LHCb

Carla Marin
cmarinbe@ub.edu
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Universitat de Barcelona
ICCUB Institute of Cosmos Sciences
Excelencia María de Maeztu

This lecture

- please ask questions anytime!
  - I'll ask some to you as well :)

- review the basics
- go into details in some examples
- state-of-the-art results from LHCb

Outline

- Introduction to flavour physics
- The LHCb detector
  - Run 1+2 detector
  - LHCb upgrade

- LHCb physics:
  - rare decays
  - CPV
  - CKM
  - Semi-leptonic decays

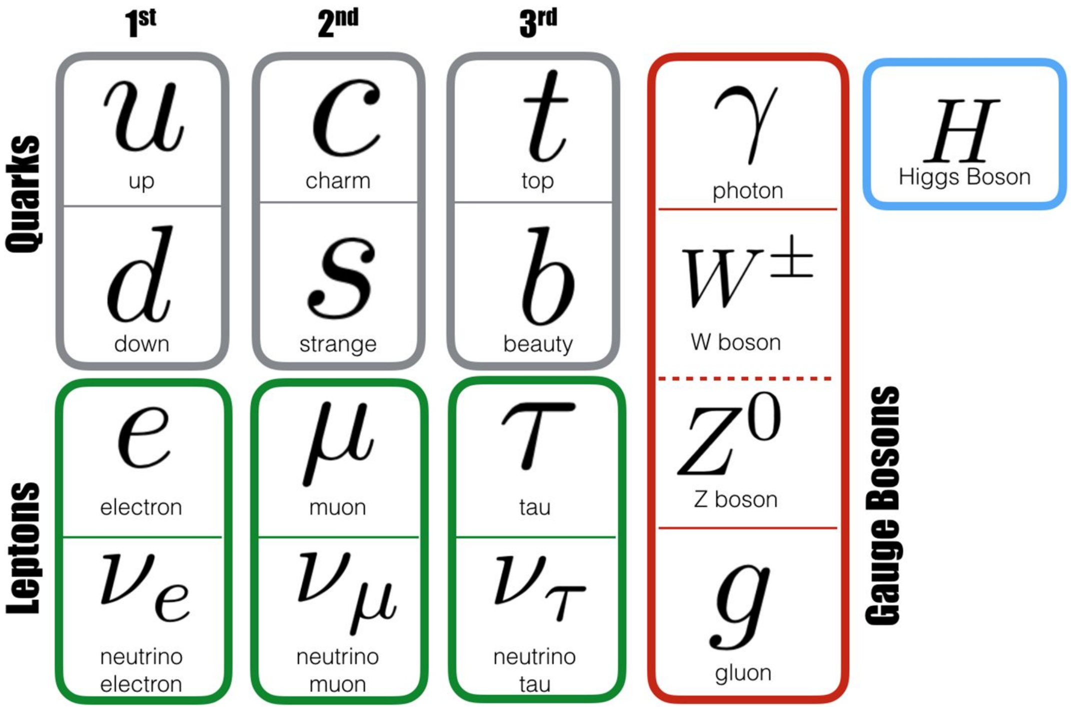
Flavour Physics

The flavour of the SM particles

Fermions classified in

- 3 families: increasing **mass** 10^1 - 10^5 MeV !
- 2 types: **electric charge**
  - up (+⅔), down (-½)
  - e (-1), neutrino (0)

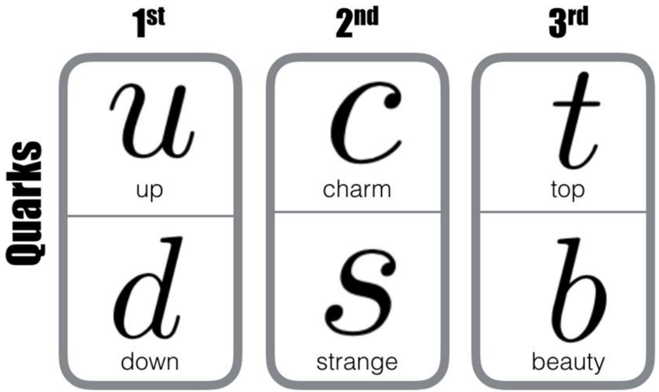
→ 6 flavours of quarks and 6 of leptons



credit: UZH-Physik Institut

Quarks and hadrons

Quarks are subject to strong interactions (QCD)
→ form hadrons: baryons and mesons



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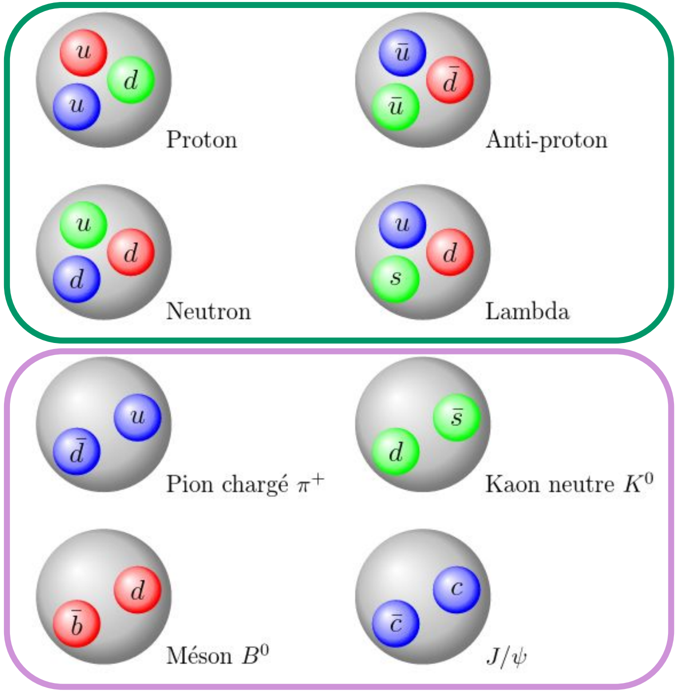
Baryons



Mesons

credit: Wikipedia

Quarks and hadrons

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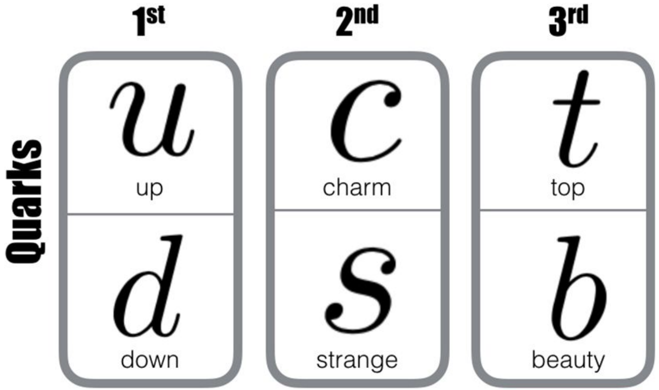
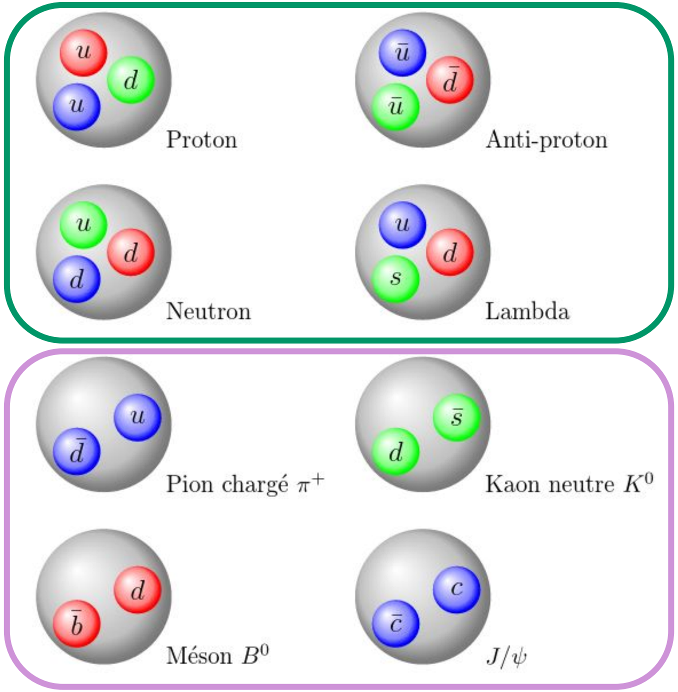
→ form hadrons: baryons and mesons

Other combinations?



credit: UZH-Physik Institut

Baryons



Mesons

credit: Wikipedia

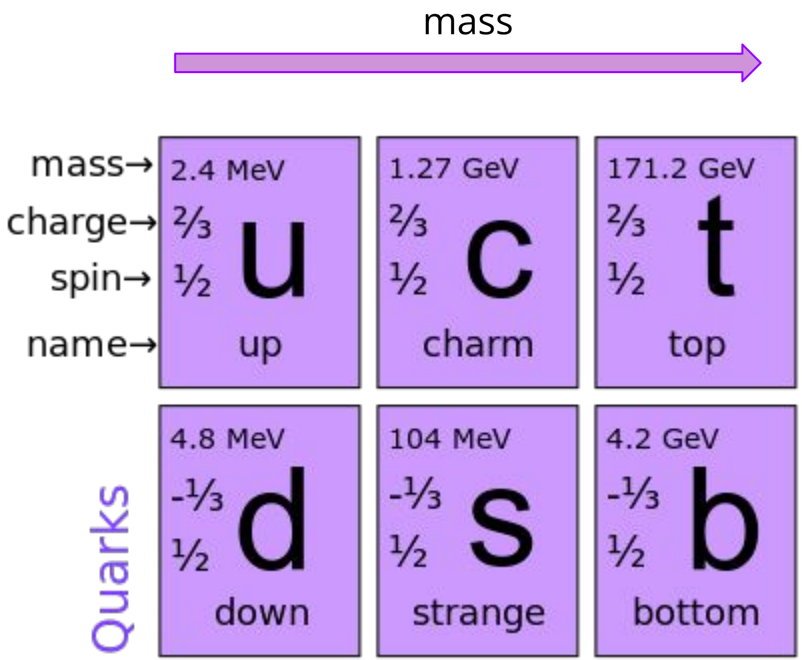
Quarks and hadrons

Quarks are also subject to weak interaction: can change flavour

- Heavy quarks decay into lighter ones, since enough energy is available
    - Lightest quarks are stable!
- Quarks form hadrons before decaying*
  → observe hadron decays

  → need to understand QCD when studying weak decays

*top quark: decays before hadronising, due to very heavy mass



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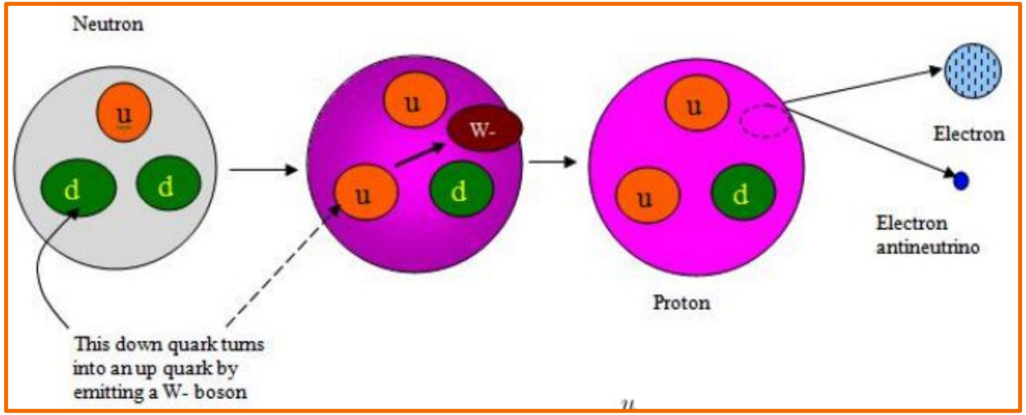
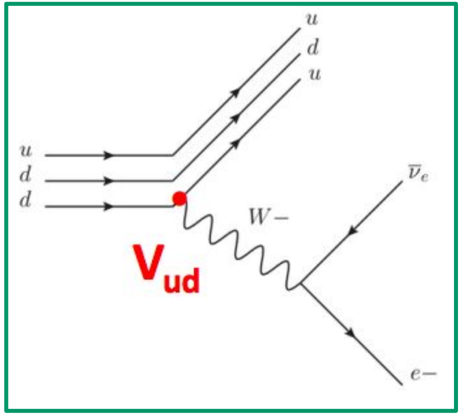
The β decay

First observed in 1896 by Becquerel
Explained by Fermi in 1931

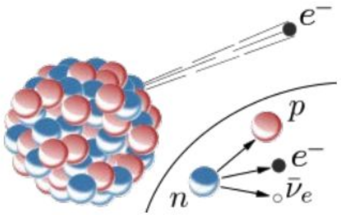
Decay n → p at hadron level (d → u at quark level)





Responsible of radioactivity:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \overline{\nu_e}$$



From light to heavy hadrons?

Light quarks cannot spontaneously turn into heavier ones, how can we study heavy quarks?

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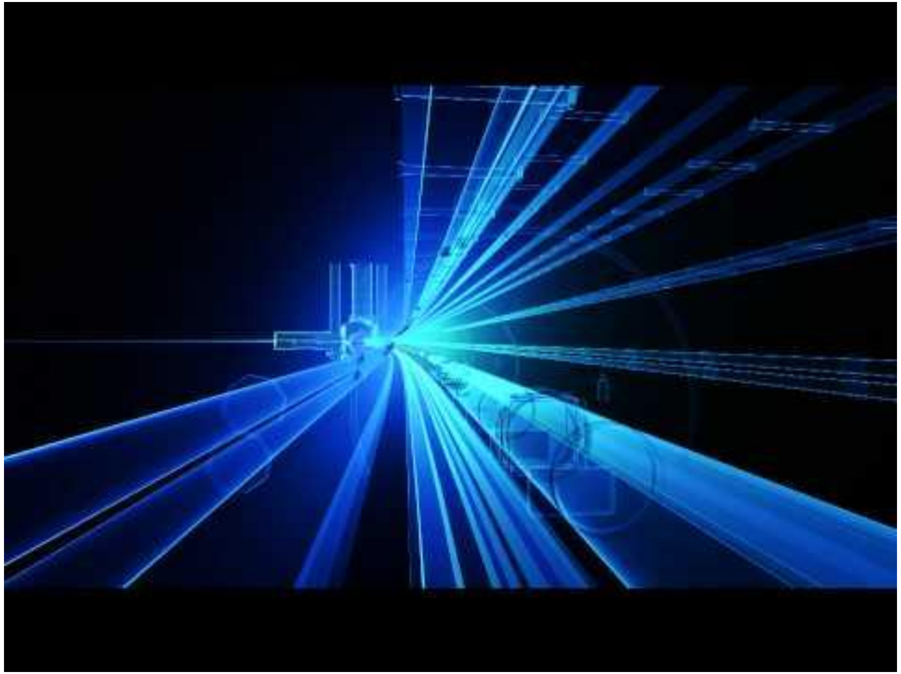
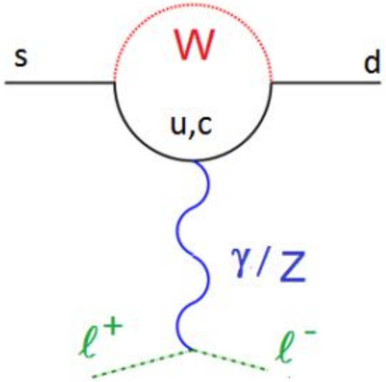


credit: ATLAS Experiment

The GIM mechanism

Proposed in 1970 by Glashow, Iliopoulos and Maiani (GIM):

- motivated by suppression of $K_L \rightarrow \mu^+\mu^-$ decays
- predicts existence of c quark (only u, d and s known then)
- loop decays are suppressed by cancellation of u and c contributions



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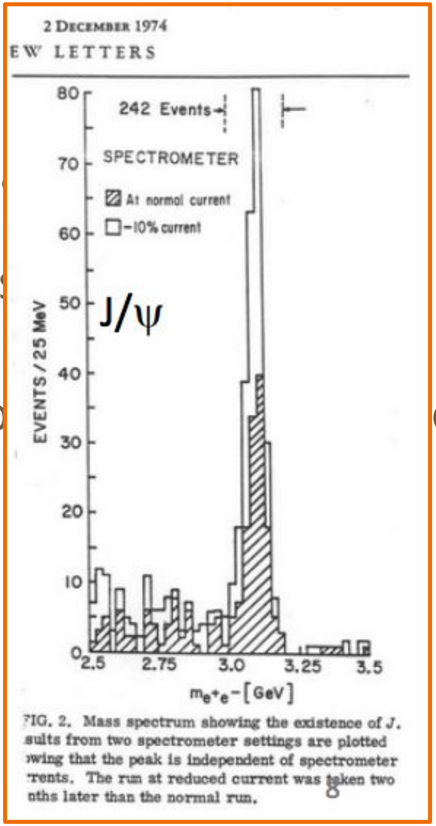
Observed in 1974 at SLAC and BNL: J/ψ (cc) particle



The CKM matrix

Describes the strength of quark flavour-changing processes

- Cabibbo matrix in 1963 for 2 quark generations
- Only 1 free and real parameter: Cabibbo angle (θ_c)
- Charge-Parity (CP) breaking not possible

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$

d', s' are weak states while d, s are mass eigenstates

The CKM matrix

Describes the strength of quark flavour-changing processes

- Cabibbo matrix in 1963 for 2 quark generations
- CPV observed for first time in $K_L \to \pi\pi$ decays (BNL, 1964)
- extended to 3 generations by Kobayashi and Masakawa in 1973

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

d’, s’, b’ are weak states while d, s, b are mass eigenstates

The CKM matrix: parameters and CPV

Unitary matrix: $VV^\dagger = 1 \rightarrow$ limits number of free parameters

- N x N matrix: $(N-1)^2$ free variables
  - ½ N x (N-1) real values → mixing angles
  - ½ (N-1) x (N-2) complex values → can cause CP asymmetry
- 2 x 2 matrix: 1 mixing angle (Cabibbo angle), no complex phases
- 3 x 3 matrix: 3 mixing angles and 1 CP-breaking complex phase

Motivation: CP breaking observed in Kaon decays

Prediction: existence 3rd generation, confirmed by b-quark observation 1976

The CKM matrix: values

No constraints from theory (only unitarity) → need to be measured

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

$|V_{ud}| = 0.97370 \pm 0.00014$ $\quad |V_{us}| = 0.2245 \pm 0.0008$ $\quad |V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$

$|V_{cd}| = 0.221 \pm 0.004$ $\quad |V_{cs}| = 0.987 \pm 0.011$ $\quad |V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}$

$|V_{td}| = (8.0 \pm 0.3) \times 10^{-3}$ $\quad |V_{ts}| = (38.8 \pm 1.1) \times 10^{-3}$ $\quad |V_{tb}| = 1.013 \pm 0.030$

CKM unitarity: weak universality

Unitarity constraint applied to diagonal terms:

$$\sum_k |V_{ik}|^2 = \sum_i |V_{ik}|^2 = 1$$

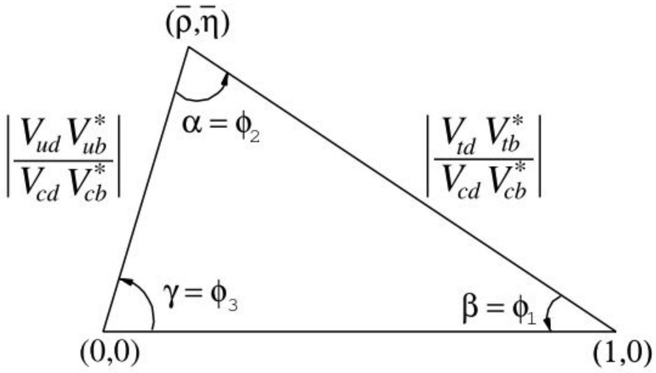
meaning: all generations couple equally to weak bosons

Note: same applies to leptons

CKM unitarity: unitary triangles

Unitarity constraint applied to off-diagonal terms (i ≠ j):

$$\sum_k V_{ik} V_{jk}^* = 0.$$



interpreted as unitary (closed) triangles in the complex plane

Test of the SM: sides and angles of the triangles can be measured independently → check that triangles are actually closed !

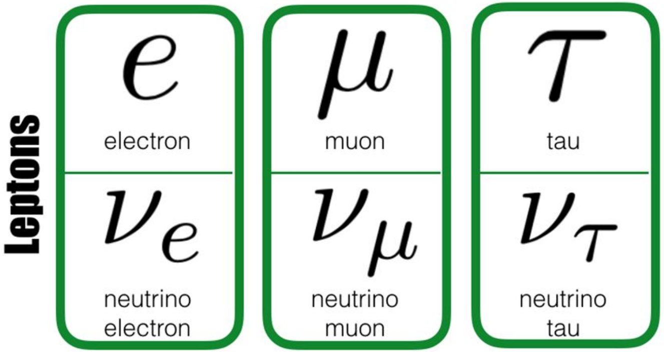
Leptons

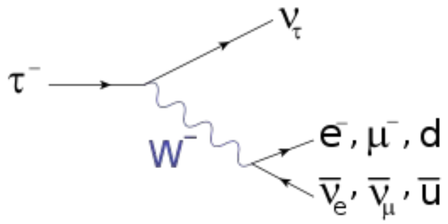
Similar structure to quarks, but not subject to strong force → no bound states

Flavour changes are also possible through weak interaction → PMNS matrix

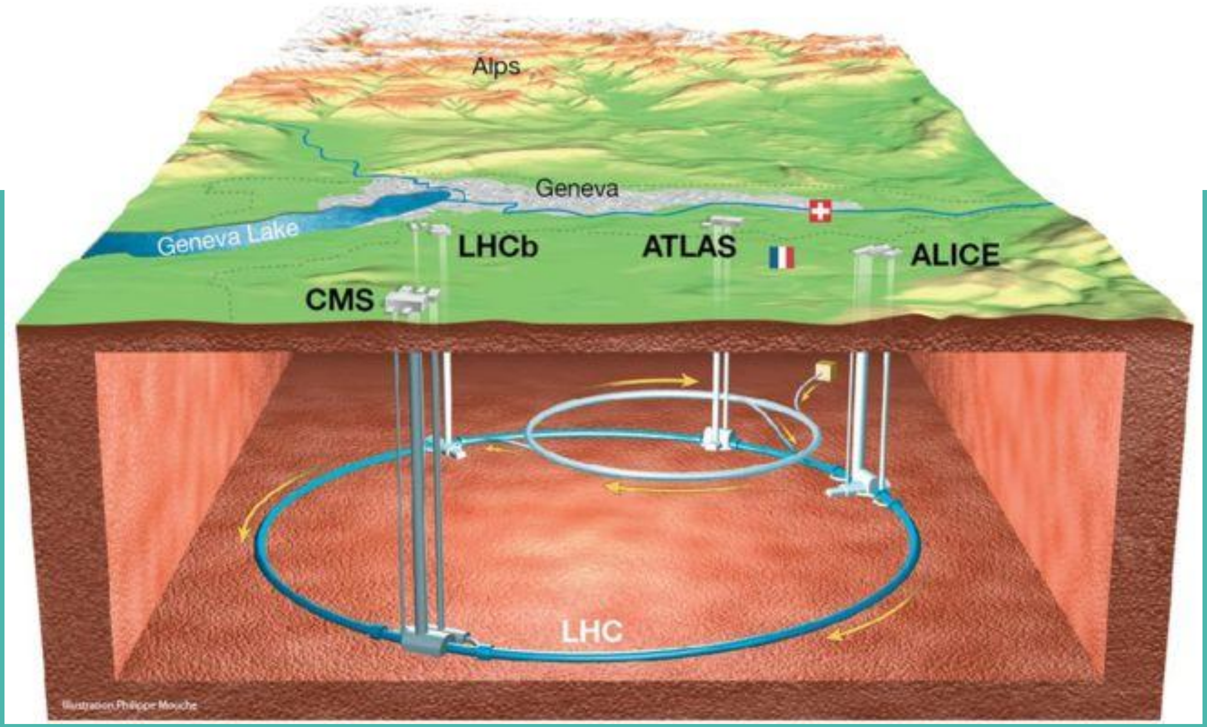
Due to lack of strong and electric charge, neutrinos are very hard to detect

See dedicated Neutrino lectures





LHCb: Large Hadron Collider Beauty experiment



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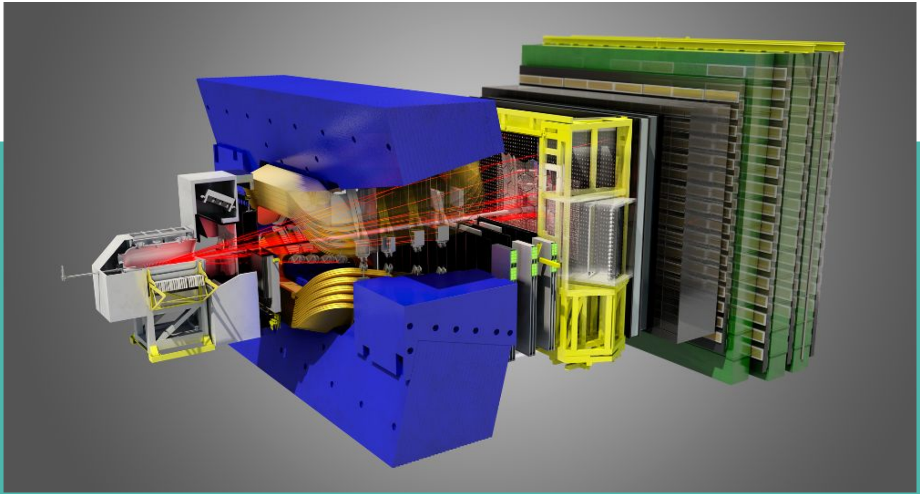
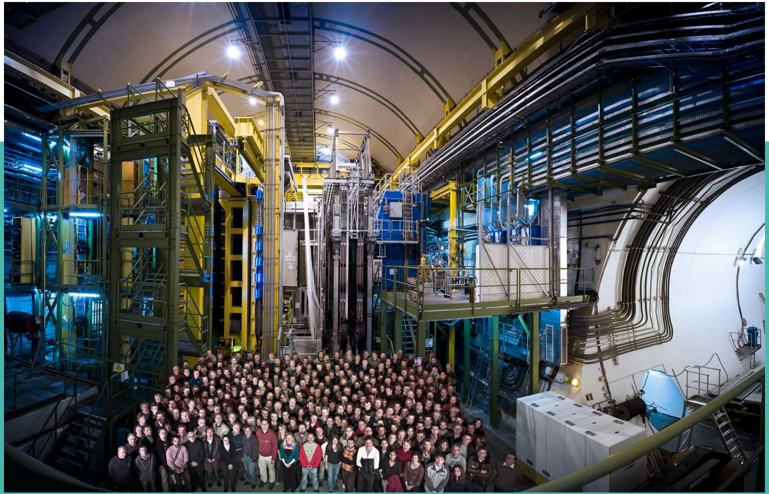
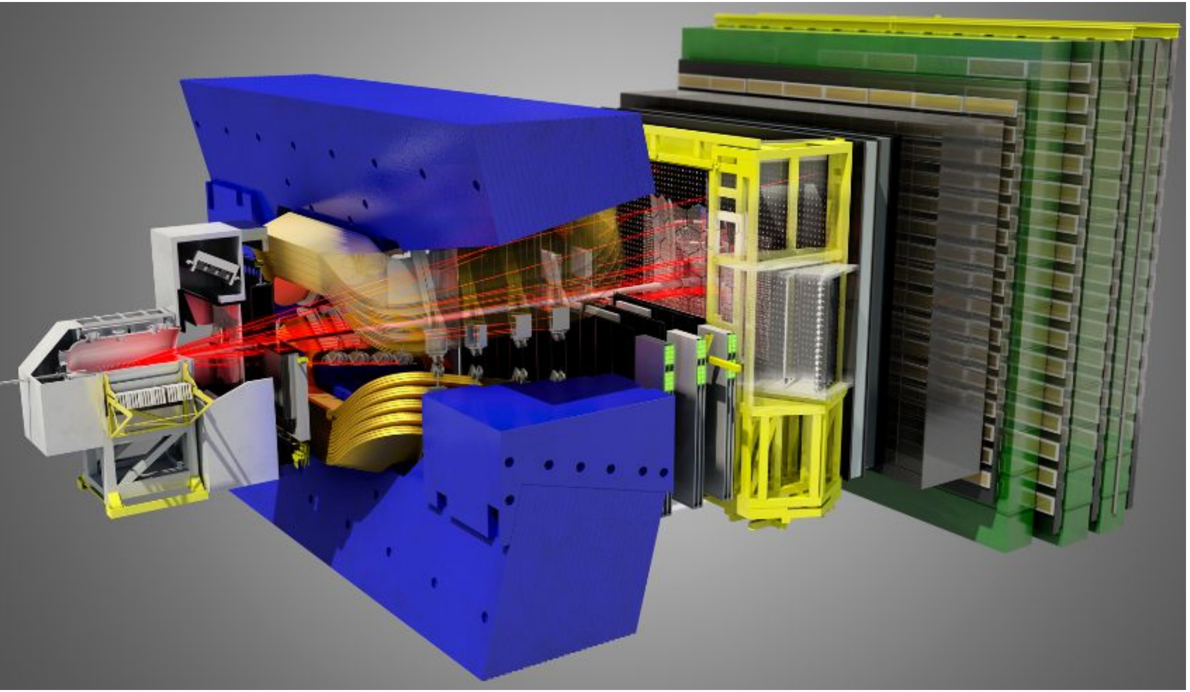




- Precision measurements heavy flavor physics
- Core physics: CPV and rare decays
- Much more: spectroscopy, QCD, heavy ions…

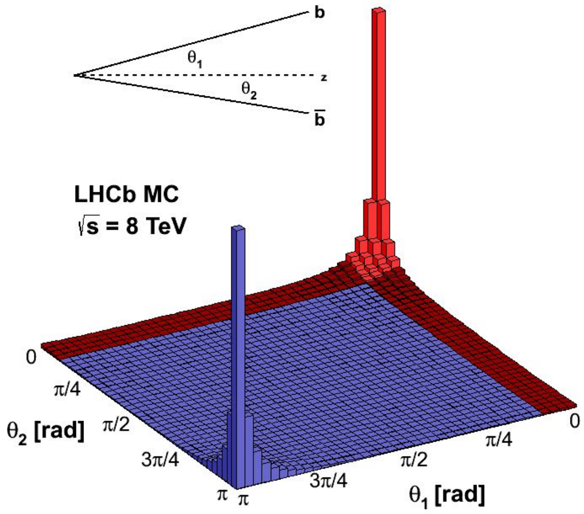
- > 900 authors and > 40 nationalities
- 87 institutes from 18 countries

Experimental setup



JINST 3 (2008) S08005

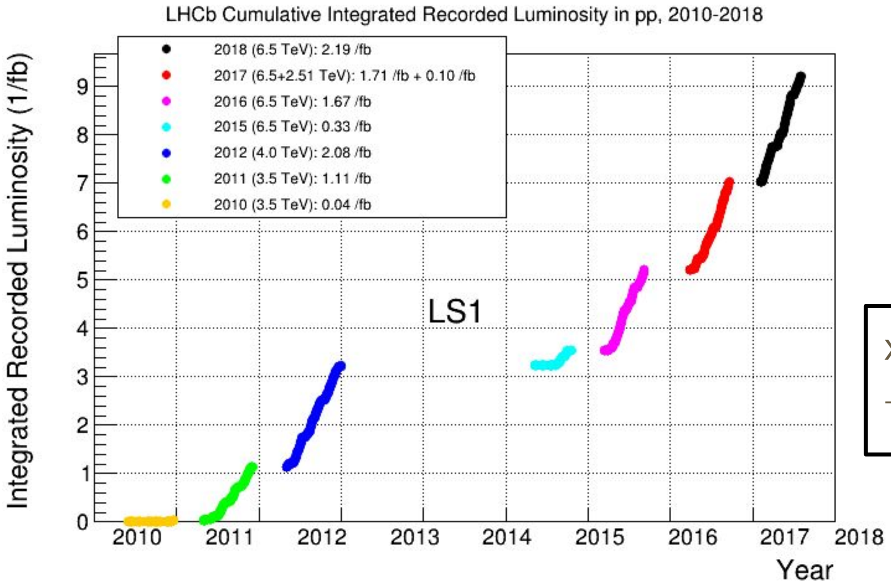
Distribution of produced b-quarks



Angular coverage: $2 \leq \eta \leq 5$

$\eta = -\ln \tan \theta/2$

LHCb dataset



Total recorded luminosity ~9 fb^{-1}:

- Run 1 (2010-2012) ~ 3 fb^{-1}
- Run 2 (2015-2018) ~ 6 fb^{-1}

x2 b-quark production from 7 to 13 TeV pp collisions
→ around x4 b-hadrons in Run 2

b hadrons

All b-hadron species produced at LHCb! [PRD100(2019)031102]

The beauty family: $B^+ = u\,\bar{b},\ B^0 = d\,\bar{b},\ \overline{B}^0 = \bar{d}\,b,\ B^- = \bar{u}\,b,$ $B_s^0 = s\,\bar{b},\ \overline{B}_s^0 = \bar{s}\,b,$

$\Lambda_b^0 = udb\ ,\ \Xi_b^0 = usb\ ,\ \Xi_b^- = dsb\ ,\ \Omega_b^- = ssb$

Lightest b-hadrons decay to 2nd and 1st generation → long lifetimes

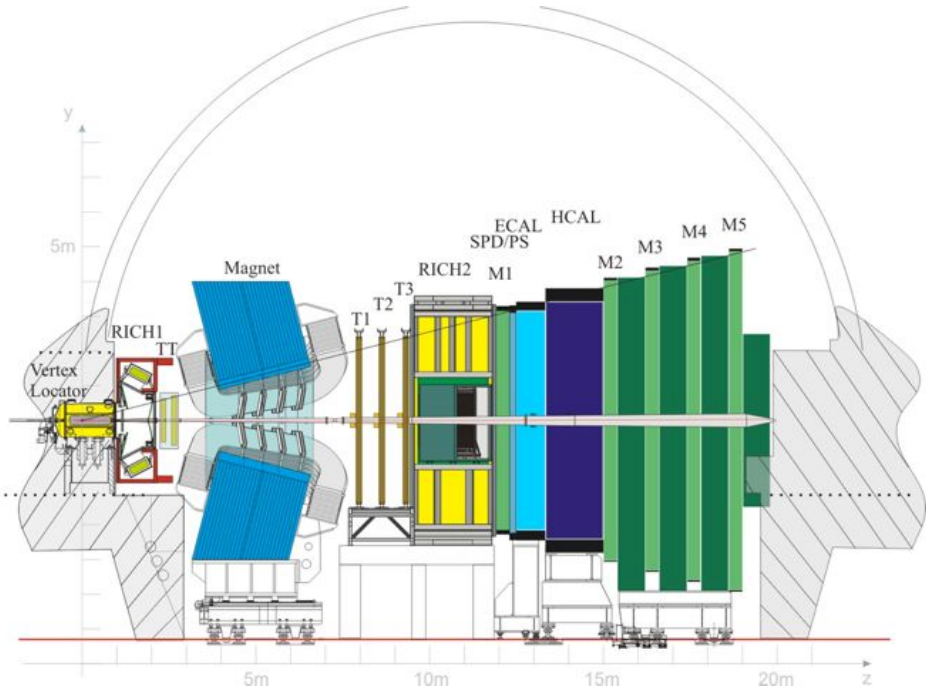
Large mass (5200 - 6000 MeV) allows many different decays:

- dominant decay: b → c ∝ V_{cb}
- suppressed: b → u ∝ V_{ub}
- FCNC: b → s, d “rare decays” ∝ $V_{tb}V_{ts/d}$

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

Large CP breaking expected in some decays

Experimental setup



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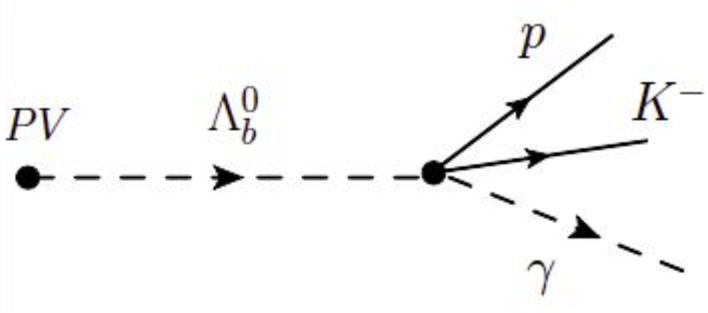
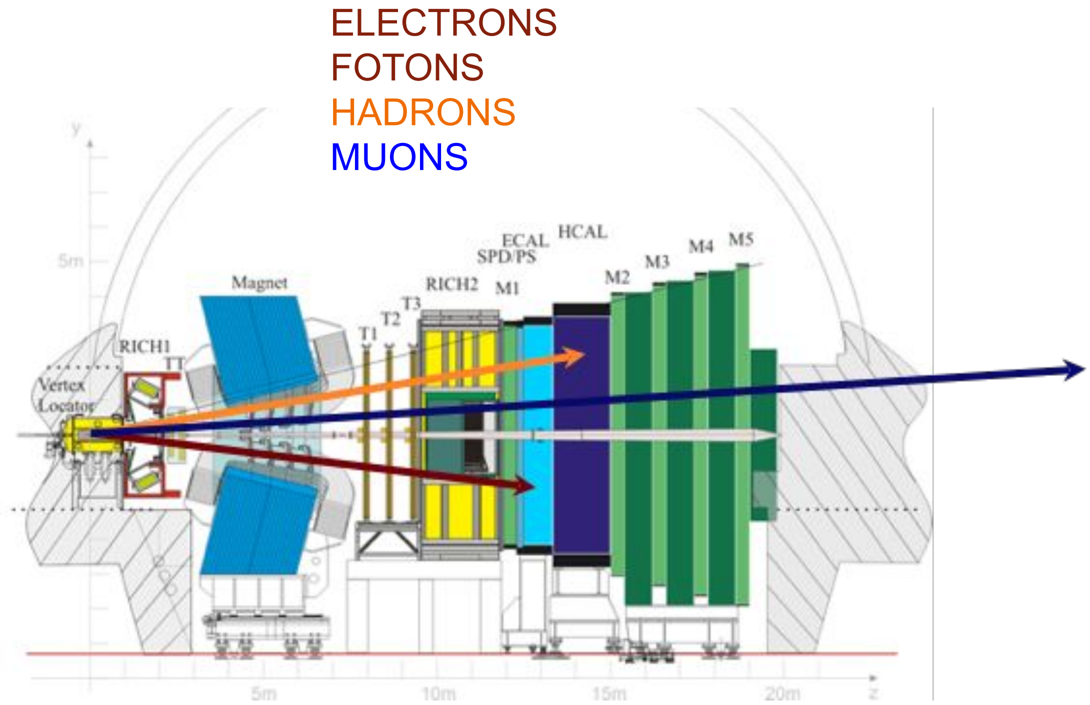
Typical decay signature



How much does Λ_b travel in the detector before decaying? $\beta\gamma \sim 100$

Experimental setup



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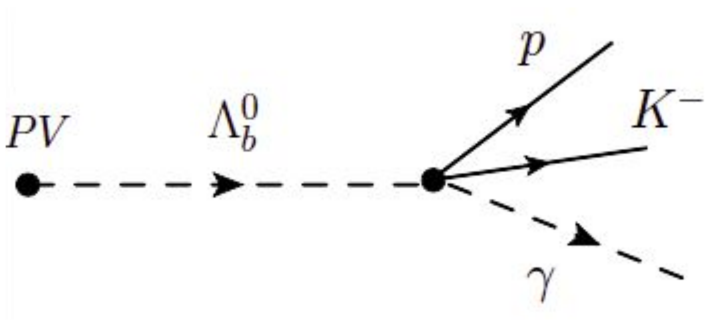

How much does Λ_b travel in the detector before decaying? $\beta\gamma$ ~ 100

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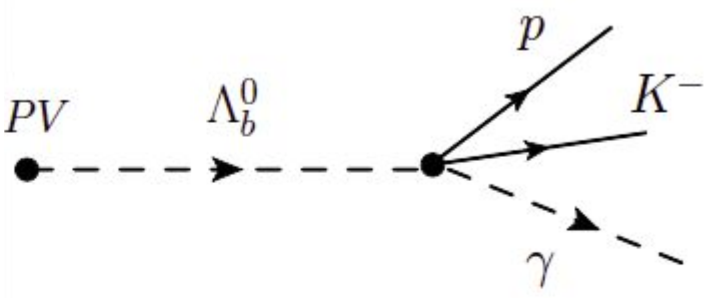
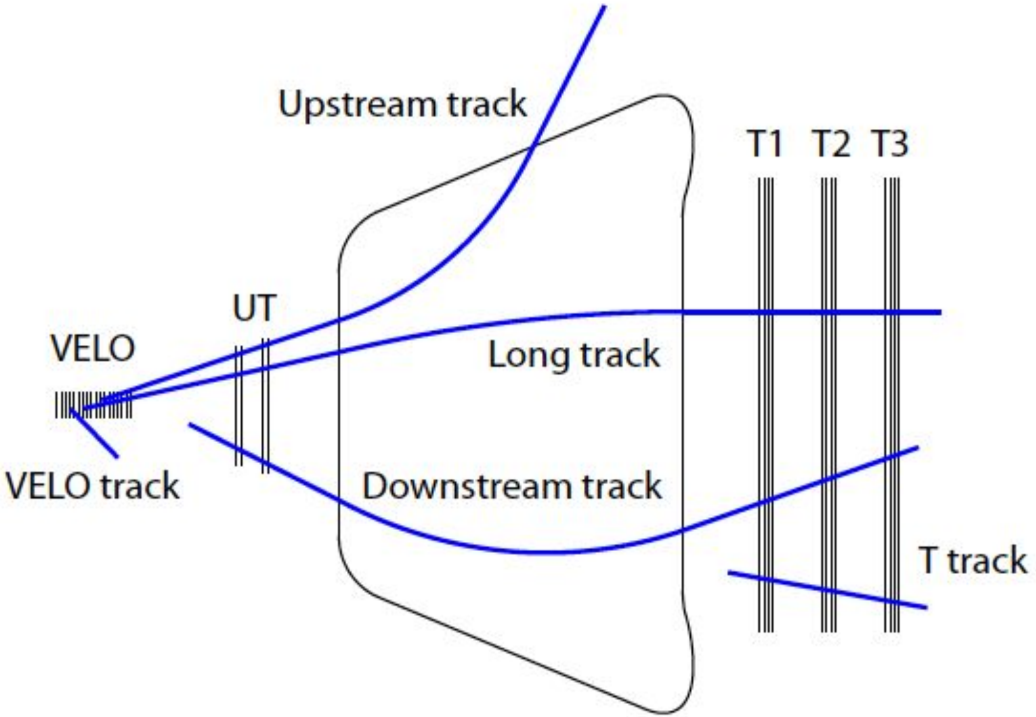
Tracking system

Reconstruct trajectories of charged particles

Identify pp and b-decay vertex

Measure particle momentum from bending in magnetic field





$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$

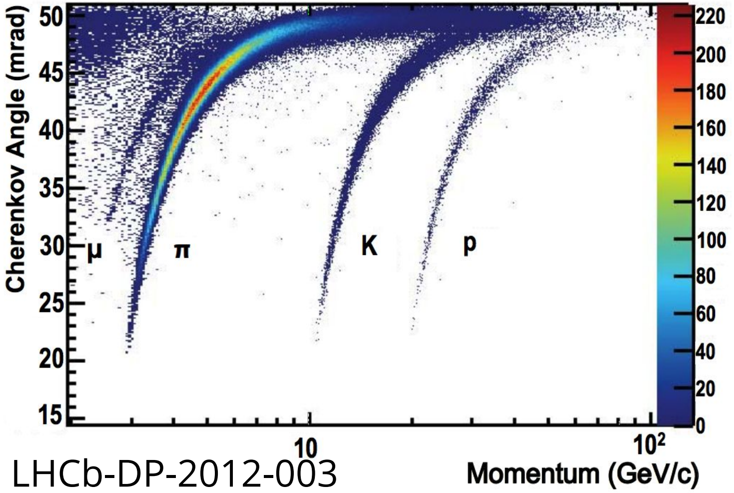
Particle identification system

- Ring Imaging Cherenkov Detectors (RICH)
  - RICH1: aerogel + C4F10 → p ∈ 2 - 60 GeV/c
  - RICH2: CF4 → p ∈ 17 - 100 GeV/c
- Goal: identify $\pi^{\pm}$, $K^{\pm}$, p

$$\cos\theta_c = \frac{1}{n\beta} = \frac{c}{nv}$$

for v > c/n
n = refractive index

Combine with p measurement from trackers ⇒ m!



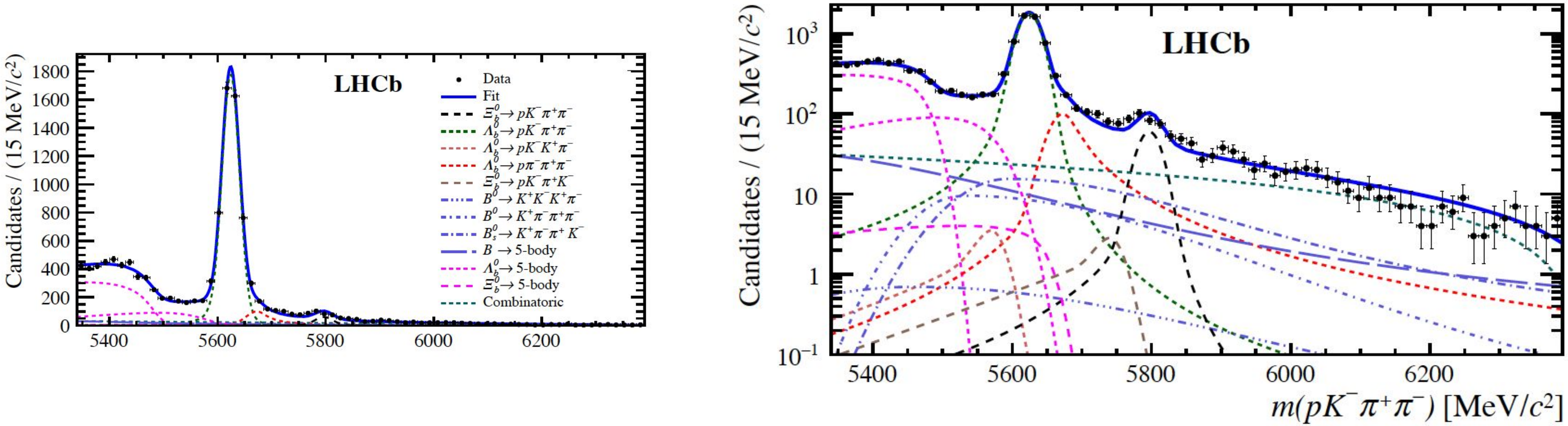
LHCb-DP-2012-003

Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability

Particle identification usage

PID is crucial to separate exclusive final states

Recent example in $\Lambda_b \rightarrow pK^-\pi^+\pi^-$ decays:



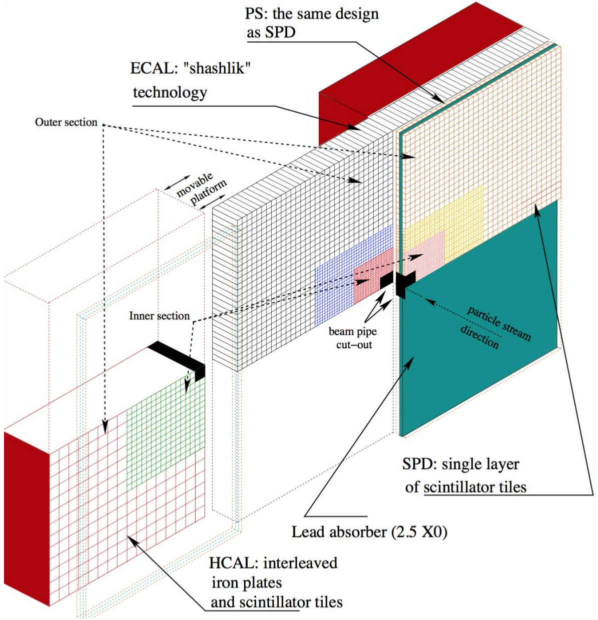
JHEP02(2018)098

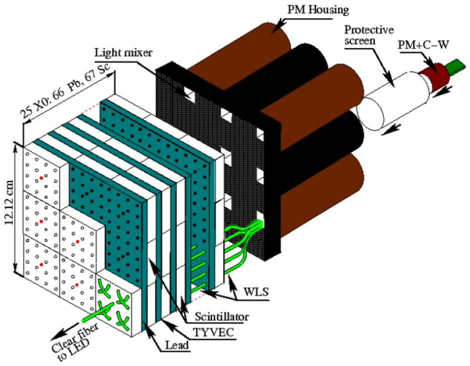
Particle identification system

- Calorimeters: identify γ, π^0, $e^\pm$
- Sashlik technology

$\Delta E/E_{ECAL}$ = 1% + 10% / √(E[GeV])

Electron ID ~90% for ~5% e→h mis-id probability





(a) ECAL module

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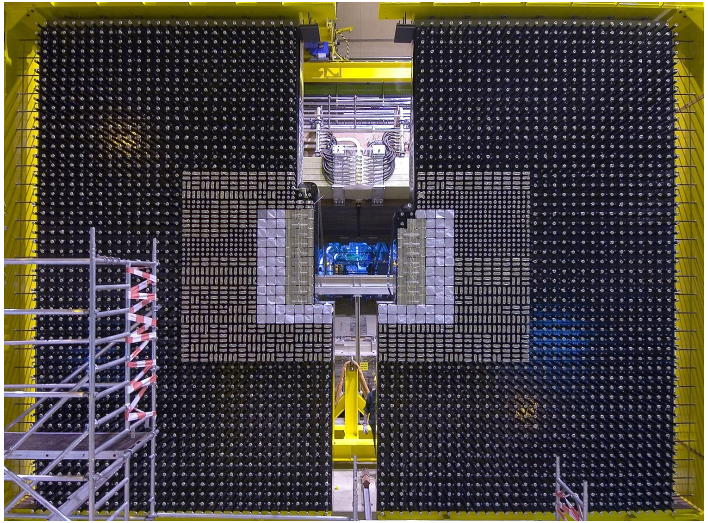
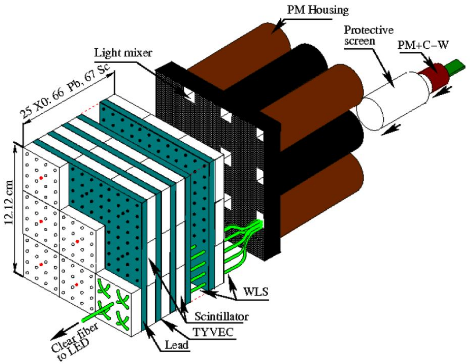


Electromagnetic calorimeter



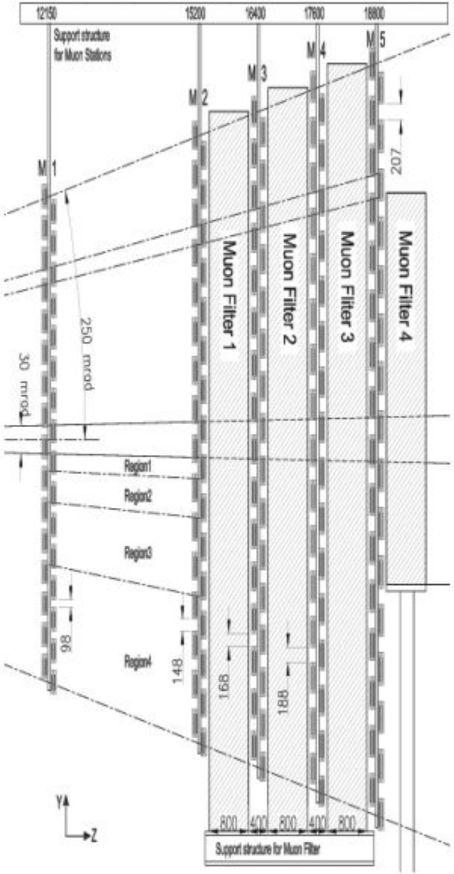
(a) ECAL module

Particle identification system

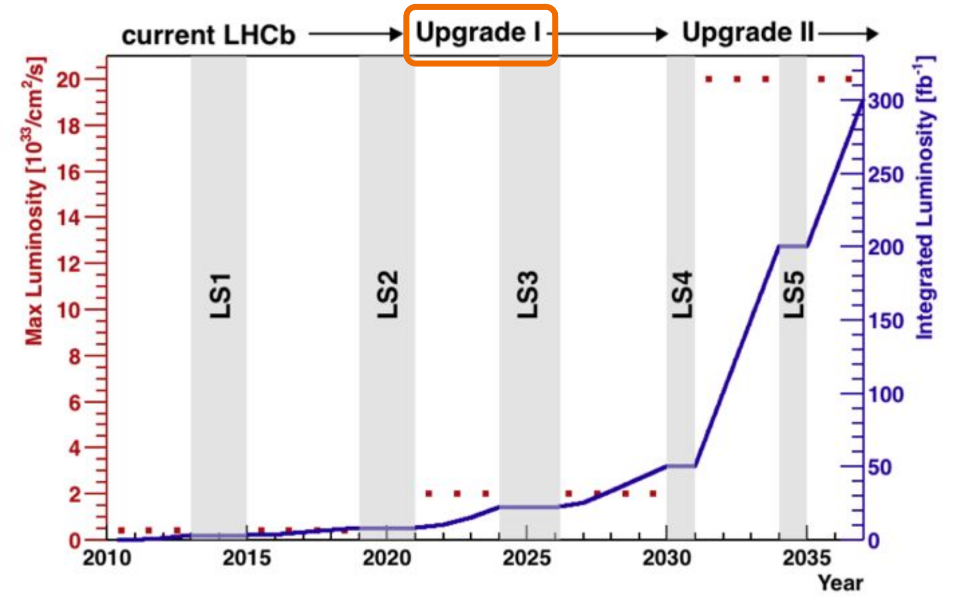
- Muon chambers: identify $\mu^{\pm}$
- Alternating layers of iron + MWPC

Muon chambers

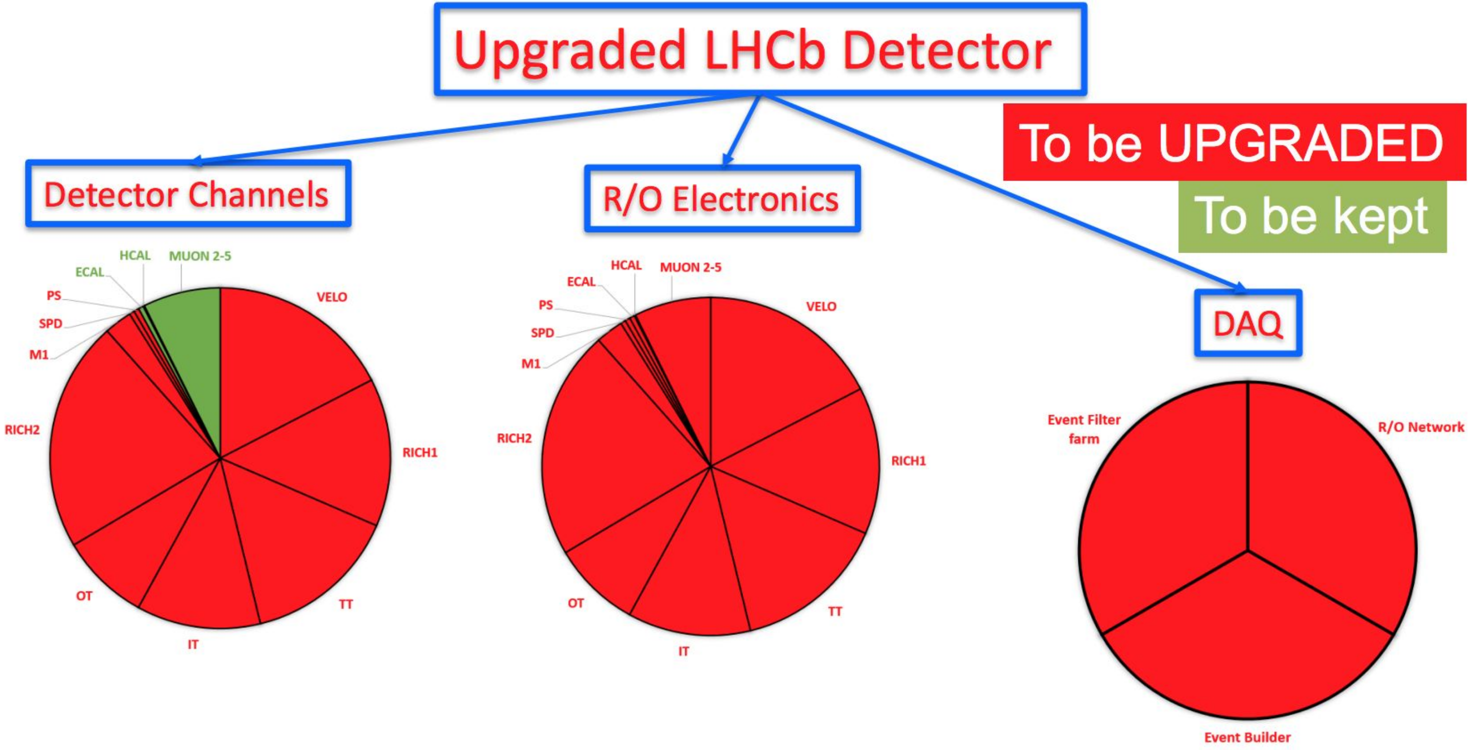
Muon ID ~ 97% for 1-3% $\pi \to \mu$ mis-id probability



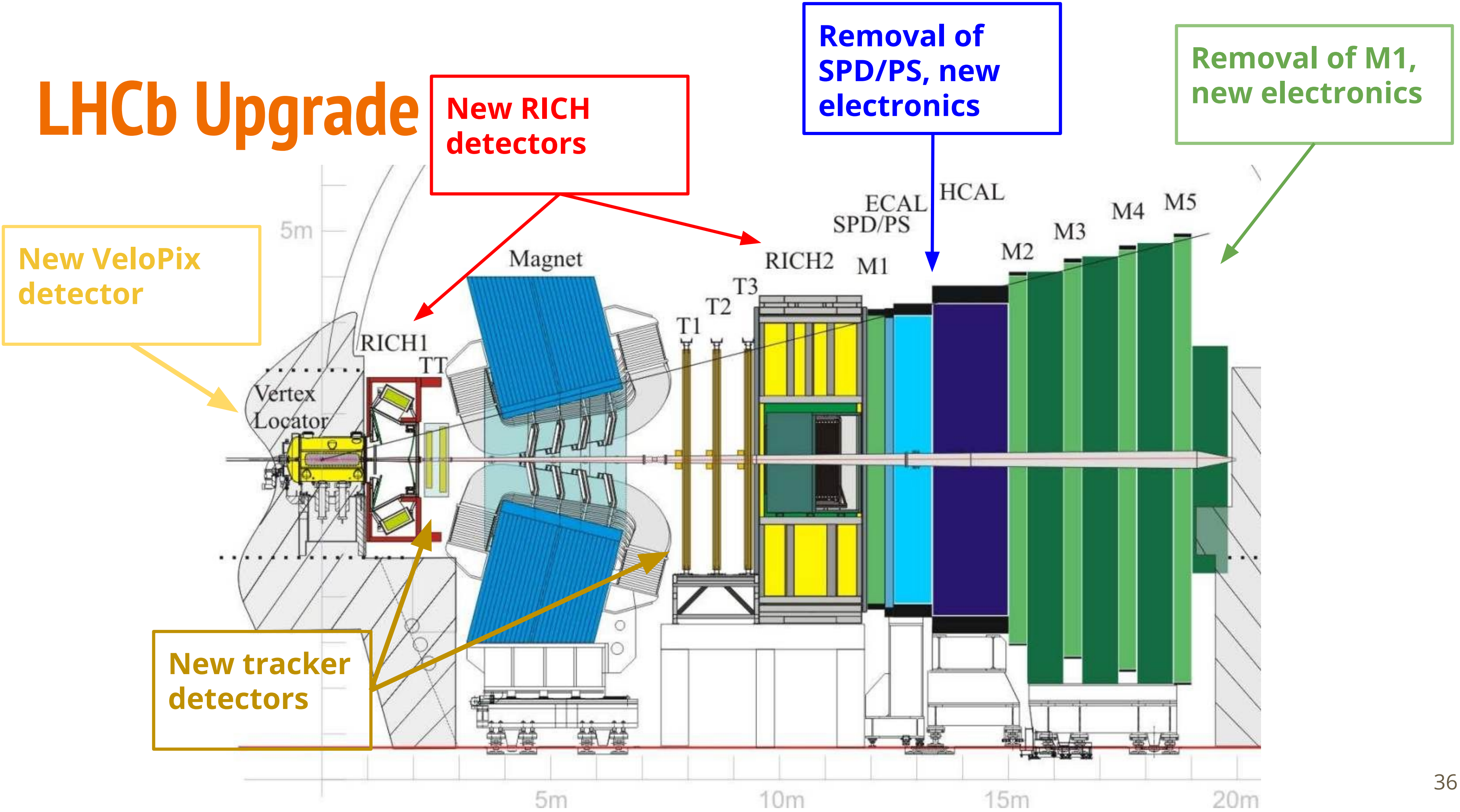
The LHCb upgrade



LHCb Upgrade: a quasi-new detector



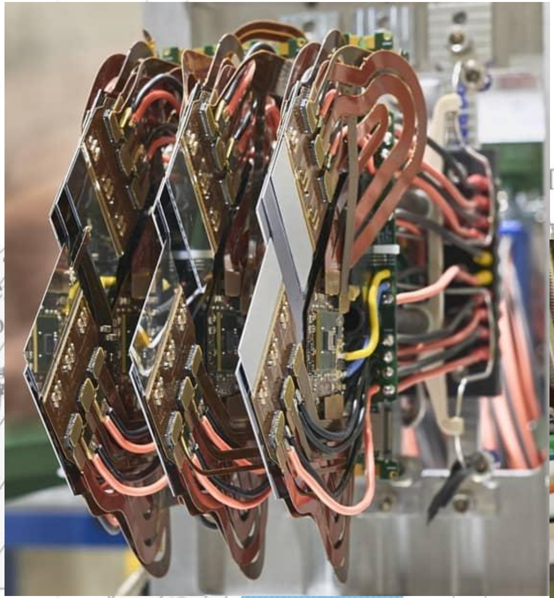
LHCb Upgrade



LHCb Upgrade

CERN-LHCC-2013-021

New VeloPix detector

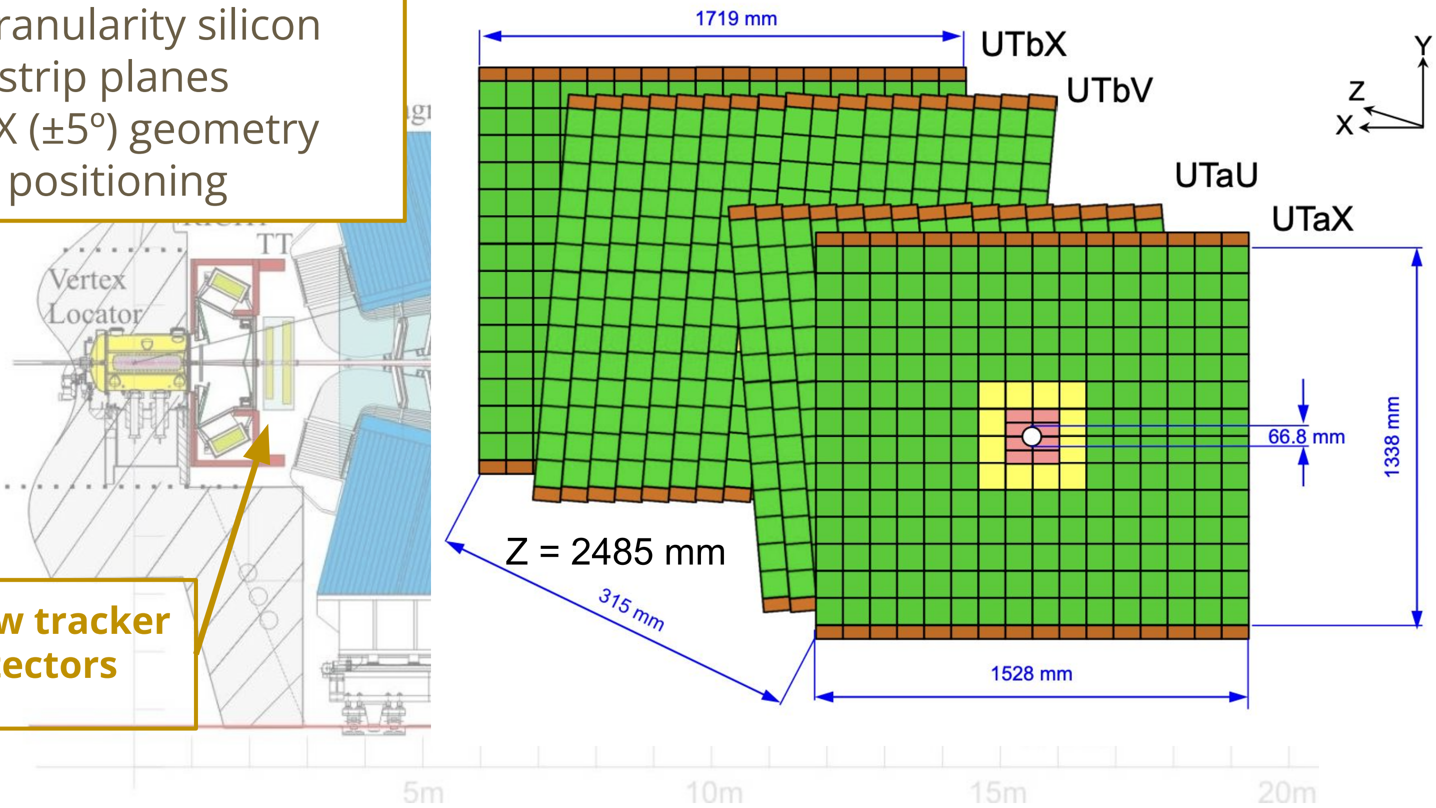


- 3.5mm to beam (5mm Run1/2)
- 41M pixels of 55x55 μm
- improved PV and IP resolutions

CERN-LHCC-2014-001

LHCb Upgrade

- high-granularity silicon micro-strip planes
- X-U-V-X (±5º) geometry for x-y positioning

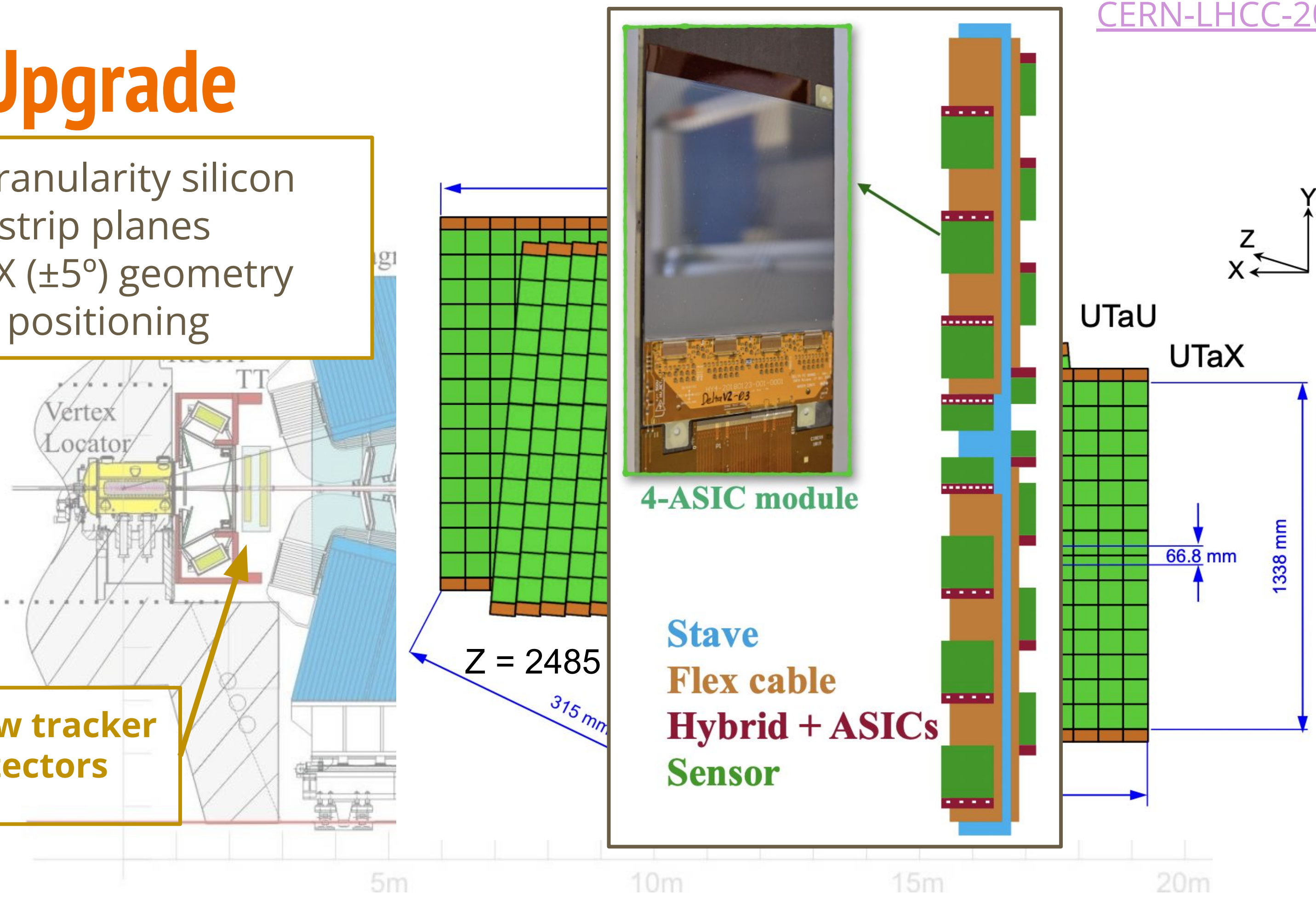


New tracker detectors

CERN-LHCC-2014-001

LHCb Upgrade

- high-granularity silicon micro-strip planes
- X-U-V-X (±5º) geometry for x-y positioning

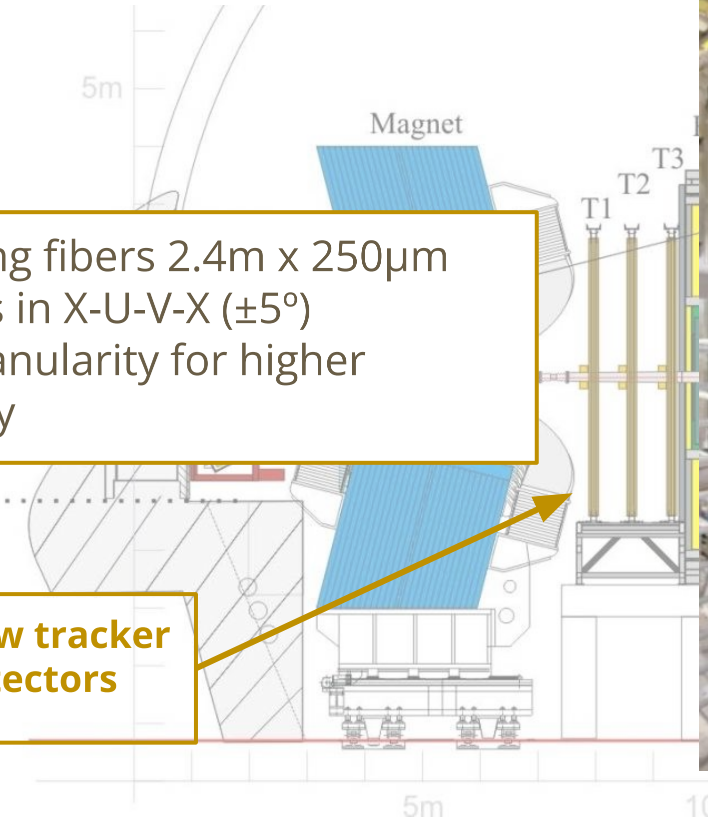


New tracker detectors

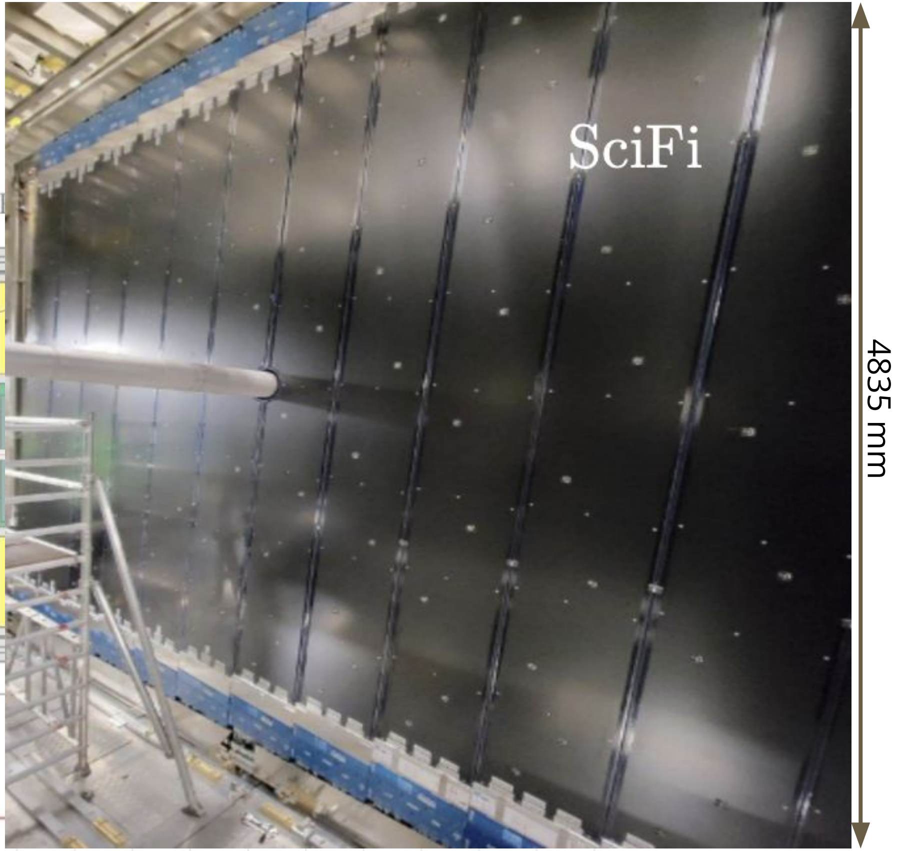
CERN-LHCC-2014-001

LHCb Upgrade

- Scintillating fibers 2.4m x 250μm
- 3x4 layers in X-U-V-X (±5º)
- higher granularity for higher occupancy

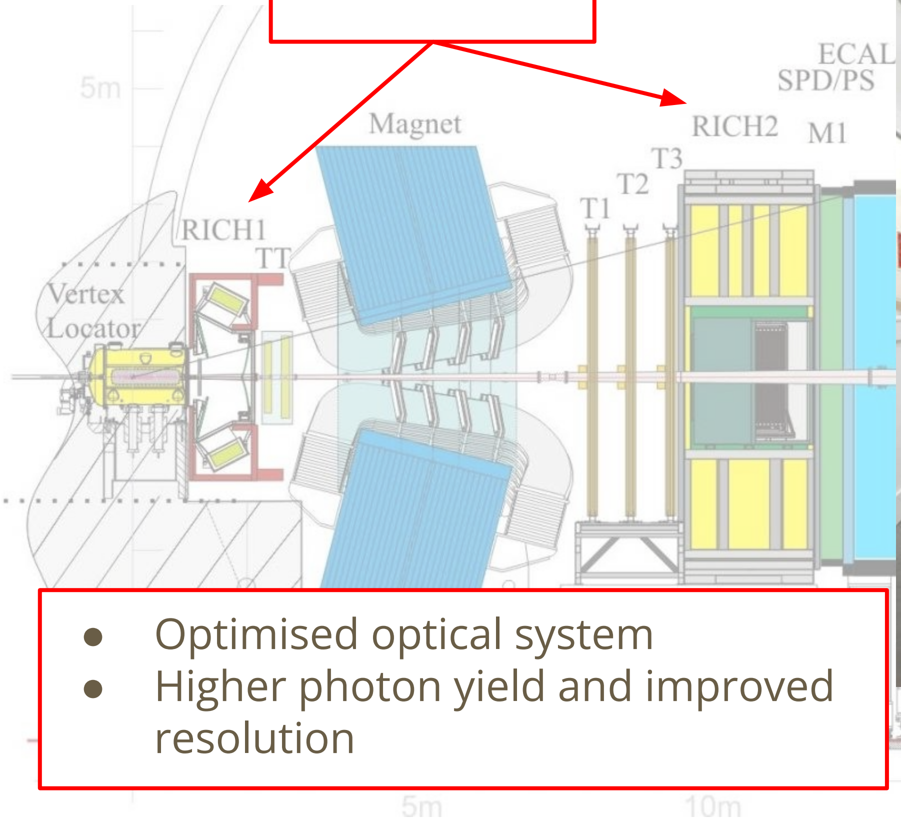


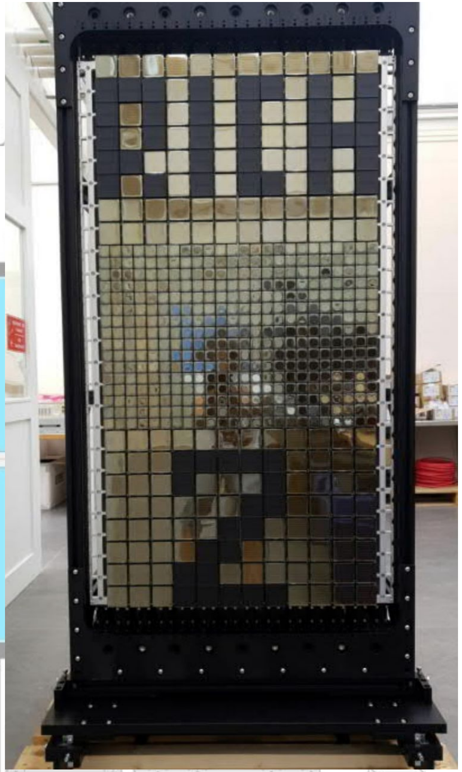
New tracker detectors



CERN-LHCC-2013-022

LHCb Upgrade





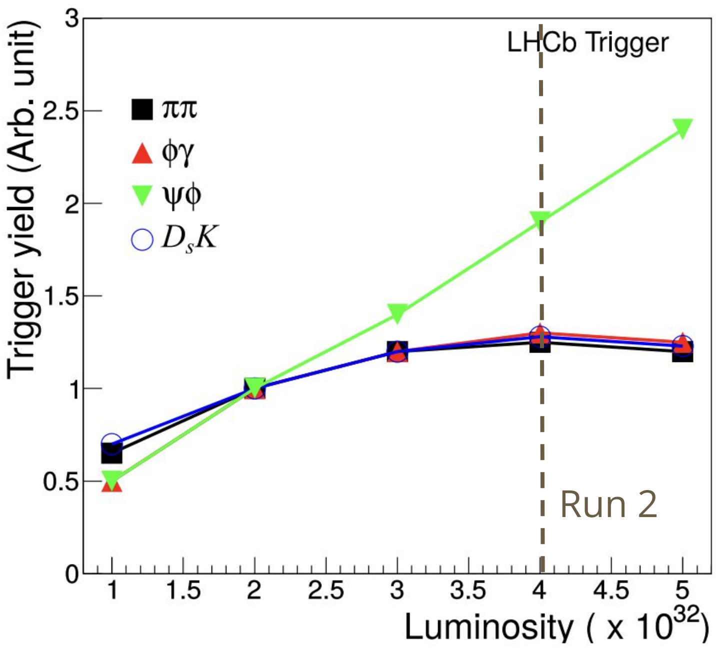
- Optimised optical system
- Higher photon yield and improved resolution

A trigger-less readout

J. Phys.: Conf. Ser. 878 012012

- Instantaneous Lumi: 2×10^{33} cm^{-2}s^{-1}
  - was 4×10^{32} in Run 2
- Hardware trigger rate limit (1 MHz) saturates fully hadronic modes

⇒ read full detector at 30 MHz and apply selections in software



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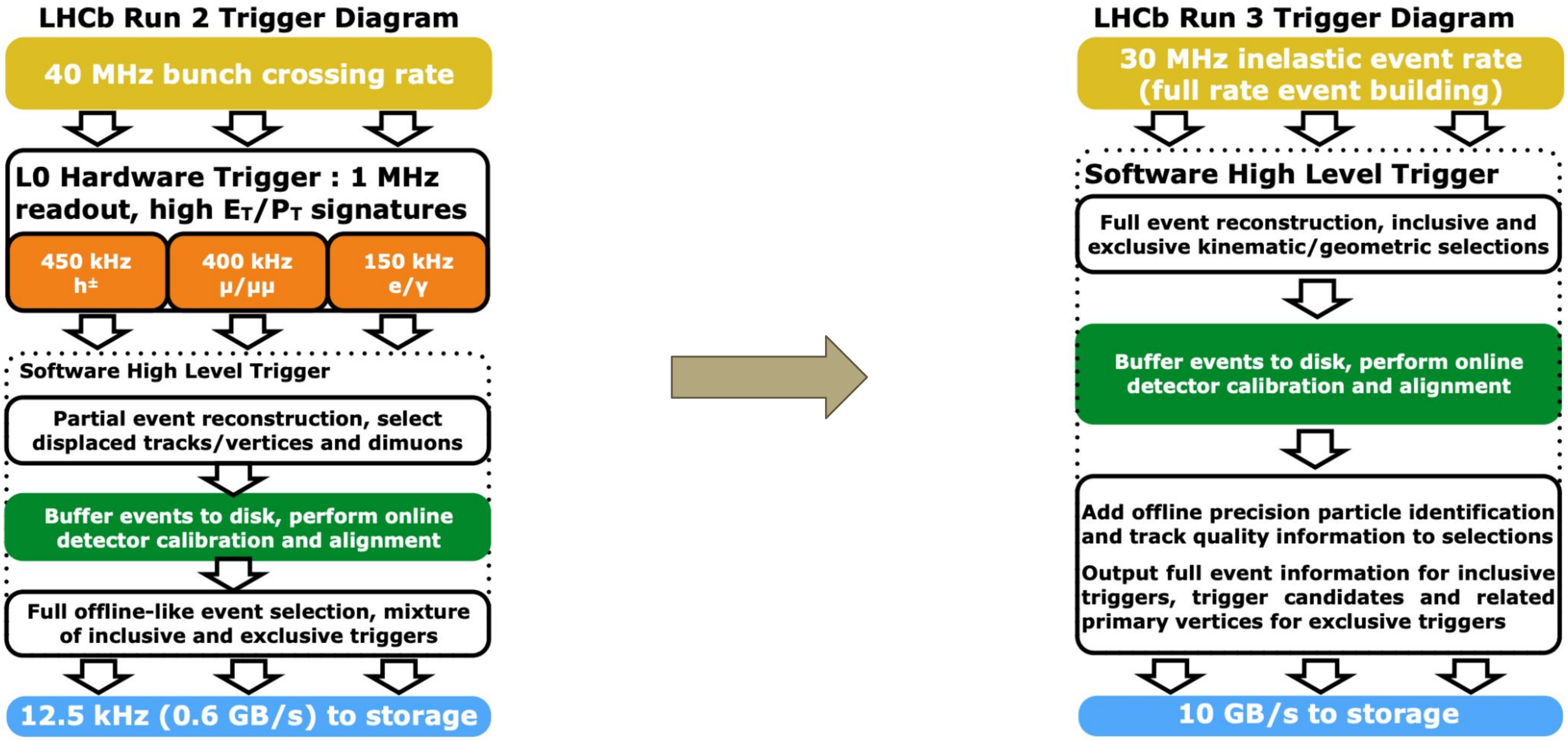
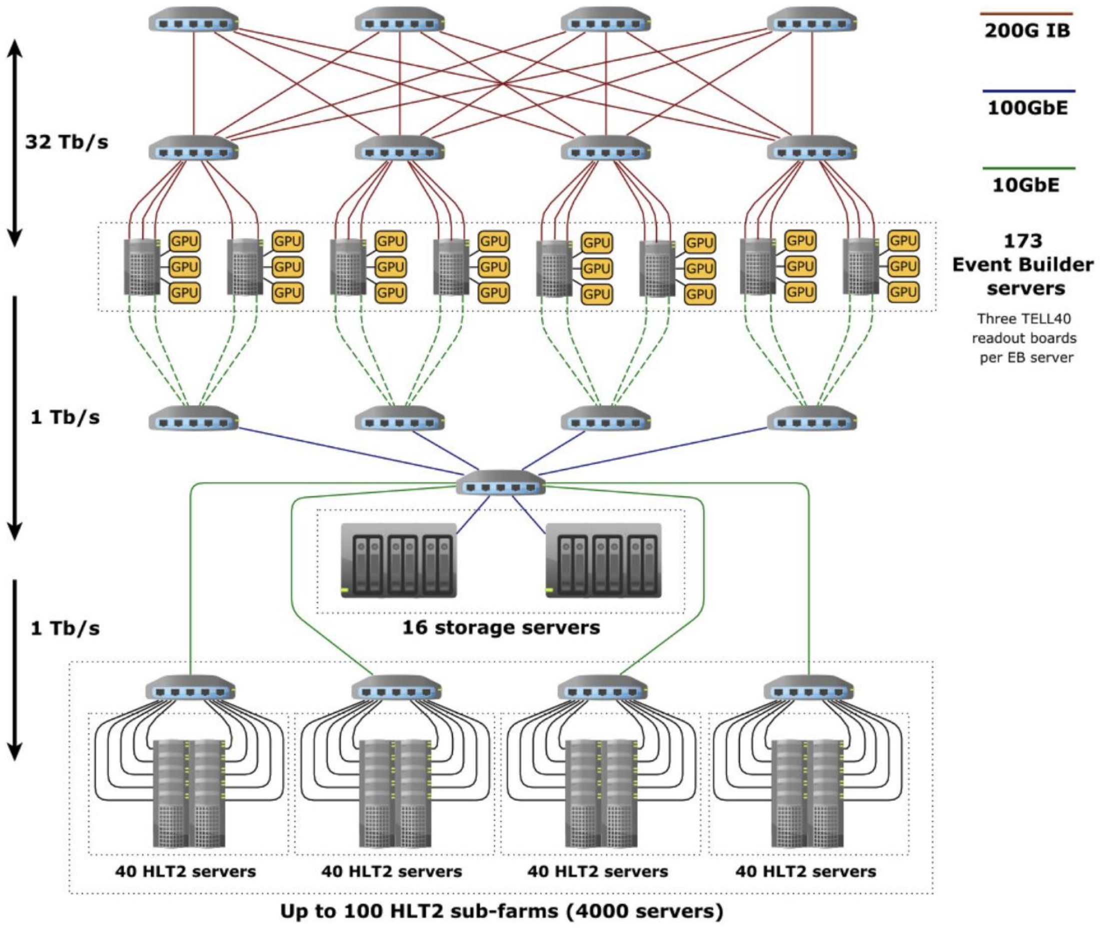


DAQ architecture

Hybrid architecture:

- HLT1: **GPUs** installed in EB servers

- HLT2: **CPUs** in Event Filter Farm



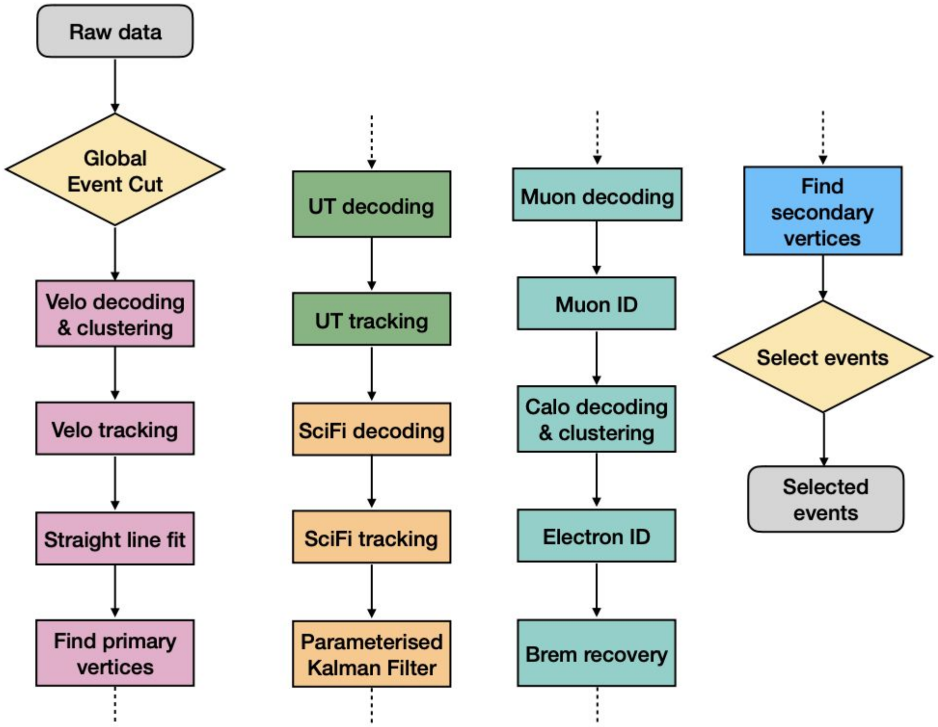
HLT1

Core based on tracking:

- VELO: tracking, vertex reconstruction
- UT: tracking, p estimate, fake rejection
- SciFi: track reconstruction, momentum measurement

PID from muon stations & Calo

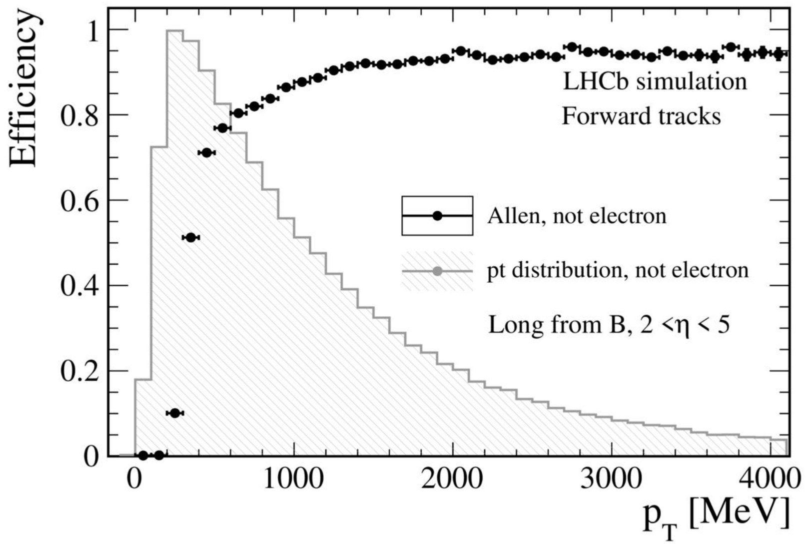
Highly parallel tasks → exploit GPUs: Nvidia RTX A5000

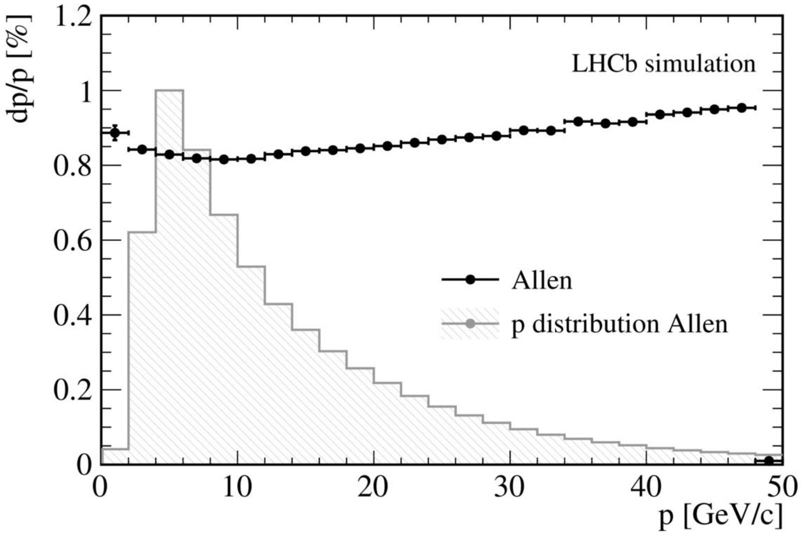


HLT1 performance: tracking

LHCB-FIGURE-2020-014

Same performance at x5 luminosity: high efficiency, good δp, low fake rate

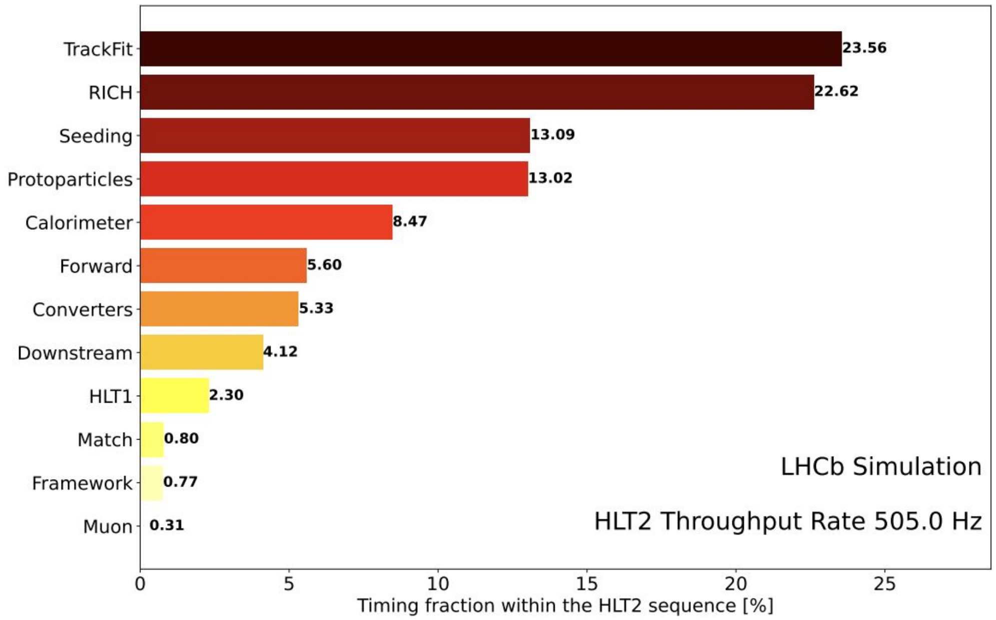




HLT2

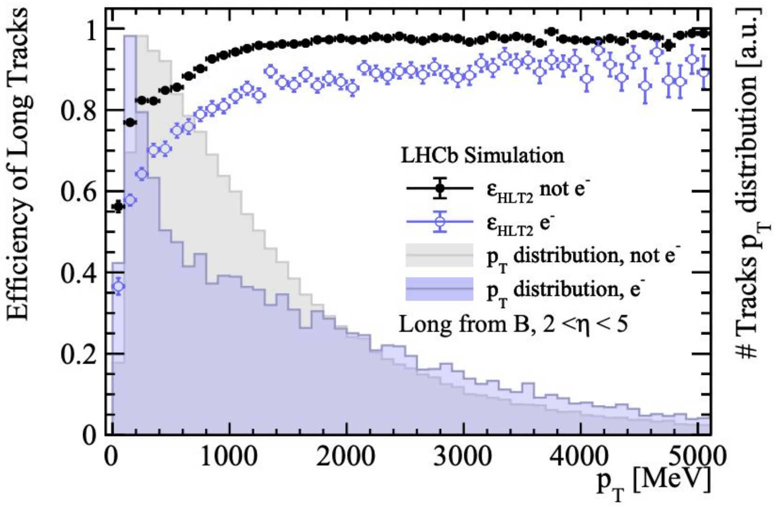
LHCB-FIGURE-2022-005

Full reconstruction of tracks and neutrals, and PID with offline-quality

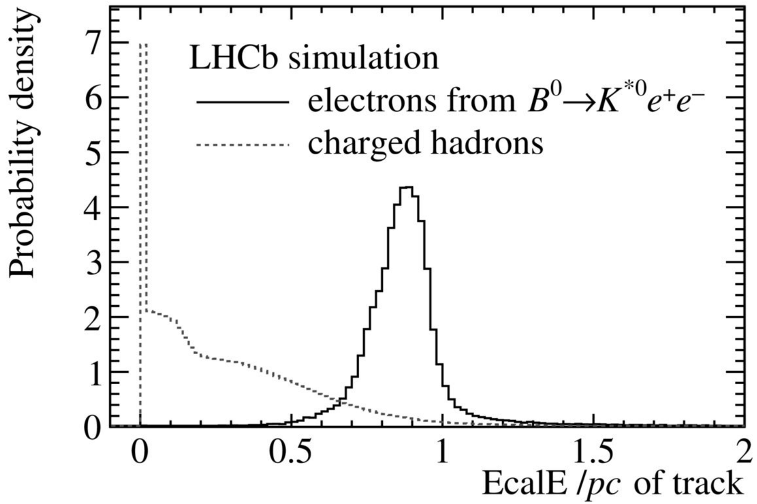


HLT2

Full reconstruction of tracks and neutrals, and PID with offline-quality



LHCB-FIGURE-2022-005



LHCB-FIGURE-2021-003

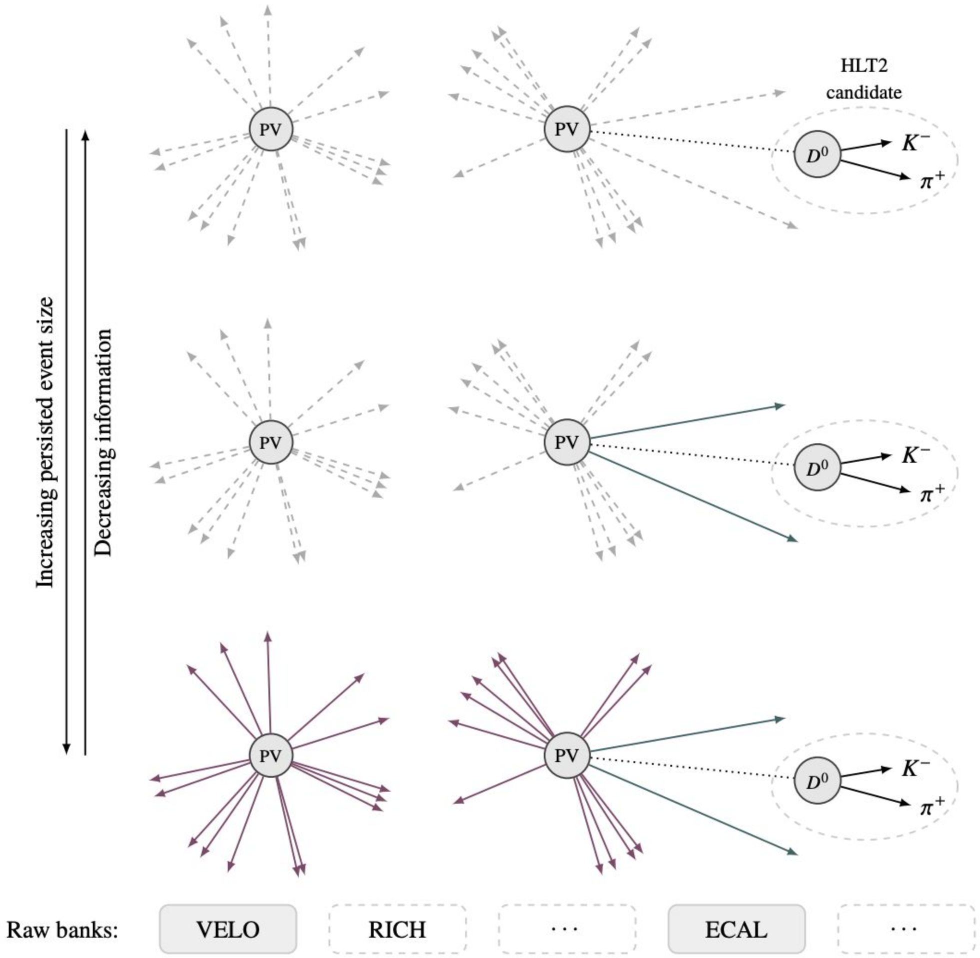
HLT2: turbo model

[JINST 14 P04006](https://doi.org/10.1088/1748-0221/14/04/P04006)

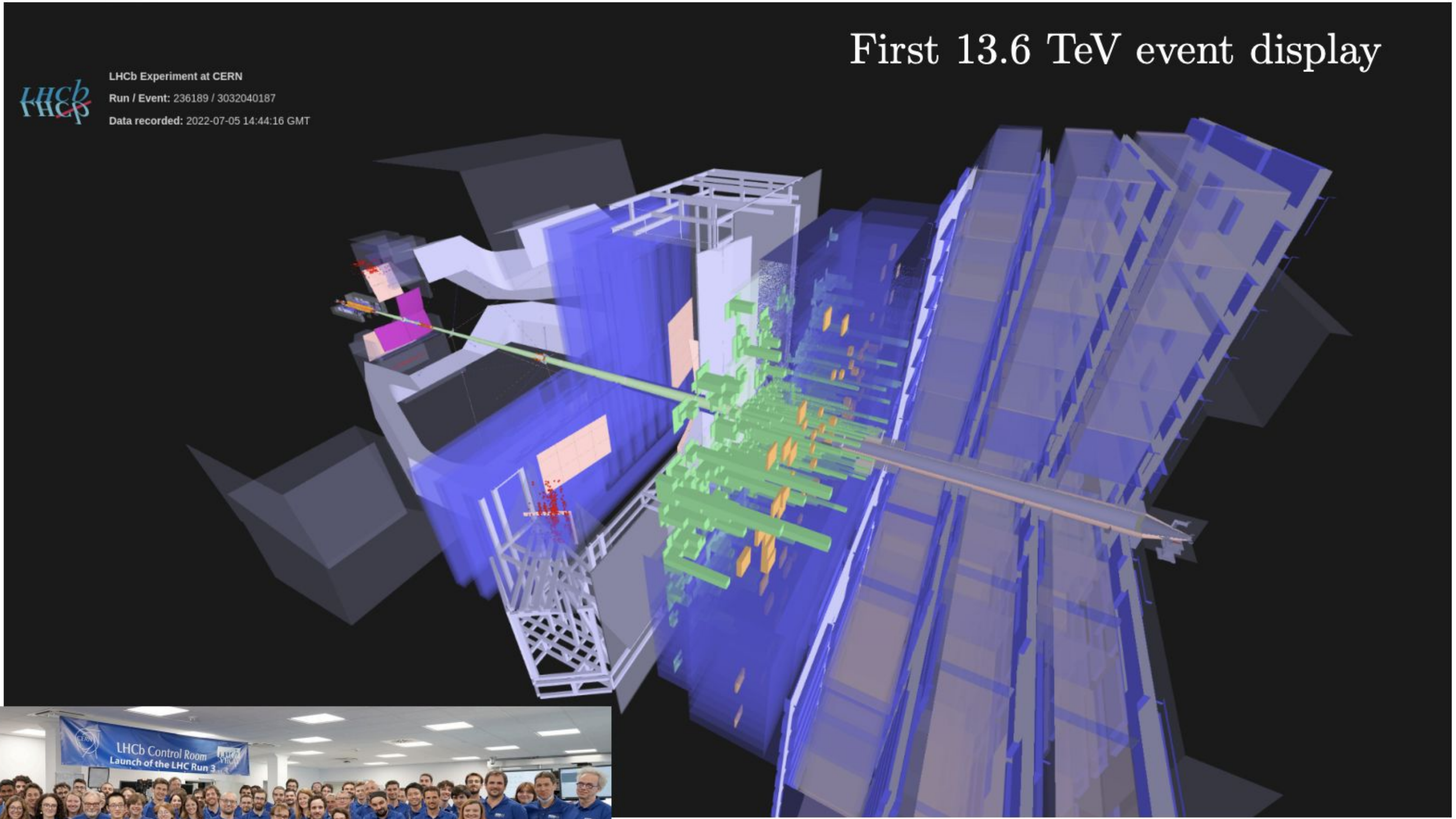
Flexible persistence model:

- **Turbo**: signal only
- **Selective**: signal + selection of reconstructed objects
- **Complete**: all reco'ed objects
- **Raw event**: detector hits

Persistence method	Average event size (kB)
Turbo	7
Selective persistence	16
Complete persistence	48
Raw event	69

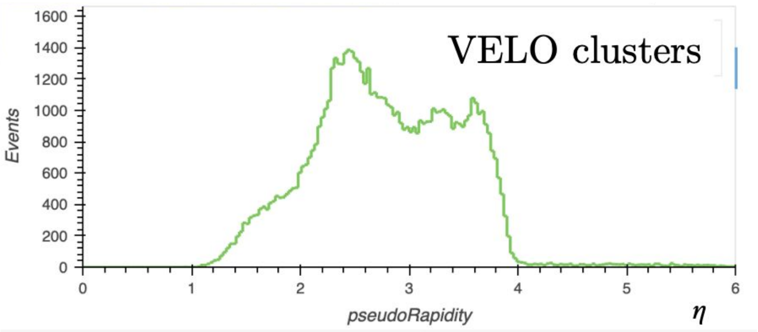


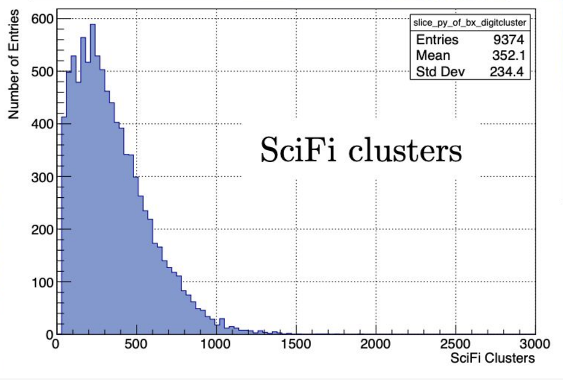
Commissioning and first data

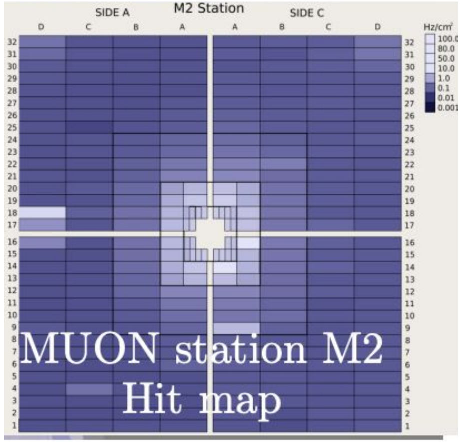


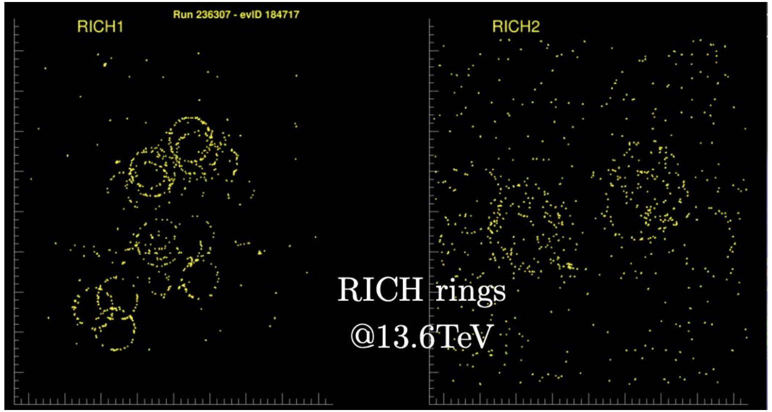
F. Blanc @ICHEP22

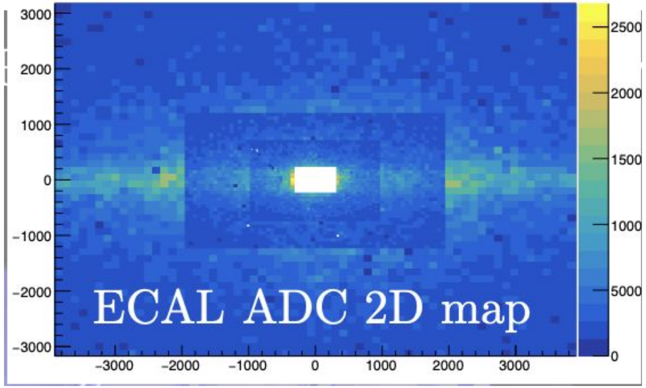
First Run 3 data







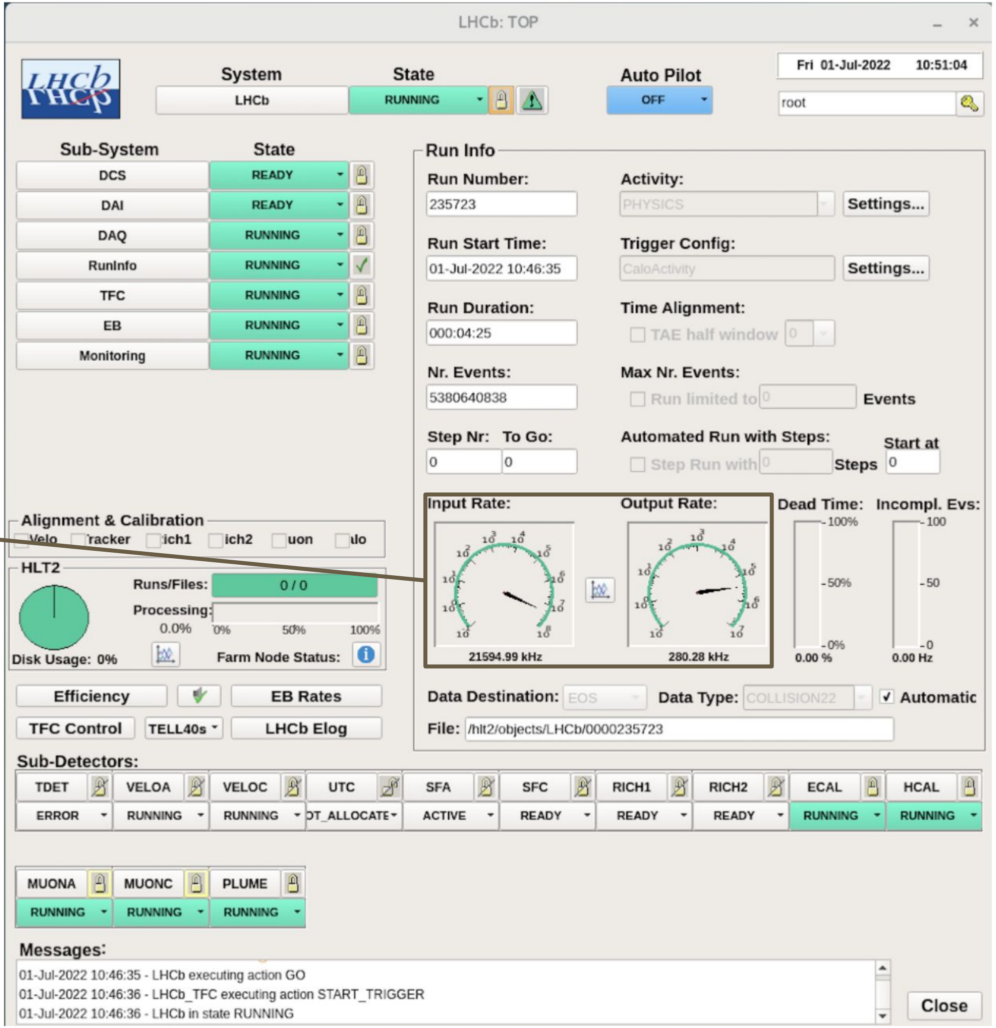




C. Agapopoulou @ICHEP

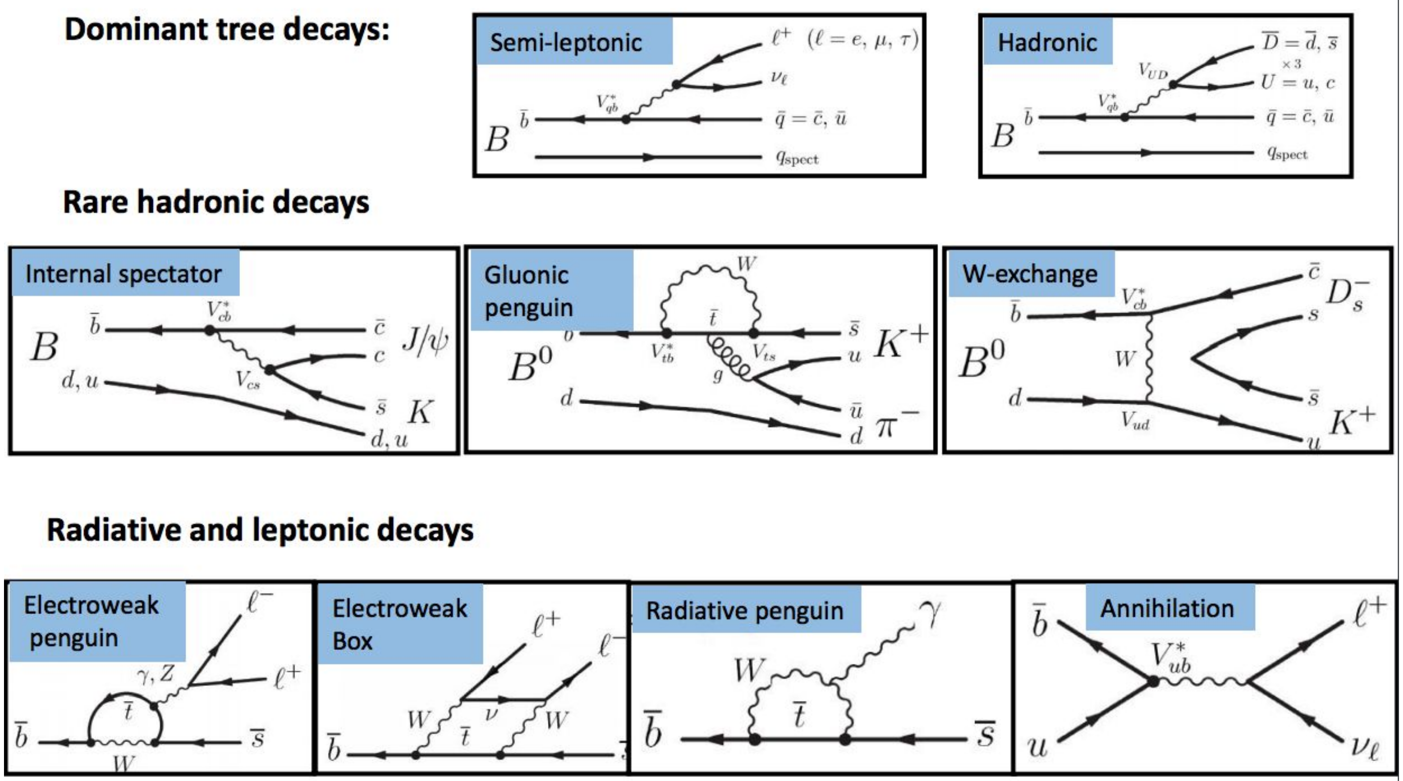
HLT1 commissioning

- LHCb DAQ running in parallel to detector commissioning since July
- ~200 GPUs installed and HLT1 running in global partition
- Triggering on ECAL clusters @20 MHz!
- Next: include trackers when ready



LHCb Physics

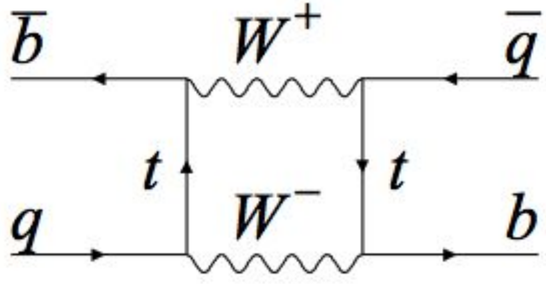
b-hadron decays

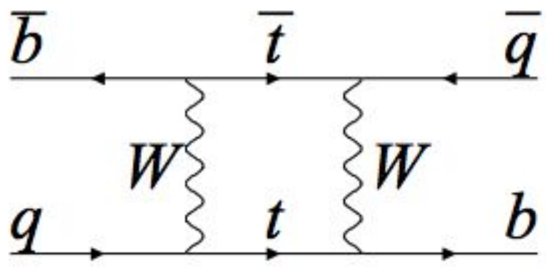


credit: A. Oyanguren

B mixing

Neutral B mesons can oscillate: $B_q \rightarrow \bar{B}_q$ or $(\bar{b}q) \rightarrow (b\bar{q})$



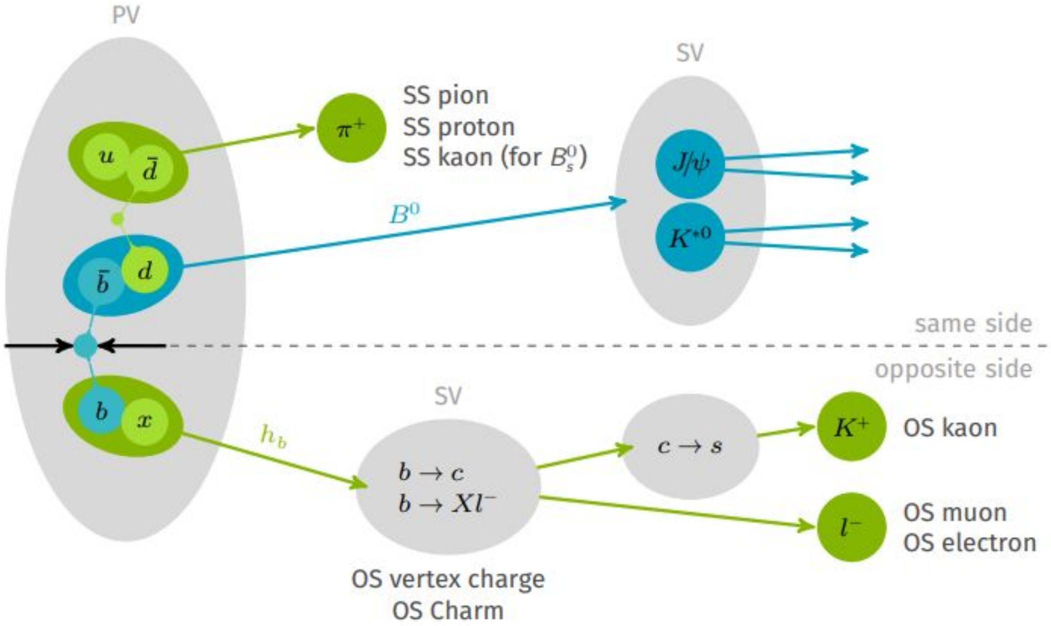


Oscillation frequency is faster in B_s system

In CPV measurements, critical to know if B has oscillated before decaying

Flavour tagging

Information from the rest of the event to → flavour of the signal b-meson



Tagging efficiency = fraction of events tagged

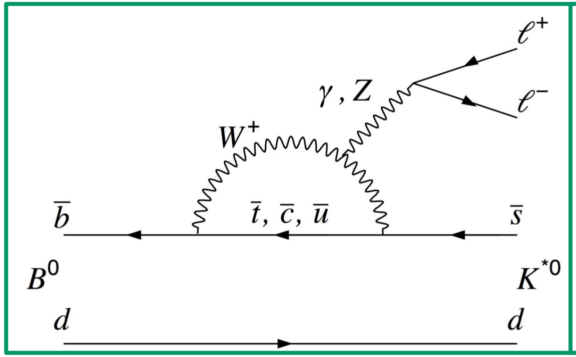
Mis-tagging fraction = fraction of tagged events with wrong tag

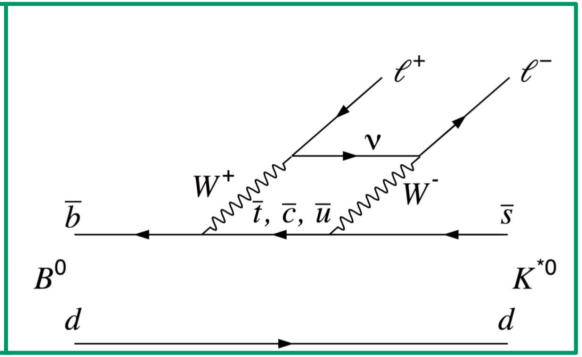
Effects need to be calibrated and included in measurements

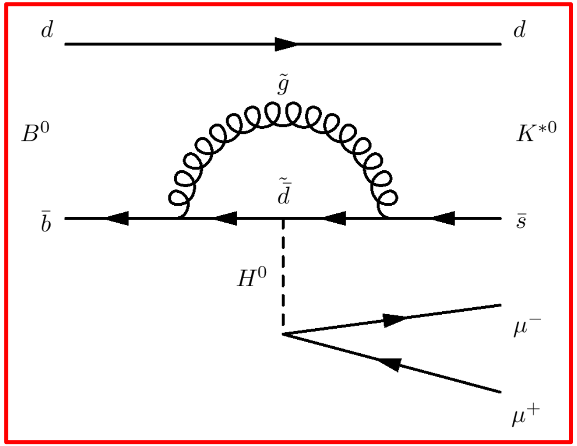
LHCb Physics:
Rare Decays

Rare b-hadron decays

- Flavour Changing Neutral Currents only allowed at loop level in SM
- Sensitive to indirect effects of New Physics (NP) in loops
- Access to much larger scales than direct searches





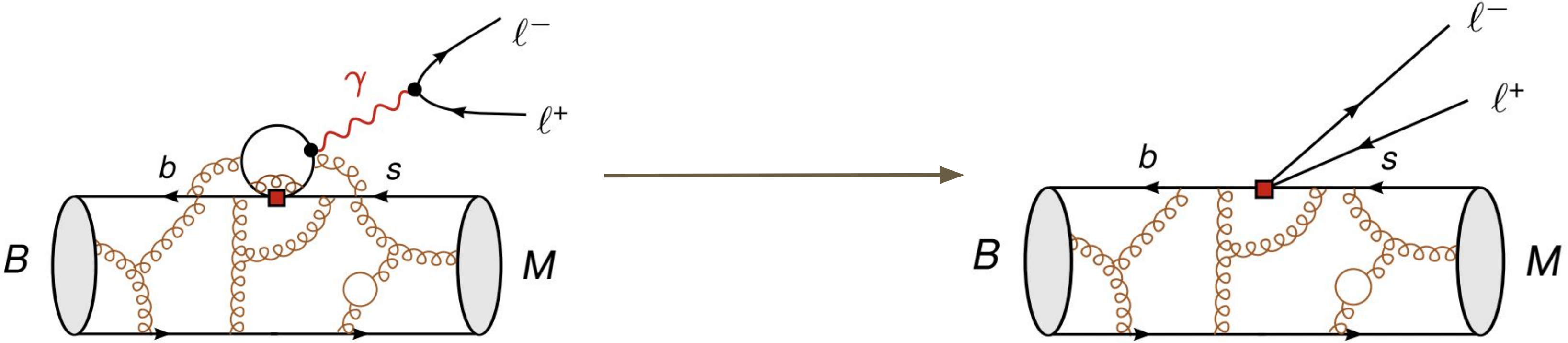


Effective Hamiltonian approach

Model independent description in effective field theory [Buchalla et al.]:

$$H_{\text{eff}} \propto V_{tb} V_{ts}^{*} \sum_{i} \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

O_i = 4-fermion operators, C_i = short distance, computed perturbatively
Form factors needed to describe hadronization process



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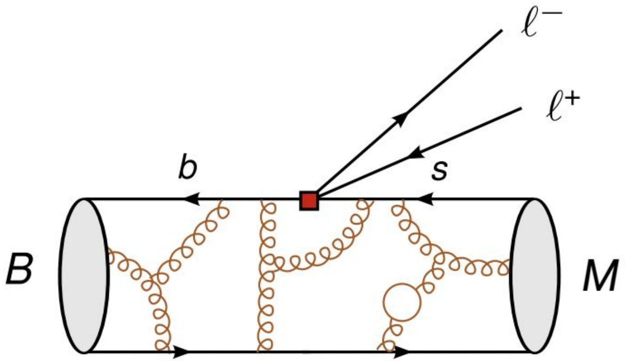
Form factors needed to describe hadronization process

$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$
$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu l)$$
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu\gamma_5 l)$$
$$O_S^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}l)$$
$$O_P^{(\prime)} \propto (\bar{s}P_{L(R)}b)(\bar{l}\gamma_5 l)$$



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$$O_S^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l} l)$$
$$O_P^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l}\gamma_5 l)$$

Wilson coefficients

Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

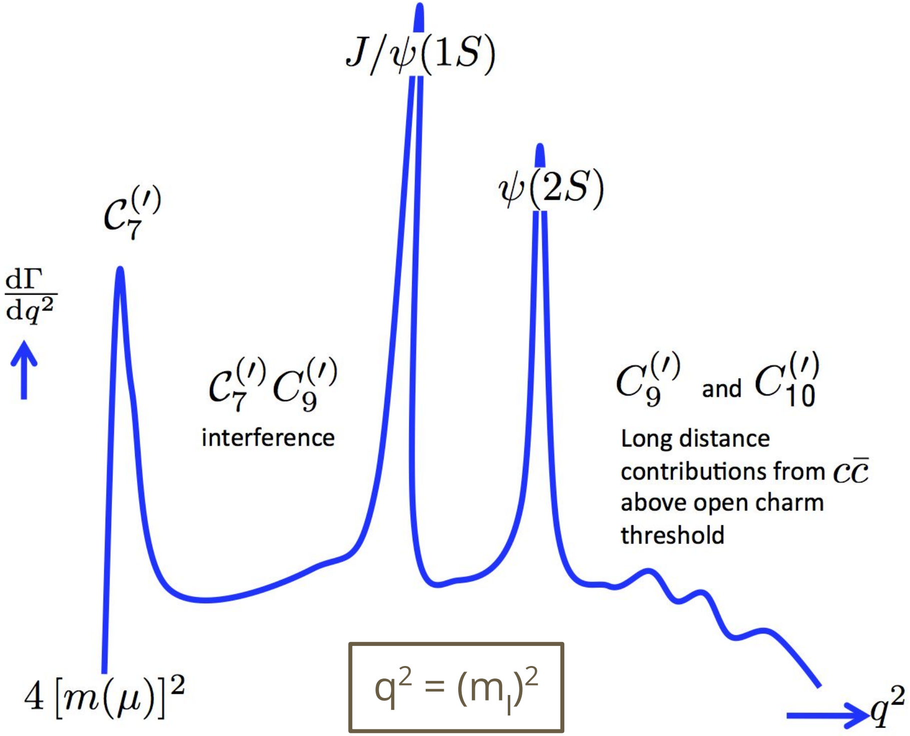
Effective Hamiltonian approach

b → sll sensitivity to Wilson coefficients varies with dilepton invariant mass, q^2

→ measurements performed in various bins and combined in global fits

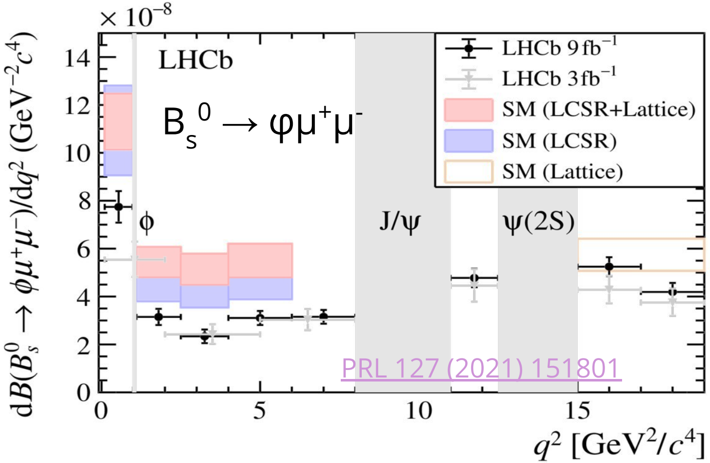
Wilson coefficients

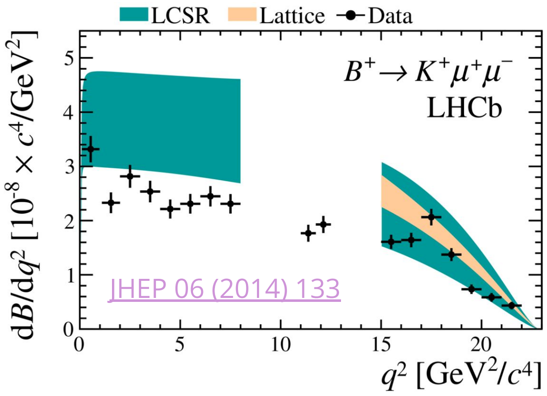
Transition	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$b \to s\gamma$	X			
$b \to \ell^+\ell^-$			X	X
$b \to s\ell^+\ell^-$	X	X	X	

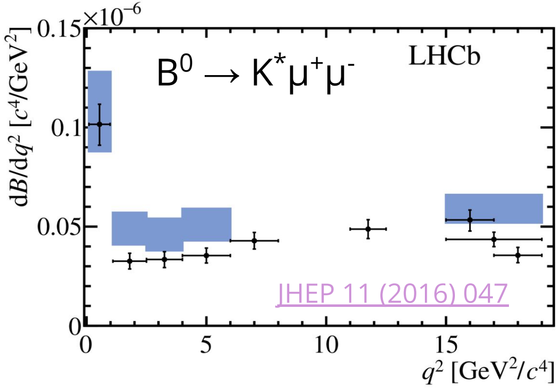


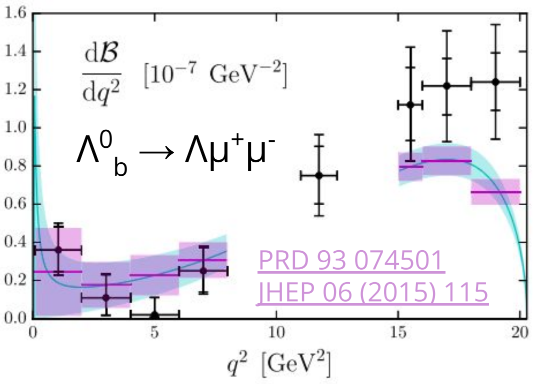
Branching ratios

Trend: $b \to s\mu^+\mu^-$ BR systematically lower than SM predictions









Angular observables

Range of observables sensitive to different WCs

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\vec{\Omega}}\bigg|_P = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l$$
$$-F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

$B_d \to K^* \mu^+ \mu^-$
[Altmannshofer et al.]

F_L: H longitudinal polarisation

A_{FB}: di-lepton forward-backward asymmetry

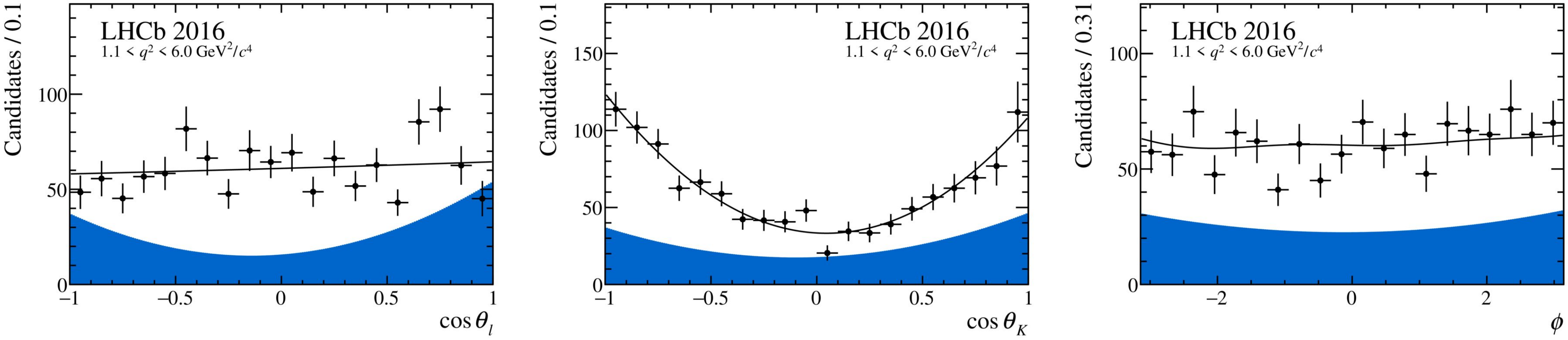
S_i: CP-averaged observables

"Clean" basis: cancellation of Form Factors at leading order [Descotes-Genon et al.]

$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

Angular observables

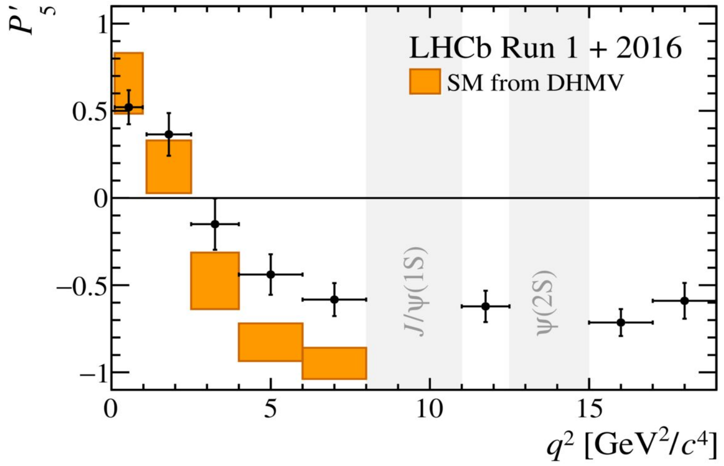
Fit decay angles using theory expression with free parameters

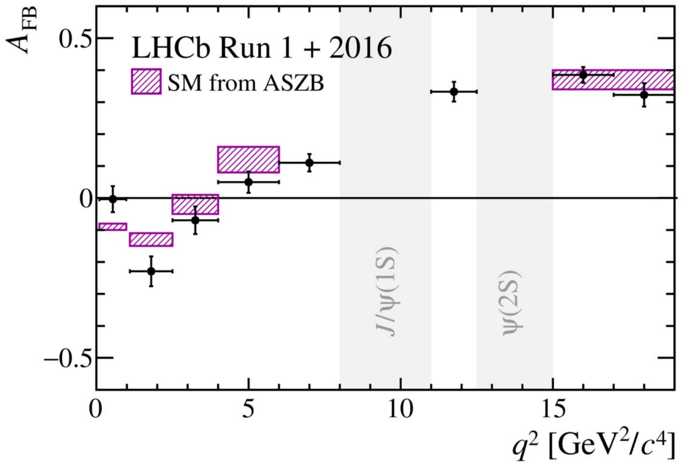


Angular analysis of $B^0 \longrightarrow K^*\mu^+\mu^-$

PRL 125 (2020) 011802

Results: angular parameters - compare them to theory predictions to test SM
Some deviations arise!



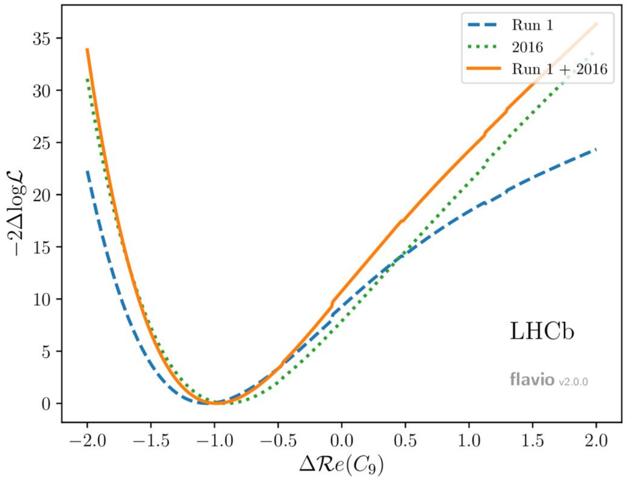


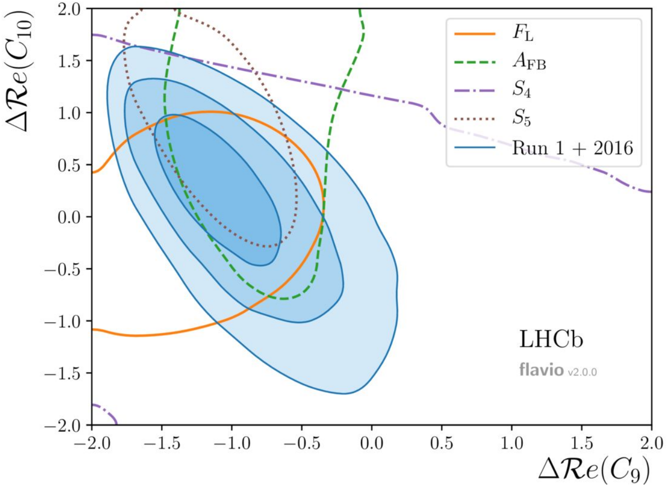
Angular analysis of $B^0 \rightarrow K^* \mu^+ \mu^-$

PRL 125 (2020) 011802

Extract values of C_i that explain the observed parameters in data:

$$C_i = C_i^{SM} + \Delta C_i$$





2.7 - 3.3 σ preference for NP with negative C_9^{NP}

Lepton Flavour Universality tests

Leptons of different species couple identically to electroweak bosons in SM
→ Lepton Flavour Universality (LFU)

Measure ratio of same b → sll process with muons and electrons in final state:

$$R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2} dq^2}$$

$H = K^+, K^{0*}, K^0_S, K^{0+}$ ...

Hadronic uncertainties cancel in ratio → very clean theory prediction

How do we measure LFU?

Observable:

$$R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2}$$

H = K^+, K^{0*}, K^0_S, K^{0+} ...

Experimentally:

$$R_H \propto \underbrace{\frac{N(B \to H\mu^+\mu^-)}{N(B \to He^+e^-)}}_{\text{events}} \times \underbrace{\frac{\epsilon(B \to He^+e^-)}{\epsilon(B \to H\mu^+\mu^-)}}_{\text{efficiency}}$$

events: count in experiment

efficiency: from simulation and calibration samples

Challenge:

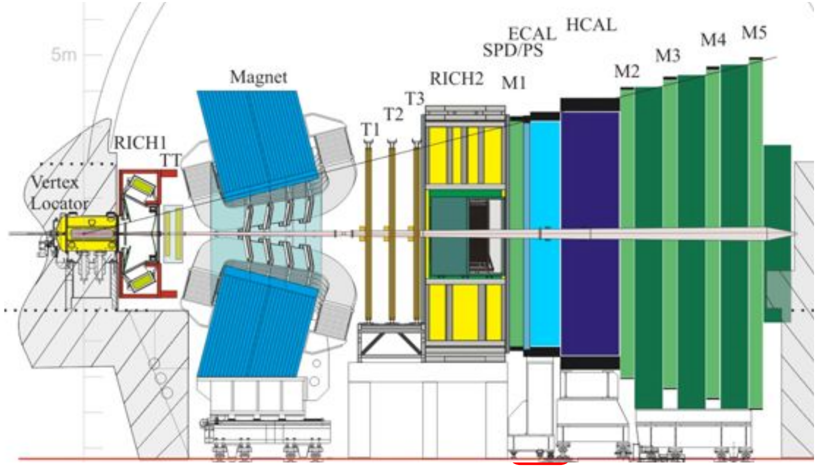
- e and μ efficiencies are very different
- hard to estimate absolute efficiencies

Challenges: hardware trigger

ECAL occupancy > Muon one
⇒ tighter thresholds for electrons:

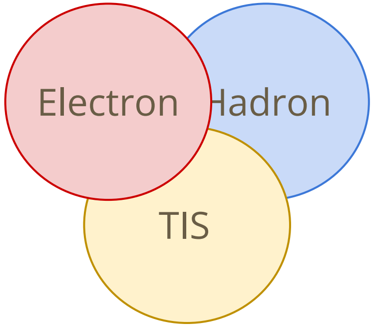
- **e p_T** > 2700/2400 MeV in 2012/2016
- **μ p_T** > 1700/1800 MeV in 2012/2016

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

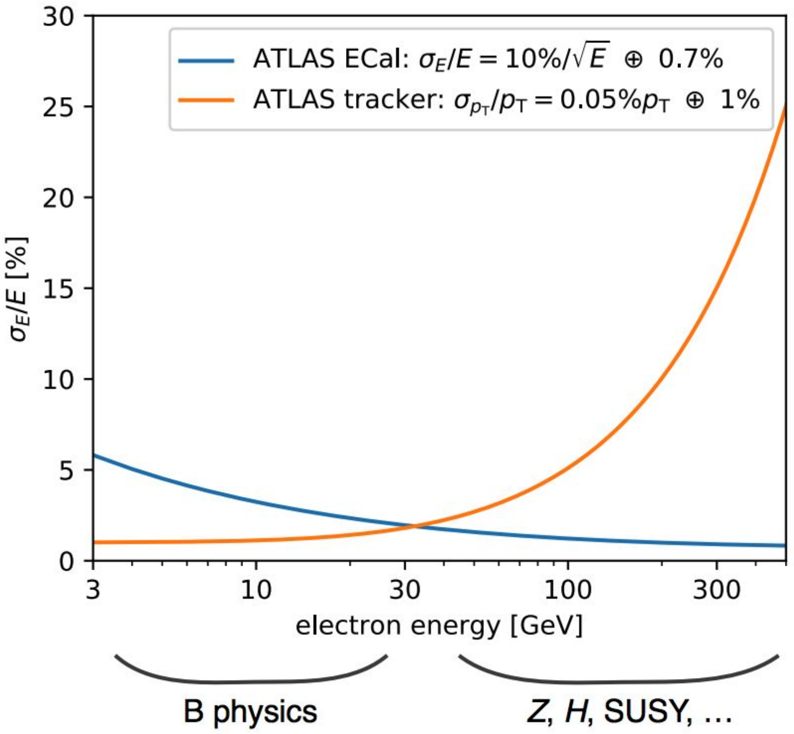


Mitigation:

- events triggered independently of the signal (TIS)
- (hadron trigger)



Challenges: resolution



by M. Borsato

Challenges: material interaction

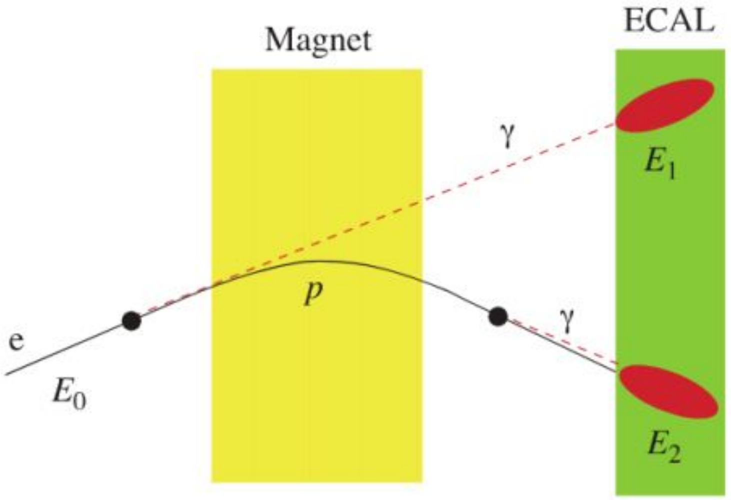
Electrons radiate much more Bremsstrahlung

Recovery procedure: match ECAL clusters to tracks before bending

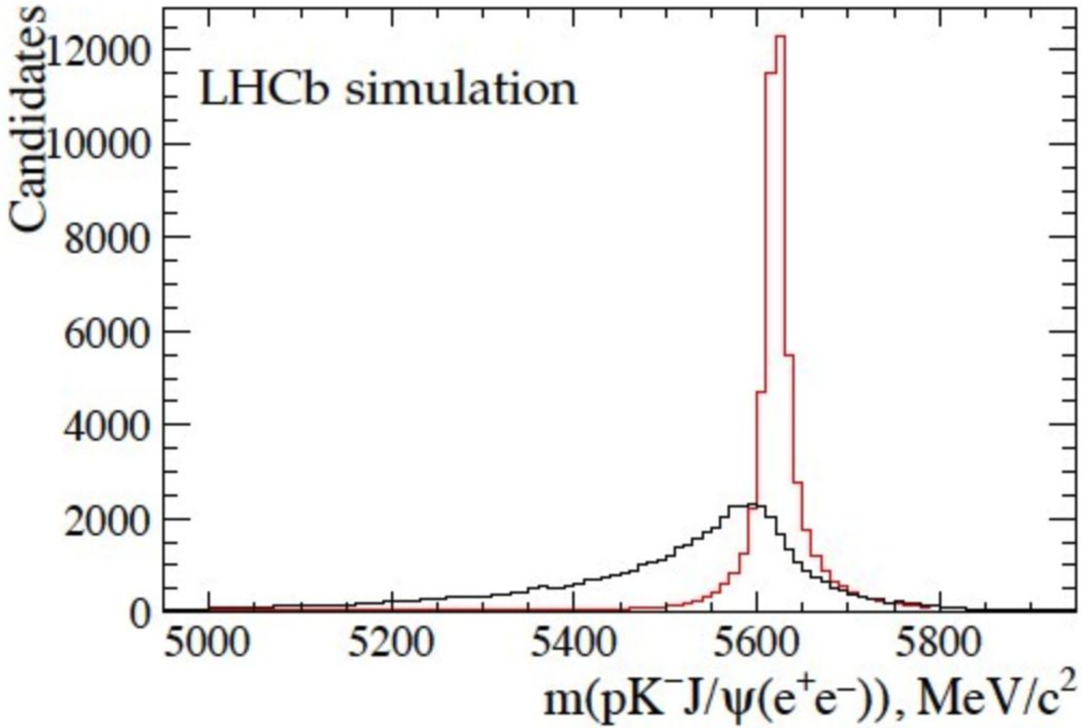
Limitations:

- miss some photons and add fake ones
- ECAL resolution worse than tracking

→ worse mass resolution for electron modes



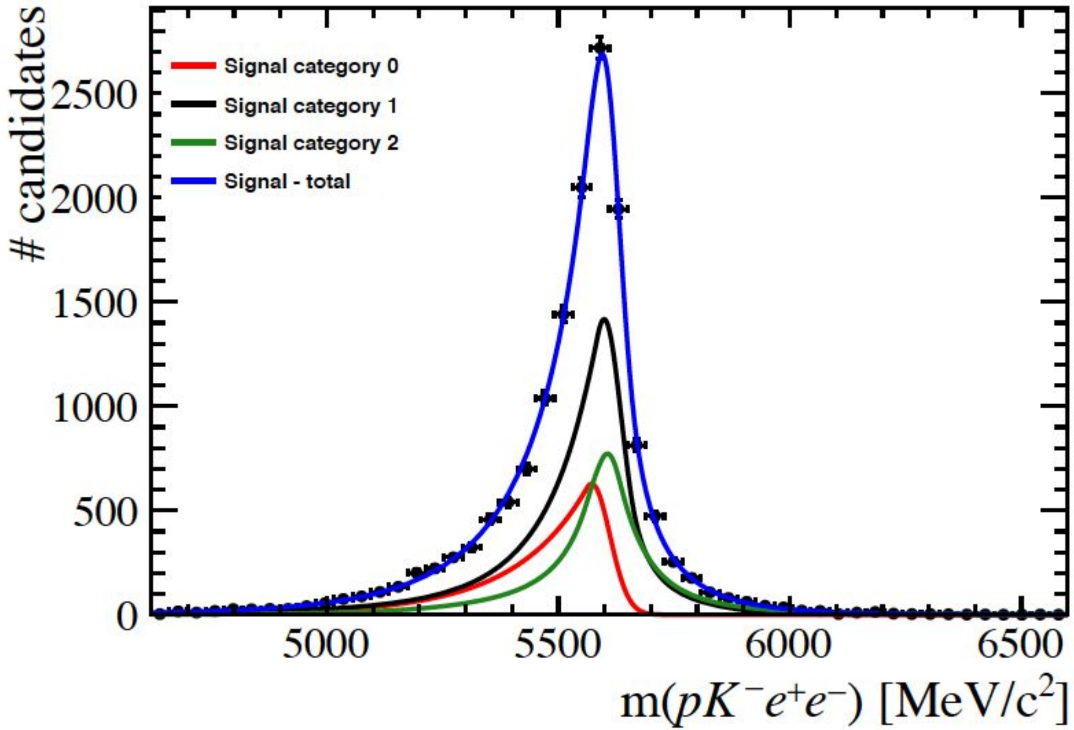
Challenges: energy loss by Bremsstrahlung



V. Lisovskyi's thesis

Challenges: recovering Bremsstrahlung

LHCb-ANA-2019-007



How do we control the efficiencies?

Exploit J/ψ modes to build double ratio to cancel systematic effects

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

LU well tested in J/ψ modes → stringent cross-check

$$r_{J/\psi} = \frac{N(B\to HJ/\psi(\mu^+\mu^-))}{N(B\to HJ/\psi(e^+e^-))} \times \frac{\epsilon(B\to HJ/\psi(e^+e^-))}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}$$

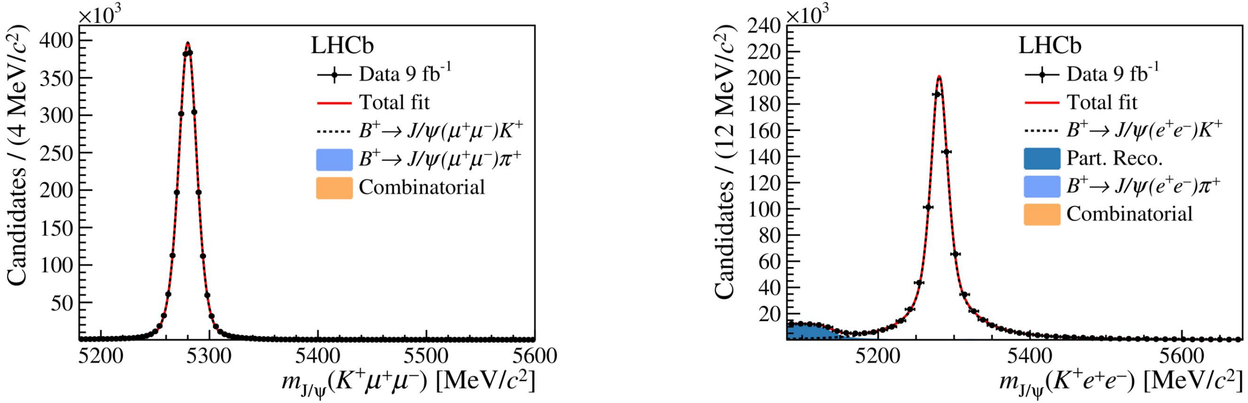
Nature Physics 18, (2022) 277-282

Checking the efficiencies in data

Stringent cross-checks with $B^+ \to J/\psi K^+$

- shows that even absolute electron and muon efficiencies are understood

$$r_{J/\psi} = 0.981 \pm 0.020$$

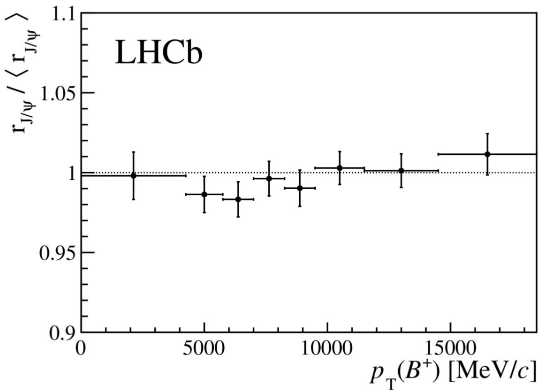


constraint m(ll) to J/ψ mass → strong improvement of mass resolution

Checking the efficiencies in data

Nature Physics 18, (2022) 277-282

Check phase-space dependency: trends and $B^+ \to \psi(2S) K^+$ decays



$$R_{\Psi(2S)} = \frac{BR(B \to K^+ \Psi(2S)(\mu^+\mu^-))}{BR(B \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{BR(B \to K^+ \Psi(2S)(e^+e^-))}{BR(B \to K^+ J/\psi(e^+e^-))}$$

$$\boxed{R_{\psi(2S)} = 0.997 \pm 0.011}$$

Effect of simulation corrections is small thanks to the double ratio:

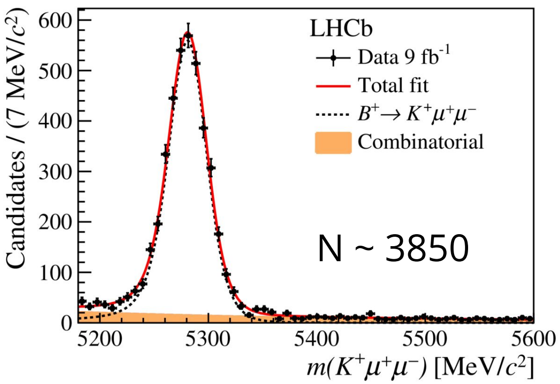
- R_K: (+3 ± 1)%
- $R_{J/\psi}$: 20%

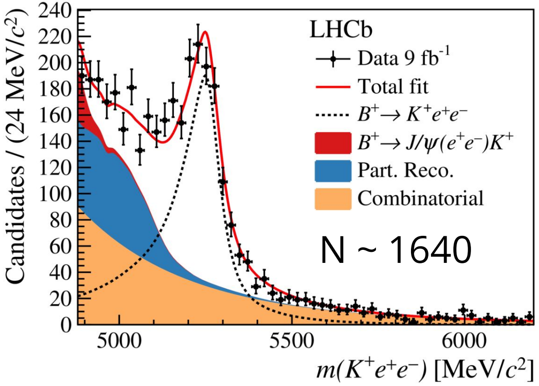
Nature Physics 18, (2022) 277-282

R_K with full LHCb data

Measurement in $1.1 < q^2 < 6.0$ GeV^2 with Run 1+2 datasets

R_K from simultaneous fit to $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ candidates





$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

most precise LFU measurement in $b \to sll$!

Tension with SM at 0.10% (3.1σ)

Overview of LHCb LFU measurements

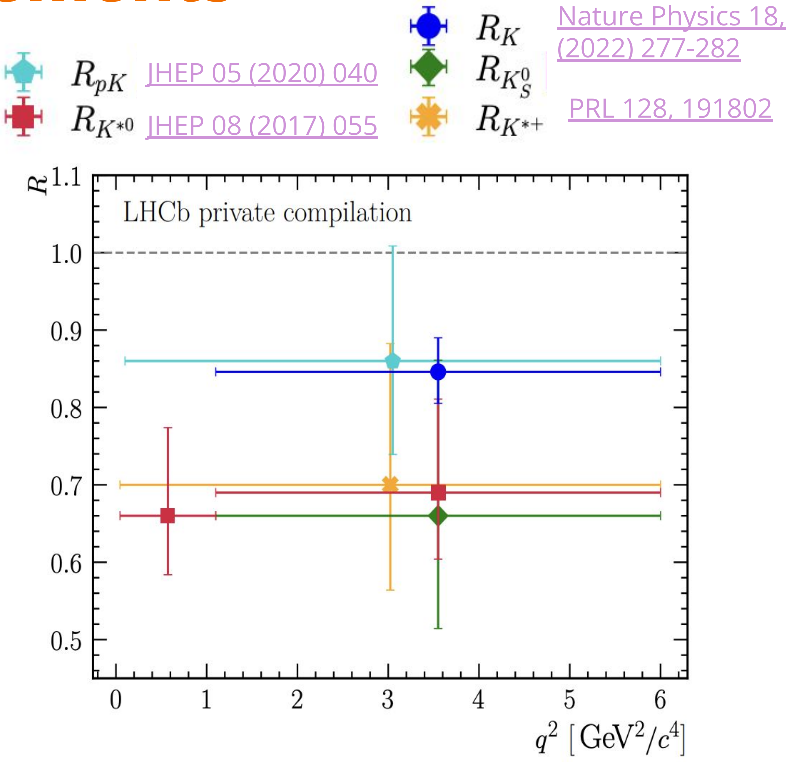
Working on final results with full Run 2 data

Unified analysis of R_K and R_{K*} ongoing

- Final Run 1 + 2 results
- Deeper understanding LFU
- High priority for collaboration

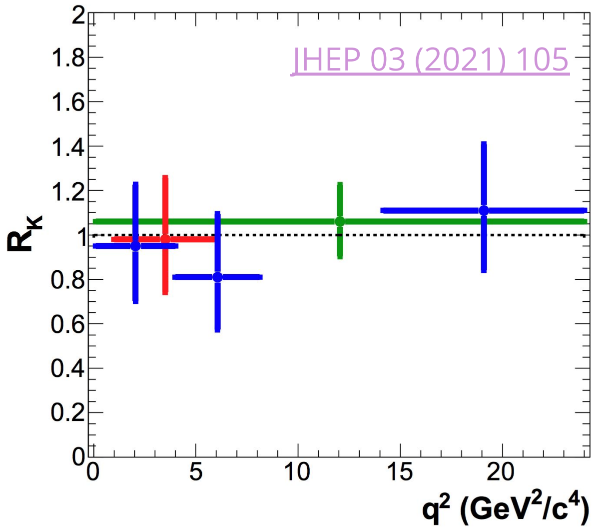
Updates and new measurements:

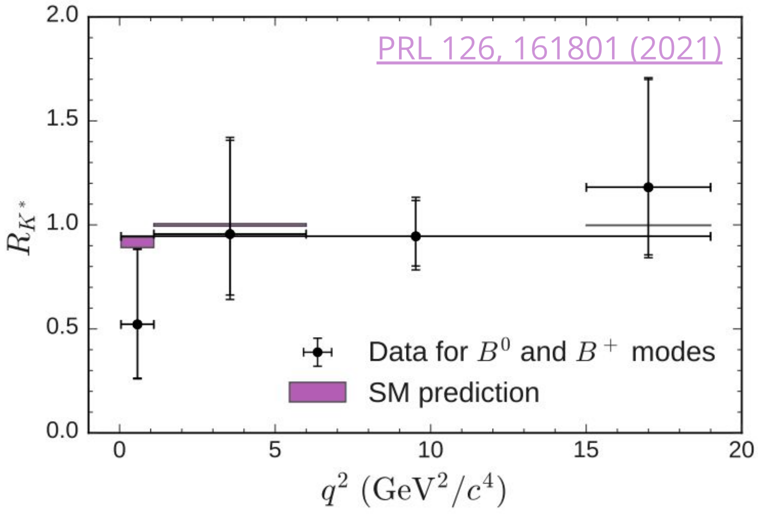
- R_{pK} full Run 1+2
- R_φ, $R_{K\pi\pi}$, etc.



Results from Belle

Weighted average of charged and neutral modes in various q^2 bins:





Results compatible with SM and LHCb measurements
Statistically limited → looking forward Belle II results!

Coherent set of anomalies

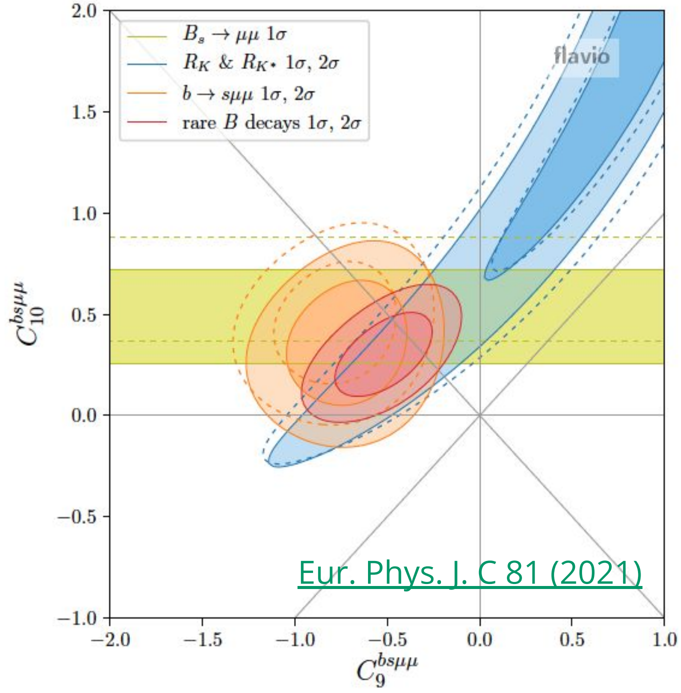
Extract C_i from global fit to all measured observables in b → sll decays

$$H_{eff} \propto V_{tb} V_{ts}^{*} \sum_{i} \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$

Preference for NP in C_9 or C_{10} can reach > 5σ

Interesting hint of NP to be pursued in next years!



Eur. Phys. J. C 81 (2021)

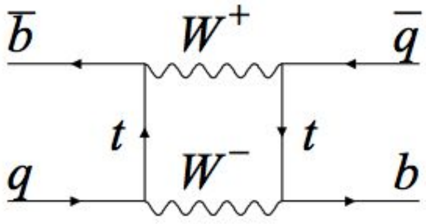
LHCb Physics:
CPV

CPV sources

- Direct CPV in the decay: $A(B \to f) \neq A(\bar{B} \to \bar{f})$

$$A_{CP} = \frac{BR(B \to f) - BR(\bar{B} \to \bar{f})}{BR(B \to f) + BR(\bar{B} \to \bar{f})}$$

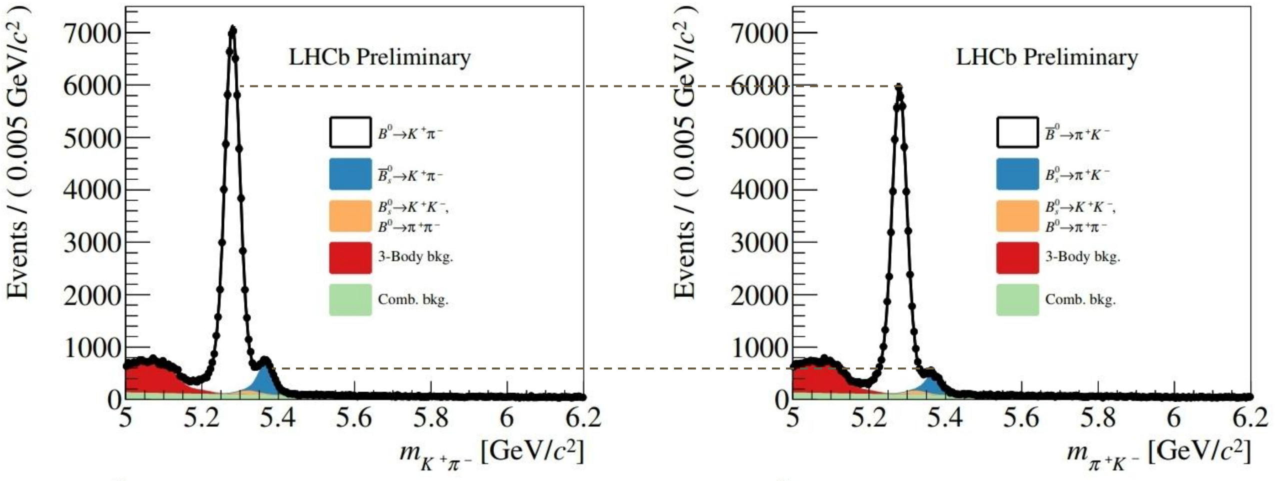
- CPV in the oscillations: $A(B \to \bar{B}) \neq A(\bar{B} \to B)$
  - need to know flavour at production
  - study time evolution



- CPV in the mixing between the two

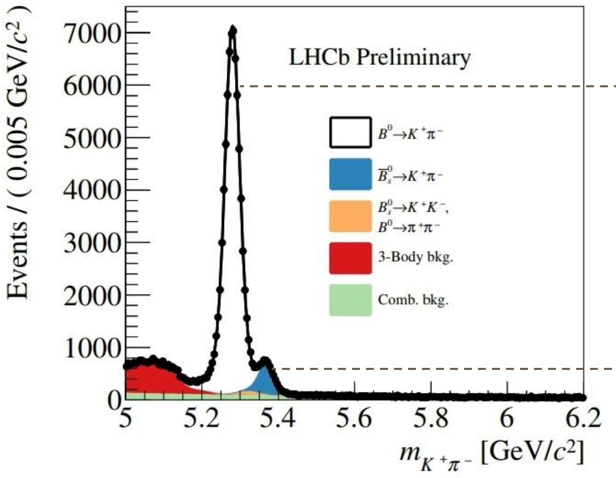
Direct CPV in $B_{(s)} \to K^+\pi^-$

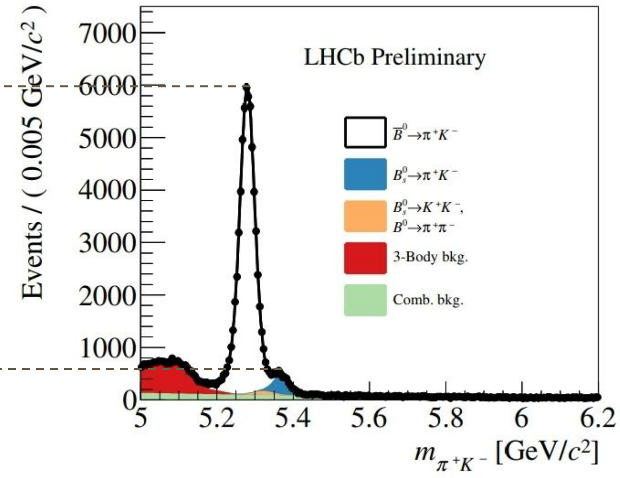
PRD98(2018)032004 826



Direct CPV in $B_{(s)} \to K^+\pi^-$

PRD98(2018)032004 826





$$A_{CP}^{raw} = A_{CP}^{Phys} + A_{prod} + A_{det}$$

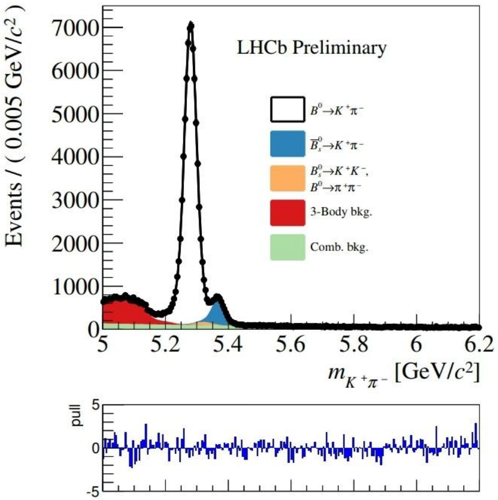
Production asymmetry in pp collisions

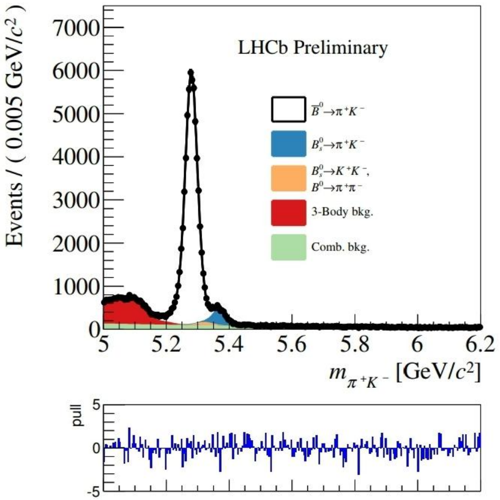
Detection asymmetry in detectors: interaction + magnetic field

[PRD98(2018)032004](#) [826](#)

Direct CPV in $B_{(s)} \to K^{+}\pi^{-}$

Measurement of A_{CP} in $B_{(s)} \to K\pi$ and relation as test of the SM





$$A_{CP}^{B^0} = -0.0831 \pm 0.0034$$
$$A_{CP}^{B_s^0} = 0.225 \pm 0.012$$

Most precise measurement

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}\left(B_s^0 \to \pi^+ K^-\right)}{\mathcal{B}\left(B^0 \to K^+\pi^-\right)}\frac{\Gamma_s}{\Gamma_d} = 0$$

$$\Delta = -0.085 \pm 0.025 \pm 0.035$$

Compatible with 0 at 2σ

Time-dependent CPV in $B_s \to \phi\gamma$

Phys. Rev. Lett. 123 (2019) 081802

Decay time distribution for decay to CP eigenstate:

$$\Gamma(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_{(s)}}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_{(s)}}{2}\right) \pm \mathcal{C}_{CP}\cos\left(\Delta m_{(s)}t\right) \mp \mathcal{S}_{CP}\sin\left(\Delta m_{(s)}t\right)\right]$$

Same for B_s and $\overline{B}_s$

Require knowledge of the B_s flavour at production

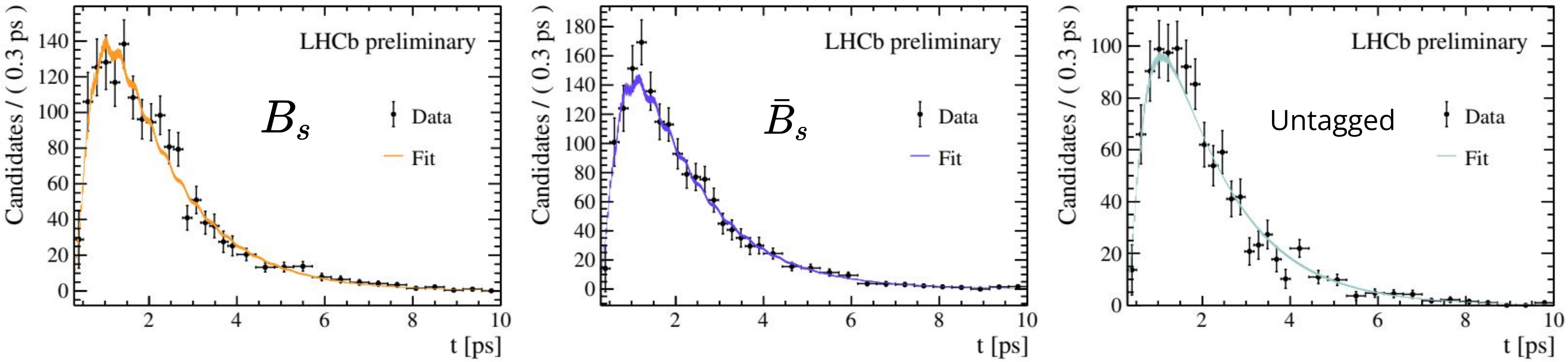
- C is related to direct CPV
- A^{Δ} from mixing and S_{CP} related to the photon polarisation
- In SM: photon is left-handed

Observation of right-handed photons would be a clear sign of NP!

Photon polarization in $B_s \to \phi\gamma$

Phys. Rev. Lett. 123 (2019) 081802

Fit decay time of decays tagged as B_s, anti-B_s and untagged :

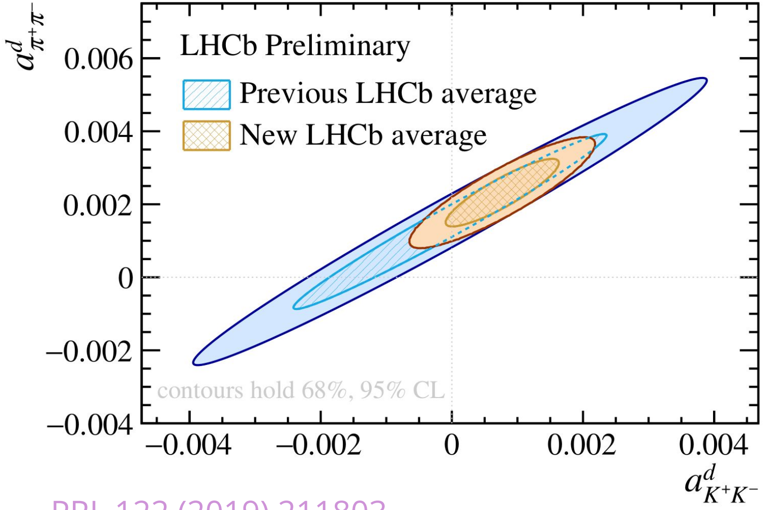


$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

CPV

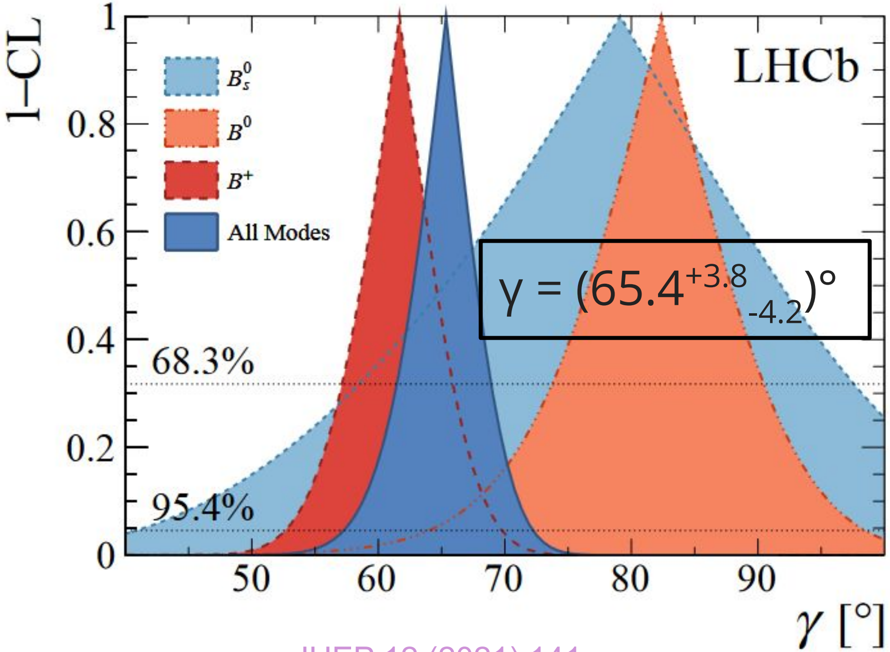
CPV in Charm decays
$D^0 \to h^+h^-$

$\Delta A_{CP} = (-0.154 \pm 0.029)\%$



PRL 122 (2019) 211803,
LHCB-PAPER-2022-024 (in preparation)

CKM angle γ



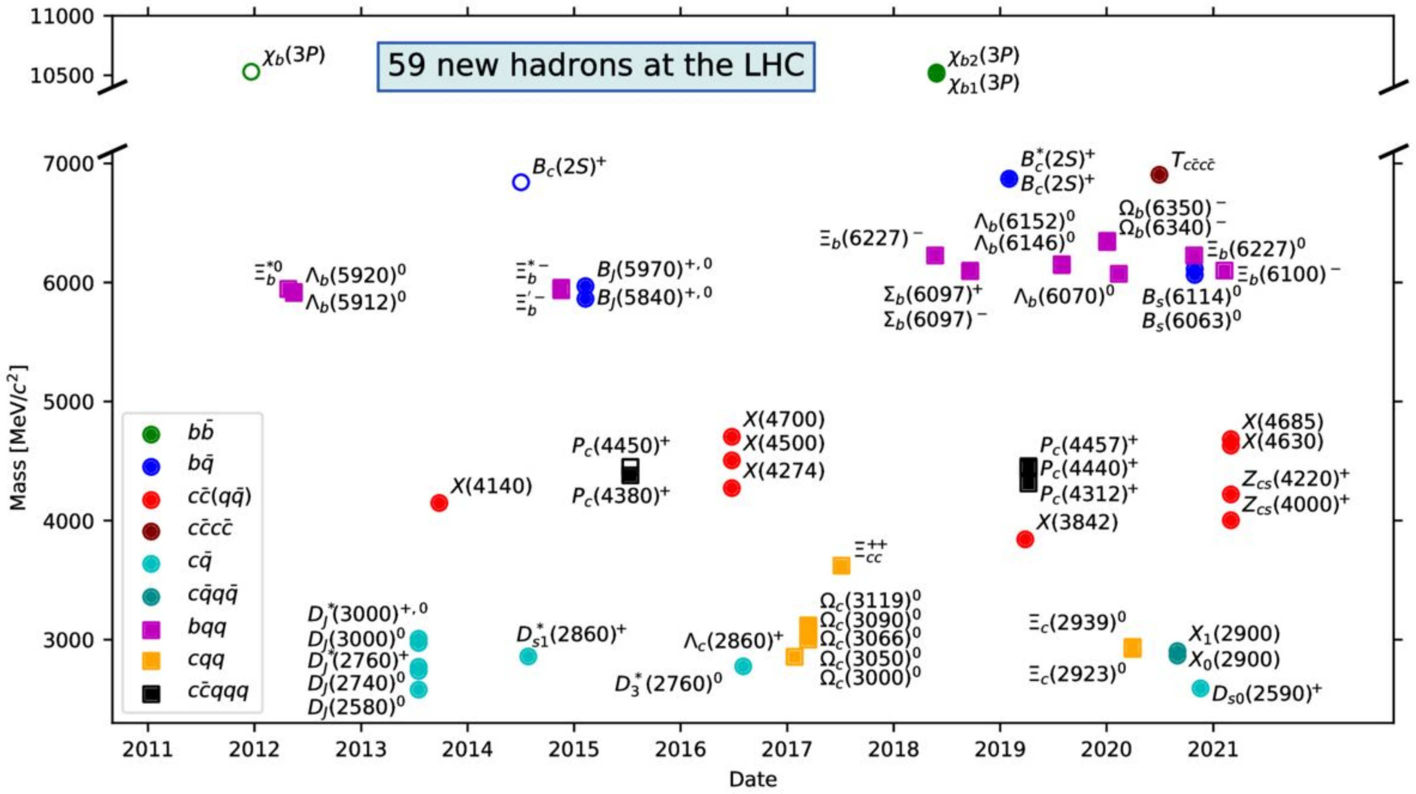
$\gamma = (65.4^{+3.8}_{-4.2})°$

JHEP 12 (2021) 141

LHCb Physics: Spectroscopy

LHCb-FIG-2021-001

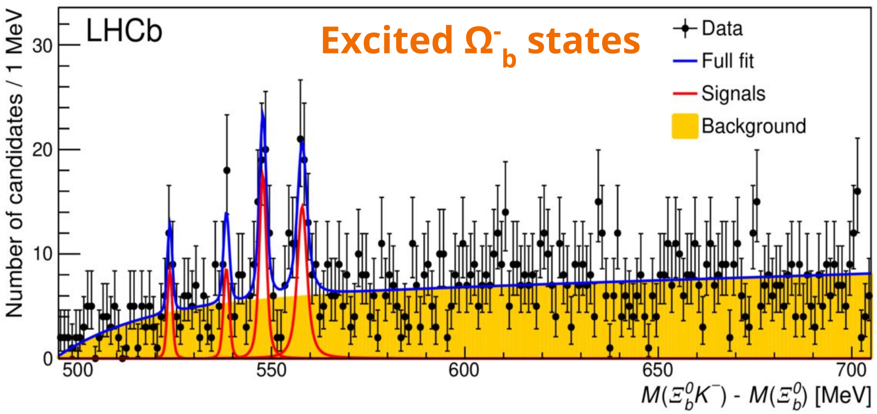
Spectroscopy



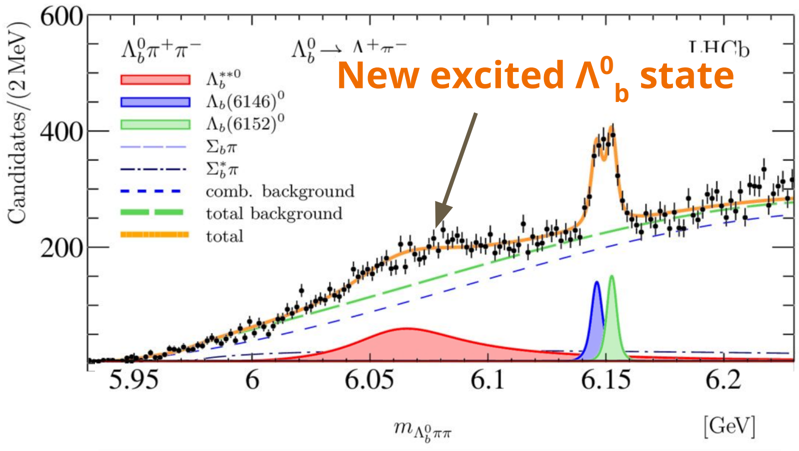
Standard hadrons

Challenge: model the spectrum to describe the data

PRL 124 (2020) 082002



JHEP 06 (2020) 136

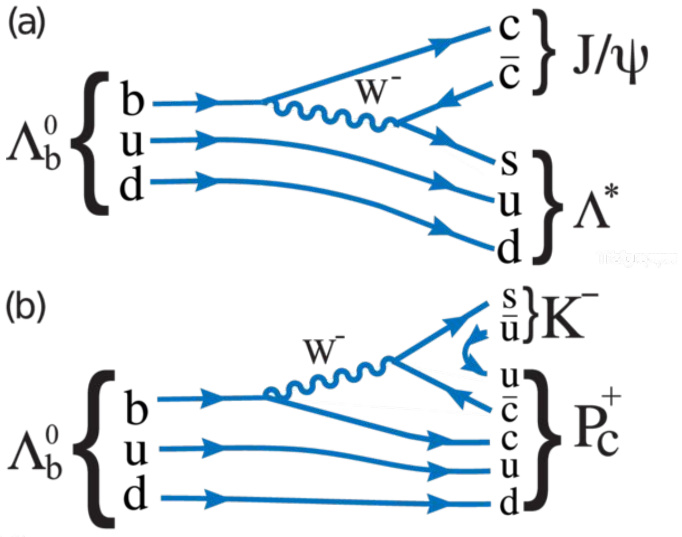


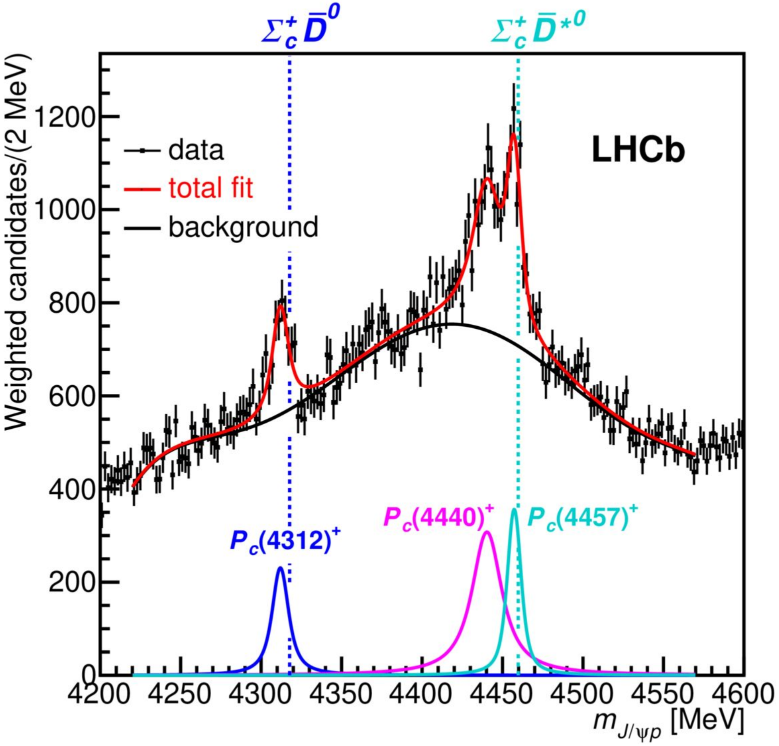
PRL 122 (2019) 222001

Exotic hadrons

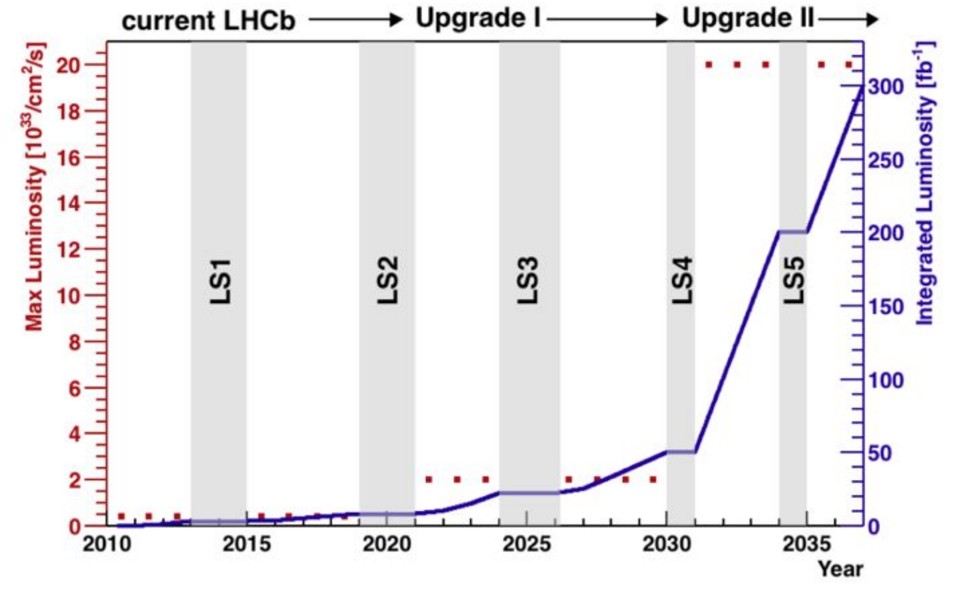
Five-quark states: pentaquarks

$\Lambda_b \rightarrow pK^- J/\psi$



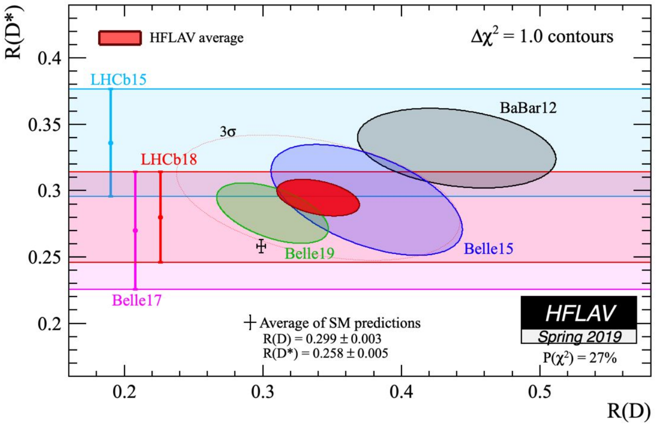


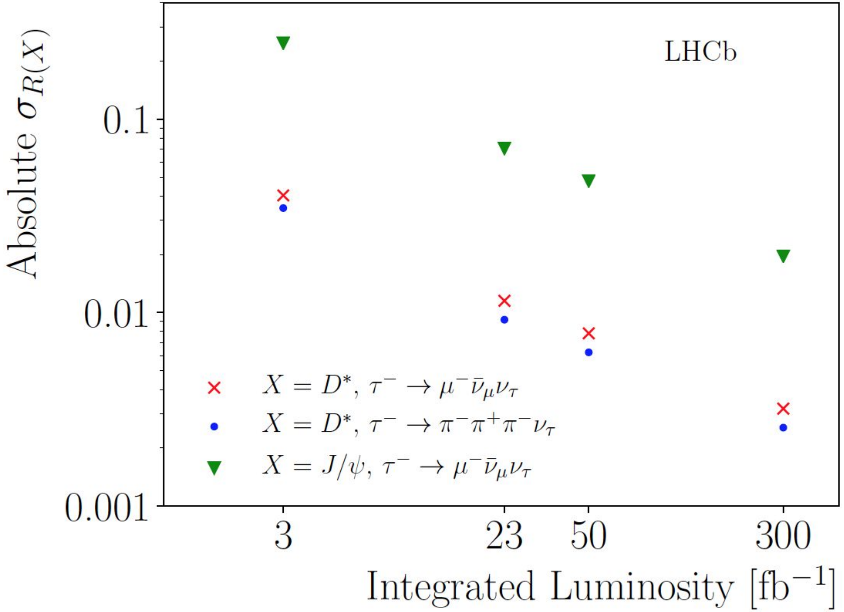
Physics prospects



arXiv:1808.08865

Prospects for LU tests in b ⟶ clν decays





R(D)-R(D*) ongoing with current dataset

Also measurements with other b hadrons:

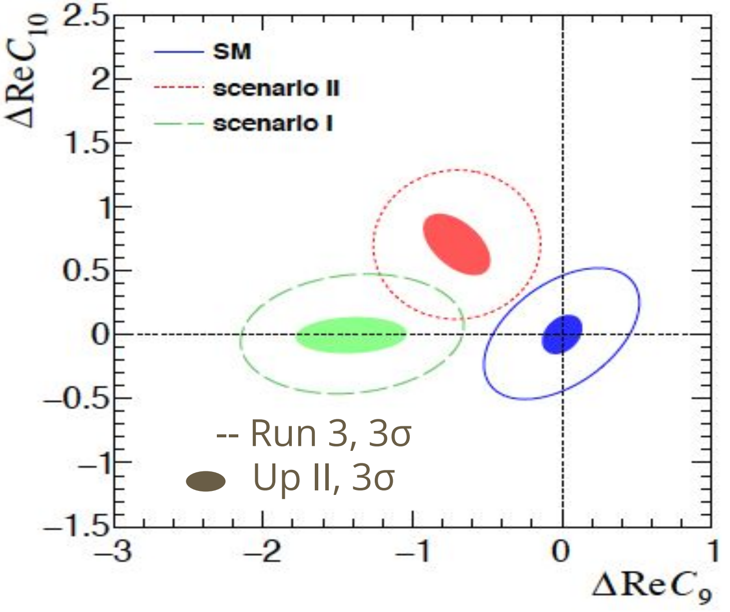
- $\sigma_{R(Ds)}$ < 6% (2.5%) and R(D$^{*(*)}_s$)
- $\sigma_{R(\Lambda c)}$ < 4% (2.5%) and R(pp) (b ⟶ ulν)

arXiv:1808.08865

Prospects for Rare Decays

- updated and completely new LFU and angular observables
  - access electron modes in several b → sll decays
  - access b → dll decays too!

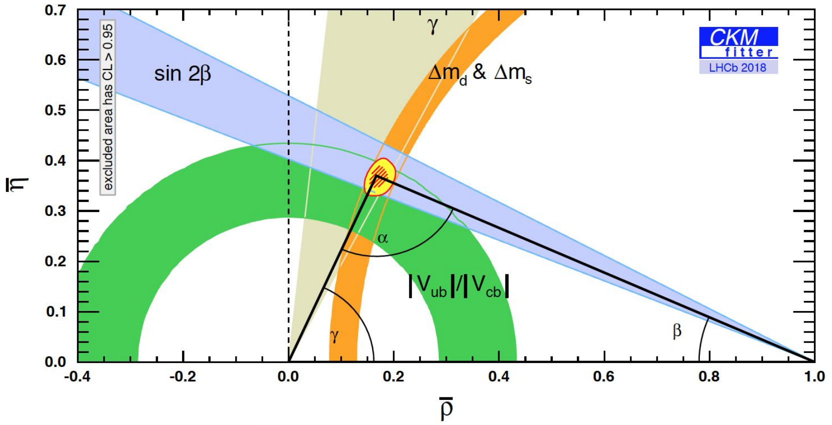
		Run 3	Run 4	Upgrade II
R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047

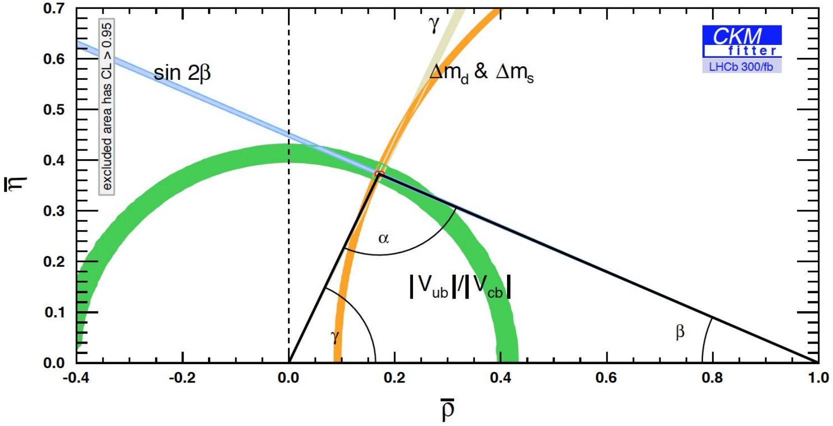


arXiv:1808.08865

Prospects for CKM measurements

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
$a_{\rm sl}^s$	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–





Conclusions

LHCb studies the flavour structure of fundamental particles

Very particular flavour structure in SM described by CKM matrix: NP models don't need to follow this → deviations from pattern = sign of NP

Rich field with variety of measurements and observables accessible:

- branching fractions
- angular distributions
- (time-dependent) CP asymmetries
- ratios of observables, eg Lepton Universality

Very active field of research with continuous progress

Thank you!

Questions?