The framework ROOT and its use in particle physics

Session 4: Intro to particle physics and final exercise

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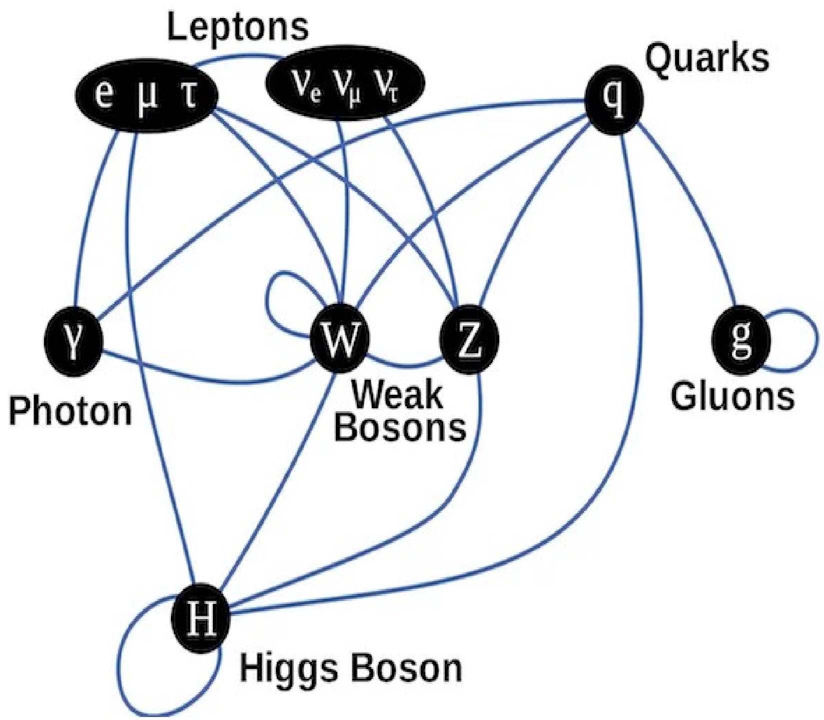
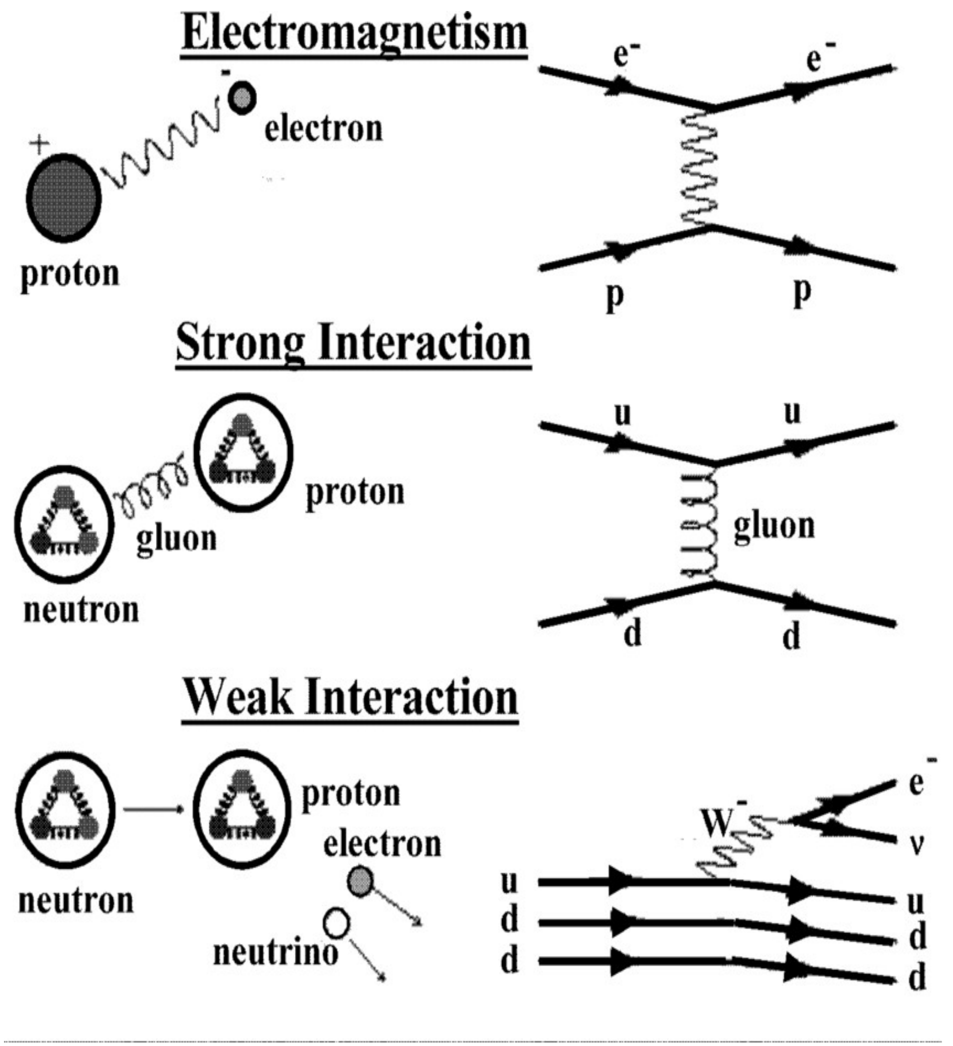
Final exercise

- We have reached the final session where we will apply the learned concepts into an exercise!
- This exercise is open data exercise from the LHCb website.
- Here we are going to calculate assymetries in the decay B→KKK.
- But first we are going to talk (a little bit) about particle physics!

The Standard Model of Particle Physics





Fundamental Particles

Force-carriers (spin = 1)

Photon or γ (electromagnetic force, visible in detectors)

W & Z (weak force, large masses so decay instantly)

gluon (strong force, zero mass but "confined" in hadrons)

Leptons (spin = 1/2, no strong interactions)

Charged (e, μ, τ, decay via weak force, visible in detectors)

Neutrinos (ν_e, ν_μ, ν_τ, nearly massless, not visible, "oscillate")

Quarks (spin = 1/2, strong interactions, "confined" in hadrons)

6 flavors (u, d, s, c, b, t) with masses from MeV to 170 GeV

Charge +2/3 (u, c, t) or –1/3 (d, c, b)

Form mesons (quark-antiquark) and baryons (3 quarks)

Energy-momentum relation

The “square” of a 4-momentum vector is

$$\underset{\rightarrow}{P}^2 = \underset{\rightarrow}{P} \cdot \underset{\rightarrow}{P} = \left(\frac{E}{c}, \vec{p}\right) \cdot \left(\frac{E}{c}, \vec{p}\right) = \frac{E^2}{c^2} - \vec{p}^{\,2}$$

$$= \frac{\left(\gamma mc^2\right)^2}{c^2} - (\beta\gamma mc)^2 = \left(\gamma^2 - \beta^2\gamma^2\right)(mc)^2$$

But we remember that $\gamma^2 - \beta^2\gamma^2 = 1$

So $\underset{\rightarrow}{P}^2 = (mc)^2$, or in eV units where $c = 1$, $\underset{\rightarrow}{P}^2 = m^2$.

We just worked out $\underset{\rightarrow}{P}^2 = \dfrac{E^2}{c^2} - \vec{p}^{\,2} = (mc)^2$

Multiply by c^2: $E^2 - \vec{p}^{\,2}c^2 = \left(mc^2\right)^2$

Rearrange: $E^2 = \vec{p}^{\,2}c^2 + \left(mc^2\right)^2$

In c = 1 units, it’s just $E^2 = p^2 + m^2$

Decay rates

Lorentz invariant form of Fermi's Golden rule

$$\Gamma_{fi} = \frac{(2\pi)^4}{2E_a\hbar}\int |M_{fi}|^2 \delta^4\left(p_a - \sum_i^N p_i\right) \prod_i^N \delta(p_i^2 - m_i^2) \frac{d^4 p_i}{(2\pi)^3}$$

Lorentz invariant Matrix Element

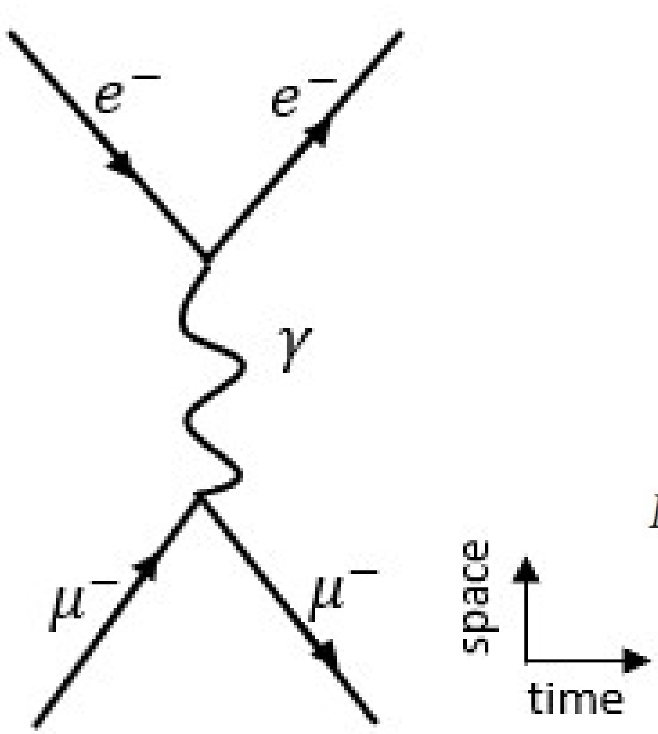
Conservation of four-momentum

Energy-momentum relation

Integration over all final 4-momentum states

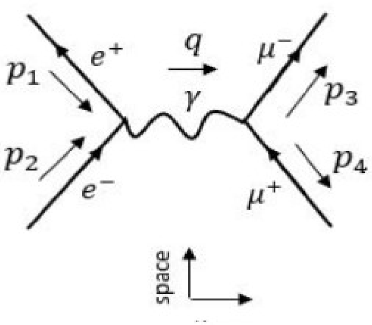
Feynman diagrams

- Represent particle decays.
- Used to calculate decay rates and cross sections.



An example

Amplitude for electron/positron annihilation followed by muon/antimuon production



$$M=\bar{v}(p_2)(-iQ_f e\gamma^{\mu})u(p_1)\frac{-ig_{\mu\nu}}{q^2}\bar{u}(p_3)(-iQ_f e\gamma^{\nu})v(p_4)$$

Kinematics of a three body decay

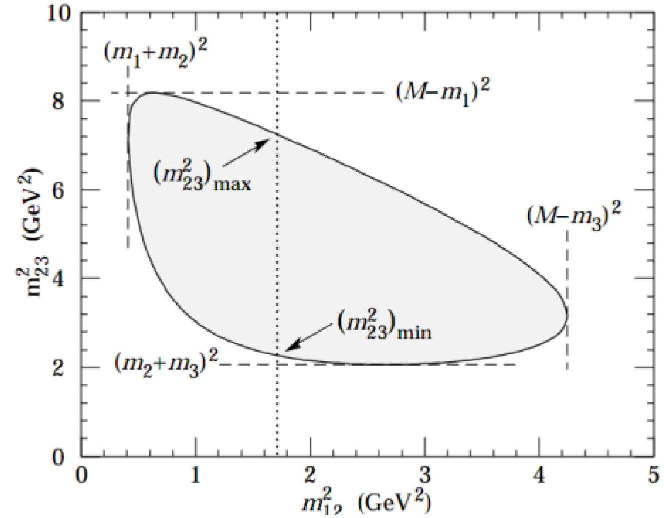
- Three-body decays have 9 degrees of freedom, reduced to 2.
- The invariant masses squared s_{12}, s_{13} and s_{23} are defined as:

$$\begin{aligned} s_{12} &= (p_1^\mu + p_2^\mu)^2 = (P^\mu - p_3^\mu)^2 \\ s_{13} &= (p_1^\mu + p_3^\mu)^2 = (P^\mu - p_2^\mu)^2 \\ s_{23} &= (p_2^\mu + p_3^\mu)^2 = (P^\mu - p_1^\mu)^2 \end{aligned} \tag{2}$$

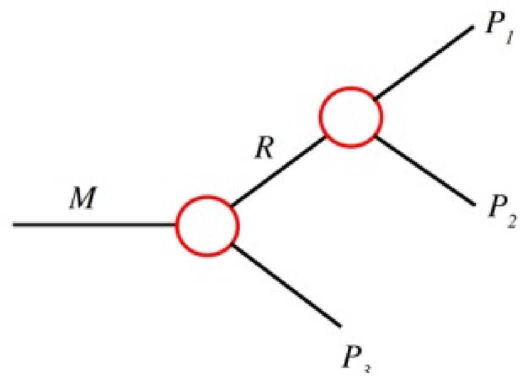
- The decay rate of a three body decay is given by:

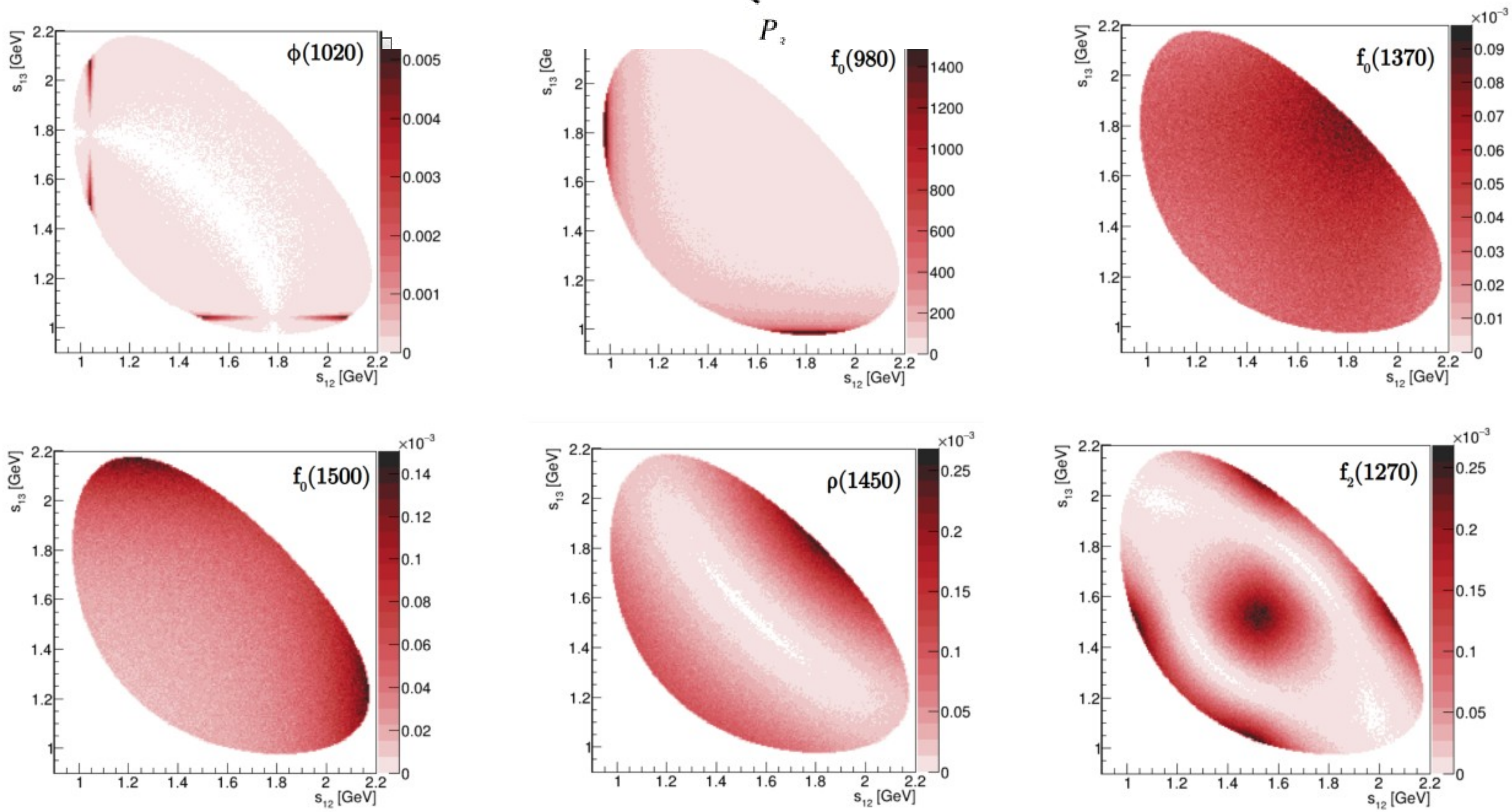
$$\frac{d\Gamma}{ds_{12}ds_{13}} = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|\mathcal{M}|^2.$$

- The 2D phase-space described by the invariant masses squared (2 of them in this case s_{12} and s_{13}) is called a Dalitz Plot (DP).
- The structure of the DP is given by $|\mathcal{M}|^2$.



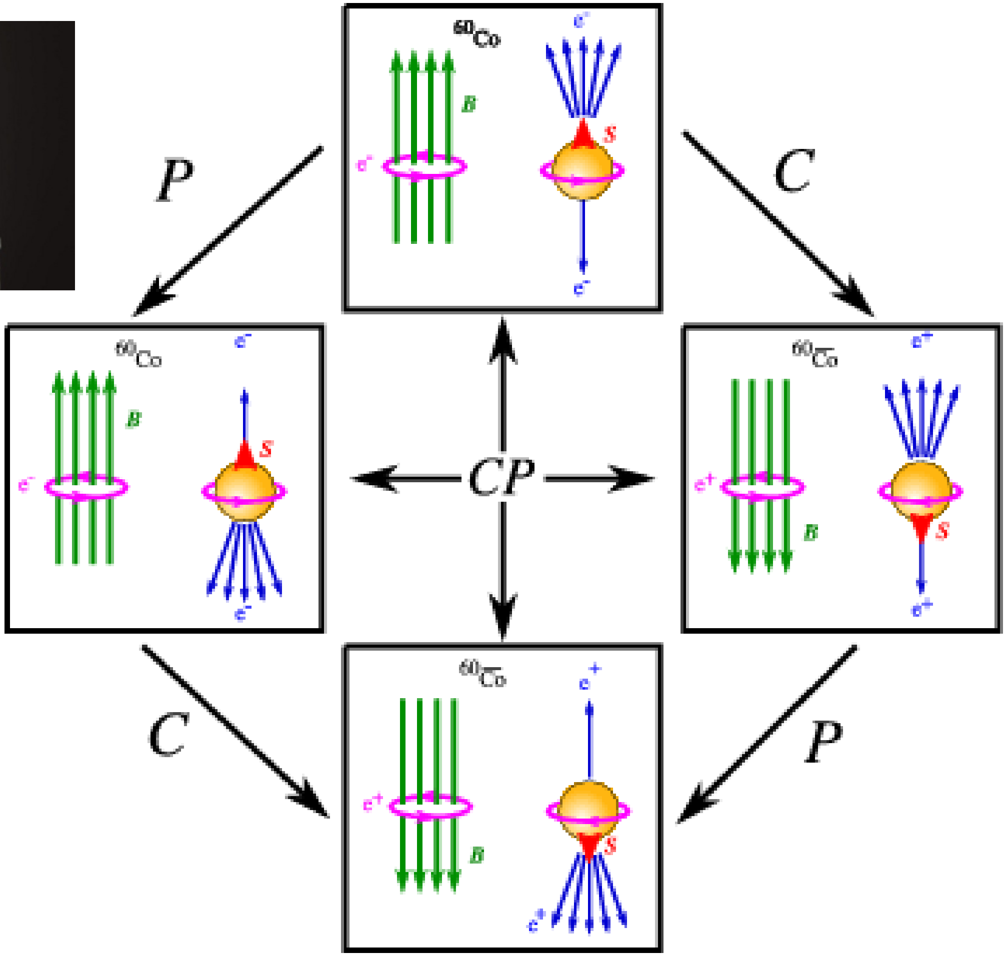
Dalitz plot examples

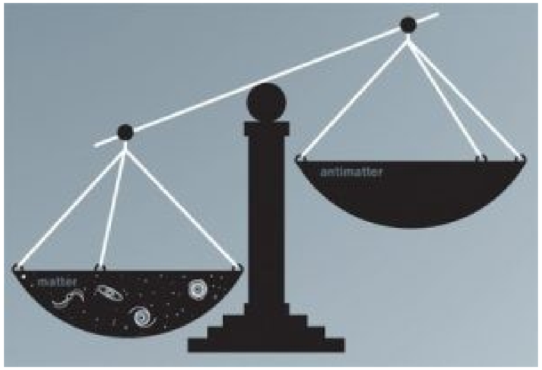


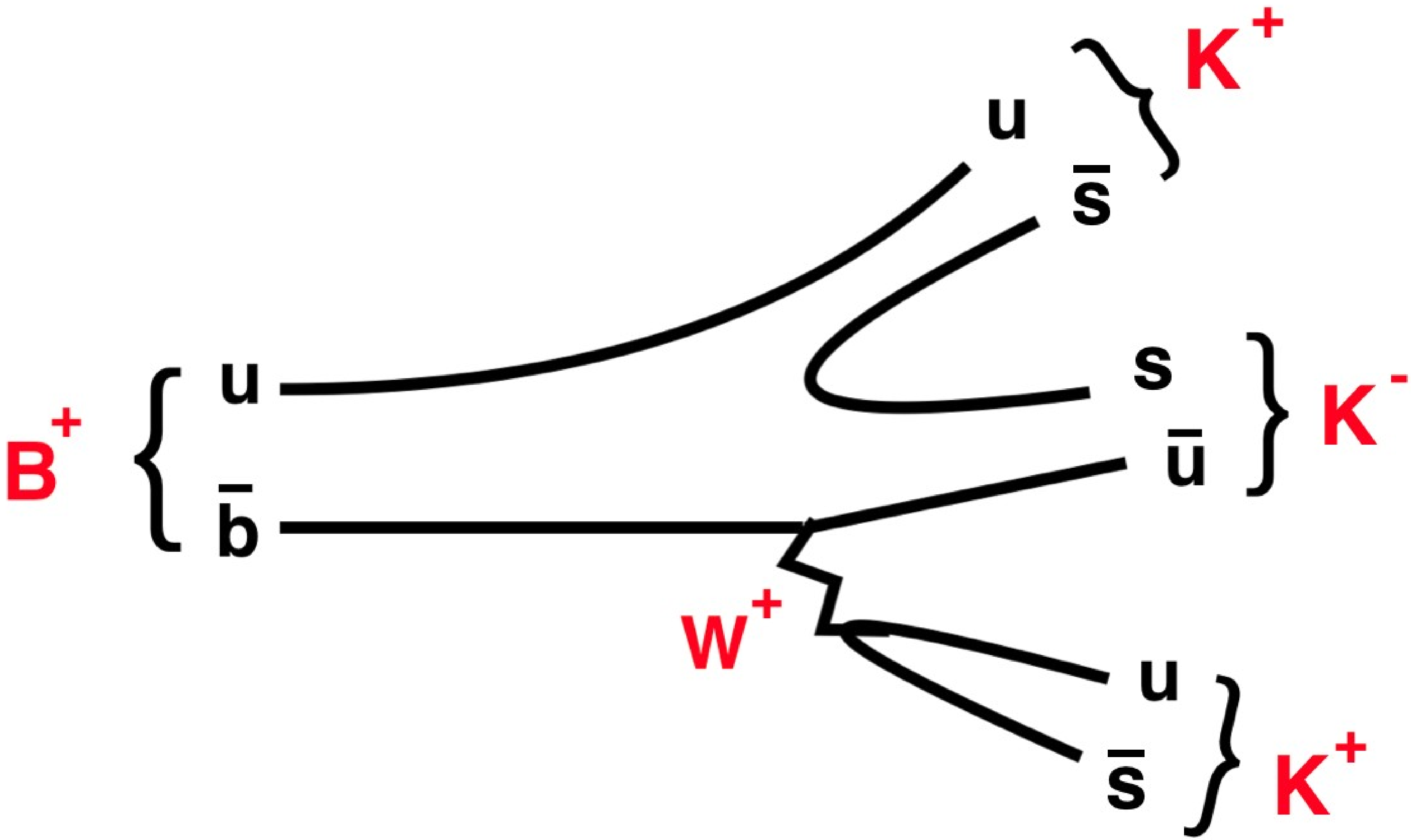


CP violation

- **Parity (P)** is the operation of $x \to -x$ for all 3 coordinates.
- **Charge Conjugation (C)** is the operation of turning a particle into an antiparticle and vice versa.







K+
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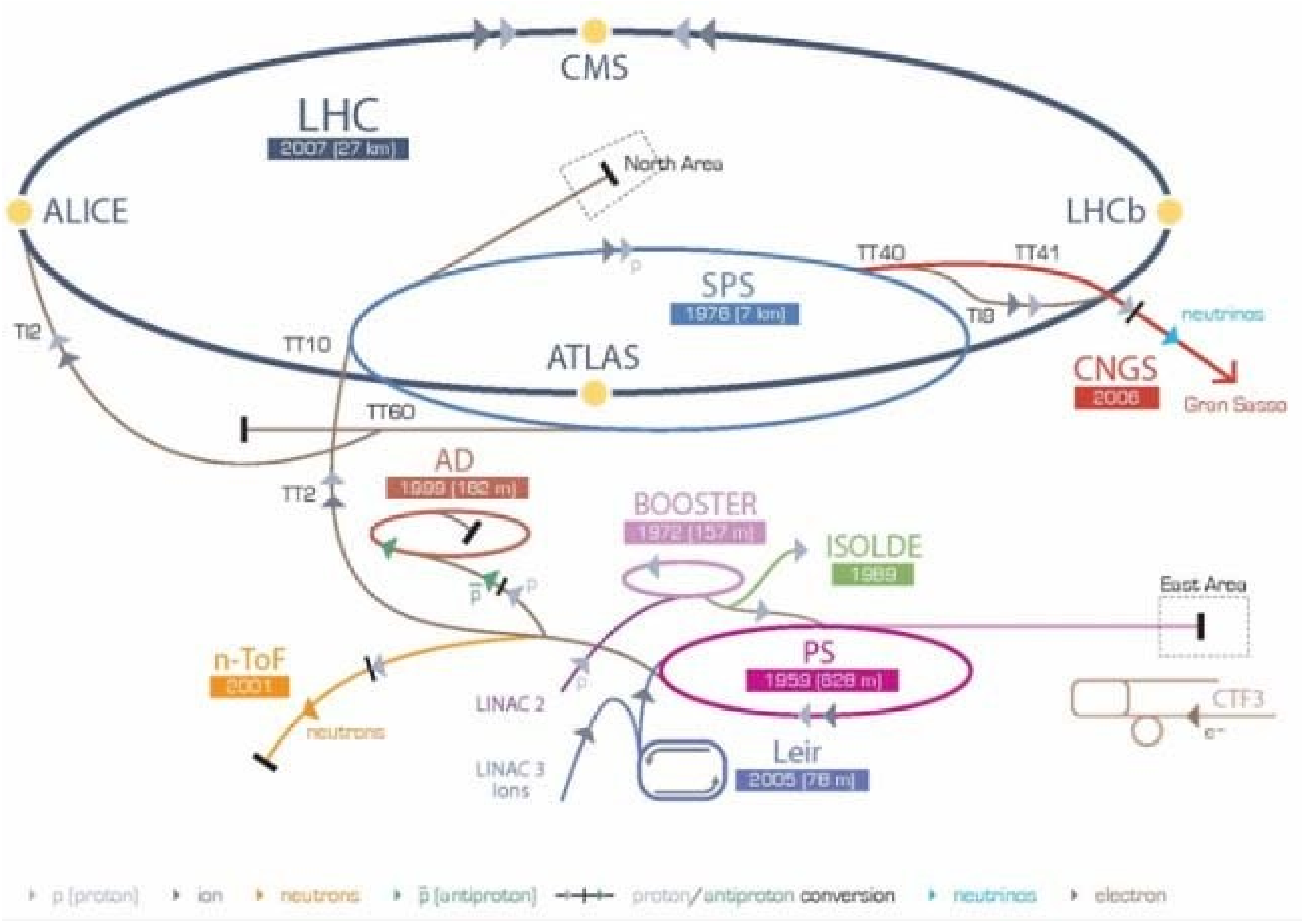
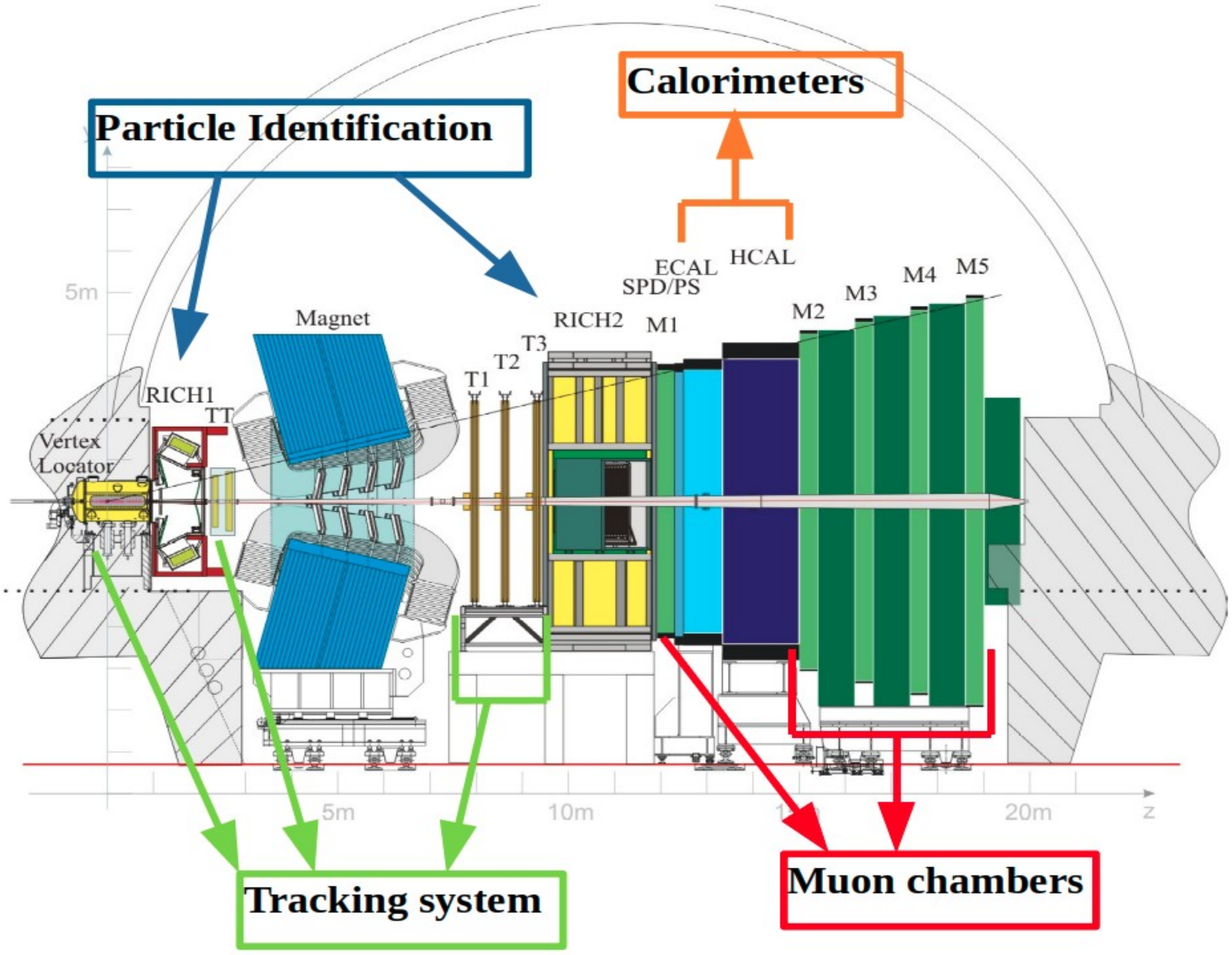
K+

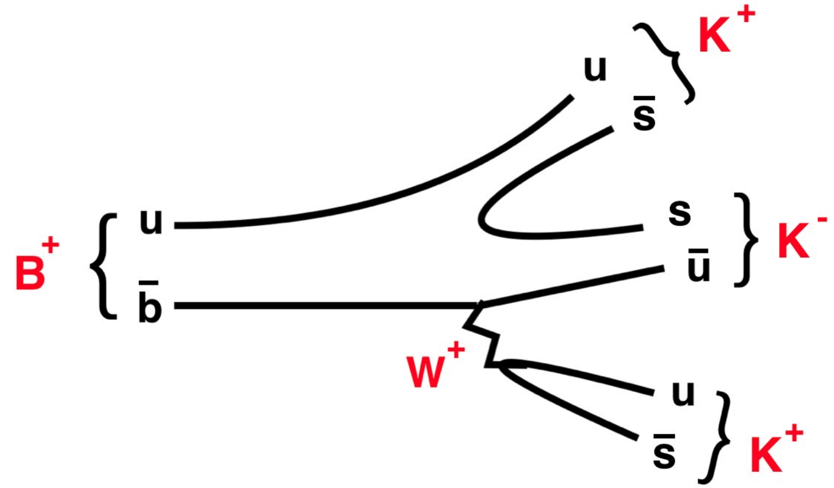
CERN Accelerators

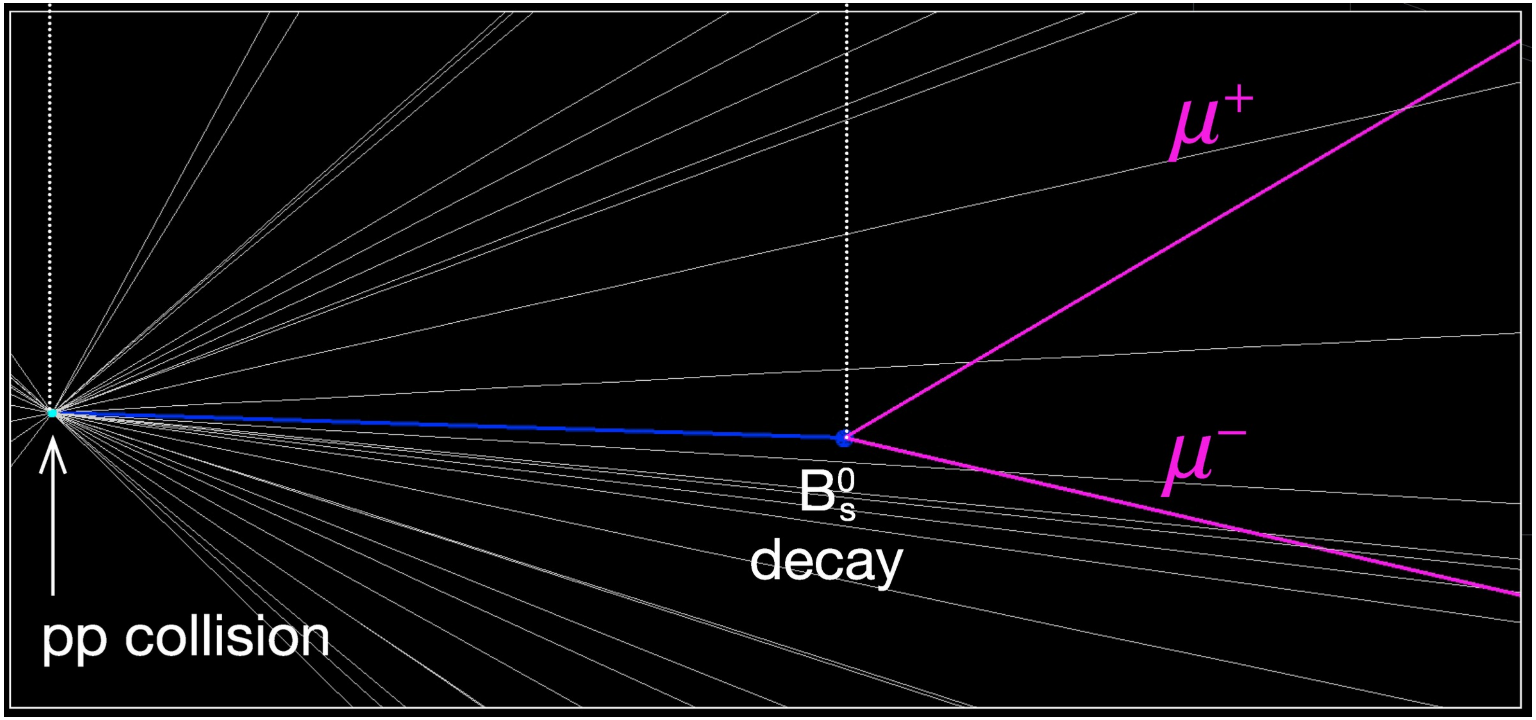


The LHCb detector



The B→KKK decay





Variables

Variable	**Description**
H1_PX	Reconstructed momentum component of particle in X direction [MeV/c].
H1_PY	Reconstructed momentum component of particle in Y direction [MeV/c].
H1_PZ	Reconstructed momentum component of particle in Z direction [MeV/c].
	The momentum is reconstructed from the curvature of the path
	of the track in the magnetic field.
H1_ProbK	Likehood of particle being Kaon [range 0 to 1].
H1_ProbPi	Likehood of particle being Pion [range 0 to 1].
	The particle likelihood is obtained from combining information from
	the RICH and tracking detectors.
H1_Charge	Particle charge (+1 or -1)
	Obtained from direction of curvature of path of the track
	in the magnetic field.
H1_isMuon	Identification of track as a muon, obtained from muon chamber hits
	(0 is false, 1 is true)
B_FlightDistance	The distance travelled by the B candidate before decaying. Obtained from
	the distance from the primary vertex to the
	vertex made by three charged tracks [mm].
B_VertexChi2	χ^2 of the quality of the vertex made by the three charged tracks.
H1_IPChi2	Impact Parameter χ^2.

Variables

Variable	Selection Cut
Track Transverse Momentum (p_{T})	$> 0.1\,\mathrm{GeV}/c$
Sum of p_{T} of Tracks	$> 4.5\,\mathrm{GeV}/c$
Track Momentum (p)	$> 1.5\,\mathrm{GeV}/c$
$B^{\pm}$ candidate mass assuming all tracks are $K^{\pm}$ (M_{KKK})	$5.05 < M_{KKK} < 6.30\,\mathrm{GeV}/c^2$
Track Impact Parameter (IP) χ^2	> 1
Sum of IP χ^2 of Tracks	> 500
$B^{\pm}$ candidate vertex fit χ^2	< 12

Table 1: The most important pre-selection cuts applied to the data sample (see text for details).

Papers

- https://arxiv.org/abs/2209.09840 Amplitude analysis of the Ds→ pipipi decay
- https://arxiv.org/abs/1110.3970 Search for CP violation in Ds→ Kkpi
- https://arxiv.org/pdf/1205.3036.pdf Second Generation of 'Miranda Procedure' for CP Violation in Dalitz Studies of B (& D & τ) Decays
- https://arxiv.org/pdf/1711.09854.pdf Laura++