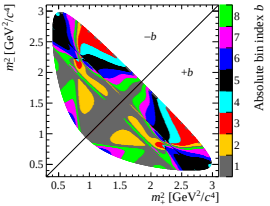
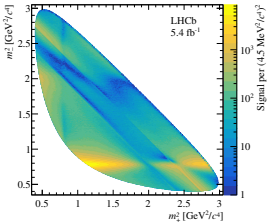






$$x = \left(3.98^{+0.56}_{-0.54}\right) \times 10^{-3}$$

$$y = \left(4.5^{+1.5}_{-1.4}\right) \times 10^{-3}$$

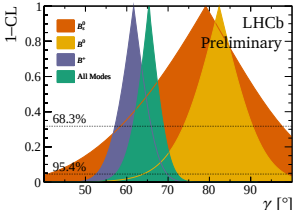
$$|q/p| = 0.996 \pm 0.052$$

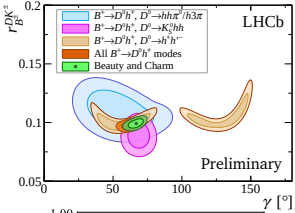
$$\phi = 0.056^{+0.047}_{-0.051}$$

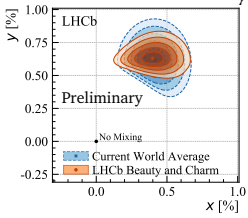
Charm mixing and CKM angle γ

[LHCb-CONF-2021-001]

- combination of measurements
  - sensitive to γ and charm mixing parameters
  - charm and beauty observables simultaneously
  - 151 observables, 52 free parameters
- most precise measurement by a single experiment
  $\gamma = \left(65.4^{+3.8}_{-4.2}\right)^\circ$
- excellent agreement with global CKM fit
  $\gamma = (65.8 \pm 2.2)^\circ$
- charm mixing parameters
  - $x = \left(0.0400^{+0.052}_{-0.053}\right)\,\%$
  - $y = \left(0.630^{+0.033}_{-0.030}\right)\,\%$
  - precision on y improved by ~ 2







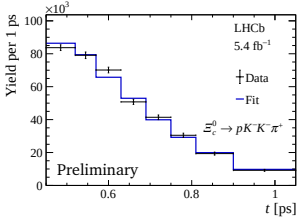
Ω_c^0 lifetime

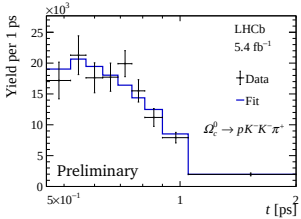
[LHCb-PAPER-2021-021] [PRL 121 (2018) 092003]

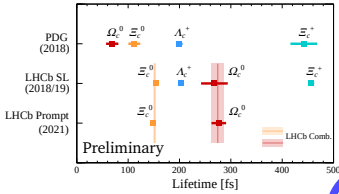
- charmed baryons: $\Lambda_c^+(udc)$, $\Xi_c^+(usc)$, $\Xi_c^0(dsc)$, $\Omega_c^0(ssc)$
- expected lifetime hierarchy:
  $\tau_{\Omega_c^0} < \tau_{\Xi_c^0} < \tau_{\Lambda_c^+} < \tau_{\Xi_c^+}$
- LHCb measured a longer Ω_c^0 lifetime in semileptonic b-baryon decays [PRL 121 (2018) 092003]
- new measurement using promptly-produced c-baryons decaying to $pK^-K^-\pi^+$:

$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs}$$
$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2 \text{ fs}$$

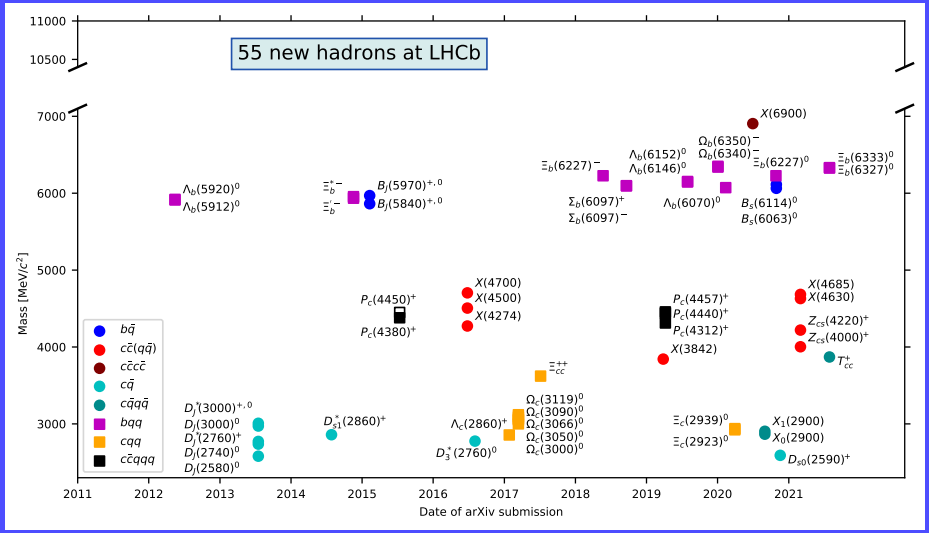
- previous results and new hierarchy confirmed:
  $\tau_{\Xi_c^0} < \tau_{\Lambda_c^+} < \tau_{\Omega_c^0} < \tau_{\Xi_c^+}$







Spectroscopy & exotic hadrons



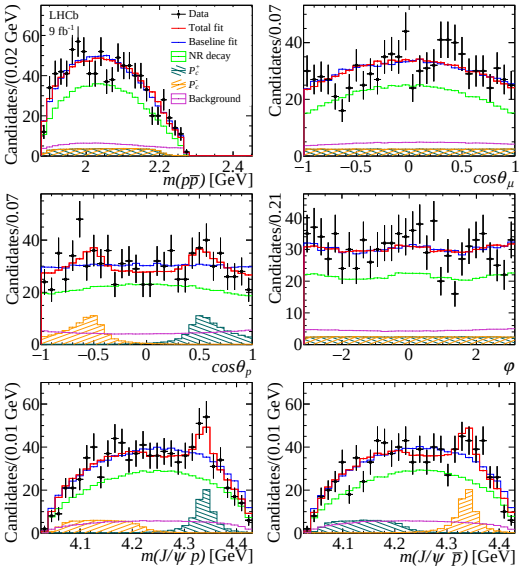
courtesy P. Koppenburg (nikhef.nl/~pkoppenb)

62 new hadrons observed at the LHC since 2012... **55 at LHCb!**

New structure in $J/\psi p$

[hep-ex/2108.04720]

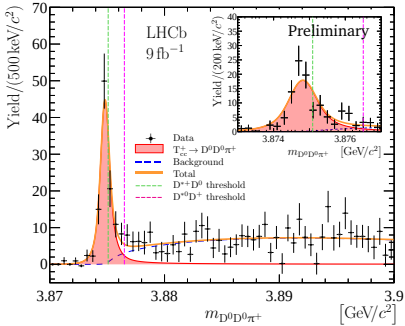
- amplitude analysis of $\sim$800 $B_s^0 \to J/\psi p\bar{p}$ decays
- new structure found in $J/\psi p$ and $J/\psi \bar{p}$ spectra
- consistent with $P_c^+ \equiv (c\bar{c}uud)$ pentaquark
  $m_{P_c^+} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})$ MeV
  $\Gamma_{P_c^+} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})$ MeV
- significance 3.1 to 3.7σ depending on J^P assignment



Observation of doubly-charmed tetraquark

[LHCb-PAPER-2021-031]

- while the b quark is heavy enough to sustain the existence of a $bb\bar{u}\bar{d}$ tetraquark decaying to two mesons, conclusions less clear for $bc\bar{u}\bar{d}$ and $cc\bar{u}\bar{d}$
- mass of Ξ_{cc}^{++} (ccu) implies that $cc\bar{u}\bar{d}$ should be close to D^0D^{*+} mass
- observed narrow state in $D^0D^0\pi^+$ spectrum near D^0D^{*+} threshold, compatible with $T_{cc}^+ \equiv cc\bar{u}\bar{d}$
  - very narrow width of $\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}$ keV
  - two heavy quarks of the same flavour $\longrightarrow$ manifestly exotic
  - clear resonant nature



- signal significance $> 20\sigma$
  - $\delta m_{BW} < 0$ significance of 4.3σ $\longleftarrow$ *i.e.* not a D^0D^{*+} molecule

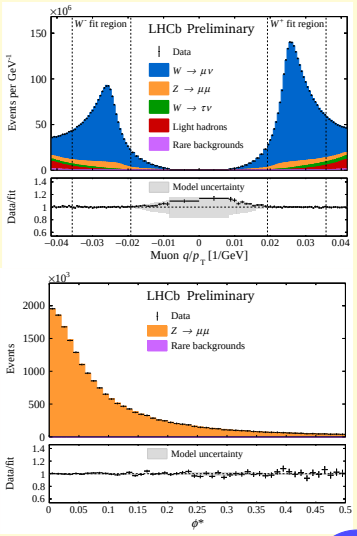
W mass measurement

[LHCb-PAPER-2021-024]

- fundamental parameter of the SM
  - limits sensitivity of global EW fits to new physics
  - measured at hadron colliders using m_T, E^T_{miss} and $p_T(\ell^\pm)$ in $W^\pm \to \ell^\pm \nu$ decays
  - average between ATLAS and LHCb measurements profits from reduced PDF uncertainty

- m_W at LHCb:
  - determined from fit to q/p_T and ϕ^*
  - control p_T^W by simultaneously fitting $Z \to \mu^+\mu^-$

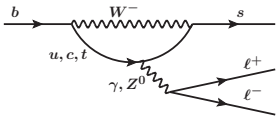
- using 2016 data sample:
  $m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV
  - $3\times$ more data already available

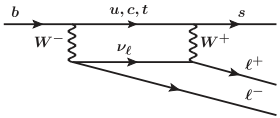


Rare decays

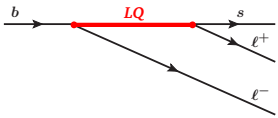
Electroweak penguins

- Flavour Changing Neutral Current are powerful probes of NP
- LHCb can probe branching fractions 10^{-6} down to 10^{-10}
- forbidden at tree level in SM $\Longrightarrow$ NP contribution can be sizeable





NP example



- $b \to s\ell^+\ell^-$ measurements present several anomalies
  - pointing to a breaking of lepton flavour universality
- 8 papers on $b \to s\ell^+\ell^-$ in the past year + 2 on photon polarization in $b \to s\gamma$

Updated $B^0_{(s)} \to \mu^+\mu^-$

- in the SM, $B^0_{(s)} \to \mu^+\mu^-$ decays are FCNC **and** helicity-suppressed
- single Wilson coefficient (axial current) and single hadronic constant known to $\pm 0.5\%$ [PRD 98 (2019) 074512]
- suppress combinatorial with BDT calibrated on data-corrected simulation
- control uncertainties by normalising to $B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-)$ and $B^0 \to K^+\pi^-$

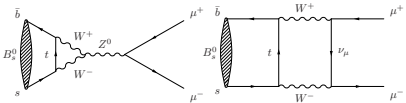
$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) = 3.09^{+0.46}_{-0.43}(\text{stat})^{+0.15}_{-0.11}(\text{syst}) \times 10^{-9}$$

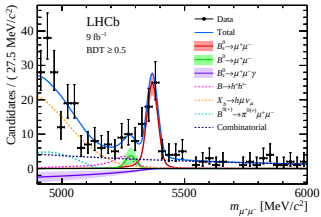
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\right) < 2.6 \times 10^{-10}\,(95\%\text{CL})$$

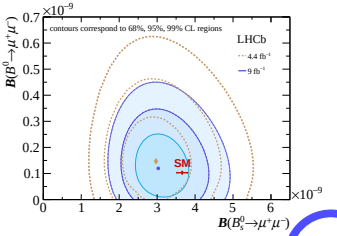
$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\gamma\right) < 2 \times 10^{-9}\,(95\%\text{CL})$$

on arXiv tomorrow!

[LHCb-PAPER-2021-007] [LHCb-PAPER-2021-008]



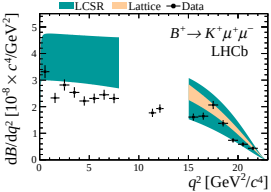




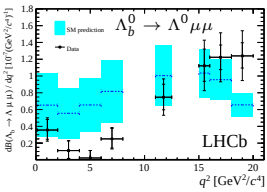
$b \to s\ell^+\ell^-$ branching fractions

[hep-ex/2105.14007]

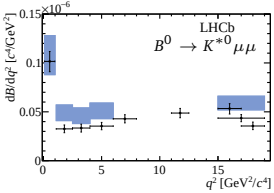
- differential branching fraction excluding $c\bar{c}$ resonances
- deficit of decays to muons found in $B^{0,+} \to K^{0,+}\mu^+\mu^-$, $B^{0,+} \to K^{*0,+}\mu^+\mu^-$, $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$
- R_K result suggests decays to electrons are SM-like
- new analysis of $B_s^0 \to \phi\mu^+\mu^-$ in agreement with Run 1, and 3.6σ tension with the SM



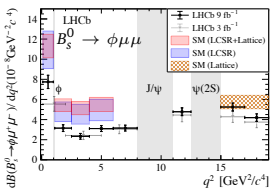
[JHEP 06 (2014) 133]



[JHEP 06 (2015) 115]



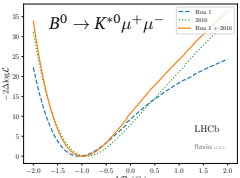
[JHEP 04 (2017) 142]

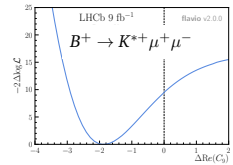


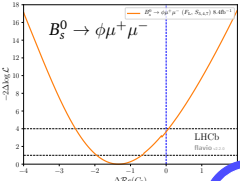
$b \to s\ell^+\ell^-$ angular observables

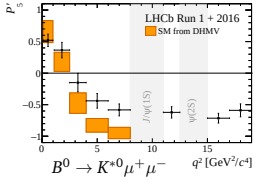
[PRL 125 (2020) 011802] [PRL 126 (2021) 161802] [hep-ex/2107.13428]

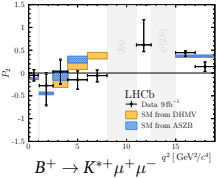
- angular observables profit from cancellation of most form factors
- sensitive to Wilson coefficients, which can be modified by NP
- $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]
  - local tension in P_5' confirmed by 2016 data
  - global tension of 3.3σ with SM
- $B^+ \to K^{*+}\mu^+\mu^-$: global 3.1σ tension with SM [PRL 126 (2021) 161802]
- $B_s^0 \to \phi\mu^+\mu^-$ consistent with SM at 1.9σ [hep-ex/2107.13428]
- coherent trends pointing at $\mathrm{Re}(\Delta\mathcal{C}_9) \simeq -1$

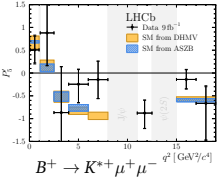












Lepton flavour universality

[hep-ex/2103.11769]

- compare amount of times $\mu^+\mu^-$ pair is emitted w.r.t. e^+e^-
- very clean theoretical prediction:

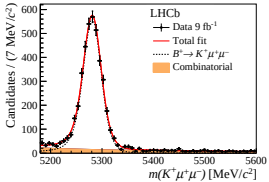
$$R_K^{\text{SM}} = \left.\frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}\right|_{[q^2_{\text{min}}, q^2_{\text{max}}]} = \mathbf{1} \pm \mathcal{O}(10^{-2})_{(\text{QED})} \pm \mathcal{O}(10^{-4})_{(\text{QCD})}$$

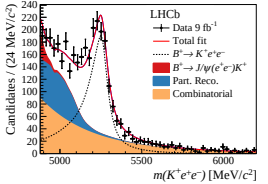
[JHEP 12 (2007) 040]
[EPJC 76 (2016) 440]

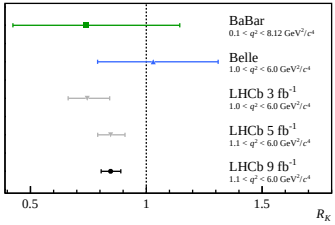
- double ratio normalized to J/ψ modes reduces systematics
- full LHCb dataset: 3.1σ evidence for LFU violation

$$R_K = 0.846\,^{+0.044}_{-0.041}$$

- measurements using other channels coming soon

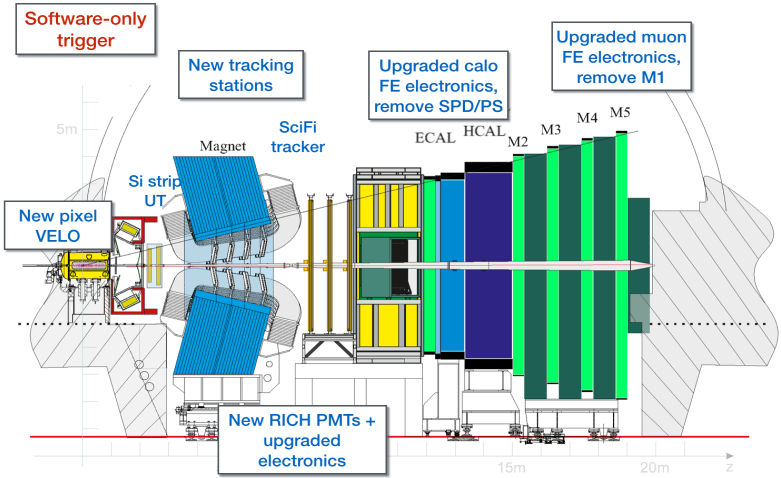




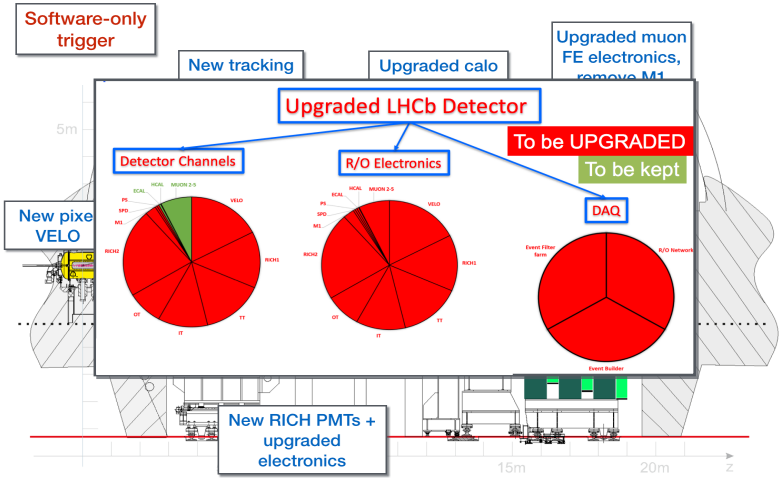


The near and the far future

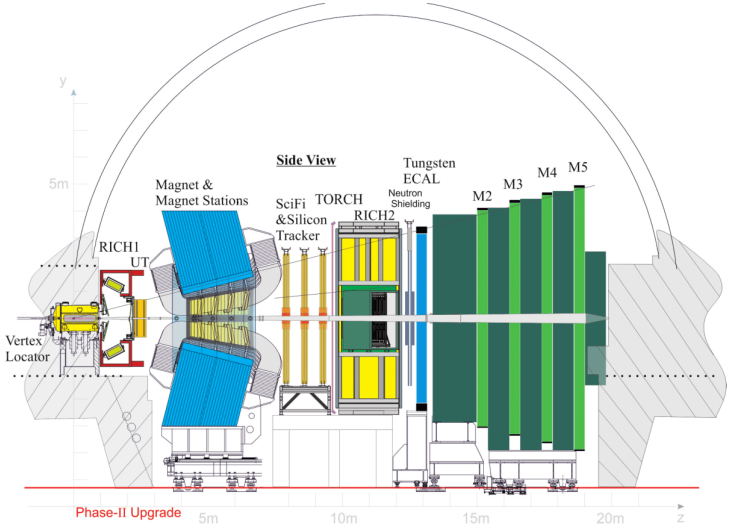
LHCb upgrade 1 (LS2, 2019)



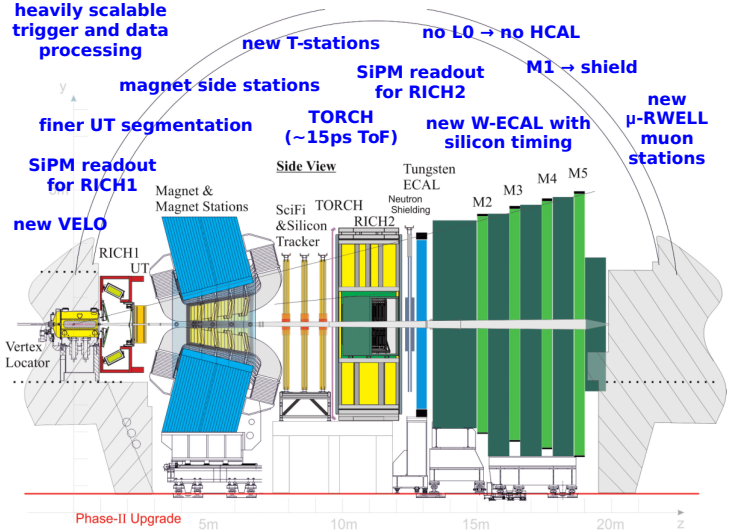
LHCb upgrade 1 (LS2, 2019)



LHCb upgrade 2 (LS4, 2030)



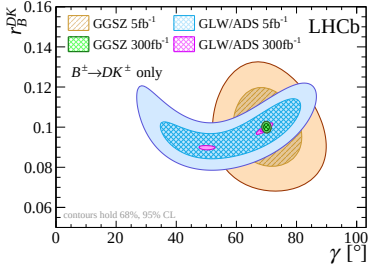
LHCb upgrade 2 (LS4, 2030)

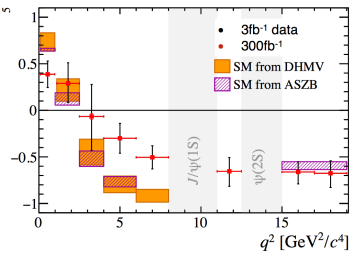


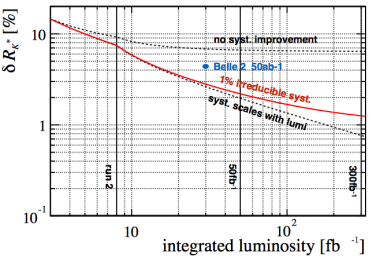
Physics potential of LHCb upgrades

[CERN-LHCC-2018-027] [CERN-LHCC-2017-003]

- many systematic uncertainties scale with $\sqrt{n}$
  - e.g. data-driven background templates
- reach $\sim$ 1-2% precision on R ratios
- access $\Delta S = S(\mu\mu) - S(ee)$ angular observables







Conclusions

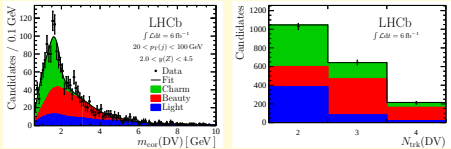
- LHCb originally designed for CPV and rare decays
  - achieved much more! Multi-purpose experiment
- Recent results include: mass difference in charm, confirmed anomalies in $b \to s\ell\ell$
  - more studies underway on other decay modes
- LHCb undergoing major upgrade right now
  - schedule suffered from pandemic, but proceeding steadily
  - detector installation & commissioning ongoing
  - real time software-based trigger will give much more flexibility
- Upgrade 2 (2030) framework TDR in drafting phase
  - potential to discover cracks in the SM and/or pave the way for NP searches!

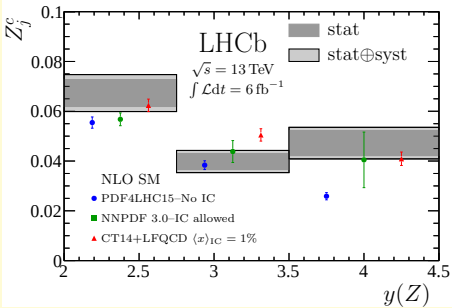
Spare slides

Intrinsic charm in proton

[LHCb-PAPER-2021-029]

- fraction of Z+jet events with charm jet
- measured for the first time in forward region
- sensitive to intrinsic charm component $|uudc\bar{c}\rangle$
- method:
  - c-tagging looks for displaced vertex with ≤ 4 tracks in jet cone
  - $m_{\text{cor}} \equiv \sqrt{m^2 + (p \sin\theta)^2} + p \sin\theta$ to separate from b vertices
- result:
  - sizeable enhancement of c-jets at high η_Z
  - consistent with 1% intrinsic charm in proton





Physics with heavy ion collisions

- QGP $\longrightarrow$ suppression of $Q\bar{Q}$ production in heavy ion collisions
  - excess can be due to photoproduction
  - 2018 data at $\sqrt{s_{NN}} = 5.02$ TeV significantly improves previous measurements [hep-ex/2108.02681]
- coherent J/ψ production studied in ultra-peripheral PbPb collisions from 2015
  - $\sigma = 4.45 \pm 0.24 \pm 0.18 \pm 0.58$ mb [hep-ex/2107.03223]
- charged particle production at $\sqrt{s} = 5$ TeV
  - compare pPb and pp collisions as a function of pseudorapidity and p_T [LHCb-PAPER-2021-015]
  - nuclear modification factor measurement constrains PDFs in previously unexplored regions