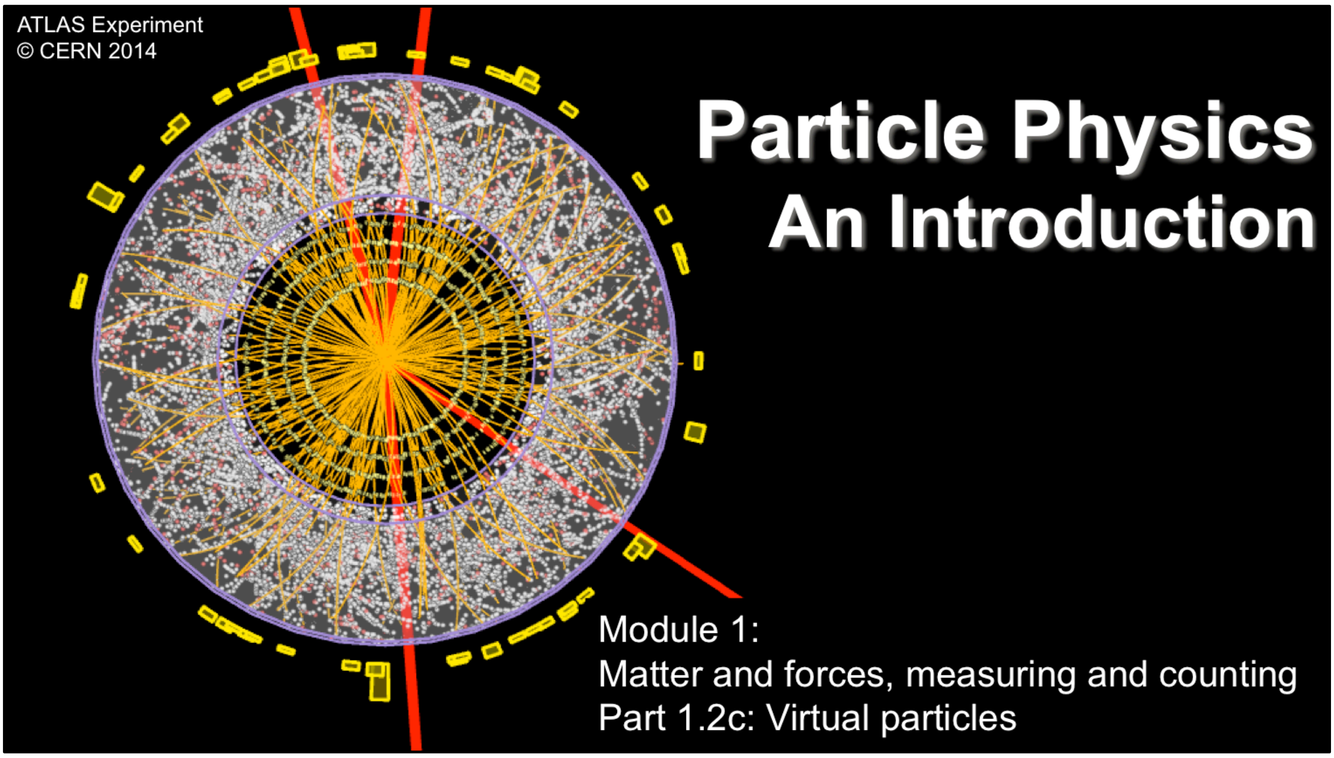
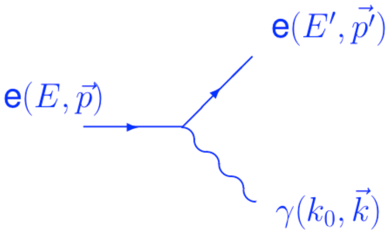


For those who are unfamiliar with the notion of virtual particles, we propose here a small review of this concept.

Electron emits a photon:

$$\begin{aligned} E^2 - \vec{p}^2 &= (E' + k_0)^2 - (\vec{p}' + \vec{k})^2 \\ m_e{}^2 &= m_e{}^2 + m_\gamma{}^2 + 2E'k_0 - 2\vec{p}'\vec{k} \end{aligned}$$



With $m_\gamma = 0$, $k_0 = |\vec{k}|$: $E' \leq |\vec{p}'| \Rightarrow$ contradiction with $m_e \neq 0$!

Conclusion:

- The electromagnetic force is transmitted by virtual photons, with $k_0^2 - \vec{k}^2 > 0$.
- Virtual photons have all the same properties as real ones, except that they have non-zero mass.

How do **forces** manage to **change the momentum** of particles at the quantum level?

- The force field, or rather its potential is created by emitting a **vector boson**, which has a certain probability amplitude of travel to its destination.
- But we must respect the conservation of energy-momentum!
- With $m_\gamma = 0$, $k_0 = |k|$ one obtains $E' \leq |p'|$ in contradiction to $m_e > 0$.
- Conclusion: The electromagnetic force is transmitted through **virtual photons** with $k_0^2 - |k|^2 > 0$. The virtual photons have mass, in contrast to the real photons.
- We retain that the relationship $E^2 - p^2 = m^2$ with the rest mass m is for the real particles, but is not respected for virtual particles.

Video calculation