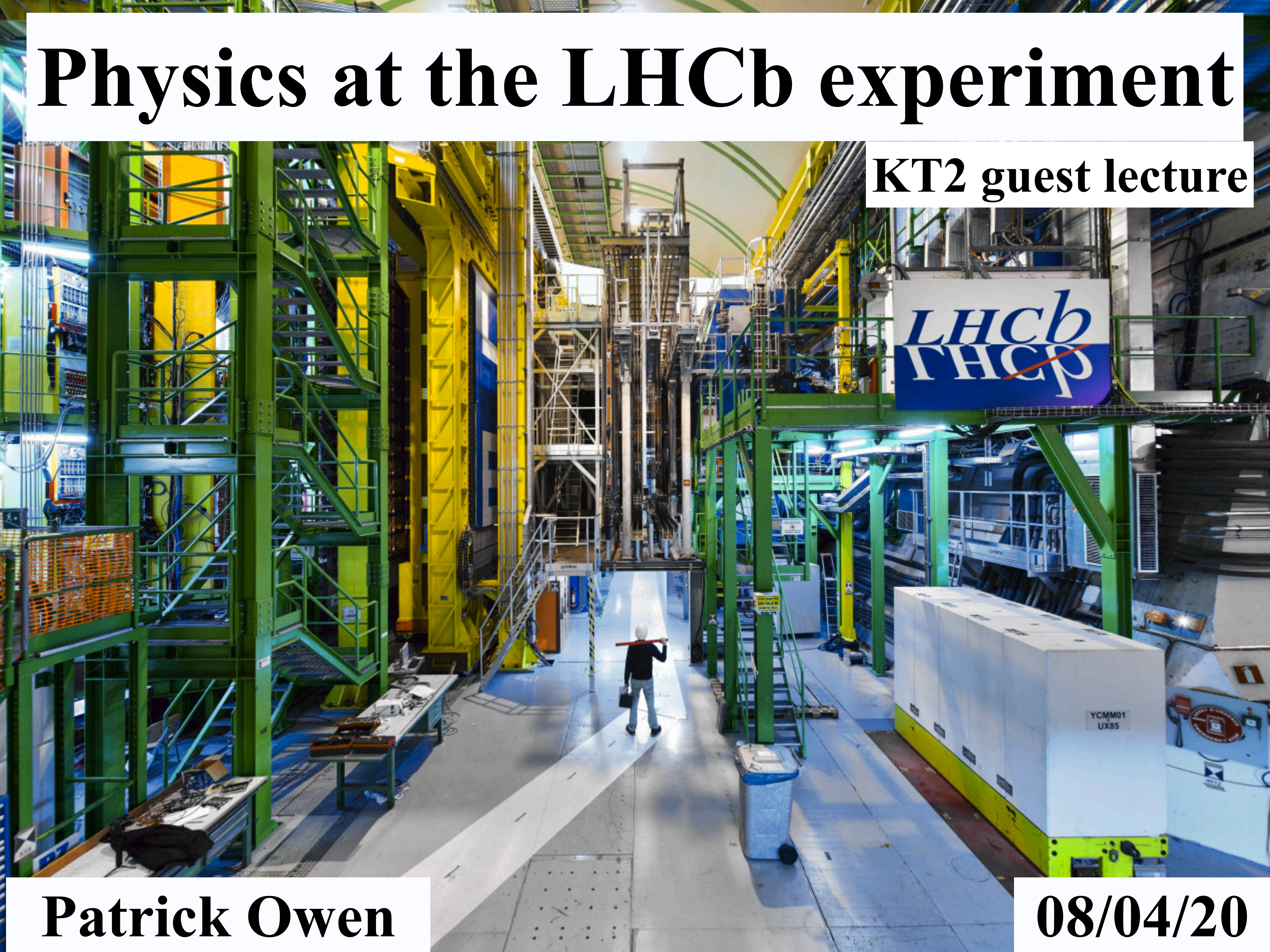
Physics at the LHCb experiment

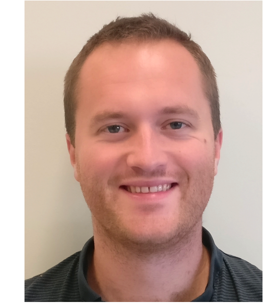
KT2 guest lecture



Patrick Owen

08/04/20

Me: Patrick Owen



Born in Oxford

Ph.D. at Imperial College, London

Since 2016 at UZH

I have been working on the LHCb experiment for 10 years.

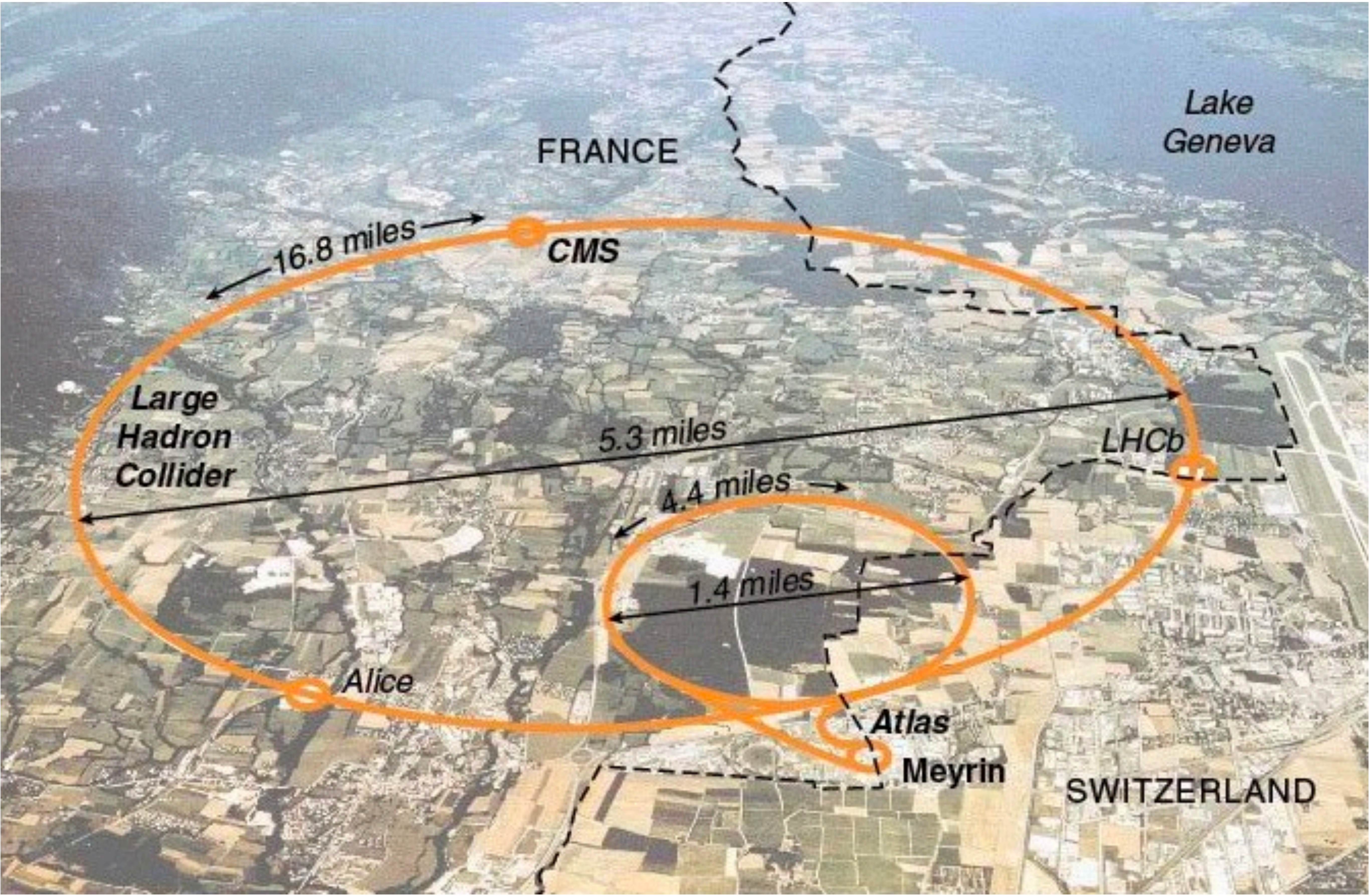
My research involves looking for new physics with beauty quark decays.

Overview

- Introduction to:
  - The LHC
  - The LHCb experiment.
- The initial raison d'etre for LHCb: CP violation.
- What we focus on in UZH: Lepton flavour universality.

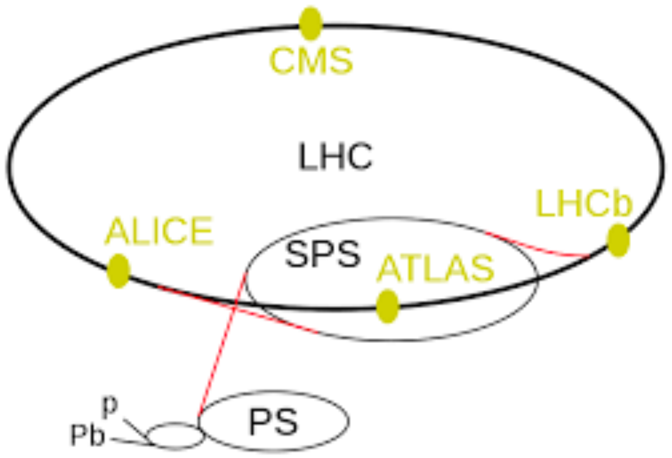
Any questions, feel free to send
a mail to: powen@physik.uzh.ch

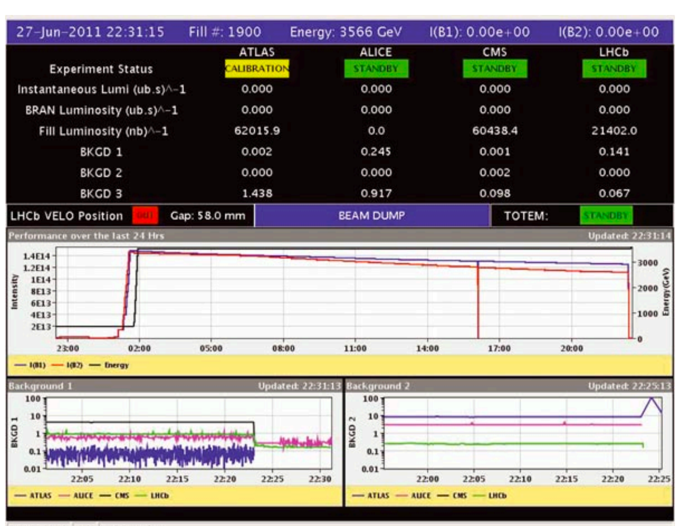
The Large Hadron Collider



The LHC in a nutshell

- The LHC is the world's highest energy particle accelerator.
  - Most of the time the LHC collides protons.
    - Protons are injected into the LHC and accelerated to 13 TeV.
    - Every 25ns, bunches of around 10^{11} protons are collided.
    - This continues for a few hours until the beam intensity is diminished enough to refill the machine.



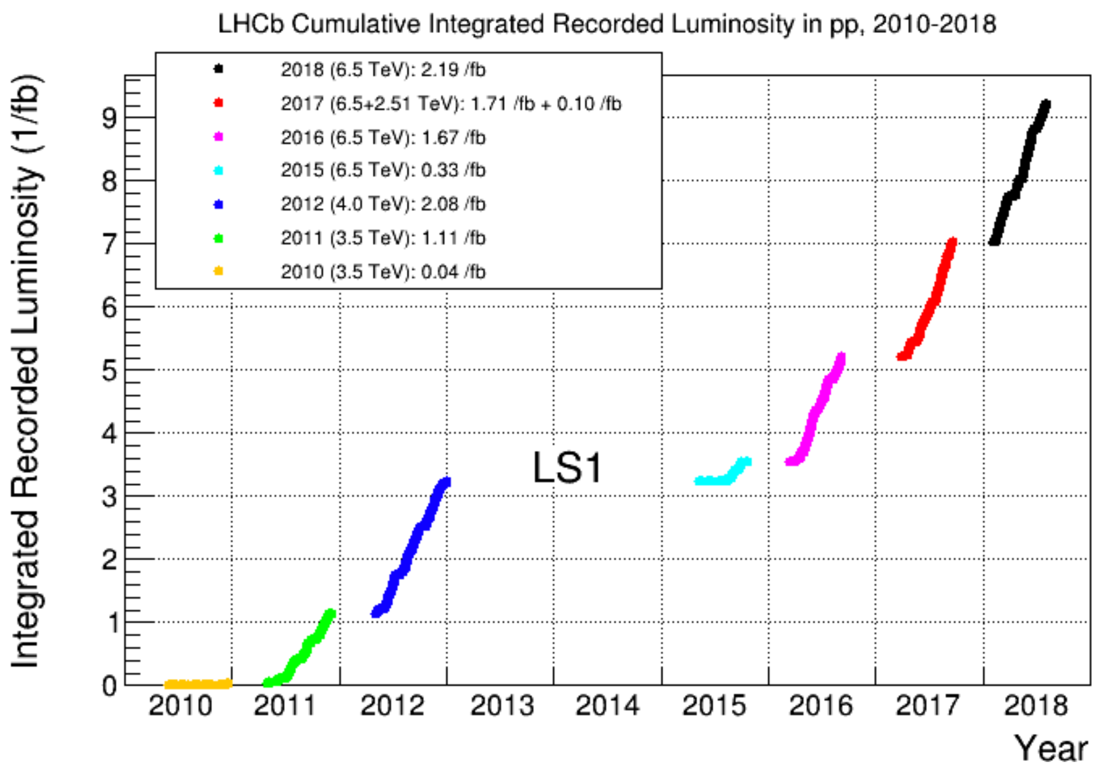


At the CERN canteen you will see LHC status screens like this during running.

The LHC data taking

- The LHC has undergone two large periods of data collection.

- For example, here is the integrated luminosity collected by LHCb so far.

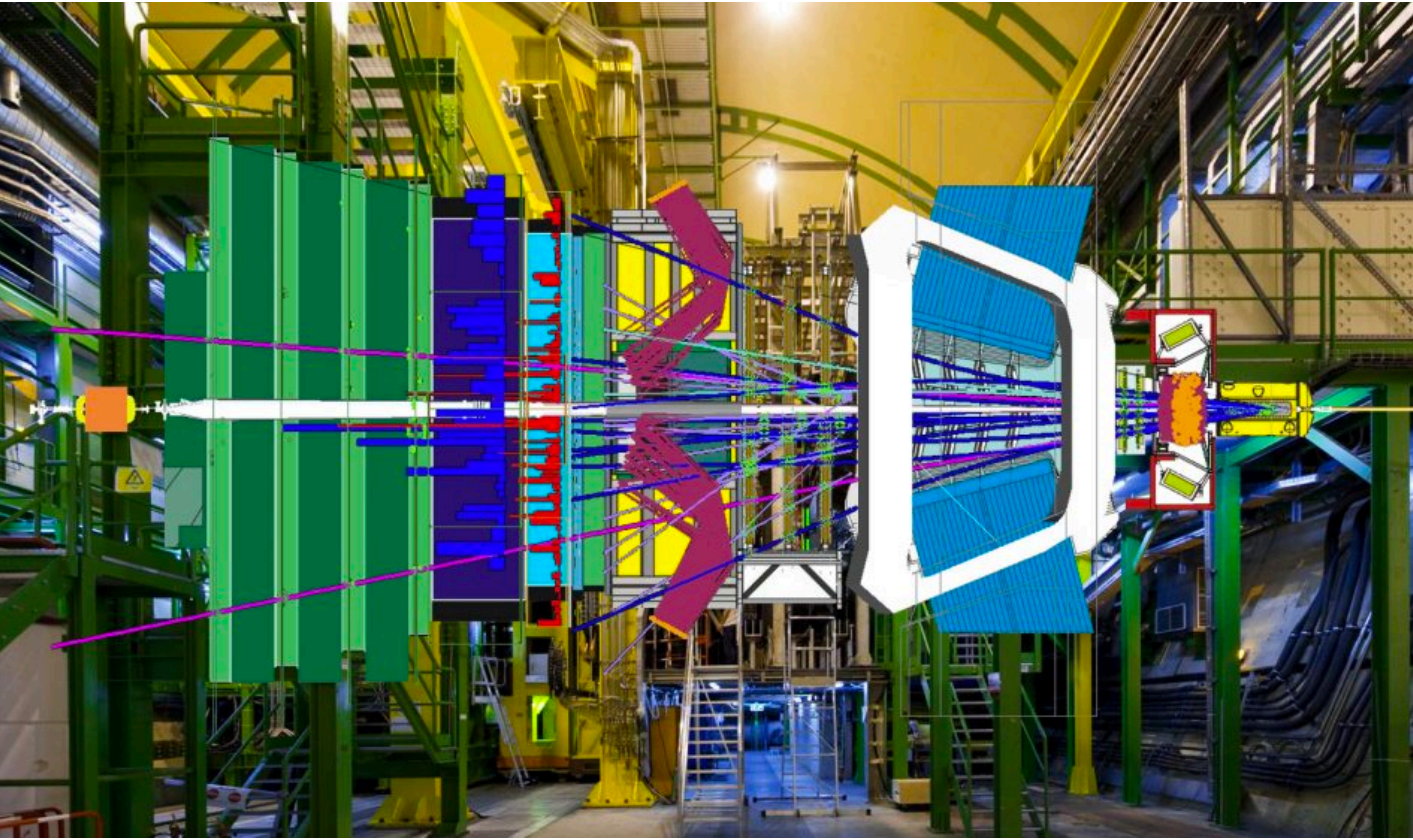


- In total we have $9fb^{-1}$, i.e. so an interaction with a cross-section of 1fb will have occurred 9 times.

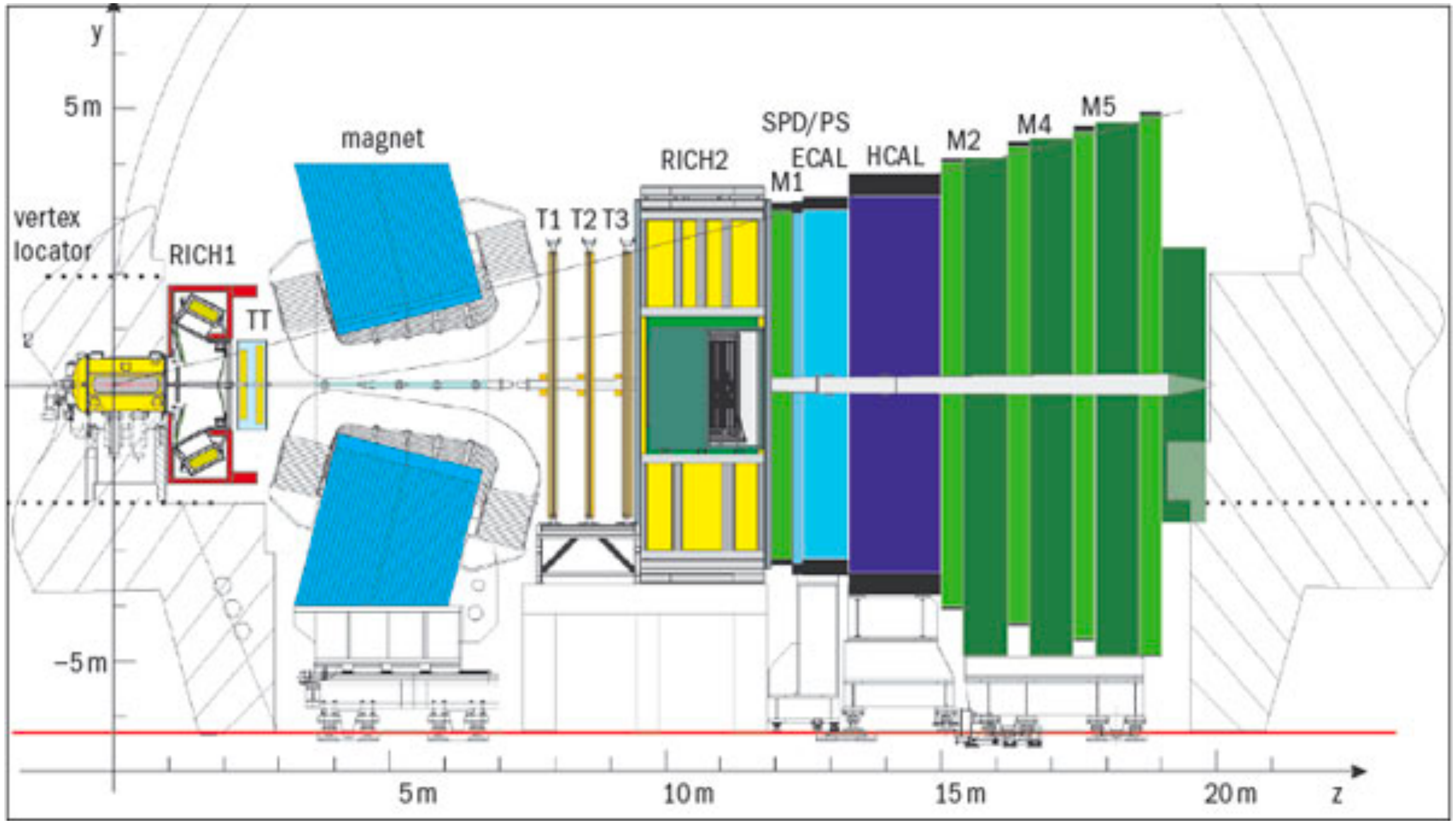
- This corresponds to around 10^{12} beauty quark decays.

LHCb

LHCb

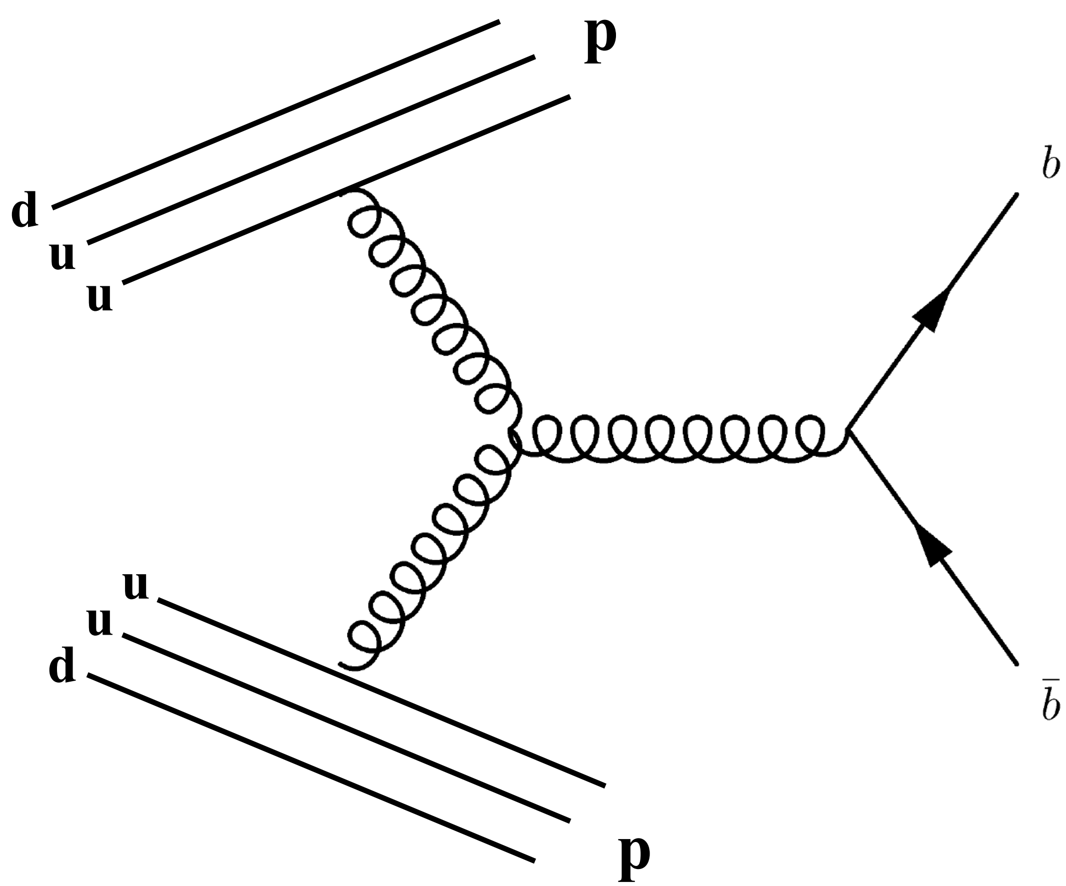


LHCb

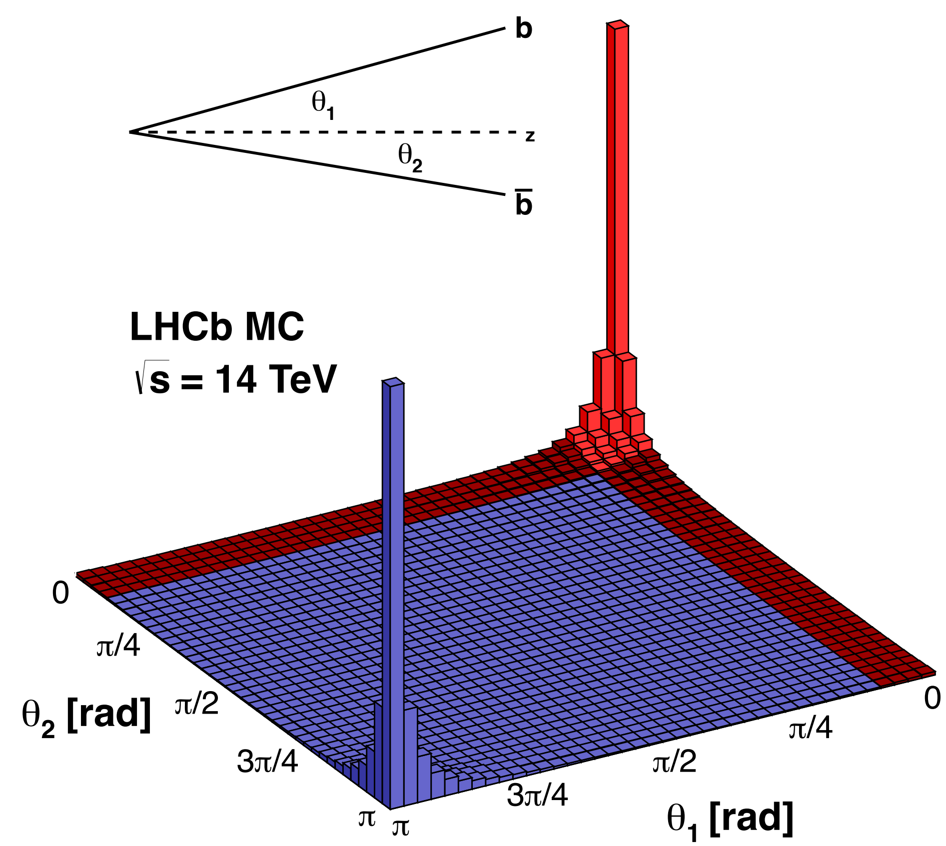


- The LHCb detector is designed to measure beauty and charm quark decays.
  - Precise tracker (Velo,TT,T-stations,magnet) to measure particle momentum.
  - Ring Imaging CHerenkov (RICH) detectors for particle identification.
  - Calorimeter and muon system to identify electrons, photons and muons.

Beauty quark production at LHCb



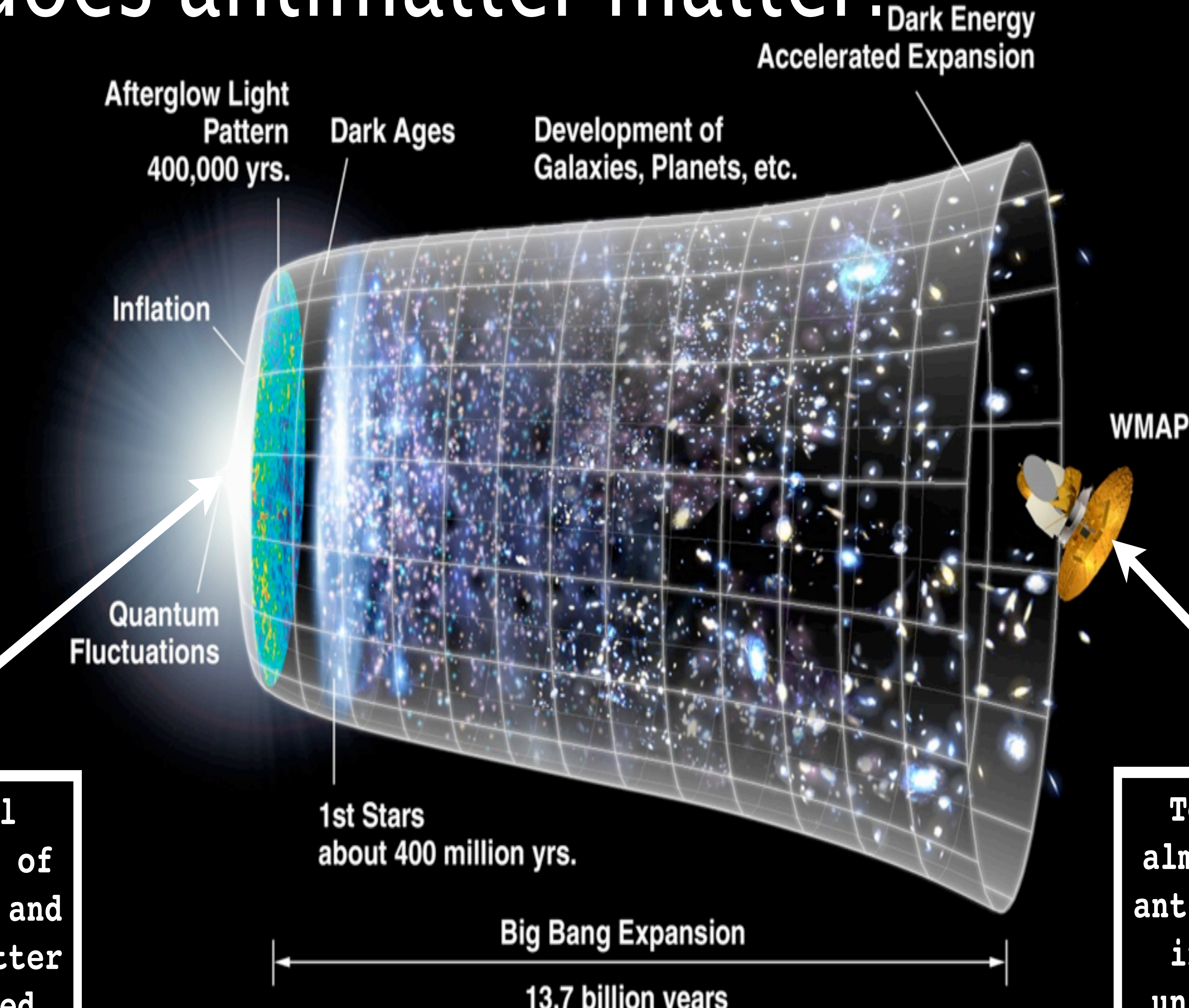
- Beauty quarks mainly produced by gluon-gluon fusion.
- They almost always come in pairs.
- At peak luminosity, around 30K pairs are produced each second.



- They are produced in the 'forward' region, i.e. along the beam line.
- This is what defines the LHCb shape as a cone along the beam direction.

CP violation

Why does antimatter matter?



Equal amount of matter and antimatter created

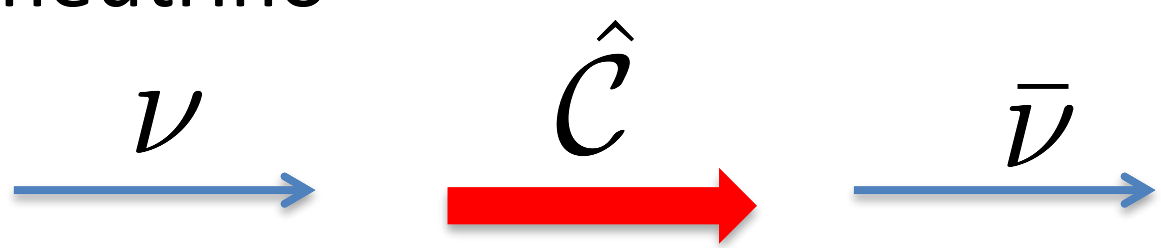
Today: almost no antimatter in the universe

So where did all the antimatter go?

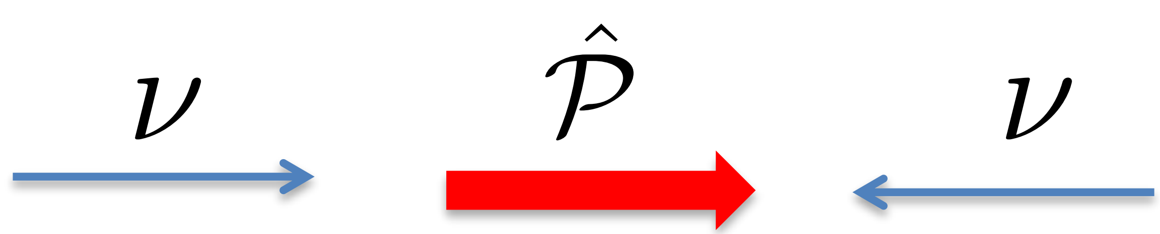
Reminder:

Charge and parity symmetries

- Charge conjugation:
  - Particle-anti-particle exchange.
    - E.g. right-handed neutrino → right-handed anti-neutrino



- Parity transformation:
  - Reversal of spatial coordinates.
    - Right-handed neutrino -> left-handed neutrino



Reminder:

Charge and parity symmetries

- Charge conjugation:
  - Particle-anti-particle exchange.
    - E.g. right-handed neutrino → right-handed anti-neutrino

$$\overset{\nu}{\longrightarrow} \quad \xrightarrow{\hat{\mathcal{C}}} \quad \overset{\bar{\nu}}{\longrightarrow}$$

Both do not interact in SM:
Weak force ‘maximally’ violates C and P symmetries

- Parity transformation:
  - Reversal of spatial coordinates.
    - Right-handed neutrino -> left-handed neutrino

$$\overset{\nu}{\longrightarrow} \quad \xrightarrow{\hat{\mathcal{P}}} \quad \overset{\nu}{\longleftarrow}$$

Reminder:

CP-violation

- Combining the C and P transformations.

$$\overrightarrow{\nu} \quad \xrightarrow{\hat{\mathcal{C}\mathcal{P}}} \quad \overleftarrow{\bar{\nu}}$$

- Thought to restore the symmetry, until 1964 when Cronin and Fitch proved that CPV existed in a kaon oscillation experiment.

- In the Standard Model, CPV arises from the CKM matrix.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

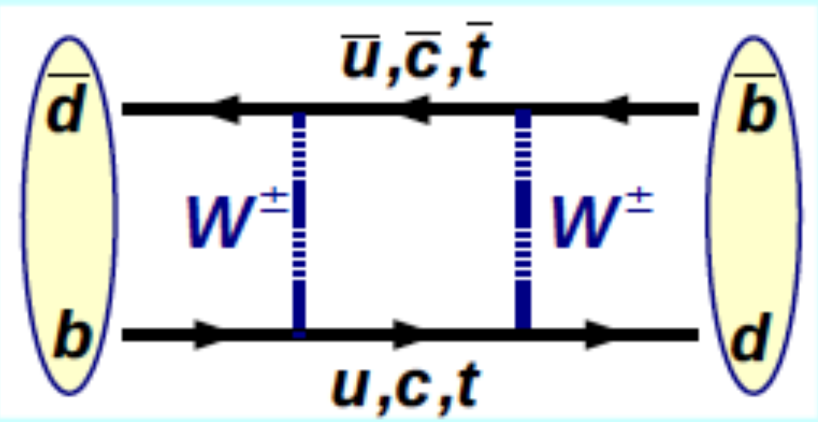
- So CPV is in the Standard Model. but 10 orders of magnitude too small to account for the matter-anti-matter asymmetry in the universe.

  - **We expect to find new sources of CP violation beyond the Standard Model.**

Manifestations of CP violation

CPV in mixing

("indirect *CP* violation")



→ interference of absorp-tive and dispersive part of mixing amplitude

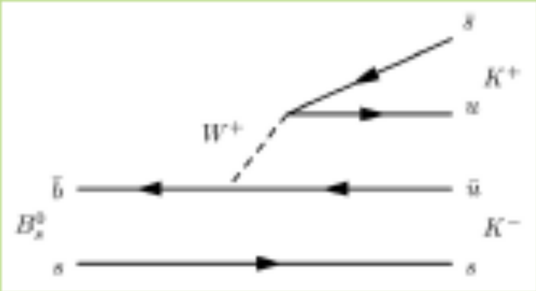
→ different mixing rate

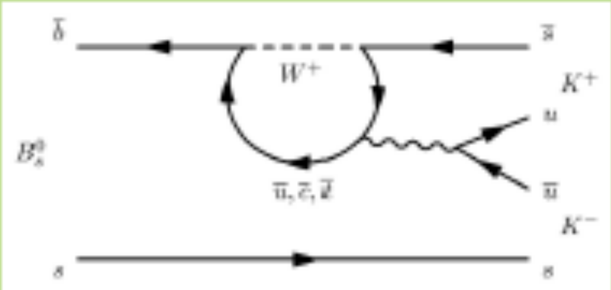
$B^0_{(s)} \to \overline{B}^0_{(s)}$ vs $\overline{B}^0_{(s)} \to B^0_{(s)}$

→ small in Standard Model

CPV in decay

("direct *CP* violation")





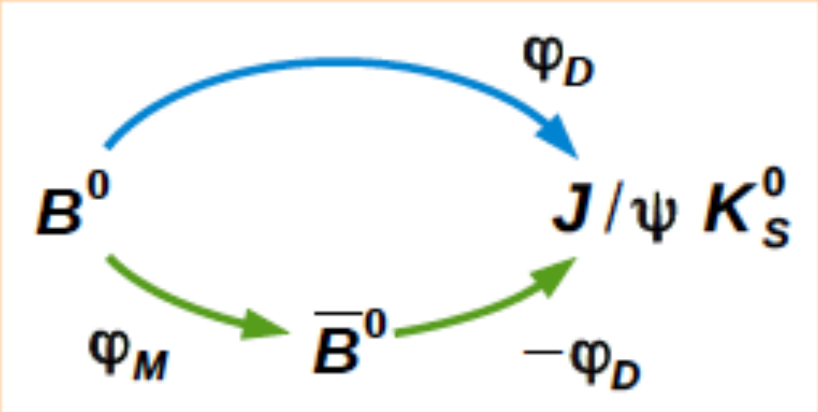
→ interference of decay diagrams with different weak and strong phases

→ different decay rates

$B \to f$ vs $\overline{B} \to \overline{f}$

→ strong phases

CPV in interference of mixing and decay



→ interference between direct decay and decay after mixing

→ different decay rates

$B^0_{(s)} \to f_{CP}$ vs $\overline{B}^0_{(s)} \to f_{CP}$

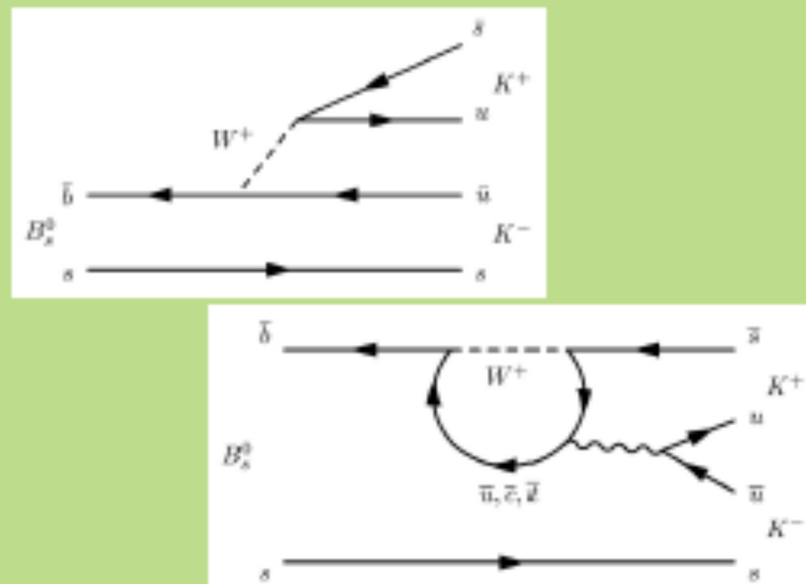
→ "golden modes"

Manifestations of CP violation

Will discuss these two today:

CPV in decay

("direct *CP* violation")

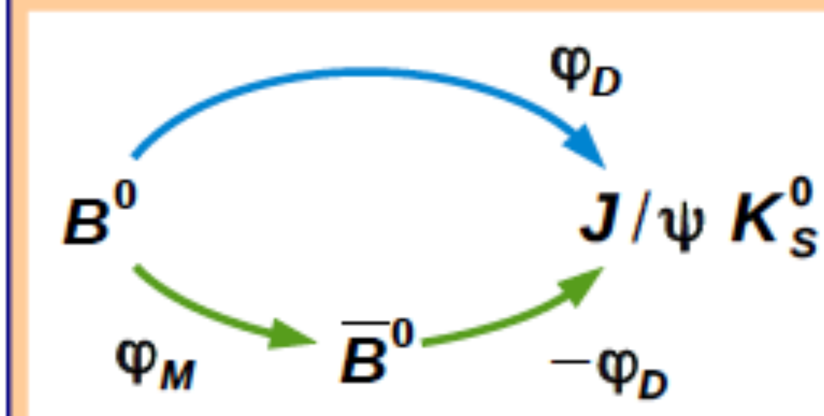


→ interference of decay diagrams with different weak and strong phases

→ different decay rates $B \to f$ vs $\overline{B} \to \overline{f}$

→ strong phases

CPV in interference of mixing and decay



→ interference between direct decay and decay after mixing

→ different decay rates $B^0_{(s)} \to f_{CP}$ vs $\overline{B}^0_{(s)} \to f_{CP}$

→ "golden modes"

Direct CP violation

- Consider the decay $B \to f$ and its CP conjugate $\bar{B} \to \bar{f}$.

- CPV in decay is a difference in decay rate $|A^P|^2$ and CP conjugate decay $|\overline{A}^P|^2$.

$$A^P = |A^P| e^{\delta_S^P} e^{\delta_W^P}$$

Strong phase

Weak phase

- With one decay amplitude, $|A^P|^2 = |\overline{A}^P|^2$ -> no CPV.

- With two decay amplitudes P and T:

$$A = A^P + A^T = |A^P| \delta_S^P \delta_W^P + |A^T| \delta_S^T \delta_W^T$$

- Then taking the difference we obtain an expression for direct CPV.

$$|A|^2 - |\bar{A}|^2 = -4|A^P||A^T| \sin(\delta_{\mathrm{S}}^{\mathrm{P}} - \delta_{\mathrm{S}}^{\mathrm{T}}) \sin(\delta_{\mathrm{W}}^{\mathrm{P}} - \delta_{\mathrm{W}}^{\mathrm{T}})$$

- So only non-zero CPV when both strong and weak phases different.

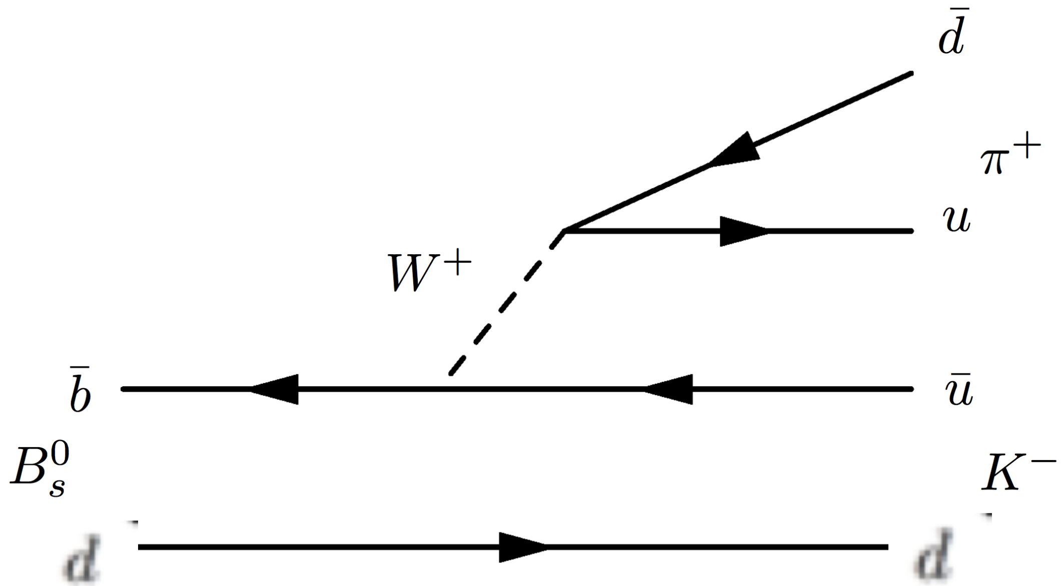
CP violation in $B^0 \to K^+\pi^-$

- CPV is maximised when the two amplitudes are of similar size.

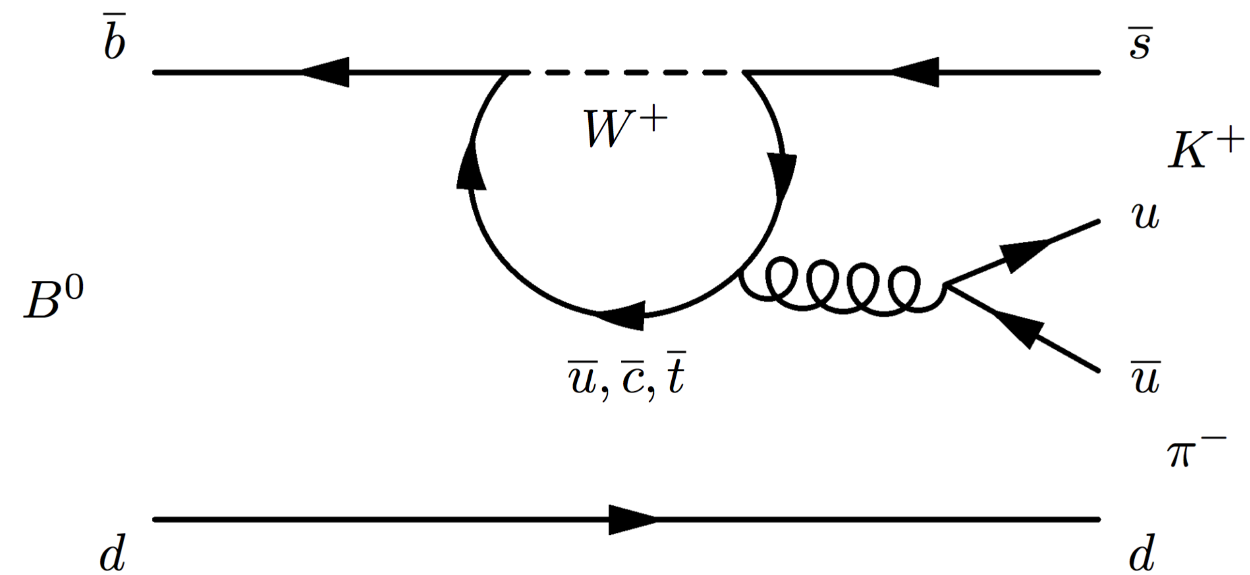
$$|A|^2 - |\bar{A}|^2 = -4|A^P||A^T|\sin(\delta_{\mathrm{S}}^{\mathrm{P}} - \delta_{\mathrm{S}}^{\mathrm{T}})\sin(\delta_{\mathrm{W}}^{\mathrm{P}} - \delta_{\mathrm{W}}^{\mathrm{T}})$$

- This is the case for the decay $B^0 \to K^+\pi.^-$

A^T



A^P

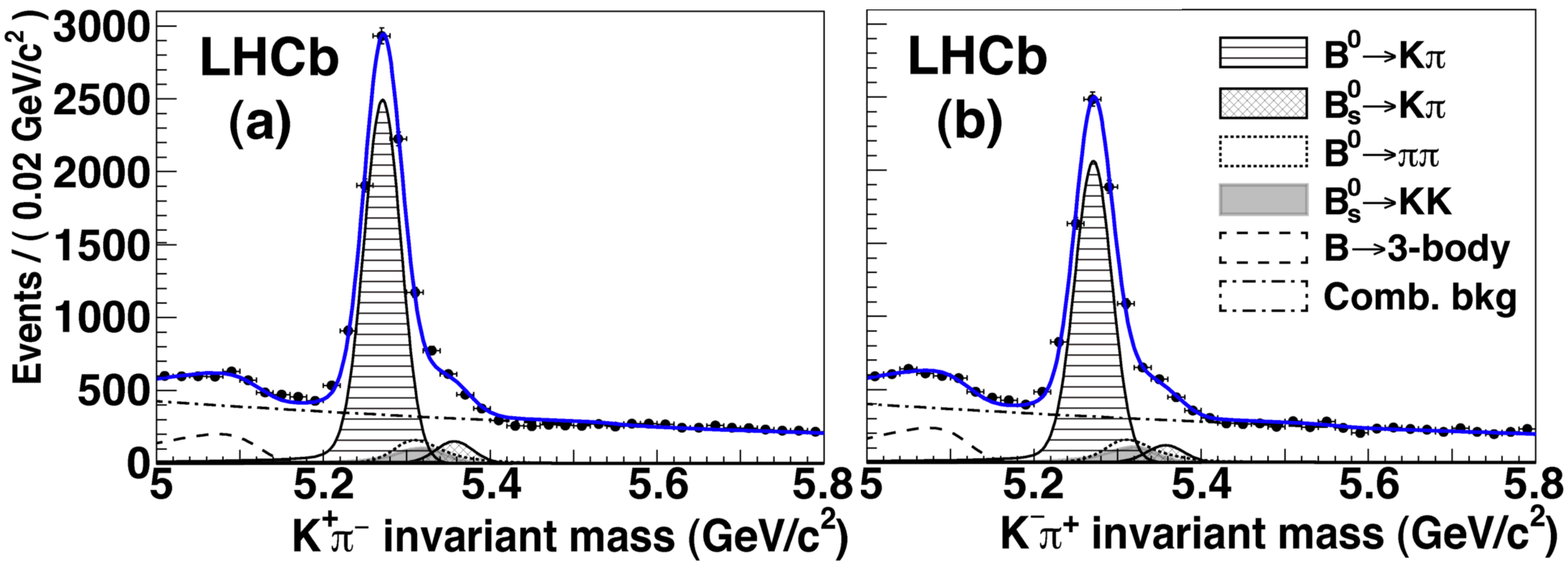


- These two amplitudes combine to give a large direct CPV. .

Seeing it in the data

- We see this in the LHCb dataset.

PHYS. REV. LETT. 108 (2012) 201601



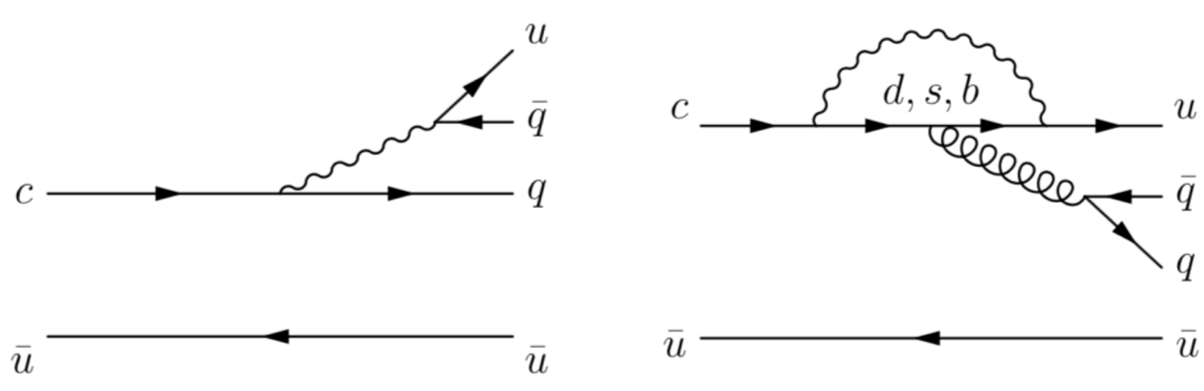
- See a visible difference in the signal yield between the decay and its CP conjugate.

CPV in charm decays

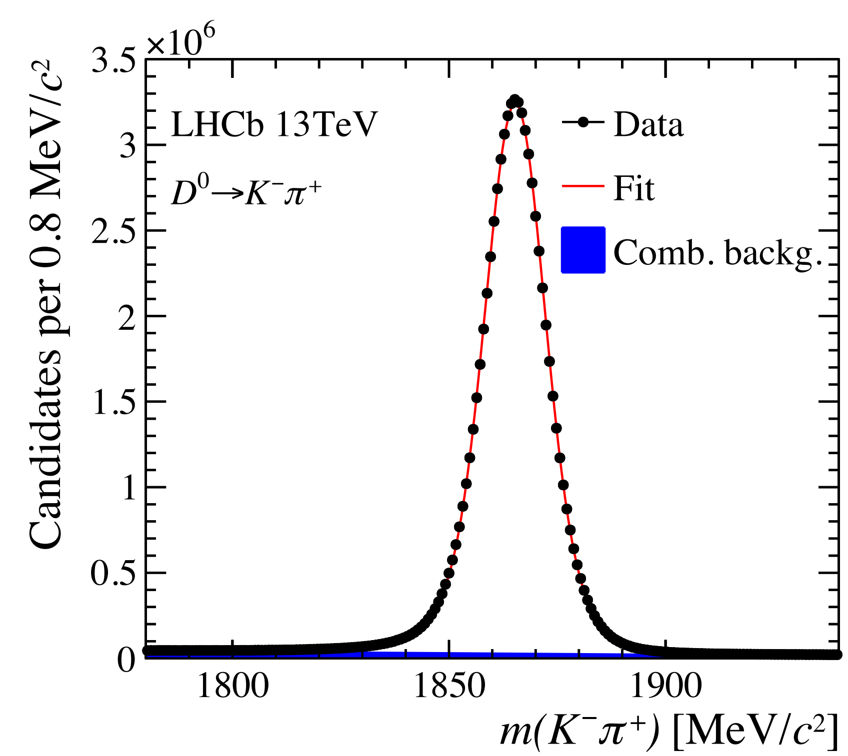
- While CPV in beauty quark decays had been long established, it had never been seen in charm quarks.

- The tree and penguin amplitude sizes were too different: $A^T >> A^P$.

D—>hh



- Therefore expect CPV to be very small.



- Fortunately, have millions of signal.

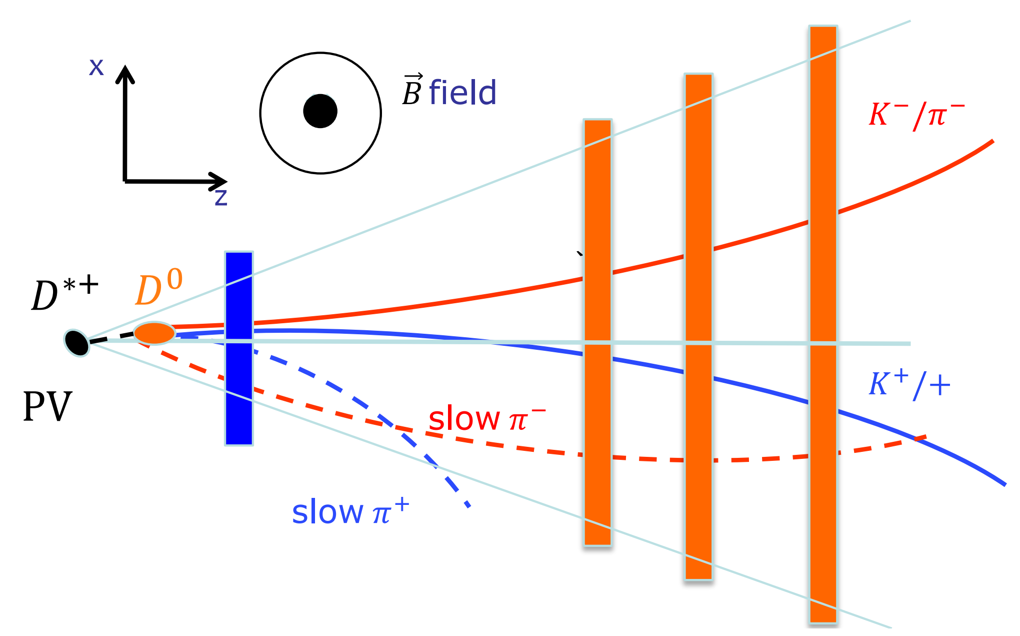
- Can detect very small CPV signals.

LHCb analysis

- In early 2019, we analysed our full 9fb^{-1} dataset in D—>hh decays.
- In order to control experimental uncertainties, compared two decays D—>KK and D—>ππ.

$$\boxed{\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

- This helps cancel experimental effects due to reconstructing particles with opposite charges.



A recent discovery

- We measured this difference to be non-zero by 5.3 standard deviations.

$$\Delta a_{CP}^{\mathrm{dir}} = (-15.6 \pm 2.9)\times 10^{-4}$$

First time discovered!

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

TODAY

- The conference organisers provided a celebratory drink to the LHCb members.

Interpretation

- Interpretation of this measurement is complicated by QCD uncertainties.
    - The charm quark is light so QCD is strong: non-peterbative techniques needed.

New physics explanation

News & Views | Published: 08 May 2019

PARTICLE PHYSICS

Charming clue for our existence

Alexander Lenz

Nature Reviews Physics **1**, 365–366(2019) | Cite this article

97 Accesses | **10** Altmetric | Metrics

The Large Hadron Collider beauty experiment (LHCb) collaboration announced the observation of charge parity (CP) violation in the decays of the D^0 meson, the lightest particle containing charm quarks, which might provide clues to why there is more matter than antimatter in the Universe and lead to a deeper understanding of the theory of the strong interaction.

QCD explanation

$SU(3)_F$ breaking through final state interactions and CP asymmetries in $D \to PP$ decays

Franco Buccella (INFN, Naples), Ayan Paul (DESY & Humboldt U., Berlin), Pietro Santorelli (INFN, Naples & Naples U.)

Feb 14, 2019 - 20 pages

Phys.Rev. D99 (2019) no.11, 113001
(2019-06-11)
DOI: 10.1103/PhysRevD.99.113001
DESY-19-025, DESY 19-025
e-Print: arXiv:1902.05564 [hep-ph] | PDF

Abstract (APS)
We analyze D decays to two pseudoscalars (π,K) assuming the dominant source of SU(3)F breaking lies in final state interactions. We obtain an excellent agreement with experimental data and are able to predict CP violation in several channels based on current data on branching ratios and ΔACP. We also make predictions for δKπ and the branching fraction for the decay Ds+→K+KL.
Abstract (arXiv)

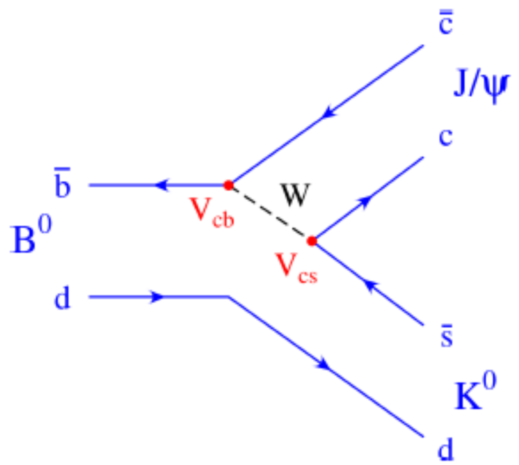
Note: 21 pages. Updated with the 2019 measurement of ΔA_{CP} from LHCb
Keyword(s): INSPIRE: symmetry breaking: flavor | symmetry breaking: SU(3) | final-state interaction | D: decay | decay: asymmetry | asymmetry: CP | CP: violation | D: branching ratio | D/s+ --> K+ K0(L)
Author supplied: Electroweak interactions

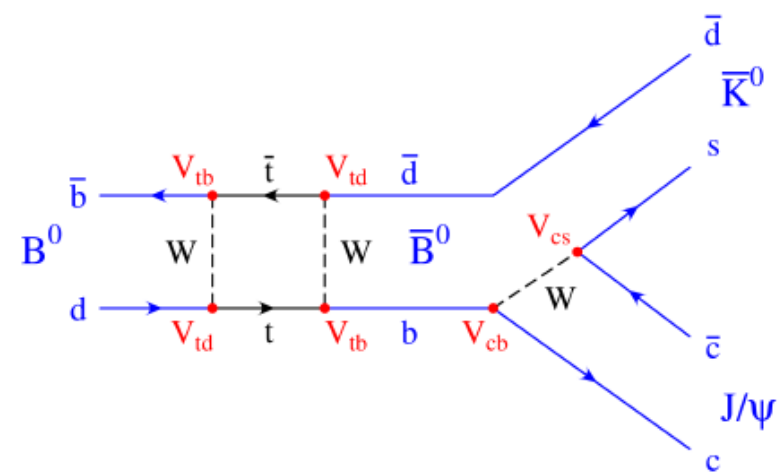
- Direct CPV often has interpretation issues due to the strong part needed to generate such effects.

- Other CPV in mixing more theoretically ‘clean’.

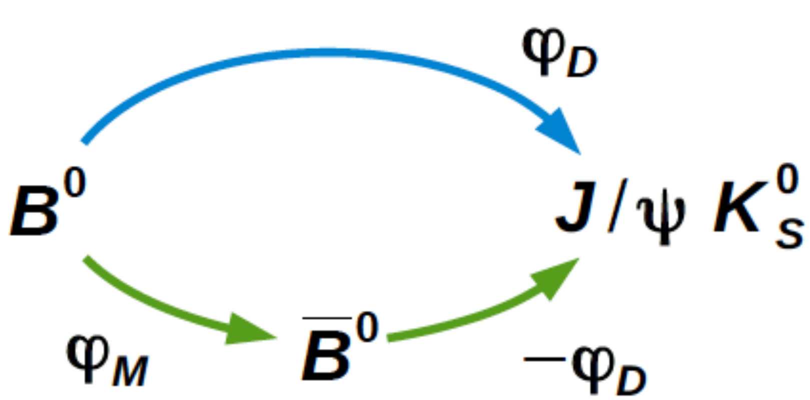
CPV in mixing and decay

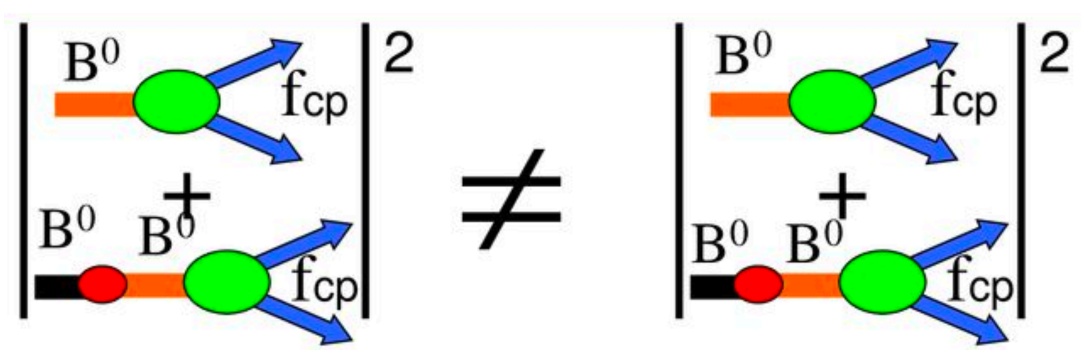
- A cleaner way to measure CPV is in the interference between mixing and decay amplitudes.
- 'Golden mode' is the decay $B^0 \to J/\psi K^0_s$
- Why? Both a B^0 and B^0 can decay into the same final state.





- You can then get interference between mixing and decay amplitudes.



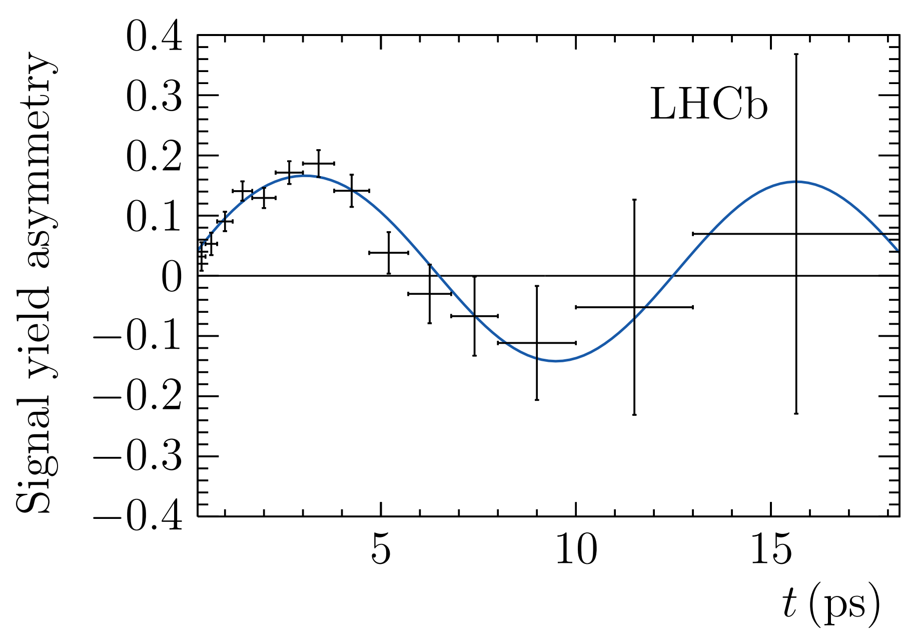


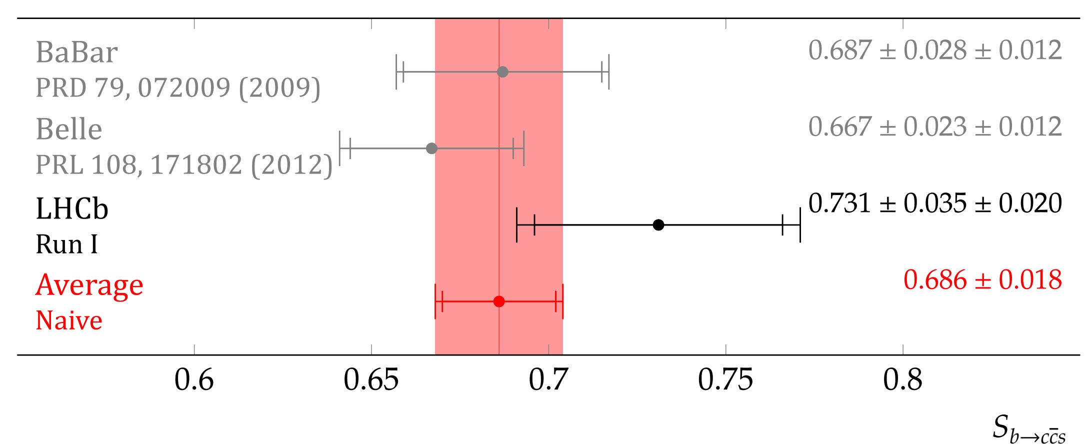
$B^0 \to J/\psi K_s^0$ analysis

- The idea to measure the asymmetry between a B^0 and B^0 decaying into the same final state.

$$a_f(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} \approx C \sin(2\beta) \sin(\Delta m t)$$

- Here is the signal yield asymmetry as measured by LHCb as a function of the decay time.





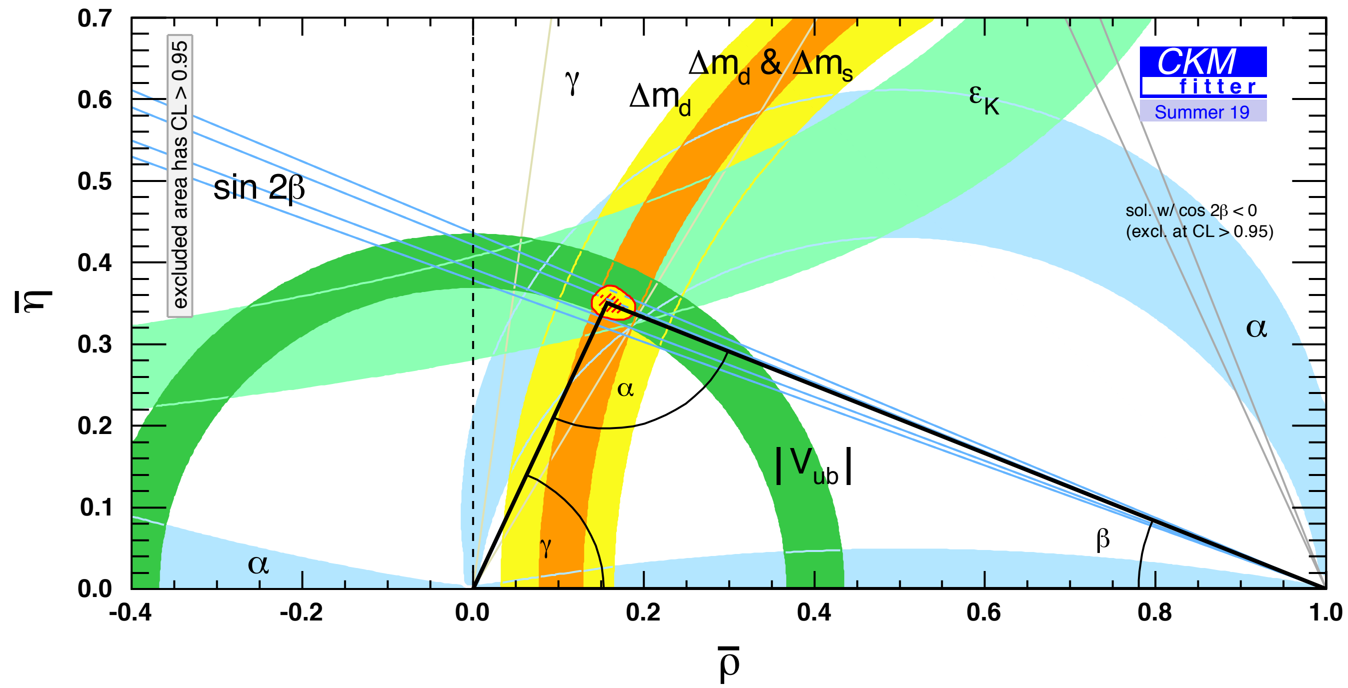
- The tricky part is to determine the flavour of the B^0.

sin(2β) and the unitarity triangle

- One can relate sin(2β) to the CKM elements of the diagrams involved.

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

- The β is the same angle as in the unitarity triangle!

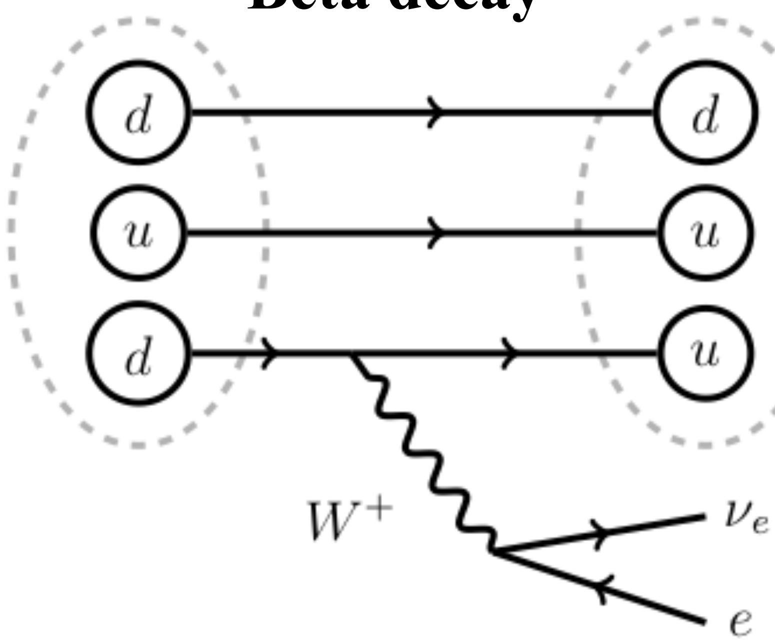


- Measuring sin(2β) and comparing it to other measurements can shed light on possible new physics.
  - At the moment is the consistency is reasonably good.

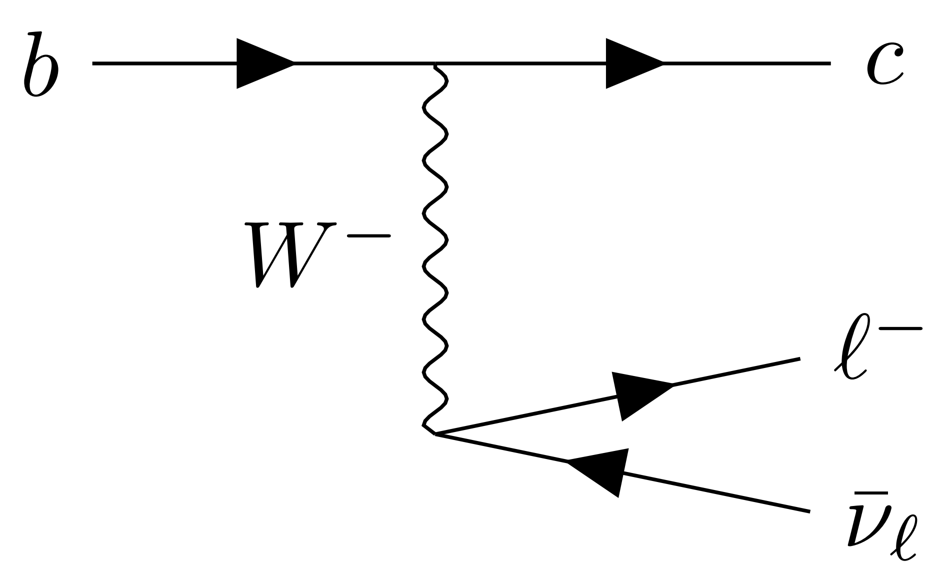
New physics with beauty quarks

- Beauty quarks decay via the weak force.

Beta decay



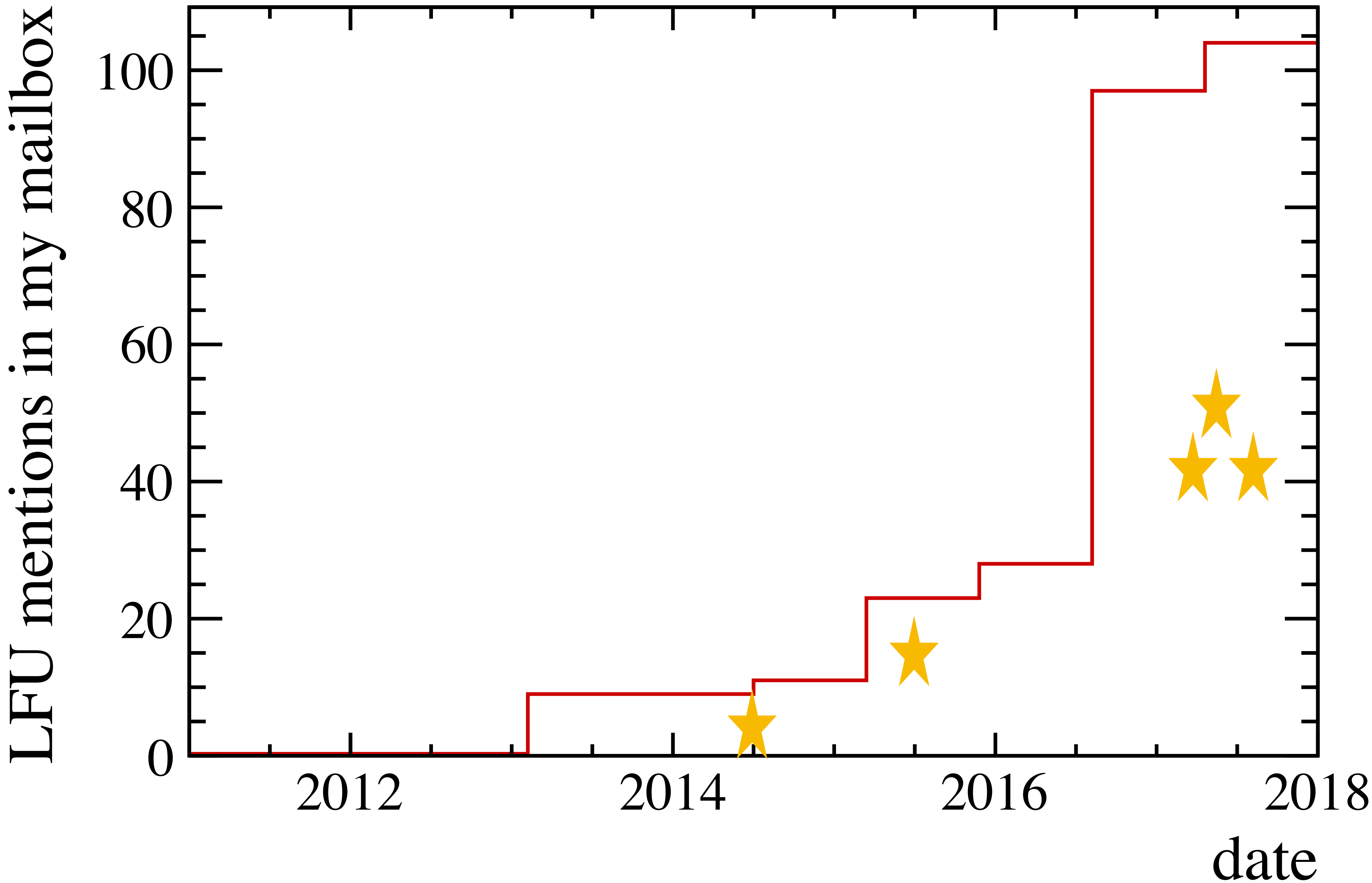
beauty decay



- W and Z bosons over 10 times heavier than decaying b-hadron.
  - Beauty quark decays can tell us about new high mass particles.
  - Can probe much heavier particles than directly. Not limited by the energy of the LHC.
  - Can still find new physics even if direct searches don't see anything.

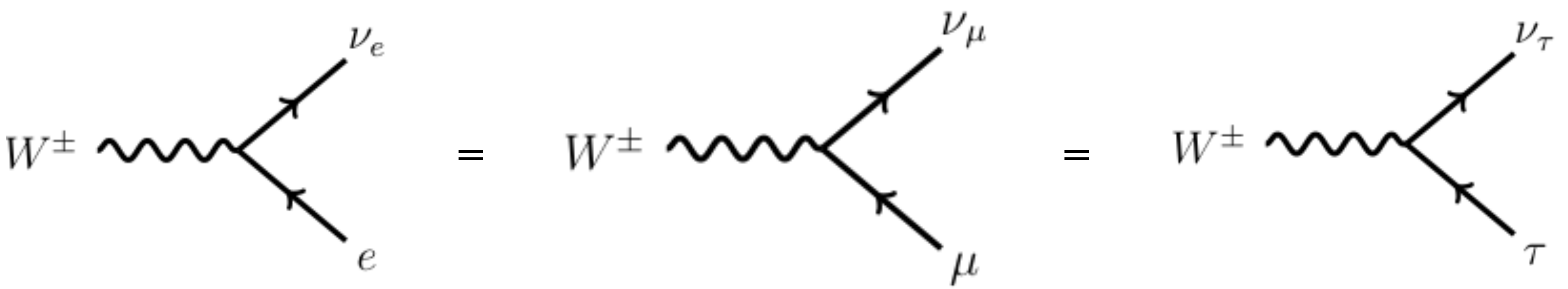
Lepton universality

★ = **Lepton universality publication**

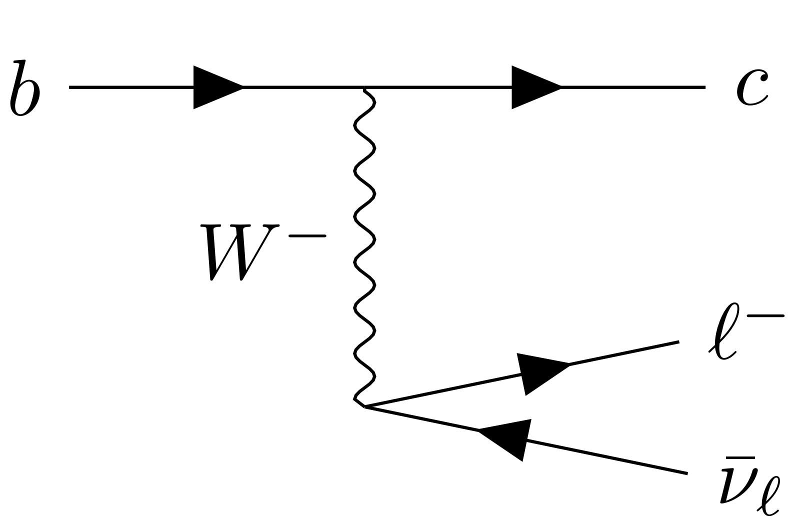


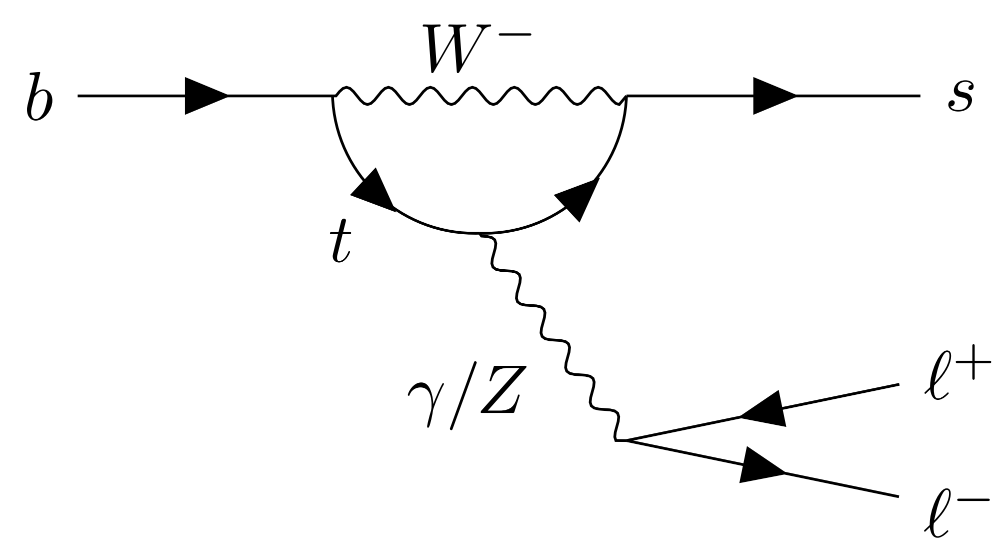
Lepton universality

In the Standard Model, the three charged leptons, apart their mass, are identical copies of each other - **a concept known as lepton universality.**



We want to test this in so-called 'semileptonic' B decays:

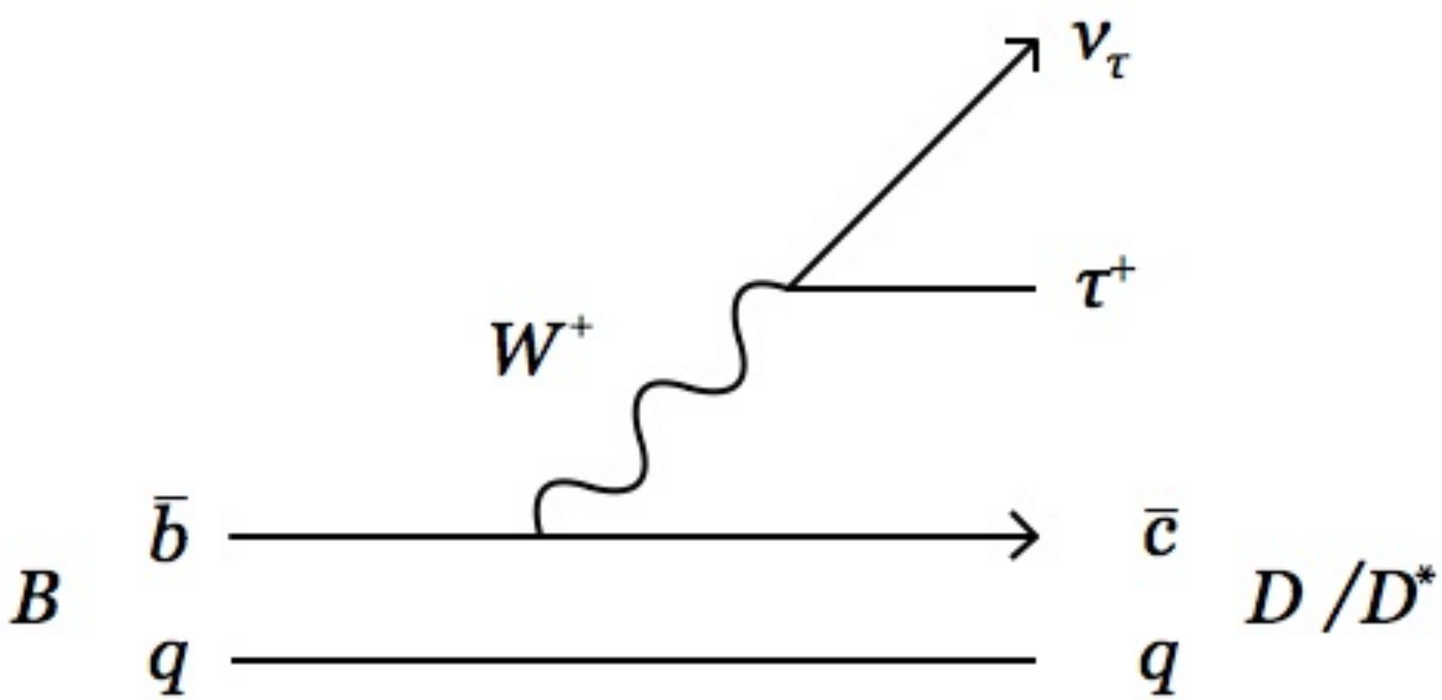




$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)} \qquad R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Why semi-leptonic decays?

- A decay is semi-leptonic if its products are part leptons and part hadrons.



$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto$$

$$\underbrace{G_F^2|V_{cb}|^2}_{\text{EW}}\,\underbrace{f(q^2)^2}_{\text{QCD}}$$

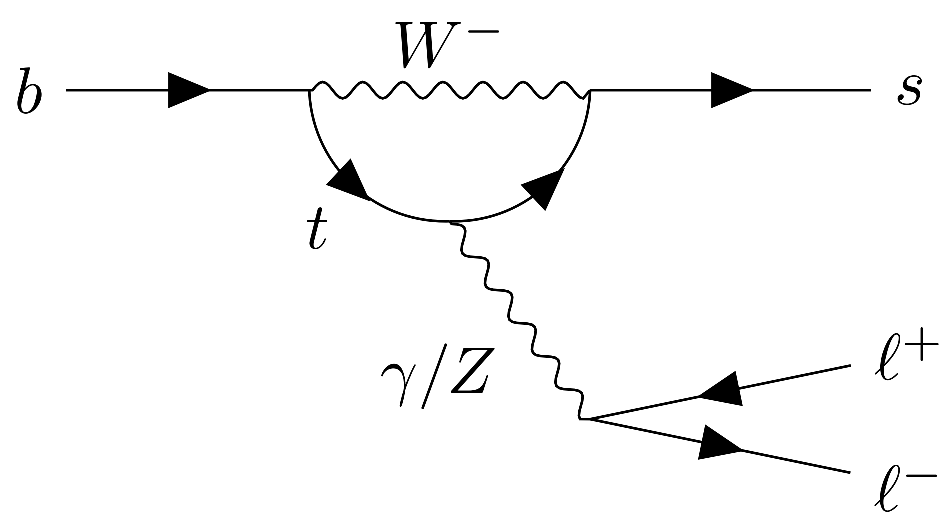
- These decays can be factorised, greatly simplifying theoretical calculations.

- Lepton universality ratios further cancel theoretical uncertainties.

Types of semi-leptonic decay

Two types of semi-leptonic B decay

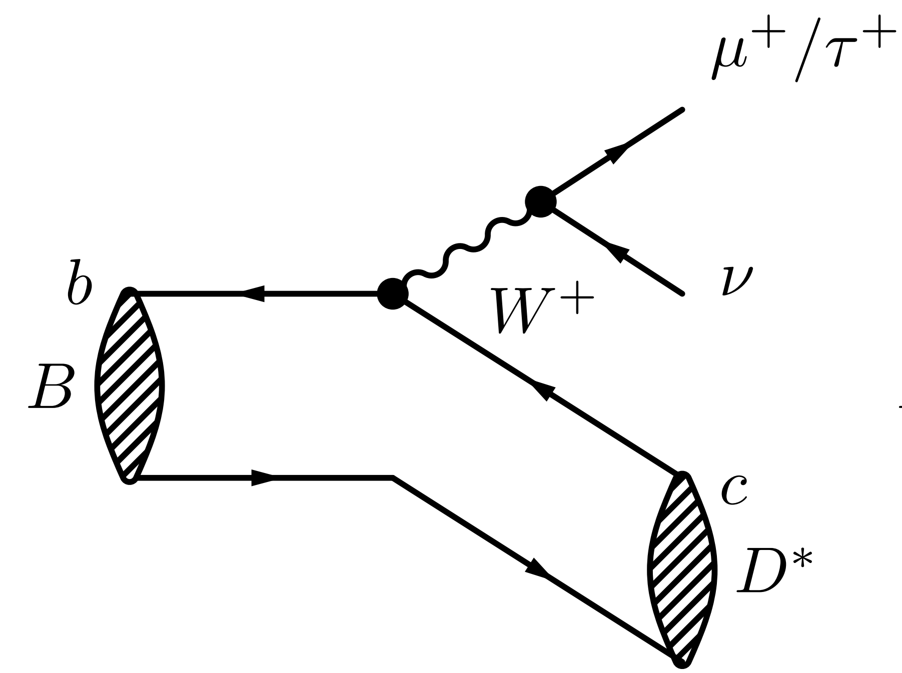
Neutral current



Forbidden at tree level - low $O(10^{-6})$ branching fractions.

NP sensitivity up to about 50 TeV

Charged current



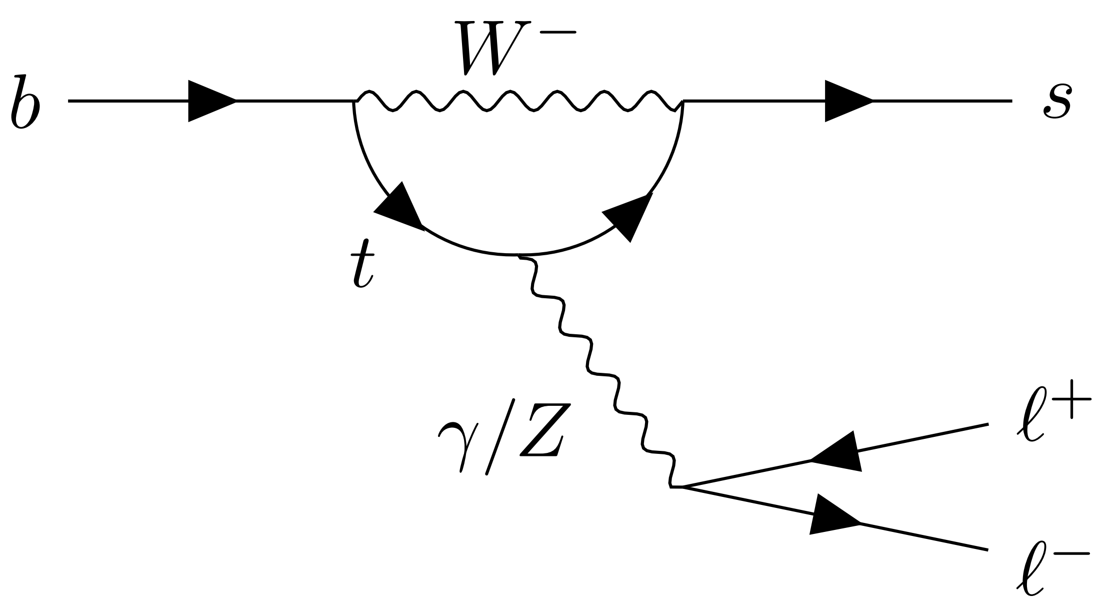
Can proceed via tree level -large O(%) branching fractions.

NP sensitivity up to about 1 TeV

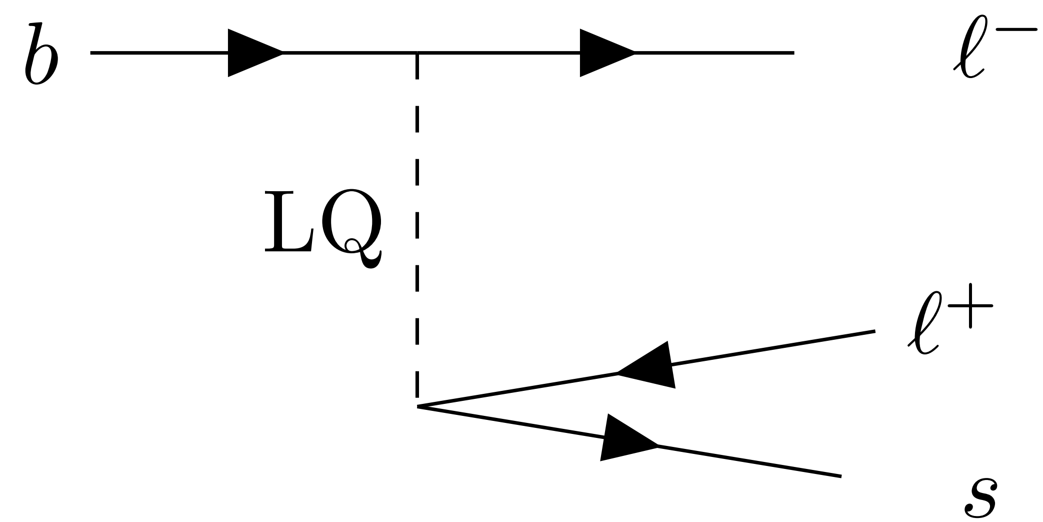
$b \to s\ell\ell$ transitions

- The idea is that because these are loop suppressed, new physics can compete quite easily with the SM decay amplitude.

SM



NP

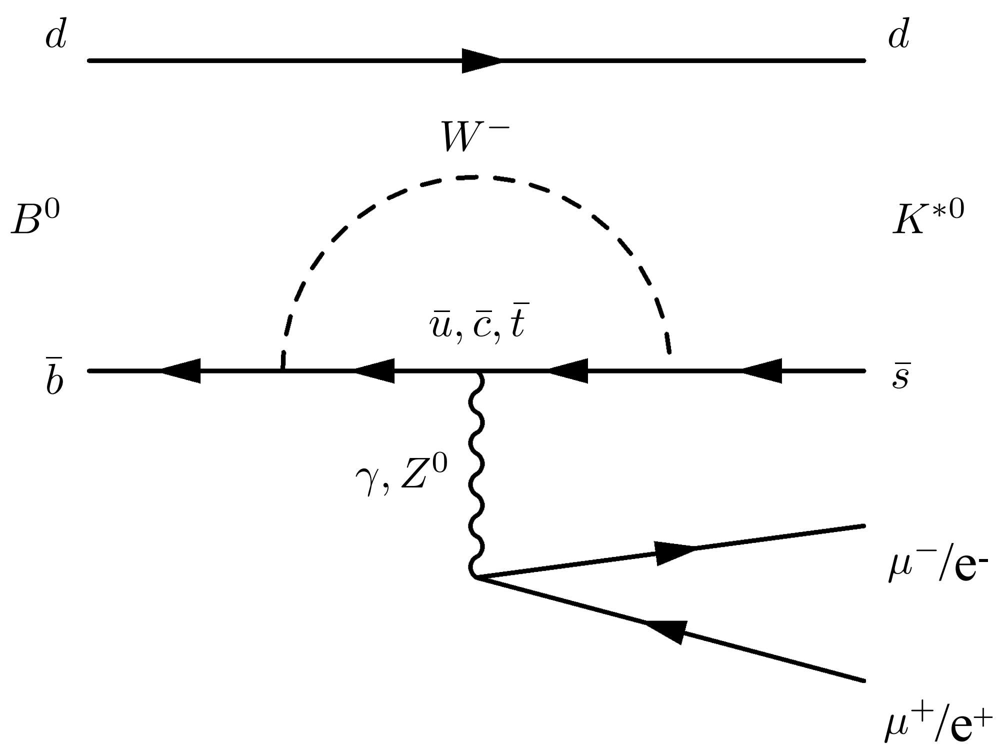


- If NP couples strongly and is light enough, it will significantly alter the behaviour compared to the SM expectation.

Lepton universality

- Lets compare decay rates when we have muons and electrons.

- In the Standard Model, this ratio should be unity.



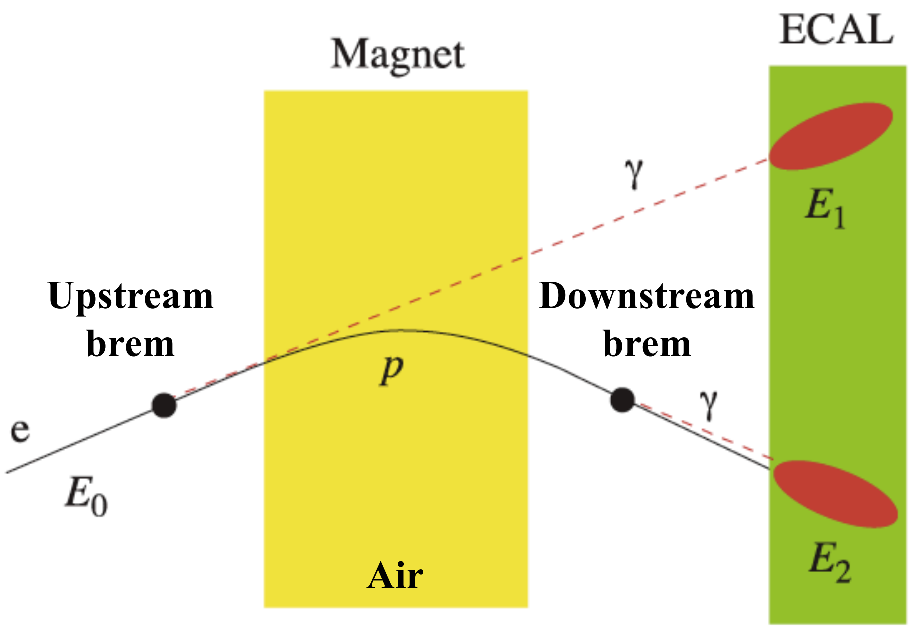
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- Two ratios:
  - **R_K:** Strange quark hadronises to ground state kaon (R_K)
  - **R_{K^*}:** Strange quark hadronises to excited state (R_{K^*}).

- Recipe for analysis:
  - Fit electron/muon signal yields.
  - Account for reconstruction efficiency.

The problem with electrons

- The main issue with electrons is their tendency to bremsstrahlung

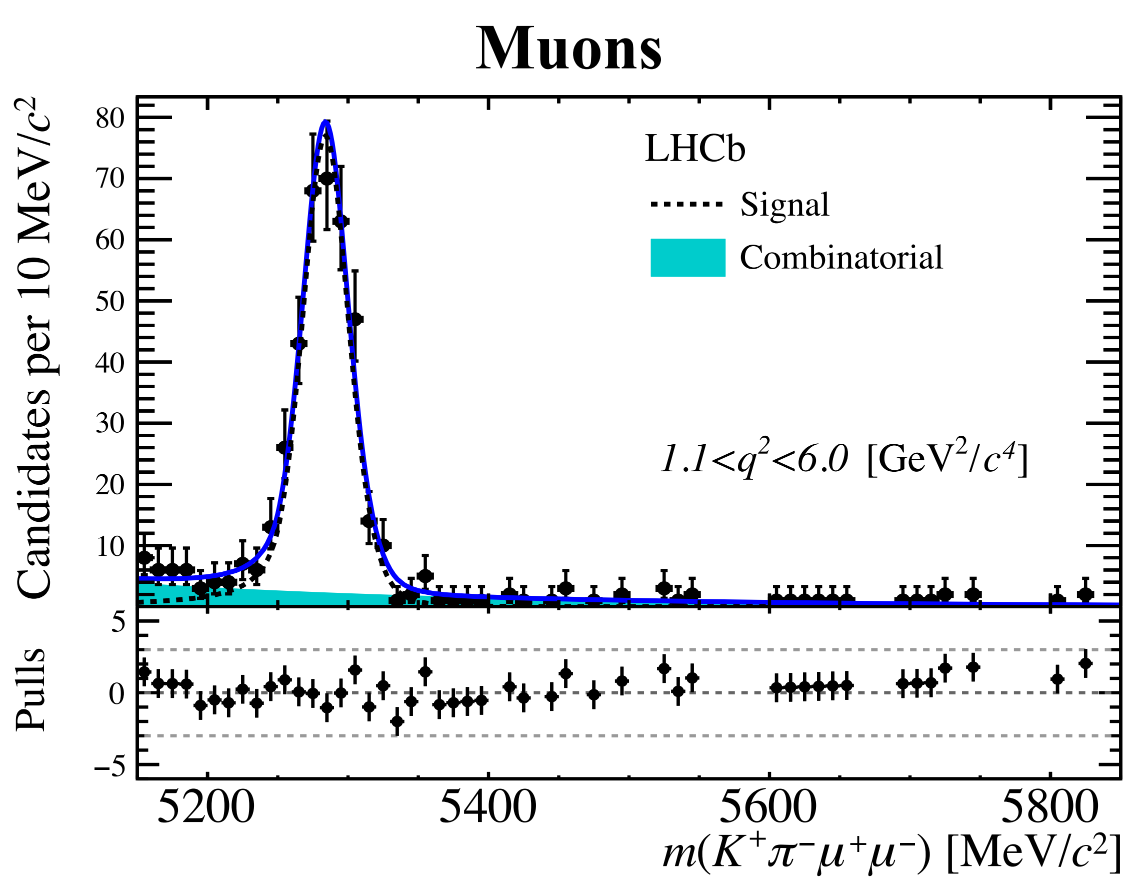


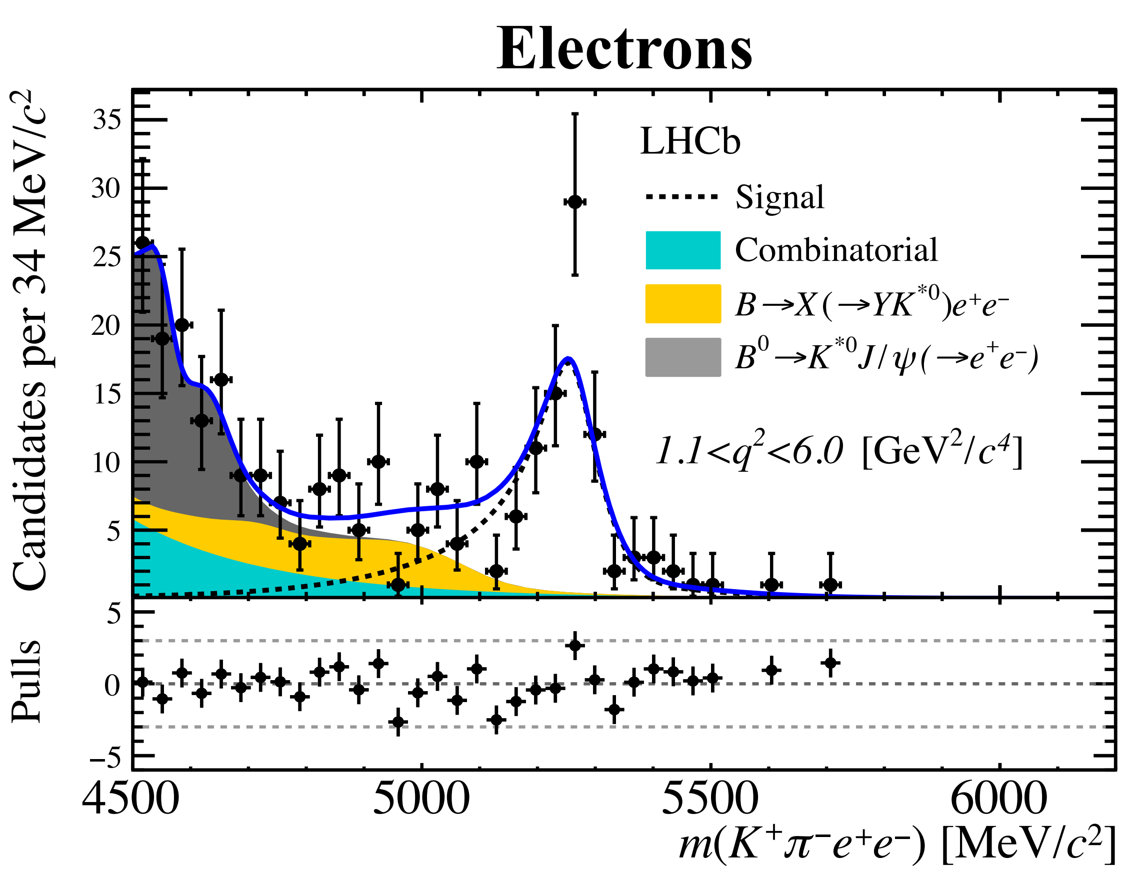
- Easier to confuse signal and background, due to a widening of the mass resolution.

- In addition, reconstruction efficiency worse for electrons
  - Electrons are more easily swept away by the magnet.
  - More difficult to 'trigger' on electrons.
- **Rule of thumb:** lose a factor three in signal when exchanging a muon with an electron.

Signal fits

- This also smears out the signal peak such the electron channel has a wider resolution.
- Also easier to confuse signal with ‘partially reconstructed’ background.





Results

- Take ratio of signal yields and correct for efficiency to get $R_{K^{(*)}}$.

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$

$$R_K = 0.846\ ^{+\,0.060}_{-\,0.054}\ ^{+\,0.016}_{-\,0.014}$$

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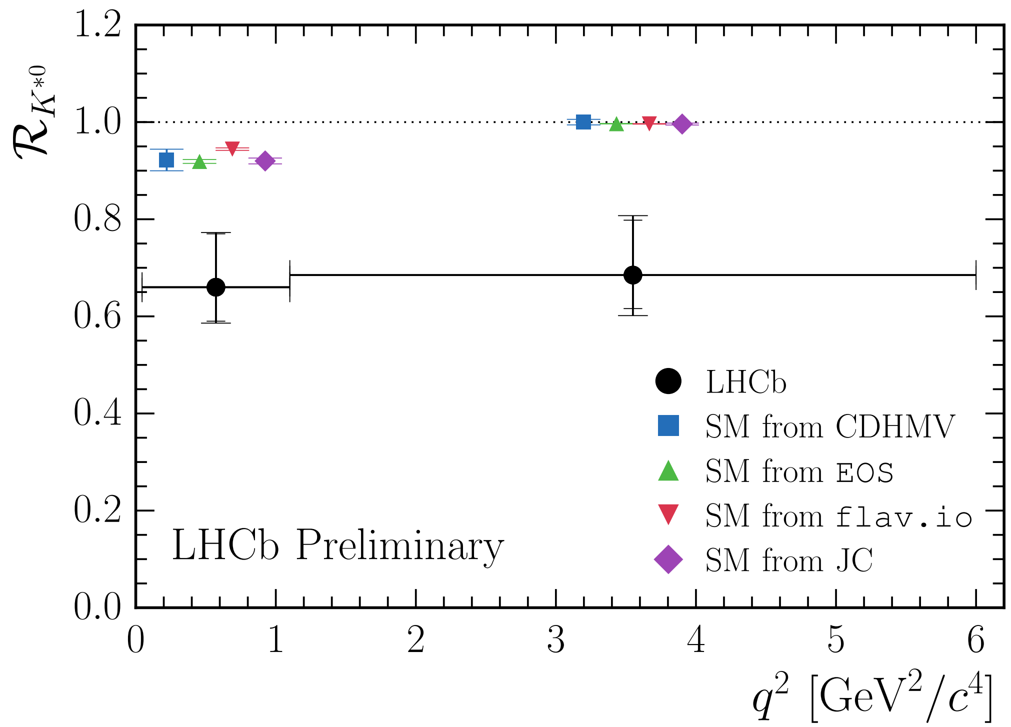
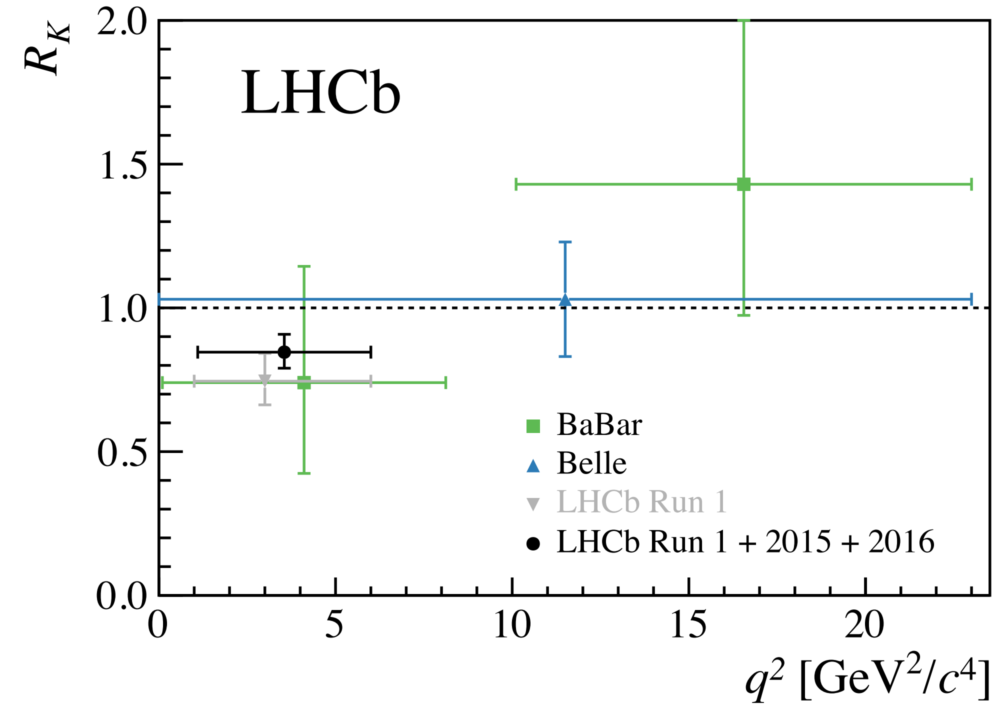




- LHCb results are 2.5 (R_K), 2.4 and 2.2σ from the SM predictions and all in the same direction.
- Error dominated by the statistical uncertainty: **we expect improvements soon.**
  - **The LHCb-UZH group is currently working on the update with more data.**

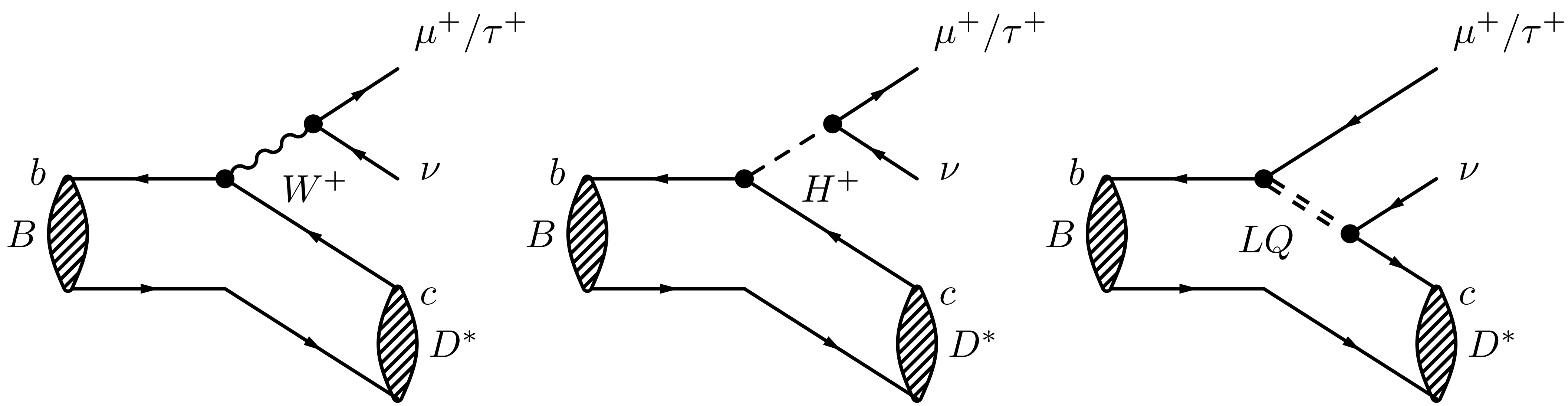
R(D*)

- Large rate of charged current decays allow for measurement in semi-tauonic decays.

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

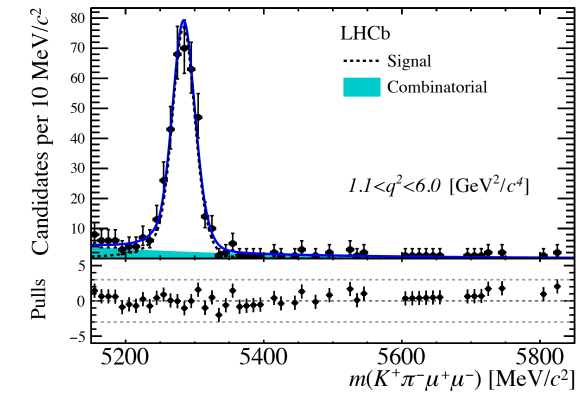
- Form ratio of decays with different lepton generations.
- Cancel QCD/expt uncertainties.

- R(D*) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs).

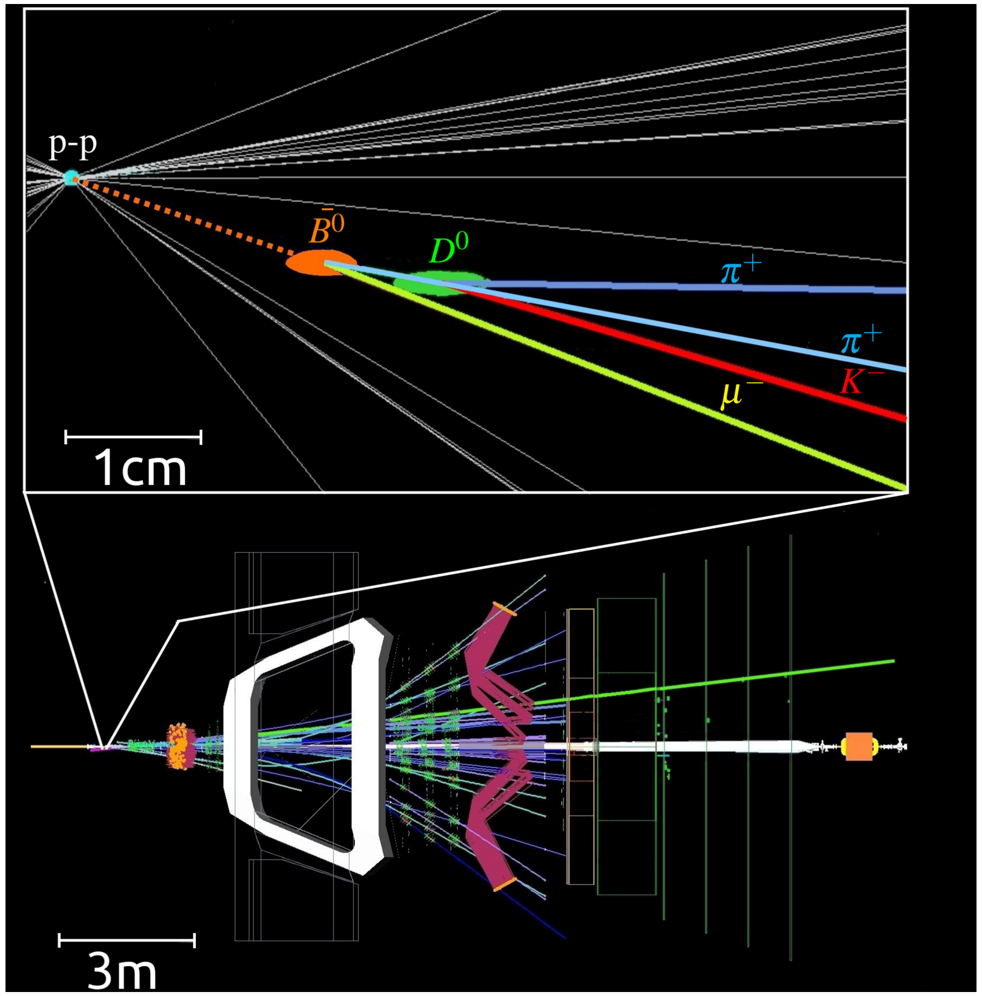


The problem with neutrinos

- At three neutrinos in the final state (two from $\tau \to \mu\nu\nu$).
  - Need a light-year of steel to absorb.
  - No sharp peak to fit in any distribution:

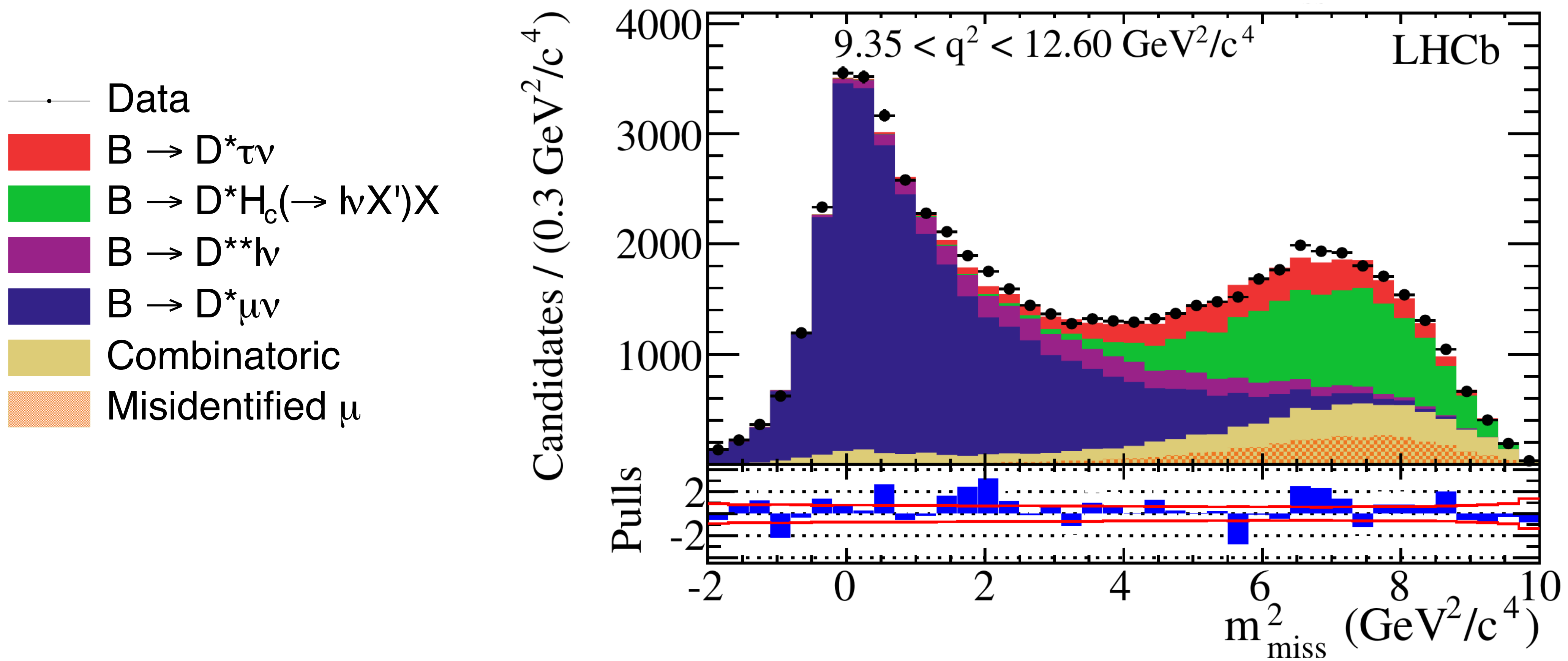


- Try to reconstruct B rest frame by using the vertex positions in our detector.
- Allows to reconstruct the missing momentum, but has large resolution.



Signal fits

- Fit variables which discriminate between muon and tauonic mode.
- For example, the ‘missing mass’, which should be zero for a single neutrino and non-zero if you are missing more particles.



- Many different backgrounds to account for.

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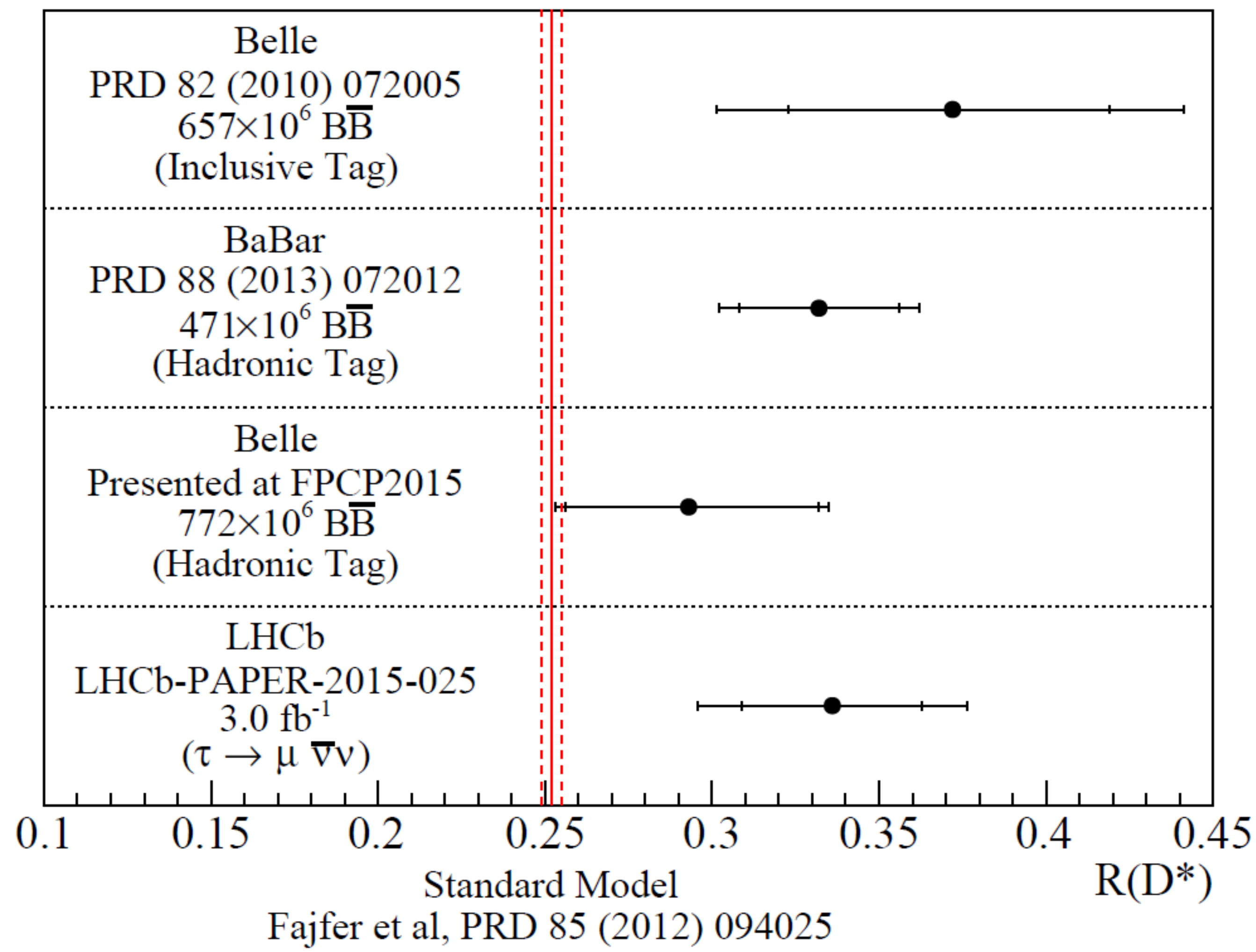
Hints of an excess?

- In addition to LHCb, the Belle and BaBar experiments have also made measurements.

- All experiments see an excess in the number of $B \to D^* \tau \nu$ candidates.

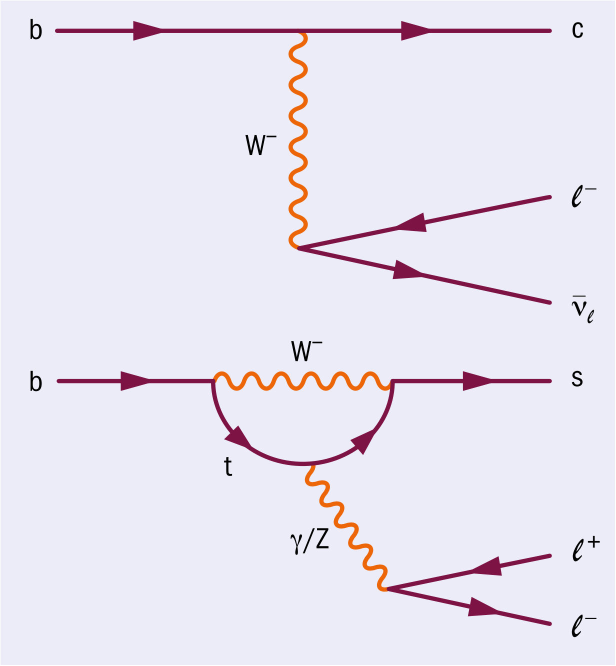
- What's interesting is that the experiments have rather different systematic sources.



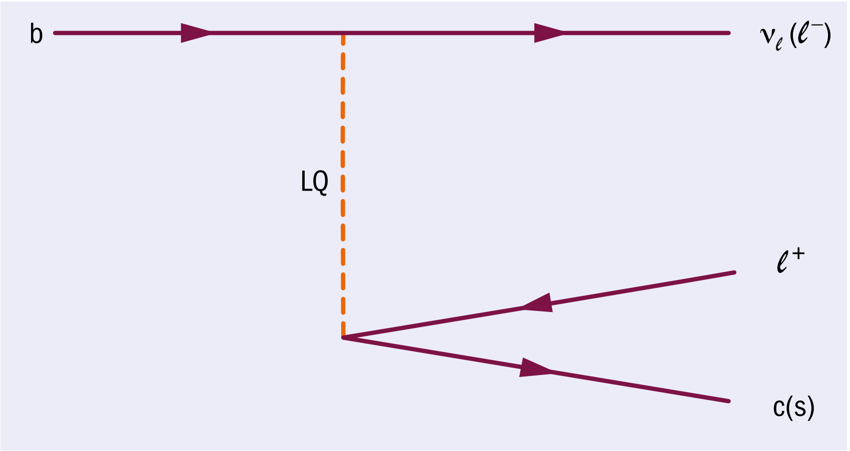
What does this all mean

- We have two sets of anomalies in charged- and neutral current semileptoinic B decays.
- They both point towards a violation of lepton universality.
- It is actually possible to explain both anomalies with a single new particle known as a leptoquark of around 2TeV mass.

SM diagrams



New physics diagram



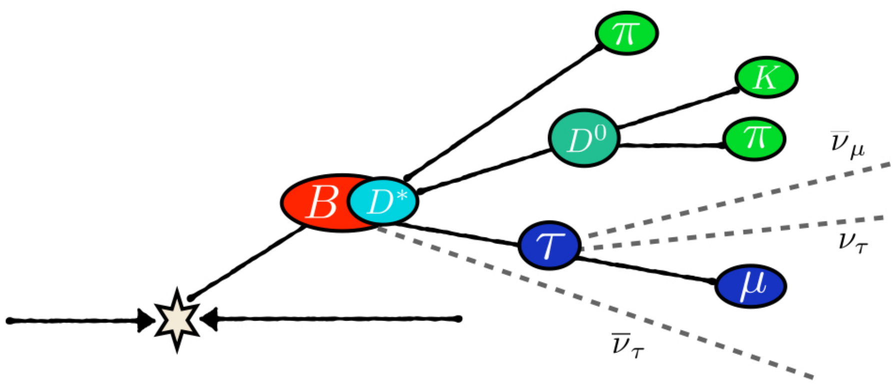
- However ..

We need more measurements

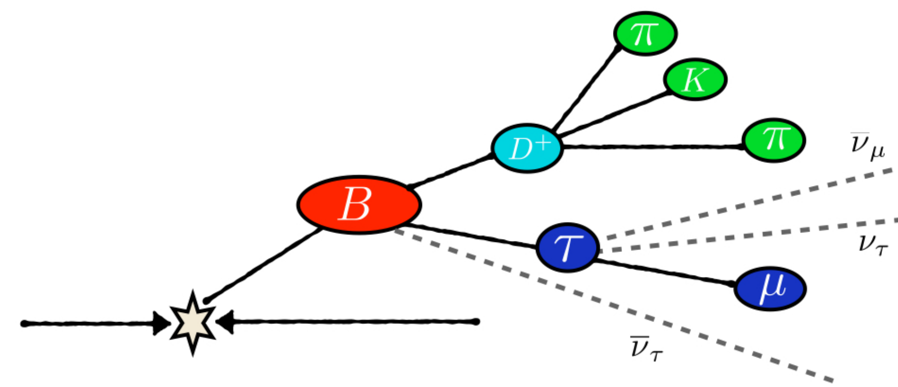
- Too early to claim any new physics yet: significance too low.
- Main priority is to clarify the existence of any NP signal.

  Improve the precision of R_{D*} ratios and R_K.

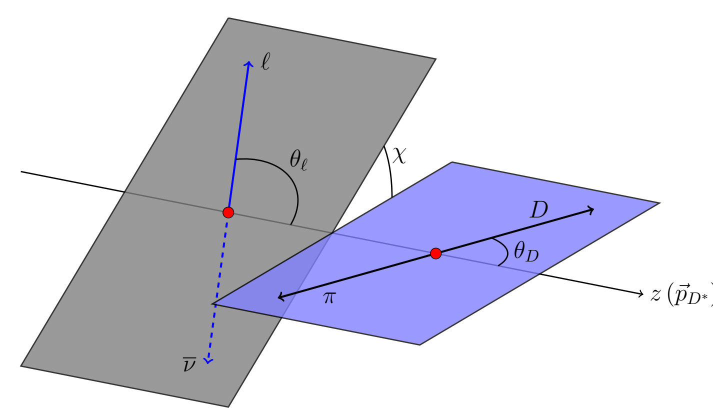
R_{D^*}



R_{D+}

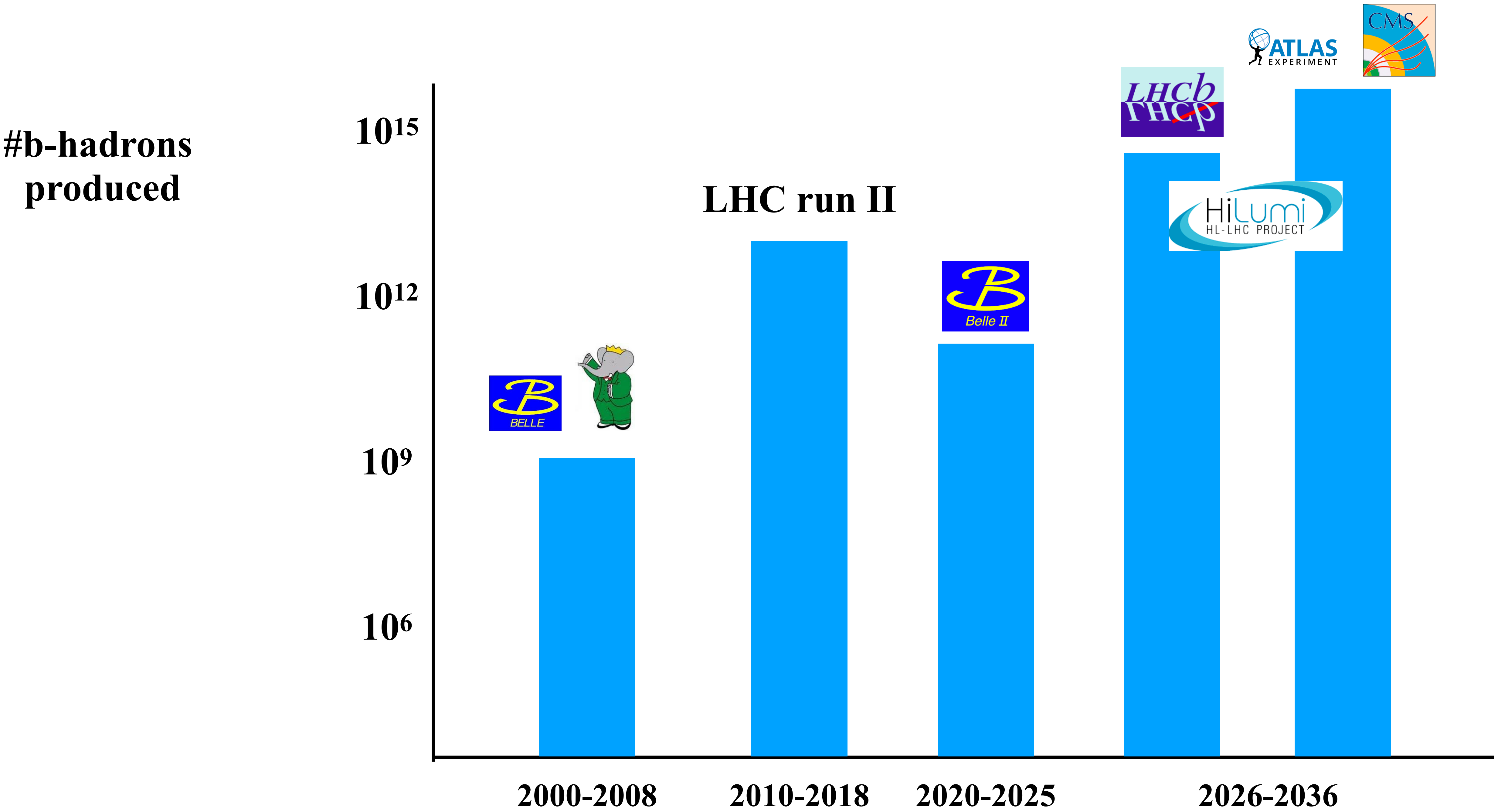


- NP can also alter angular distribution of decay products.



- We are currently doing these next steps in the LHCb-UZH group.

In the future



- At ATLAS and CMS, 10^9 B-hadrons (B-factory dataset) will be produced **every ~20 seconds.**
- **Although we hope to conclude on these anomalies much earlier than then!**

Summary

- I hope I have given you a flavour of what physics the LHCb collaboration is doing.
- The LHCb-UZH group is mainly working on clarifying these hints of lepton universality.
  - We already have lots of data in hand to shed light on these hints of new physics.
  - Exciting times to be on LHCb!
  - If you are interested, we also made a youtube video with Prof. Isidori's group: https://www.youtube.com/watch?v=9dLyTS0Xscw&t=1s