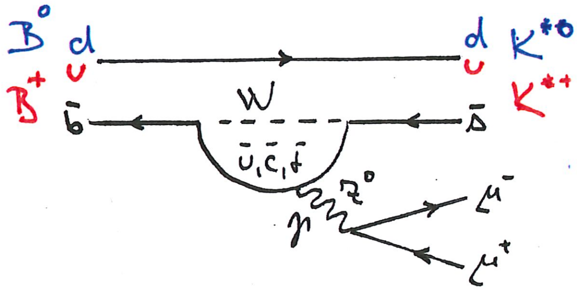
LHCb Calorimetry

Motivation

- We have seen several tensions with the SM in the realm of $b \to sll$ transitions last week



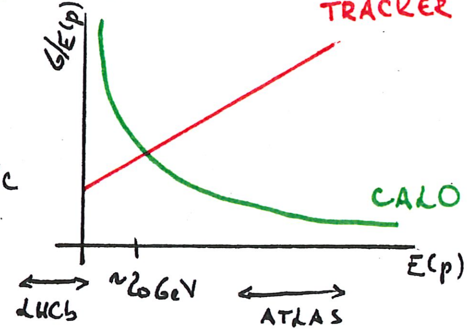
- tension in P_5': most measurements are of $B^0 \to K^{*0}\mu\mu$
  - $K^{*0} \to K^{\pm}\pi^{\mp}$ ⇒ 2 charged particles easy to detect
  - $K^{*+} \to K^{\overset{0}{+}}\pi^{\overset{+}{0}}$ ⇒ neutral particle + charged particle tricky to detect
- Lepton flavor universality tensions: we need to reconstruct well also e^-, not just μ^-

⇒ We NEED calorimeters

Calorimetry

= detection of particles and measurement of their properties through total absorption in a block of matter
⇒ destructive process (well, except for μ^-: no strong interaction, $m_\mu \approx 200\, m_e$, radiation power $P(t) \propto \frac{1}{m^2}$ → μ^- just fly through)

- can measure both charged and neutral particles
- high energy measurement
  - usual magnetic spectrometers have momentum resolution $\sigma_p/p \propto p/L^2$ ← magnetic field lenght
  - in a CALO, in an ideal case, all the energy from the shower is contained inside ⇒ $E \sim N$ ⇒ $\sigma \sim \sqrt{N} \sim \sqrt{E}$ ⇒ $\sigma/E \propto 1/\sqrt{E}$
    ⇒ relative CALO resolution gets better with E!
    (e.g. for CMS, relative CALO resolution is better than the relative tracker resolution at $E > 15$ GeV)



- they are fast: response < 100 ns ⇒ triggering
- electromagnetic calorimeters (ECAL)
  - contains complete γ and e^- showers
- hadronic calorimeters (HCAL)
  - contains most of charged AND neutral hadron showers

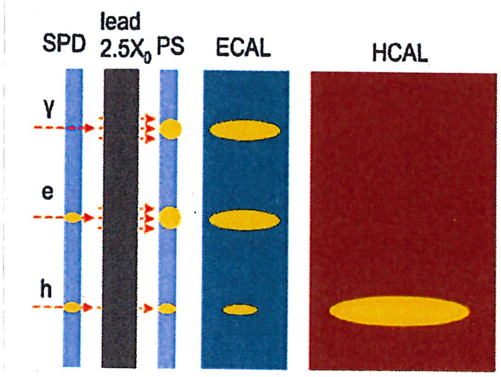
LHCb CALO system

- LHCb designed to be a very 'light' detector
  - we don't want particles to scatter (or stop), since that would worsen the momentum resolution
    - multiple scattering (Molière): $\xrightarrow{\text{angle}} \Theta_0 \propto \frac{1}{E}\sqrt{\frac{x}{X_0}}$ ← important for particles with $p < 80$ GeV at LHCb

      thickness

      radiation lenght ($E(x) = E_0 e^{-x/x_0}$)
  - thickness of LHCb is 8 cm of aluminium over 9 m in tracking system
    - minimum ionizing particle looses ~ 40 MeV
      - small effect (LHCb tracks 2-200 GeV)
      - still bigger than momentum resolution (~ 10-30 MeV)

        directly affects mass resolution!
  - → we need a rather thin CALOs



- Scintillating Plane Detector (SPD)
  - 15 mm thick scintilator
  - 1 bit output: 1: signal > treshold (charged particle)

    0: no signal (neutral particle, mostly γ)
- Preshower Detector (PS)
  - 15 mm thick scintilator
  - both with SPD very thin → not so much affected by aging
- shower energy estimated by weighted combination of PS & ECAL

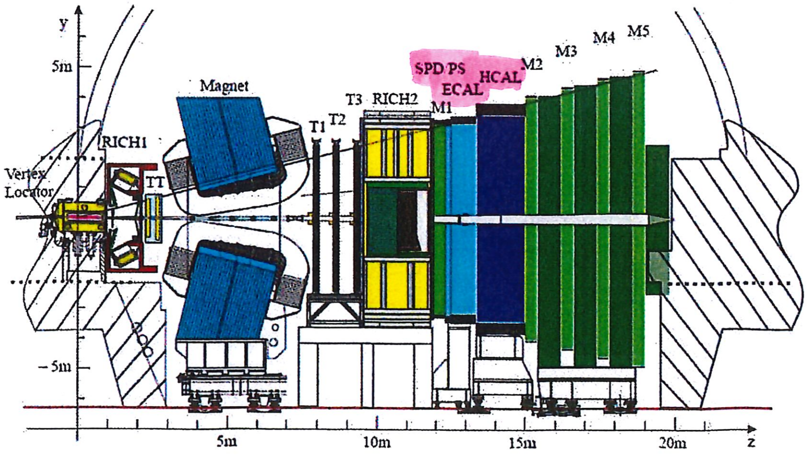
  $E = \alpha E_{PS} + \beta E_{ECAL}$

- ECAL

  distance a particle travels between interactions
  - 66 layers of 4mm scintilator between 2mm thick lead ($25X_0$, $1{,}2\ \lambda_{int}$)
    - cells are smaller aroud the beampipe, 3 sets of sizes (x-y):

      40×40, 60×60, 120×120 mm

      ↑ inner, ↑ middle, ↑ out
  - small segmentation
    - → minimal pile-up
  - cost effective
  - radiation hard
  - fast (25 ns!)
  - resolution $0{,}1/\sqrt{E} \oplus 0{,}01$



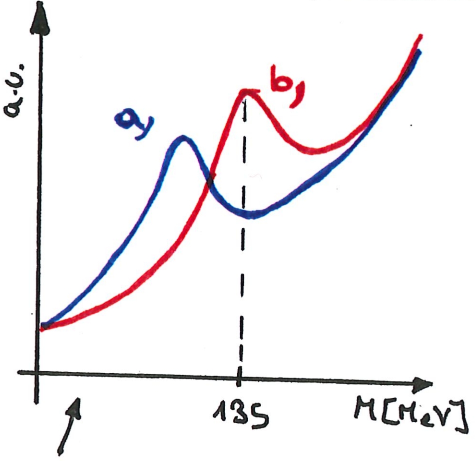
- ECAL calibration
  - uses π^0 (135 MeV) → $\gamma\gamma$ (99%)
    - note the low mass, e.g. ATLAS uses $Z \to ee$

  1, take γ-pairs and calculate π^0 invariant mass

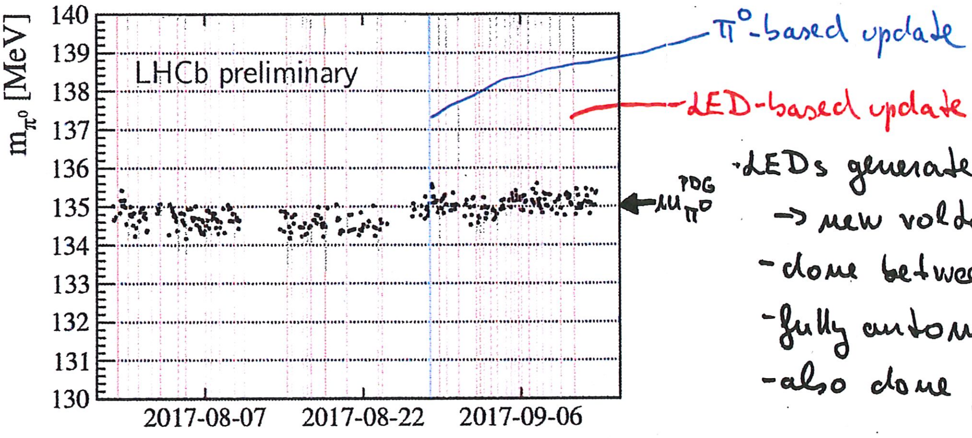
  2, we get something like a,
  → reweight to get peak at 135 MeV

  3, do it again: combinatoric cells might be misscalibrated

  4, We get b, and weight $w = w_1 \cdot w_2$



needed ~ 140 hours of collisions
→ performed ~ every month



- LEDs generate signal in PMTs
  → new voltage setting
- done between fills (~10 hours)
- fully automatic
- also done for HCAL

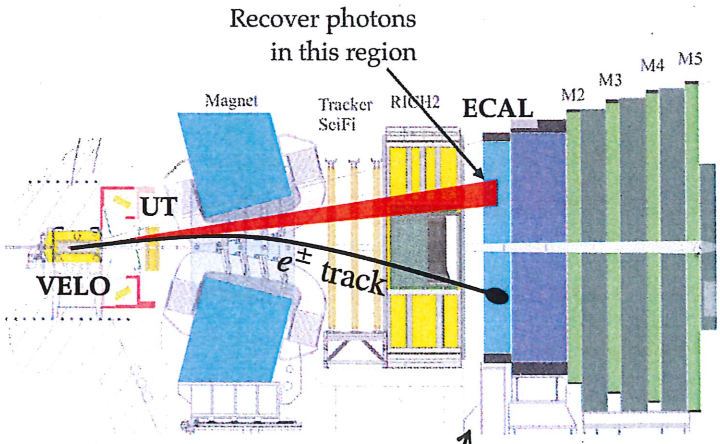
- HCAL
  - layers of scintillator between iron ($1X_0$, $1\lambda_{int}$)
  - very fast: 40 MHz readout (25 ns = space between collisions) without dead time → we (only) use it for trigger
  - inspired by ATLAS's Tile-Cal
  - resolution $0{,}8/\sqrt{E} \oplus 0{,}1$: good enough for triggering)

- LHCb UPGRADE
  - removing PS, Pb plate, SPD and also M1 → even less material to transverse → better ECAL resolution
  - ECAL & HCAL stays (new front-end electronics)
    - HCAL aging is OK for our purposes
    - ECAL aging: inner regions will be replaced in LS3 (2025)
      - new technology: high granularity sampling CALO, where absorber is W

LHCb electron reconstruction

- at e^- energies relevant for b-physics ($\sim < 30$ GeV) trackers are performing better than CALOs
- LHCb doesn't measure e^- with low energy
  - ECAL treshold at 3,5 GeV
  - large combinatorics
  + excelent separation below RICH tresholds (RICH1: 2,6 GeV, RICH2: 4,4 GeV)

- biggest problem when measuring e^-: BREMSSTRAHLUNG
  - the Bremsstrahlung source is not bending in the magnetic field, but by interaction with the detector material!
    - caused by Coulomb field of atoms
  - if emitted before the magnet, we can't measure momentum in the tracking system!
  -> that's why we use **ECAL**!


Recover photons in this region

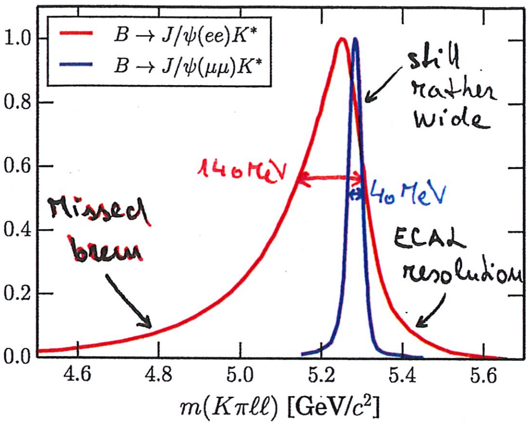
note this is a sketch of upgraded LHCb

- hits in VELO + UT
  - -> extrapolate to ECAL
  - -window detemined by extrapolation uncertanity
- take all clusters in ECAL with $E_T > 75$ MeV and add them to $p_{e^\pm}$

more than 2,5% e^- energy

=> better momentum resolution
=> better PID, $\pi^\pm$ don't emit Bremsstahlung

- recovery is not perfect : ECAL resolution is worse than tracking resolution
  emitted γ can be out of ECAL
  emitted γ can be too soft
  - assuming each $e^\pm$ emits 1 hard brem (most common) and the probability of recovery is uncorrelated among e^- and e^+, the probability of Bremsstrahlung recovery is $\simeq 50\%$
- recovery significantly improves dielectron mass resolution
  → in $B \to K^{(*)}ee$ decays also the B-mass resolution
- let's go back to LFU measurements
  - we compare $b \to s\mu\mu$ and $b \to see$ processes by using R_X:



$$R_X := \frac{\displaystyle\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to X\mu\mu)}{dq^2}\, dq^2}{\displaystyle\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B\to Xee)}{dq^2}\, dq^2}$$

2 rare channels

complicated reconstruction

=> We use double ratios!

adding $B \to XJ/\psi$

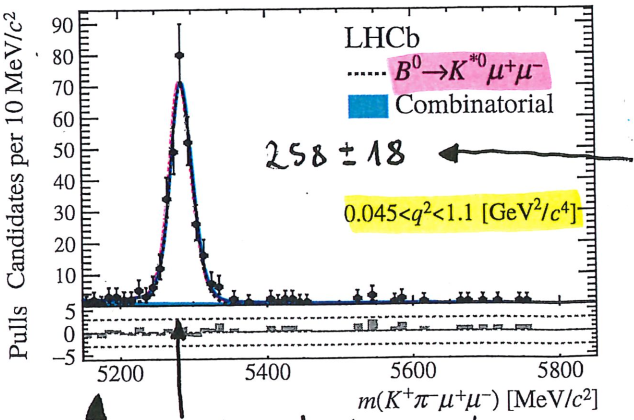
$$R_X^{exp} := \frac{\dfrac{N_{X\mu\mu}\cdot 1/\varepsilon_{X\mu\mu}}{N_{XJ/\psi(\mu\mu)}\cdot 1/\varepsilon_{XJ/\psi(\mu\mu)}}}{\dfrac{N_{Xee}\cdot 1/\varepsilon_{Xee}}{N_{XJ/\psi(ee)}\cdot 1/\varepsilon_{XJ/\psi(ee)}}} = \frac{N_{X\mu\mu}}{N_{XJ/\psi(\mu\mu)}}\cdot\frac{N_{XJ/\psi(ee)}}{N_{Xee}}\cdot\frac{\varepsilon_{Xee}}{\varepsilon_{XJ/\psi(ee)}}\cdot\frac{\varepsilon_{XJ/\psi(\mu\mu)}}{\varepsilon_{X\mu\mu}}$$

largely reduces uncertainties

- This doesn't solve all our problems,
  let's have a look at some R_K^* analysis plots:

$B^0 \to K^{0*} J/\psi(\mu\mu)$ events: 274 000

$B^0 \to K^{*0} J/\psi(ee)$ events: 58 000



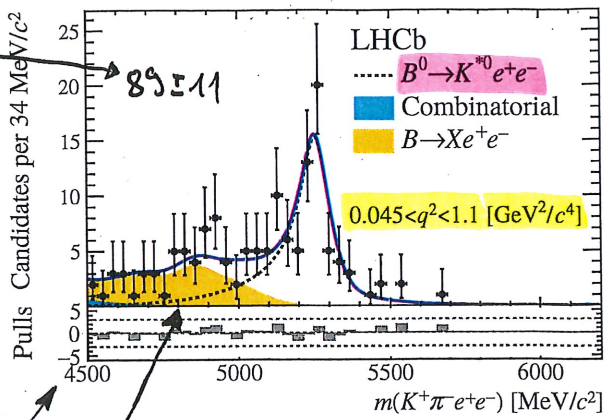
258 ± 18

almost no background

less events

more events

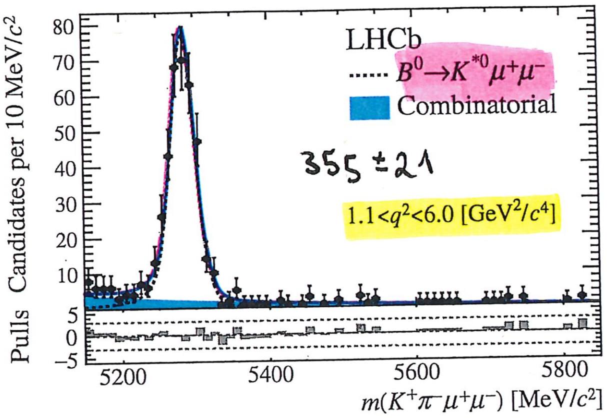
larger mass range to pick up the background



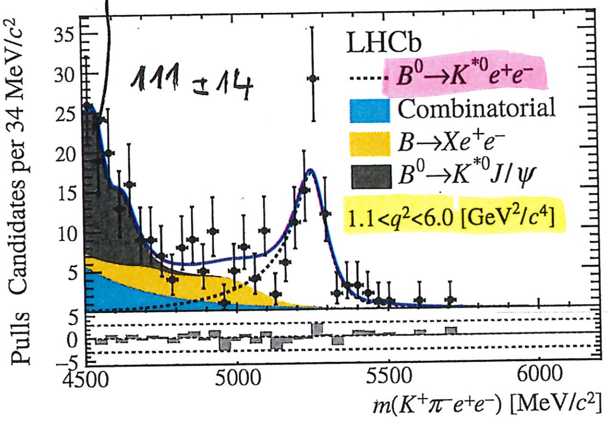
89 ± 11

large non-K^* contribution

large fraction of $K^* J/\psi$ contribution "leaking" from higher q^2



355 ± 21



111 ± 14

⇒ signal resolution is essential to separate signal from partially reconstructed background

- LHCb improved e^- reconstruction significantly over the years
  - 1st R_K result ($3\,fb^{-1}$): $\varepsilon(B\to Kee)/\varepsilon(B\to K\mu\mu) = 13\%$
  - 2nd R_K result ($5\,fb^{-1}$): $\varepsilon(B\to Kee)/\varepsilon(B\to K\mu\mu) = 30\%$

+ upgrade: even less material

+ data-driven e^- tracking efficiency measurement