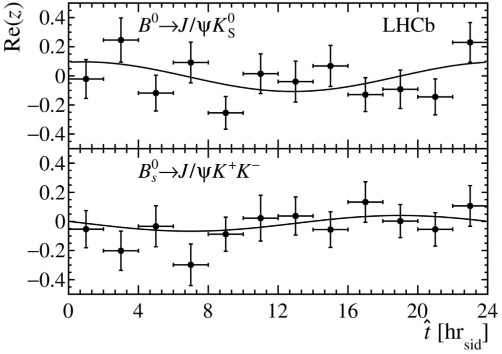
# Review of Lorentz Invariance Violation constraints in the b-sector from LHCb

*Probing space-time properties at HEP experiments*, Belgrade 2023





**Maarten van Veghel**

on behalf of the LHCb collaboration

Nikhef

# How are b-quarks connected to LIV?

- **CPT** violation implies **Lorentz Invariance Violation** (LIV)
  - [Greenberg, PRL 89 (2002)]

- **Mass** and **lifetime** differences between *particle* and *antiparticles* implies CPT violation
- These are / can be *directly* measured, but there is a far more precise way!

***Neutral meson mixing!***

- Some neutral mesons can **oscillate from particle to antiparticle** and back via Weak interaction
- CPTV appears as mass and lifetime differences relative to very small, but known mass and lifetime differences
- Encoded in one complex parameter ***z***

$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2}$$

# Neutral meson mixing and CP / CPT violation

- Due to the particle-antiparticle oscillations, one gets the following type of Hamiltonian

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = H|\psi(t)\rangle. \qquad H = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

- Eigenstates of the Hamiltonian are different from their flavour-specific eigenstates
  - Causes a mass and lifetime splitting
    - **Light and heavy eigenstates dictated by Weak interaction**
      - e.g. for the $B^0$ meson **$10^{-10}$ MeV** level mass splitting
    - These tiny differences enhance CPT violating / LIV effects!

$$|P_L\rangle = p\sqrt{1-z}|P^0\rangle + q\sqrt{1+z}|\overline{P}^0\rangle$$
$$|P_H\rangle = p\sqrt{1+z}|P^0\rangle - q\sqrt{1-z}|\overline{P}^0\rangle$$

$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2}$$

# Neutral meson mixing and LIV

- □ Standard Model Extension (SME)
  - EFT framework with CPT- & Lorentz-violating terms
    - [Kostelecky, PRD55 (1997) 6760]

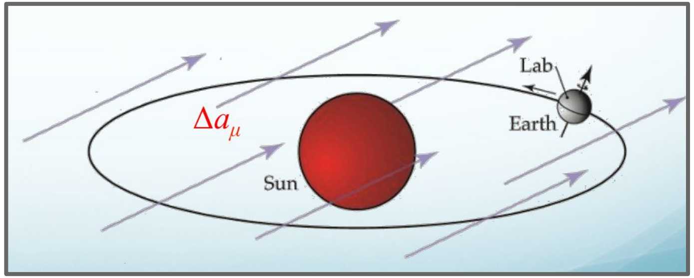
$$z \simeq \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

- One type of parameter has direct connection to quark propagation / mass like term
  - Real four-vector vacuum expectation value
  - Valence quarks have opposite signed terms

$$\mathrm{Re}(z)\Delta\Gamma = 2\mathrm{Im}(z)\Delta m$$

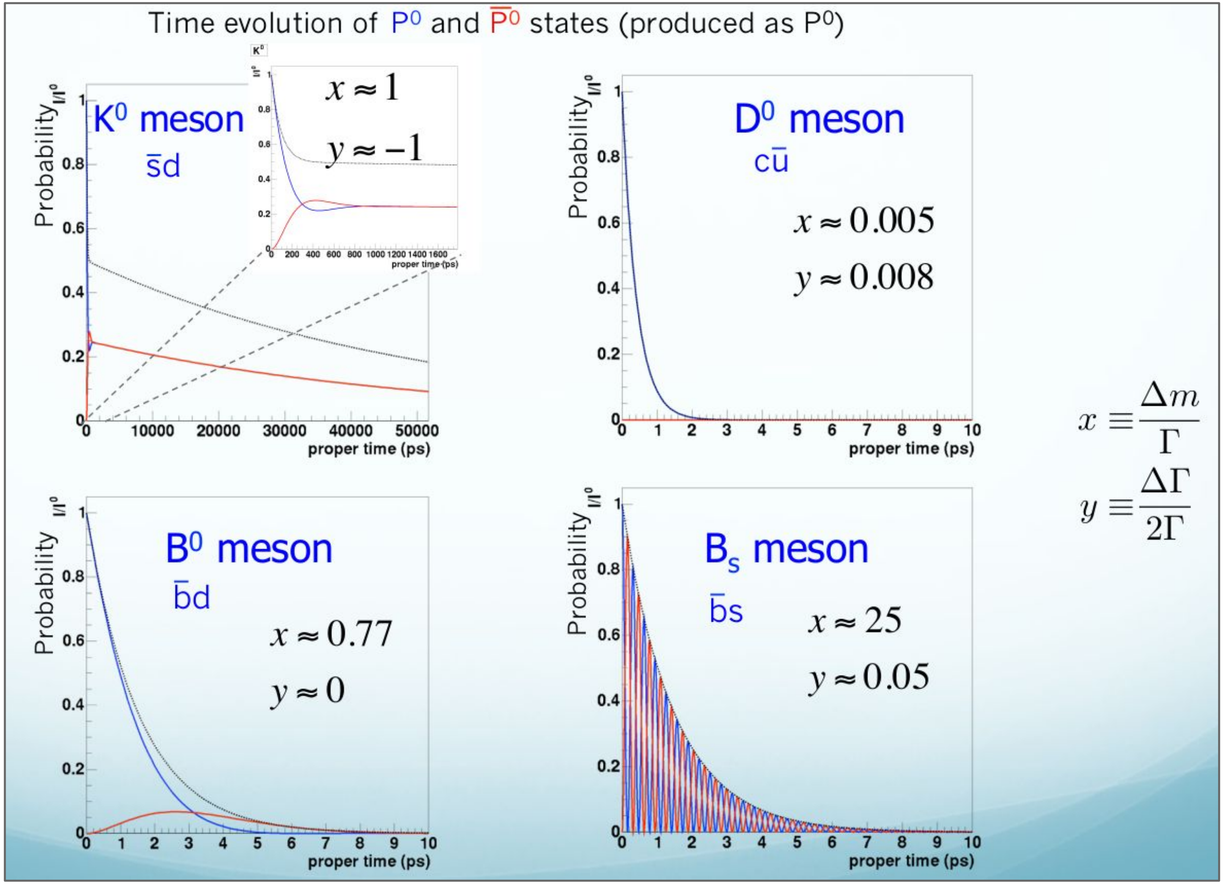
$$\Delta a_0 \equiv a_0^{q_2} - a_0^{q_1}$$

- Real-valuedness gives important experimental constraints
  - Will come back to this
- Four-vector causes LIV
  - ***z*** depends on four-momentum of particle!



# Neutral meson mixing in action

LHCb-TALK-2016-193

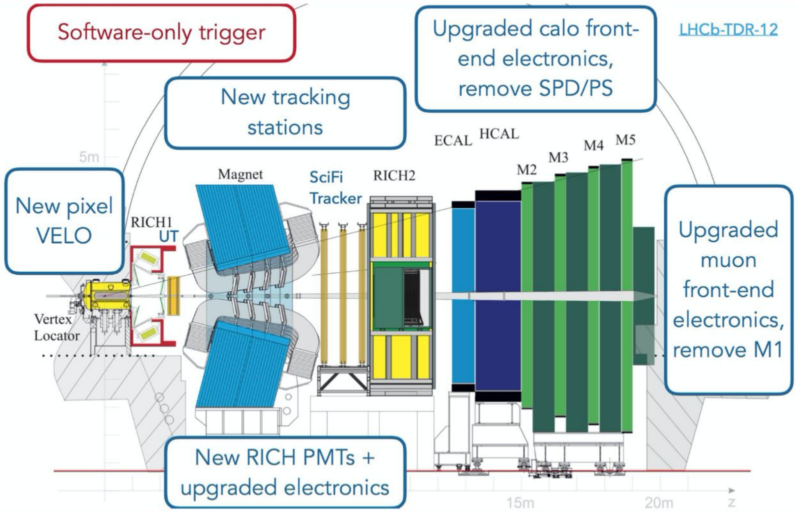



$$x \equiv \frac{\Delta m}{\Gamma}$$

$$y \equiv \frac{\Delta \Gamma}{2\Gamma}$$

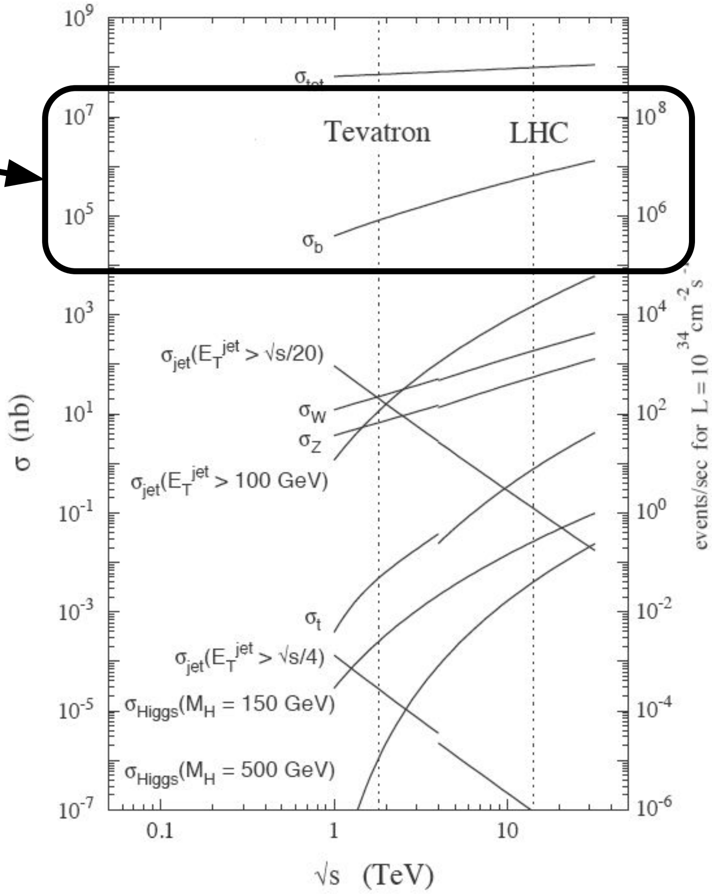
# The LHCb experiment

- **LHCb** studies mainly decays of ***beauty*** and ***charm*** **hadrons** with **high production rates**



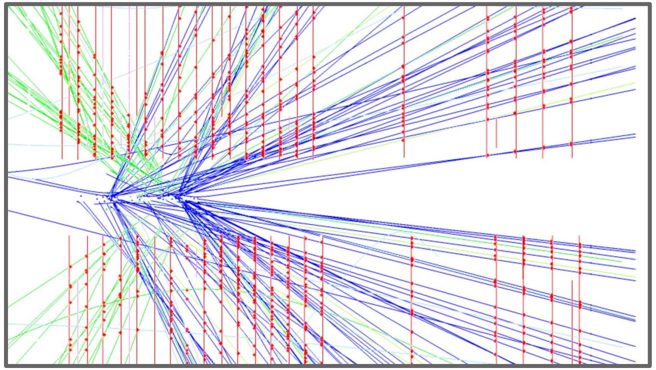

- **LHCb** is a forward spectrometer at the *pp* collider LHC
  - High-precision tracking / vertexing
  - Excellent PID, incl. hadron separation

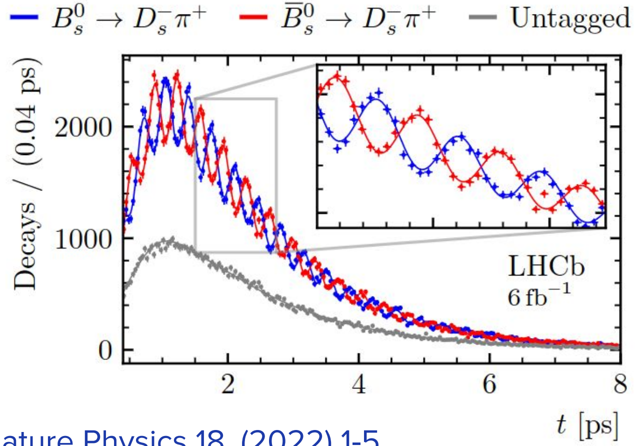
[CERN-LHCC-2003-022](CERN-LHCC-2003-022)

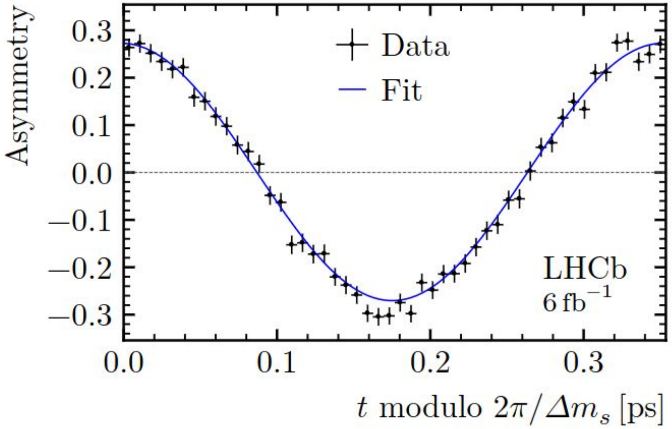


# Lifetime, CP/CPT related measurements at LHCb

- The **Vertex Locator** (VELO) of LHCb has silicon sensors close to interaction to *measure tracks and vertices* of **displaced** heavy-flavour **particles**
- Neutral **B meson mixing** can be studied in **great detail!**
  - Shown here the oscillation frequency / mass difference Bs meson mass eigenstates






Nature Physics 18, (2022) 1-5

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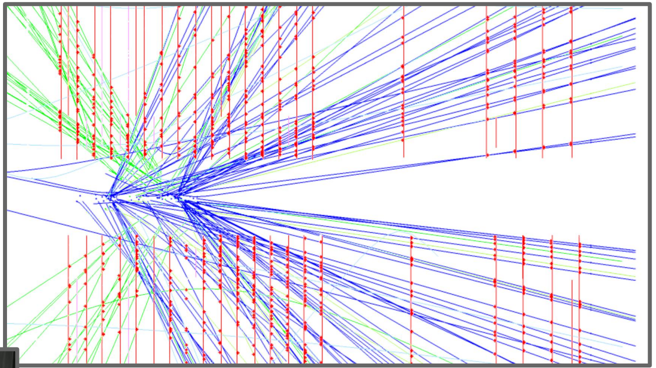

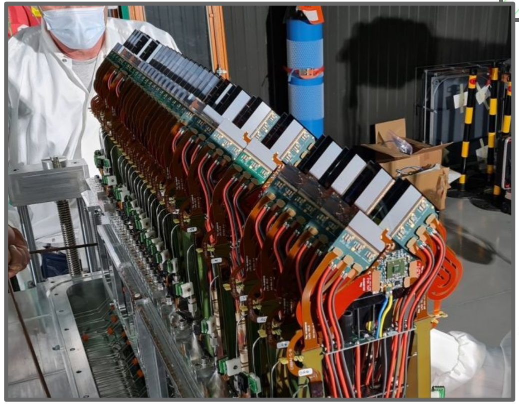

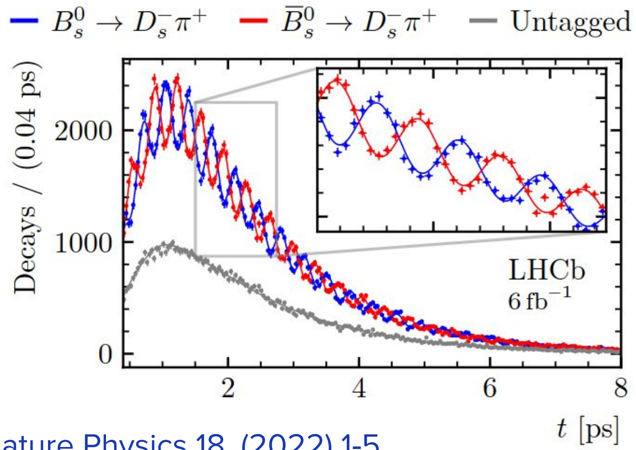


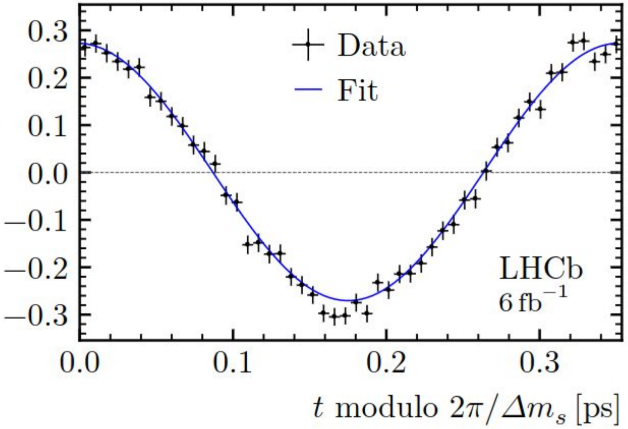


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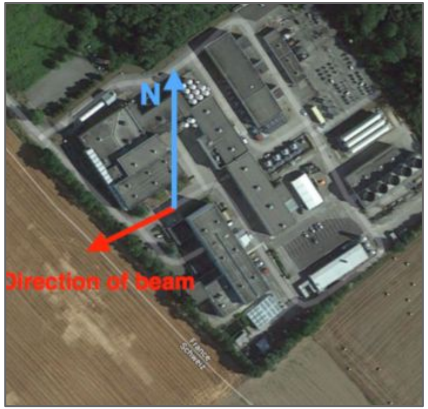
# Location of LHCb



- SME parameters depend on **location** and **direction** of LHCb
    - Location: latitude 46’14’’29’’’ and longitude 6’5’’47’’’
    - Direction of beam: Azimuth $\theta$ = 236’17’’44’’’
        - points upwards by 3.6 mrad
- Angle beam with Earth rotational axis
    - $\cos\chi \simeq -0.38$



# Location of LHCb and sidereal dependence

LHCb-TALK-2016-193

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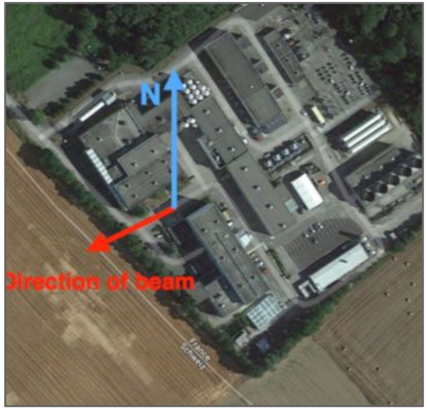
  - Location: latitude 46’14’’29’’’ and longitude 6’5’’47’’’
  - Direction of beam: Azimuth θ = 236’17’’44’’’
    - points upwards by 3.6 mrad
- □ Angle beam with Earth rotational axis
  - cosχ≂ −0.38
- Quite an **optimal** location, close to maximal sidereal sensitivity




$$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m + i\Delta\Gamma/2} \rightarrow$$

$$\mathcal{R}e(z) = \frac{\gamma}{\Delta m}\left[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})]\right]$$

High sensitivity from small $\Delta m$ and $B$ meson boost: $\langle\gamma\beta\rangle \approx 20$

Angle of $B$ meson with Earth rotational axis. $B$ mesons mostly along beam: $\cos(\chi) \approx -0.38$

Sidereal frequency

# Which final states of the decays are best?

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- **Realness of SME parameter** has **important** consequences

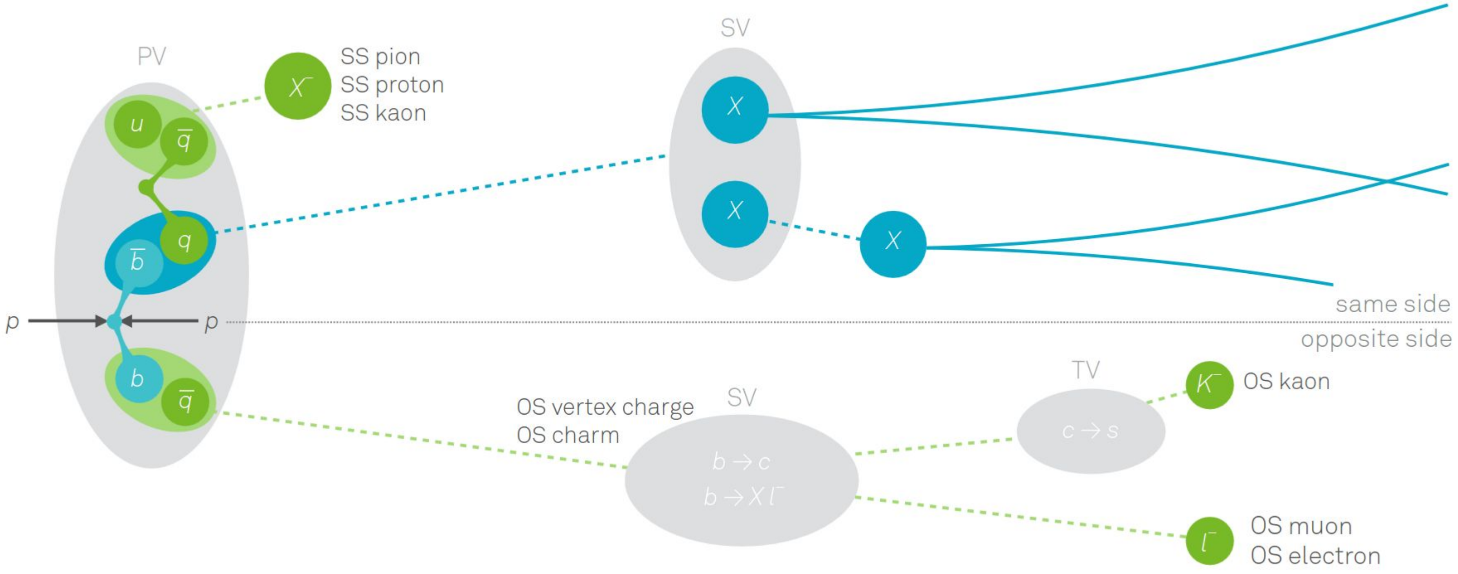
> - *CPT*-violating parameter:
>
> $$z = \frac{\beta^\mu \Delta a_\mu}{\Delta m + i\Delta\Gamma/2}$$
>
> - SME constraint: $\Delta a_\mu$ is real
>   - $\Delta\Gamma$ small for *B* mesons: Re(z) ~400 larger than Im(z)

- Decays to **flavour-specific** final states
  - Sensitive to **imaginary** part of ***z***
- Decays to ***CP* eigenstates**
  - Sensitive to **real** part of ***z***
  - *More specific details on sensitivity later*

$B_s^0 \to J/\psi\, K^+ K^-$ $\quad$ $B^0 \to J/\psi\, K_S^0$

# Asymmetries with CP eigenstates? *flavour tagging*

- Asymmetry between particle being **initially a meson versus anti-meson**
  - Produced in flavour-specific state
- **Disentangle** initial flavour one needs **flavour tagging**
  - **B hadron production** processes correlate initial flavour with underlying event
  - ***Charges of co-produced particles*** reveal initial flavour



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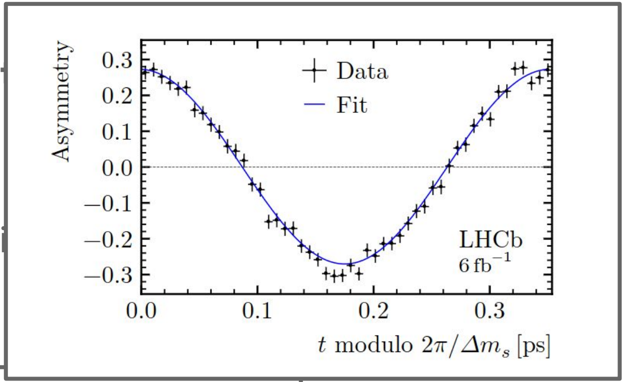


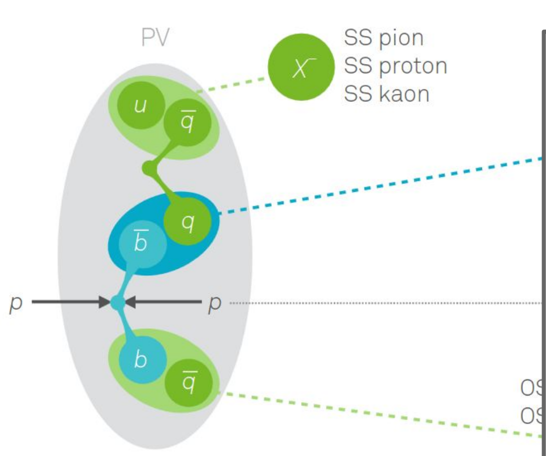


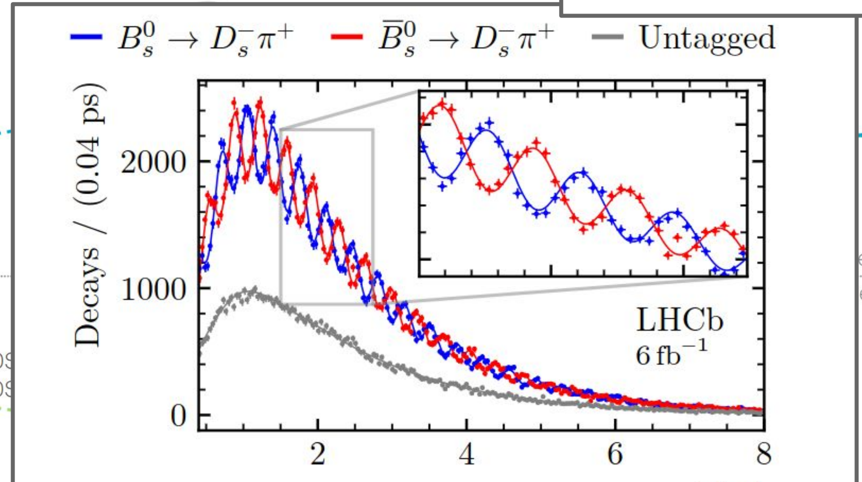


[Nature Physics 18, (2022) 1-5]

# $B^0$ meson

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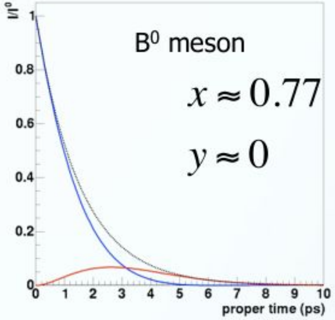
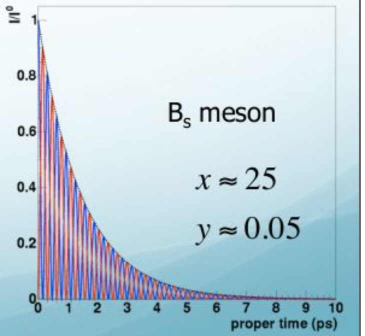
- $B_d$ system: $B_d \rightarrow J/\psi\, K_S$

$$\frac{d\Gamma_f}{dt} \propto e^{-\Gamma t}\Big[\left[1+\zeta D_f \mathcal{R}e(z) - S_f \mathcal{I}m(z)\right]\cosh(\Delta\Gamma t/2) + \left[D_f + \mathcal{R}e(z)(C_f+\zeta)\right]\sinh(\Delta\Gamma t/2) + \zeta\left[C_f - D_f \mathcal{R}e(z) + \zeta S_f \mathcal{I}m(z)\right]\cos(\Delta m t) - \zeta\left[S_f - \mathcal{I}mz(C_f+\zeta)\right]\sin(\Delta m t)\Big]$$




- $B_s$ system: $B_s \rightarrow J/\psi\, \varphi$
  - More complicated
    See next slide...



# $B^0_s$ meson

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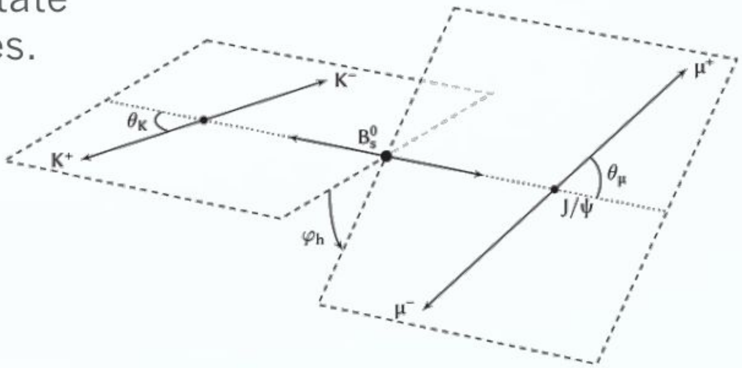
- *CP* eigenvalue of final state depends on decay angles.

$$B_s^0 \to J/\psi\, K^+ K^-$$




- Four "helicity" states → ten terms (including interferences)

$$\frac{\mathrm{d}^4\Gamma_{J/\psi\, K^+K^-}}{\mathrm{d}t\,\mathrm{d}\vec{\Omega}} \propto \sum_{k=1}^{10} h_k(t) f_k(\vec{\Omega})$$

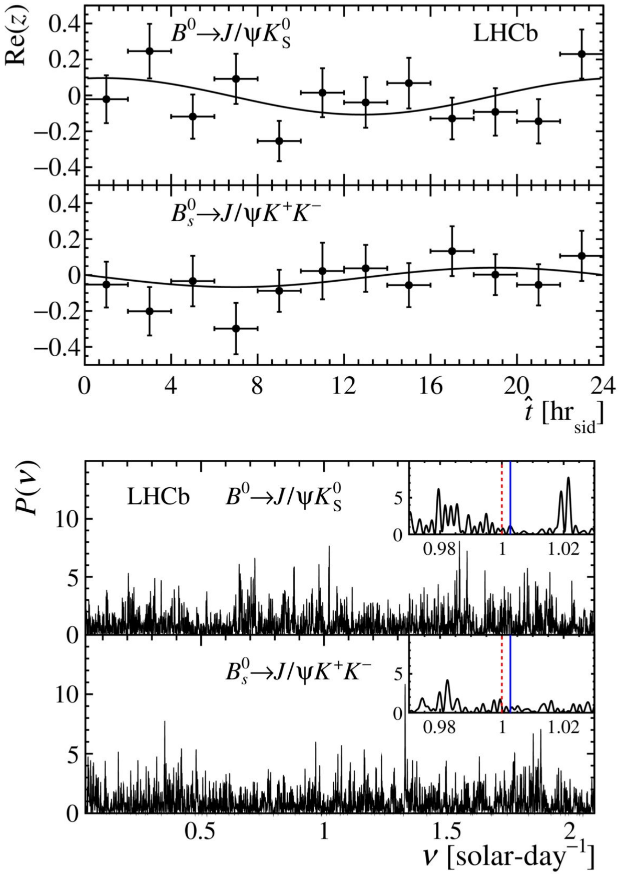
| $k$ | $h_k(t)$ |
|---|---|
| 1 | $\lvert A_0(t)\rvert^2$ |
| 2 | $\lvert A_\parallel(t)\rvert^2$ |
| 3 | $\lvert A_\perp(t)\rvert^2$ |
| 4 | $\mathcal{I}m(A_\parallel^*(t)A_\perp(t))$ |
| 5 | $\mathcal{R}e(A_0^*(t)A_\parallel(t))$ |

| $k$ | $h_k(t)$ |
|---|---|
| 6 | $\mathcal{I}m(A_0^*(t)A_\perp(t))$ |
| 7 | $\lvert A_S(t)\rvert^2$ |
| 8 | $\mathcal{R}e(A_S^*(t)A_\parallel(t))$ |
| 9 | $\mathcal{I}m(A_S^*(t)A_\perp(t))$ |
| 10 | $\mathcal{R}e(A_S^*(t)A_0(t))$ |

$$A_l^*(t)A_m(t) = \frac{A_l^*(0)A_m(0)e^{-\Gamma_s t}}{1+\zeta C_f}\Big[a_k\cosh(\Delta\Gamma_s t/2) + b_k\sinh(\Delta\Gamma_s t/2) + c_k\cos(\Delta m_s t) + d_k\sin(\Delta m_s t)\Big],$$

Coefficients $a_k$,$b_k$,$c_k$,$d_k$ given in [PRL 116 (2016) 241601]

# Results for $B^0$ and $B^0_s$




[Phys. Rev. Lett. 116 (2016) 241601](#)

- $B_d$ system (SME):

$$\Delta a_0 - 0.38\Delta a_Z = (-0.10 \pm 0.82 \pm 0.54) \times 10^{-15}\,\text{GeV}$$
$$0.38\Delta a_0 + \Delta a_Z = (-0.20 \pm 0.22 \pm 0.04) \times 10^{-13}\,\text{GeV}$$
$$\Delta a_X = (+1.97 \pm 1.30 \pm 0.29) \times 10^{-15}\,\text{GeV}$$
$$\Delta a_Y = (+0.44 \pm 1.26 \pm 0.29) \times 10^{-15}\,\text{GeV}$$

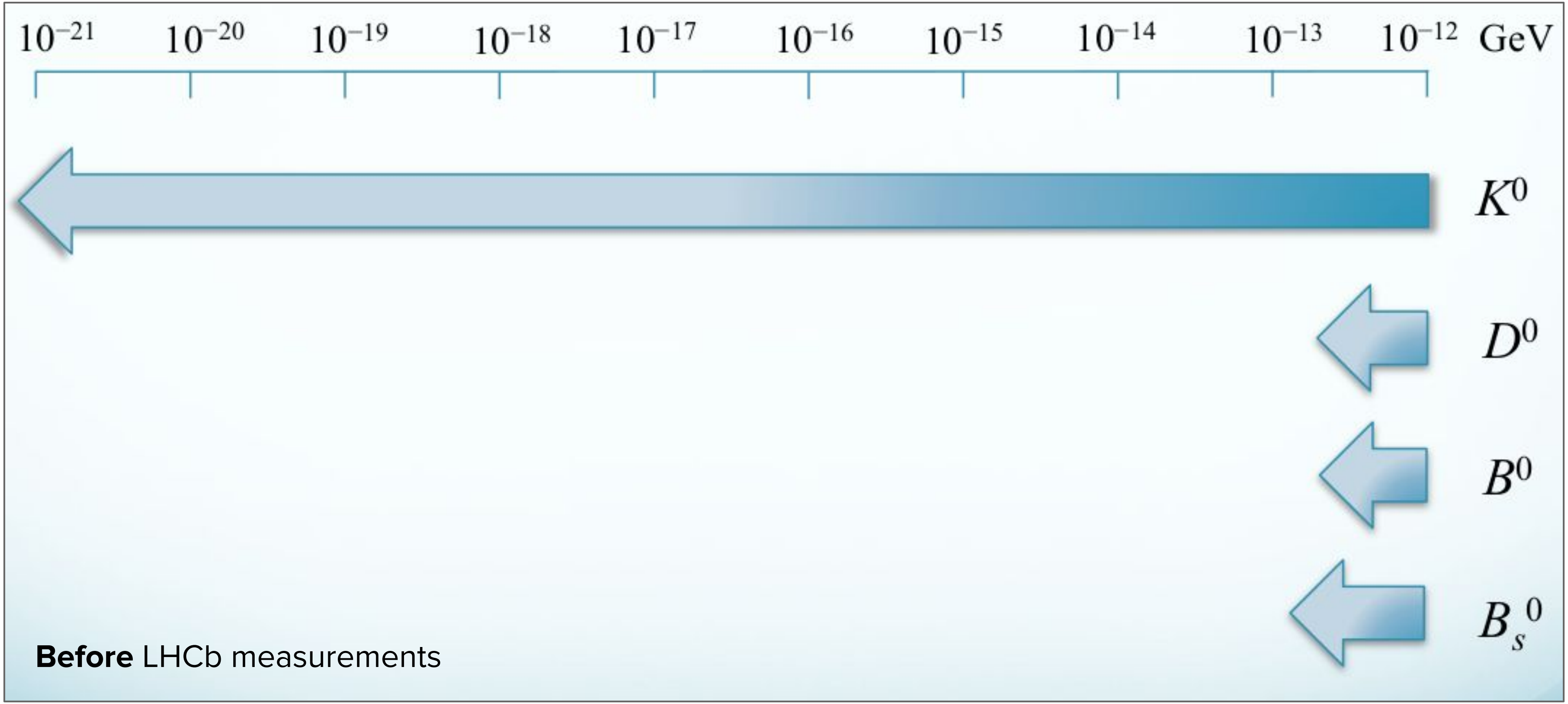
- $B_s$ system (SME):

$$\Delta a_0 - 0.38\Delta a_Z = (-0.89 \pm 1.41 \pm 0.36) \times 10^{-14}\,\text{GeV}$$
$$0.38\Delta a_0 + \Delta a_Z = (-0.47 \pm 0.22 \pm 0.08) \times 10^{-12}\,\text{GeV}$$
$$\Delta a_X = (+1.01 \pm 2.08 \pm 0.71) \times 10^{-14}\,\text{GeV}$$
$$\Delta a_Y = (+3.83 \pm 2.09 \pm 0.71) \times 10^{-14}\,\text{GeV}$$

**Set SME constraints, and did general sidereal dependence scan, consistent with no LIV**

# LIV constraints in neutral meson mixing

LHCb-TALK-2016-193



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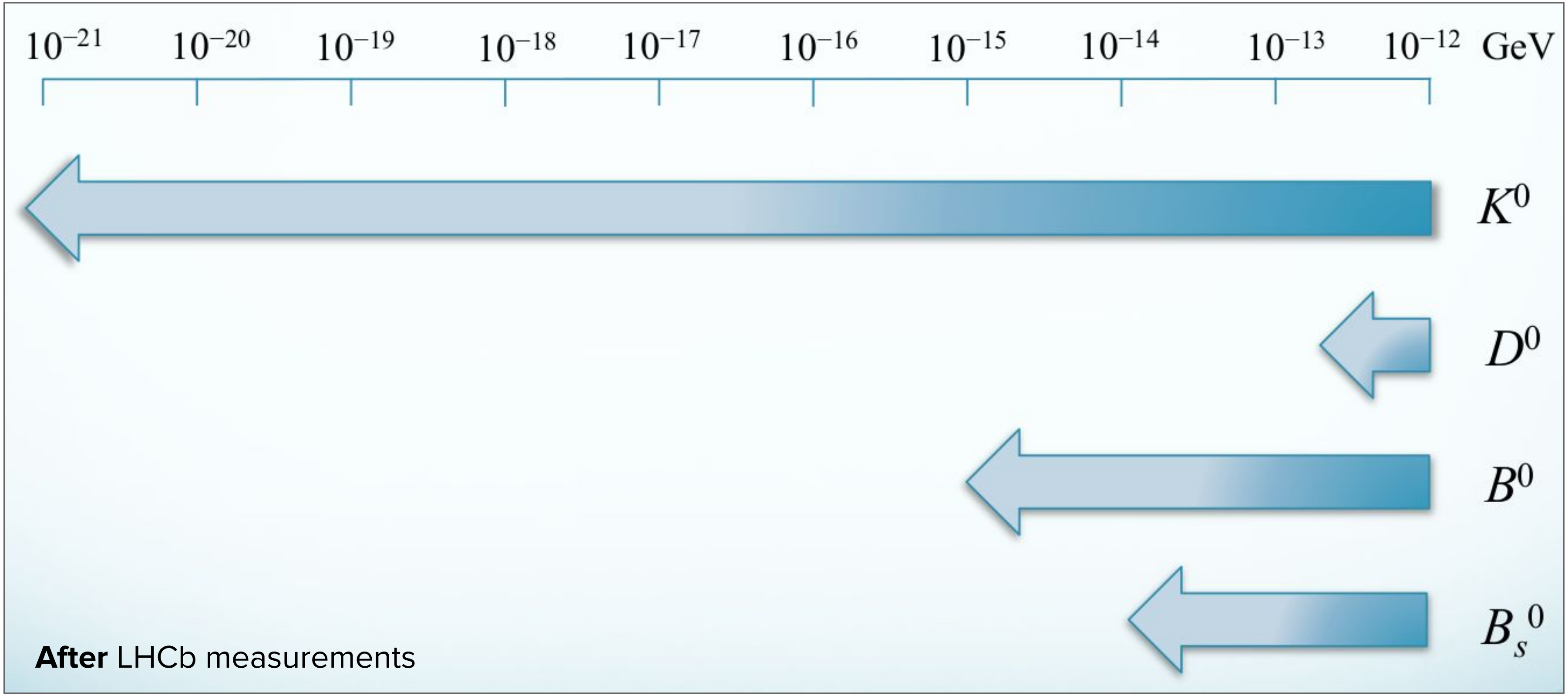
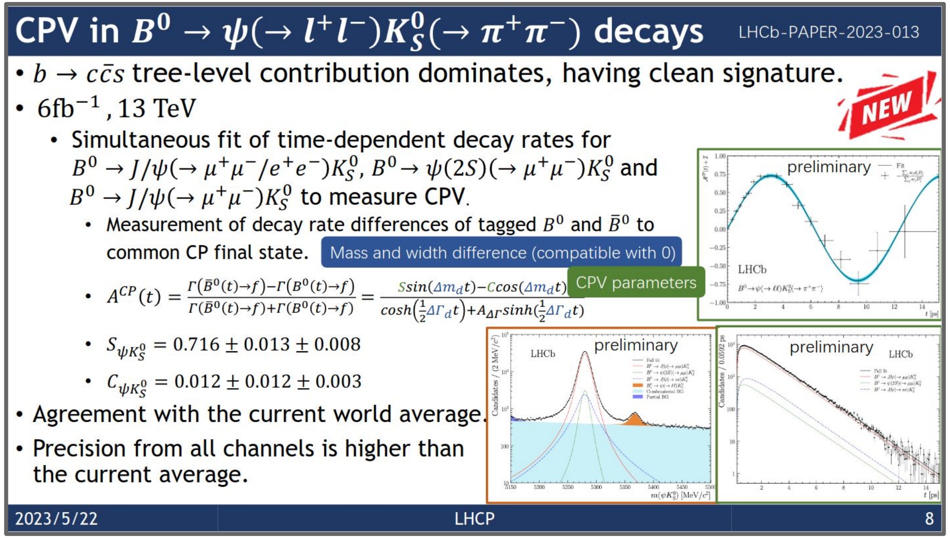


# Recent CP violation measurements from LHCb
## *and what it means for LIV / CPT*

- *Fresh from **LHCP!***
  - Legacy measurements from old LHCb detector
  - Both relevant $B^0$ and $B_s$ modes
  - Could be extended / updated with LIV measurement




[LHCb-TALK-2023-091](LHCb-TALK-2023-091)

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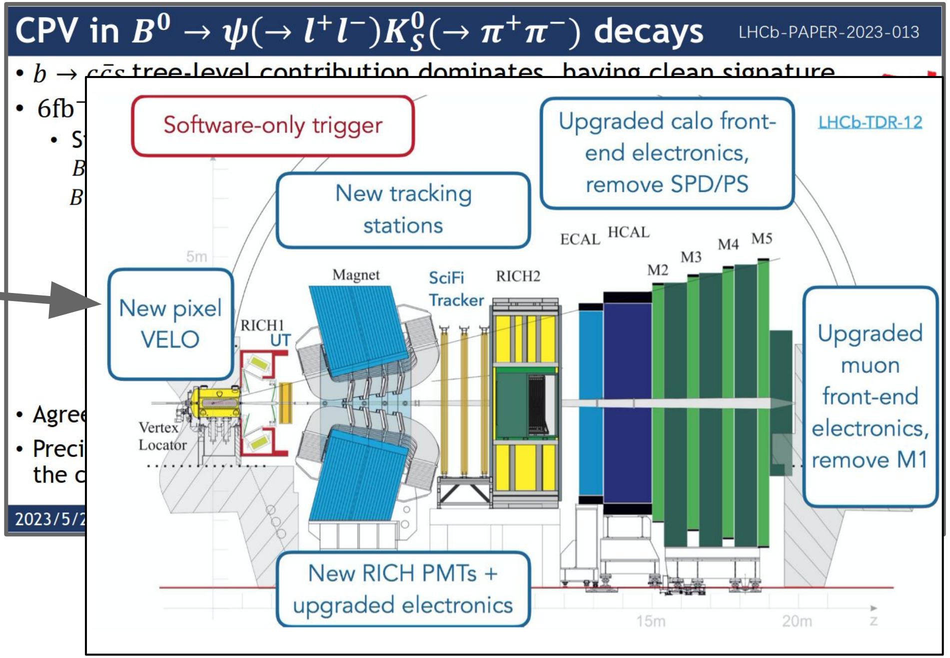
- **LHCb Upgrade I**
  - Commissioning well underway
  - **Full software trigger** and **higher luminosity gives** plenty of new opportunities!



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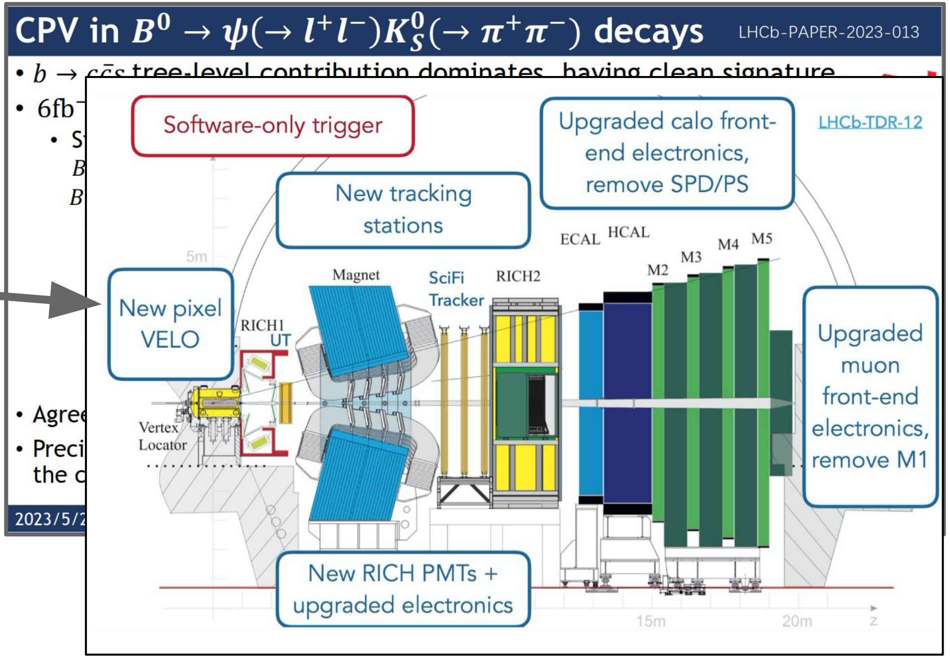
- **LHCb Upgrade I**
  - Commissioning well underway
  - **Full software trigger** and **higher luminosity gives** plenty of new opportunities!
- **But LHCb also is a laboratory for *charm…***



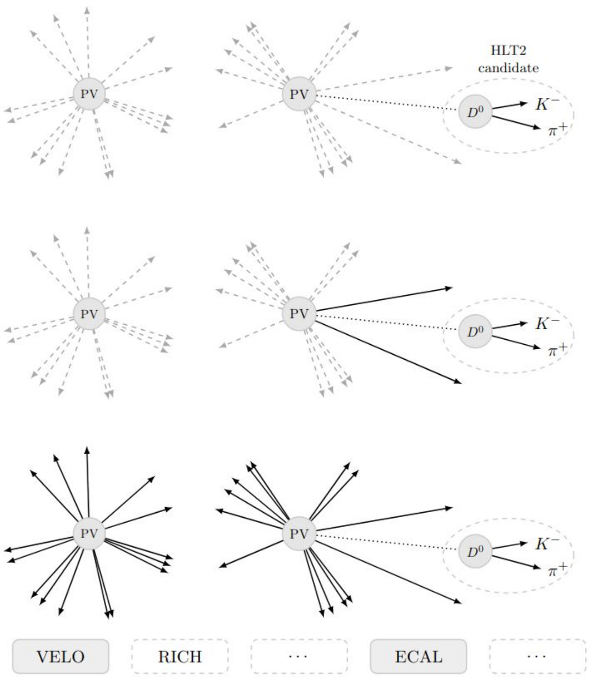
# Charm prospects

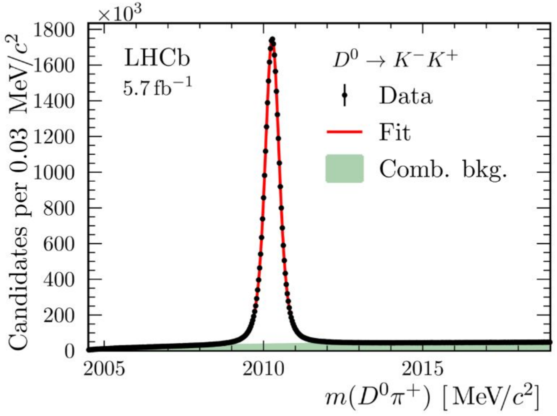
- In general, **small mixing parameters plague sensitivity**

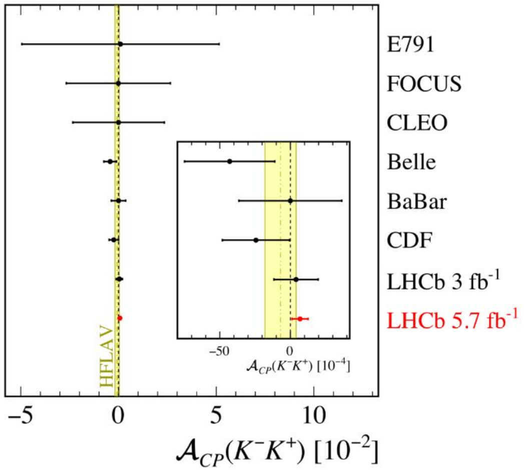
$$A_{CPT}(t) = A^{\mathrm{dir}} - \sqrt{R_D}\sin\phi(x\cos\delta + y\sin\delta)\Gamma t + (\mathrm{Re}(z)y - \mathrm{Im}(z)x)\Gamma t$$

- But **LHCb** has a **huge data set** of charm mesons!
  - In part due to *new developments in software trigger*
  - Started during Run 2 (2015-2018)

LHCB-TDR-018



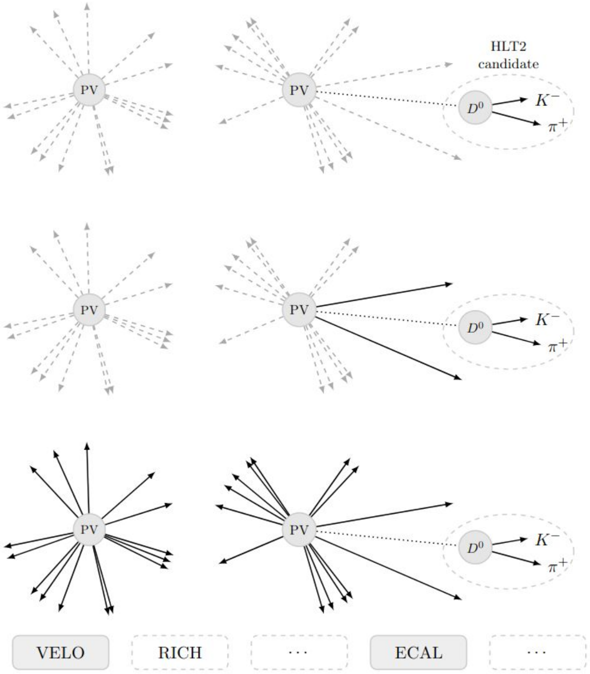




LHCb-PAPER-2022-024

# General prospects

- New detector has this software as default plus many more improvements
- **LHCb** will have **higher luminosity, new detector and software!**
- Prospects from 2016

LHCB-TDR-018




- Table from JvT & v.Veghel [PLB 742 (2015) 236]

LHCb-TALK-2016-193

**Expected statistical sensitivities for LHCb Run 1 (3 fb$^{-1}$)**

| System | Parameter | Current best limit | | LHCb 3 fb$^{-1}$ | Decay mode |
|---|---|---|---|---|---|
| $D^0$ | $\lvert\mathrm{Re}(z)y - \mathrm{Im}(z)x\rvert$ | $(0.83 \pm 0.77)\%$ † | [17] | 0.02% † | $D^0 \to K^-\pi^+$ |
| | $\Delta a_\mu$ | $\sim 3 \times 10^{-13}$ GeV | [17] | $1 \times 10^{-14}$ GeV | $D^0 \to K^-\pi^+$ |
| $B^0$ | $\mathrm{Im}(z)$ | $(-0.8 \pm 0.4)\%$ | [18] | 0.1% | $B^0 \to D^{(*)-}\mu^+\nu_\mu$ |
| | $\mathrm{Re}(z)$ | $(1.9 \pm 4.0)\%$ | [6, 11] | 7% | $B^0 \to J/\psi K^0_S$ |
| | $\Delta a_\mu$ | $\mathcal{O}(10^{-13})$ GeV | [13] | $1 \times 10^{-15}$ GeV | $B^0 \to J/\psi K^0_S$ |
| $B^0_s$ | $\mathrm{Im}(z)$ | – | | 0.4% | $B^0_s \to D^-_s\pi^+$ |
| | $\mathrm{Re}(z)$ | – | | 2% | $B^0_s \to J/\psi\phi$ |
| | $\Delta a_\mu$ | $\mathcal{O}(10^{-12})$ GeV | [16] | $1 \times 10^{-14}$ GeV | $B^0_s \to J/\psi\phi$ |

† Assuming that $x \approx y \approx 0.5\%$.

Possible future measurements

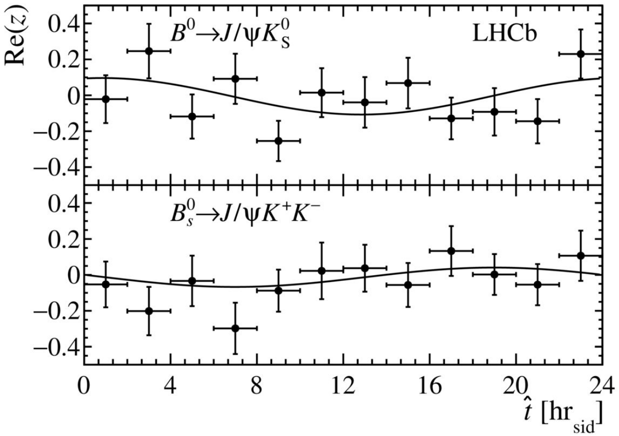
Covered by this measurement

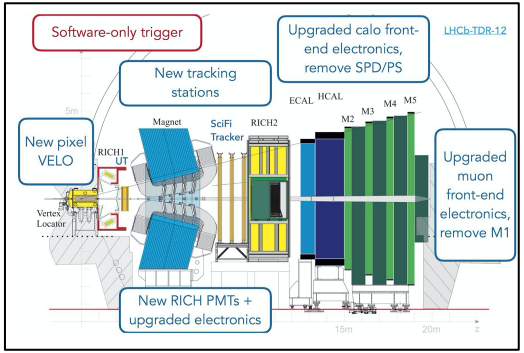
**For charm still applies! B sector will also have quite some gains**

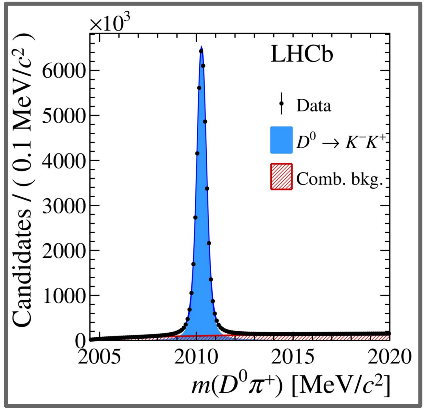
# Conclusion

Phys. Rev. Lett. 116 (2016) 241601

- Access to ***small mass differences*** through **neutral meson mixing**
  - One particular, quark-flavour specific, four-vector in SME
- Constraints for LIV in b-quark sector from LHCb are world leading
  - ***high yield***, ***high boost*** **of both beauty and charm mesons**
- **LHCb** has set constraints for B and Bs mesons
  - b-quark (and other valence quark) constraints in SME
- **More opportunities** at **LHCb** for SME constraints
  - Even with 'old' Run 2 (higher boost as well)
  - Particularly charm




Phys. Rev. Lett. 122 (2019) 211803

# Backup

# Systematic uncertainties

Phys. Rev. Lett. 116 (2016) 241601

Table 3: Systematic uncertainties on $\Delta a_\mu$ for $B^0$ mixing and on $\Delta a_\mu$ and $z$ for $B_s^0$ mixing. Contributions marked with – are negligible.

| $\boldsymbol{B^0}$ **mixing**<br>Source | $\Delta a_{\parallel}$ | $\Delta a_{\perp}$<br>[$\times 10^{-15}$ GeV] | $\Delta a_{X,Y}$ |
|---|---|---|---|
| Mass correlation | – | – | 0.04 |
| Wrong PV assignment | – | 1 | – |
| Production asymmetry | 0.28 | 1 | 0.05 |
| External input $C_f$, $S_f$ | 0.46 | 4 | 0.28 |
| Decay width difference | 0.07 | – | – |
| Neutral kaon asymmetry | – | 1 | – |
| Quadratic sum | 0.54 | 4 | 0.29 |

| $\boldsymbol{B_s^0}$ **mixing**<br>Source | $\Delta a_{\parallel}$ | $\Delta a_{\perp}$<br>[$\times 10^{-14}$ GeV] | $\Delta a_{X,Y}$ | $\mathcal{R}e(z)$ | $\mathcal{I}m(z)$ |
|---|---|---|---|---|---|
| Mass correlation | 0.10 | 3 | 0.24 | 0.001 | 0.002 |
| Peaking background | 0.14 | 3 | 0.15 | 0.003 | – |
| Decay-time acceptance | 0.30 | 7 | 0.65 | – | 0.001 |
| Angular acceptance | 0.07 | – | – | 0.002 | 0.001 |
| Quadratic sum | 0.36 | 8 | 0.71 | 0.003 | 0.002 |

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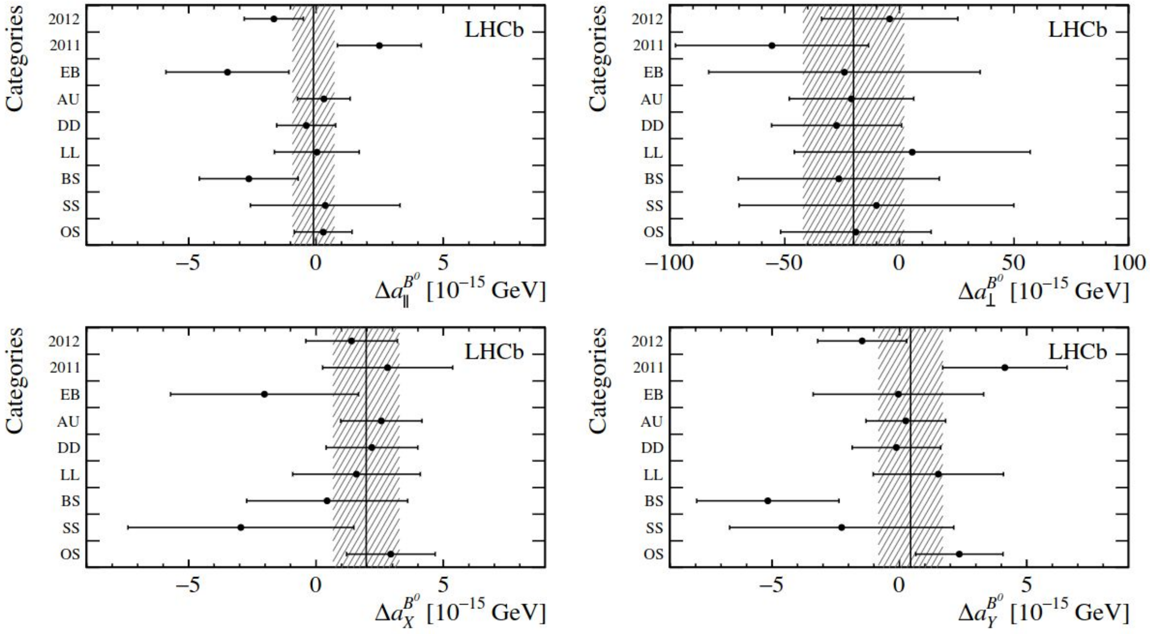



Figure 1: Fit results when splitting the $B^0$ sample into several different subsamples. The vertical bands indicate the fit result from the full sample. All uncertainties are statistical only. The abbreviations for the subsamples are explained in the text.

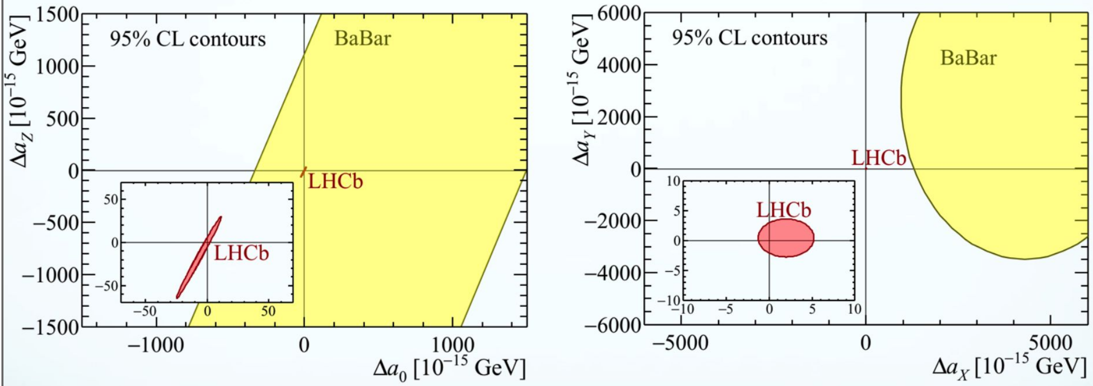
# LHCb results in context of others

LHCb-TALK-2016-193

- Boost BaBar: $\beta\gamma = 0.5$ (Cf. LHCb: 20)
- BaBar used inclusive dilepton $B$ decays
- Used $\Delta\Gamma_d = 0.00261$ (SM prediction) [arXiv:1511.09466]
- Corresponds to Re(z) of O(2); $|z|^2$ terms cannot be ignored

→ O($10^3$) times more precise

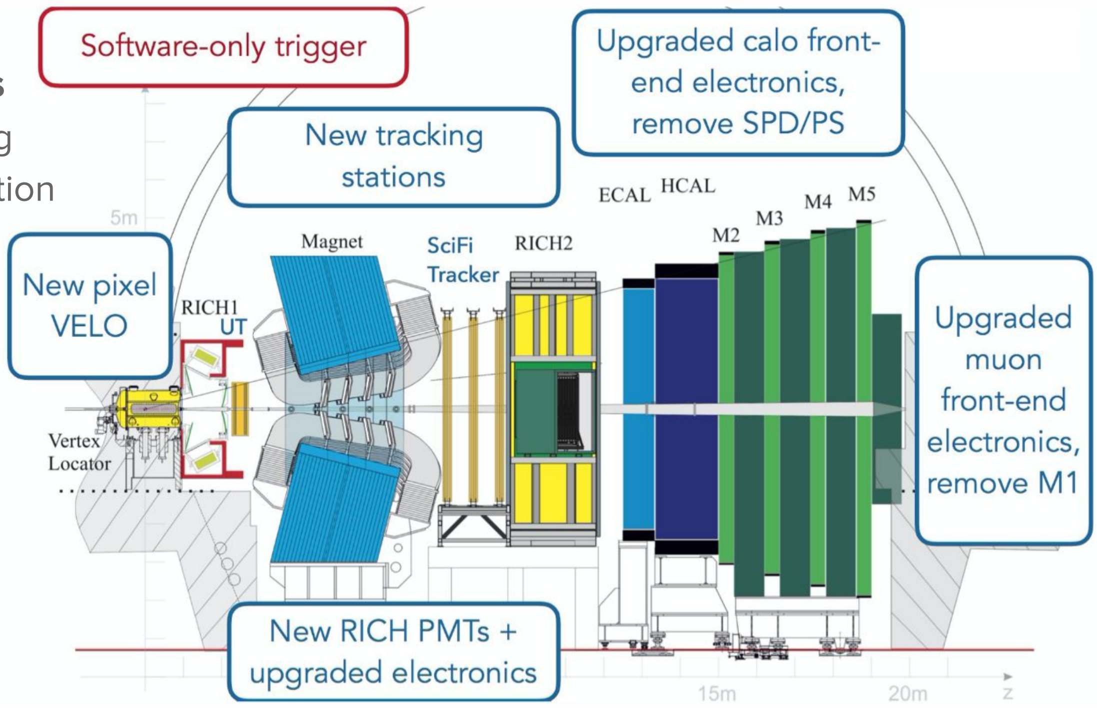
[PRL 100 (2008) 131802]



# The *upgraded* LHCb experiment

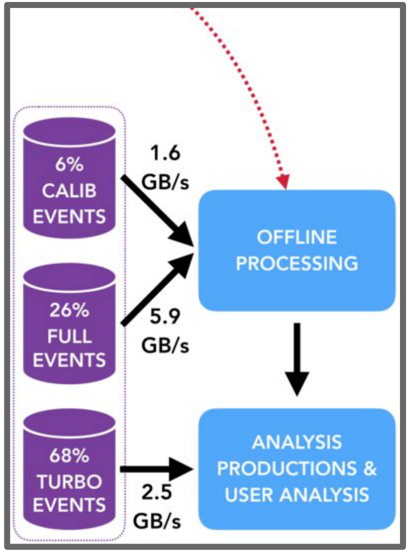
LHCb-TDR-12

- Single-arm **forward** spectrometer designed for **beauty / charm physics**
  - High-precision tracking / vertexing
  - Excellent PID, incl. hadron separation
- **Physics program in practice far more general**
  - Electroweak
  - Exotica, LLPs, …
  - Fixed-target, heavy ions
- **Think of it more as a general purpose detector!**



# ***Selective* Persistence**

LHCB-TDR-018




| Event size | Persisted Objects |
|---|---|
| O(10 kB) | Only **signal** candidate is saved<br>**default** |
| O(10 - 100 kB) | **Signal** together with **custom set** of reconstructed objects<br>***selective persistence*** |
| O(100 kB) | **Full events** all reco'd objects<br>**Calib events** also all raw hits |