Heavy flavour physics at the LHC

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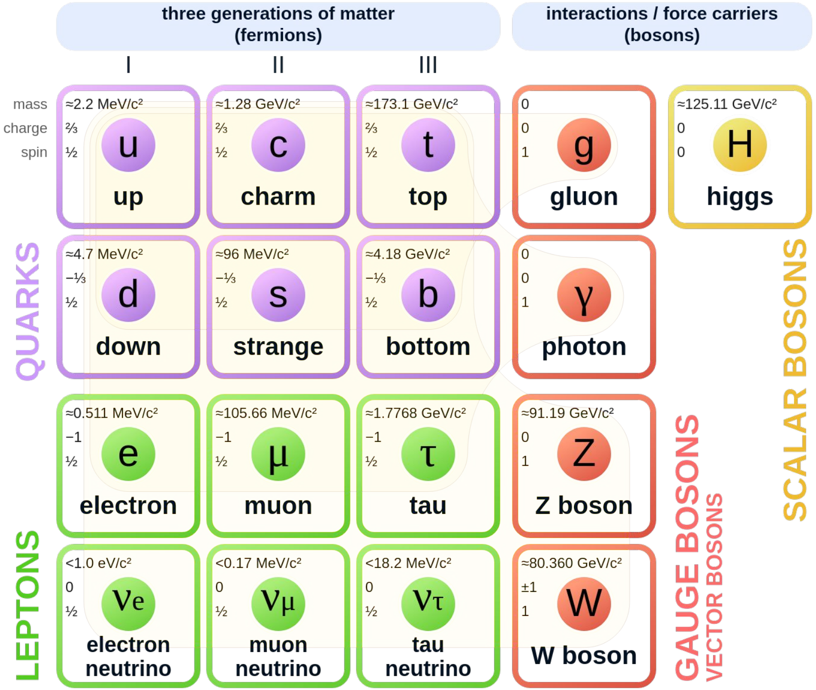
Summary

- Overview about the Standard Model of particle physics
- Particle identification and associated technologies
- Example of physics studies
  - → *CP* violation in three-body *B*-meson decays
  - → Rare *B*-decays
- Conclusion / perspectives

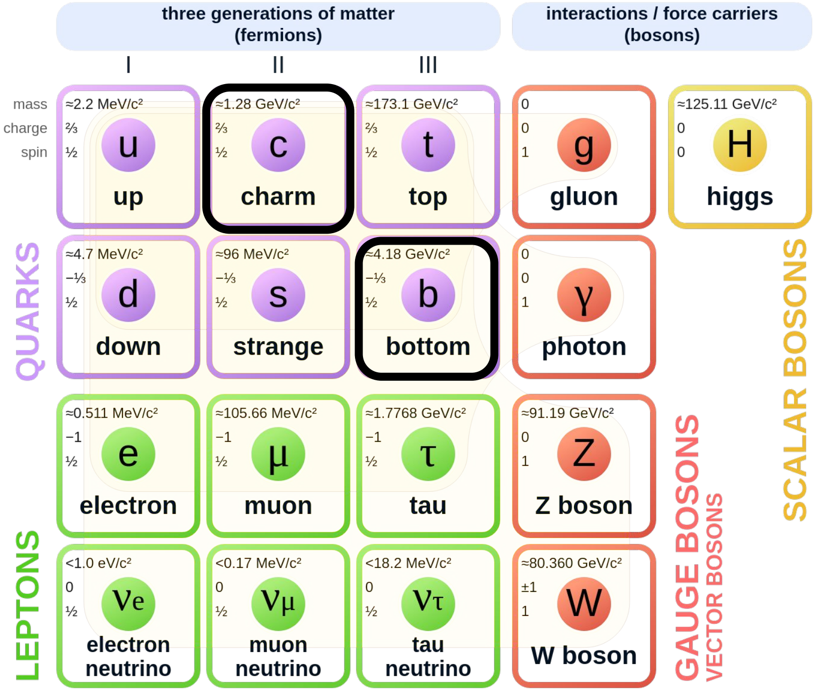
The Standard Model of particle physics

The Standard Model of Particle Physics



Flavour: quantum number that distinguishes quarks and leptons

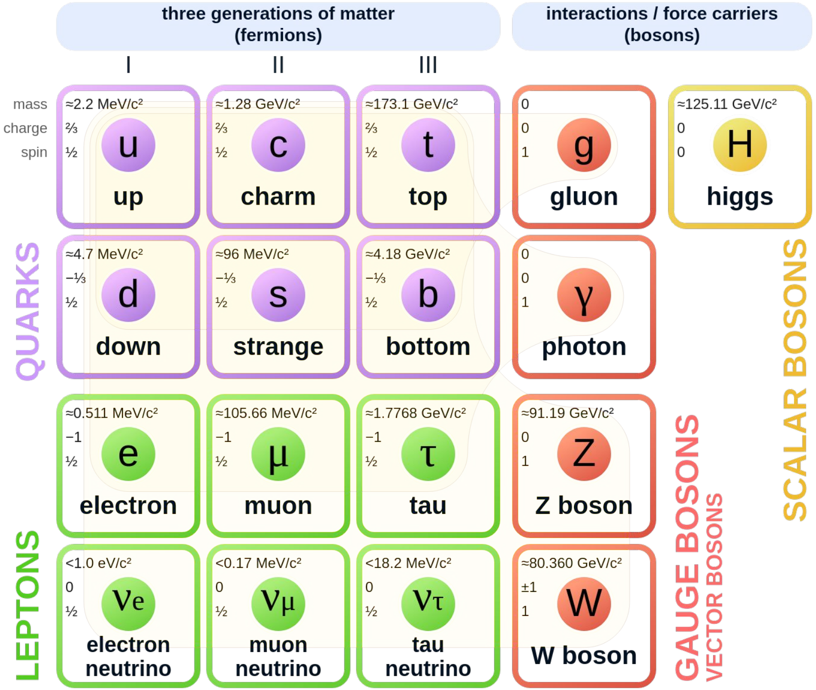
The Standard Model of Particle Physics



Flavour: quantum number that distinguishes quarks and leptons

Heavy flavours

The Standard Model of Particle Physics



Flavour: quantum number that distinguishes quarks and leptons

Some take-away lessons about the SM

- ❑ Quarks and leptons are both elementary
- ❑ Leptons have integer electric charge; quarks have fractional charge
- ❑ Quarks and leptons are subjected to different *fundamental interactions* (weak, strong, EM)
- ❑ Two or more quarks combine to form hadrons
  → Hadrons = baryons + mesons
- ❑ Free hadrons are believed to be unstable and *decay* into other particles
  → The proton seems to be an exception
  → Decay = interaction

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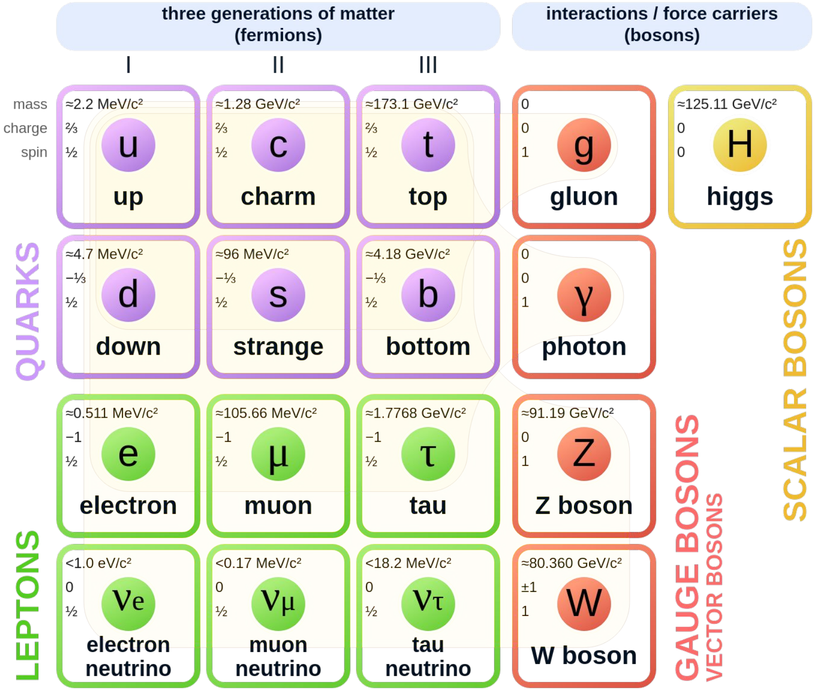

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For more details: Philipe de Fabritiis lectures

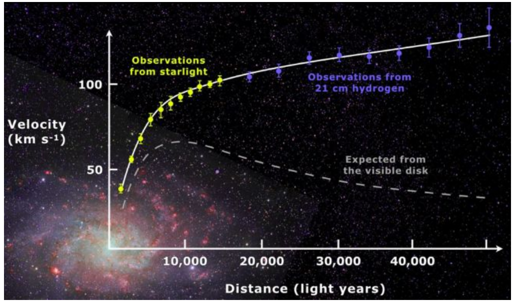
Scientific theory

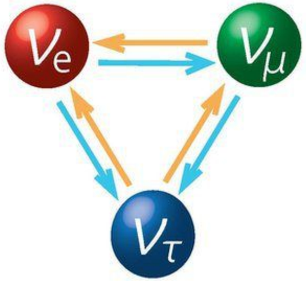
- ❑ Theory with solid mathematical model which gives prediction that can be tested by experiments
  ✅ Scientific theory
- ❑ A solid mathematical model which gives prediction that can be tested by experiments and measurements but no good interpretation
  ✅ Still scientific theory

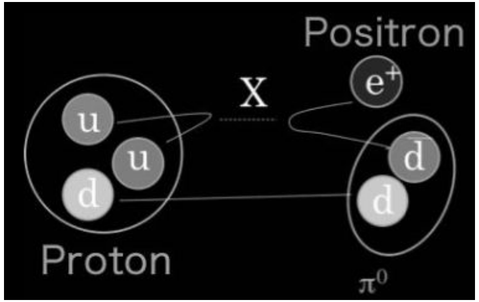
The Standard Model has turned out to be astonishingly successful when compared to measurements

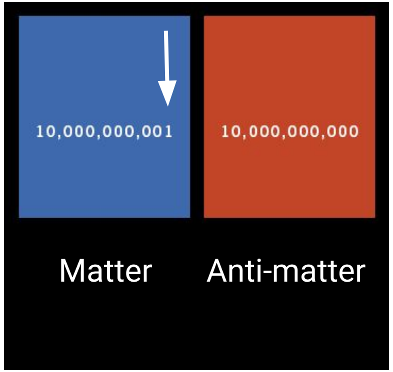
(Some) unsolved problems / puzzles in particle physics

- ☐ Dark matter
- ☐ Neutrino masses
- ☐ Proton decay
- ☐ Baryon asymmetry









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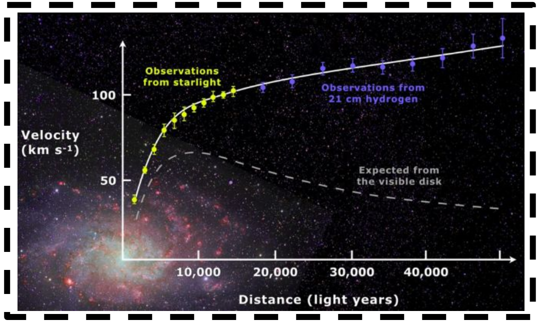

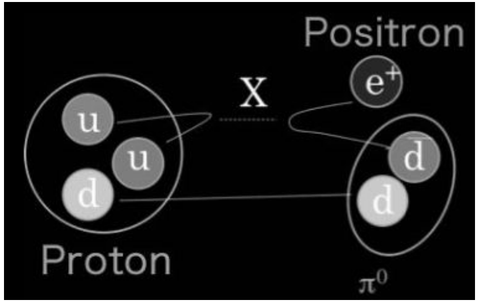

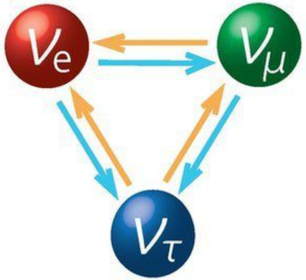

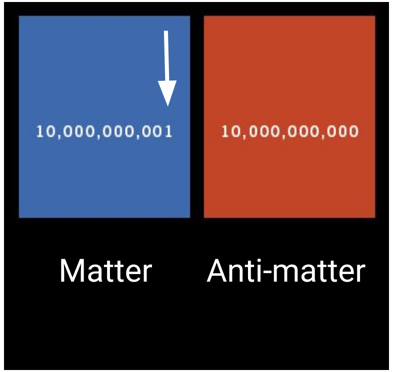

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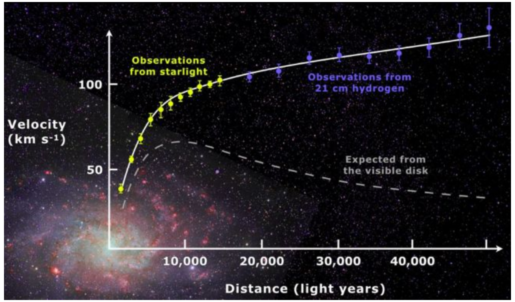

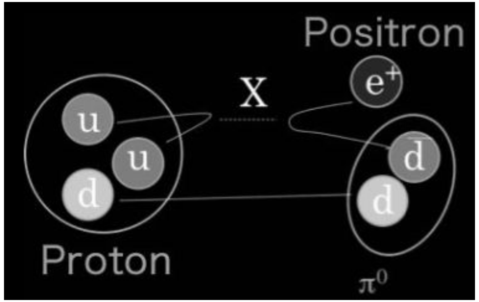

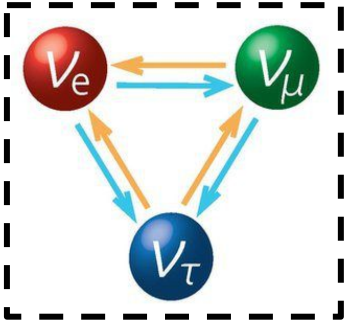

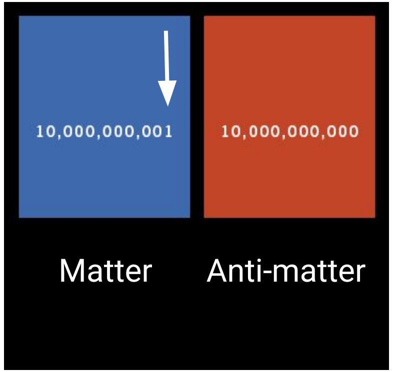

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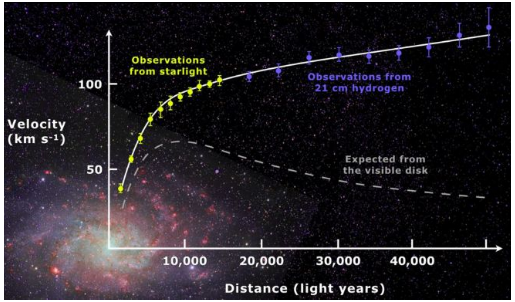

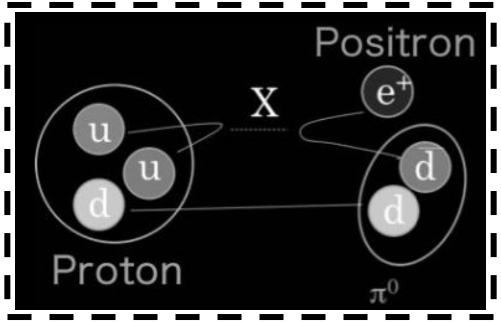

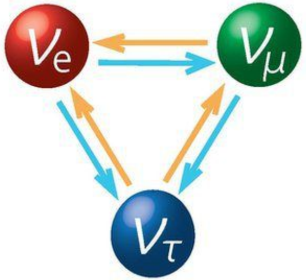

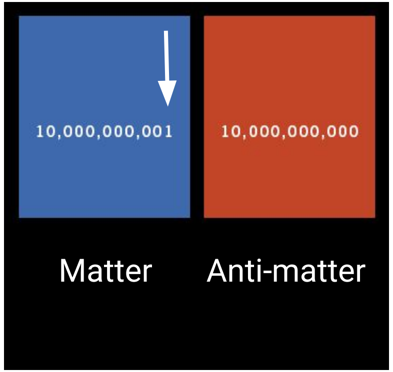

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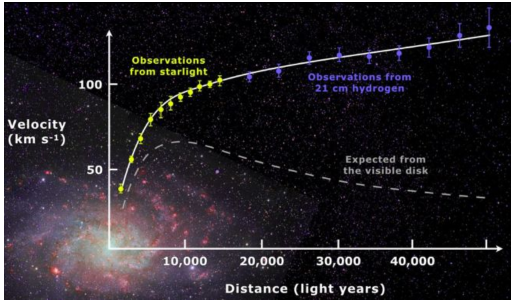
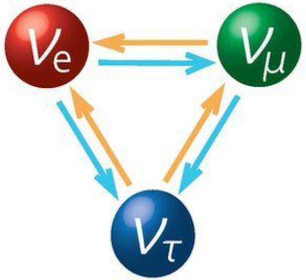
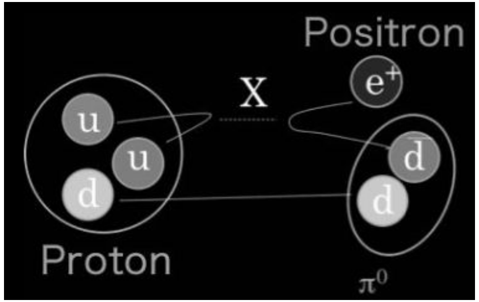
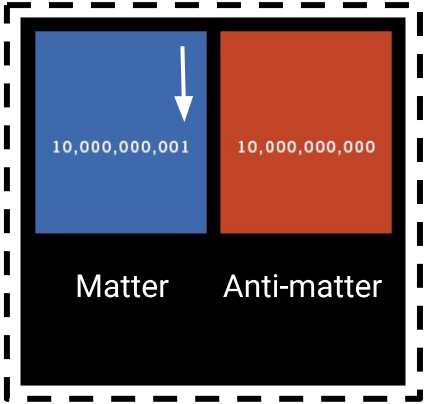




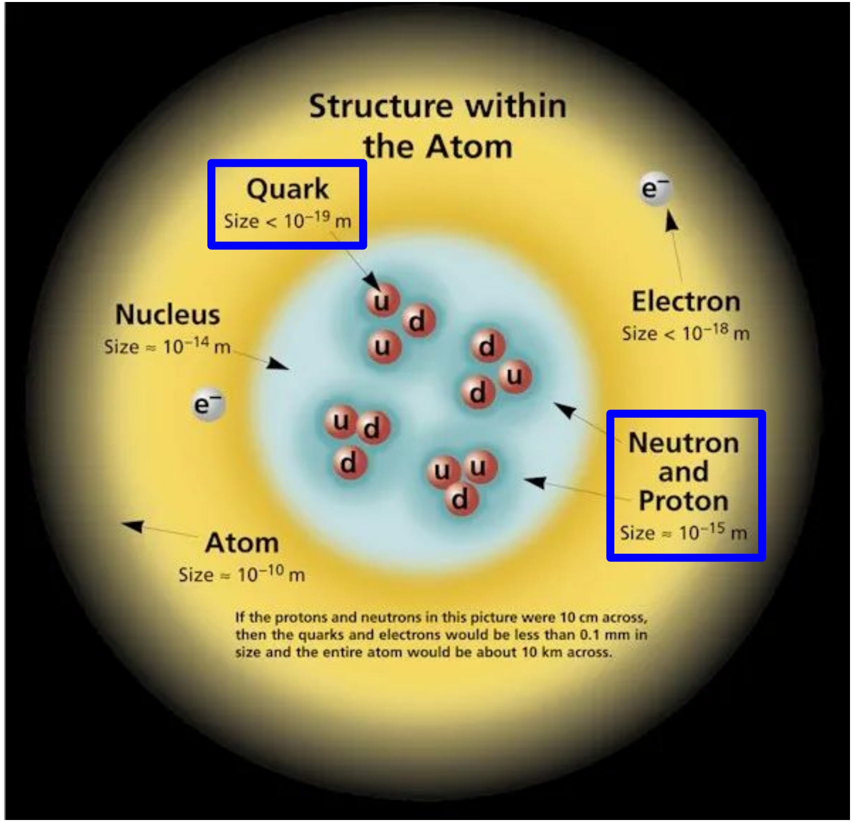




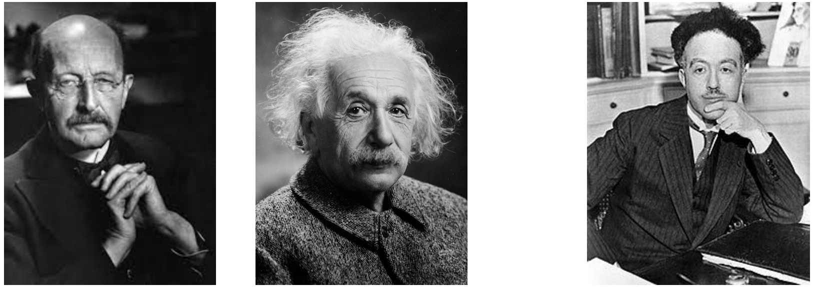
Why flavour is important?

- ❑ Most of the parameters in the SM are related to the flavour sector
  → Quark/lepton masses, mixing angles
- ❑ The flavour sector provides the only source of ***CP*-violation** in the SM
  → Necessary for baryogenesis in the SM
- ❑ Indirect measurements can probe mass scales well beyond directly accessible at the current particle accelerators

How to probe elementary particles?



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



$$E = h\nu = \frac{hc}{\lambda} \qquad p = \frac{h}{\lambda}$$

$$10^{-15}\mathrm{m} \Rightarrow E > \mathrm{GeV}$$

$$1\mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$$

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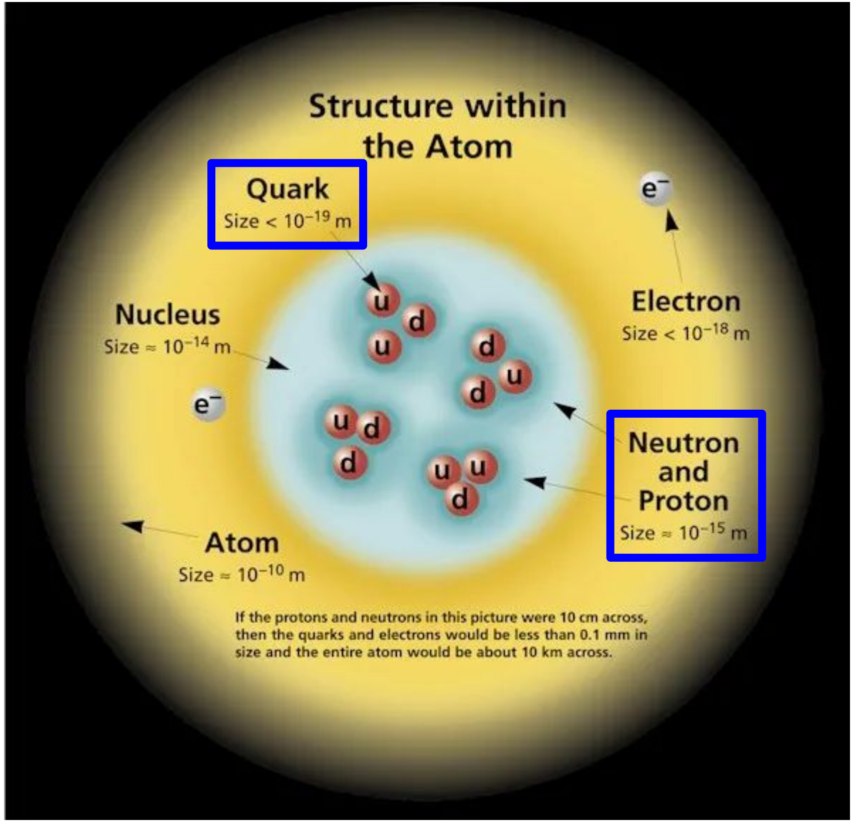

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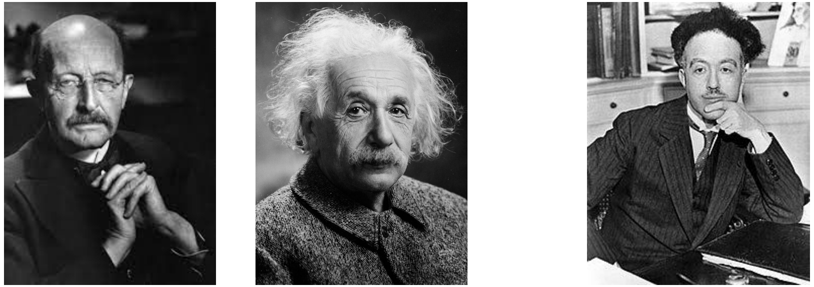

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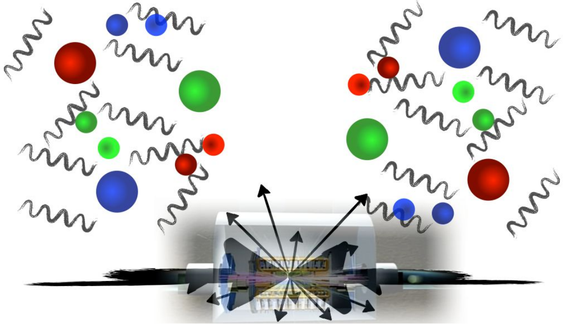


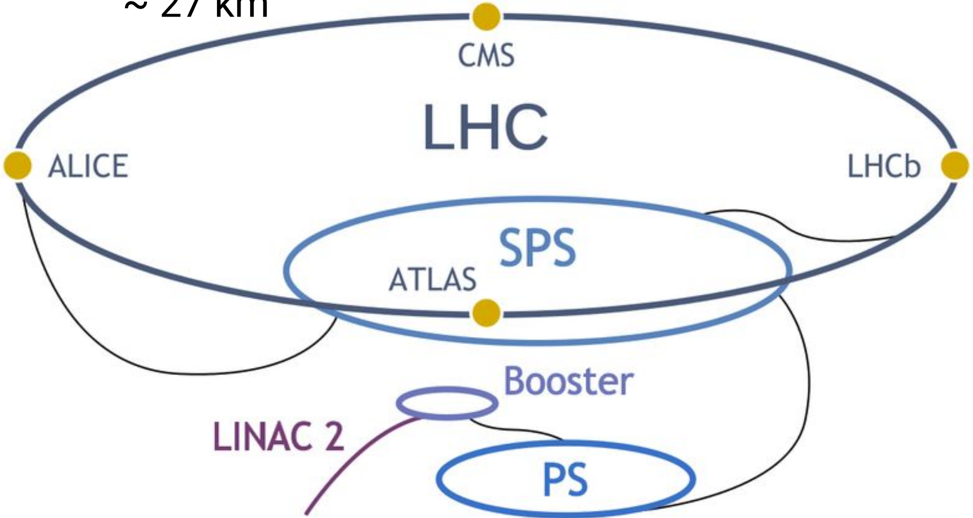
The Large Hadron Collider


3/3/2022


20/7/2022

$$E_p = 7\,\mathrm{TeV} \Rightarrow v_p = 0.999999991\,\mathrm{c}$$

~ 27 km



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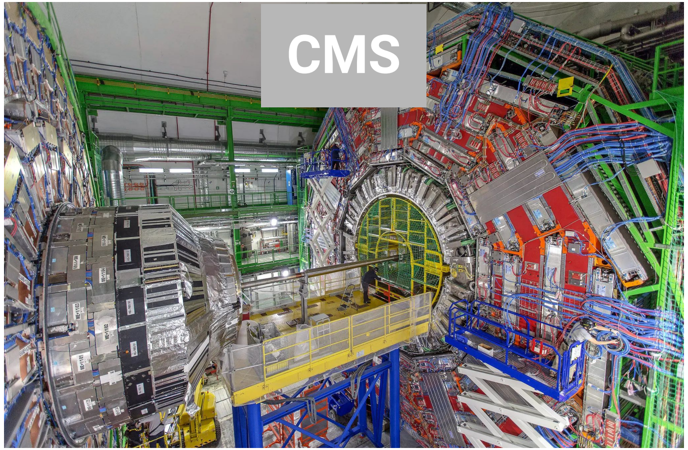
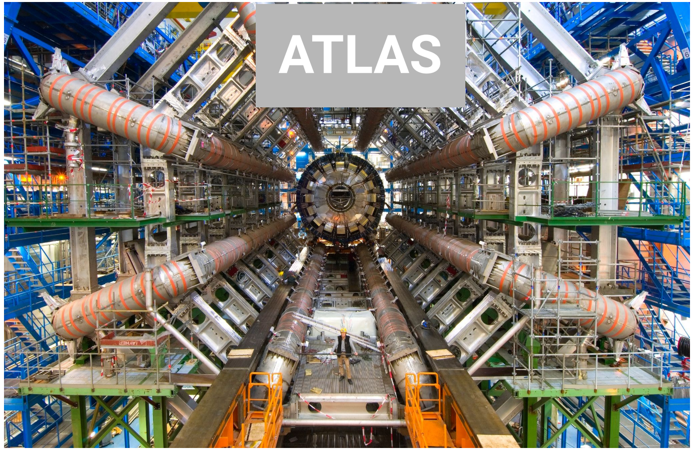
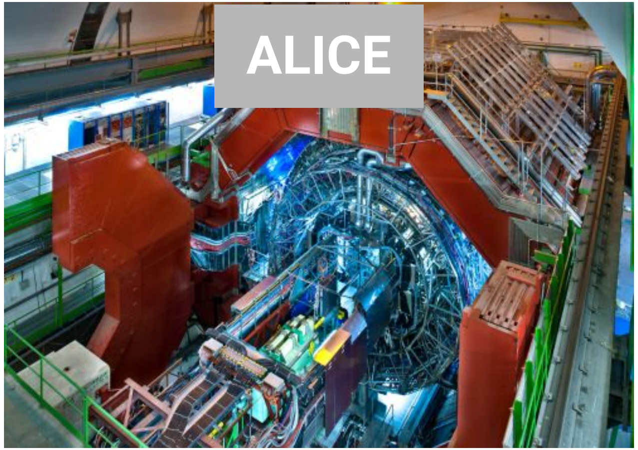

CMS


ATLAS

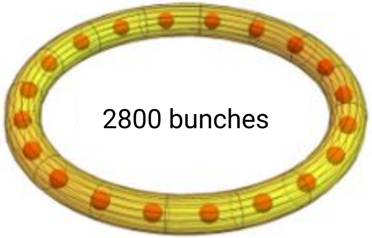

LHCb

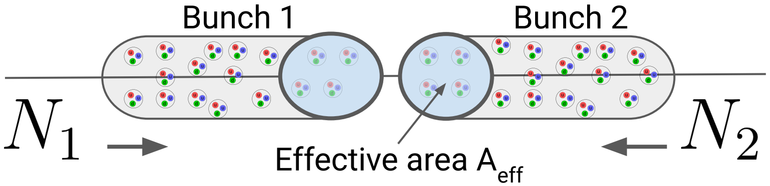

ALICE

Taking a closer look

- ❑ Beams: cylinder-like bunches ~7.5 cm long and $A_{\text{eff}} \sim 16\text{x}16\ \mu\text{m}^2$
- ❑ Each bunch contains $N \sim 10^{11}$ protons
- ❑ Between each consecutive bunch there are 7.5 m
  → Bunch spacing $t = 7.5\ \text{m}/3.10^8\ \text{m/s} \rightarrow t = 25\ \text{ns}$
- ❑ Luminosity

$$\mathcal{L} = \frac{N_1 N_2}{A_{\text{eff}} t} \sim 10^{34} \text{cm}^{-2} \text{s}^{-1}$$





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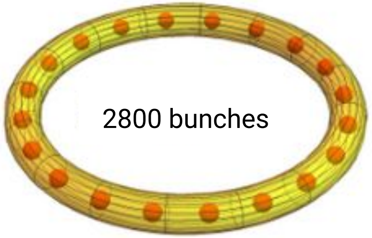

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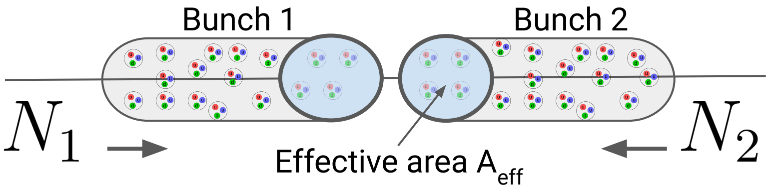
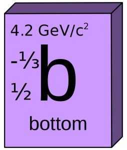


- What about **beauty**?

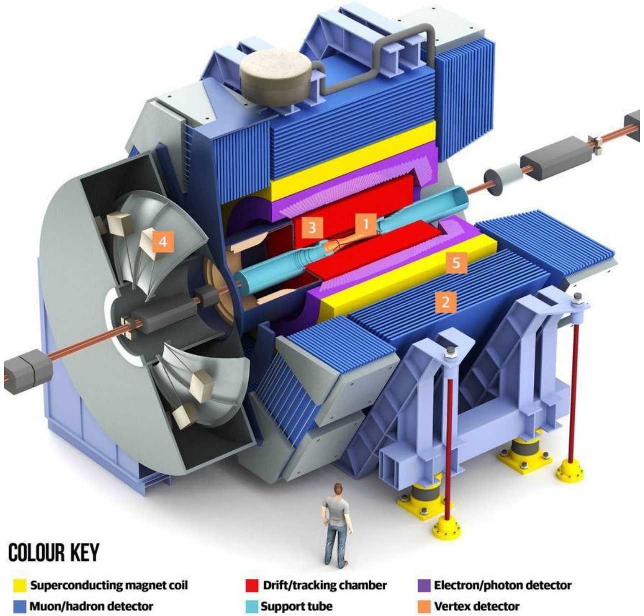


  → 10^{12} $b^{-}b^{+}$ produced in one year of data taking at 14 TeV

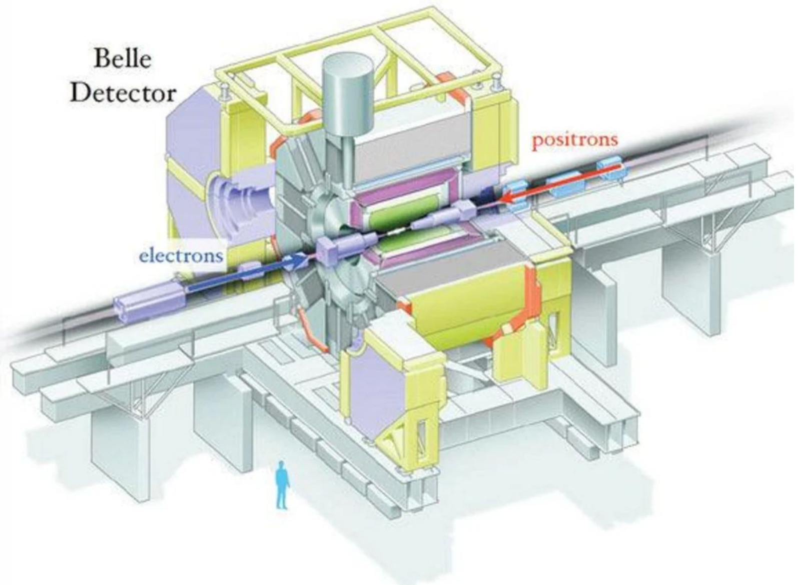
B-factories

- Electron-positron collider operating in the 2000’s
- *B*-mesons produced via Υ(4S)
- Environment much cleaner

BaBar (SLAC)



Belle (KEK)



Particle identification
and
associated technologies

When can we detect a particle?

Particles can only be measured, if they

1. **live long enough** after creation to reach the detector

→ The majority of particles are short-lived

	γ	p	n	$e^{\pm}$	$\mu^{\pm}$	$\pi^{\pm}$	$K^{\pm}$
τ_0	∞	∞	∞	∞	2.2 μs	26 ns	12 ns
L_{track} (p = 1 GeV)	∞	∞	∞	∞	6.1 km	5.5 m	6.4 m

→ Track length $\boldsymbol{L_{\text{track}} = v\tau = c\beta\gamma\tau_0}$ where τ_0 is the lifetime at rest

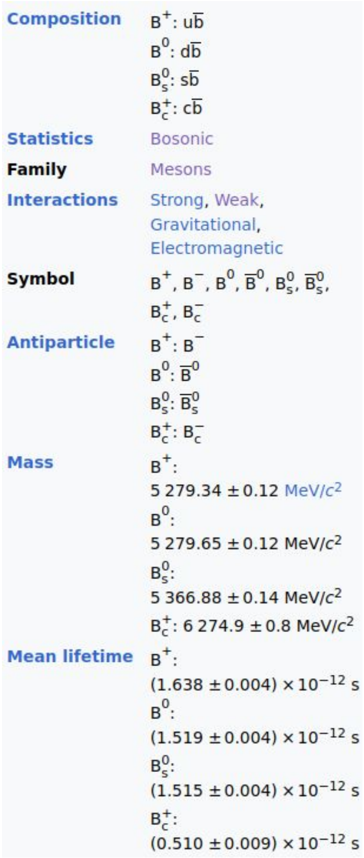
→ Small but finite life-time: ***B*-mesons have ps lifetimes (~10^{-12} s)**

2. **interact with the detector**

→ Deposition of energy (dE/dx), transferred into a detector signal

→ Neutrinos interact only weakly: need large detector volumes or giant fluxes (reactor experiments)

B-mesons



Composition	B^+: $u\bar{b}$ B^0: $d\bar{b}$ B^0_s: $s\bar{b}$ B^+_c: $c\bar{b}$
Statistics	Bosonic
Family	Mesons
Interactions	Strong, Weak, Gravitational, Electromagnetic
Symbol	B^+, B^-, B^0, $\overline{B}^0$, B^0_s, $\overline{B}^0_s$, B^+_c, B^-_c
Antiparticle	B^+: B^- B^0: $\overline{B}^0$ B^0_s: $\overline{B}^0_s$ B^+_c: B^-_c
Mass	B^+: 5 279.34 ± 0.12 MeV/c^2 B^0: 5 279.65 ± 0.12 MeV/c^2 B^0_s: 5 366.88 ± 0.14 MeV/c^2 B^+_c: 6 274.9 ± 0.8 MeV/c^2
Mean lifetime	B^+: $(1.638 \pm 0.004) \times 10^{-12}$ s B^0: $(1.519 \pm 0.004) \times 10^{-12}$ s B^0_s: $(1.515 \pm 0.004) \times 10^{-12}$ s B^+_c: $(0.510 \pm 0.009) \times 10^{-12}$ s

Source: wikipedia

Energy loss mechanisms

Heavy charged particles

- Inelastic collisions with atomic electrons
- Elastic scattering from nuclei
- Bremsstrahlung
- Cherenkov radiation
- Nuclear reactions
- Hadronic reactions

Light charged particles

- Inelastic collisions with atomic electrons
- Elastic scattering from nuclei
- Bremsstrahlung
- Cherenkov radiation
- Nuclear reactions
- Transition radiation

Photons

- Photoelectric effect
- Compton scattering
- Pair production
- Rayleigh scattering
- Photonuclear reactions

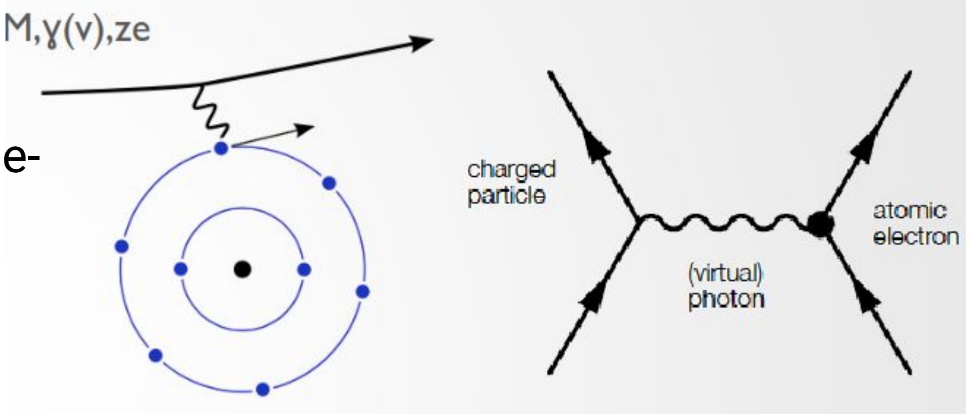
Neutral particles

- Elastic nuclear scattering A(n,n)A
- Inelastic nuclear scattering A(n,n')A*
- Radiative capture (n,γ)
- Fission (n,f)
- Hadronic showers

Interaction of **heavy** charged particles with matter

Energy loss by ionization

- ❑ “Heavy” particle: $Mc^2 >> m_ec^2$
- ❑ Interaction dominated by collision with e-
- ❑ Quantum mechanical derivation by H. Bethe (1930) and F. Bloch (1933)



$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

Energy loss depends on the properties of the incident particle and target material

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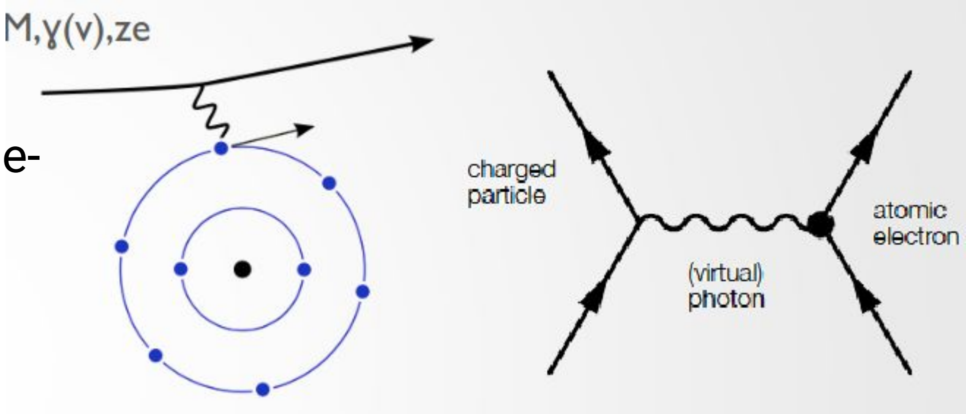

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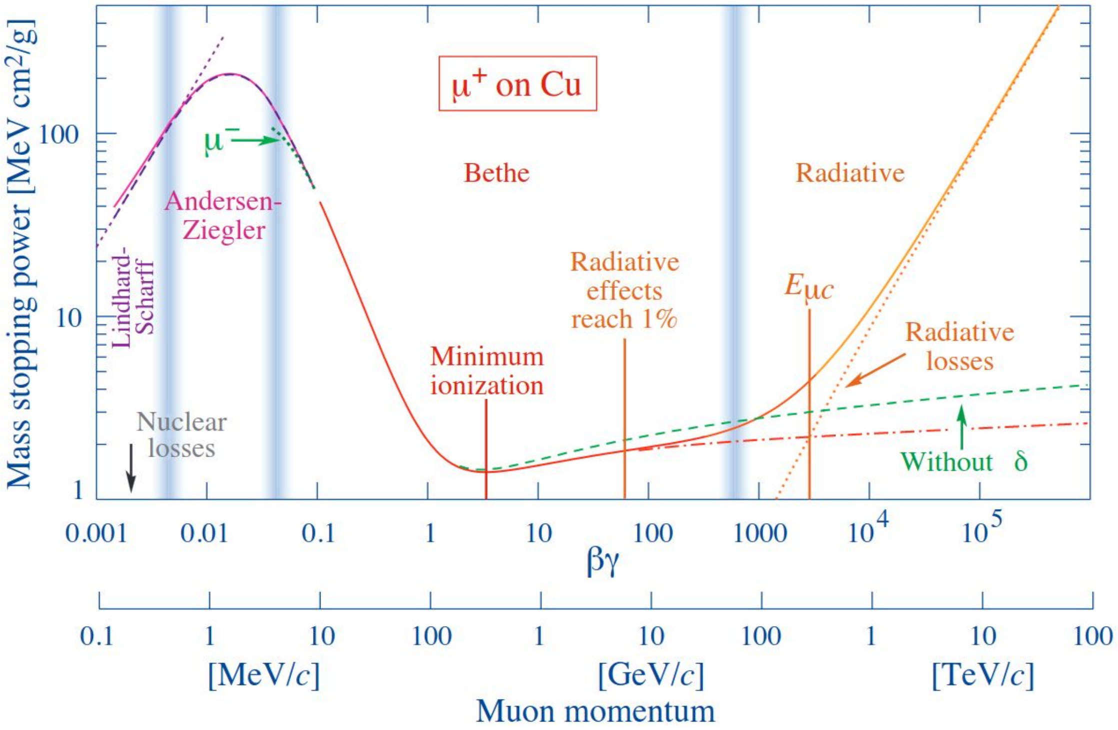
Energy loss depends on the properties of the incident particle and target material

Interaction of **heavy** charged particles with matter

Energy loss by ionization

- Ionization is a universal detection principle of semi-conducting sensors, gaseous detectors, etc
- Valid in the region 0.1 < $\beta\gamma$ < 1000 (accuracy of a few percent)
- Distinct zones and several corrections applied to the equation
- There is a broad minimum at $\beta\gamma$ ~ 3-3.5 → Minimum ionizing particles (MIP)
- At $E_{\mu c}$, the energy loss by ionization becomes equal to the energy loss by radiation

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

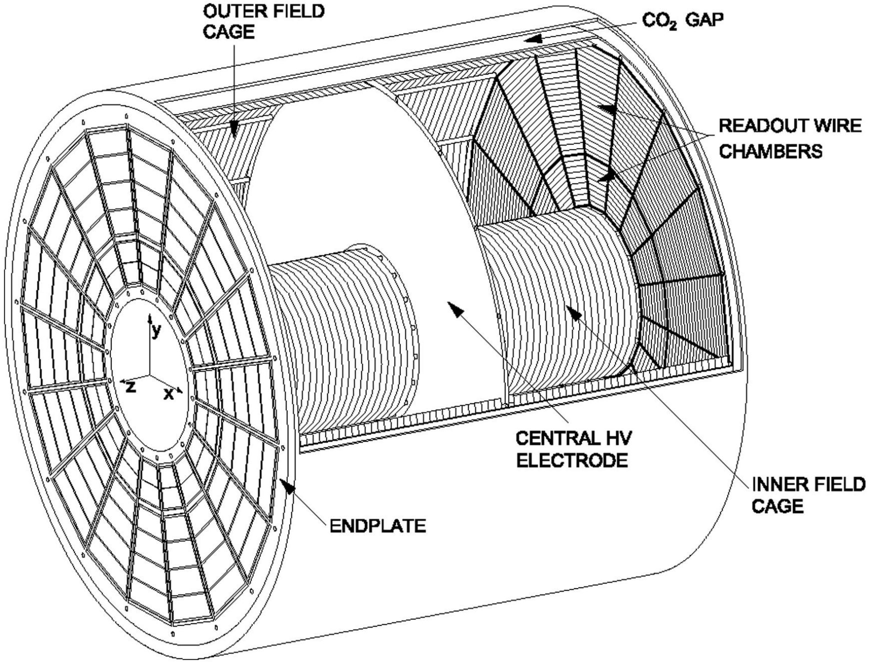


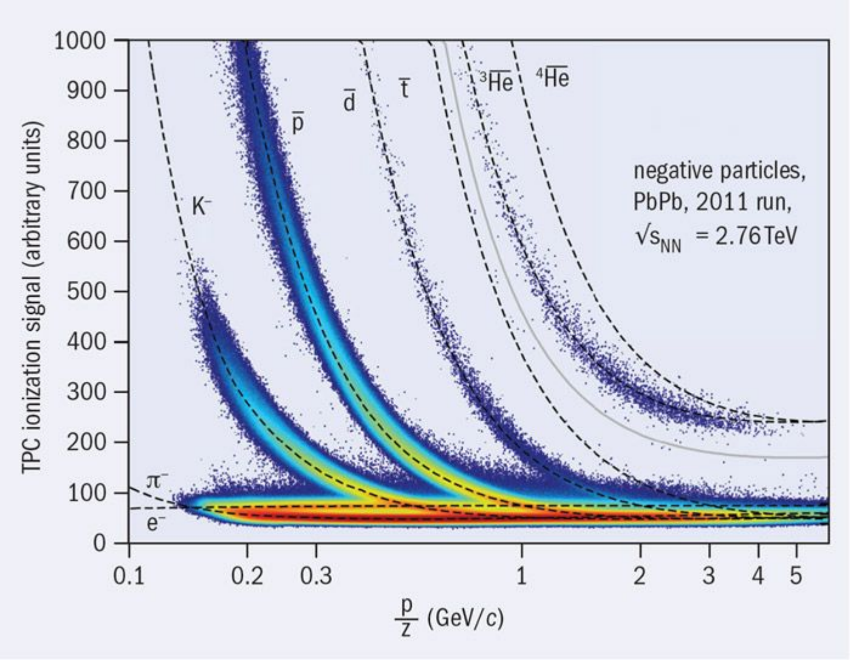
Source: PDG 2022

Interaction of charged particles with matter

Example: particle identification in a TPC (ALICE experiment)

Time Projection Chamber (TPC)



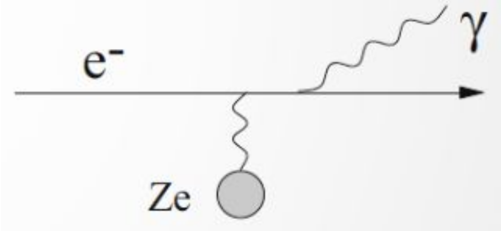


Source: CERN courier

Interaction of charged particles with matter

Energy loss by radiation: Bremsstrahlung

- **Acceleration of charged particles in the Coulomb field of the nucleus**
- QED process (Fermi 1924, Weizsäcker-Williams 1938), emission of a real photon



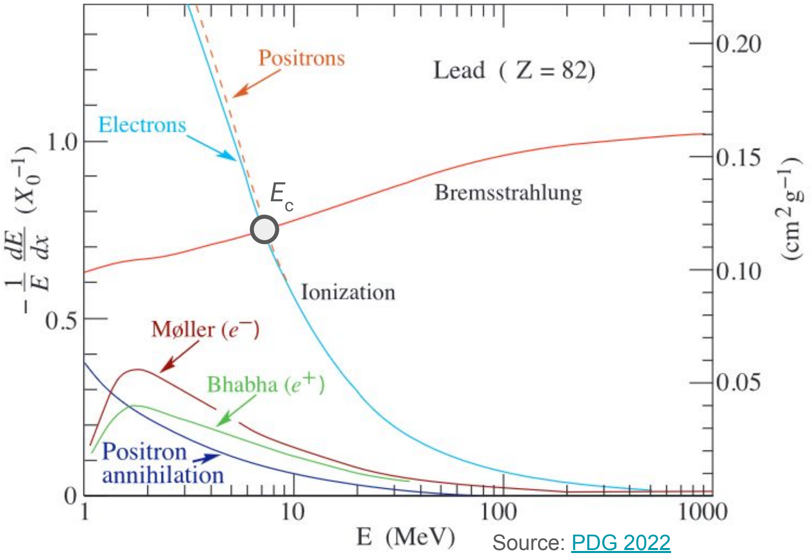
$$\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \Rightarrow -\left\langle\frac{dE}{dx}\right\rangle_{brem} \propto \frac{E}{m^2}$$

→ The muon Bremsstrahlung is suppressed by a factor $(m_\mu/m_{e-})^2$ = 40000

- Radiation length X_0

$$X_0 \approx \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}} \Rightarrow \frac{dE}{dx} = \frac{E}{X_0} \Rightarrow E = E_0 e^{-x/X_0}$$

→ After passing a layer of material of thickness X_0 the electron has 1/e (~37%) of its initial energy

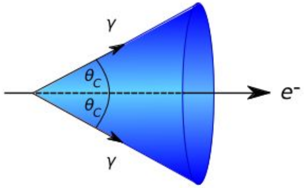


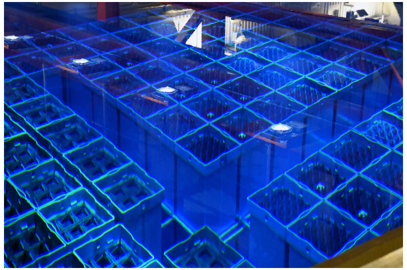
Source: PDG 2022

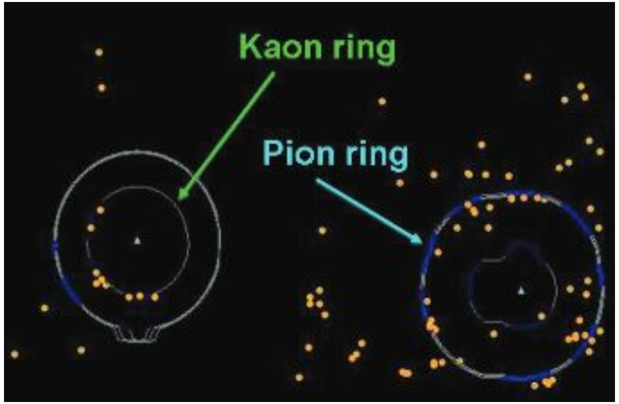
Interaction of charged particles with matter

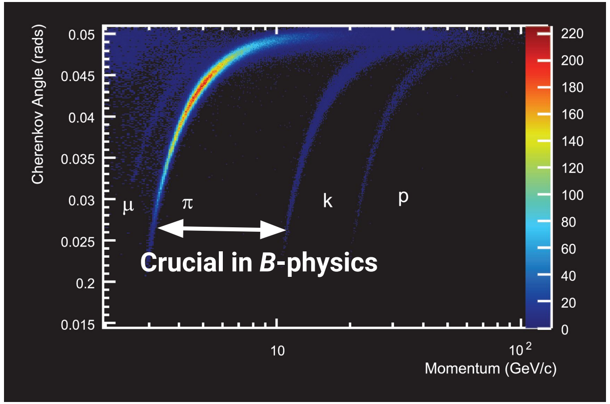
Energy loss by radiation: Cherenkov emission

- **Charged particles emit radiation if they travel faster than th local speed of light (v = c/n)**
- Cherenkov light is emitted in a cone with $\cos(\theta_c) = 1/\beta n$
- There is a threshold for light production at $\beta = 1/n$
- Cherenkov emission is a weak effect and causes no significant energy loss (<1%)
- Refractive index (n) selected according to the momentum region to be covered



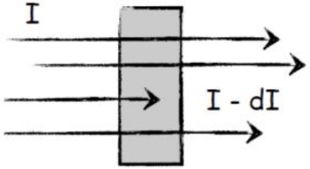




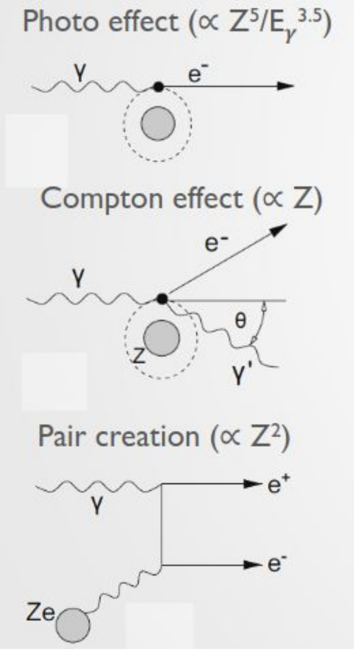


Interactions of photons with matter

High energy photons typically interact by absorption



$N = N_0 e^{-\mu x}$, $\mu(E, Z, \varrho)$: absorption coefficient

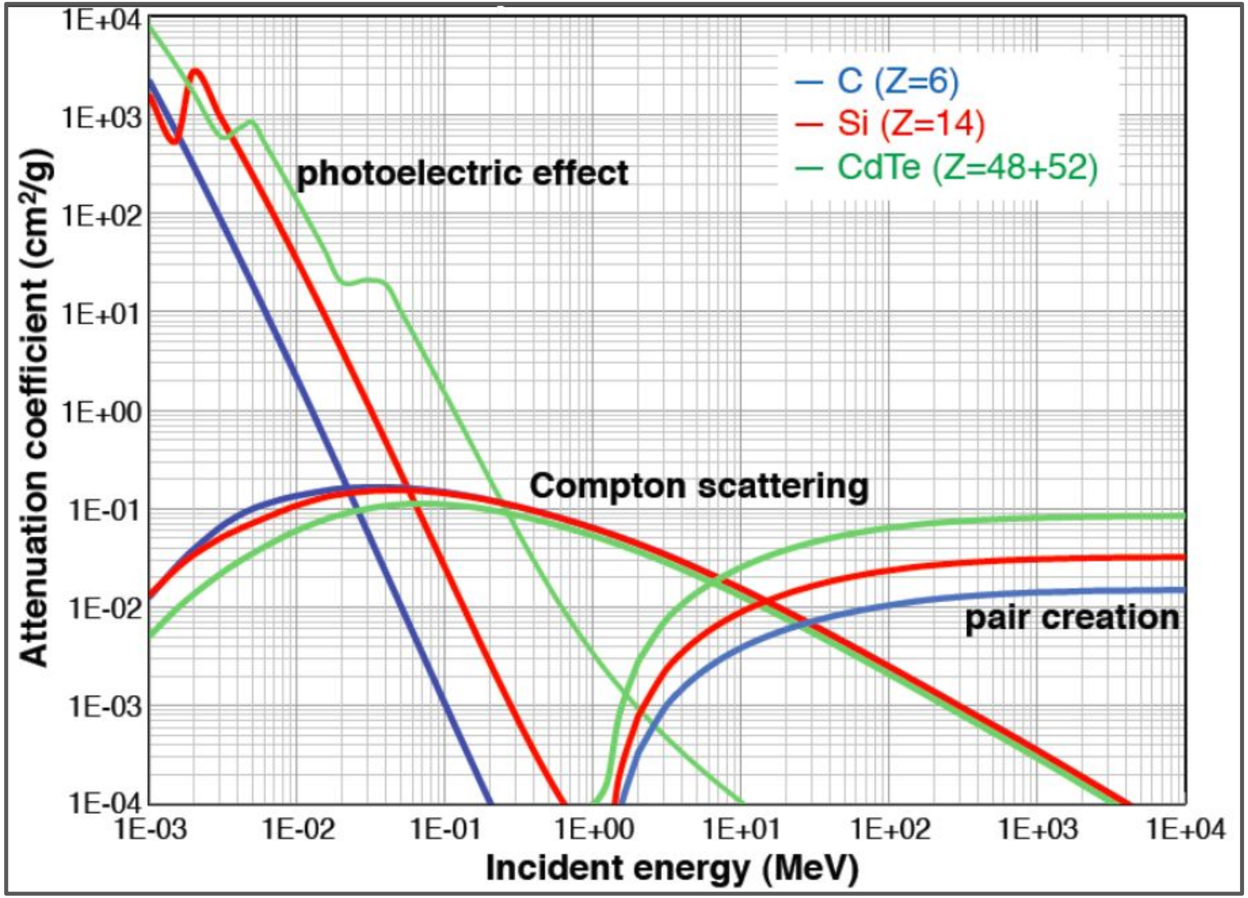


- **Photoelectric effect**: the photon loses its energy to an atom which emits an electron

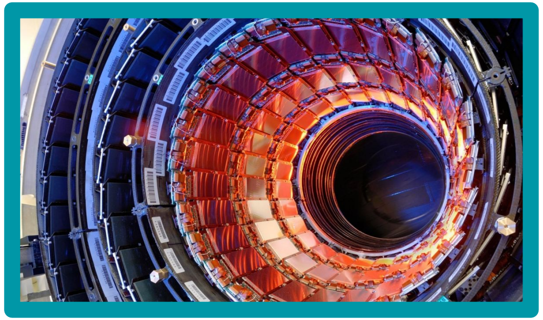
  → Secondary emission of characteristic x-rays and Auger electrons when the holes are re-filled
- **Compton effect**: (quasi-) elastic scattering on an electron in the atomic shell (>>E_{bind})
- **Pair production**: the photon converts to an e^+e^- pair in the electric field of the nucleus

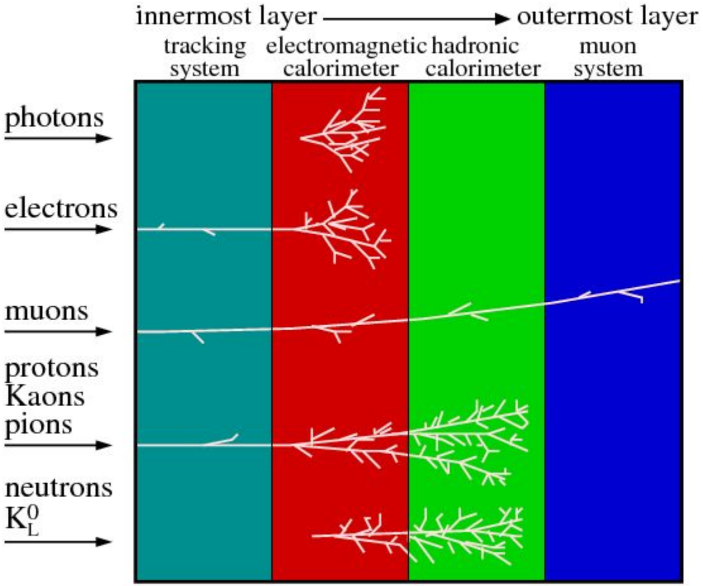
  → From E > 1.022 MeV, dominant process with Bremsstrahlung at high energies

Interactions of photons with matter

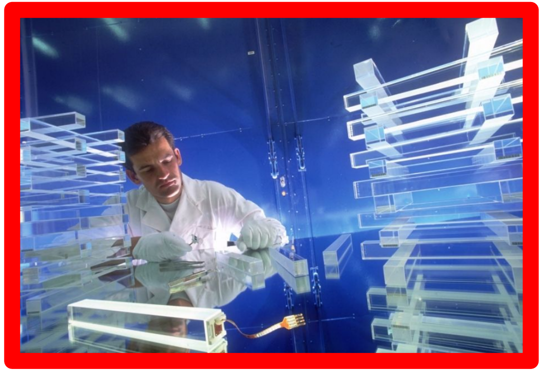


Building your own detector

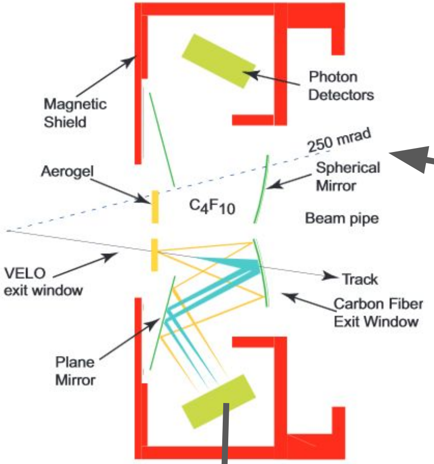


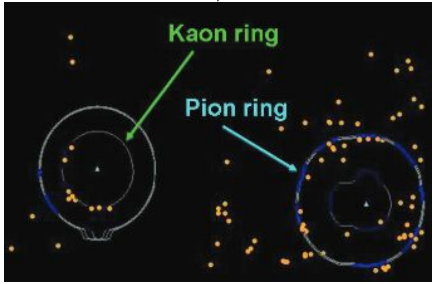


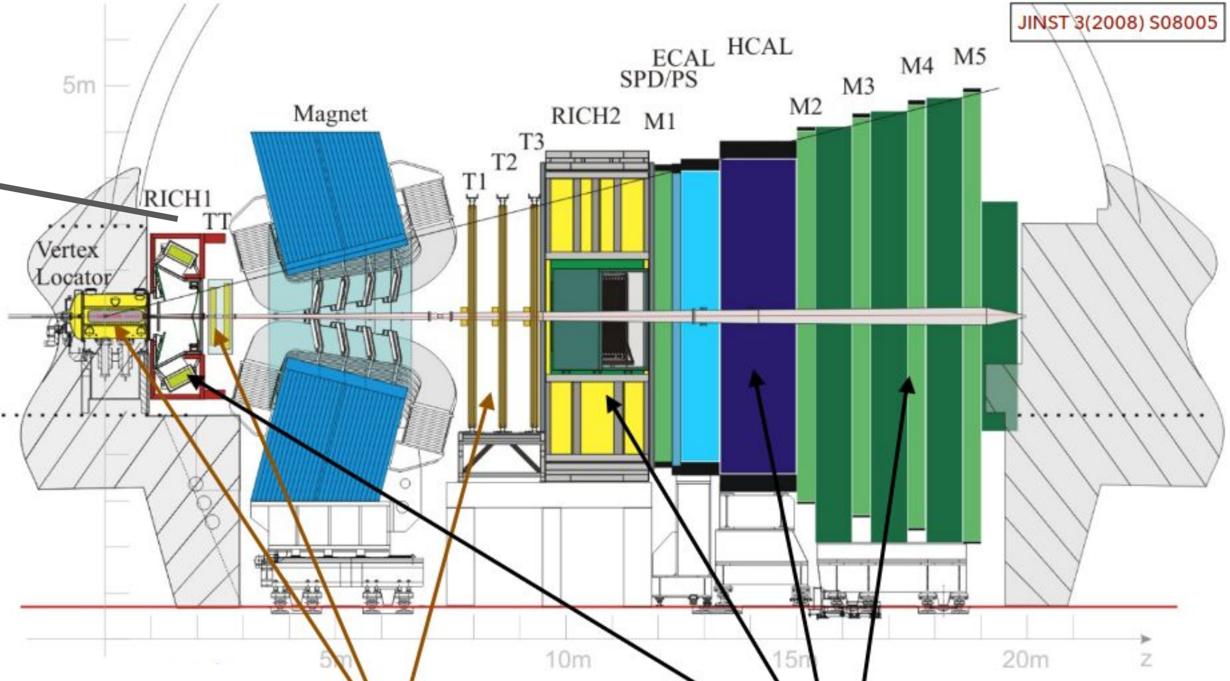
C. Lippmann – 2003



The LHCb experiment







vertex locator and tracking

particle identification and first trigger level

Physics studies

1) *CP* violation

CP violation

- **Baryogenesis** studies the origin of the matter / antimatter asymmetry (or “baryon asymmetry”) of the universe
- LHCb goal: understand what happened after the Big Bang that allowed matter to survive
- Intrinsically related to discrete symmetries charge C and parity P

$$\begin{tikzcd}
q_L \arrow[r, leftrightarrow, "C"] \arrow[d, leftrightarrow, "P"'] \arrow[dr, leftrightarrow, "CP"] & \bar{q}_L \arrow[d, leftrightarrow, "P"] \\
q_R \arrow[r, leftrightarrow, "C"'] & \bar{q}_R
\end{tikzcd}$$

Some processes involving **weak interaction** violate the *CP* symmetry

CP violation

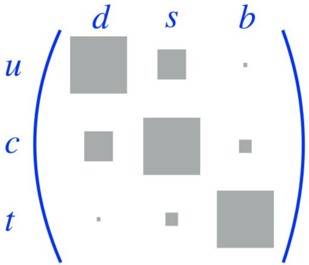
❑ 1973: Cabibbo-Kobayashi-Maskawa matrix

→ describes the probability of flavour transition

Wolfenstein parametrisation

Phys. Rev. Lett. 51 (1983) 1945

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \qquad \lambda \approx 0.23$$

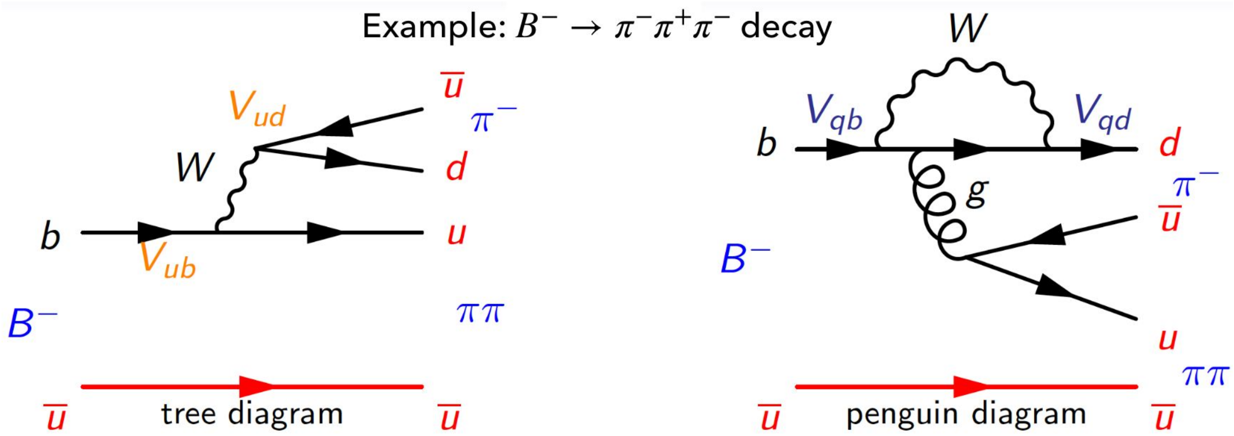


A complex phase in V_{CKM} is necessary to observe CP violation

CP violation

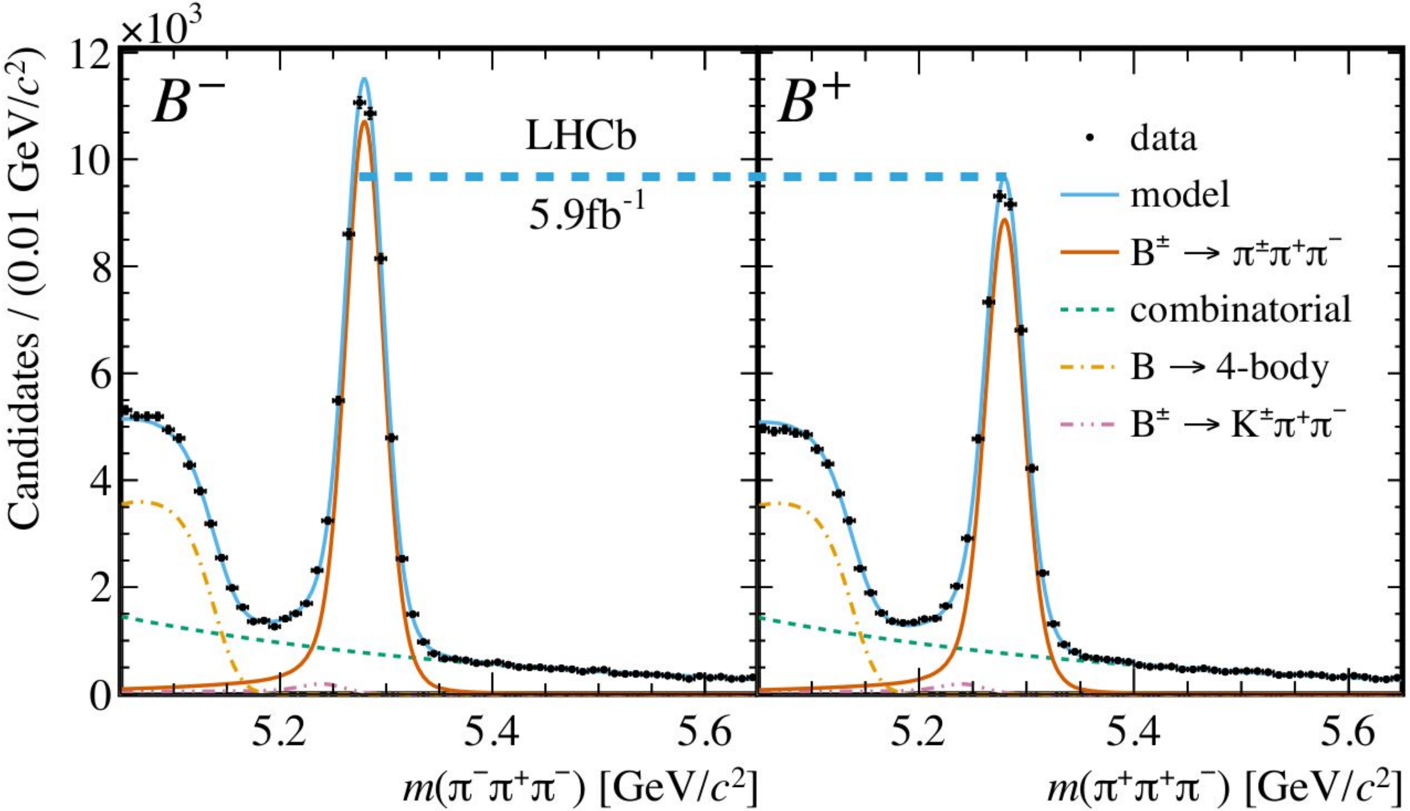
To observe *CP* violation in decays: at least 2 interfering amplitudes must contribute to the same final state with different weak and strong phases

$$A_{CP} = \frac{|A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2}{|A(B \to f)|^2 + |A(\bar{B} \to \bar{f})|^2} = \frac{2|A_2/A_1|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)}{1 + |A_2/A_1|^2 + |A_2/A_1|\cos(\delta_1 - \delta_2)\cos(\phi_1 - \phi_2)}$$

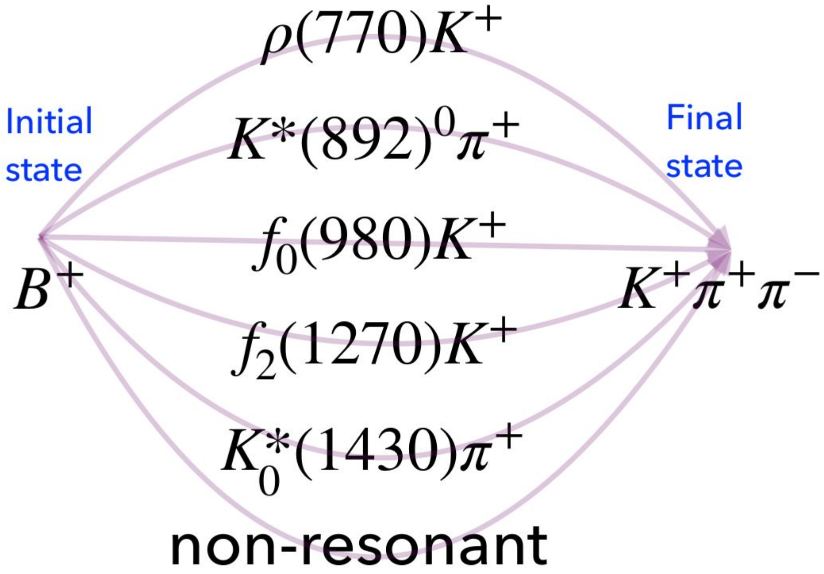

Example: $B^- \to \pi^-\pi^+\pi^-$ decay

CP violation at LHCb

Reconstruction of the $B^{\pm}$ invariant masses



CP violation at LHCb



Initial state

Final state

B^+

$\rho(770)K^+$

$K^*(892)^0\pi^+$

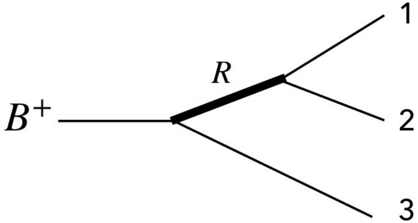
$f_0(980)K^+$

$f_2(1270)K^+$

$K_0^*(1430)\pi^+$

non-resonant

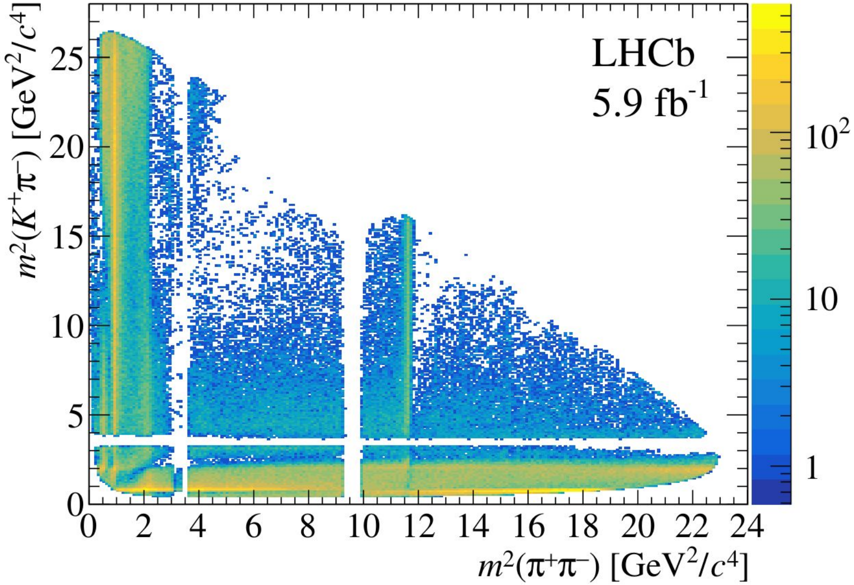
$K^+\pi^+\pi^-$



$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\,|\,\mathscr{M}\,|^2\,\mathrm{d}m_{ij}^2\,\mathrm{d}m_{jk}^2$$

$$m_{ij}^2 = (E_i + E_j)^2 - (p_i + p_j)^2$$

Dalitz plot



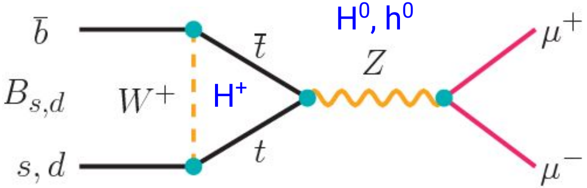
Physics studies

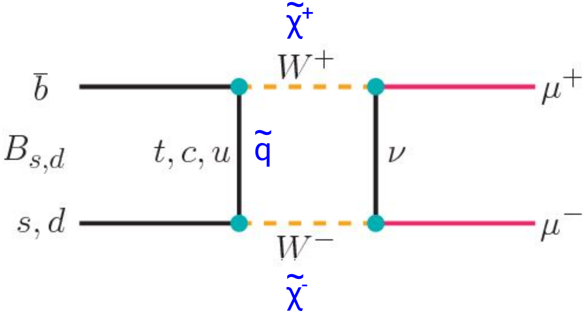
2) Rare decays

Rare B meson decays

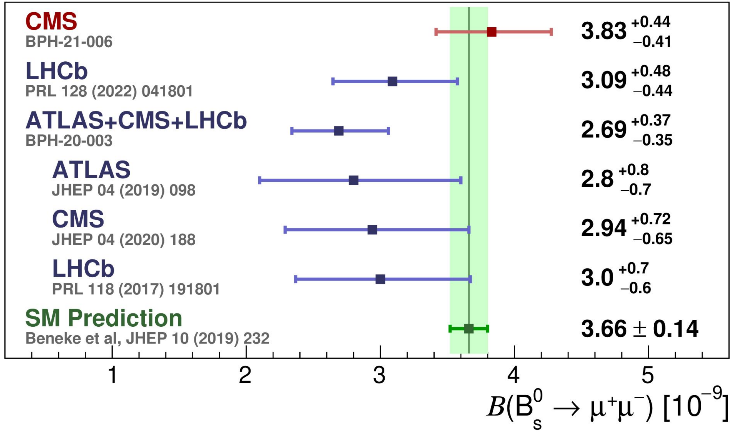
$B_{s/d} \to \mu^+\mu^-$

- **Indirect search principle**: precise measurements of low energy phenomena tells us about unknown physics at energies far beyond direct searches
  → To probe processes where loop diagrams important, as here non-SM particles may contribute
- Very small Branching Ratio (BR) in the SM :-(
- Clean experimental signature :-)





Tension between measurements

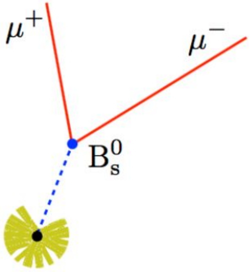


Source: CMS collab.

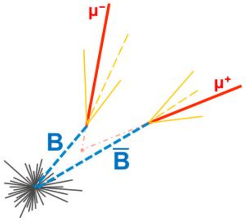
Rare B meson decays

$B_{s/d} \rightarrow \mu^+\mu^-$

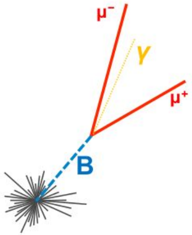
Signal vs background



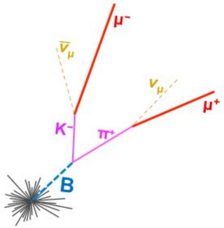
- **signal**
  - two muons from one displaced vertex
  - momentum aligned with flight direction



- **combinatorial**
  - muons from different b decays
  - bb→μμX, μqX

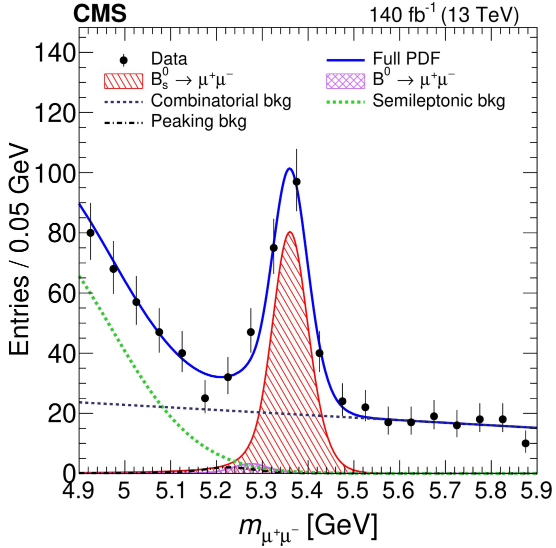


- **semileptonic**
  - partially reco'd b-hadron
  - B→hμν, hμμ
  - with single hadron mis-ID
  - populates left sideband



- **hadronic**
  - mis-reco'd B mesons
  - B→Kπ, B_s→KK
  - double hadron mis-ID
  - peaks in signal region

Source: N. Leonardo



Phys. Lett. B 842 (2023) 137955

Conclusions

- Several aspects of the Standard Model still to be tested
- LHC run 3 just started! Much more data to analyse
- Next generation of particle colliders being studied

Conclusions

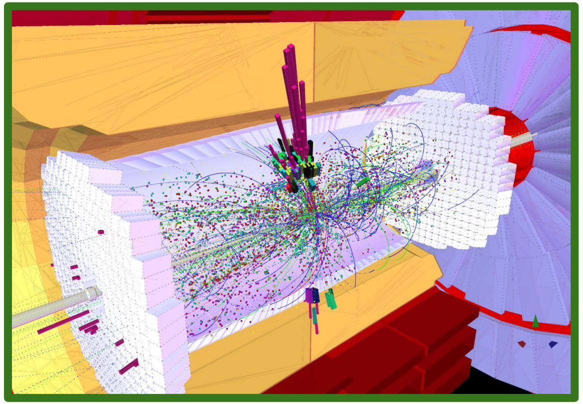
❑ Several aspects of the Standard Model still to be tested

❑ LHC run 3 just started! Much more data to analyse

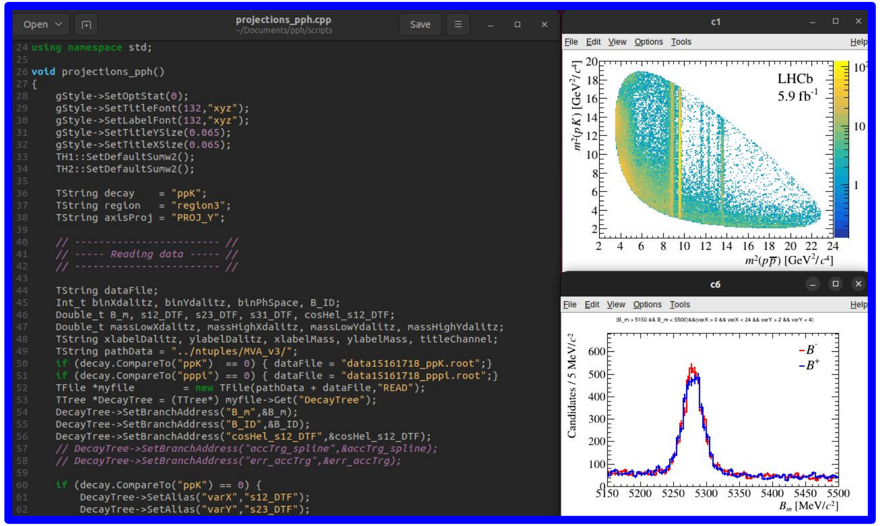
❑ Next generation of particle colliders being studied

❑ **How could YOU contribute?**

Simulations

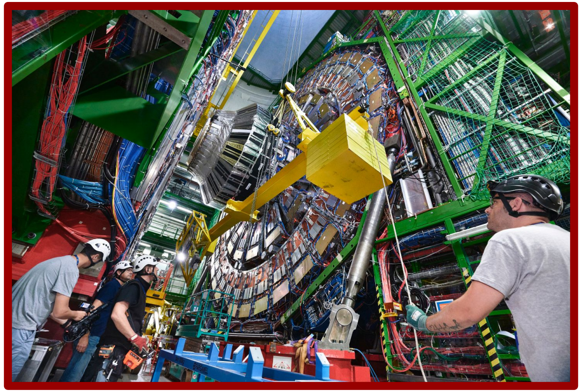


Data analysis



```cpp
using namespace std;

void projections_pph()
{
    gStyle->SetOptStat(0);
    gStyle->SetTitleFont(132,"xyz");
    gStyle->SetLabelFont(132,"xyz");
    gStyle->SetTitleYSize(0.065);
    gStyle->SetTitleXSize(0.065);
    TH1::SetDefaultSumw2();
    TH2::SetDefaultSumw2();

    TString decay    = "ppK";
    TString region   = "region3";
    TString axisProj = "PROJ_Y";

    // ------------------------ //
    // ----- Reading data ----- //
    // ------------------------ //

    TString dataFile;
    Int_t binXdalitz, binYdalitz, binPhSpace, B_ID;
    Double_t B_m, s12_DTF, s23_DTF, s31_DTF, cosHel_s12_DTF;
    Double_t massLowXdalitz, massHighXdalitz, massLowYdalitz, massHighYdalitz;
    TString xlabelDalitz, ylabelDalitz, xlabelMass, ylabelMass, titleChannel;
    TString pathData = "../ntuples/MVA_v3/";
    if (decay.CompareTo("ppK")  == 0) { dataFile = "data15161718_ppK.root";}
    if (decay.CompareTo("pppi") == 0) { dataFile = "data15161718_pppi.root";}
    TFile *myfile        = new TFile(pathData + dataFile,"READ");
    TTree *DecayTree = (TTree*) myfile->Get("DecayTree");
    DecayTree->SetBranchAddress("B_m",&B_m);
    DecayTree->SetBranchAddress("B_ID",&B_ID);
    DecayTree->SetBranchAddress("cosHel_s12_DTF",&cosHel_s12_DTF);
    // DecayTree->SetBranchAddress("accTrg_spline",&accTrg_spline);
    // DecayTree->SetBranchAddress("err_accTrg",&err_accTrg);

    if (decay.CompareTo("ppK") == 0) {
        DecayTree->SetAlias("varX","s12_DTF");
        DecayTree->SetAlias("varY","s23_DTF");
```

Instrumentation



Backup

Hadron collider environment

- Particle Identification (ID) is a crucial aspect of most High Energy Physics experiments: the detectors used depend on the physics under study
- High energetic collisions occur at the interaction vertex

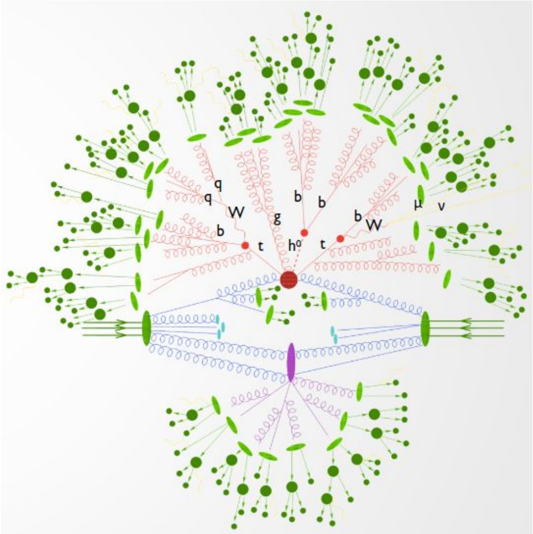
  → The resulting events should be reconstructed as fully as possible, where usually many particles emerge from the interaction point

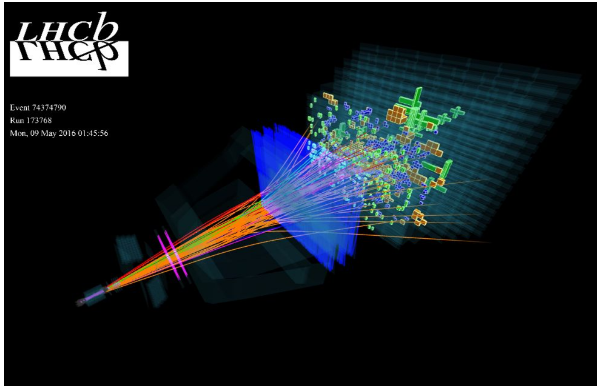
  → Heavy SM particles cascade-decay

  → Decay length typical for *B*-mesons: ~7 mm

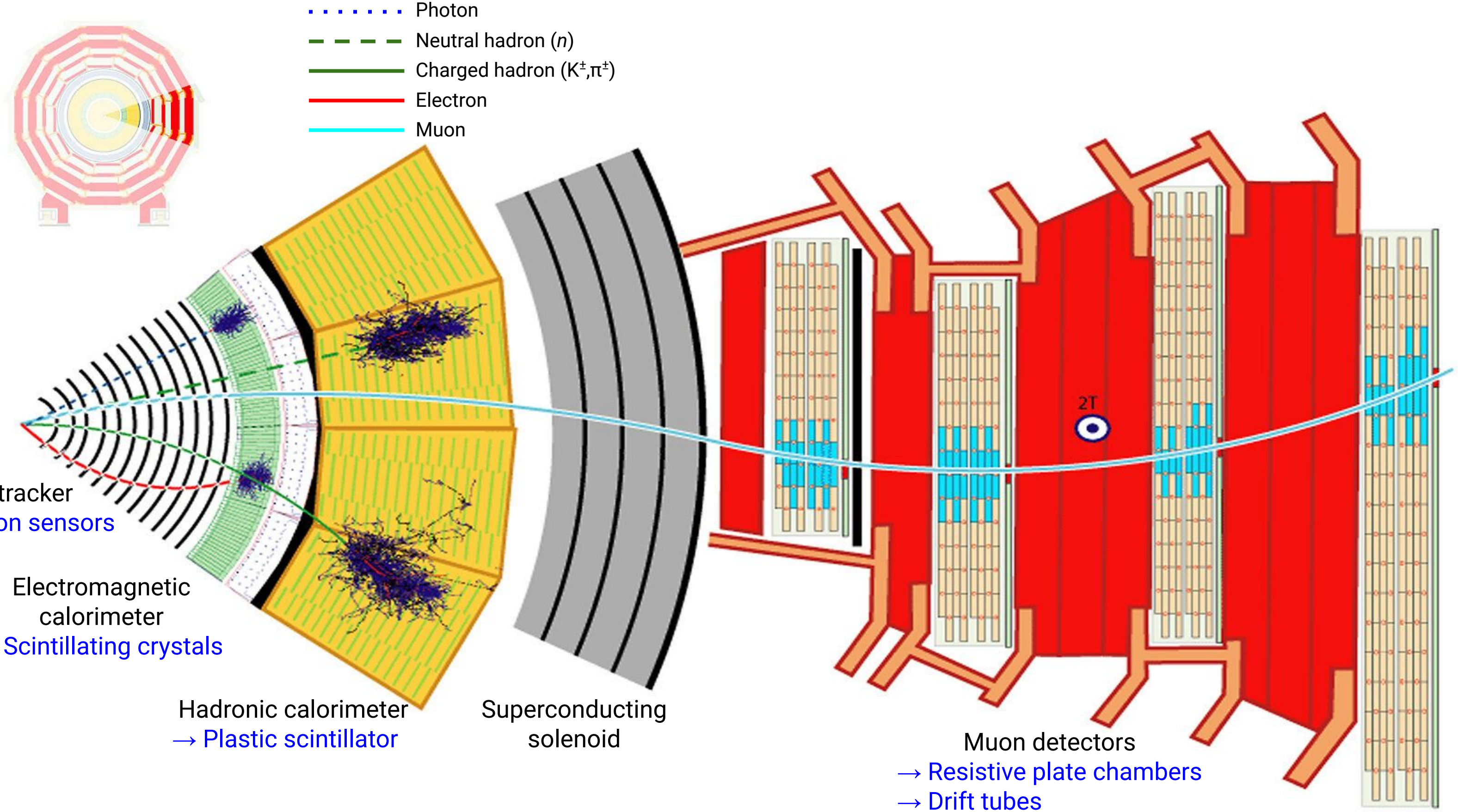
  → The interaction of secondary particles with the detector material is governed by the SM at low energies
- Many aspects of detector technology and conceptual design are governed by the need to isolate leptons (e/μ) and hadrons (π/*K*)

Particle identification is a big challenge!





The CMS experiment



Photon

Neutral hadron (*n*)

Charged hadron ($K^{\pm}$,$\pi^{\pm}$)

Electron

Muon

Silicon tracker
→ Silicon sensors

Electromagnetic
calorimeter
→ Scintillating crystals

Hadronic calorimeter
→ Plastic scintillator

Superconducting
solenoid

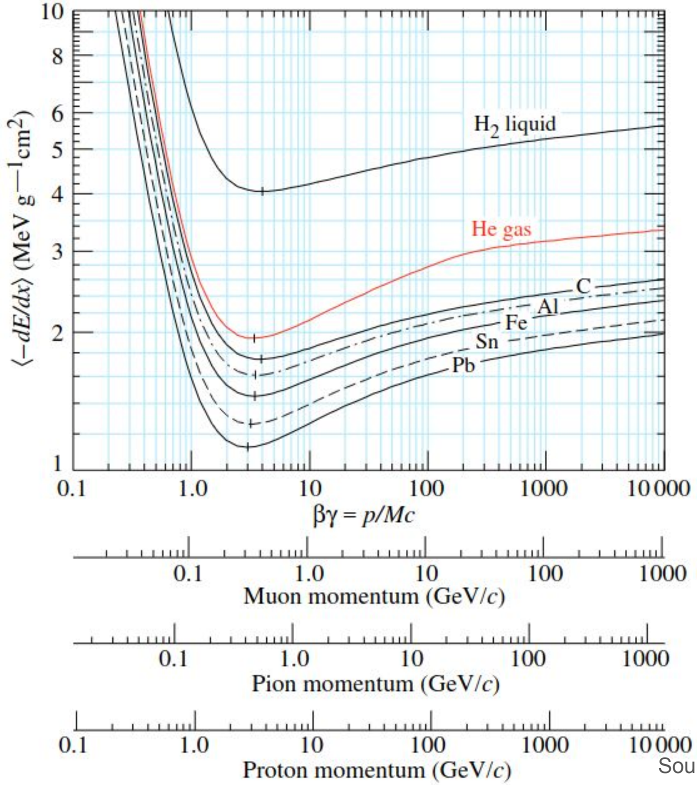
Muon detectors
→ Resistive plate chambers
→ Drift tubes

Interaction of **heavy** charged particles with matter

Energy loss by ionization

- Ionization is a universal detection principle of semi-conducting sensors, gaseous detectors, etc
- Valid in the region 0.1 < $\beta\gamma$ < 1000 (accuracy of a few percent)
- Distinct zones and several corrections applied to the equation
- There is a broad minimum at $\beta\gamma \sim$ 3-3.5 → Minimum ionizing particles (MIP)
- At $E_{\mu c}$, the energy loss by ionization becomes equal to the energy loss by radiation

$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

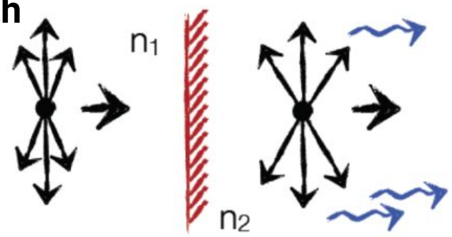


Source: PDG 2022

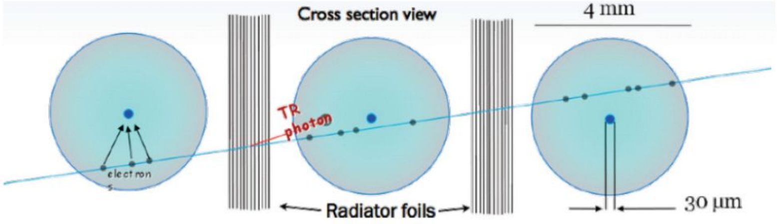
Interaction of charged particles with matter

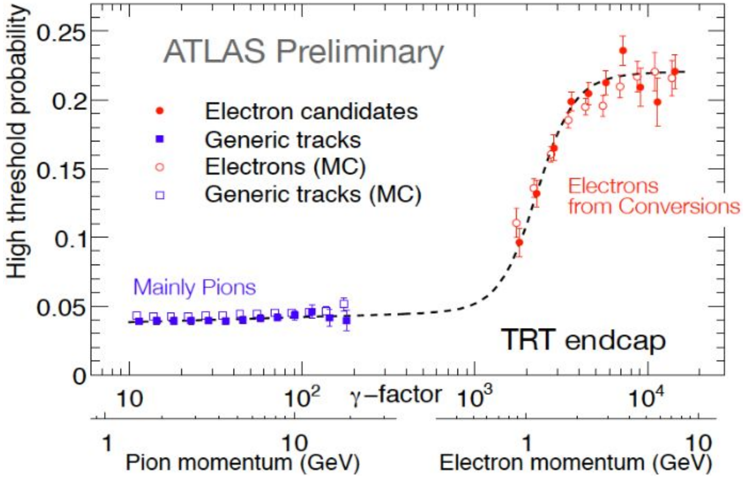
Energy loss by radiation: Transition radiation

- **If a particle traverses a surface separating two materials with different refraction index $n_1 \neq n_2$, radiation is emitted**
- Typical emission angle: $\theta \propto 1/\gamma$
- For ultra-relativistic particles (γ > 1000), hard UV radiation is emitted, closely collimated with the particle
- Measuring the intensity (γ) allows to identify charged particles when their momentum is known
  → Photons will be seen in same detector as the ionization from the track
- Only x-ray (E > 20 keV) photons can traverse the many radiators without being absorbed



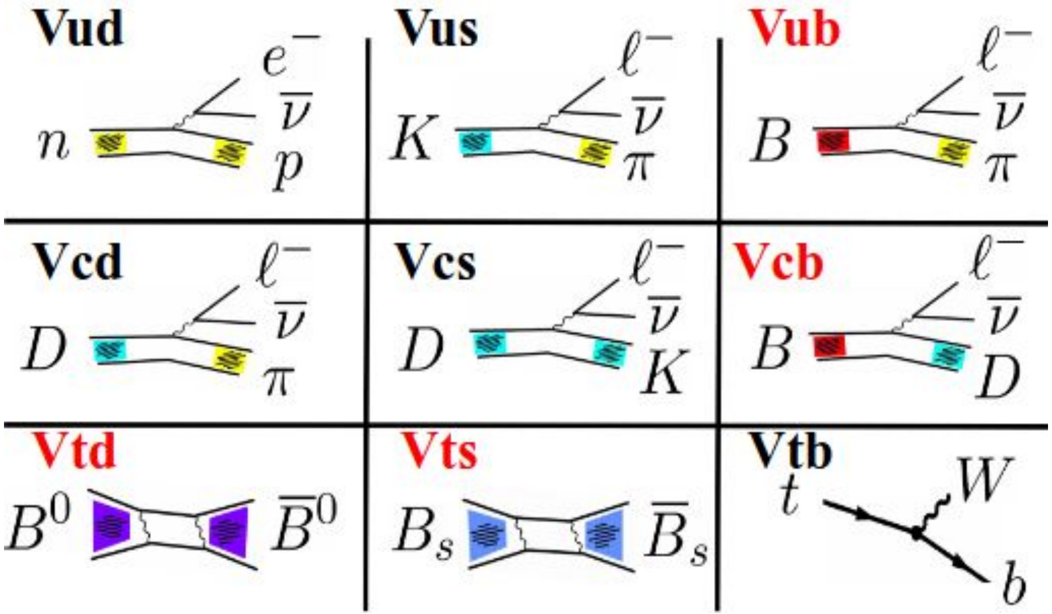
$$S = \frac{1}{3}\alpha z^2 \gamma \hbar \omega_P$$





CP violation

- ☐ 1973: Cabibbo-Kobayashi-Maskawa matrix
  → describes the probability of flavour transition



Open-charm cross sections

- **Open-charm mesons:** a charm quark + a light quark
- Single-parton Scattering (SPS): one parton of each colliding hadron interacts with each other
  → Parton = quarks and gluons
- Double-parton Scattering (DPS): two partons of each incoming proton can interact
- **Production cross-section** for J/ψ with D^0, D^+ and D_s^+ estimated by the LHCb collaboration
  → possibility of complementary studies with CMS
- From ~1 TeV the DPS contribution to the total cross-section starts to become important