LHCb latest results and new perspectives

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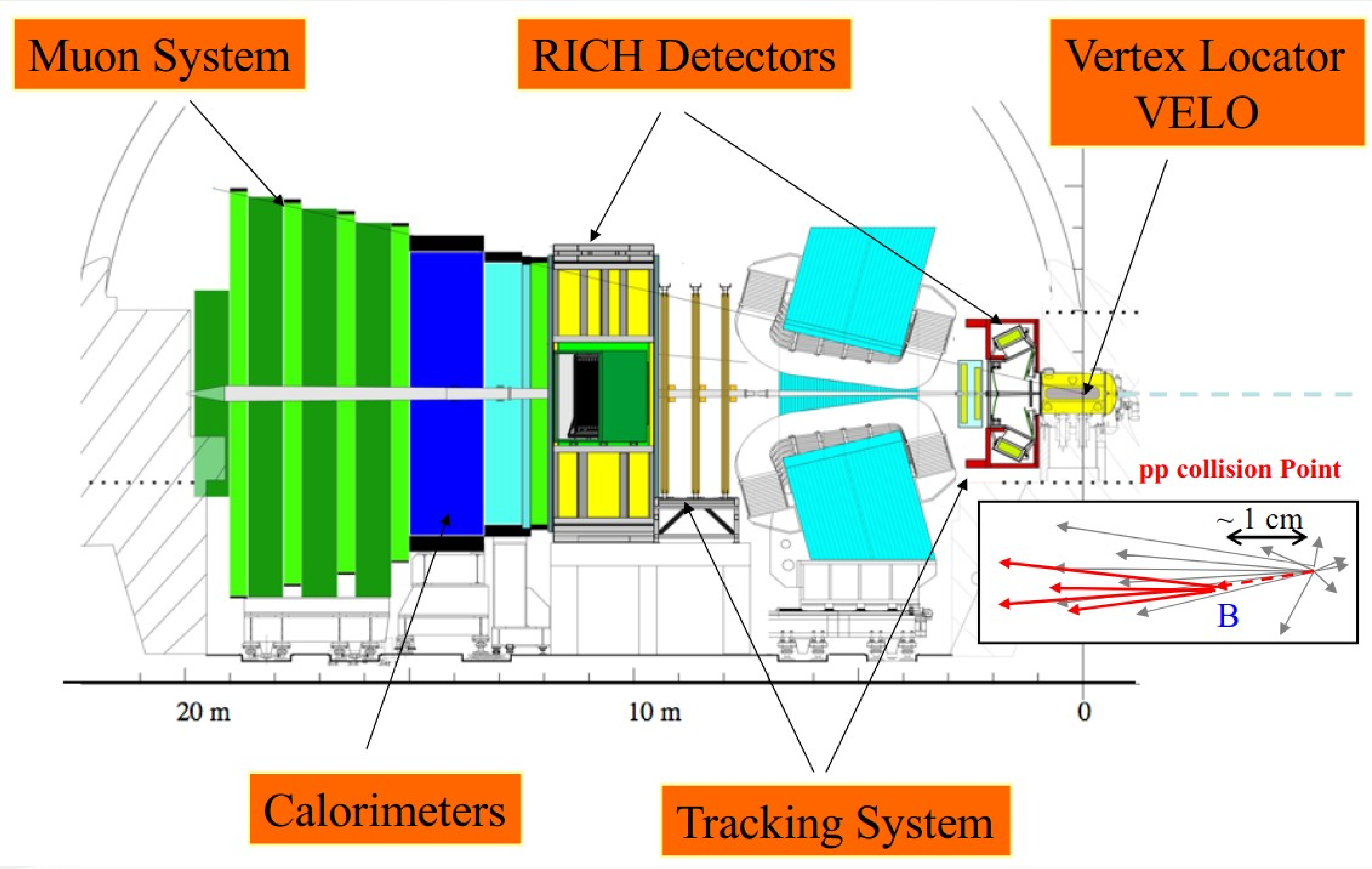
on behalf of LHCb

outline

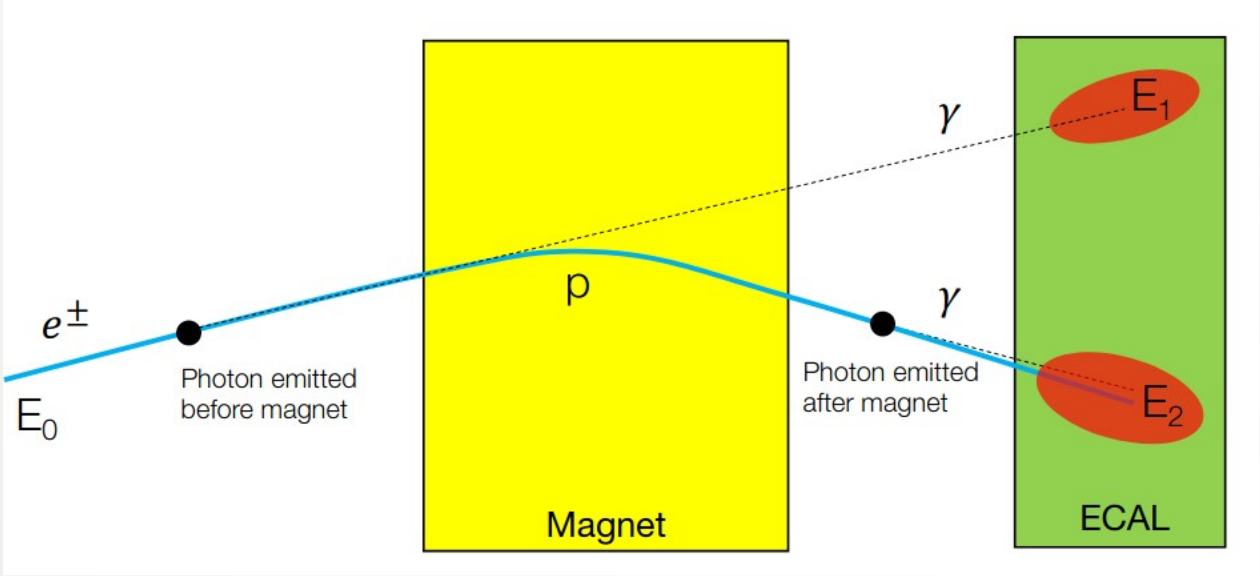
- Updates on lepton universality
- CKM γ and mixing parameters measurements
- CP violation measurement: 2 body K-π puzzle
- Spectroscopy
- Future and conclusions

LHCb detector

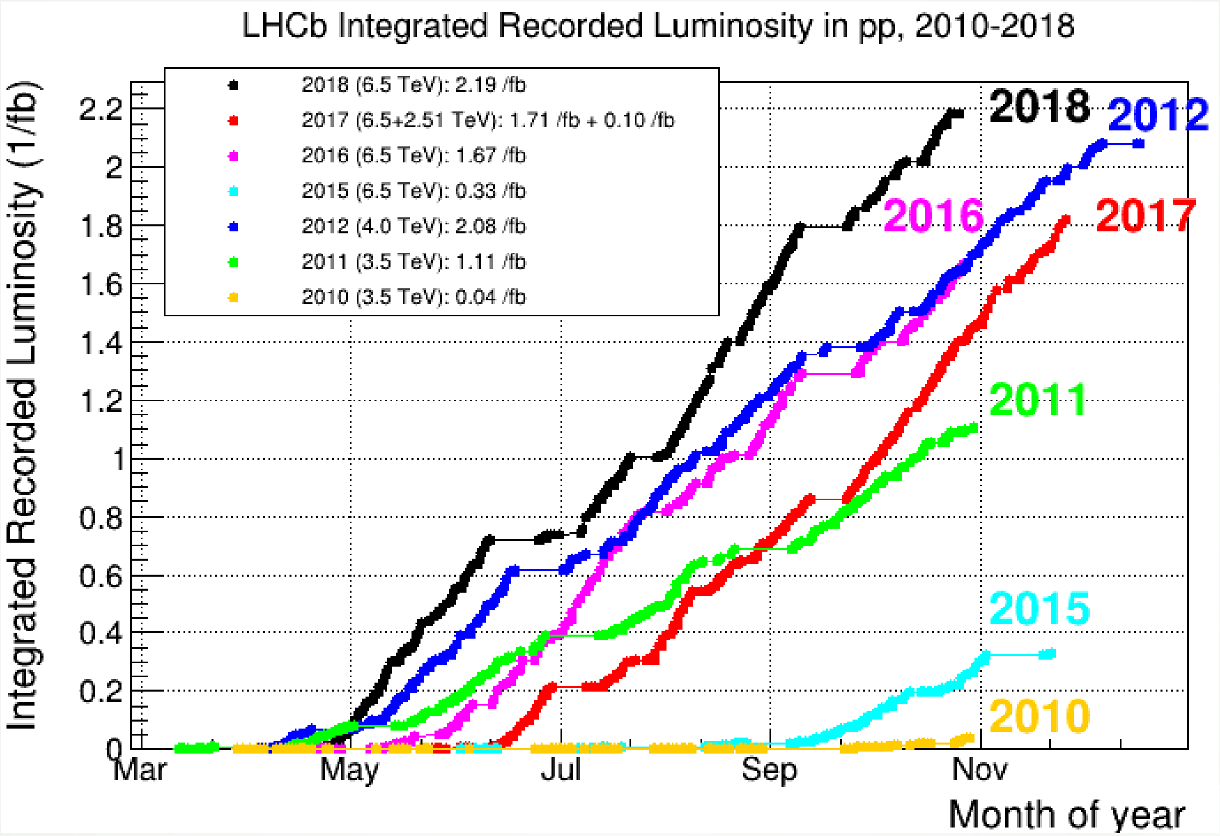


LHCb detector

- Electrons radiate bremsstrahlung photons when interacting with detector.
  - When it happens before the magnet it lead to increased uncertainties on momentum and energy.
- Bremsstrahlung recovery: seaches for energy deposits in the calorimeter and adds back to electron energy.



Data aquisition



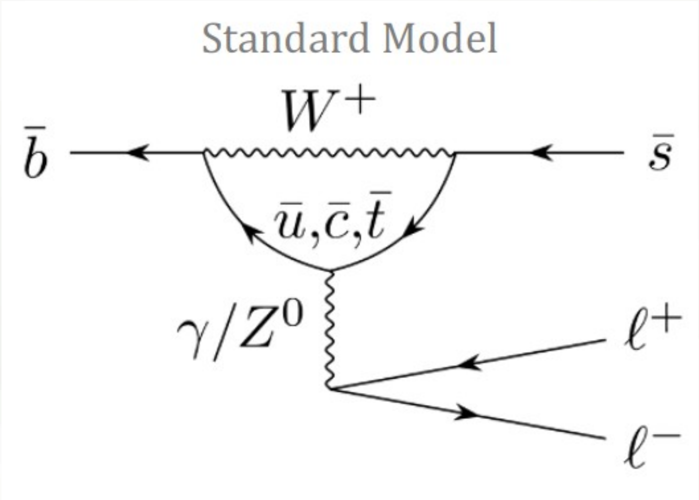
- Large heavy flavour dataset collected (9.0 fb^{-1}) during run 1 and 2.
  - Precision tracking
  - Excellent PID using RICH
- Trigger described in details here: Int.J.Mod.Phys. A30 (2015) no.07, 1530022

Lepton Universality

Lepton universality overview

arXiv:2110.09501v2[hep-ex]

- $B \rightarrow s\, l^+ l^-$ transitions are flavour-changing neutral currents (FCNC) which means they are suppressed in the standard model (SM).
- Branching fractions of $O(10^{-7})$-$O(10^{-8})$.
- In the SM coupling of gauge fields to the three charged leptons (e, μ, τ) are identical → Lepton Universality (LU)



Lepton universality overview

- Ratios of the form:

$$R_H = \frac{B \to H\,\mu\,\mu}{B \to H\,e\,e} \approx 1$$

in SM, except for small corrections due to different lepton masses.

- Easy method to be applied:
  - Hadronic uncertainties cancel in ratio ($O(10^{-4})$).
  - QED corrections up to $O(10^{-2})$.

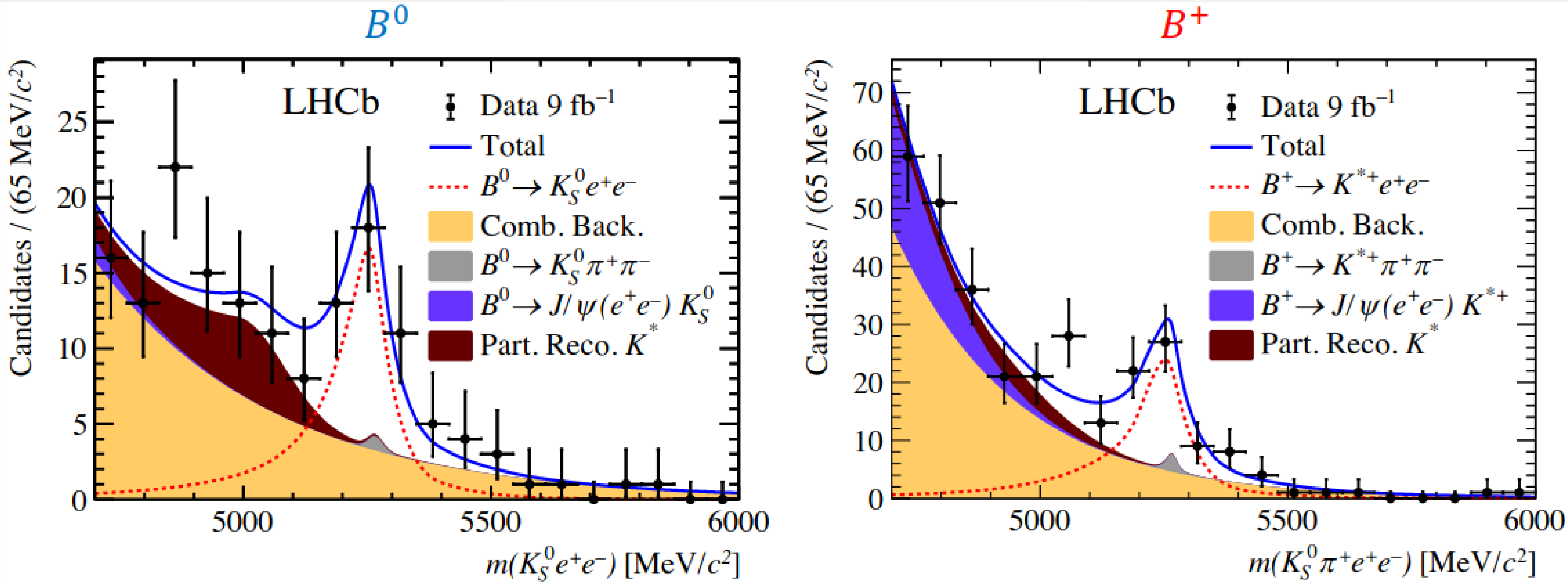
Significant deviation from unitity → New physics (NP) beyond SM

Lepton universality Run II

- Two tests for LU using 9.0 fb^{-1} dataset
- $B^0 \rightarrow K_s^0 l^+ l^-$: $$R_{K_s^0} = \frac{B^0 \rightarrow K_s^0 \mu\mu}{B^0 \rightarrow K_s^0 e e}$$
- $B^+ \rightarrow K^{*+} l^+ l^-$: $$R_{K^{*+}} = \frac{B^+ \rightarrow K^{*+} \mu\mu}{B^+ \rightarrow K^{*+} e e}$$
- Isospin partners of $B^+ \rightarrow K^+ l^+ l^-$ and $B^0 \rightarrow K^{*0} l^+ l^-$ and the same NP is expected.

Lepton universality Run II

arXiv:2110.09501v2[hep-ex]



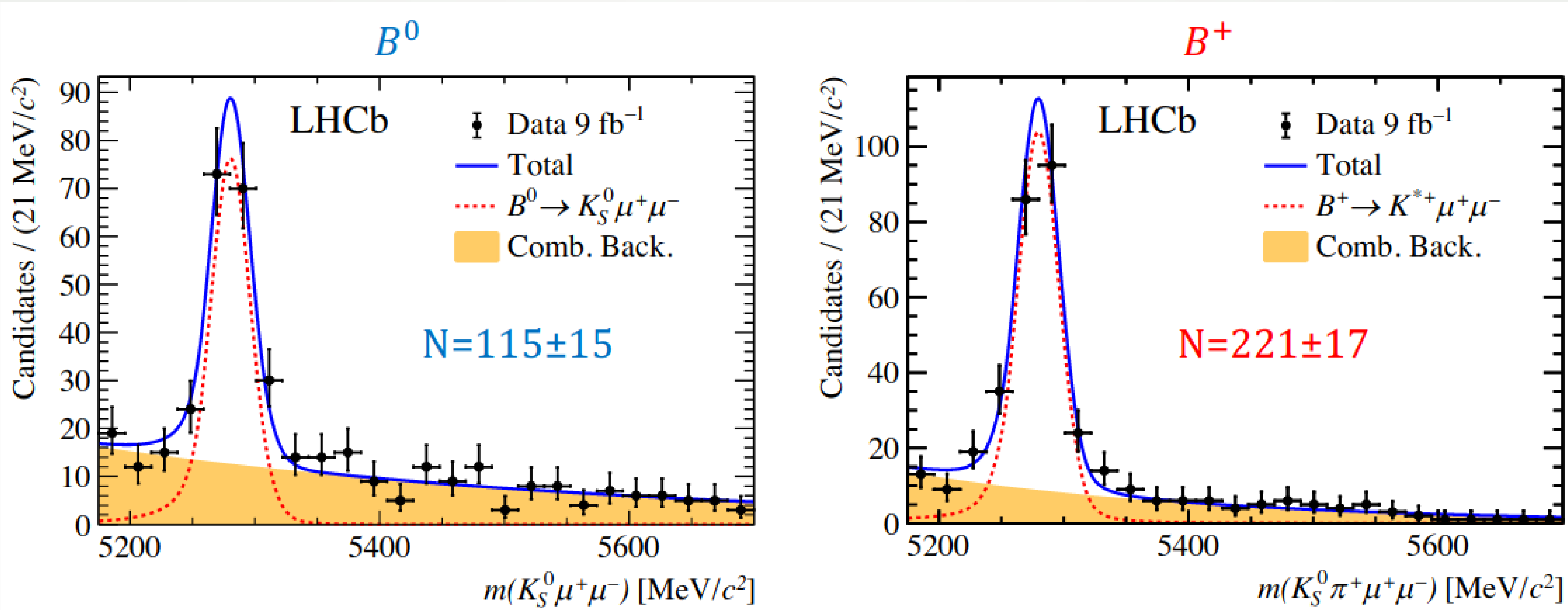
$B^0 \to K_S^0 \ell^+ \ell^-$ significance: 5.3σ

$B^+ \to K^{*+} \ell^+ \ell^-$ significance: 6.0σ

- Yields and R_{Ks} are extracted from a simultaneous maximum likelihood fits to data.
- First observation for both channels!

Lepton universality Run II

arXiv:2110.09501v2[hep-ex]

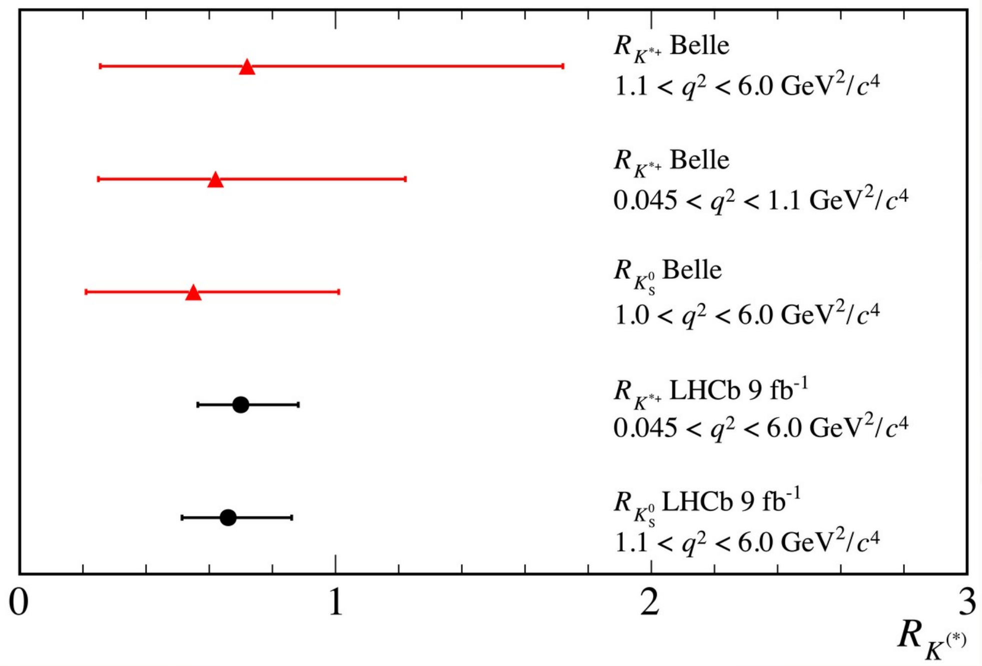


- Yields and R_{K^*} are extracted from a simultaneous maximum likelihood fits.

Lepton universality Run II

arXiv:2110.09501v2[hep-ex]

- $B^0 \to K_s^0 l^+ l^-$: $R_{K_s^0} = \frac{B^0 \to K_s^0 \mu\mu}{B^0 \to K_s^0 e e} = 0.66^{+0.20}_{-0.15}(stat)^{+0.02}_{-0.04}(syst)$ **1.5σ**
- $B^+ \to K^{*+} l^+ l^-$: $R_{K^{*+}} = \frac{B^+ \to K^{*+} \mu\mu}{B^+ \to K^{*+} e e} = 0.70^{+0.18}_{-0.13}(stat)^{+0.03}_{-0.04}(syst)$ **1.4σ**
- Same pattern seen in other LU tests

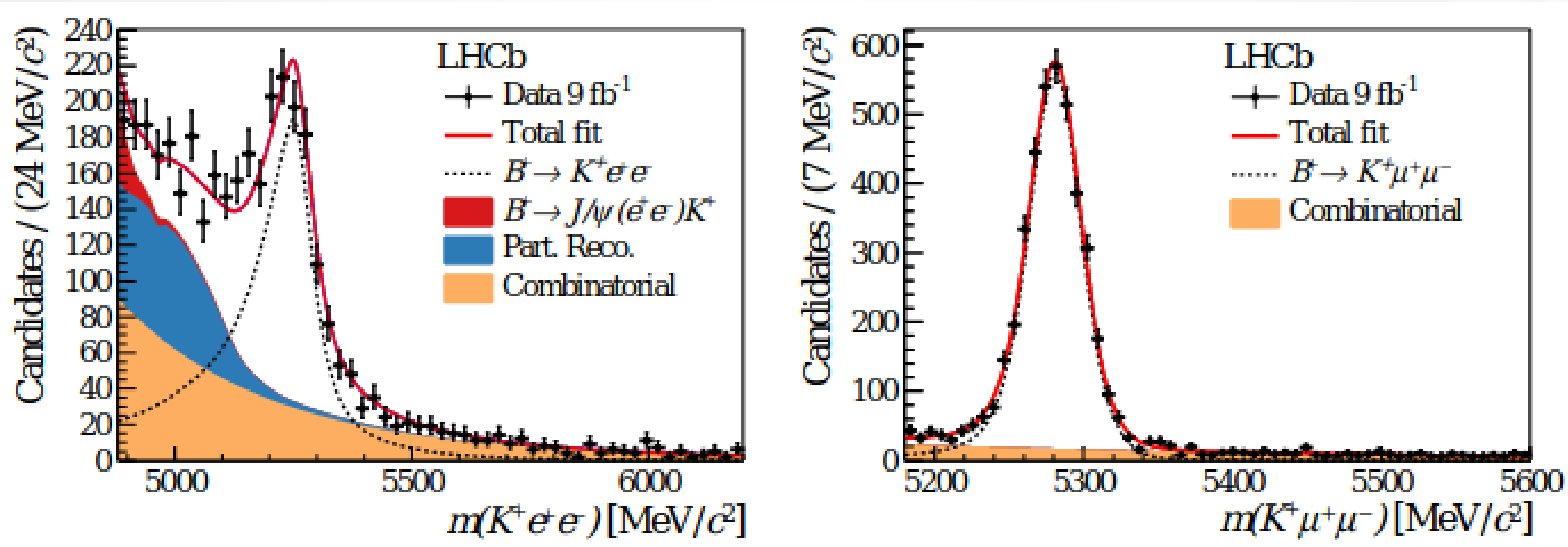


Lepton universality Run II

arXiv:2103.11769v2[hep-ex]

- The lhcb also investigated the LU in the isospin partner $B^+ \rightarrow K^+ l^+ l^-$

$$R_{K^+} = \frac{B^+ \rightarrow K^+ \mu \mu}{B^+ \rightarrow K^+ e e}$$



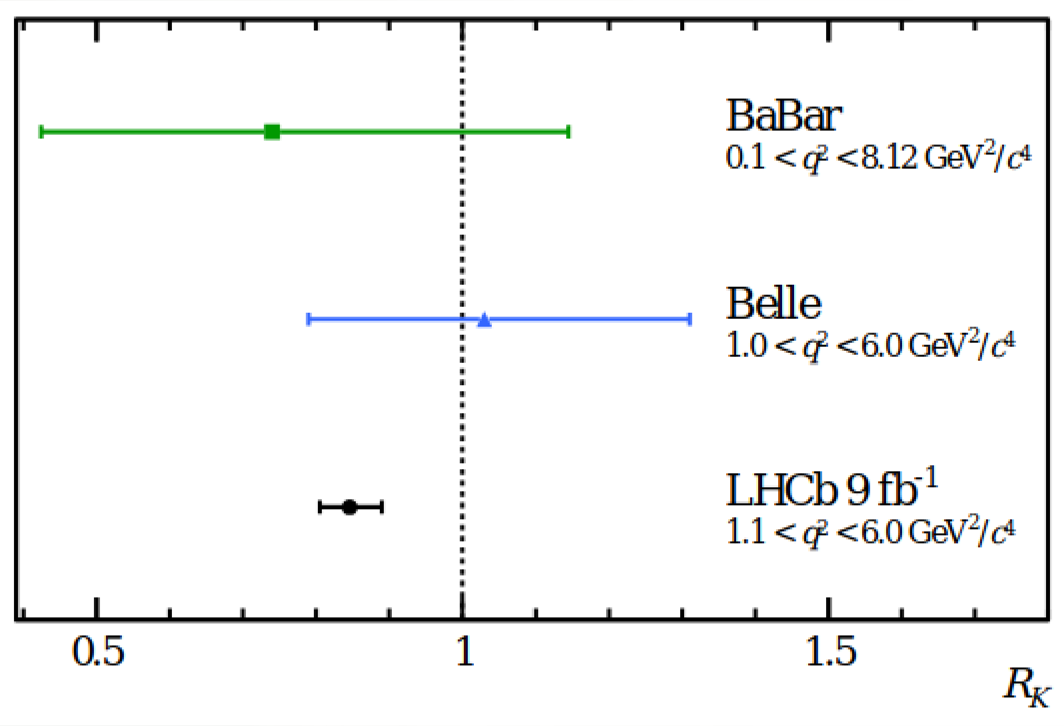
Lepton universality Run II

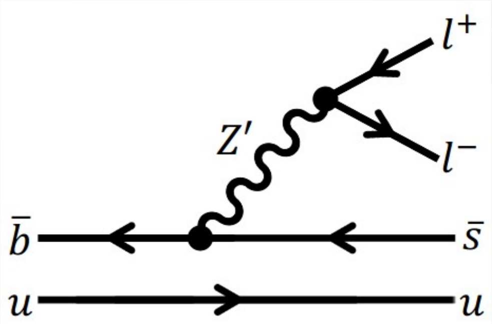
arXiv:2103.11769v2[hep-ex]

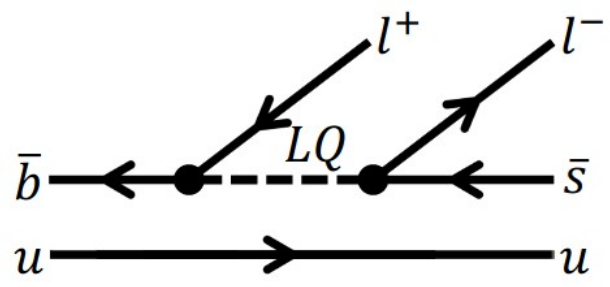
- $B^+ \rightarrow K^+ l^+ l^-$:

$$R_{K^+} = \frac{B^+ \rightarrow K^+ \mu\mu}{B^+ \rightarrow K^+ e e} = 0.846^{+0.042}_{-0.039}(stat)^{+0.013}_{-0.012}(syst)$$

3.1σ

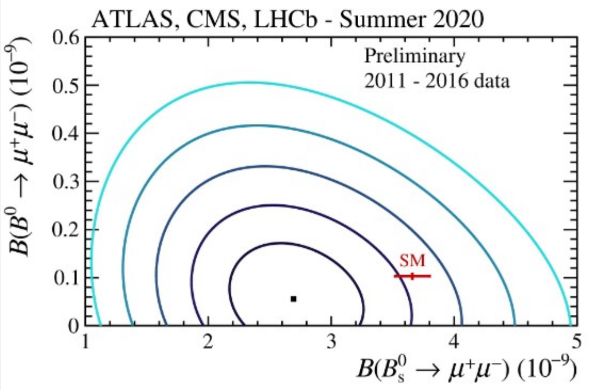


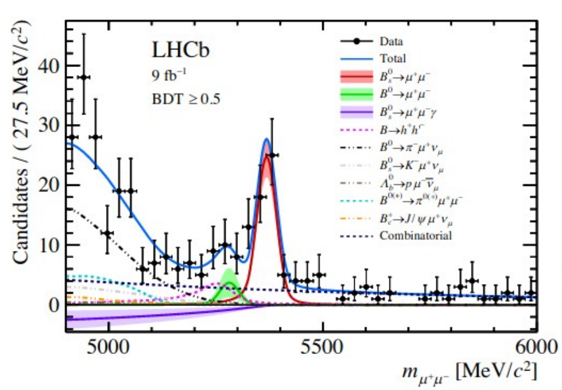




Flavour Anomalies

- In addition to LU violation, several other anomalies in $b \rightarrow s\, l^+ l^-$ decays emerged over the past decade:
  - Branching fractions of $b \rightarrow s\, \mu^+ \mu^-$ decays. JHEP 1406 (2014) 133; JHEP 04 (2017) 142; Phys. Rev. Lett., 127 (2021) 15
    - Multiple measurements below SM predictions.
  - Branching fraction of $B^0_{(s)} \rightarrow \mu^+ \mu^-$ decays. ATLAS-CONF-2020-049; ArXiv:2108.09284



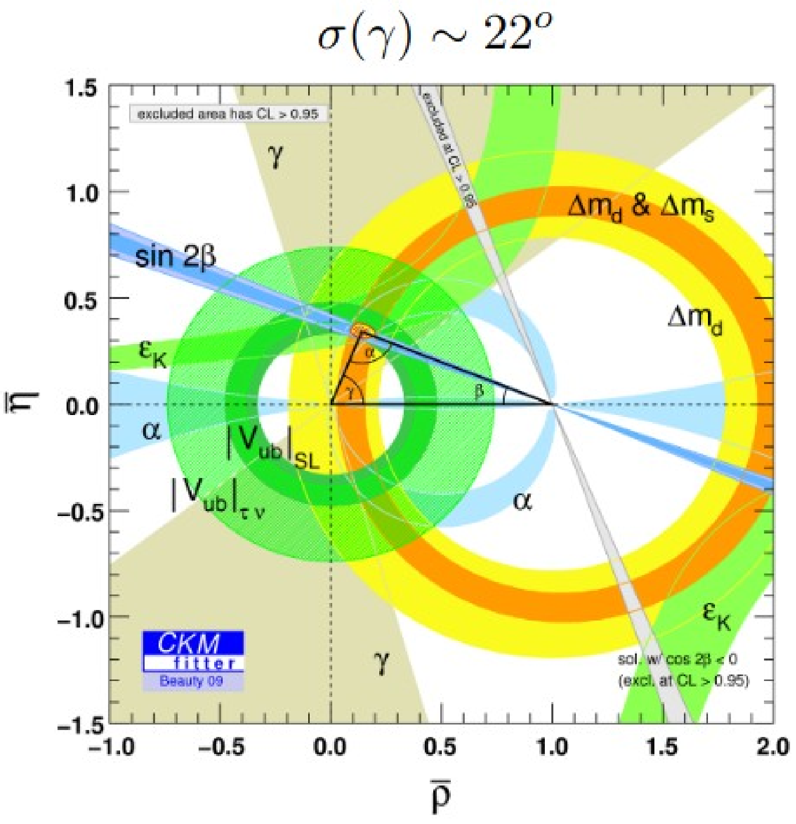


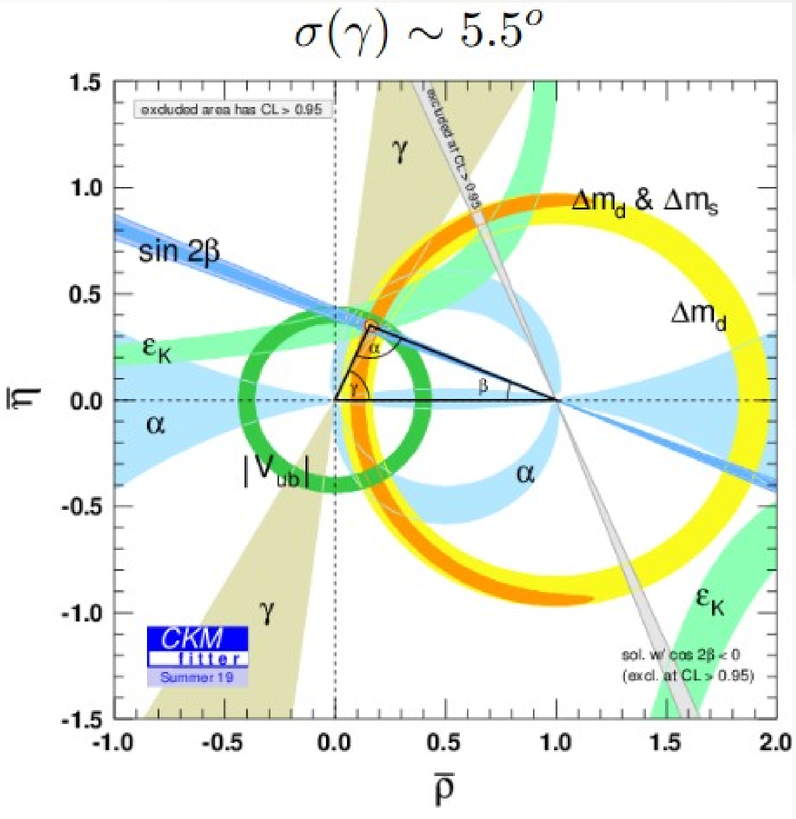
  - Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^+ \rightarrow K^{*+} \mu^+ \mu^-$.
    - Some observables offering complementary evidence for NP with a standard devition above 3σ. JHEP 02 (2016) 104; Phys. Rev. Lett., 125 (2020) 1; Phys. Rev. Lett., 126 (2021) 161802

CKM γ and mixing parameters

CKM γ overview

- Huge progress in measurement of CKM parameters, largely driven by the LHCb experiment

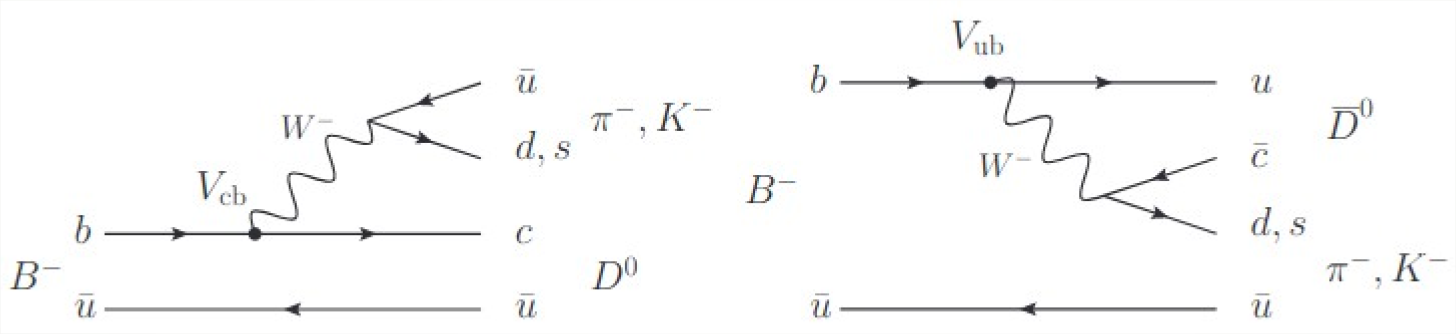




CKM γ combination

arXiv:2110.02350v1[hep-ex]

- CKM γ is measured in decays sensitive to interference between favored $b \to c$ and supressed $b \to u$ transitions.



- Unkown parameters from a single $B \to Dh$ decays can be obtained by combining D-decays modes to overconstrains.

CKM γ combination

arXiv:2110.02350v1[hep-ex]

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	[26]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	[30]	Run 1&2	**Updated**
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	[36]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[37]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[38–40]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[41]	Run 1	**New**
–	$D^0 \to h^+h^-$	[42–45]	Run 1&2	**New**
–	$D^0 \to K^+\pi^-$	[46]	Run 1	**New**
–	$D^0 \to K^+\pi^-$	[47]	Run 1&2(*)	**New**
–	$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	[48]	Run 1	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[49, 50]	Run 1&2	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[51]	Run 1	**New**

CKM γ combination results

arXiv:2110.02350v1[hep-ex]

- The combination uses a total of 151 input observables to measure 52 free parameters. Most notably,

$$\gamma=\left(65.4^{+3.8}_{-4.2}\right)^{o}$$

most precise measurement from a single experiment.

- Charm mixing parameters (most precise to date):

$$x=\left(0.400^{+0.052}_{-0.053}\right)\%$$

$$y=\left(0.630^{+0.033}_{-0.030}\right)\%$$

CP violation

K-π puzzle

Phys. Rev. Lett. 126 (2021) 091802

- Isospin symmetry predicts that

$$A_{CP}\left(B^0 \rightarrow K^+ \pi^-\right) = A_{CP}\left(B^+ \rightarrow K^+ \pi^0\right)$$

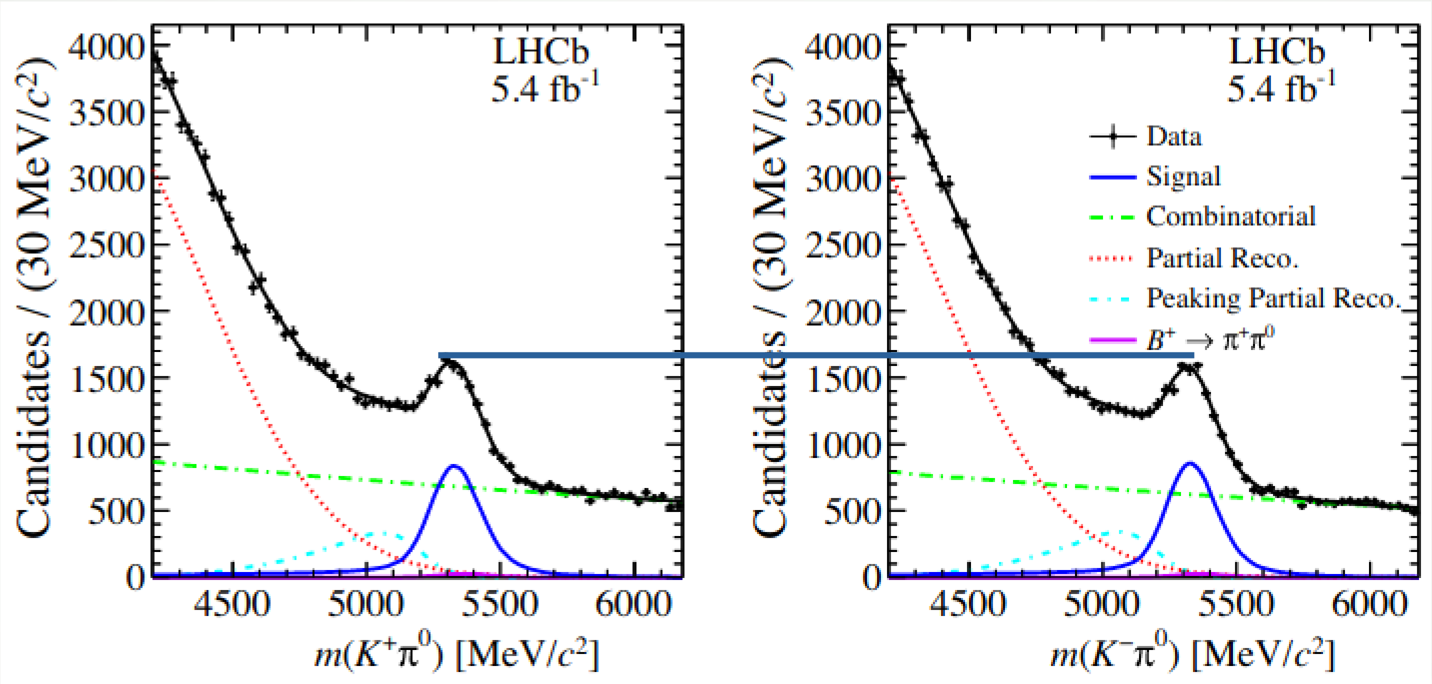
- But BaBar and Belle measured these asymmetries to be different at more than 5σ.

$$A_{CP}\left(B^0 \rightarrow K^+ \pi^-\right) = -0.084 \pm 0.004$$
$$A_{CP}\left(B^+ \rightarrow K^+ \pi^0\right) = 0.040 \pm 0.021$$

- Possibly NP in electroweak penguin sector.

K-π puzzle results

Phys. Rev. Lett. 126 (2021) 091802



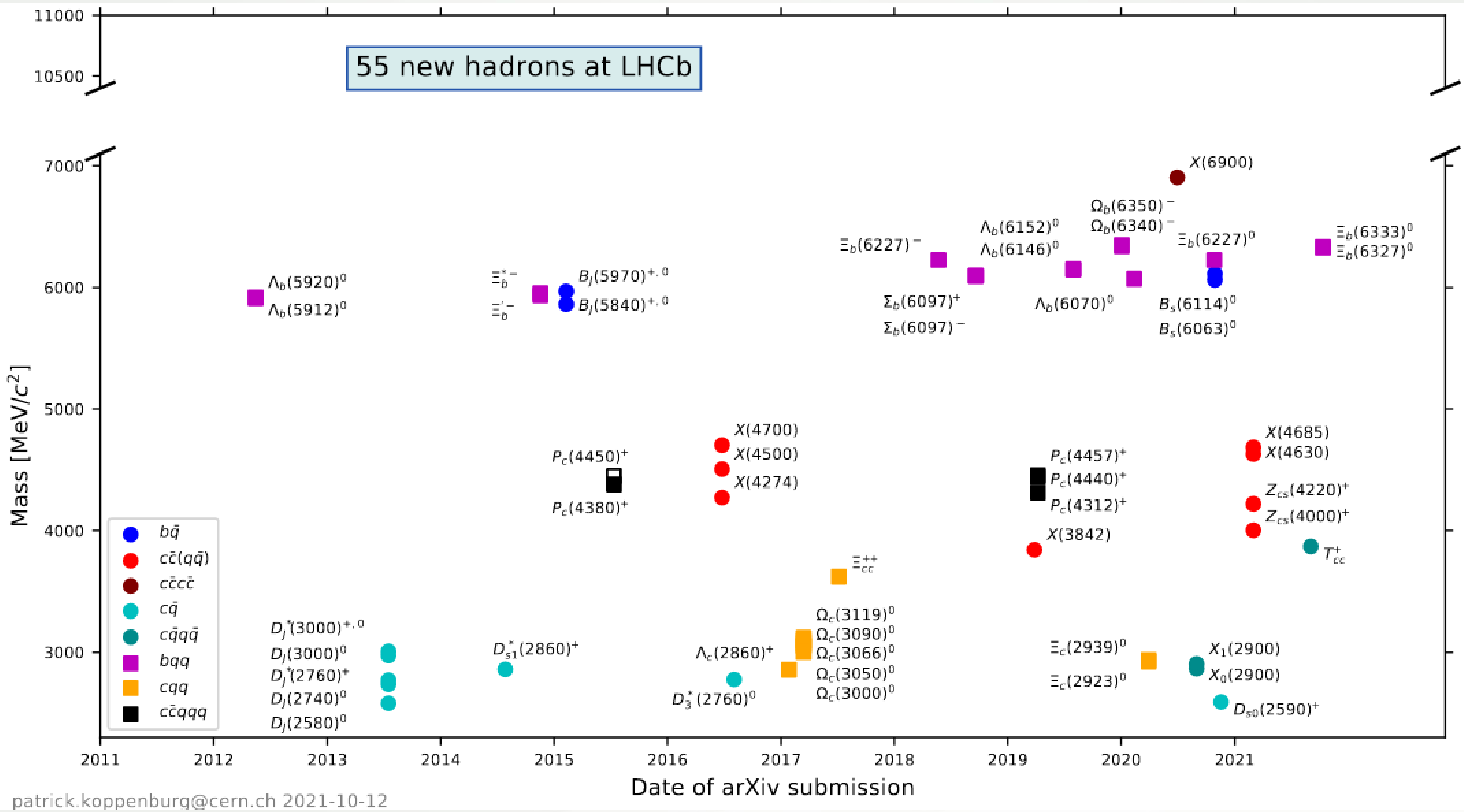
- Use $B^+ \rightarrow J/\psi K^+$ as control channel to cancel detection/production asymmetries. (result already comparable with world average!).

$$A_{CP}(B^+ \rightarrow K^+ \pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$ 1.5σ

$$\Delta A_{CP}(K\pi) \equiv A_{CP}(B^0 \rightarrow K^+ \pi^-) - A_{CP}(B^+ \rightarrow K^+ \pi^0) = 0.115 \pm 0.014$$ >8.0σ

Spectroscopy

Exotic tetra and pentaquarks



https://www.nikhef.nl/~pkoppenb/Masses_LHCb.pdf

T_{cc} tetraquark

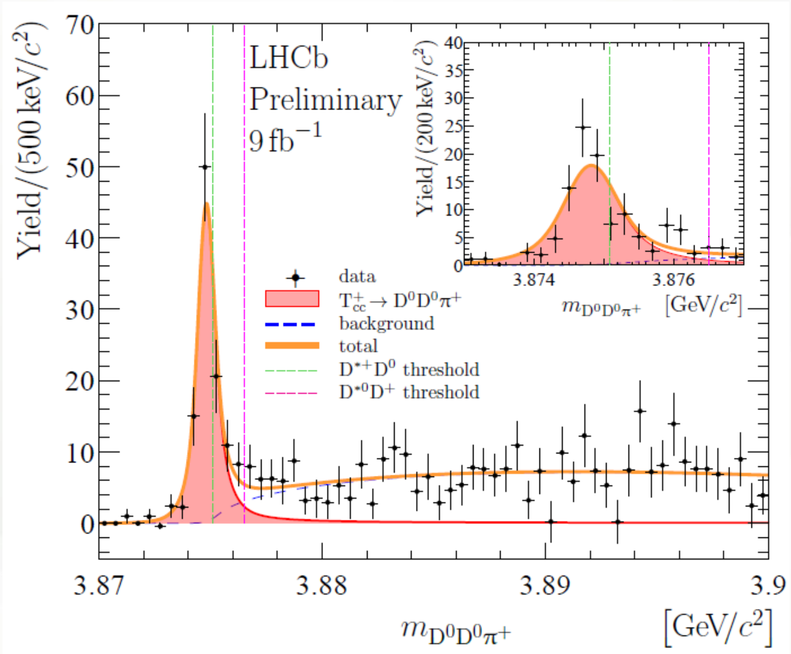
arXiv:2109.01056v2[hep-ex]

- All exotic states so far decay via strong interaction.
  - A discovery of a log-lived exotic state stable wrt strong interaction would be intriguing.
  - A hadron with two heavy quarks Q and two light quarks q, $Q_1Q_2\overline{q}_1\overline{q}_2$, is a prime candidate → $bb\overline{u}\overline{d}$ hadron state.
  - Before LHCb, no consensus whether $bc\overline{u}\overline{d}$ and $cc\overline{u}\overline{d}$ exists and were narrow enough to be detected.
- Prediction: Phys. Rev. Lett. 119 (2017) 202001
  - $T(bb\overline{u}\overline{d})$ with $J^P = 1^+$ at 10,389 ± 12 MeV (near $B^{(*)}\overline{B}^{(*)}$ threshold)
  - $T(cc\overline{u}\overline{d})$ with $J^P = 1^+$ at 3882 ± 12 MeV (near $D^{(*)}\overline{D}^{(*)}$ threshold)

T_{cc} tetraquark

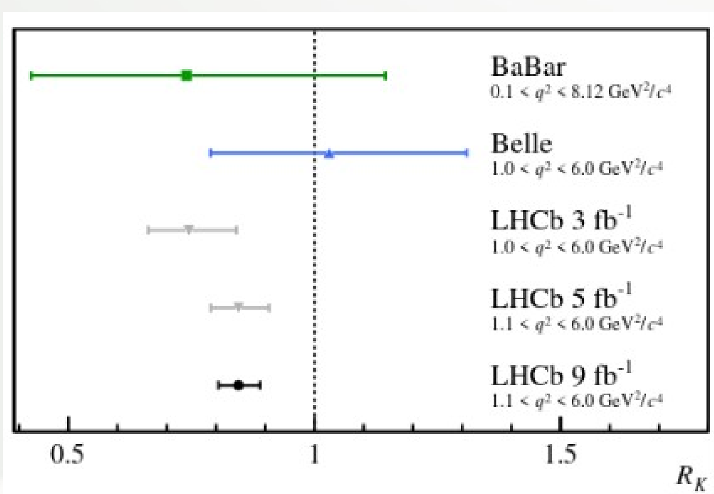
arXiv:2109.01056v2[hep-ex]

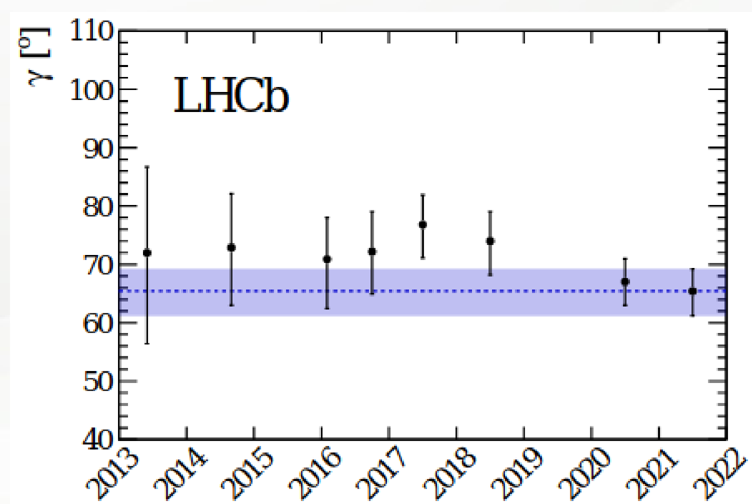
- The LHCb analysed the $D^0D^0\pi^+$ final state and observed a $T(cc\bar{u}\bar{d})$ state with mass of about 3875 MeV/c^2.
- Narrow peak just below the $D^{(*)}\bar{D}^{(*)}$ mass threshold, as predicted.
- Reinforces the possibility of a $T(bb\bar{u}\bar{d})$ tetraquark state that is stable wrt to strong interactions.



The future

- The LHCb upgrade for Run3/Run4 aims to:
  - Collect ~50 fb^{-1} at L = 2 X 10^{33} cm^{-2} s^{-1}
  - ~5 visible interactions
  - 40 *MHz* readout of detector
  - Full software trigger will lead to a factor two gain for hadronic channels.
- Upgrade 2 for Run5/Run6
  - Collect ~300 fb^{-1} at L = 1.5 X 10^{34} cm^{-2} s^{-1}

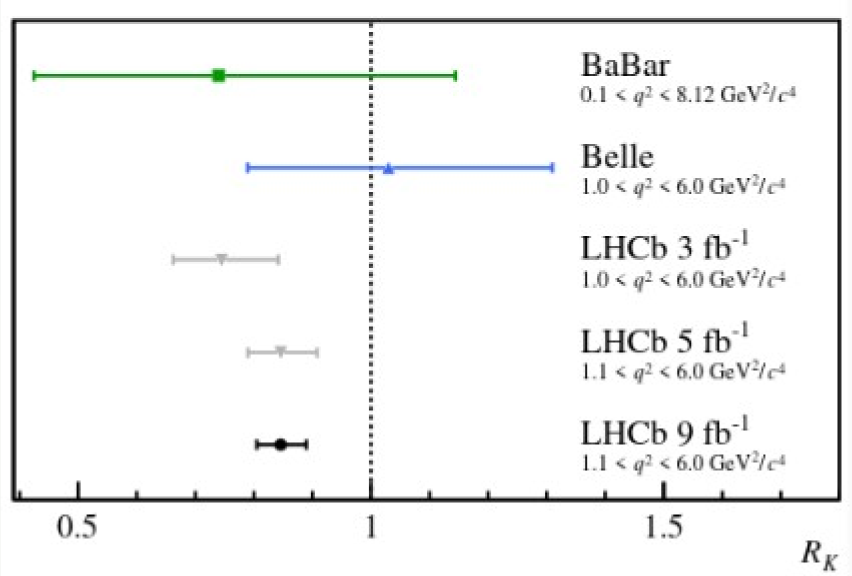


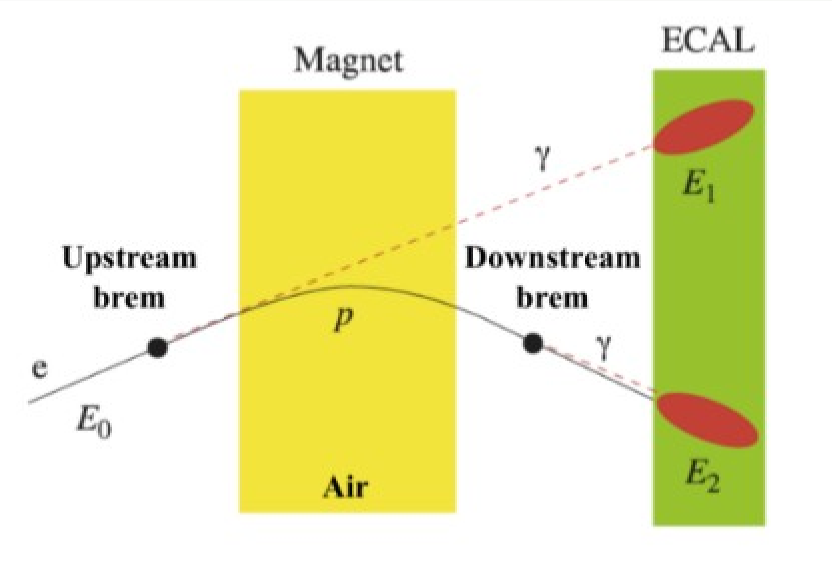


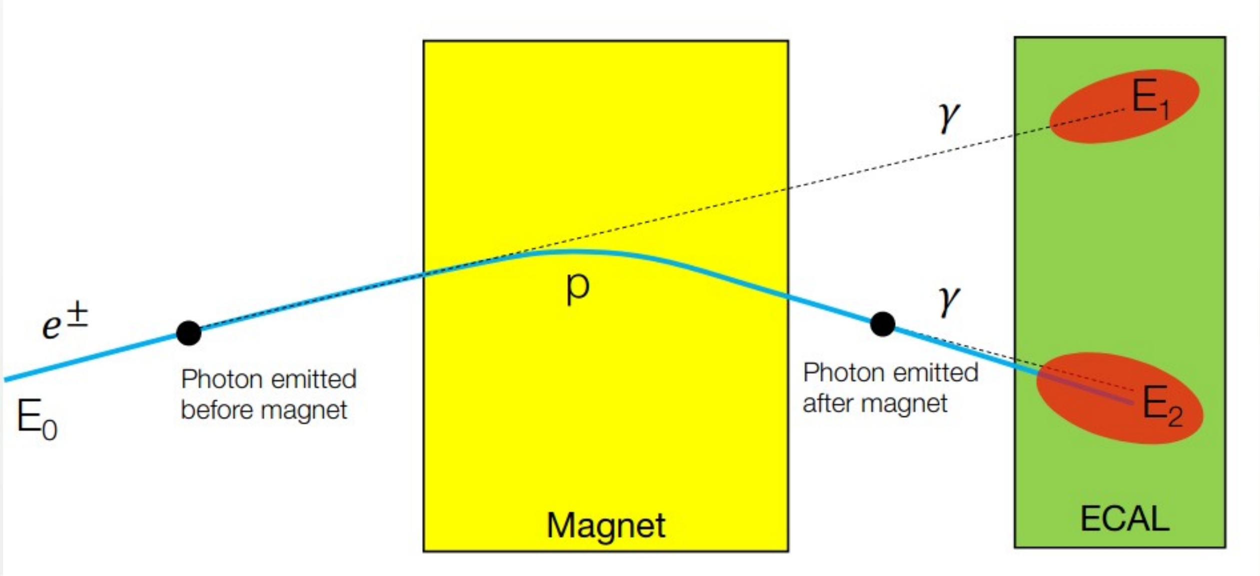
Conclusions

- Many important results from LHCb Run 2 dataset:
  - Evidence of LU violation.
  - Improved precision of CKM γ measurement.
  - CP violation in the B → hh decays leads to a intriguing K-π puzzle.
  - Many new exotic states observed.
- Many important results to come in the next 2 years.
- LHCb uograde to increase the dataset by a factor 5-10 will help to pin down many evidences revealed so far.

backup


BaBar
0.1 < q² < 8.12 GeV²/c⁴
Belle
1.0 < q² < 6.0 GeV²/c⁴
LHCb 3 fb⁻¹
1.0 < q² < 6.0 GeV²/c⁴
LHCb 5 fb⁻¹
1.1 < q² < 6.0 GeV²/c⁴
LHCb 9 fb⁻¹
1.1 < q² < 6.0 GeV²/c⁴
0.5
1
1.5
R_K


ECAL
Magnet
γ
E1
Upstream brem
Downstream brem
p
γ
e
E0
Air
E2


E1
γ
p
e±
γ
Photon emitted before magnet
Photon emitted after magnet
E0
E2
Magnet
ECAL