Draw me a flavour experiment

Louis Henry
CERN, 24/11/2022

What, why, and how?

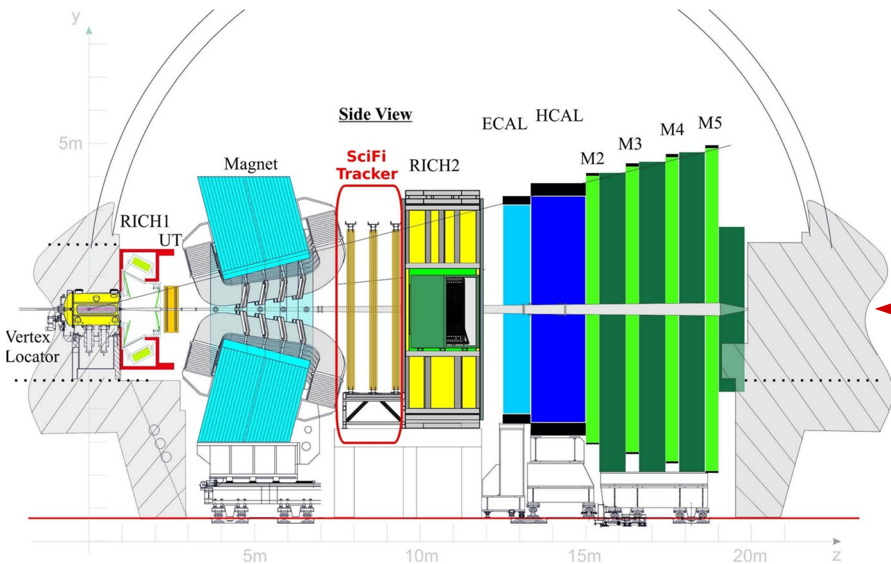
- LHCb is a 26 years old project

LETTER OF INTENT

Last update
28 March 1996

A Dedicated LHC Collider Beauty Experiment
for Precision Measurements of CP-Violation

- Far from being a fixed-shape experiment → things keep changing all the time.
    - Design changed a lot before building, Turbo stream in Run 2, full software trigger in Run 3.
- Not continuous, planned improvement. What really happens is that we keep re-examining past trade-offs and well-established solutions.



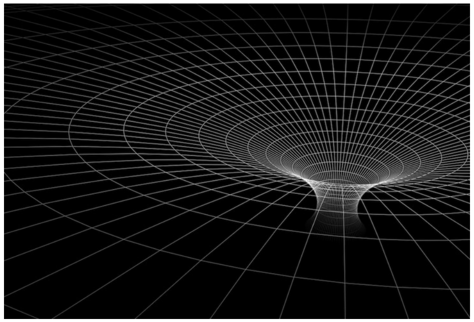
This is only a definitive answer if we kind of forgot the question we were asking ourselves

- So what's up for Upgrade 1.5? Upgrade 2? Well that's partly up to you, really.

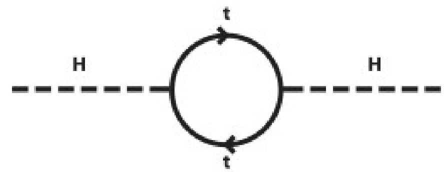
Building flavour

Missing bricks in the Standard Model

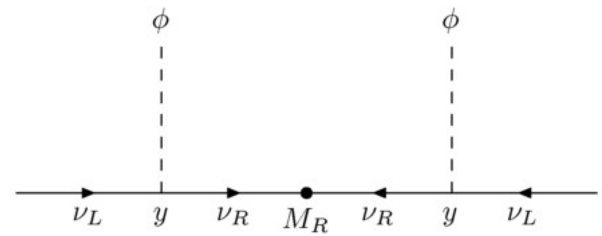
Gravity

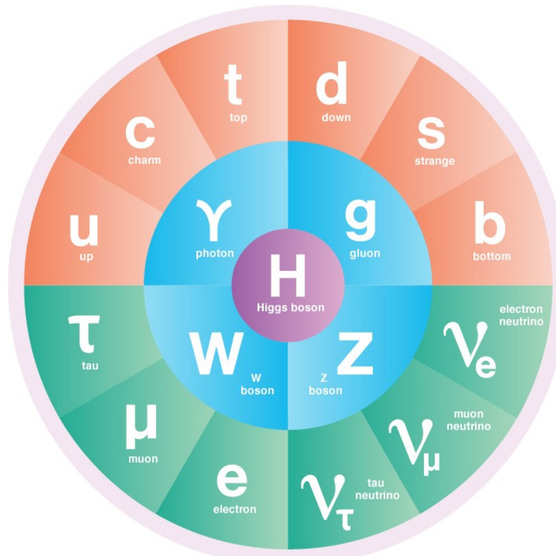


Higgs naturalness

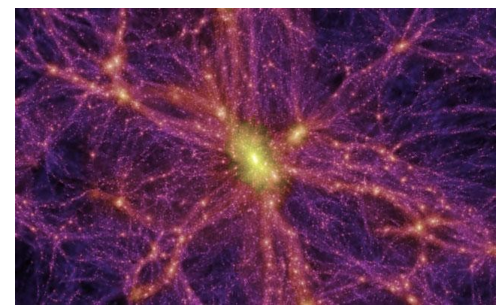


Neutrino mass

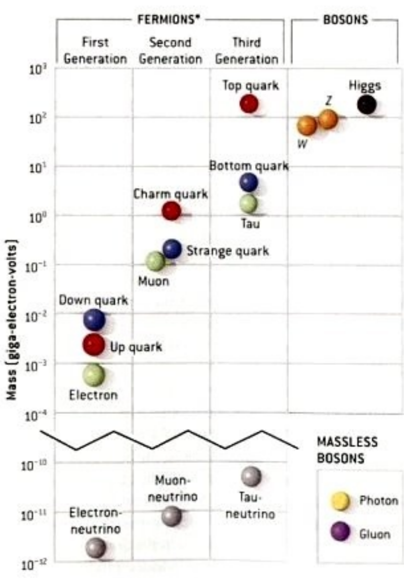




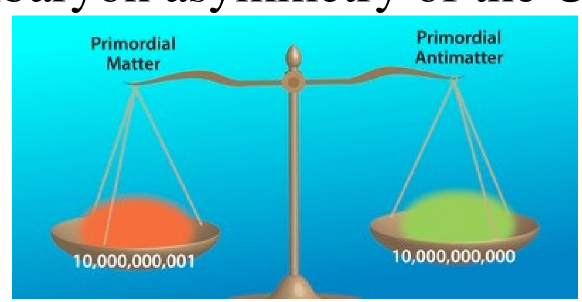
Dark matter candidate



Mass hierarchy



Baryon-antibaryon asymmetry of the Universe.

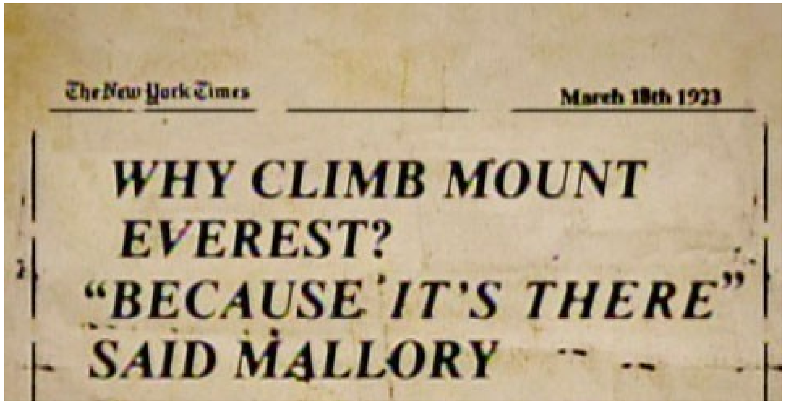


Why flavour physics?

- New physics (BSM) searches need:
  - **A precise theoretical prediction**: “CP violation in the quark sector only originates from one term”, “The 3x3 CKM matrix is unitary”, “All interactions respect lepton universality and lepton flavour”.
  - **A precise observable:** pertains to phenomenology, but here our job is straightforward: quarks are never seen alone in nature → we need to cancel out hadronic uncertainties if possible.
  - **A precise measurement**: now that’s our job.

- I would add: **a good reason for theory to be wrong.** There surely are lots of areas in physics that fulfill all 3 criteria but that do not get O(1B)€ detectors built.

- **Observation 1**: we’re still looking for 4x the normal matter, and why matter exists at all.
- **Observation 2**: CP violation would start explaining the matter/antimatter asymmetry of the Universe.
- **Observation 3**: Additional matter could introduce additional CP violation.



Sorry Mallory, but it would not cut it here

How to train your meson: a matter of accelerators

- Our generalistic flavour experiment will focus on $B_{(s)}$ and D mesons.
  - Strange hadrons also possible but can be much more long-lived → different experimental object.
  - Top quark does decay weakly but very different decay topology.

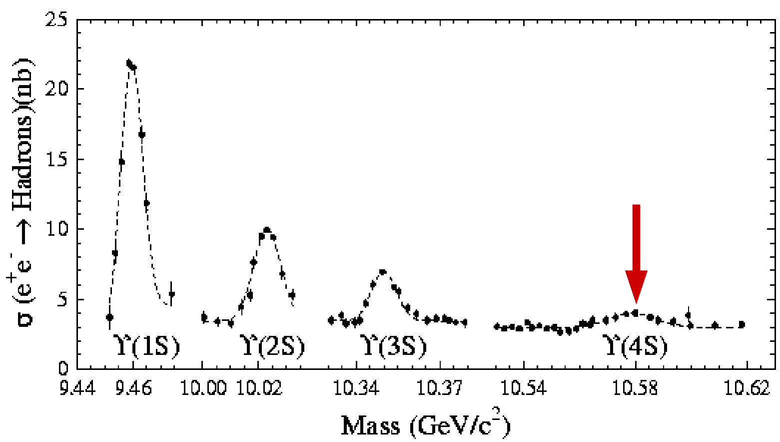
- Mass: a few GeVs → energy will not be a problem.
- Lifetime: 10^{-12} s for the B ($c\tau \sim 0.5$ mm) → needs to be accelerated a bit.

- **Production** of $B_{(s)}$ mesons:
  - Brute force → collide stuff, get energy, get quarks, and get lucky.
  - Υ(4S, 5S) resonances decay into pairs of $B_{(s)}$ mesons. Correlated so the flavour of one gives the flavour of the other.

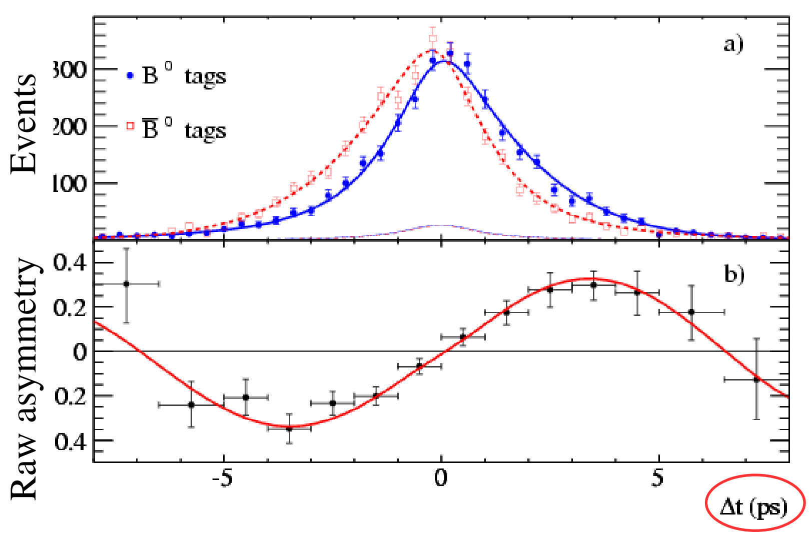
- What to **collide** to get there?
  - Messy packets of quarks with unknown initial energy.
  - Pairs of electron positrons that annihilate with known initial energy and no debris.

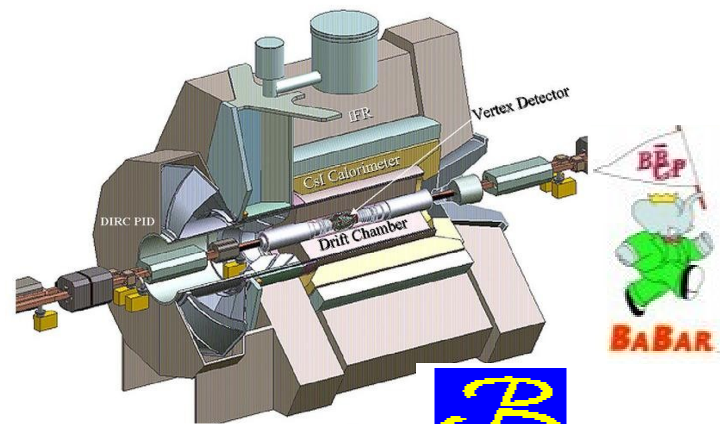
“The” natural answer for flavour physics: B factories

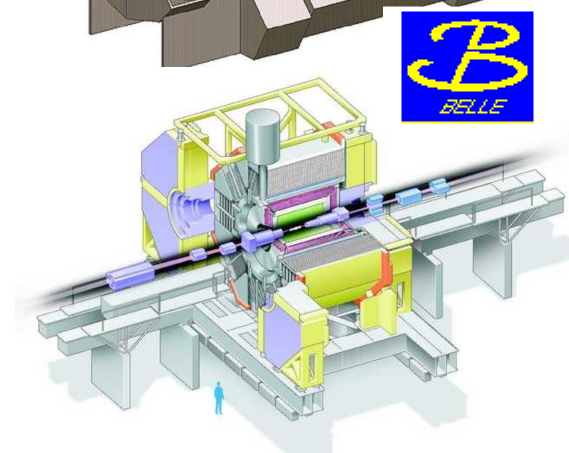
- Asymmetric e+e- colliders at $\Upsilon(4S)$ pole → >96% decays
  - Known initial energy, clean environment, good flavour tagging

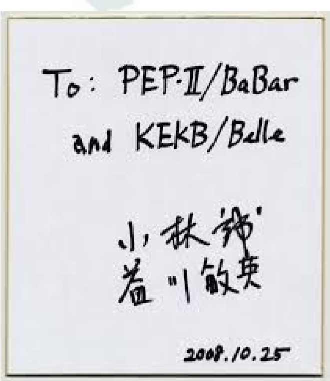


- First precise B-meson oscillations measurement!









Kobayashi and Maskawa’s “thank you” note

And yet

And yet here we are

So why anything at the LHC?

- 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.
  - Before LHCb, a few experiments had tried, and all but CDF had failed **triggering** on beauty.

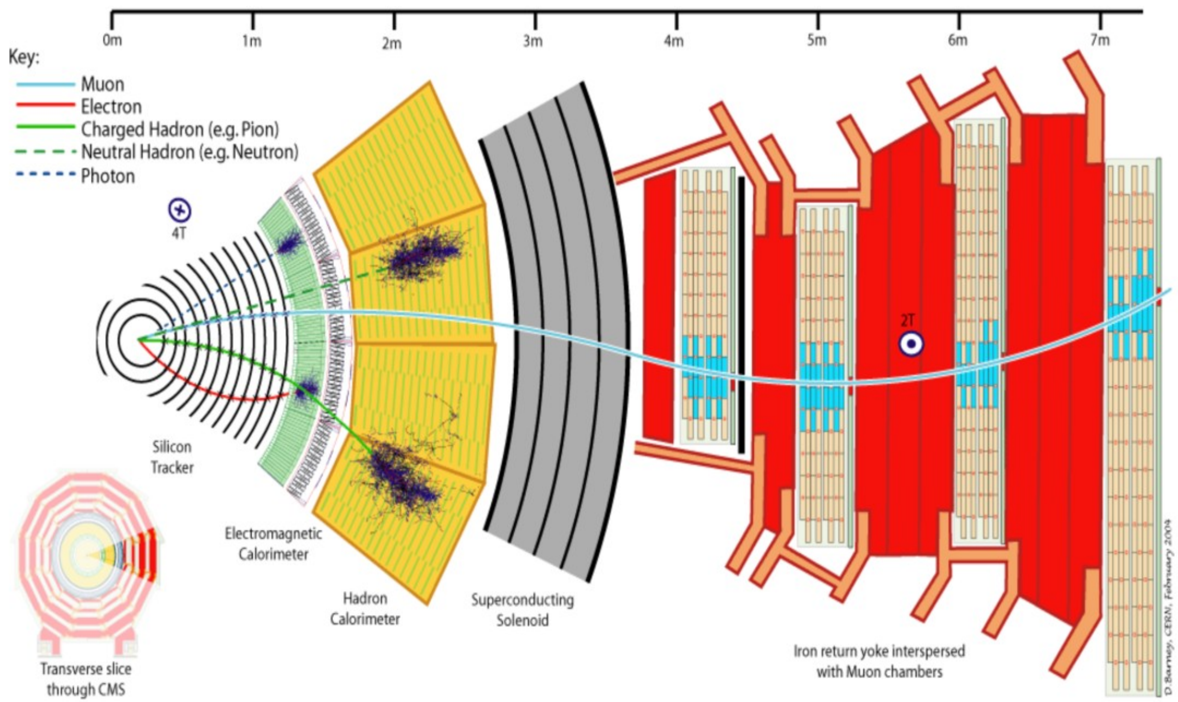
How to do flavour physics at a totally not flavour-specific accelerator

(This is also valid for detectors)

The LHCb detector: what is that job we want?

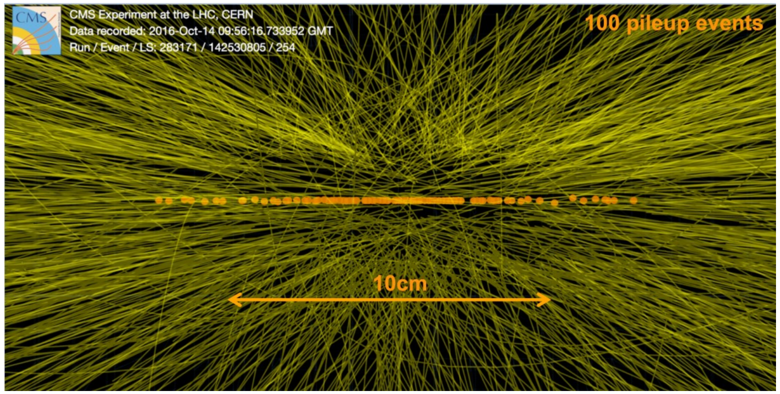
- First things first, we won't do much flavour if we do not distinguish kaons from pions from muons → need good **PID**.
  - **Need**: manageable rates. If Cherenkov, photomultipliers need to be outside of acceptance.
- We need excellent **vertex separation** for time-dependent analyses...
  - **Need**: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

Generic particle physics detector: the barrel design



- Inner tracker, R as small as possible
- Magnet in the middle for momentum precision.
- Another tracking part somewhere also in the middle
- And then, calorimeters, shielding, muon chambers, more shielding.

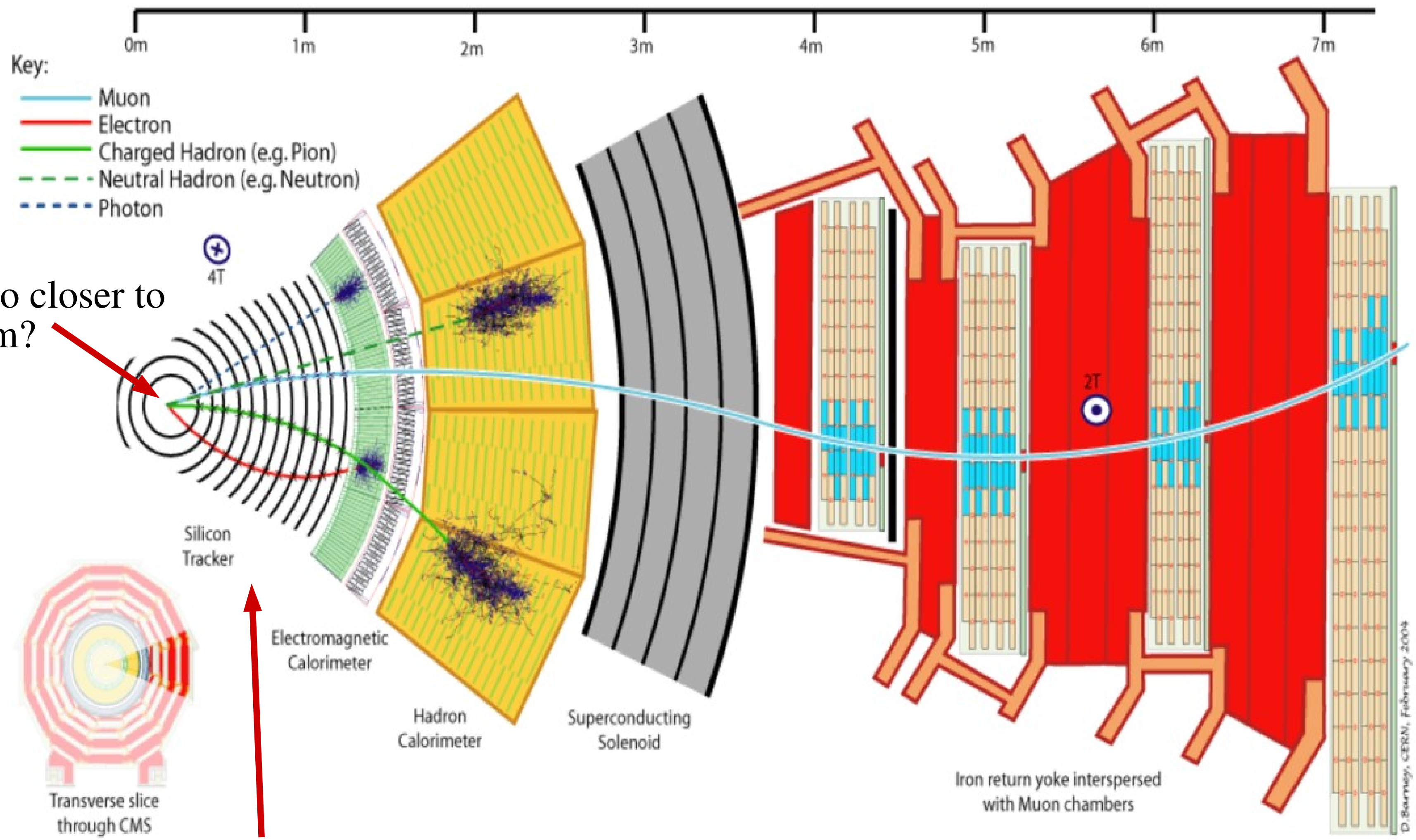
- Hermetic:
  - missing energy measurements possible;
  - some hard processes induce jets, which are better resolved
- Mostly transverse:
  - Looking at collisions 'from above';
  - hard processes that take most advantage of high energy are in transverse region



Generic particle physics detector: the end of the barrel

Short lever arm → need large B

Can it go closer to the beam?

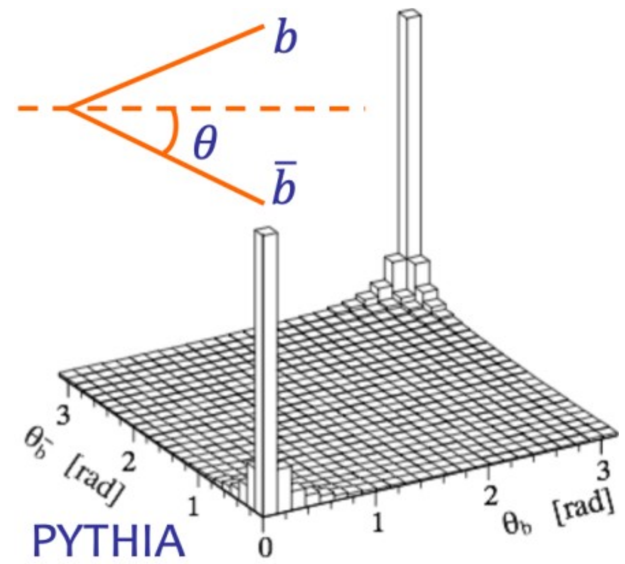


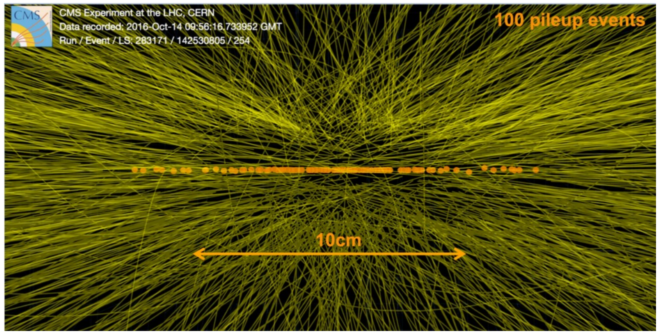
Tracks curved from origin

PID a bit limited

Physics comes to the rescue

- Most $c\bar{c}$ and $b\bar{b}$ pairs are produced close to the axis.
  - Only need to cover 4% of the solid angle for 25% of the pairs.
- First gain: we can put a lot of stuff outside of the acceptance!
  - Cherenkov detectors with PMTs can operate
  - Now can consider the apparatus to close a detector around the beam when stable.
- Second gain: it's rather cheaper to instrument further away.
  - Can afford a longer detector, nice for momentum resolution.
- What do we sacrifice?
  - Statistics: 25% is not 100%
  - Jets, neutrinos, anything with missed energy.
  - And we see pp interactions from the front → pile-up is tougher.
    - Probably will need to reduce luminosity

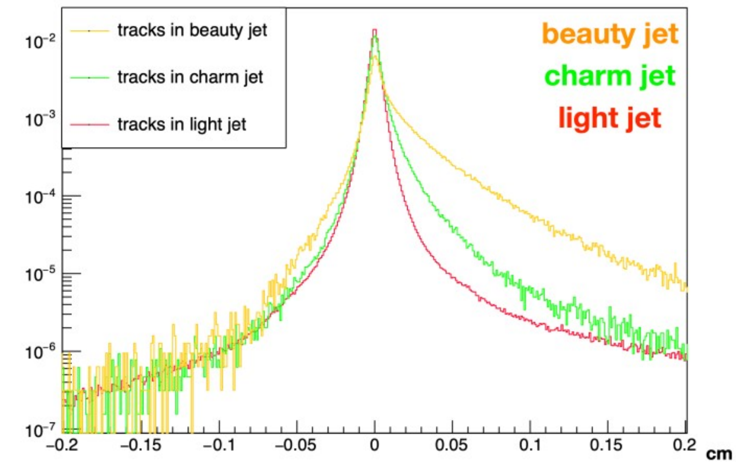


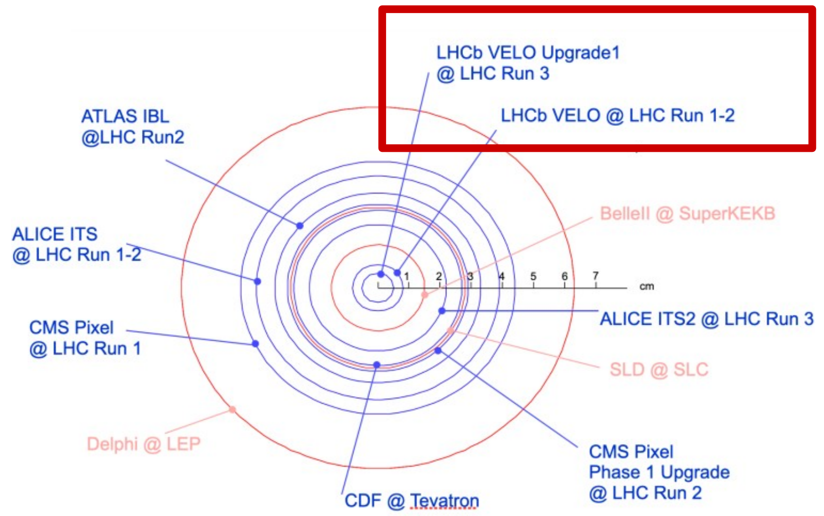


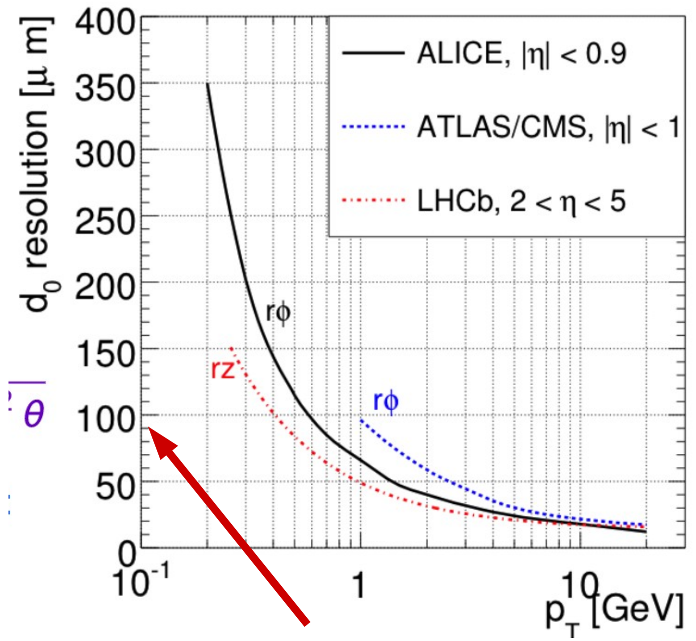
Imagine this coming at you

Vertex location: the VELO

- Triggering on beauty is one of the main challenges.
  - What if a subdetector could quickly measure vertex displ.?
- VELO in secondary vacuum: way thinner beam pipe.
- As you know (but at first, not obvious), VELO closes around the beam.
  - Smaller distance to primary vertex than any other experiment!



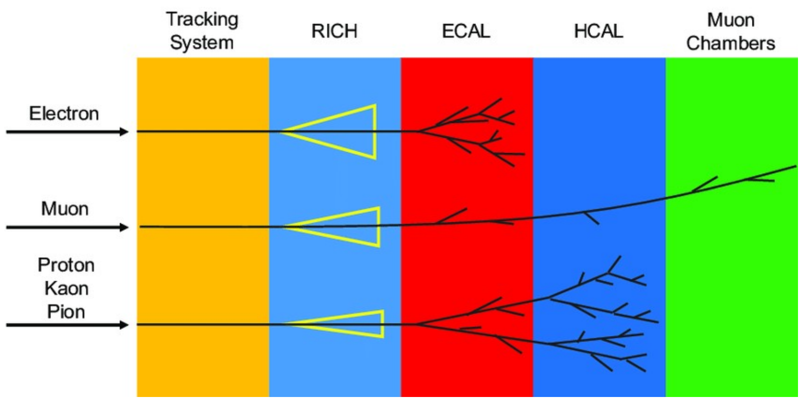




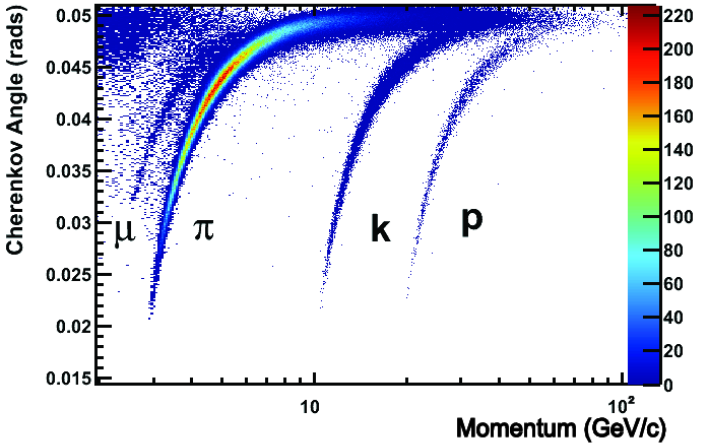
roughly the target

Particle identification: the ways of the ID

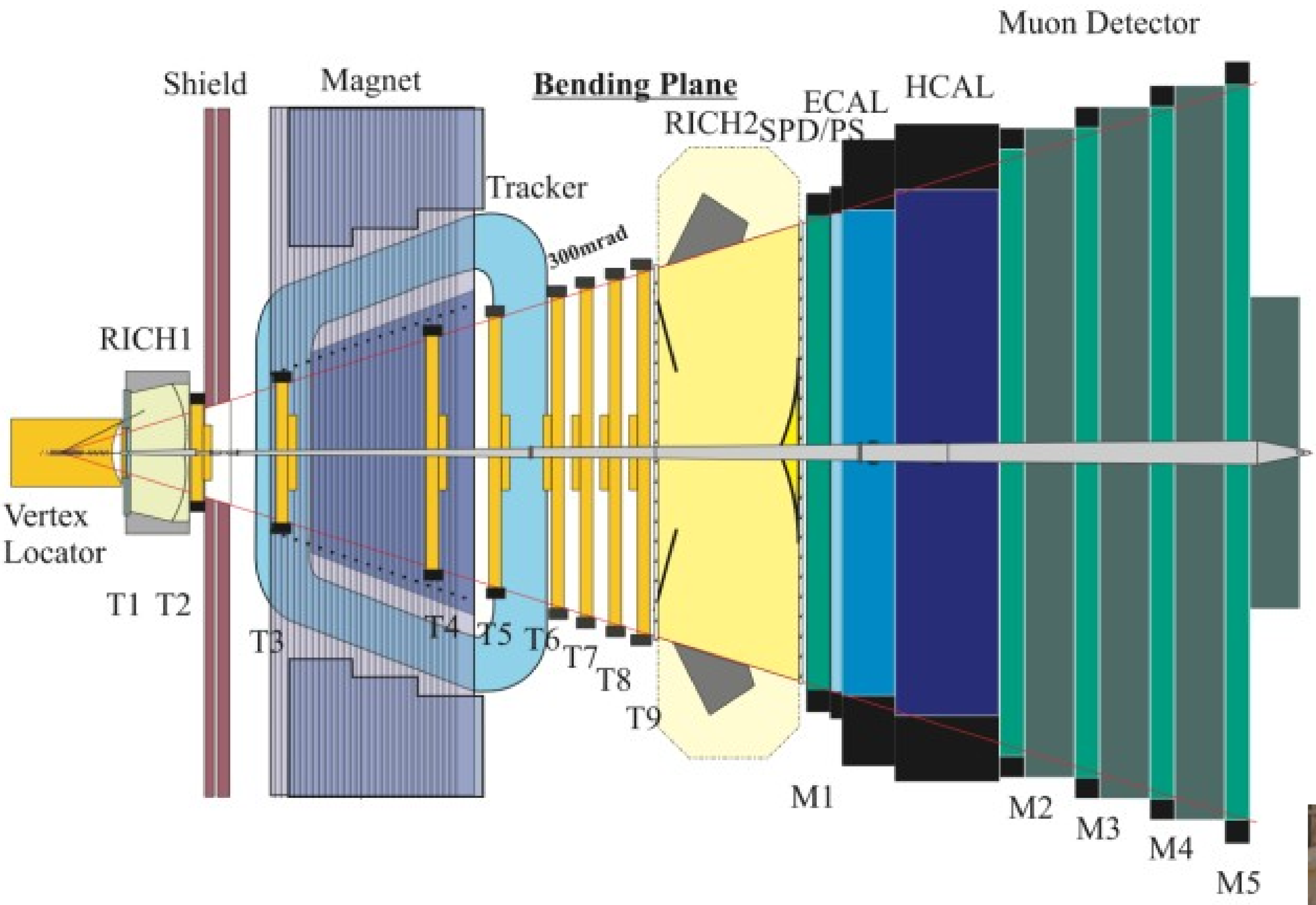
- Momentum is given by the tracking system, but need one more information for the mass:
  - $\beta = v/c$
  - Energy
  - Interaction with material: energy loss, transition radiation.
- Energy seems difficult: due to the open design, calorimetry will not be our main focus.
- Interaction with material is already used in the design
  - Passive photon, electron and muon identification.



- If we can shield PMTs, we may use Cherenkov radiation:
  - The angle of the light cone is correlated with β
  - Requires good momentum resolution, which we have!
- Sensitivity starts around 2 GeV/c and discrimation stops around 100 GeV/c



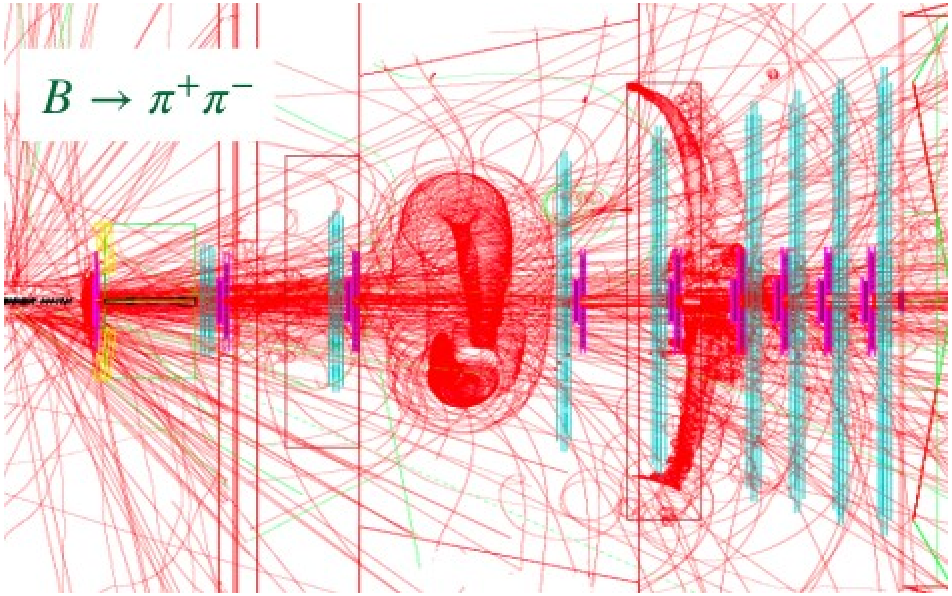
So that's what you ordered, right?



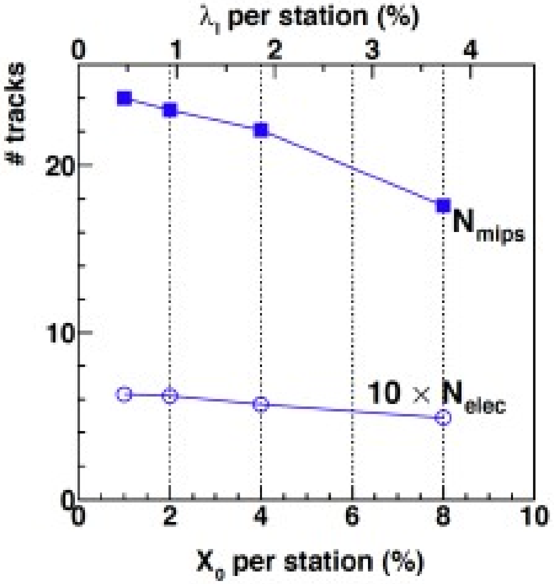
The best is the enemy of the good

- What is there not to like?
  - Lots of tracking stations to get precise measurements of trajectories everywhere.
  - Shield away the pesky particles that would be out of acceptance anyway.

- Yes but…



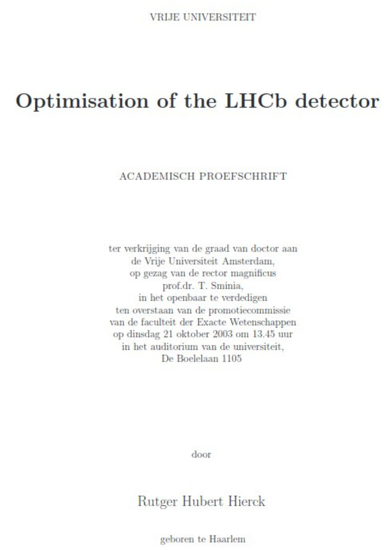
Where's $W \to AlD^0$?



Sometimes, more is less

Back to the drawing board

- Previous plots are part of a Ph.D. work → impetus to rework the whole experiment came from the work of a Ph.D. student!
- As it happens, putting tracking stations in the magnet, where particles can and will spiral, makes things tough.
- More material does not just mean decreased calorimeter precision, but scattering and possible loss of particle.


VRIJE UNIVERSITEIT

Optimisation of the LHCb detector

ACADEMISCH PROEFSCHRIFT

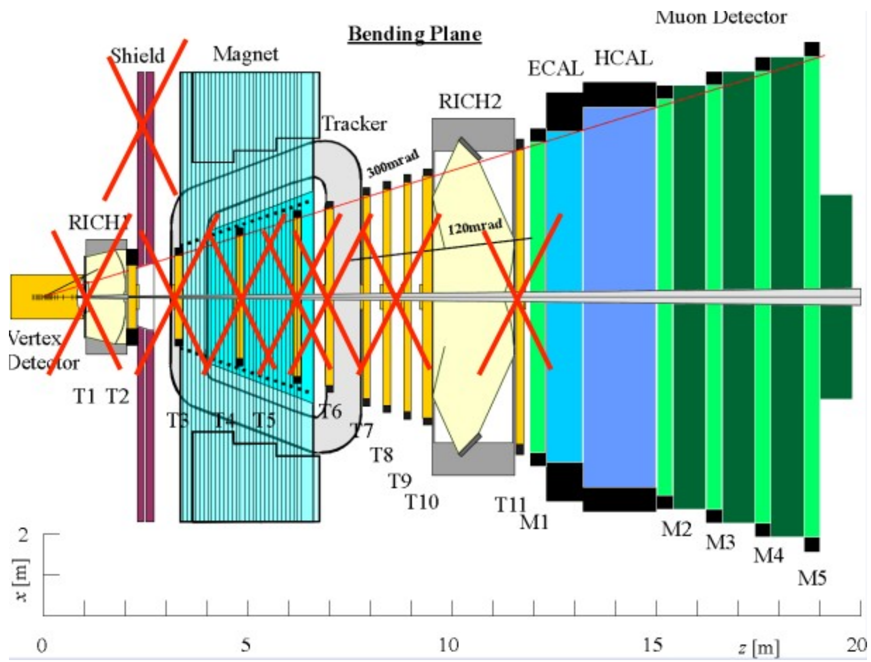
ter verkrijging van de graad van doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. T. Sminia,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der Exacte Wetenschappen
op dinsdag 21 oktober 2003 om 13.45 uur
in het auditorium van de universiteit,
De Boelelaan 1105

door

Rutger Hubert Hierck

geboren te Haarlem

CERN-THESIS-2003-025



Triggering on beauty

- Whole design informed by one of the main challenges: how do we trigger on a beauty signature?
  - Beauty decays have more pT than minimum bias → calorimeter
  - Displaced vertex → needs good, fast tracking
  - Beauty decays tend to have muons in them
- Hybrid design:
  - L0: hardware trigger on fast signatures
  - HLT1: look for displaced vertices.

L0: a hard process happened, possibly beauty-like

↓

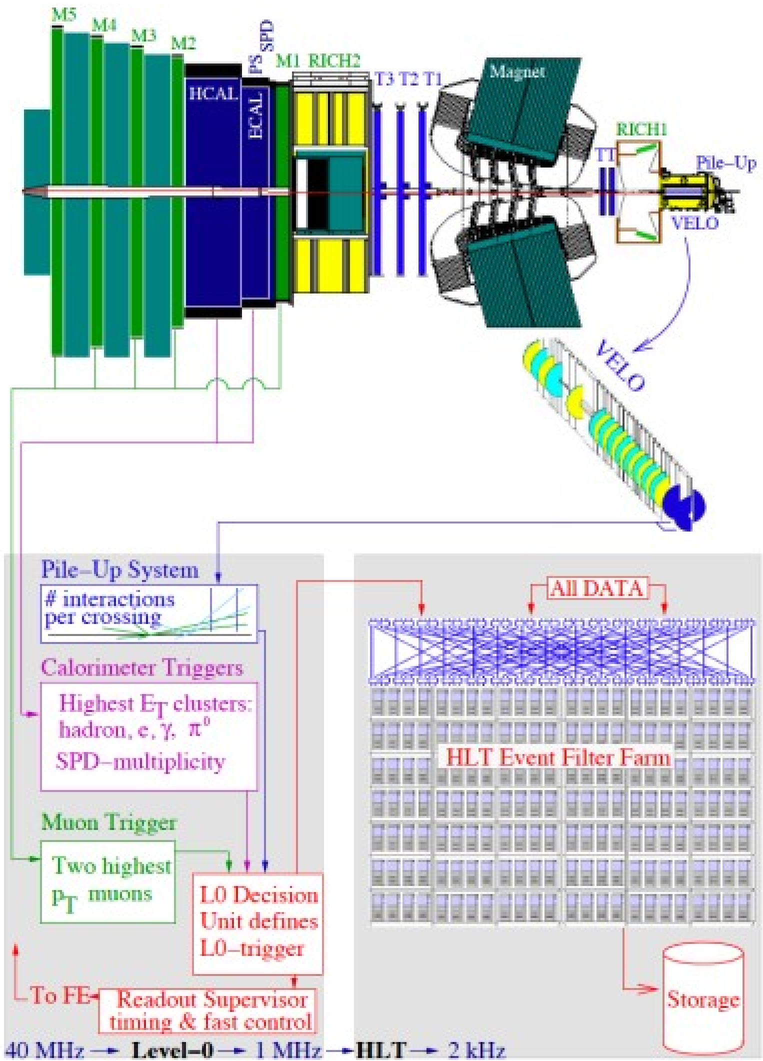
HLT1: there is beauty or charm in there

↓

HLT2: one of the N (o(10^2)) decays of interest is there

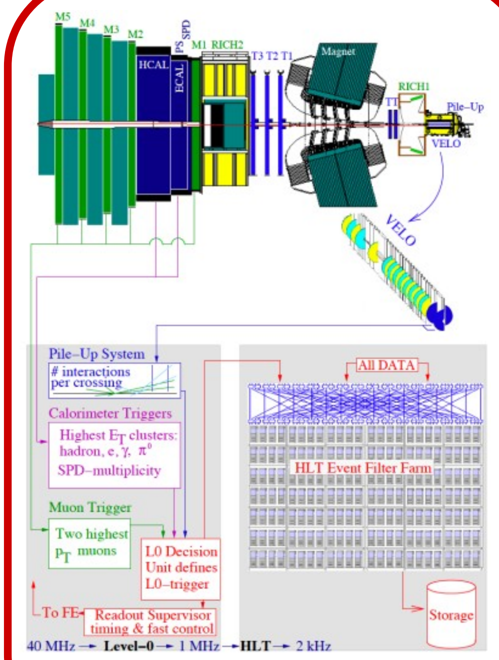
↓

FULL: here is the full event, take your time



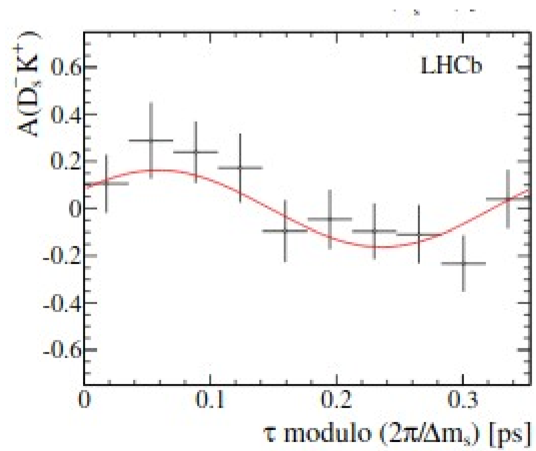
BW=50 GB/s (>2005)

OK so now we're set: the Run 1 situation

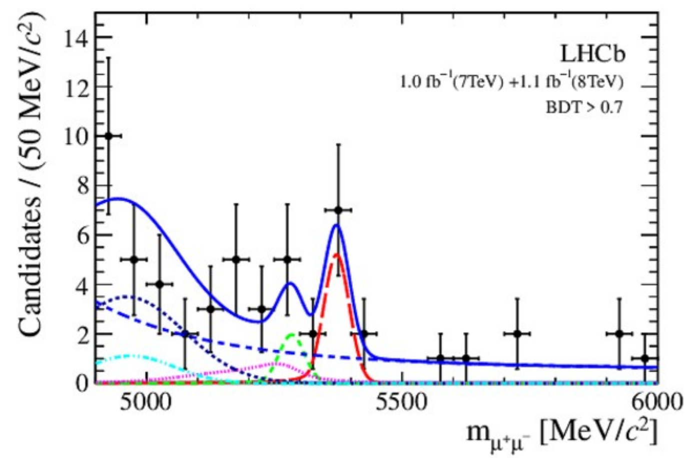


BW=50 GB/s (>2005)

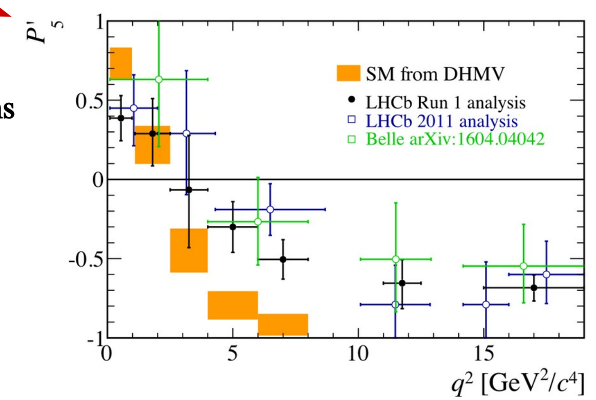
We can do time-dependent CPV!
World-leading on φ_s



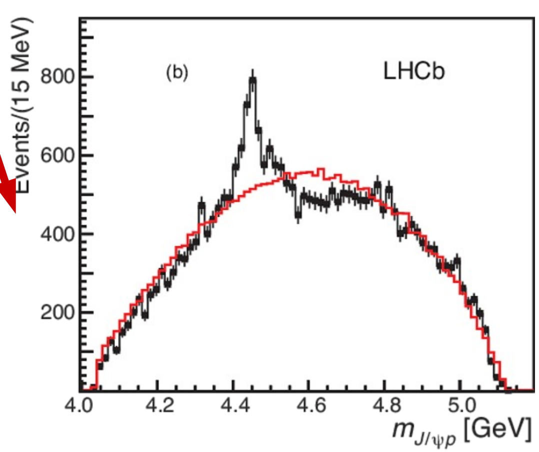
We can look for super rare decays! **$B_s \to \mu\mu$**



We can find hints for New physics!
B→K*μμ angular deviations



We can do spectroscopy!
Pentaquarks!



Always further: the Turbo stream

- Charm production is very, very frequent. And lots of D^0 go to Kpi.
  - Can't save all the events where this happens … but we kind of would like to: charm CPV is feeble.

Frequency of events saved to disk x Average size of events < LIMIT

- Run 2 idea: only save the part of the event that was in the trigger.
  - Easier said than done, requires having a close-to-offline quality in the trigger.
  - Alignment applied online → precursor of RTA

L0: a hard process happened, possibly beauty-like

↓

HLT1: there is beauty or charm in there

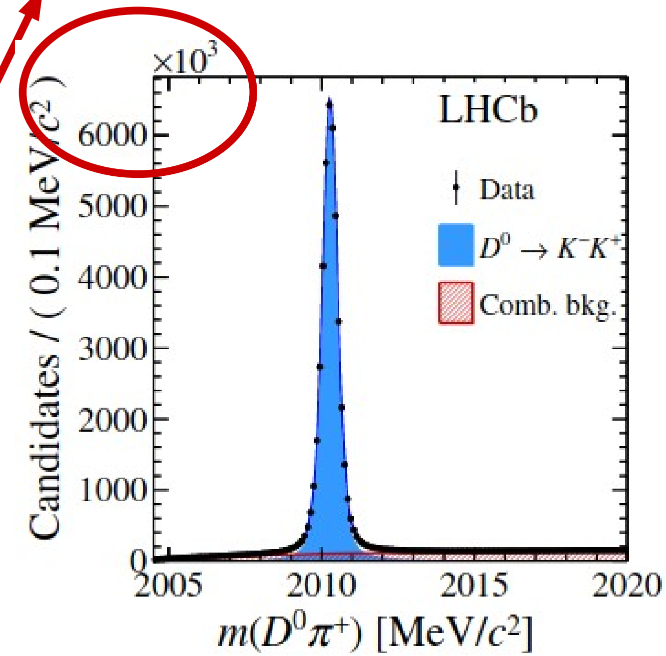
↓

HLT2: one of the N (o(10^2)) decays of interest is there

↓

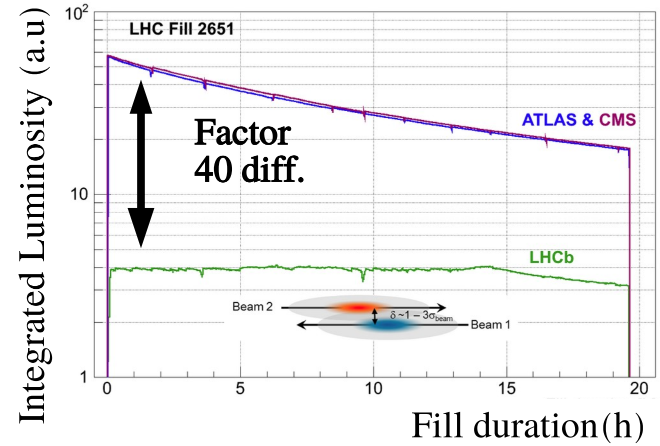
FULL: here is the full event, take your time

TURBO: we know what you want, here it is

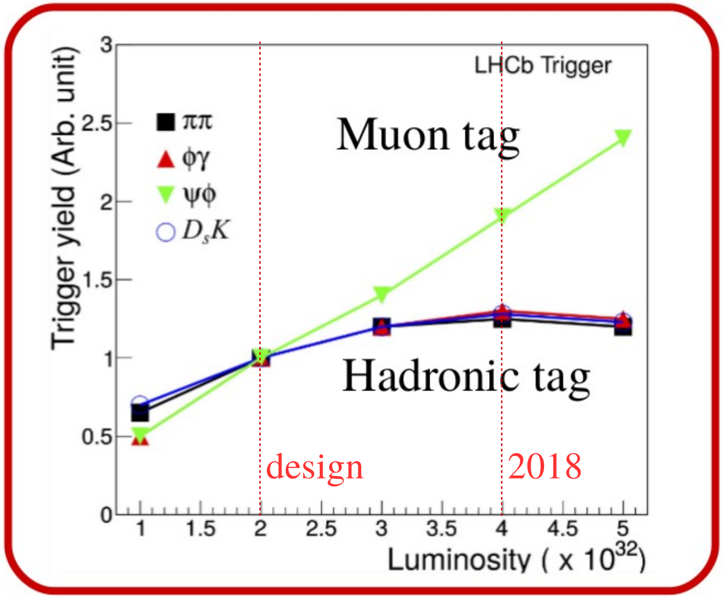


The LHCb upgrade: why?

- Most of Run 1-2 measurements limited by statistics.



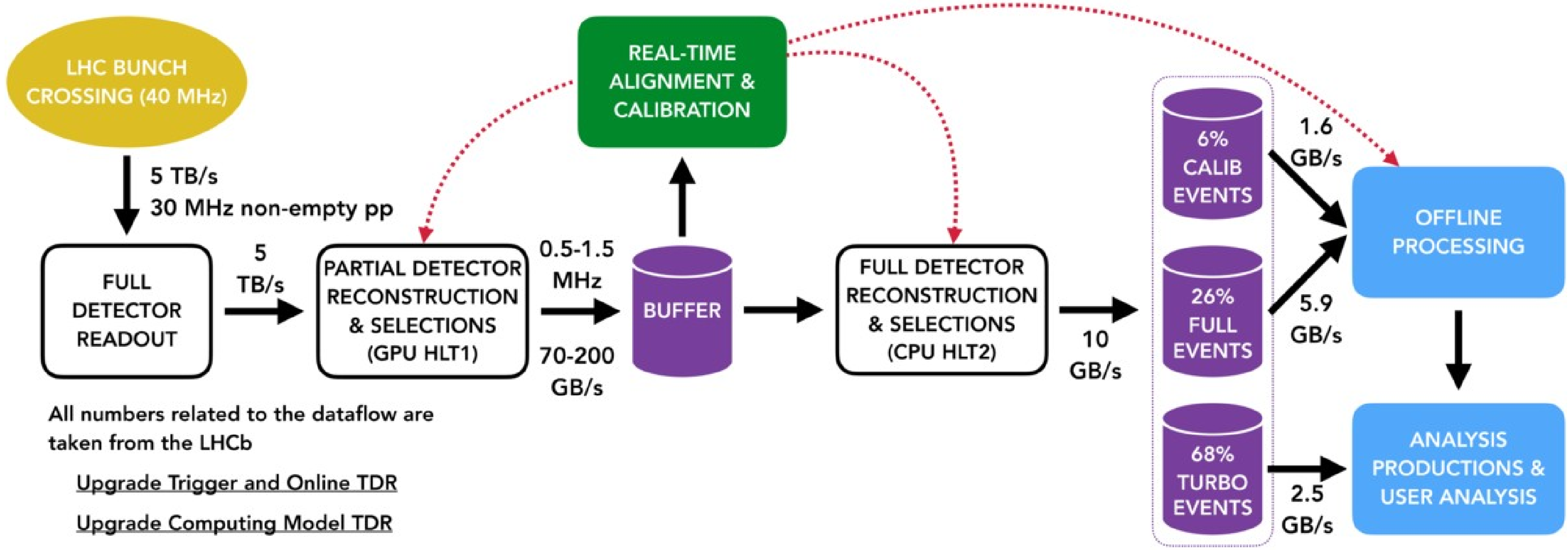
- From 2010 to 2018, LHCb levelled luminosity.
  - Remember: partly a consequence of the geometry of.
  - If levelling reduced, possible to increase luminosity in LHCb.
  - We were already at twice the design luminosity.



- L0 hadronic prescaling saturates! Need another handle than pure p_T.
  - Not a hundred ways around it: need to perform tracking.

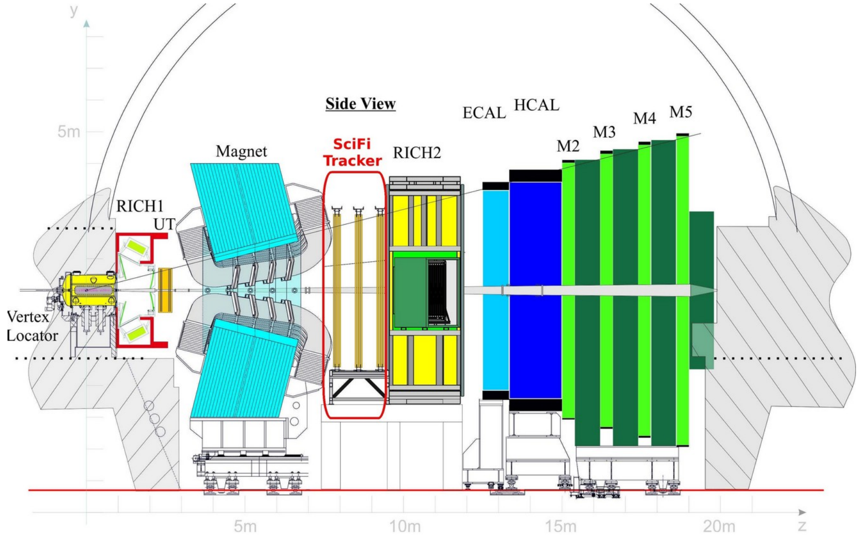
- LHCb upgrade design driven by harsher radiation environment and necessity to overhaul trigger and DAQ scheme.

A hydra of challenges

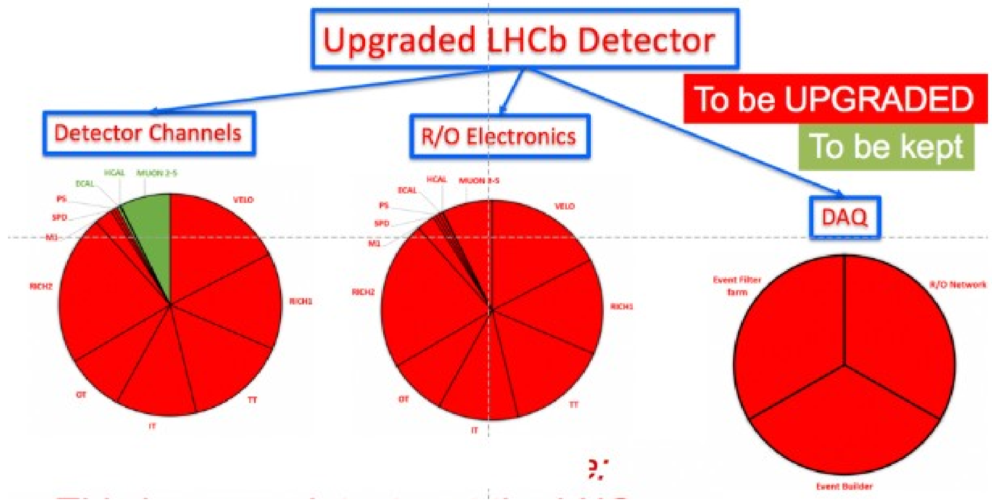


- Will be the topic of a future talk but: removing L0 involves other challenges.
- What it implies for the detector:
  - Full detector readout at 30 MHz
  - Being able to partly reconstruct tracks at 30 MHz (formerly 1 MHz)
  - Being able to reconstruct most exclusive decays at 1 MHz (formerly O(100 kHz))
  - Did I mention we needed higher radiation resistances?

So what changes?



Nothing?...

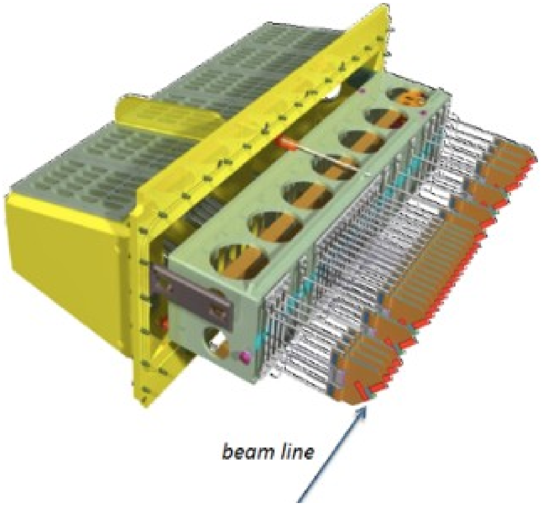


... fair enough.

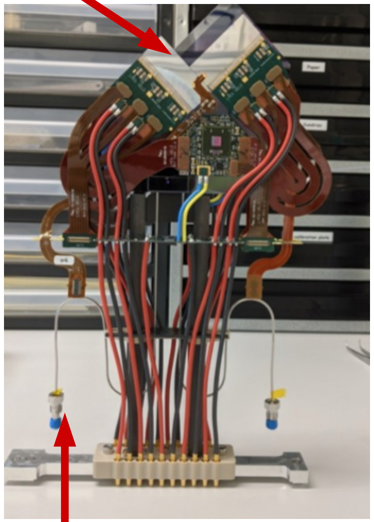
- General layout of the detector obeys physics imperatives → not the only solution, but a stable one.
- Don’t fix what ain’t broken: the base goal is to do the same thing, but being able to do it faster and in a harsher environment.
  - Of course, we always strive for more.
  - Balance between ‘pointless’ improvement and helping everyone with local improvements.

From VELO to VELO Pixel

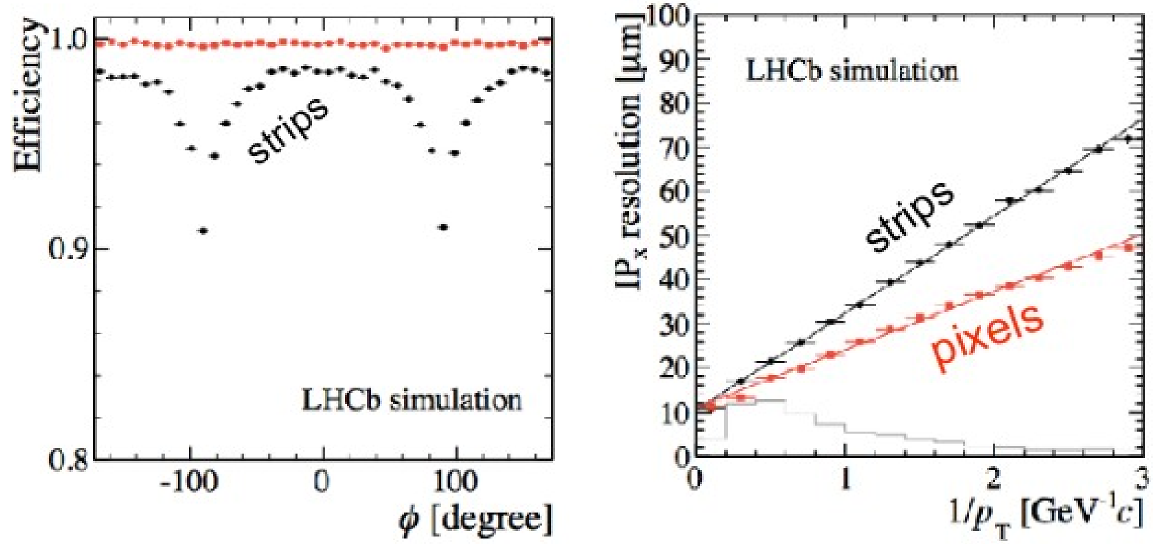
- Mission: give very good vertex position & impact parameter, fast and efficient way.
  - No magnetic field → tracks will be straight!
- VELO used to have strips → going to pixels.
  - Considerable data rates → custom-made ASIC
  - Need cooling
  - More radiation resistant + better monitoring → can go closer to the beam!
- Change of geometry helps pattern recognition.



Pixels

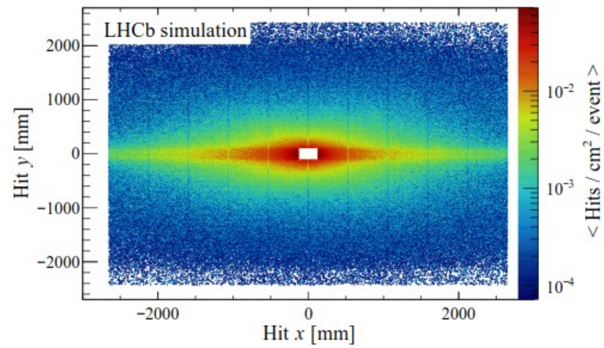


Evaporative CO2 cooling



Life cycle of a forward tracker

- Mission: measure track downstream to get momentum
  - Precision key for momentum measurement & track association
  - Large area to cover → need a cheap technology for large areas
  - Very non-uniform fluence → tempting to combine with more precise and radiation-hard technology in the center.

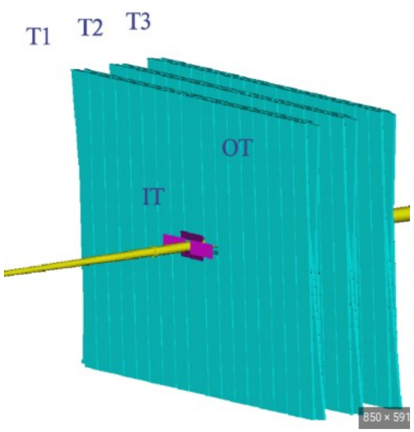


The Forward tracker development cycle

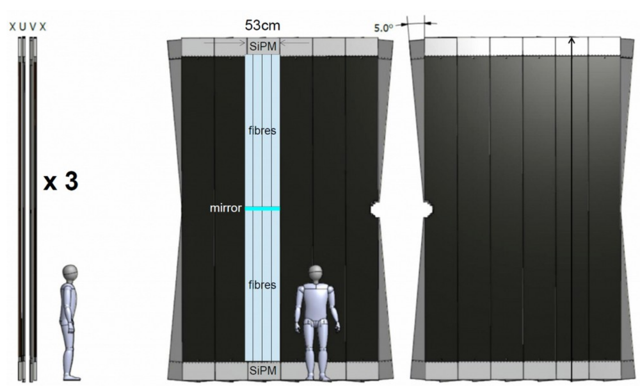
Need y info in centre, monolithic cannot cope with fluences…

Hybrid design: precise tracker in the middle, rest covered by cheaper tech ← → Monolithic design *(You are here)*

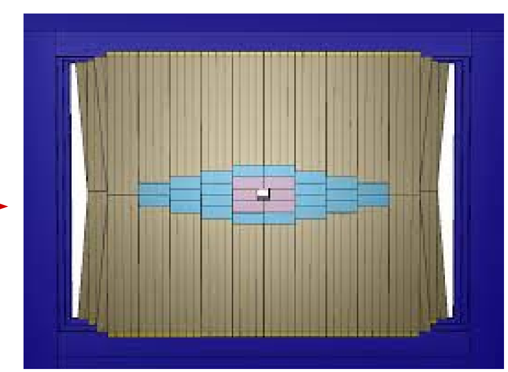
Costly, difficult to operate, slower reconstruction



Run 1&2: IT & OT



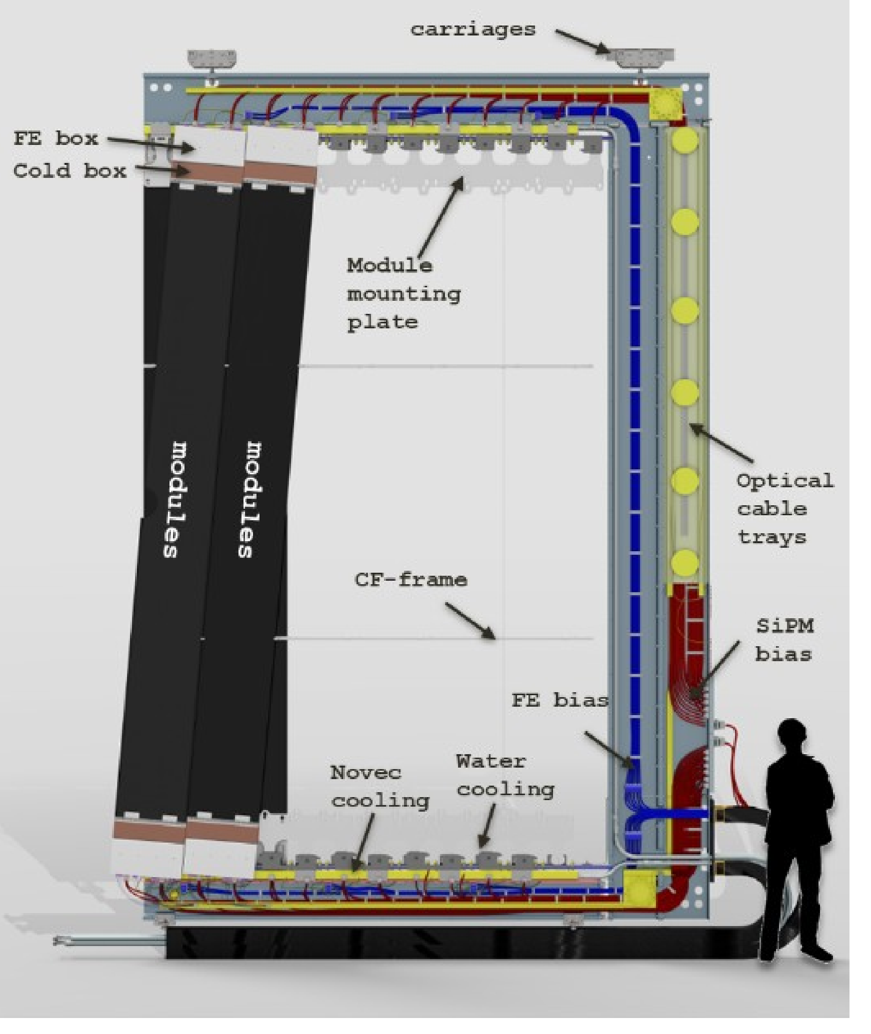
Run 3&4: SciFi



Run 5+: MightyTracker?

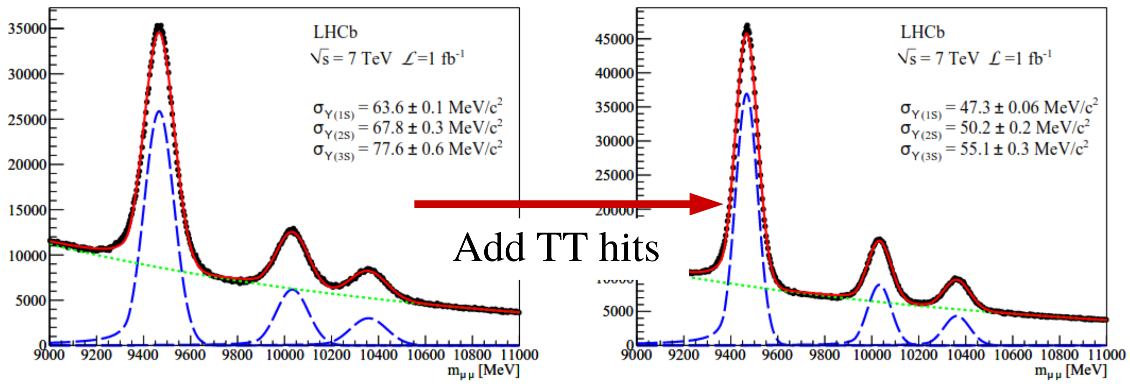
SciFi geometry from first principles.

- Made of 3m long fibres, at the end of which you find silicon PMTs. StarterTalk by Sophie Hollitt
  - Only 1-dimensional info (+z, considering we know where we put it).
- Why not N/2 fibres horizontal, and N/2 vertical?
  - Too many ghost hits.
  - OK so just a tilt. But which?
- Bending of the magnet is mostly in x-z.
  - Need less information in y.
  - Momentum resolution will depend much more on x.
- After lots of optimisation: tilt angle of 5 degrees.
  - 3 stations, X-U-V-X.
  - X: vertical layer
    U (V): vertical layer with a (-)5 degree tilt → y info.

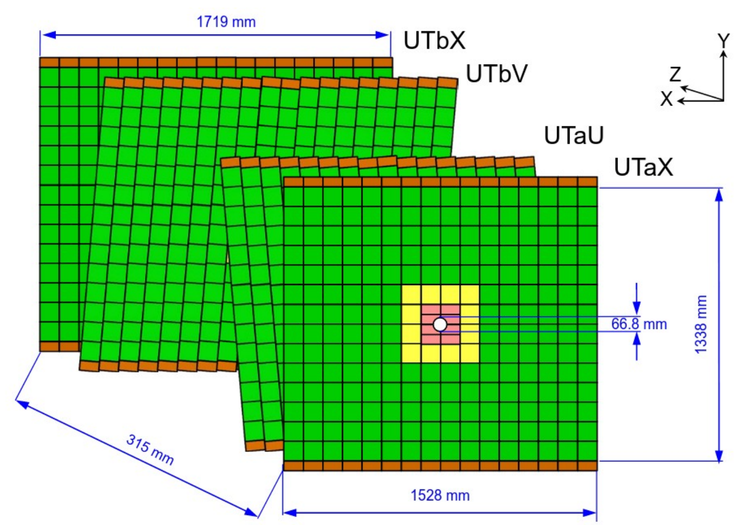


Upstream tracker: why and how

- Missions:
  - Gives an estimate of the momentum of VELO tracks → helps tracking by reducing tolerance windows and fake rates, improves momentum measurement.
  - Quite a few decays include K_S and Λ, which fly → allows to study more of them



- Region of weak magnetic field, and close to the VELO → will rely on extrapolation.
  - X-U-V-X geometry
- Smaller area to cover → can afford silicon strips!
  - Y information partly recovered.

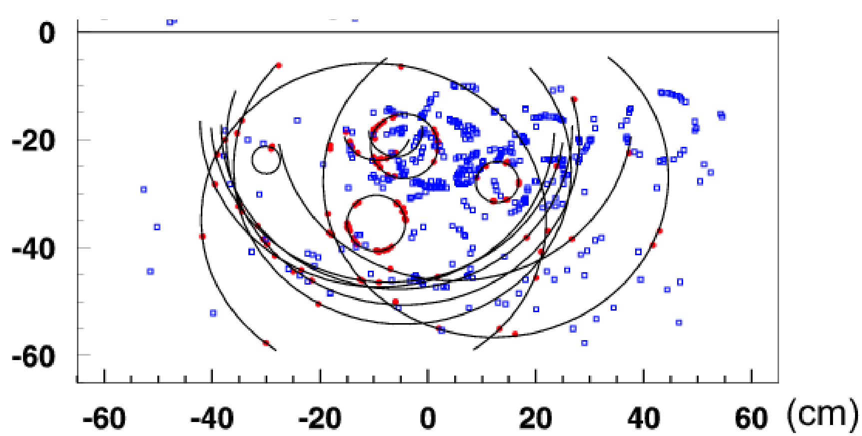


The RICH detectors

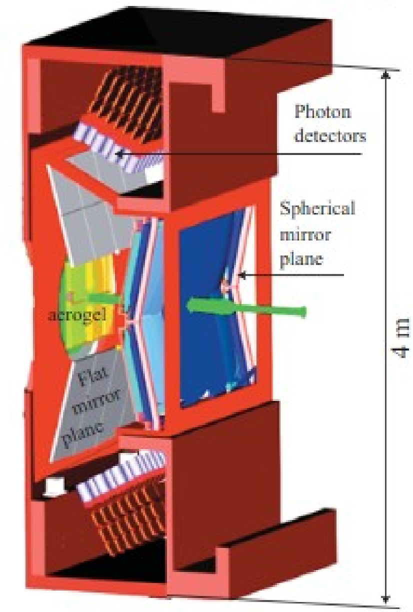
- Mission: get PID fast enough for HLT2, on charged tracks.
  - RICH 1: all angular acceptance, p in 1.5 – 50 GeV/c
  - RICH 2: reduced acceptance, p in 1.5 – 100 GeV/c

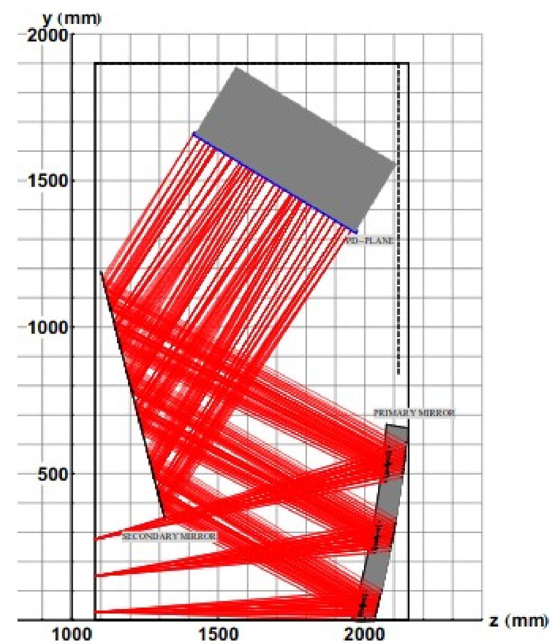
Parameter		C_4F_{10}	CF_4
L	[cm]	$\sim$110	167
n		1.0014	1.0005
θ_c^{max}	[mrad]	53	32
$p_{thresh}(\pi)$	[GeV/c]	2.6	4.4
$p_{thresh}(K)$	[GeV/c]	9.3	15.6
$p_{thresh}(p)$	[GeV/c]	17.7	29.7

  - Removal of aerogel radiator in RICH1:too small γ yield.
- Photons redirected using mirrors onto PMTs to measure the light.
- Complex task to get the rings, angles, and track association.



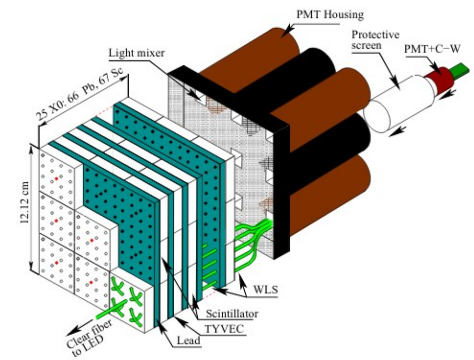
RICH1



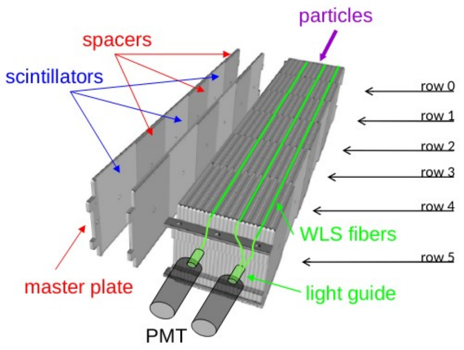


Calorimetry & muon chambers

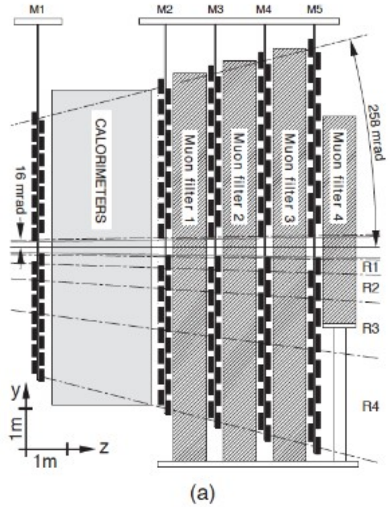
- **Electromagnetic calorimeter:**
  - Mission: provide information about photons and electrons.
  - Technology: shashlik of lead and scintillator
  - Use tracking, cluster shape to do so.



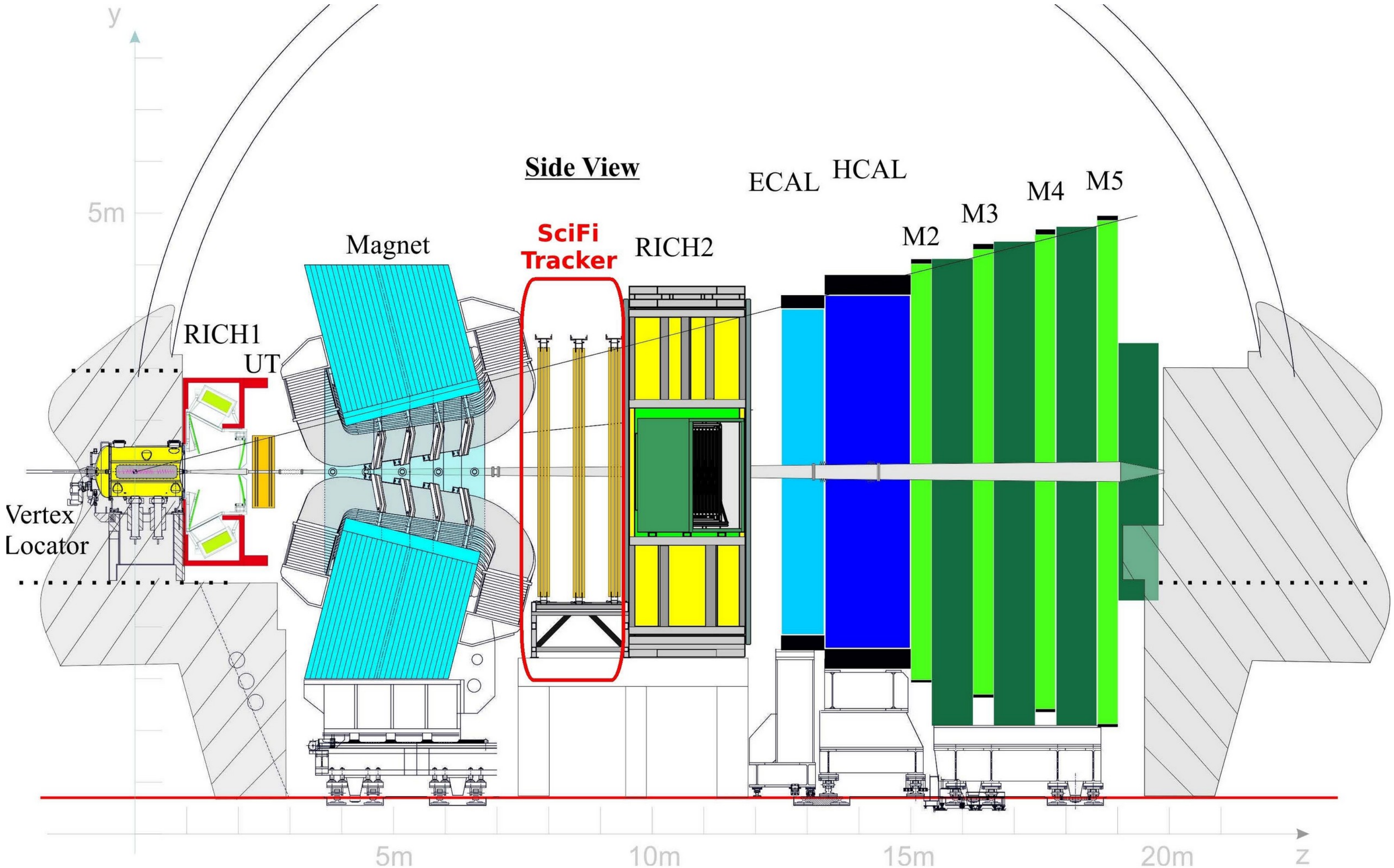
- **Hadronic calorimeter:**
  - Mission: used to be central to the L0, still helps PID.
  - Technology: interleaved iron plates and silicon tiles.
  - Also acts as a shield for the muon chambers.



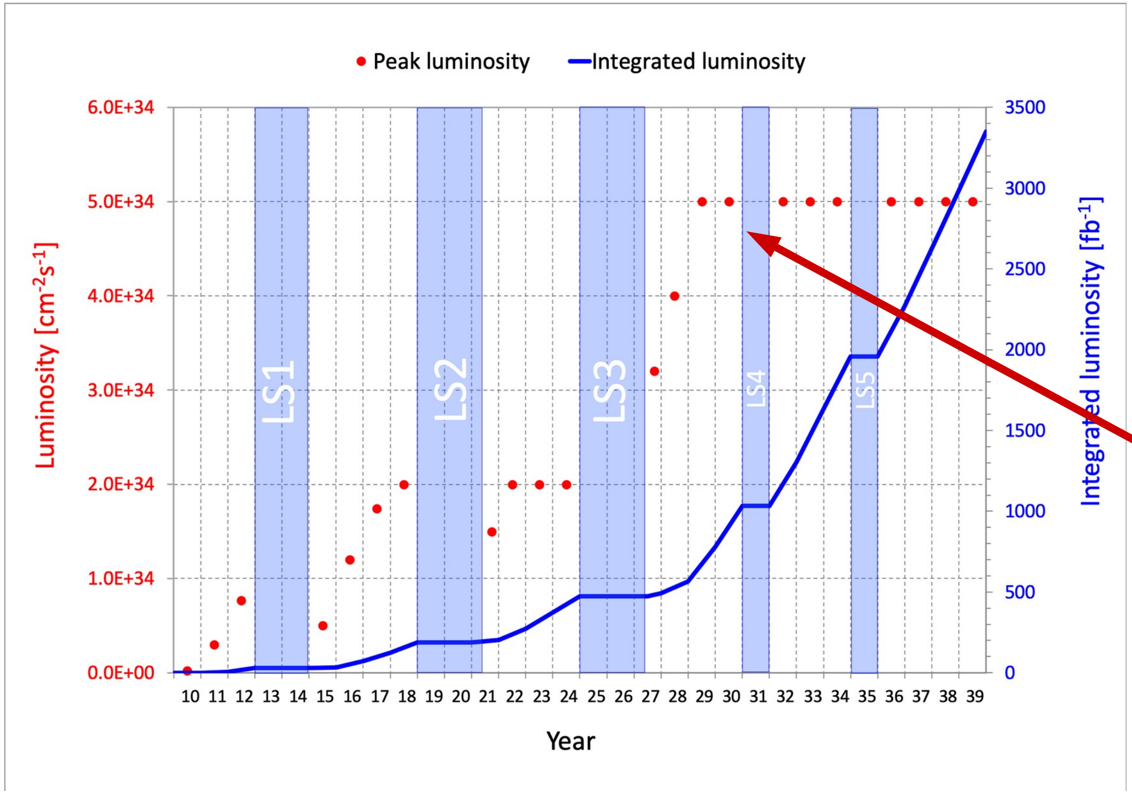
- **Muon chambers:**
  - Mission: tag (long) tracks as muons, must run also in HLT1
  - Technology: MWPC (cheap to cover large areas, and fast to read)
  - After all that material, rather confident remaining tracks are muons.
    - Confirmed through use of intermediate shields
  - Need to measure the track well → good to have long lever arm.



So now, I think we're set…



… right?



Analysts:

Detector designers:

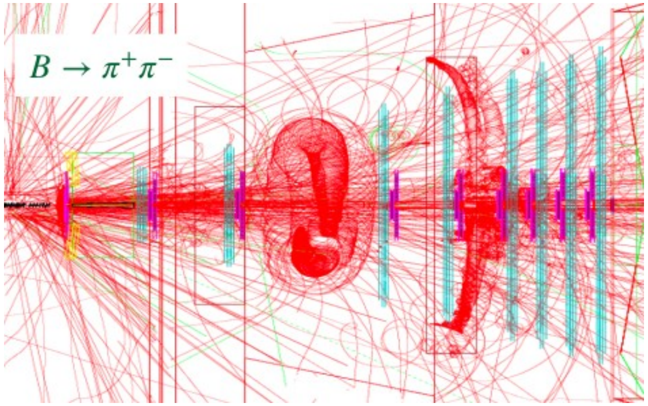
Conclusion

- The current LHCb is an answer, not the answer, to the question:

  Can we trigger and work on beauty at a hadronic machine with L = $1x10^{34}$.$cm^{2}s^{-1}$?

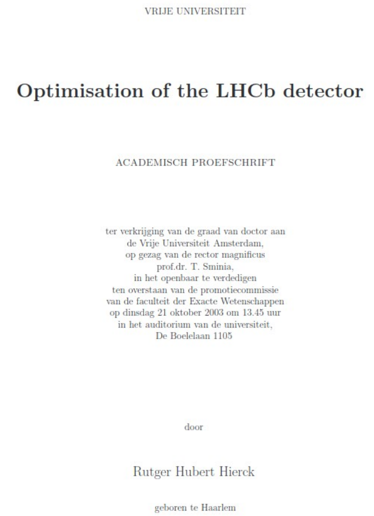
- When conditions, technology, lifetime, software, change, this answer must evolve with it.

- LHCb many successes partly due to physics-driven design:
  - Charm CPV: TURBO stream instrumental
  - Any CPV measurement: vacuum-operated VELO
  - Amplitude, angular analyses: rely on track momentum helped by lever arm and small material budget



- The difference between an unworkable idea and a brilliant idea goes down to small factors.

- Detector design allows to express creativity and possible to shine as a Ph.D. student.
  - Just ask what the current detector owes to this work,



VRIJE UNIVERSITEIT

Optimisation of the LHCb detector

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. T. Sminia,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der Exacte Wetenschappen
op dinsdag 21 oktober 2003 om 13.45 uur
in het auditorium van de universiteit,
De Boelelaan 1105

door

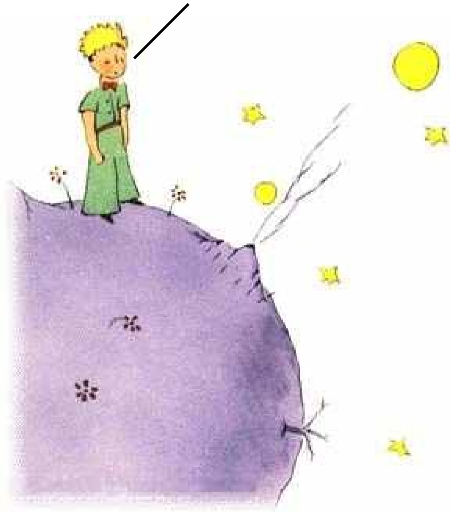
Rutger Hubert Hierck

geboren te Haarlem

Thank you*

*: and thanks a lot to Paula Collins for her help

Please, draw me an Upgrade 2



Reading list:

The History of LHCb
List of LHCb TDRs
Optimisation of the LHCb detector
LHCb performance in Run 1
LHCb performance in Run 2 (proceeding)
LHCb figures cheat sheet

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 pπ) Ξ^- (as Λπ)	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**: $4x10^{32}$ $cm^{-2}s^{-1}$ → $2x10^{33}$ $cm^{-2}s^{-1}$. Upgrade 2: $2x10^{34}$.
- **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.