Istituto Nazionale di Fisica Nucleare
SEZIONE DI CAGLIARI

Overview of the LHCb experiment

Andrea Contu on behalf of the **LHCb Collaboration**

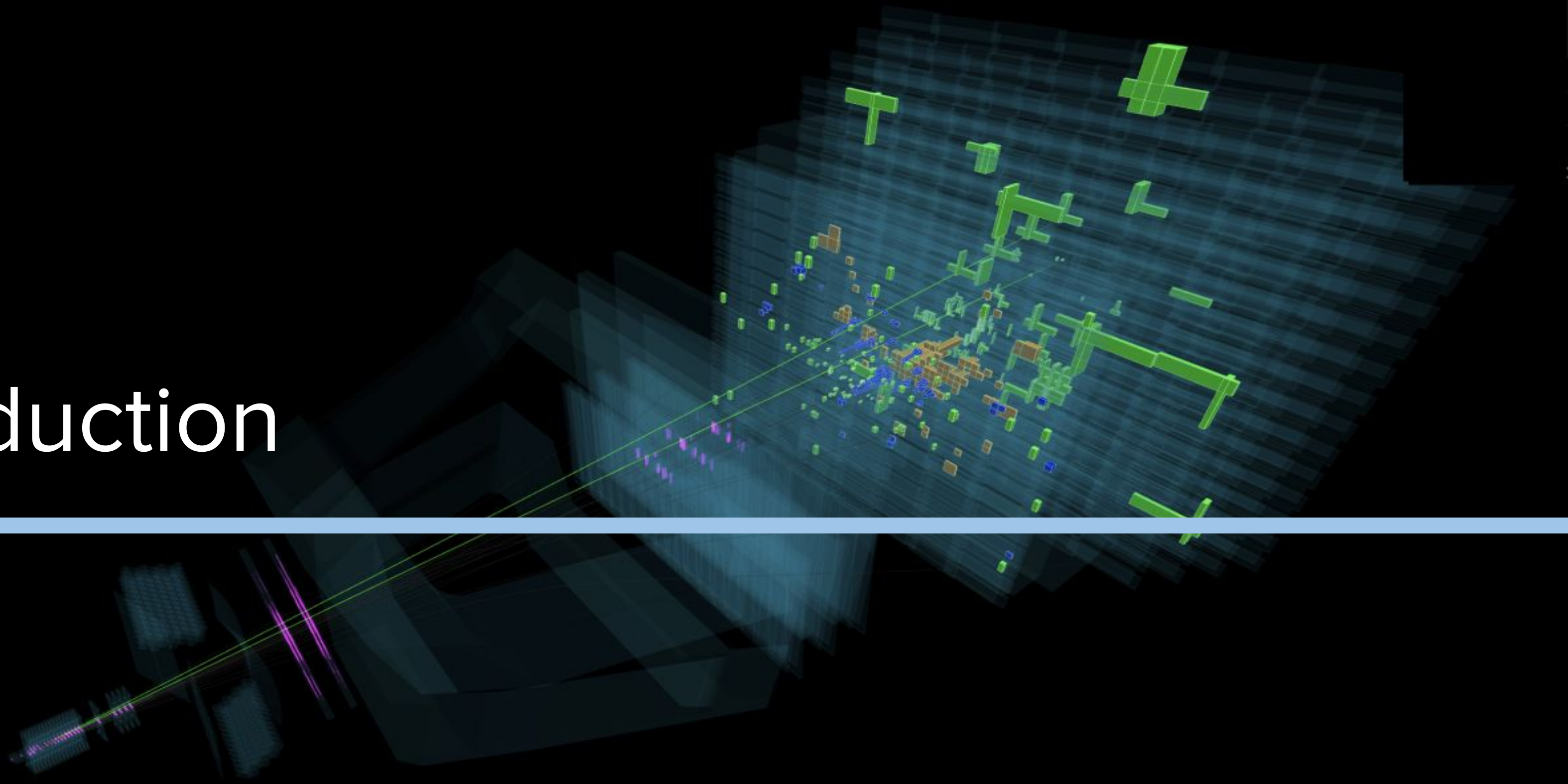
8th International conference on High Energy Physics in the LHC Era

9-13 January 2023

Outline

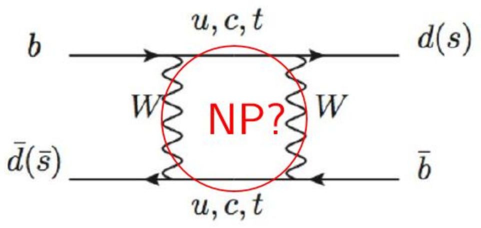
- Introduction to LHCb detector and physics
- Selected recent measurements
  - LFU in $b \rightarrow sl^+l^-$ (for LFU in $b \rightarrow cl\nu$ see Iaroslava Bezshyiko's talk)
  - CKM structure and CPV in beauty and Charm
  - W mass measurement
  - Antiproton production in p-He collisions
  - Spectroscopy
- A look into the future: the upcoming LHCb upgrade and Upgrade II

Introduction

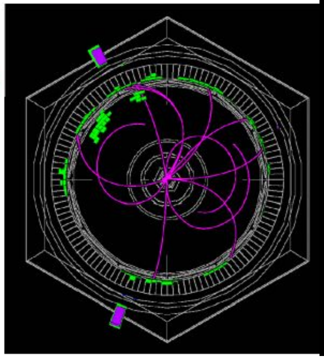


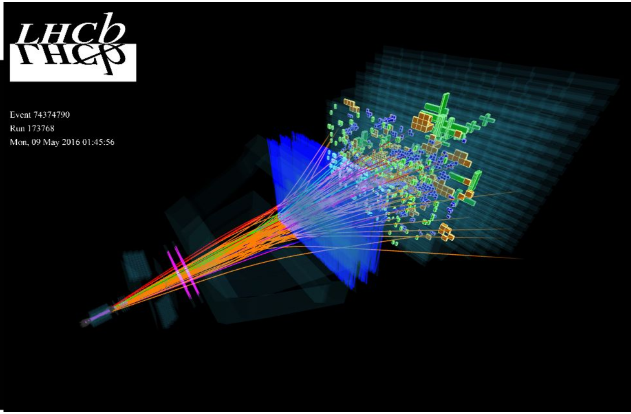
Why study flavour physics (at hadronic machines)?

It may answer fundamental questions



- **Why are there 3 fermion generations? Only 3?**
- **Hierarchy in Yukawa couplings?**
- **CPV in quark sector is too small to explain the matter-antimatter asymmetry in the universe. Are there other sources of CPV?**
- **Flavour physics provides a unique window into new physics through indirect searches (potentially sensitive to higher energy scales than direct searches)**



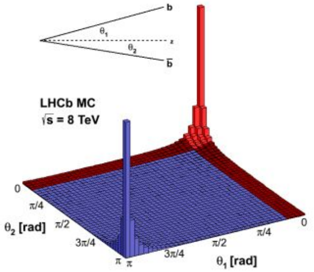


The LHCb Collaboration

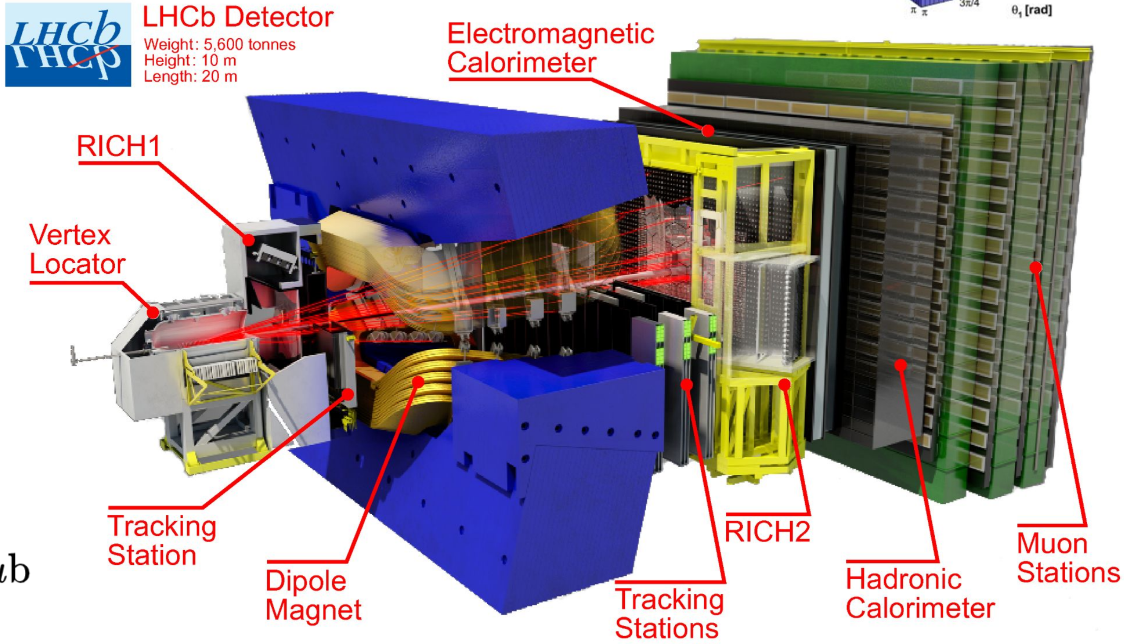
- About 1400 scientists, engineers and technicians
- 86 different universities and laboratories from 18 countries

The LHCb detector in Run 1 and Run 2 (2011-2018)

- Excellent particle identification, IP and momentum resolution (~13 µm on the transverse plane and Δp/p ~ 0.5% – 0.8%, respectively.)
- Huge beauty and charm production



JINST 3 S08005 (2008)
IJMP A 30, No. 07, 1530022 (2015)



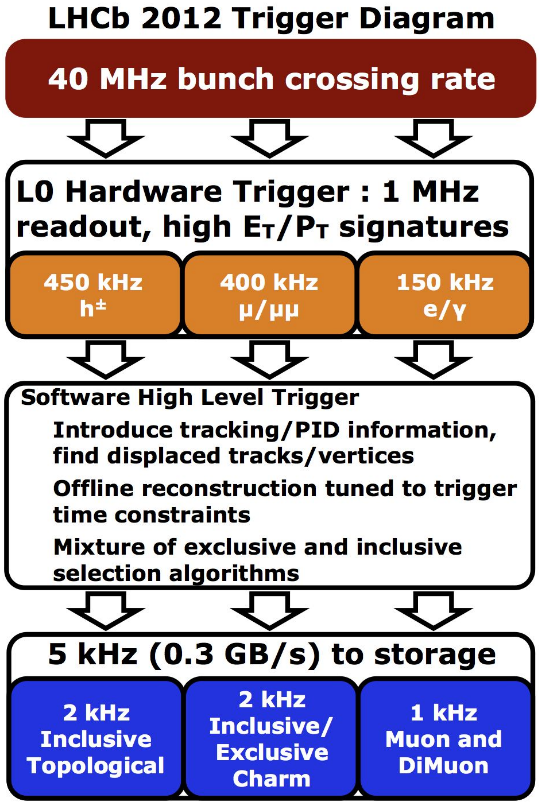
$$\sigma(pp \to b\bar{b}X)_{2<\eta<5} = 144 \pm 1 \pm 21\mu\text{b}$$

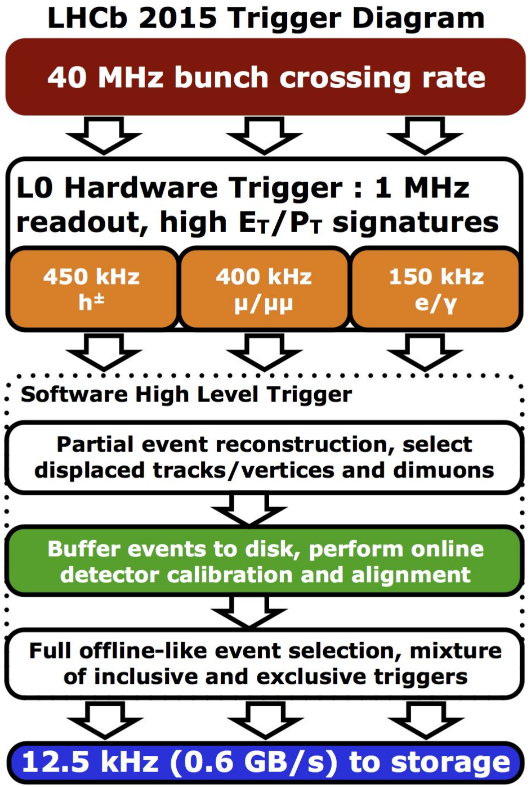
[PRL 119, 169901 (2017)]

$$\sigma(pp \to c\bar{c}X)_{p_T < 8\ \text{GeV/c},\ 2.0<y<4.5} = 2369 \pm 3 \pm 152 \pm 118\ \mu\text{b}.$$

[JHEP 05 (2017) 074]

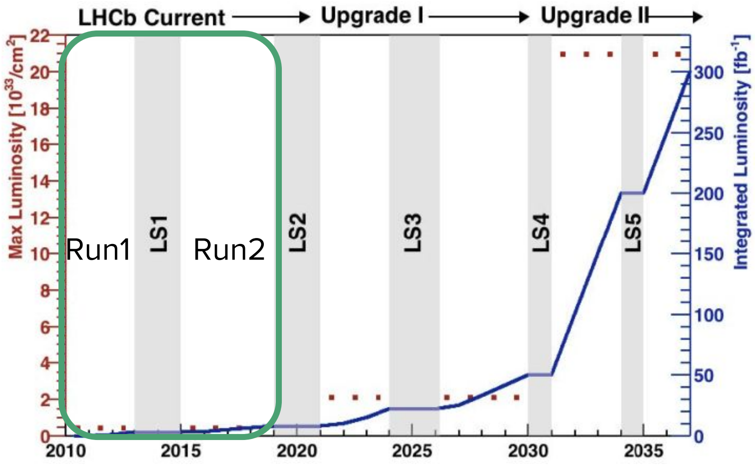
LHCb Trigger System

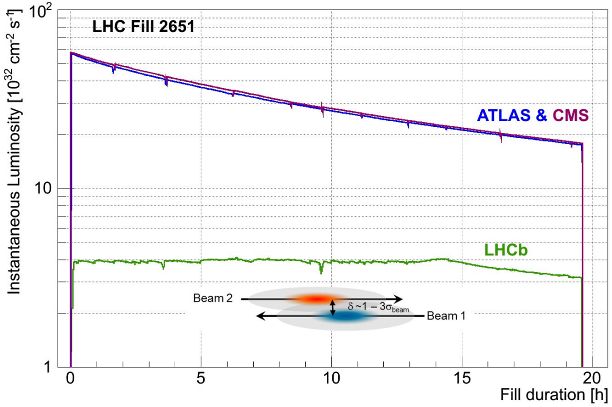


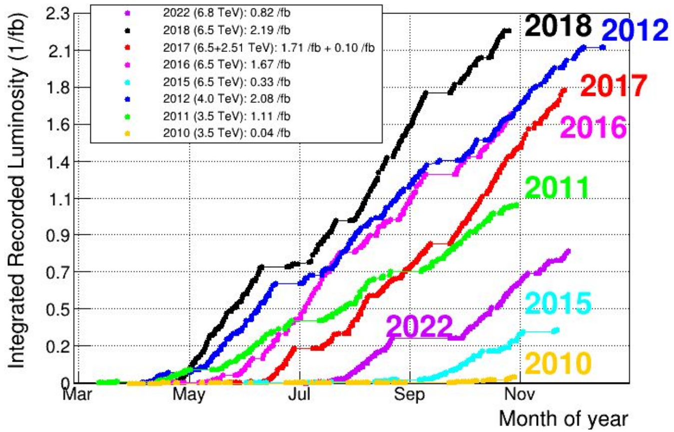


Run1 and Run2 data takings

- Running with luminosity levelling at $\mathcal{L} = 4 \times 10^{32} \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$, **2x design luminosity!**
- Roughly 1.5 interactions per bunch crossing
- Total of 9 fb^{-1} collected

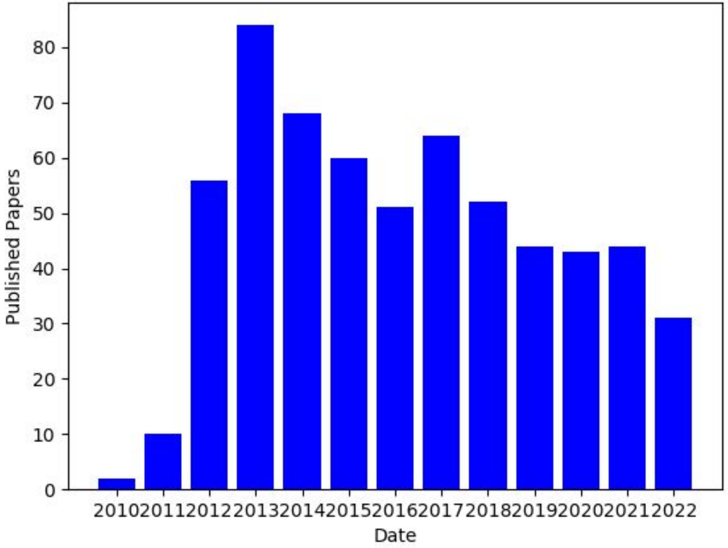






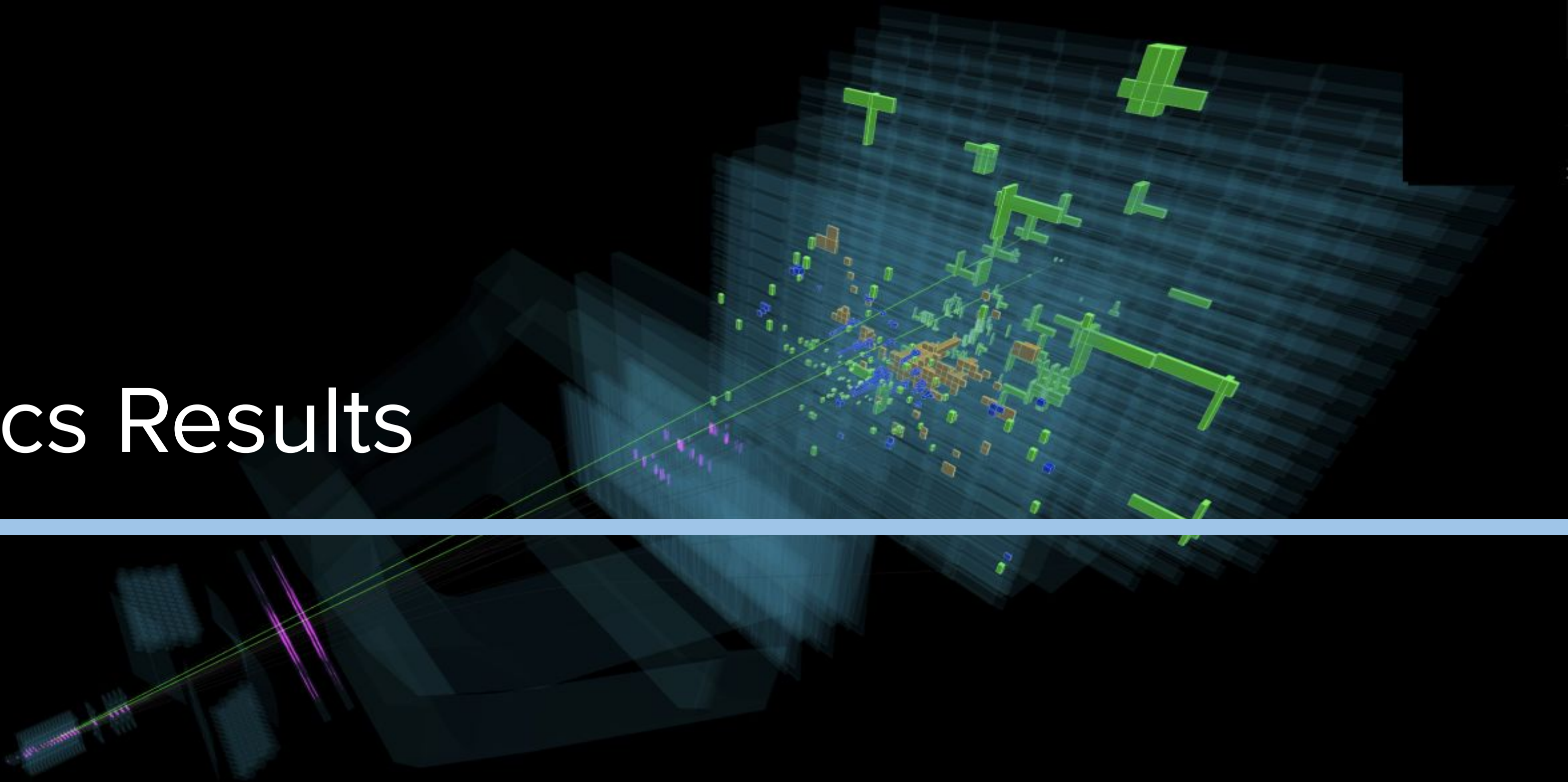
Not just a flavour physics experiment

More than 600 papers!

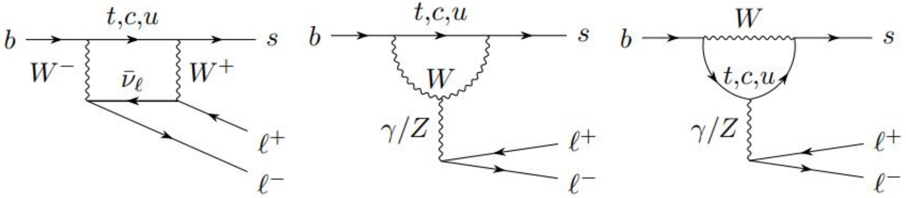


- Mixing and CP violation in B decays
- Rare B/D/K decays
- Charm decays
- Semileptonic B decays
- Spectroscopy and exotic hadrons
- Hadron production
- Heavy ion physics, fixed target with SMOG
- Electroweak physics, QCD
- Exotics (dark matter, long-lived particles)

Physics Results

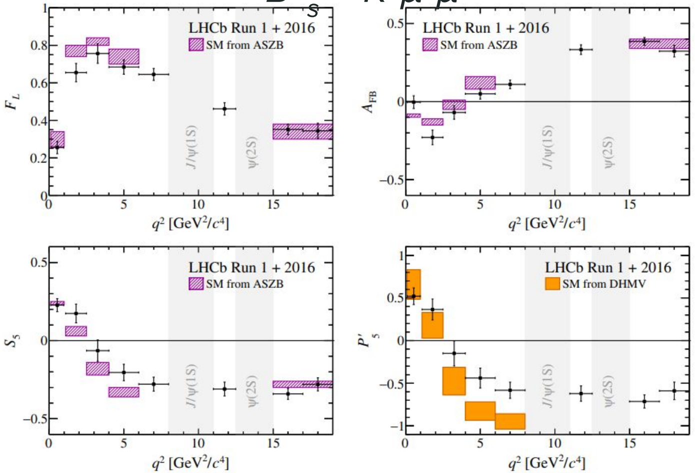


Probing NP with $b \rightarrow sl^+l^-$

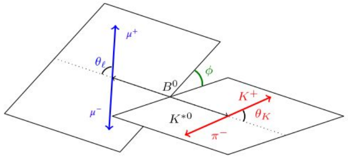


- Suppressed at tree level, potentially sensitive to NP at the TeV scale
- Dimuonic channels show discrepancies with SM at roughly 3 sigmas in differential decay rates and angular analyses

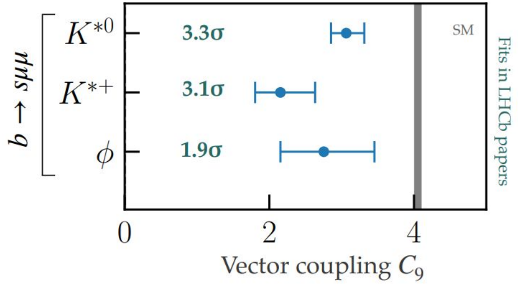
$B^0_s \rightarrow K^*\mu^+\mu^-$



PRL 125, 011802 (2020)



From R. Quagliani CERN Seminar



PRL 126, 161802 (2021) JHEP11(2021)043

However charm loops may mimic discrepancies in C_9 in angular analysis

LFU tests are theoretically a cleaner probe

LHCb LFU tests (superseded)

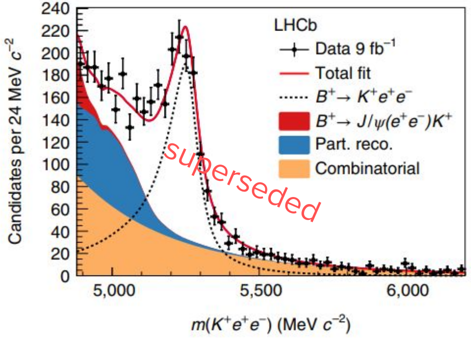
Nature Physics 18, 277–282 (2022)

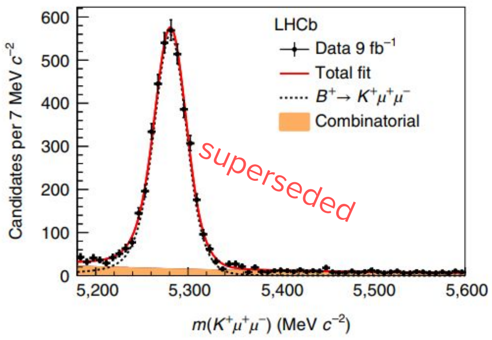
- Can NP be generation dependent?
- Measure differential branching fraction vs dilepton invariant mass

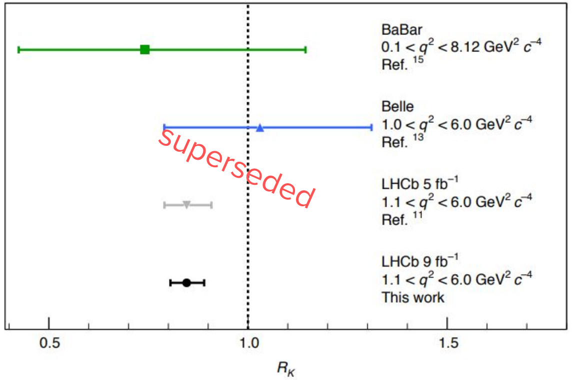
$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}\ (B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}\ (B\to He^+e^-)}{dq^2} dq^2}$$

- Experimentally accessible through a double-ratio measurement

$$R_K = \frac{\mathcal{B}\ (B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}\ (B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}\ (B^+ \to K^+e^+e^-)}{\mathcal{B}\ (B^+ \to J/\psi(\to e^+e^-)K^+)}$$







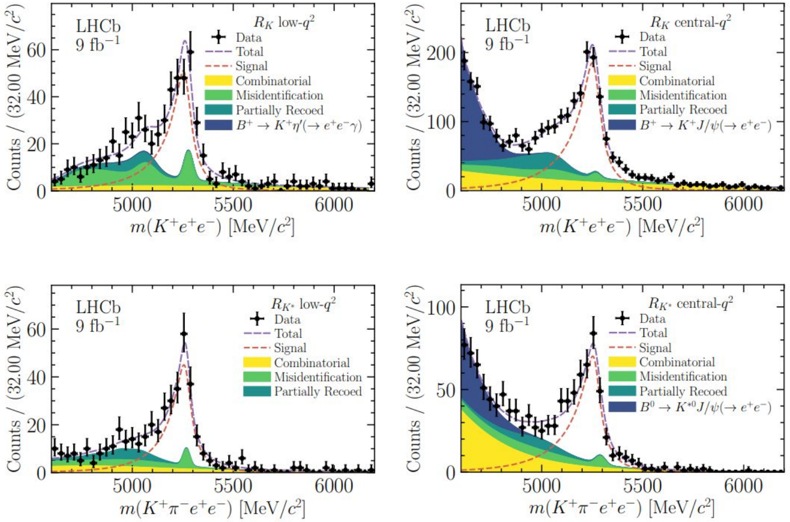
Tension with the SM at 3.1σ

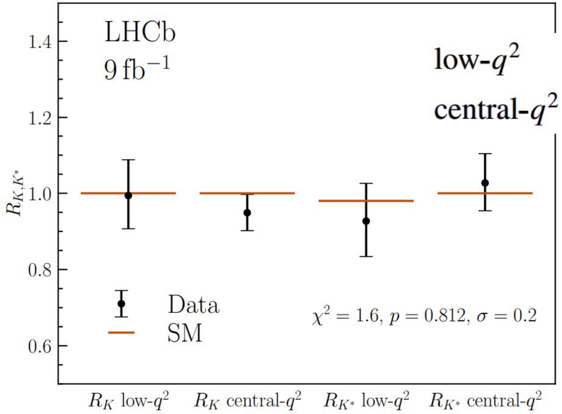
arxiv:2212.09153

arxiv:2212.09152

Improved lepton universality measurement

- Simultaneous analysis of R_K and R_{K^*}
- Most precise and accurate LFU test in $b \to sll$ transitions
- **New data driven treatment of misidentified background**





low-q^2 : $q^2 \in [0.1, 1.1]\,\mathrm{GeV}^2/c^4$

central-q^2 : $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$

- Dominant systematic from misidentified backgrounds estimation from data driven method
- Measurement still statistically dominated

Details at R. Quagliani CERN Seminar

The CKM matrix

- Describes the transition between quark flavours via weak interaction

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

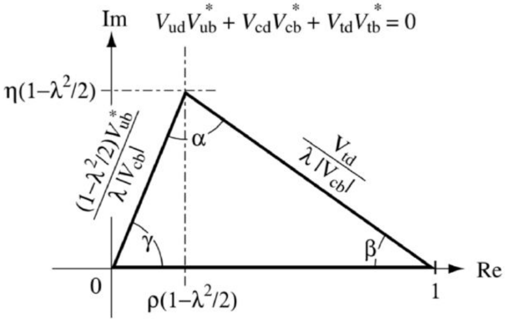
$$= \underbrace{\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5\left[1-2(\rho+i\eta)\right]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3\left[1-(\rho+i\eta)(1-\lambda^2/2)\right] & -A\lambda^2 + A\lambda^4\left[1-2(\rho+i\eta)\right]/2 & 1-A^2\lambda^4/2 \end{pmatrix}}_{\text{Wolfenstein parametrisation}} + \mathcal{O}(\lambda^6)$$

$$\lambda = \sin(\theta_c) \approx 0.22, \quad \eta \approx 0.3$$

- Unitarity conditions ➔ unitarity triangles

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



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$$\lambda = \sin(\theta_c) \approx 0.22, \quad \eta \approx 0.3$$

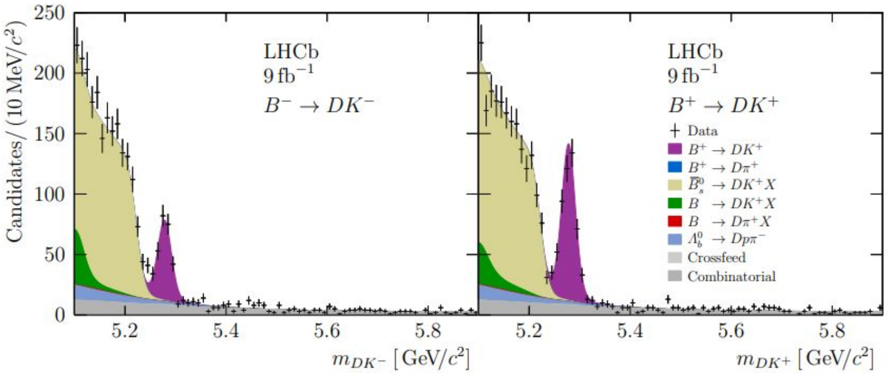
- 3 quark generations allow for CPV through the phase η
- **Due to the CKM structure the B system is favourable for CPV studies, on the contrary, CPV in the Charm sector is predicted to be small since amplitudes are dominated by the first two generations**

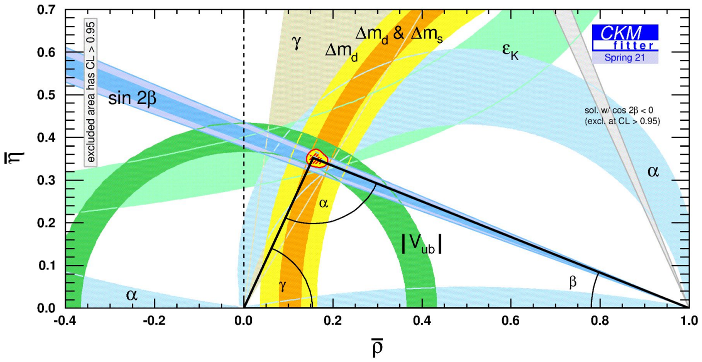
arxiv:2209.03692

CKM γ angle from $B^{\pm} \to D(\to K\pi\pi\pi)K^{\pm}$

- Precision measurements of the consistency of the unitarity triangles are a powerful tests of the SM.
- Recent LHCb measurement with the full dataset

$$\frac{\Gamma\left(B^{\pm}\to D\left[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}\right]K^{\pm}\right)}{\Gamma\left(B^{\pm}\to D\left[K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{\pm}\right]K^{\pm}\right)}=\frac{r_{K3\pi}^2+(r_B^K)^2+2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K+\delta_{K3\pi}\pm\gamma)}{1+(r_{K3\pi}^2 r_B^K)^2+2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K-\delta_{K3\pi}\pm\gamma)}$$





$$\gamma = (54.8^{+6.0}_{-5.8}(\text{stat.})^{+0.6}_{-0.6}(\text{syst.})^{+6.7}_{-4.3}(\text{ext.}))^{\circ}$$

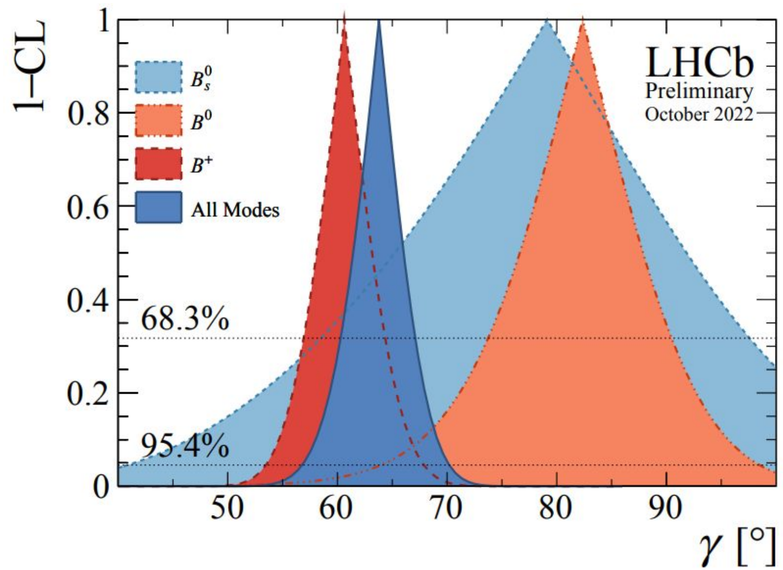
Second most precise single-channel determination!

LHCb-CONF-2022-003

γ combination

A combination of all LHCb γ determinations
(+ charm mixing and asymmetries)

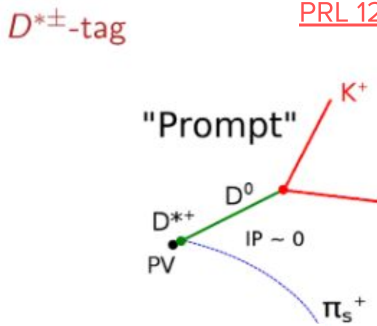
B decay	D decay	Ref.	Dataset
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]	Run 1&2
D decay	Observable(s)	Ref.	Dataset



$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

In agreement with previous and global determinations, statistically limited

Observation of CPV in charm with ΔA_{CP}



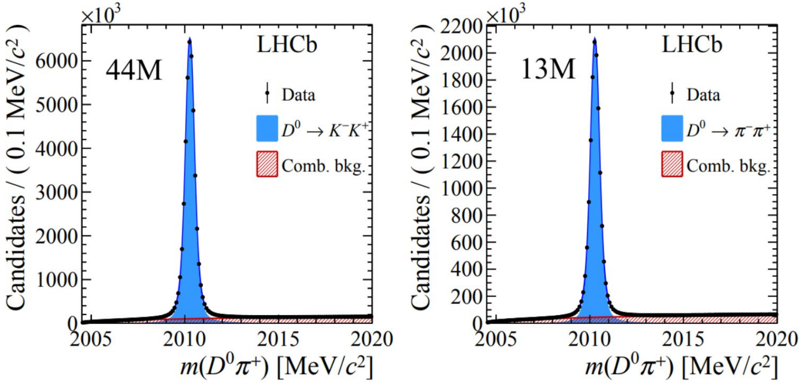
- CPV in charm predicted small in SM $O(10^{-4})$
- Full Run 1 + Run 2 dataset , D* and semileptonic tag
- Observable is mainly sensitive to direct CPV

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

assuming universal a_{cp}^{ind}

$$\simeq \Delta a_{CP}^{dir} + \frac{\Delta\langle t\rangle}{\tau_{D^0}} a_{CP}^{ind} \qquad \Delta\langle t\rangle = \langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}$$

- Experimentally robust as production and detection asymmetries cancel to first order
- Additional measurements are needed to have a better understanding!



$\Delta a_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

CP violation observed at 5.3σ!

arxiv:2209.03179

Time-integrated *CP* asymmetry in $D^0 \rightarrow K^- K^+$ decays

- Measuring time integrated asymmetries of single channels is **much harder**

$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})} = \frac{1 - |\overline{A}_{\overline{f}}/A_f|^2}{1 + |\overline{A}_{\overline{f}}/A_f|^2}$$

- However the observable is the yield asymmetry, which must be corrected for to extract the physical asymmetry

$$A_{raw} = \frac{N(D\to f) - N(\bar{D}\to \bar{f})}{N(D\to f) + N(\bar{D}\to \bar{f})} = A_{CP} + A_P + A_D$$

A_P is the production asymmetry in pp collisions

A_D is the detection asymmetry due to the detector

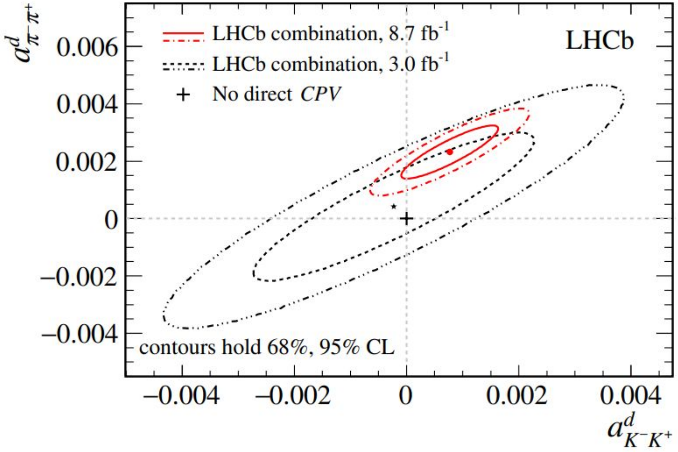
- A_P and A_D have to be determined and corrected for using calibration samples

arxiv:2209.03179

Time-integrated *CP* asymmetry in $D^0 \to K^- K^+$ decays

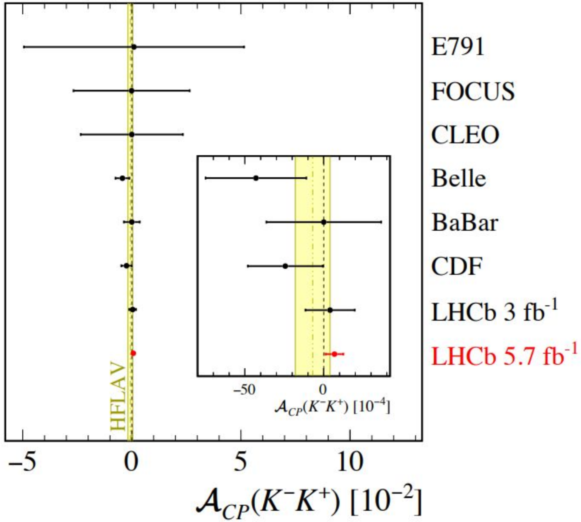
- Measurement from LHCb using the full Run 2 dataset

$$\mathcal{A}_{CP}(K^- K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}.$$



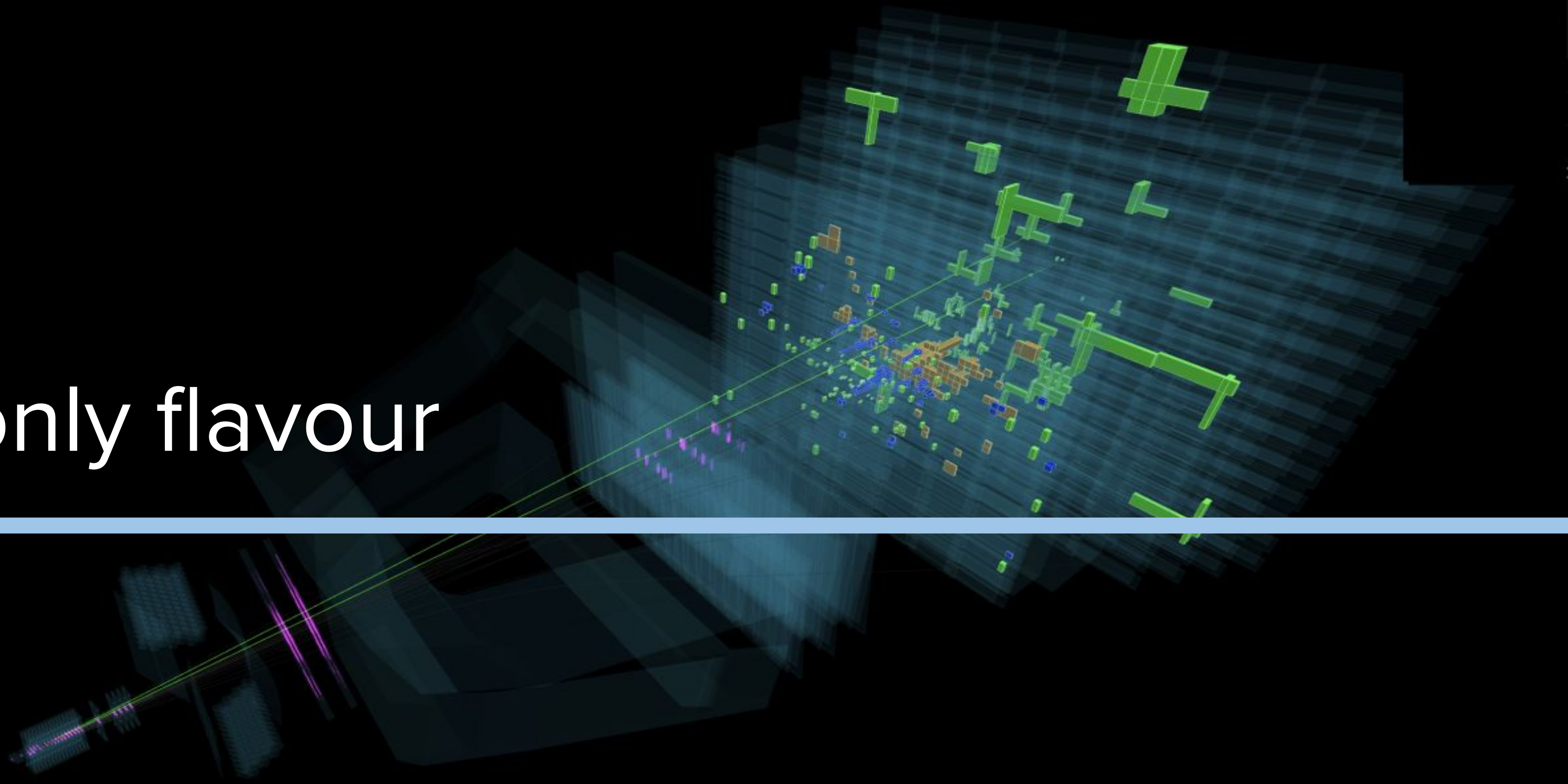
In combination with ΔA_{CP}

$$a^d_{K^-K^+} = (\;7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$



Measurements statistically limited, exciting times for Charm CPV with ongoing and future upgrades

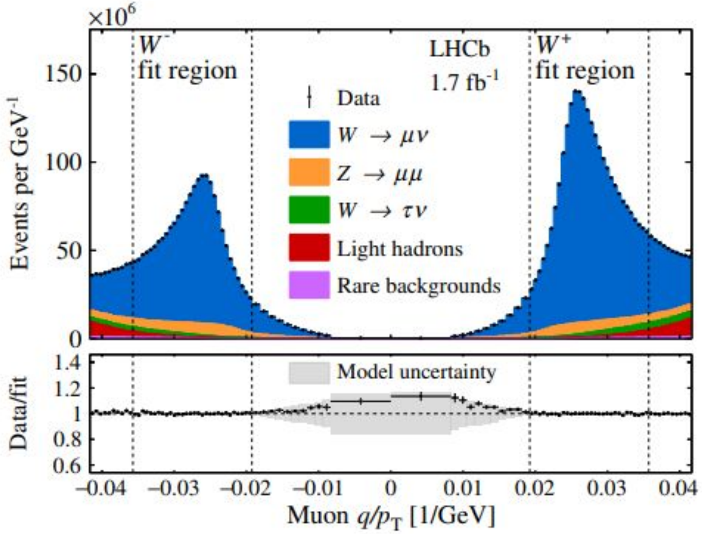
Not only flavour

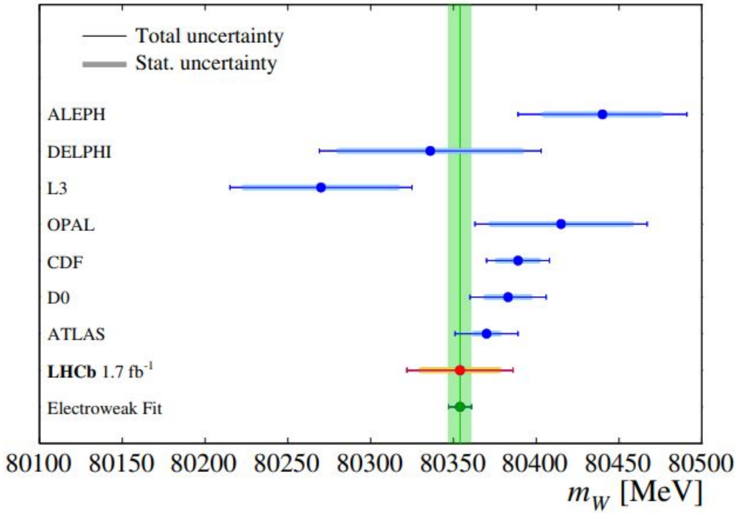


JHEP 01 (2022) 036

W boson mass measurement

- First LHCb measurement of W mass, 1.7 fb^{-1} of 13 TeV data
- **Anti-correlation in PDF uncertainties wrt ATLAS and CMS**





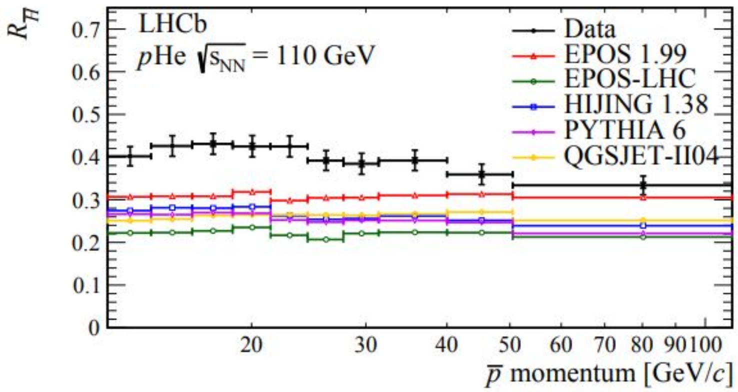
Excellent prospects for a full Run2 analysis

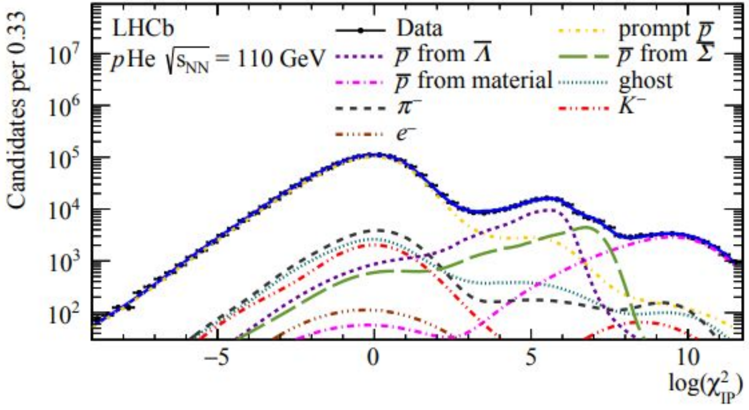
arxiv:2205.09009

Measurement of antiproton production

- Looks at p-He (SMOG) data in hyperon decays
- Measure proton-antiproton ratio from hyperon decays
- Extremely useful for the interpretation of results from space-based experiments
- Dominant Λ component measured exclusively

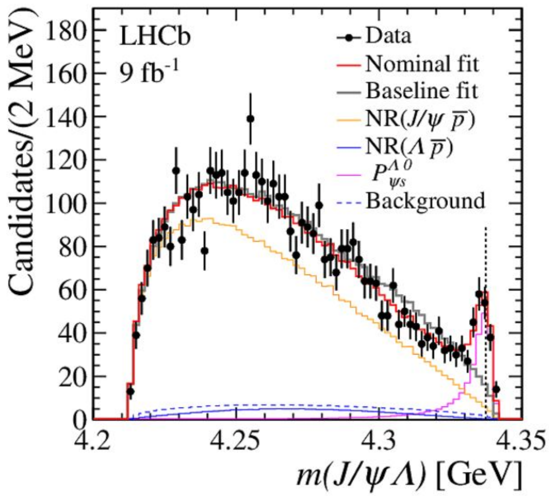
SMOG: System for Measuring Overlap with Gas
- Noble gas (He, Ne, Ar) injected into the LHC vacuum around the LHCb interaction region
- Energy between SPS and RHIC





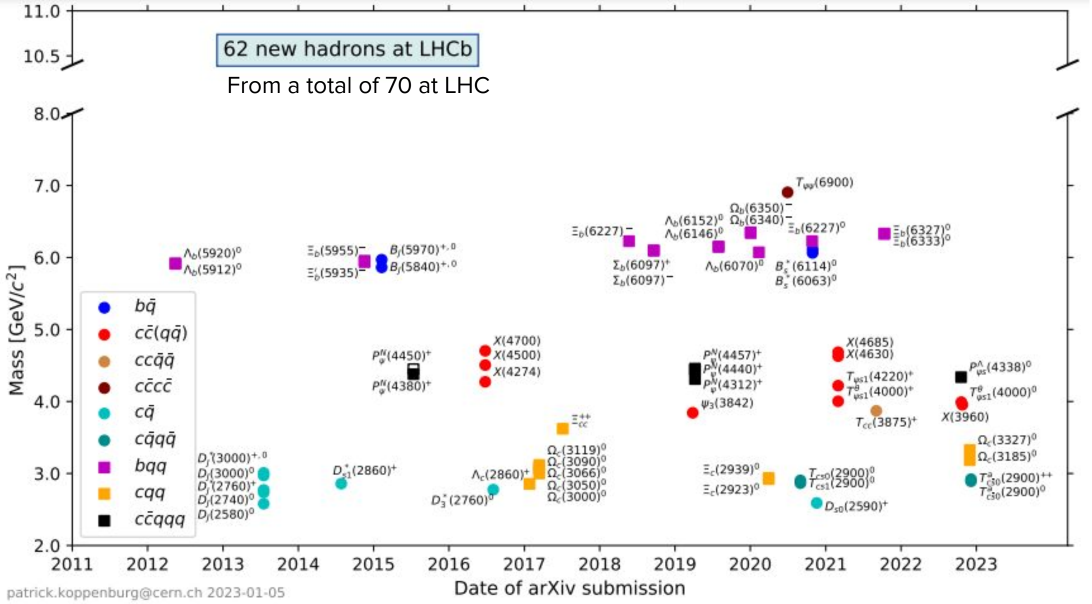
Exotic hadrons, tetra/penta -quarks

arxiv:2210.10346



J/ψΛ structure at 4.338 GeV in ***B⁻→J/ψΛp̄⁻*** decays

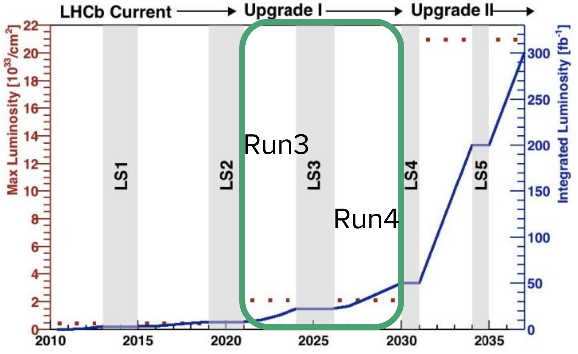
Consistent with a pentaquark candidate with strangeness

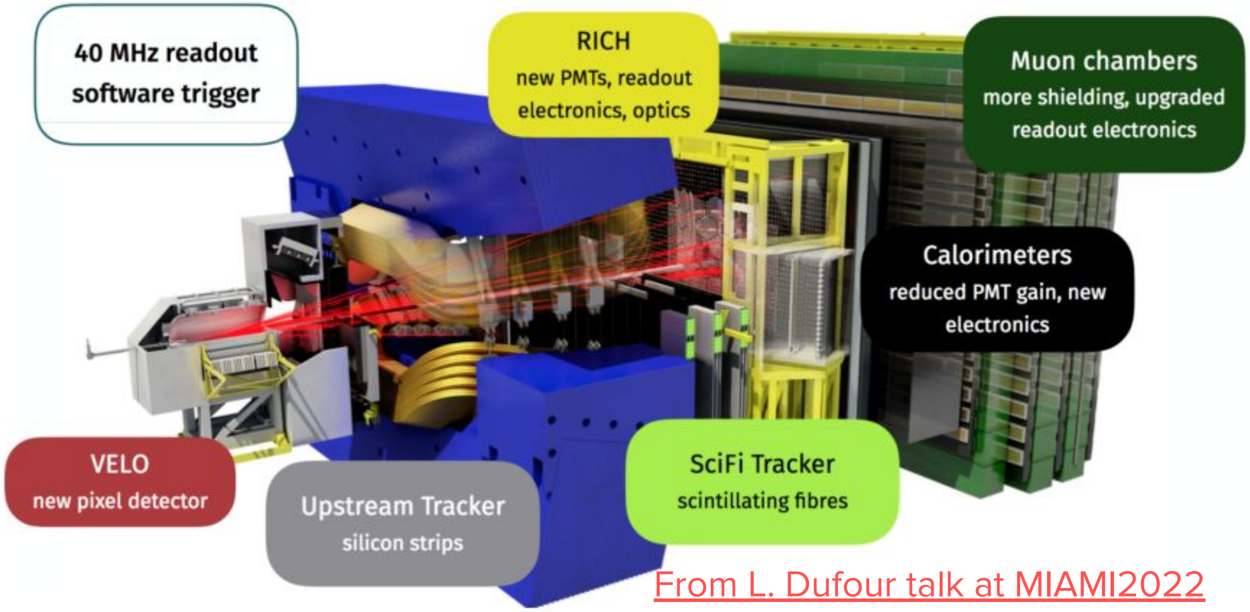


Full list and more plots at this link

The LHCb Upgrade

The upgraded LHCb



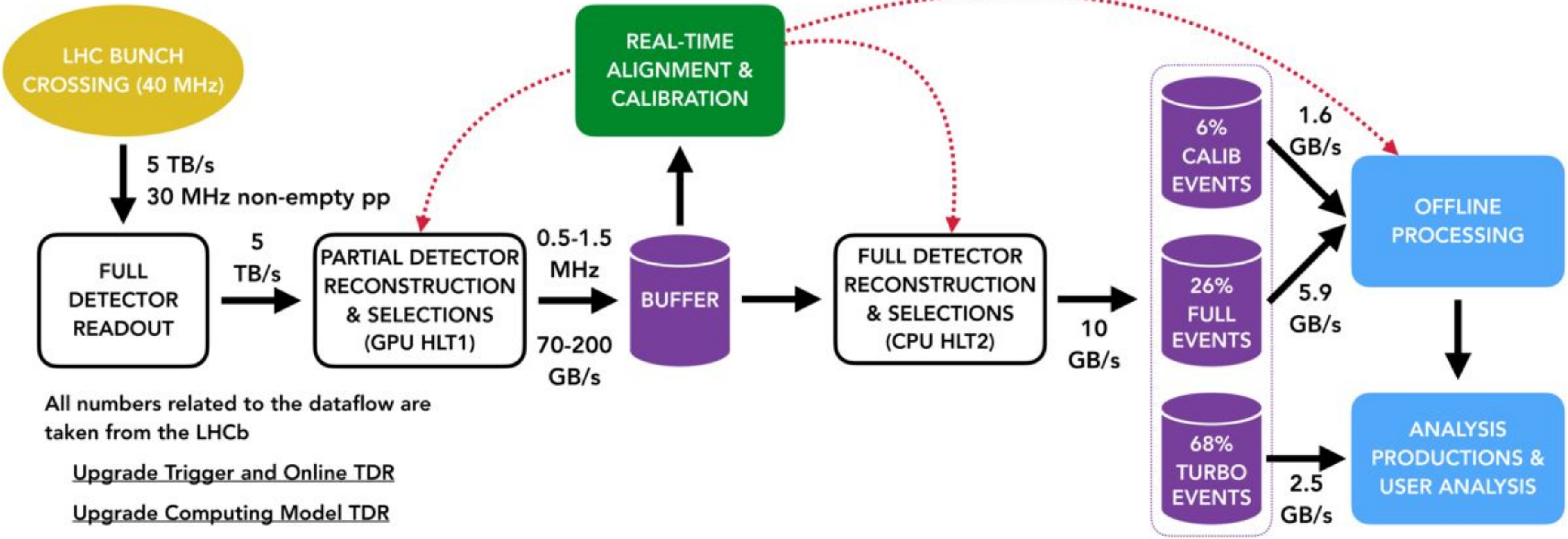


From L. Dufour talk at MIAMI2022

- Aim to collect ~50 fb^{-1} at roughly $\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1}
- Keeping at least the same performance on Run 1&2

The upgrade DAQ and trigger

Fully software trigger, overcomes L0 rate limitations in Run1&2 and builds on the successes of Run1 and Run2 (e.g. real time alignment and calibration)

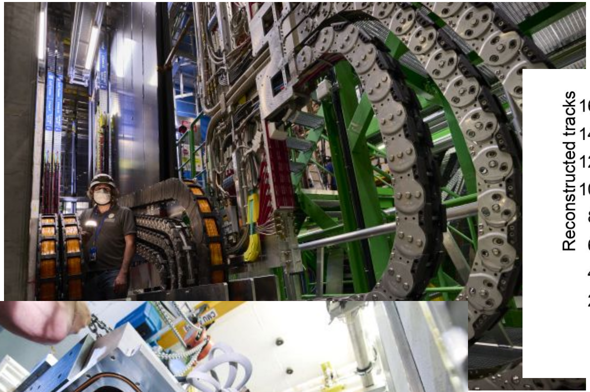


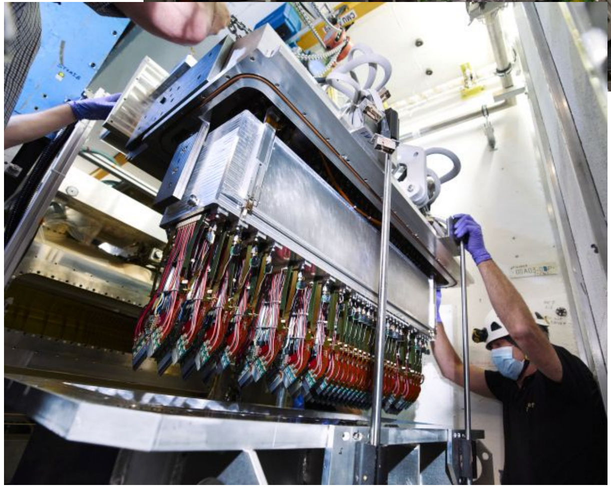
All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

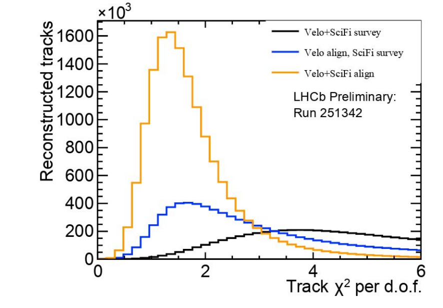
Upgrade Computing Model TDR

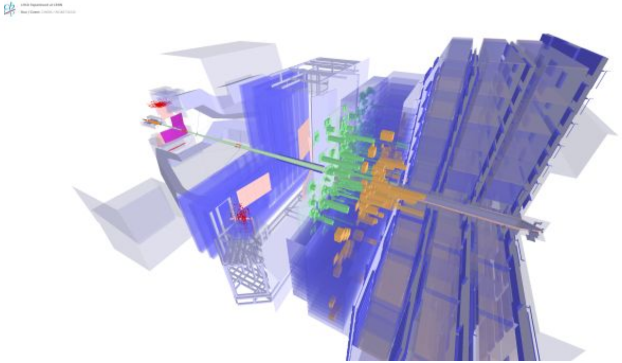
Installation and commissioning of the upgraded detector

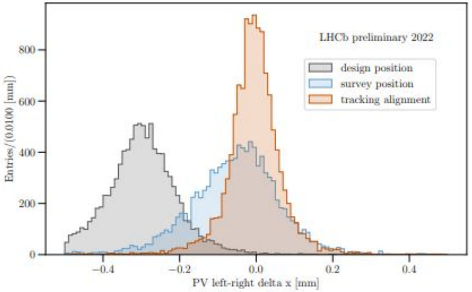




LHCb-FIGURE-2022-018





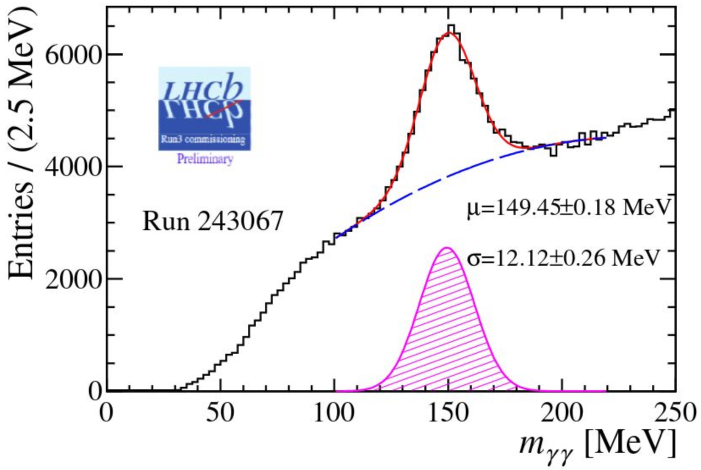


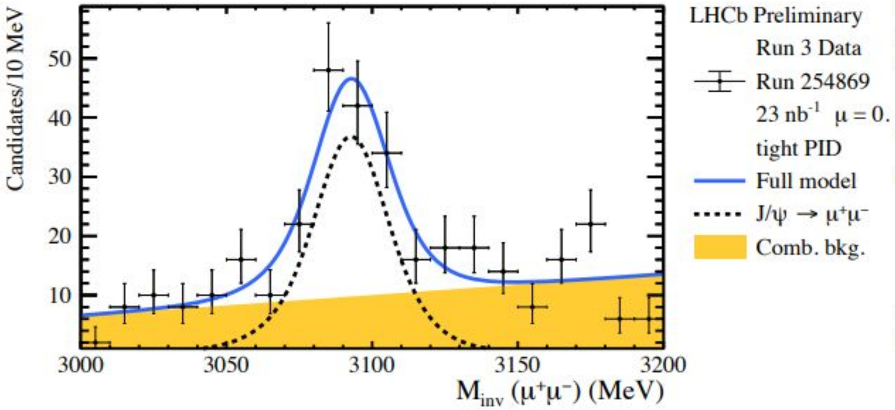
LHCb-FIGURE-2022-016

First mass peaks!

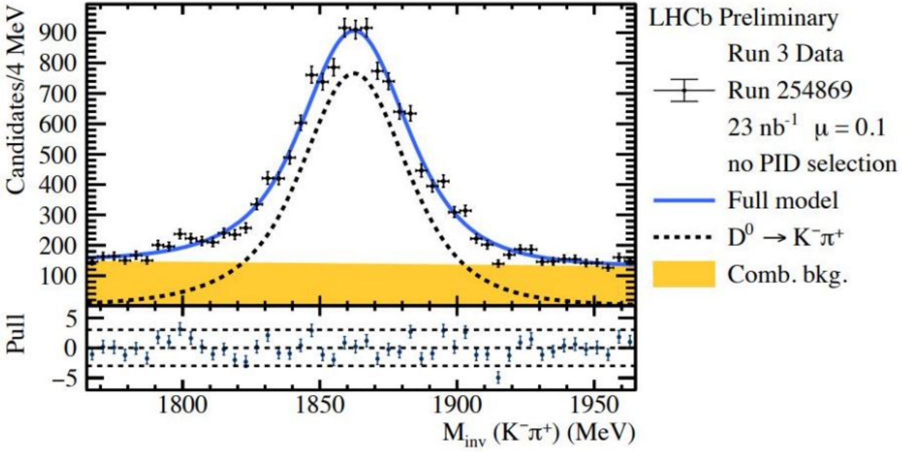
Now working hard on understanding the new detector and improving calibration and alignment

LHCb-FIGURE-2022-019

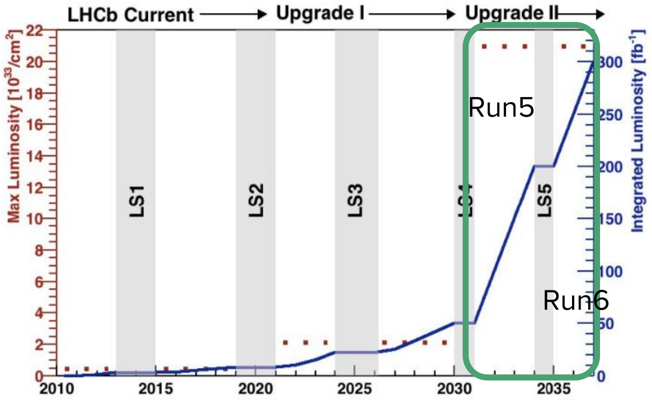




LHCb-FIGURE-2022-034



LHCb in Run 5&6 ?

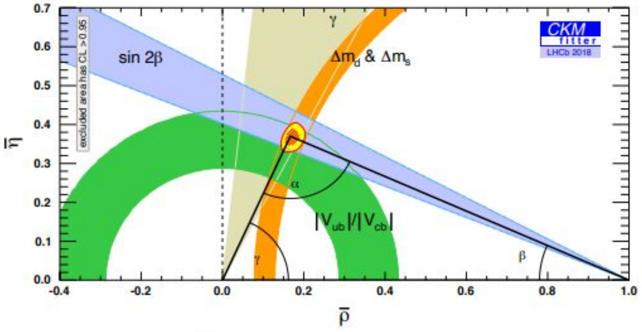


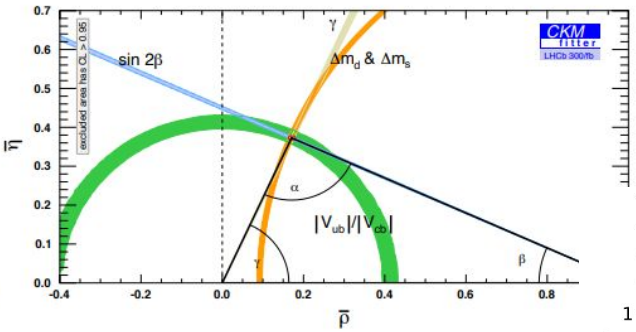
[LHCb-TDR-023](#)

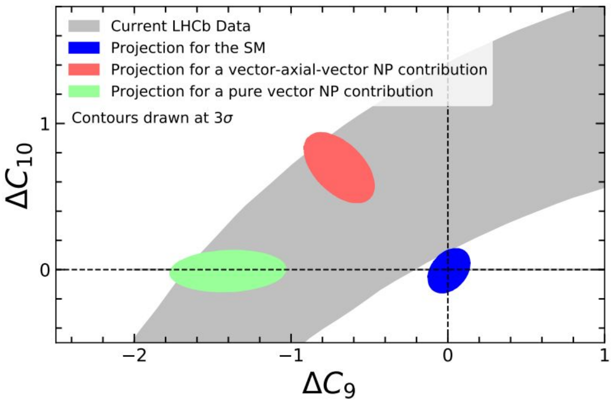
- Target: ~300 fb^{-1}
- Pile-up: ~40
- 200 Tb/second data produced
- To keep the same performance in more difficult conditions, timing will be required in some sub-detectors
- A lot of R&D on new technologies
- Sub-detector TDRs expected after Run 3

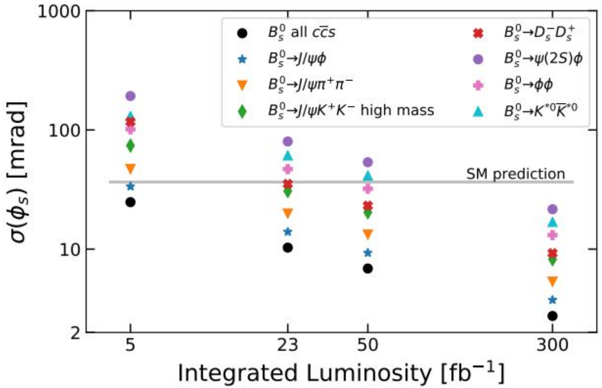
LHCb-TDR-023

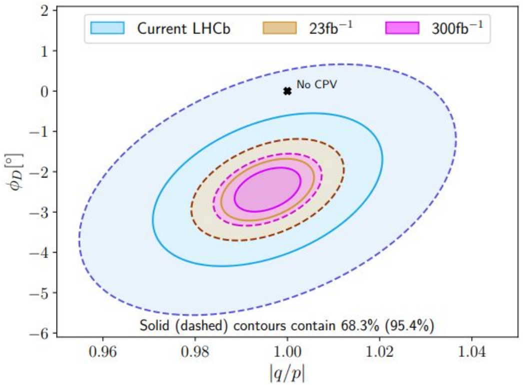
What could be achieved in Upgrade II?







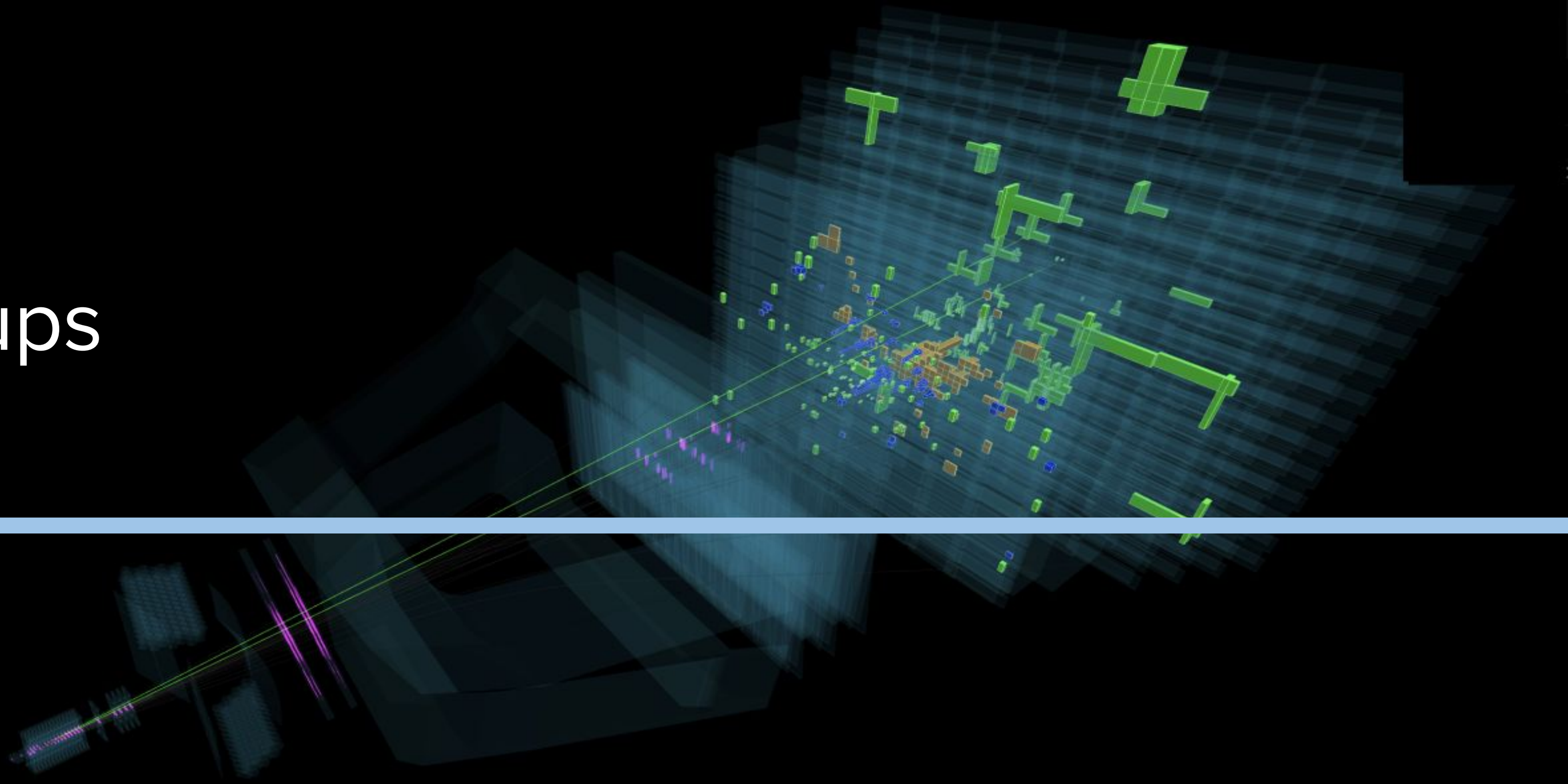




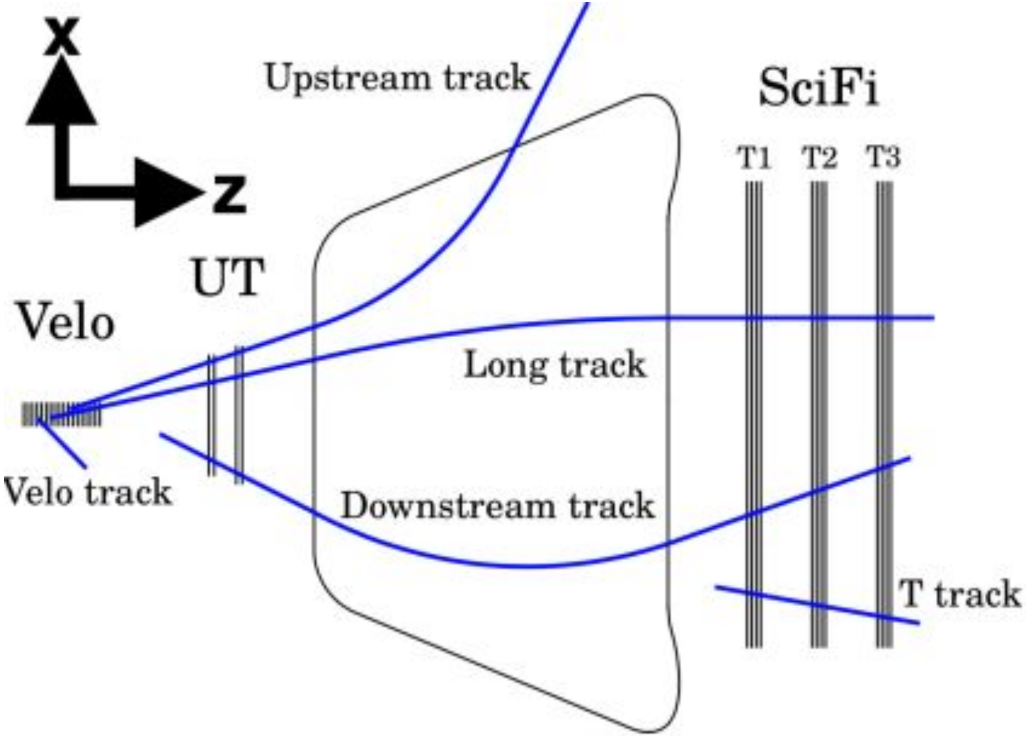
Conclusions

- **LHCb brought many interesting results in Run 1&2, with world leading measurements in the flavour sector**
- **LHCb showed capabilities that go well beyond its design (e.g. EW physics, heavy ions, etc..)**
- **I could only show a small fraction of its physics output!**
- **Now focused on Run3 to get the new detector in shape to acquire an even larger dataset (not just in size but also in physics reach!)**
- **We are also thinking at the far future and started R&D towards an even more capable detector!**

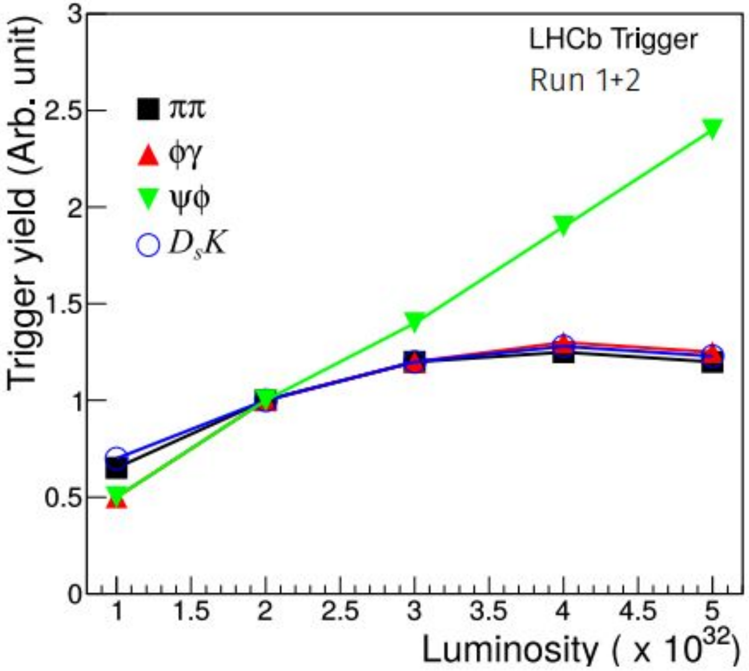
Backups



Track types in LHCb



Trigger yield vs lumi in Run 1&2



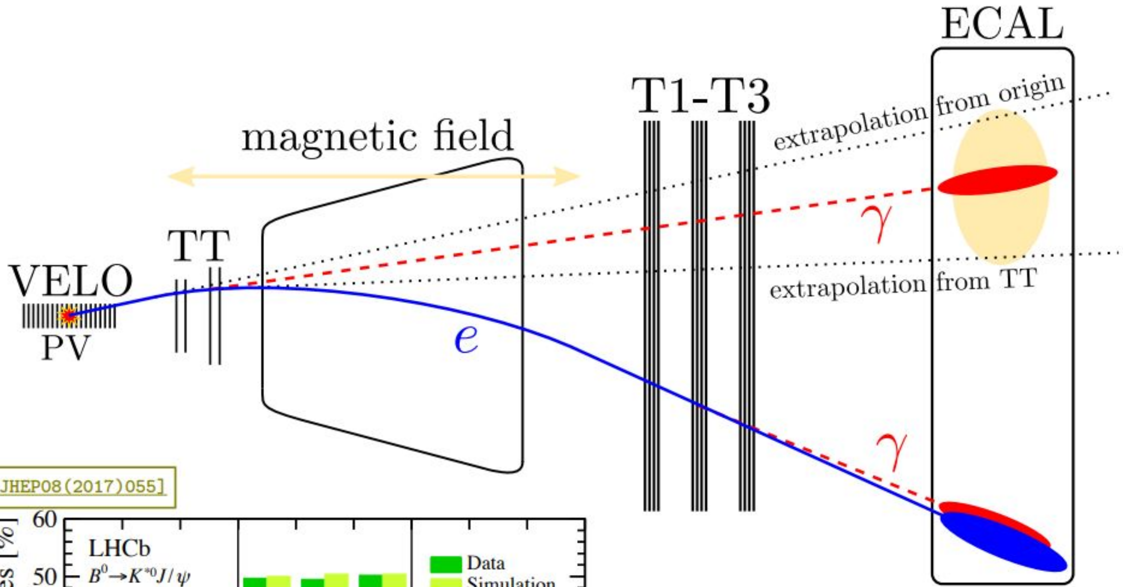
Physics performance projections

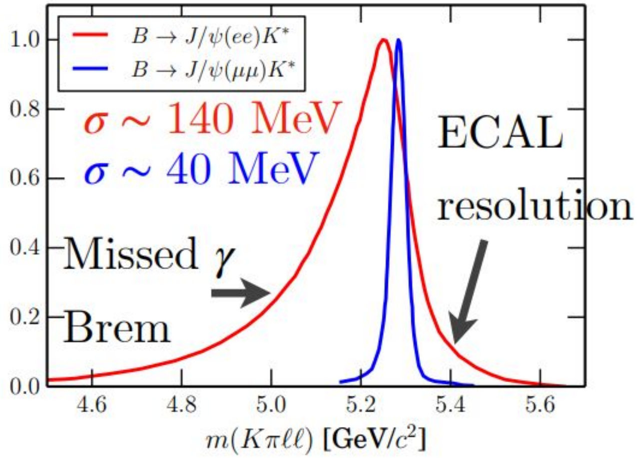
Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_{\rm S}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$($B_s^0 \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}$($B_s^0 \to \phi\gamma$)	0.32	[51]	0.093	0.062	0.025
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

LFU q^2 regions

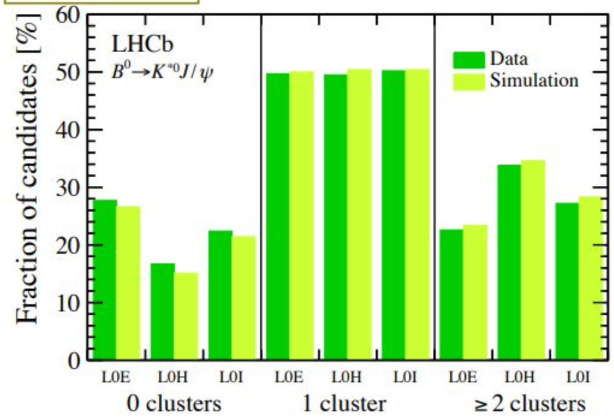
low-q^2 region:	$0.1 < q^2 < 1.1\,\mathrm{GeV}^2/c^4\,,$
central-q^2 region:	$1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4\,,$
electron J/ψ region:	$6 < q^2 < 11\,\mathrm{GeV}^2/c^4\,,$
muon J/ψ region:	$\lvert m(\ell^+\ell^-) - M_{J/\psi}^{\mathrm{PDG}}\rvert < 100\,\mathrm{MeV}/c^2\,,$
electron $\psi(2S)$ region:	$11 < q^2 < 15\,\mathrm{GeV}^2/c^4\,,$
muon $\psi(2S)$ region:	$\lvert m(\ell^+\ell^-) - M_{\psi(2S)}^{\mathrm{PDG}}\rvert < 100\,\mathrm{MeV}/c^2\,,$

Challenges in LFU tests: electrons and energy losses





[JHEP08(2017)055]



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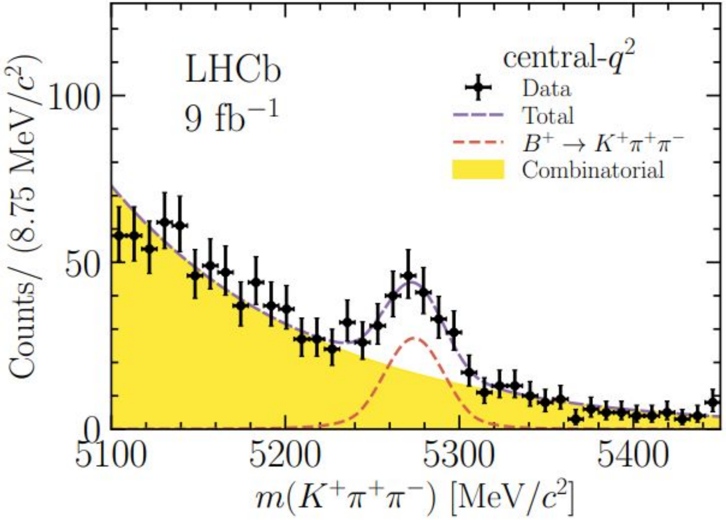
- Brem recovery is O(50%) efficient
- Well described in simulation

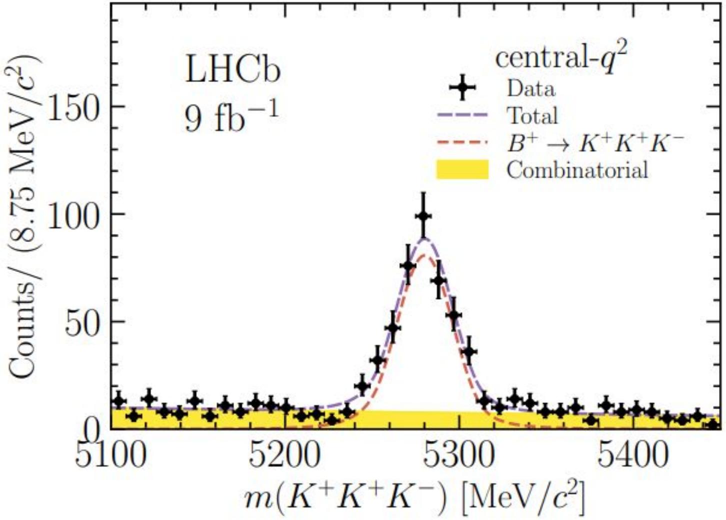
Wider fit range than muons

- more background,
- more sensitive to peaking structures
- lineshapes are brem-dependent

Misidentified background in electron mode

- Simple backgrounds from double-misidentification can be isolated inverting PID criteria (close to nominal selection) after full selection (i.e $K^{+,*0}h^+h^-$) on electron mode





- Similar structures (see *backup*) also for R_{K^*}, however unknown Dalitz for $K^{*0}h^+h^-$
- Single misidentification background as well, often unknown
- ***Developed a new inclusive data-driven treatment of misidentified background***

Mass fit to rare mode electrons: simultaneous fit $R_{K,K^{*0}}$