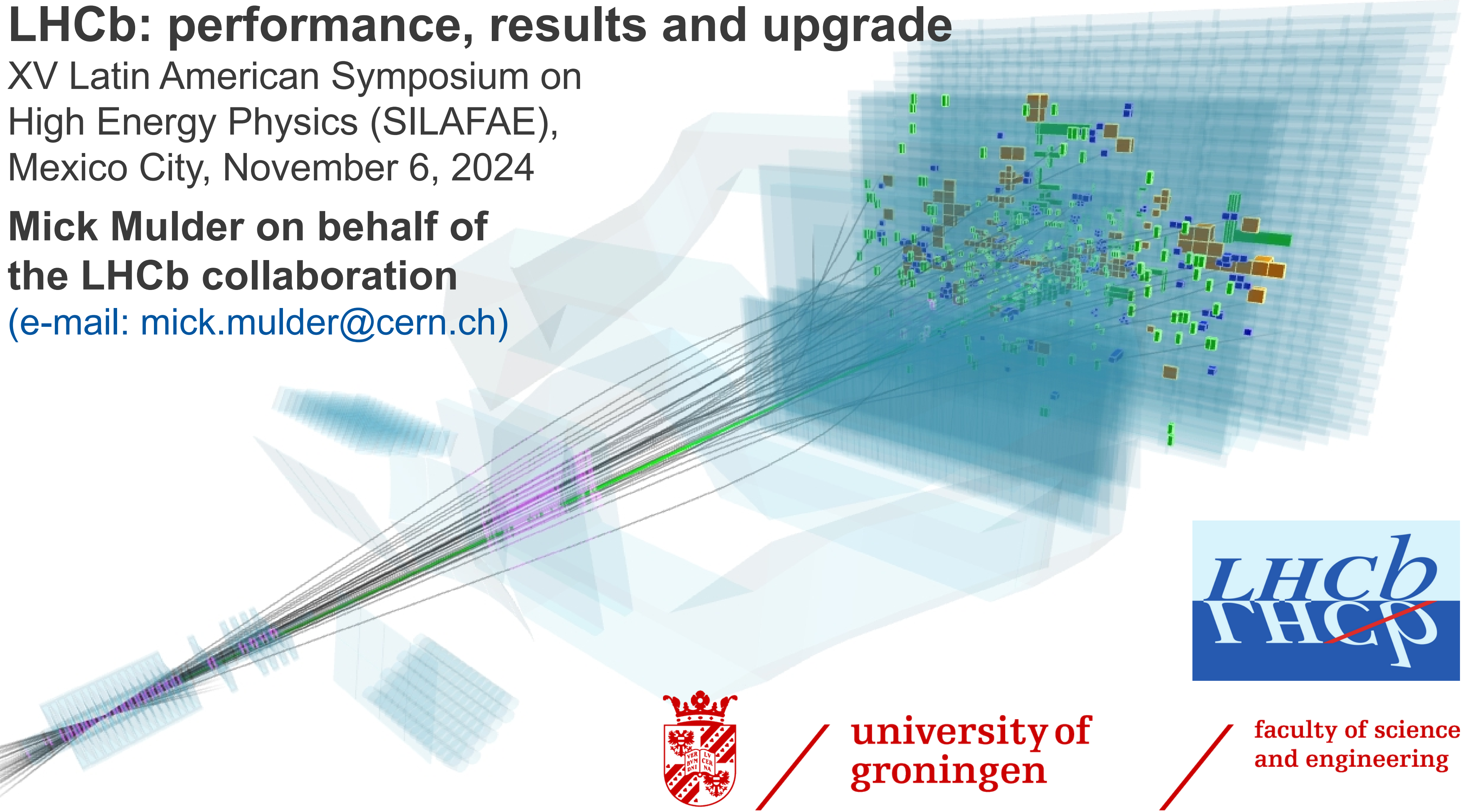
LHCb: performance, results and upgrade

XV Latin American Symposium on High Energy Physics (SILAFAE), Mexico City, November 6, 2024

Mick Mulder on behalf of the LHCb collaboration
(e-mail: mick.mulder@cern.ch)



LHCb

university of groningen

faculty of science and engineering

LHCb physics programme

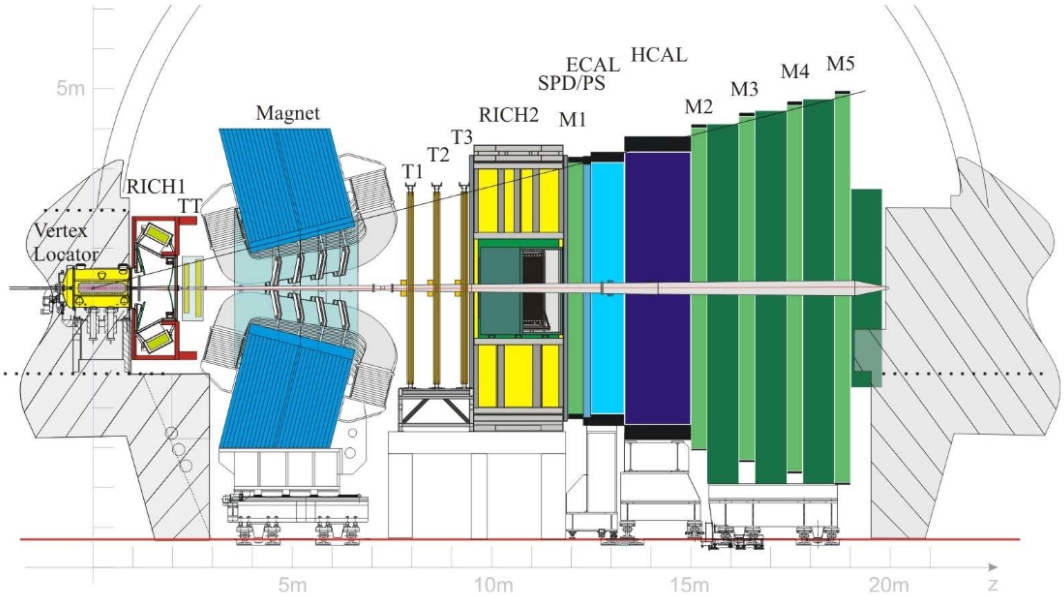
- LHCb originally designed for
  - Mixing and CP violation in B decays
- Fits in long tradition of **indirect measurements** to “discover” new particles, for example:
  - Charm quark in
  - Top quark from B meson mixing

LHCb technical proposal (1998)

Since its discovery, CP violation has been detected only in the decay amplitude of K_L mesons. Experimental efforts in the kaon sector will continue for some time. In the B-meson system there are many more decay modes available, and the Standard Model makes precise predictions for CP violation in a number of these. The B-meson system is therefore a very attractive place to study CP violation, and to search for a hint of new physics.

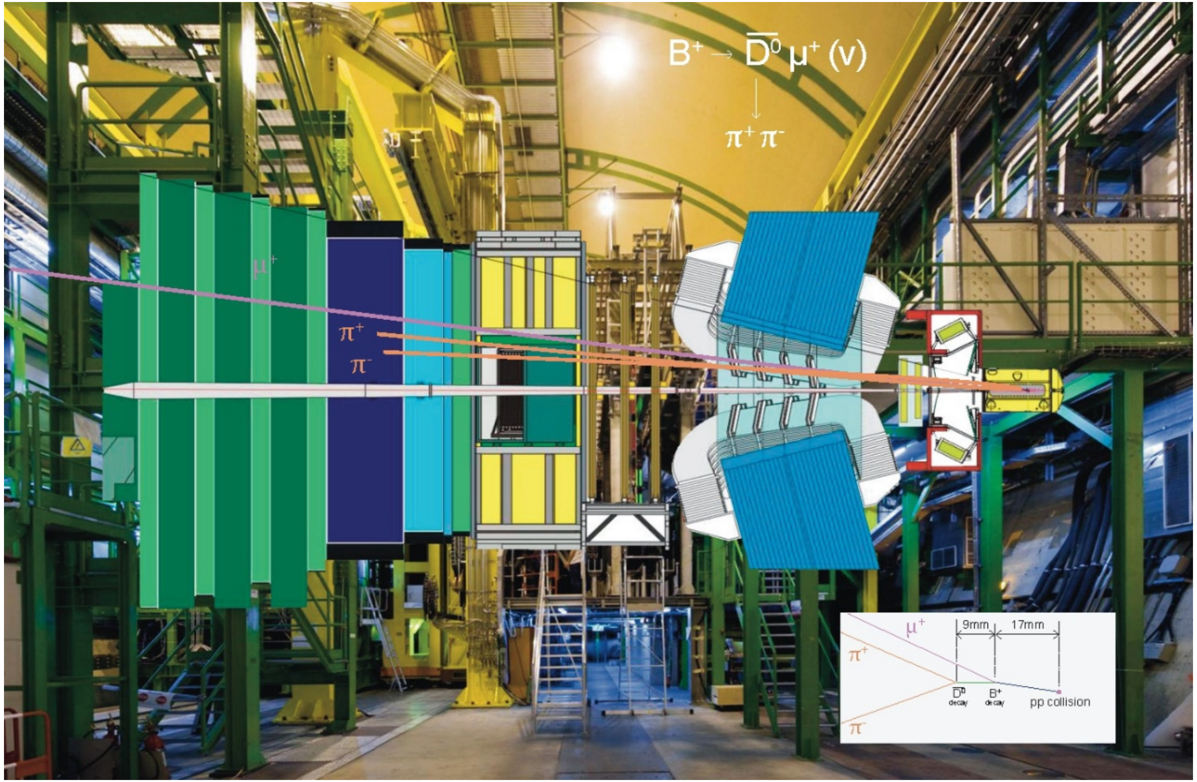
LHCb experiment

- Forward spectrometer at the LHC, optimised for -hadrons
- cross section at 13 TeV in acceptance
- pairs/s in LHC Run 1 & 2 (and 20 x more)



LHCb detector

LHCb detector



LHCb collaboration

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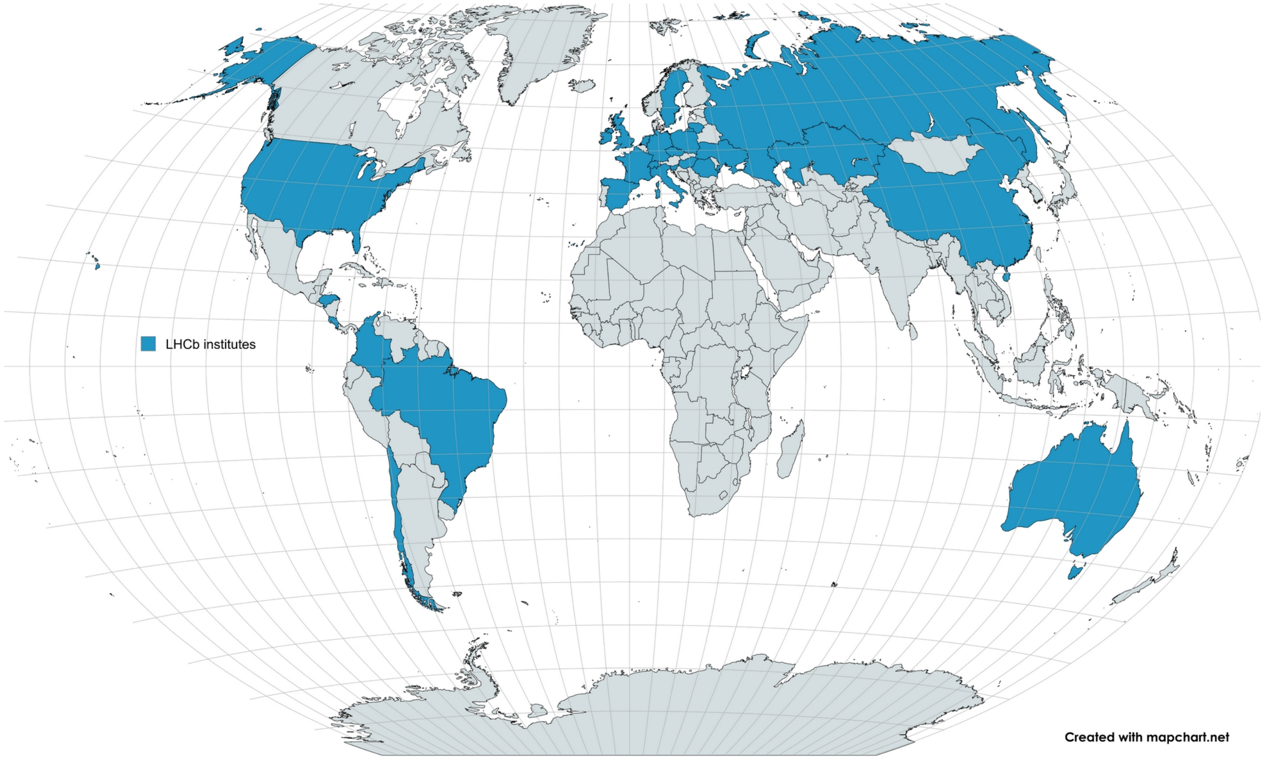
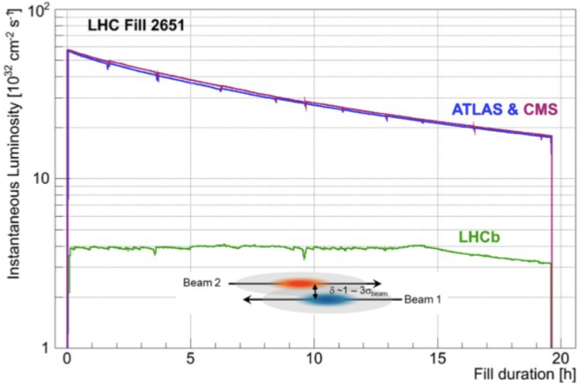
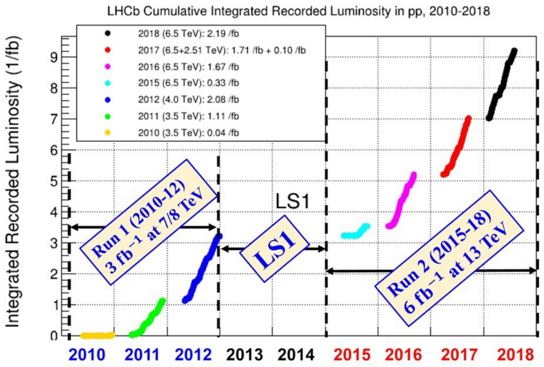


LHCb Run 1 & 2 data taking

- Running with LHC luminosity levelling (, 2x design luminosity)
  - **stable data-taking conditions**
- Corresponds to 1.5 interactions per bunch crossing
- Total of collected
  - around   pairs produced!





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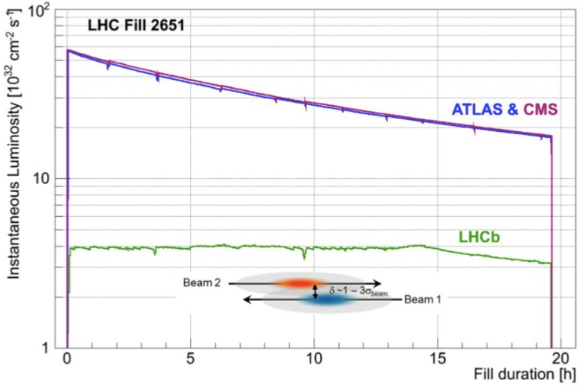
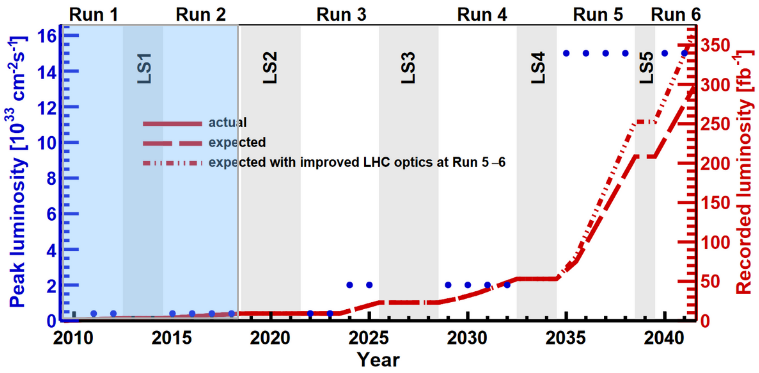
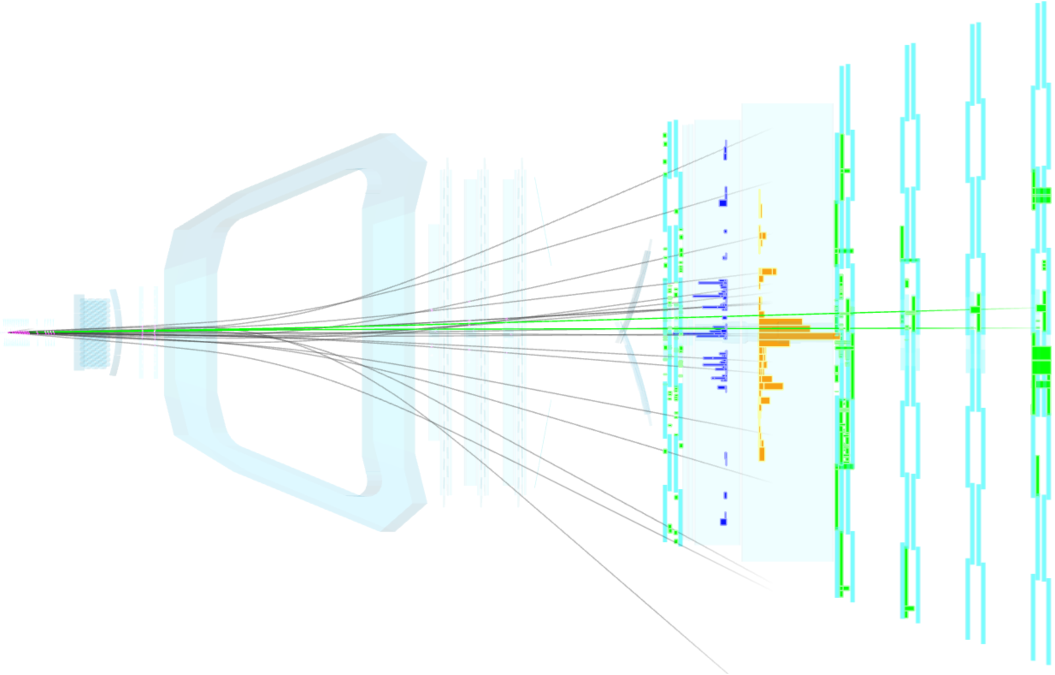


- Total of collected
  - around   pairs produced!
- **Only the beginning!**



LHCb performance

- Very good momentum resolution
  ()
  Sufficient to separate decays
- Excellent charged particle identification:
  ID ~ 97 % w. 1-3% mis-id
  ID ~ 90 % w. ~ 5% mis-id
  required to reject hadronic B decays & separate



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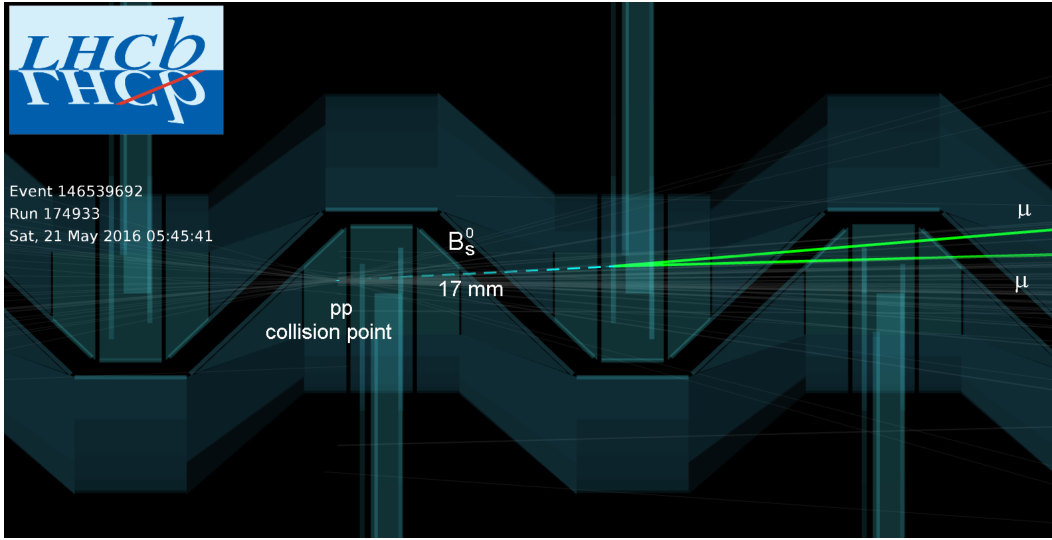
  Sufficient to separate decays
- Excellent charged particle identification:
  ID ~ 97 % w. 1-3% mis-id
  ID ~ 90 % w. ~ 5% mis-id
  required to reject hadronic decays & separate
- Clear separation of hadron decay vertex and pp collision:
  45 fs decay time resolution
  3% of lifetime
  essential to reduce backgrounds



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LHCb physics programme

- LHCb originally designed for:
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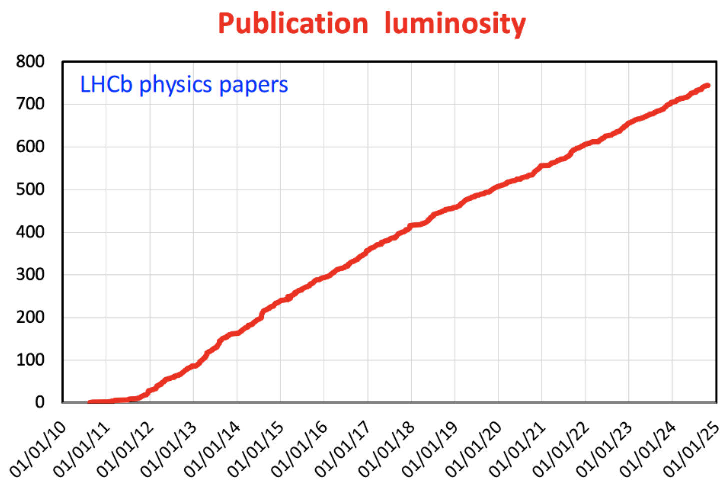
- But LHCb has found general purpose:
  - Rare B decays
  - Charm decays
  - Semileptonic B decays
  - Spectroscopy and exotic hadrons
  - Hadron production (B and quarkonia)
  - Heavy ion physics, fixed target
  - Electroweak physics, QCD
  - Exotics (dark matter, long-lived particles)

Check out the LHCb publication pag



LHCb physics programme

Check out the LHCb publication pag

- LHCb originally designed for:
  - **Mixing and CP violation in B decays**
- But LHCb has found general purpose:
  - **Charm decays**
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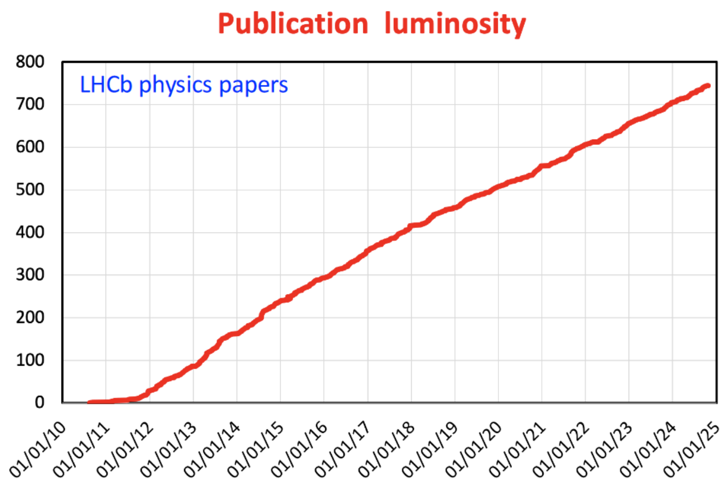
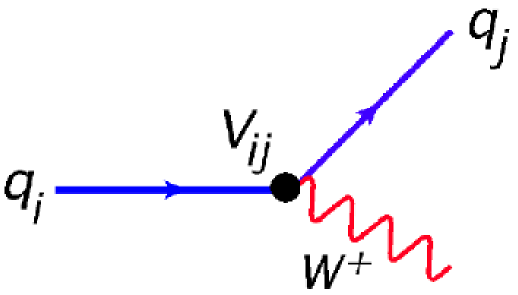
  - **Spectroscopy and exotic hadrons**
  - Hadron production (B and quarkonia)
  - Heavy ion physics, fixed target
  - **Electroweak physics, QCD**
  - Exotics (dark matter, long-lived particles)
- **Today: selected results from LHCb Run 1 and 2**
- **Many more interesting results, just a small flavour!**



Mixing and CP violation

CKM matrix

- Mass and flavour eigenstates of quarks are not equal ☾ W boson transforms quarks



CKM matrix

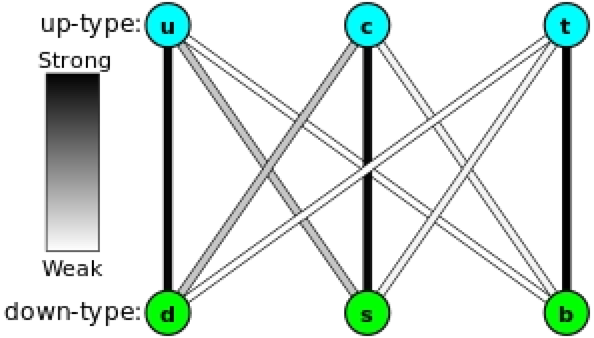
- Mass and flavour eigenstates of quarks are not equal ☾ W boson transforms quarks
- Probabilities described with 3x3 unitary CKM matrix (**almost diagonal, almost real)**

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak states}} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{\text{CKM matrix}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass states}}$$

CKM matrix

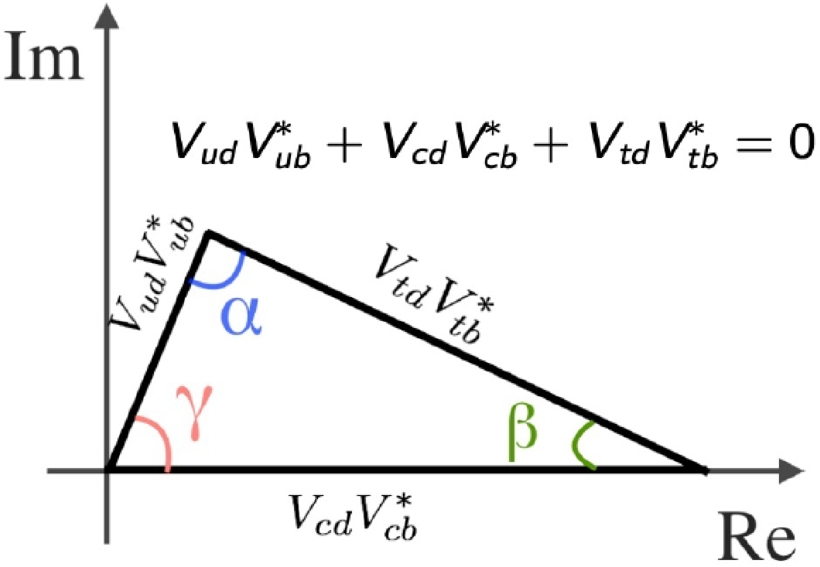
- Mass and flavour eigenstates of quarks are not equal ☾ W boson transforms quarks
- Probabilities described with 3x3 unitary CKM matrix (**almost diagonal, almost real)**
- Only three real, one imaginary parameter remain in SM (due to unitarity)
- **Imaginary element causes CP violation** (opposite phase for particle, anti-particle)
- **Before LHCb, only 1st and 2nd generation were well constrained**

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak states}} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{\text{CKM matrix}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass states}}$$



Unitarity triangle

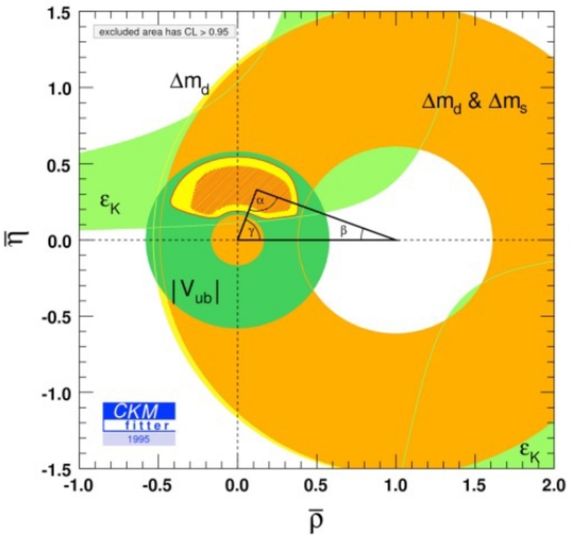
- Unitarity of CKM matrix leads to two types of conditions: real, , orthogonal,
- **Unitarity triangles** formed with orthogonal relations
- **In case of New Physics, unitarity conditions are broken!** ☾ test consistency of unitary triangles with measurements testing each angle and side



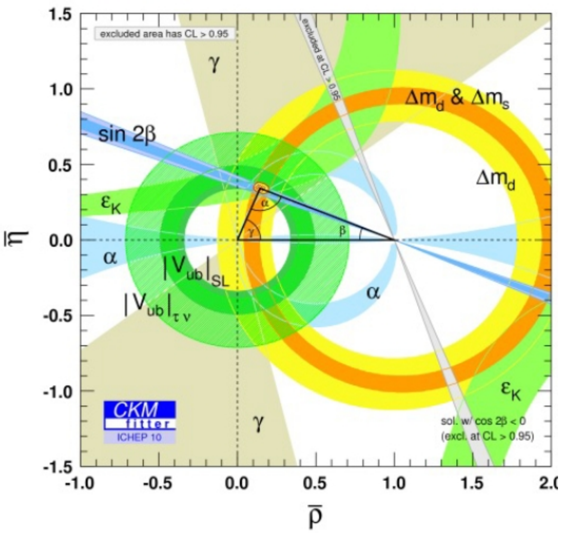
Constraining the unitarity triangle

Significant progress over last decades with crucial role for LHCb (since 2011)

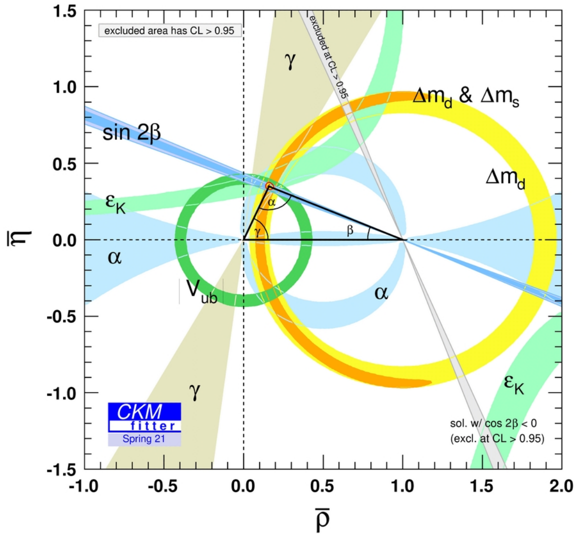
1995



2010



2021



Any sign of inconsistency could point to New Physics

CKMfitter.in2p3.fr

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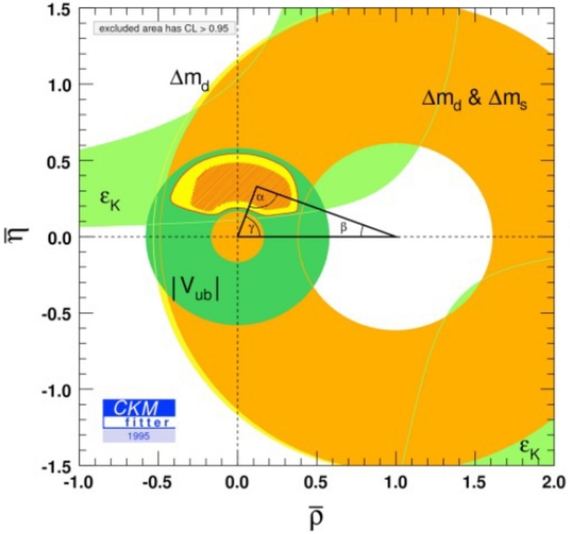
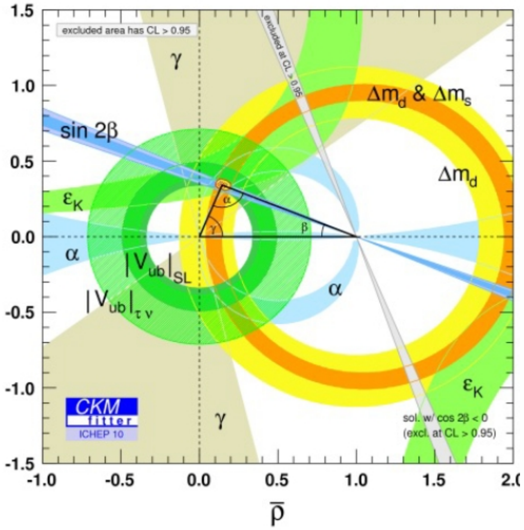
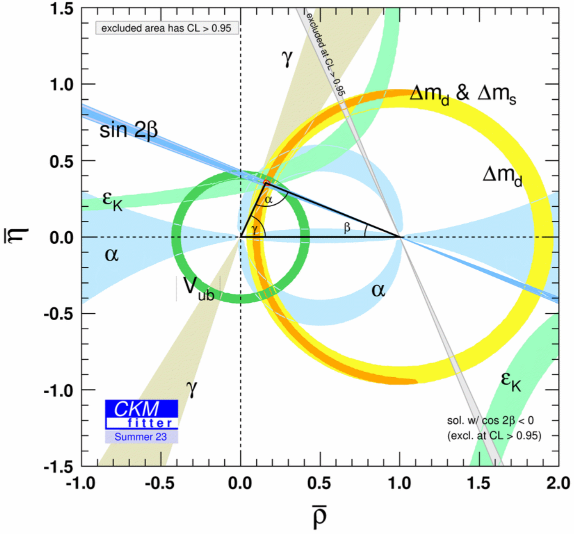


2010



2023



Any sign of inconsistency could point to New Physics

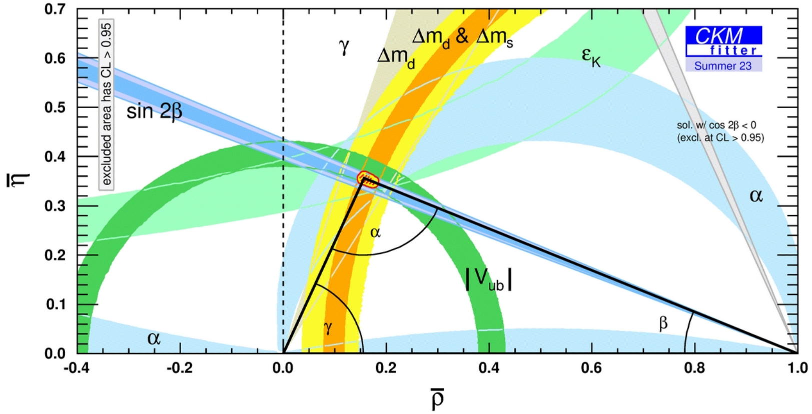
CKMfitter.in2p3.fr

CKM angle

- Only angle accessible in tree-level decays
- Theoretically clean

$$\gamma = \arg\left(-\frac{V_{ub}^{*} V_{u}}{V_{cb}^{*} V_{c}}\right)$$

2023



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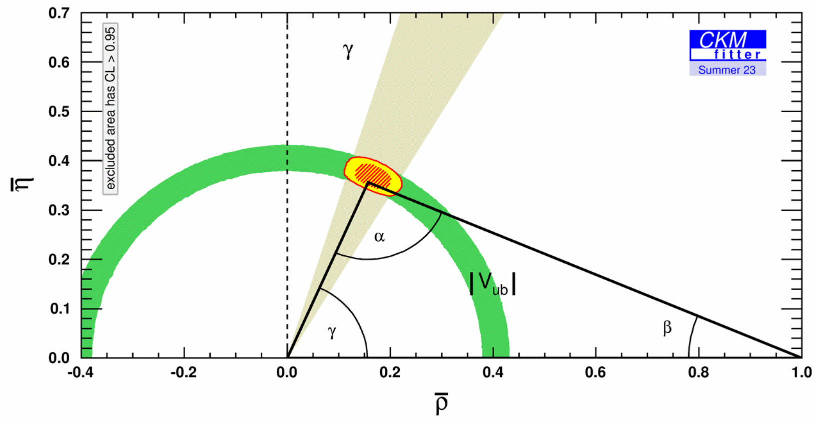
2023

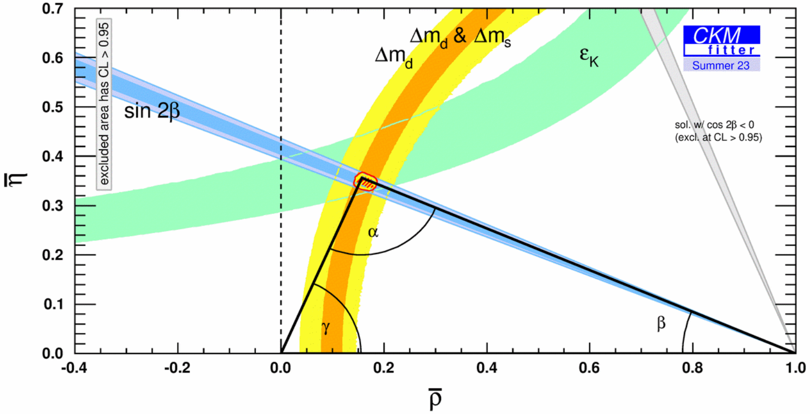


CKM angle

$$\gamma = \arg\left(-\frac{V^*_{ub}V_{u}}{V^*_{cb}V_{c}}\right.$$

- Only angle accessible in tree-level decays
- Theoretically clean
- World Average from direct measurements:
- World Average from indirect measurements (CKMFitter 2023):

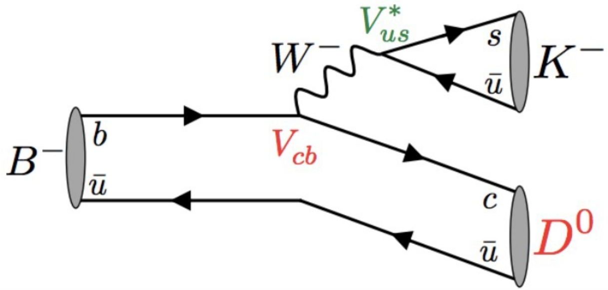
2023

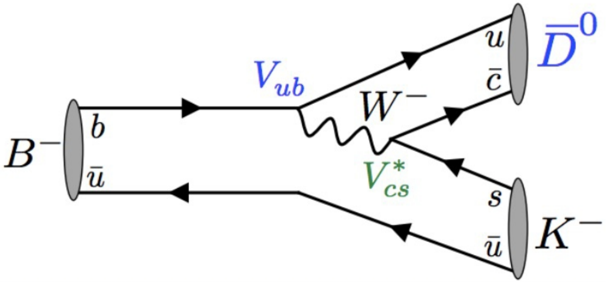


- LHCb's goal: bring uncertainty from direct measurements of down to uncertainty from indirect measurements

Measuring CKM angle

- Use **interference** of and diagrams $\gamma = \arg\left(-\frac{V_{ub}^{*} V_{u}}{V_{cb}^{*} V_{c}}\right.$





- Interference only possible when decay to same final state
- Extract from combination of measurements (where or)

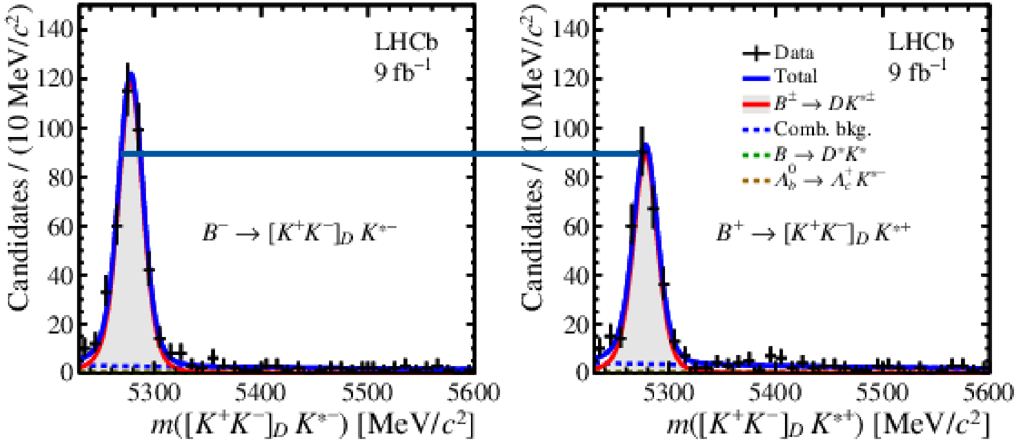
Measurement of in decays

- D meson reconstructed in many possible final states:

[arXiv:2410.21115]

- Relatively challenging mode due to decay,
  low reconstruction efficiency
- Result:
  illustrative of measuring
  many modes required
  to reach ultimate precision

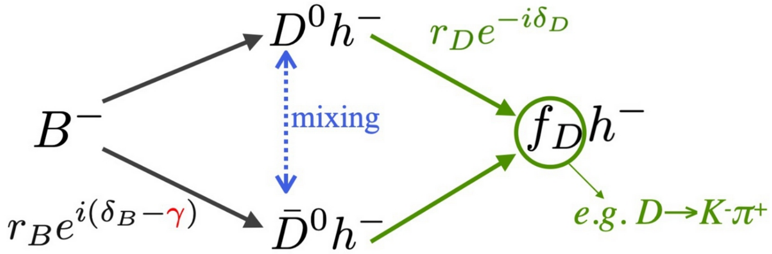
Direct CPV: more decays than decays!



New combination

LHCb-CONF-2024-004;
update of [JHEP 12(2021)141]

- Combination of 198 observables to determine 53 free parameters
- Simultaneous determination of and charm mixing parameters
- External inputs from BESIII, CLEO-c



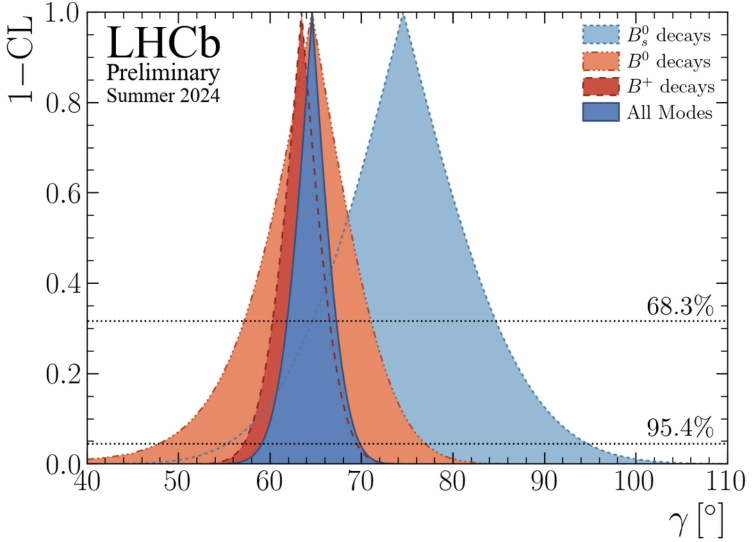
B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp$	[35]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$	[19]	Run 1&2	New
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[36]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp\pi^0$	[37]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[38]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[39]	Run 1&2	As before
$B^\pm \to D^* h^\pm$	$D \to h^\pm h'^\mp$ (PR)	[35]	Run 1&2	As before
$B^\pm \to D^* h^\pm$	$D \to K^0_S h^+h^-$ (PR)	[20]	Run 1&2	New
$B^\pm \to D^* h^\pm$	$D \to K^0_S h^+h^-$ (FR)	[21]	Run 1&2	New
$B^\pm \to DK^{*\pm}$	$D \to h^\pm h'^\mp$	[22]†	Run 1&2	Updated
$B^\pm \to DK^{*\pm}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$	[22]†	Run 1&2	Updated
$B^\pm \to DK^{*\pm}$	$D \to K^0_S h^+h^-$	[22]†	Run 1&2	New
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^\pm h'^\mp$	[40]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^\pm h'^\mp$	[23]	Run 1&2	Updated
$B^0 \to DK^{*0}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$	[23]	Run 1&2	Updated
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	[24]	Run 1&2	Updated
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[41]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[25, 42]†	Run 1&2	Updated
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[43]	Run 1&2	As before
D decay	**Observable(s)**	**Ref.**	**Dataset**	**Status since Ref. [14]**
$D^0 \to h^+h^-$	ΔA_{CP}	[44–46]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[46–48]	Run 2	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[49, 50]	Run 1&2	As before
$D^0 \to h^+h^-$	ΔY	[51–54]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (double tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[55]	Run 1	As before
$D^0 \to K^+\pi^-$ (single tag)	$R_{K\pi}$, $A_{K\pi}$, $c_{K\pi}^{(\prime)}$, $\Delta c_{K\pi}^{(\prime)}$	[27, 56]	Run 1&2	Updated
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[57]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[58]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[59]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[60, 61]	Run 2	As before
$D^0 \to \pi^+\pi^-\pi^0$	ΔY^{eff}	[26]	Run 2	New

† Results presented at ICHEP 2024, but not yet publically available.

New combination

LHCb-CONF-2024-004;
update to [JHEP 12(2021)141]

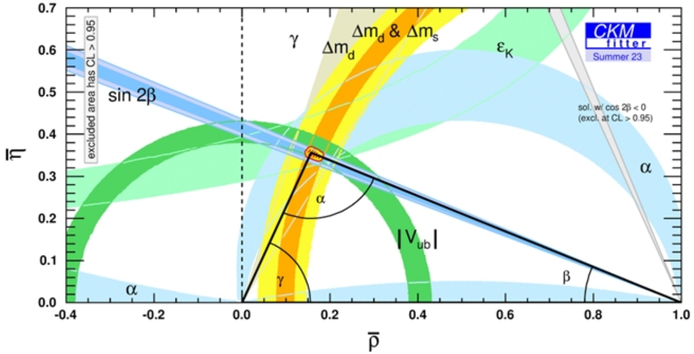
- Most precise single experiment result, ,
  in agreement with and 20% better than previous average
- Previous tension between and modes resolved
- In agreement with global fits:
  ,
- Still statistically limited
  (systematic uncertainty is 1.4),
  so improvements expected in Run 3!



CKM angle

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

- The angle is sensitive to top-quark interactions; therefore **only sensitive to loop diagrams, in this case B-meson oscillation**
- **Use interference of and meson decay to same final state**, resulting in



(ignoring lifetime difference in - system)

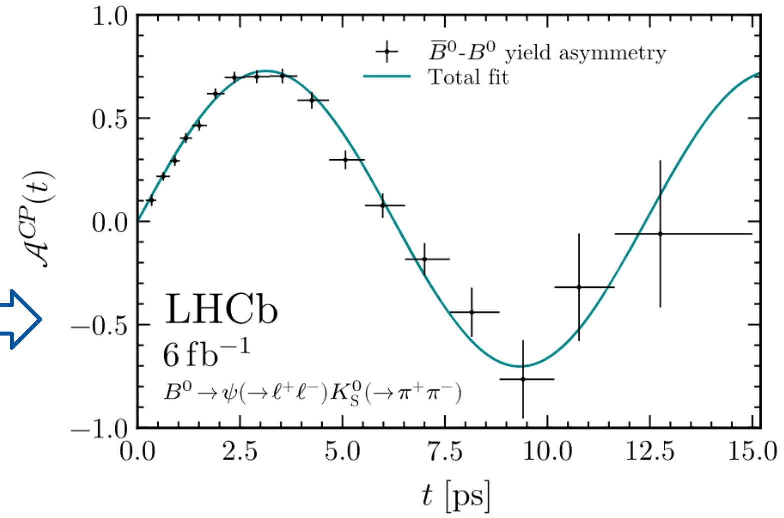
- -type decays excellent to measure :
  for these decays ,
  where due to non-tree decays is correction of ~1%

Recent measurement of

- Use three modes, namely
  and ,
  to get the most out of Run 2 data
- Combine with Run 1 measurement
- Results of combination:

  i.e. asymmetry is shaped like sine
- Consistent with CKMFitter, UTFit, best single experiment measurement

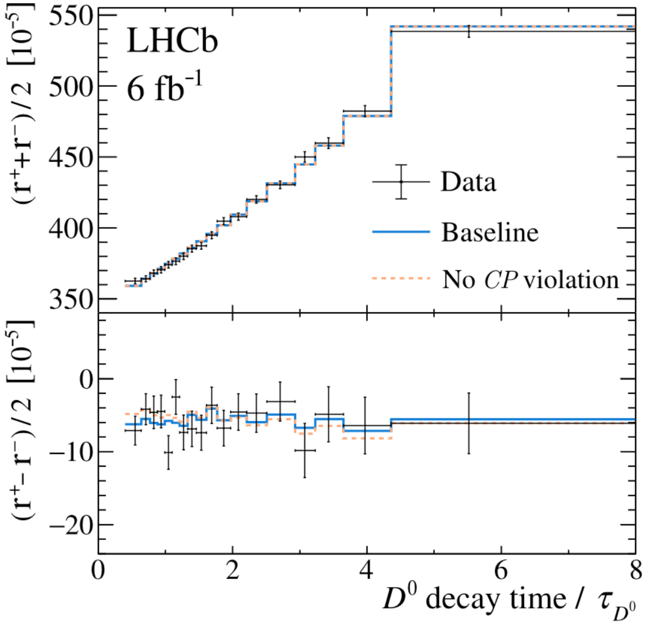
[Phys. Rev. Lett. 132 (2024) 021801]



Charm mixing and CPV

[PRL 122 (2019) 211803]; [arXiv:2407.180

- Unique CP violation test, asymmetries !
- **LHCb discovered CPV in charm in 2019:**
  , difference in time-integrated CP asymmetries of
- **New this year**: time-dependent asymmetry of prompt meson decays to , , tagged using , with full Run 1, 2 dataset
- **Interference** between mixing and decay of to either final state ☾ test mixing + CP violation
- Use ratio of wrong sign vs. right sign decay,
  ,
- **Most precise mixing measurement; no sign of CP violation in mixing or interference**
- Parallel analysis using from semileptonic decays provides additional constraints



[LHCb-PAPER-2024-044, in preparation]

CP violation: summary

LHCb has provided stringent tests of CP violation and CKM matrix

- Strongest constraints on CKM angles and (closing the triangle)
- Observation of mixing and CP violation in charm decays

And more I could not show today:

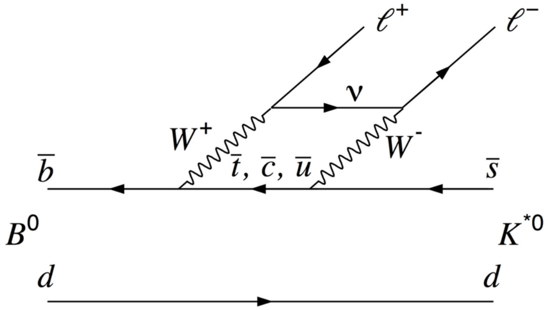
- : world-leading in (angle in unitarity triangle) [PRL 132 (2024) 051802]
- CP violation in mixing with semileptonic decays [PRL 114 (2015) 041601, PRL 117 (2016) 061803]
- tests with semileptonic decays () [PRL. 126 (2021) 081804, PRD101 (2020) 072004, Nature Physics 11 (2015) 743]
- Search for direct CPV in [arXiv:2409.01414]

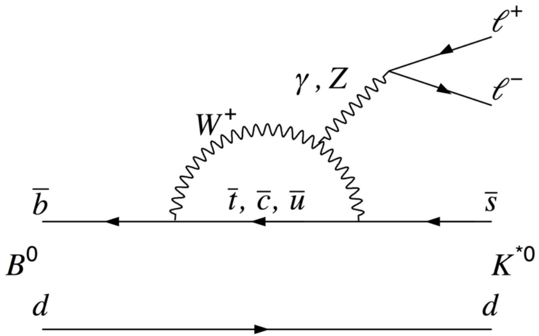
More on CP violation by Melissa Cruz Torres (past Monday, 16:45)

Rare decays and lepton universality

Rare B decays:

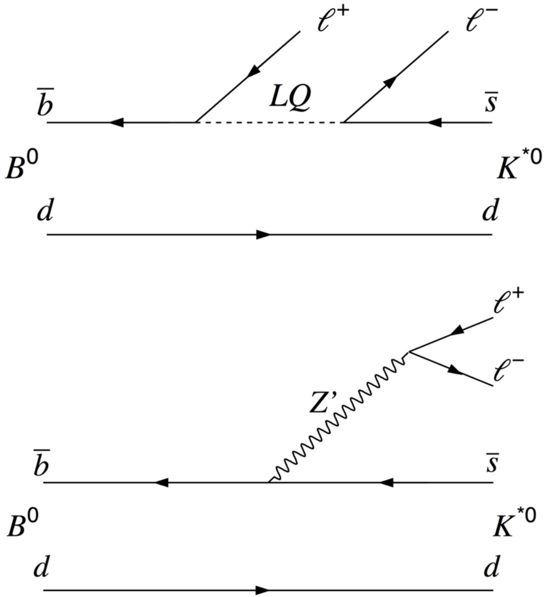
- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)





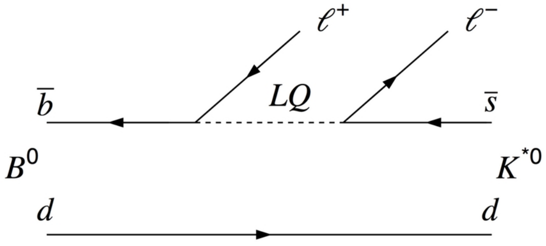
Rare B decays:

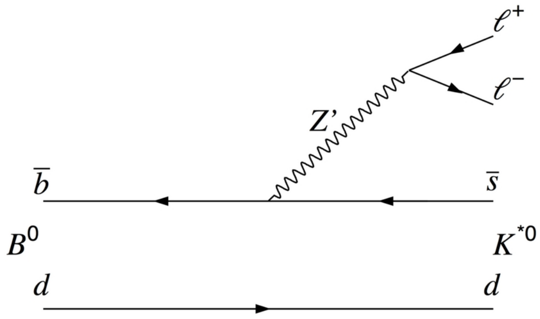
- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)
- Transition uncommon in Standard Model, **sensitive to small contributions from heavy new particles**!



Rare B decays:

- Test Standard Model with weak interaction loop diagrams (Flavour Changing Neutral Currents)
- Transition uncommon in Standard Model, **sensitive to small contributions from heavy new particles**!
- Observables:
  - Leptonic decays (e.g.) ☾ in backup
  - Branching fractions
  - Angular distributions
  - Lepton universality
- Large variety of channels and observables

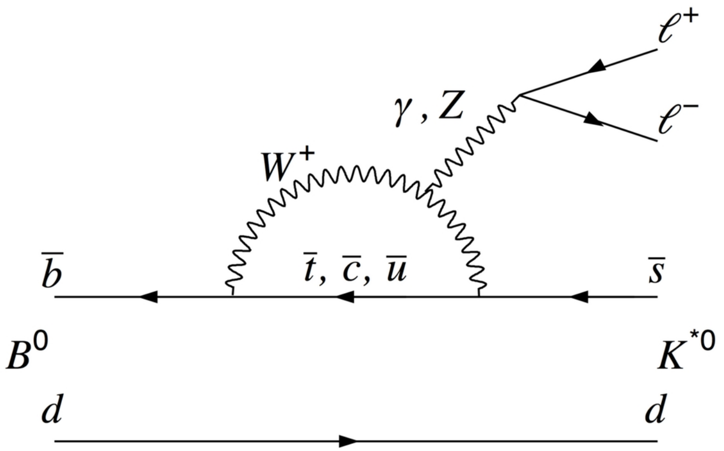




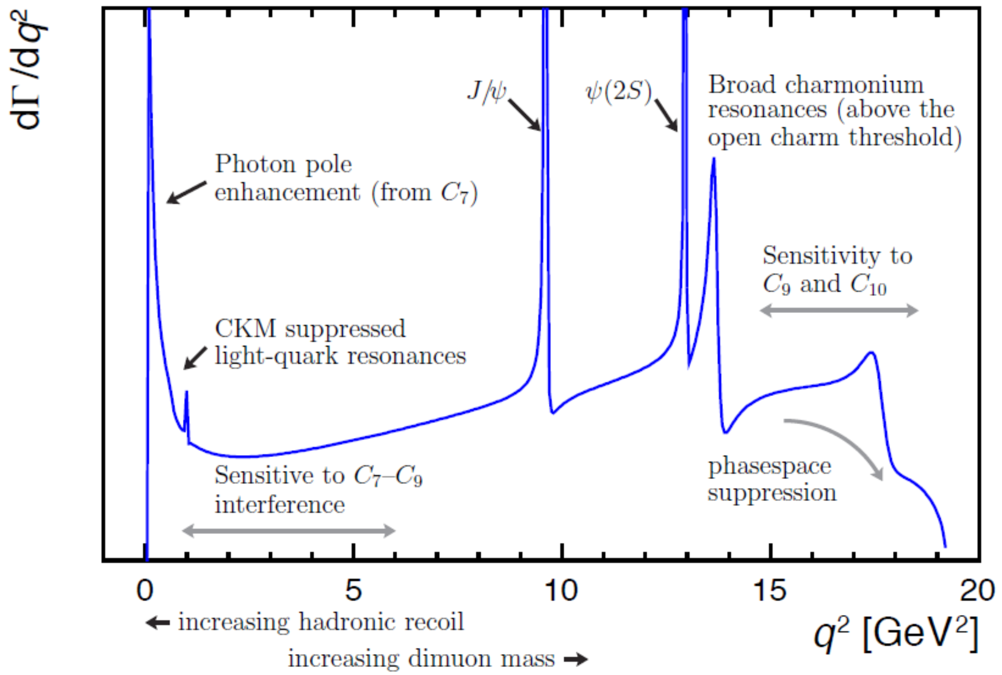
Semileptonic rare decays:

Physics depends on :

- Resonances (e.g.)
- Photon pole at low
- Vector or axial vector current

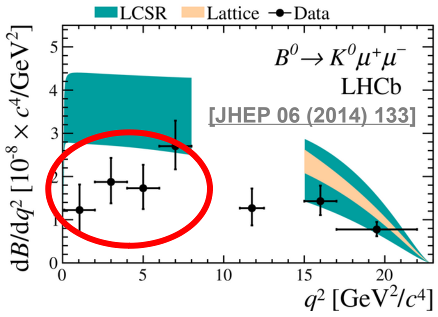


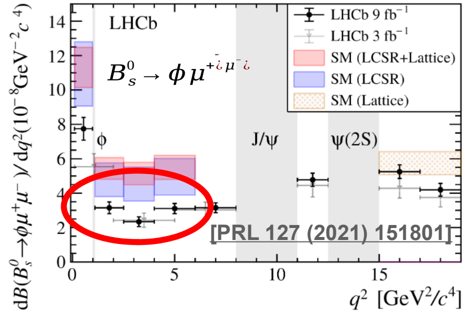
T.Blake et al. arXiv:1606.00916

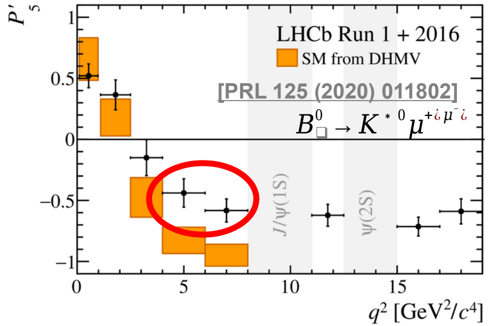


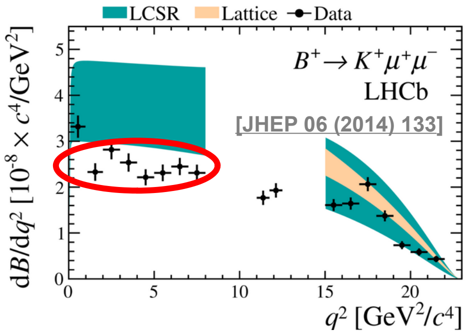
Semileptonic rare B decays: anomalies

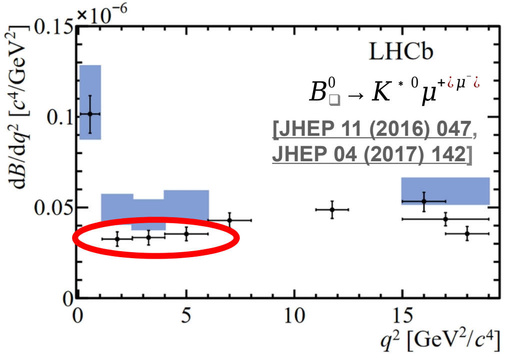
Measurements of semileptonic rare B decays deviate from predictions….

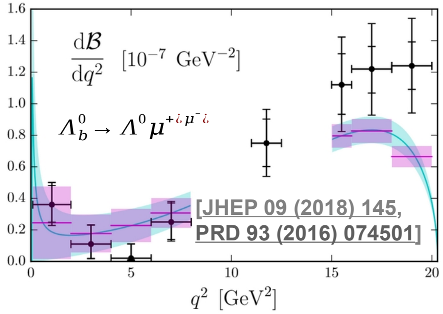












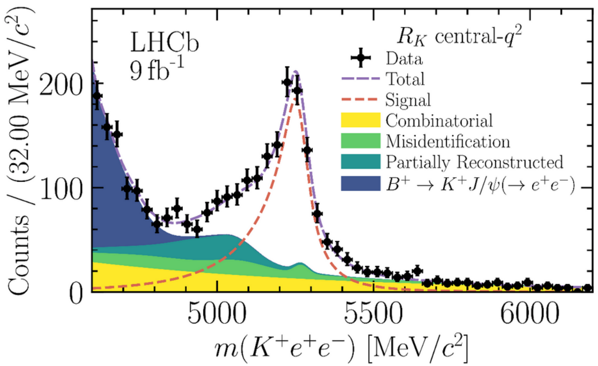
Note: these deviations are consistent (interpreted in EFT framework, see backup)

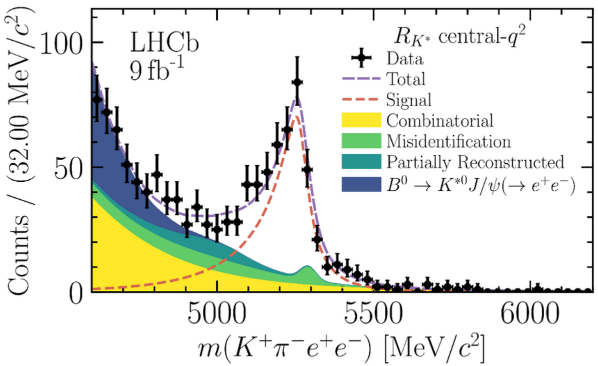
Lepton universality:

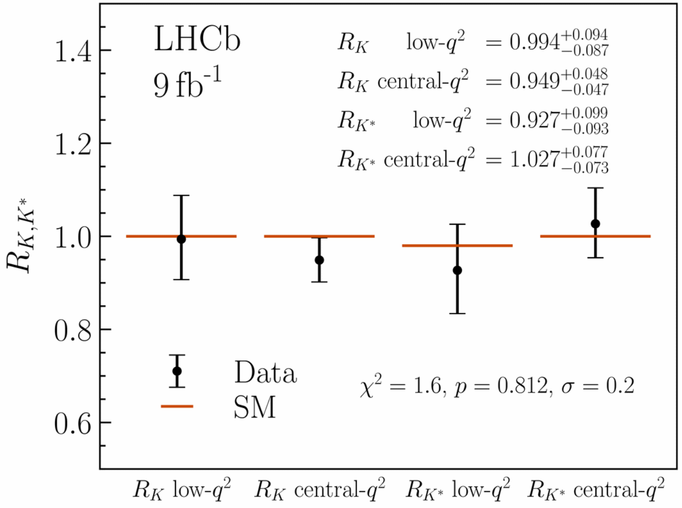
- From SM expect equal muonic, electronic decay rate
- Measure double ratio with respect to modes
- **Consistent with SM**, shift versus previous results due to contribution from misID backgrounds

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

[PRL 131 (2023) 051803, PRD 108 (2023) 032002]



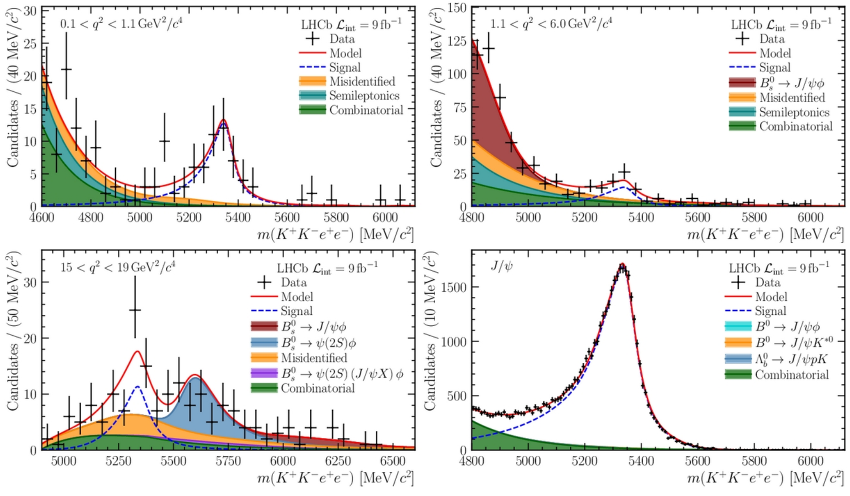


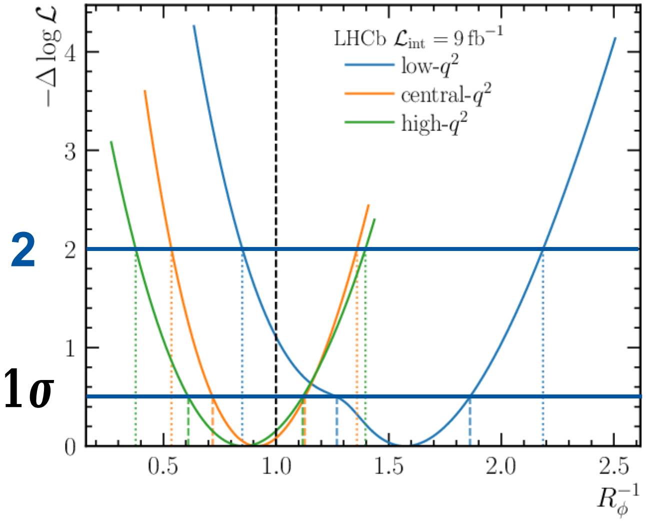


Lepton universality:

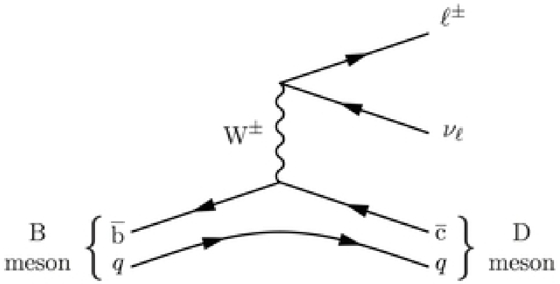
[arXiv:2410.13748]

- First measurement with :
  lower statistics but higher purity due to very narrow resonance
- First LHCb measurement at high above resonances
- **Consistent with SM, much more limited by statistics than**





Semileptonic decays & LFU



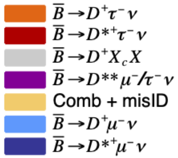
- Semileptonic most common decay mode!
- **Include neutrino in final state ☾ missing mass**
- Still, used at LHCb for
  - -hadron production measurements
  - Mixing and CP violation tests
  - measurements
- **Test lepton universality: vs. rates**

$$R\left(D^{(*)}\right) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

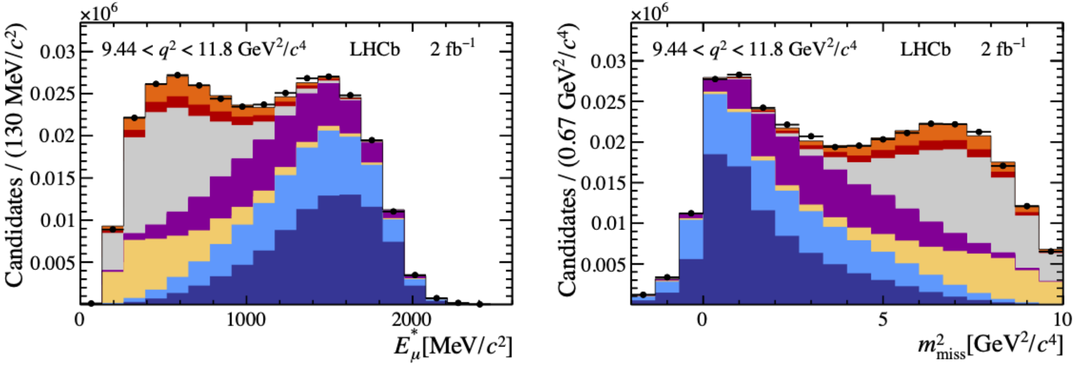
- Precise SM prediction available
- **At least 1 neutrino produced in decay: more missing mass**
- LHCb does or

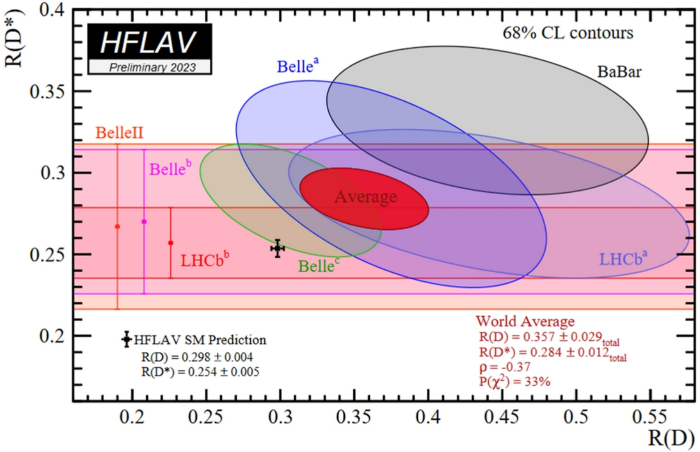
muonic

[arXiv:2406.03387]



- Simultaneous determination with 2015, 2016 data, using
- Multidimensional fit in 3 variables ()



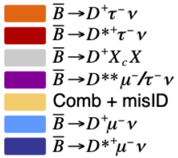


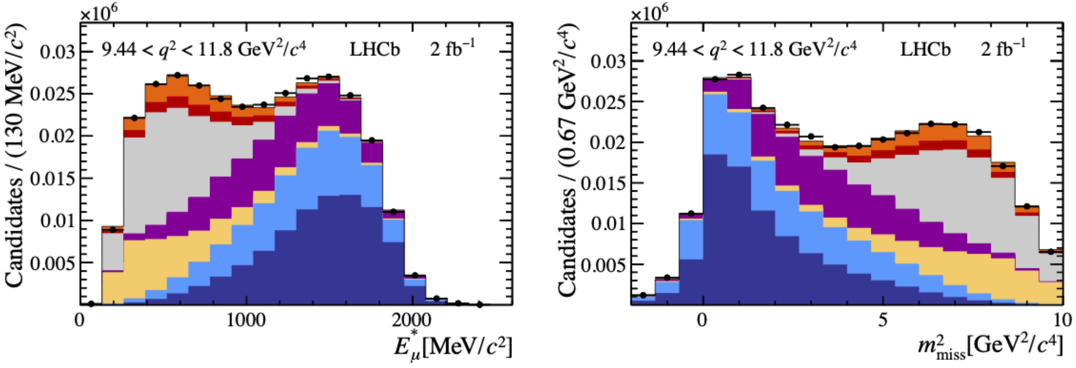
muonic

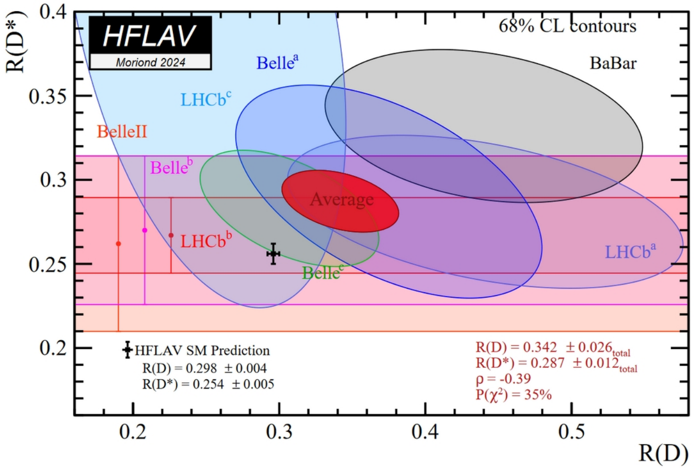
[arXiv:2406.03387]

- Simultaneous determination with 2015, 2016 data, using
- Multidimensional fit in 3 variables ()
-

- By itself 0.8 from SM predictions, preliminary average
- Work on extending LFU tests to full dataset ongoing







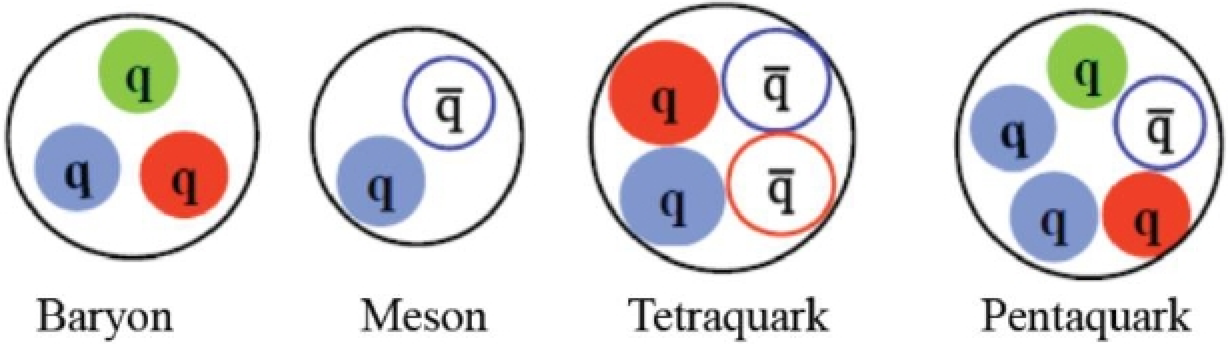
Summary: rare decays, lepton universality

- **Deviations found in rare decays, both and** (branching fraction and angular observables)
- **Lepton universality holds in semileptonic loop-level decays**

  (consistent with New Physics in equal to)
- **Deviations from lepton universality found in semileptonic tree-level decays:**

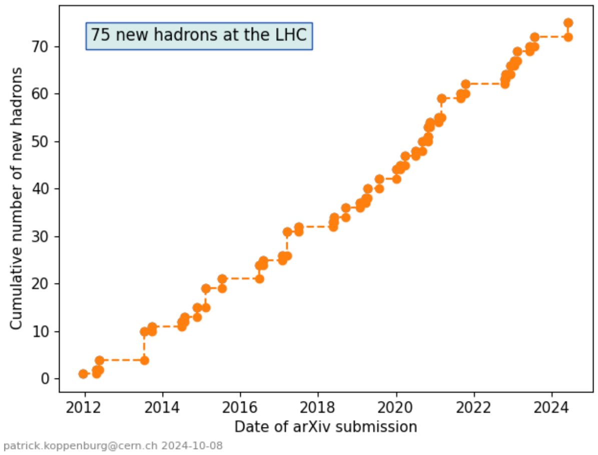
  (consistent with New Physics in only)
- Consistent interpretations possible (with Effective Field Theory)
- Much more I could not show:
  - Charm and strange decays [LHCb-PAPER-2024-047, in preparation]
  - Radiative () decays [LHCb-PAPER-2024-030, in preparation]
  - Lepton Flavour / Lepton Number / Baryon Number Violation [arXiv:2405.13103]

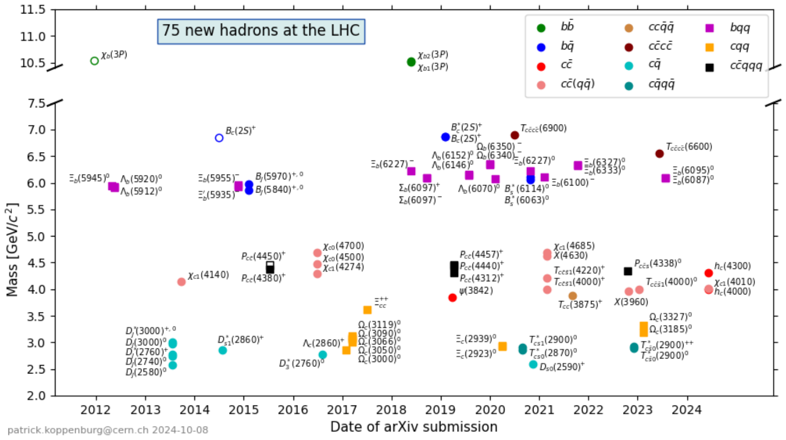
Spectroscopy and exotic hadrons



Spectroscopy

- Many new hadrons discovered at LHC: 75 total, 67 at LHCb





Spectroscopy

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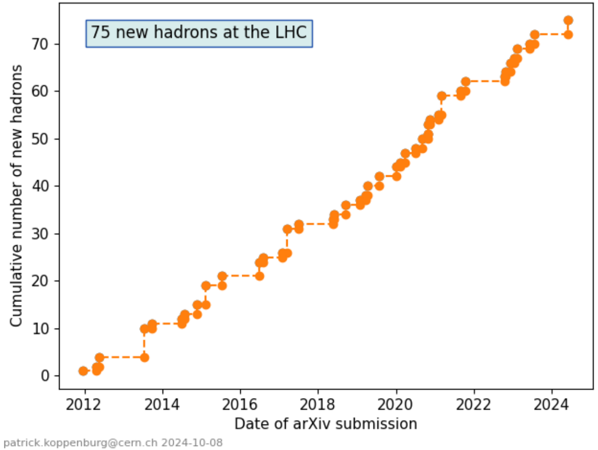
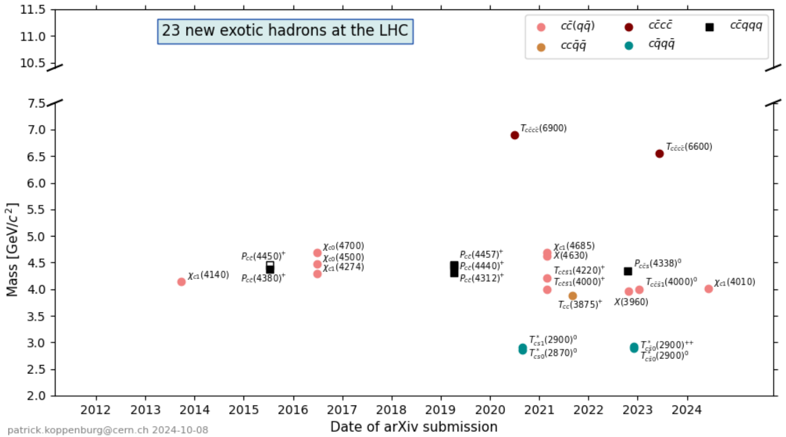
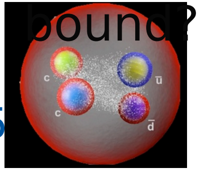
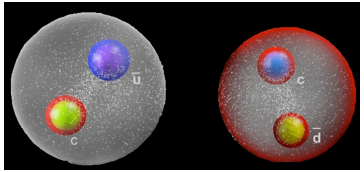




- **23 new hadrons are exotic: (partially) four- or five-quark states**
- Nature of states is unclear: tightly (tetra/pentaquark) or loosely bound (hadronic molecule)?
- Key to study of non-perturbative QCD
- New naming scheme proposed by LHCb: [arXiv:2206.15

tightly or loosely-bound?

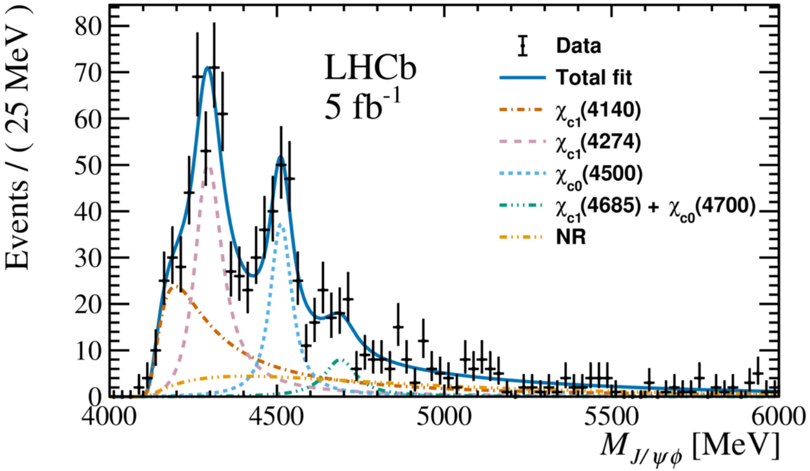




states in diffractive processes

[arXiv:2407.14301]

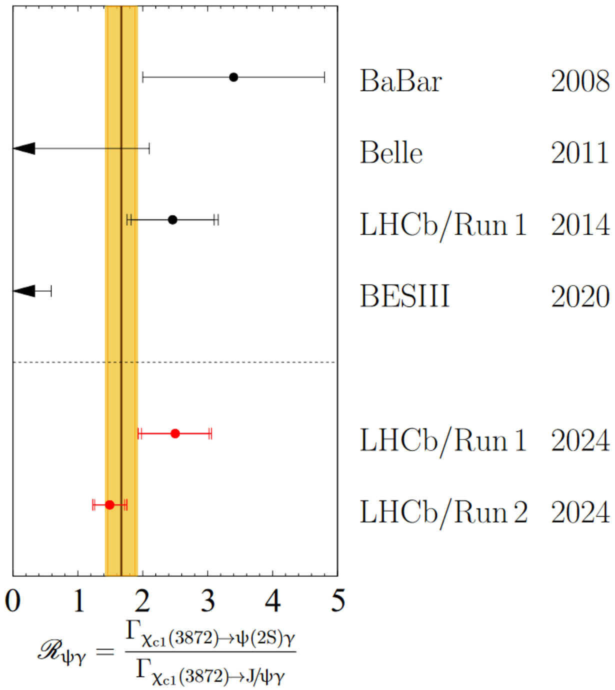
- Measurement of cross section in pp interactions with no other activity: diffractive processes
- Surprisingly, observed resonant structures in mass spectrum; evidence for (), observation of ()
- Consistent with previous “charmonium-like” states found in decays!
- First such a correspondence apart from state



: what state is it?

[arXiv:2406.17006]

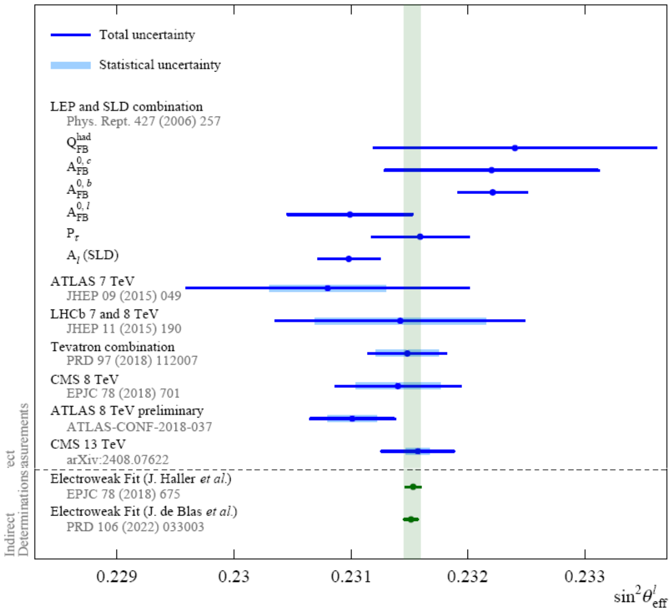
- best-known non-conventional state (“charmonium-like”), discovered 2003
- Existence at threshold of mass suggests loosely bound molecule
- Prompt production in hadron collisions suggests conventional -state
- This paper: measure
- Generally larger than 1 for non-molecular states, which is exactly what is measured!
- Looks like has a significant compact component, either or tetraquark



Weak mixing angle at LHCb

- Weak mixing angle
  fundamental parameter of SM
- Previously tested at LEP; since 2015, LHC started to contribute
- Strategy: measure
  from forward-backward asymmetry
  in decay, in bins of
  difference in pseudorapidity

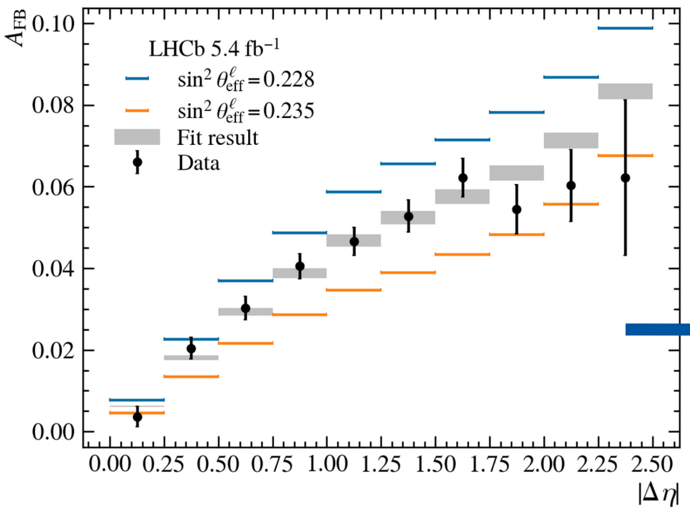
[arXiv:2410.02502]

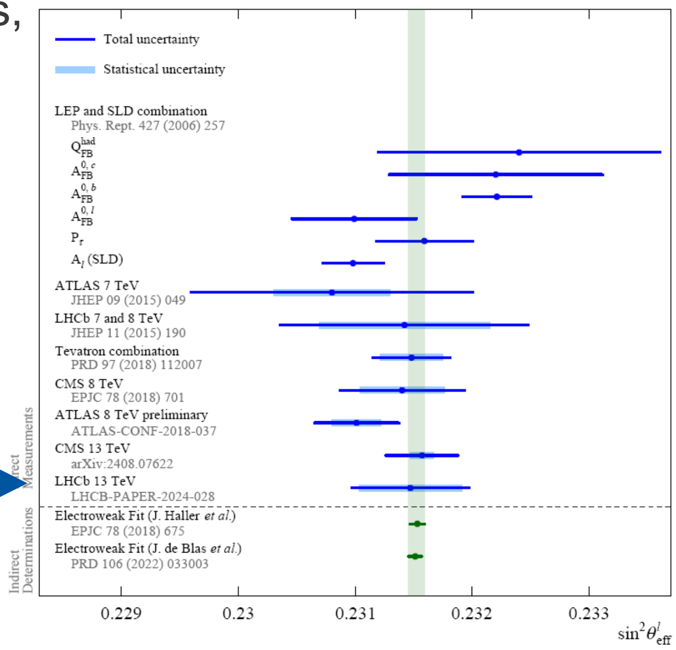


Weak mixing angle: results

[arXiv:2410.02502]

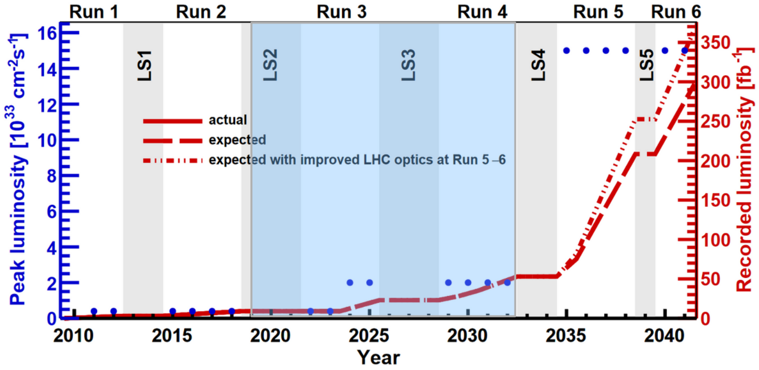
- LHCb finds , resp.
  statistical, systematic, theoretical (PDF) uncertainties, **consistent with other estimates**
- **Improvement in precision of previous LHCb measurement by more than factor 2**
- Still limited by statistical uncertainties!





LHCb detector upgrades

LHCb Upgrade 1



Goals:

- **Luminosity increase by factor 5**;
  collect ~ by 2026, by 2033
- **Hardware trigger removed**
  2x efficiency in hadronic/electronic modes

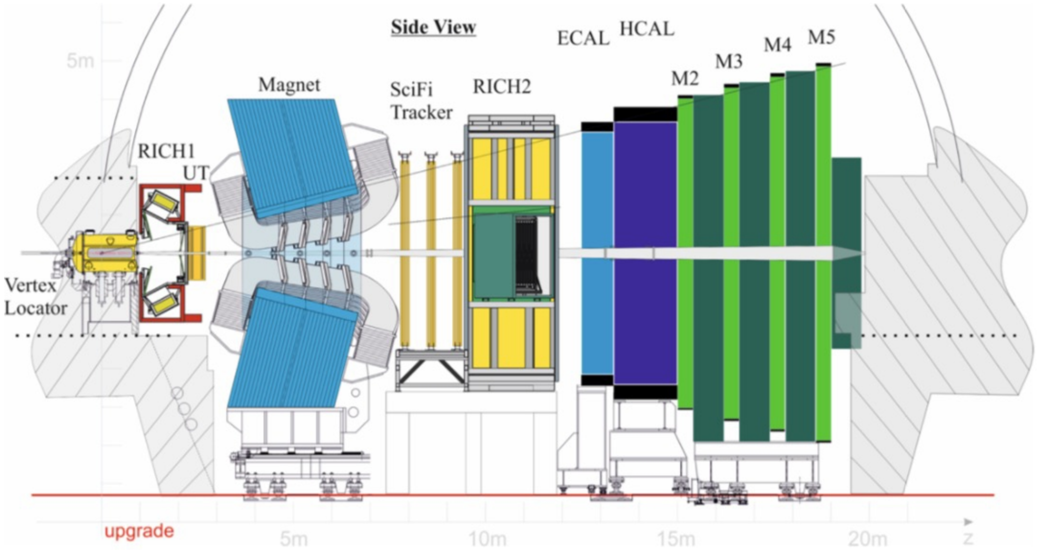
Required

- Upgrade of most detectors, **fully replaced tracking detectors** (higher granularity)
- Full readout and DAQ replacement to read out detector at 40 MHz

LHCb Upgrade 1 detector

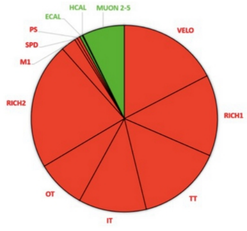
A whole new detector!

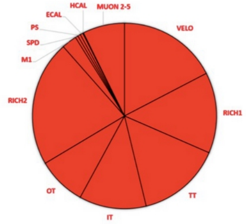
CERN-LHCC-2011-001



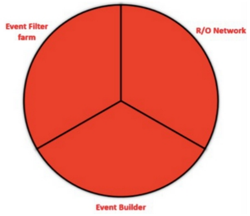
Detector channels

Readout





DAQ



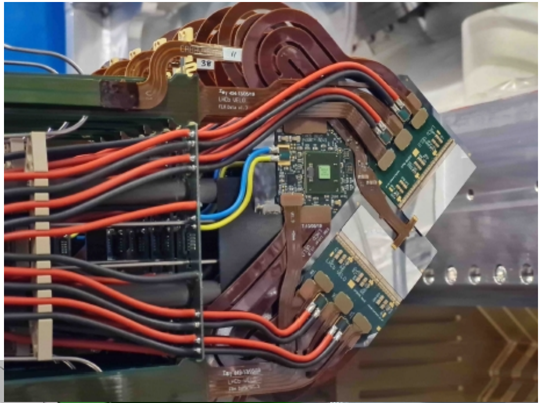
VELO

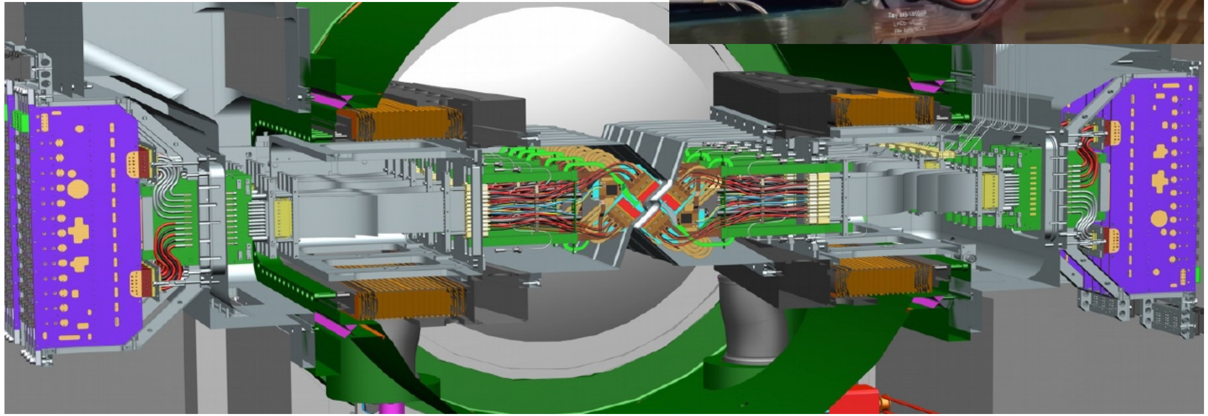
CERN-LHCC-2013-021

New pixel detector (replacing strips)

- Within vacuum of LHC beam pipe; 2 moveable halves (5.1 mm from beam closed, 30 mm open)
- Dedicated RF foil for protection
- Very radiation hard
- Data rate: 3 Tbit/s

Performing well now, after recovery from January 2023 incident





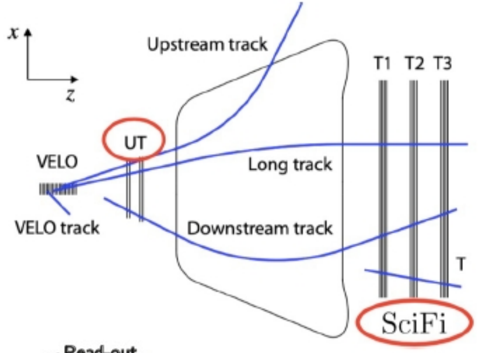
SciFi

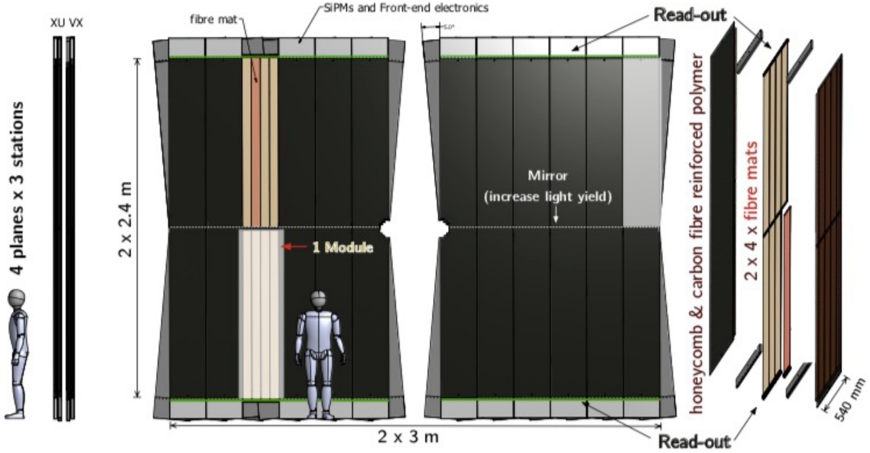
CERN-LHCC-2014-001

Scintillating **Fi**bretracker developed for high occupancy

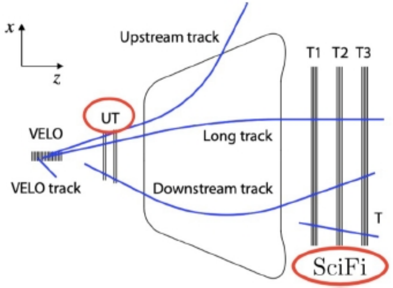
- Spatial resolution 80 µm
- Hit efficiency > 99%

Performing well, with occupancy even higher than in design specifications



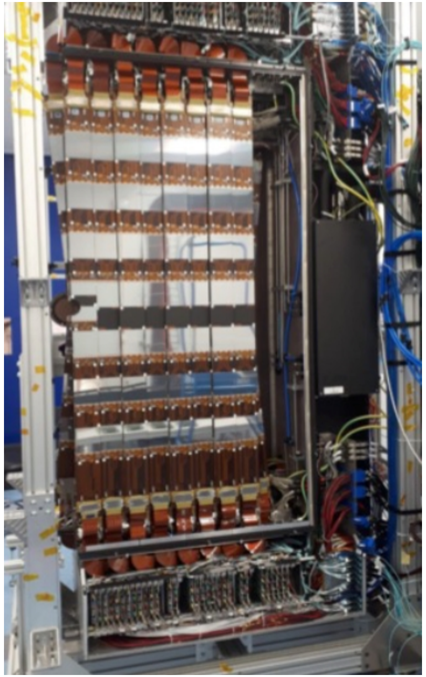


Upstream Tracker



CERN-LHCC-2014-001

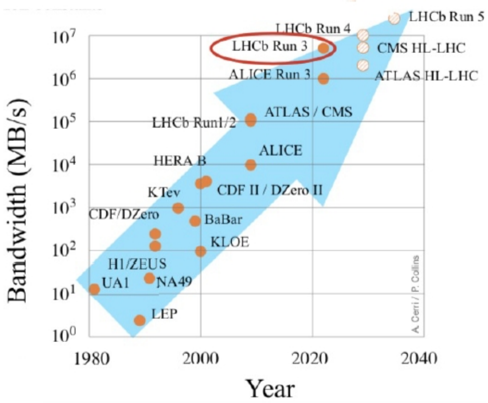
- 4 planes made of **silicon strips** with finer segmentation and improved acceptance
  - Fast pT determination for track extrapolation, reduction of ghost tracks
  - Detect long-lived particles decaying after VELO ()
- **Successfully running together with rest of detector**

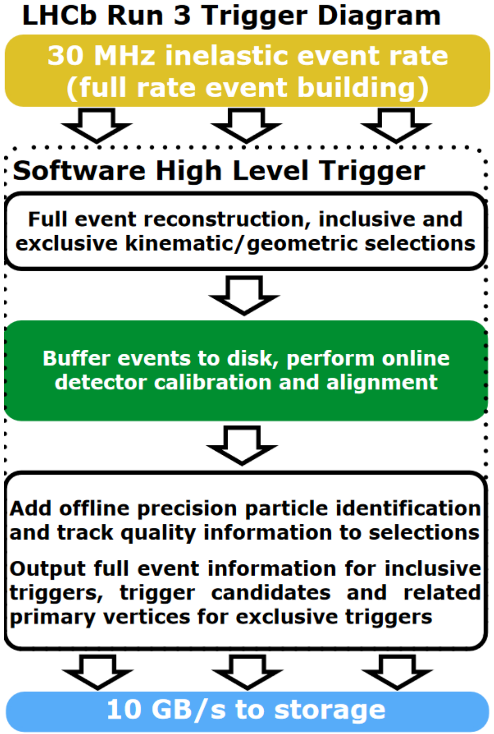


Trigger

CERN-LHCC-2014-016
CERN-LHCC-2020-006

- All subdetectors read out at 30 MHz – Real Time Analysis with software trigger
- HLT1 reduces 30 MHz to 1 MHz with partial event reconstruction (tracking, vertexing, muon ID), based on GPUs in new data centre
- Calibrate detector in "real-time" such that HLT2 u best-quality tracking, PID
- Hadronic yield is 2x that of Run 2
- **40 Tbit/s is highest throughput of all LHC**

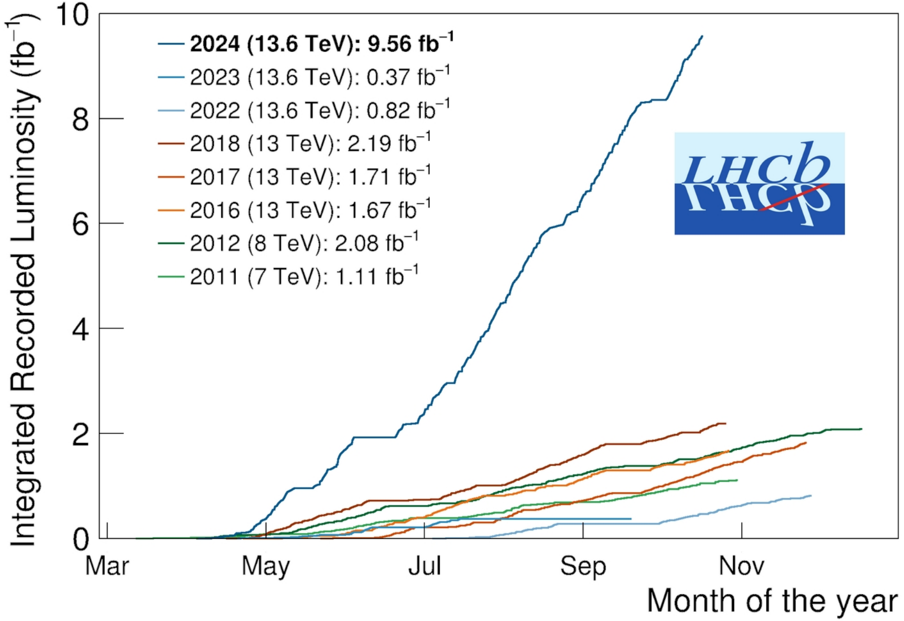




And how was 2024?

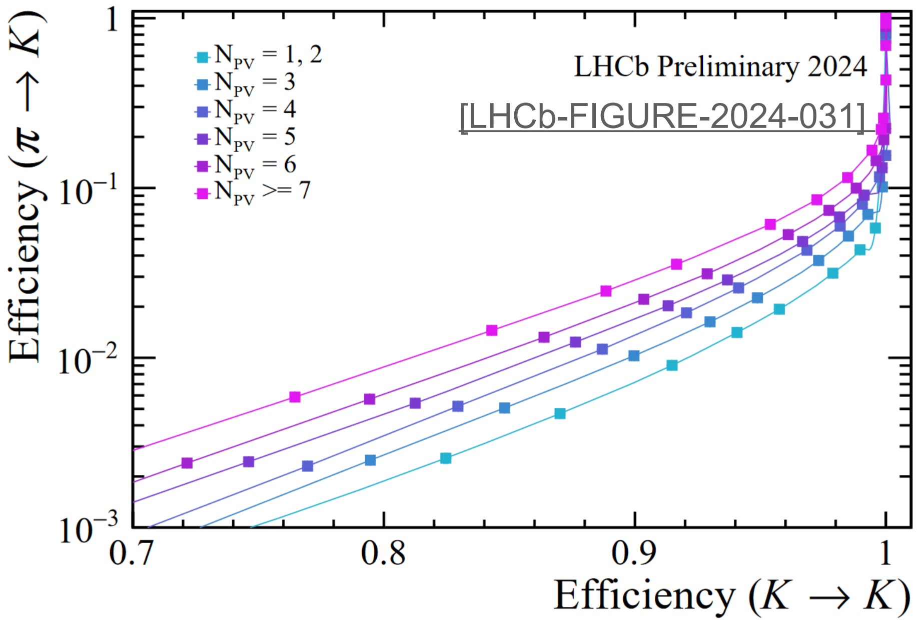
- A lot of hard work finally yielded fruit in 2024
- **Total of 9.56 collected, same as all of Run 1 and 2!**
- **Note: some of this data was affected by start-up issues** (until about mid-June)
- How does performance look like in good quality data?

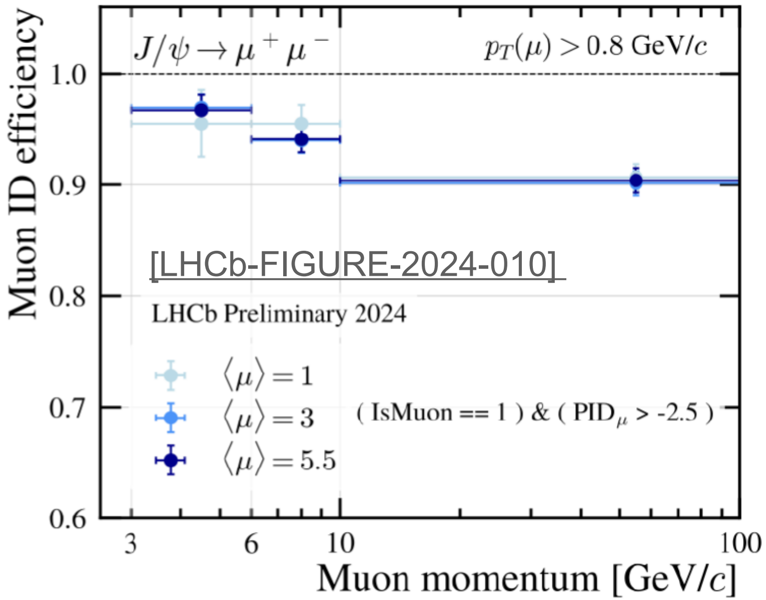
Link to luminosity plots



Upgrade performance: particle ID

- Particle ID holding up under harsher Run 3 conditions

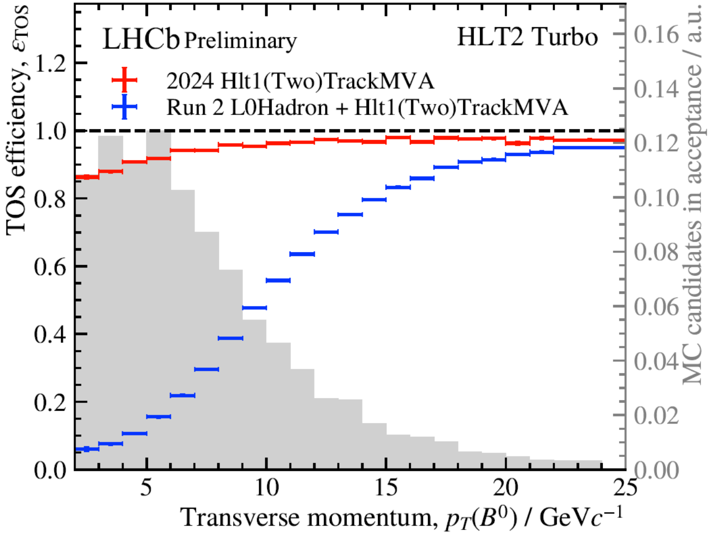




Upgrade performance: trigger

- Trigger performance much better for hadrons…

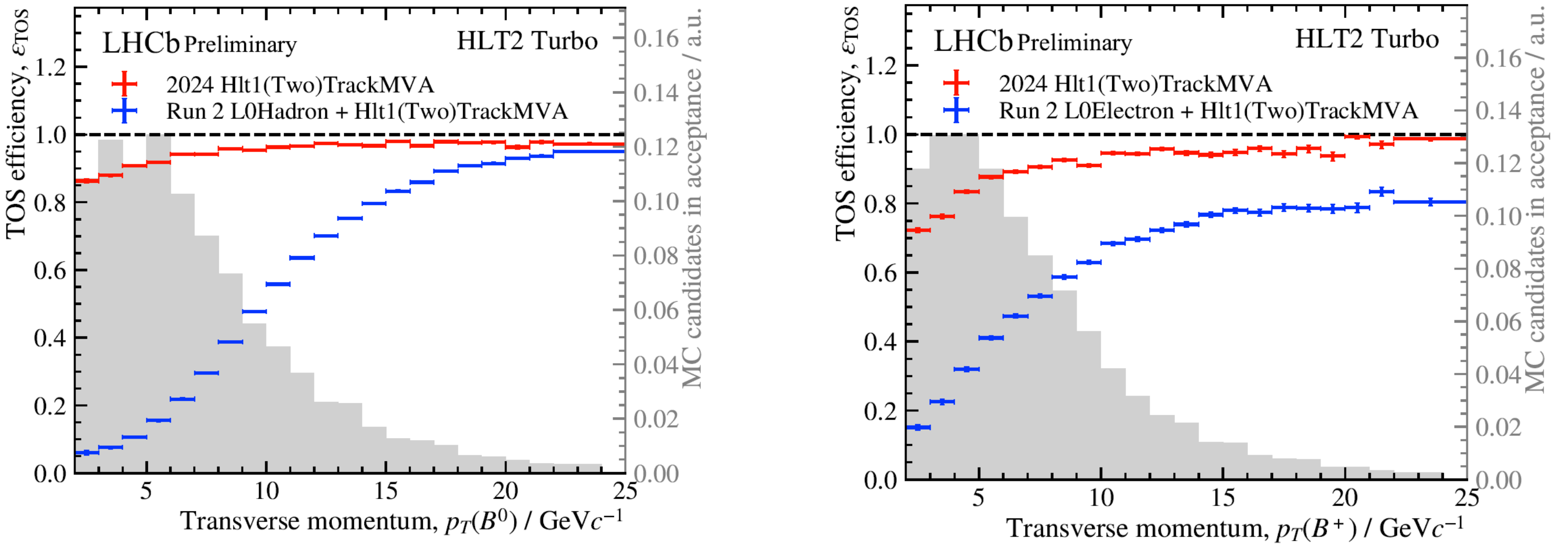
[LHCb-FIGURE-2024-030]



Upgrade performance: trigger

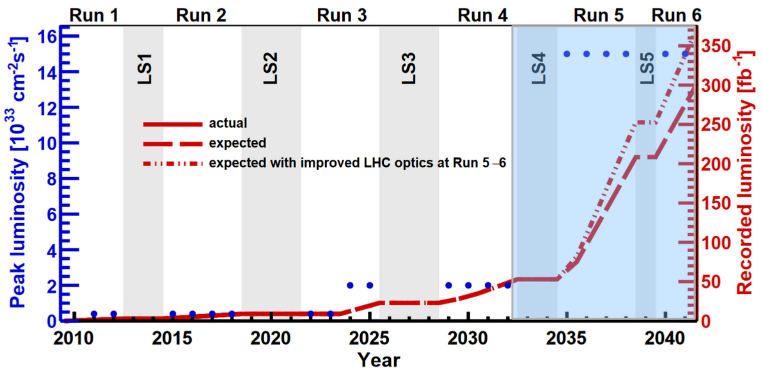
- Trigger performance much better for hadrons… and electrons!

[LHCb-FIGURE-2024-030]



Upgrade 2

Goal: increase of luminosity by facto
aim for 300 fb-1 after Run 6



Upgrade 2

Goal: increase of luminosity by factor aim for 300 fb-1 after Run 6

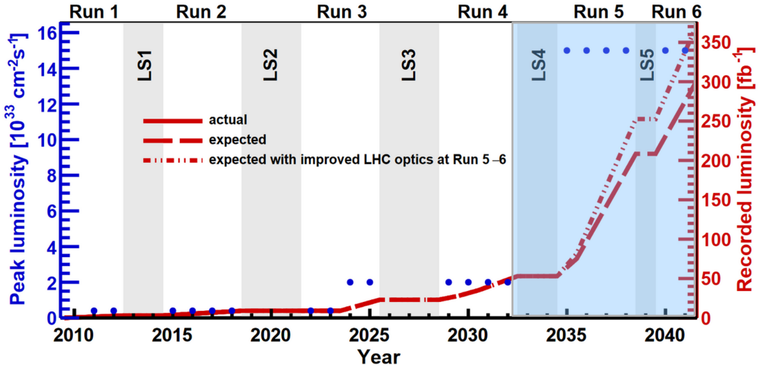
- Will reach unprecedented precision

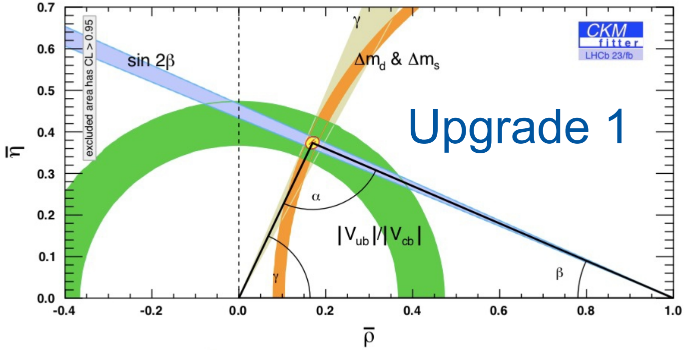
Detector environment will be challeng

- Pile-up ~40 interactions
- 200 Tb/s of produced data

Detector upgrades: performance in harsher environment

- Better granularity
- Fast timing (~10 ps)
- Radiation hardness





Upgrade 2

Goal: increase of luminosity by factor 7 aim for 300 fb-1 after Run 6

- Will reach unprecedented precision

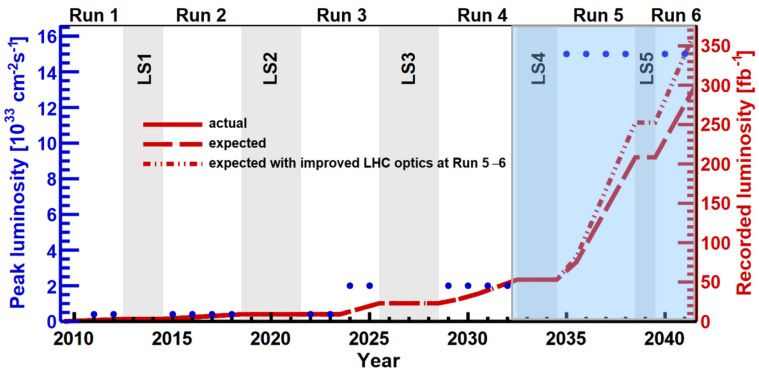
Detector environment will be challengi

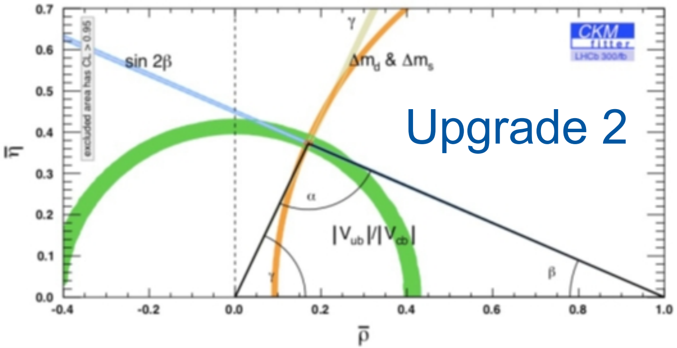
- Pile-up ~40 interactions.
- 200 Tb/s of produced data.

Detector upgrades: performance in harsher environment

- Better granularity
- Fast timing (~10 ps)
- Radiation hardness

Large step, e.g. in constraining unitarity triangle





Conclusions

- **LHCb achieved excellent performance over Runs 1 and 2**, collecting at

- **Unitarity triangle tested to high precision;** Standard Model still holds on
- Rare decays and lepton universality tests strongly probe new heavy particles; **eagerly awaiting new results to resolve hints of New Physics**
- **Fantastic set of spectroscopy and electroweak results, many of which were never expected**

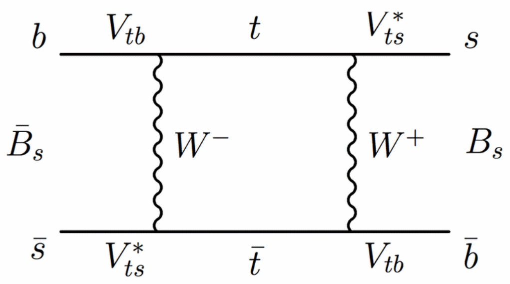
- **LHCb Upgrade 1 detector running well! Collected 9.56 in 2024, more than total Run 1 and 2 dataset; most of it should be useful for physics analysis**
- Work for Upgrade 2 is ongoing to make the ultimate step in precision

¡Gracias por su atención!

Meson mixing

- Neutral flavoured mesons () only have non-zero quantum numbers that are not invariant for weak interaction!

- Very dependent on meson system
- Described with Hamiltonian, oscillation frequency and lifetime difference



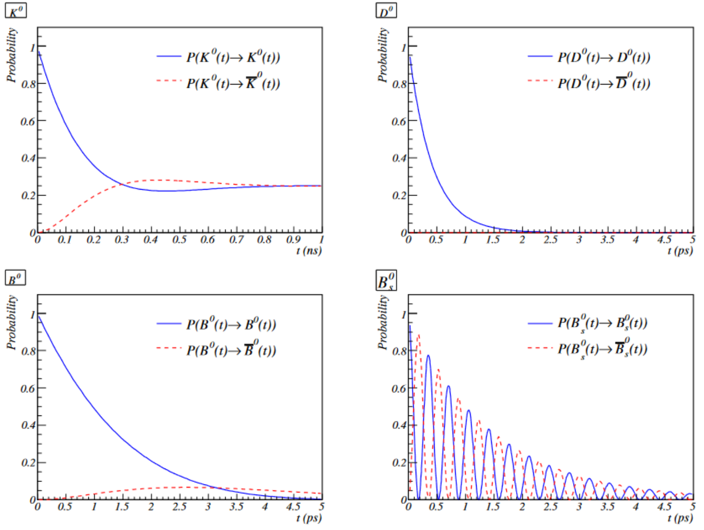
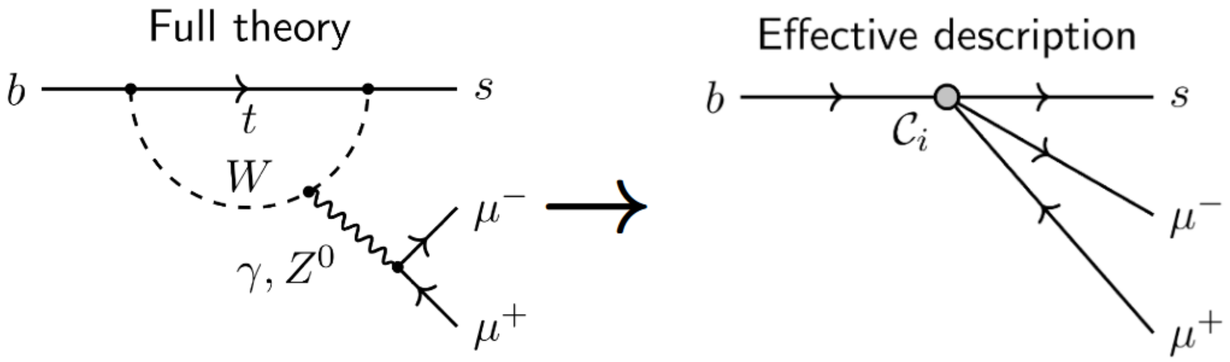


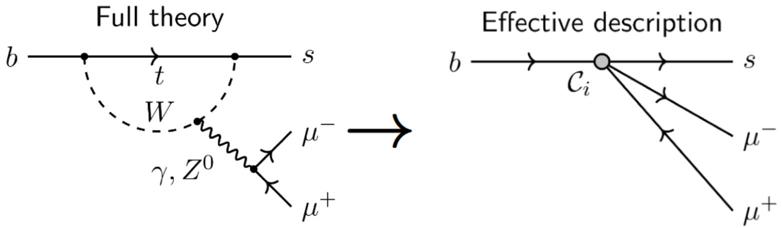
Figure 3.3: *If one starts with a pure P^0-meson beam the probability to observe a P^0 or a $\bar{P}^0$-meson at time t is shown,* $\text{Prob}(t) = \frac{e^{-\Gamma t}}{2}\left(\cosh \frac{1}{2}\Delta\Gamma t \pm \cos \Delta m t\right)$.

Effective field theory

- Are anomalies consistent with each other?
- **Use effective field theory at B-hadron scale, just like beta decay four-point interaction!**



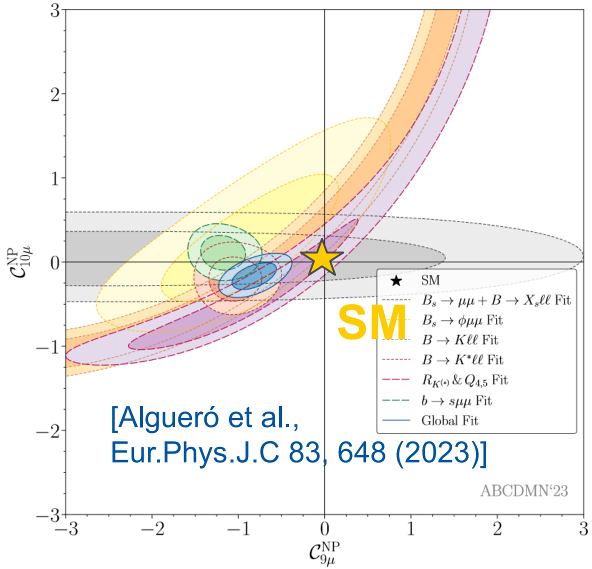
Effective field theory



- An EFT probes different couplings:

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i \mathcal{C}_i \mathcal{O}_i$$

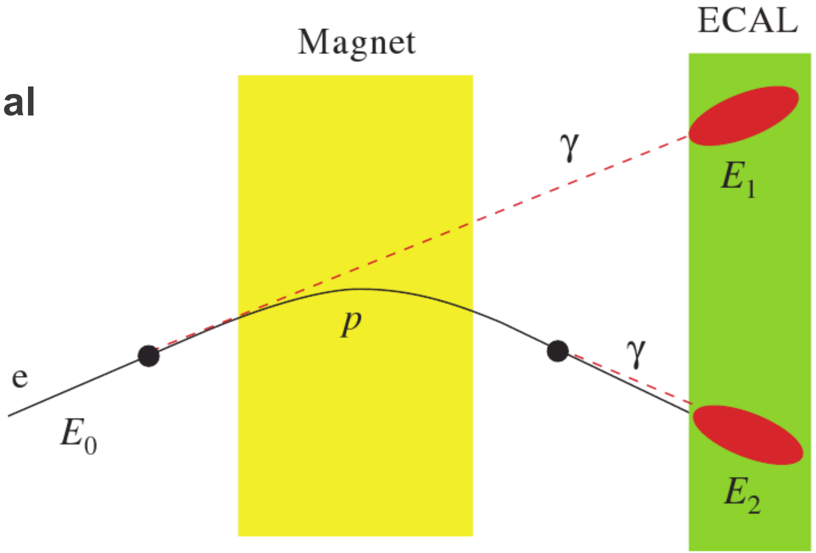
- Fermion operators , Wilson coefficients
- Grouped by leptonic current: (SM,NP)
  - photon penguin
  - (axial) vector
  - (pseudo) scalar
- Note: operators, coefficients with opposite quark current handedness from SM marked with , (negligible in SM)
- **Global fits indicate consistent deviation: universal reduction in** ?



Measurements with electrons at LHCb

[arXiv:2103.11769]

- **Electrons provide extra challenge in LHCb, because of significant bremsstrahlung in material**
- If bremsstrahlung is emitted before magnet, momentum is underestimated
- Recover bremsstrahlung by searching for photon clusters in calorimeter
- If found, correct electron momentum
- **Still, mass shape worse for electron modes**



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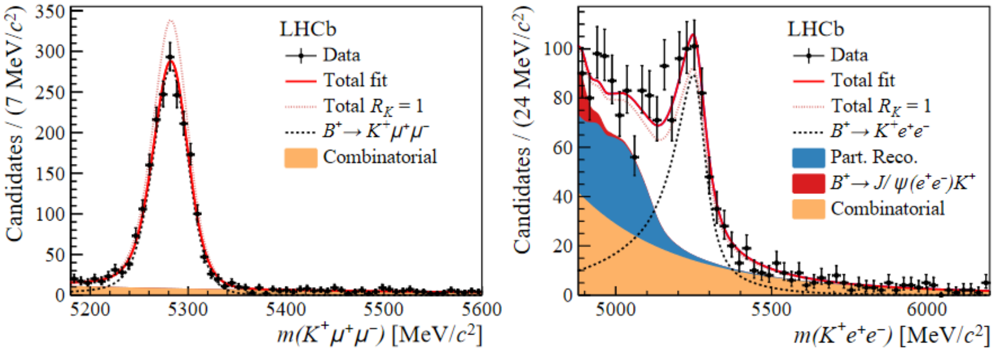
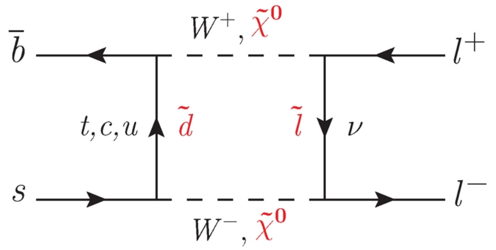
From previous result, LHCb [PRL122(2019)191801]



- **Additionally, electrons more difficult for hardware trigger (than muons)**
- Electron sample divided based on hardware trigger category: electron, rest-of-event, or hadron trigger

Leptonic: decays

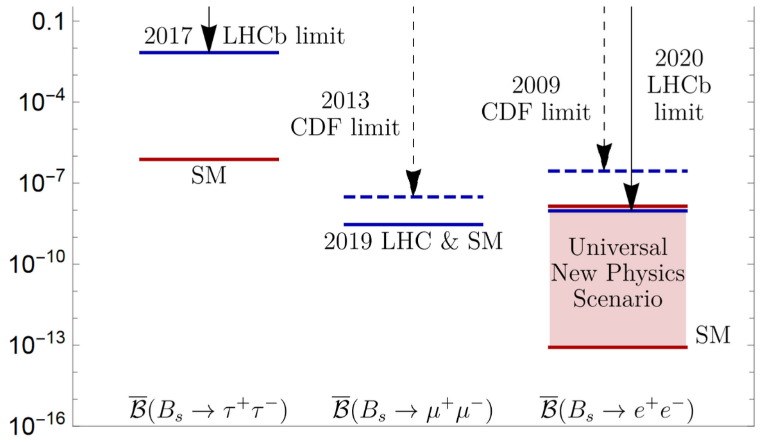
- Excellent decays to study transition
  - **Precise theory predictions (4% uncertainty)**
  - Helicity suppression: **very rare in SM**
  - **Scalar contributions not helicity suppressed enhanced relative to SM!**
- Only in current experimental reach



Fleischer et al., JHEP 05 (2017) 156

- Predictions

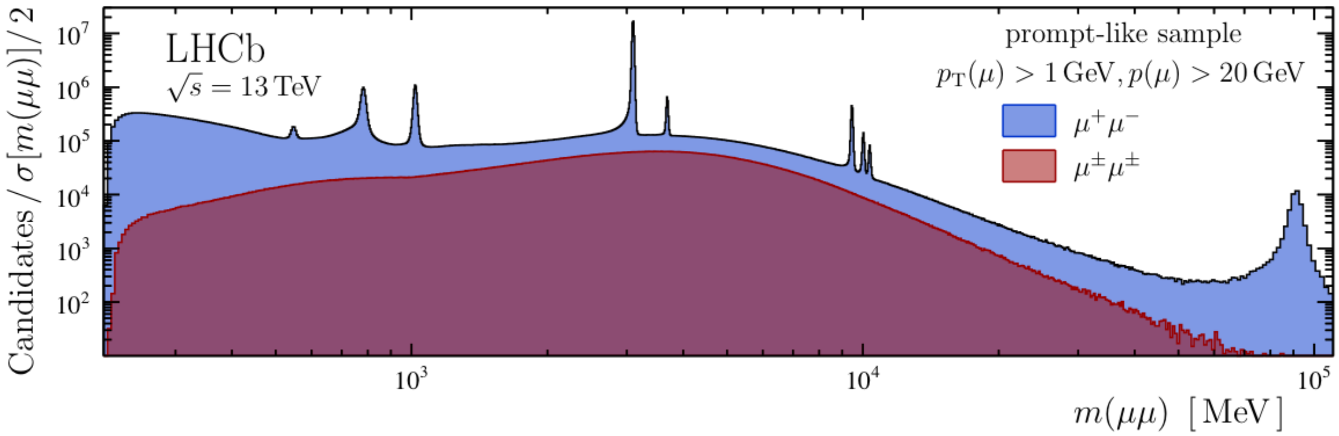
Bobeth et al. PRL 112 (2014) 101801
Beneke et al. JHEP 10 (2019) 232

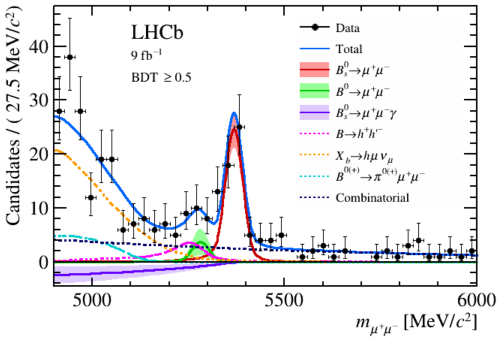


  - (extra clean test)

Searching for

[PRL 120 (2018) 061801]



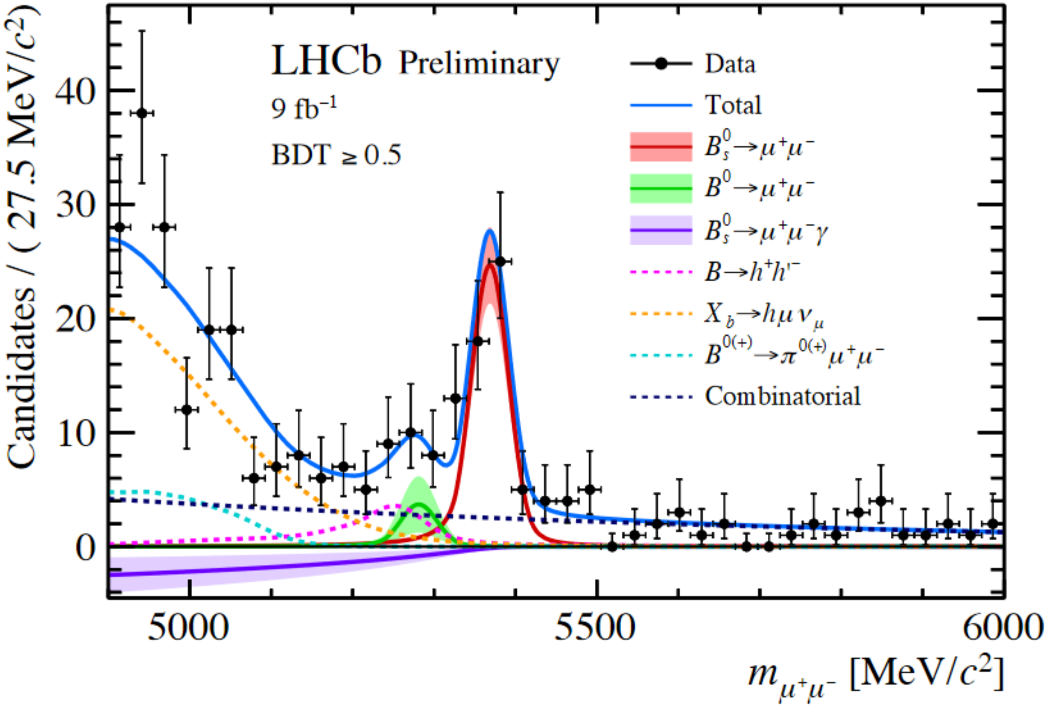


Branching fraction of

[LHCb-PAPER-2021-007]

-
  with significance > 10
- **Similar uncertainty to previous LHC combination**

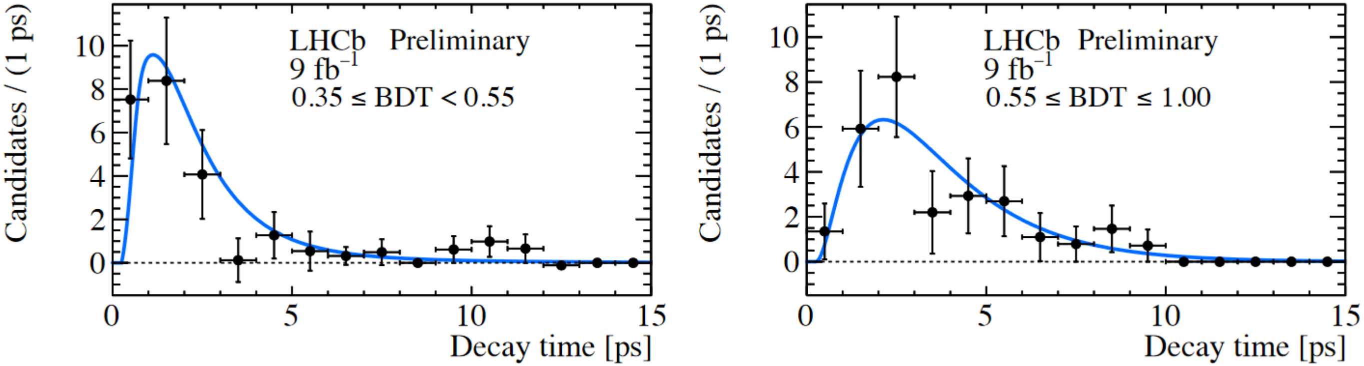
- and
  compatible with background-only at 1.7, 1.5
- Measurement of
  is testing CP state of decay (more data needed)



Effective lifetime

[LHCb-PAPER-2021-007]

- decay proceeds through CP-odd state in SM;
- CP-even, CP-odd states of have different lifetime ☾
  measure effective lifetime to test CP-even contribution, scalar NP
- **ps** (previously ps)
- 1.5 sigma from SM2.2 sigma from extreme non-SM
- **Run 3 data needed to start providing significant constraints**



Plume and SMOG

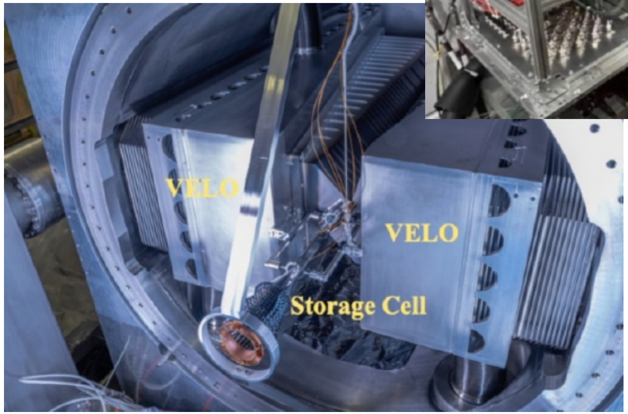
CERN-LHCC-2021-002

Probe for LUminosity MEasurement (PLUME):
new dedicated luminometer

- Quartz tablets + PMTs for online+offline per- bunch luminosity measurement
- **Running continuously, accurate luminosity estimate**

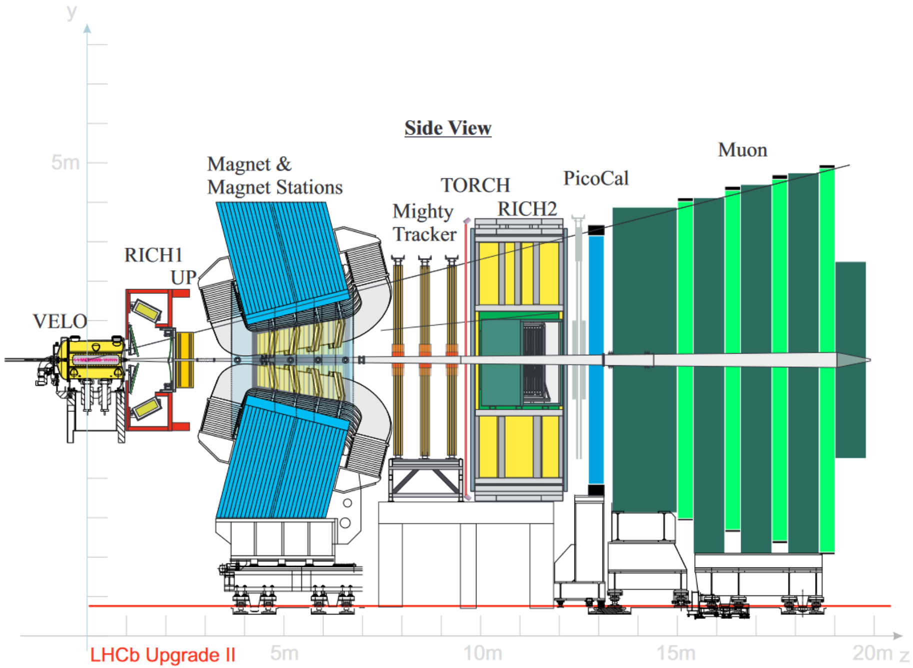
SMOG2 gas system for fixed-target physics

- New storage cell for gas upstream of nominal interaction point
- Gas density increased by up to two orders of magnitude → much higher luminosity
- Gas targets: He, Ne, Ar
  (+ possibly H_2, D_2, N_2, Kr, Xe)
- Simultaneous p-p and p-gas data taking
- **Running smoothly and data taken in parallel**



CERN-LHCC-2019-005

LHCb Upgrade 2 detector



Advantages of -hadrons

- Heaviest quark forming hadrons decaying weakly
- Many possible decay modes,
  and even more observables!
  - Very rich spectrum of possibilities!
  - O(600) modes (incl. searches) for , O(100) for
- Weak decay of -hadron crosses generations:
  - No large branching fractions (largest)
  - Sensitive to small SM and New Physics effects!
- Lifetime and boost at LHCb give decay length of ;
  precise lifetime measurement possible