Intro to LHCb

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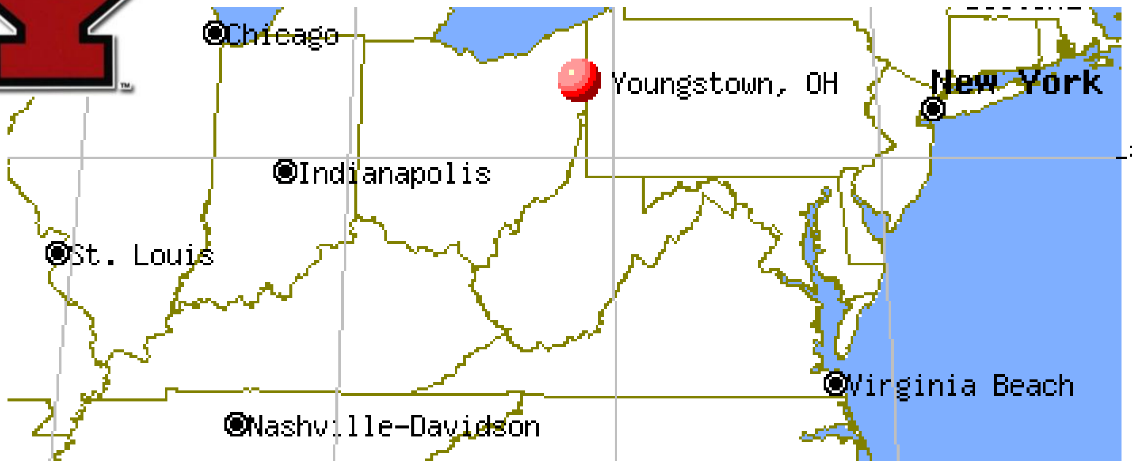
DEPARTMENT OF PHYSICS

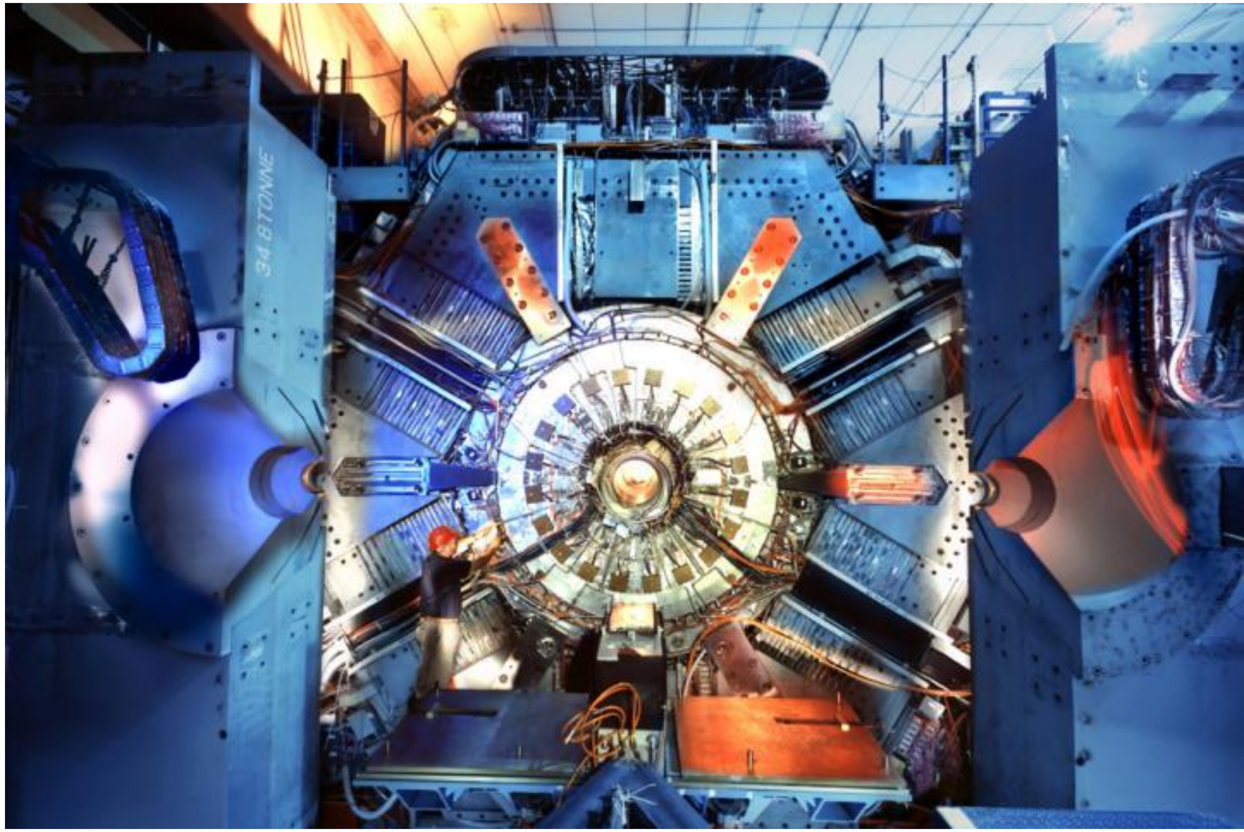
About me

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



About me

- 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

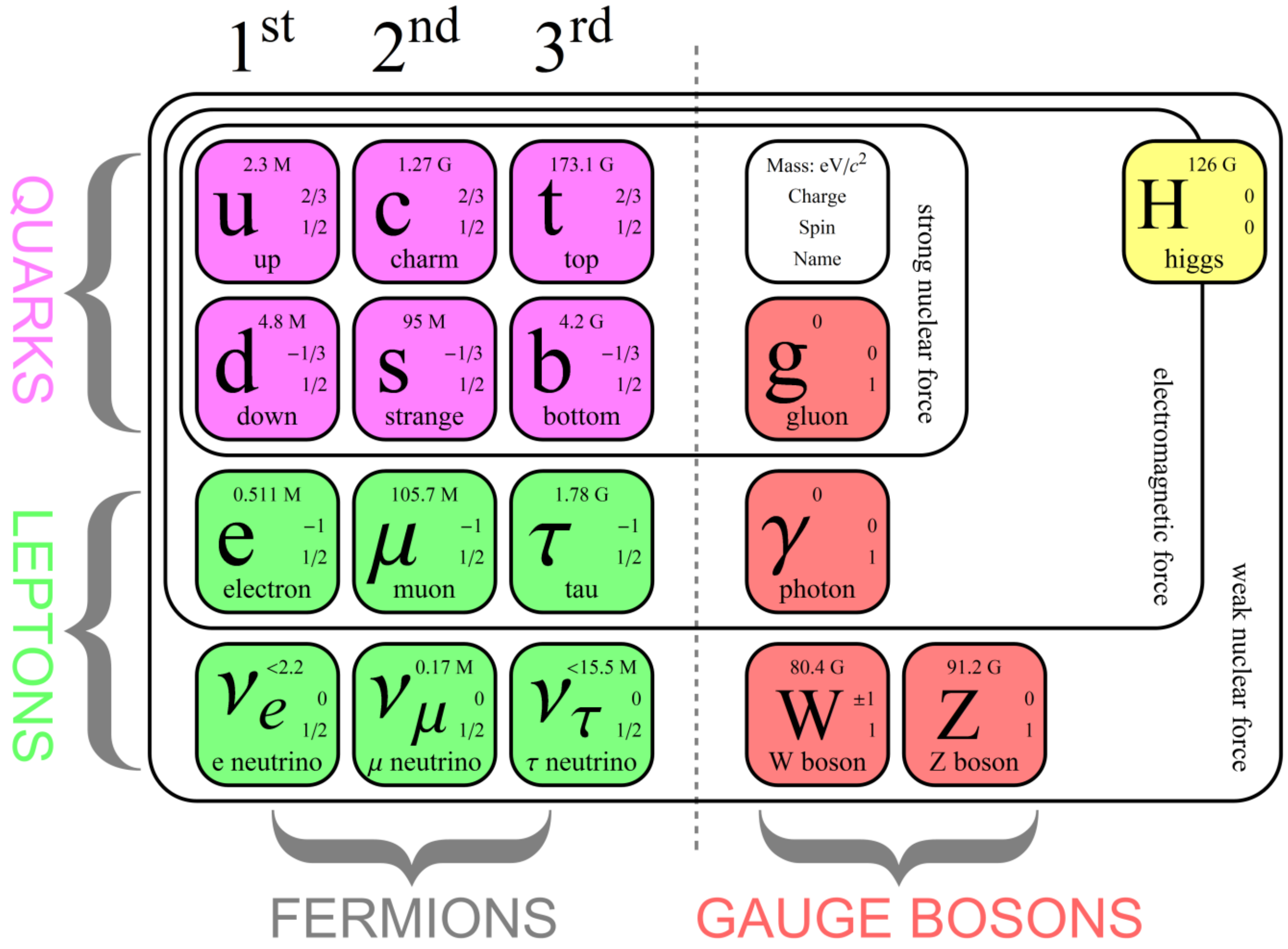


About me

- PostDoc at UMD as group switched to LHCb
  - First followup to BaBar Colleagues' hint of Lepton Flavor Universality violation and first measurement of $\bar{B} \rightarrow X_c \tau \bar{\nu}$ at a hadron collider.
  - Developed new ways of doing analysis, including for "1-track+neutral" B decays

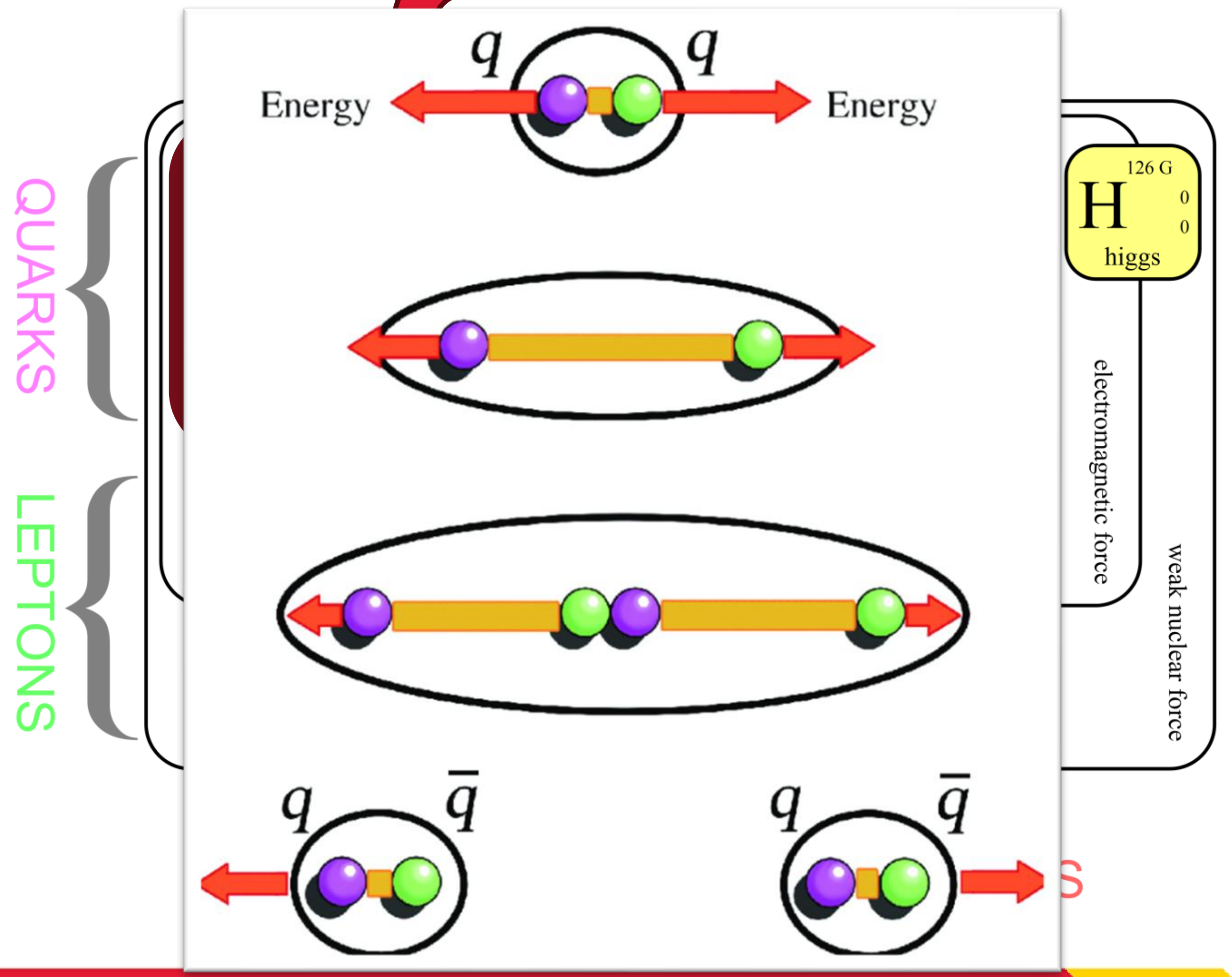
- Assistant professor here since '23

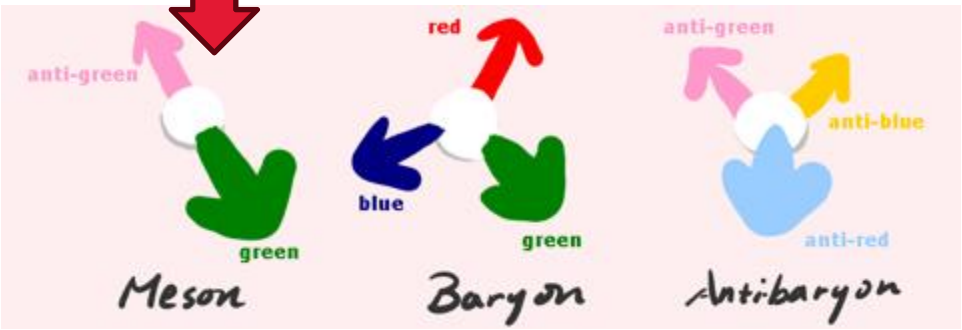
The “Zoo” of Particle Physics



- 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



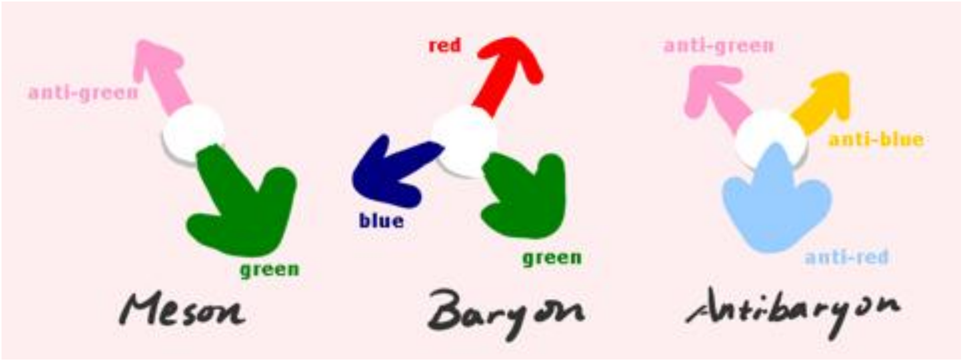


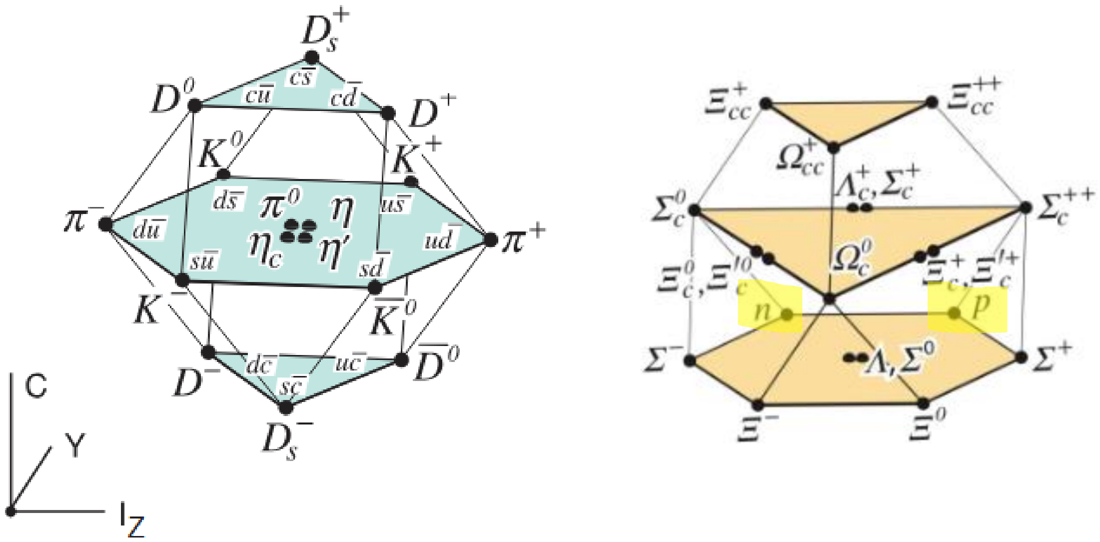
- Of note, the strong force is so strong that the energy stored in the field of a color dipole grows enormously quickly with distance, eventually far exceeding $2mc^2$ needed to create more quarks and short out the dipole
  - Quarks eventually bind themselves into "colorless" hadrons
  - Like how atoms 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!
  - The lightest of these are stable under the strong and electromagnetic forces but decay weakly, giving them (relatively) longer lifetimes





Some quick nomenclature for the meson zoo

- $B \rightarrow$ heavy-light, contains a b quark

- $D \rightarrow$ heavy-light, contains a c quark
  - $D_s^+ \rightarrow$ heavy-light, contains a c quark and an s quark

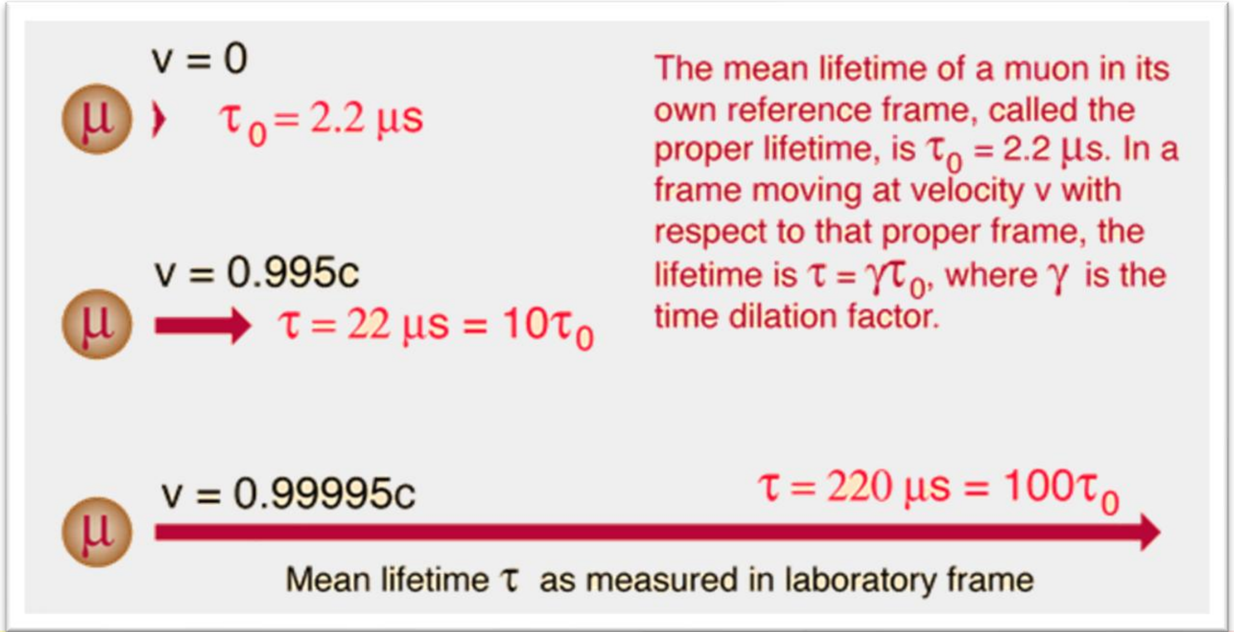
- $K \rightarrow$ light-light, contains a s quark
  - long-lived

- $\pi \rightarrow$ light-light, contains only light quarks u and d
  - long-lived

Lifetimes

- Recall: the lifetime is related to the (uniform!) probability per little dt that the particle decays within that dt of time
- 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, that's because it is, except for a factor of ln(2) ☺
- Anyway, how do we measure such short lifetimes?
  - The secret sauce is time dilation! This mean lifetime is a clock, and we know all moving clocks move slow with respect to us
- 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



What do we actually see?

- Even with time dilation, some of these guys *do not* live long enough to be directly spotted with our detector
- Roughly only those guys with $c\tau \gtrsim 1\, m$ or so will move through our detectors. That leaves just a handful of guys we actually "see": $p, e^-, \mu^-, \pi^+, K^+$ plus photons (gamma rays)
    - To study the shorter-lived particles, we build up combinations of the longer lived products, working backwards up the tree
        - This can be very simple 1->2 or very complicated like the figure!
        - **Let's talk experiment first then come back to this**

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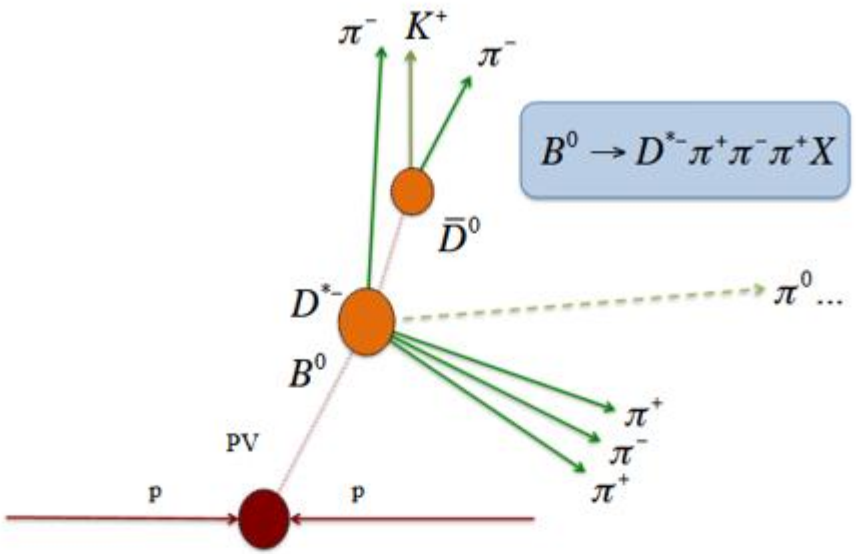
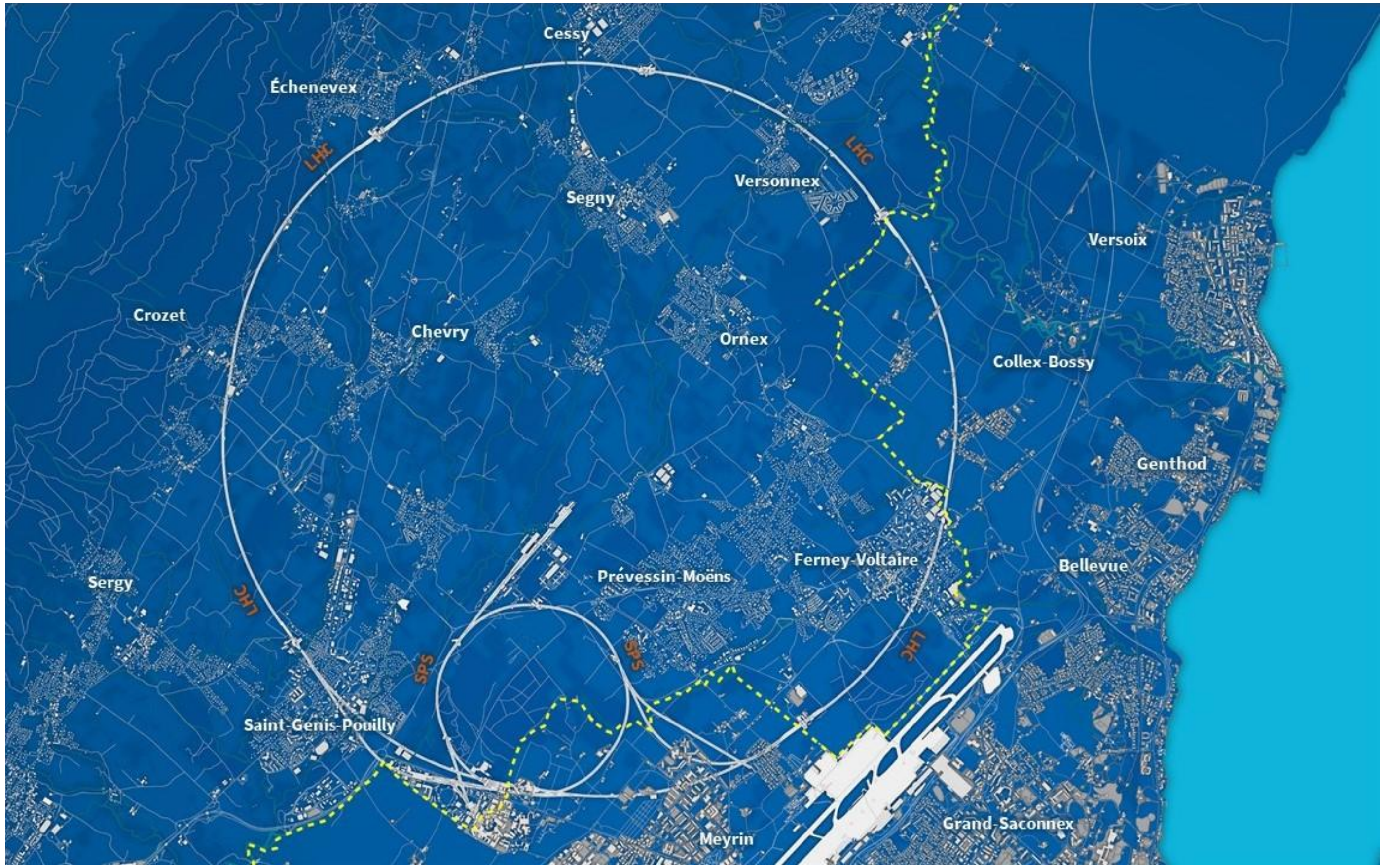
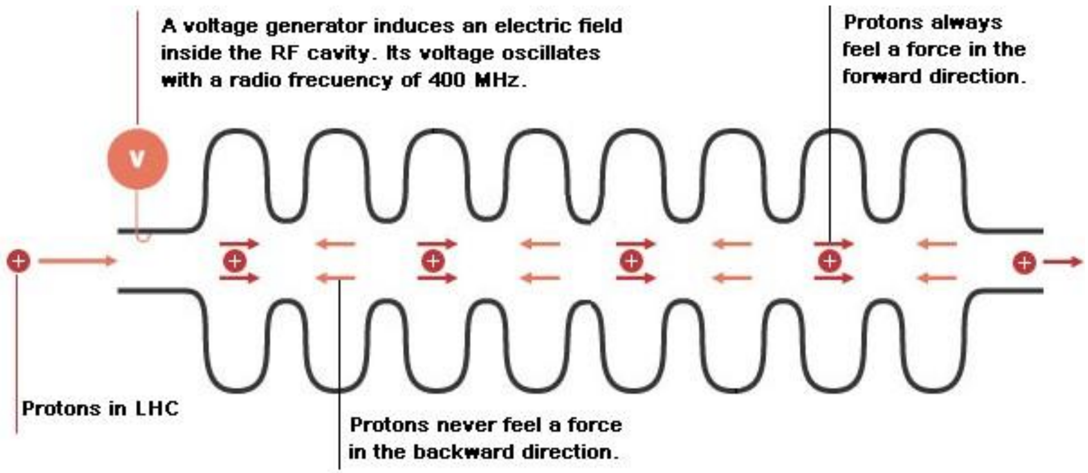


CERN's Large Hadron Collider (LHC)

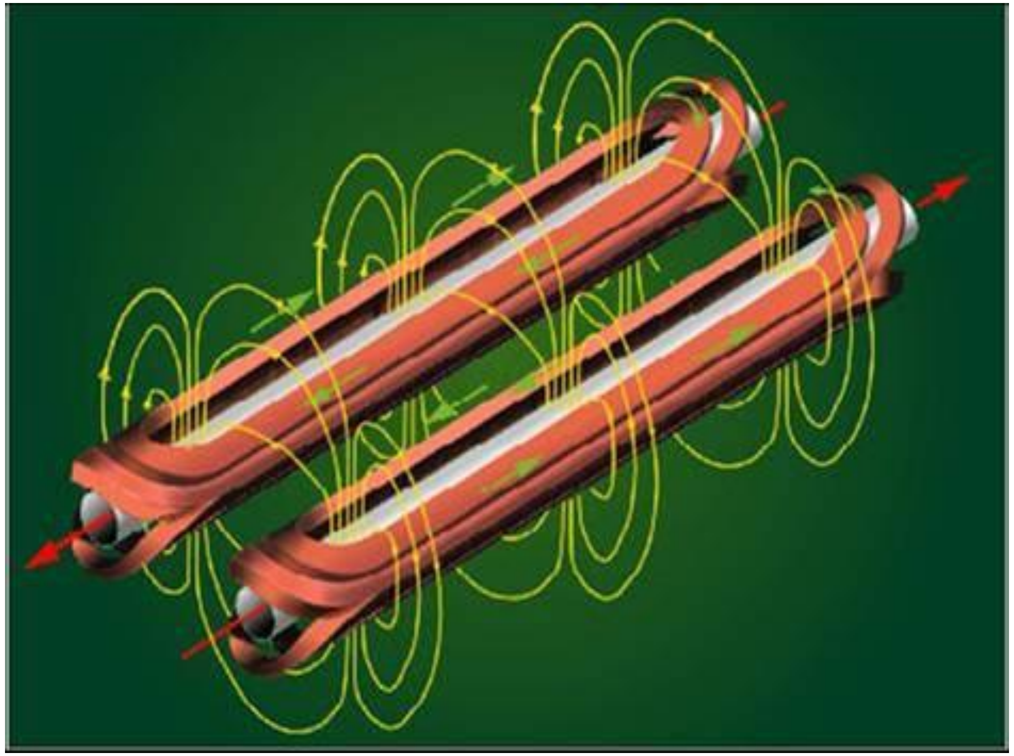


A Complex Machine of Simple Principles



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

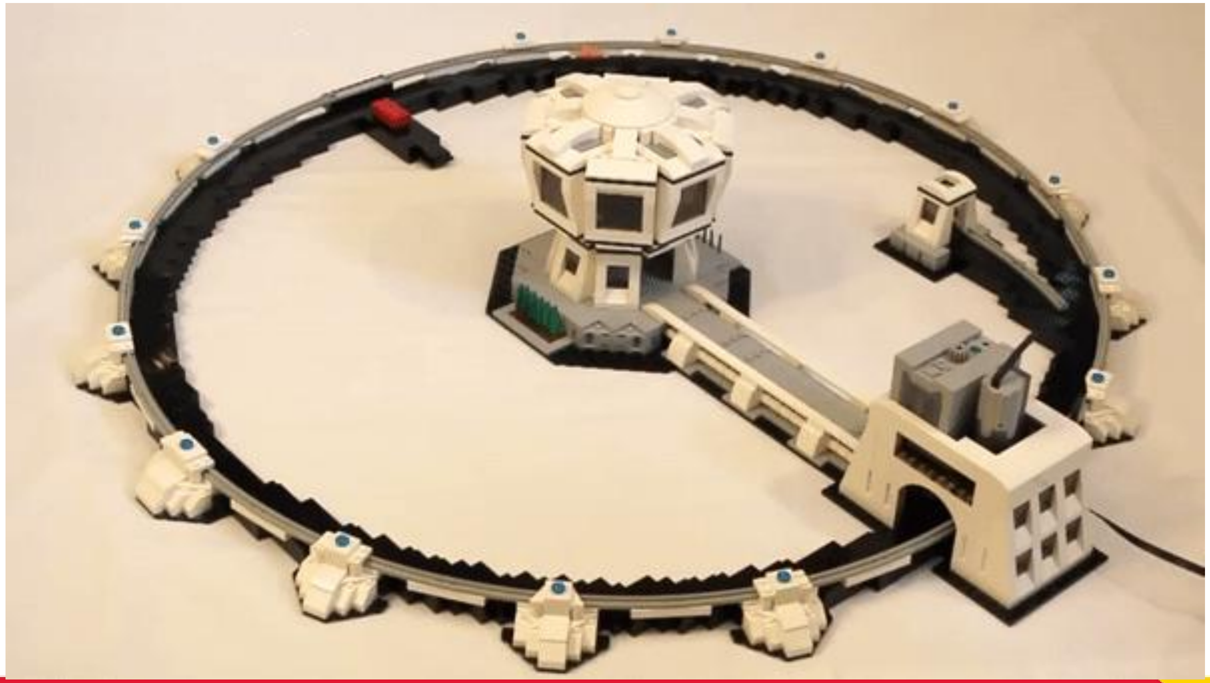
(note, because a wave is involved, this means the beam <u>can’t</u> be continuous, contrary to what the word “beam” might evoke – it is pulsed or “bunched”)

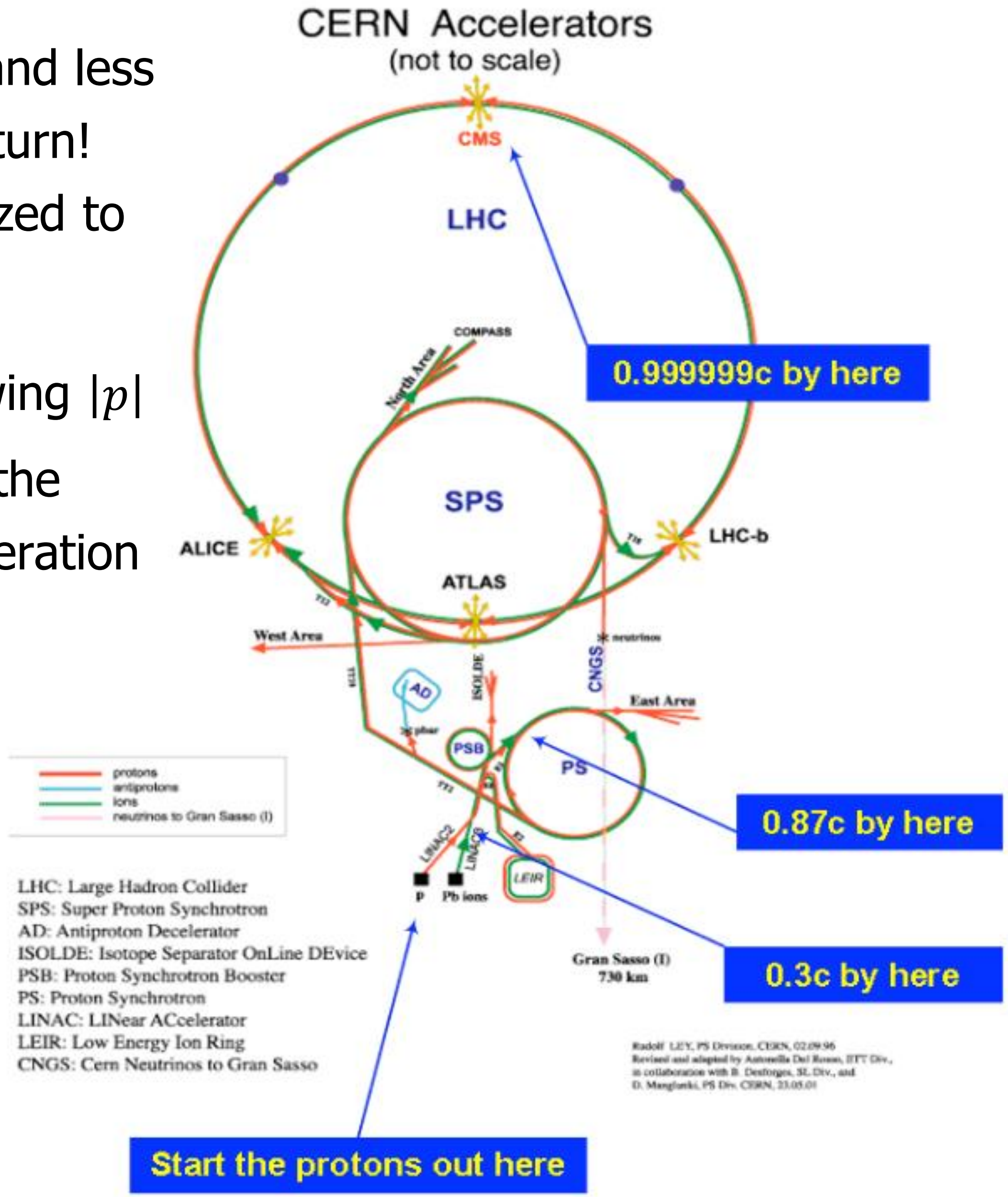


Beam is steered and shaped using $\vec{F} = q\vec{v} \times \vec{B}$

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

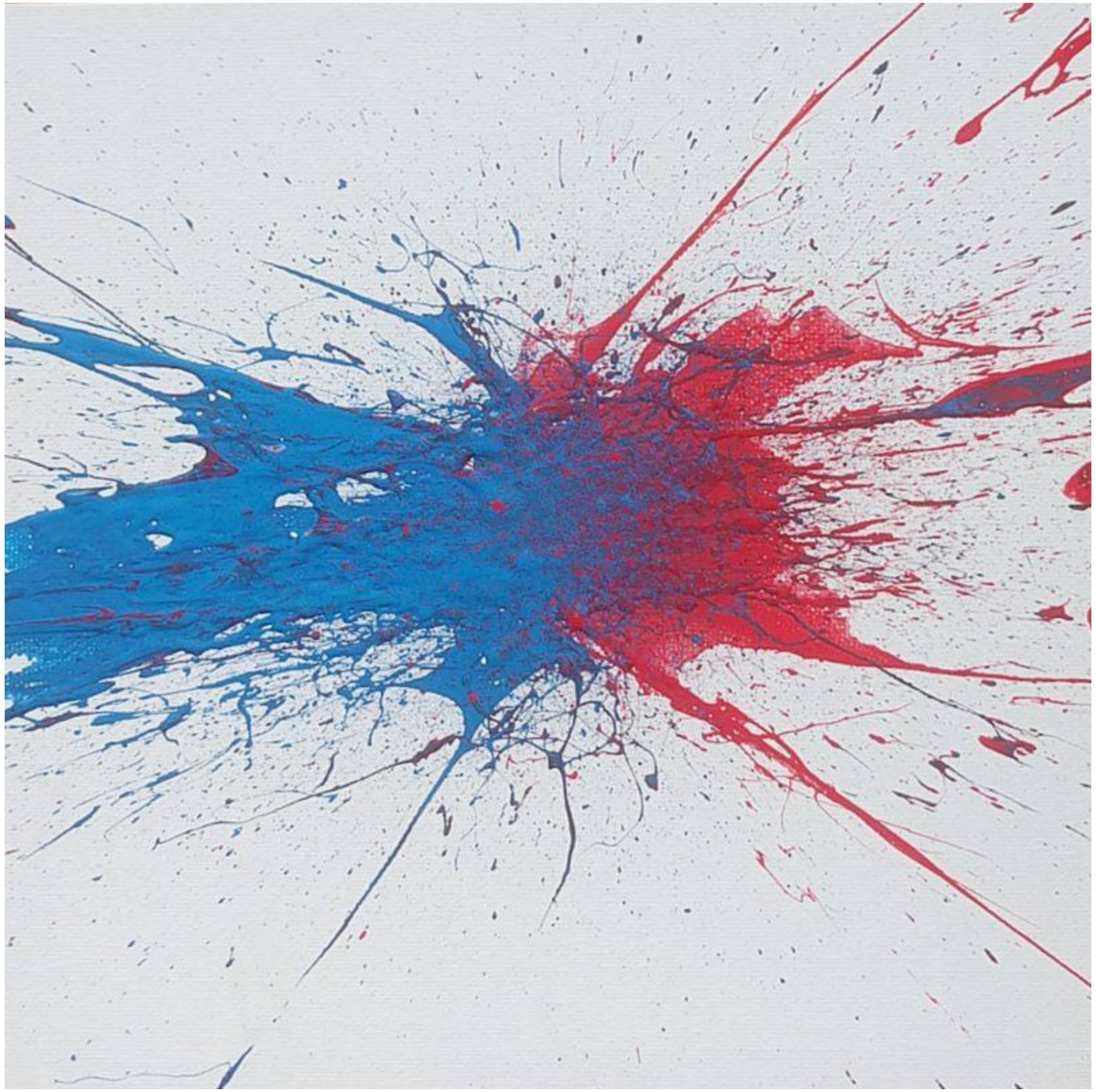
- Each trip builds energy, and the magnetic forces do less and less to actually turn the path, they have to get stronger each turn! ("Synchrotron" because the magnetic fields are synchronized to the beam energy)
    - Relativistically, $\vec{F} = \frac{d\vec{p}}{dt} \neq m\vec{a}$ and $\frac{d\vec{p}}{|p|}$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



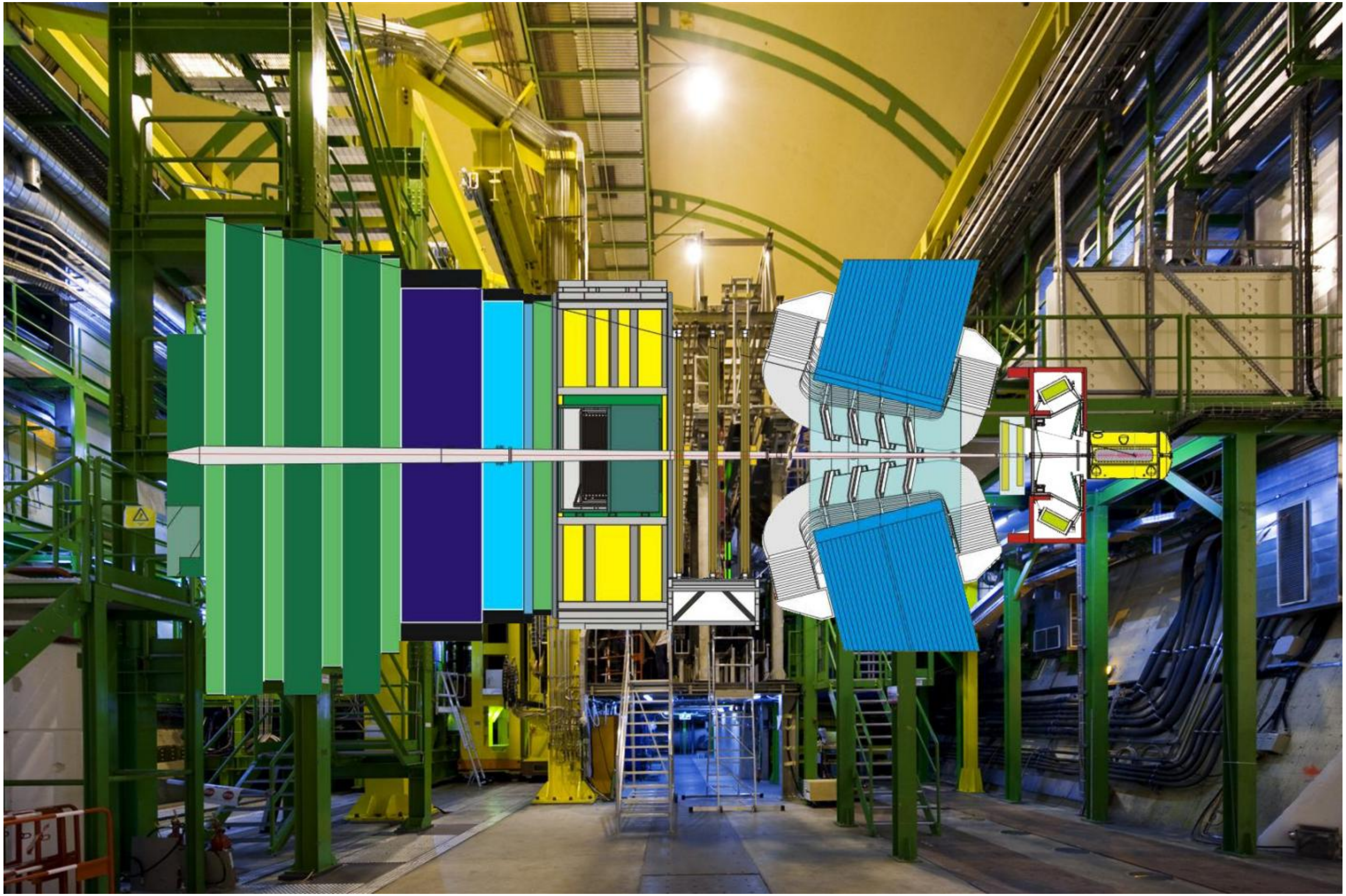


Collisions

- 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



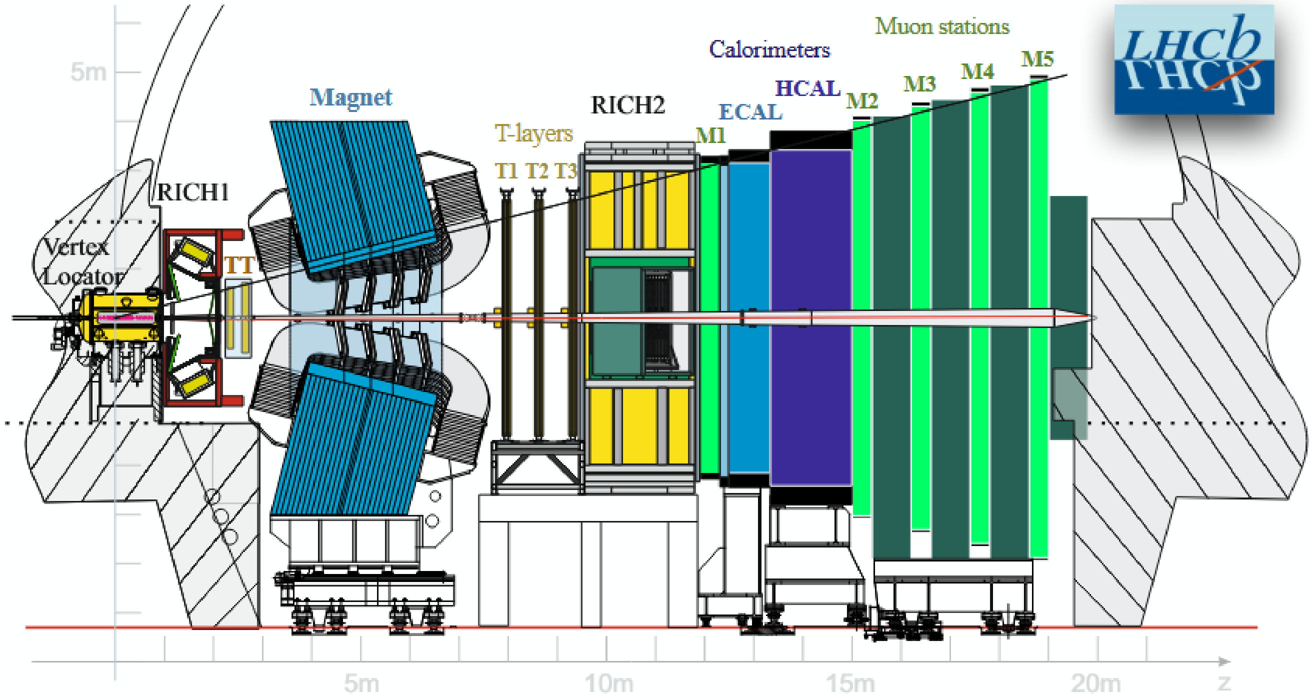
“Colliding Colour: Collision #7” by Sascha Mehlhase

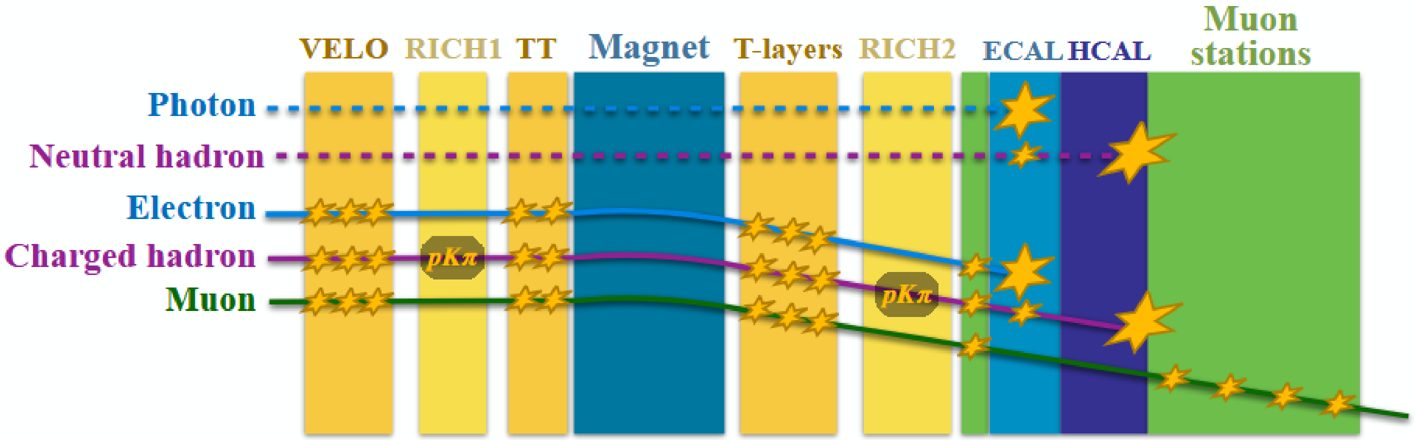


The Detector

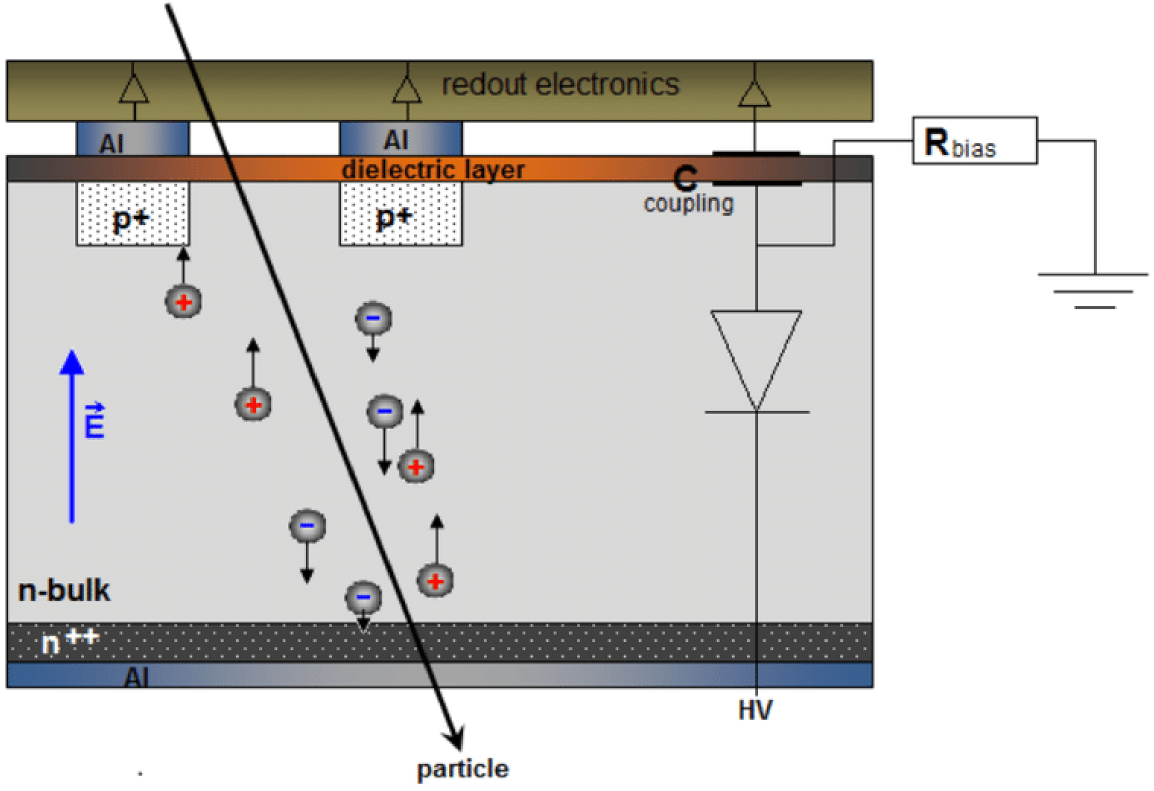
- Bookshelf stack of radiation detectors using different technologies each playing a crucial role to reconstruct the "story" of a collision

- 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
  - If the signal is large enough w.r.t. noise, it's a "hit"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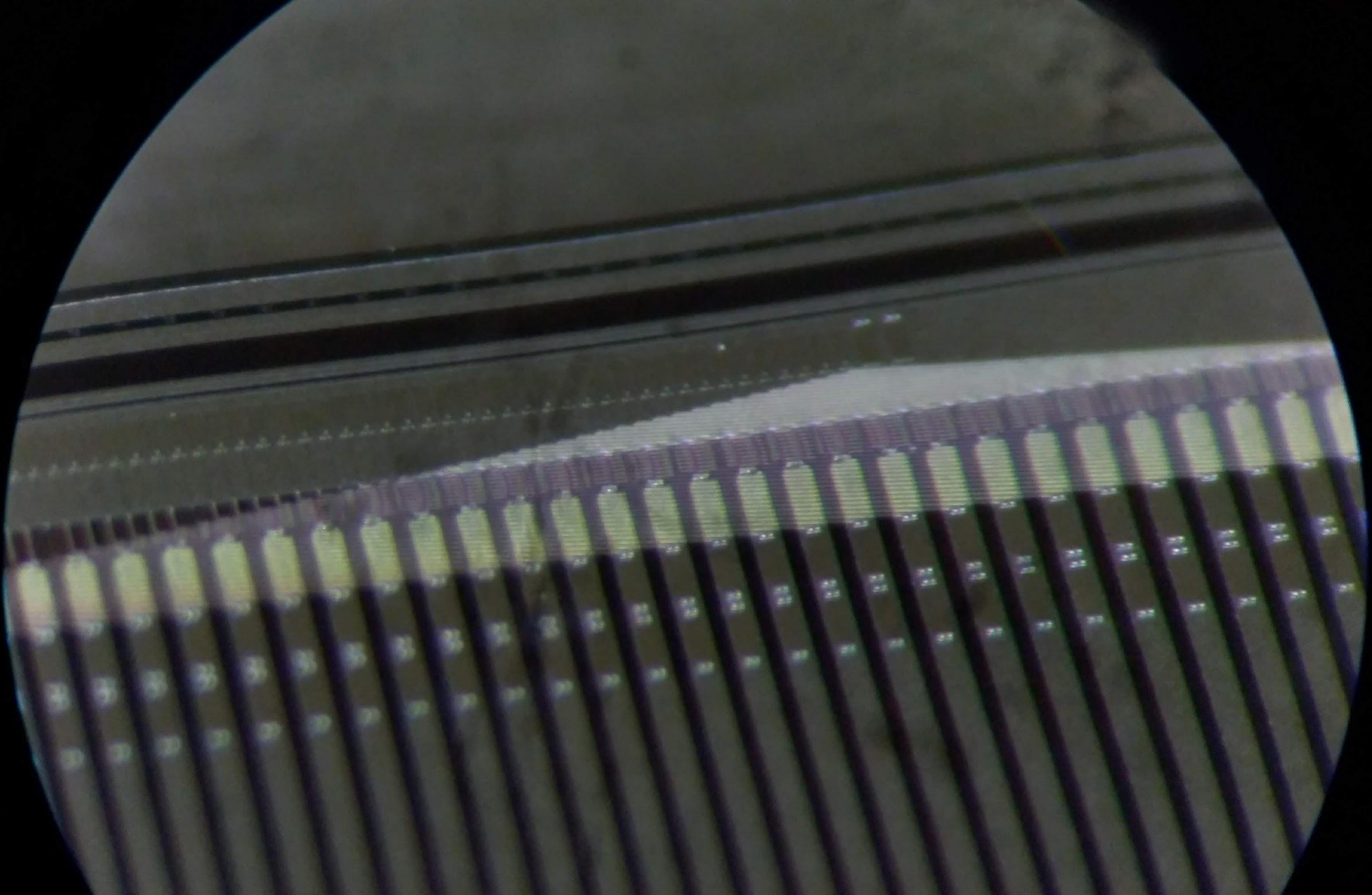
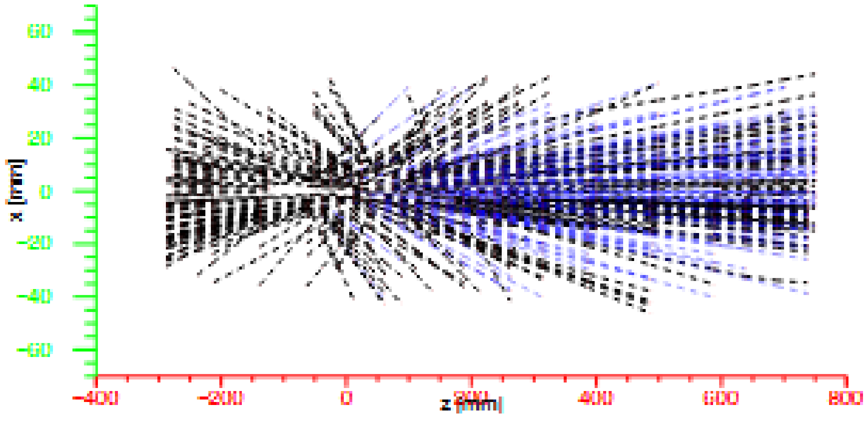
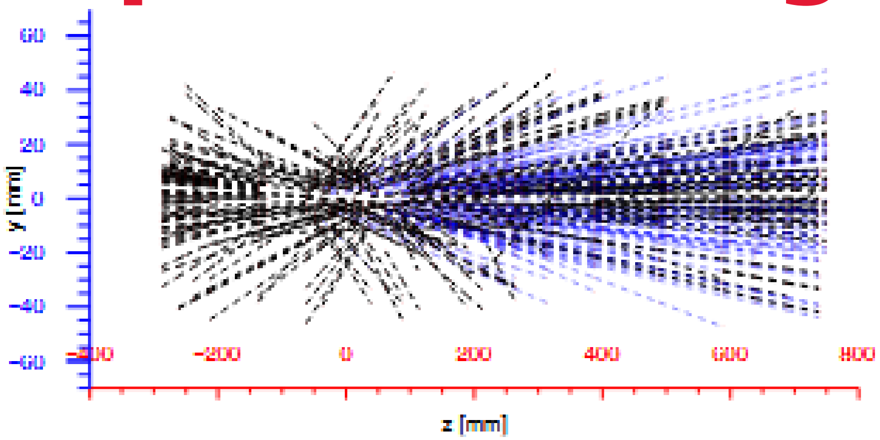


Detective Work: “pattern recognition”



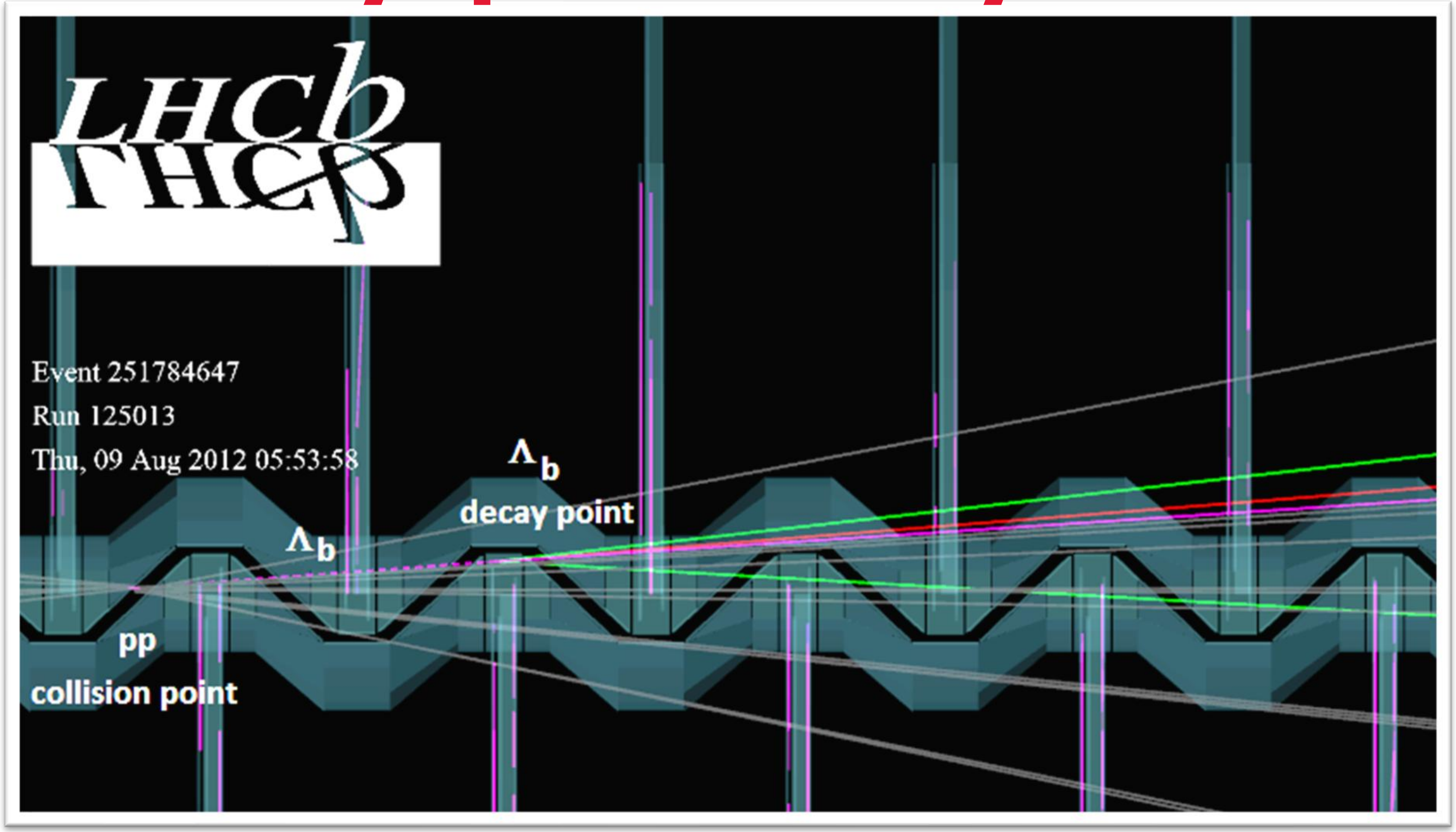


- Images from our detector closest to the collision, the “Pixel VELO” (VErtex Locator)
- Called “Pixel VELO” because the hits indeed correspond to individual X-Y “pixel” volumes
  - As opposed to long, thin strips
- Here the job is quite clear: follow the trail and “connect the dots!”

Looking for heavy quark decays

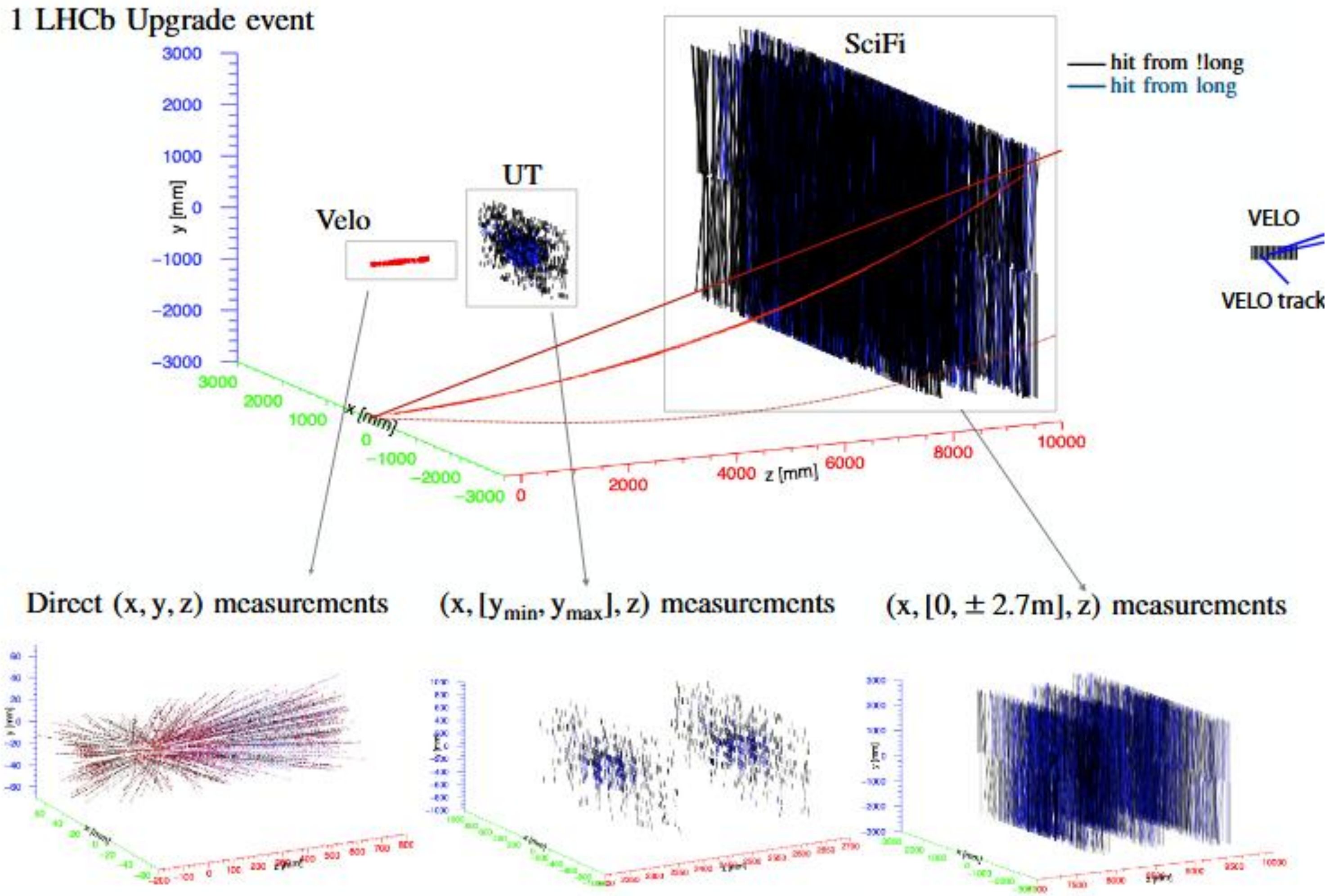
- Most of the “connect the dots” line point to the collision, but some lines will come together mm or cm from the others

- 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”



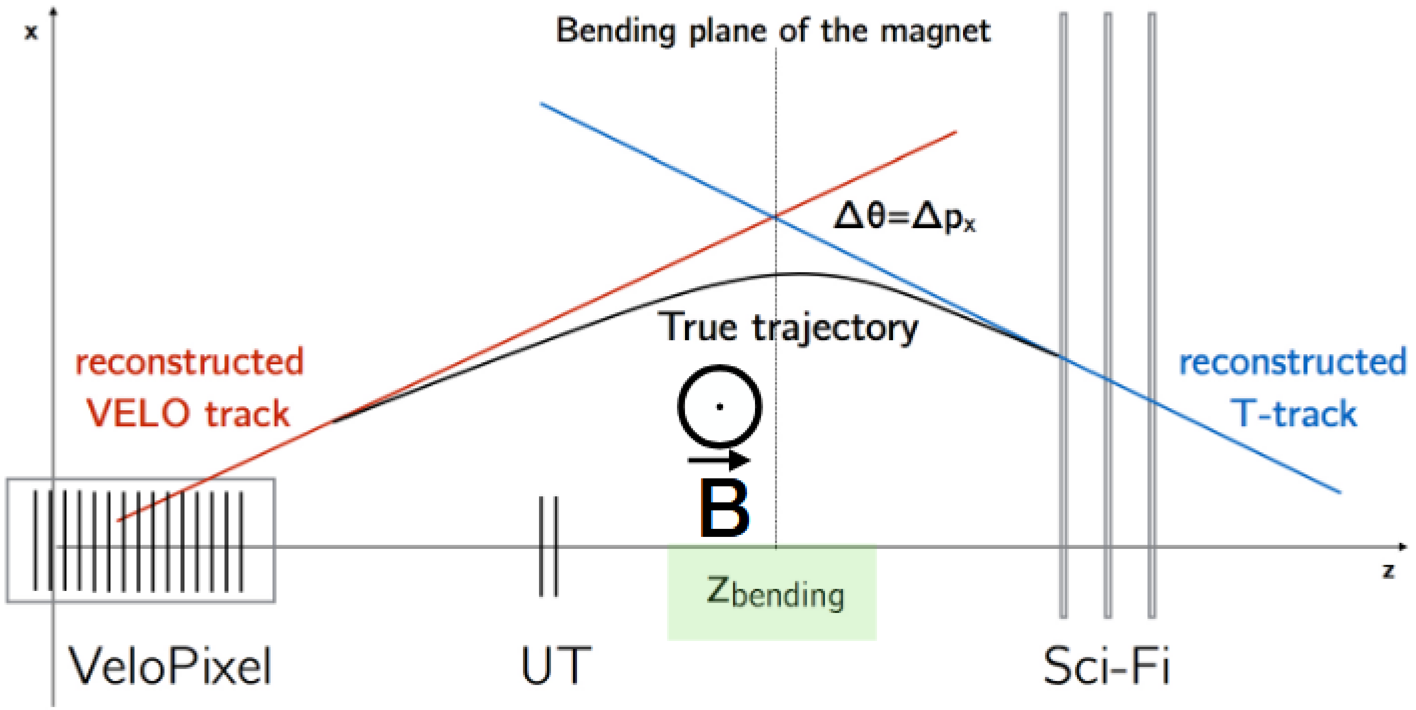
Combine information to tell the whole story

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



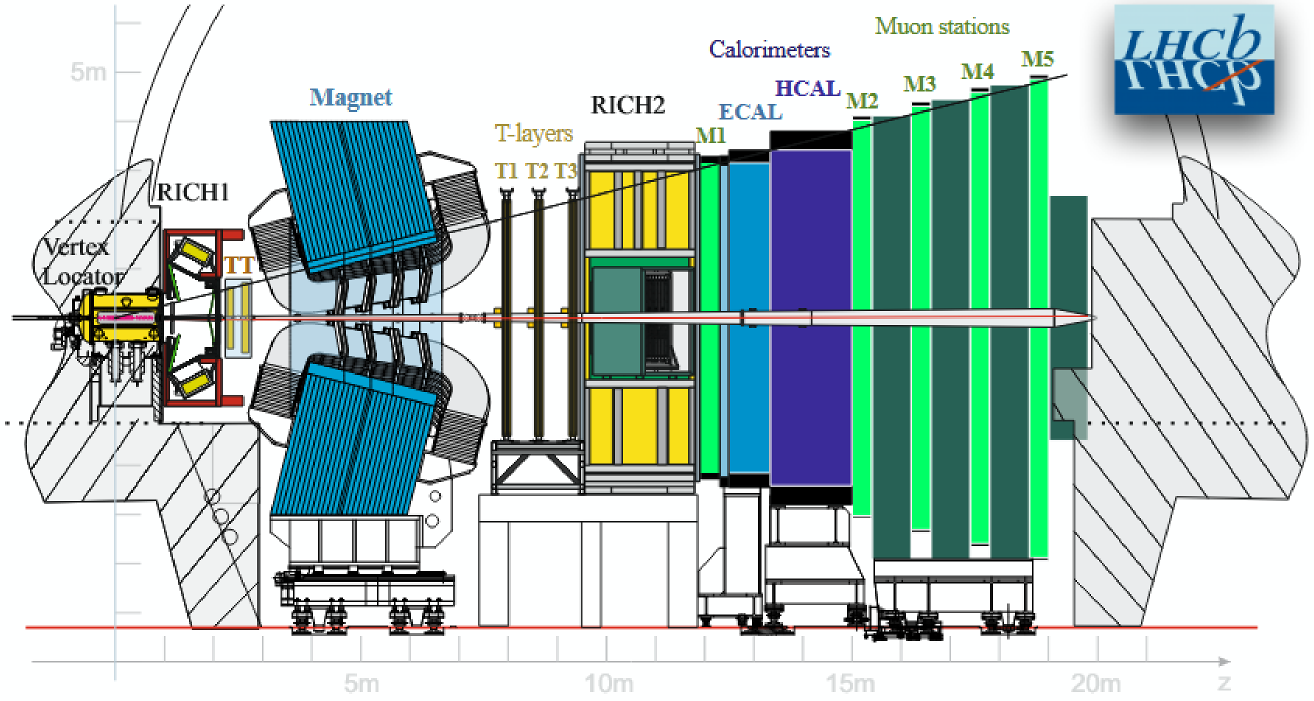
The Magnet

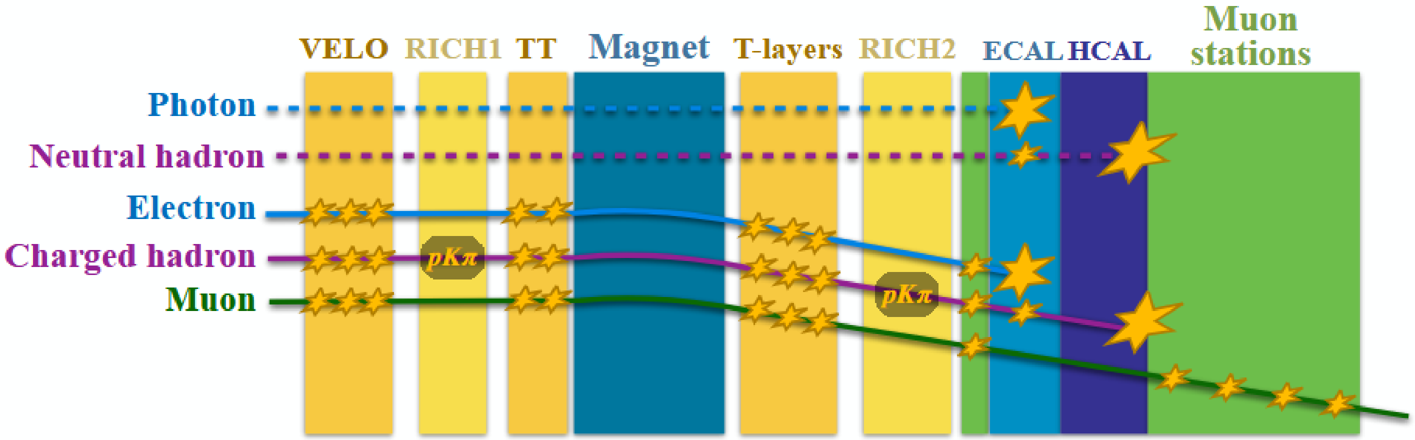
- It's not enough to follow straight lines, we need to know about the energy and momentum of these particles so we can use relativity to work backwards from the pieces
- LHCb's Magnet bends particles according to the sign of their charge and their momentum
  - $\Delta slope \sim q/p$
  - "Magnetic dipole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



Whodunnit?

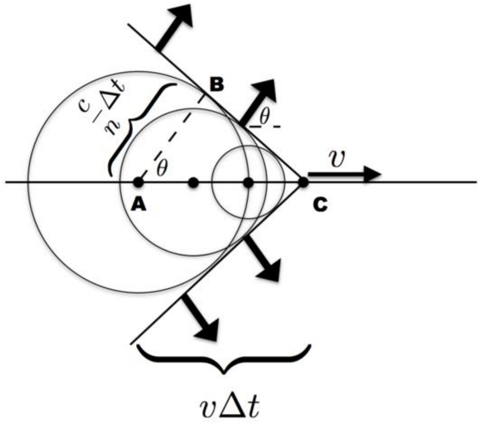
- Different kinds of charged particles are identified according to which other detectors they interact with
  - Electrons will be stopped by the electromagnetic calorimeter
  - Muons will pass through all the material in their way
  - Charged hadrons (protons and light mesons) look alike in their interaction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



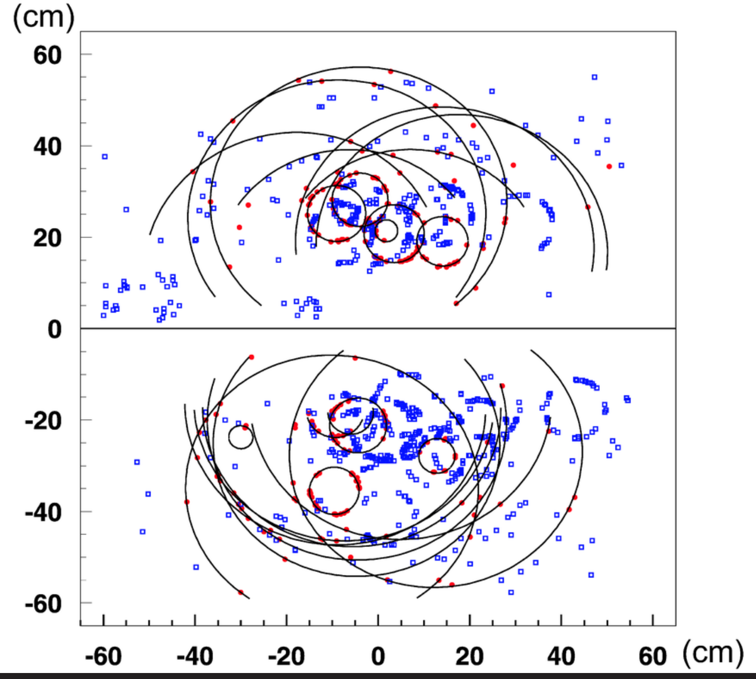


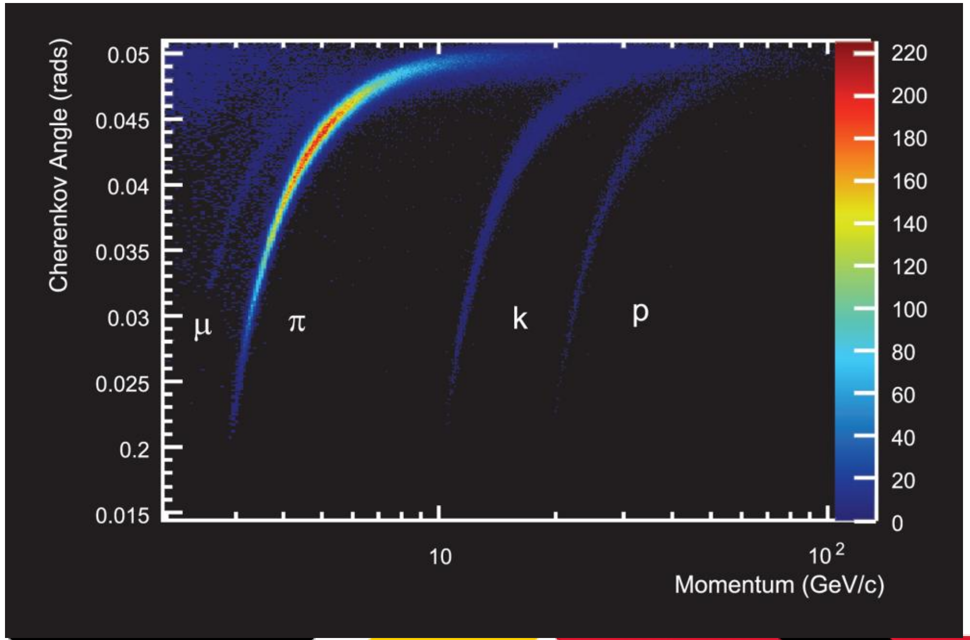
Whodunnit?

- 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!



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



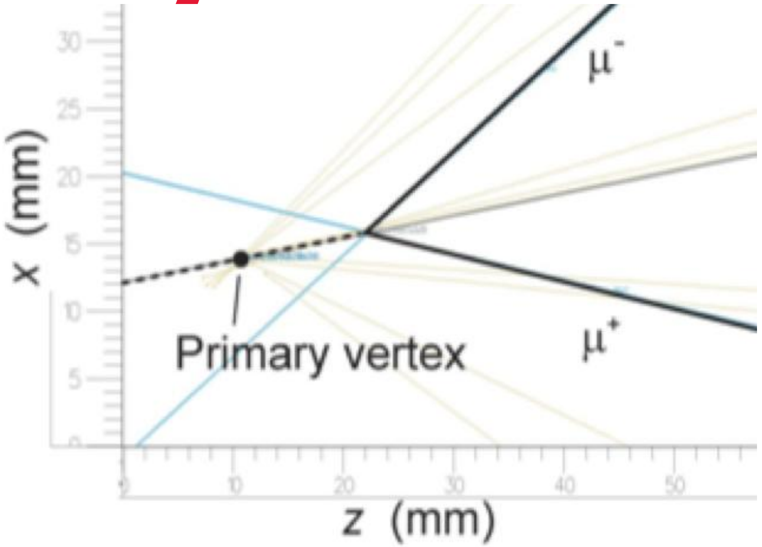


Combining using relativity

- Okay, so you have some particles that form a vertex, you can infer/guess their identity from among your options based on how they interact
- Next you want to try to add them together using relativity under the hypothesis that they come from a single particle, where

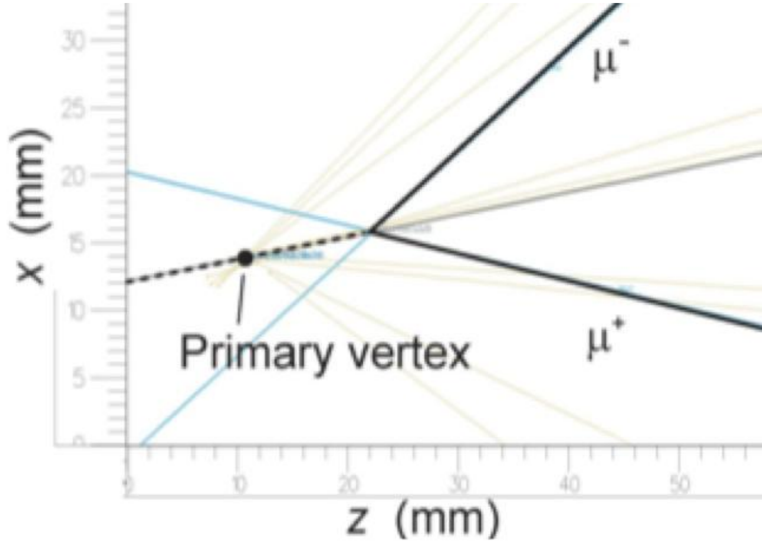
$$m_{combination}c^2 = \sqrt{(E_1 + E_2)^2 - c^2(\overrightarrow{p_1} + \overrightarrow{p_2})^2}$$

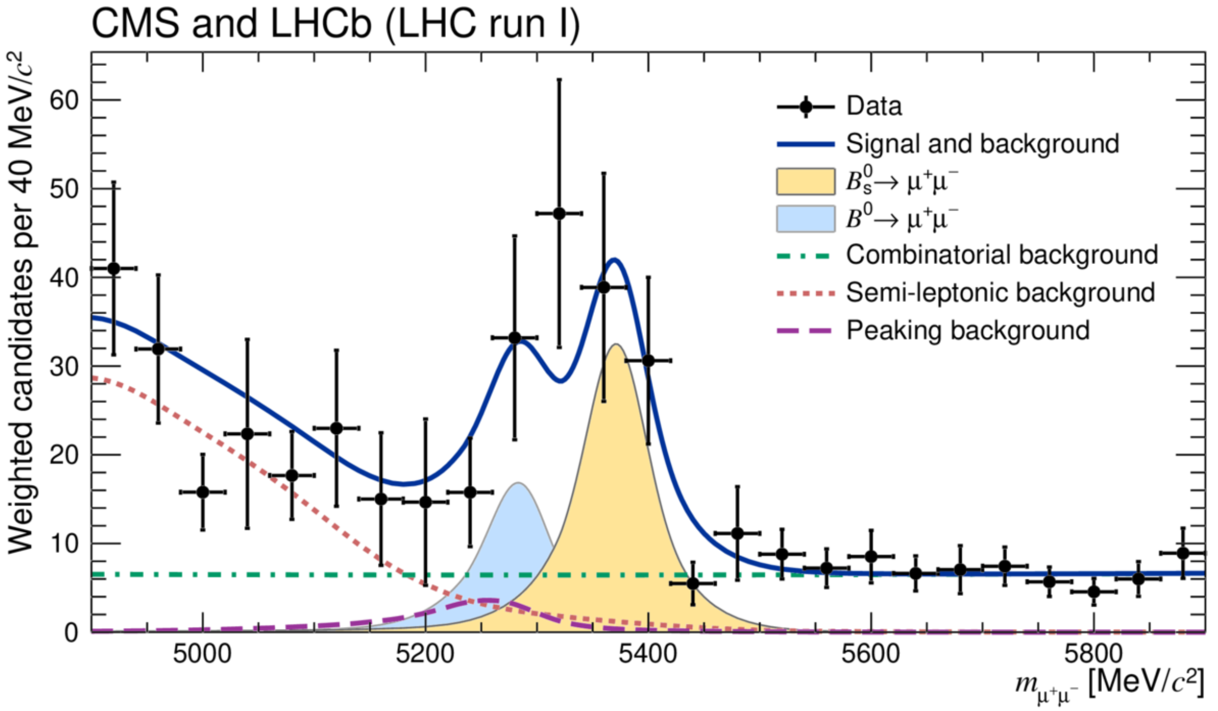
- But how do you know if you got the right combination?



Combining using relativity

- How do you know if the combination you've picked out is right? Statistics?
- By histogramming these values a signal may or may not appear over top of all your random wrong guesses
- This is where machine learning (AI if you're in marketing) really can strut its stuff: real heavy particle decays have many subtle correlations in many different characteristsics you can measure
  - Different ML classifiers can learn these details and give you responses to help increase the purity of your signal

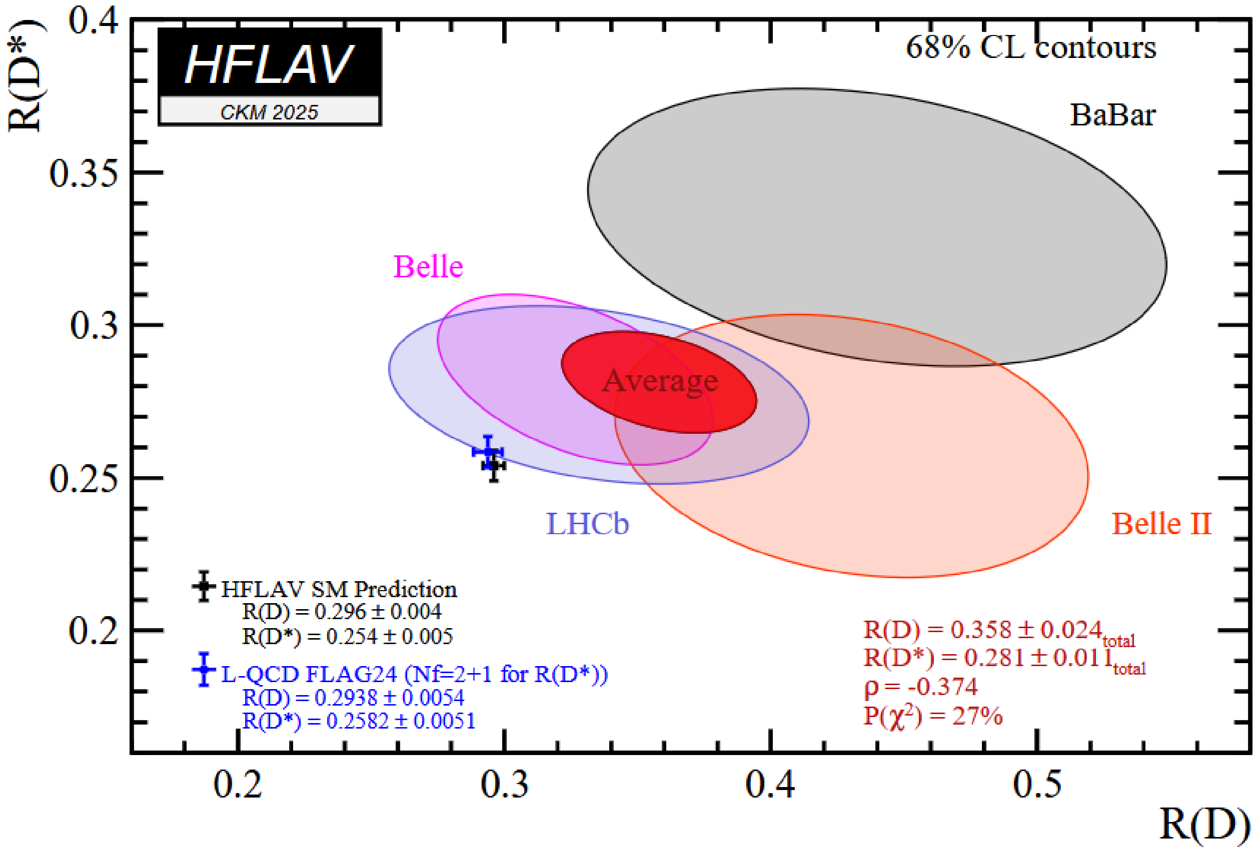




A LITTLE CONTEXT FOR OUR CODING EXERCISE LATER

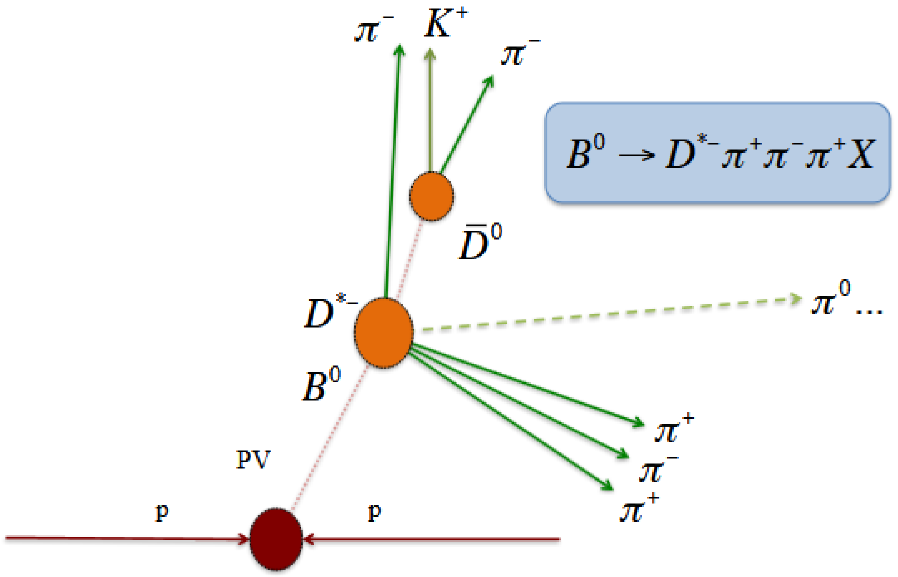
Case study:

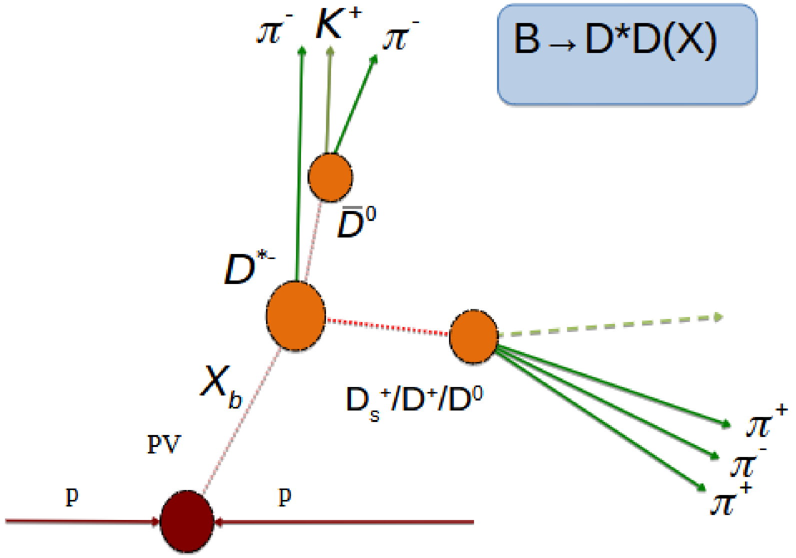
- Here we have a quite complicated series of reactions!
    - This is a particular reaction which is directly related to a very particular exciting anomaly in the field, where decays like this happen at a higher rate than expected relative to similar reactions with lighter leptons
- We can build up “candidates” for this decay chain, but as you can guess there are a lot of random and wrong combinations that can happen



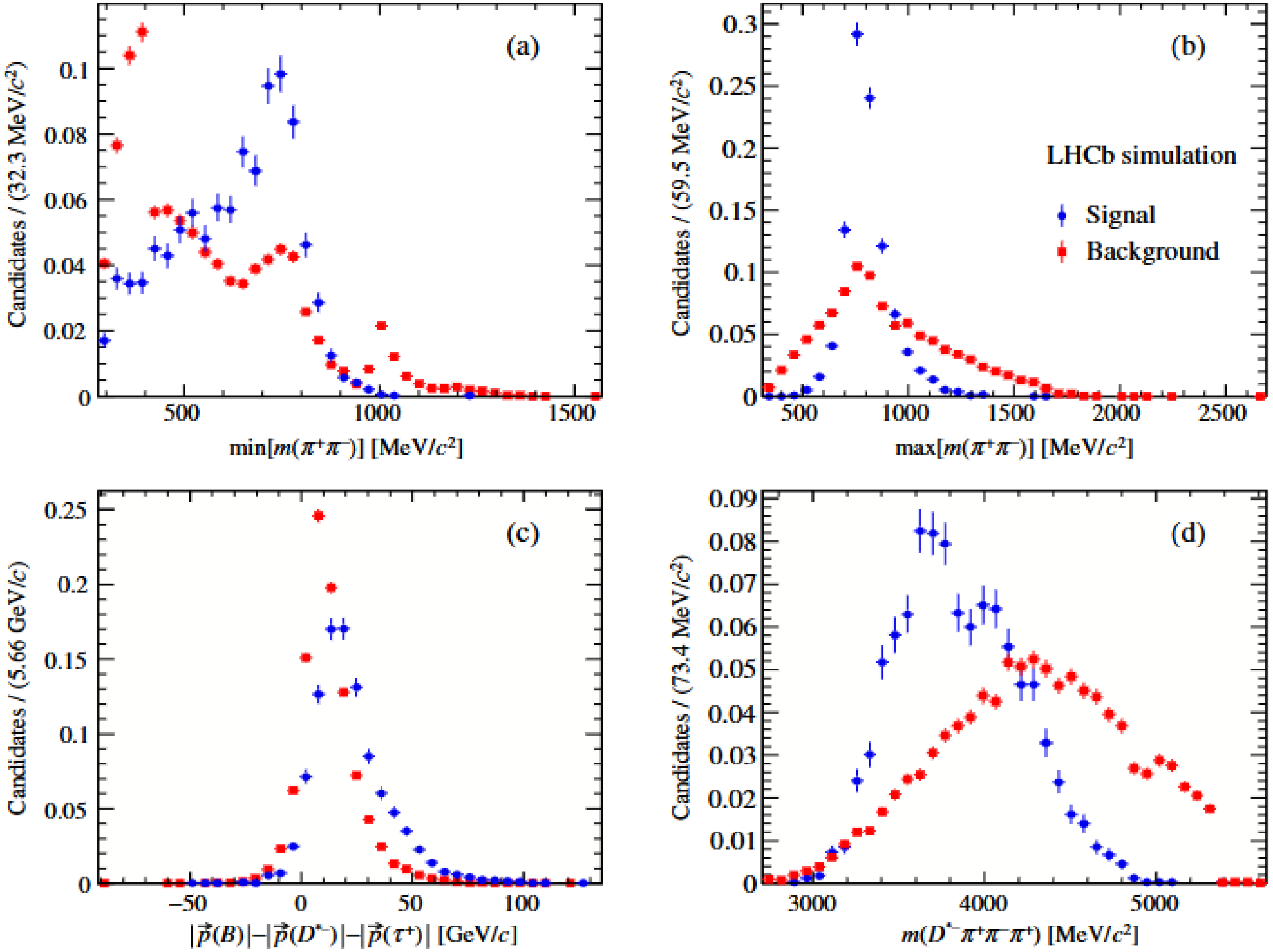
Backgrounds

- 2 main sources of *non-random* backgrounds
  - In the real analysis, different ML models were trained against either of these guys
- Things to note:
  - One has the three π mesons originate from the B^0 decay point
    - **You'll get a hands-on chance to play with building tools to fight this background later in the workshop!**
  - The other looks a lot like the signal, but has no τ!
    - Here AI/ML techniques are key
    - The trick is that there are substructures in these 3π combinations which are very different when they come from D_s vs τ





ML to the rescue



(plus 14 more variables) BDT