Beauty hadrons at LHCb: Experimental challenges, physical milestones, and new physics exploration

Monica Pepe Altarelli
CERN

ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS, 58th course
Erice, 15-24 June 2022

Why b (I)

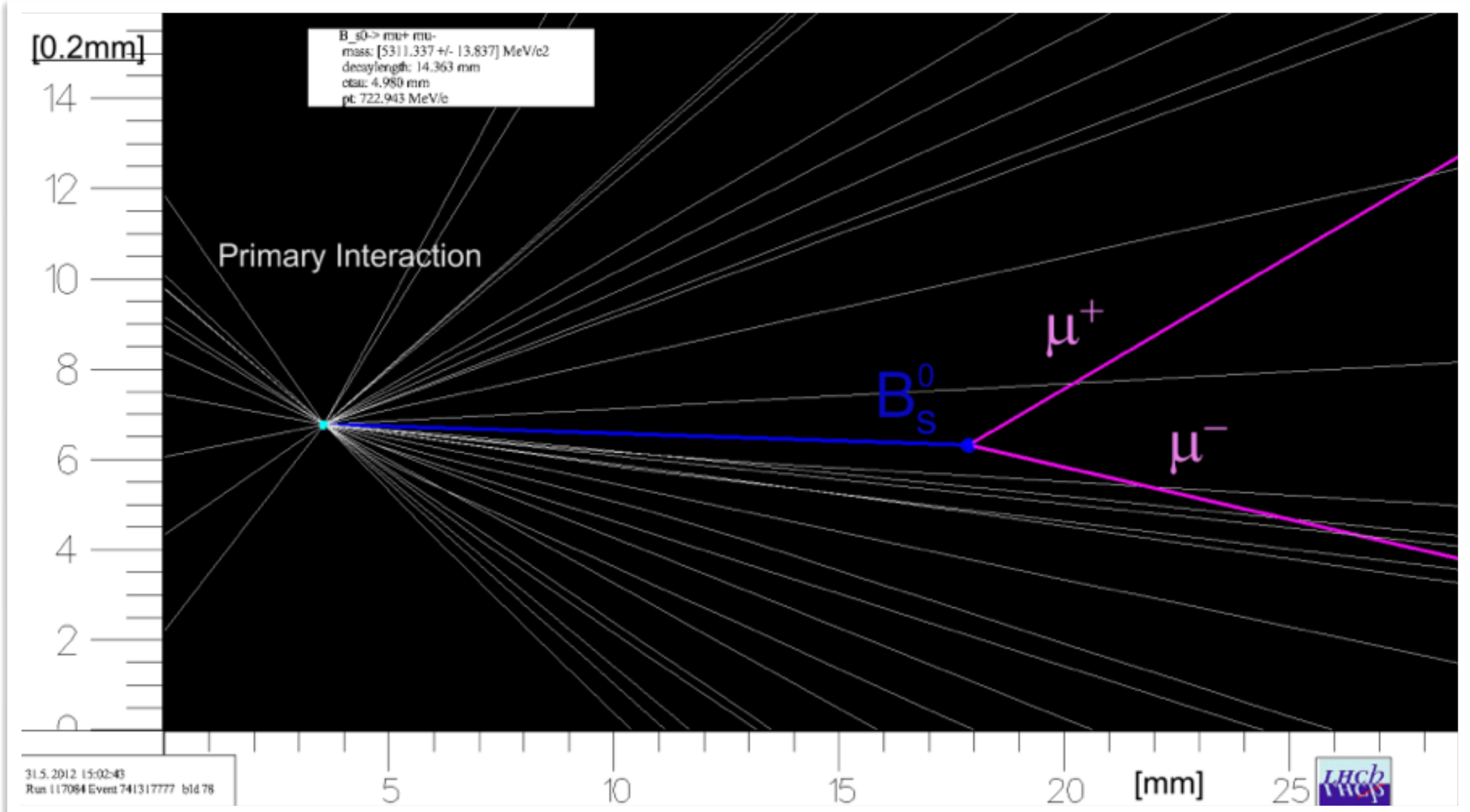
- The heaviest quark that binds in hadrons
- A large variety of decays: a vast laboratory
- Heavy mass → more theoretically accessible
  - $\Lambda_{\rm QCD}/m_b \sim 0.1$
  - Asymptotic freedom: $\alpha_s(m_b) \sim 0.2$

This allows systematic approximations, which are exploited in the various applications of heavy quark theory

- $\Upsilon(4S)$ is a clean source of B mesons at e^+e^- colliders
- Lifetime long enough for experimental detection → production and decay spatially separated

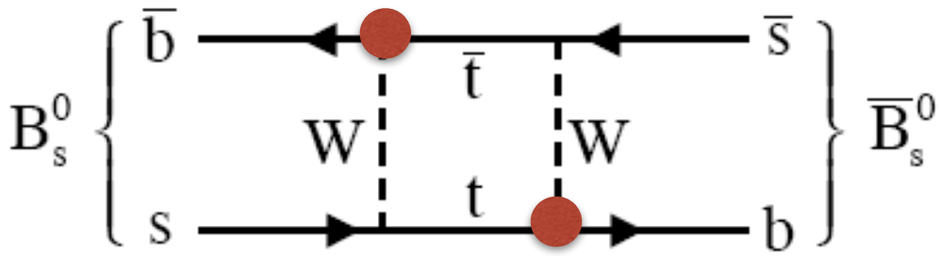
A reconstructed $B_s \to \mu^+\mu^-$ decay vertex

- $d = \beta\gamma c\tau = (p/m)c\tau$ (flightpath)
- $\tau_{\text{beauty}} \sim 1.5 \cdot 10^{-12}$ sec $\qquad \tau \sim 1/(m^5 |V_{cb}|^2)$
- @LHC: $p \sim 100\,\text{GeV}$, $m \sim 5\,\text{GeV} \rightarrow\ d = 20 \cdot 3 \cdot 10^{10} \cdot 1.5 \cdot 10^{-12} \sim 1\,\text{cm}$



Why b (II)

- Sizeable CP violation (CPV) expected in many decays
  - Large CPV effects expected in quantum loops that involve quarks from all three generations (quark mixing matrix cannot produce CPV in a world with only two families!)
  - Quark loops are not suppressed (neither by GIM: $m_t > m_W$ nor by CKM: $|V_{tb} = 1|$)



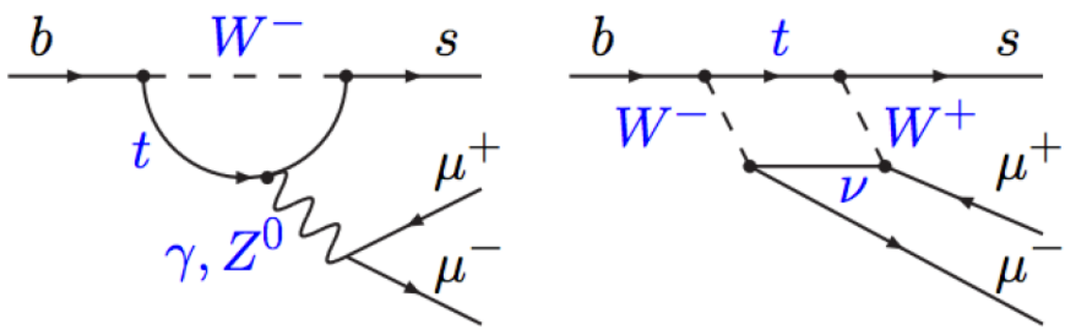
- The observed baryon asymmetry in the Universe requires CPV beyond the SM (in SM, CPV many orders of magnitude below observation of baryon to photon ratio $\eta = \frac{N_B}{N_\gamma} \simeq 6 \times 10^{-10}$)

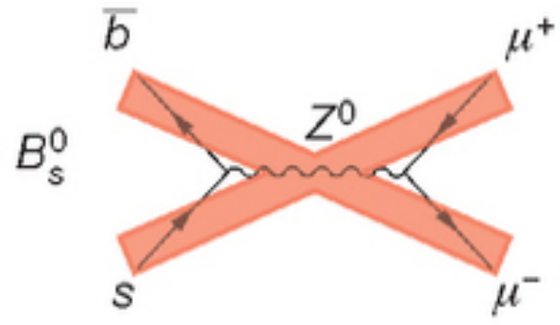
We need more CP violation!

- CP violation beyond the SM must exist!
- Where might we find it?
  - quark sector, e.g. as deviations from CKM predictions
  - lepton sector, e.g. as CP violation in neutrino oscillations
  - other new physics: almost all TEV-scale NP contains new sources of CP violation and precision measurements of flavour observables are generically sensitive to additions to the Standard Model

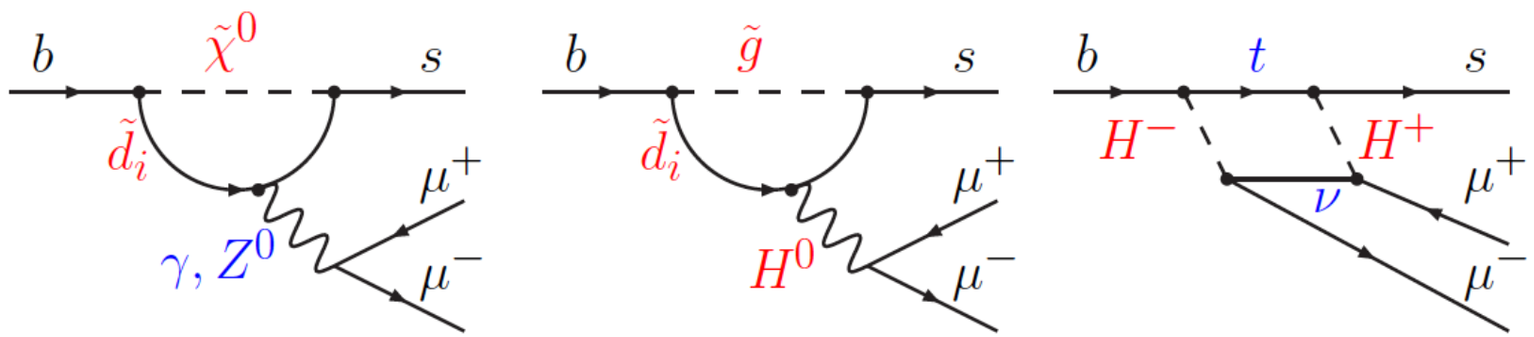
Why b (III)

- In the SM, some decays are forbidden at tree level and can only occur at loop level (penguin and box), e.g. $B_s \to \mu^+\mu^-$ → Rare Flavour Changing Neutral Currents





- A new particle, too heavy to be produced at the LHC, can give sizeable effects when appearing in a loop



- Strategy: use precisely-predicted observables to look for deviations
- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS

A lesson from history

- New physics can show up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation and CKM before discovery of beauty and top
  - Neutral currents before the discovery of Z
- In general, a data-driven approach, in which we test precise SM predictions looking for discrepancies, has historically paved the way to important discoveries in particle physics.
- This approach is particularly relevant in the absence of direct collider production of new particles

CKM matrix

- V_{CKM}: non trivial flavour mixing originating from the Higgs sector: $V_{ij} \rightarrow \delta_{ij}$ if we switch off the Hiiggs interactions

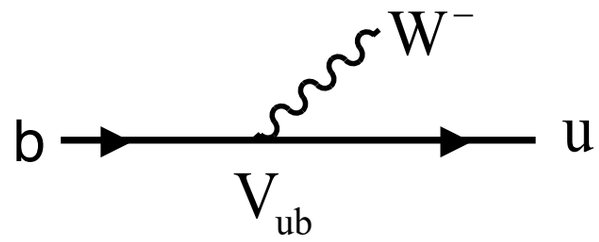
- V_{CKM} describes the rotation between flavour (d', s', b') and mass (d, s, b) eigenstates

Flavour eigenstates

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

Mass eigenstates

- V_{ij} proportional to transition amplitude from quark i to quark $j \rightarrow$ V_{CKM} quark mixing matrix



- V_{CKM} induces flavour-changing transitions within and across generations in the charged sector at tree level ($W^{\pm}$interaction).

Hierarchy in quark mixing

$\lambda \sim 0.22$

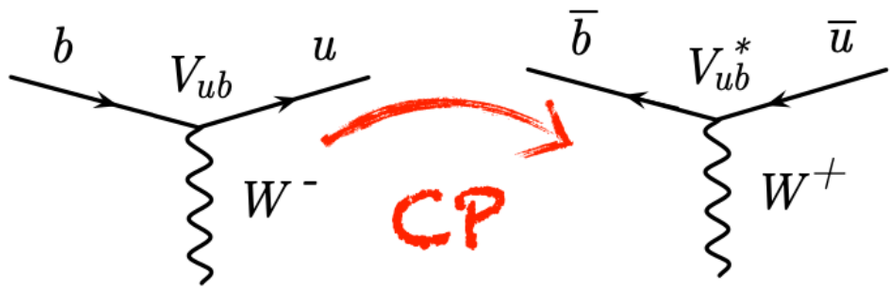
$$V \approx \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{pmatrix}$$

d s b — u c t

- Each quark has a preference to transform into a quark of its own generation.
- Very suggestive pattern
- No known reasons
- Completely different in neutrino sector

- For $N = 3$ (3 families) , three mixing parameters and one phase [For $N = 2$, one mixing angle θ_c and no phase]

- This phase is responsible for CP violation: weak-interaction couplings differ for quarks and antiquarks because CP flips the sign of imaginary numbers $e^{i\varphi}$



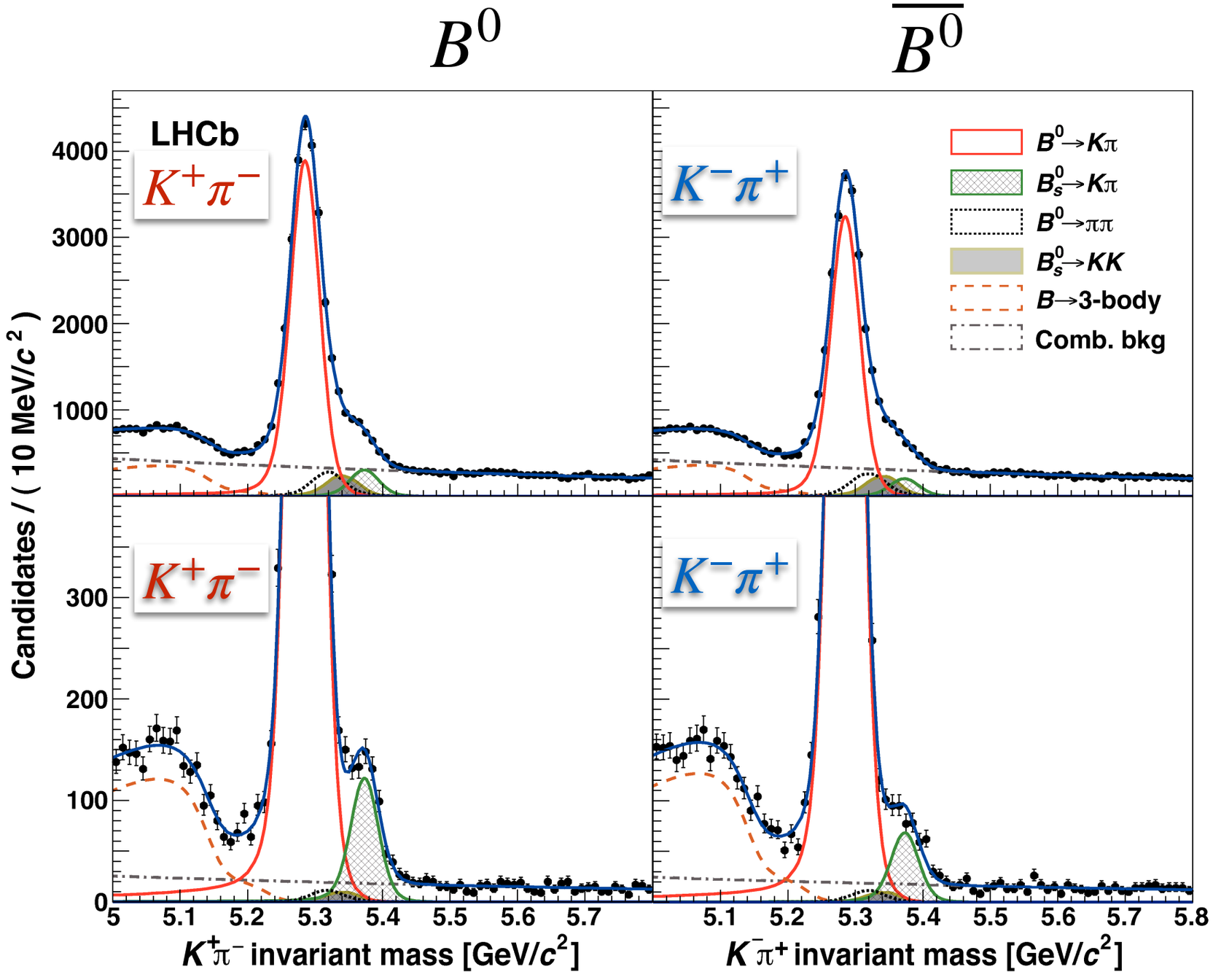
$V_{ub} \neq V_{ub}^*$

CP violation in $B^0_{(s)}$ meson decays

- CP acts differently on particles and antiparticles
- Separate into B^0 and $\overline{B^0}$ from different charge combinations of K and π

$B^0 : [\bar{b}d]$

$B^0_s : [\bar{b}s]$

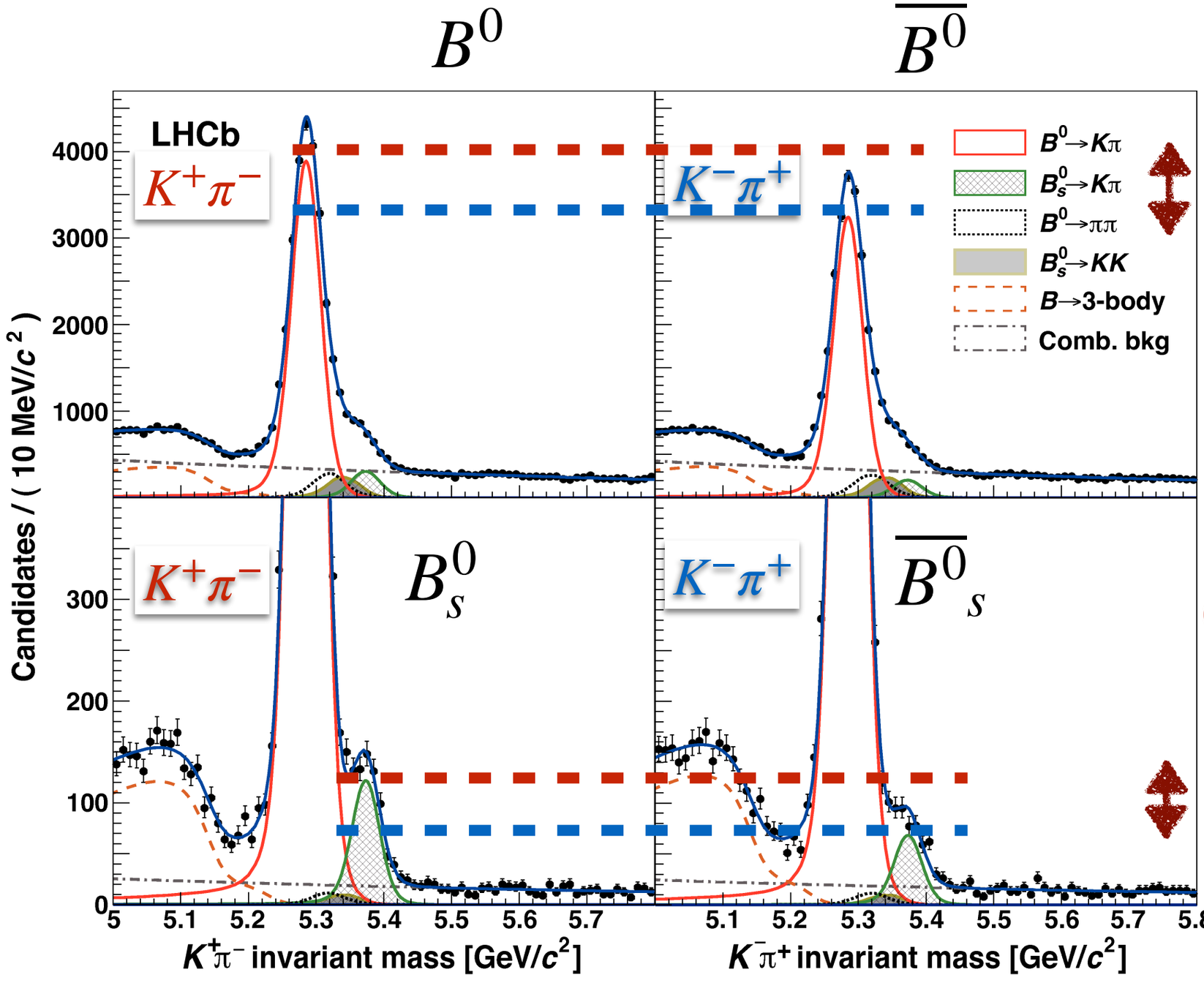


CP violation in $B^0_{(s)}$ meson decays

- CP acts differently on particles and antiparticles
- Separate into $B^0_{(s)}$ and $\overline{B^0}_{(s)}$ from different charge combinations of K and π

$B^0 : [\bar{b}d]$

$B^0_s : [\bar{b}s]$



CP Violation

Rates are different!

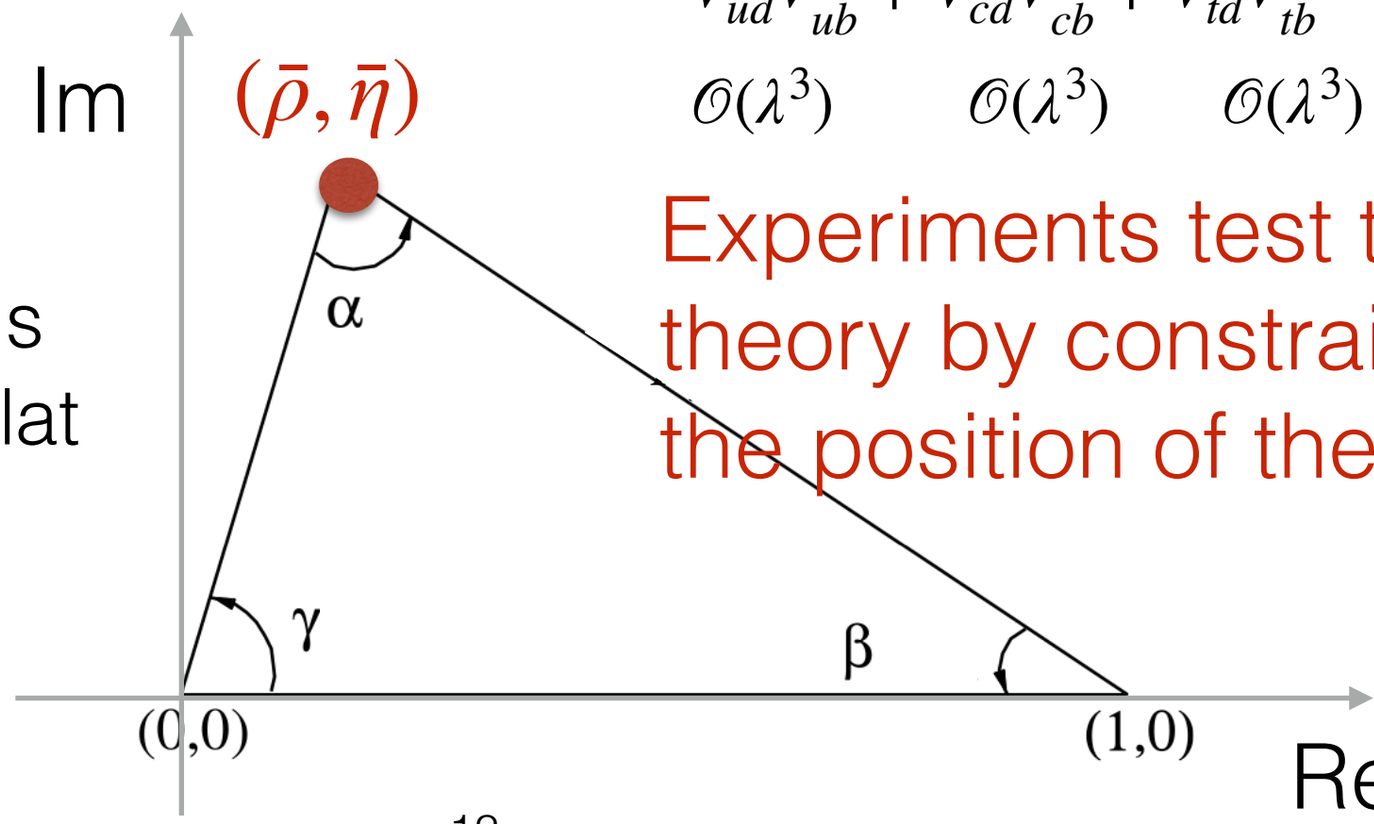
CP Violation

Unitarity Triangle

- Unitarity of CKM matrix implies relations of the form
$\sum_i V_{ij} V_{ik}^* = \delta_{j,k}$, with $j \neq k$
- Each of these 6 unitarity constraints can be seen as the sum of 3 complex numbers closing a triangle in the complex plane

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
$$\mathcal{O}(\lambda^3) \qquad \mathcal{O}(\lambda^3) \qquad \mathcal{O}(\lambda^3)$$

CP violation in the quark sector ($\bar{\eta} \neq 0$) is translated into a non flat UT



Experiments test the theory by constraining the position of the apex

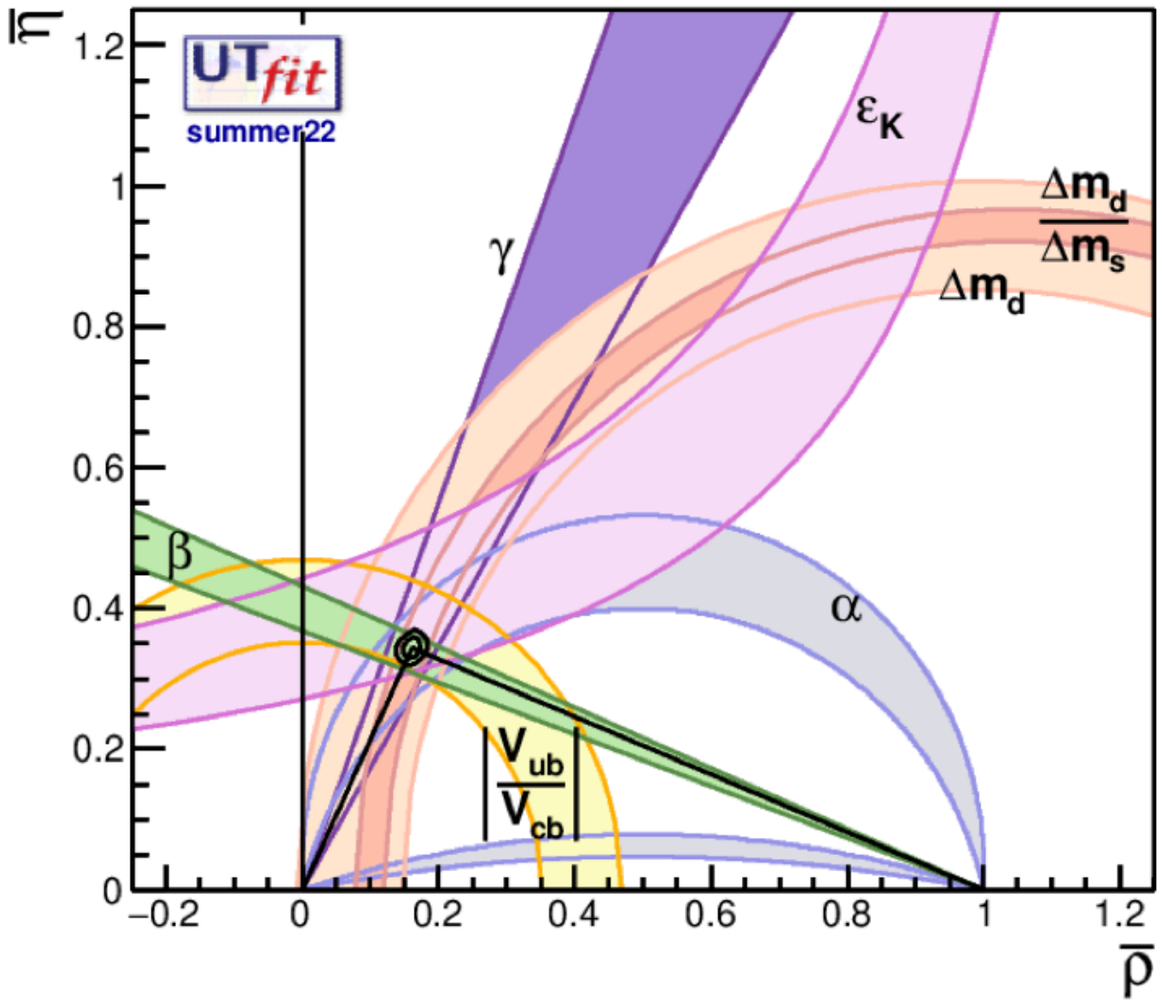
Consistency of CKM fits

- The physics impact of the measurements of the the CKM elements is not so much in their absolute values (matrix is not predicted) but rather in testing the (in)consistency of the “ensemble” of measurements and how precisely the SM description of flavour and CP violation holds.
- “Redundant" measurements are performed, which test different combinations of flavour parameters

Consistency of CKM fits

- Impressive effort from community and tremendous success of CKM paradigm!

- Constraints from many different quark transitions. Extensive measurements on K, D and B mesons performed at different experiments. Constraints depend also on theory input.
- At the current level of precision, all measurements are consistent and intersect in the apex of the UT
- New Physics effects (if there) are small!



$$\bar{\rho} = 0.161 \pm 0.009 \quad \sim 6\%$$

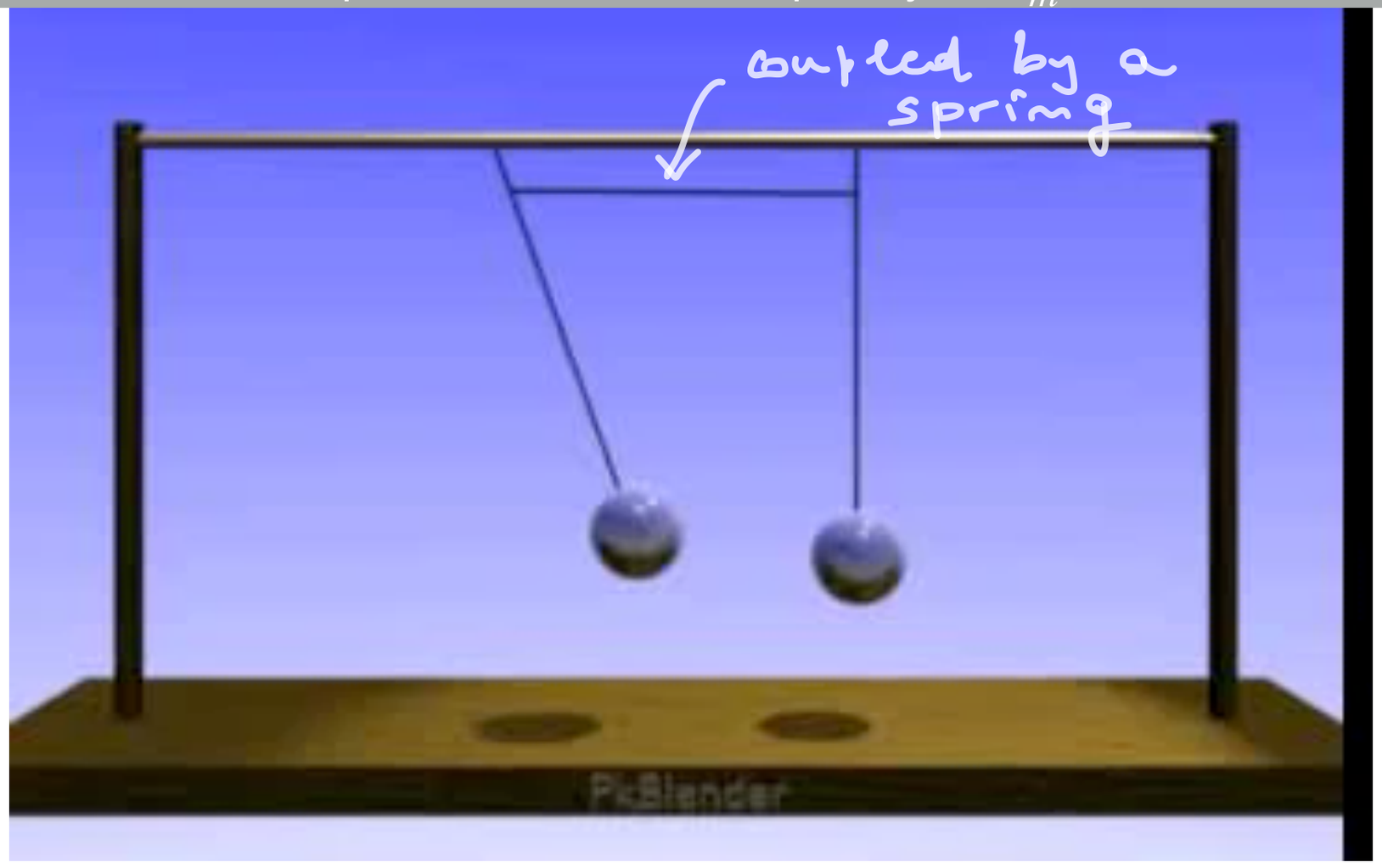
$$\bar{\eta} = 0.344 \pm 0.010 \quad \sim 3\%$$

M.Bona LHCP '22 UTfit, similar plots from CKMfit

One example: neutral meson oscillations

Mechanical analogue: the coupled pendulum

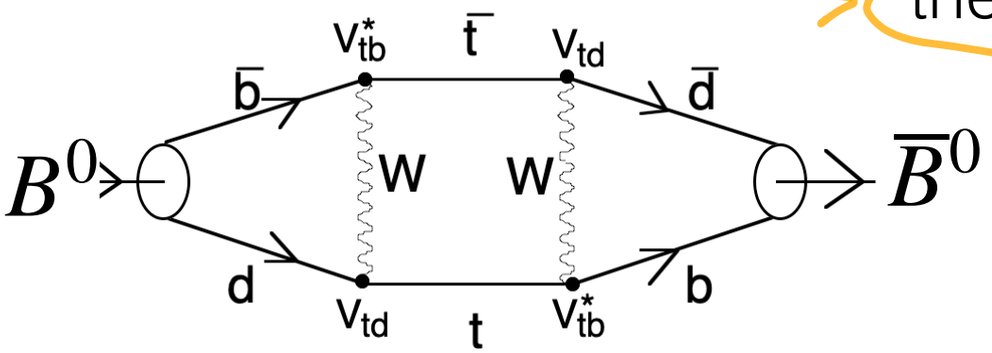
One pendulum may be thought of as the K^0 and the other as the $\overline{K}^0$. When one pendulum is excited, it will slowly transfer its energy to the other and back. This beating corresponds to the oscillation between a meson and its antiparticle. The beat frequency is Δ_m

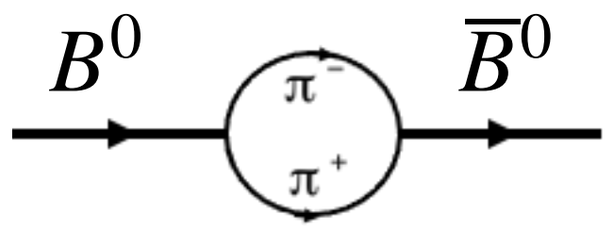


Neutral meson oscillations

- Flavour eigenstates $M^0, \overline{M}^0$ can mix into each other
  - via short-distance (box diagrams) or long-distance processes

the equivalent of the spring





$K^0 \leftrightarrow \overline{K}^0,\ D^0 \leftrightarrow \overline{D}^0,\ B^0 \leftrightarrow \overline{B}^0$

- $\Delta S = 2, \quad \Delta C = 2, \quad \Delta B = 2$

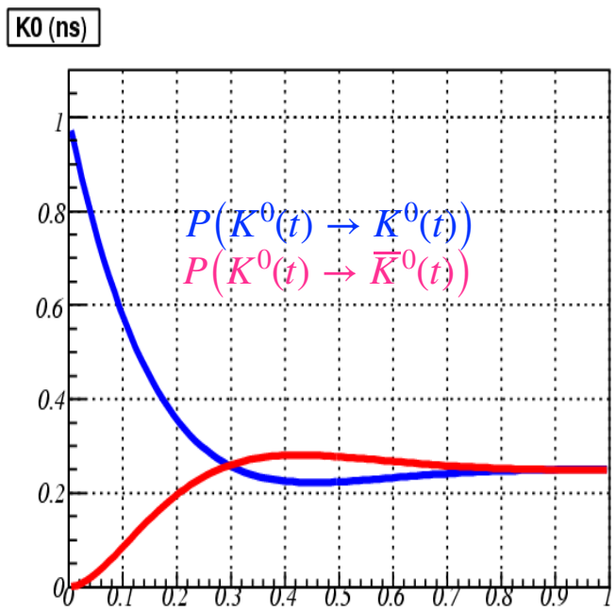
Large for B_d^0, small for D^0& K^0

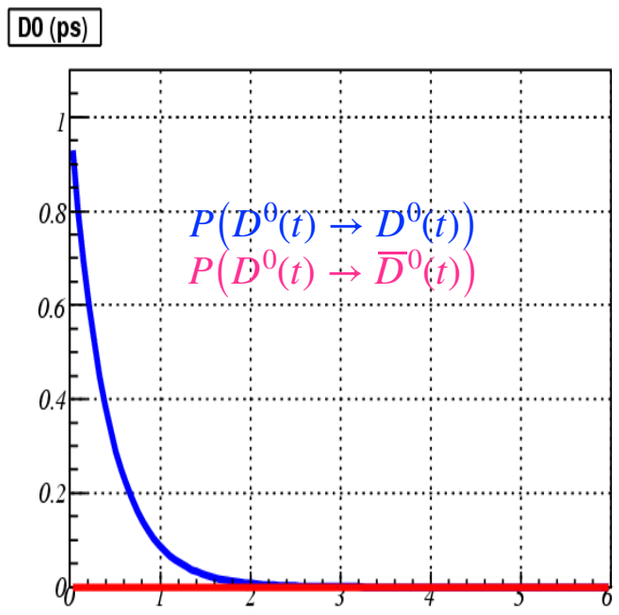
Large for K^0, small for D^0& B_d^0

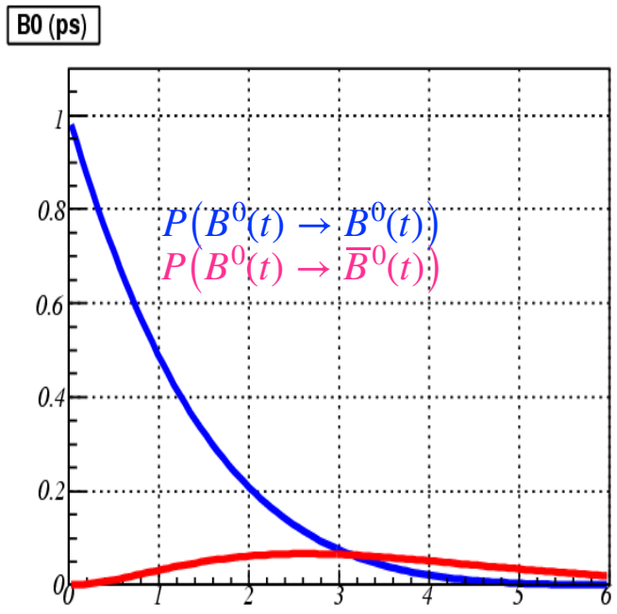
- Formalism is the same even if difference in mass and CKM elements results in dramatically different phenomenology

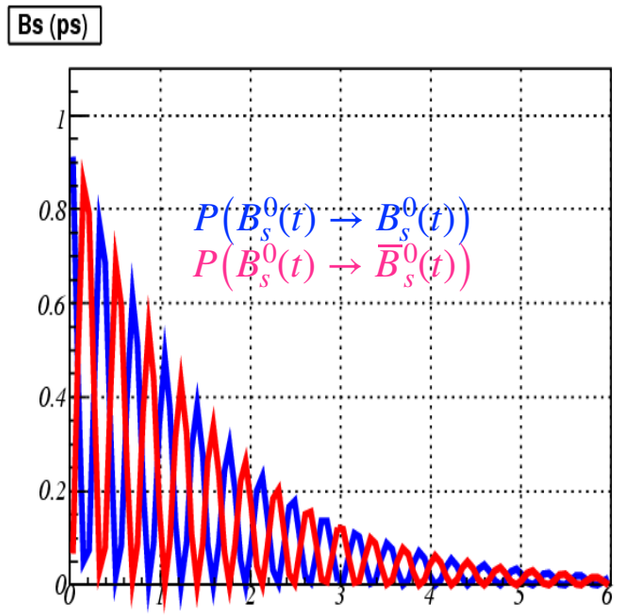
- Physical states: eigenstates of effective Hamiltonian
  $|M_{L,H}\rangle = p\,|M^0\rangle \pm q\,|\overline{M}^0\rangle$, with $|M^0\rangle, |\overline{M}^0\rangle$ flavour eigenstates,
  CP violation in mixing when $|q/p| \neq 1$, $\Delta m = m_H - m_L,\ \Delta\Gamma = \Gamma_L - \Gamma_H$

Compare the mesons









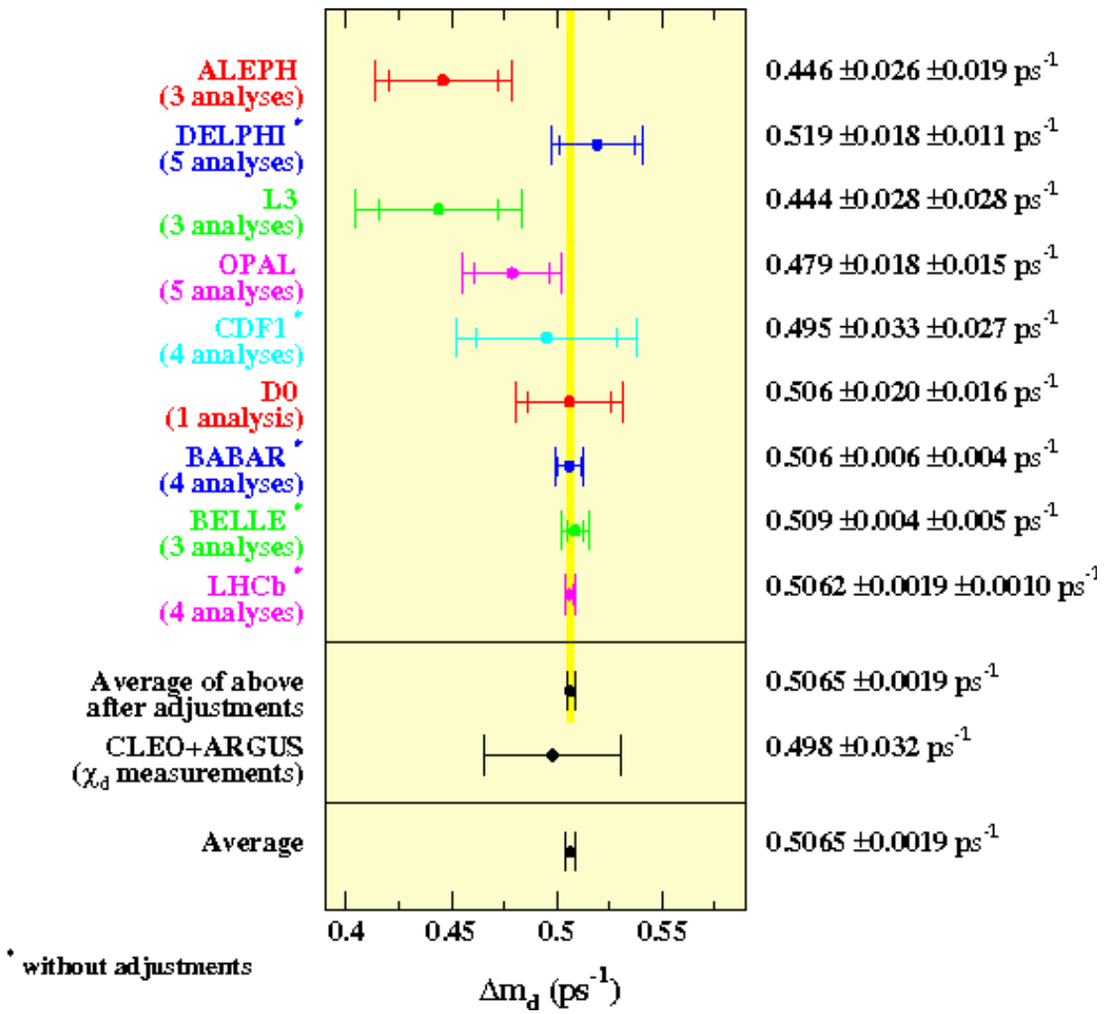
Probability to observe an M^0 or $\overline{M}^0$ at time t starting from a pure M^0 meson

- Oscillation frequency Δm depends on mixing rate, $\Delta\Gamma$ depends on widths of decays into common final states ($K^0 \to \pi^+\pi^- \to \overline{K}^0$) (large for K^0, small for D^0, B_d^0)
- $x = \Delta m/\Gamma$ gives the average number of oscillations before decay

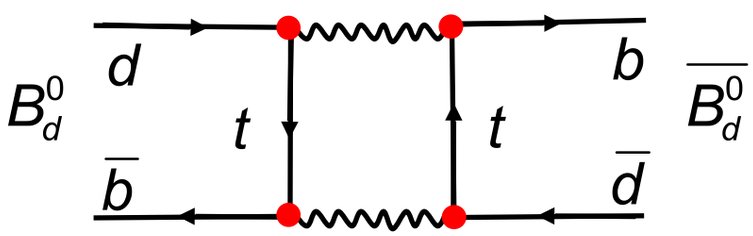
	Δm $(x = \Delta m/\Gamma)$	$\Delta\Gamma$ $(y = \Delta\Gamma/(2\Gamma))$
K^0	large	$\sim$ maximal
	~ 500	~ 1
D^0	small	small
	$(0.63 \pm 0.19)\%$	$(0.75 \pm 0.12)\%$
B^0	medium	small
	0.770 ± 0.008	0.008 ± 0.009
B_s^0	large	medium
	26.49 ± 0.29	0.075 ± 0.010

- B^0mixing, first observed by Argus in 1987, then measured precise by B factories, LHCb…
- B_s^0 mixing first measured by CDF in 2006 and then by LHCb

$B^0 \leftrightarrow \overline{B}^0$ oscillations

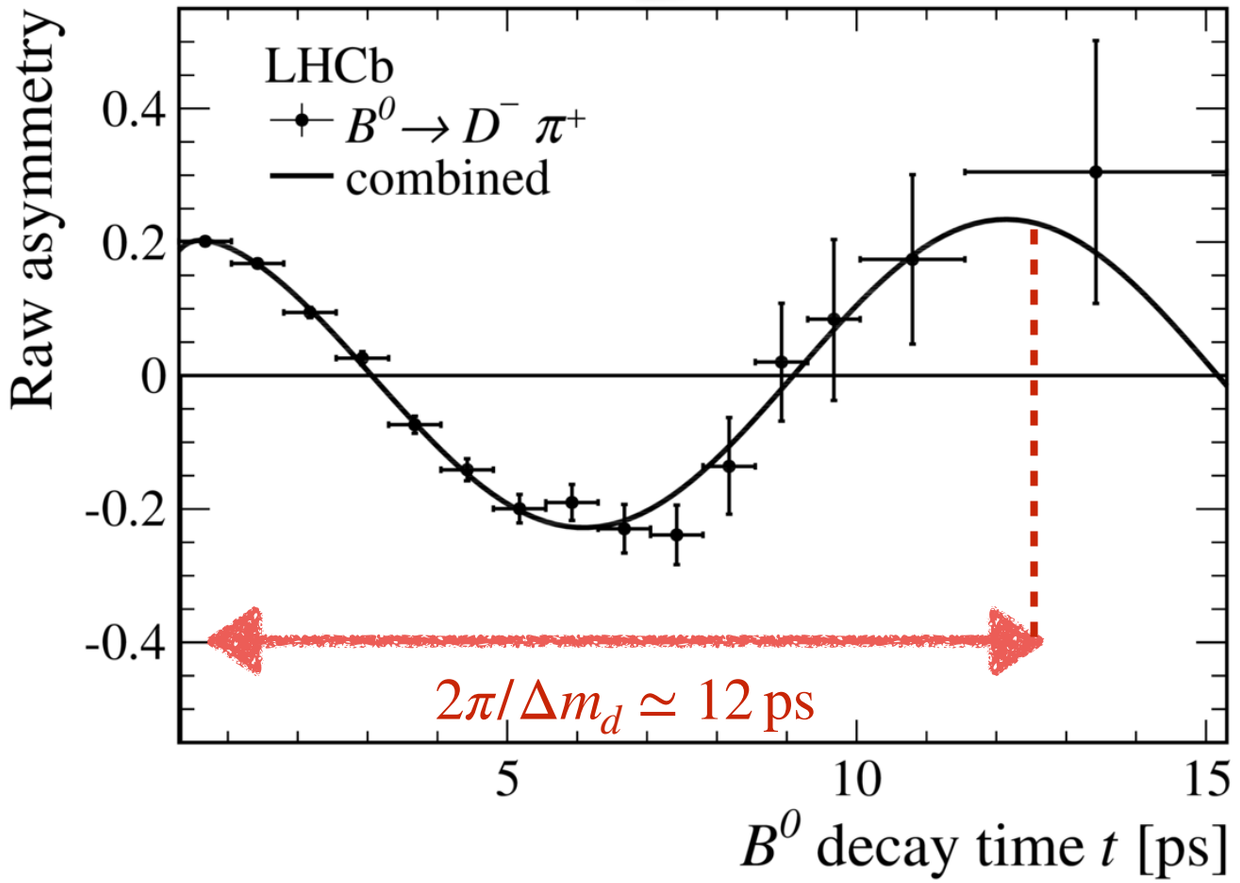


$$\Delta m_d = 0.5065 \pm 0.0019 \text{ ps}^{-1}$$



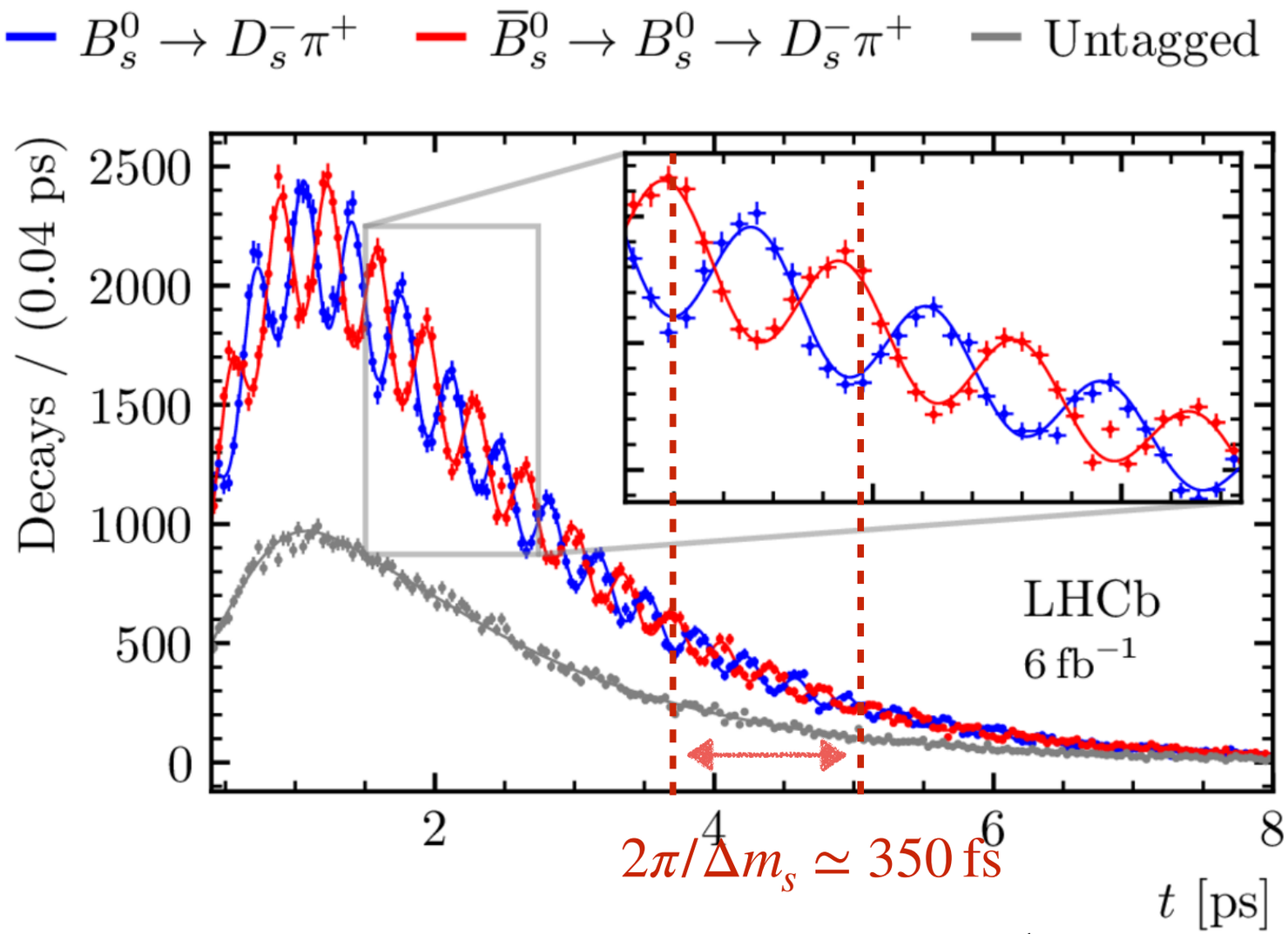
$$\Delta m_d \sim m_t^2 \, |V_{tb} V_{td}|^2 \sim m_t^2 \cdot \mathcal{O}(\lambda^2)$$

Phys. Lett. B719 (2013) 318



One period of B^0 oscillations $\Delta T \simeq 12\,\text{ps} \rightarrow$ oscillation frequency $\Delta m_d \simeq 0.5\,\text{ps}^{-1}$

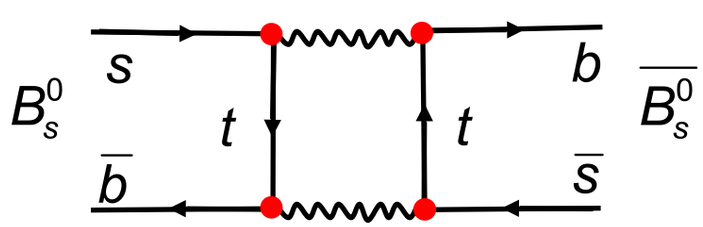
$B_s^0 \leftrightarrow \overline{B}_s^0$ oscillations



- Different flavour at decay and production
- Same flavour at decay and production

Nature Physics 18 (2022)

- $\Delta m_s = 17.741 \pm 0.0057\ \text{ps}^{-1}$ 0.03% accuracy



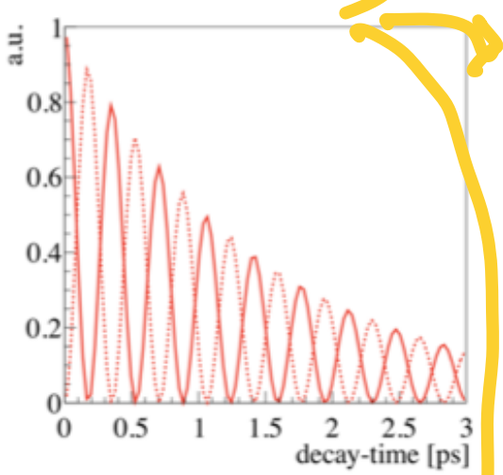
$\Delta m_s \sim m_t^2 |V_{tb}V_{ts}|^2 \sim m_t^2 \cdot \mathcal{O}(\lambda^4)$

One period of B_s^0 oscillations $\Delta T \simeq 350\,\text{fs} \rightarrow$ oscillation frequency $\Delta m_s \simeq 17.8\,\text{ps}^{-1}$ (~35 times faster than B_d^0 oscillations)

$B_s^0 \leftrightarrow \overline{B}_s^0$ oscillations, experimentally

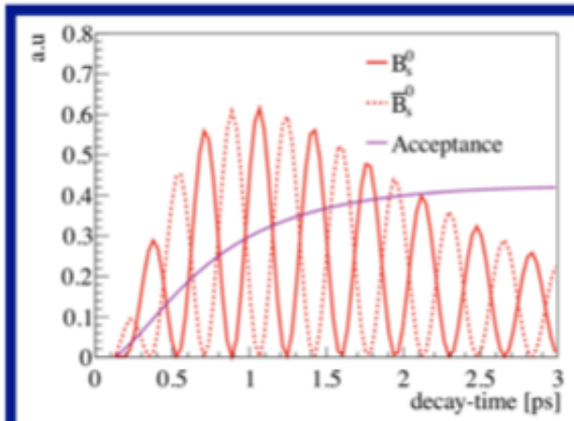
Detector effects

Perfect



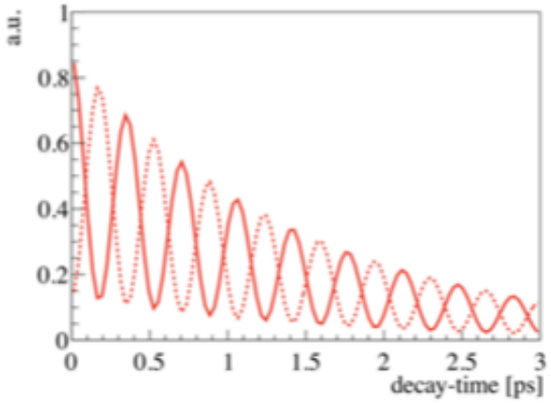
$$P(t) \sim e^{-\Gamma_s t}(\cosh(\frac{\Delta\Gamma_s t}{2}) \pm \cos(\Delta m_s t))$$

Decay-time acceptance



- decay-time distorted by selection requirements
- selection efficiency depends on decay-time introducing acceptance

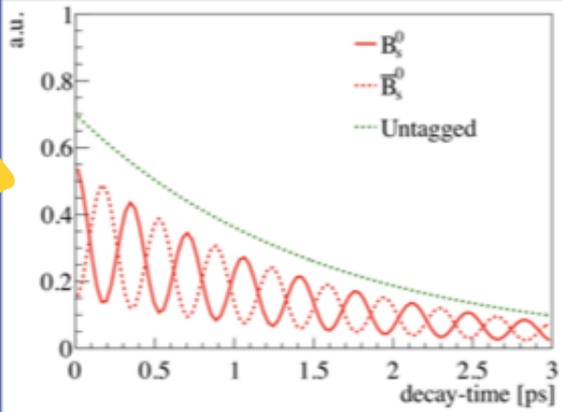
Decay-time resolution



- finite decay-time resolution of the detector leads to a dilution of observed oscillation

Dilution: $D_{res} \sim e^{-\frac{1}{2}\Delta m_s^2 \sigma^2}$

Flavour tagging



- decay-rates depend on the initial flavour, which is provided by dedicated algorithms

Dilution:

$$D \sim (1-2\omega) = 1 - 2\frac{\#wrong\ tag}{\#all\ tag}$$

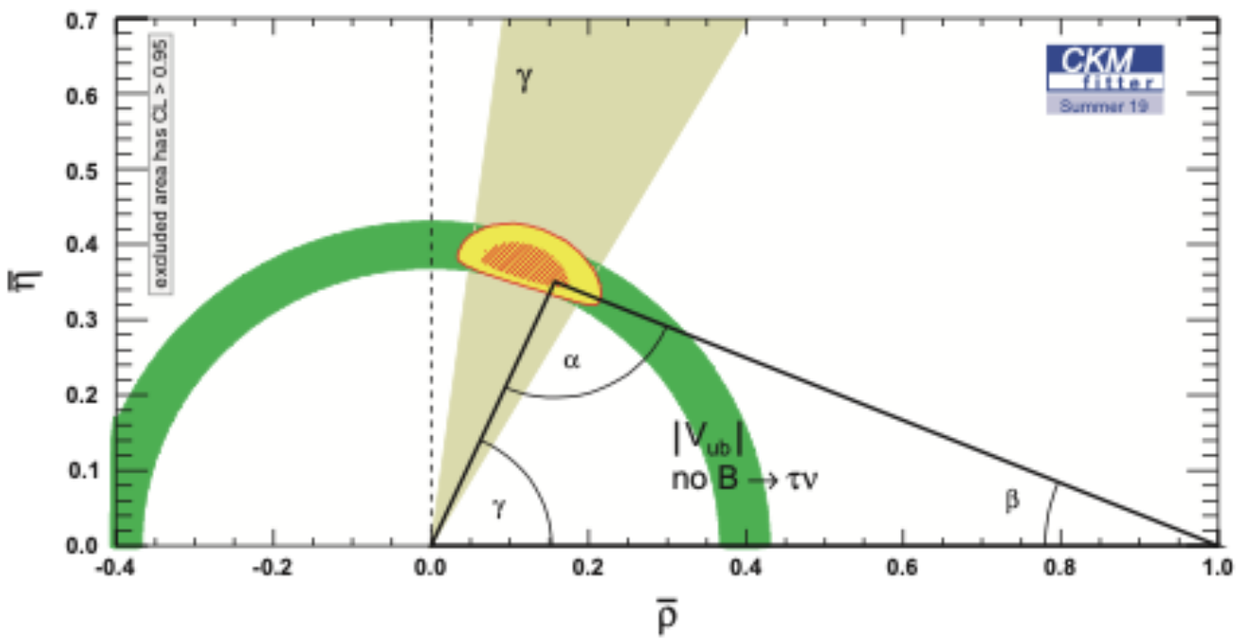
$$\epsilon_{tag} = \frac{\#wrong + \#right}{\#all\ tag + \#untagged}$$

Requires excellent time resolution:
$\sigma_t \approx 45$ fs (LHCb)

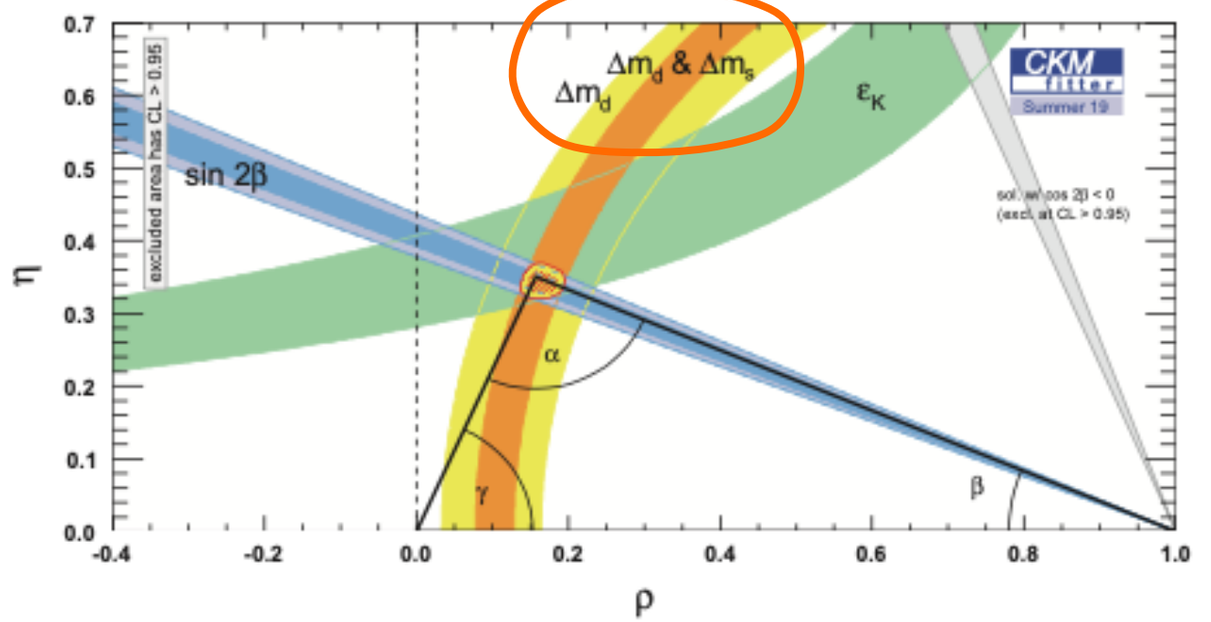
Tagging power
$\epsilon_{eff} = \epsilon_{tag}(1-2\omega)^2 \approx 6\,\%$ (LHCb)

Impact of B-meson mixing measurements

Tree-level observables



Loop observables



The ratio $\Delta m_d / \Delta m_s$ in the SM benefits from the cancellation of many uncertainties

- "What is particularly noteworthy in the so-called CKM fits is the consistency of the the tree-level determinations of CKM elements, with those obtained from loop observables, such as K-$\overline{K}$ or B-$\overline{B}$ mixing" (G.Isidori)

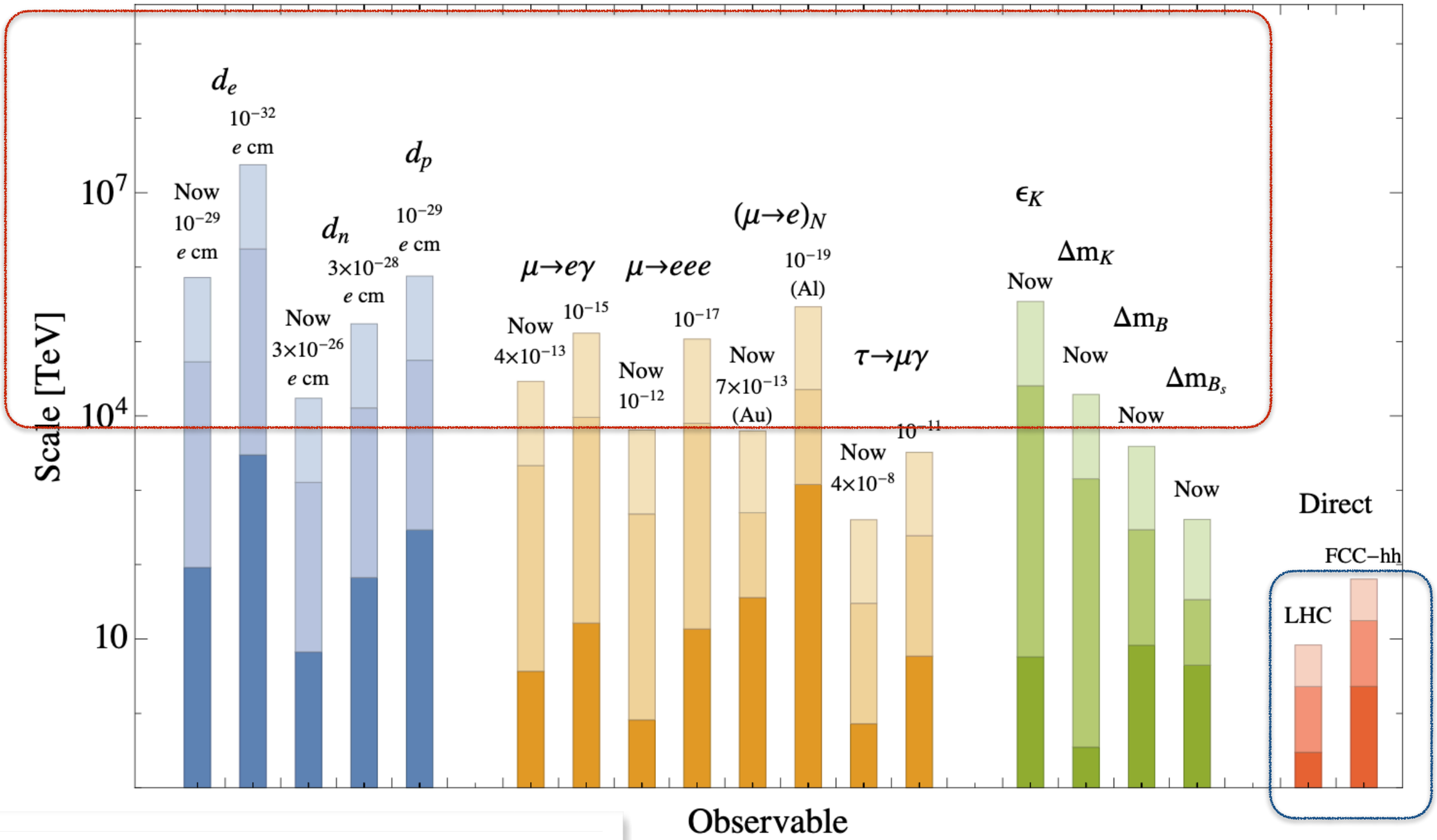
The flavour problem

- A systematic data-theory comparison, allowing for possible New Physics effects has been completed for all meson-anti-meson mixing amplitudes→ no significant deviations (at 5 - 30% depending on the amplitudes)→this can be translated into quantitative bounds on couplings and masses of possible new particles

$$\mathbf{NP} \sim \frac{\mathbf{C_{NP}}}{\Lambda^2}$$

- Serious constraints on NP models and serious quantitative bounds on couplings and masses of possible new particles

Energy reach of various indirect precision tests of physics beyond the SM compared to direct searches



Matt Reece,
DOE Basic Research Needs HEP R&D

Ways out

- Either New Physics is very heavy

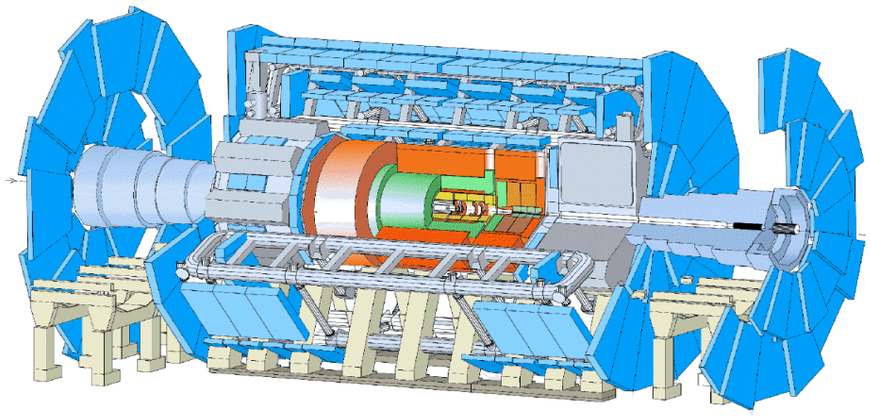
- or, if we want to keep the NP scale in the TeV range, it must have a highly non-generic flavour breaking pattern (e.g. **Minimal Flavour Violation**, in which the flavour breaking structure of the SM also holds beyond the SM and bounds on NP scale are reduced to few TeV)

- Can we see deviations from the SM with more precise measurements? If yes, where?

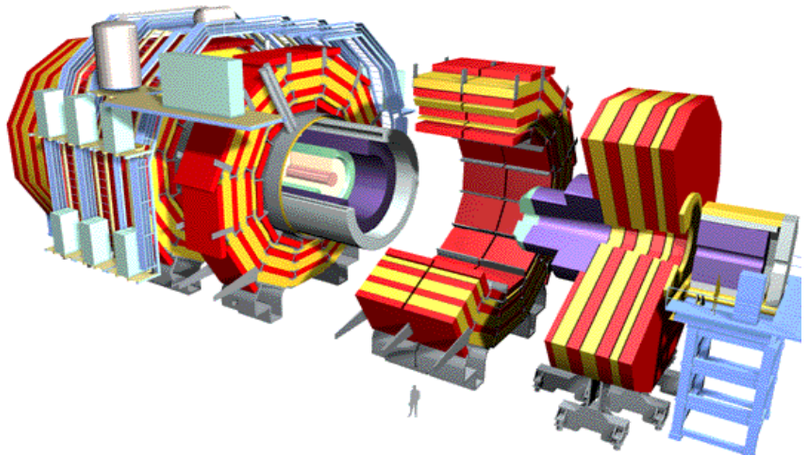
- Rare K and B decays are potential candidates

The main actors in b-physics today

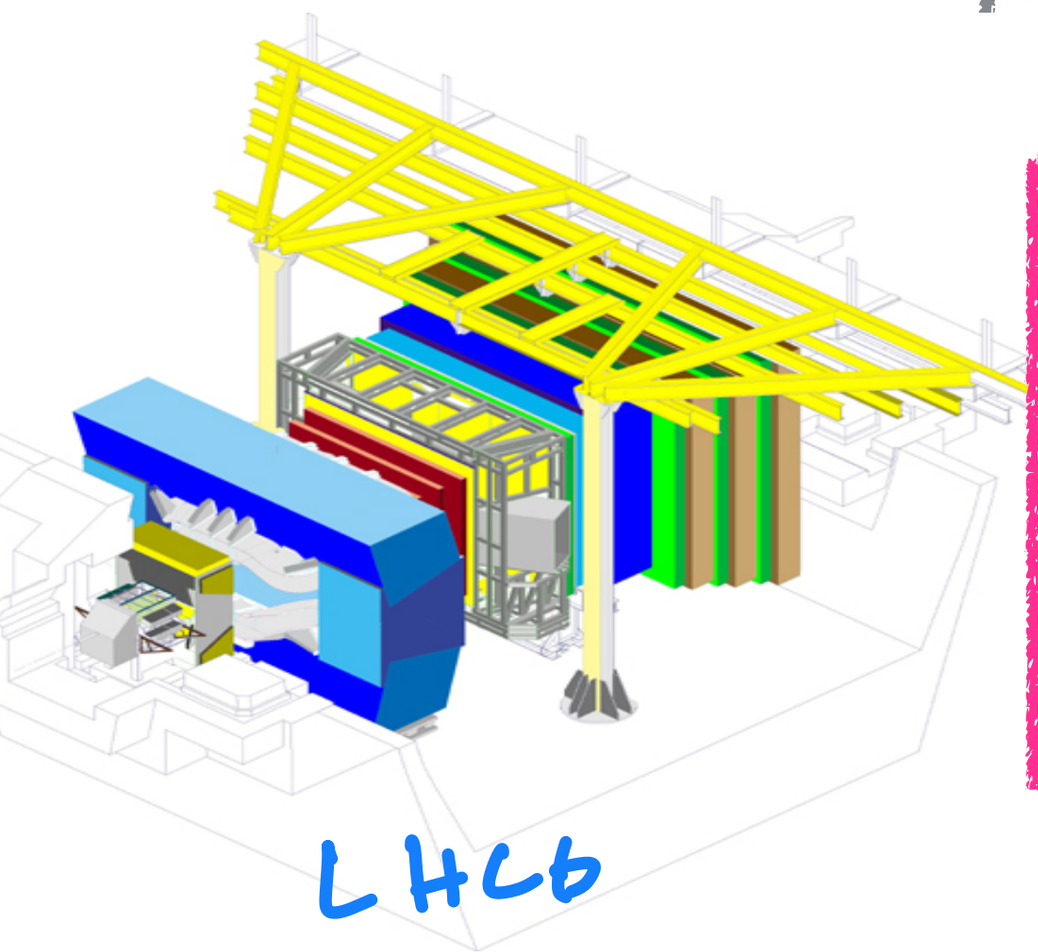
ATLAS



CMS

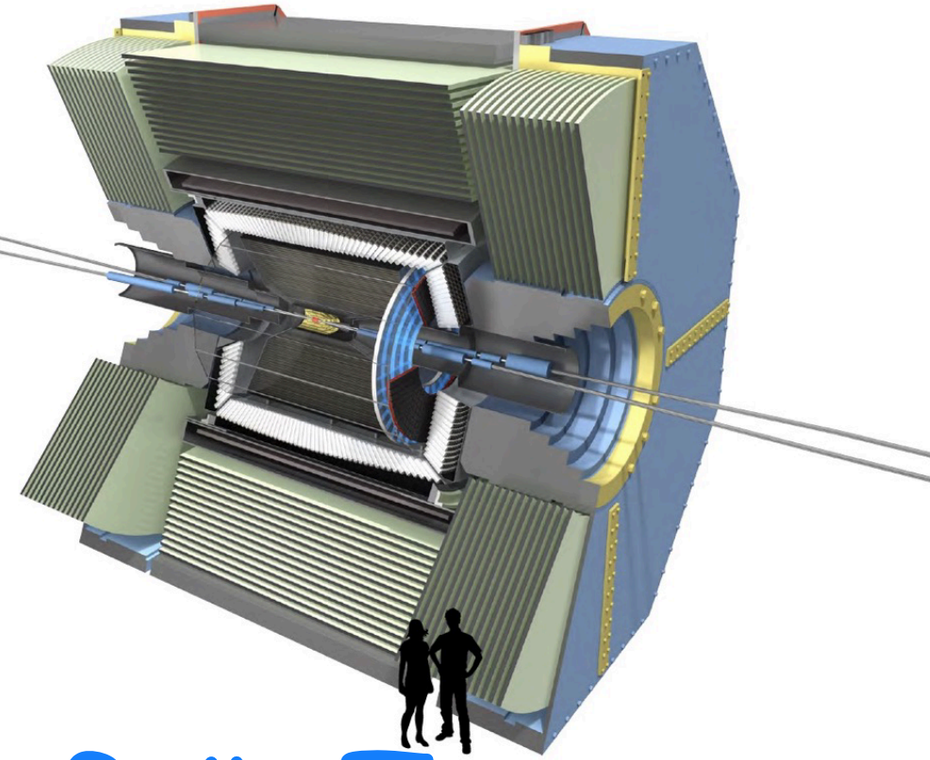


ATLAS and CMS @ LHC are “General Purpose Detectors”, but can measure a few flavour observables, mainly with muons in final state



LHCb

LHCb @ LHC and Belle II @KEK are dedicated detectors for flavour physics performing a wide range of measurements



Belle II

The LHCb collaboration

- ~1500 members and ~1000 authors from 88 institutes in 19 countries
- ~ 600 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

The LHCb collaboration

- ~1500 members and ~1000 authors from 88 institutes in 19 countries
- ~ 600 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

CKM & CPV

EW and QCD

Spectroscopy

Semileptonic decays

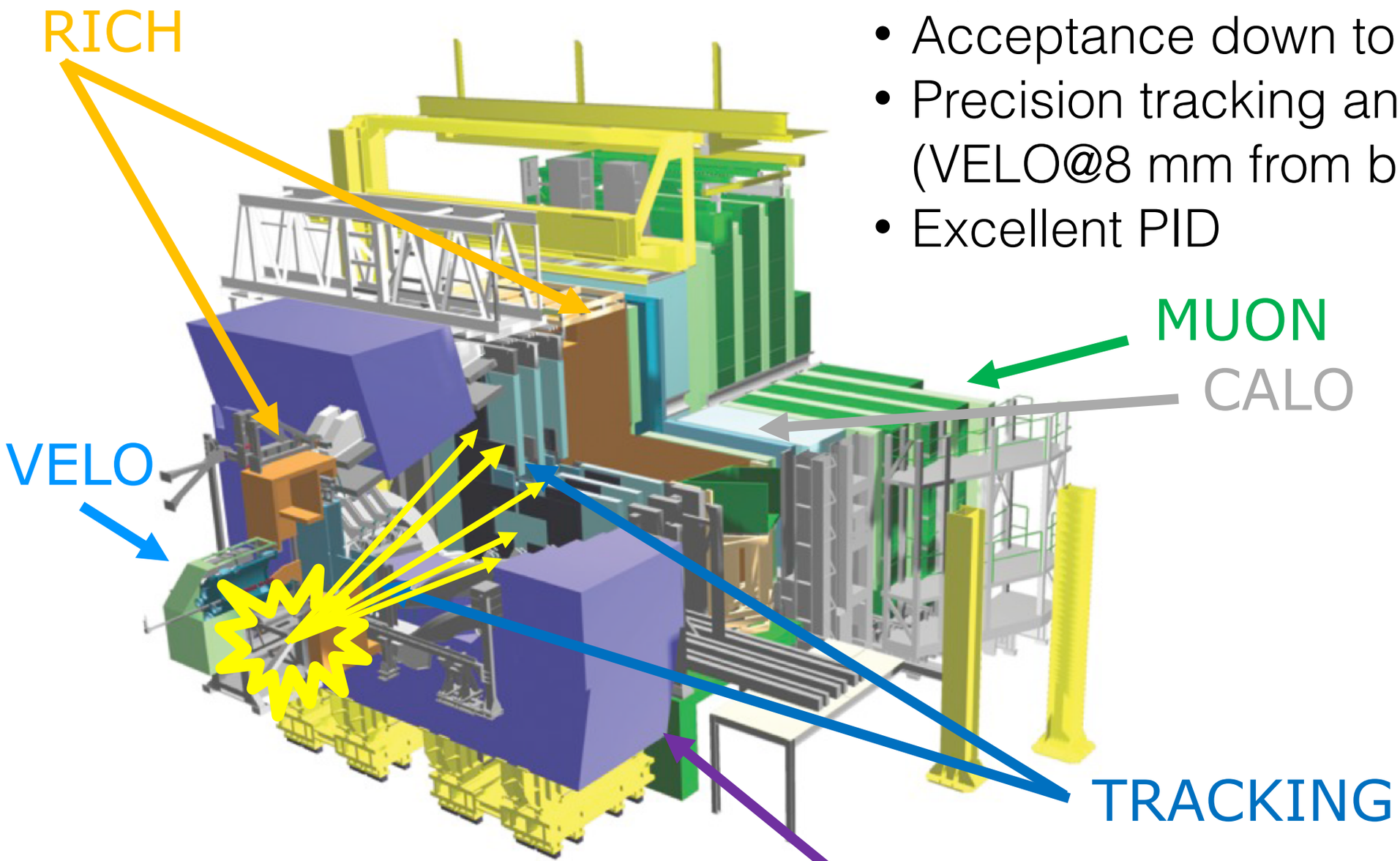
Rare decays

Ions and fixed target

Exotica searches

LHCb detector: the essentials

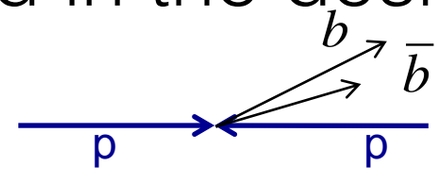
- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VELO@8 mm from beam)
- Excellent PID



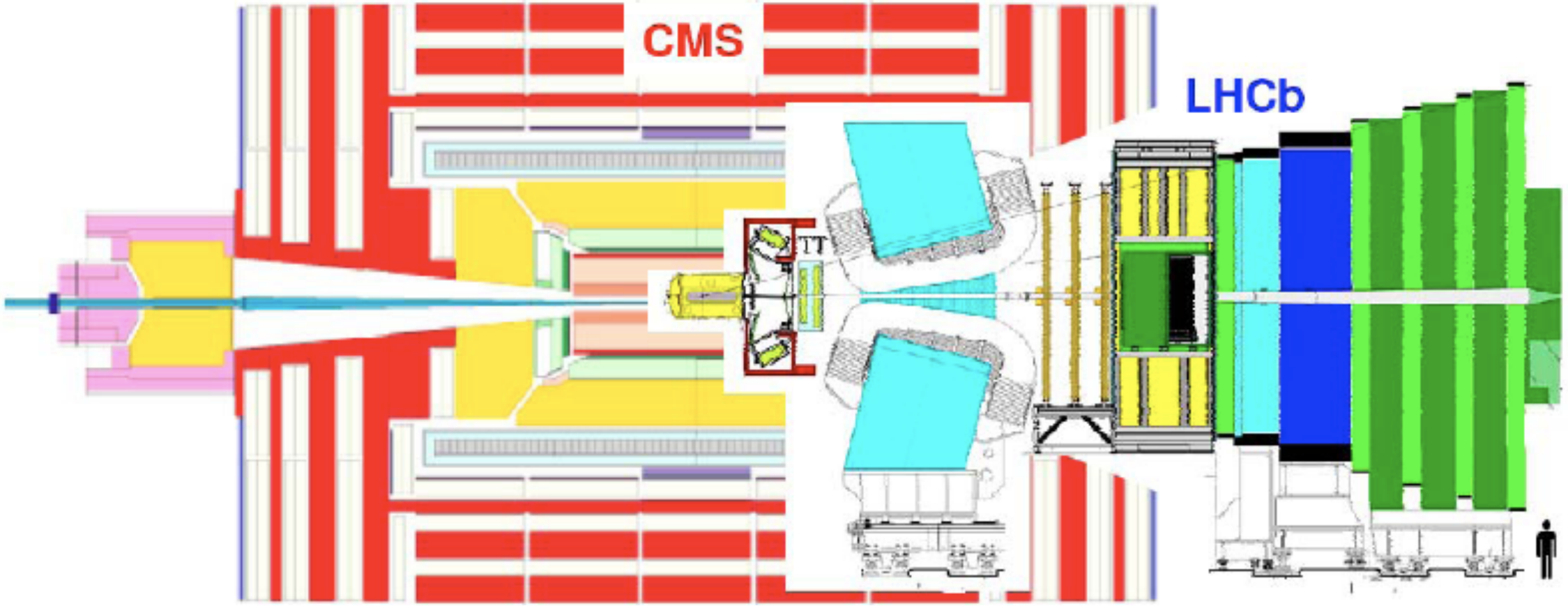
JINST 3 (2008) S08005

A forward spectrometer

- Why does LHCb look so different?
- The B mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector



~1/4 $b\bar{b}$ events in acceptance

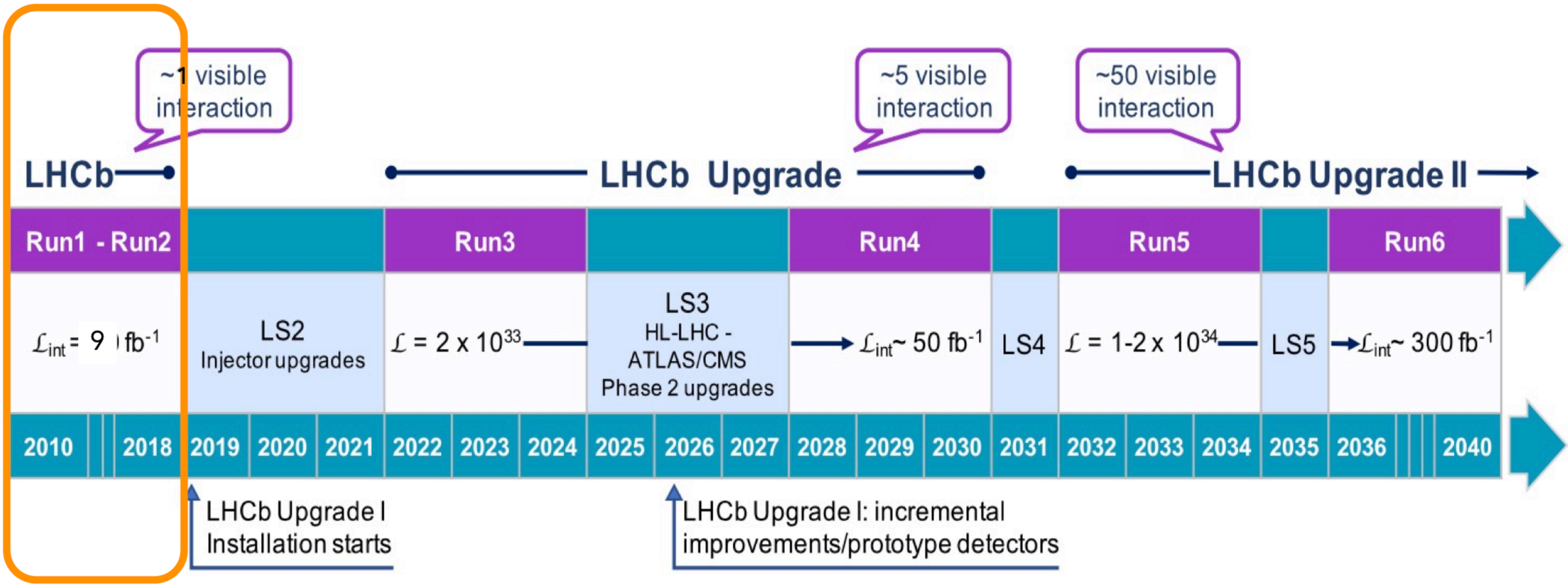


The trigger

- For LHCb, more data is more important than higher energy
  - Direct searches @ATLAS/CMS: more energy → new particles could appear above threshold
  - Indirect searches: precision measurements → gain from increased production rates

- However, digesting more data is a true challenge!
  - At 13 TeV and $\mathscr{L}$=2x10^{33}/cm^2/sec, ~100 kHz $b\bar{b}$ and ~1MHz $c\bar{c}$ pairs in detector acceptance
  - Most interesting b-hadron decays occur at 10^{-5} probability or lower
  - Big challenge → requires powerful trigger

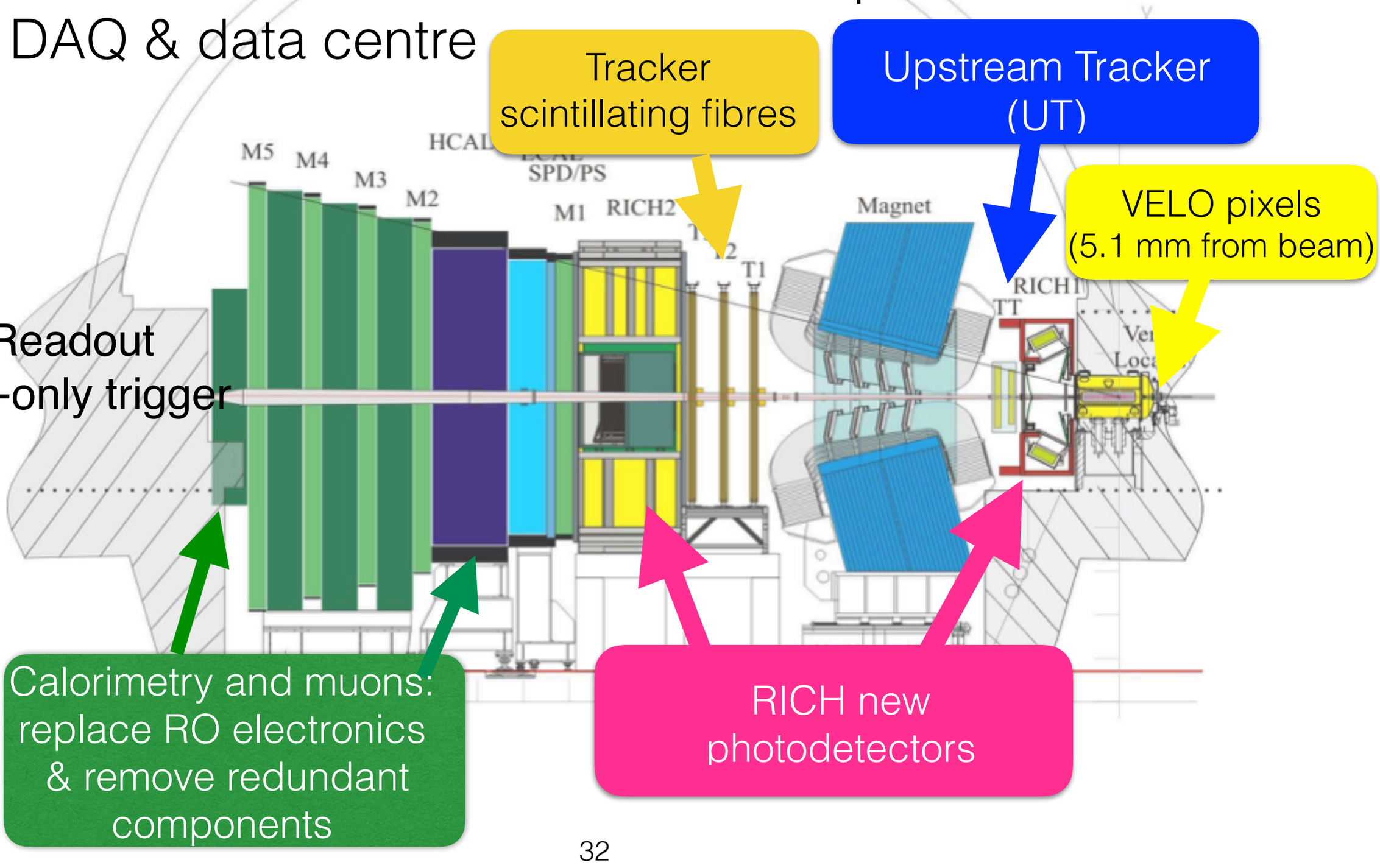
The LHCb schedule



The LHCb upgraded detector

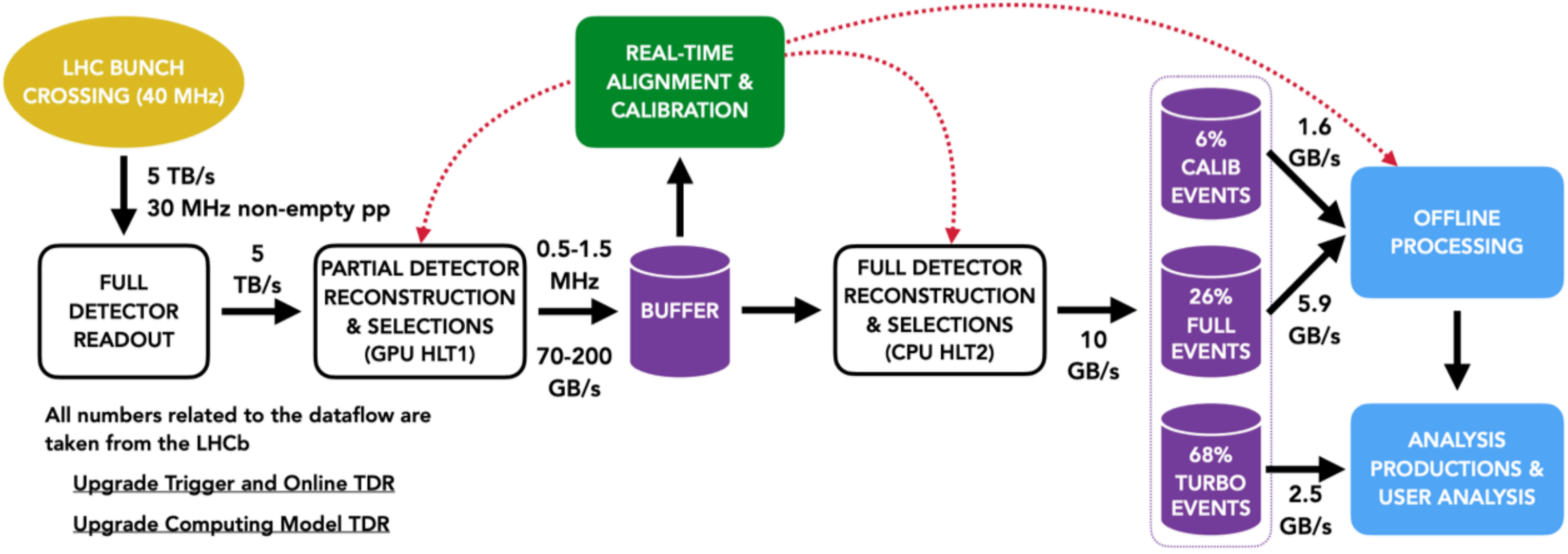
- Major upgrade of all sub detectors to handle increased rates
- Less than 10% of all channels will be kept!
- NEW DAQ & data centre

40 MHz Readout
Software-only trigger

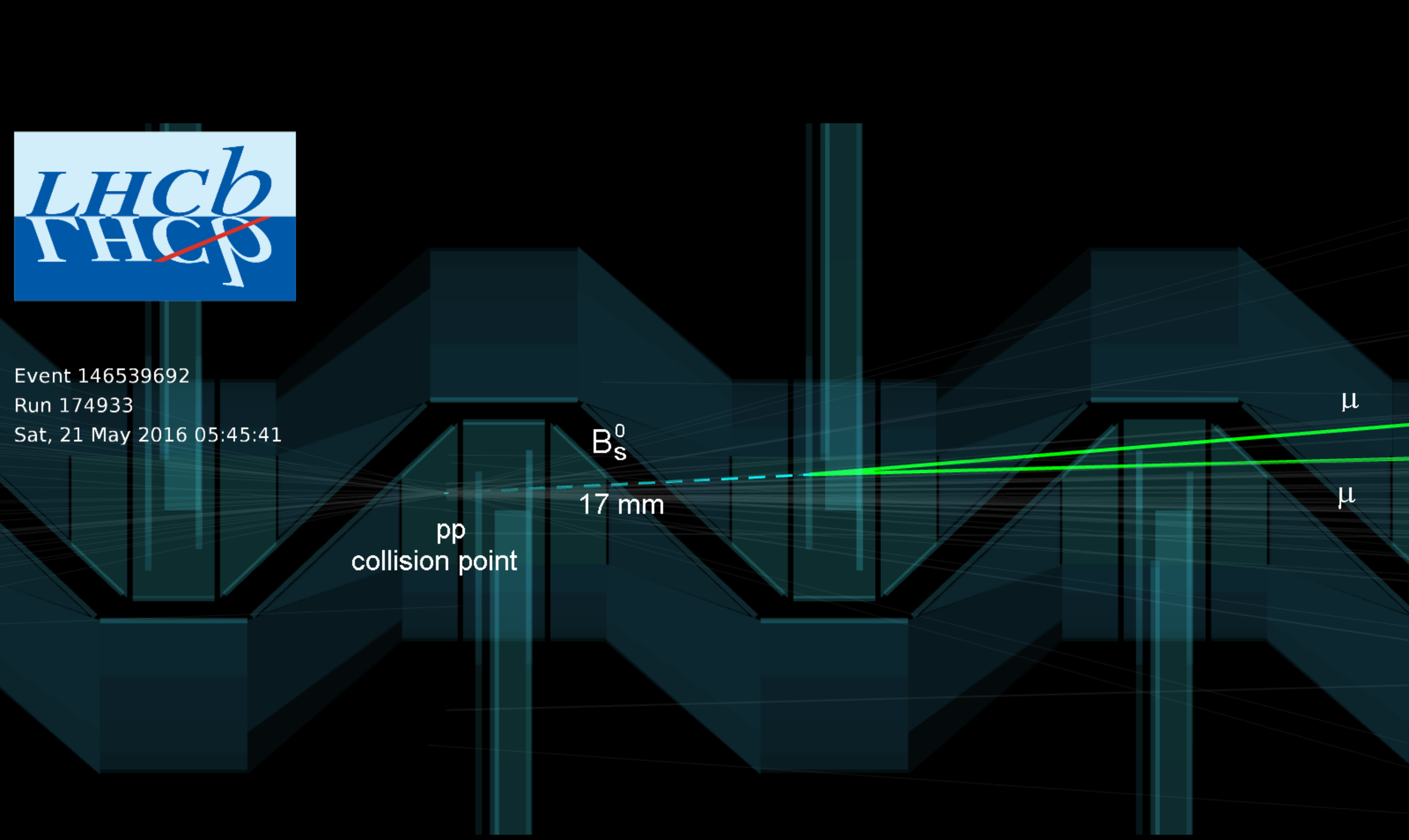


Run 2 to Upgrade

- “L0” hardware trigger removed, a full software trigger will process 30 MHz of inelastic collisions → factor ~10 increase in hadronic yield in Run 3

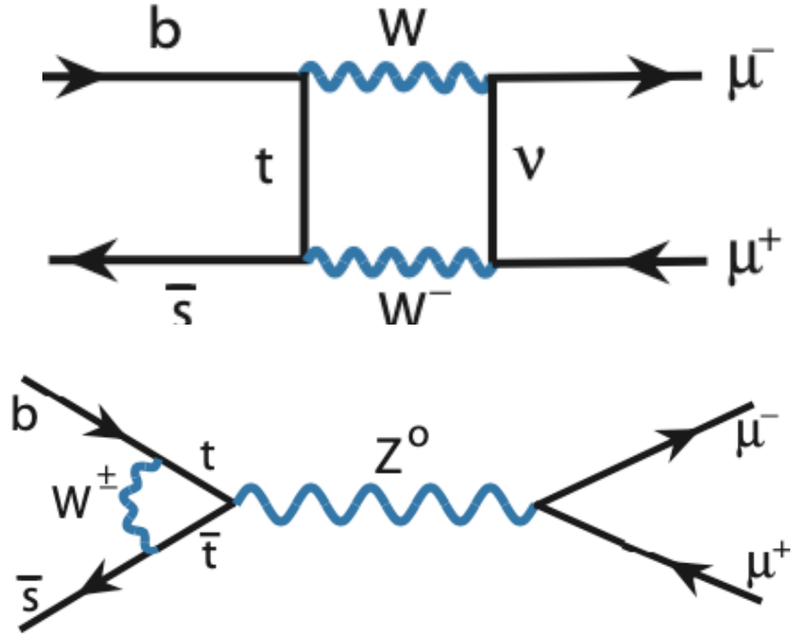


- Two-stage software trigger:
  - HLT1 (GPUs): partial event reconstruction and coarse selection, reduces rate to ~ 1 MHz
  - HLT2: full event reconstruction (with offline-quality reconstruction, alignment&calibration)
  - Buffering between HLT1 & HLT2 → real-time alignment & calibration



leptonic B decays

One of the milestones of flavour programme $B_{(s)} \to \mu^+\mu^-$

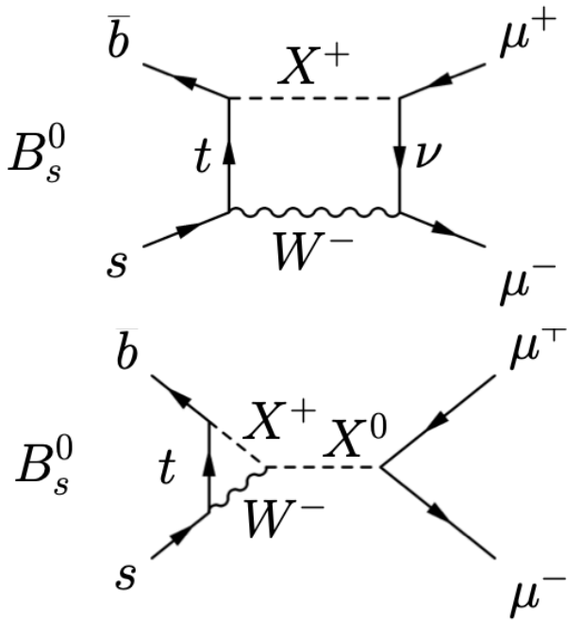


- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for B_s) and helicity ~ $\left(\frac{m_\mu}{M_B}\right)^2$
  - Theoretically "clean" → precisely predicted:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$
$$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = (2.81 \pm 0.16)\% \ .$$

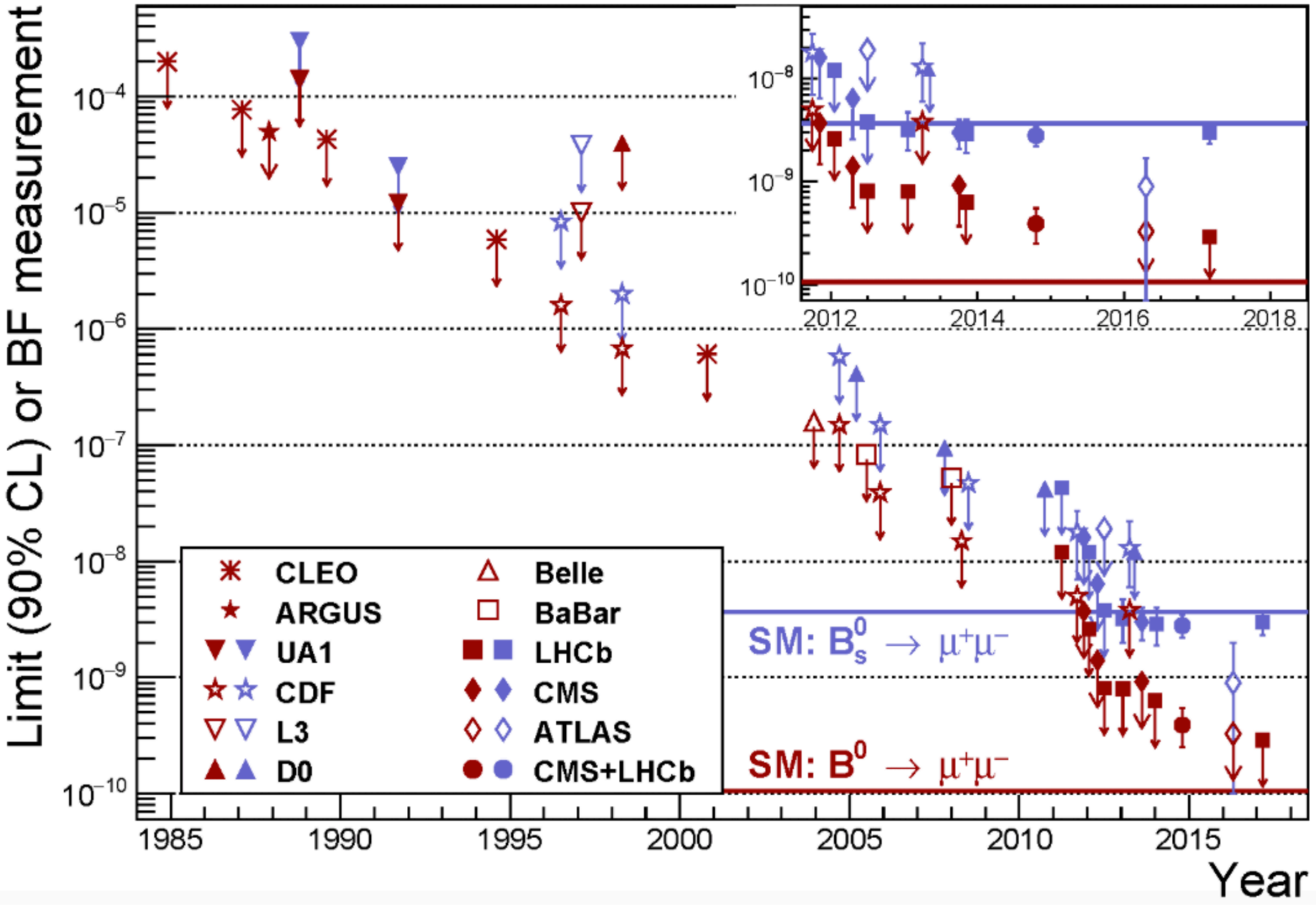
(~5%)

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

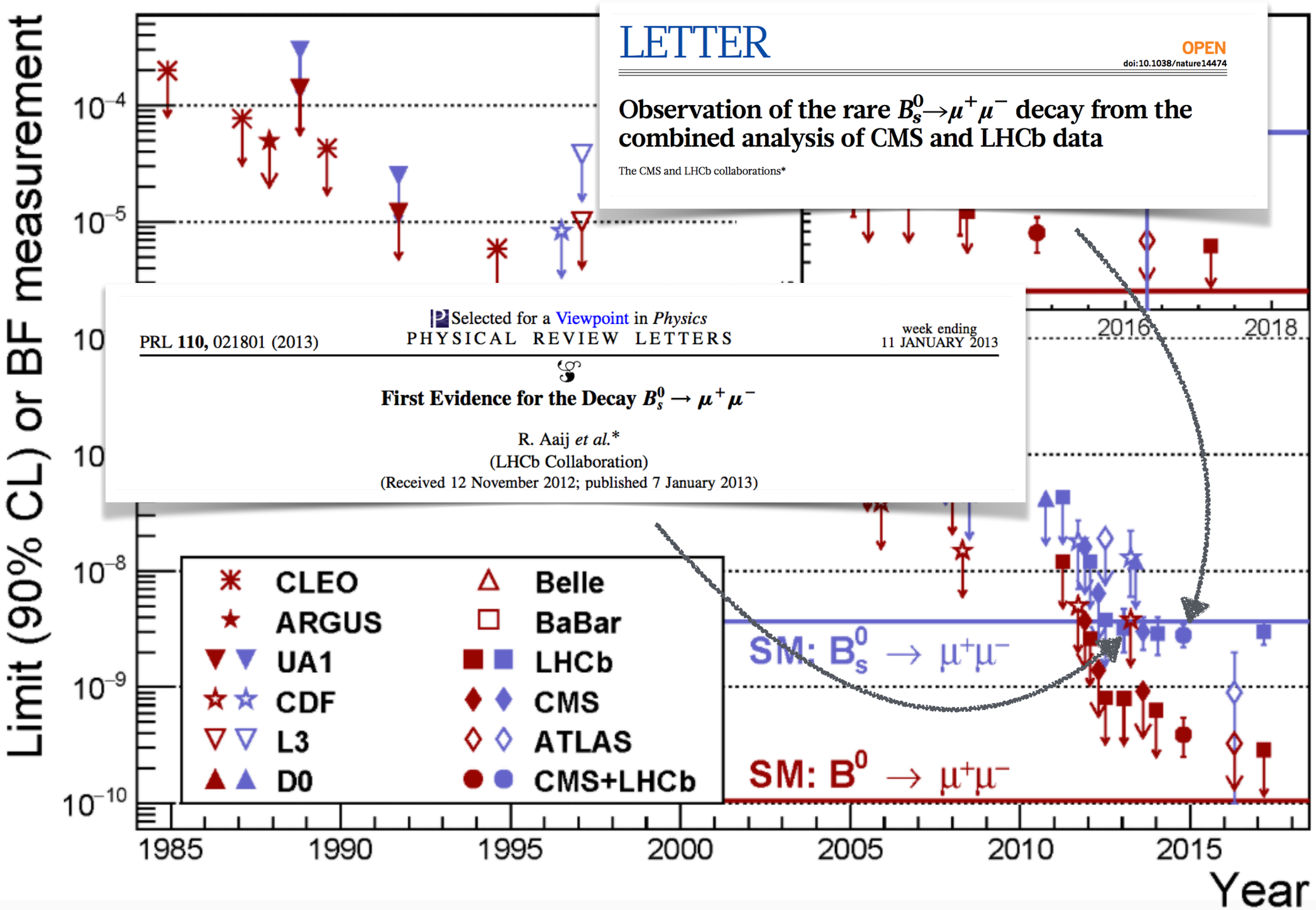


- Sensitive to New Physics
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

30 years of effort!



30 years of effort!



LETTER

OPEN

doi:10.1038/nature14474

Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*

Selected for a Viewpoint in *Physics*

PRL **110,** 021801 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

First Evidence for the Decay $B_s^0 \to \mu^+\mu^-$

R. Aaij *et al.**

(LHCb Collaboration)

(Received 12 November 2012; published 7 January 2013)

Latest LHC combination

- **LHCb**, PRL 118 (2017) 191801

$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$

$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @95 % CL

- **CMS**, JHEP 04 (2020) 188

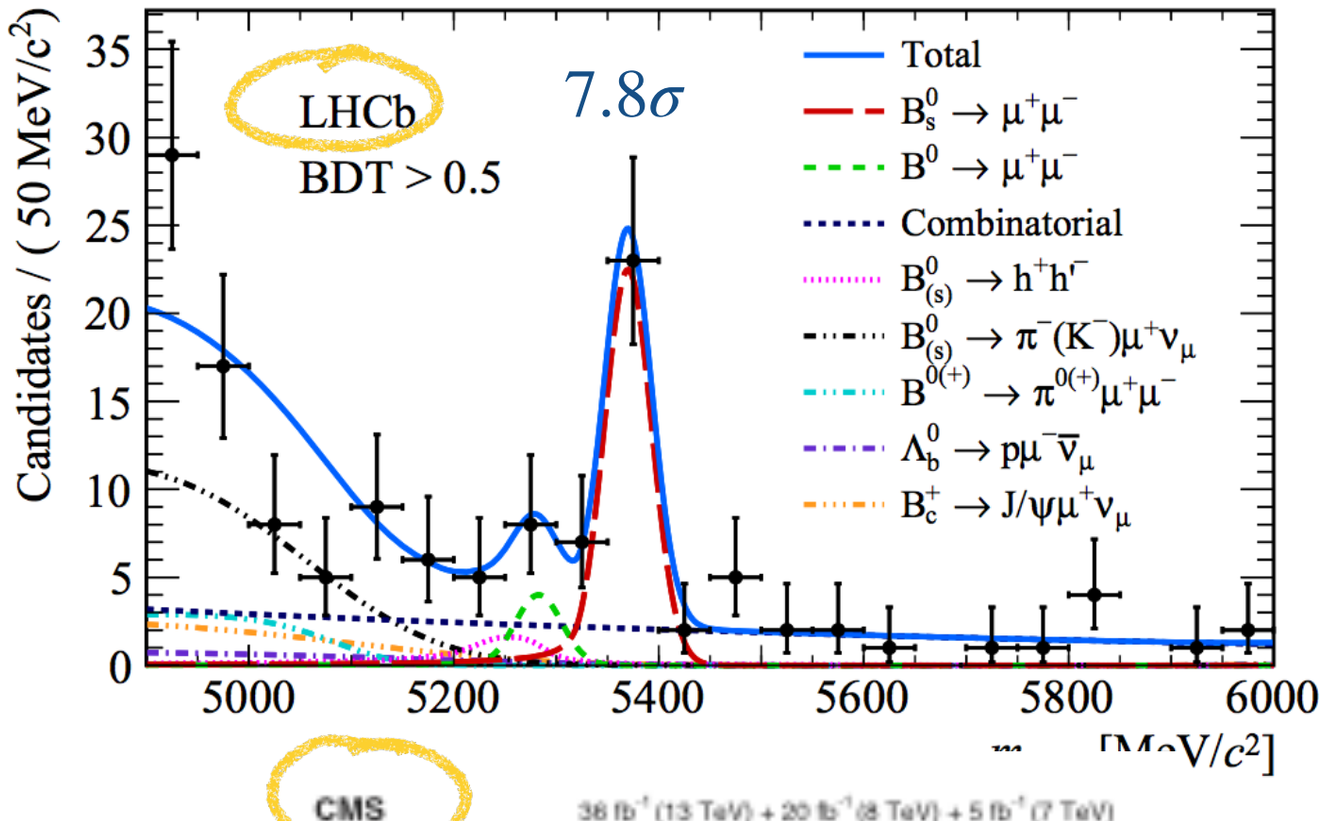
$B(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7\,(\text{exp}) \pm 0.2\,(\text{frag})) \times 10^{-9}$

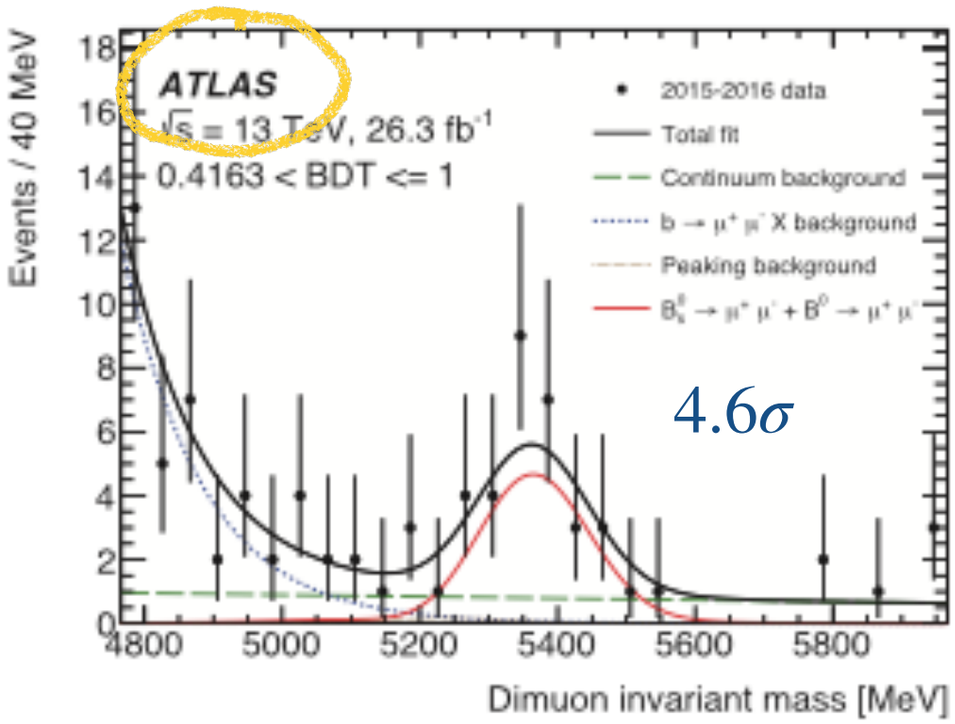
$B(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ @95 % CL

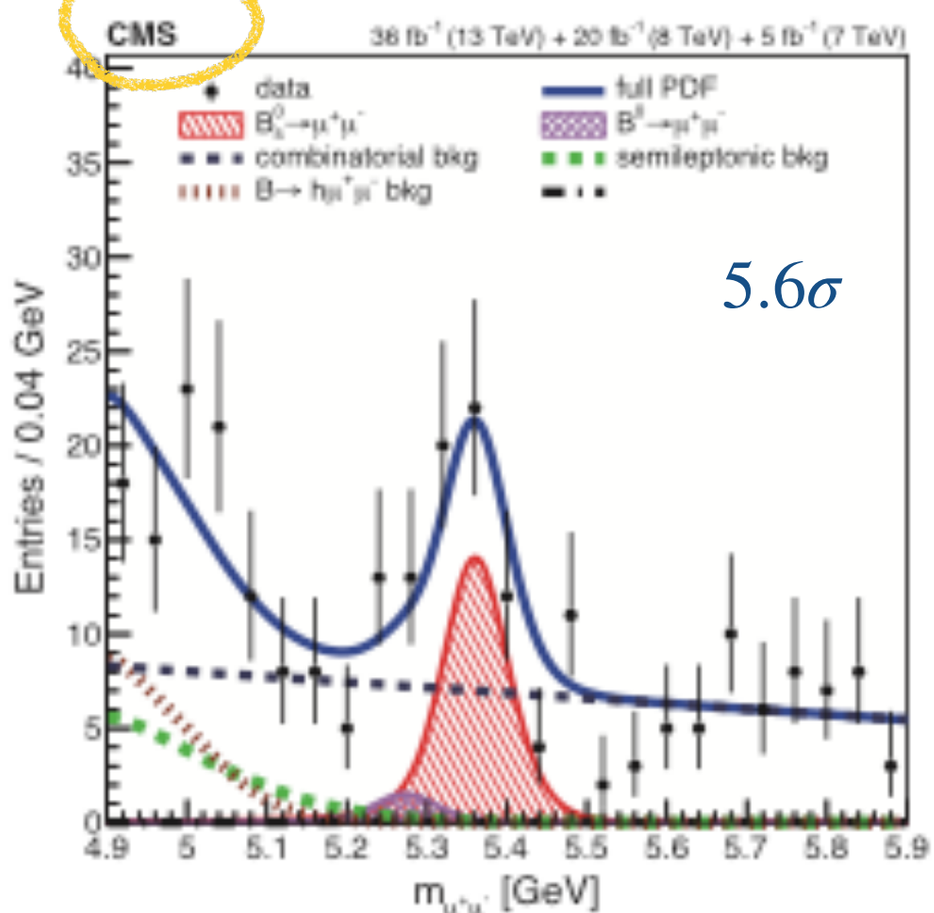
- **ATLAS**, JHEP 04 (2019) 098

$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$

$B(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @95 % CL







Latest LHC combination

LHCb-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049

- **LHCb**, PRL 118 (2017) 191801

$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ 7.8σ

$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @95 % CL

- **CMS**, JHEP 04 (2020) 188

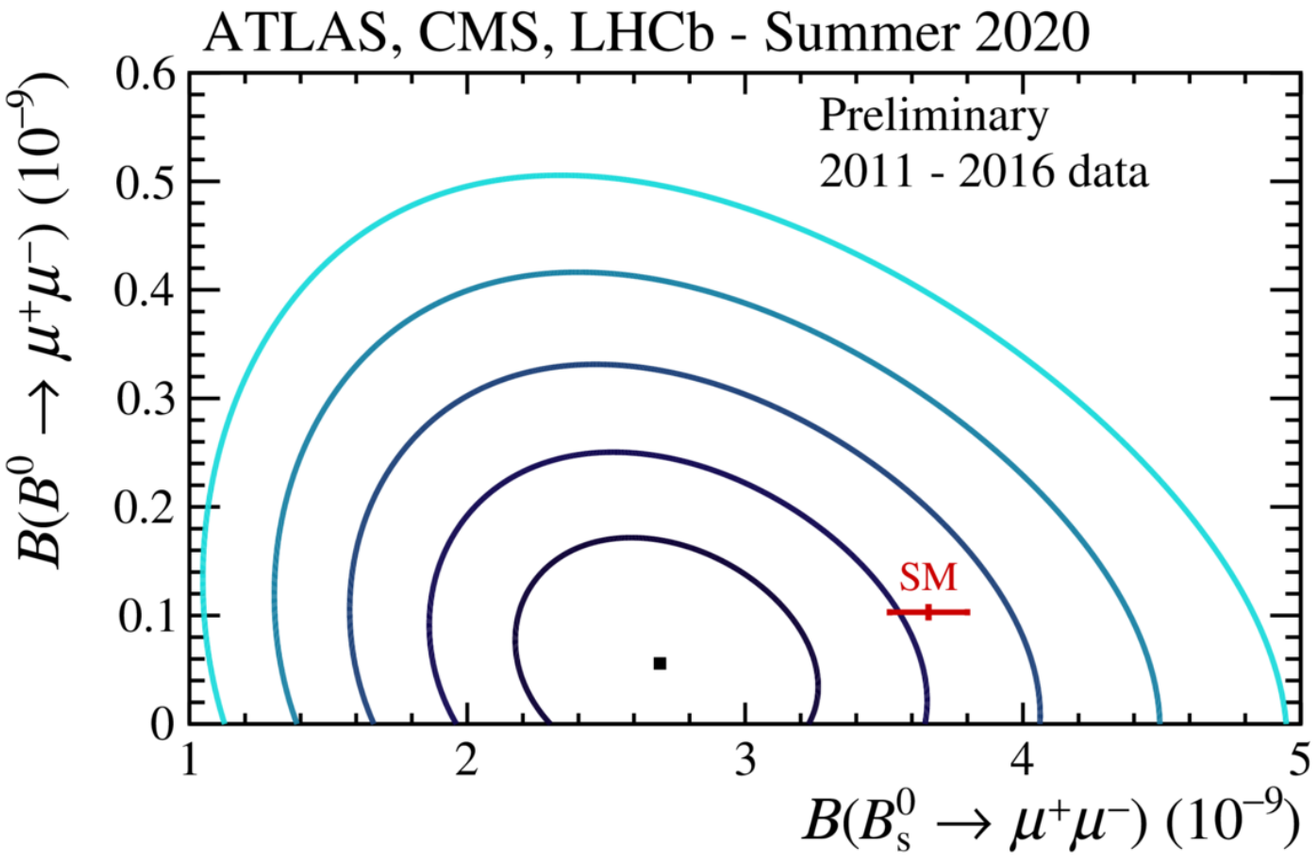
$B(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7\,(\text{exp}) \pm 0.2\,(\text{frag})) \times 10^{-9}$ 5.6σ

$B(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ @95 % CL

- **ATLAS**, JHEP 04 (2019) 098

$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$ 4.6σ

$B(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @95 % CL



Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$ has started

$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$

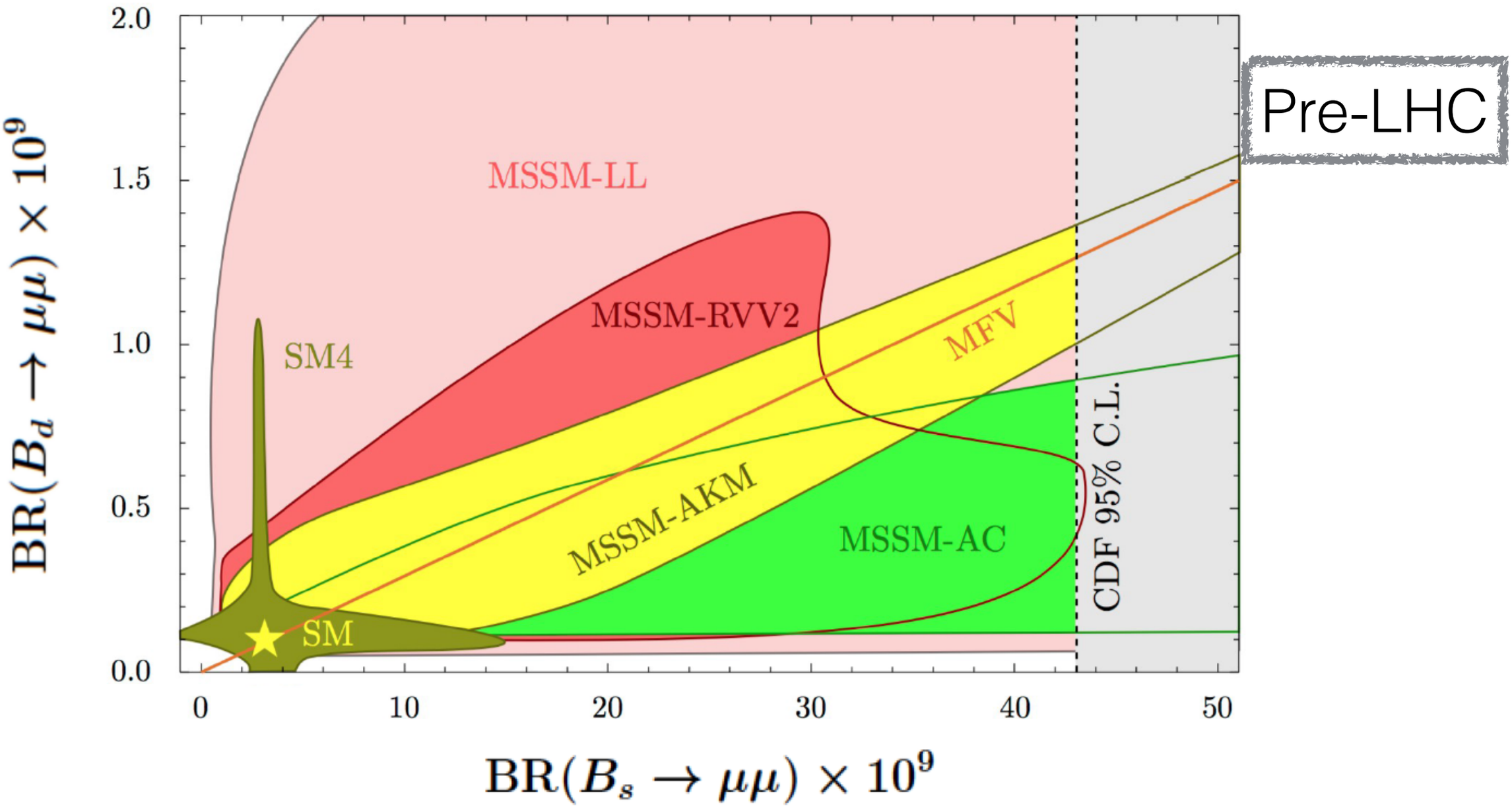
$\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}$ @95 % CL

2.1 σ below SM prediction (2D compatibility)

The SM stands its ground

- Sizeable effects expected in many MSSM models

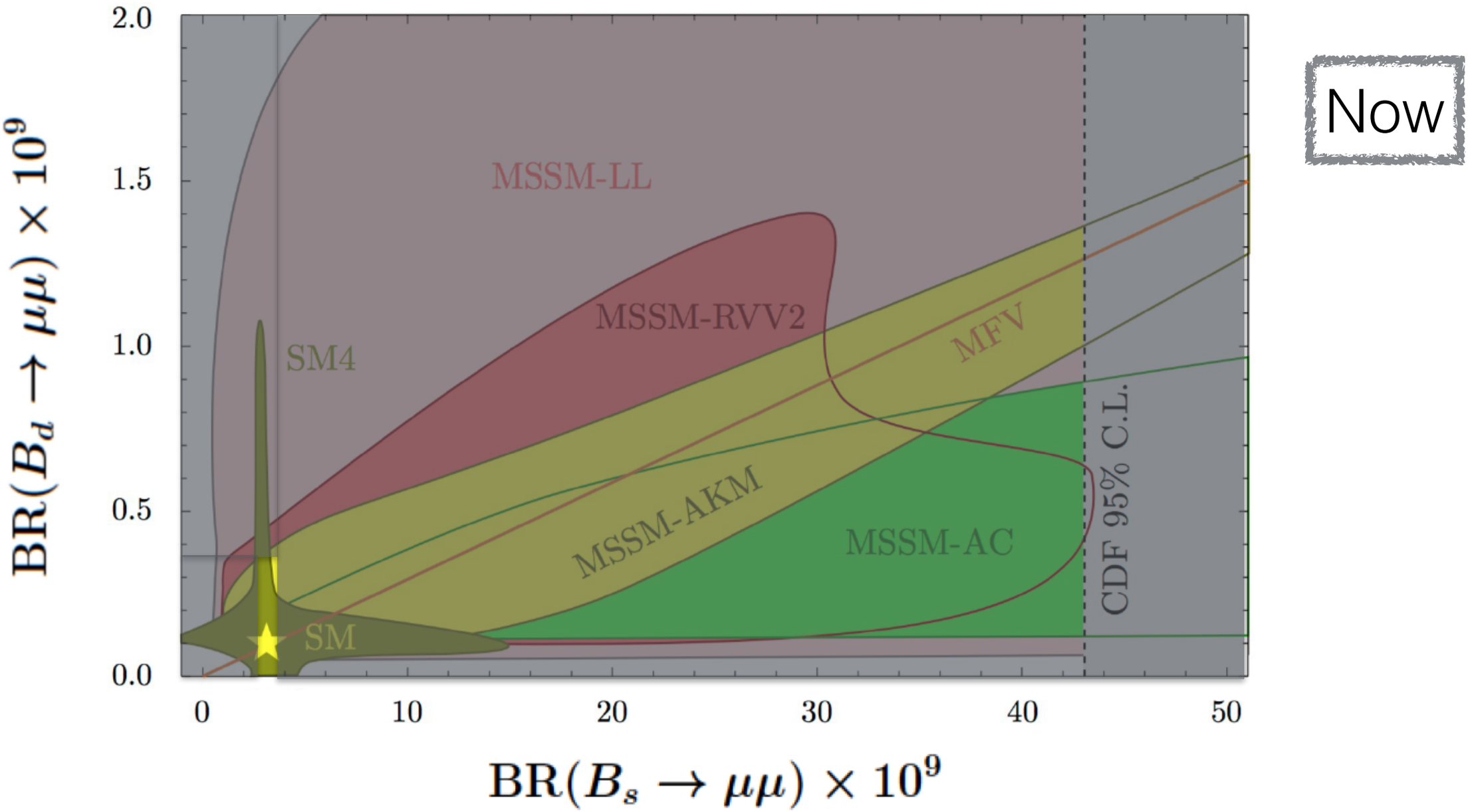
Straub, arXiv:1107.0266



The SM stands its ground

- Sizeable effects expected in many MSSM models (cancellation of helicity suppression)

Straub, arXiv:1107.0266



Now

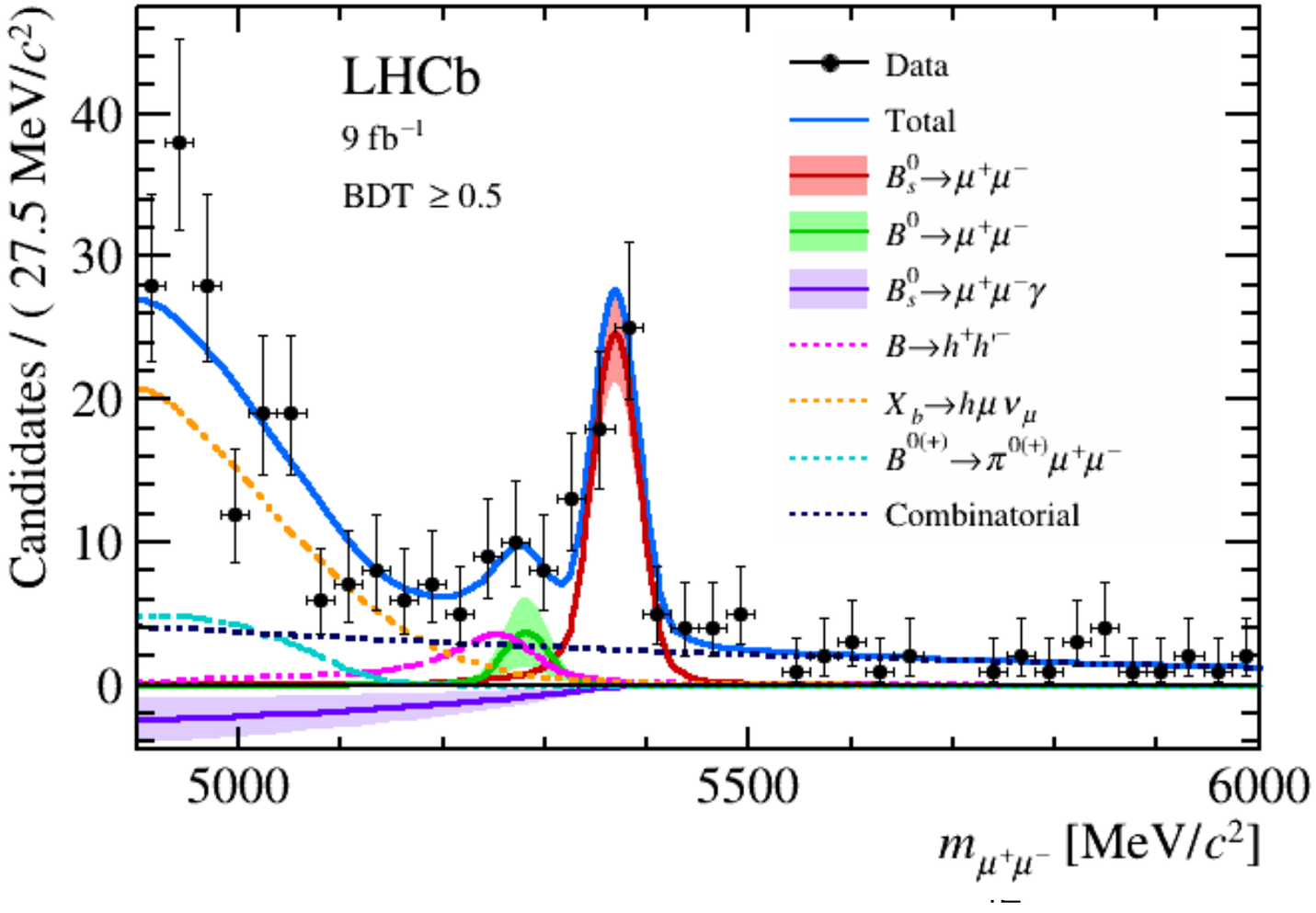
LHCb update with full dataset

- LHCb analysis based on full Run 1 and Run 2 data (9 fb^{-1})

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\,@\,95\,\%\,\mathrm{CL}$$

- Consistent with SM expectation at current level of precision



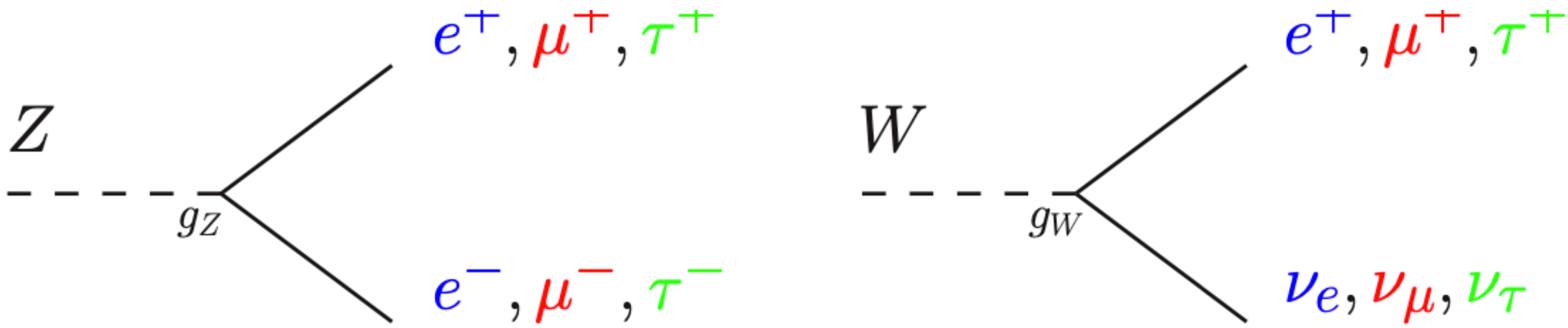
- $B_s \to \mu^+\mu^-$ found with significance >10 σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)
- Result dominated by statistical uncertainty
- Expect 10% precision with ATLAS/CMS Run 2

PRL 128 (2022) 041801

Tests of Lepton Flavour Universality

Lepton Flavour Universality

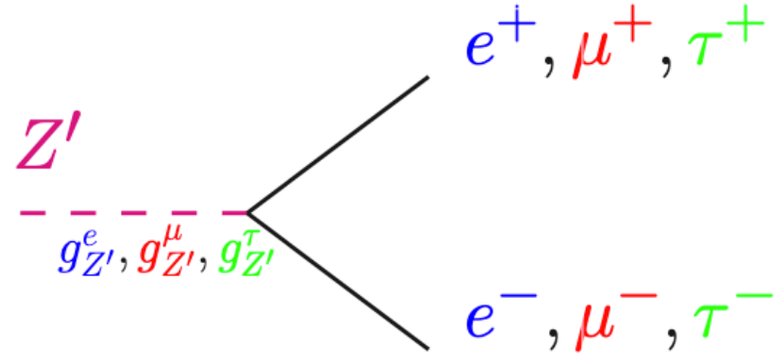
- The property that the three charged leptons (**e**, μ , τ) couple in a universal way to the SM gauge bosons



- In the SM the only flavour non-universal terms are the three lepton masses: $m_\tau, m_\mu, m_e \leftrightarrow$ 3477 / 207/ 1 (boring!)

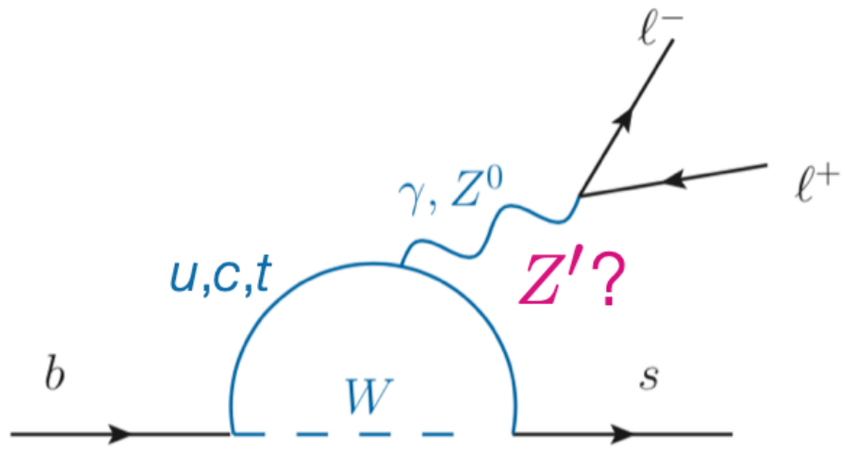
Lepton Flavour Universality II

- The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behaviour at high energies, as signalled by their different mass



- If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. **e**/μ or μ/τ)

- Test LFU in $b \to s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams



The family of R ratios

- Comparing the rates of $B \to He^+e^-$ and $B \to H\mu^+\mu^-$ allows precise testing of lepton flavour universality

$$R_{\rm H}\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \, \frac{{\rm d}\Gamma(B\to H\mu^+\mu^-)}{{\rm d}q^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \, \frac{{\rm d}\Gamma(B\to He^+e^-)}{{\rm d}q^2}} \quad , \quad q^2 = m^2(\ell\ell)$$

B: $B^+, B^0, B^0_{\rm s}, \Lambda^0_{\rm b}$

- These ratios are clean probes of NP : H: $K^+, K^{*0}, pK, \phi \ldots .$

  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons

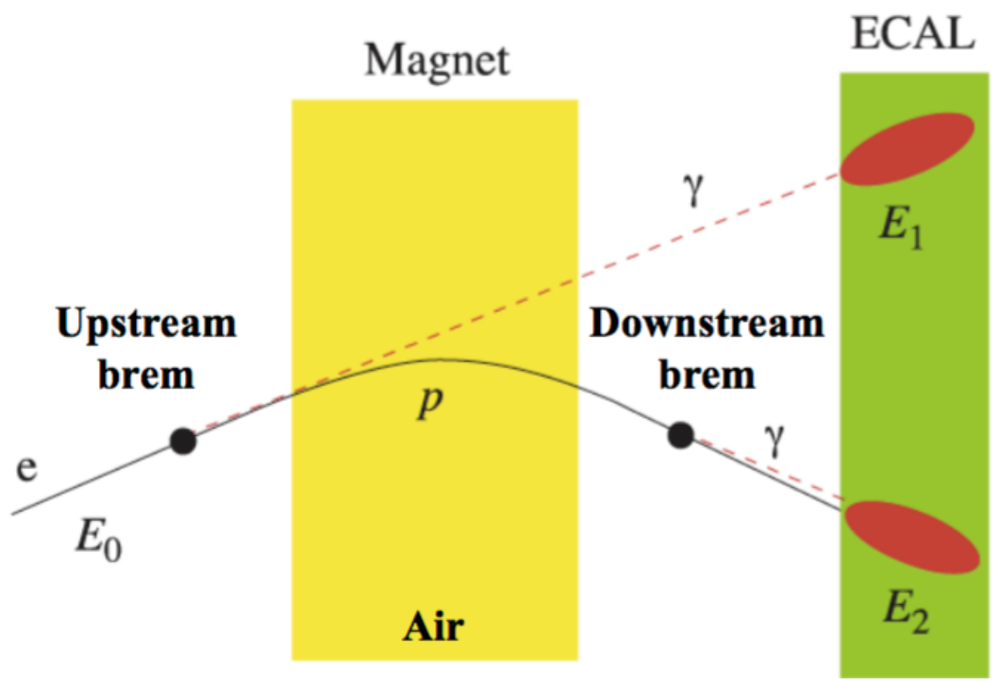
  - Small theoretical uncertainties because hadronic uncertainties cancel : $R_{\rm H} = 1$ in SM, neglecting lepton masses, with QED corrections at ~% level (when physical observables defined with LHCb choice of cuts on q^2 and on the reconstructed B mass, see Bordone, Isidori, Pattori)

Lepton identification is anything but universal!

- High occupancy in calorimeters→ trigger thresholds are higher for electrons (~2.5 to 3.0 GeV) than for muons (~1.5 to 1.8 GeV)
- Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution. Two situations :

  - Downstream brem (wrt dipole bending magnet) Photon energy in the same calorimeter cell as the electron and momentum correctly measured
  - Upstream of the magnet Photon energy in different calorimeter cells than electron and momentum evaluated after bremsstrahlung

JHEP 08 (2017) 055



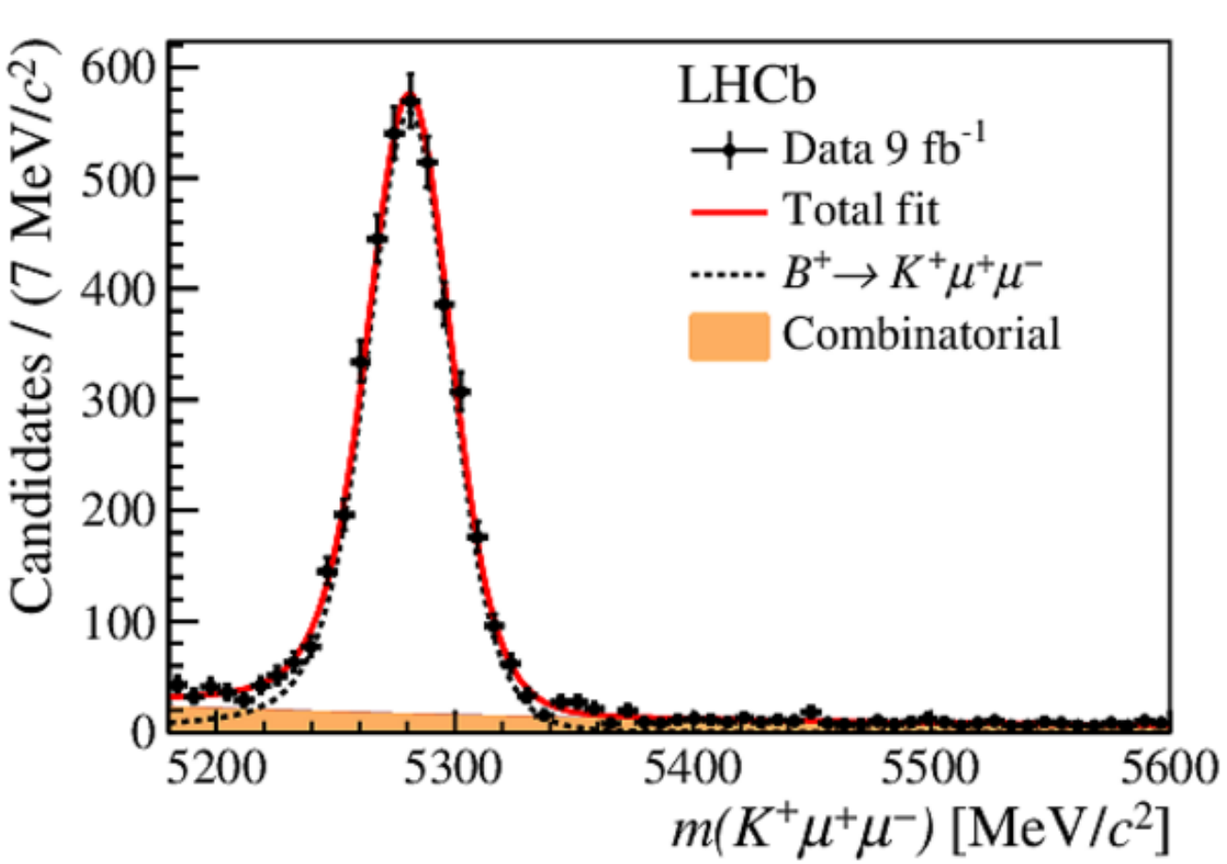
→ Look for photon clusters compatible with electron direction before magnet and "add" the cluster energy back to the electron momentum (if $E_T > 75\text{MeV}$)

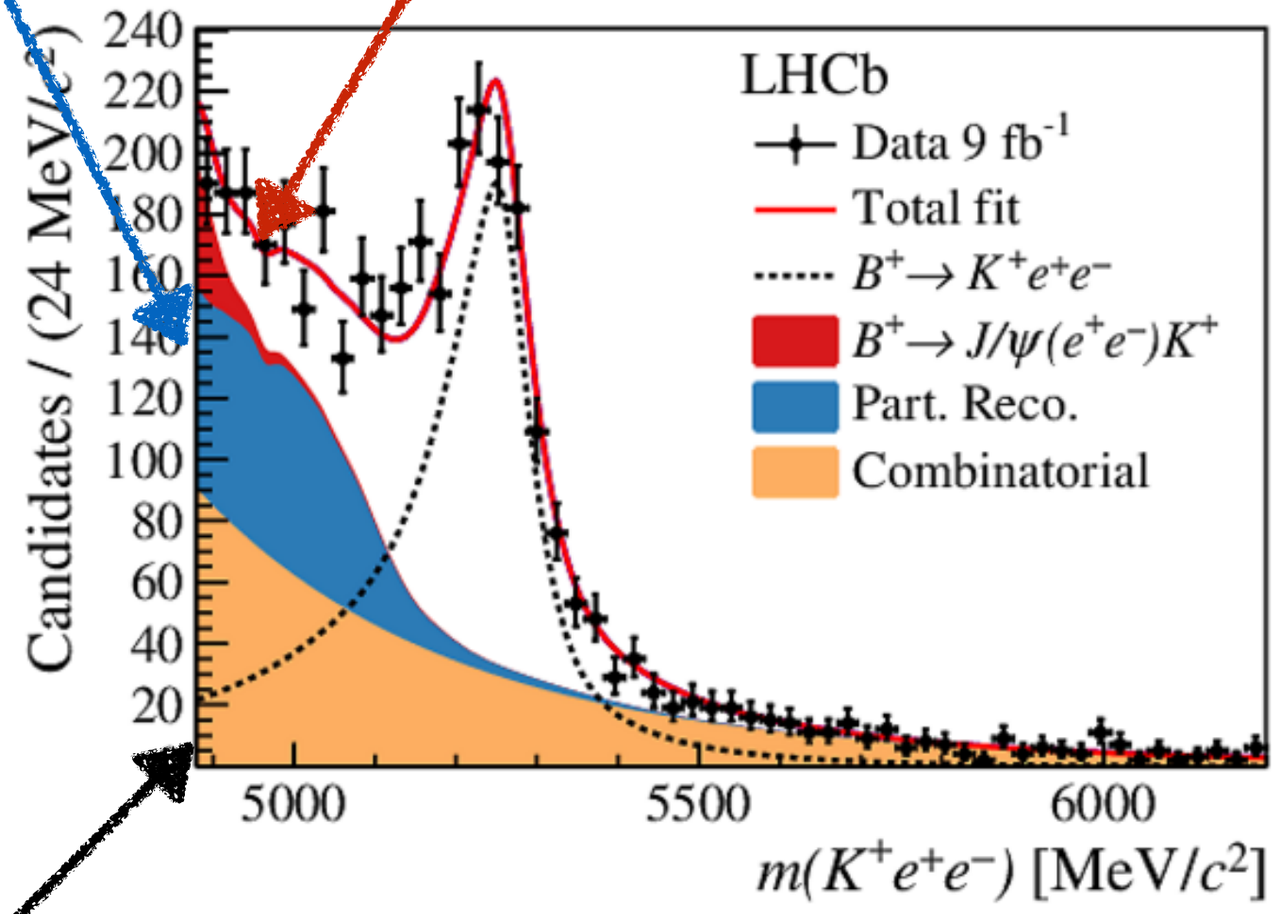
muons vs electrons

- Even after Bremsstrahlung recovery di-electron pair and B meson still have degraded mass resolution

Partially reconstructed background, mainly from $B^{0,+} \to K^{*0,+} e^+ e^-$ where a pion is lost

$B^+ \to K^+ J/\psi(e^+e^-)$ events where a photon is not reconstructed





Longer radiative tail due to bremsstrahlung

arXiv:2103.11769
Nature Physics

Measure as a double ratio

- To mitigate muon and electron differences, measurement performed as a double ratio with "resonant" control modes $B^0 \to J/\psi H$, which are not expected to be affected by NP:

$$R_{\mathrm{H}} = \frac{\mathcal{B}(B^0 \to H\mu^+\mu^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to He^+e^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to e^+e^-))}$$

$$R_H = \frac{N(B \to H\mu^+\mu^-)}{\varepsilon(B \to H\mu^+\mu^-)} \times \frac{\varepsilon(B \to He^+e^-)}{N(B \to He^+e^-)} \times \frac{N(B \to HJ/\psi(e^+e^-))}{\epsilon(B \to HJ/\psi(e^+e^-))} \times \frac{\varepsilon(B \to HJ/\psi(\mu^+\mu^-))}{N(B \to HJ/\psi(\mu^+\mu^-))}$$

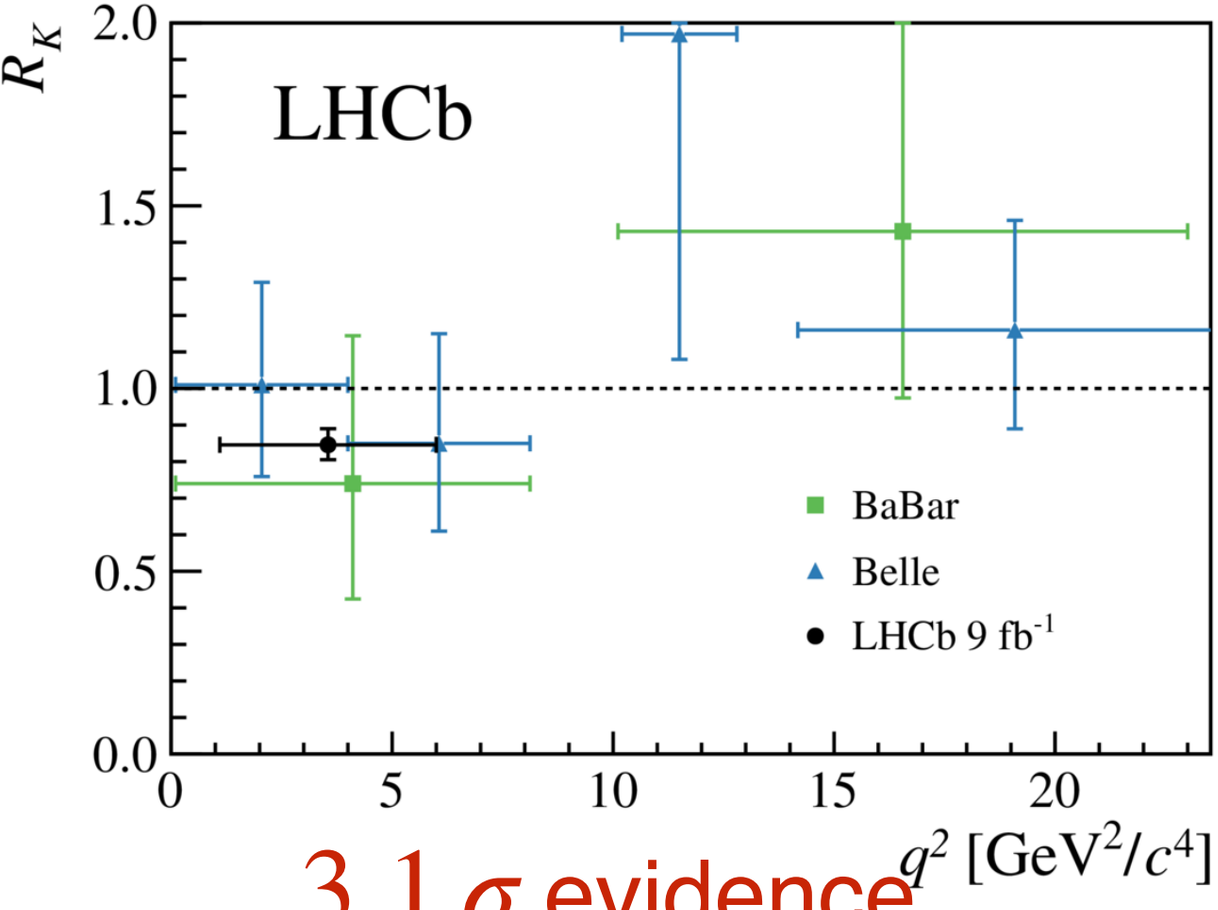
→ Relevant experimental quantities: yields & (trigger, reconstruction and selection) and efficiencies for the four decay modes

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio. Note, however, that the cancellation does not apply to background.
- $r_{J/\psi} = \dfrac{B(B \to HJ/\psi(\mu^+\mu^-))}{B(B \to HJ/\psi(e^+e^-))}$ known to be compatible with unity within 0.4%
- Analyses performed blind

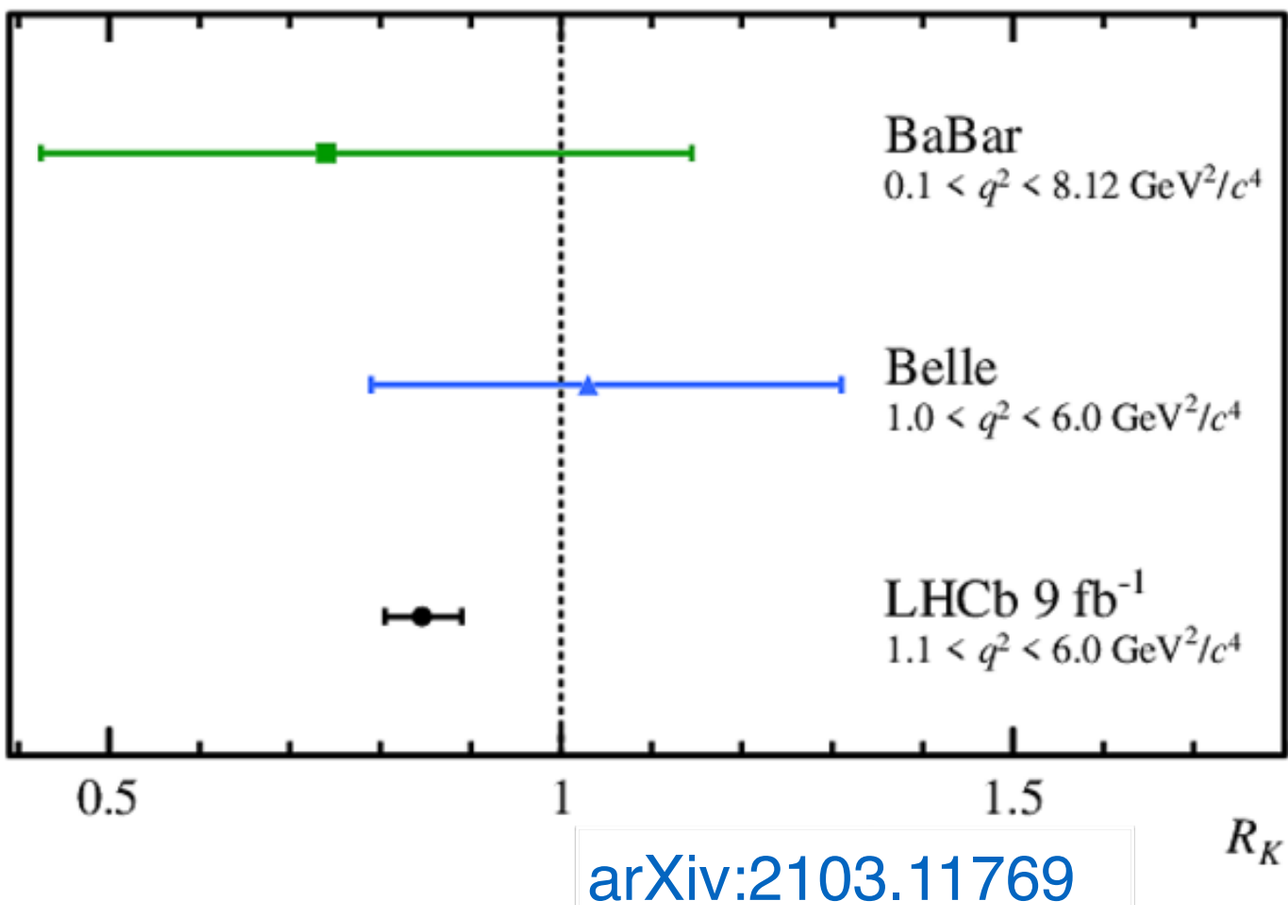
R_K $(B^+ \to K^+\ell^+\ell^-)$

- $R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.846^{+0.042}_{-0.039}\,(\mathrm{stat})\,^{+0.013}_{-0.012}\,(\mathrm{syst})$

Dominant systematics (~1%) is due to modelling of signal and background components used in the fit



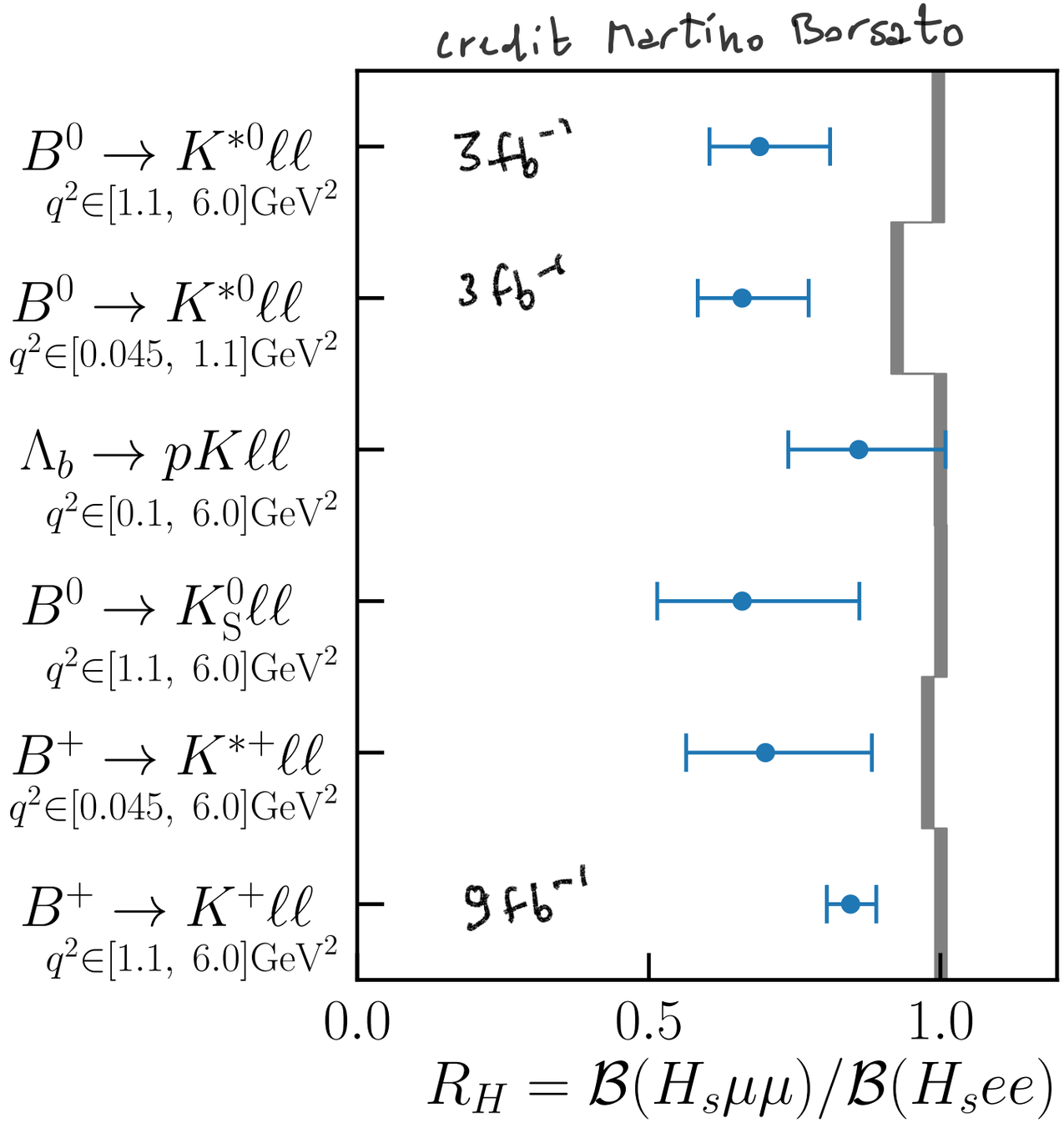
3.1 σ evidence



arXiv:2103.11769
Nature Physics

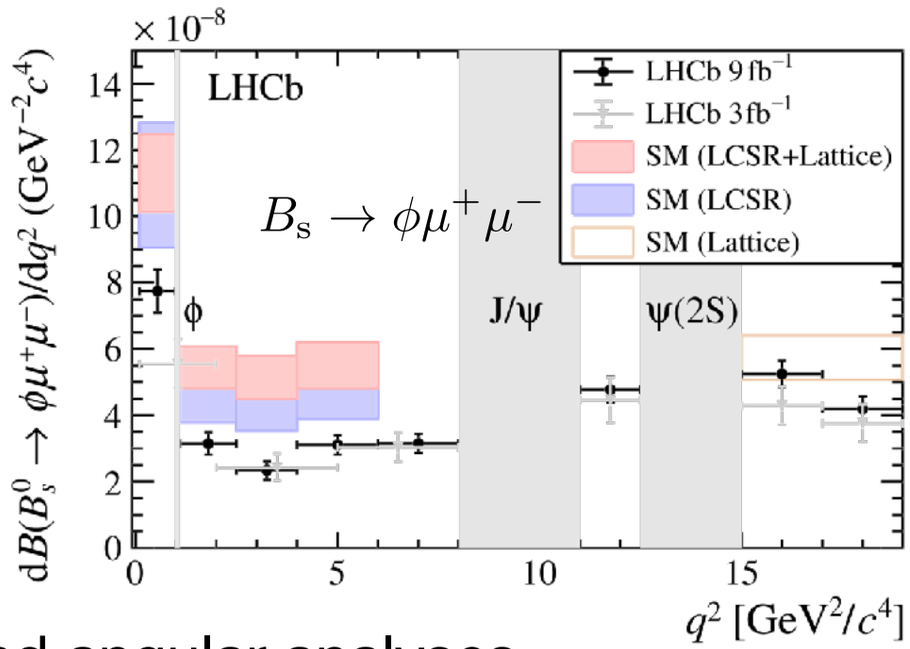
A very intriguing pattern

Summary of R_H

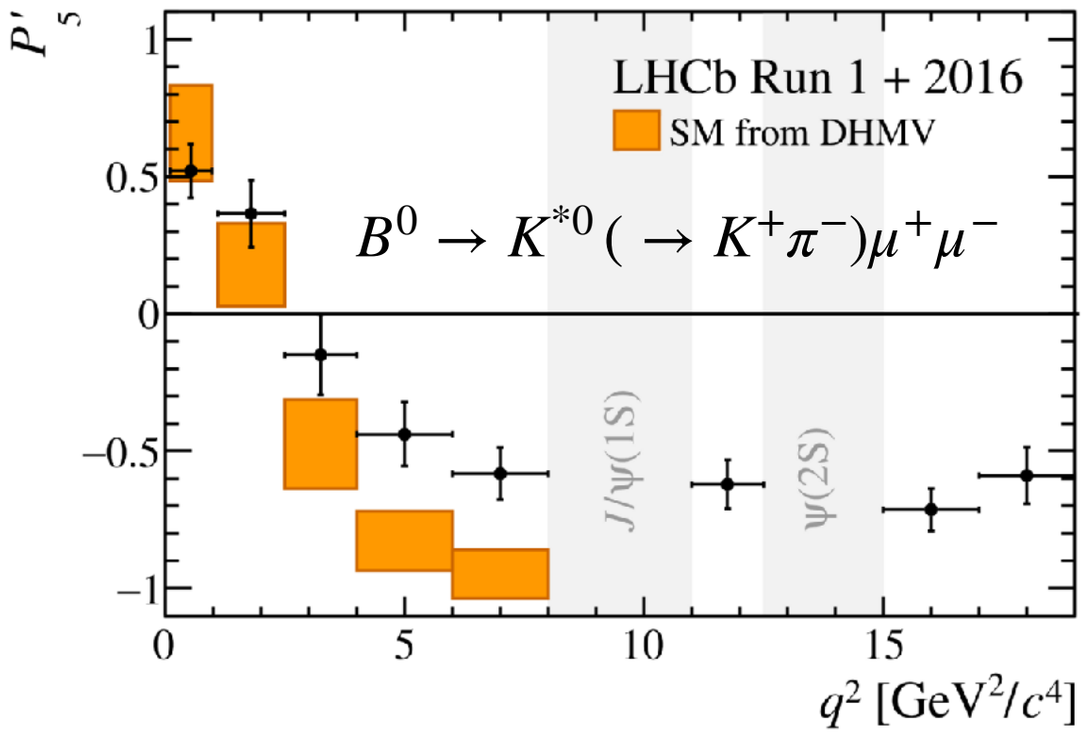


- Coherent set of $b \to s\ell\ell$ tensions in BFs

$B^+ \to K^+\mu^+\mu^-, B^0 \to K^{(*)0}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-$.

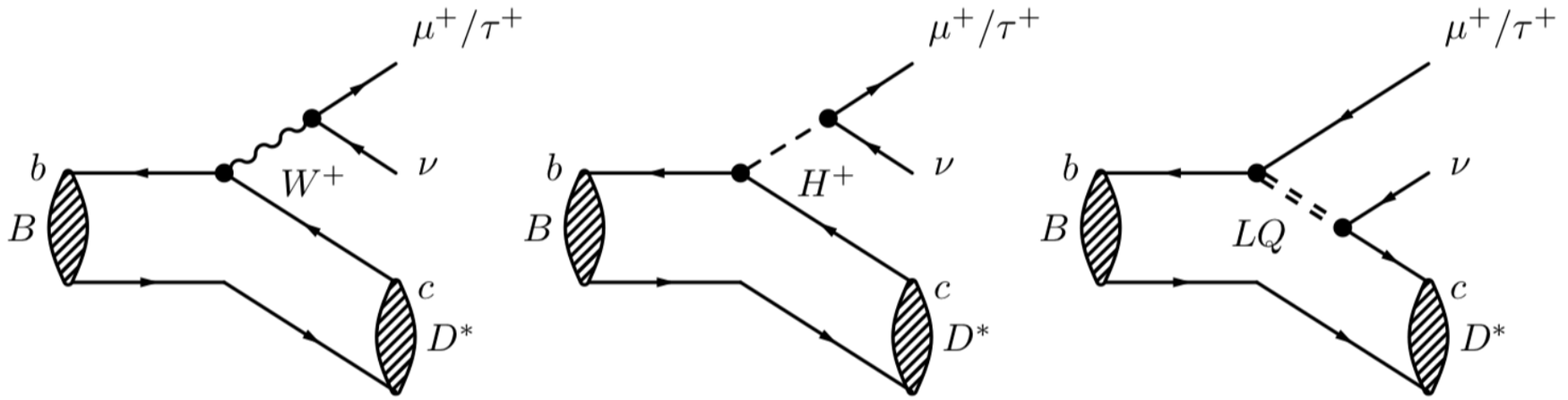


- and angular analyses



Another puzzling result in tree-level b → c transitions

LFU studies in $B \to D^{(*)}\tau\nu$ decays



- Different class of decays (tree-level charged current with V_{cb} suppression)

- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\,\%$, problem is the background

- Lepton-universality ratio R(D*) : $R(D^*) = \dfrac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$

  - sensitive to any NP model coupling preferentially to third generation leptons

- Predicted theoretically at ~1%: $R(D)_{\mathrm{SM}} = 0.299 \pm 0.003$, $R(D^*)_{\mathrm{SM}} = 0.258 \pm 0.005$

HFLAV average, 2019

- Studied by Belle, BaBar and LHCb

Experimental challenges

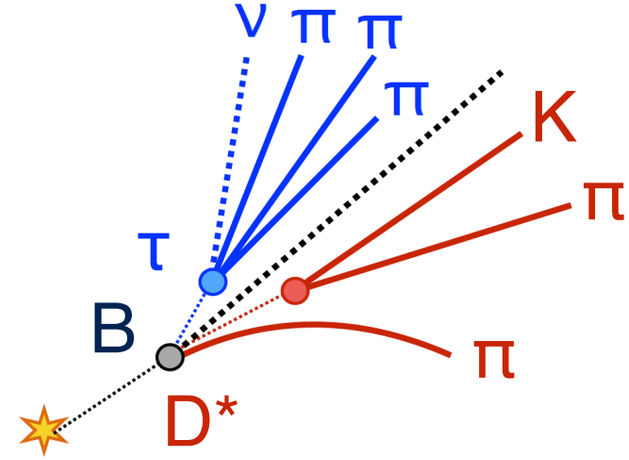
- $B^0 \to D^{*-}\tau^+\nu_\tau$: at least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$)

- At the LHC, as opposed to B factories, the rest of the event does not provide any useful kinematic constraint. However, profit from large boost and excellent vertexing capabily

- LHCb used both $\tau^+ \to \mu^+\nu\bar{\nu}$ and $\tau^+ \to \pi^+\pi^-\pi^+$

$$\begin{cases} \tau^+ & \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau \\ D^{*-} & \to \overline{D}^0(\to K^+\pi^-)\pi^- \end{cases}$$

Three-prong mode used for the first time!



  - A semileptonic decay with no (charged) lepton in final state (one *K*, five π)
    → Zero background from $B^0 \to D^{*-}\mu^+\nu_\mu X$

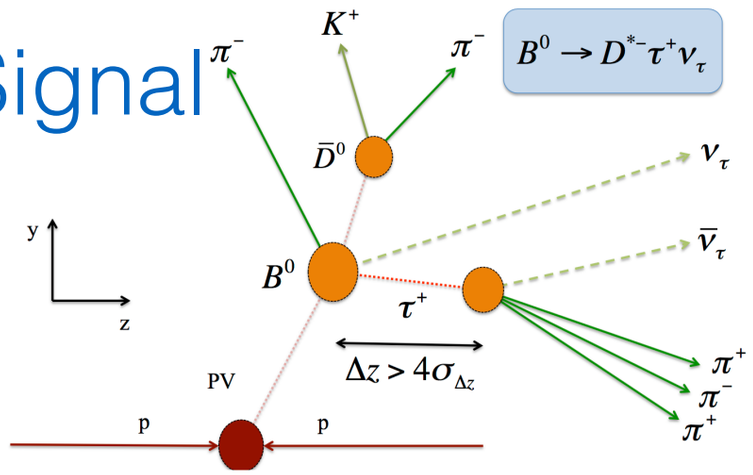
  - However, signal to noise ratio less than 1% → need at least 10^3 rejection!

  - Large background, notably from $B \to D^{*-}3\pi X$ (BF~100 x signal) and $B \to D^{*-}D_S^+(X)$ (BF~10 x signal, same vertex topology)

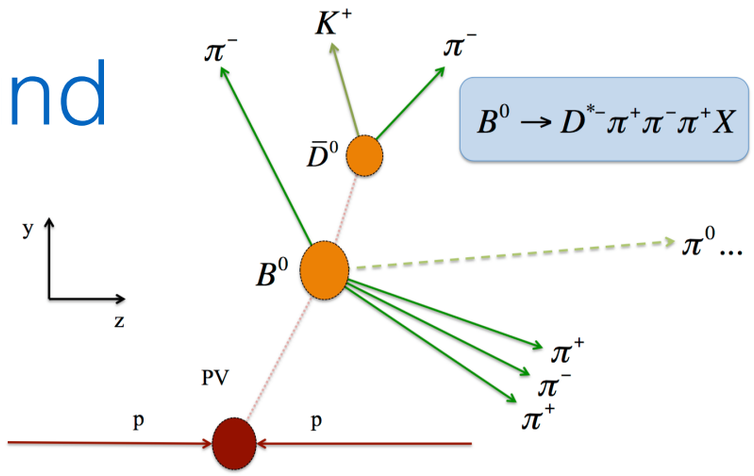
Background reduction

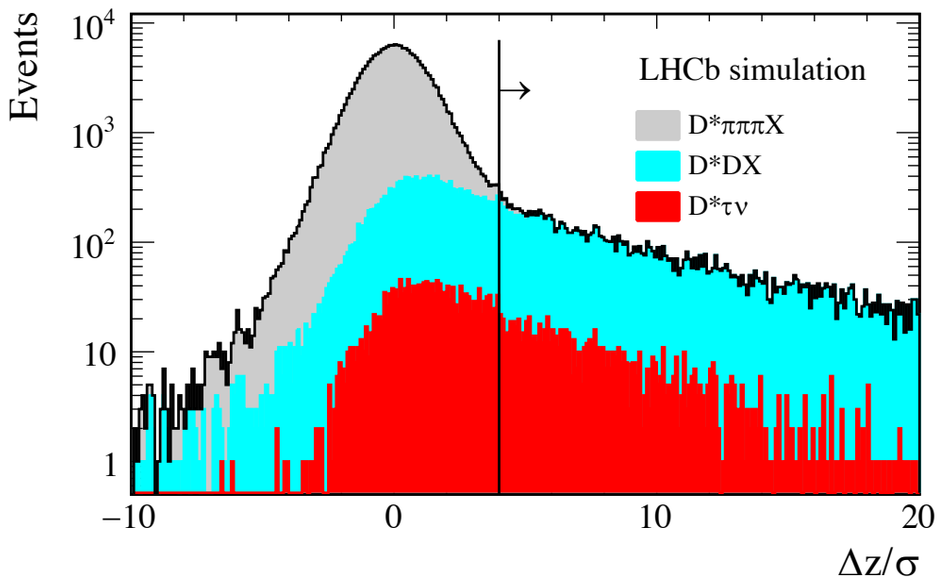
- Separation between B and 3π vertices ($\Delta z > 4\sigma_{\Delta z}$) crucial to obtain the required rejection of $B \to D^{*-}3\pi X$

Signal



Background



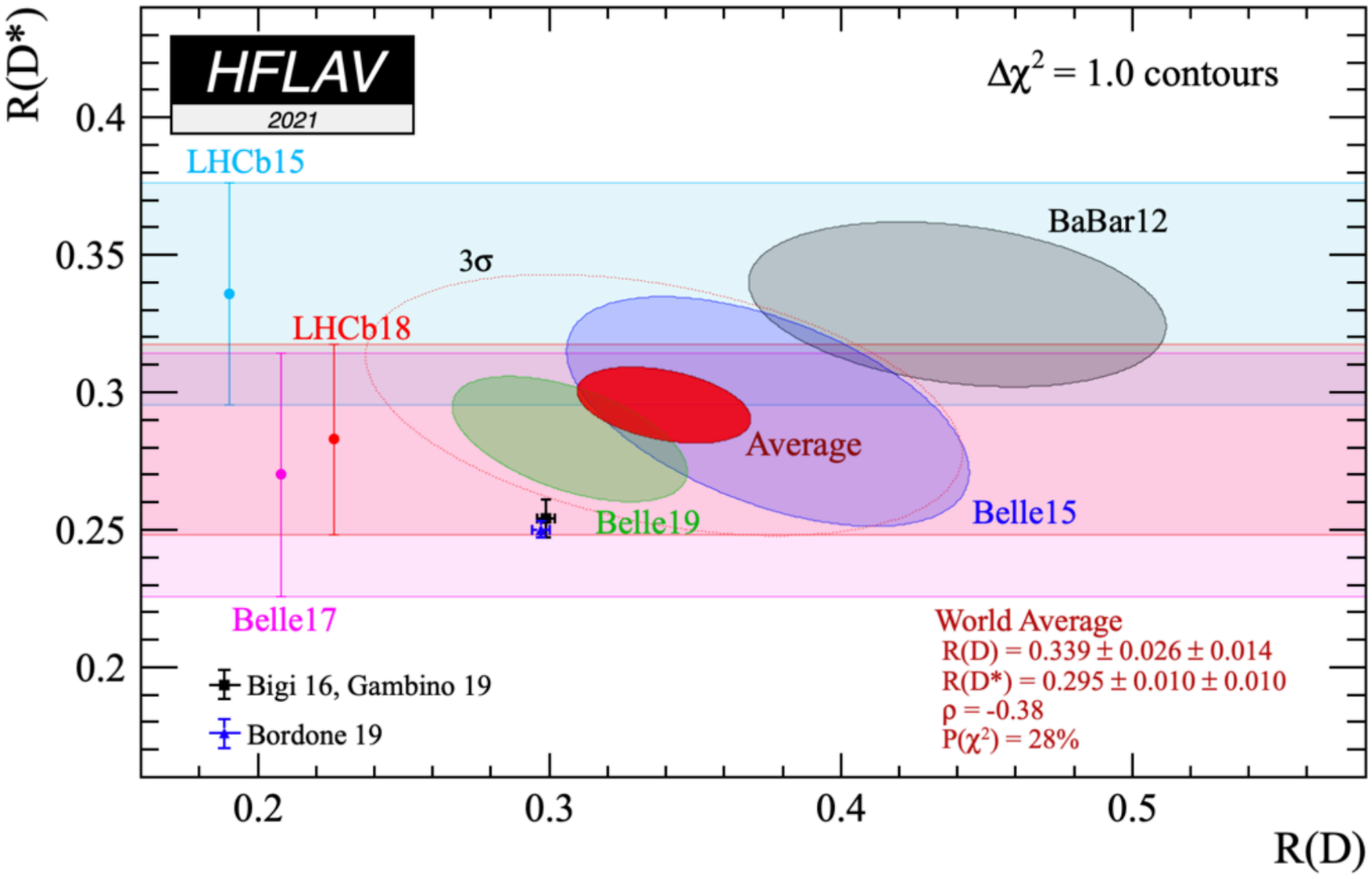


- Remaining double-charm background ($B \to D^{*-}D_S^+(X)$ suppressed by employing a multivariate classifier

PRL120 (2018) 171802
PRD 97 (2018) 072013

$$R(D^{*-}) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$$ ~1.1σ > SM

$R(D)$ vs $R(D^*)$



BaBar to deliver another precise measurement of $R(D^{(*)})$ after a decade, more data-driven

- All experiments see an excess wrt SM predictions: $\sim 3.4\sigma$ tension
- intriguing as it occurs in a tree-level SM process ($\Lambda_{\rm NP} \lessapprox 3\,\text{TeV}$)
- 2.9σ effect on $R(D^*)$

Take home message

- Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP. This is particularly relevant in the absence of direct collider production of new particles.

- Many world record results. For some topics we have moved from exploration to precision measurements.

- Most of these results show good compatibility with the SM, but hints of LFU violation are still persisting! This has generated a lot of interesting theoretical ideas but….

- need more data to test these hints: full analysis of Run 2 but also results from ATLAS and CMS (ATLAS, CMS), while waiting for the high-precision results from the LHCb upgrade and Belle II


SM

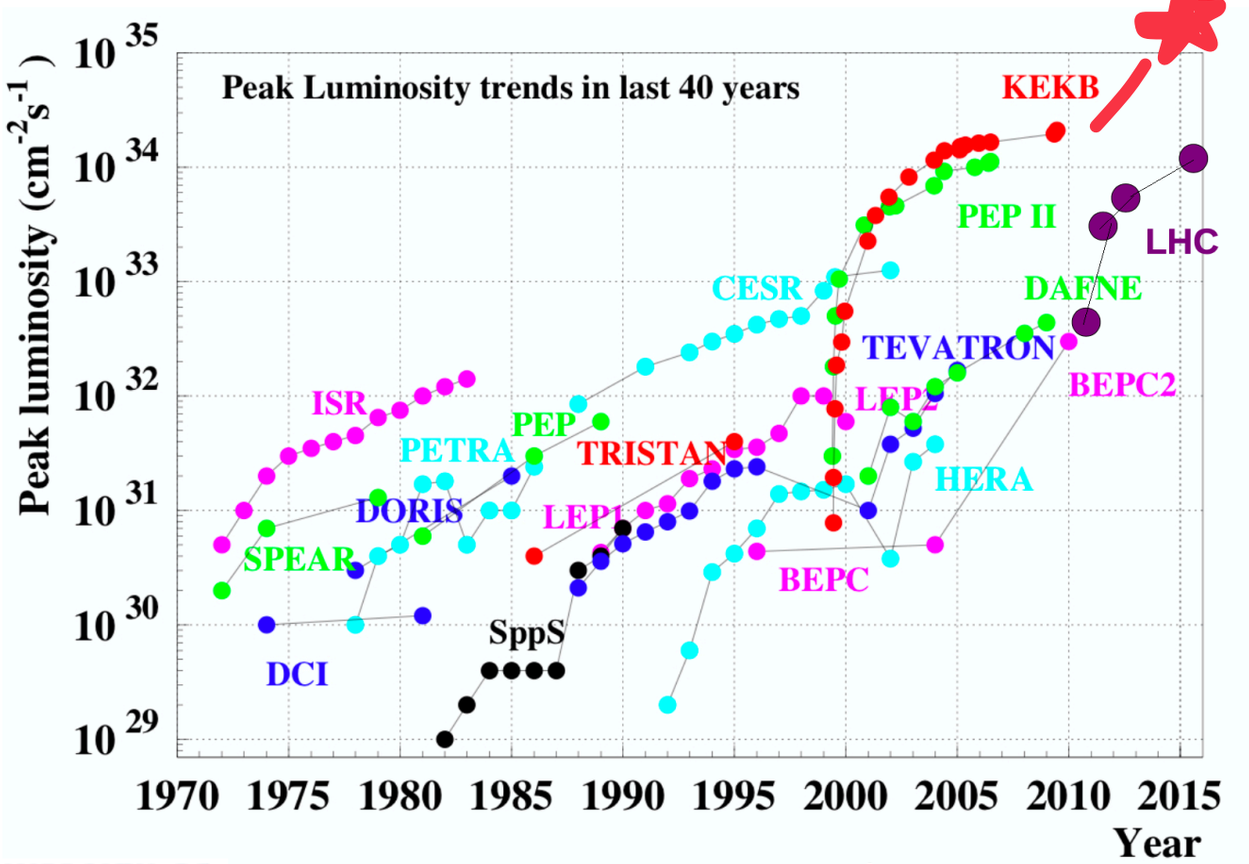
Supplementary material

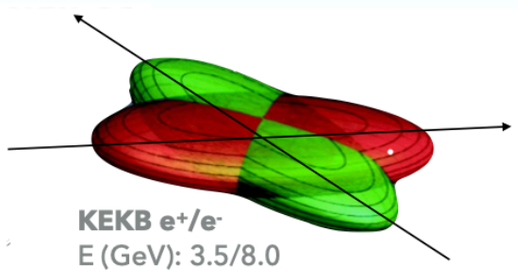
BELLE II @ SuperKEKB

- Operates at the $\Upsilon(4S)$ with energy-asymmetric e^+e^- collisions → CM boosted with $\beta\gamma \sim 0.28$

- Completed major upgrade to the accelerator to reach 30xKEKB ($\mathscr{L} = 6\,10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
  - 2x higher beam currents
  - 20 x smaller beam spot (σ_y=60 nm)

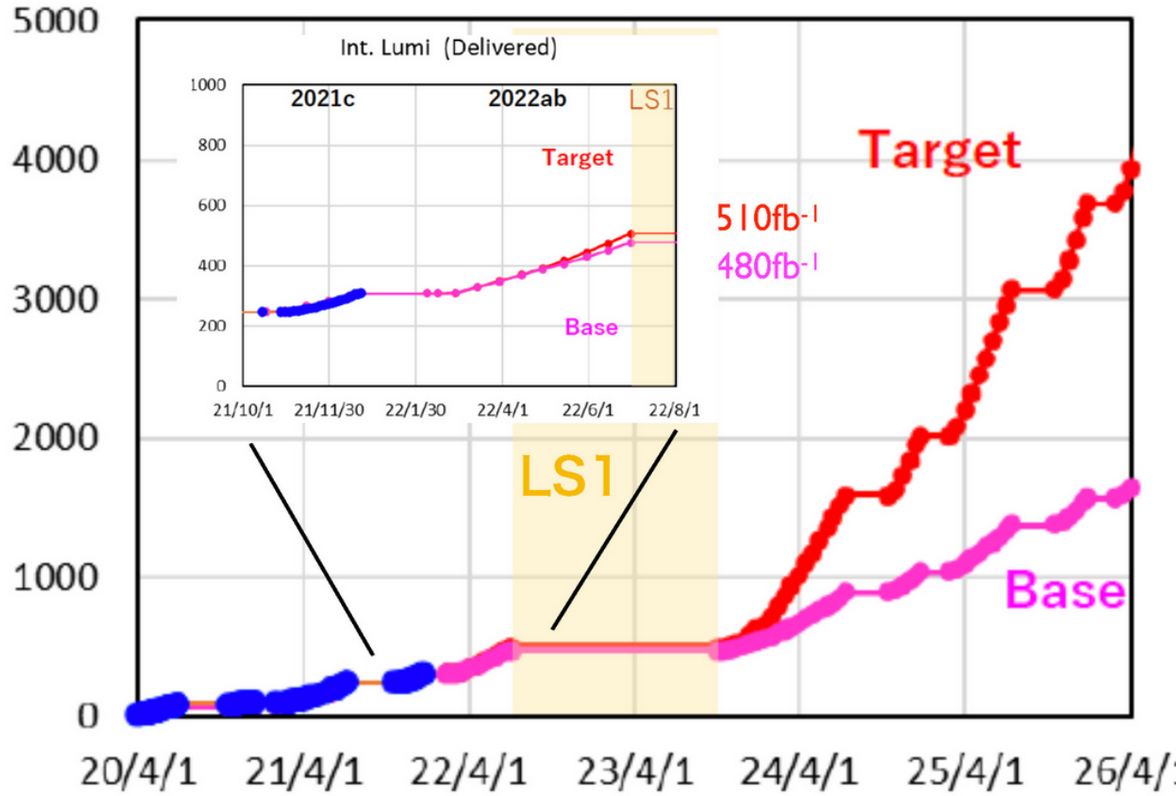
- Nano-beam scheme
  - idea is to have a very strong vertical focusing at the interaction point by making the crossing angle even larger than the previous machine, together with smaller beam emittances.





BELLE II status

- SuperKEKB performance below expectations, but $\mathscr{L}_{\rm inst}$ exceeding KEKB by ~ a factor 2
- $\mathscr{L}_{\rm int}$~1/3 of full Belle dataset
- Long shutdown1 starting summer ’22
- Performance mostly exceeding that of BELLE (e.g., tracking and vertexing, neutral reconstruction, μ -id, flavour-tagging..)



- World’s best $D^{0,+}, \Lambda_c^+$ lifetimes!
- Measurements of $B(B \to K^* \ell^+ \ell^-)$, with $\ell = e, \mu$, currently limited by stat.uncertainty, with similar precision for electrons and muons; electron channel will become competitive with 1/ab
- Will provide essential independent check of anomalies with few 1/ab

BELLE II (dis)advantages

- B mesons ~1/4 of total $\sigma(e^+e^- \to \text{hadrons})$
- "Clean environment": only two B-mesons produced ($50\,\% B^+B^-, 50\,\% B^0\overline{B}^0$)
- Detector acceptance approaches 4π and is quite uniform
- Very high efficiency to learn the flavour of a neutral B-meson when studying its partner in the same $\Upsilon(4S)$ decay (flavour tagging) is ~40%
- Electrons measured almost as well as muons; also they do better than LHCb in inclusive modes and in modes with neutrals
- Coherent B-meson production
- Relatively poor time resolution of ~900 fs on decay-time difference of the two B -mesons compared to B lifetime of ≈ 1500 fs
- Cross-section ~1.1 nb (although very high $\mathscr{L}$)
- Only $B^+B^-, B^0\overline{B}^0$ can be studied with precision; B_s are produced at the $\Upsilon(5S)$, but cross-section ~0.06 nb and time resolution not good enough to study mixing and CPV
- Studies of other b-hadron species are impossible as the accelerator does not have enough energy to produce them.

ATLAS&CMS (dis)advantages

- Large $b\bar{b}$ cross-section $\sigma_{b\bar{b}} \sim 600\mu\text{b}\ @\sqrt{s} = 13\ \text{TeV}$
- All species of b-hadrons produced $(B_\text{u}, B_\text{d}, B_\text{s}, B_\text{c}, \Lambda_\text{b}, \Sigma_\text{b}, \Xi_\text{b} \dots)$
  $\mathscr{L}_\text{peak} \sim 2 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and $\int \mathscr{L}\,\text{d}t \approx 160\,\text{fb}^{-1}\ @\sqrt{\text{s}} = 13\ \text{TeV}$
- $\sigma_{b\bar{b}}/\sigma_\text{inel} \sim \text{few}\ 10^{-3}$, and most interesting b-hadron decays occur at 10^{-5} probability or lower → trigger is a major issue
- Large boost (decay vertices well separated)
- Excellent tracking, muon and electron ID (but muons triggered and reconstructed more efficiently) but no ability of distinguishing pions, kaons and protons
- Limitations to readout bandwidth → b-hadron decays with low p_T cannot be selected and readout
- Many particles in event not associated with the two b-hadrons
- Large pileup (up to 40 in 2018)

LHCb (dis)advantages

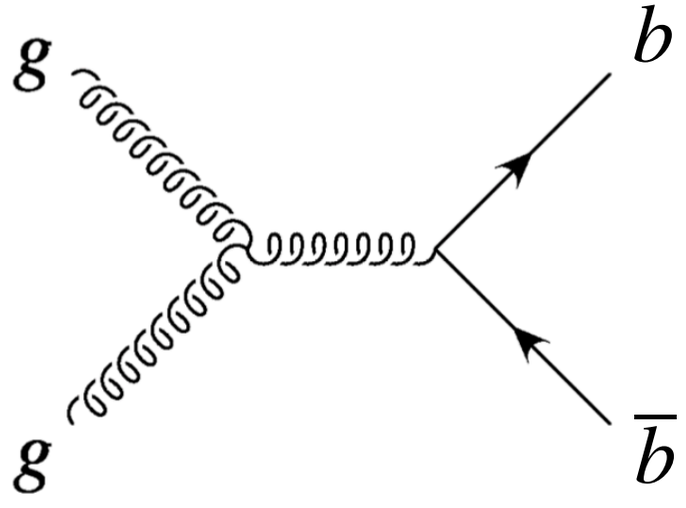
- Large $b\bar{b}$ cross-section $\sigma_{b\bar{b}} \sim 600\mu\text{b}\ @\sqrt{s} = 13\ \text{TeV}$
- All species of b-hadrons produced ($B_\text{u}, B_\text{d}, B_\text{s}, B_\text{c}, \Lambda_\text{b}, \Sigma_\text{b}, \Xi_\text{b} \ldots$)
- $\mathscr{L}_\text{peak} \sim 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ and $\int \mathscr{L}\,\text{d}t \approx 9\,\text{fb}^{-1}$

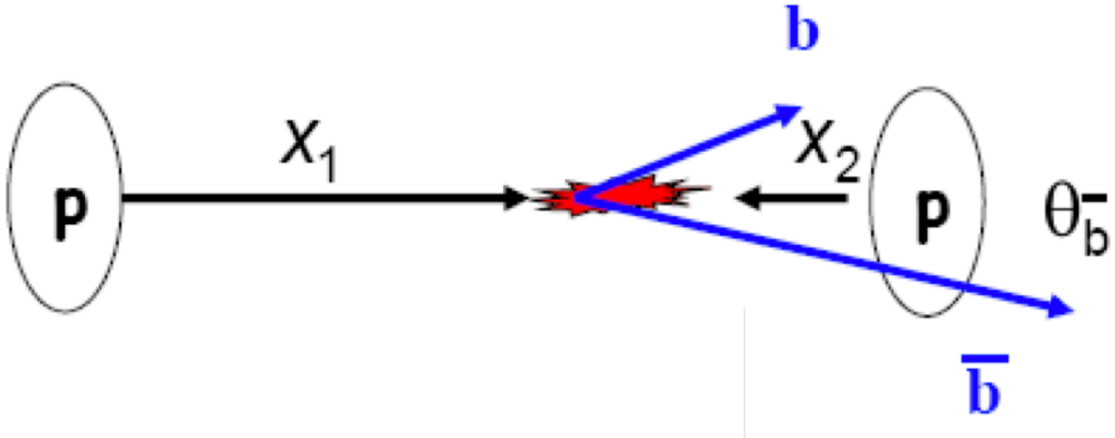
  (to be raised to 2x10^{33} cm^{-2} s^{-1} in Run 3)

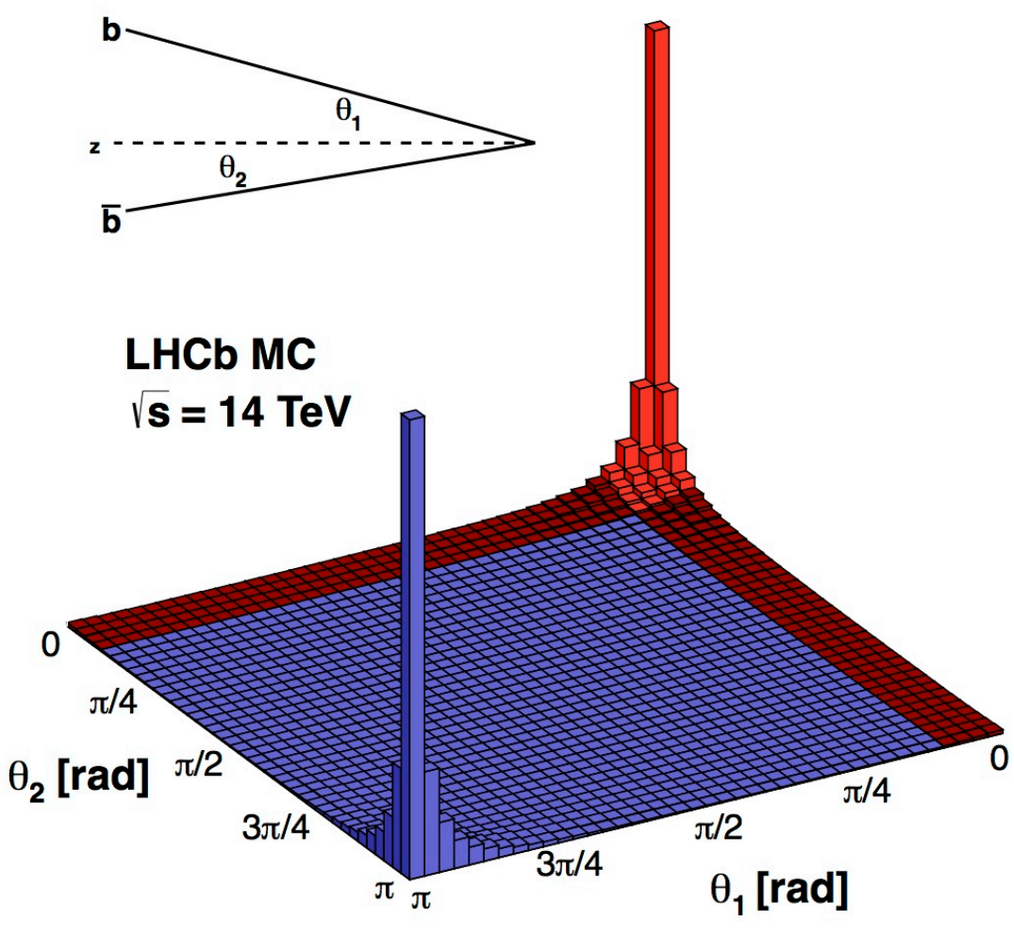
- $\sigma_{b\bar{b}}/\sigma_\text{inel} \sim \text{few}\ 10^{-3}$, and most interesting b-hadron decays occur at 10^{-5} probability or lower → trigger is a major issue
- Large boost (decay vertices well separated with resolution of $\approx 45\,\text{fs}$)
- Excellent tracking, muon and electron ID (but muons triggered and reconstructed more efficiently) and PID with ability of distinguishing pions, kaons and protons
- Ability to trigger on b-hadron decays with low p_T
- Many particles in event not associated with the two b-hadrons
- ~1 visible interaction/bunch crossing (to be raised to ~5 in Run 3)

A forward spectrometer

- Dominant $b\bar{b}$ production mechanism at the LHC is through gluon-gluon fusion in which the momenta of the incoming partons are strongly asymmetric in the laboratory frame→ centre of mass energy of $b\bar{b}$ pair boosted along direction of the higher momentum gluon, and both b hadrons are produced in the same forward (or backward) direction.

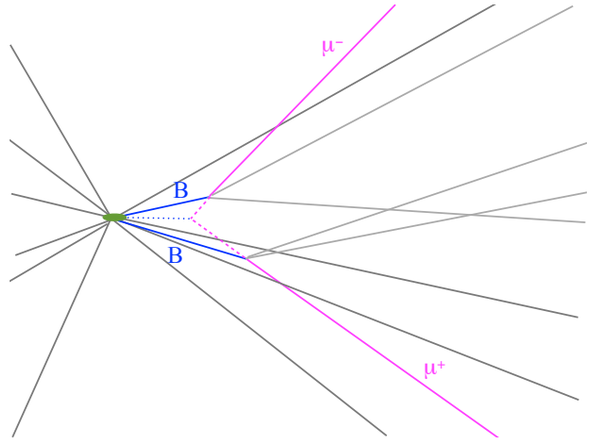






How do you find a needle in a haystack?

- Schematic $B^0_{(s)} \to \mu^+\mu^-$ selection requirements:
  - two oppositely-charged muon tracks with common vertex displaced from primary vtx
  - $m_{\mu\mu}$ peaking at the $B^0_{(s)}$ mass
- In practice, complex analysis due to very low signal and large background rates
- Most abundant background is combinatorial
  - muons from two different b-quark semileptonic decays
  - strongly suppressed with multivariate classifier (BDT) using e.g., track isolation, topological and geometrical information



- Use of normalisation channels with well-known BRs, same topology and/or trigger and cancel uncertainties in ratios :
  - Use large samples of $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \frac{N_{B^0_s\to\mu^+\mu^-}}{N_{\text{norm.}}} \times \frac{f_d}{f_s} \times \frac{\varepsilon_{\text{norm.}}}{\varepsilon_{B^0_s\to\mu^+\mu^-}} \times \mathcal{B}_{\text{norm.}}$$

largest systematics to $B_s \to \mu^+\mu^-$ from b-quark fragmentation probability ratio f_s/f_d (~3%)

R_K measurement ($9\,\mathrm{fb}^{-1}$)

- Performed in q^2 interval $1.1 < q^2 < 6.0\,\mathrm{GeV}^2$

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

- Rare and J/ψ mode share identical selection apart from cut in q^2

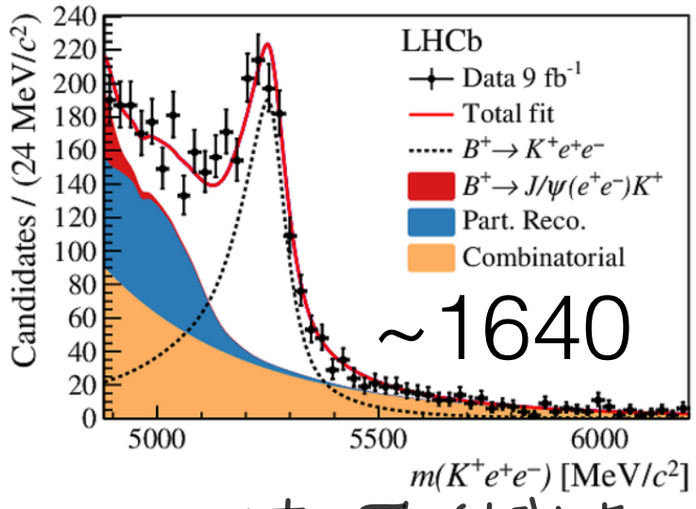
$$R_K = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}} \frac{\varepsilon^{J/\psi}_{\mu^+\mu^-}}{\varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}} \frac{\varepsilon^{\mathrm{rare}}_{e^+e^-}}{\varepsilon^{J/\psi}_{e^+e^-}}$$

- Yields determined from fits to the invariant mass distributions

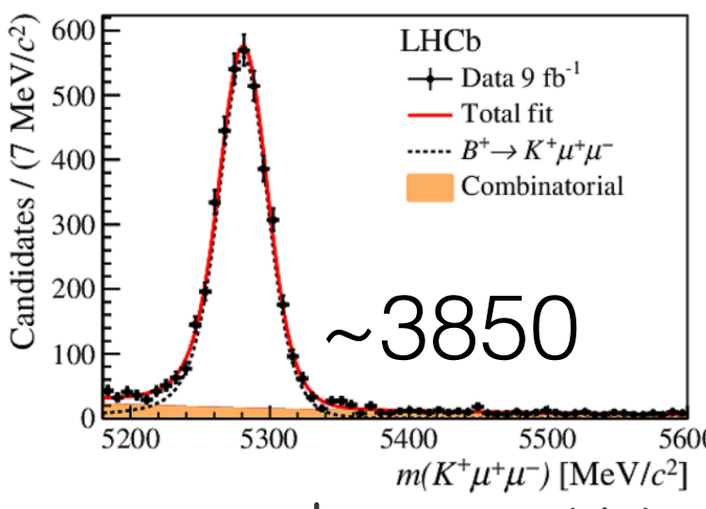
- Efficiencies computed using simulation calibrated with control channels in data

arXiv:2103.11769
Nature Physics

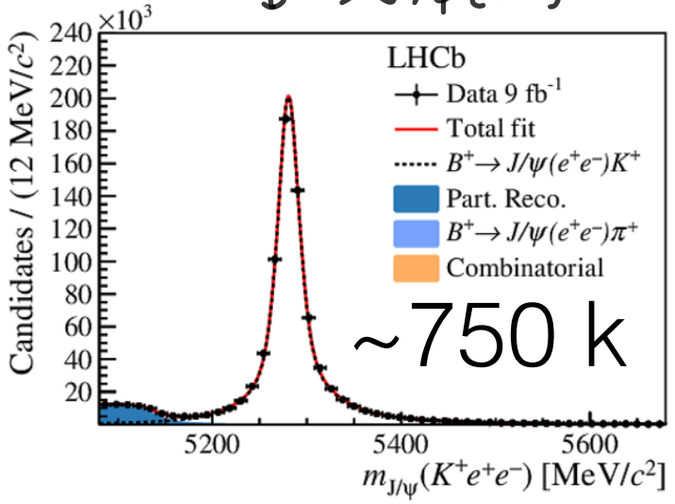
$B^+ \to K^+e^+e^-$



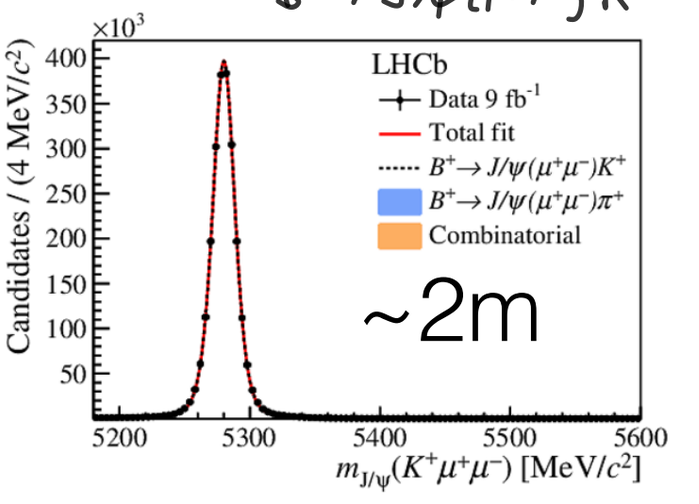
$B^+ \to K^+\mu^+\mu^-$



$B^+ \to J/\psi(e^+e^-)K^+$



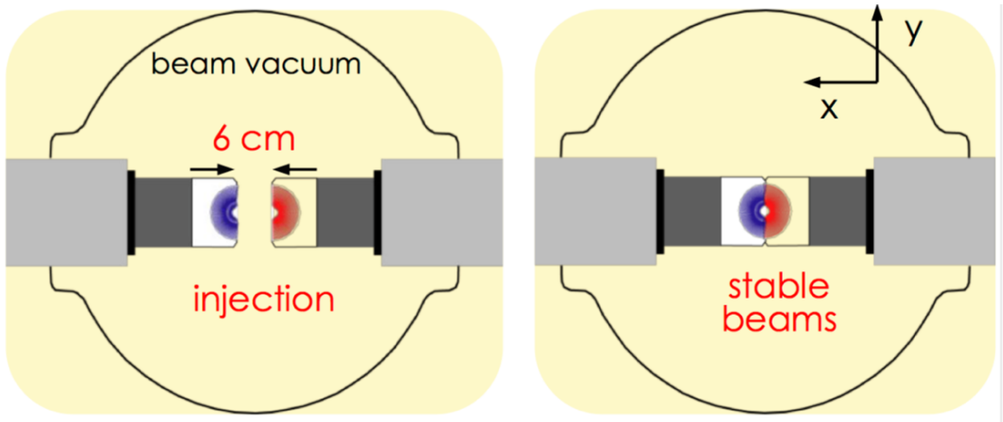
$B^+ \to J/\psi(\mu^+\mu^-)K^+$



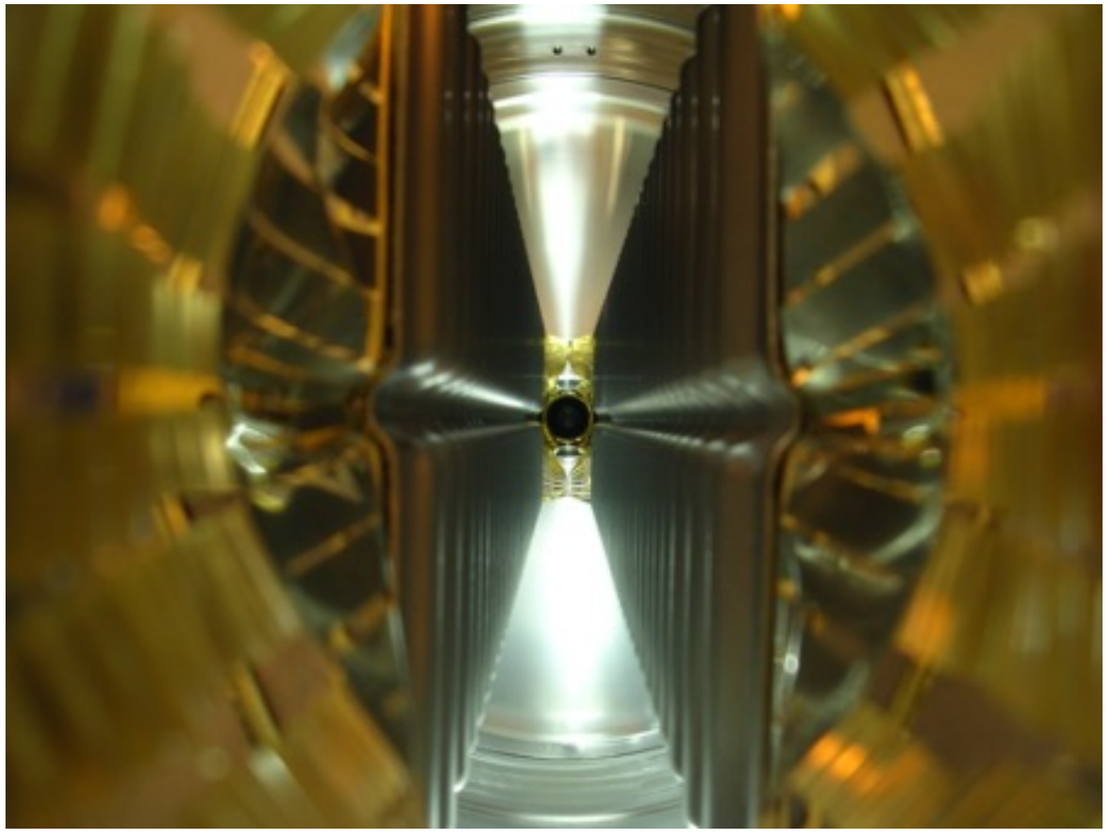
VErtex LOcator (VELO)

- A precise particle detector, which surrounds the pp collision point inside LHCb (21 stations, each made of two silicon half disks with R-ϕ silicon strip sensors)

- Retractable for safe operations outside of stable beam conditions

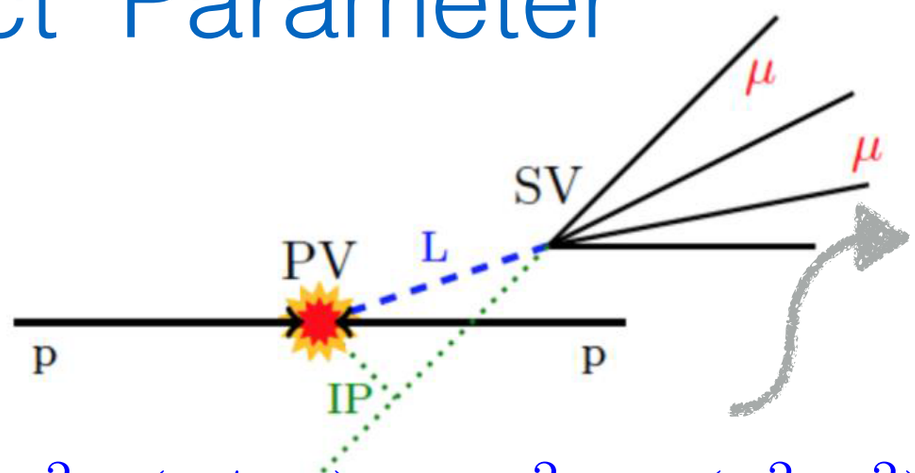


- Active area just 8.2 mm from beams



VELO performance

- Impact Parameter



JINST 9 (2014) P09007

$$\sigma_{IP}^2 = \frac{{r_1}^2}{{p_T}^2}\ \sigma_{MS}^2(x/X_0)\ +\ \sigma_{extrap}^2(\sigma_1^2, \sigma_2^2)$$

- r_1 is radius of first measured point
- x/X_0 is fractional radiation length before second measured point
- σ_1 and σ_2 are measurement errors of first and second point

  - IP resolution optimised by positioning sensors as close as possible to LHC beams, minimising material before first VELO hits, having small inter-strip pitch (from 40 to 100 μm)

  - IP resolution <35 μm for p_T>1GeV/c

- Decay time

$$t = ml/p$$

$$\sigma_t = \left(\frac{m}{p}\right)^2 \sigma_l^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$

  - Run 1 decay time resolution ~45 fs

  - Excellent decay time resolution essential to resolve fast $B_s^0 - \overline{B}_s^0$ oscillations :~45fs << 350 fs, oscillation period

Particle Identification in flavour experiments is very important!

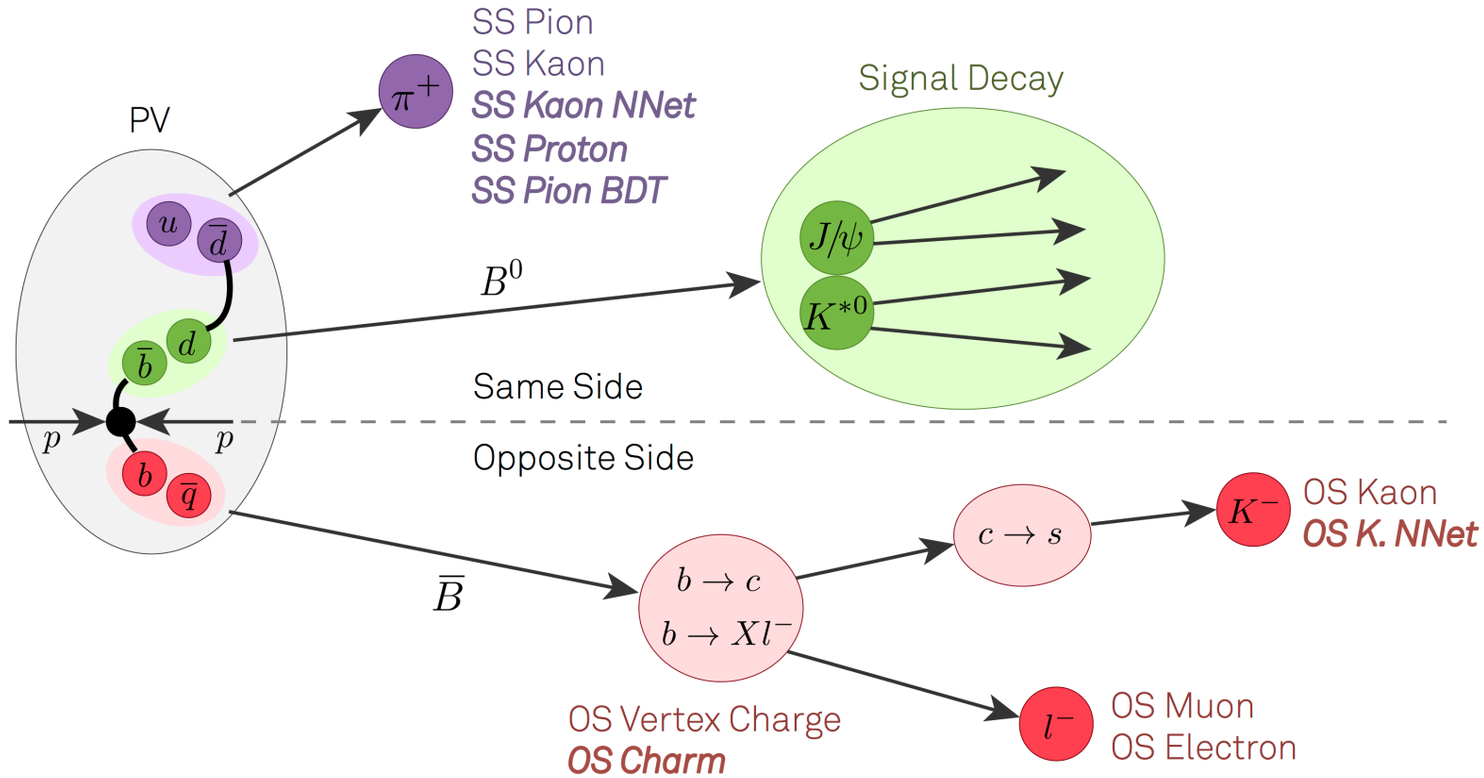
- To reduce the combinatorial background
  - Many of the interesting decay modes of b- and c-hadrons involve hadronic multi-body final states. In reconstructing the invariant mass of the decaying particle, it is important to be able to select the charged hadrons of interest to reduce combinatorics

- To discriminate final states of otherwise identical topologies, e.g. $B \to h^+h^-$ $(h = \pi, K)$

- To help in flavour tagging

Flavour tagging

- Key info required for the measurement of CP violation is the knowledge of flavour at production



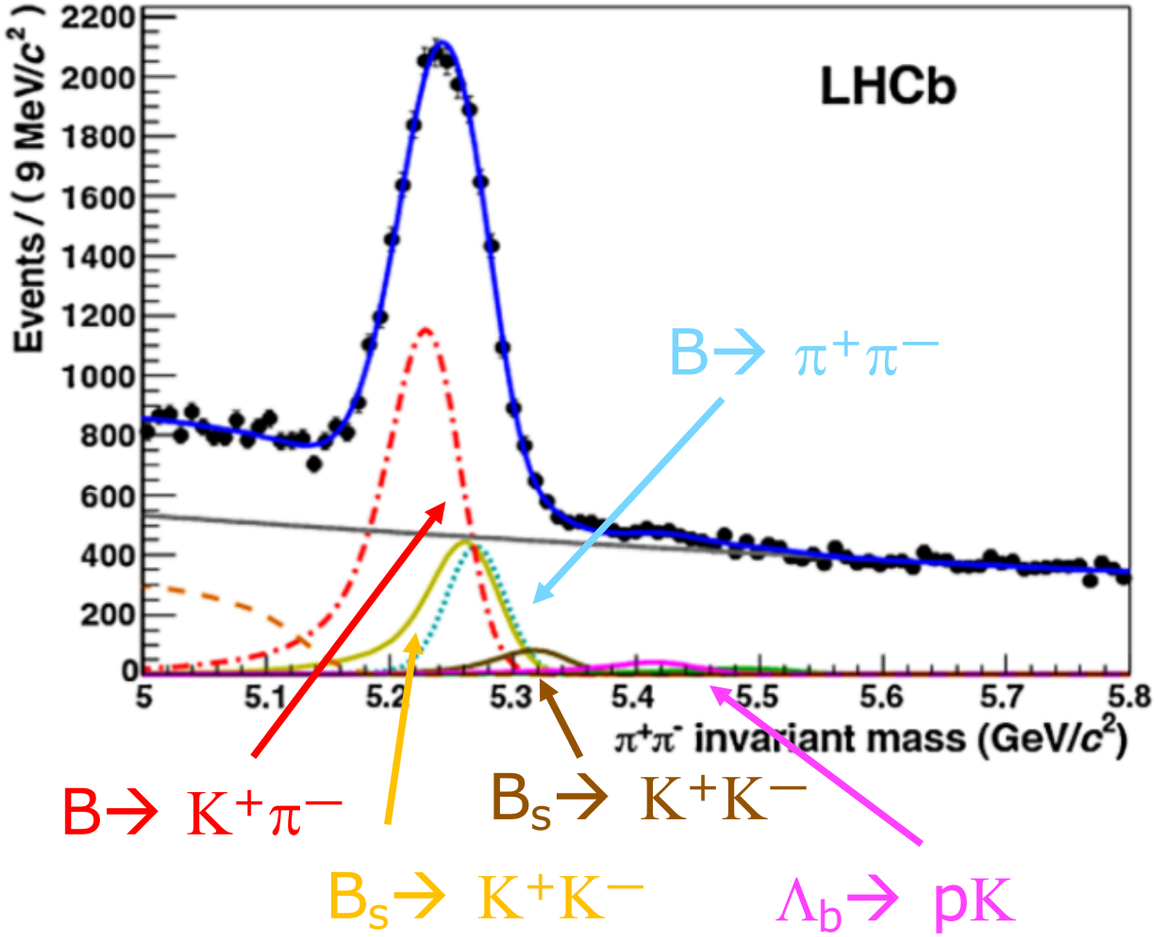
- Opposite side K (in addition to μ, e) and same side taggers (particle generated from the remnants of the signal *b* fragmentation (π, K, p)

- Tagging power $\epsilon_{eff} = \epsilon(1-2\omega)^2 \approx 6\,\%$ (LHCb) (figure of merit giving effective statistical reduction of sample size)

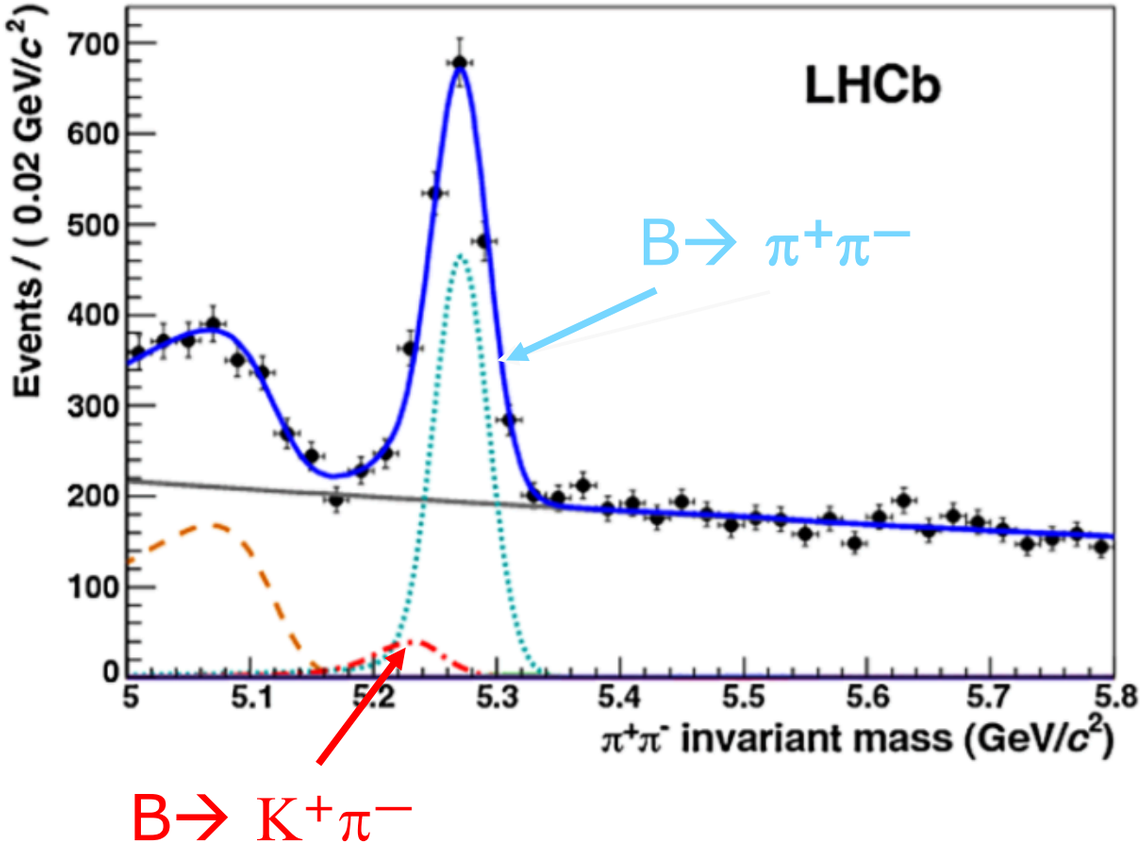
Impact of Particle Identification

- .. through two Ring-Imaging Cherenkov detectors (RICH)
- Invariant mass distribution for $B \to h^+h^- (h = \pi, K)$ before and after use of the RICH information
- Signal under study is $B \to h^+h^-$

before

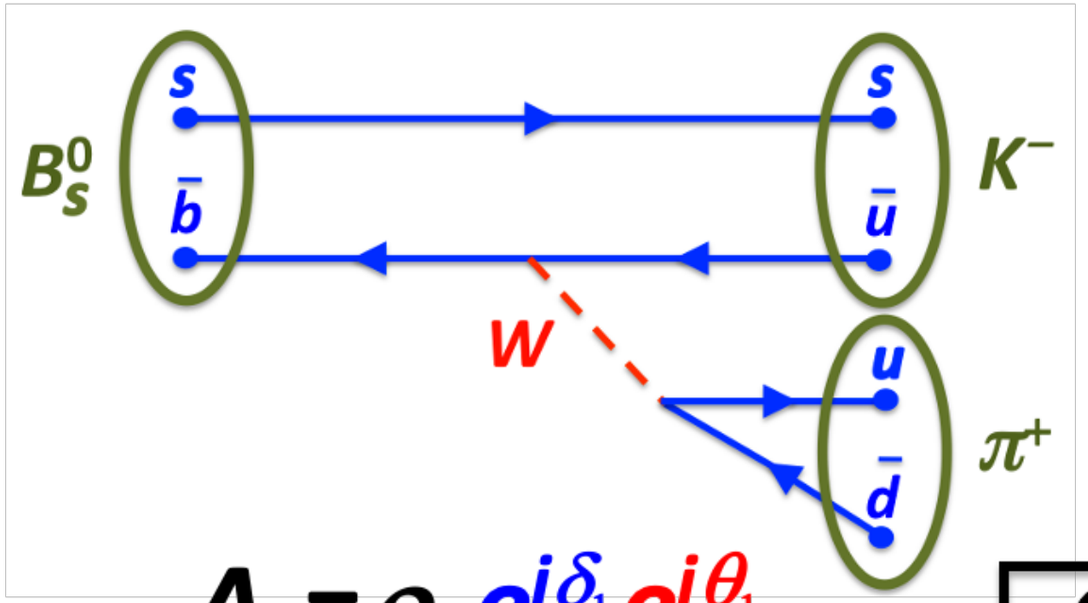


after

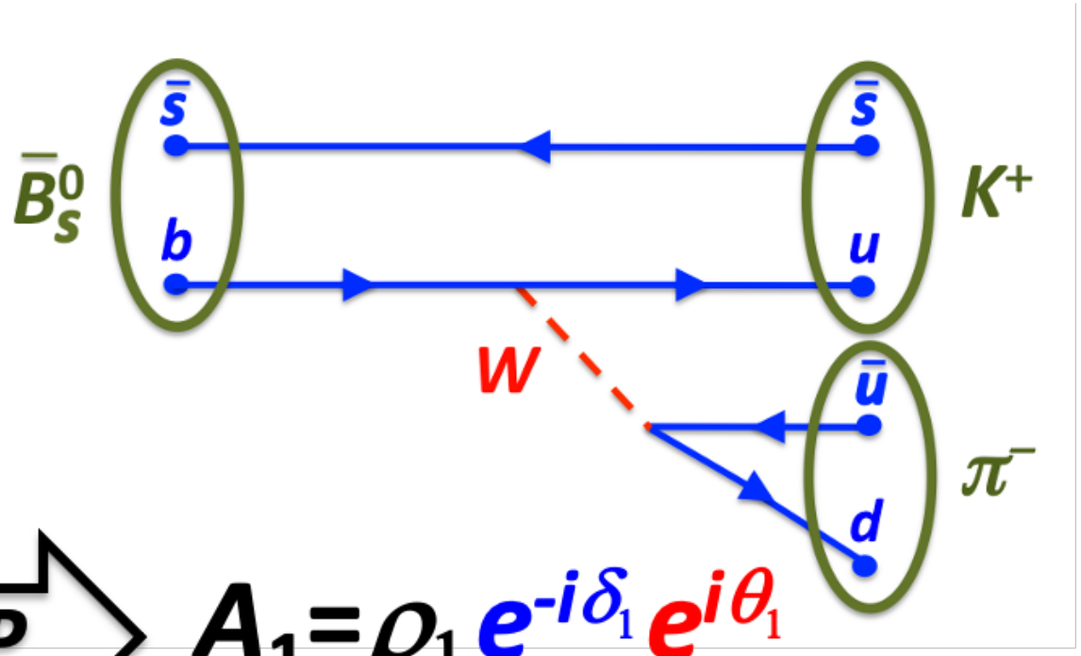


Eur.Phys.J.C 73 (2013) 2431

CP Violation primer

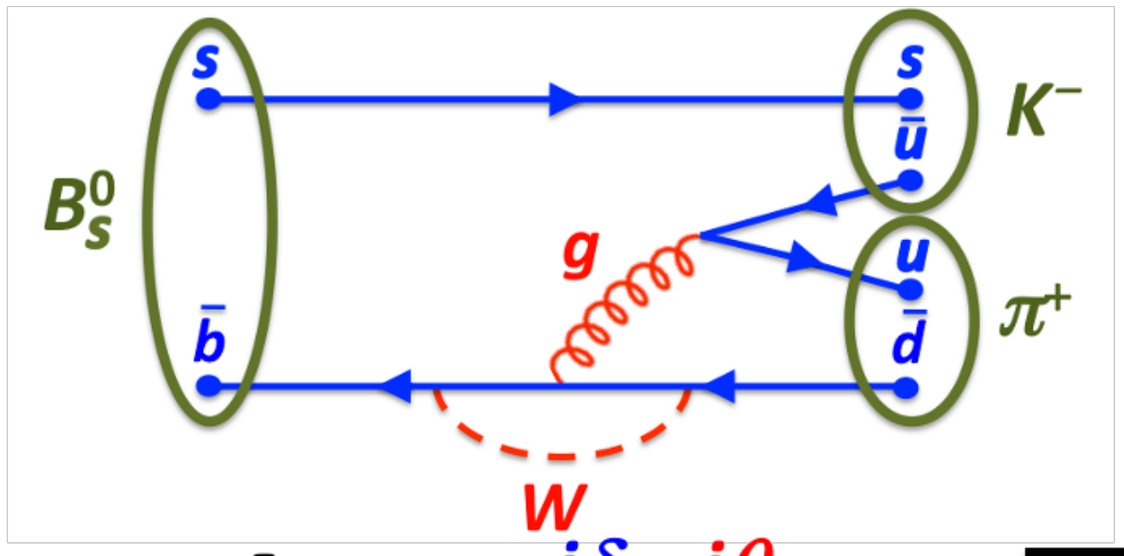


$$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1}$$

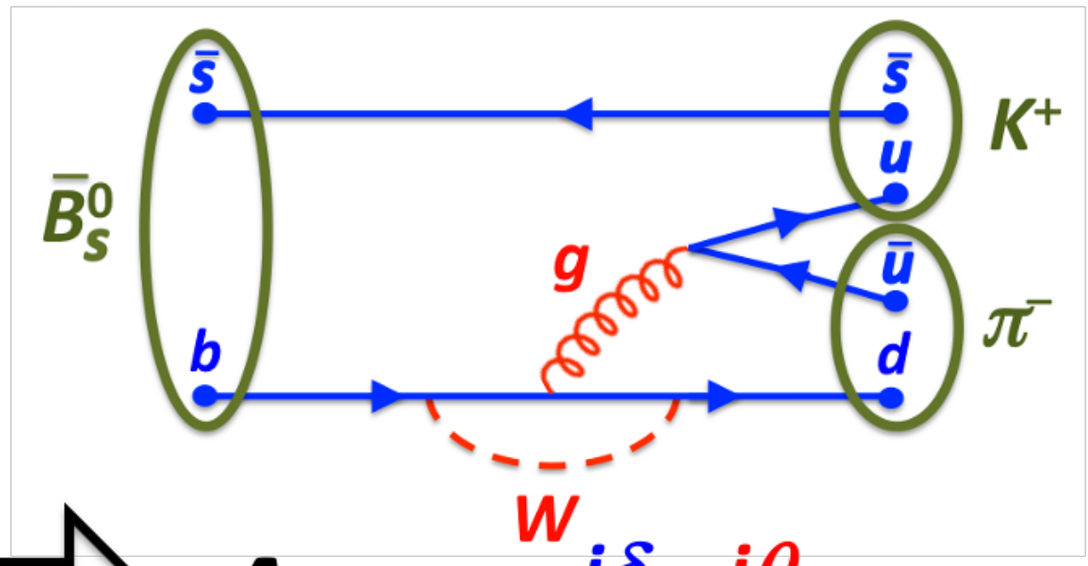


CP

$$A_1 = \rho_1 e^{-i\delta_1} e^{i\theta_1}$$



$$A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2}$$



CP

$$A_2 = \rho_2 e^{-i\delta_2} e^{i\theta_2}$$

CP Violation primer

- With two different amplitudes contributing to the same physical transition

$$|\bar{A}_1+\bar{A}_2|^2 - |A_1+A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1-\delta_2)\sin(\theta_1-\theta_2)$$

that differs from zero if weak phase differ $\delta_1 \neq \delta_2$ and strong phases differ $\theta_1 \neq \theta_2$

→the asymmetry becomes observable!

R_K cross-checks

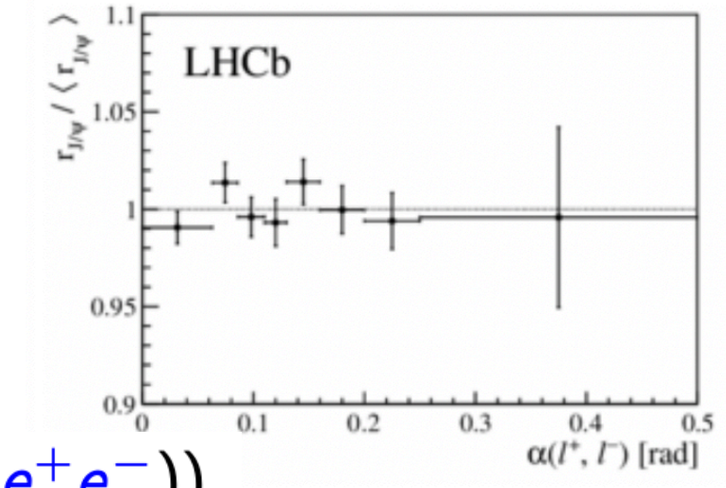
- Large number of crosschecks performed before unblinding the results
- To ensure that the efficiencies are under control, measure

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

arXiv:2103.11769
Nature Physics

- Very stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio

- $r_{J/\psi} = 0.981 \pm 0.020$ - checked across datasets, samples and as a function of kinematics



$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 0.997 \pm 0.011$$

validation of the double-ratio procedure at q^2 away from J/ψ

- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus R_K) changes by ~3%