Flavour at LHCb: where are we (going)?

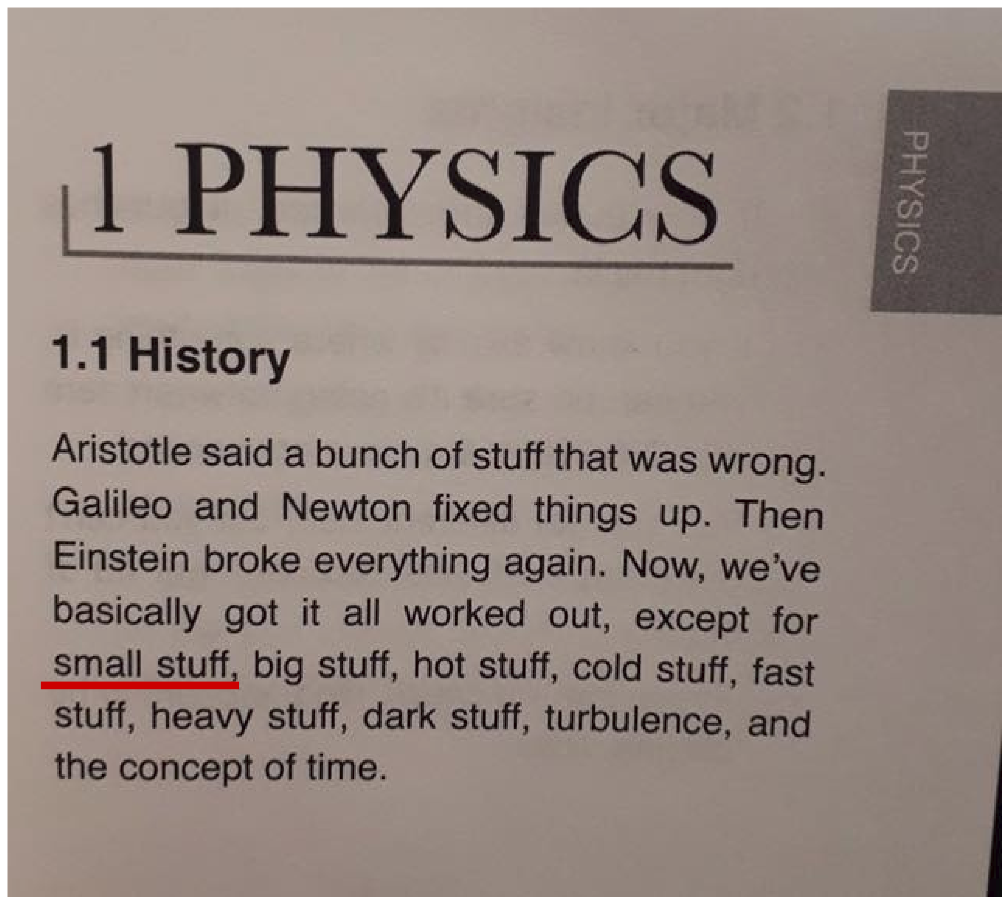
Louis Henry
APC, Paris, 08/02/2019

So, who’s talking?

- Post-doctoral researcher in LHCb, currently at IFIC; Ph.D. in LPNHE Paris (2016).
- Physics analyses:
  - As a main analyst:
    - Update of $B_{(d,s)} \to K_S h^+ h'^-$ (h: π,K) branching fractions with full Run 1 dataset.
    - Amplitude analysis of $B_d \to K_S K^+ K^-$
    - Amplitude analysis of $\Lambda_c \to pK^-\pi^+$
  - Supporting role:
    - Measurement of branching fractions of Λ_c and Ξ_c decays with a Λ in the final state
    - Search for $\Xi_b^- \to \Xi^-\gamma$ modes.
- Detector development:
  - Deputy convener of SciFi Simulation & Software
  - Responsible for stand-alone tracking in the SciFi upgrade
  - Contributor to a fixed-target + bending crystals proposal at Physics Beyond Colliders

Red: touched upon in this seminar

Flavour at LHCb: where are we (going)?



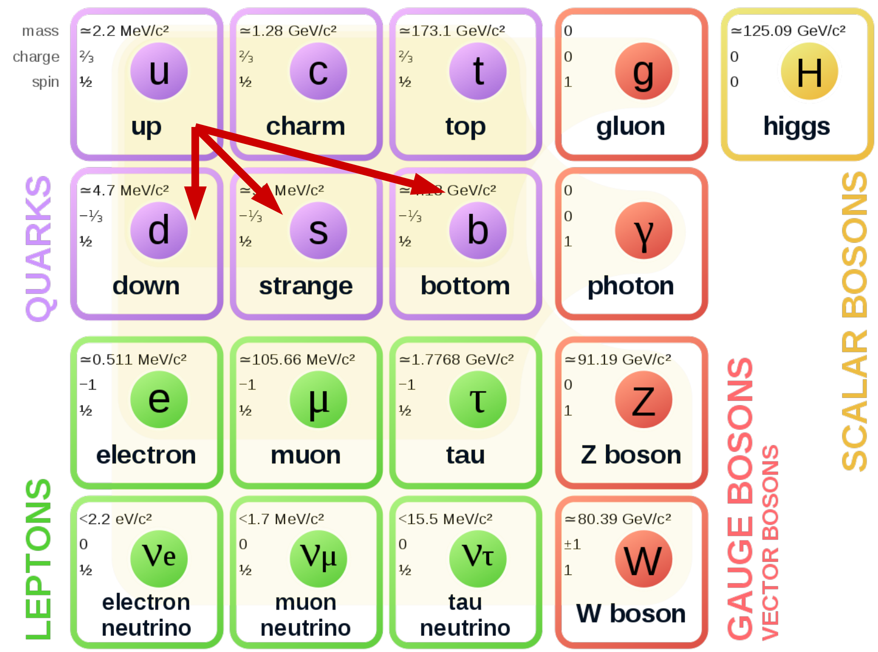
1 PHYSICS

PHYSICS

1.1 History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.

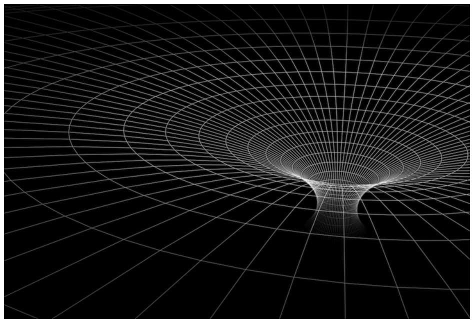
Flavour physics in the Standard Model



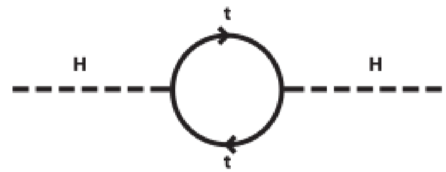
- Flavour physics is the study of transitions between "flavours" of quarks.
- These transitions occur, in the Standard Model (SM), through the charged current of the weak interaction, carried by W bosons.
- Because it deals a lot with hadrons, flavour physics need both a good understanding of **weak** and **strong** interactions.
- Flavour physics is a playground for **indirect searches** for new physics : observables that can be cleanly measured and that have precise theoretical predictions.

Missing bricks in the Standard Model

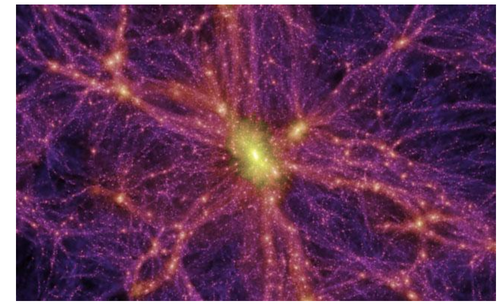
Gravity

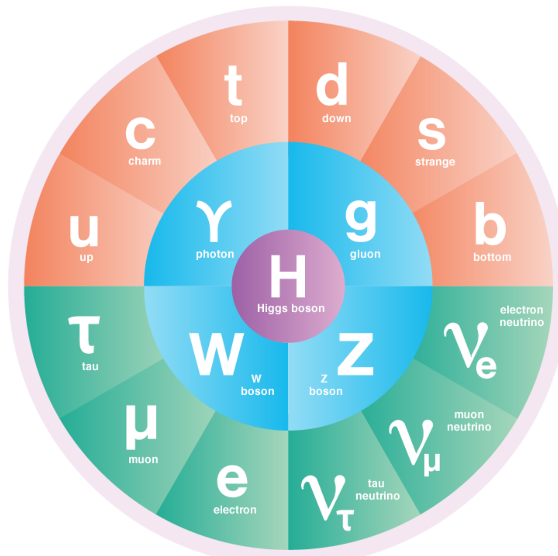


Higgs naturalness

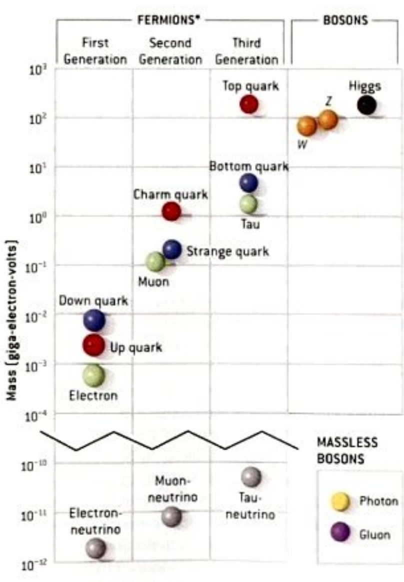


Dark matter candidate

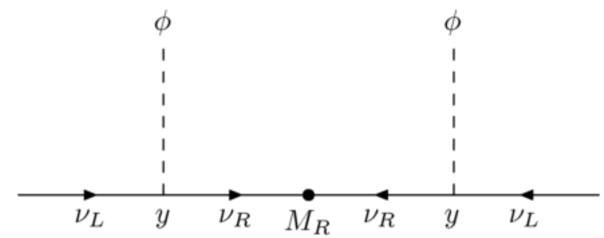




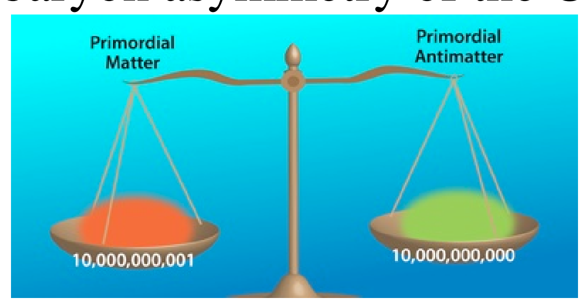
Mass hierarchy



Neutrino mass



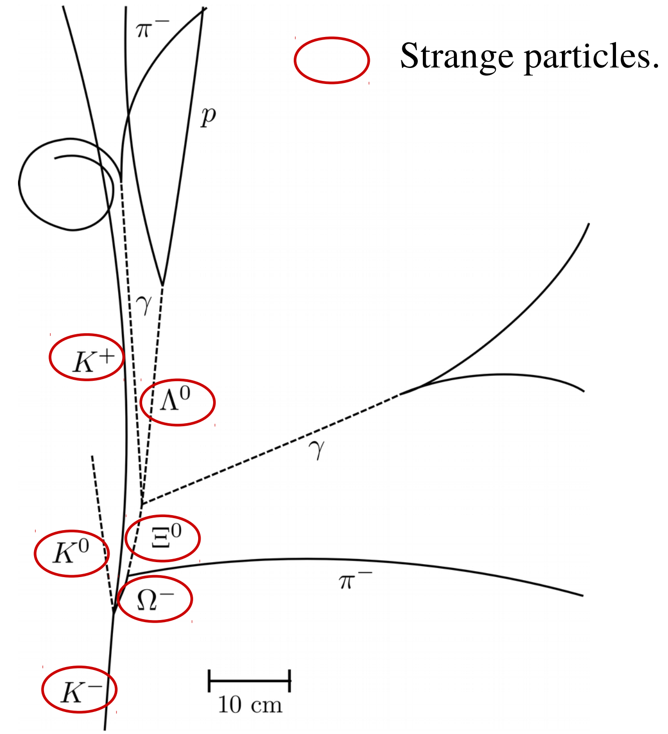
Baryon-antibaryon asymmetry of the Universe.



Building flavour

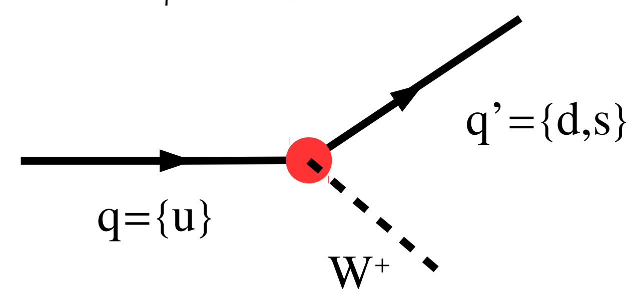
Building flavour: “strange” particles and Cabibbo angle

- Problem in the 60’s: the particle zoo is expanding too fast.
- Introduction of the quark model and SU(3): u, d and s are now three states, same under strong interaction.
  - 1969 Nobel prize 
- But why are some particles living so long?
  - Weak interaction coupling (d→u) different from (s→u)?
  - Right: picture of a bubble-chamber observation of Ω.
- To preserve universality of the weak interaction, need to consider a mixing angle between weak and strong eigenstates.



Cabibbo

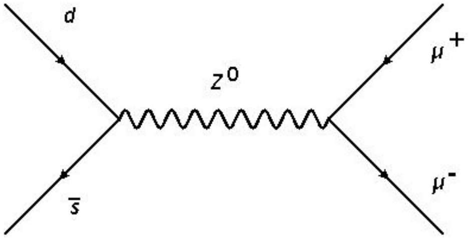
$$d_{weak} = \underbrace{\cos(\theta_c)}_{\substack{V_{ud} \\ \sim 0.97}} d + \underbrace{\sin(\theta_c)}_{\substack{V_{us} \\ \sim 0.22}} s \longrightarrow \boxed{V_{ud} \quad V_{us}}$$



Coupling prop. to $V_{Uq}{}^{T} V_{Dq'} = V_{uq'}$

Building flavour: the charm quark and the GIM mechanism

- Why are there no flavour-changing neutral currents ($s \to d$)?
  - If so, we would see $K^0 \to \mu^+\mu^-$ decays



- GIM prediction (1970): if there is a 4th quark, up-type and with a large mass, that would explain the suppression.
  - Gaillard, Lee and Rosner: $m_c \sim 1.5$ GeV from K mixing.
- Charm quark first observed in 1974 → 1976 Nobel Prize

Cabibbo

$$V_{ud} \quad V_{us}$$

GIM

$$V_{cd} \quad V_{cs}$$

~-0.22 ~0.97

The 1976 Nobel Prize in Physics

On 11 November 1974, the world of high energy physics was electrified by the news of the discovery of a new particle with remarkable properties. Just as remarkable was the fact that two groups had found it—one a group from Massachusetts Institute of Technology and Brookhaven National Laboratory led by Samuel C. C. Ting, and the other a Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-LBL) collaboration led by Burton Richter. The sudden but permanent impact of that discovery on the field has been recognized by the award of this year's Nobel Prize in Physics to Richter and Ting, only 2 years after the great discovery.

Ting's group was studying production of an electron in conjunction with its antiparticle—the positron—in proton-nucleon collisions at Brookhaven. They found (*1*) a remarkable yield of electron-positron pairs of rest energy 3.1 Gev, indicating the production of a new particle, which they named *J*. Richter's collaboration was studying the process in reverse: what is formed when beams of electrons and positrons are made to collide head-on and annihilate to produce other forms of matter. Data taken near a total electron-positron energy of 3.1 Gev had shown erratic, irreproducible behavior, convincing the SLAC-LBL experimentalists to go back and explore that region again more carefully. During their next running period it only took a few days to find (*2*) that at precisely 3.098 Gev the rate of annihilation increased more than a hundredfold, indicating resonant production of a new particle, which they named ψ.

By chance, Ting was on his way to SLAC to attend a committee meeting when the SLAC-LBL discovery occurred. Both results were presented in a memorable session at SLAC, attended by a huge crowd that included not only the usual physicists but many staff people swept up in the excitement. The euphoria spread worldwide, and in my experience not since the discovery of parity nonconservation (including the perhaps more profound discovery in 1964 of the violation of CP invariance) has an experiment had such a sudden and revolutionary psychological impact. This immediate recognition of the importance of *J*/ψ came about because of its relatively large rest mass, more than three times that of the proton, its relatively long lifetime, and the ease of formation by the colliding electron-positron beams. The intervening 2 years have confirmed the original expectation: the ψ (*3*) had led to the apparent discovery of a new property of matter called charm.

Richter, after obtaining his degree at MIT, went to Stanford in 1956 determined to carry out experiments testing the foundations of quantum electrodynamics—the marriage of the Maxwell theory to the Dirac electron theory and to quantum mechanics. Richter first made measurements of the production of electron-positron pairs by 100-Mev gamma-rays, under conditions designed to strain the theory to the utmost. The results agreed with quantum electrodynamics. Around this time, G. K. O'Neill of Princeton made the audacious suggestion that intense electron beams could be stored and made to collide with each other at rates so high that processes of interest to high energy physics would be observable. Ordinary scattering of electrons at large momentum transfer would provide a quite sensitive test of electrodynamics at small distances. Richter, along with W. C. Barber and B. Gittelman, joined with O'Neill and built at Stanford a pair of electron storage rings with the 550-Mev linear electron accelerator as injector, and they successfully observed the electron-electron collisions. Again quantum electrodynamics was verified, this time on a distance scale small compared to the size of the proton.

Burton Richter

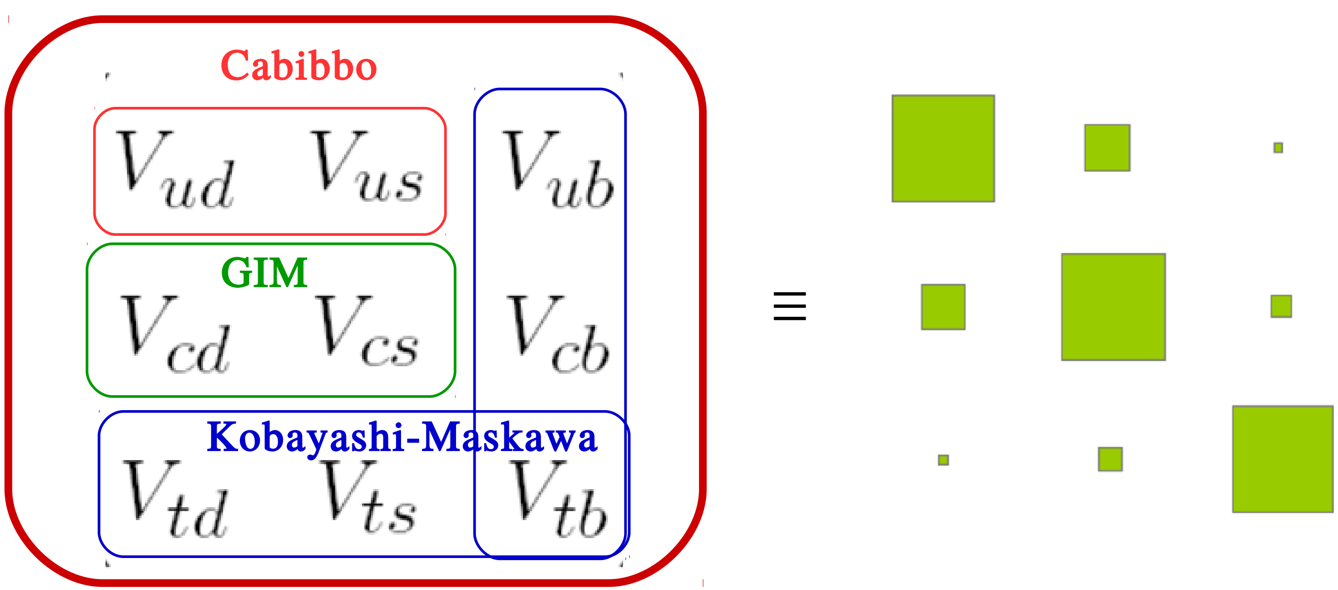
Samuel C. C. Ting

19 NOVEMBER 1976

825

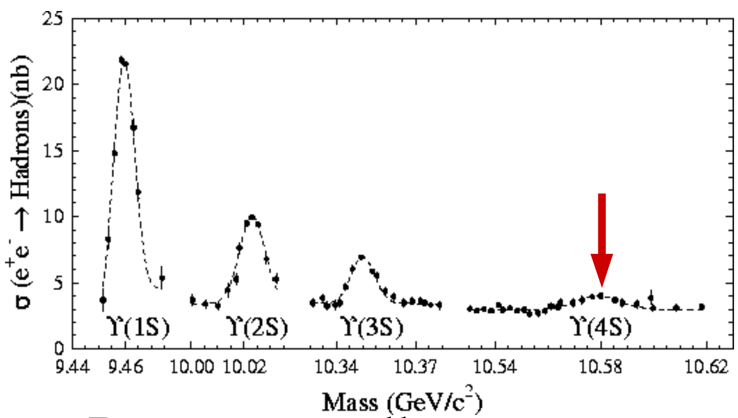
Building flavour: the third generation and CP violation

- End of the 50's: we already know that C(harge) and P(arity) symmetries were violated by the weak interaction, but what about their product, CP?
- 1964: Cronin and Fitch observe CP violation (CPV) in kaon decay.
  - And, yes, that's another Nobel Prize (1980). 
- Need CPV to explain matter-antimatter asymmetry in the Universe (Sakharov conditions).
- Kobayashi and Maskawa (1973): with at least 3 quark generations, there is one irreducible phase in the quark sector → CPV.
- Scheme vindicated by the discovery of the b quark (1977), the t quark (1994), and measurement of CPV in the *b*-quark sector → Nobel prize in 2008.

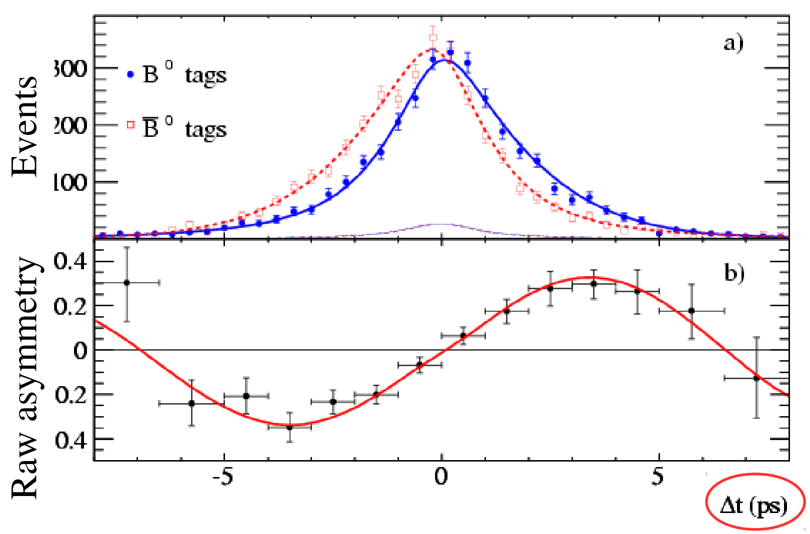


Dawn of the precision era: the B factories (1)

- e^+e^- colliders are much cleaner than hadronic ones → more suited to precision physics.
- B-factories (BaBar and Belle) ran during the 2000's at (mainly) $\Upsilon(4S)$ pole → >96% decays to $B\bar{B}$.



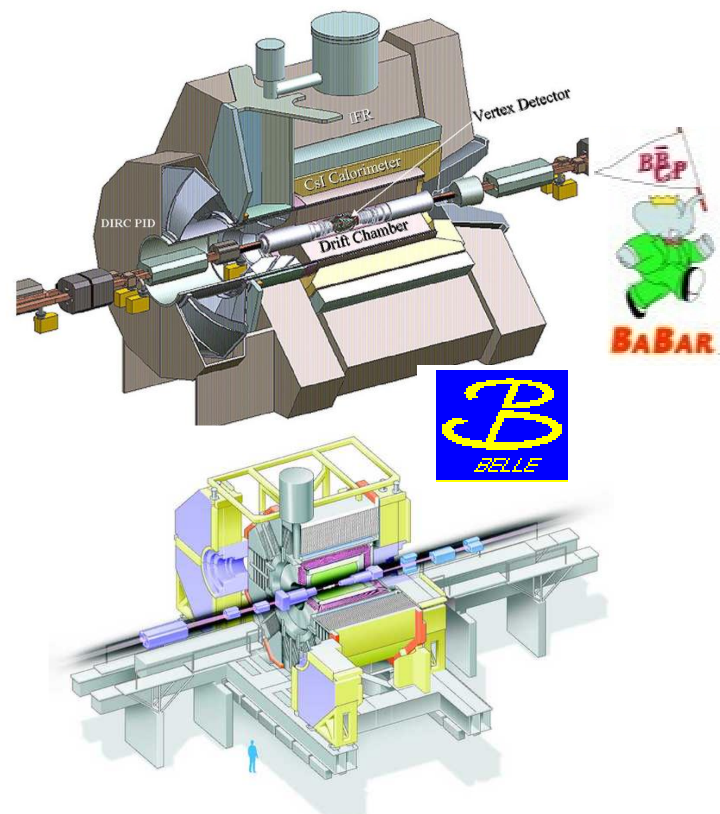
- First precise B-meson oscillations measurement!



$B = \bar{b}$ • d,u

B_d, B^+

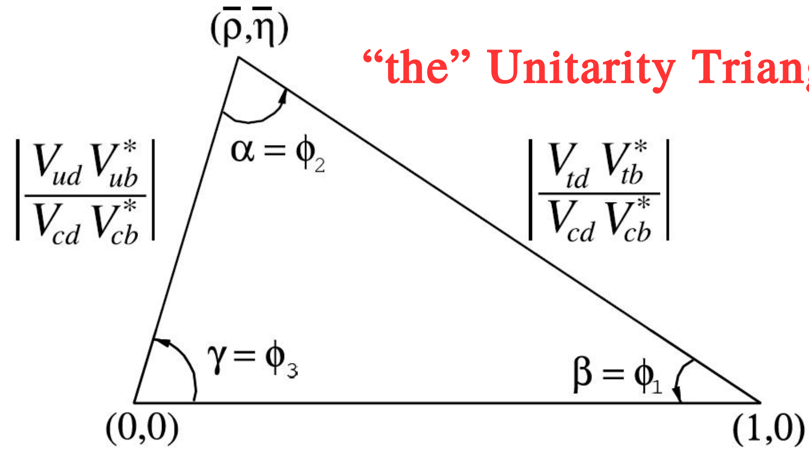
Heavy (~5.2 GeV) but lives O(100ps) → with proper boost, possible to separate production and decay.



Dawn of the precision era: the B factories (2)

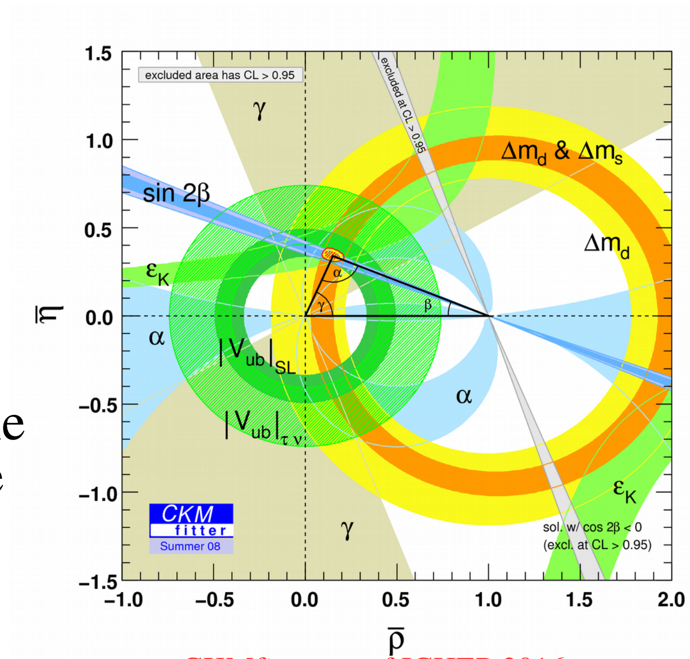
- So there is CPV in the beauty sector, but real question is: does the CKM paradigm hold?
- The CKM matrix is 3x3 and unitary → constrained.

$$V_{ud}^*V_{us} + V_{cd}^*V_{cs} + V_{td}^*V_{ts} = 0,$$
$$\boxed{V_{ud}^*V_{ub} + V_{cd}^*V_{cb} + V_{td}^*V_{tb} = 0,}$$
$$V_{us}^*V_{ub} + V_{cs}^*V_{cb} + V_{ts}^*V_{tb} = 0,$$
$$V_{cd}^*V_{ud} + V_{cs}^*V_{us} + V_{cb}^*V_{ub} = 0,$$
$$V_{td}^*V_{ud} + V_{ts}^*V_{us} + V_{tb}^*V_{ub} = 0,$$
$$V_{td}^*V_{cd} + V_{ts}^*V_{cs} + V_{tb}^*V_{cb} = 0.$$

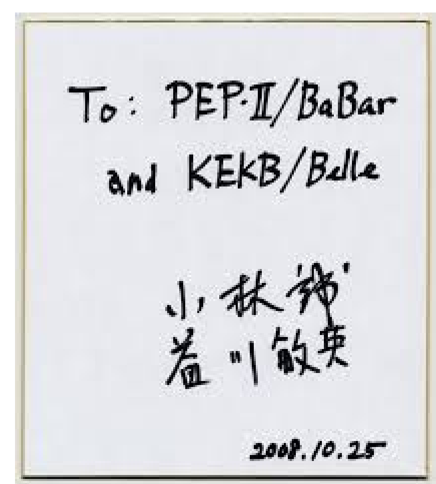


"the" Unitarity Triangle (related to B_d)

- Any new physics etc. could show as the triangle not closing.
- Constraints coming from various domains of physics: kaon, B_d, B_s, nuclear physics...
- Right: state of the Unitarity Triangle in 2008. Compatible with a triangle → model is self-consistent.

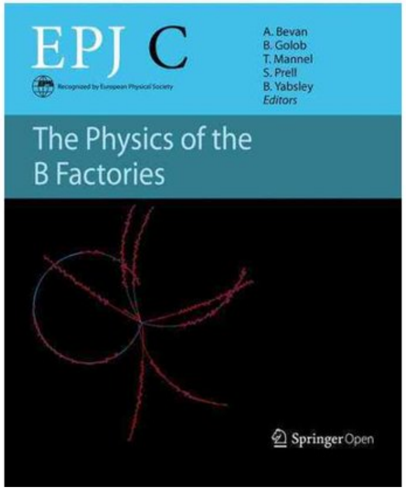


CKMfitter, as of ICHEP 2016



Kobayashi and Maskawa's "thank you" note

Legacy of the first precision era



- Of course in physics, we do not try to confirm theories but to challenge them.
- Some tantalising tensions at the shutdown of BaBar (2008) and Belle (2010).
  - Example: K-π puzzle, extraction of V_{ub} inclusive vs exclusive, $R_{D(*)}$…
- Even without anomalies, SM far from being fully explored.
- Need to explore with more precision the rest of the *b* sector: B_s, Λ_b, Ξ_b…
  - Easier at a hadronic machine that produces all of them altogether.
- Charm CP violation still to be discovered at that point.
  - Very small in the SM (absence of the top quark in the loop) → need millions of events.

N(evts) = Luminosity x Cross-section

↑ with upgrade of the accelerator and of the detector

↑ going to a hadronic collider

- However, operating at a hadronic collider is a challenge that requires very careful design.

Flavour at LHCb: where are we (going)?

That is also valid for detectors

The LHCb detector: what is that job we want?

- First things first, we won't do much flavour if we do not distinguish kaons from pions from muons → need good **PID**.
  - **Need**: manageable rates. If Cherenkov, photomultipliers need to be outside of acceptance.

- We need excellent **vertex separation** for time-dependent analyses...
  - **Need**: vertex resolution of order tens of microns.

- … and we need it to be **fast**. Due to collision rate, need a good trigger → displaced vertices signal *b* or *c* hadrons.
  - **Need**: inner tracker as close to the beam as possible.

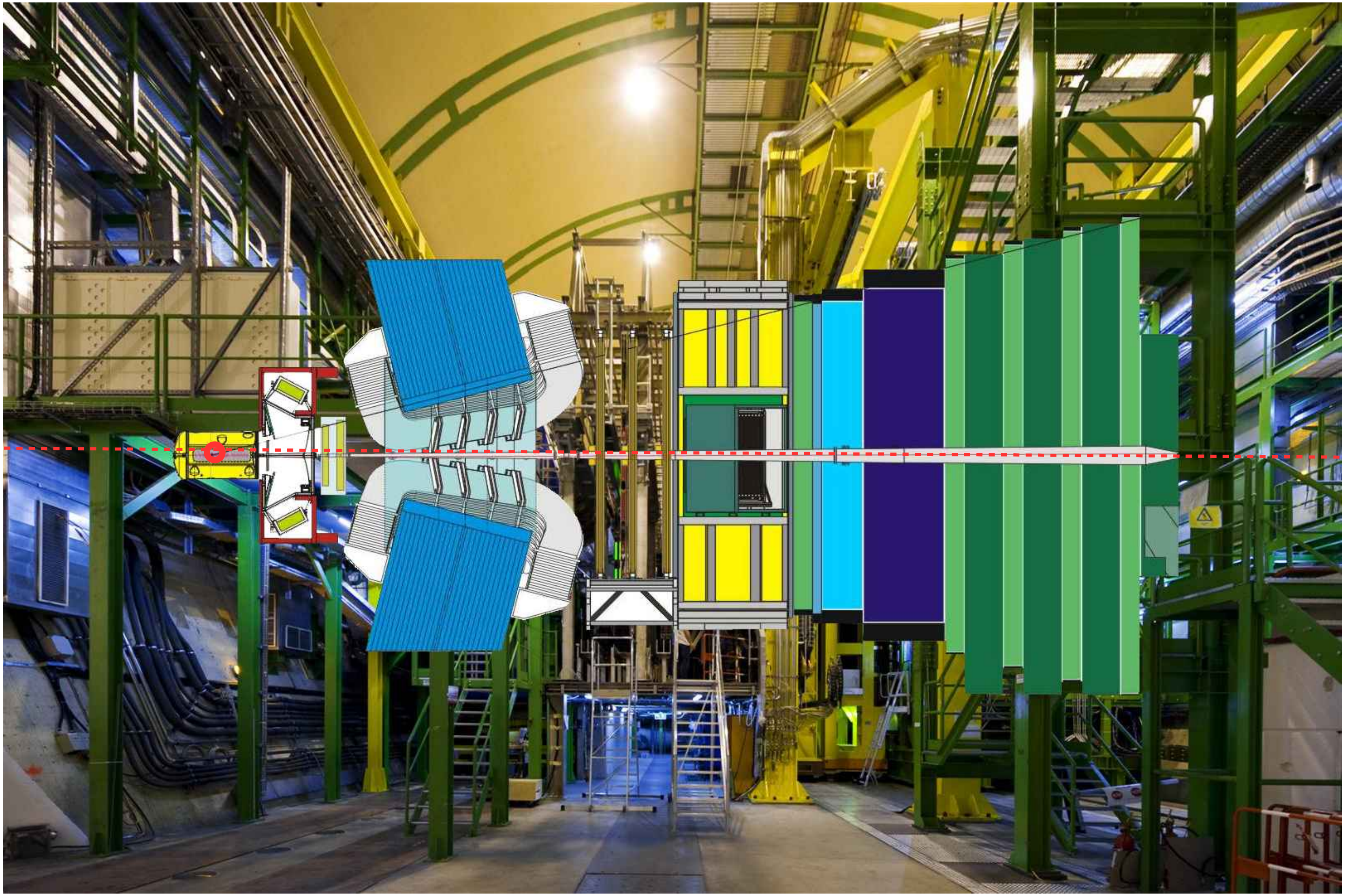
- **Tracking** is also key to perform angular and amplitude analyses.
  - **Need**: tracking stations as far as possible (tracking performance increases with leverage).

- (Good) **Calorimetry** gives access to a wide range of hadron decays, e.g. radiative decays, and helps with electron reconstruction.
  - **Need**: a good electromagnetic (e,γ) calorimeter providing space information.

The LHCb detector

The LHCb detector

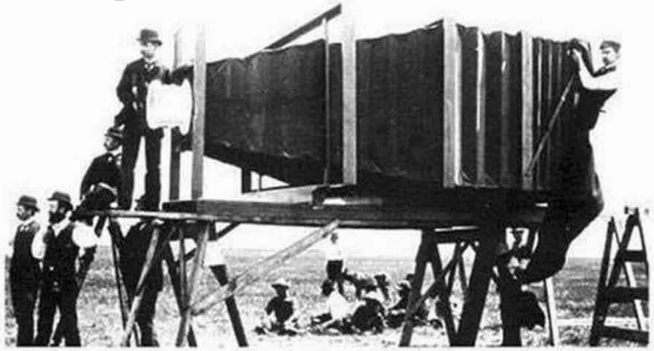
Beam pipe



Single-arm forward spectrometer [JINST 3(2008) S08005.]

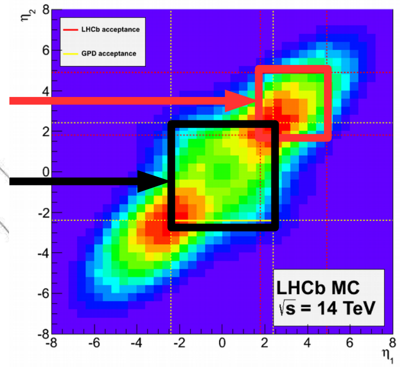
The LHCb detector: sketch

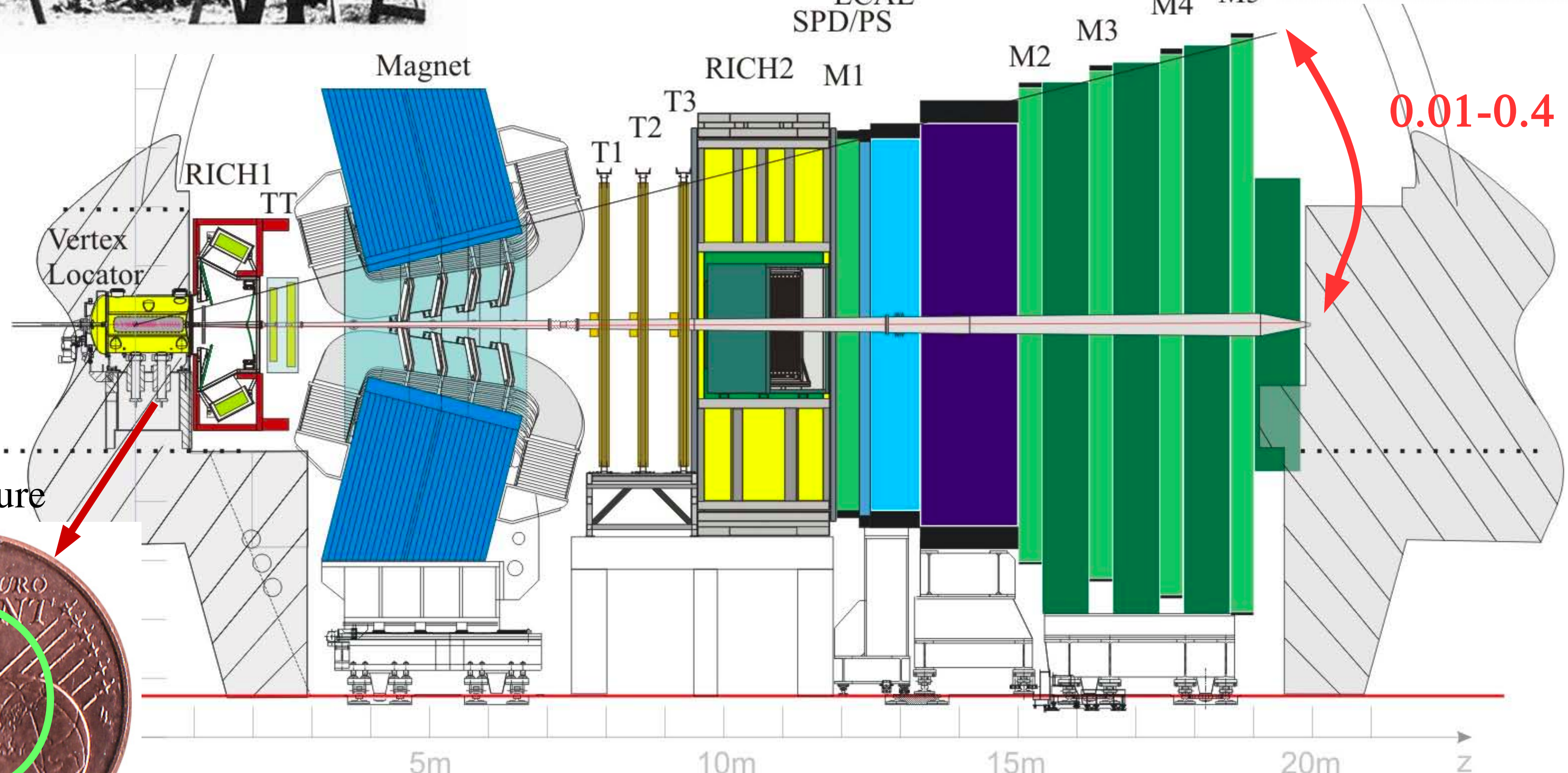
First picture of a camera (reversed)



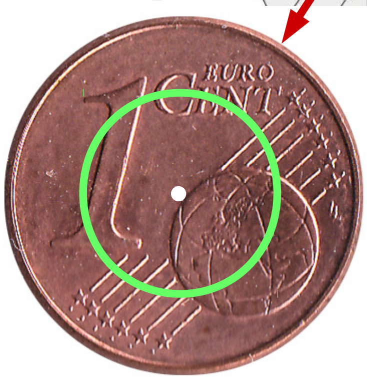
LHCb
(25%)

ATLAS, CMS
(45%)



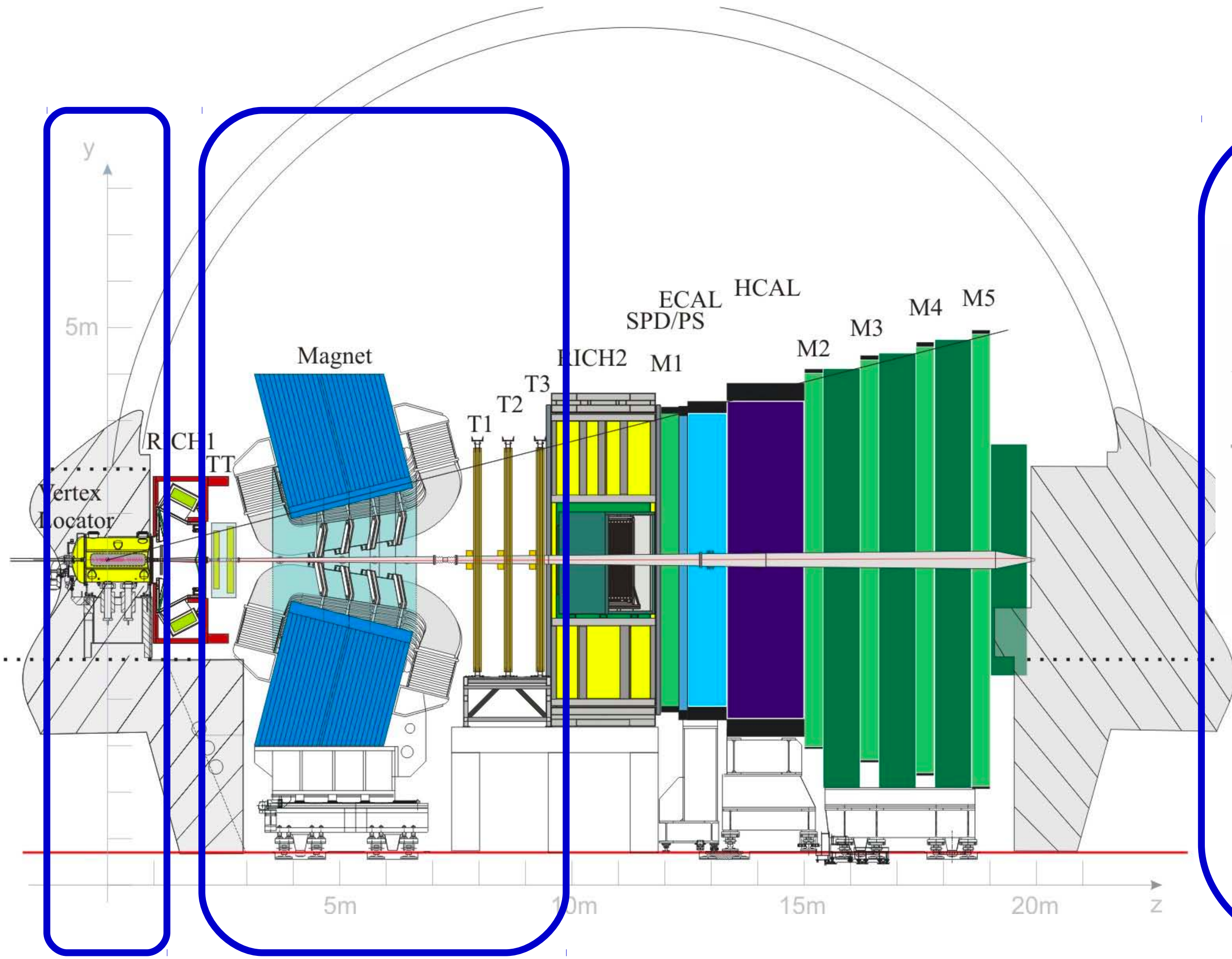


5.5mm aperture



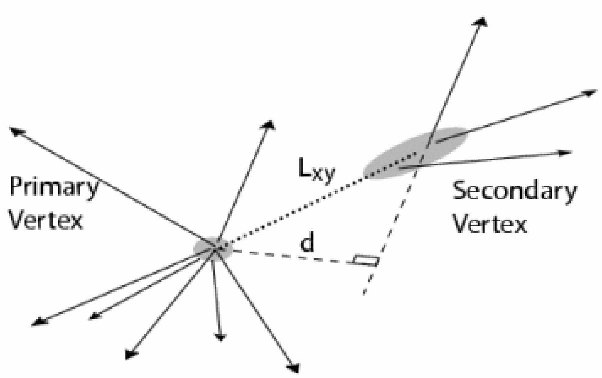
[JINST 3(2008) S08005.]

The LHCb detector: tracking subsystems



>8m arm's length

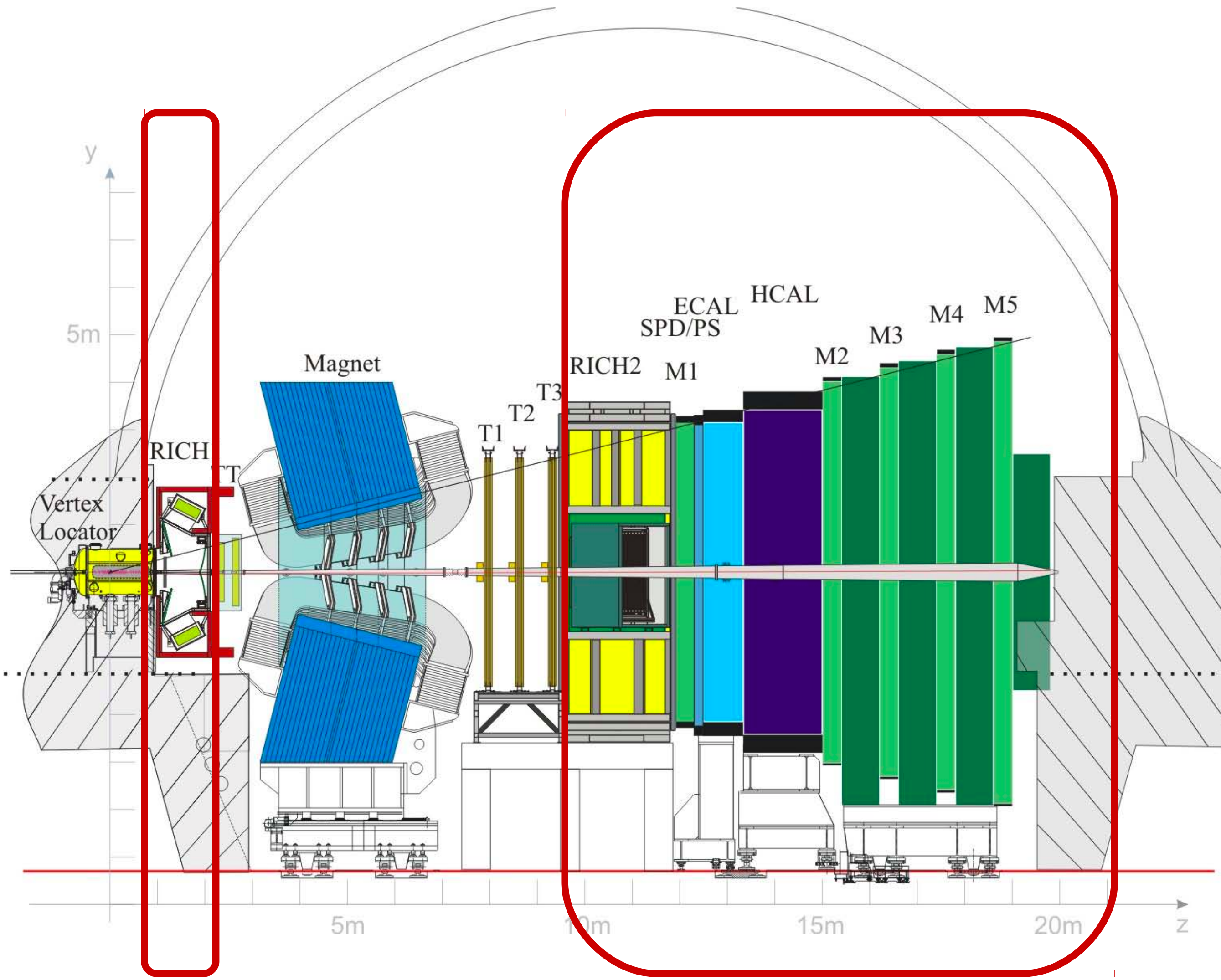
(Secondary) vertex location



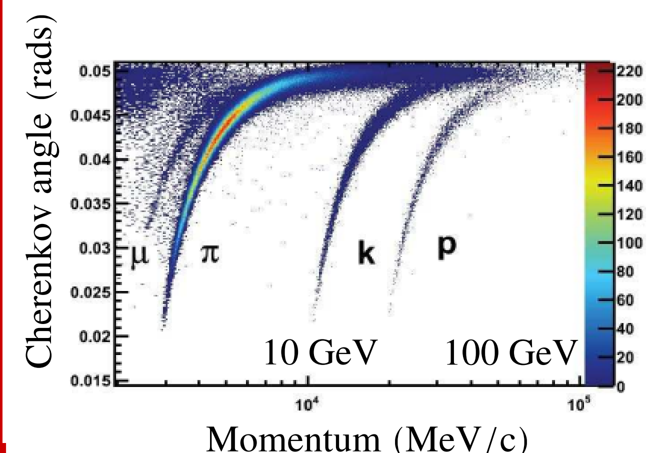
Momentum measurement

$\delta p/p \sim 0.5\%$
for Long tracks

The LHCb detector: particle identification

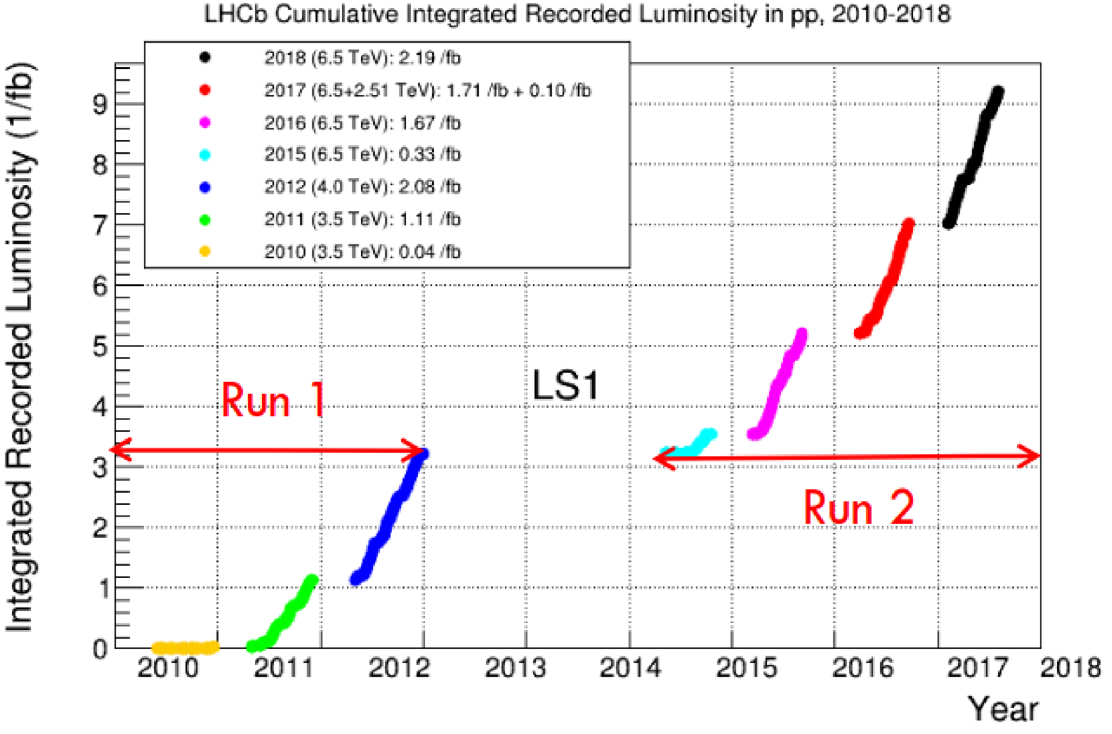


Cherenkov radiations + calorimetry



95% K/π separation efficiency for 5% misID

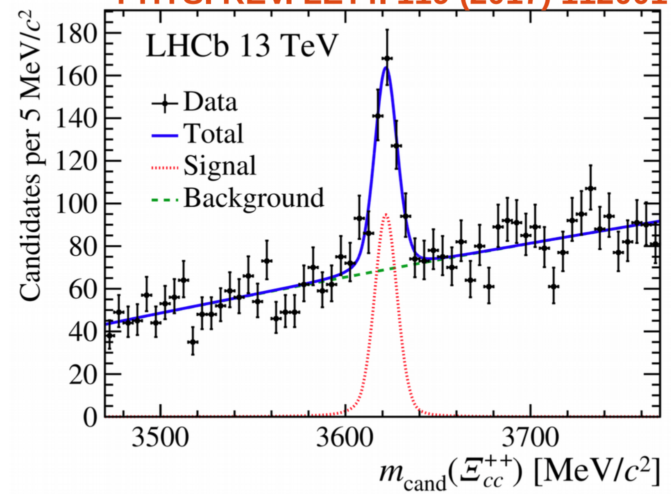
Flavour at LHCb: where are we (going)?



Spectroscopy: rainy, with a chance of hadrons

- "Single-arm forward **spectrometer**" → LHCb, apart from being a flavour detector, yields exceptional insight on hadronic physics.
- Top: discovery of the Ξ_{cc}^{++} baryon.
- Bottom: discovery of five Ω_c excited states.
- Measurement of masses and lifetimes are crucial input to hadronic physics.
- Confirmation of the Z(4430) observation, tetraquark candidate. [PHYS. REV. D92 (2015) 112009].
- "First" observation of pentaquark states ($uudc\bar{c}$).

PHYS. REV. LETT. 119 (2017) 112001



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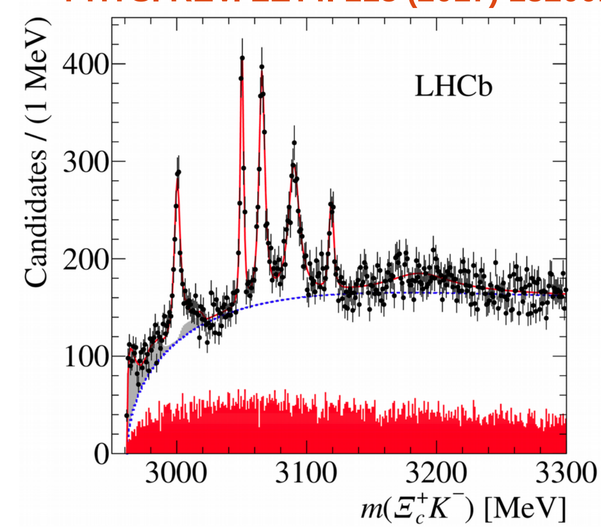

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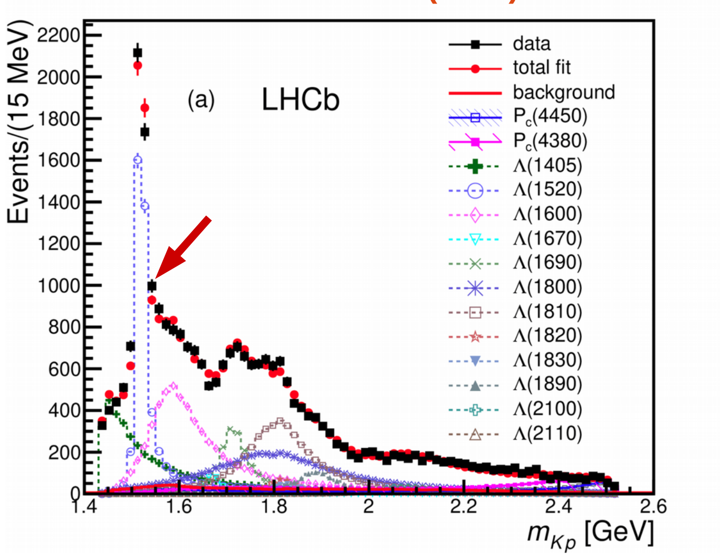

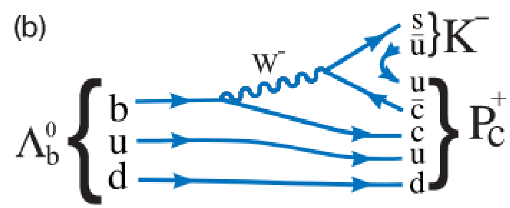


Le Monde

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PHYSIQUE

Les pentaquarks, nouvelles particules découvertes par le CERN

L'étude des propriétés des pentaquarks pourrait permettre de mieux comprendre comment est constituée la matière ordinaire.

Le Monde avec AFP · Publié le 15 juillet 2015 à 13h33 - Mis à jour le 15 juillet 2015 à 11h55

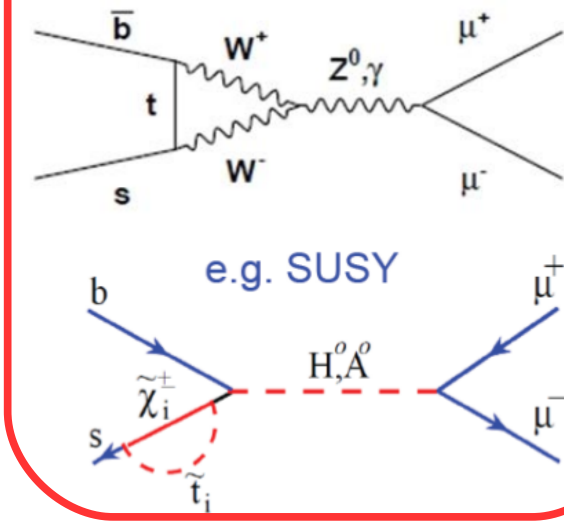
Lecture 1 min.

Precision tests of the SM: rare decays

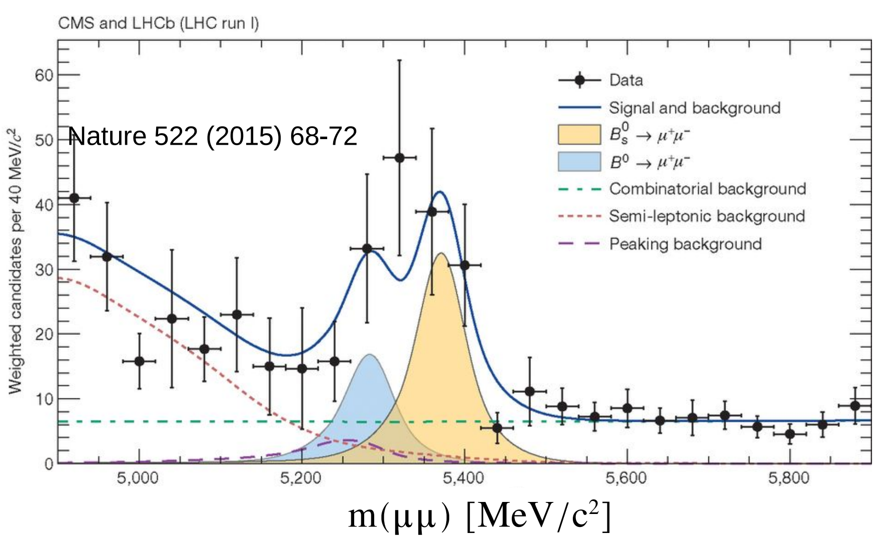
- Rare decays are (most often) decays that are extremely suppressed in the SM and proceed through loops.
  - Loop: possibility for NP to "plug in" and enhance rates.
- $B_s \rightarrow \mu^+\mu^-$ is such a channel, and also has clear experimental signature accessible by LHCb, but also ATLAS and CMS.
- SM prediction: [PRL 112 101801 (2014)]

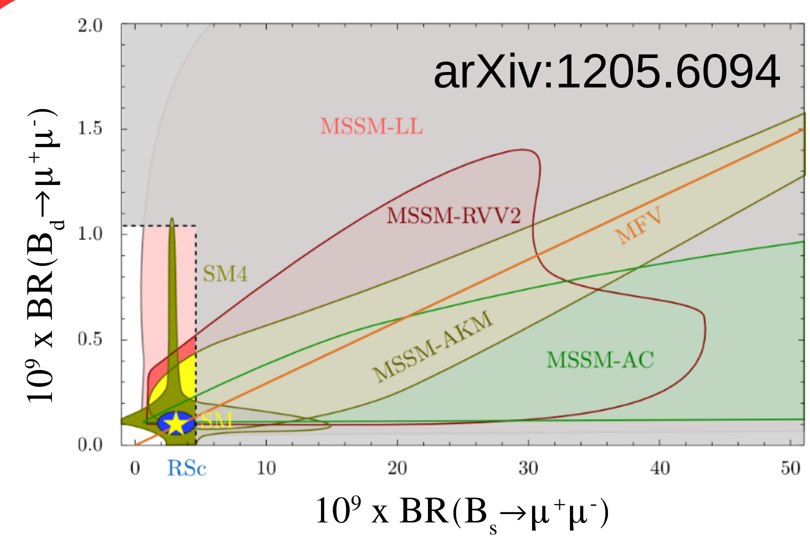
$$\mathcal{B}(B_s^0 \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

FCNC + helicity suppression
→ very rare decay in the SM



- 2012: first observed, 2015: joint LHCb+CMS analysis, 2017: new LHCb paper

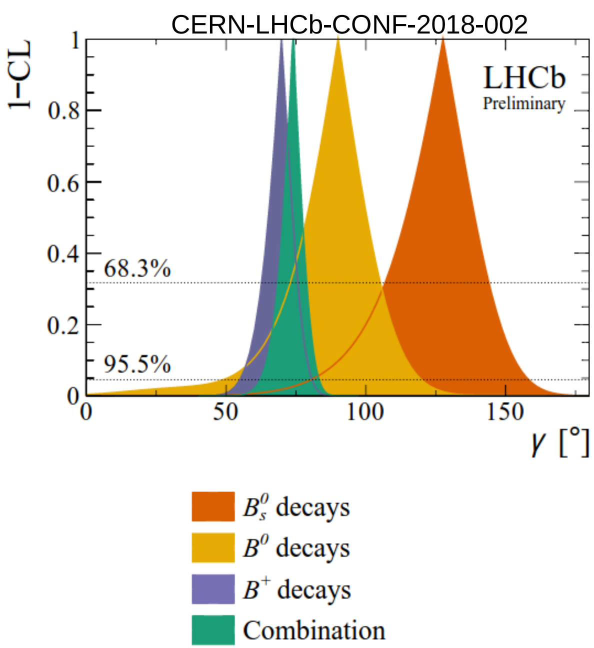




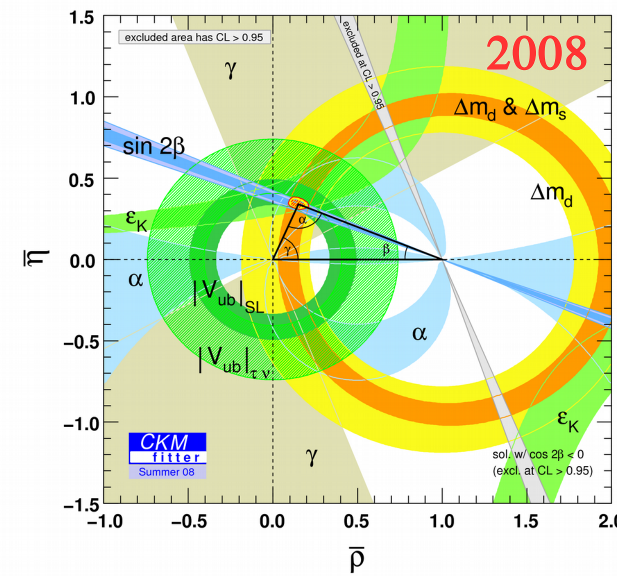
Extremely powerful null test

Precision tests of the SM: the unitarity triangle

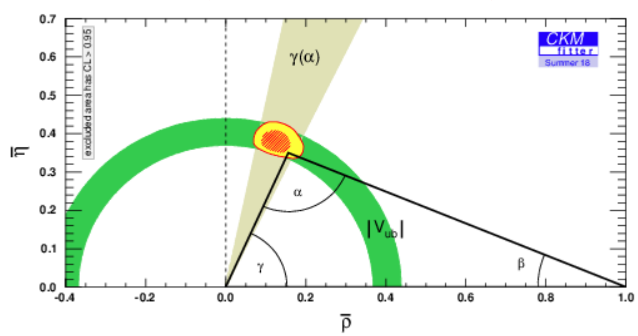
- Progresses are far from being only LHCb
  - B-factories have continued analysing their data since they stopped data-taking.
  - Other experimental and **theoretical** inputs have improved.
- Main improvements on:
  - Δm_d and Δm_s: (way) more statistics.
  - γ angle: 5° uncertainty (world average), dominated by LHCb.
- Extracted from B to open charm decays.

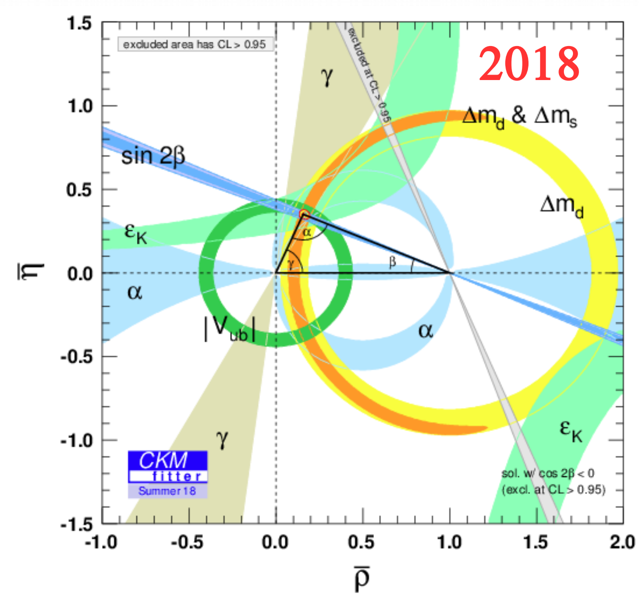


Theoretically very clean (tree-level observable). Prime goal to improve it.



Tree-level triangle ("SM candle")



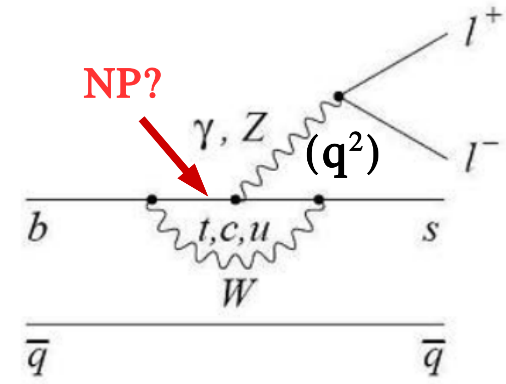


Precision tests of the SM: lepton-flavour universality

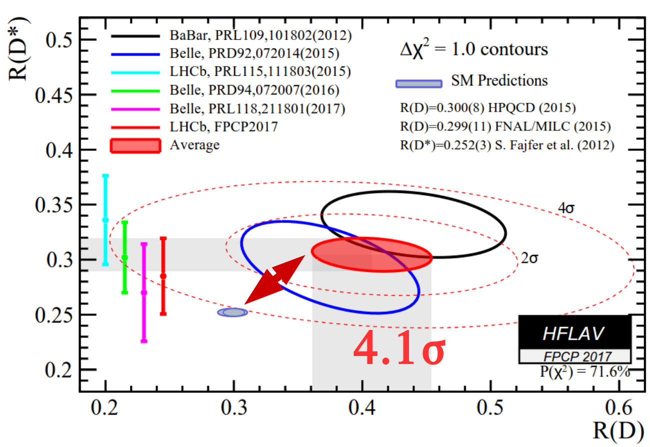
- In the SM, leptons are exactly the same apart from their mass (and neutrino oscillations).
  - Clean theoretical observable: ratio of branching fractions of $b \to X l^+ l^-$, e.g.

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

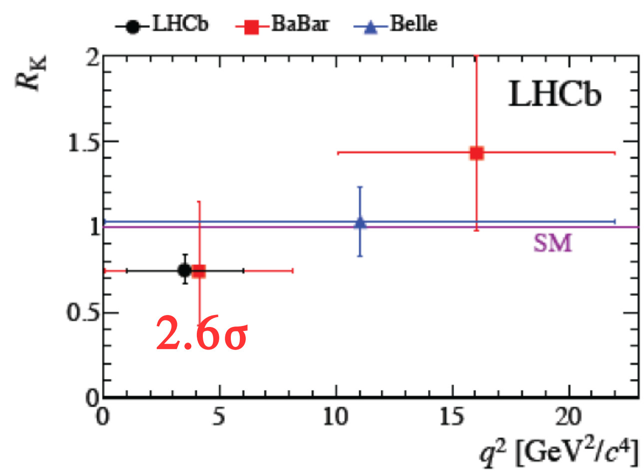
- Harder than it looks:
  - at LHCb, electrons are difficult and response is not universal.
  - Tau leptons decay with at least one neutrino.



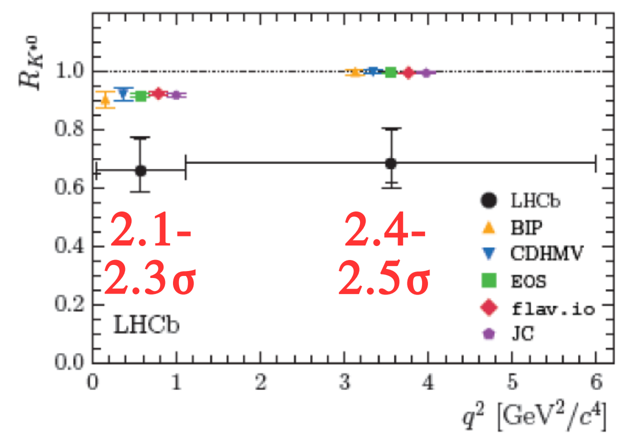
Example of a b→sll diagram



With τ/μ



With μ/e



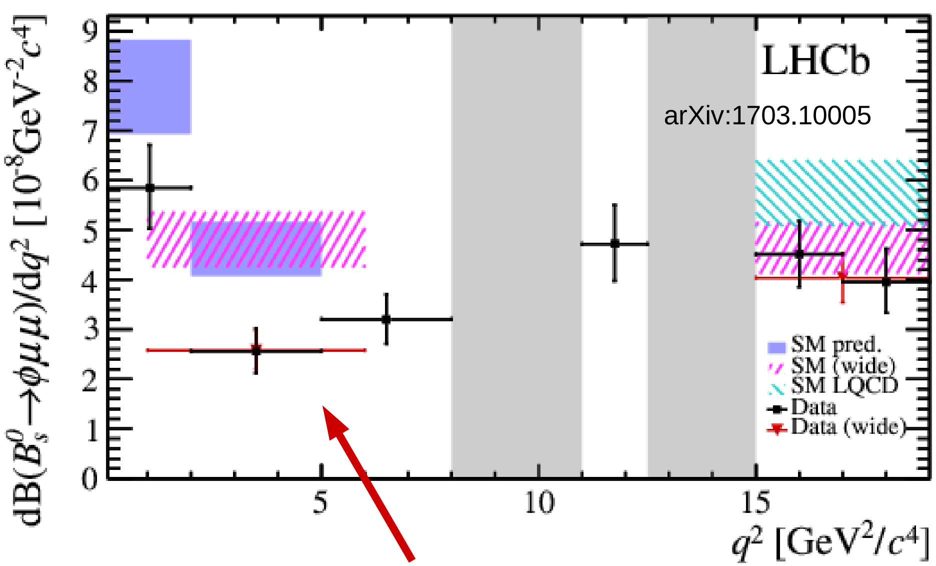
With μ/e

Deviations observed in both R_D, R_{D*}, R_K and R_{K*} modes.

Precision tests of the SM: angular analyses of $b \to s\mu^+\mu^-$

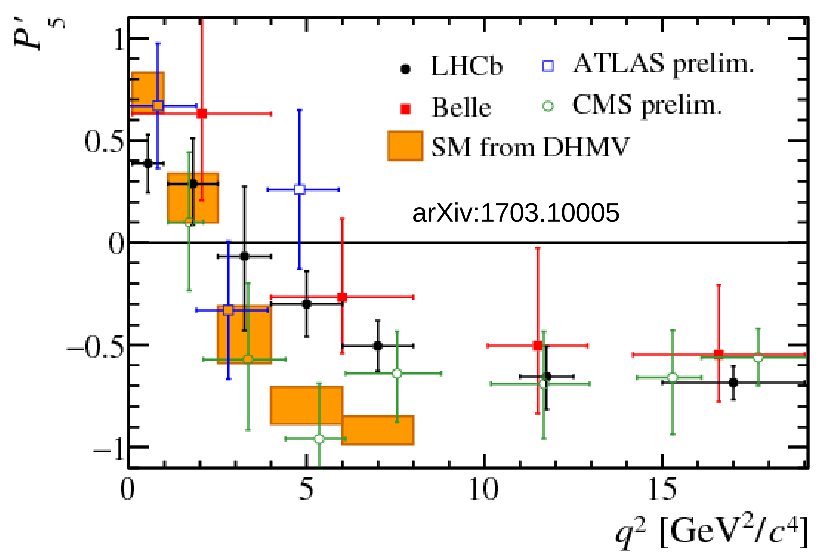
- Another way of accessing "clean" theoretical observables is to perform angular analyses as a fonction of the di-muon momentum q^2.
  - Differential branching fractions.
  - "Optimised" angular observables.
- Pros: relies on muons only, avoiding complicated corrections to electrons in LHCb.
- Cons: charm-loop corrections cannot be cancelled out by the ratio → veto some regions.

$B_s \to \varphi\mu\mu$ differential branching fraction



Local >3σ deviation

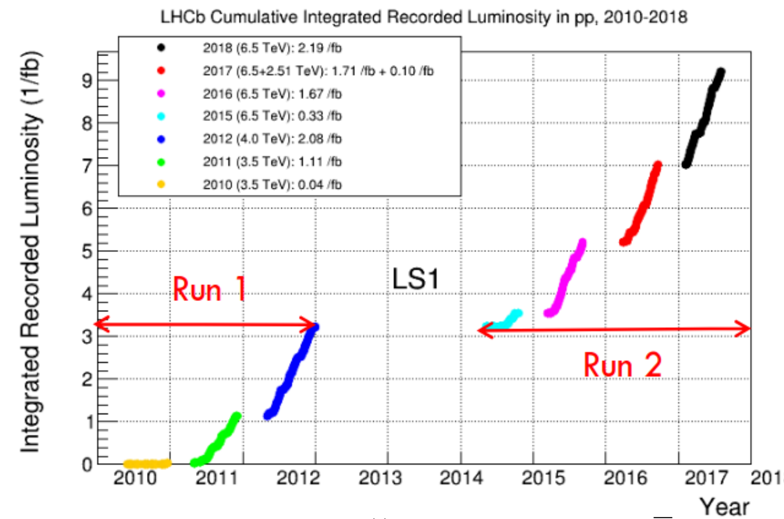
P_5' angular variable differential distribution in $B_d \to K^*\mu^+\mu^-$ decays.



Overall 3.4σ deviation

Precision tests of the SM at LHCb: where are we?

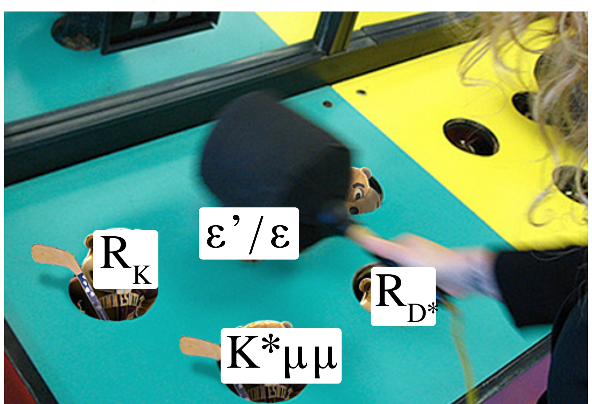
- Most results presented are only on Run 1.
  - Expected 4 times as many events in Run 2.
  - Quick maths: expected to double the significance.
- Run 2 data has single-handedly the potential to confirm some anomalies or to discard them.
- Being analysed → 2019 could see results of prime importance.



Reminder: y x10^{11} → ~ number of $b\bar{b}$ pairs.

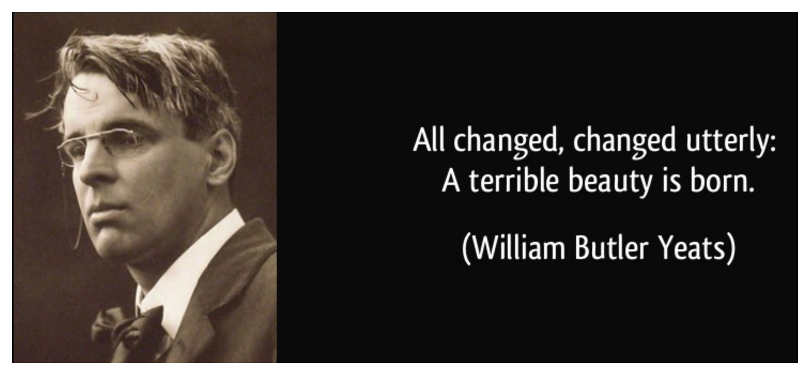
- **Not the whole story: powerful null tests by the same experiments!**
- Discussing the anomalies would take a full seminar but take-home message: data alone cannot do everything: need theorists input.

2019 should tell us if



"Whack-an-anomaly" game goes on

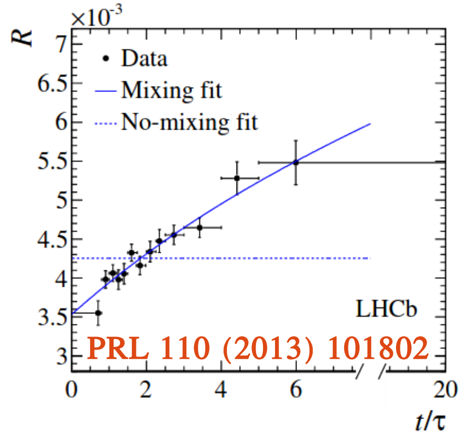
or

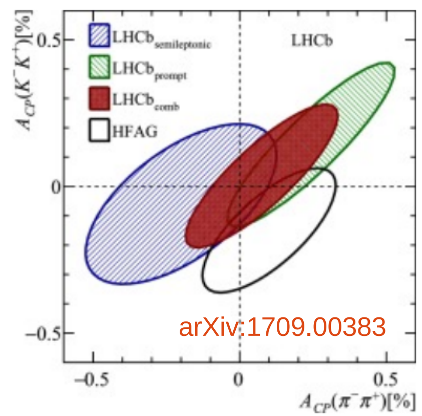


We got new physics, at last

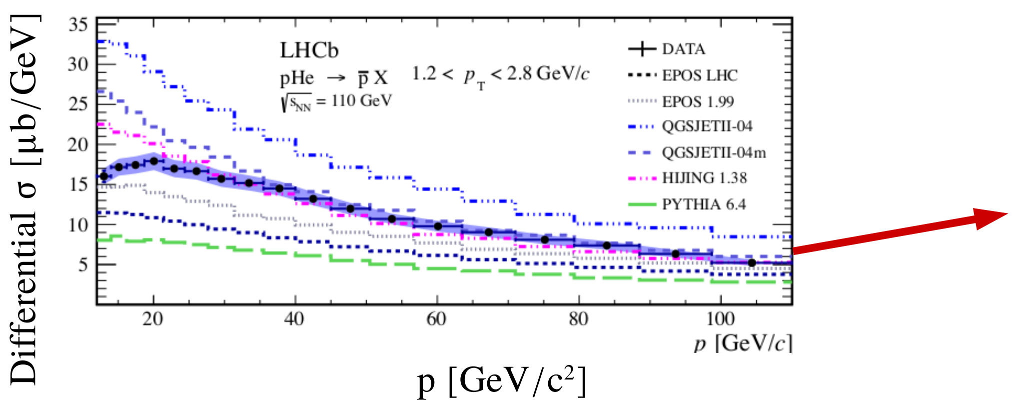
LHCb-wide: where are we?

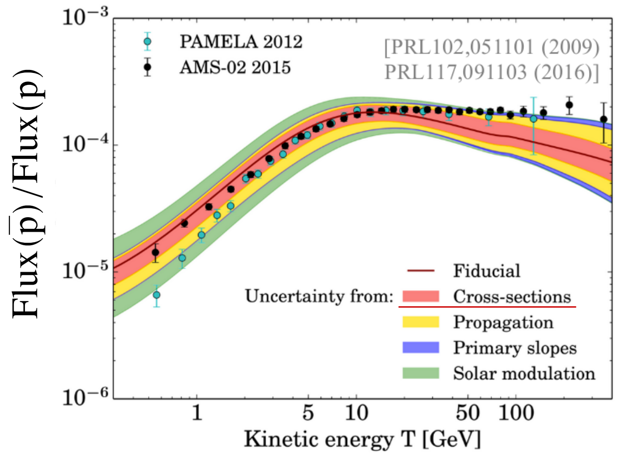
- This presentation has covered a large variety of physics and yet many important results not shown here, for instance:
  - Charm mixing and improved constraints on CPV in charm





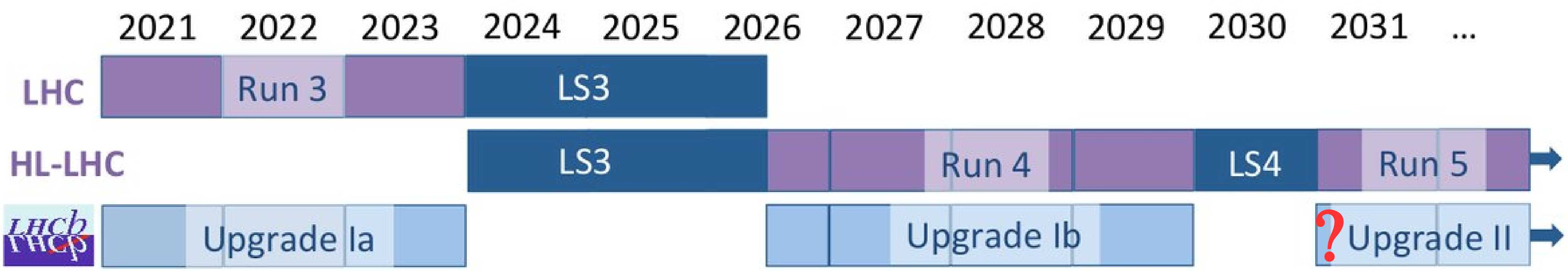
  - Fixed-target running mode: measurement of anti-proton production in p-He collisions.[Phys. Rev. Lett. 121, 222001] → uncertainty from cross-section in AMS/PAMELA

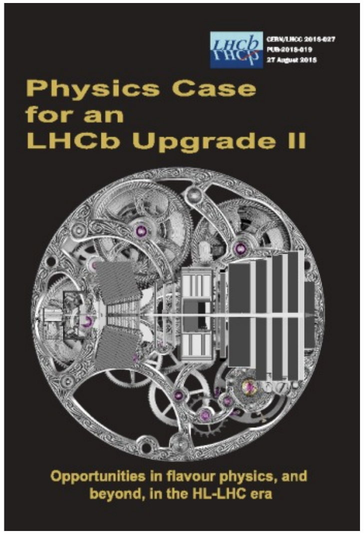




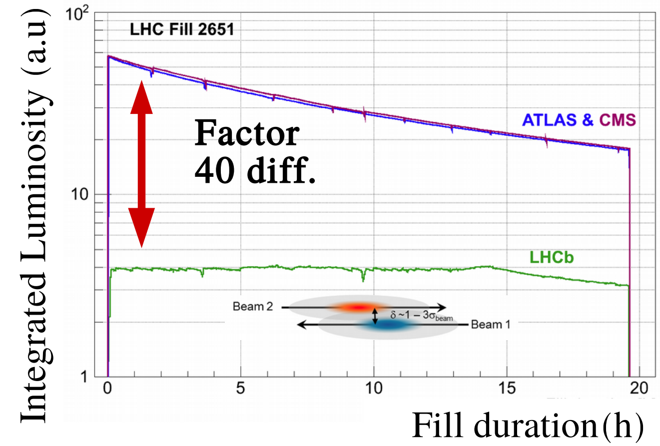
Aside from B anomalies, varied and successful physics programme with impact ranging way beyond flavour.

Flavour at LHCb: where are we going?

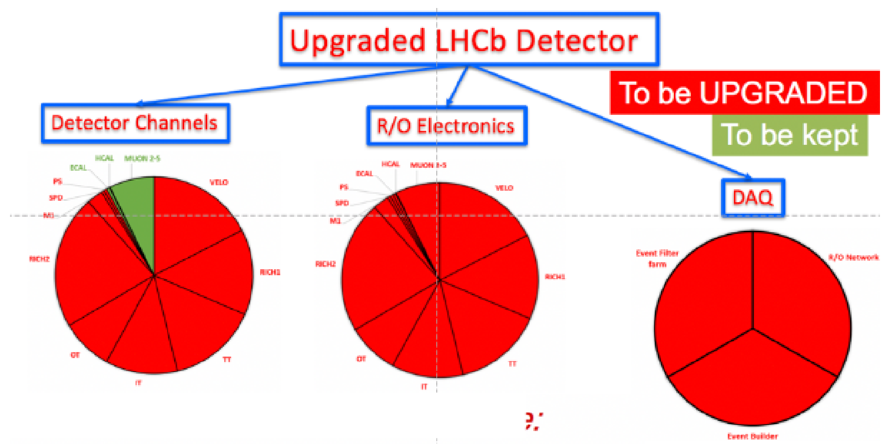




The LHCb upgrade: why, and why now?



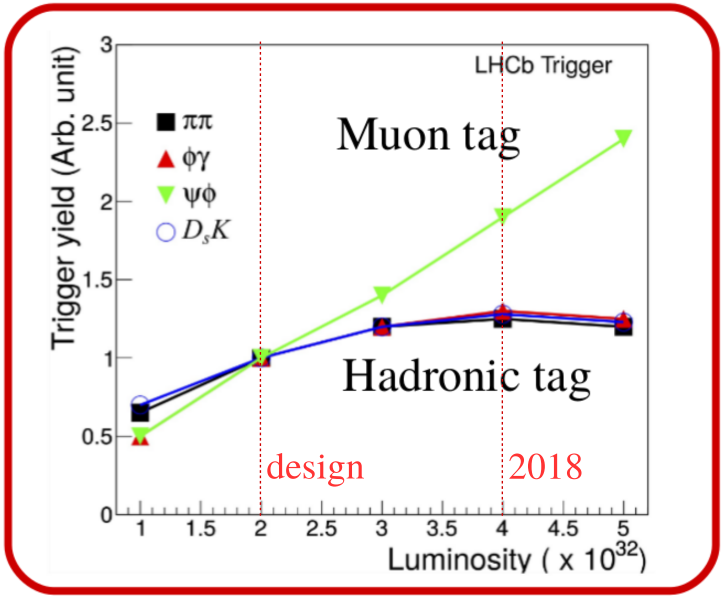
- Most of the measurements reported are limited by statistics.
- From 2010 to 2018, LHCb levelled the luminosity during a given LHC fill by defocusing beams.
  - If levelling reduced, possible to increase luminosity in LHCb.
  - We were already at twice the design luminosity.
- Necessitates overhaul of the detector: faster readout needed, better granularity and radiation resistance, especially the tracking subsystems.
- Upgrade has already started! Has to be done by 2021.
- For all intents and purposes, this is a new detector.



The LHCb detector is dead, long live LHCb

The LHCb upgrade: trigger system

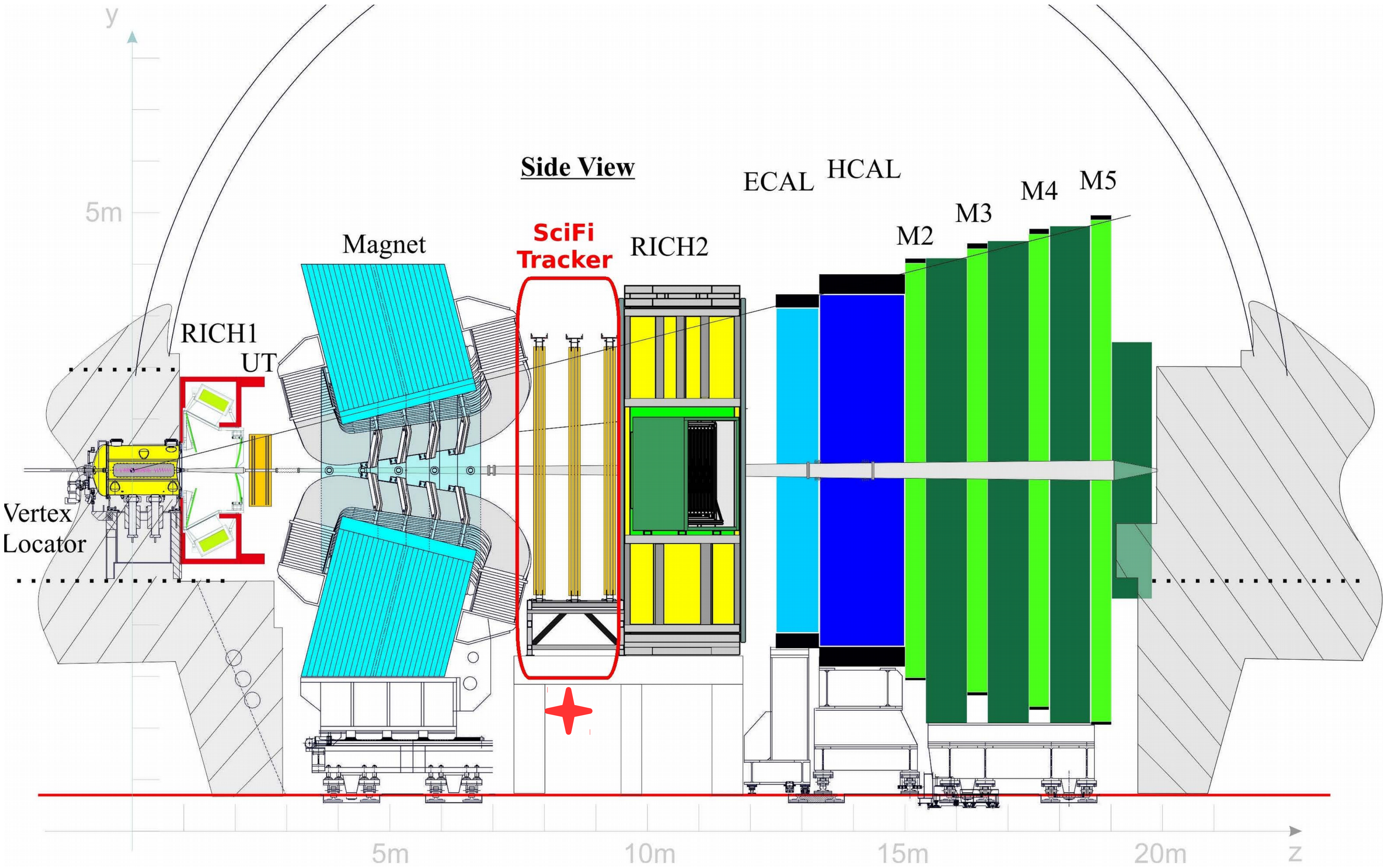
- It is useless to produce more interesting events if we are unable to study them.
- LHCb used to rely on hardware + software trigger.
- At such high luminosities, hardware trigger cannot discriminate and starts rejecting random events.
- **Full software trigger** needed:
  - Means not only reconstruction at 25ns but alignment and calibration.
  - Even more pressure on sub-detectors to deliver data fast → need to develop more efficient algorithms.



Trigger today

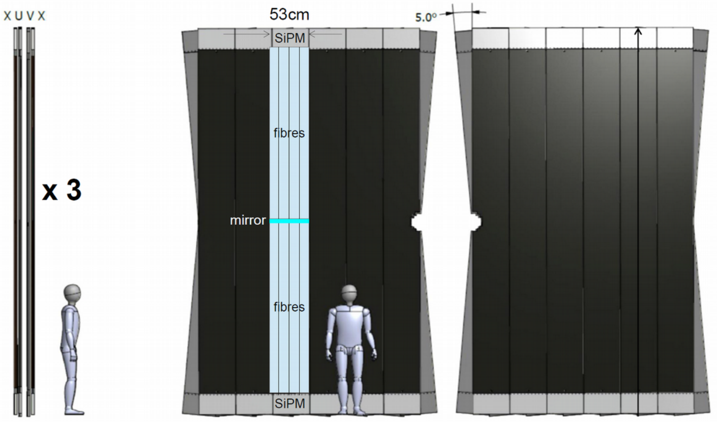
Real-time analysis of tomorrow

The LHCb upgrade: overview

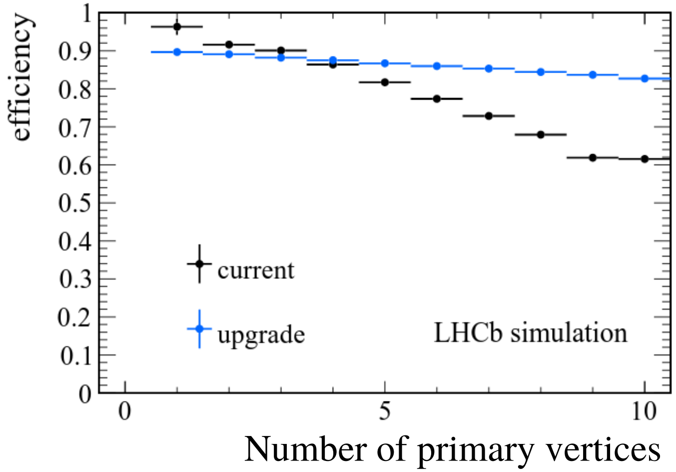


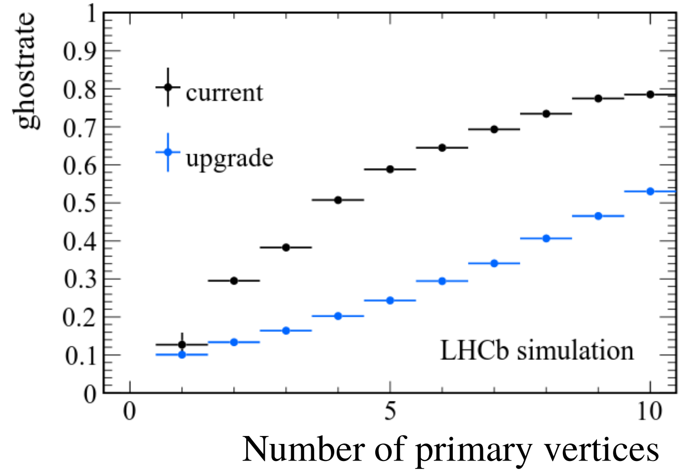
The LHCb upgrade: example of the SciFi subdetector

- Previous forward tracker was a combination of silicon microstrips and straw tubes.
  - Straw tubes difficult to operate at upgrade luminosity.
  - Need faster readout.
- Upgrade to scintillating fibers, each 2.5m long.



- Right: performances of the current (black) and projected (blue) detectors in Run3 conditions.

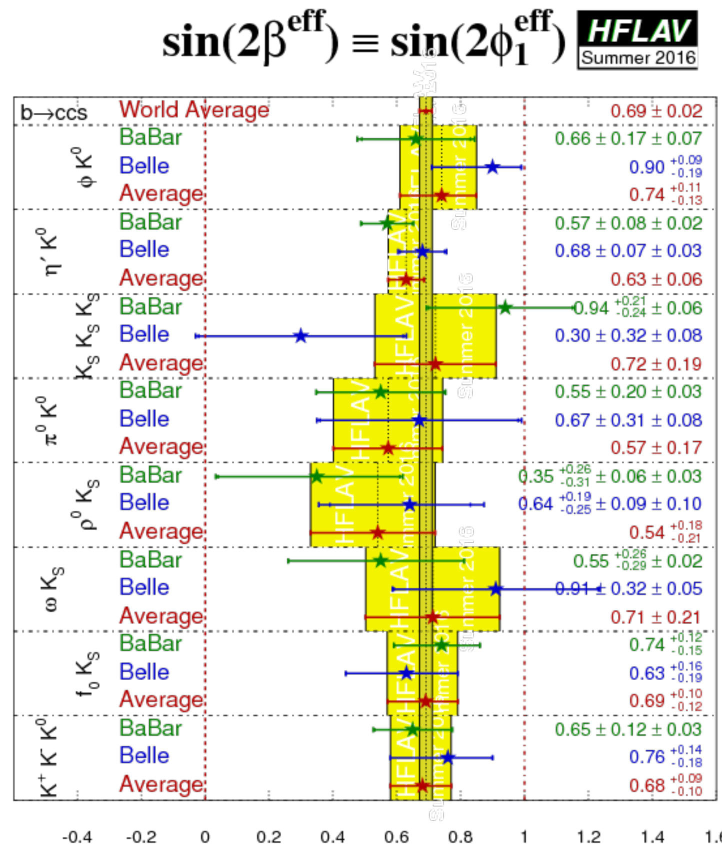




- Everything has to be thought again, from tracking algorithms to data decoding (preparation for tracking).
- Example from personal experience: transition from naive decoding to more optimised one → gain of factor ~4 speed.

What to do with all this data? The example of charmless decays

- More data does not only mean reducing uncertainties on statistically limited measurements.
- Some analyses are only possible once a certain amount of data is accumulated.
- Example: charmless physics:
  - Charmless b decays suppressed at tree level($\rightarrow$ BR < 10^{-4}).
  - Not dealing with muons but with kaons and pions $\rightarrow$ poorer efficiency than J/Ψ modes.
  - Can be used e.g. to extract weak phases in loop-dominated processes that are sensitive to NP $\rightarrow$ comparison value extracted from tree-dominated $b \rightarrow c\bar{c}s$ decays.
- Best sensitivity through full amplitude analysis.
  - Sensitivity to strong phases, no trigonometric ambiguity, more transitions.



Expected phase transition for charmless analyses at LHCb, from first observations to full-fledged amplitude analyses extracting weak phases

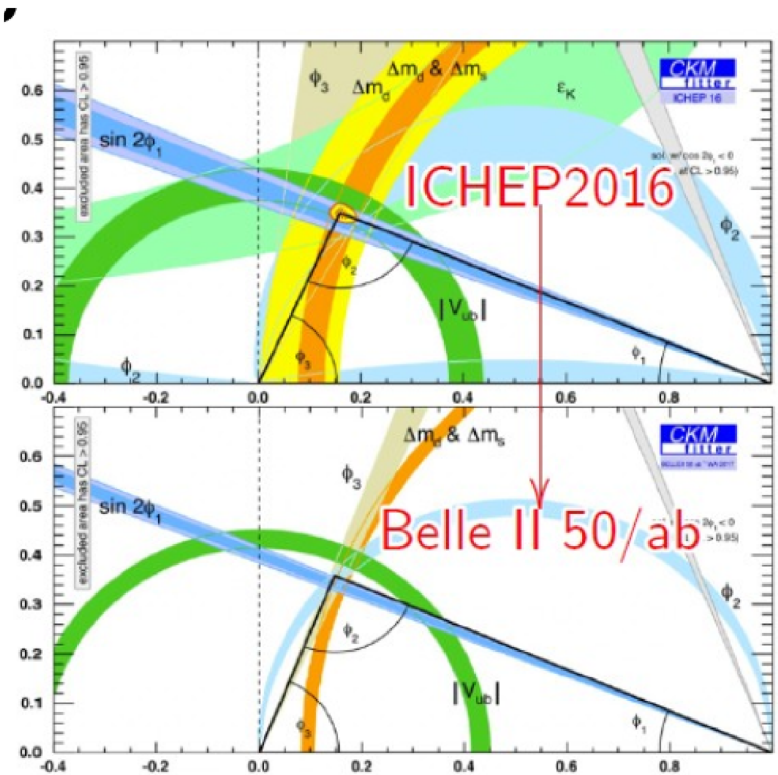
Flavour beyond LHCb

Belle 2: competition or coworker?

N(evts) = Luminosity x Cross-section

The Belle 2 way — The LHCb way

- Belle 2 is a super B factory with luminosity x 50 compared to previous ones.
- Pros of a B factory:
  - you know what you order → precise flavour tagging, better ability to deal with neutrinos or inclusive decays.
  - better handling of K^0 mesons, electrons, gamma, π^0.
- Cons of a B factory:
  - you know what you order → less rich zoology of initial states (b baryons, B_s mesons…)
  - despite high luminosity, much lower cross-section → more $b\bar{b}$ pairs in LHCb.
- For instance, better place to shed light on the "K-π" puzzle.
  - $A_{CP}(B^+ \to K^+\pi^0) \neq A_{CP}(B \to K^+\pi^-)$.

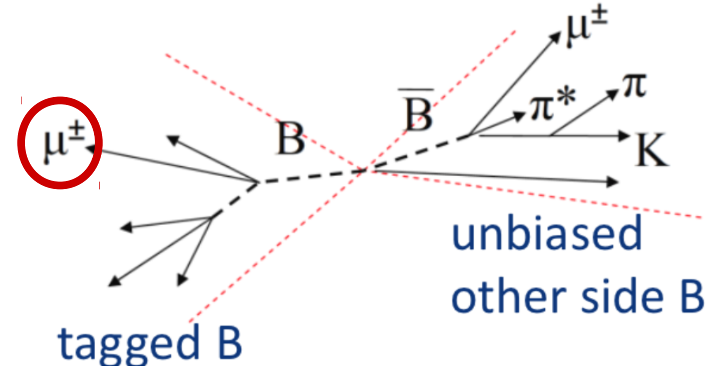


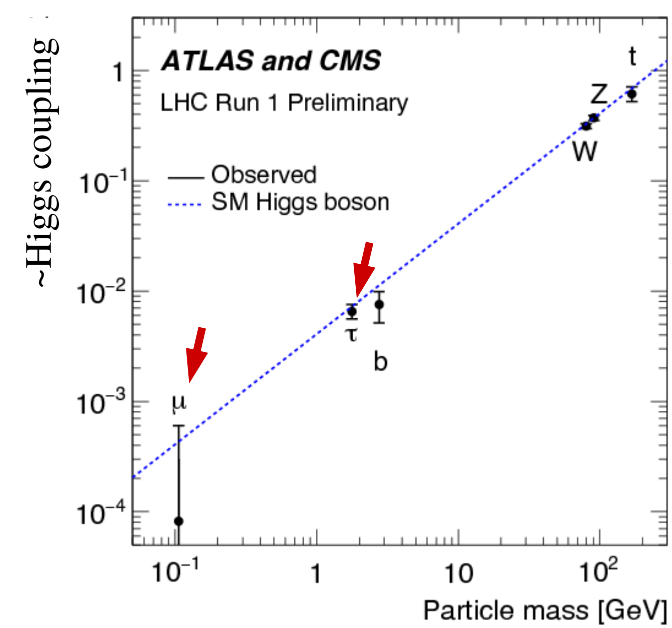
Unitarity triangle

Personal summary: Belle has more final states, LHCb has more initial states.

And ATLAS and CMS?

- Already contributed to the field of flavour physics (e.g. with the $B_s \to \mu^+\mu^-$ CMS contribution).
- Much larger datasets than LHCb → opportunity to study modes for which LHCb is very statistically limited (rare decays, B_c^+ ($\bar{b}c$ mesons)decays).
- Very different experimental techniques → interesting cross-check.
- Challenge is partly on the trigger, optimised for much higher-p_T signatures.
- CMS has parked near the end of Run 2 part of its dataset for flavour physics.
- Goal was collecting sample of ~10^{10} unbiased B decays.
- A more precise measurement of Higgs couplings to leptons will characterize any new physics contribution and its relation to the (hidden) Higgs sector.

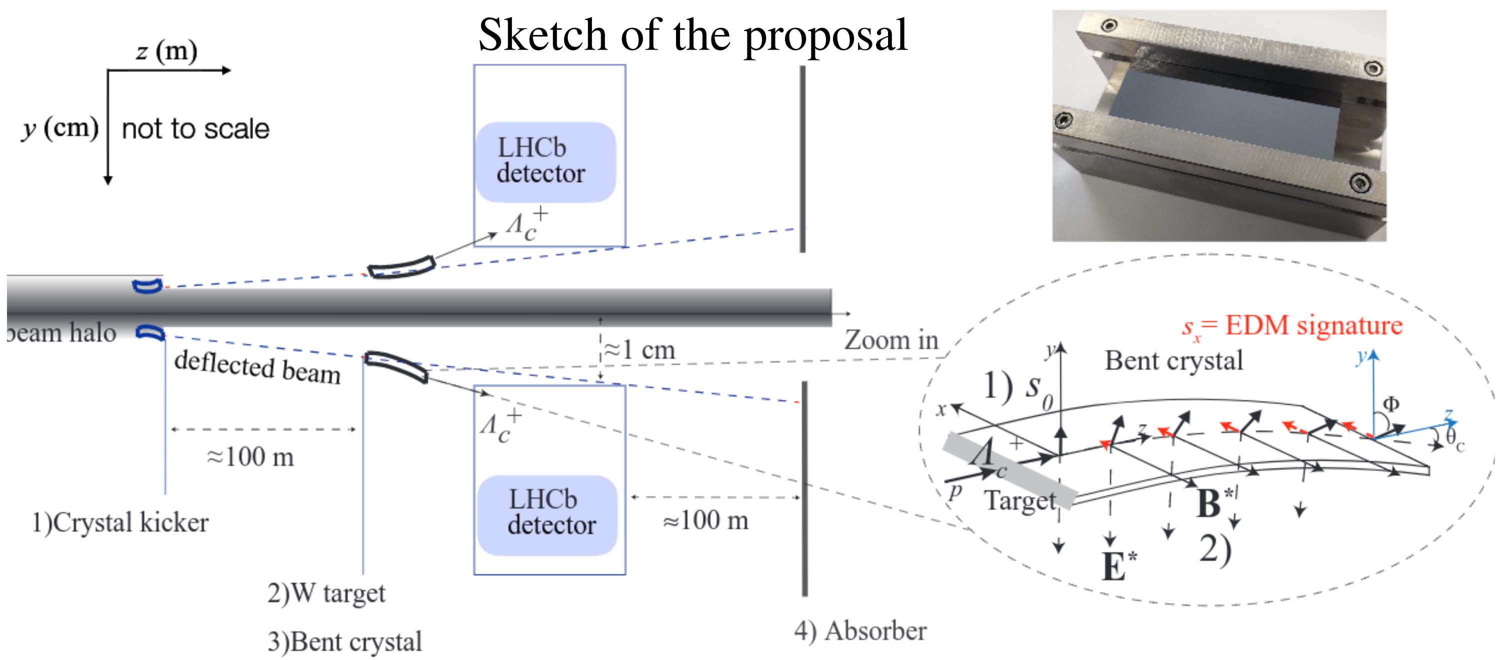




Fixed-target opportunities at the LHC

- Since 2016, Physics Beyond Collider group at LHC, investigating opportunities at LHC.
- Proposal for the measurement of electric and magnetic dipole moments of the **charm quark** and, more recently, the **τ lepton**, using bent crystals.
- Related to B anomalies and long-standing (g-2) muon dipole moment anomaly?
- Principle:
  - Dipole moments are usually measured through spin rotation in a magnetic field.
  - Charmed baryons and τ leptons live too shortly and need ~1000T magnetic field.
  - High-momentum charged particles going through a bent crystal feel fields of order 1000T.

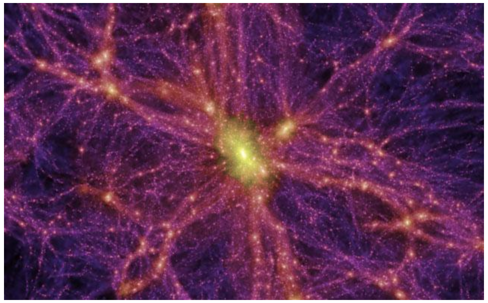
Sketch of the proposal



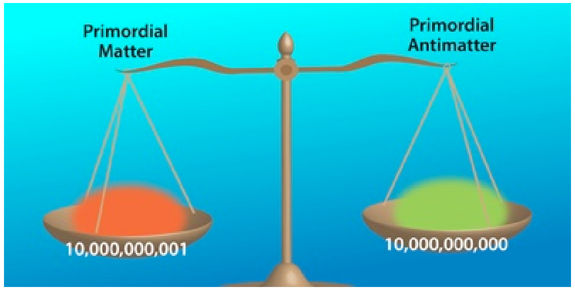
Placing flavour back in the general landscape

- Lately under the spotlight due to the so-called “B anomalies”.
- If they are confirmed, does not automatically yield the answer to **any** of the issues.
- Indirect searches, while powerful, can only tell you that something is there, and a bit about that something.

Astrophysical observations



Dark matter



Baryon asymmetry of the Universe

Particle physics

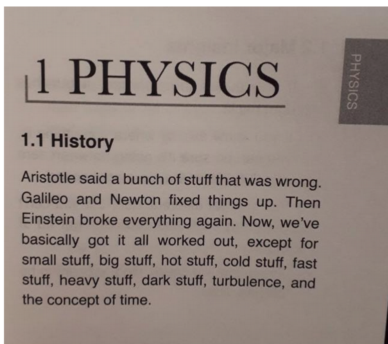
- Look for CPV
- Look for unknown particles/interactions

Astrophysics

- Look for excesses of antimatter
- Find dark-matter

They have to go together

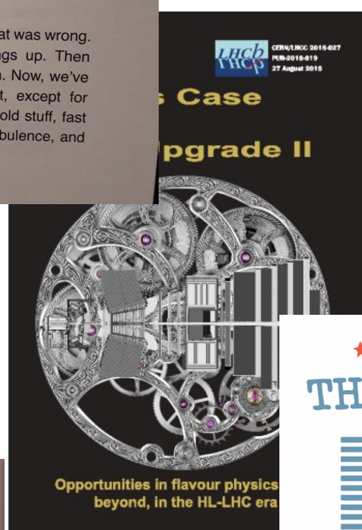
Thank you!

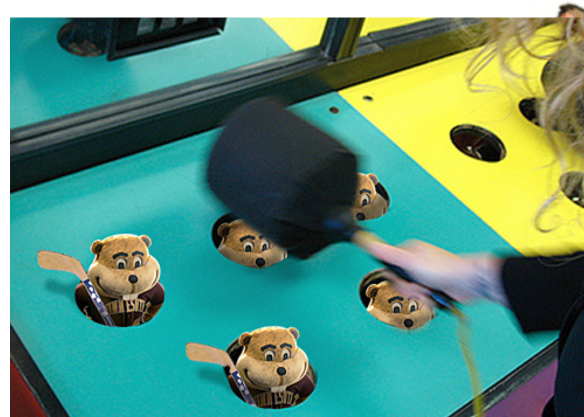


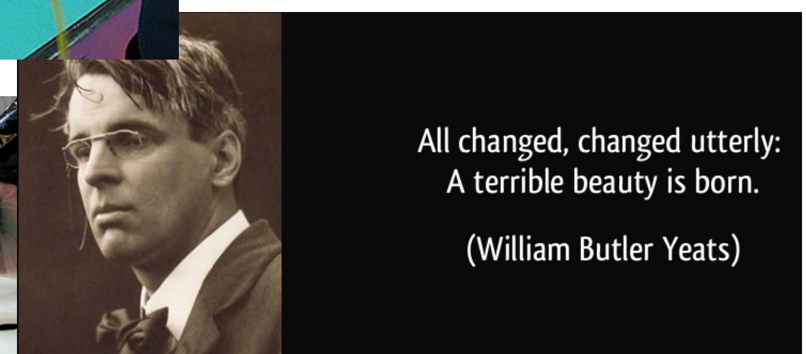
1 PHYSICS

1.1 History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.







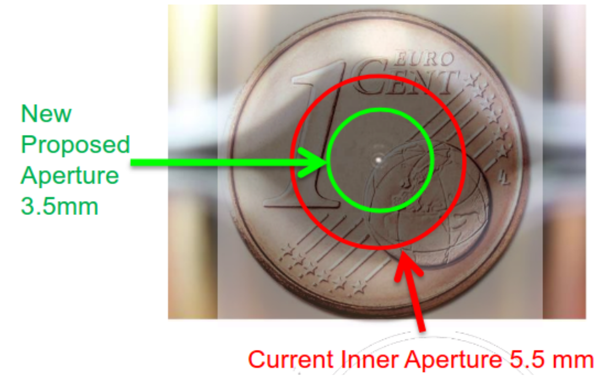
Backup: my LHCb cheat sheet

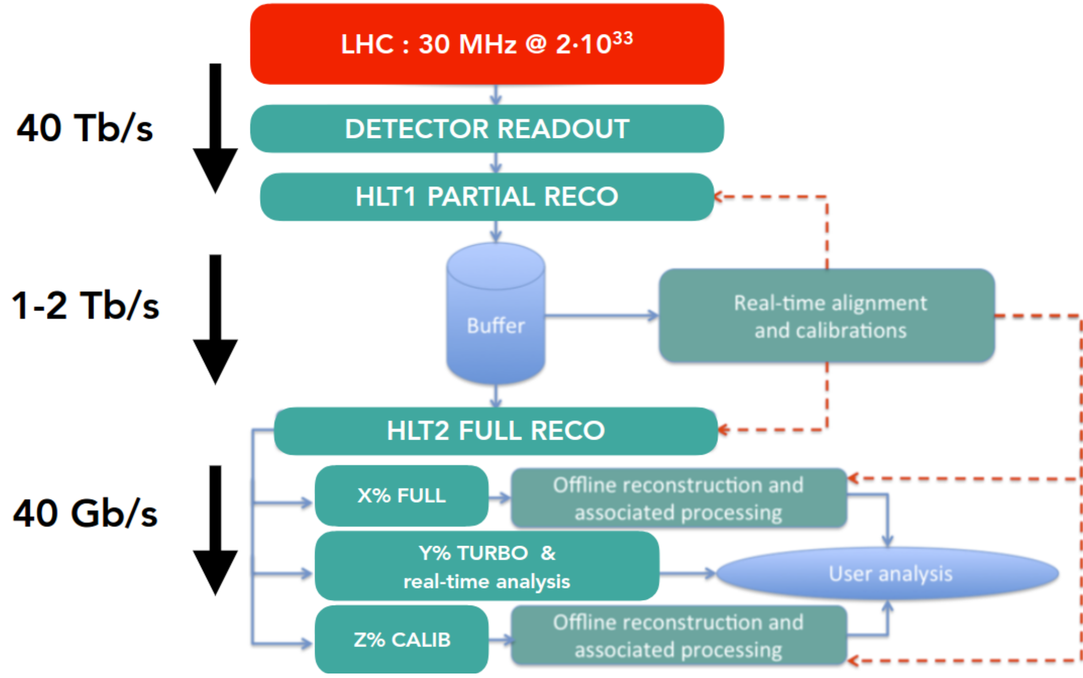
- **Luminosity**: fb^{-1}.
- **Acceptance**: 0.01-0.4 rad, ~25% of producted bb pairs.
- **$b\bar{b}$ cross-section** in acceptance: **72 – 154 μb** (7-13 TeV).
  - So ~ 200 billions of pairs in acceptance for Run 1.
- **B-daughter energy:** 10-100 GeV, max. ~20 GeV transverse energy: ~10% of that.
- **Decay-time resolution: 0.02-0.05 ps, linear with delta(t).**
- **Charmless branching fraction**: 10^{-4}–10^{-6}.
  - Typical ε(rec) ~ 10^{-3} → number of events from hundreds to tens of thousands.
- **Tagging power**: ~5%.
- (Visible) **interactions per crossing**:
  - Run 2: (1.5)
  - Upgrade: 7.6 (5.2)

Final-state particles	
μ	The stuff golden modes are made of.
p, $K^{\pm}$, $\pi^{\pm}$	Bread and butter, however possible mis-ID.
$e^{\pm}$	Challenging (brehmstrahlung).
γ, n	Challenging (only in calorimeter).
π^0 (as 2γ) K^0_S (as $2\pi^{\pm}$) Λ^0 (as $p\pi$) Ξ^- (as $\Lambda\pi$)	Difficult: either displaced or made of γ.
K^0_L	(Nigh?)impossible.
υ	Indirect constraints, but initial state is not known.

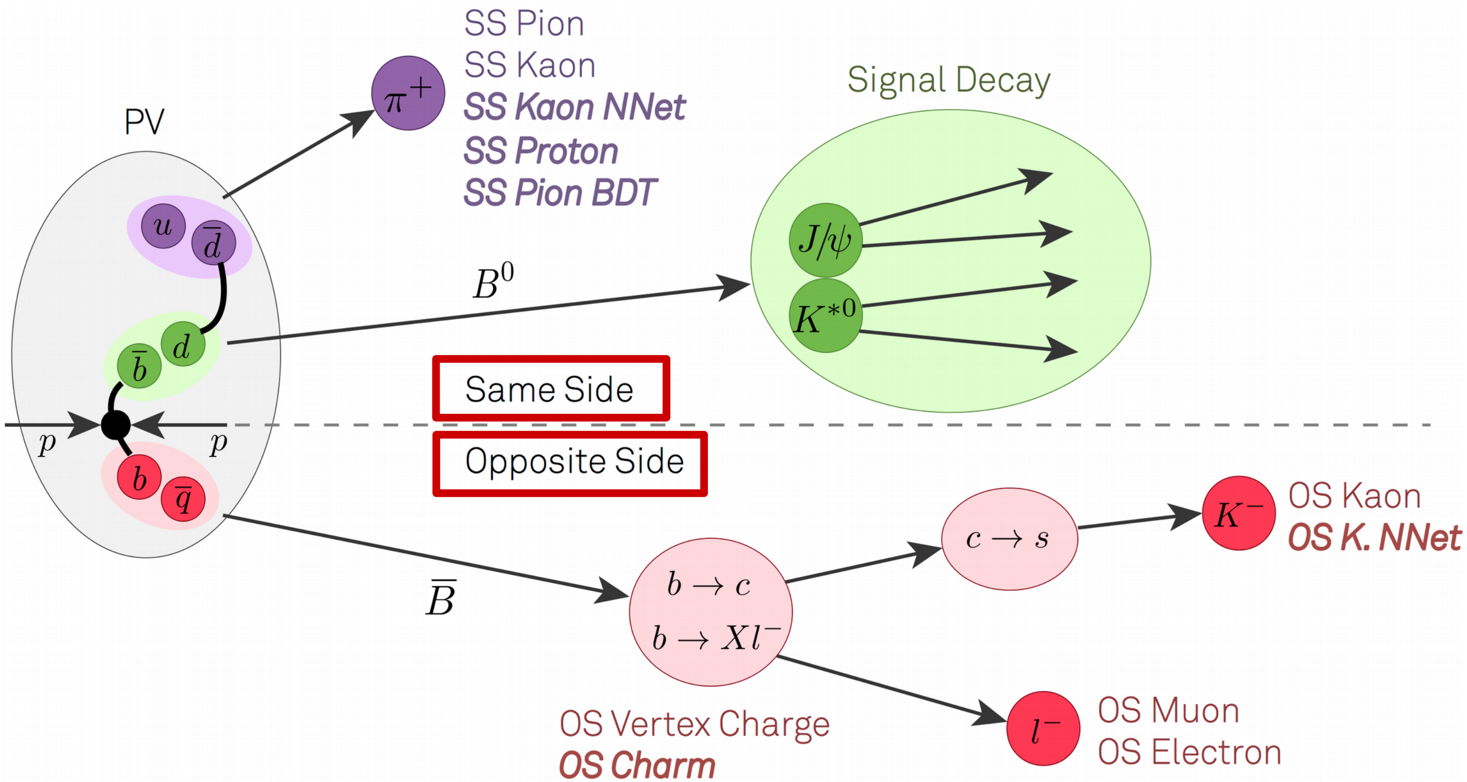
Backup: my Upgrade cheat sheet

- **Peak luminosity**: 4×10^{32} cm^{-2}s^{-1} → 2×10^{33} cm^{-2}s^{-1}. Upgrade 2: 2×10^{34}.
- **VeLo**: from silicon strips to pixel detector, smaller aperture.
- **TT, IT, OT**: from silicon + straw tubes to silicon strips/fibers.
- **Rich**: replace HPDs and electronics.
- **Calorimeters**: reduce PMT gain and new electronics.
- **Muon**: new electronics.





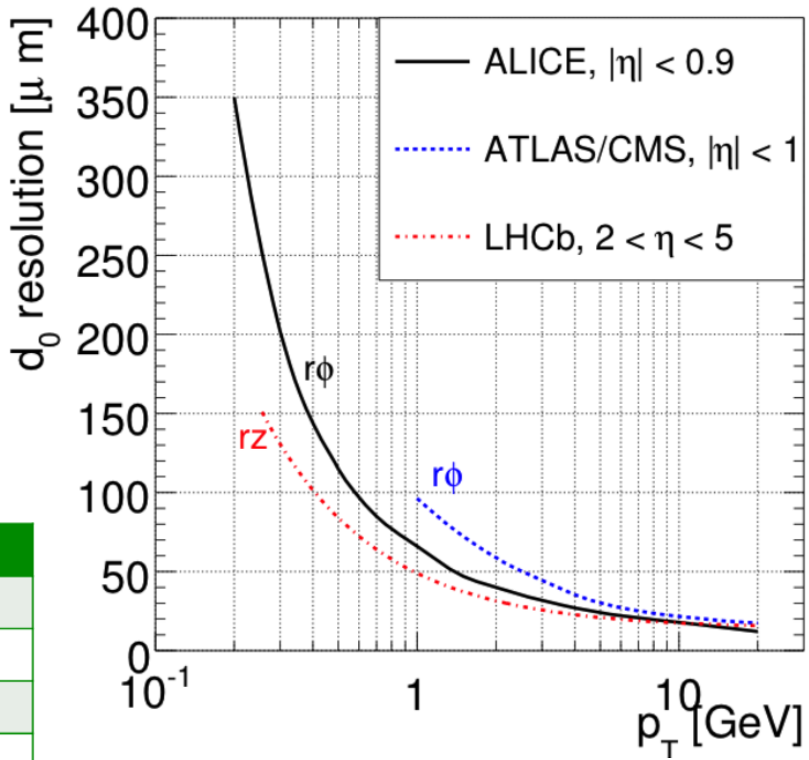
Backup: flavour tagging at LHCb



Combined tagging power: 3-8%

Backup: tracking comparisons with the other LHC detectors

- From here.



Comparison of (barrel) tracker layouts

	ALICE	ATLAS	CMS
R inner	3.9 cm	5.0 cm	4.4 cm
R outer	3.7 m	1.1 m	1.1 m
Length	5 m	5.4 m	5.8 m
|η| range	0.9	2.5	2.5
B field	0.5 T	2 T	4 T
Total X_0 near η=0	0.08 (ITS) + 0.035 (TPC) + 0.234 (TRD)	0.3	0.4
Power	6 kW (ITS)	70 kW	60 kW
rφ resolution near outer radius	~ 800 μm TPC ~ 500 μm TRD	130 μm per TRT straw	35 μm per strip layer
p_T resolution at 1GeV and at 100 GeV	0.7% 3% (in pp)	1.3% 3.8%	0.7% 1.5%

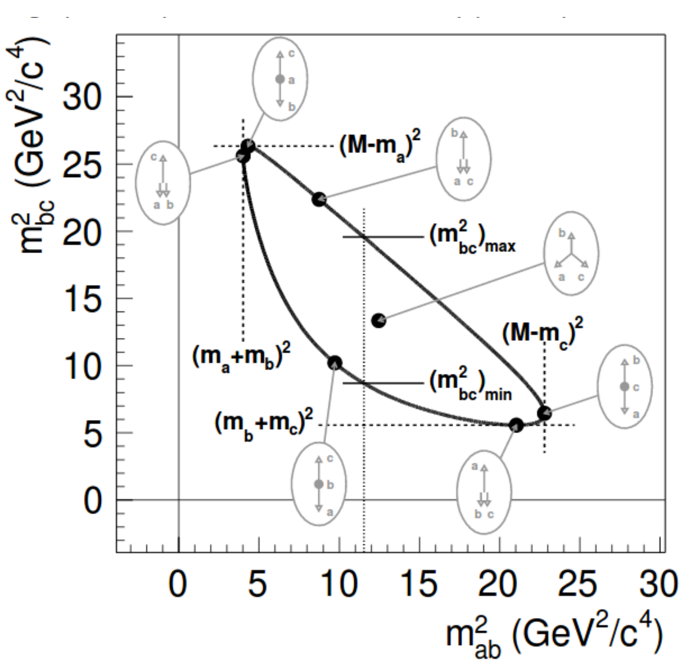
Backup: the Dalitz plot

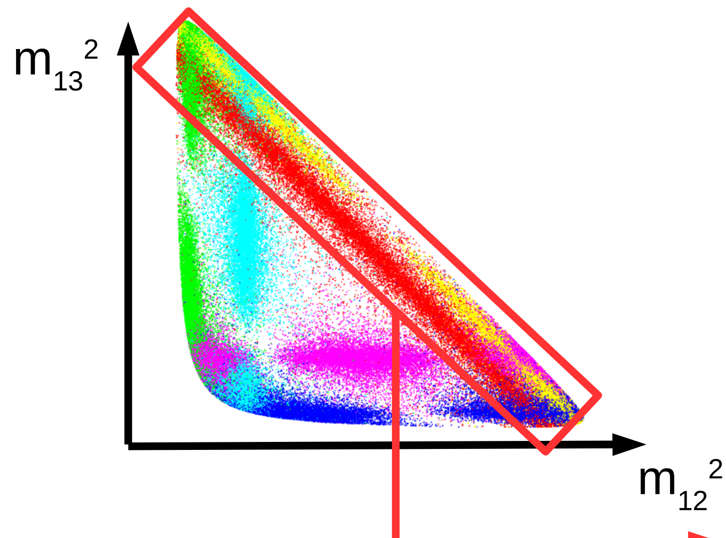
(Spin0) → 3x(Spin0) decay →3x4 degrees of freedom (d.o.f)	12
Conservation of momentum	-4
Mass constraints	-3
All particles are pseudoscalars → isotropic decay	-3

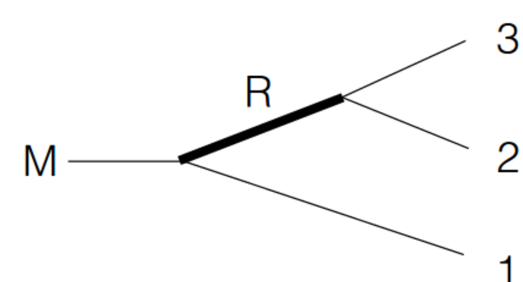
- Decay amplitude can be written

  →in absence of dynamics, amplitude flat. $d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|\mathcal{M}|^2 \boxed{dm_{12}^2 dm_{13}^2}$

Dalitz-plot coordinates







Possibility to probe (non)resonant structure and measure their relative phases → invaluable insight into hadronic and weak physics

Backup: the isobar approach

- Isobar approach: A_f written as coherent sum of partial amplitudes (isobars). Can be resonant or nonresonant.

$$\boxed{\overset{(-)}{\mathcal{A}} = \sum_{n}^{N} \overset{(-)}{\mathcal{A}}_n,} \qquad \overset{(-)}{\mathcal{A}}_n = \overset{(-)}{a}_n F_n\left(m_{ij}^2, m_{jk}^2\right),$$

$$F_n\left(m_{ij}^2, m_{jk}^2\right) = X_L(|\mathbf{p}^*|r')X_L(|\mathbf{q}|r)T_n(L,\mathbf{p},\mathbf{q})R_n(m_{ij}),$$

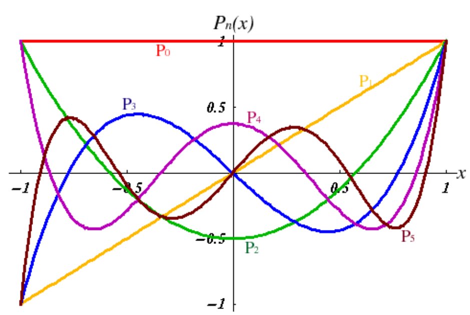
(L = angular momentum of bachelor and pair)

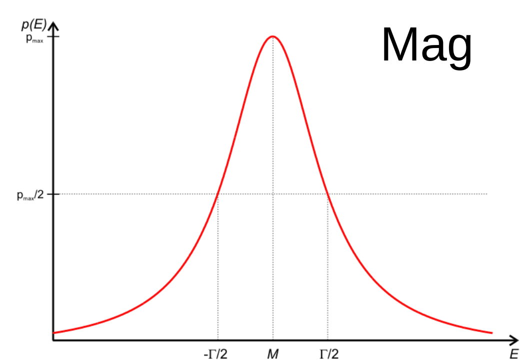
Blatt-Weisskopf barrier factors

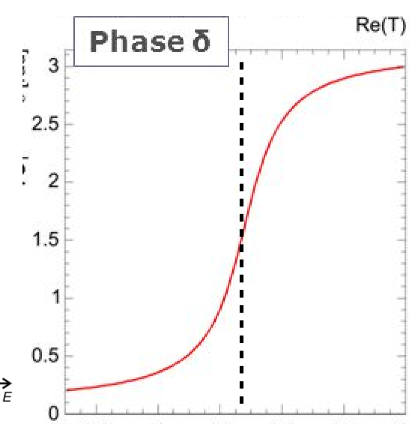
Zemach tensor (angular dependence

Lineshape (Breit-Wigner, Flatte...)

$$\begin{aligned} F_0(x) &= 1 \\ F_1(x) &= \sqrt{\frac{x}{x+1}} \\ F_2(x) &= \sqrt{\frac{13x^2}{(x-3)^2+9x}} \end{aligned}$$







Backup: Belle 2 vs LHCb

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 13\,\text{TeV}$) LHC
Production cross-section	$1\,\text{nb}$	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	$10\,\text{Hz}$	$\sim 100\,\text{kHz}$	$\lesssim 1\,\text{MHz}$
Pile-up	0	1.7	1–40
Trigger efficiency	$100\,\%$	20–$80\,\%$	
B hadron mixture	B^+B^- ($\sim 50\,\%$), $B^0\overline{B}^0$ ($\sim 50\,\%$)	B^+ ($40\,\%$), B^0 ($40\,\%$), B_s^0 ($10\,\%$), Λ_b^0 ($10\,\%$), others ($< 1\,\%$)	
B hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\overline{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
$B\overline{B}$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Effective flavour tagging efficiency	$\sim 30\,\%$	$\lesssim 6\,\%$	

Backup: prospects on few quantities...

- From L. Silvestrini @ Manchester 2016 (to be taken with a grain of salt).

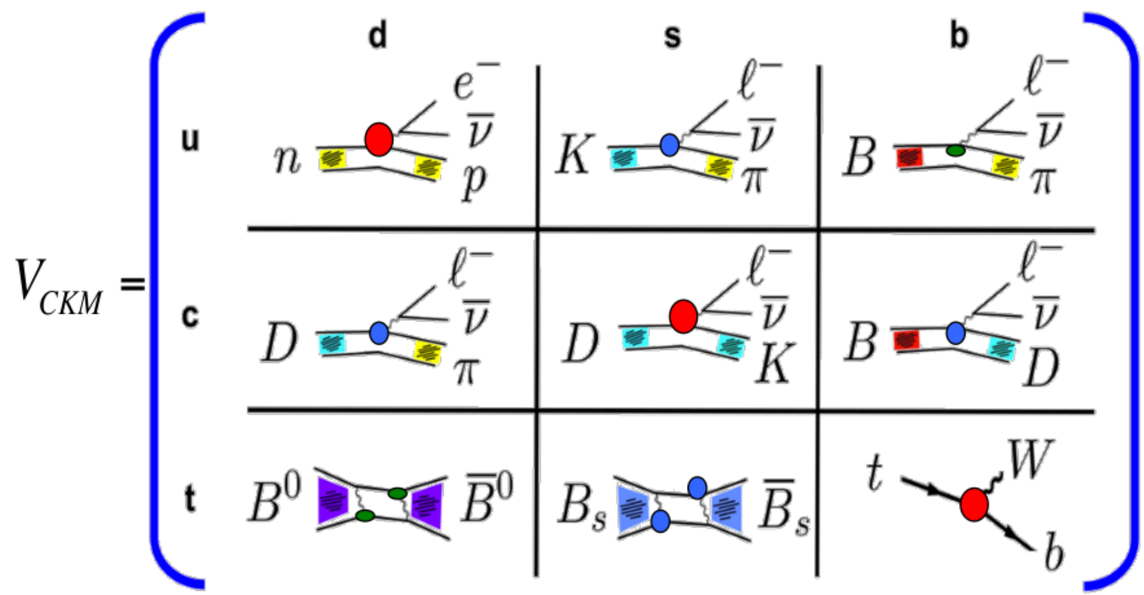
Parameter	Error				
	Now	50/fb	300/fb	1000/fb	3000/fb
ΔM_d [ps^{-1}]	0.002	0.0005	0.0002	0.0001	0.00006
ΔM_s [ps^{-1}]	0.021	0.005	0.002	0.001	0.0006
$\sin 2\beta$	0.022	0.008	0.0026	0.0018	0.001
γ [°]	6.5	0.9	0.4	0.2	0.09
α [°]	5.5	1	Belle II		
β_s [°]	4	0.26	0.11	0.06	0.034
V_{us}	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$			
V_{cb}	2.7%	1%	Belle II		
V_{ub}	10%	1%	Belle II		
x		$1.5 \cdot 10^{-4}$	$4.5 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$
y		10^{-4}	$3 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	10^{-5}
$\lvert q/p \rvert$		0.01	0.003	0.002	0.001
ϕ [°]		3	0.9	0.6	0.3
A_Γ		$4 \cdot 10^{-5}$	$12 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
$\alpha_s(M_Z)$	0.0005	0.0002			
m_t	760 MeV	250 MeV	theory limited		
m_b	50 MeV	10 MeV			
B_K	1.3%	0.1%			
F_{B_s}	5 MeV	1 MeV			
F_{B_s}/F_{B_d}	1.4%	0.5%			
$F_{B_s}\sqrt{B_{B_s}}$	3.8%	3%			
ξ	2.5%	0.5%			

Backup: … and a few more

- From B. Golob @ Manchester 2016

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1} (2018)		LHCb 50 fb^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (0.9^\circ)$		0.3°	0.6°	~	0.3°
	α [°]	85 ± 4 (Belle+BaBar)		1			
	γ [°] $(B \to D^{(*)} K^{(*)})$	68 ± 14		1.5	4	!	1
	$2\beta_s (B_s \to J/\psi \phi)$ [rad]	$0.07 \pm 0.09 \pm 0.01^*$			0.025	!	0.009
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$		0.018	0.2	?	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$		0.011			
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$		0.033			
	$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	$-0.17 \pm 0.15 \pm 0.03^*$			0.12	!	0.03
	$\beta_s^{\rm eff}(B_s \to K^{*0} \bar{K}^{*0})$ [rad]	–			0.13		0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$		0.04		?	
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3} (1 \pm 2.4\%)$					
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3} (1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$		1.4%		~	
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3} (1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$		3.0%		!	
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3} (1 \pm 10.8\%)$		2.4%		!	
Leptonic and Semi-tauonic	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96 (1 \pm 26\%)$		5%		~	
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7		7%			
	$R(B \to D\tau\nu)$ [Had. tag]	$0.440 (1 \pm 16.5\%)^\dagger$		3.4%		~	
	$R(B \to D^*\tau\nu)^\dagger$ [Had. tag]	$0.332 (1 \pm 9.0\%)^\dagger$		2.1%	...	!	
Radiative	$\mathcal{B}(B \to X_s \gamma)$	$3.45 \cdot 10^{-4} (1 \pm 4.3\% \pm 11.6\%)$		6%			
	$A_{CP}(B \to X_{s,d} \gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$		0.5			
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$		0.035			
	$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	–			0.13	!	0.03
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$		0.07			
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7		–			
Electroweak penguins	$\mathcal{B}(B \to K^{*+} \nu\bar{\nu})$ $[10^{-6}]$	< 40		30%			
	$\mathcal{B}(B \to K^{+} \nu\bar{\nu})$ $[10^{-6}]$	< 55		30%			
	C_7/C_9 $(B \to X_s \ell\ell)$	~20%		5%			
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–		–			
	$\mathcal{B}(B_s \to \mu\mu)$ $[10^{-9}]$	$2.9^{+1.1}_{-1.0}{}^*$			0.5	!	0.2

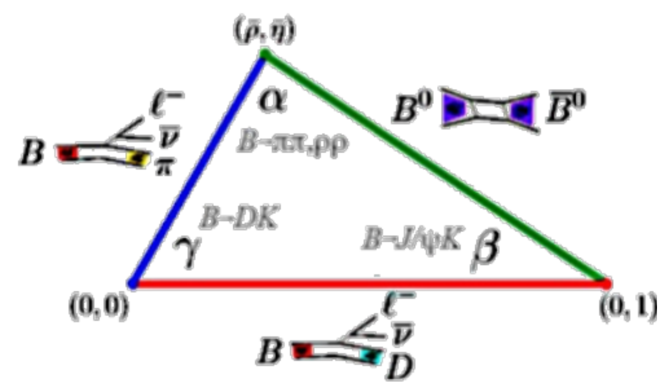
Backup: How to measure CKM



λ : measured from $|V_{ud}|$and $|V_{us}|$ in nuclear and (semi-)leptonic Kaon decays.

A : determined from $|V_{cb}|$ and λ.

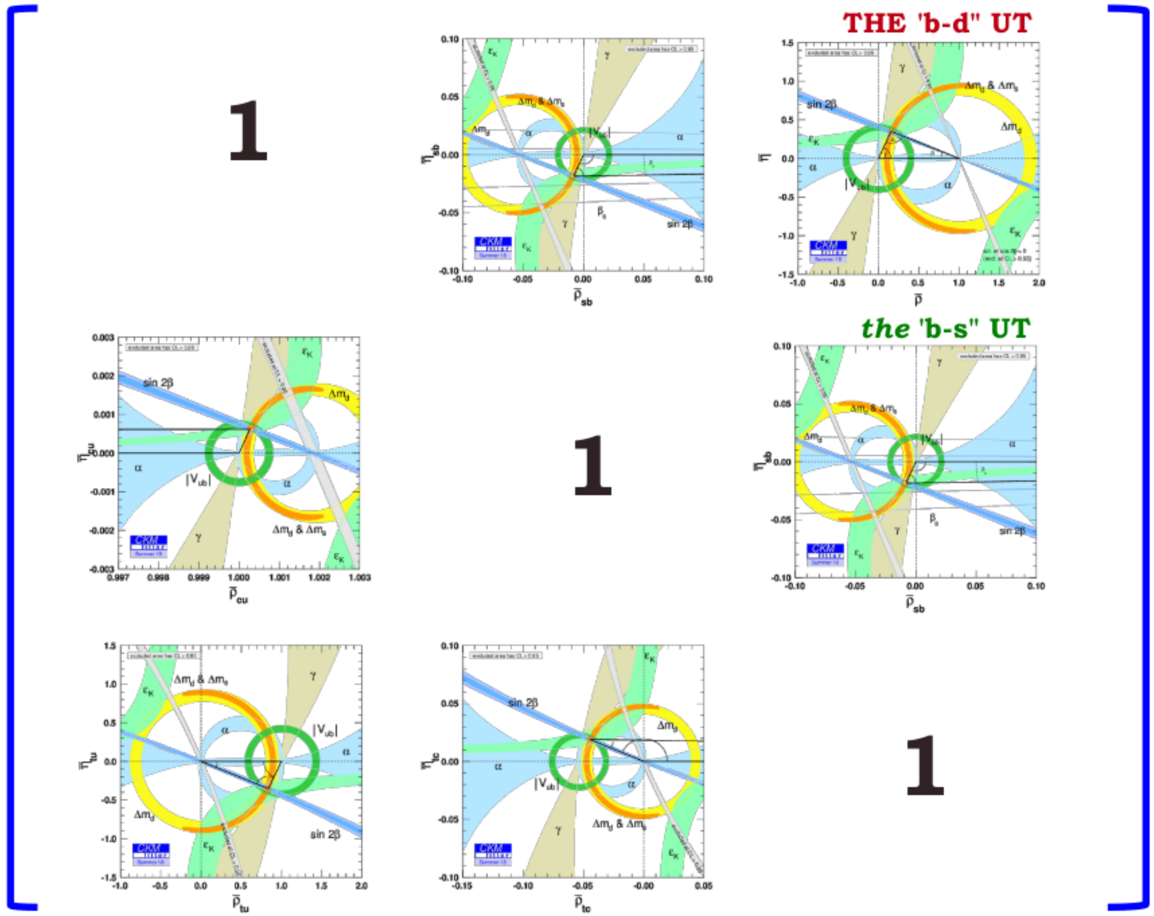
$\overline{\rho}+i\overline{\eta}$: determined from the angles and sides of the Unitarity Triangle.



Credits to Olivier Deschamps

Backup: the six triangles

$$V_{CKM}^{+} V_{CKM} =$$



Credits to Olivier Deschamps