Lecture 13:

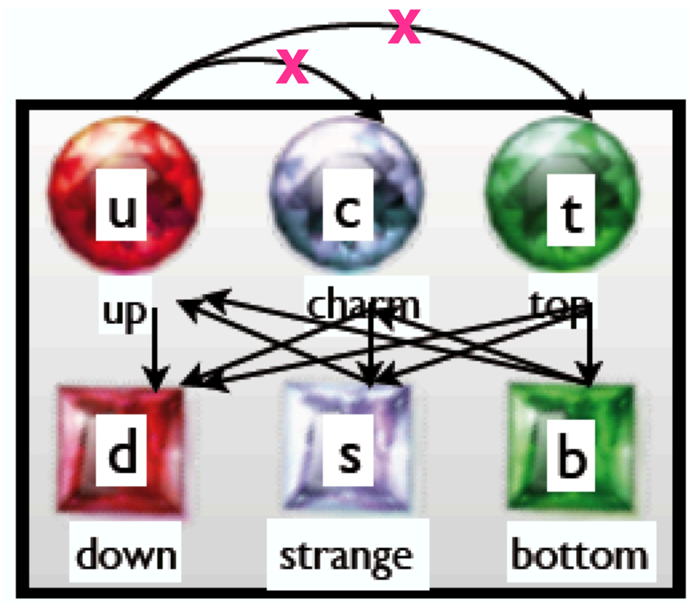
(Heavy Quark) Flavour Physics at LHC

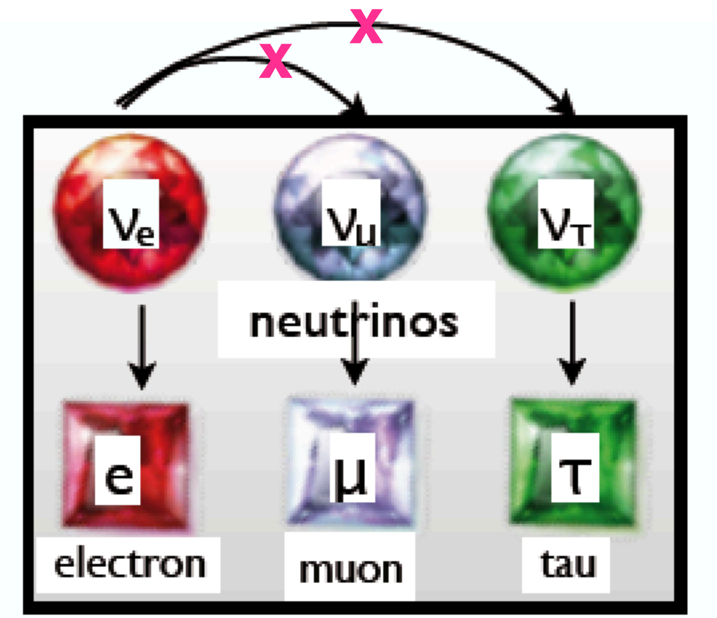
- flavour physics - intro
- CKM quark mixing matrix
- goals of flavour physics
- heavy flavour at LHC
- the LHCb experiment
- new particles (bound states)
- B^0_s-$\overline{B^0}_s$ oscillations
- rare decays

flavour physics

- flavour physics deals with the transitions between different kinds (flavours) of fermions.

- in the Standard Model (SM), only some of all possible transitions are realised at the Lagrangian (tree diagram) level!





- transitions only via W-exchange (“charged currents”)
- no flavour-changing neutral currents (FCNC)

the four pillars in the SM governing the pattern of flavour violation:

1. Charged current interactions are only between LH quarks and between LH leptons.

2. The quark flavour violating processes are governed by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix
   which depends on three real parameters and one complex phase that is required for the description of the observed violation of CP symmetry.

3. Due to the Glashow-Iliopoulos-Maiani (GIM) mechanism, the flavour changing neutral current (FCNC) transitions between quarks (having the same charge) are absent at leading order in weak coupling expansion, that is at tree-level.

4. Asymptotic freedom in Quantum Chromodynamics (QCD) allows to include the effects of strong interactions in meson decays at short distance scales using perturbation theory

the CKM quark mixing matrix

(Cabibbo-Kobayashi-Maskawa)

- unitary matrix containing information about the strength of flavour-changing weak decays
- technically, it specifies the mismatch of quantum states of quarks when they propagate freely (mass eigenstates) and when they take part in the weak interactions (weak eigenstates).
  - important for the understanding of CP violation.

    1973: observation of CP-violation could not be explained in the four-quark model; generalisation of 4-quark Cabibbo mixing matrix to 6-quark (3-generation) CKM matrix

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

weak eigenstates — mass eigenstates

V_{ij}: describes probability for transition of on quark with flavour i to another quark of flavour j : probability proportional to $|V_{ij}|^2$

the CKM quark mixing matrix

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- 3x3 unitary matrix
- can be parametrised by:
  - – 3 mixing angles θ_{ij}
  - – 1 CP violating phase δ

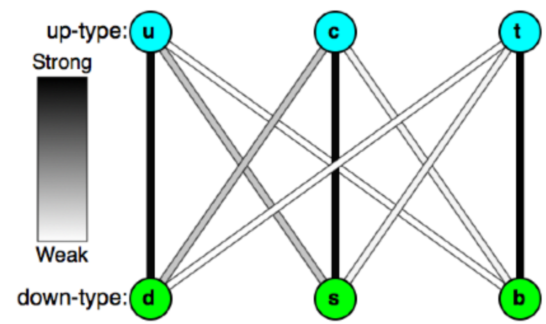
common parametrisations:

$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$; $s_{ij}, c_{ij} \geq 0$

experimentally: $s_{13} \leq s_{23} \leq s_{12} \leq 1$



the CKM quark mixing matrix

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

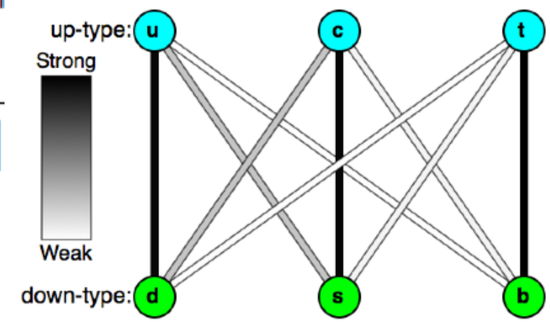
- 3x3 unitary matrix
- can be parametrised by:
  - 3 mixing angles $\theta_{\rm ij}$
  - 1 CP violating phase δ

alternativ parametrisation (Wolfenstein):

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

with $s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \qquad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|$

$$s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar\rho + i\bar\eta)\sqrt{1-A^2\lambda^4}}{\sqrt{1-\lambda^2}[1-A^2\lambda^4(\bar\rho + i\bar\eta)]}$$



the CKM quark mixing matrix

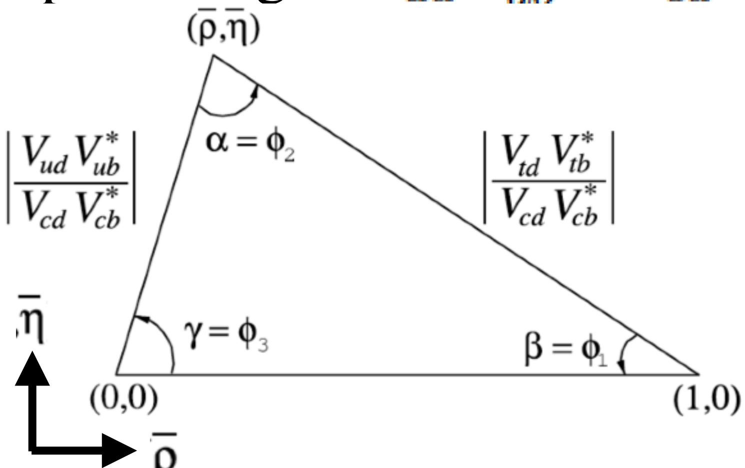
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- 3x3 unitary matrix
- can be parametrised by:
  - 3 mixing angles θ_{ij}
  - 1 CP violating phase δ

unitarity imposes:

- $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$
- $\sum_j V_{ij} V_{kj}^* = \delta_{ik}$

vanishing 6 combinations can be represented by triangles in complex plane, e.g. $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$ gives:

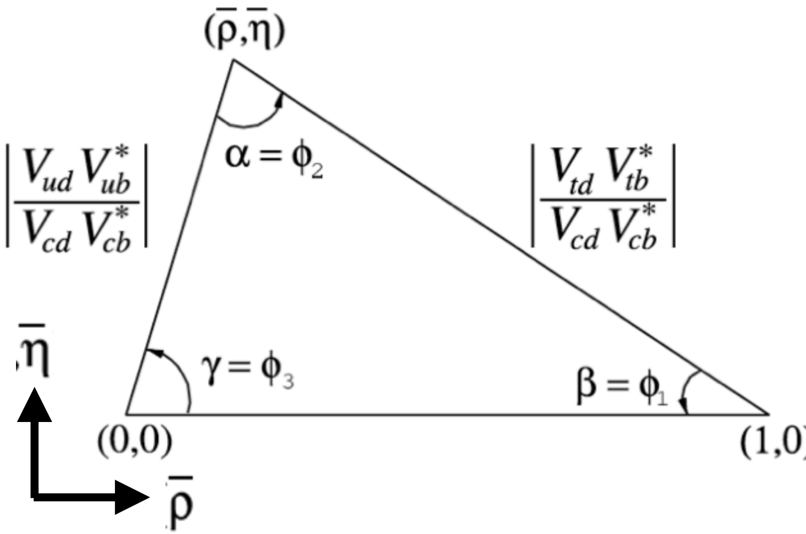


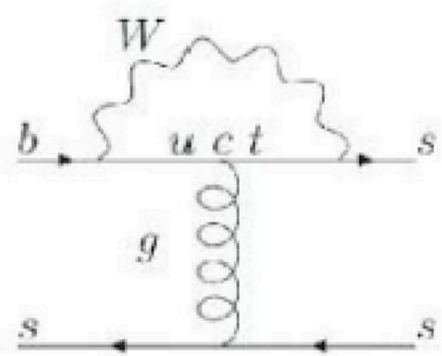
unitary matrix A <–> AA*=1:
A* is conjugate transpose of A:
$(A_{ij})^* = \overline{(A_{ji})}$

goals of flavour physics:

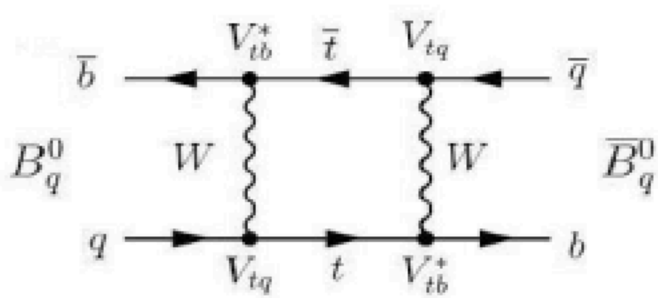
- measure and overconstrain CKM matrix elements (fundamental parameters of SM!)

- processes dominated by loop-levels in the SM are particularly sensitive to new physics (BSM):

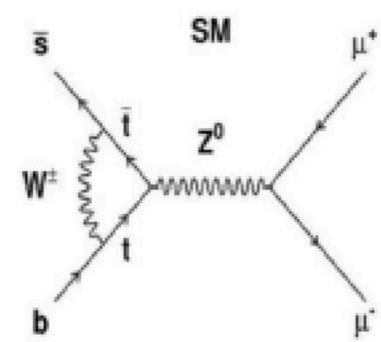




rare decays
"Penguin"

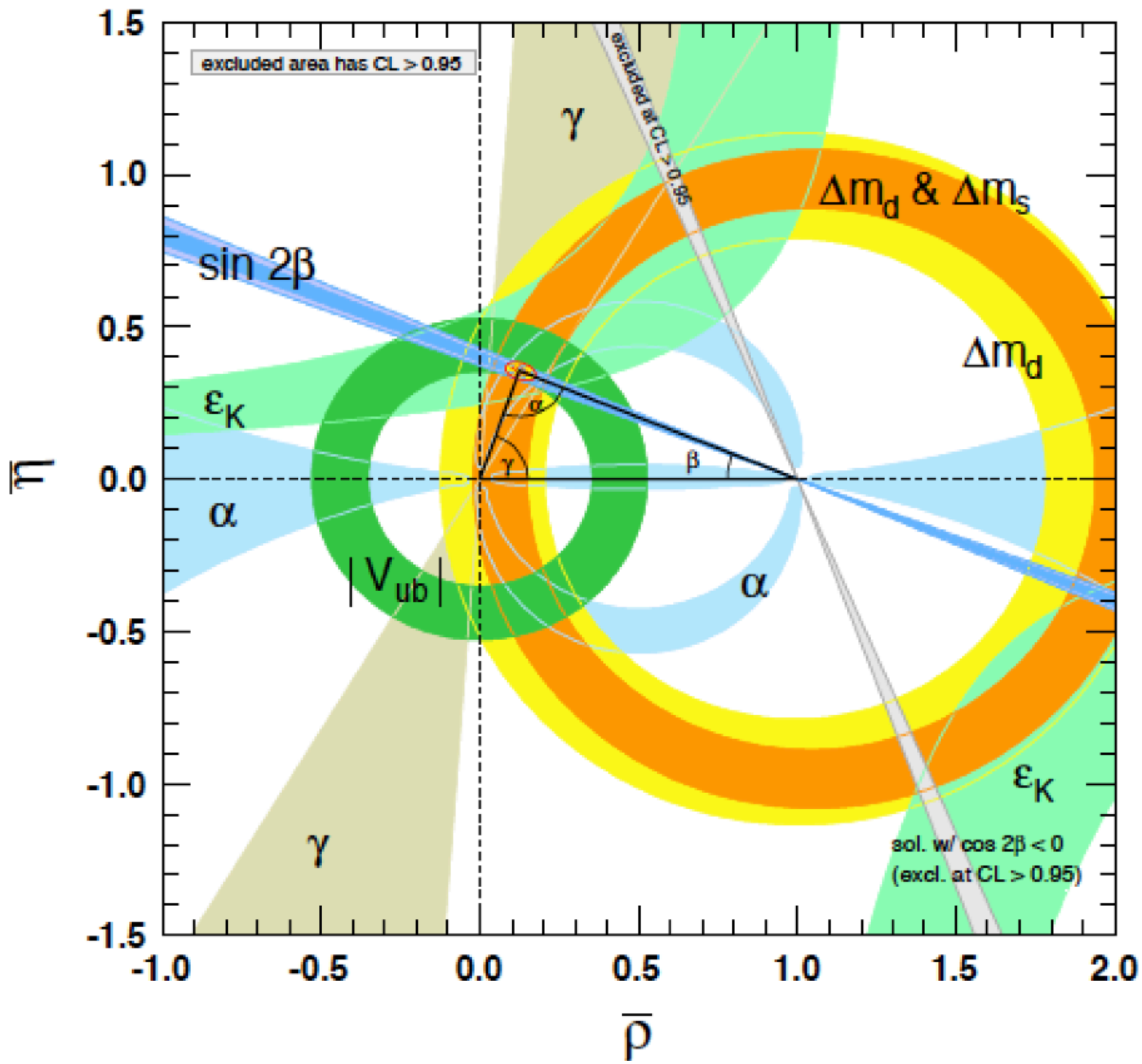


mixing!
"box"



rare decays

CKM experimental status:



$$V_{CKM} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

heavy flavour physics at the LHC

- basically, physics of c- and b-flavoured hadrons:
  - can be tagged (identified) by lifetime (secondary vertices) and large invariant masses
  - hadronic corrections through QCD perturbation theory for $\Lambda^2 / m_Q^2 << 1$
  - huge production cross sections at LHC :
    O(1 mb) for c-quarks
    O(100 μb) for b-quarks

- the top-quark is usually *not* discussed in this category, although it is the heaviest of all quarks (decays before forming hadrons; see separate lecture)

heavy flavour physics at the LHC

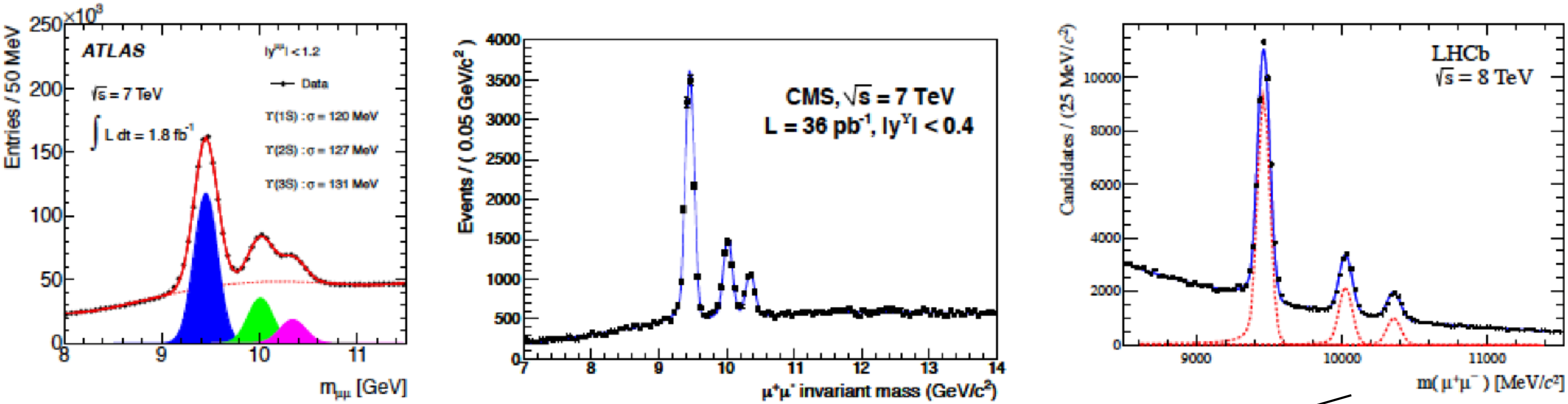
- properties of heavy flavoured hadrons –> tests of QCD (including new and so far unobserved states)
- more details on CP violation –> evolution of (asymmetric) universe
- mixing and rare decays (loops and boxes) –> search for new physics

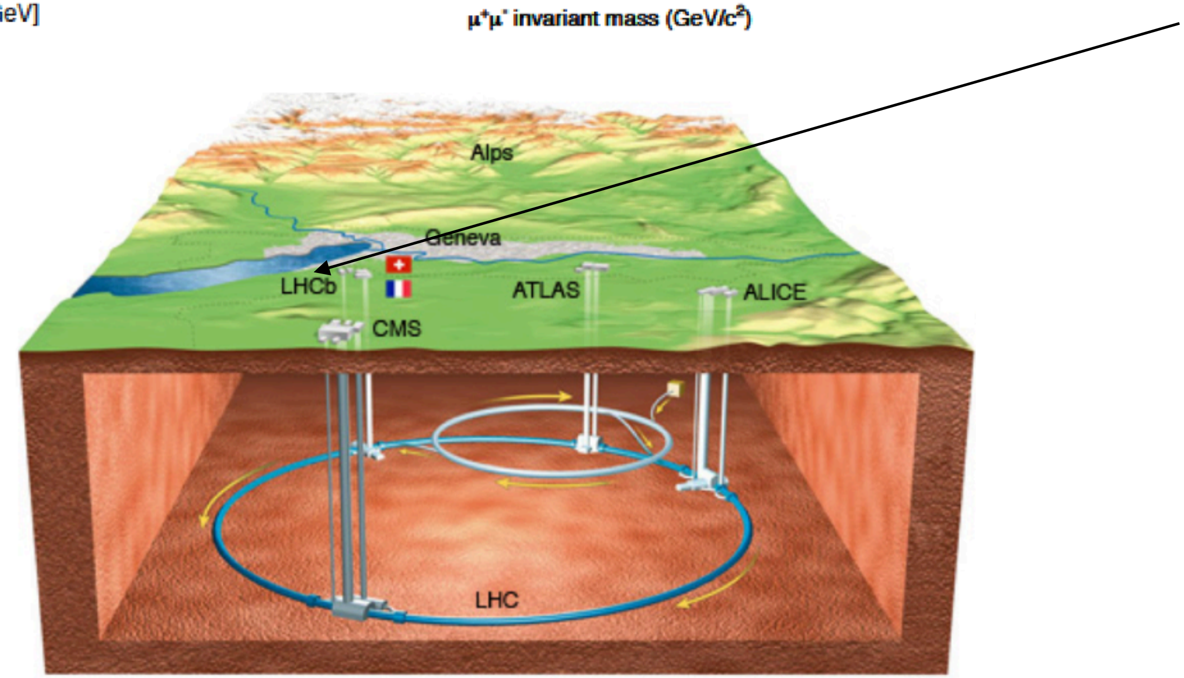
tools:

- precision tracking (inv. mass resolution; reduction of comb. back.)
- precision (secondary) vertex tagging
- particle ID (e.g. μ-ID; Cherenkov detector; calorimetry; …)
- efficient triggering

precision tracking:

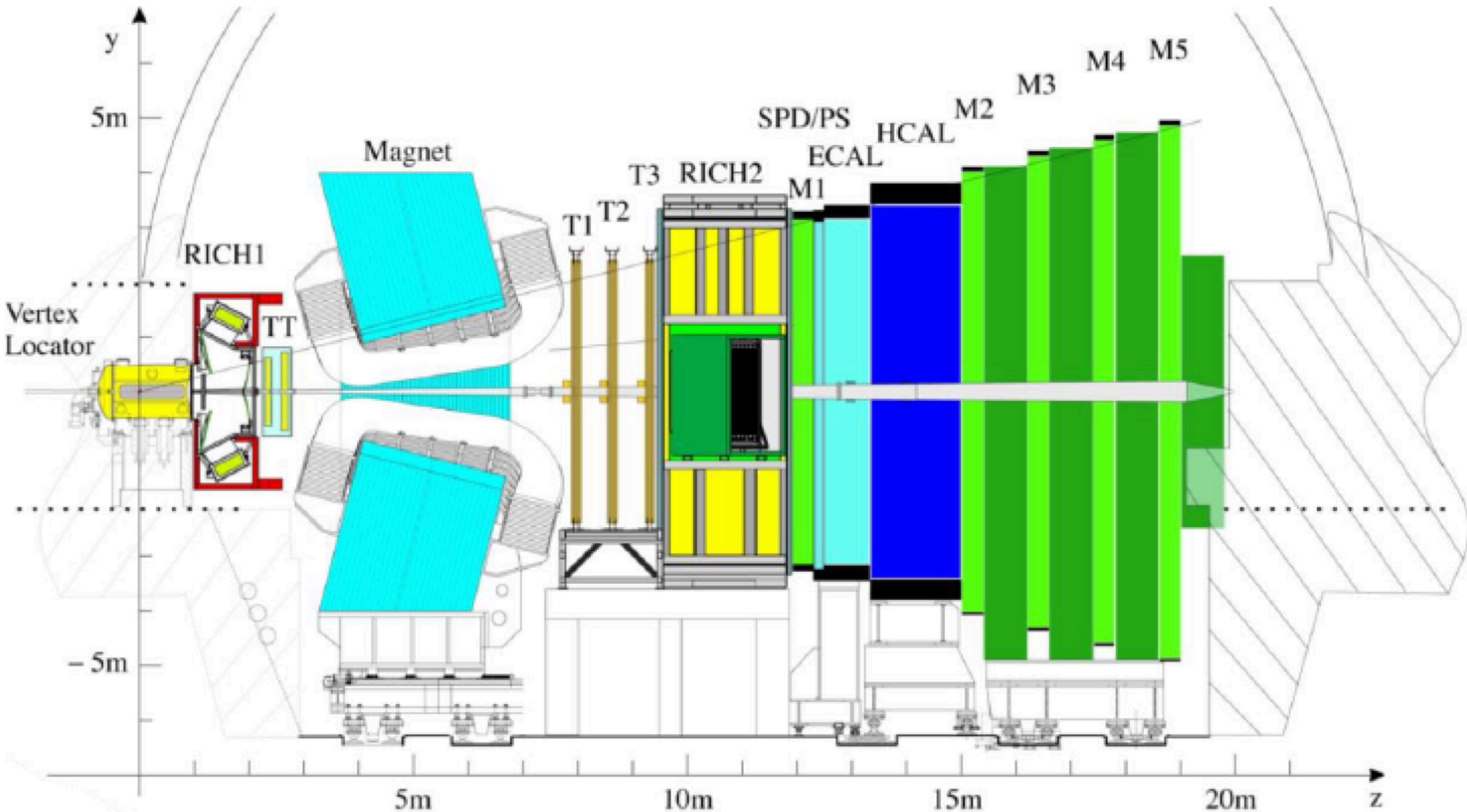
e.g. dimuon invariant mass of Υ resonances





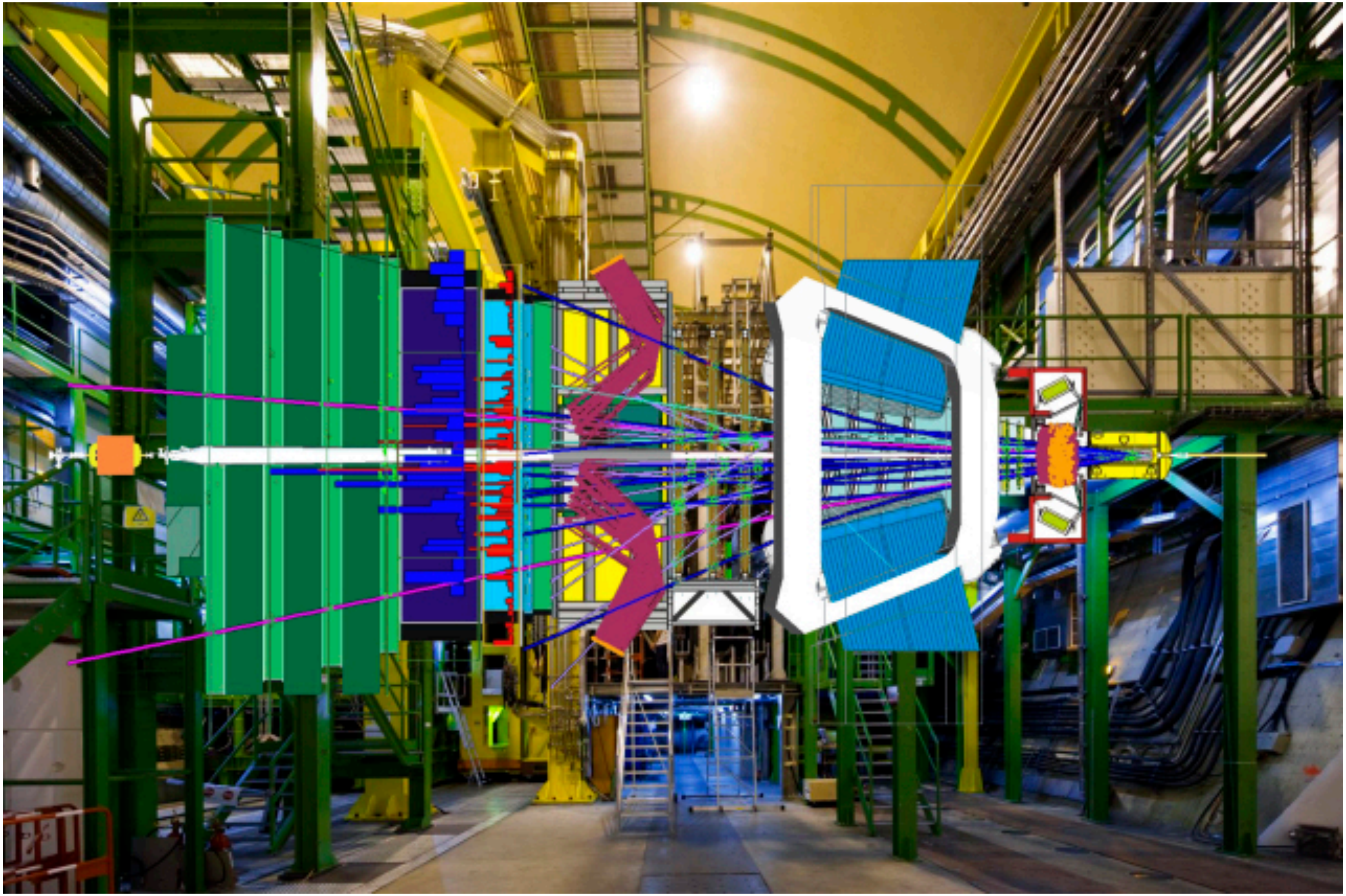
the LHCb experiment

a forward spectrometer at the LHC



the LHCb experiment

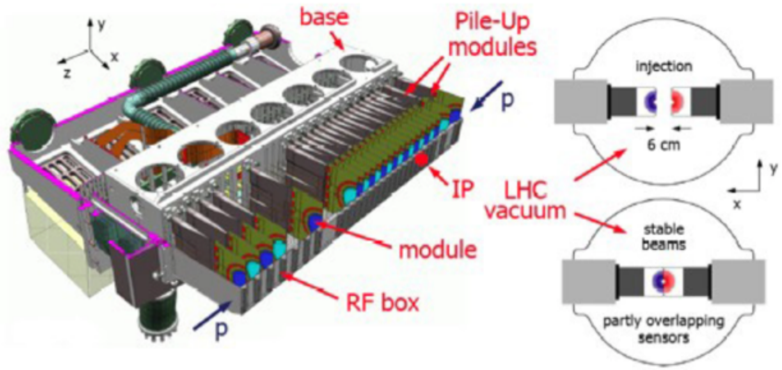
the LHCb experiment



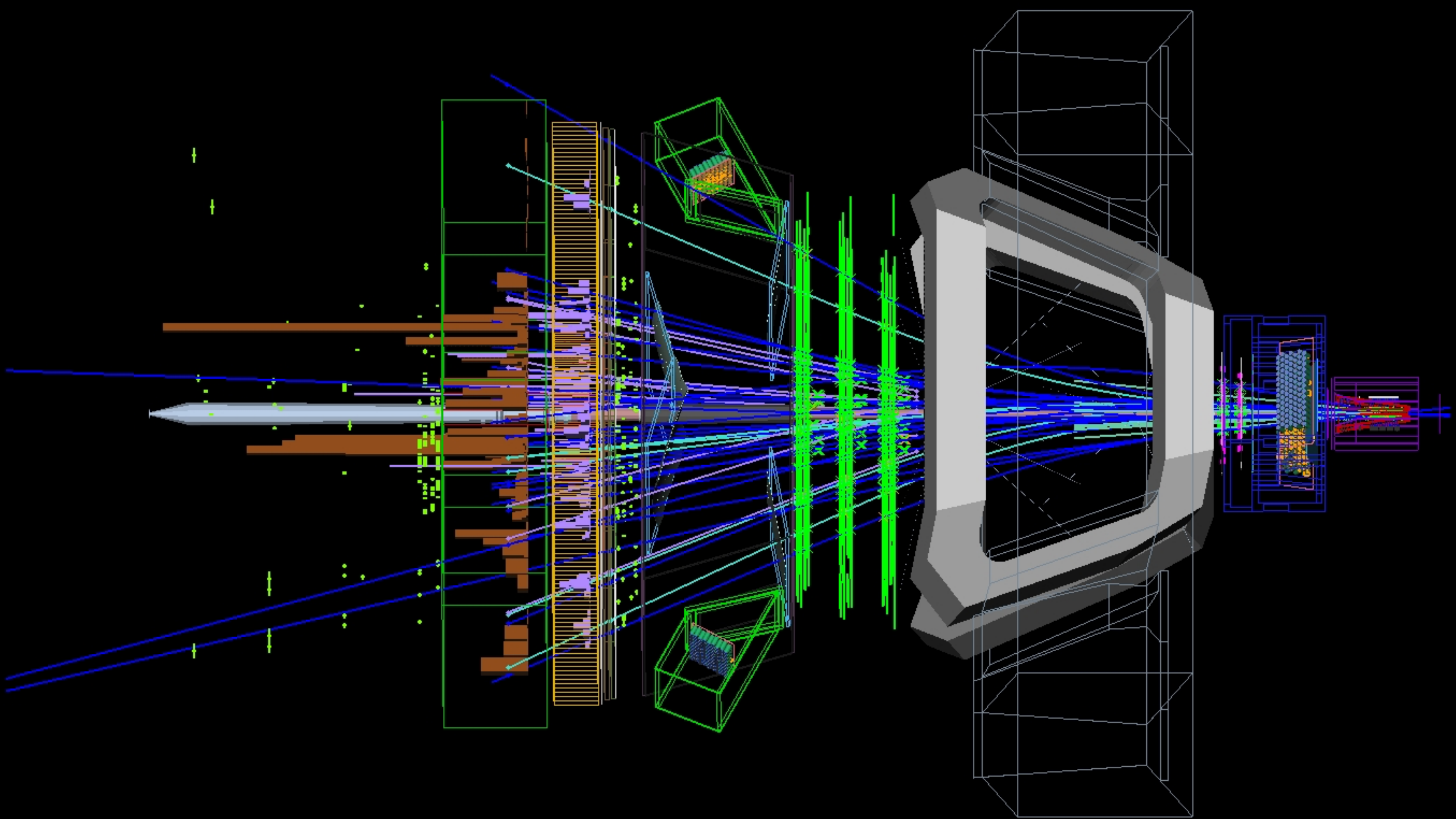
the LHCb vertex locator (VELO)

42 Si detector elements
in beam-pipe vacuum
surrounding proton beam

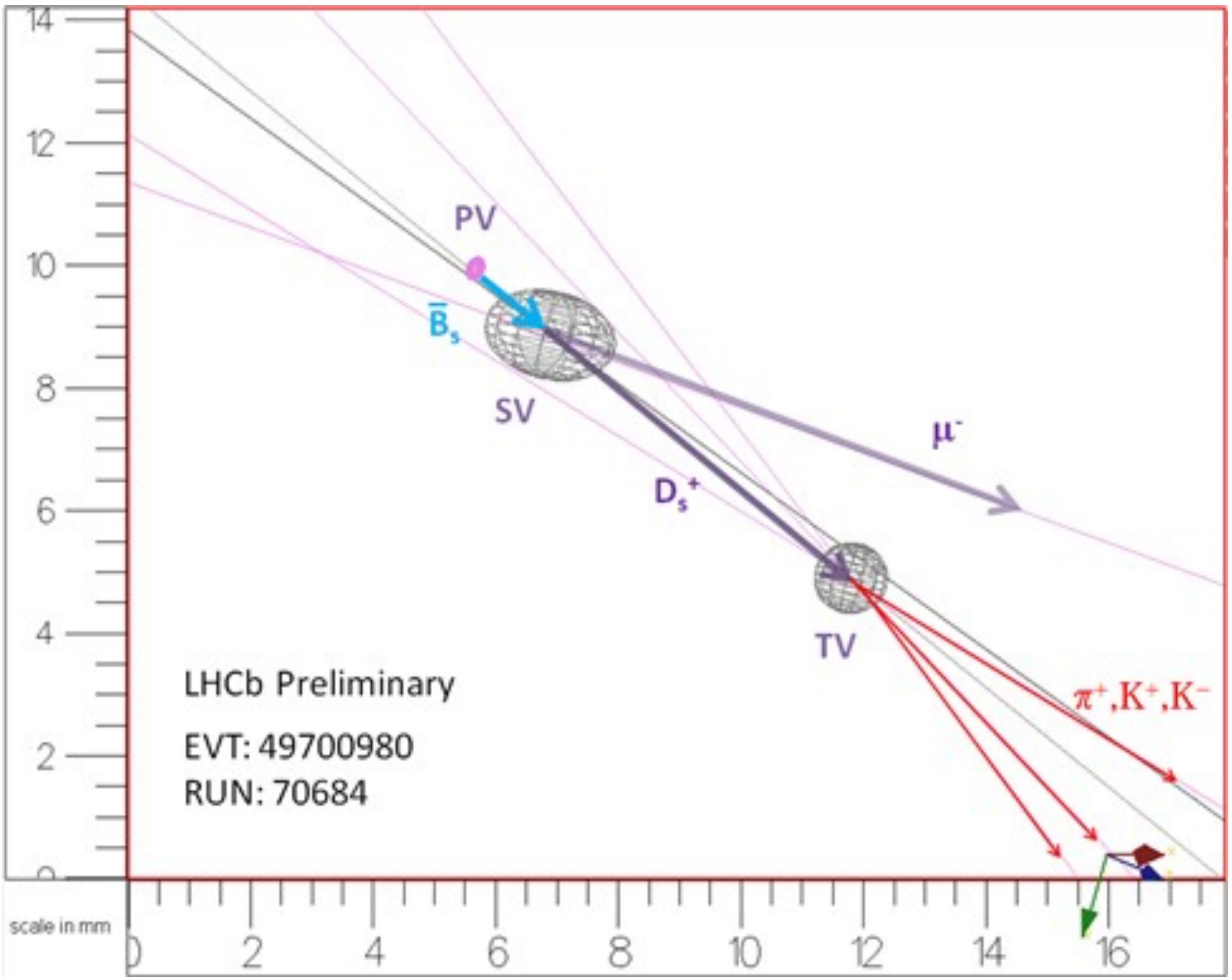
can locate B-hadron decays
to within 10 μm



2 half-shells, retractable
during LHC beam filling and
acceleration



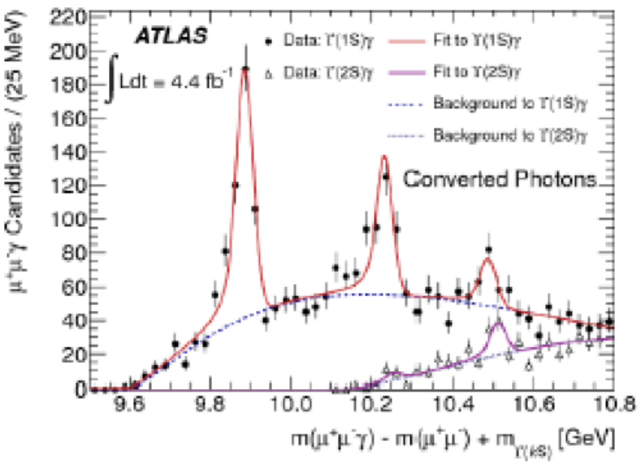
close-up of an LHCb event candidate for a decay $B^0_s \rightarrow D^+_s\ \mu^-$ and subsequent $D^+_s \rightarrow \pi^+ K^+ K^-$ decay



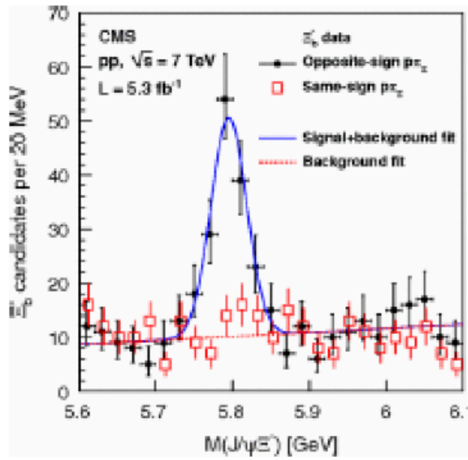
new particles discovered at LHC:

(bound hadronic states)

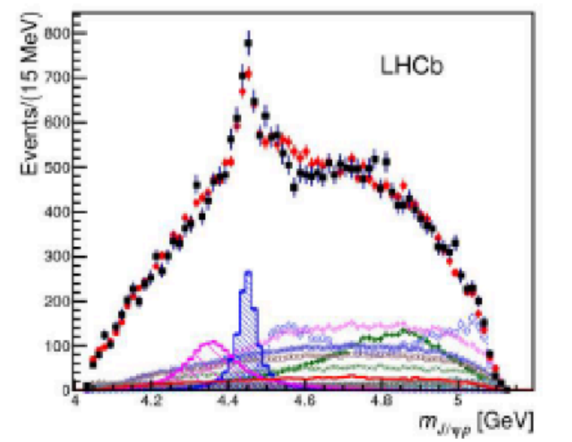
[PRL 108 (2012) 152001]



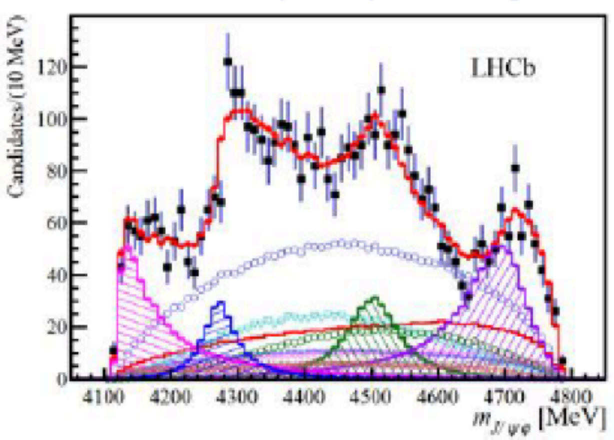
[PRL 108 (2012) 252002]



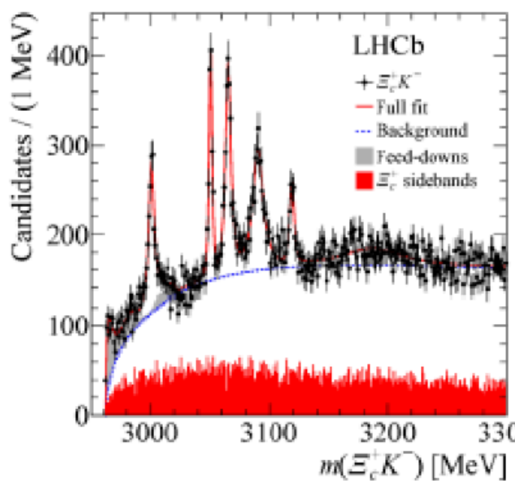
[PRL 115 (2015) 072001]



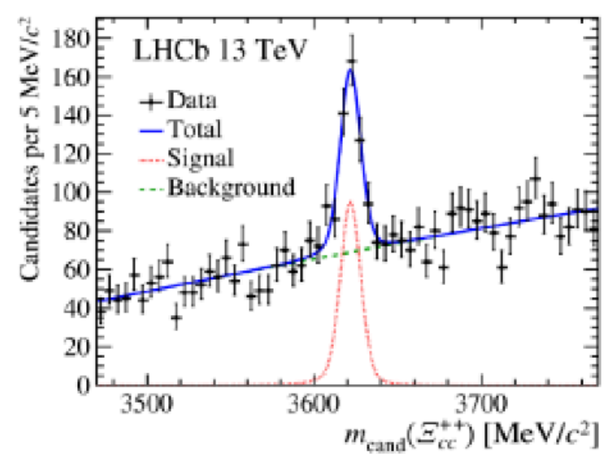
[PRL 118 (2017) 022003;
PRD 95 (2017) 012002]



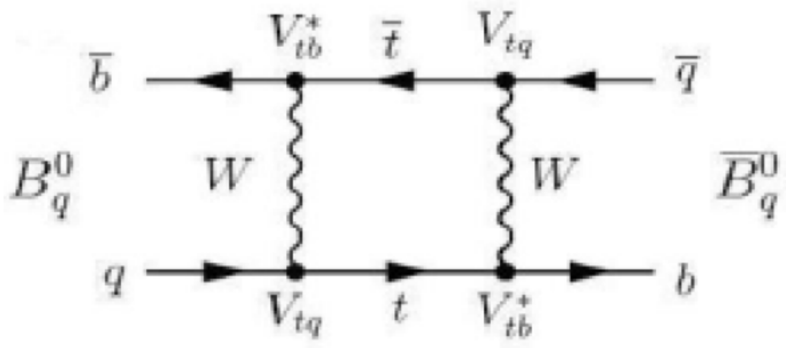
[PRL 118 (2017) 182001]



[PRL 119 (2017) 112001]



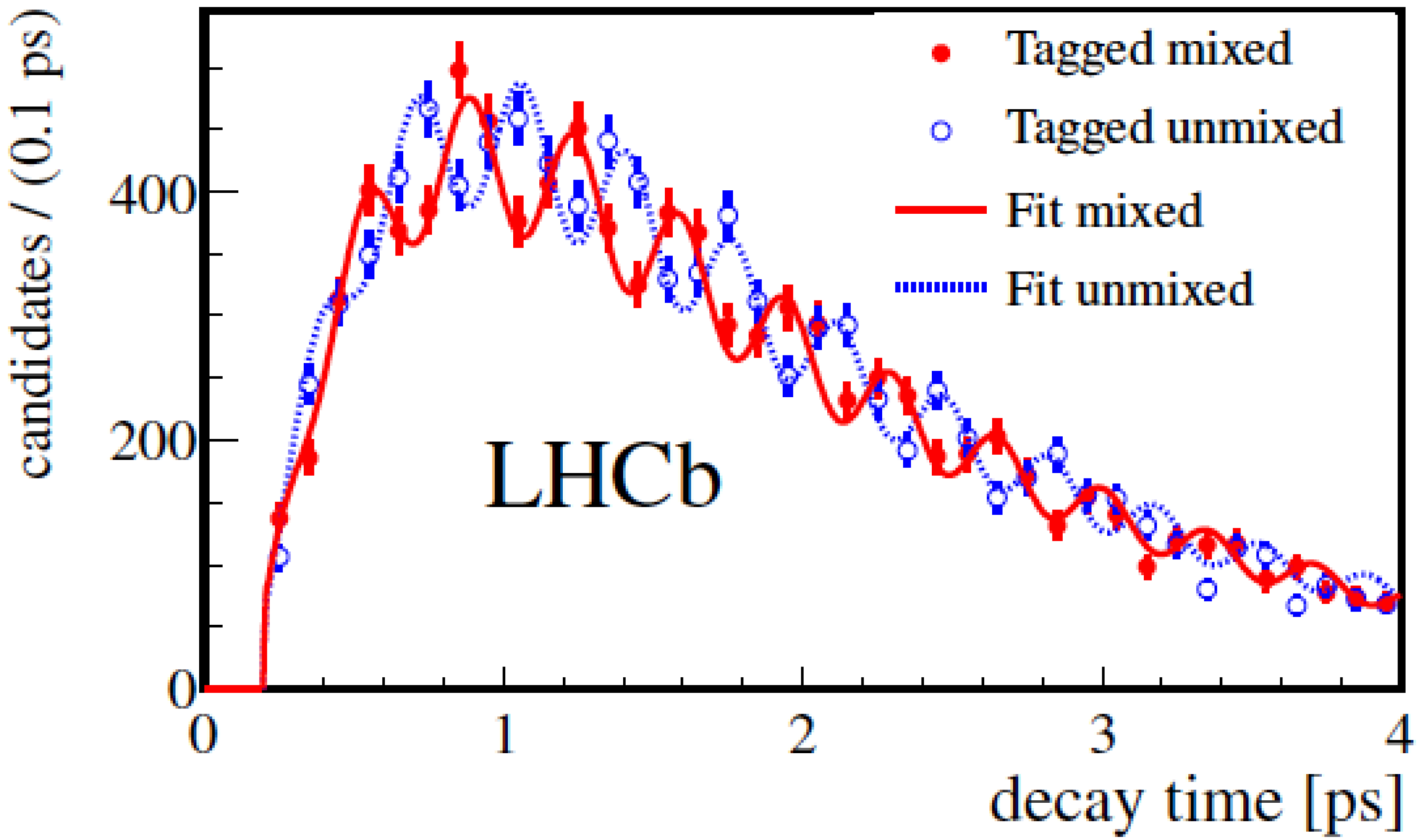
B^0_s - $\overline{B^0_s}$ oscillation (LHCb)



- use B0s candidates in the flavour-specific decay mode $B^0_s \rightarrow D^-_s \pi^+$
- flavour of B^0_s at the time of its decay is given by charge of decay products
- combination of tagging algorithms used to determine the flavour of B^0_s at production time. Use opposite site and same side taggers (OST, SST)
- OST: reconstruction of second B hadron in event –> information on signal B0s flavour (since normally b-$\bar{b}$ production)
- SST: make use of the fact that the s-quark needed for hadronisation of the B0s must have been produced in association with an $\bar{s}$-quark (showing up e.g. in a Kaon)

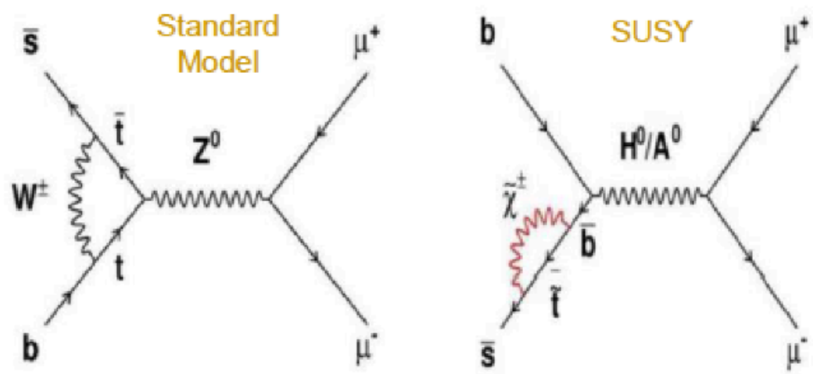
B^0_s - $\overline{B^0_s}$ oscillation (LHCb)

fitted decay time distributions

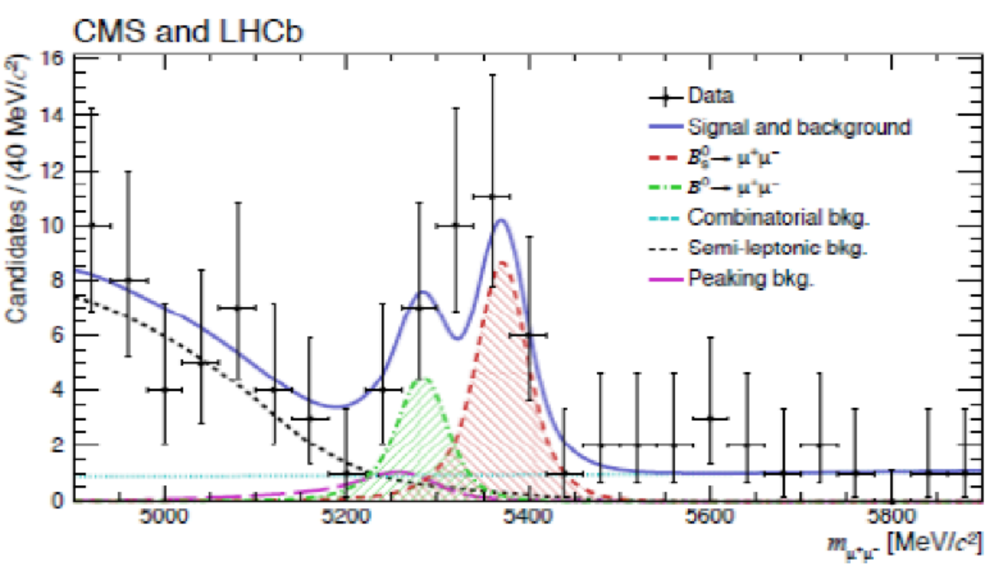


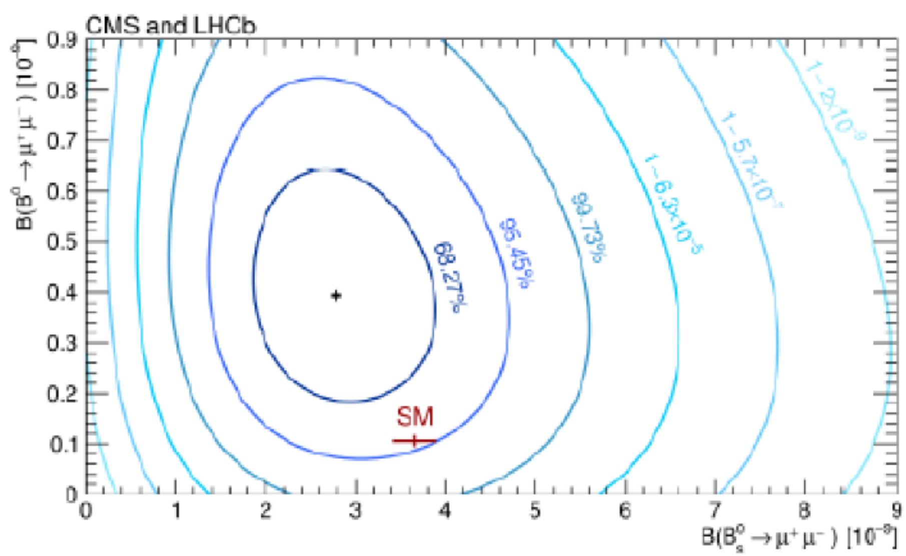
mixed: different flavours at production and decay
unmixed: same flavour at production and decay

rare decays: $B_s \to \mu^+\mu^-$



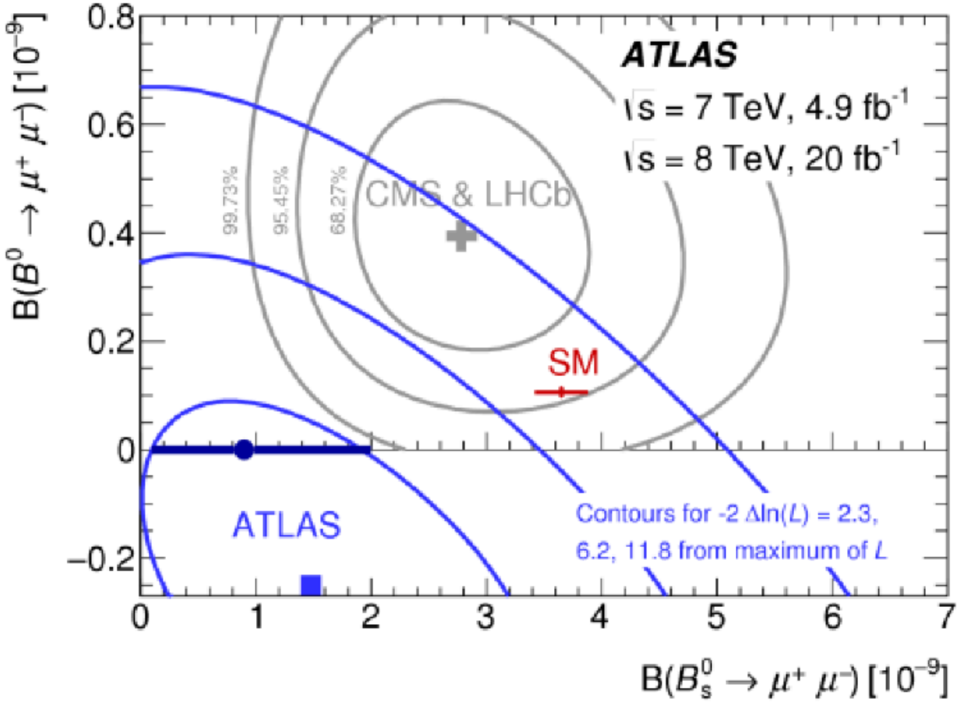
run-I: combined CMS & LHCb provides evidence for $B_s \to \mu^+\mu^-$





rare decays: $B_s \rightarrow \mu^+\mu^-$

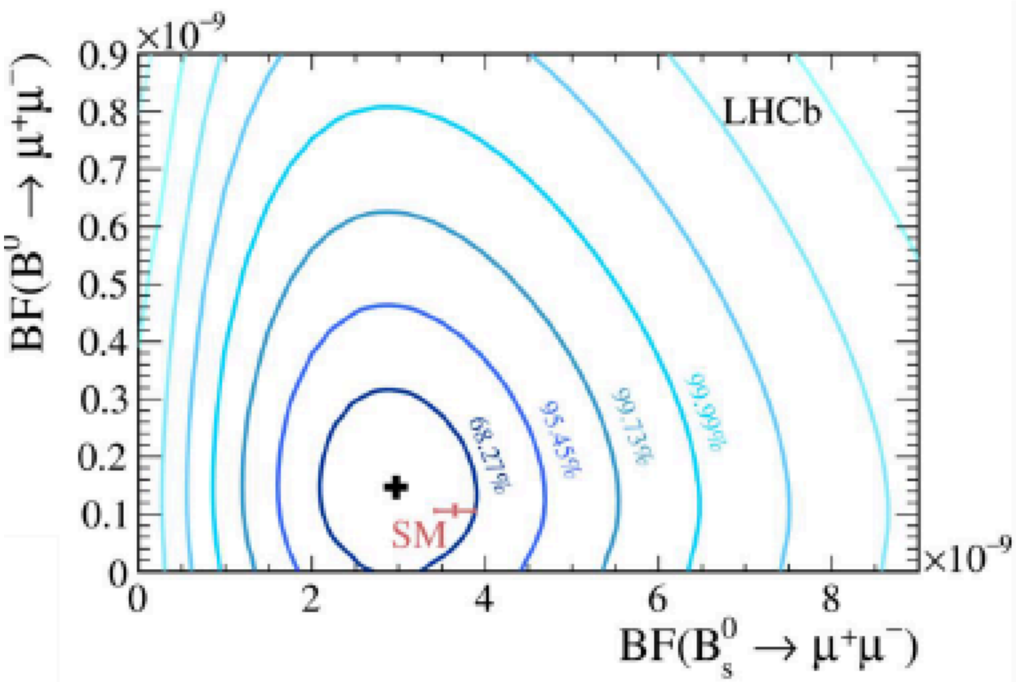
… + ATLAS:



- compatible with SM, but speculations about possibility for New Physics

rare decays: $B_s \to \mu^+\mu^-$

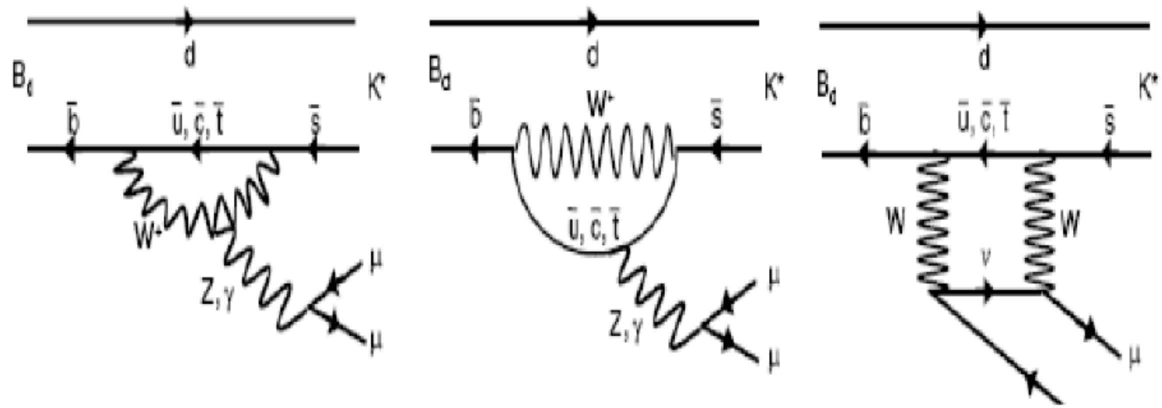
new results from run-II (LHCb):



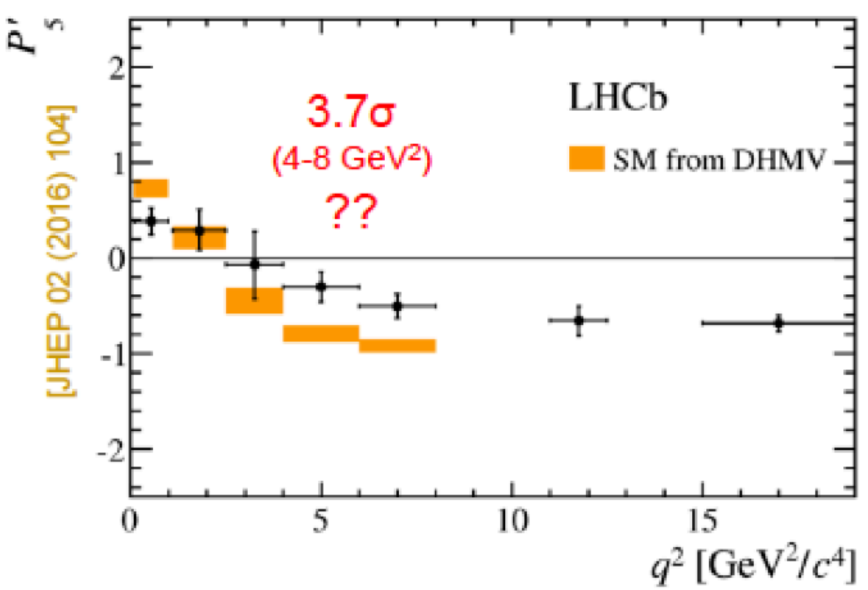
PRL 118 (2017) 191801

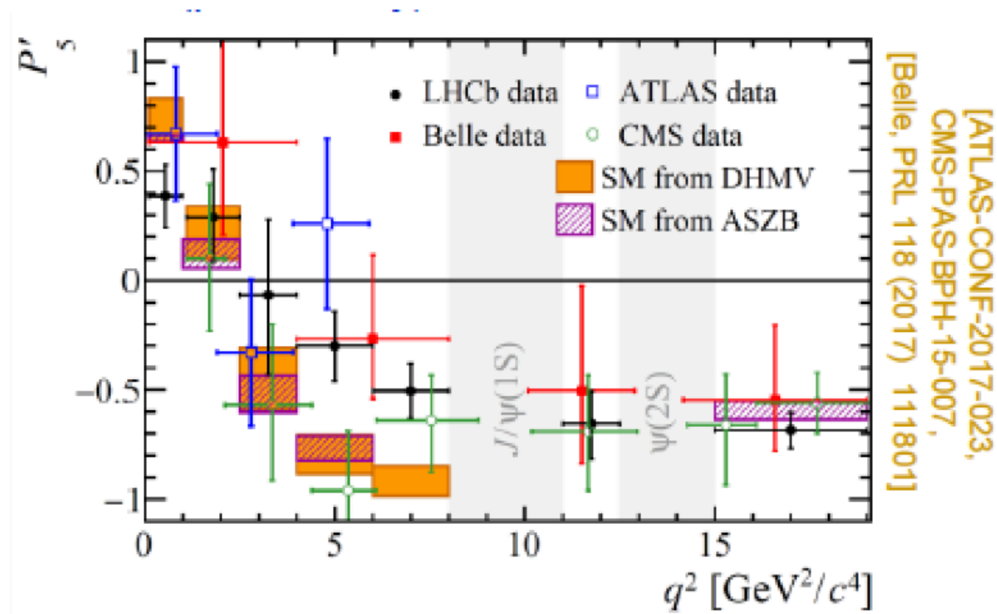
- very compatible with SM
- tight constraints on New Physics models

rare decays: $B_s \to K^*l^+l^-$



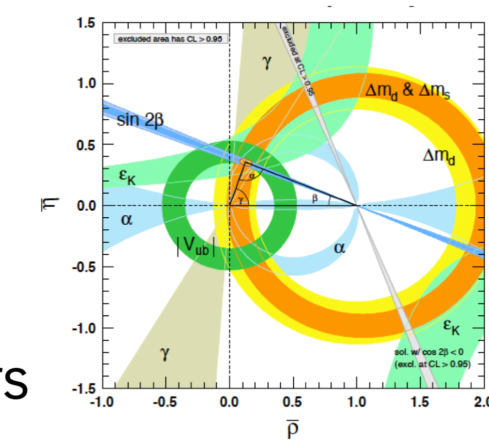
P5': constructed from angular observables, robust against form-factor uncertainties





- conclusions unclear (theo. uncertainties?) -> more data, upgrade detectors

Summary



- flavour physics: precision tool to
  - determine fundamental SM parameters (CKM matrix elements)
  - search for effects of New Physics BSM (loops, boxes)

- vast amount of data from LHC (LHCb, ATLAS, CMS) and from e^+e^- b-factories (BELLE)

- in general, very good agreement with SM predictions; however few signatures of deviation (2-3 s.d.), awaiting clarification with future data (BELLE-II; LHC plus detector upgrades)

Literature:

- Introduction to flavour physics, Y. Grossman, cds.cern.ch/record/1272886/files/p111.pdf
- flavour physics, Tim Gershon, https://warwick.ac.uk/fac/sci/physics/staff/academic/gershon/lectures/lecture1.pdf , + lecture2, 3 and 4
- heavy flavour physics, T. Gershon, M. Needham, arXiv:1408.0403 [hep-ex]
- reviews within the Particle Data Group book:
  http://pdg.lbl.gov/2017/reviews/