Intro to LHCb

measurements in particle physics

Phoebe M Hamilton

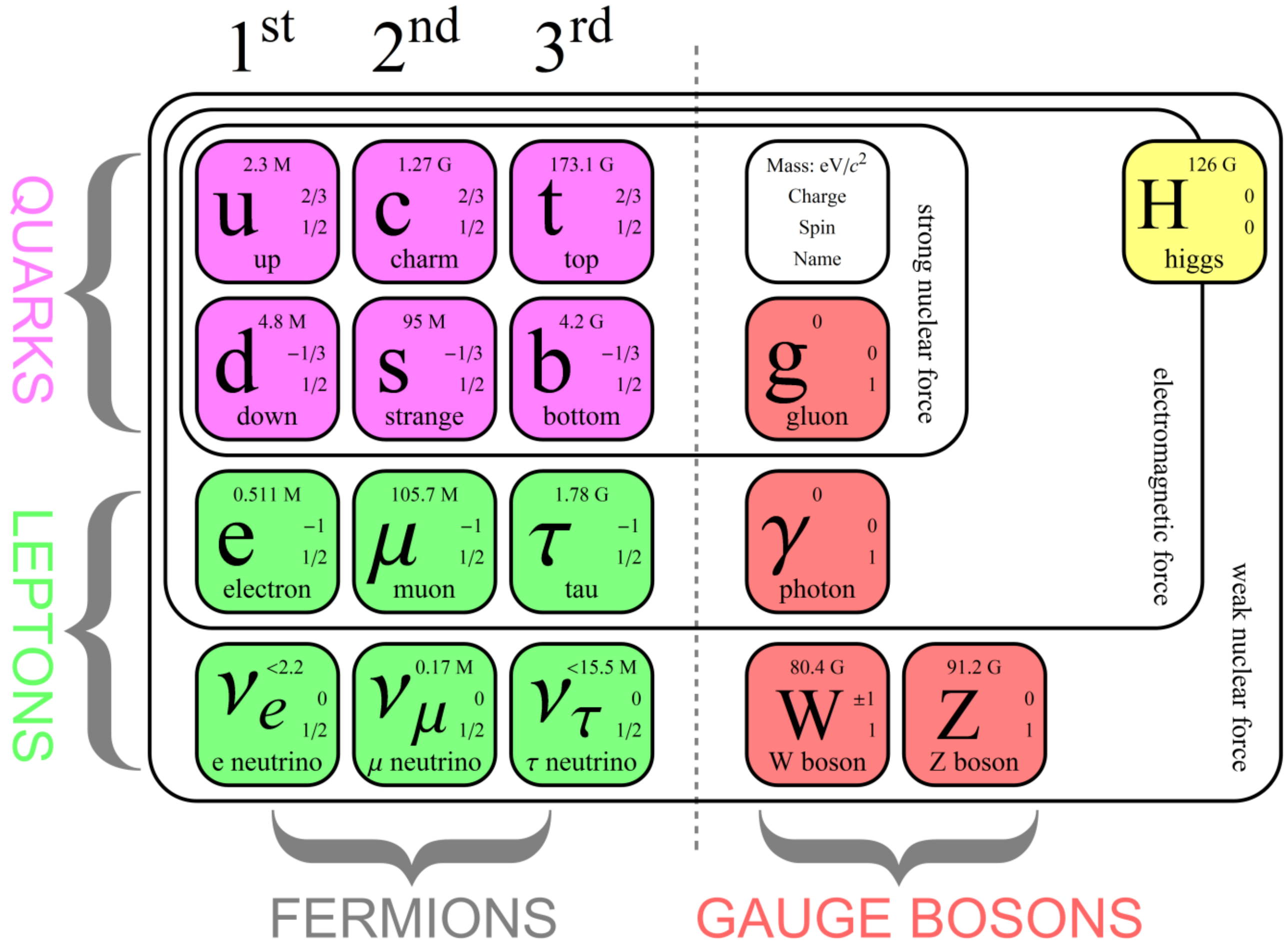
DEPARTMENT OF PHYSICS

About me

- Undergraduate studies in physics at Youngstown State University in Youngstown, OH

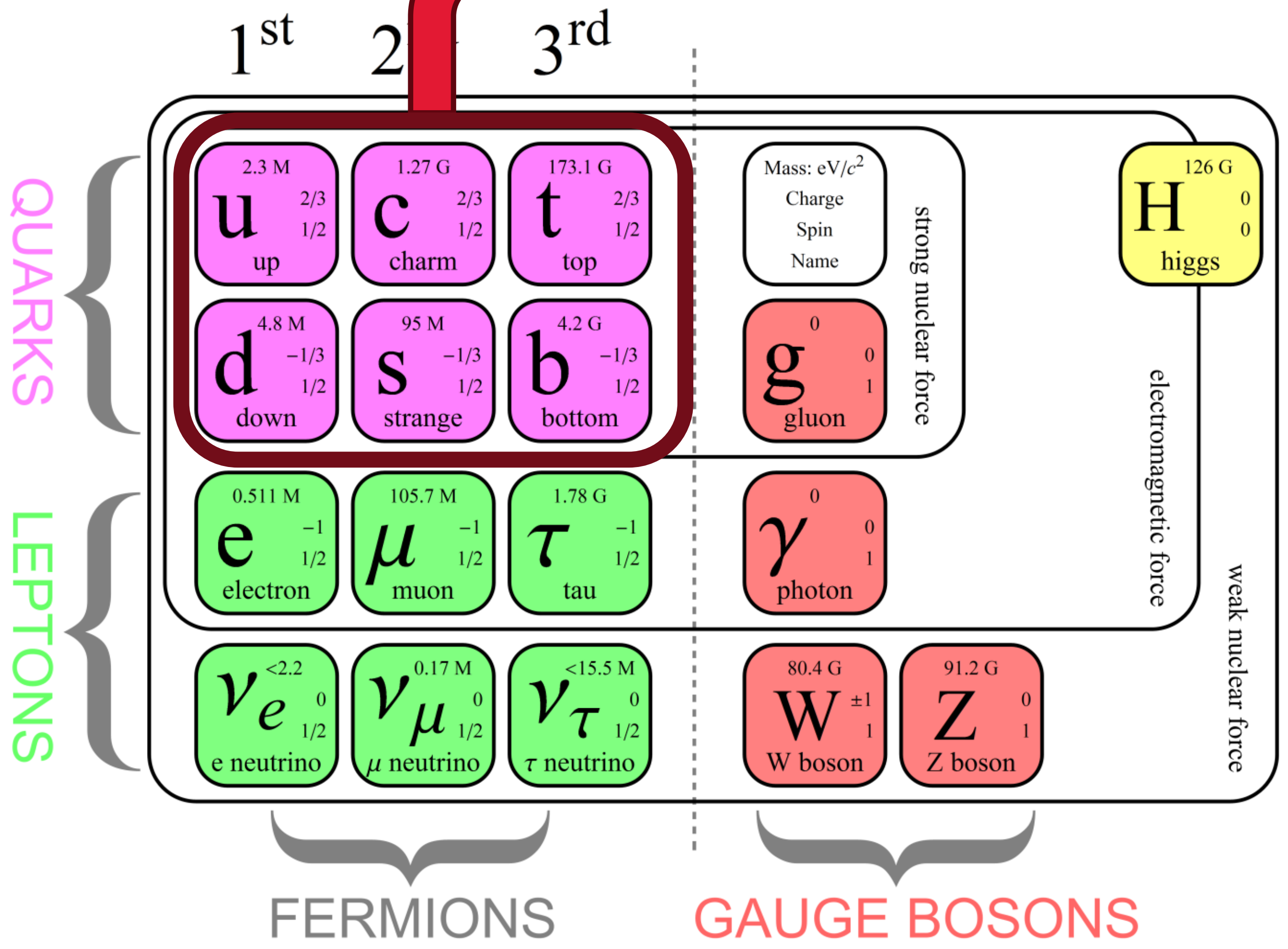
- Physics PhD right here at UMD, working on the *BABAR* experiment at SLAC
  - Studied unique “finalscan” data as well as antideuteron (antimatter version of ${}^{2}_{1}H^{+}$) production
- PostDoc at UMD as group switched to LHCb
  - First followup to BaBar Colleagues’ hint of Lepton Flavor Universality violation and first measurement of $\bar{B} \to X_c \tau \bar{\nu}$ at a hadron collider.
  - Developed new ways of doing analysis, including for “1-track+neutral” B decays
- Assistant professor here since ‘23

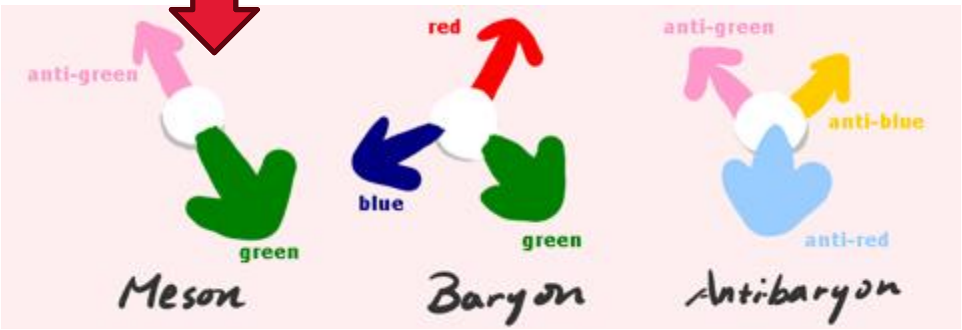
The "Zoo" of Particle Physics



- All the known fundamental (as far as we can tell!) particles organized according to their interaction properties under the strong, weak, and electromagnetic forces
  - Matter particles (fermions) which either do (quarks) or do not (leptons) experience the strong nuclear force
  - Force carriers (gauge bosons) which transmit the fundamental forces

The "Zoo" of Particle Physics



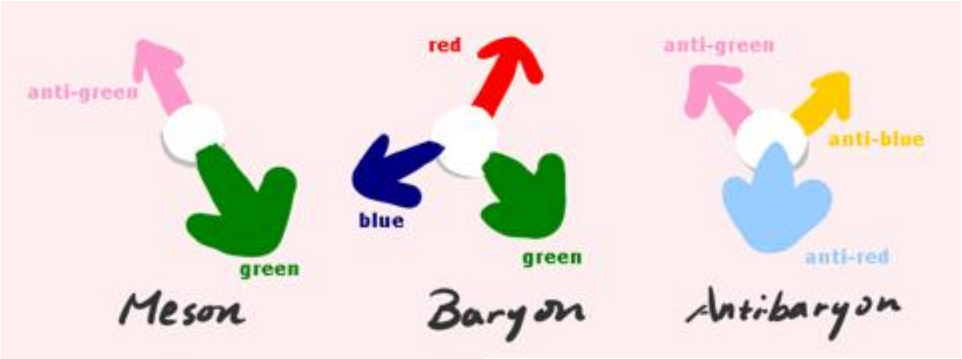


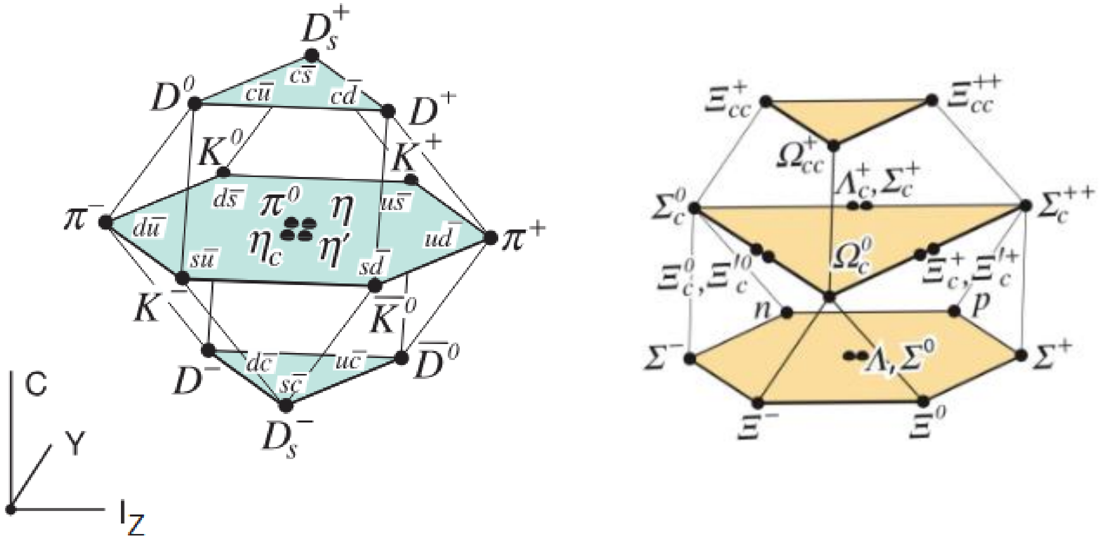
- Of note today, the strong force is so strong the energy density stored in the color fields between two separated quarks is so large as to create new quarks from the stored energy
  - Quarks eventually bind themselves into "colorless" hadrons
  - Like how atoms are composed of electrically charged objects but are neutral overall

The “Zoo” of Particle Physics

- The simple rules for creating color neutral objects combined with the various kinds of quarks makes for a beautiful symmetric zoo of mesons and baryons

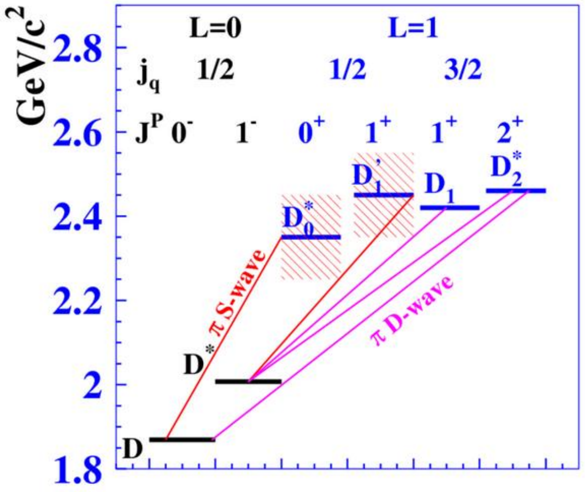
- All told, the mesons are usually the simplest laboratory for us to study the properties of heavier quarks
  - Especially those composed of a heavier quark and a light (up or down) quark – these are like the hydrogen atom in terms of symmetry and simplicity
    - Not that anything about the strong force is simple!

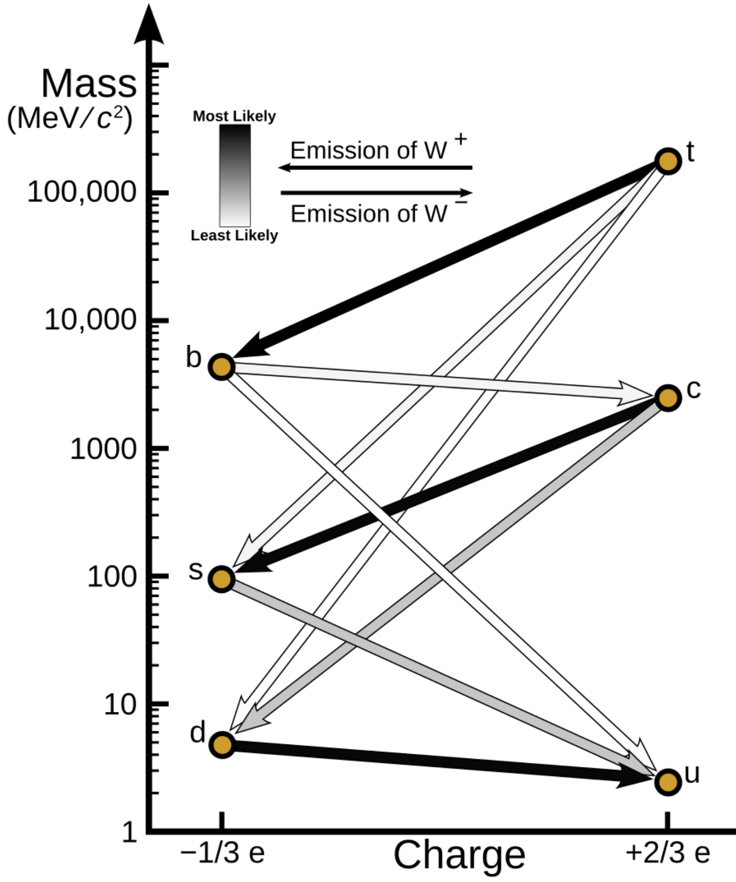




Heavy-Light Mesons

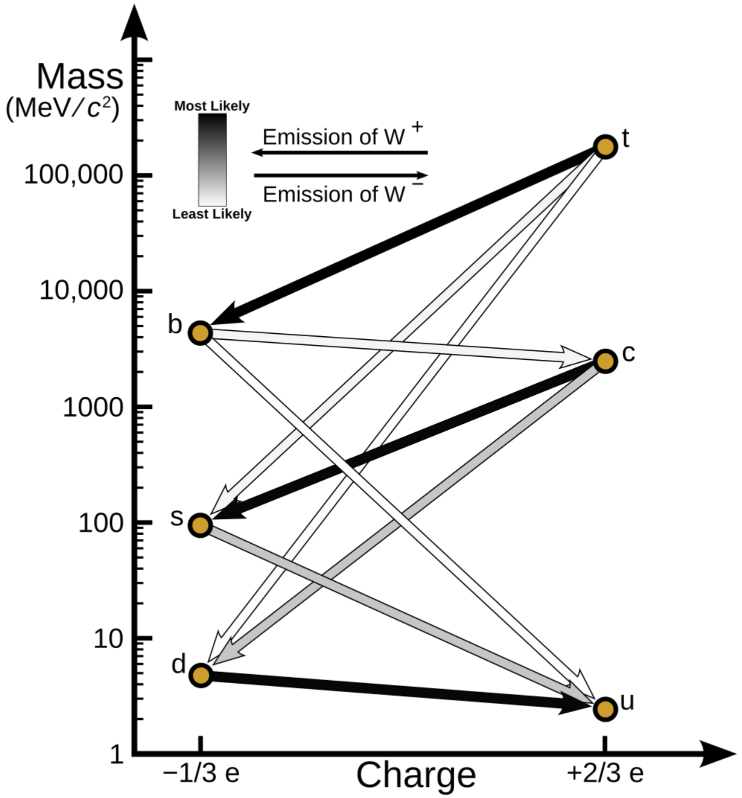
- In fact, these can be quite a bit hydrogen-like, with fine and hyperfine structure and various energy splittings, all telling us about the nature of the strong force holding them together!
- What's important here is that the *lightest* heavy-light states are *stable* as far as the strong and electromagnetic forces care.
- They can only decay to lighter particles by the weak interaction changing their identities!





Heavy-Light Mesons

- They can only decay to lighter particles by the weak interaction changing their identities!
- But the weak force is weak, the probability of this transmutation happening in any given moment is small
  - This probability is also constant in time, that is, for any moment the particle is still around, the probability it decays in the very next moment is always the same – these objects are "too simple to age"!
- The smallness of the probability (due to the weakness of the force) is what causes them to have detectable lifetimes rather than immediately disintegrating

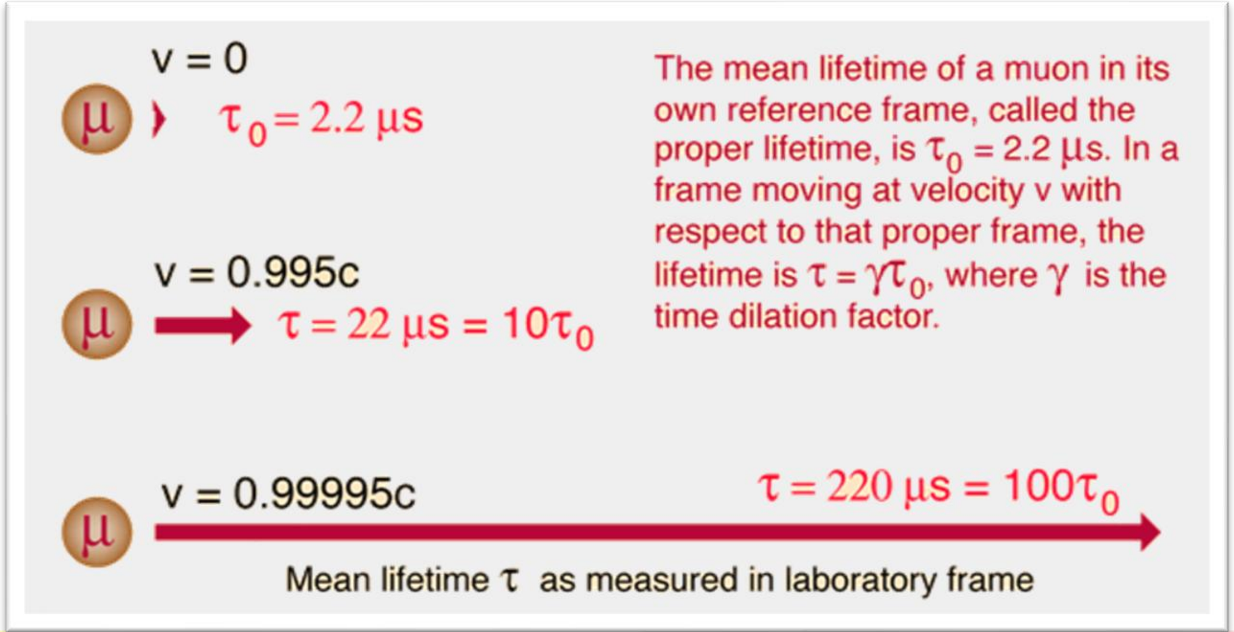


Lifetimes

- We characterize this all in terms of a "mean lifetime" – "if I start with a large collection of these guys, about how long do I have to wait until $1/e$ of them are gone"
  - If that sounds like a half-life to you, that's because it is, except for a factor of ln(2) ☺
  - We'll see better tomorrow how this lifetime arises from the statements I made about probability before – though maybe some are remembering their diff. eq. already!

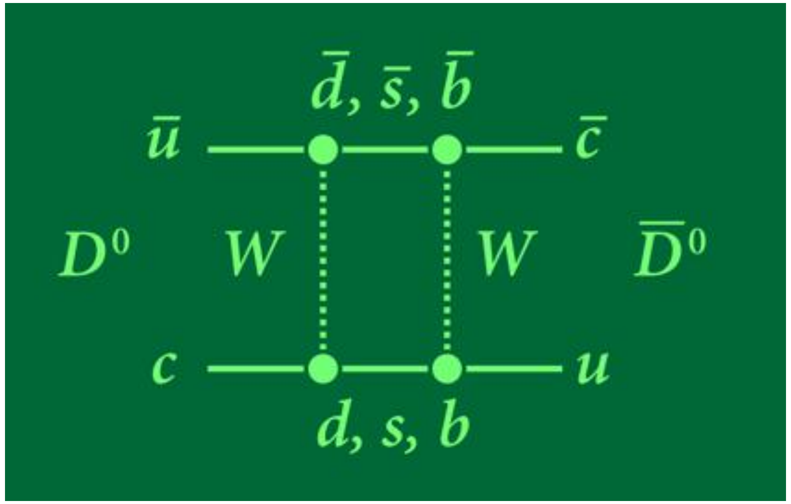
- Anyway, how do we measure such short lifetimes?
  - The secret sauce is time dilation! This lifetime $1/e$ is like a clock, and *all* moving clocks run slow!
- Heavy-light mesons mean lifetimes:
  - $D^0 - 4.1 \times 10^{-13} s$
  - $B^0 - 1.5 \times 10^{-12} s$

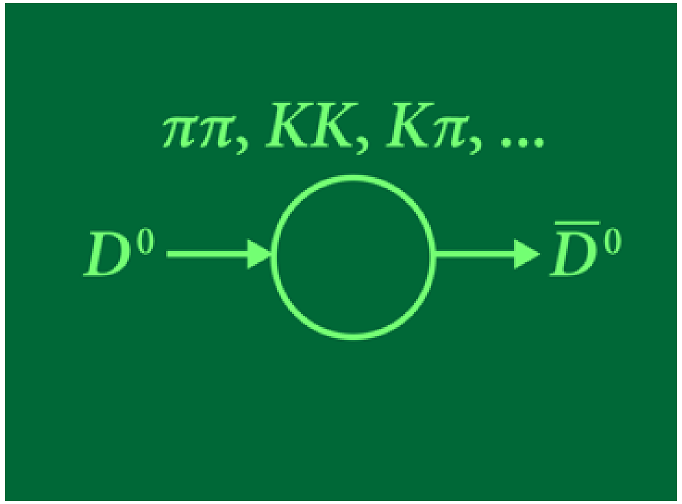
Type	Name	Symbol	Energy (MeV)	Mean lifetime
Lepton	Electron / Positron	e^- / e^+	0.511	$> 4.6 \times 10^{26}$ years
	Muon / Antimuon	μ^- / μ^+	105.7	2.2×10^{-6} seconds
	Tau lepton / Antitau	τ^- / τ^+	1777	2.9×10^{-13} seconds
Meson	Neutral Pion	π^0	135	8.4×10^{-17} seconds
	Charged Pion	π^+ / π^-	139.6	2.6×10^{-8} seconds
Baryon	Proton / Antiproton	p^+ / p^-	938.2	$> 10^{29}$ years
	Neutron / Antineutron	$n / \bar{n}$	939.6	885.7 seconds
Boson	W boson	W^+ / W^-	80,400	10^{-25} seconds
	Z boson	Z^0	91,000	10^{-25} seconds



Neutral mesons

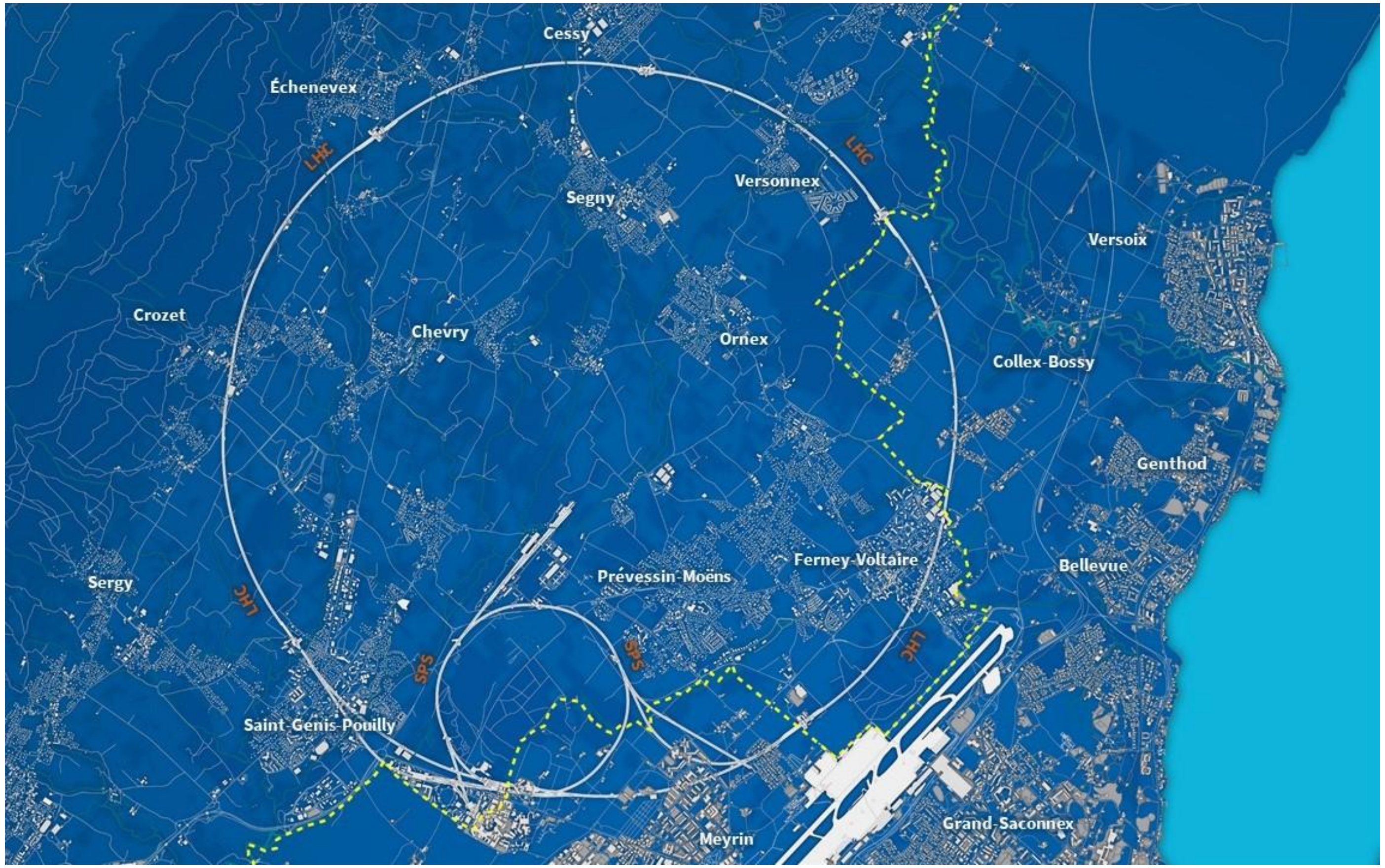
- The neutral mesons with a heavy quark - $K^0(\bar{s}d), D^0\ (c\bar{u}), B^0(\bar{b}d)$ are especially interesting to us at LHCb
- They have the surprising property that they "mix" with their matter-antimatter mirror selves
  - So, e.g., $D^0(c\bar{u}) \Leftrightarrow \bar{D}^0(\bar{c}u)$. Since we still have one quark and one antiquark, we haven't violated any (anti)matter conservation!
    - A principle of quantum mechanics: everything that is not forbidden is mandatory!
- So there's very good reason to look for and study the production and decay of these guys! – Let's get an idea of how we do that



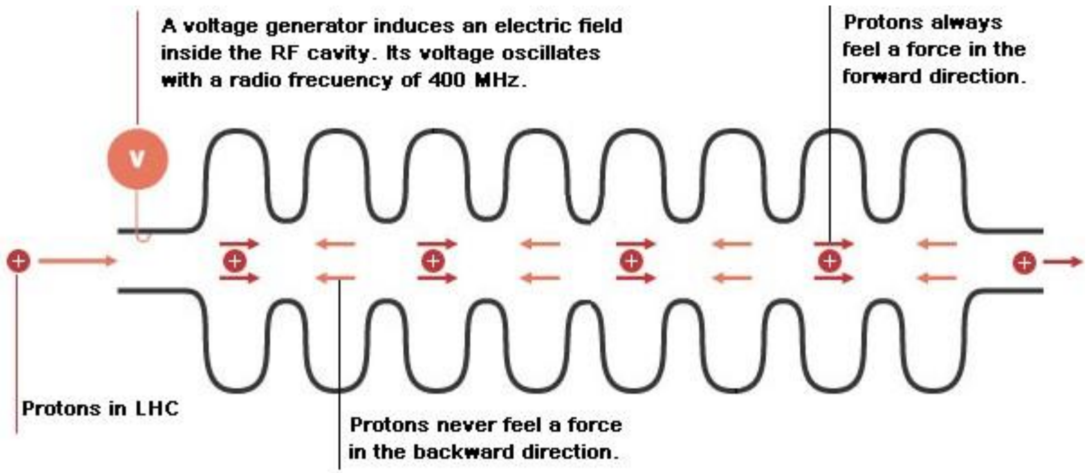


From protons to plots

CERN's Large Hadron Collider (LHC)

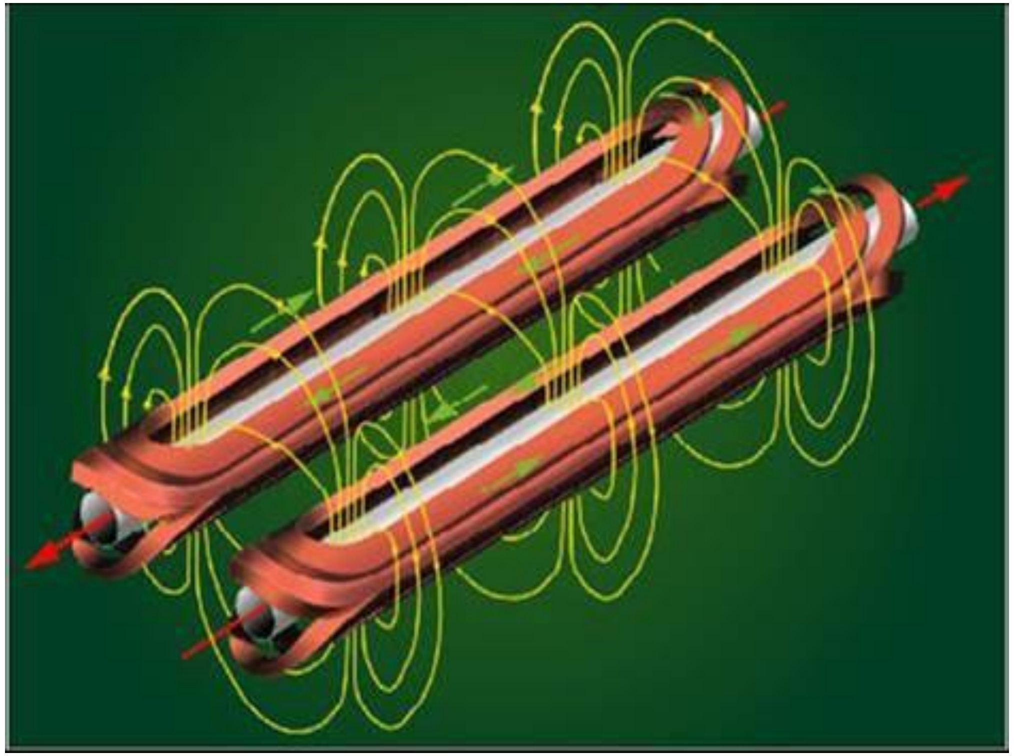


A Complex Machine of Simple Principles



Protons are accelerated via $\vec{F} = q\vec{E}$ force, "riding an electromagnetic wave"

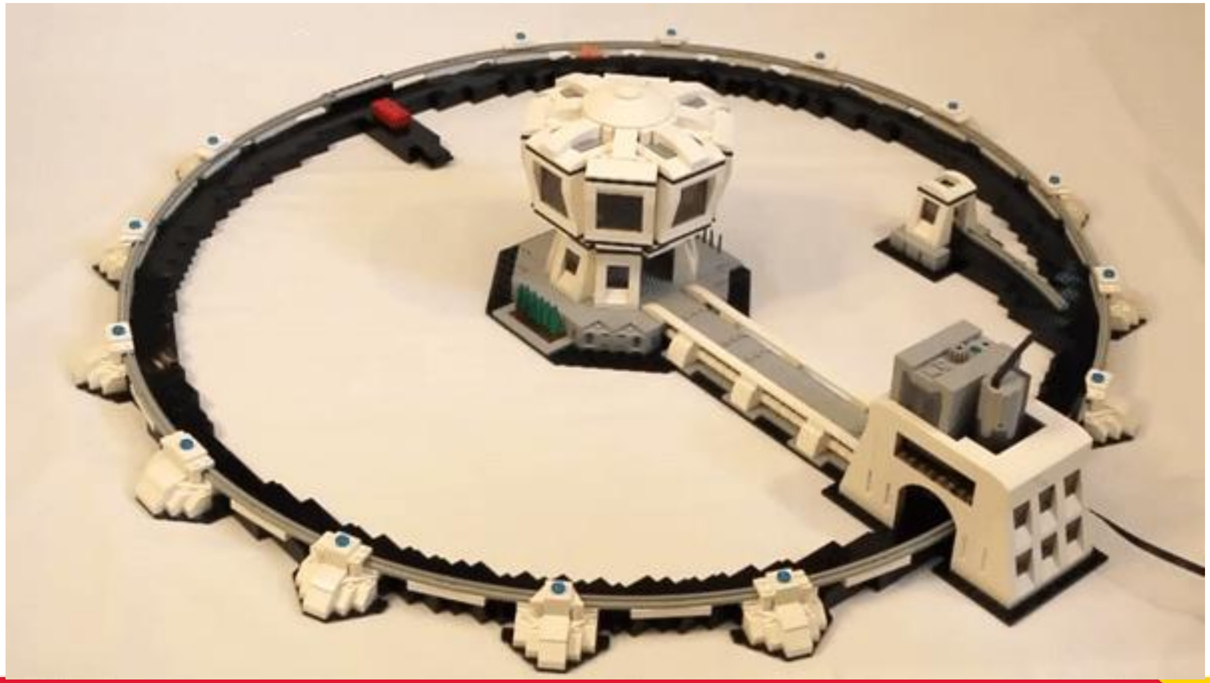
(note, because a wave is involved, this means the beam can't be continuous, contrary to what the word "beam" might evoke – it is pulsed or "bunched")

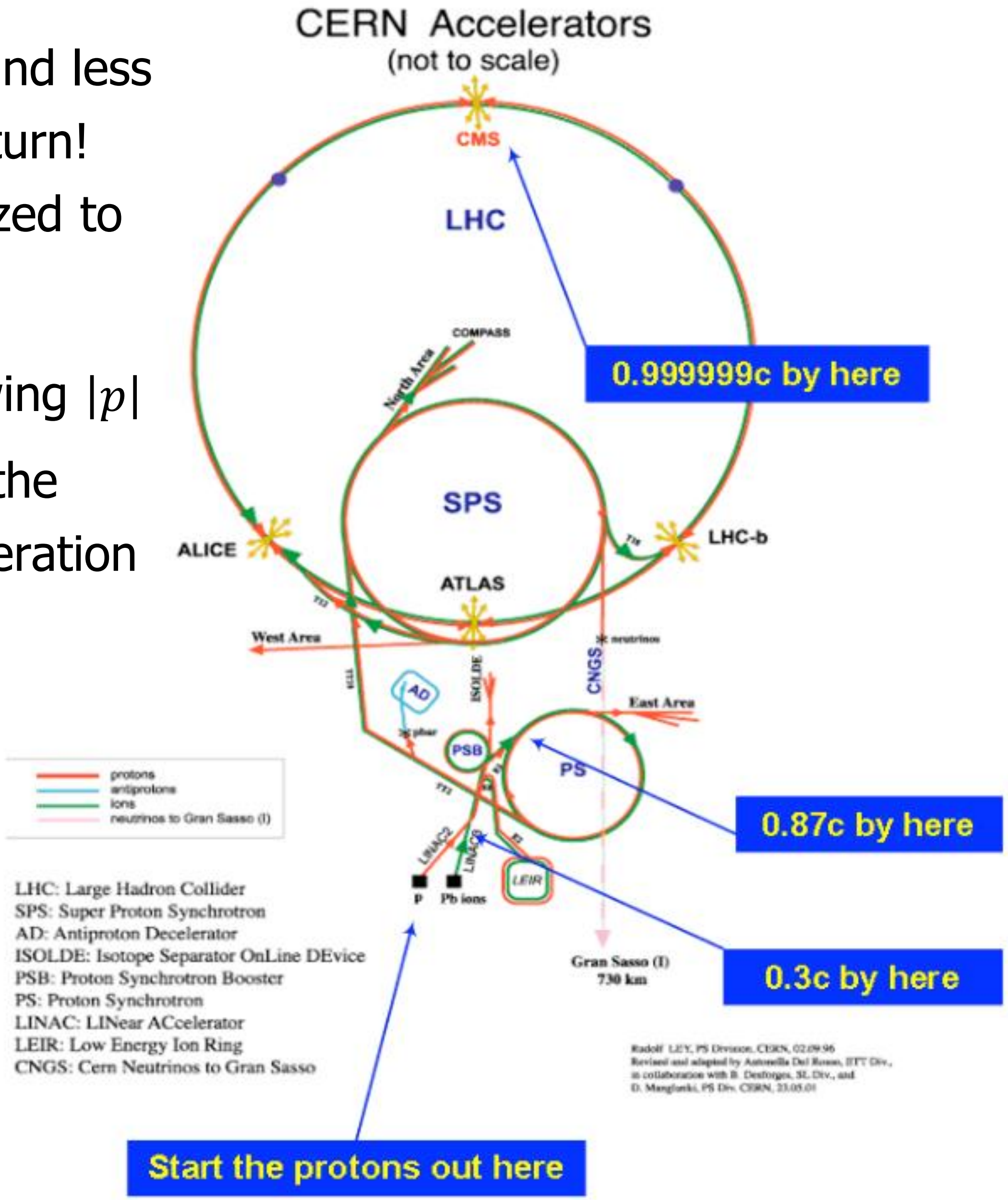


Beam is steered and shaped using $\vec{F} = q\vec{v} \times \vec{B}$

(note, if you look closely, the magnetic field is opposite in each pipe, because $\vec{v}$ is opposite!)

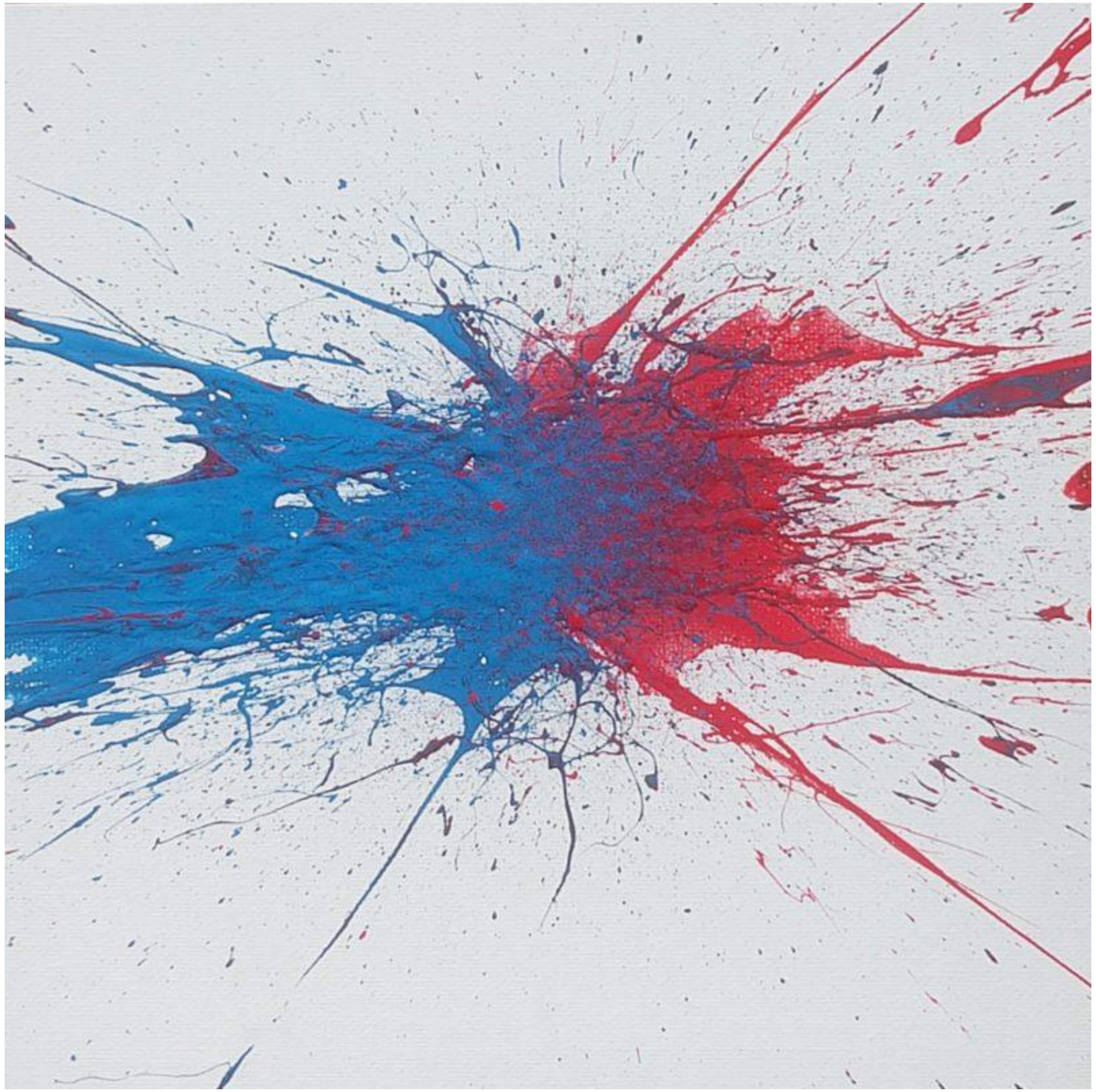
- Each trip builds energy, and the magnetic forces do less and less to actually turn the path, they have to get stronger each turn! ("Synchrotron" because the magnetic fields are synchronized to the beam energy)
  - Relativistically, $\vec{F} = \frac{d\vec{p}}{dt} \neq m\vec{a}$ and $\frac{d\vec{p}}{|p|}$ shrinks with growing $|p|$
  - Eventually, the electromagnets reach their limit, and the beam must be sent to a bigger ring to continue acceleration



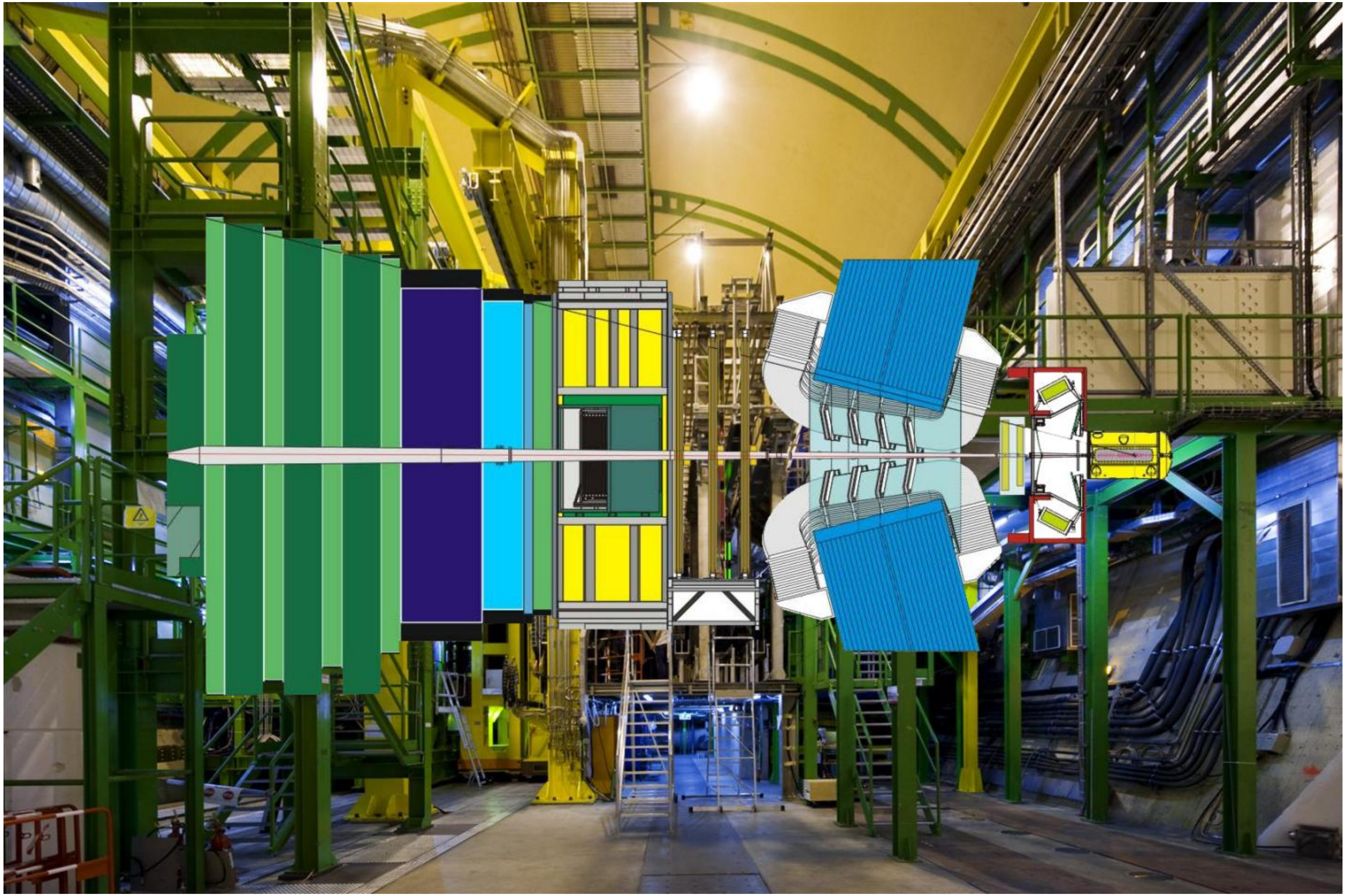


Collisions

- Eventually, at the target energy, the two counter-rotating beams are steered into one-another to produce high-energy collisions
- But all this work and energy (see what I did there?) to get collisions is useless without something to study them
- The story of the collision unfolds over a very small space in less than a nanosecond
  - The most interesting particles decay to more stable ones (proper mean lifetime $\gtrsim 10\ ns$) long before they could be directly studied
  - Big detectors are designed to look at all the remnants to reconstruct the story of the collision



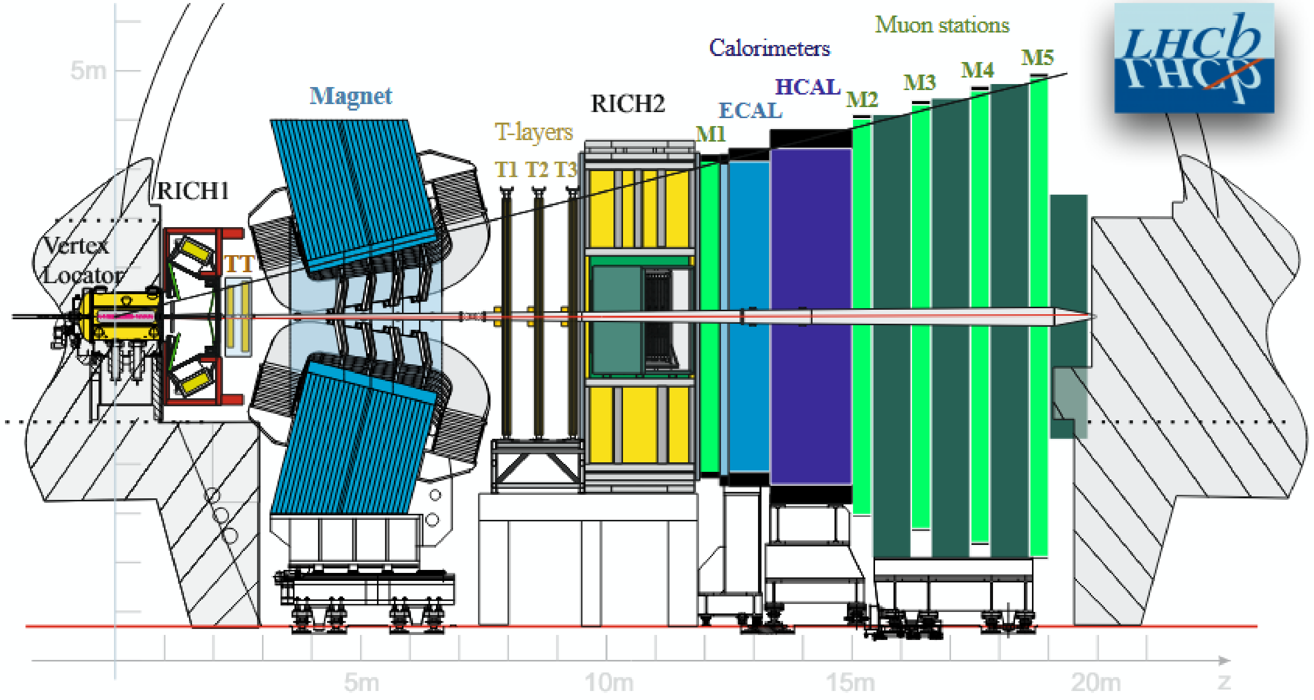
“Colliding Colour: Collision #7” by Sascha Mehlhase

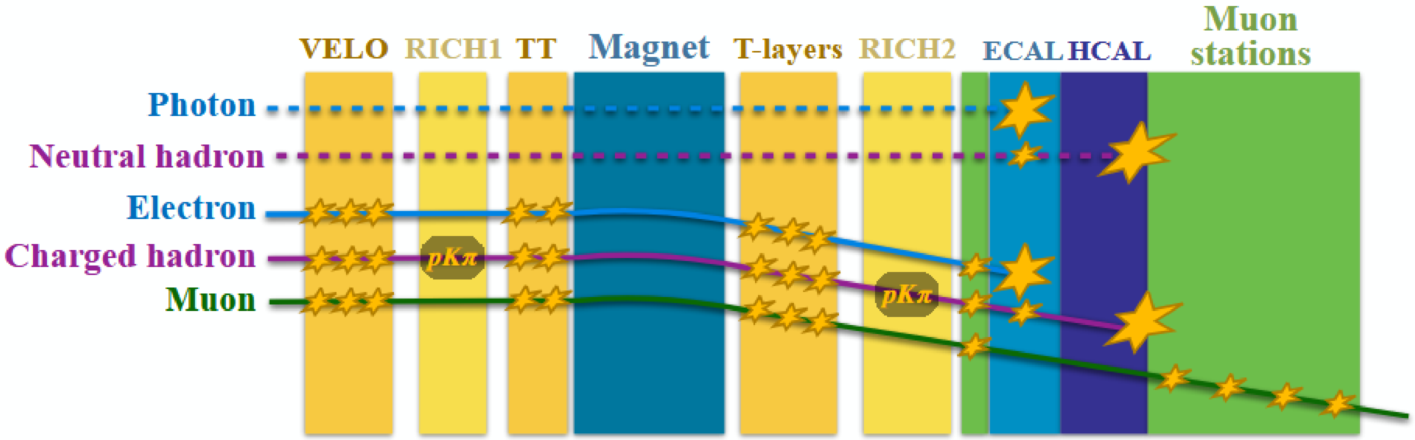


The Detector

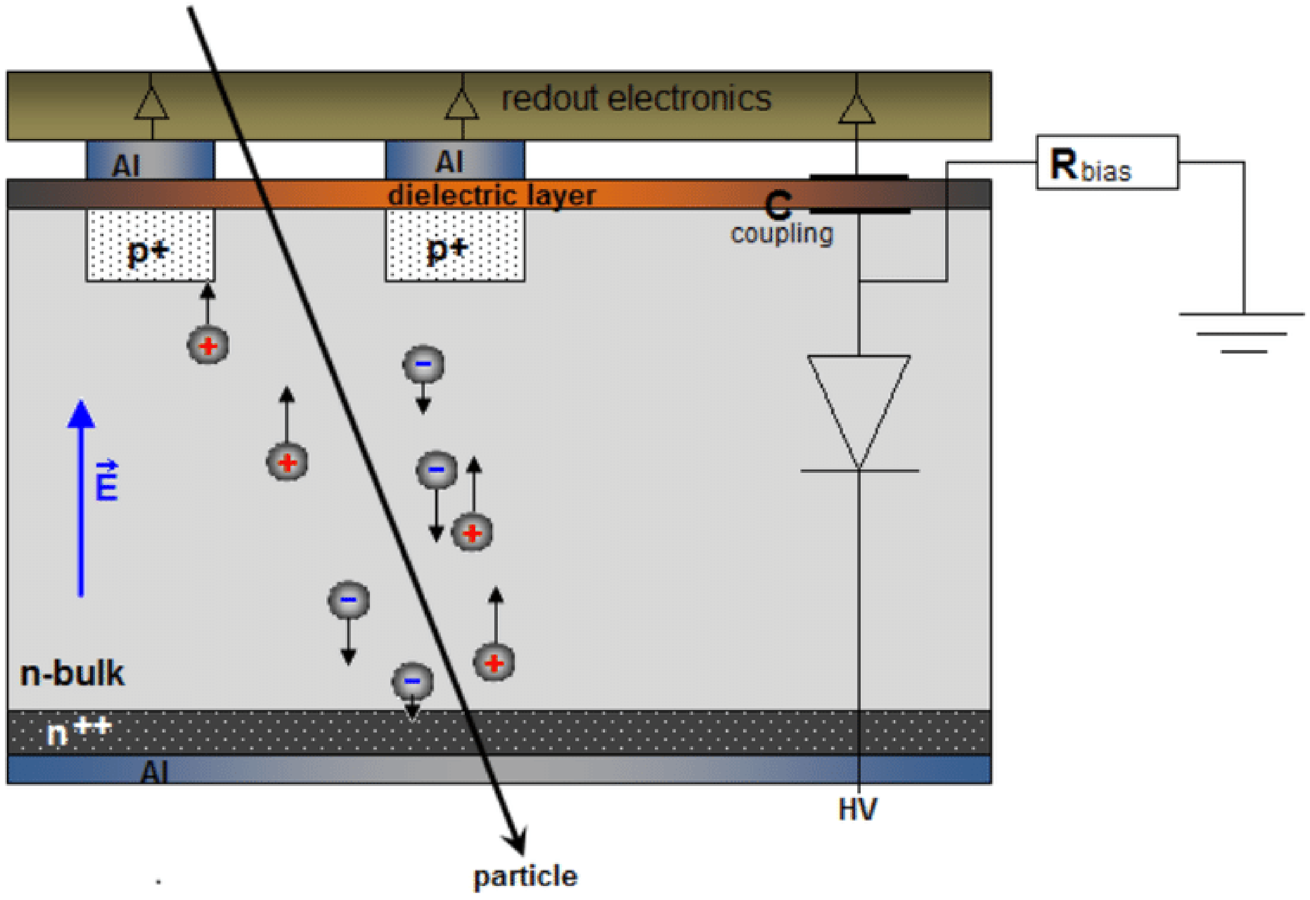
- Bookshelf stack of radiation detectors using different technologies each playing a crucial role to reconstruct the “story” of a collision

- We’ll come back to how they fit together
- For now, lets talk about how we reconstruct *charged particles*





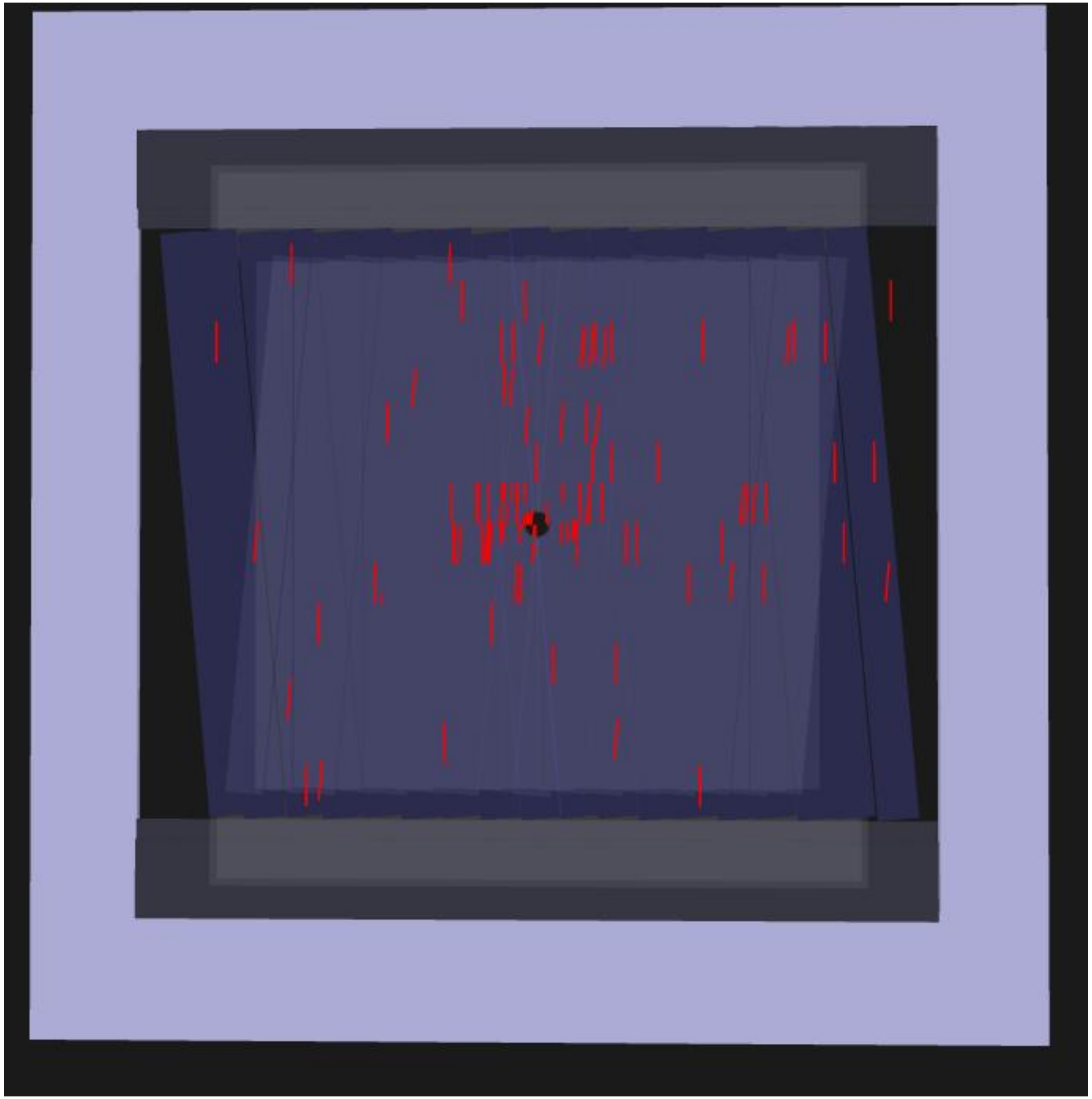
Principles of Radiation Detectors



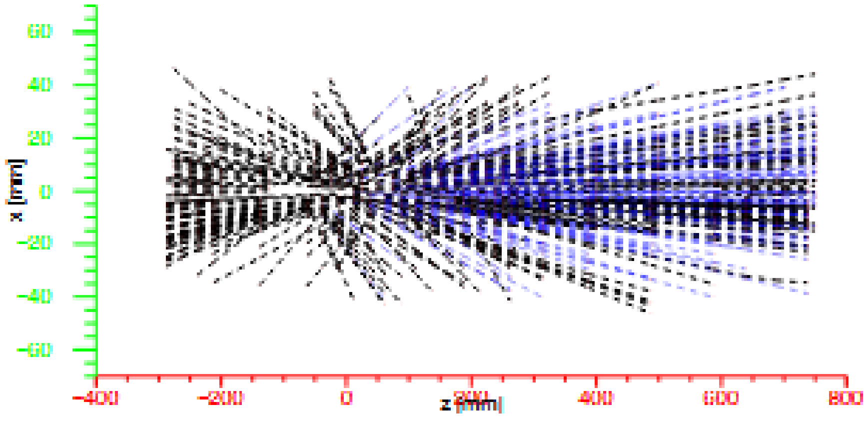
- For charged particles: start with some prepared medium which responds to being ionized, and set up electronics to see that response
- Ex: silicon structure which is essentially a big diode array
- Apply a backwards voltage on the diode
  - At high enough backwards voltage, no free charge carriers in material left to conduct – insulator!
- Particle ionizes the material-> a small amount of current flows! Amplify that signal

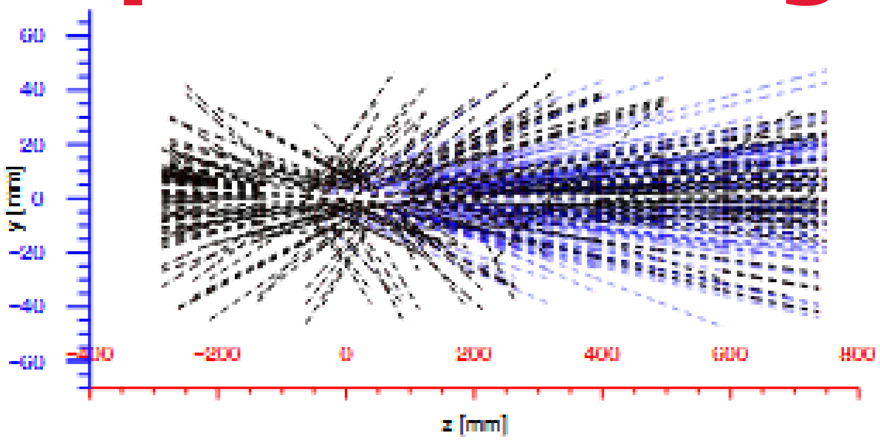
It's a hit!

- When a signal above an expected minimum size is detected, we have a "hit"
- A "hit" tells us that a charged particle moved through this bit of volume on its way out from the collision



Detective Work: “pattern recognition”



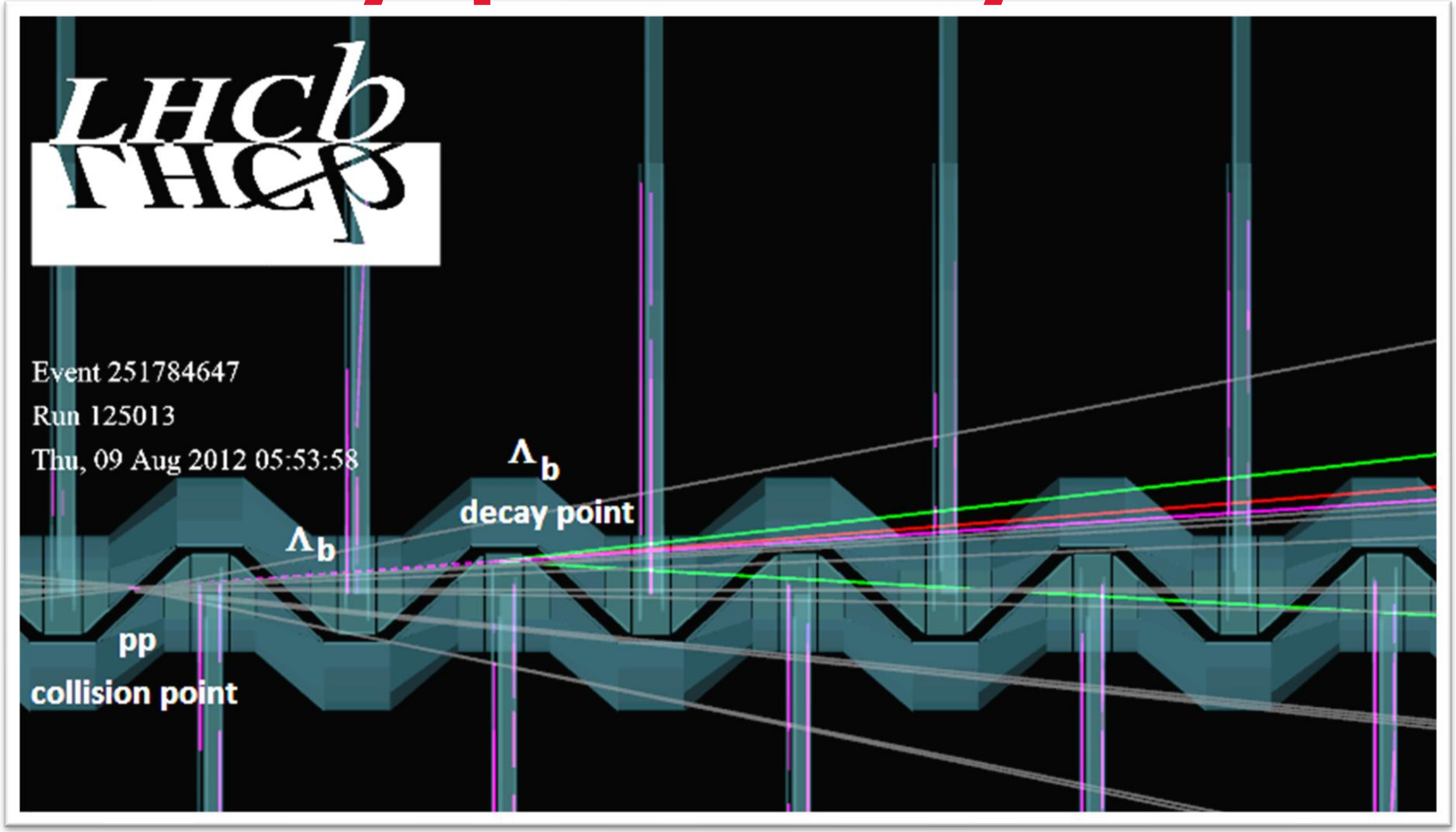


- Images from our detector closest to the collision, the “Pixel VELO” (VErtex Locator)
- Called “Pixel VELO” because the hits indeed correspond to individual X-Y “pixel” volumes
  - As opposed to long, thin strips
- Here the job is quite clear: follow the trail and “connect the dots!”

Looking for heavy quark decays

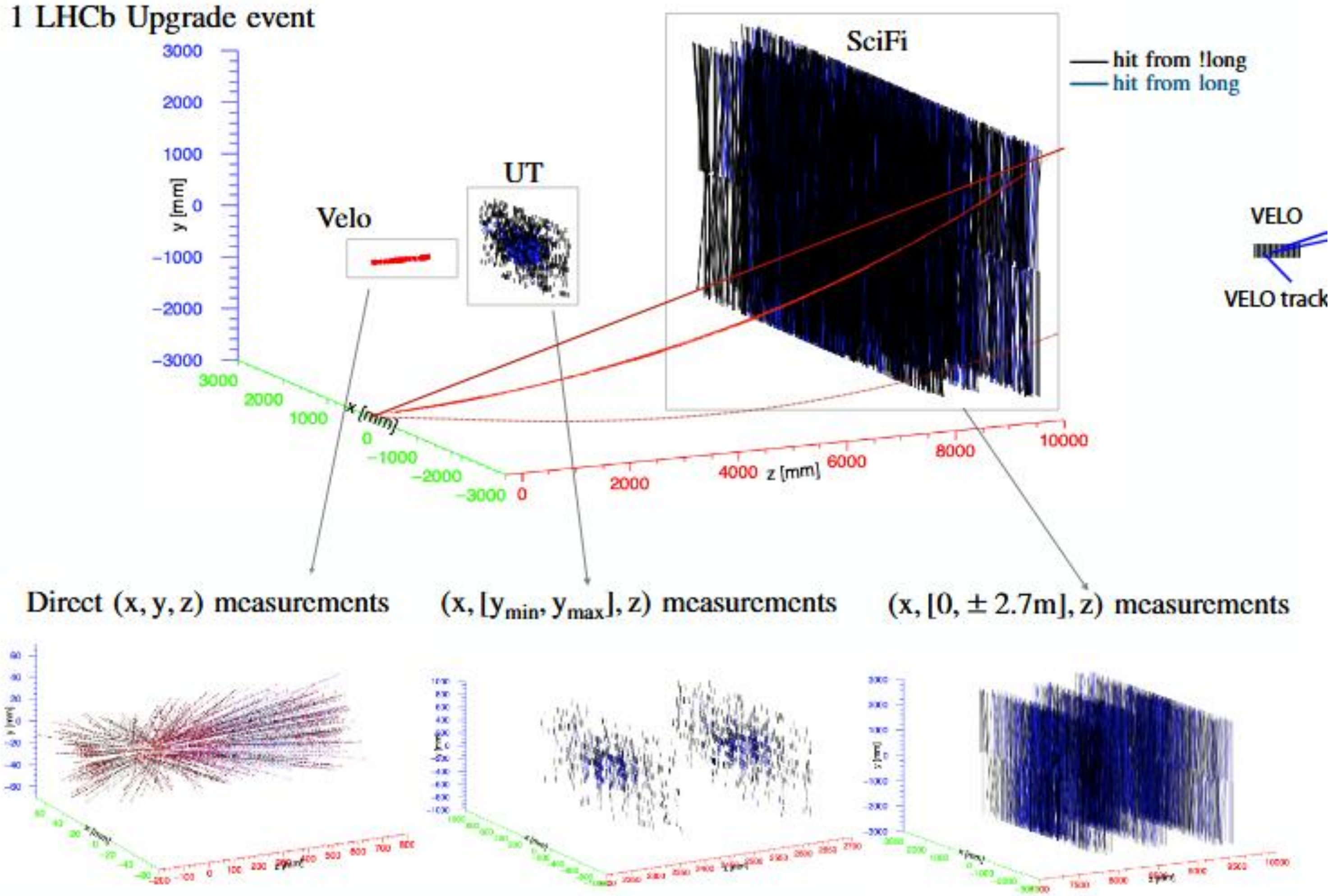
- Most of the "connect the dots" line point to the collision, but some lines will come together mm or cm from the others

- This is the signature of a particle containing a heavy quark – a "displaced vertex"
    - vertex in the sense of "where two or more trajectories meet"



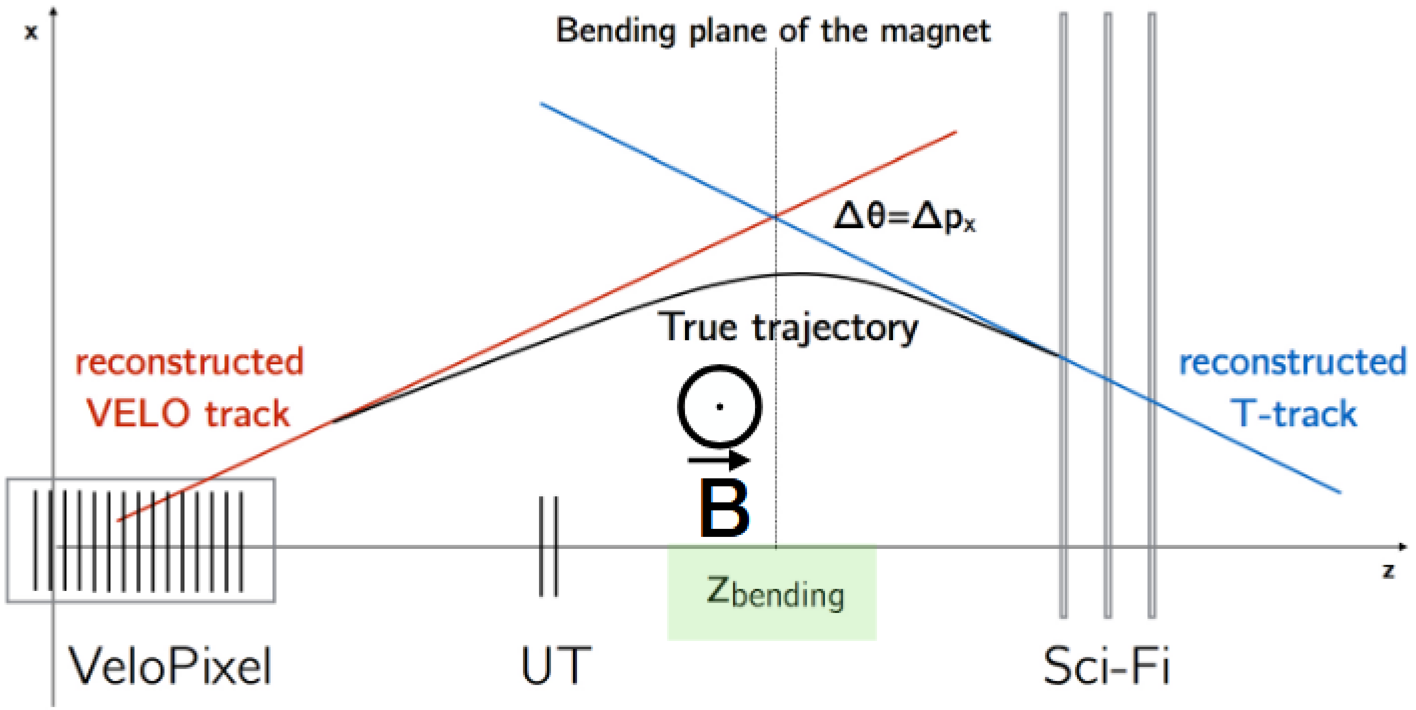
Combine information to tell the whole story

- Different detector technologies with different kinds of “hits” in different places all working together!



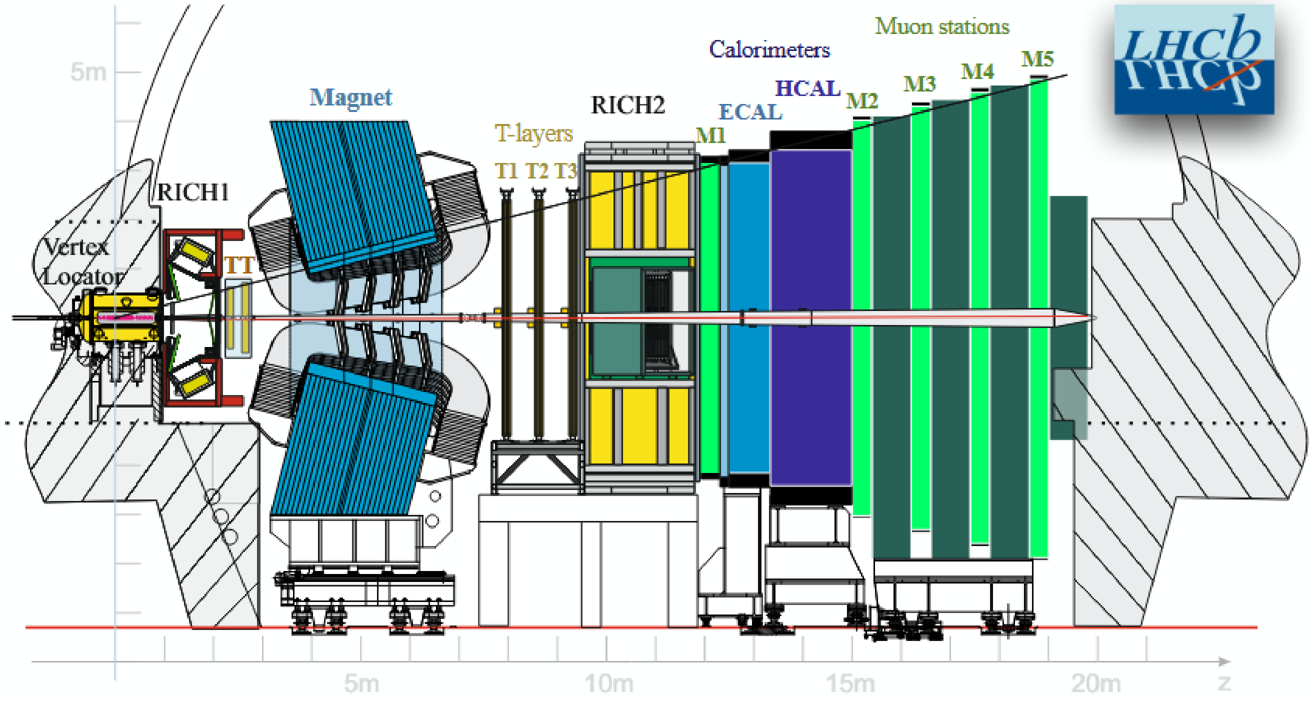
The Magnet

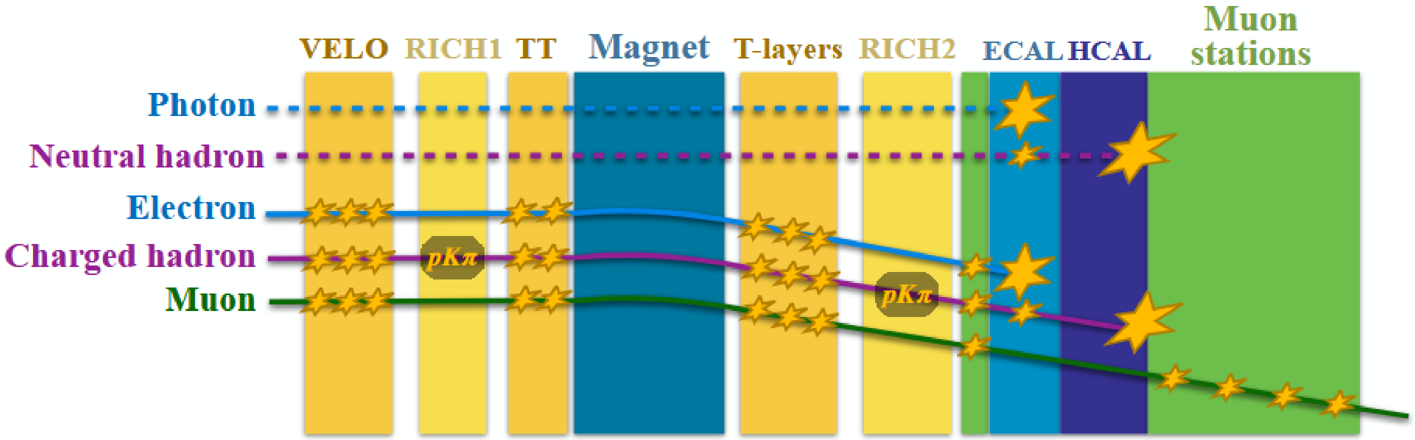
- It's not enough to follow straight lines, we need to know about the energy and momentum of these particles so we can use relativity to work backwards from the pieces
- LHCb's Magnet bends particles according to the sign of their charge and their momentum
  - $\Delta slope \sim q/p$
  - "Magnetic dipole spectrometer"



Whodunnit?

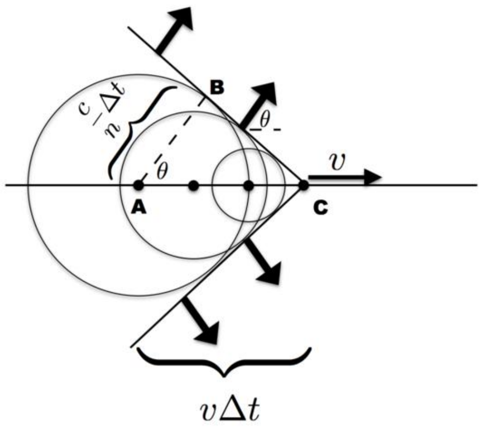
- Different kinds of charged particles are identified according to which other detectors they interact with
  - Electrons will be stopped by the electromagnetic calorimeter
  - Muons will pass through all the material in their way
  - Charged hadrons (protons and light mesons) look alike in their interaction with the detector



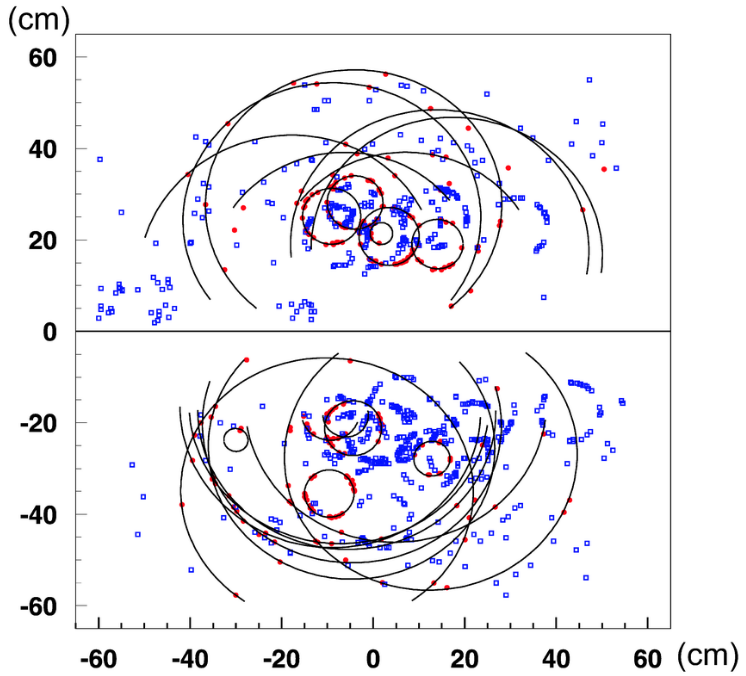


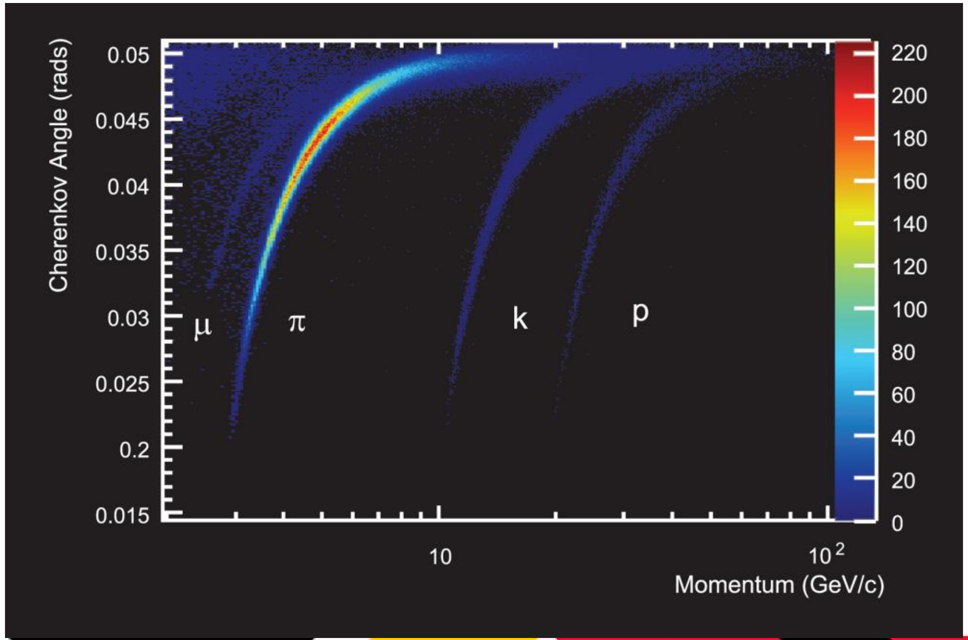
Whodunnit?

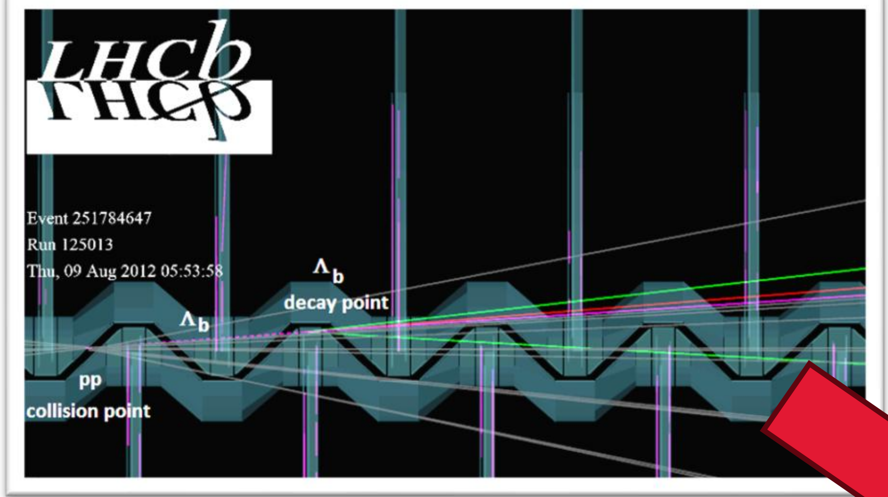
- Different kinds of charged hadrons can be sorted by specialized detectors which use Cherenkov light to measure c/v
  - Know momentum p, Cherenkov light estimates v, can decide which m is most consistent!



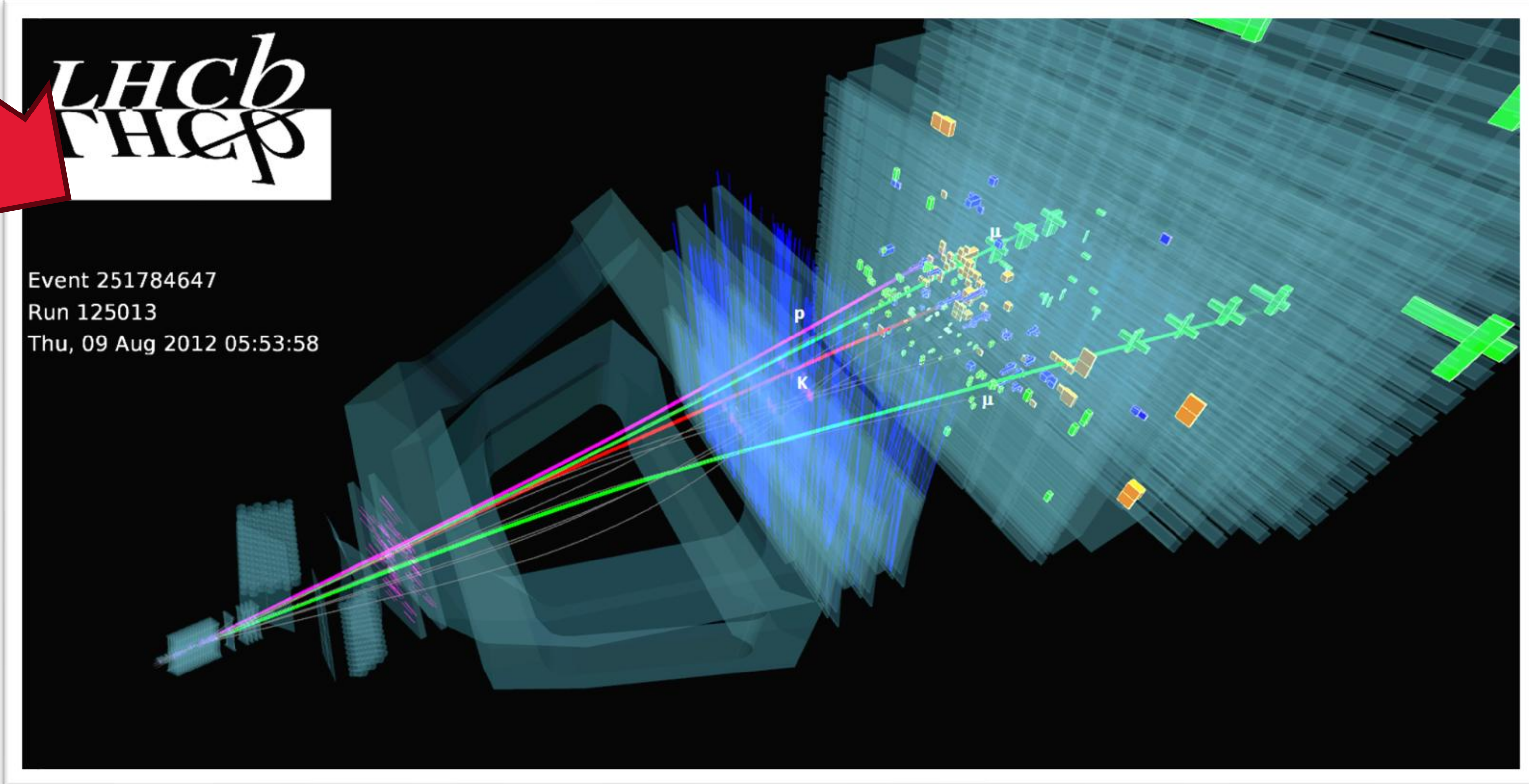
$$n \cos\theta = \frac{c}{v}$$







Who's gonna dig through this mess?



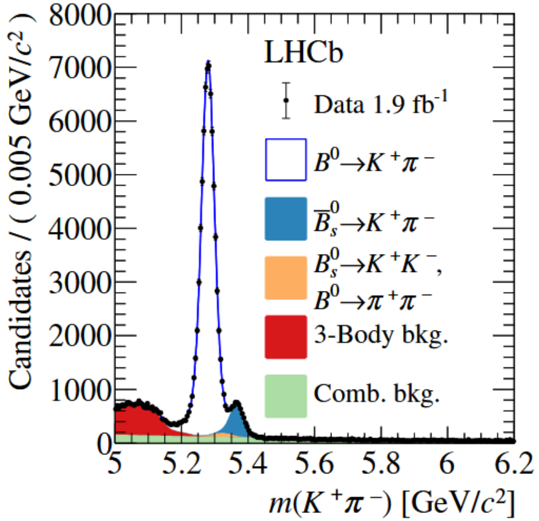
- Specialized algorithms search reconstructed events for combinations of particles consistent with the desired decay pattern the user asks for and "combine" them to find the location of a possible decay and the energy and momentum of the particle before decaying (conservation!)

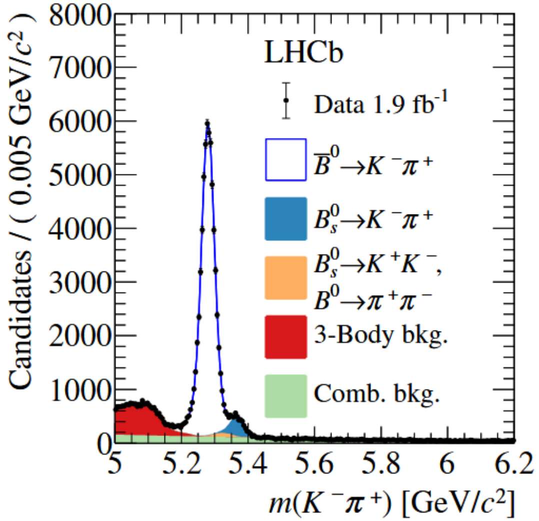
- You'll get the chance to do this search for yourself tomorrow!

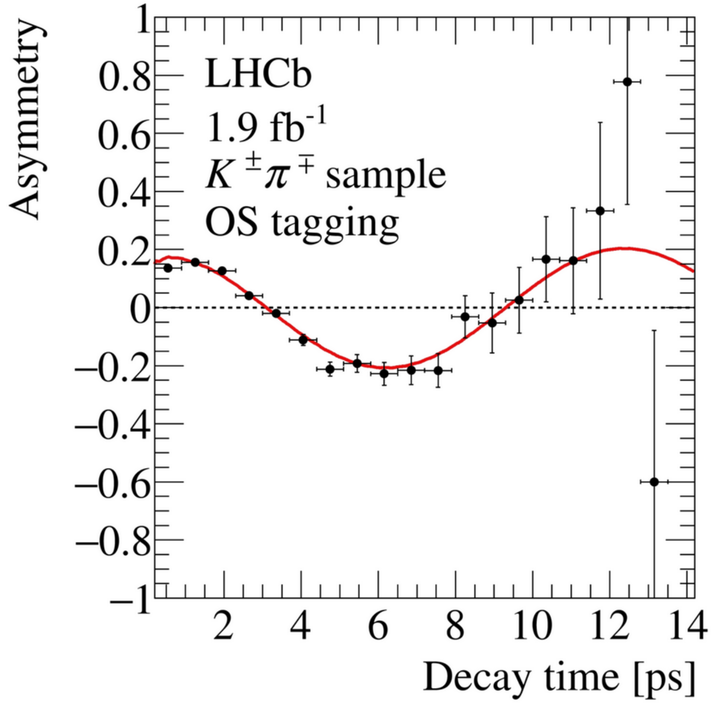
Data written out to “tuple” (big table)

Row	Kplus_PE	Kplus_PX	Kplus_PY	Kplus_PZ	muplus_PE	muplus_PX	muplus_PY	muplus_PZ
0	20793.111	-3460.695	-2111.169	20388.142	13734.393	-2661.61	-569.06	13461.59
1	30792.753	1041.2073	1440.1424	30737.466	73304.547	2426.39	3052.15	73200.7
2	39558.490	3041.4617	-566.4382	39434.237	8213.3875	1398.72	1305.61	7986.71
3	29966.491	511.78266	-2043.155	29888.300	68701.031	3018.09	-1191.57	68624.28
4	11780.331	-429.2007	1033.5191	11716.659	34419.558	-2139.35	547.06	34348.49
5	106940.46	2243.9405	2099.7302	106895.15	17450.839	169.29	742.14	17433.91
6	38748.784	2986.2447	1575.0738	38598.265	18785.714	1354.84	-509.05	18729.58
7	44742.961	3481.7164	744.74321	44598.339	20978.266	3656.19	475.35	20651.46
8	37785.167	-2457.935	2016.3177	37647.950	24718.865	-1045.94	791.63	24683.81
9	28193.227	-862.3066	1727.6479	28122.695	60727.573	982.14	1952.44	60688.14
10	33983.423	36.733953	1955.3788	33923.509	22208.994	-577.05	2047.92	22106.59
11	83581.343	2041.3978	-1813.895	83535.260	25717.256	468.68	-992.93	25693.59
12	23329.205	-2102.449	516.56757	23223.285	9150.4168	-955.24	1171.29	9024.11
13	58110.384	-3703.198	2179.7841	57949.184	13490.897	-2392.02	-204.38	13275.15
14	22328.904	357.85283	1352.1422	22279.585	4354.8866	-102.68	857.68	4267.05
15	25843.393	-1137.769	1423.6157	25774.329	26839.854	-2072.82	93.86	26759.32
16	13460.131	697.15159	923.9441	13401.183	17656.254	173.23	1215.75	17613.18
17	13523.188	-312.9163	2021.2027	13358.508	23117.745	90.08	2375.05	22995
18	30315.084	699.72915	3717.6999	30074.070	40753.629	2274.22	4014.87	40491.43

And the sausage is made







- The statistical signature of particle decays is accumulation of data at certain values of key variables like the "invariant mass" (more from Prof Franco Sevilla on that!)
- We employ a variety of statistical techniques and both classical and machine learning algorithms to extract features and parameter estimates from the data – always pushing for maximum robustness, especially with machine learning
  - It can be surprisingly easy sometimes to accidently mislead yourself or bias your measurement!

That’s all for now!

- We hope you have a great, educational time here over the next two days!