

Flavour physics.

DESY Summer Student Lectures 2018

Sam Cunliffe
24.08.2018

Goals for this lecture

- 0) What is flavour and “flavour physics”.
- 1) Understand the basics and motivations of flavour physics
 - Enough to talk to us even if you don’t end up working in our field.
 - Know the names and rough idea behind four of the important b-physics experiments.
 - Know enough to “get the gist” of a flavour physics paper.
- 2) Know a bit about “recent anomalies” and their implications.
 - Real cutting-edge physics results.

What?

Experiments

Observables

A touch of CP violation

Rare decays and anomalies

The field in 2018

What is the Standard Model?

Precision of statement

- An effective relativistic quantum field theory gauge invariant under $SU(3) \cdot SU(2) \cdot U(1)$.
- A Lagrangian density which is the closest we've come to finding the Lagrangian density of nature.
- A collection of quantum fields and their couplings.
- A collection of quantum fields and their interactions.
- A collection of different types of squiggly lines and rules to draw them.
- A framework for theorists to calculate predictions of measurable quantities
- A table of particles on wikipedia.
- A set of rules for really small and really fast things.

Amount of QFT lectures necessary

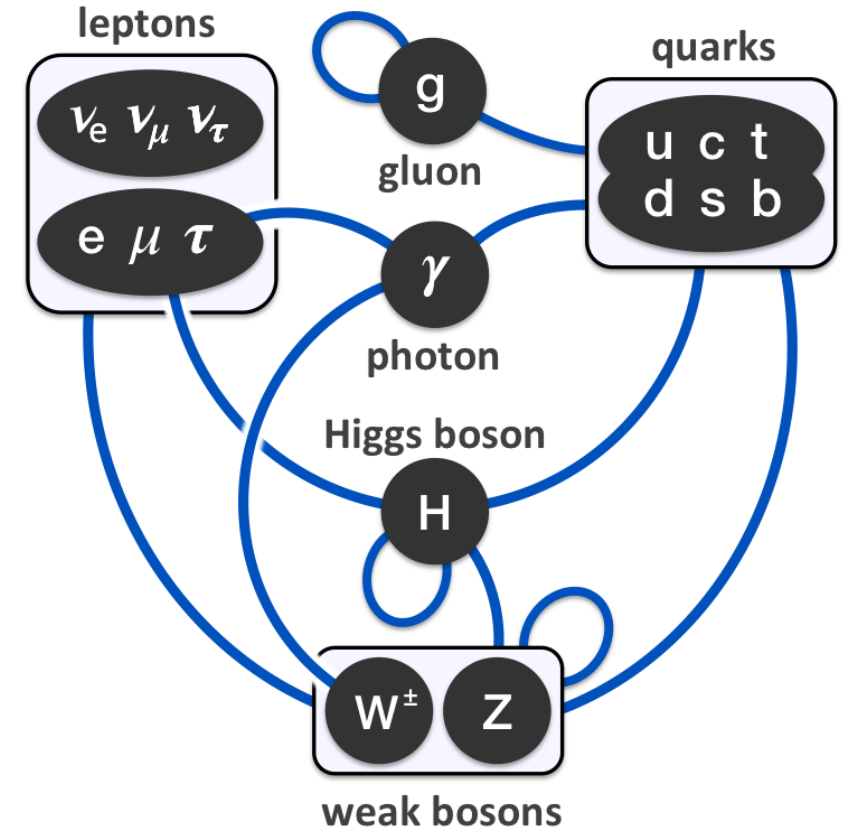
What is the Standard Model?

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LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
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Figure: MissMJ /Wikimedia Commons

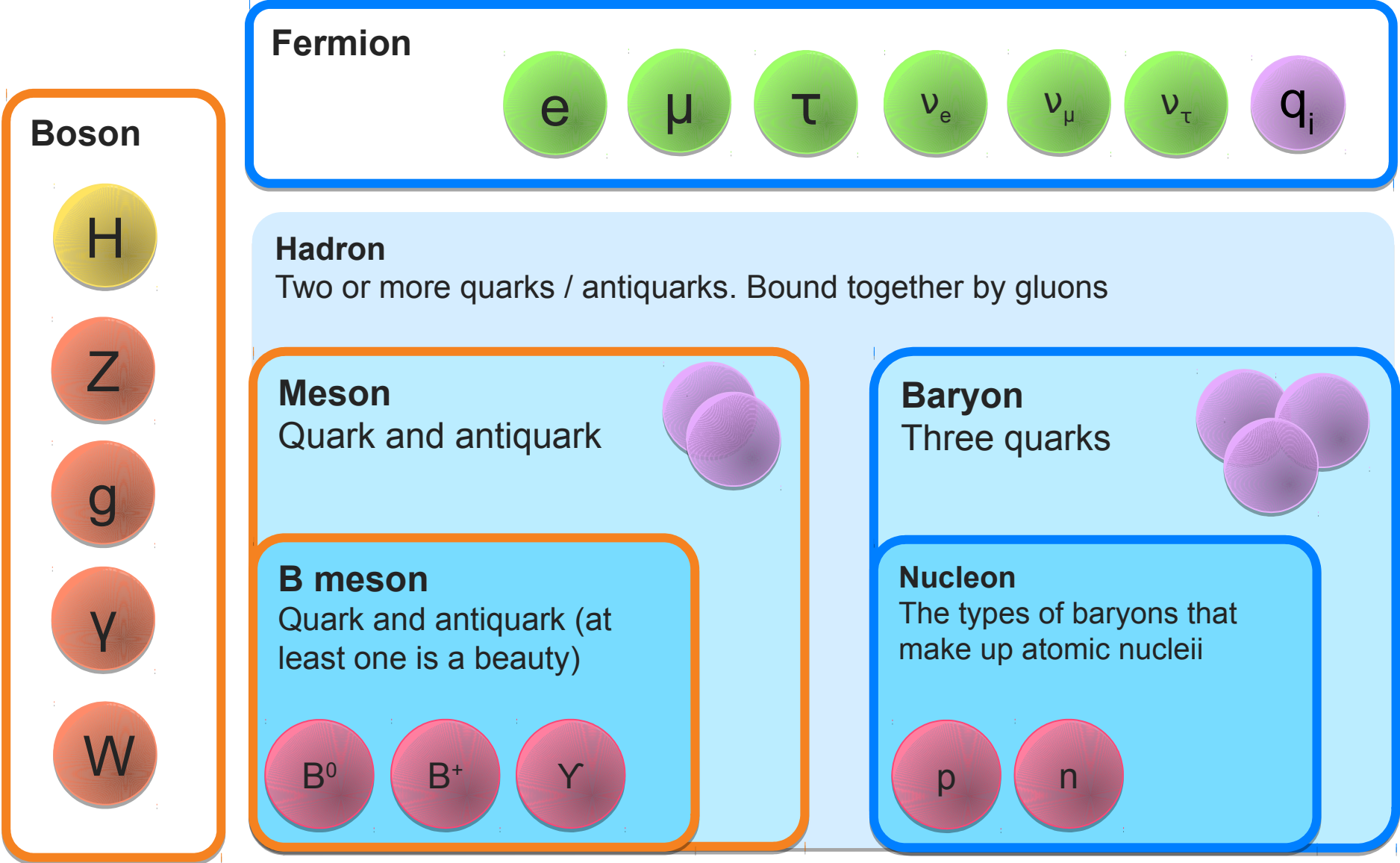
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				H Higgs



Figures: MissMJ, Eric Drexler /Wikimedia Commons

Particle Jargon



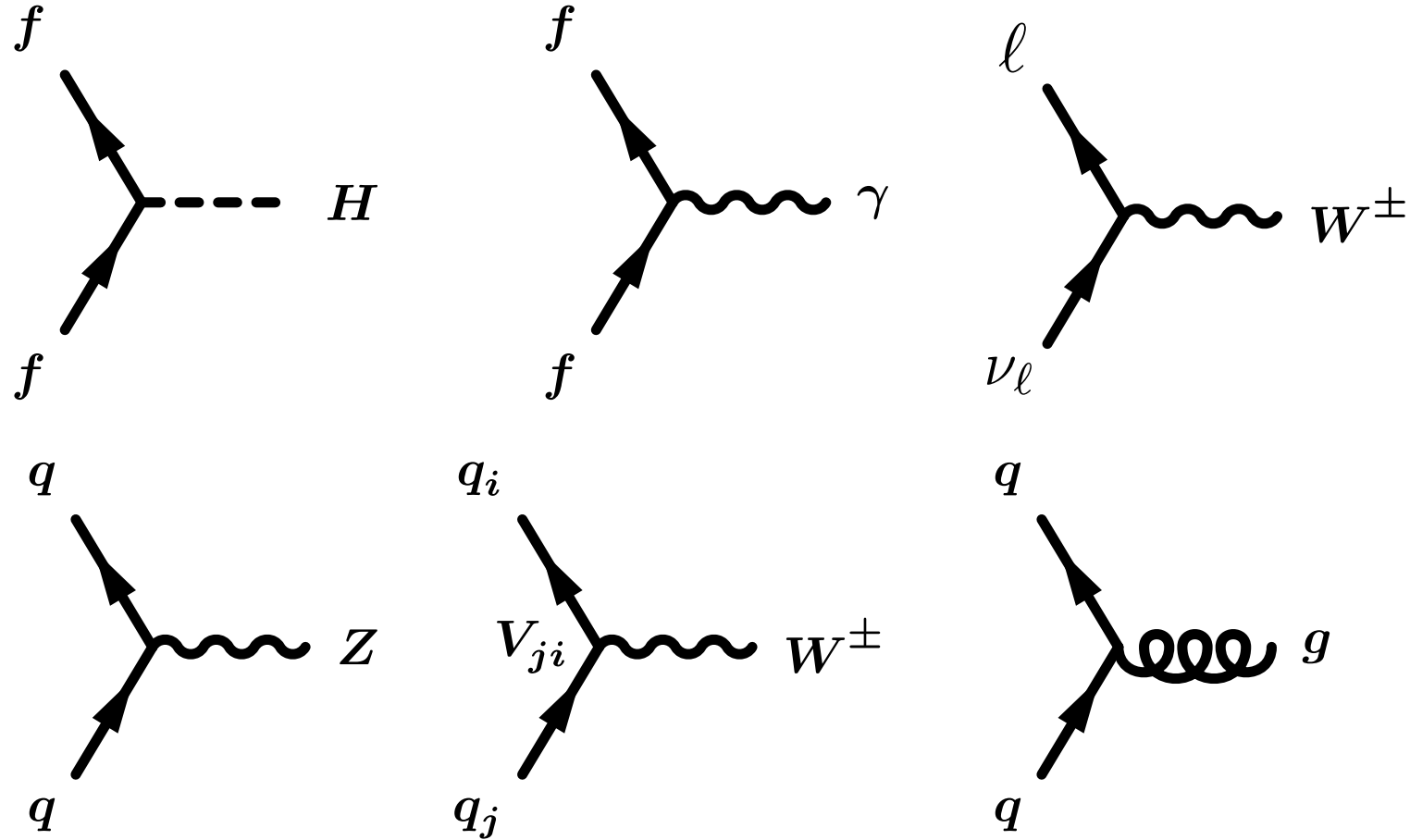
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$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + h.c. \\ & + \chi_i y_{ij} \chi_j \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

What is flavour?



Figure: Benreis /Wikimedia Commons

What is flavour?

Fischbrötchen

Bismarckhering, Matjes oder Lachs

Sie gehören zu Hamburg wie die Schiffe und der Hafen: leckere, frisch belegte Fischbrötchen! Ob mit Matjes, Bismarckhering, Lachs oder Krabben - Hauptsache, es schmeckt! Unsere Tipps für die besten Fischbrötchen der Stadt.



1 / 16



Figure: Benreis /Wikimedia Commons

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Figure: Benreis /Wikimedia Commons

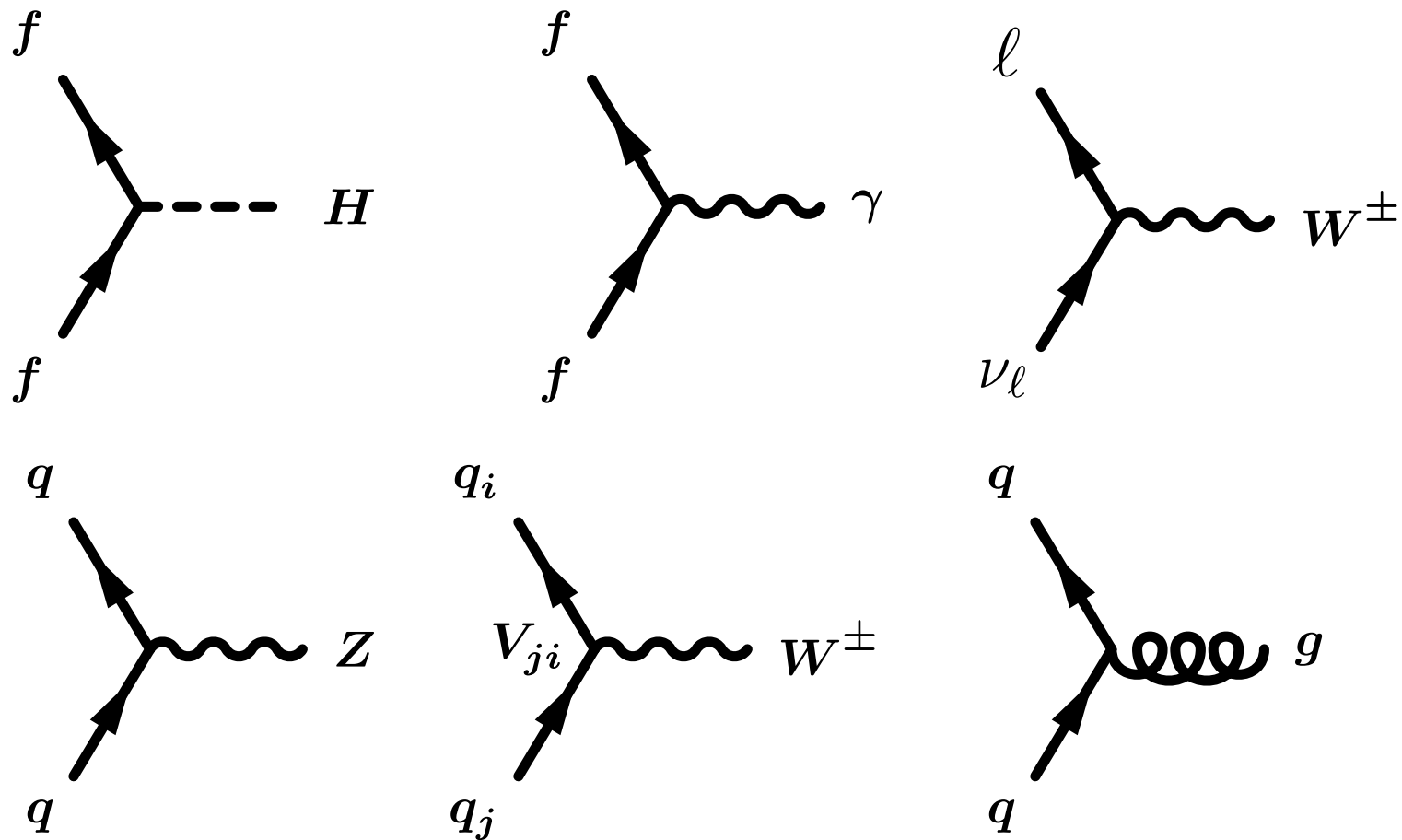
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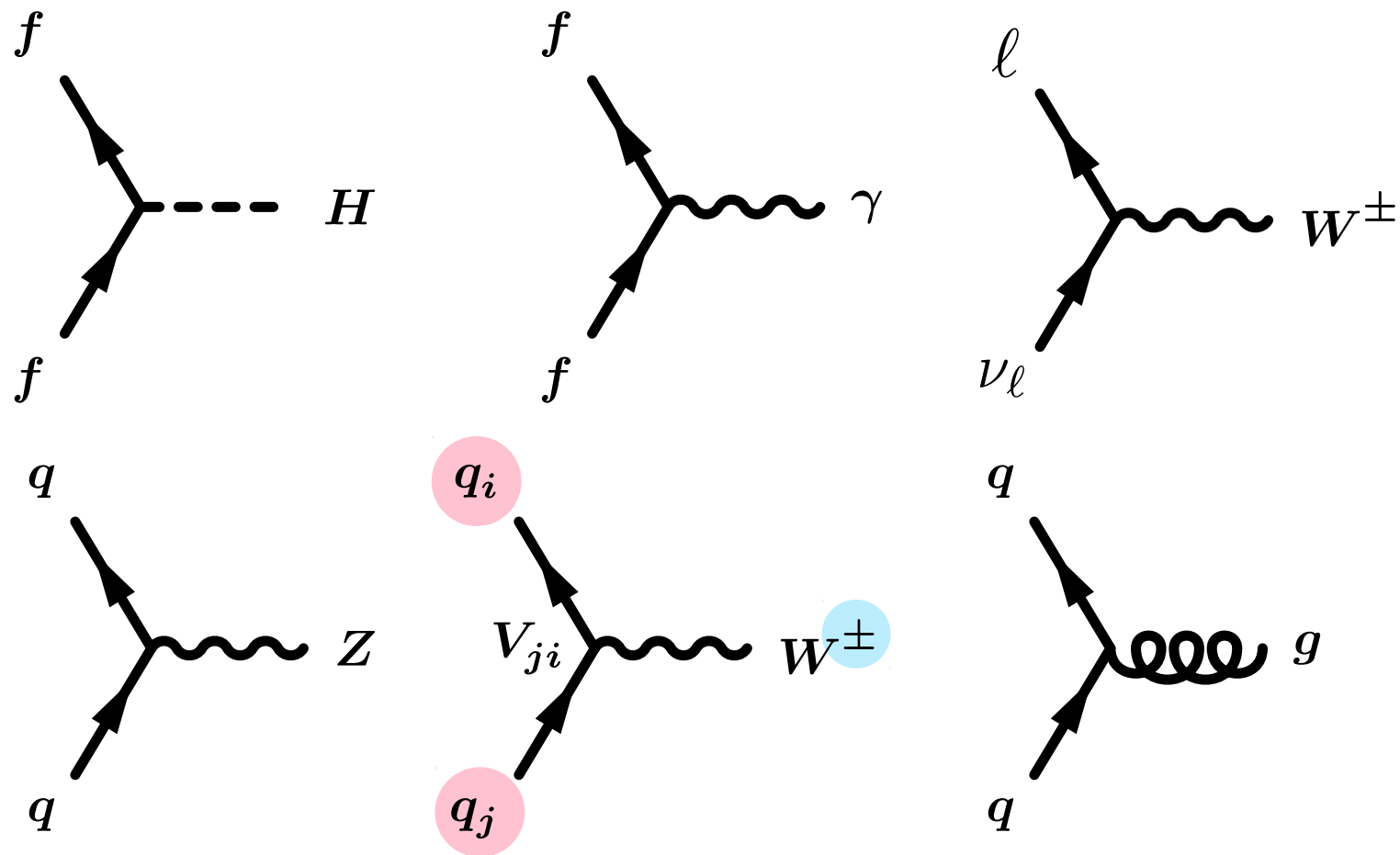
Depends a bit on nomenclature, *but*:

- **Columns:** Families / generations
- **Rows:** types (p.s. sorted by charge)
- **Cells:** flavour

Remember this?

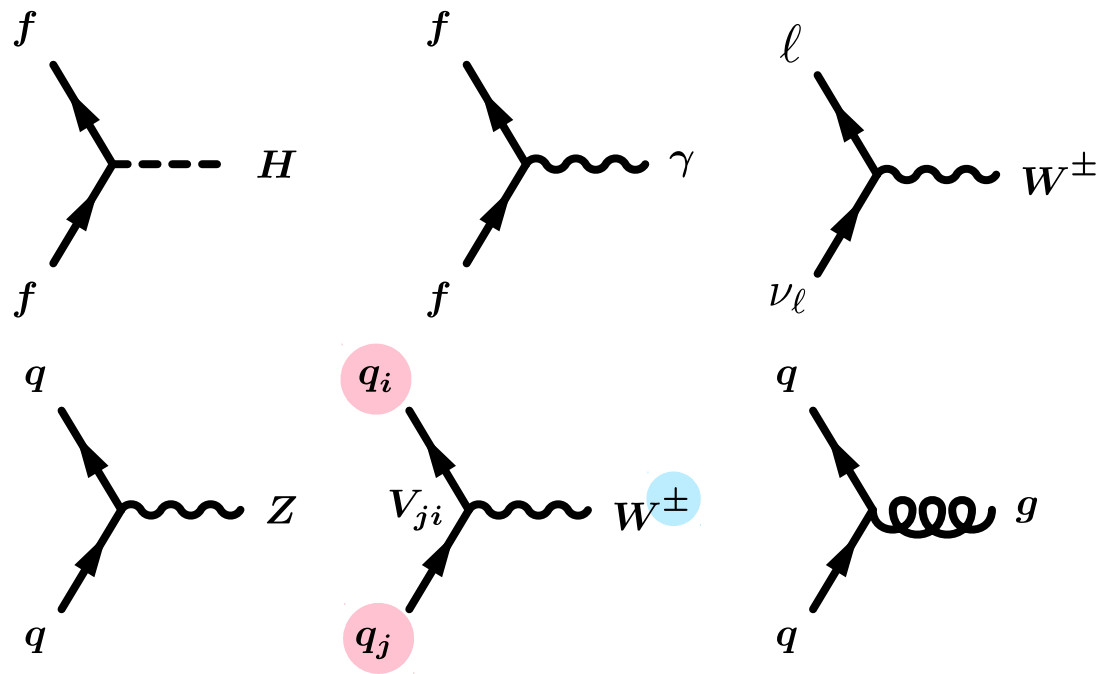


How to change flavour?



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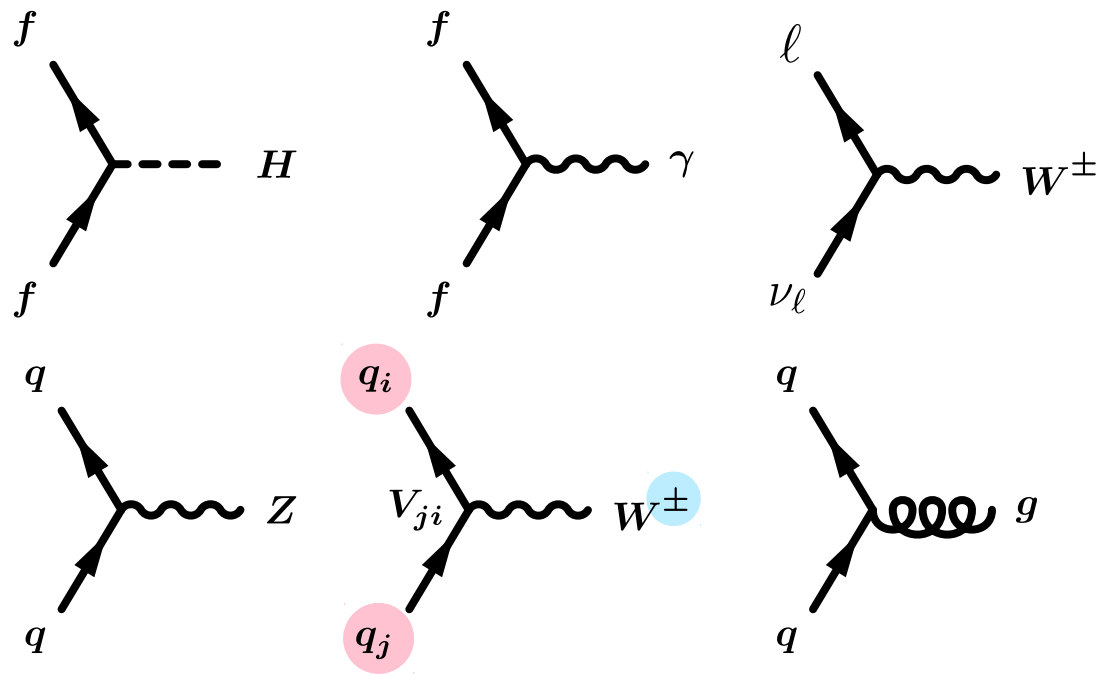
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					GAUGE BOSONS
					SCALAR BOSONS



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

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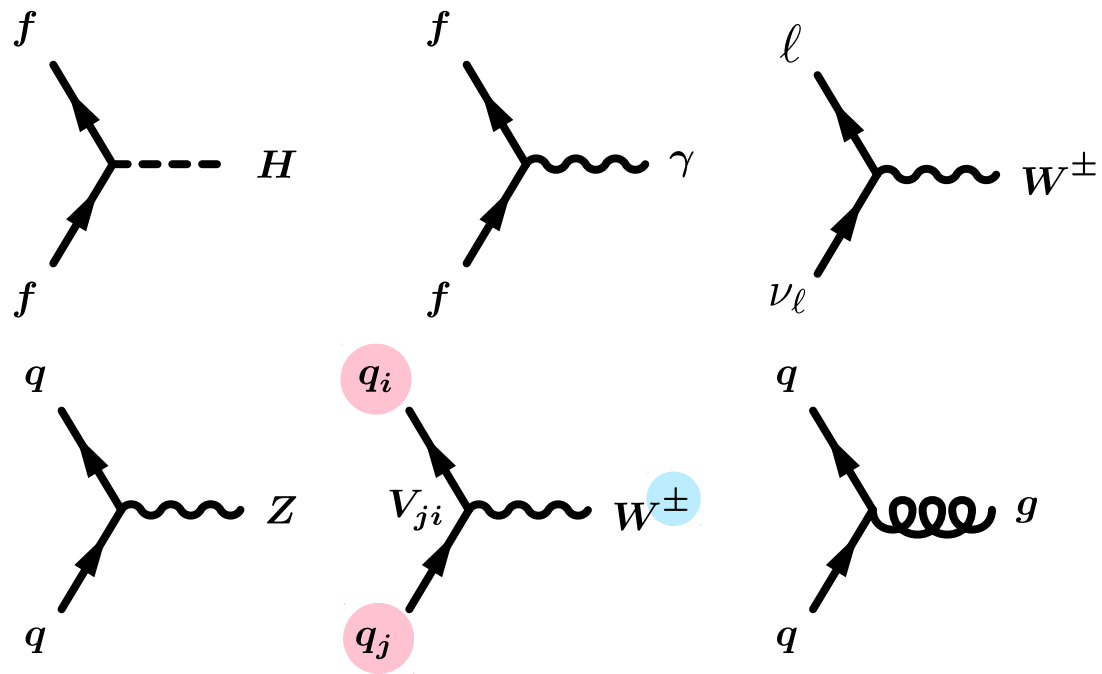
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0.225 0.973 0.0412

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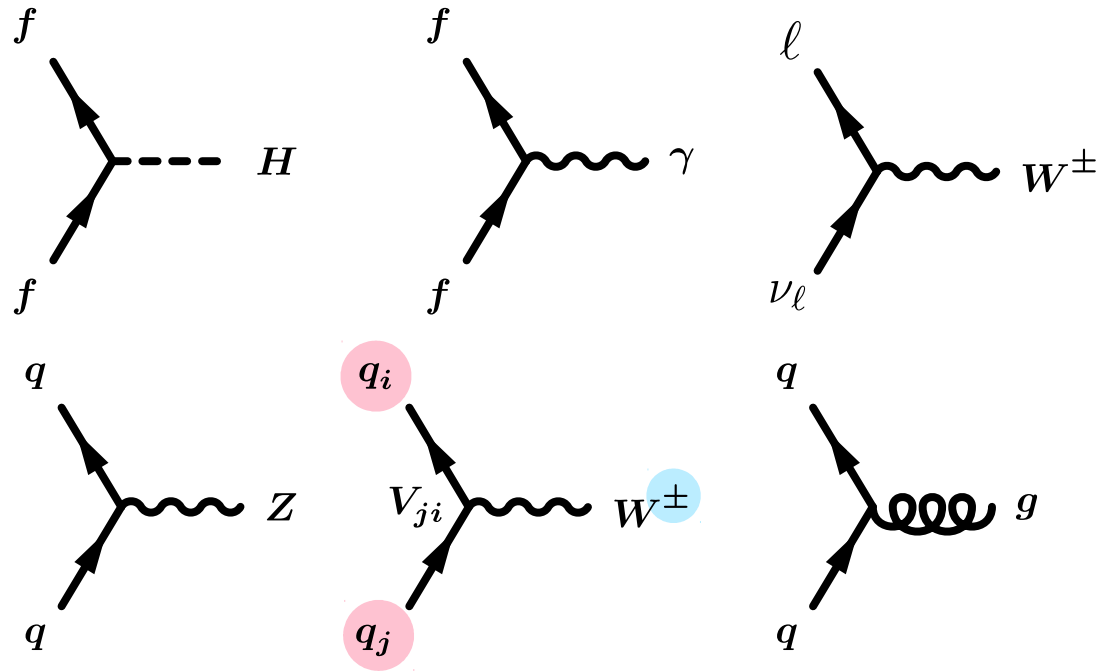
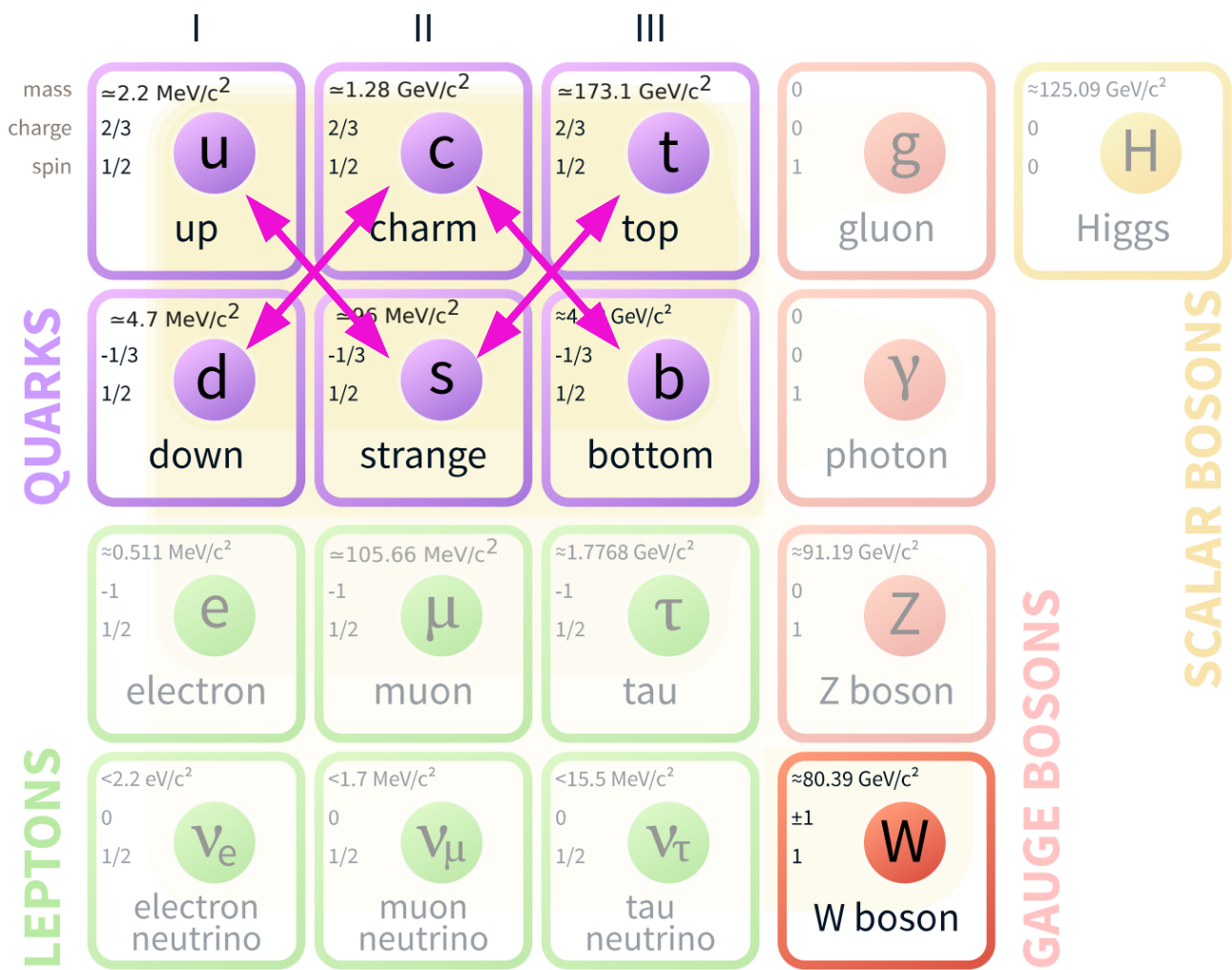
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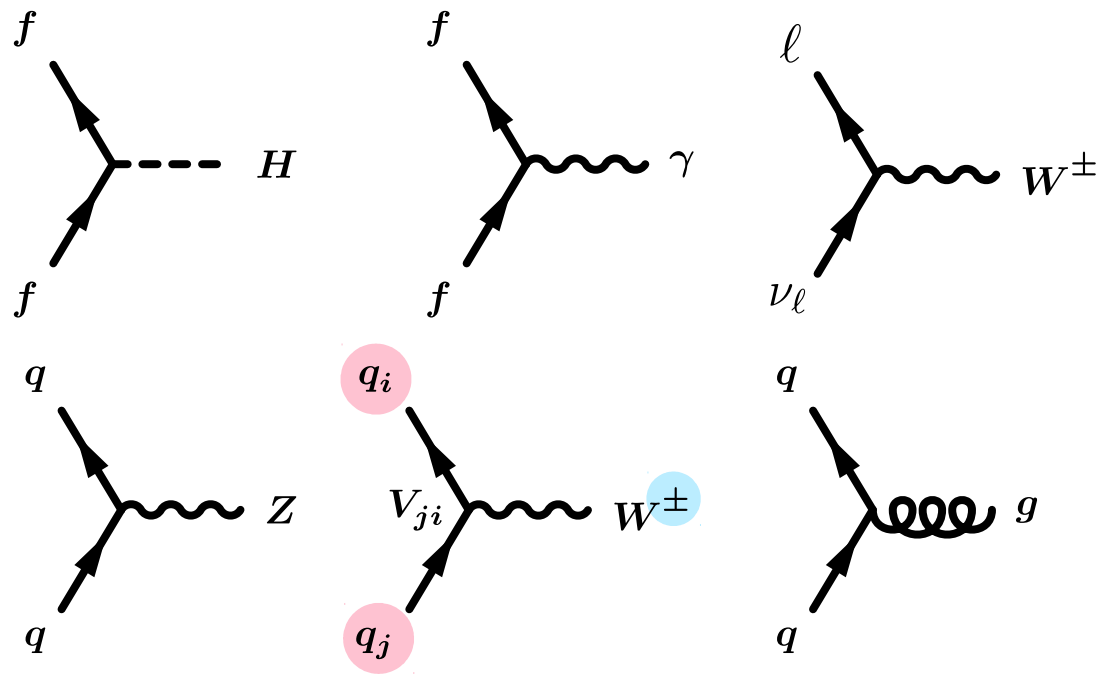
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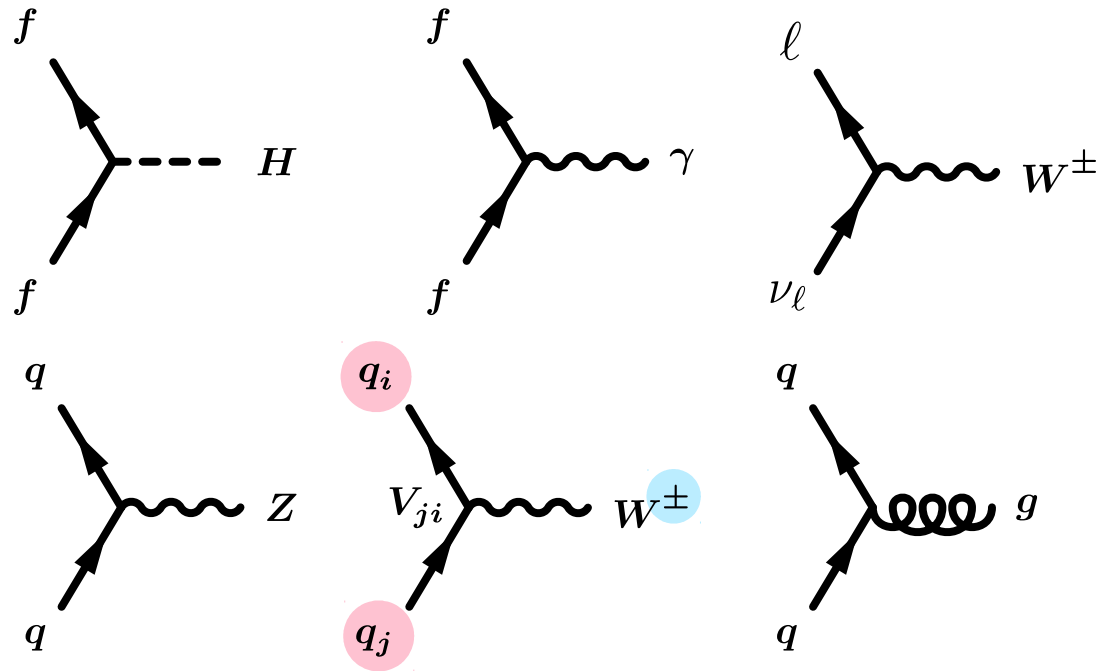
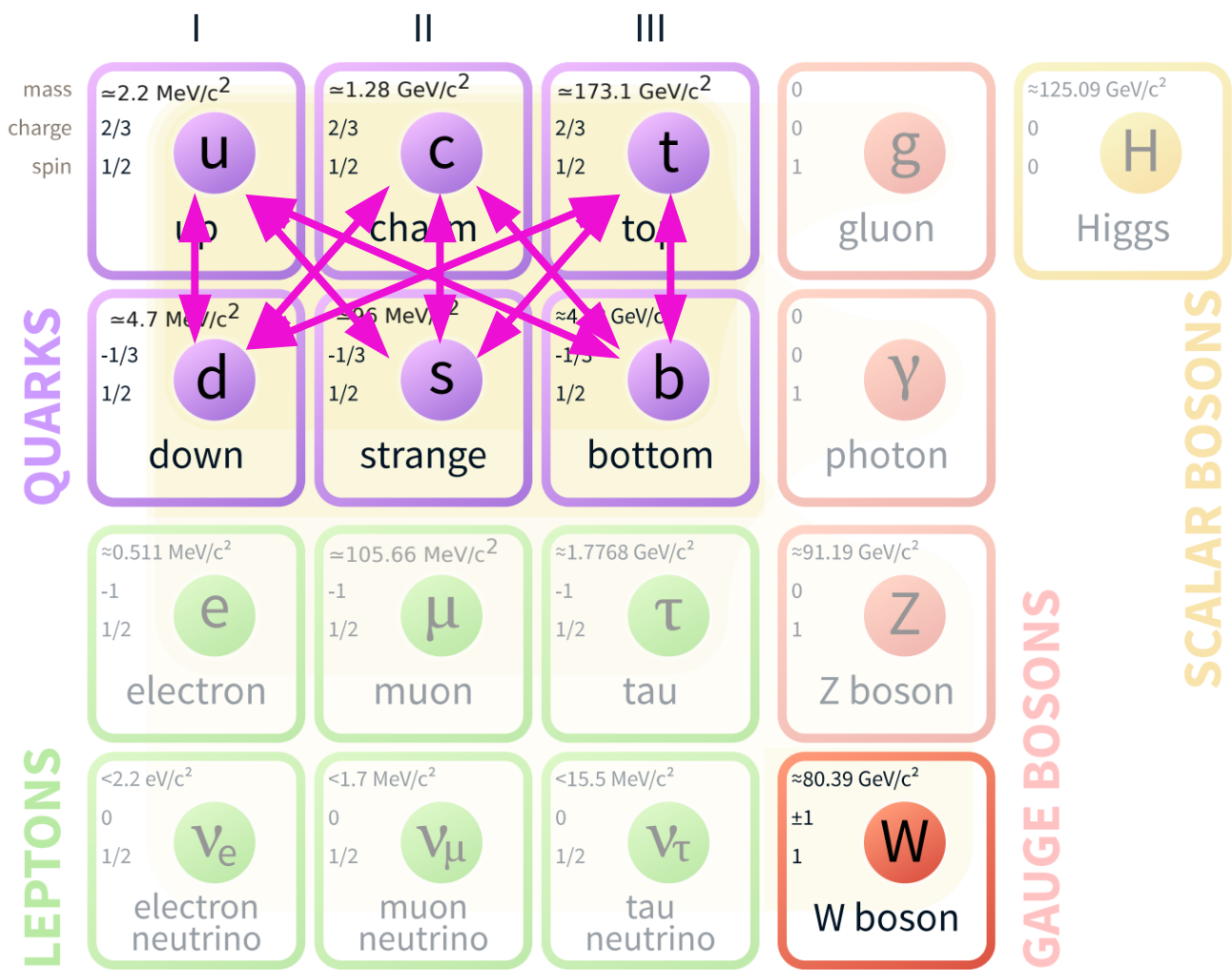
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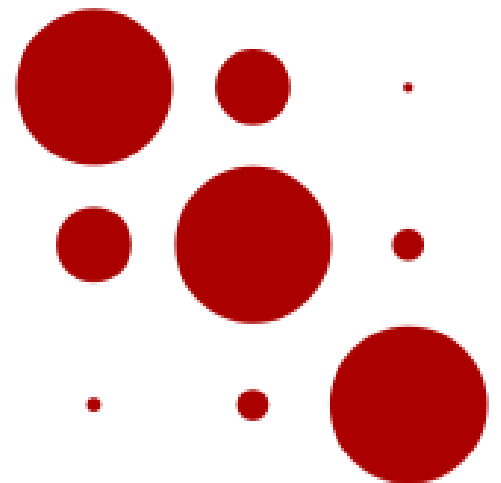


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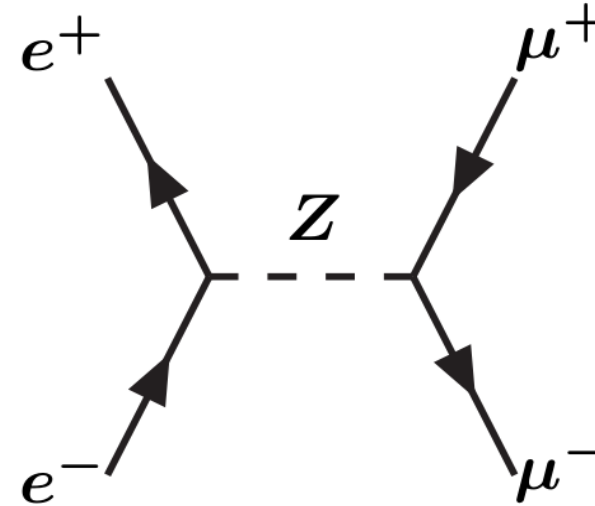
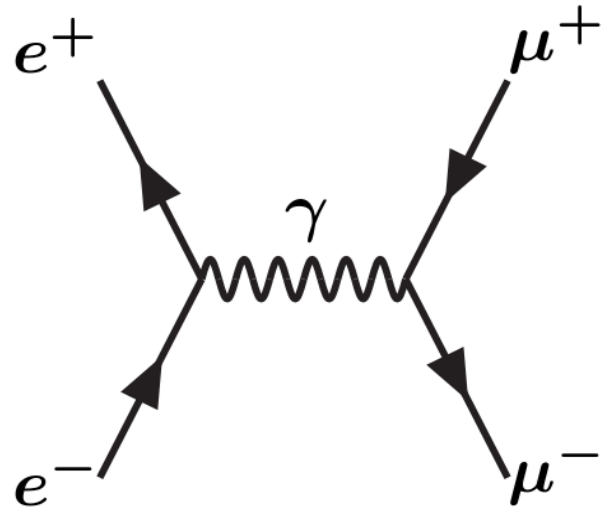
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$$V_{CKM}$$

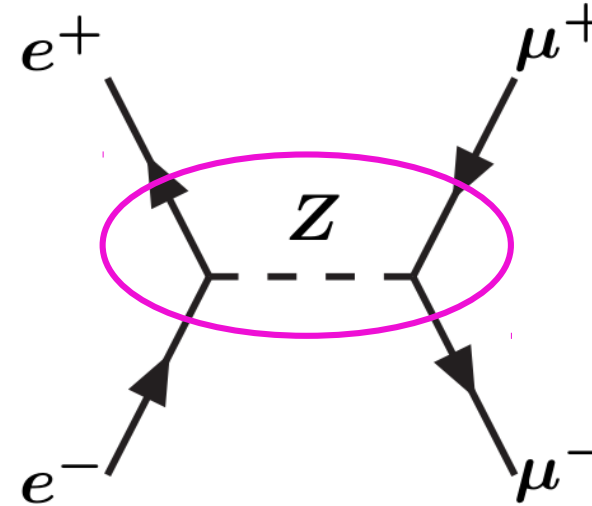
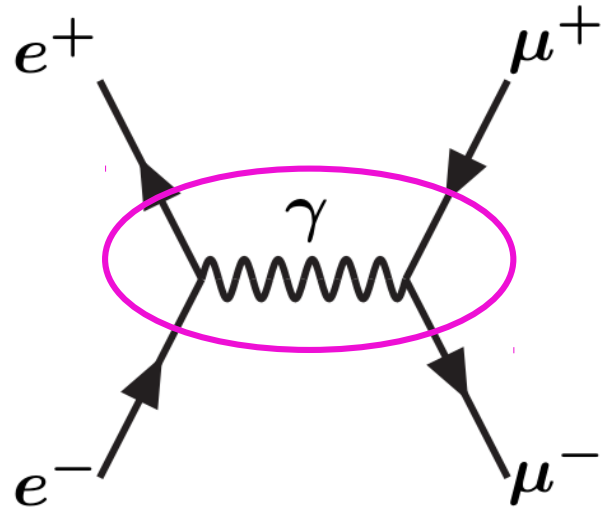


Quiz time



What is special about the particles in the middle.
Is this weird?

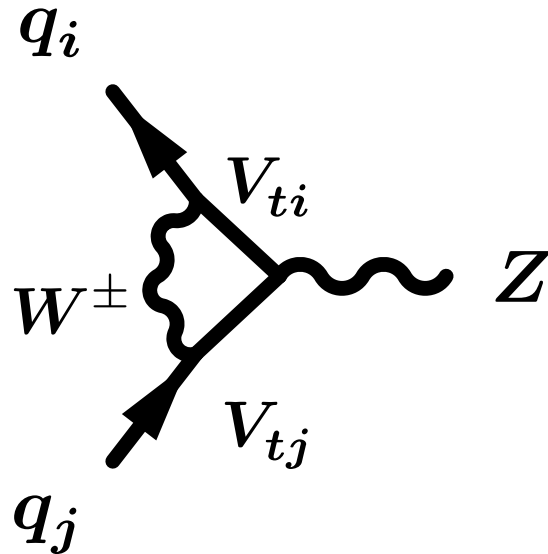
Quiz time



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Can't change columns directly

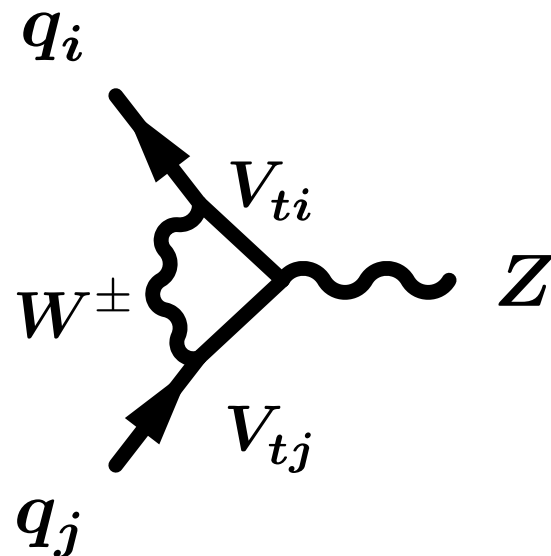
- To change column one is forced to change row first.
- Combines three of the SM vertices
 - $\therefore$ **must** involve virtual particles



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Summary and caveats

- The Standard Model is a set of rules.
- It's a little ad-hoc. But it's the most precise theory we have at the moment.
- All of what I've been saying is true “within the Standard Model”.
 - If you're playing according to the SM's rules.
- We think/hope/expect it's **not** really how nature is.
- It's just our best guess at the moment.

You should know: there are problems with the Standard Model

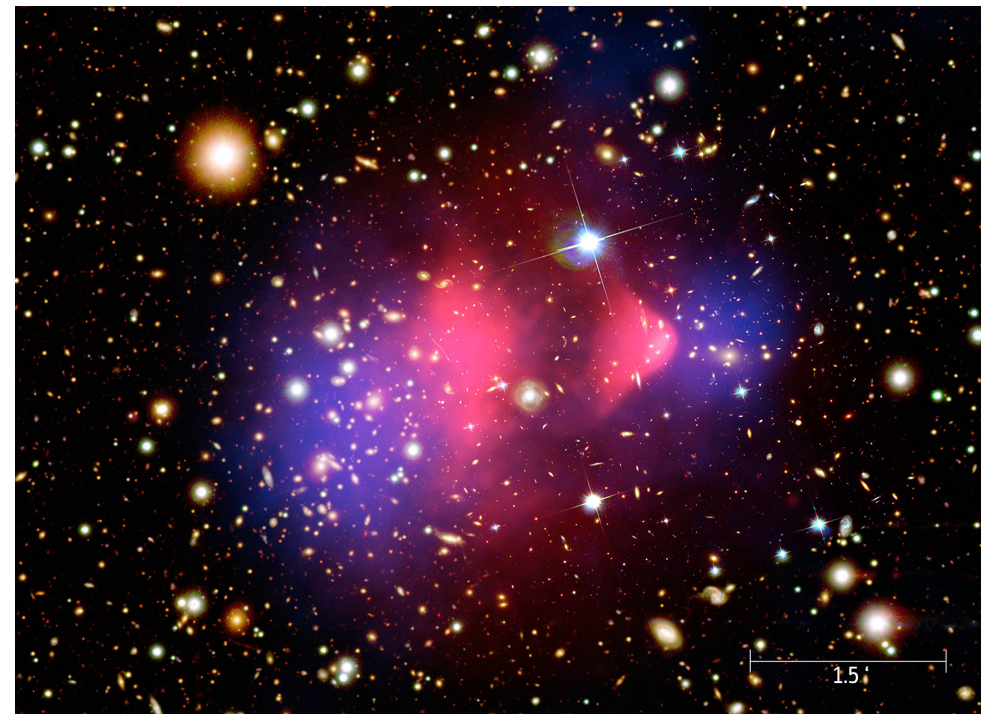
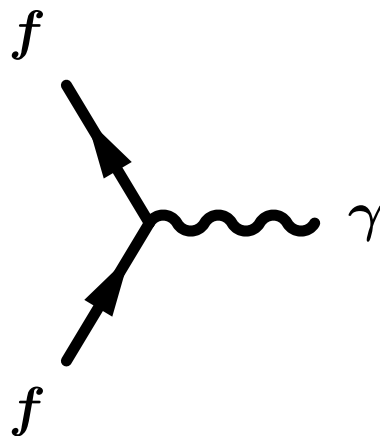
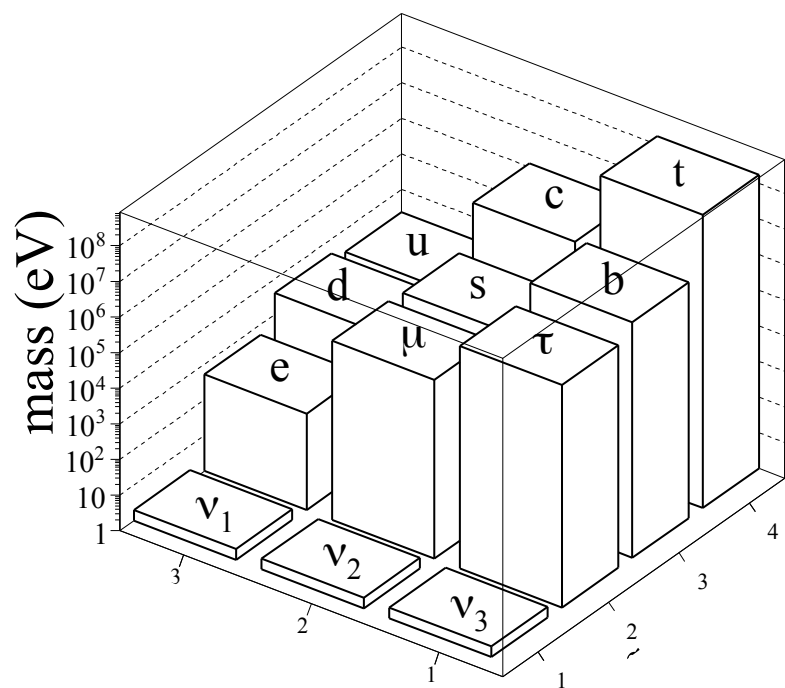
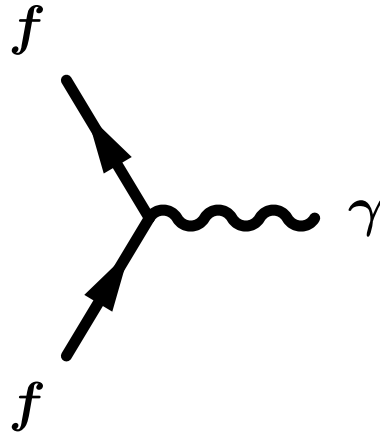


Photo: NASA/Chandra X-ray Observatory / Wikimedia Commons

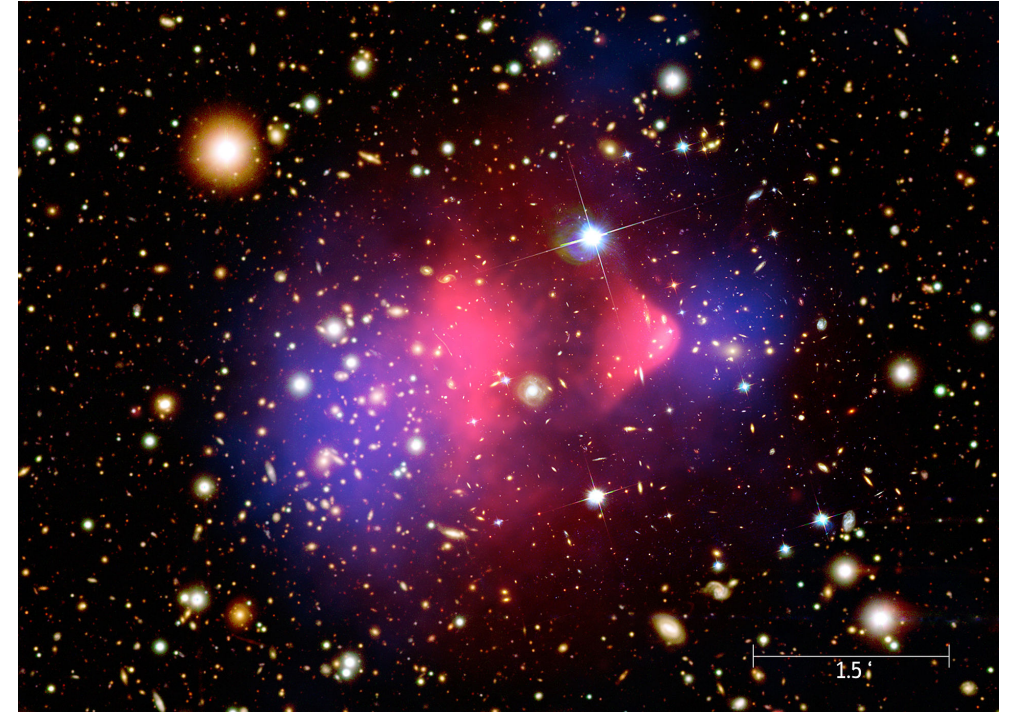
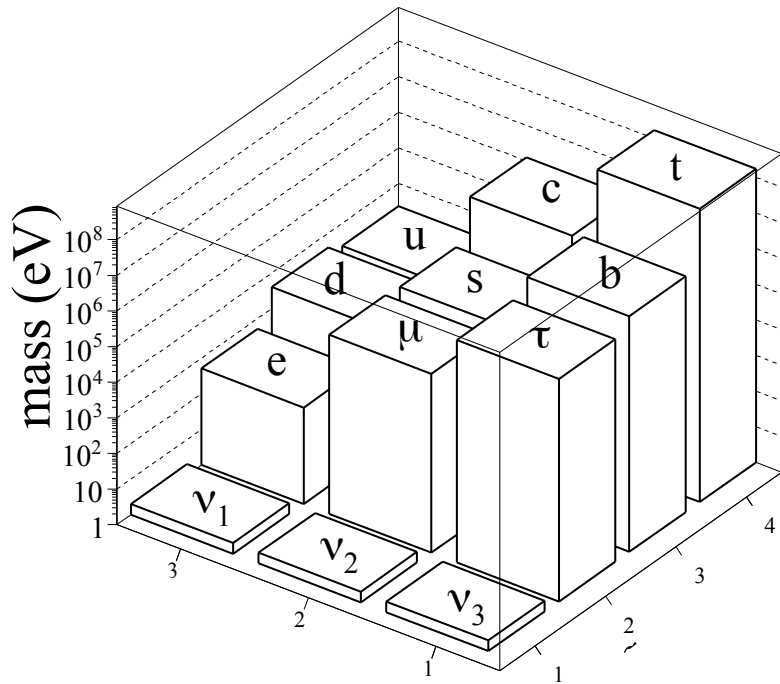
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You should know: there are problems with the Standard Model

Matter-antimatter asymmetry (in nature)



Mass values
(in particular: neutrino masses)



Dark matter

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{pmatrix} \text{large} & \text{small} & \text{very small} \\ \text{small} & \text{large} & \text{small} \\ \text{very small} & \text{small} & \text{large} \end{pmatrix} \quad \text{CKM Structure}$$

Photo: NASA/Chandra X-ray Observatory / Wikimedia Commons

Disclaimer

I'm about to specialise

- I'm going to focus on b-physics.
- There are lots of things that have to be locked away.
- Starting points for a Google/Wikipedia adventure:
 - CP violation in kaon decays (Cronin and Fitch)
 - CKM Matrix $\rightarrow$ unitarity triangle (do some maths).
 - CLEO experiment
 - HERA-B experiment (here at DESY)
 - Neutral B mixing
 - Modern kaon experiments (NA62)
 - Neutrino mass hierarchy

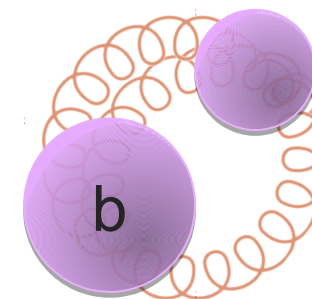
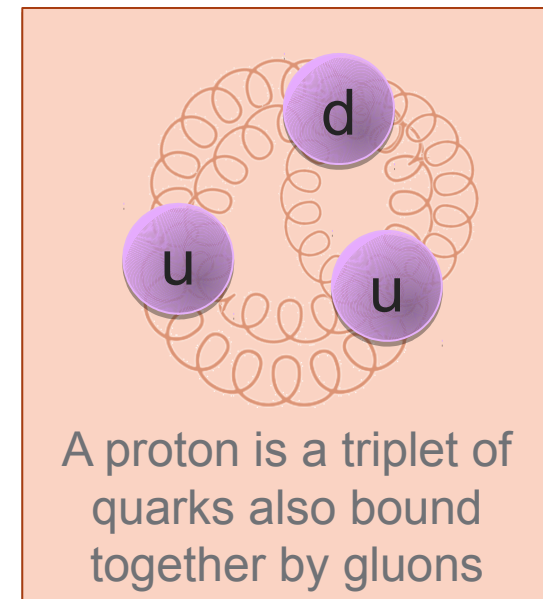


Photo: Theodor Lachanas / Wikimedia Commons

B mesons

Containing a b quark

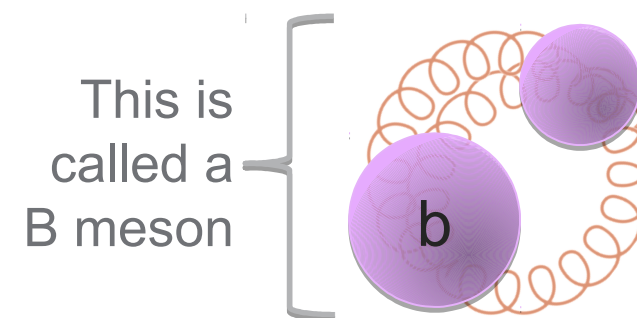
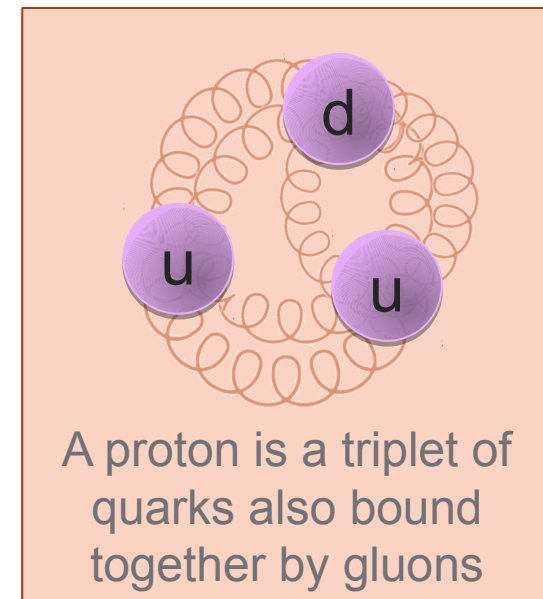
- Massive enough to decay in interesting ways, light enough to hadronise
 - Can create hadrons at modest accelerators *c.f.* top, Higgs
 - ... $B^0(d\bar{b})$, $B^+(u\bar{b})$, $B_s(s\bar{b})$, $B_c(c\bar{b})$, $\Lambda_b(udb)$, $\Upsilon(b\bar{b})$
- The “Goldilocks” quark? Decays in interesting ways.
- Not all decay modes are interesting but many are
 - Information hidden in the corner elements of V_{CKM} ?
 - Decay modes asymmetric in matter vs. antimatter
 - Rare decays (typically flavour-changing neutral current modes)
- Tests for lepton non-universality (LNU) lepton flavour violation (LFV)



B mesons

Containing a b quark

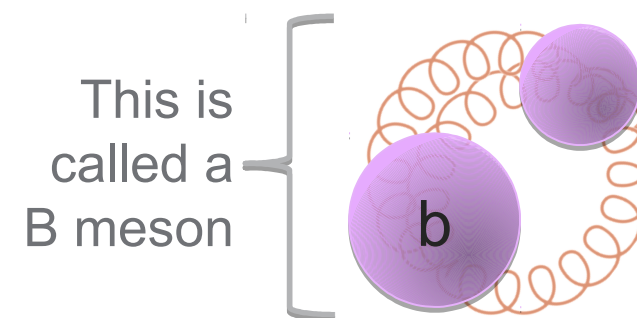
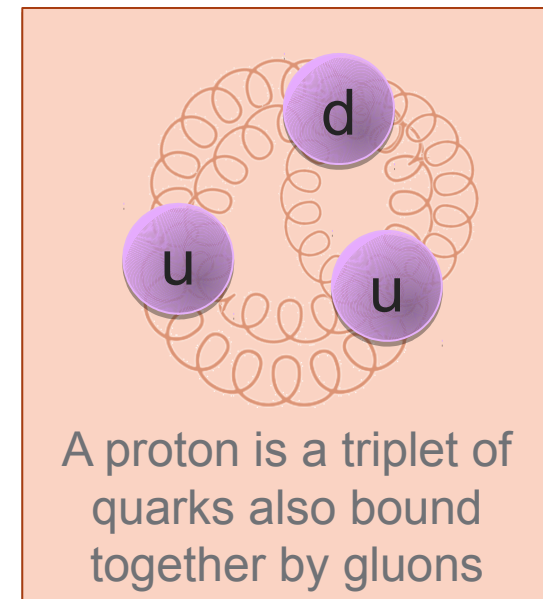
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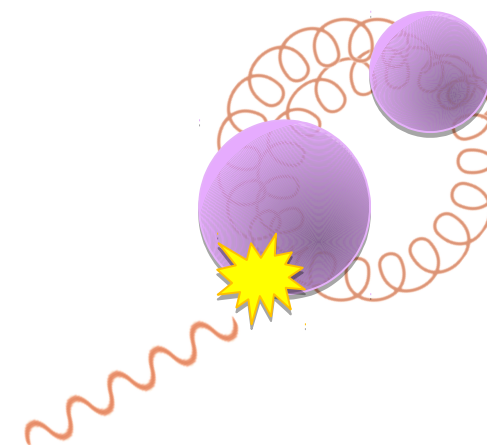
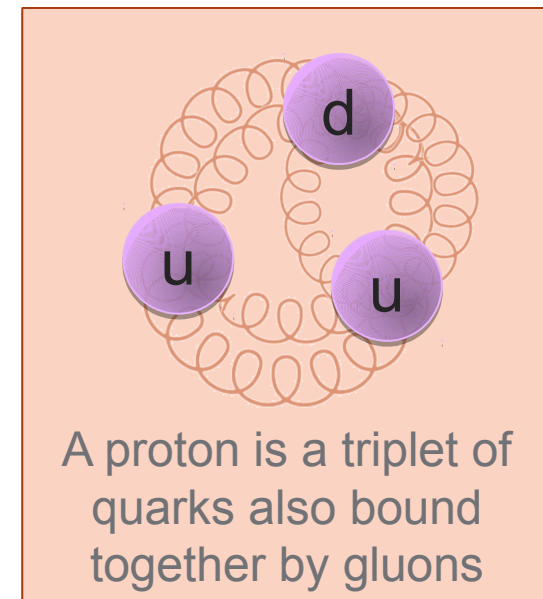
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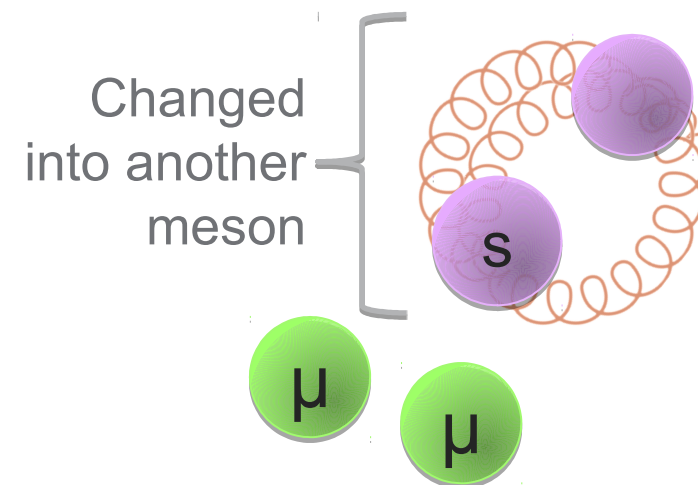
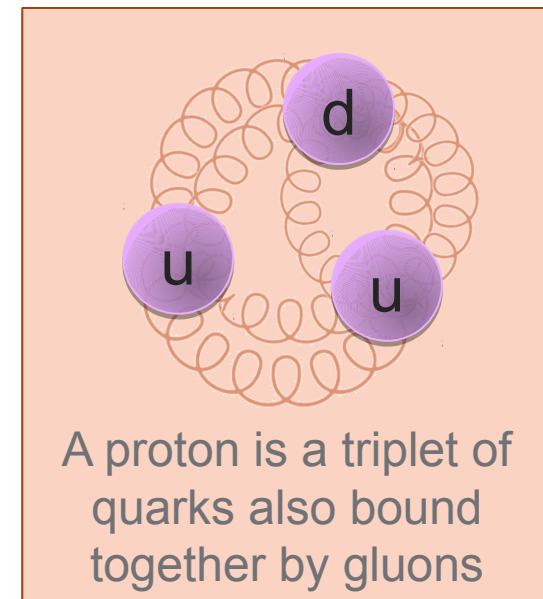
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B mesons

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...plus some leptons

More questions

B mesons (and Υ) contain b quarks.

- What are the names of particles containing c, s, d/u quarks?
- What is the mass of the B^0 meson? Where do you need to go to find this out?

$\Upsilon(4S)$ is an excited version of the Υ with a mass of something like $10.58 \text{ GeV}/c^2$

- What is the quark content of the Υ ?
- What does it decay to? Where do you need to go to find this out?

[Easy/bonus question]

One of the things on the previous slide is ***not*** a B meson (like the title says).

- Which?

What?

Experiments

Observables

A touch of CP violation

Rare decays and anomalies

The field in 2018

Experiments

Dramatis personae

- B factory
 - Collides e^+e^- at precisely the energy to create an $Y(4S)$.
 - This is a meson made of a $b\bar{b}$ pair. It decays almost 100% to $B\bar{B}$. Hence “factory”.
- What other designs are there?
 - Fixed target (HERA B)
 - “Pseudo” fixed target (LHCb)
 - General purpose detectors (CDF, D0, CMS, ATLAS)

Experiments

Dramatis personae

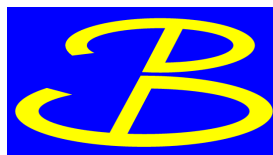
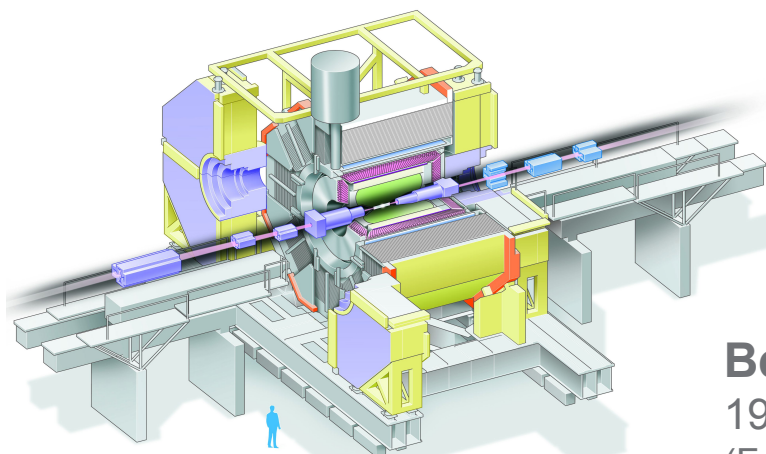
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The B factories

$$e^+e^- \rightarrow Y(4S) \rightarrow BB$$

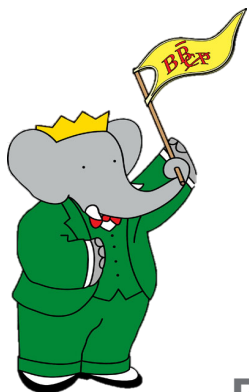
$$\sqrt{s} = 10.58 \text{ GeV (asymmetric beams)}$$

BB system is clean and well constrained



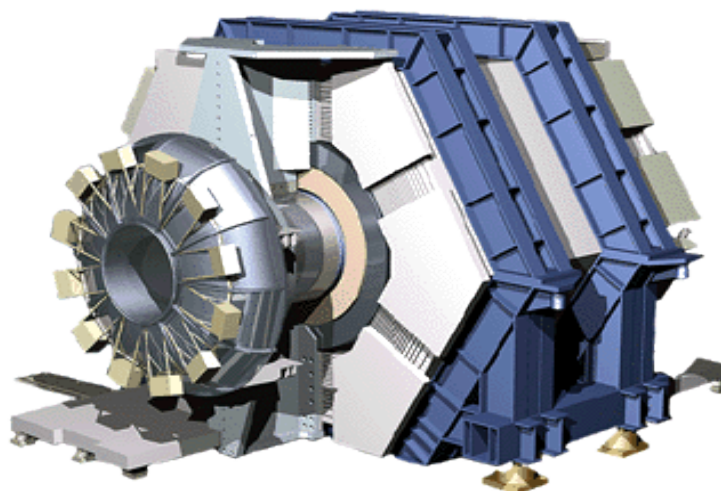
Belle

1999–2010, Japan
(French for 'beauty')



BaBar

1999–2008, USA
(The king of the elephants,
name sounds like BB)

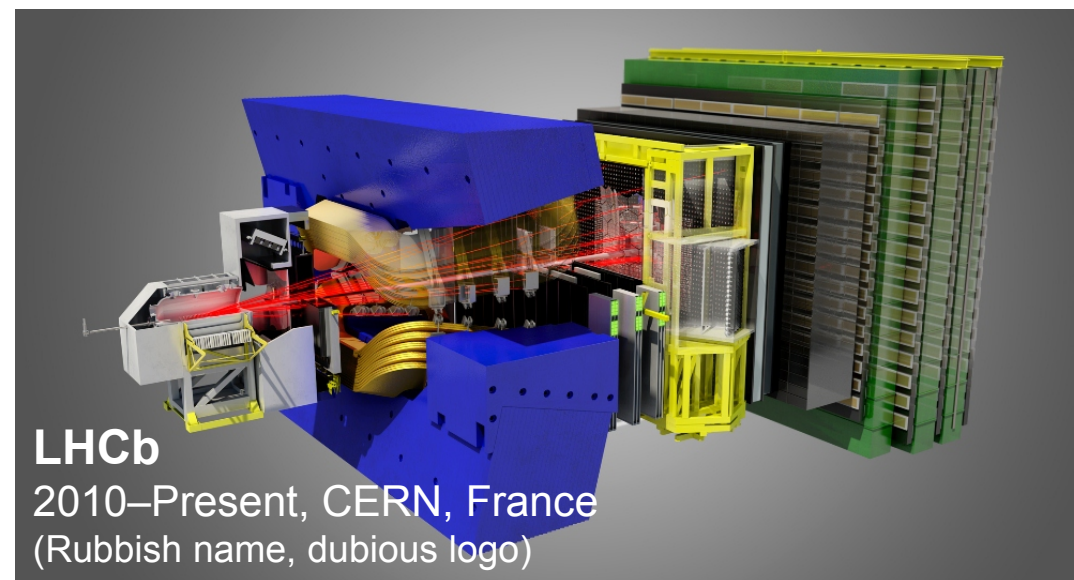
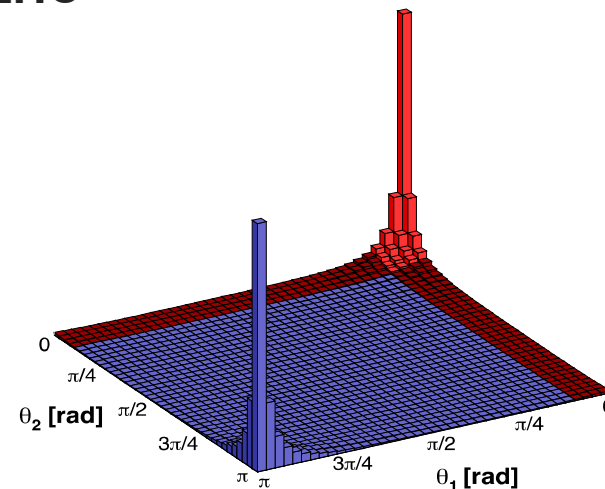


LHC

$$pp \rightarrow bb + ?$$

$$\sqrt{s}_{2012} = 4+4 \text{ TeV}$$

BB system is not
well constrained

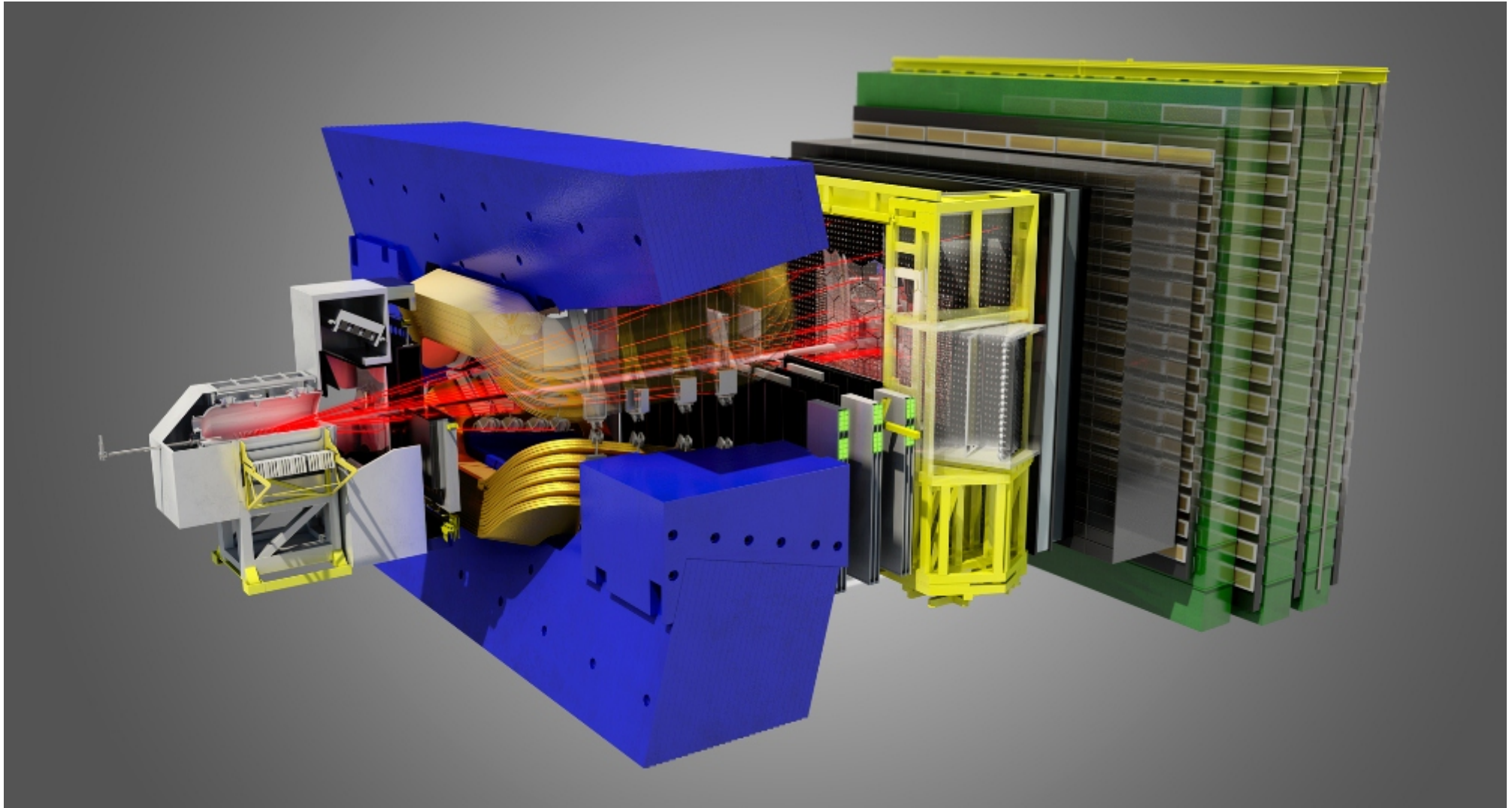


LHCb

2010–Present, CERN, France
(Rubbish name, dubious logo)

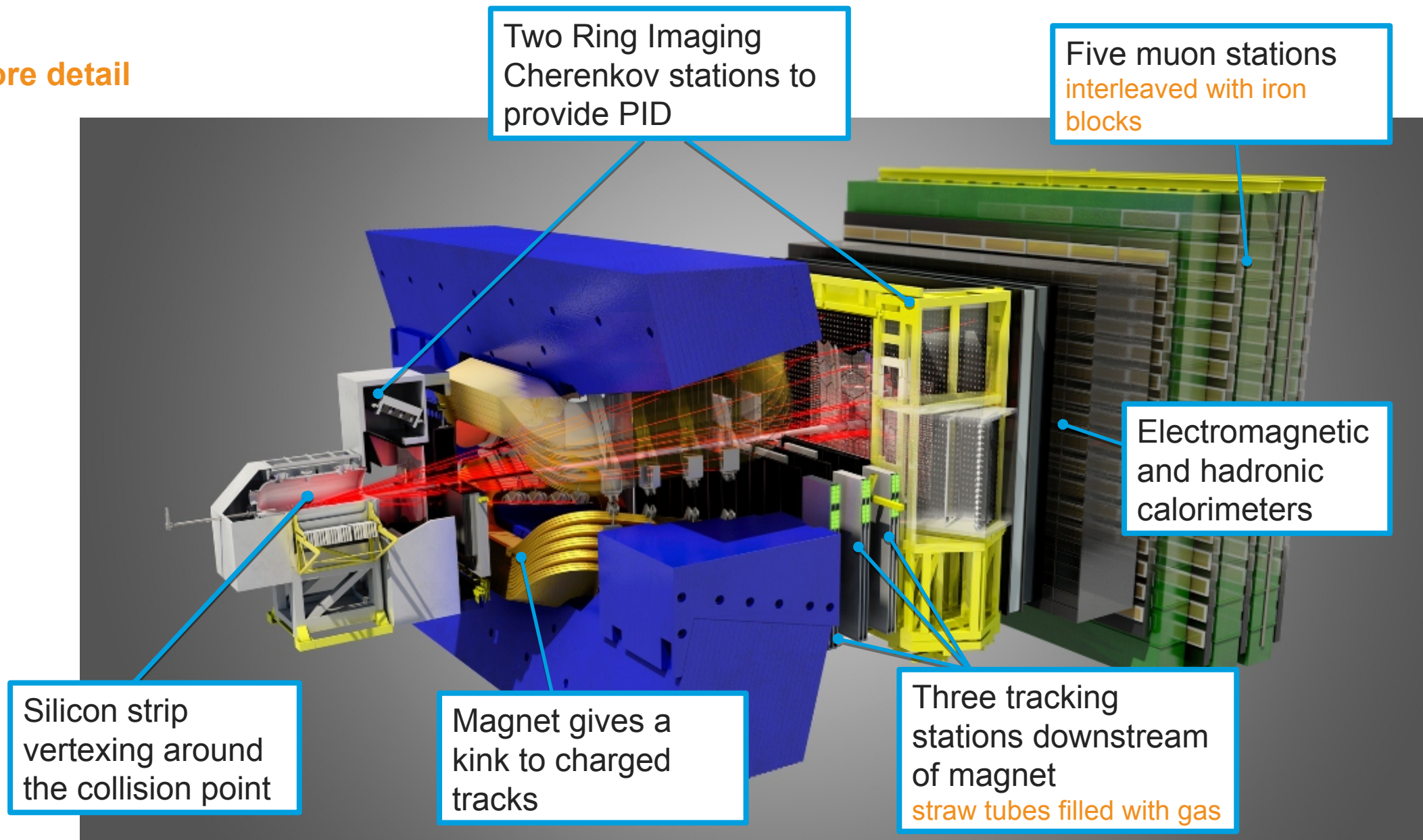
LHCb

A little bit more detail



LHCb

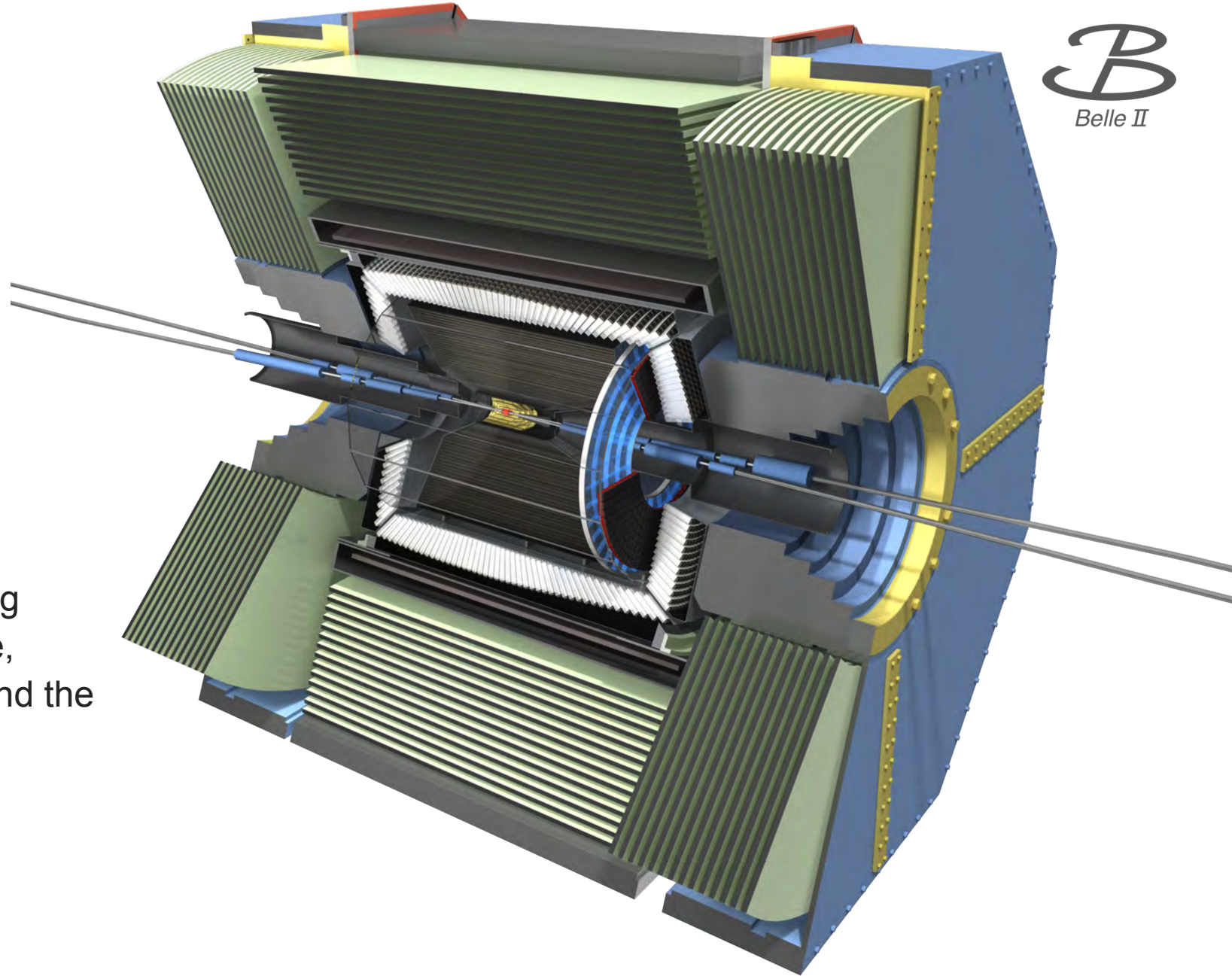
A little bit more detail



Belle II

New kid on the block

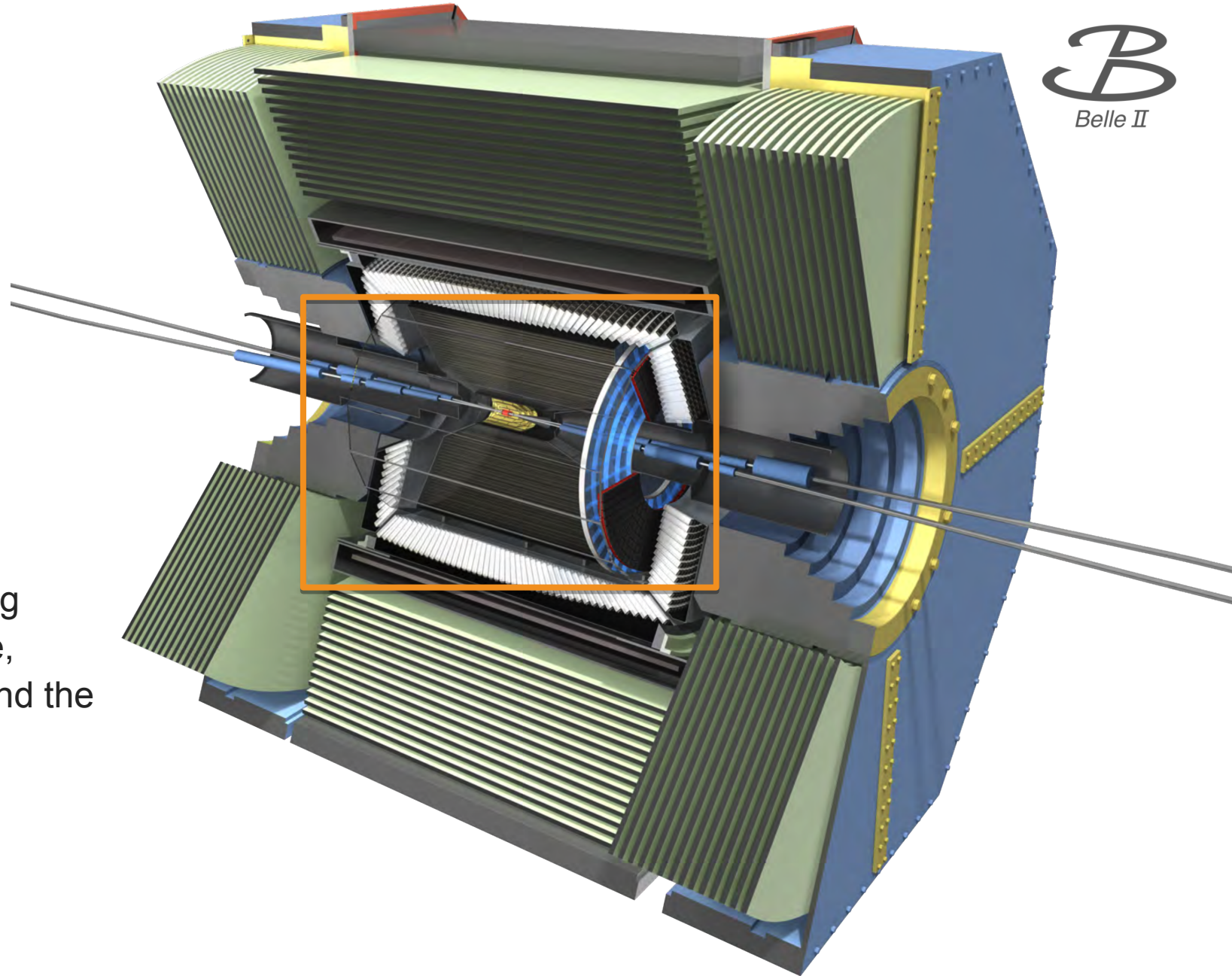
- An upgrade to Belle
 - New, larger tracker.
 - New particle ID system.
 - New high-precision vertexing
 - Faster read-out.
 - Fancier diagram.
 - Very similar logo.
- DESY works mostly on the vertexing system, but also: analysis, software, magnetic field mapping, tracking, and the electro-magnetic calorimeter.
- But why bother at all ... ?



Belle II

New kid on the block

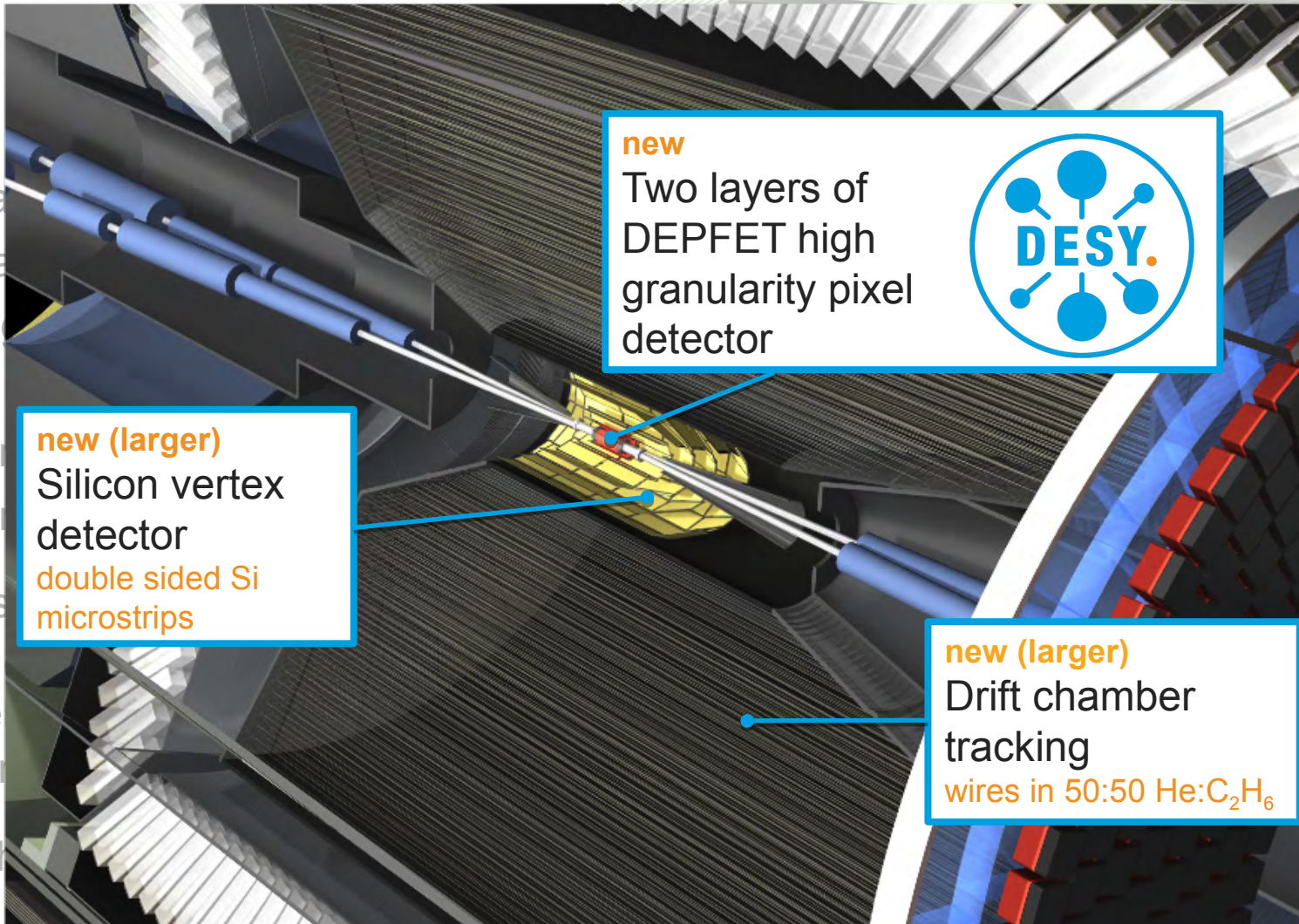
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Belle II

New kid on the block

- An upgrade
 - New, larger
 - New pixel
 - New high
 - Faster
 - Fancier
 - Very similar
- DESY works on the system, but the magnetic field is electro-magnetic
- But why both



Belle II

New kid on the block

- An upgrade to Belle
 - New, larger tracker.
 - New particle ID system
 - New high
 - Faster re
 - Fancier
 - Very similar logo.

- DESY will build the new Belle II system, a new particle ID system and the electro-magnetic calorimeter.

- But why bother at all ... ?

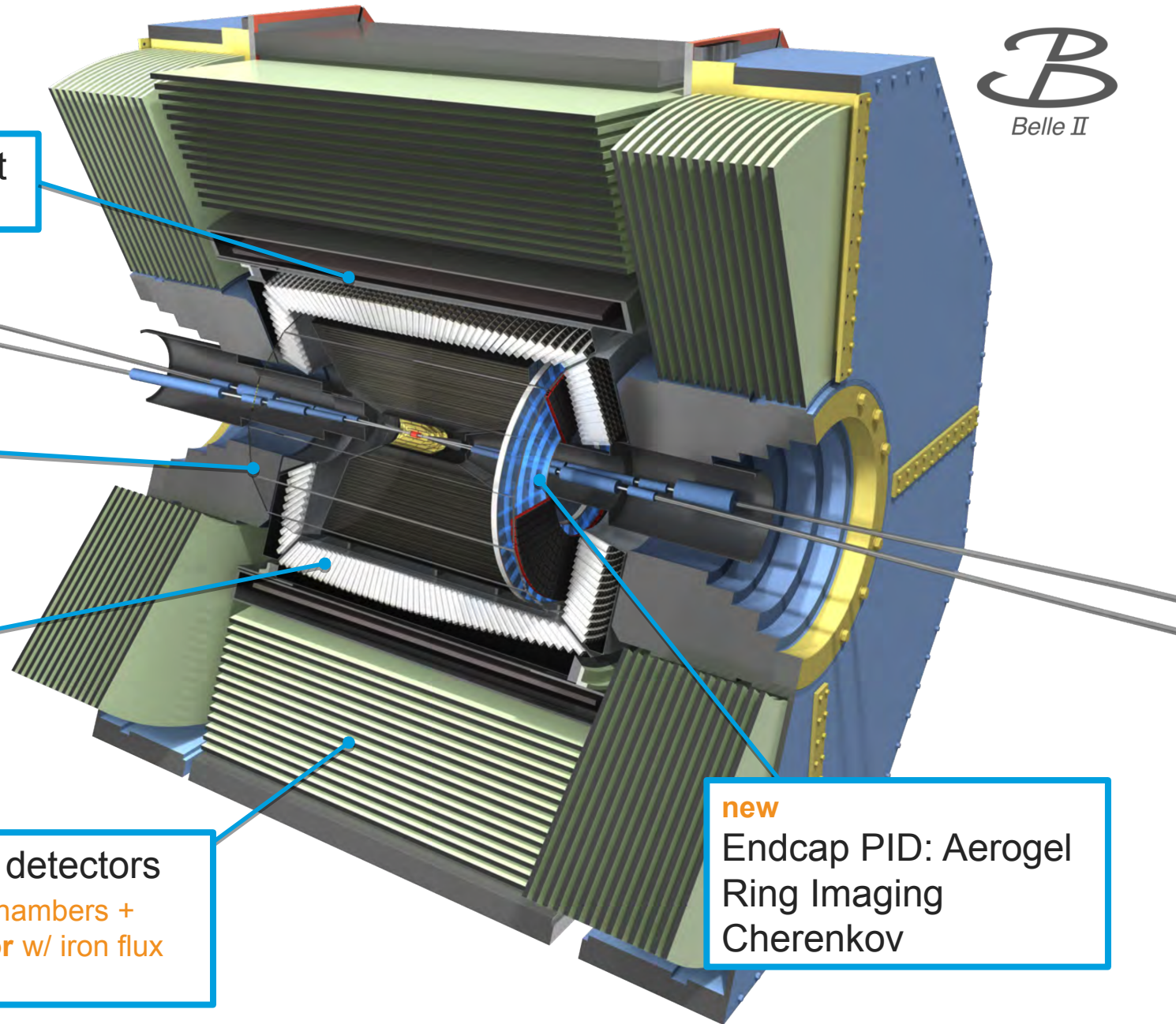
new
Barrel particle ID
quartz bars totally
internally reflect
Cherenkov photons

Electromagnetic
calorimeter
CsI(Tl) crystals... **new readout**

K_L and muon detectors
Resistive plate chambers +
(new) scintillator w/ iron flux
return

new
Endcap PID: Aerogel
Ring Imaging
Cherenkov

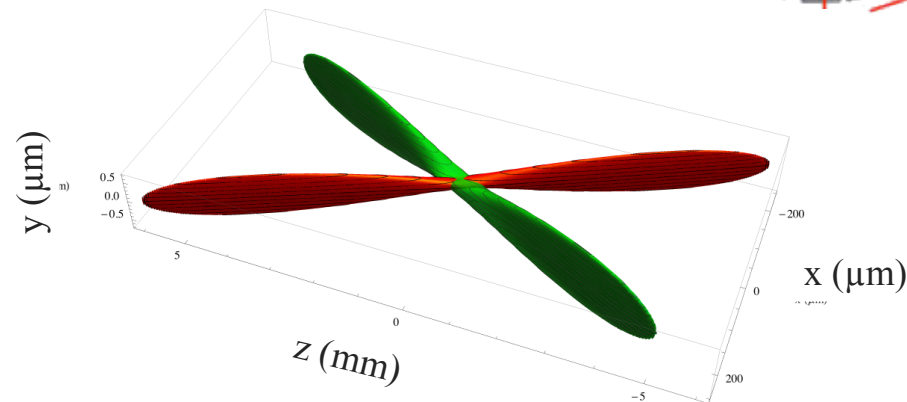
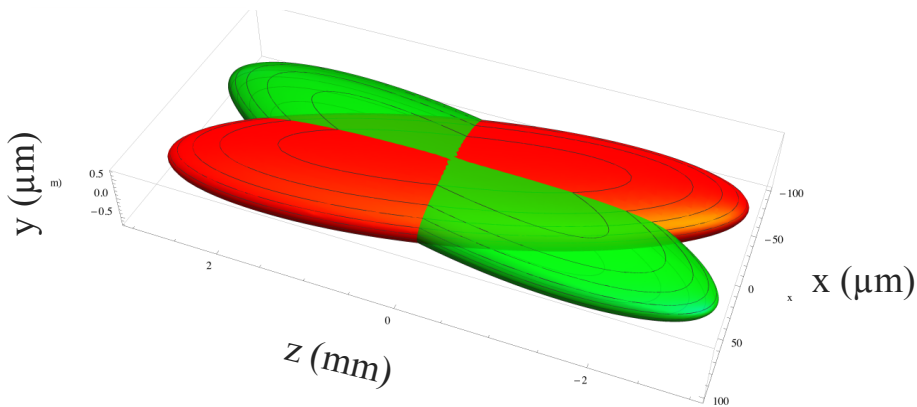
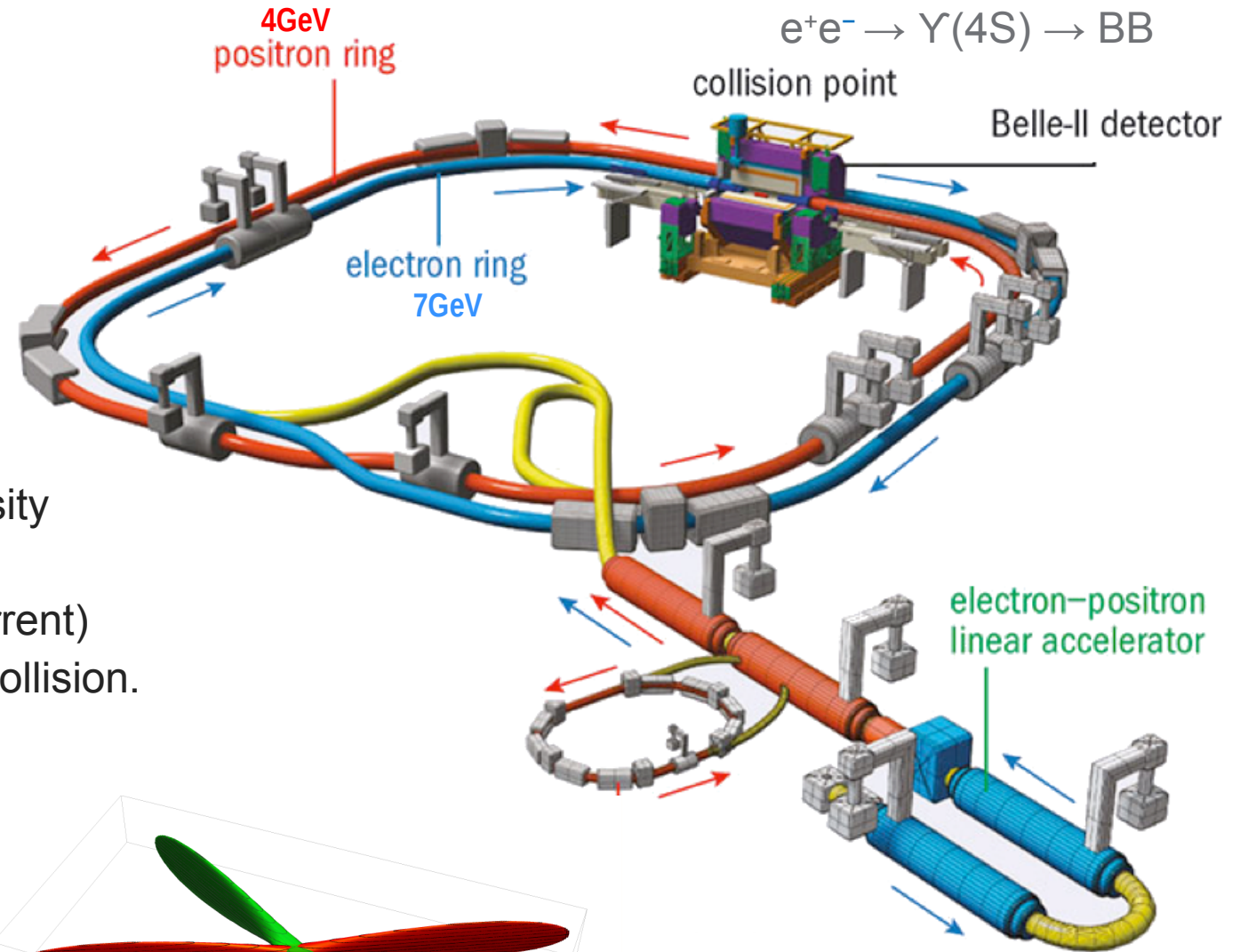
magnet
1.5T



Why bother at all ... ?

Accelerator people are very smart

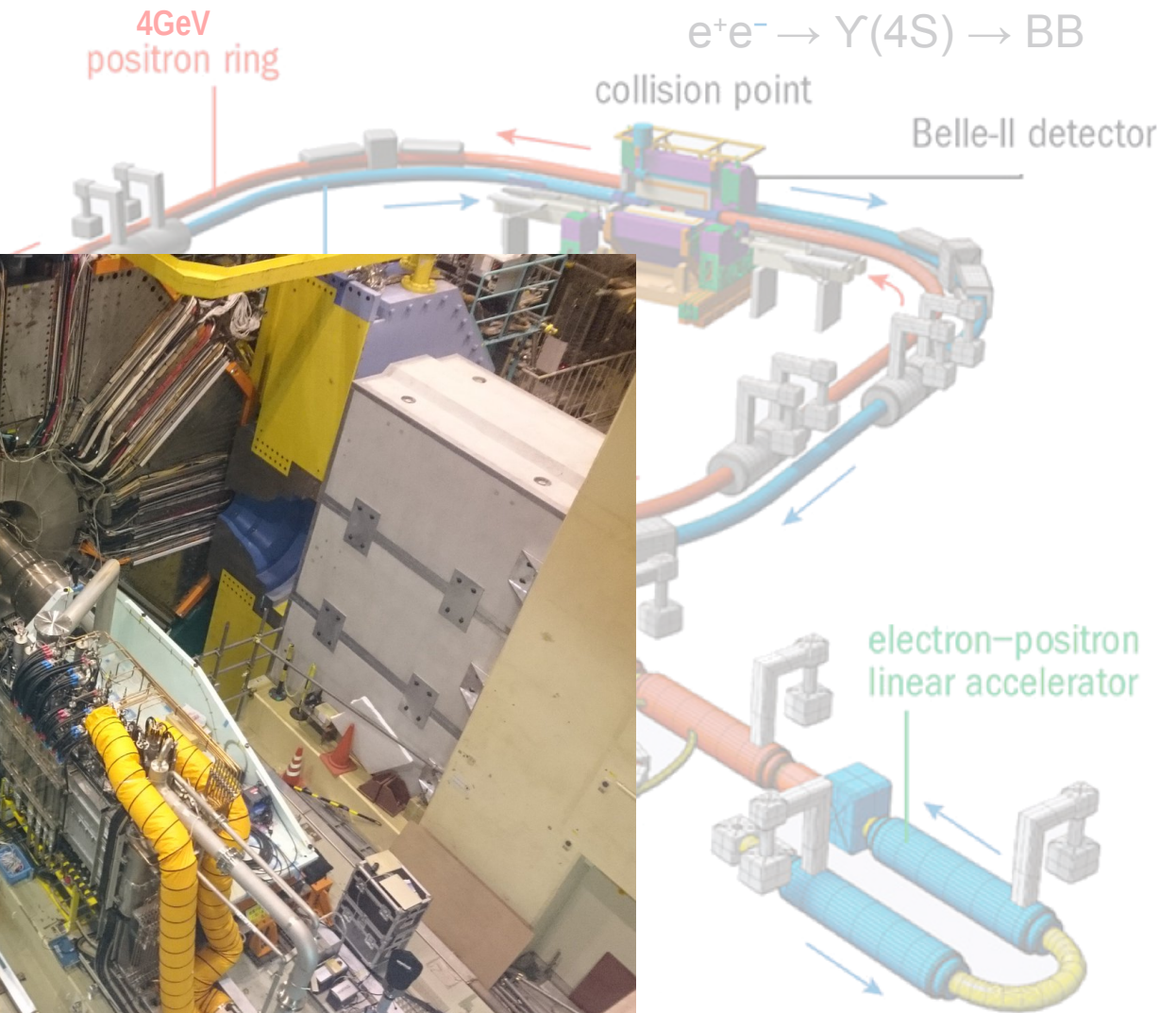
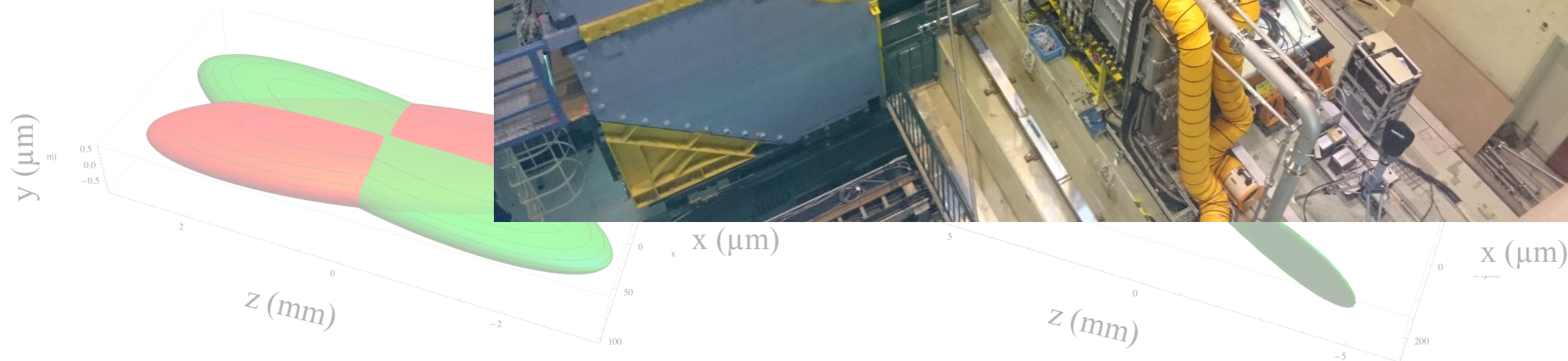
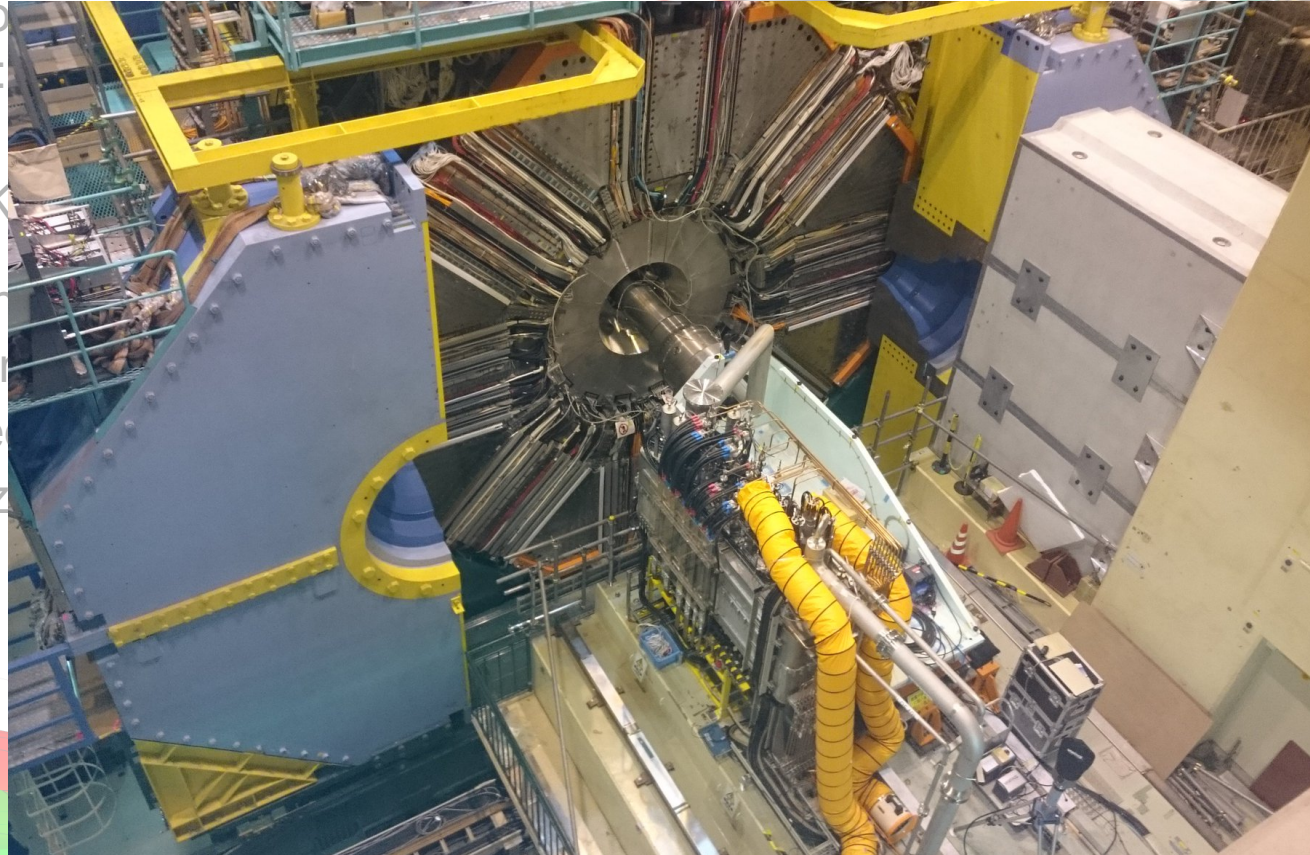
- A big part of the reason comes from an upgraded accelerator:
 - Belle → Belle II
 - KEKB → SuperKEKB
- A factor 40 increase in instantaneous luminosity (something like ~ the number of collisions)
 - ×2 from upgraded ring (higher beam current)
 - ×20 from squeezing the beams before collision.



Why bother at all ... ?

Accelerator people are very smart

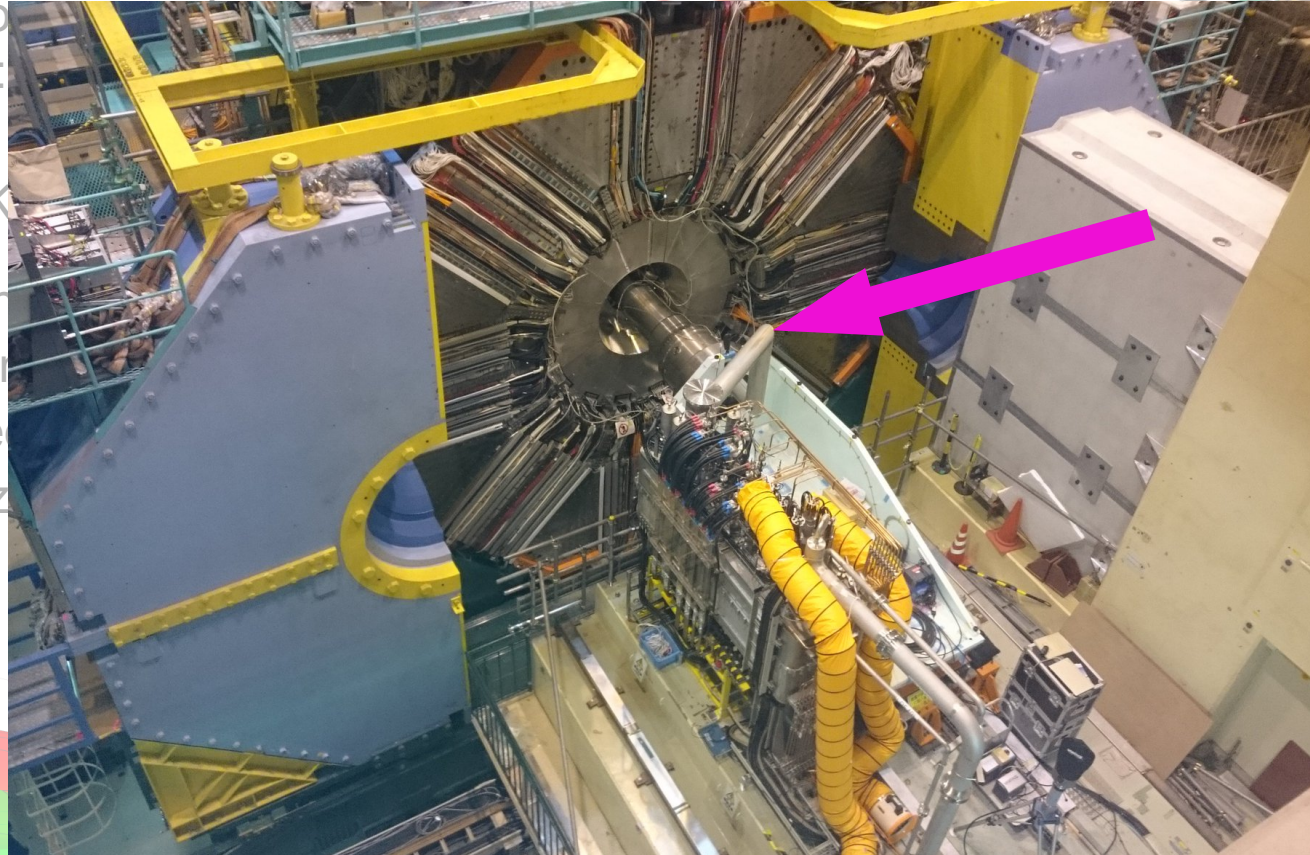
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 - Belle $\rightarrow$ Belle II
 - KEKB $\rightarrow$ SuperKEKB
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 - $\times 2$ from upgraded
 - $\times 20$ from squeezing



Why bother at all ... ?

Accelerator people are very smart

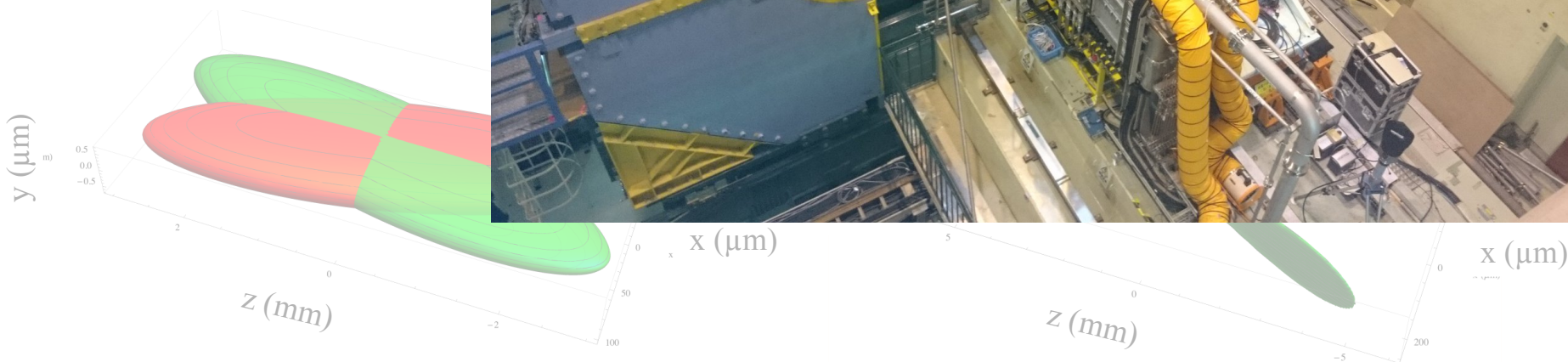
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4GeV
positron ring

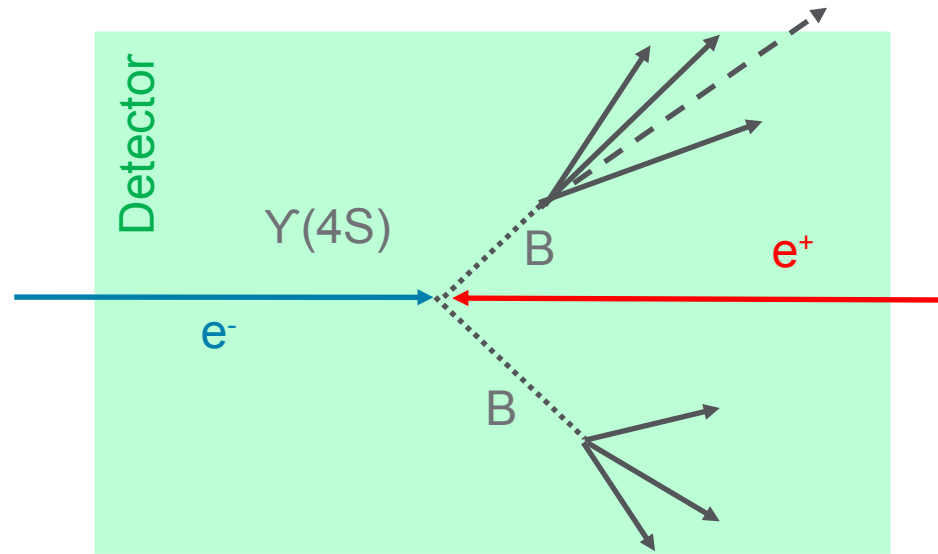
$e^+e^- \rightarrow Y(4S) \rightarrow BB$
collision point
Belle-II detector

electron-positron
linear accelerator

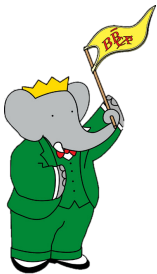


The B factories

BB system is clean and well constrained



- Collision energy is well known
- Good at neutral particles / missing energy / neutrino final states / taus



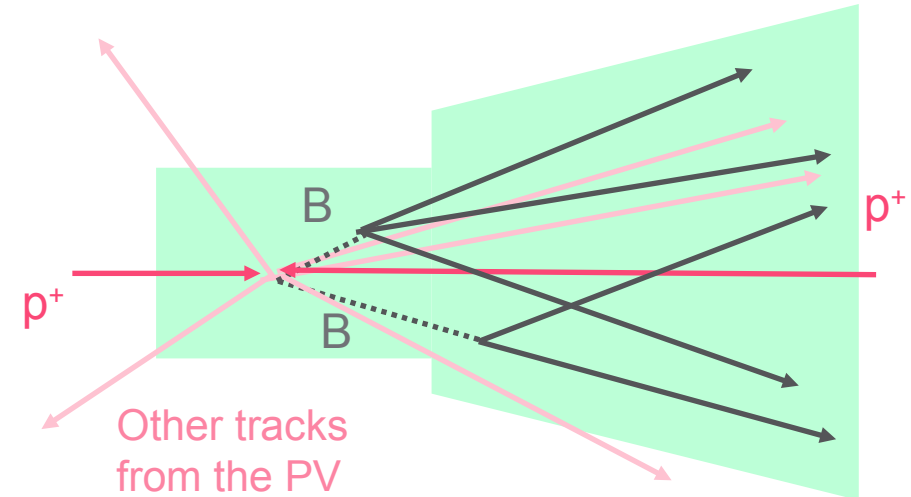
- Single particle tracking
- Good at vertexing B decays
- Good at hadron identification

LHC

$$pp \rightarrow bb + ?$$

$$\sqrt{s}_{2012} = 4+4 \text{ TeV}$$

BB system is not well constrained



- Collision energy not well known
- Higher energy, running longer @ high production
- Very good at muons



What?

Experiments

Observables

A touch of CP violation

Rare decays and anomalies

The field in 2018

Observables

Ratio, difference, asymmetry

- Almost all flavour physics papers are measuring some kind of **constructed observable**.
- The branching ratio / branching fraction is the ratio of the rate decay for $B \rightarrow f$ to all decays of the B.

$$\begin{aligned}\mathcal{B}(B \rightarrow f) &\equiv \frac{\Gamma(B \rightarrow f)}{\Gamma_{\text{T}}} \\ &= \frac{N_{B \rightarrow f}}{\epsilon_{B \rightarrow f}} \frac{\epsilon_{\text{norm.}}}{N_{\text{norm.}}} \mathcal{B}(\text{norm.})\end{aligned}$$

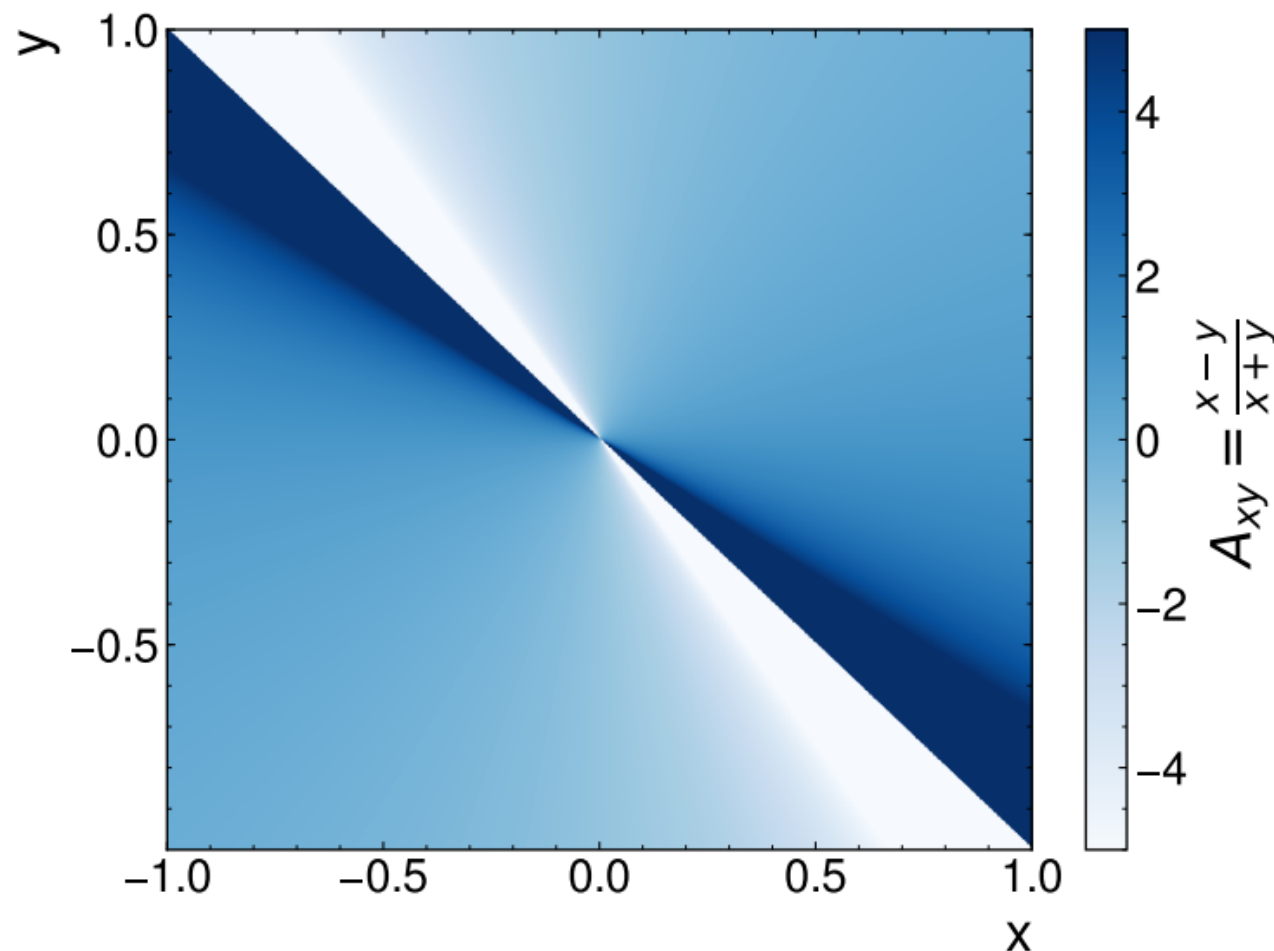
- It's very common to make either: a **ratio**, a **difference**, or **asymmetry**, or some combination of the three.
- The first two are easy. Usually denoted “R” and Δ .
- Examples: R_{D^*} , R_{K^*} , angular observables.

Observables

Ratio, difference, asymmetry

- Often we form asymmetries
 - “CP asymmetries”
 - or “isospin asymmetries”
 - or “time-dependent-CP-asymmetries”.
- These are all the same basic quantity **formed between rates of different decay modes**.
- That quantity is the difference over the sum.

$$\frac{x - y}{(x + y)}$$



Yet more questions

Here are some observables that I've mentioned already ..

$$\frac{\mathcal{B}(B^+ \rightarrow D^* \tau^+ \nu_\tau)}{\mathcal{B}(B^+ \rightarrow D^* \mu^+ \nu_\mu)}$$

$$\frac{\mathcal{B}(B \rightarrow K^* \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^* e^+ e^-)}$$

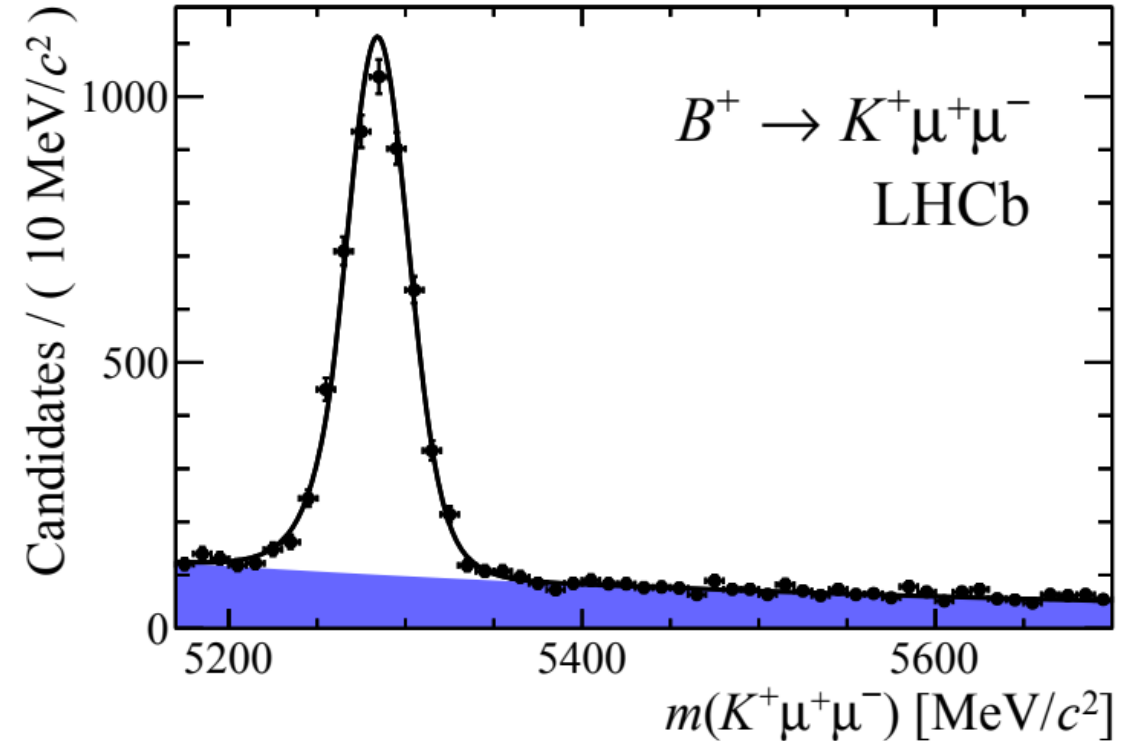
$$\frac{\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) - \Gamma(B^0 \rightarrow K^+ \pi^-)}{\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) + \Gamma(B^0 \rightarrow K^+ \pi^-)}$$

- Can you tell me the names just by looking at the definitions?
- Why do we make them like this?

How to do a b-physics measurement

A template

- 1 Figure out a smart observable to measure.
Smart means:
 - Minimises experimental uncertainties.
 - Is sensitive to some kind of extension to the SM –or– noone else ever did it before.
- 2 Look for candidate B meson decays for whatever final state you care about.
- 3 Make some event selection cuts to minimise the background.
- 4 Make a histogram of something (probably something like the **invariant mass**).
- 5 Either count the candidates you have, or fit signal + background model → returns you a “yield”.
- 6 Relate the yield or fit parameters to your observable.



$$m_{K\mu\mu} \equiv \sqrt{((p_K + p_\mu + p_\mu)^\alpha (p_K + p_\mu + p_\mu)_\alpha)}$$

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