Part II
The Weak Force

Preliminary

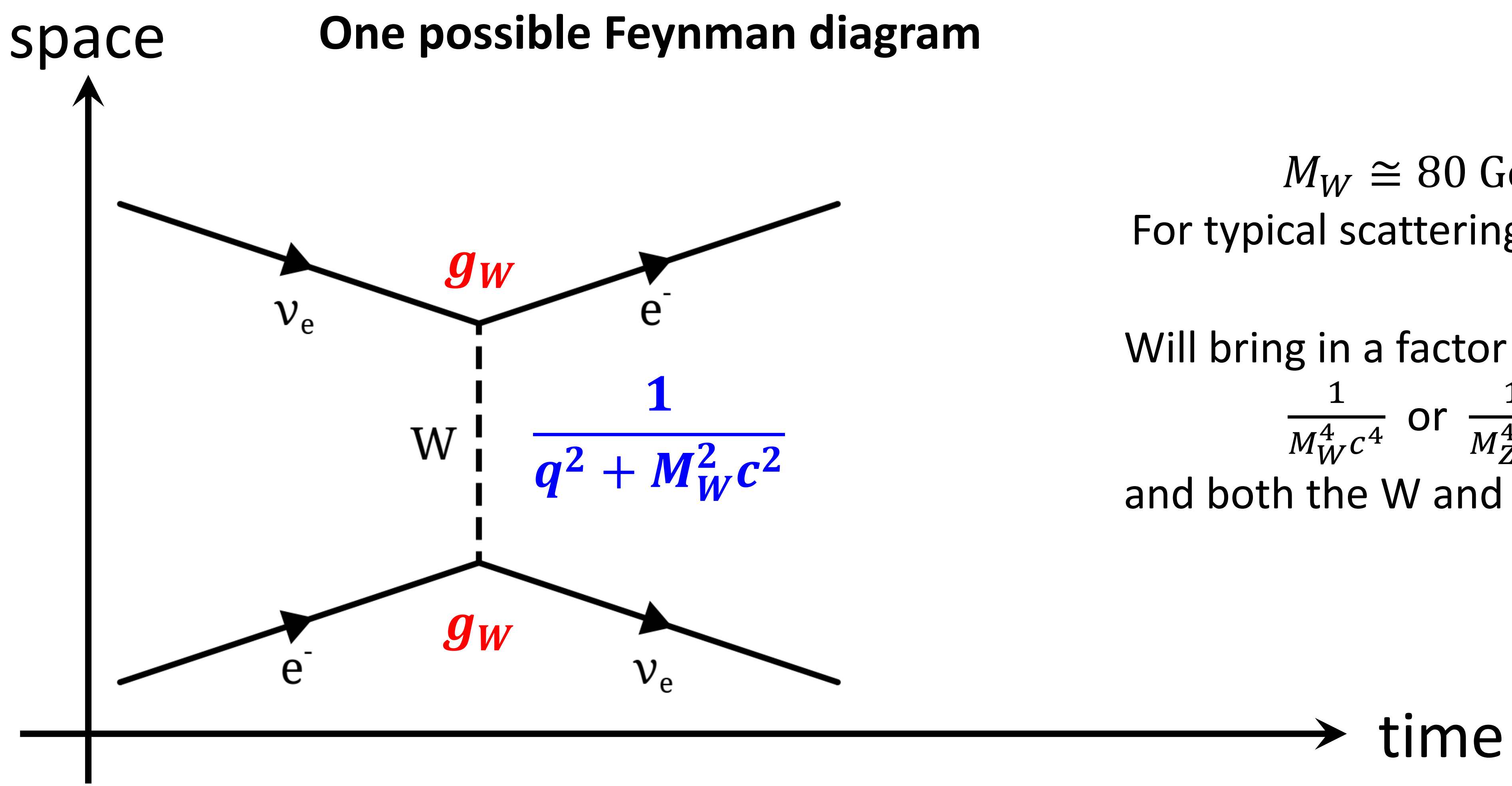
As we progress through, you'll want to take note of the charges of the various quarks.

	Family		
Charge	**1**	**2**	**3**
-1/3	**d**	**s**	**b**
+2/3	**u**	**c**	**t**

Antiquarks have opposite charge to the quarks

Suppose we fire a ν_e beam at an electron (e^-)

One possible Feynman diagram



$M_W \cong 80 \text{ GeV}/c^2$

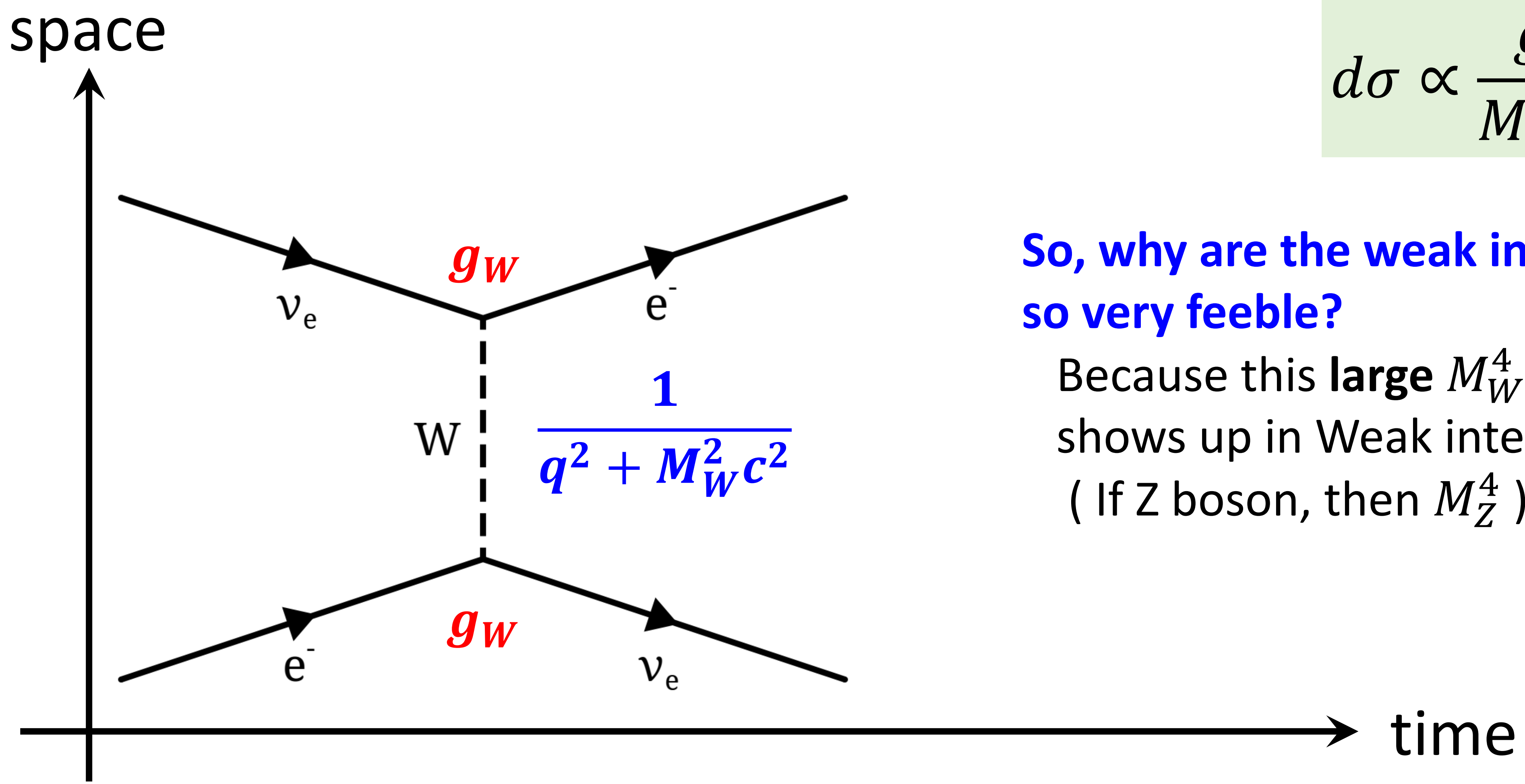
For typical scattering $q^2 \ll M_W^2 c^2$

Will bring in a factor of

$\frac{1}{M_W^4 c^4}$ or $\frac{1}{M_Z^4 c^4}$

and both the W and Z masses are HUGE!

$$d\sigma \propto \frac{g_W^4}{(q^2 + M_W^2 c^2)^2} \Rightarrow d\sigma \propto \frac{g_W^4}{M_W^4 c^4}$$



$$d\sigma \propto \frac{g_W^4}{M_W^4 c^4}$$

So, why are the weak interactions so very feeble?

Because this **large** M_W^4 factor (always) shows up in Weak interactions or decays!
(If Z boson, then M_Z^4)

Consequence #1) Small cross-sections:

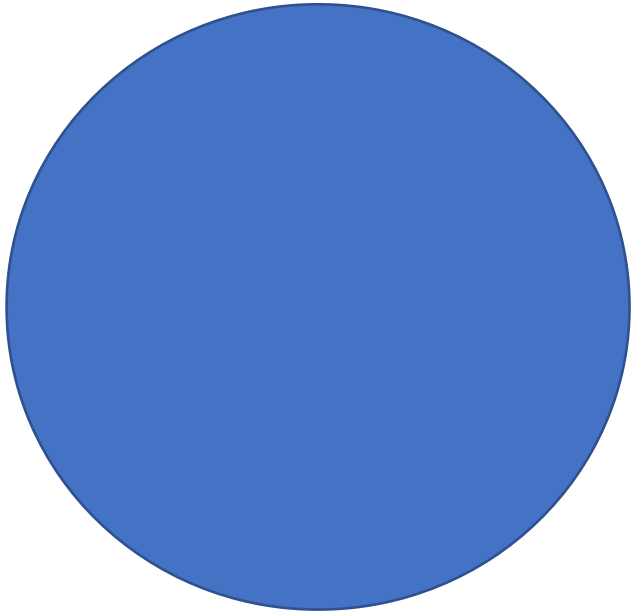
Example, a neutrino can pass through the entire Earth without interacting!

Just to set the scale

Strong force

$pp \rightarrow X$ @ 5+5 GeV

$\boldsymbol{\sigma \sim 5 \times 10^{-26}}\mathrm{cm}^2$

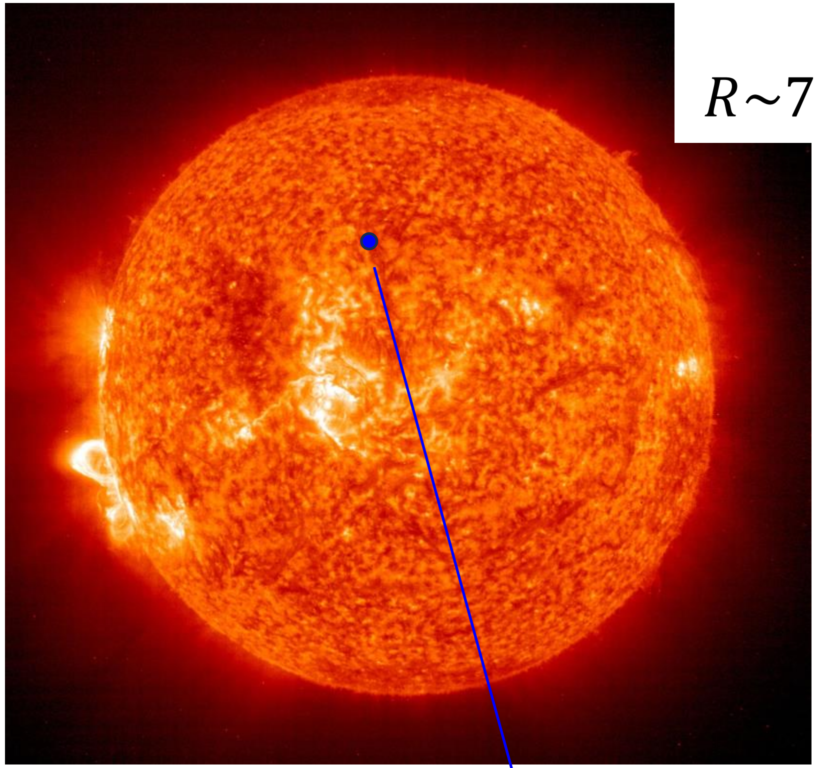


Weak force

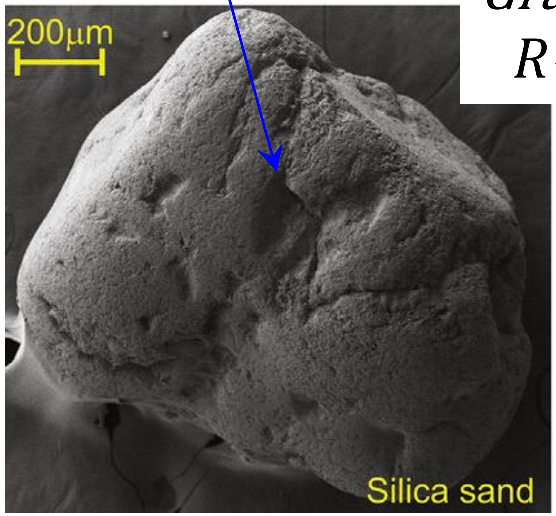
$\nu p \rightarrow X$

$\boldsymbol{\sigma \sim 10^{-38}\mathrm{cm}^2}$ $(\mathrm{E}_\nu = 1\ \mathrm{GeV})$

$\boldsymbol{\sigma_{strong} \sim 10^{12} \times \sigma_{Weak}}$



Sun:
$R \sim 7 \times 10^{11}$ mm



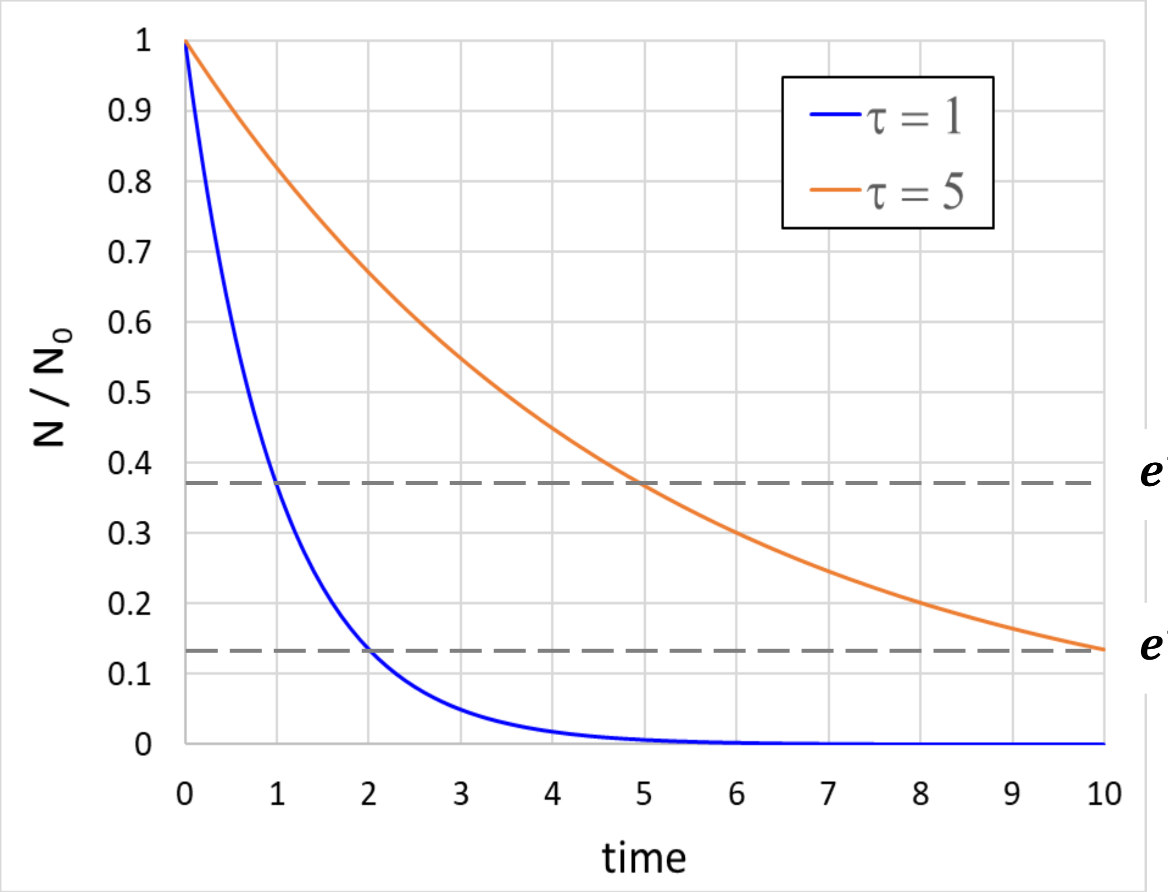
Grain of sand
$R \sim 0.7$ mm

To put the ratio of "strength" in perspective, imagine shooting a grain of sand at:

- ❑ Another grain of sand (Weak)
- ❑ The Sun (Strong)

and trying to get a strike!

Decays



e^{-1}

e^{-2}

Decay rates

$$N = N_0 e^{-\Gamma t}$$

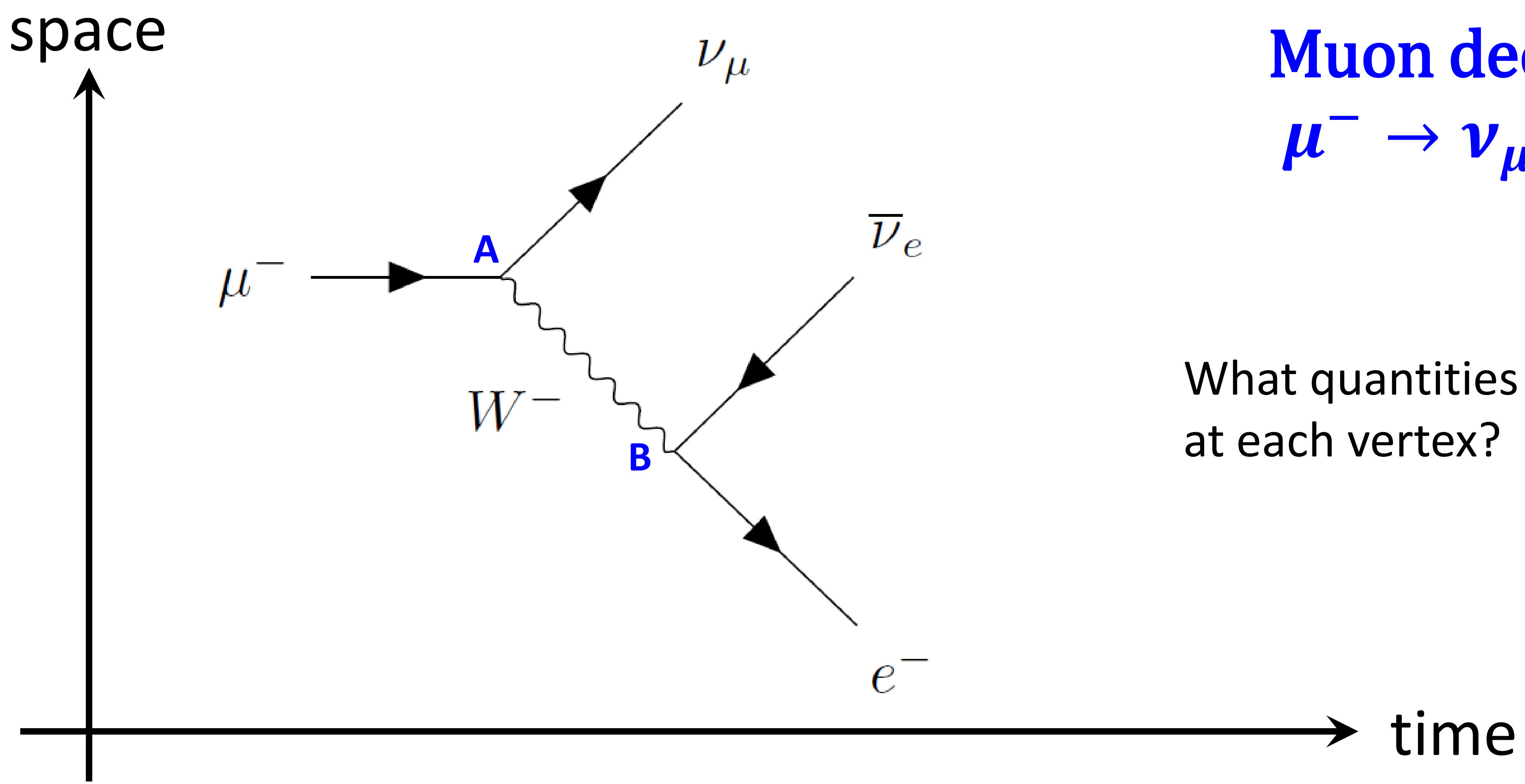
$$N = N_0 e^{-t/\tau}$$

$$\tau = \frac{1}{\Gamma} = \text{Lifetime } [s]$$

Short lifetimes ⇔ Large decay rates

Aside: Lifetime t is related to half-life by $t_{\frac{1}{2}} = \tau \ln(2)$

Simplest weak decay



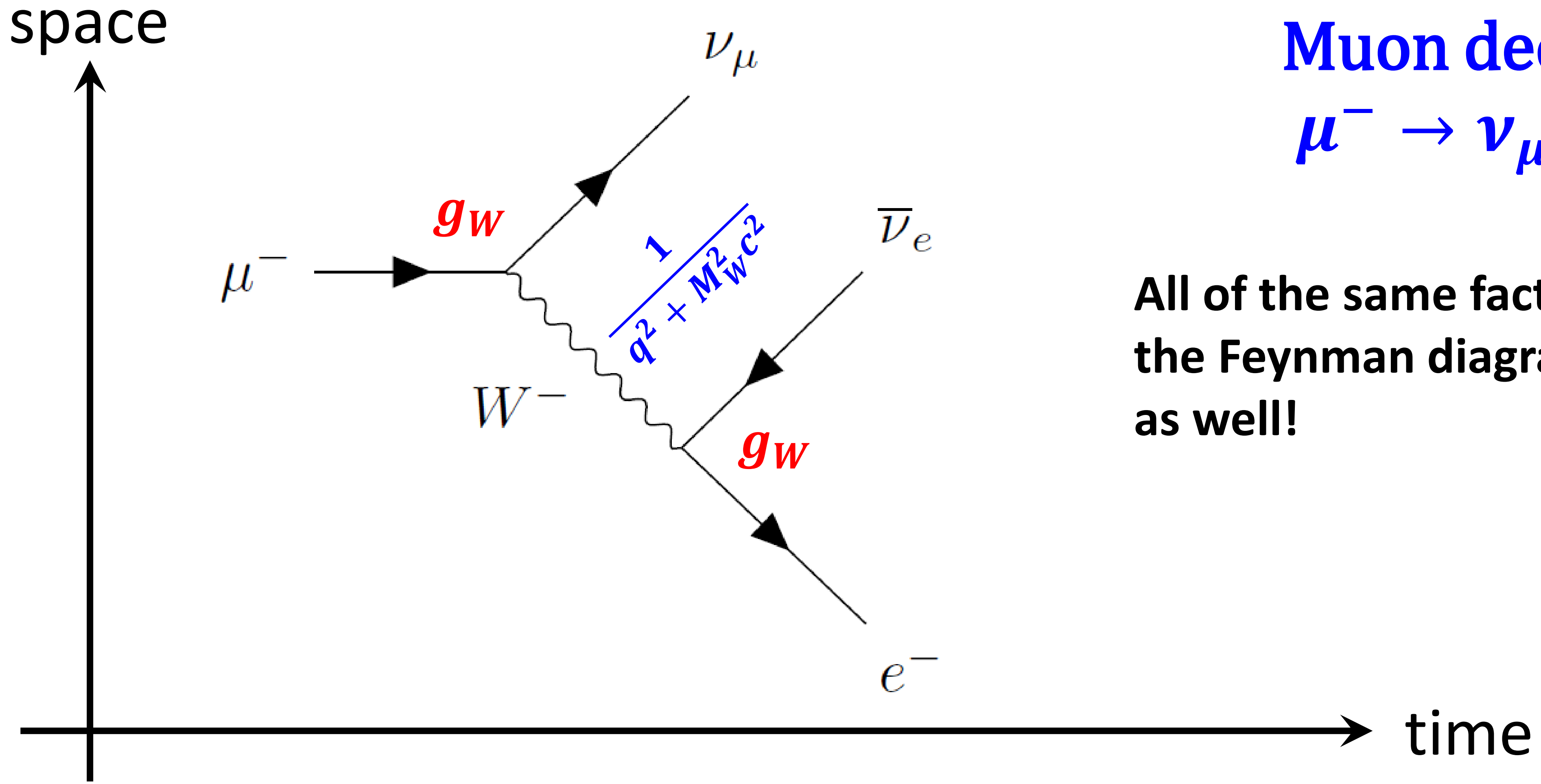
Muon decay

$\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$

What quantities are conserved at each vertex?

- ❑ The W- boson mediates the decay. It's a **2-step process**
  - ❑ At **A**: $\mu^- \rightarrow \nu_\mu + W^-$
  - ❑ At **B**: $W^- \rightarrow e^- + \bar{\nu}_e$

Simplest weak decay



Muon decay

$$\mu^- \rightarrow \nu_\mu e^- \overline{\nu}_e$$

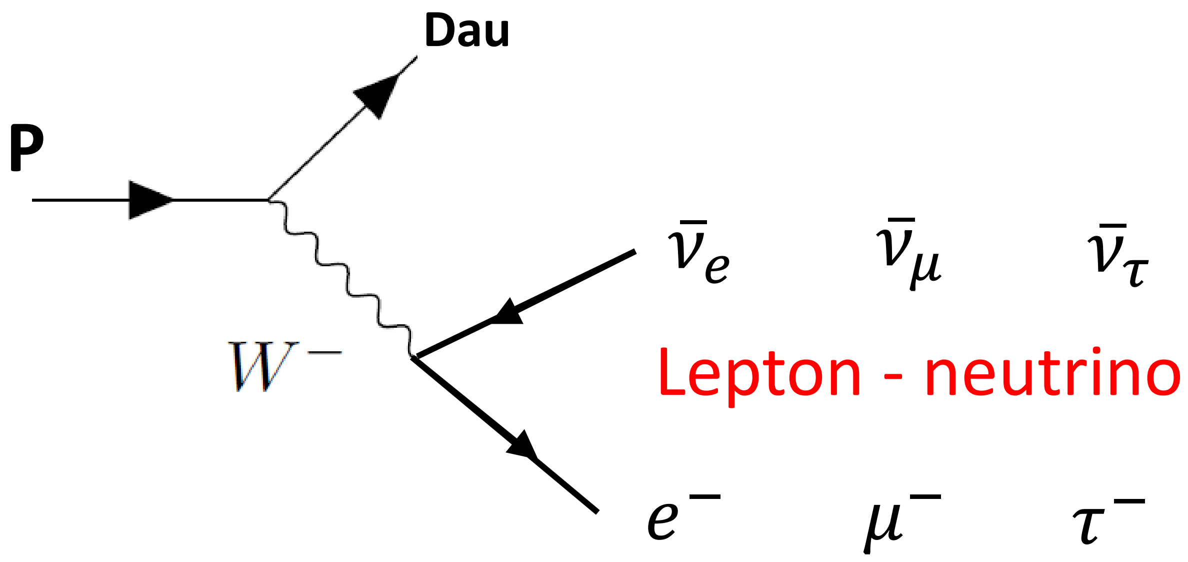
All of the same factors enter into the Feynman diagram for decays as well!

$$\Gamma \propto \frac{g_W^4}{M_W^4 c^4}$$

=> Weak decay rates very small (say, compared to EM or Strong decays)

Since $\tau = 1 / \Gamma$ this mean weak decays result in **LARGE LIFETIMES!**

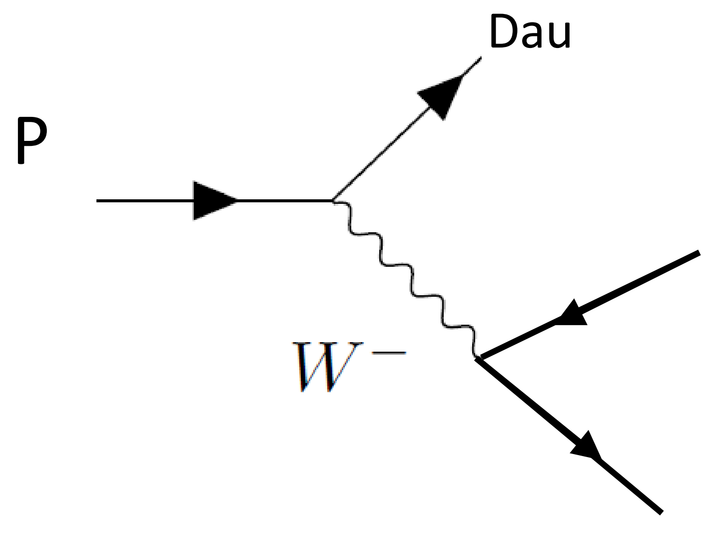
Can W decay into other leptons?



*** There must be sufficient energy to create the lepton pair.**

	Parent		Dau		W^-			
	n	$\rightarrow$	p	$+$	e^-	$+$	$\bar{\nu}_e$	**YES**
Mass (MeV /c^2)	939.6		938.3		0.5		tiny	
	n	$\rightarrow$	p	$+$	μ^-	$+$	$\bar{\nu}_\mu$	**NO**
Mass (MeV/c^2)	939.6		938.3		105		tiny	
	$\bar{B}^0$	$\rightarrow$	D^+	$+$	τ^-	$+$	$\bar{\nu}_\tau$	**YES**
Mass (MeV /c^2)	5279		1869		1777		tiny	

What about quarks?



d	s	s	d

Quark + antiquark

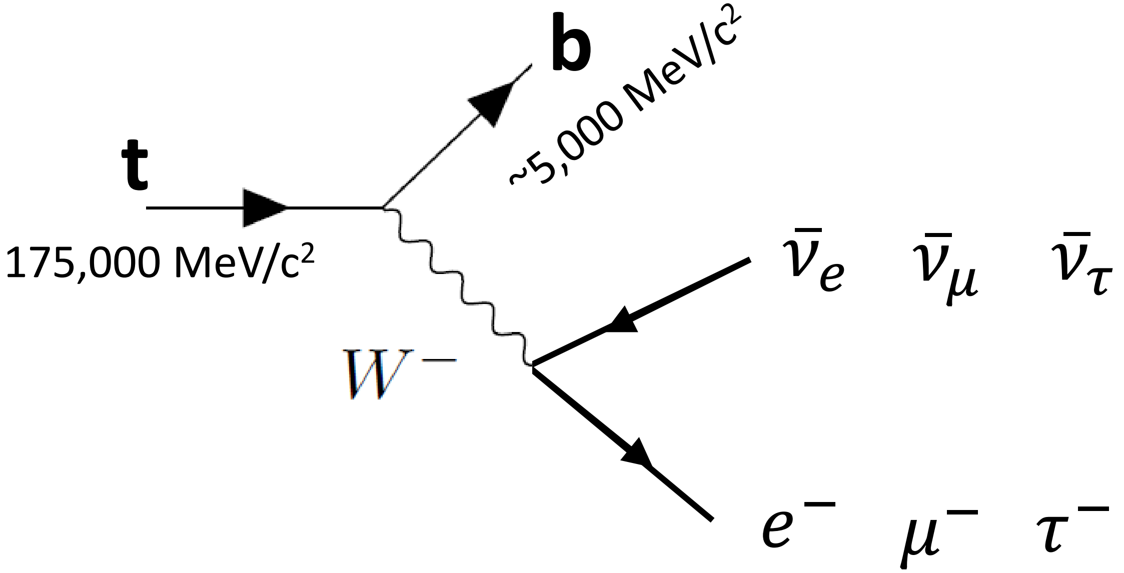
$\bar{u}$	$\bar{c}$	$\bar{u}$	$\bar{c}$

- ❑ These quarks/antiquarks will combine to form 1 (or more) hadrons
- ❑ Also limited by energy conservation!

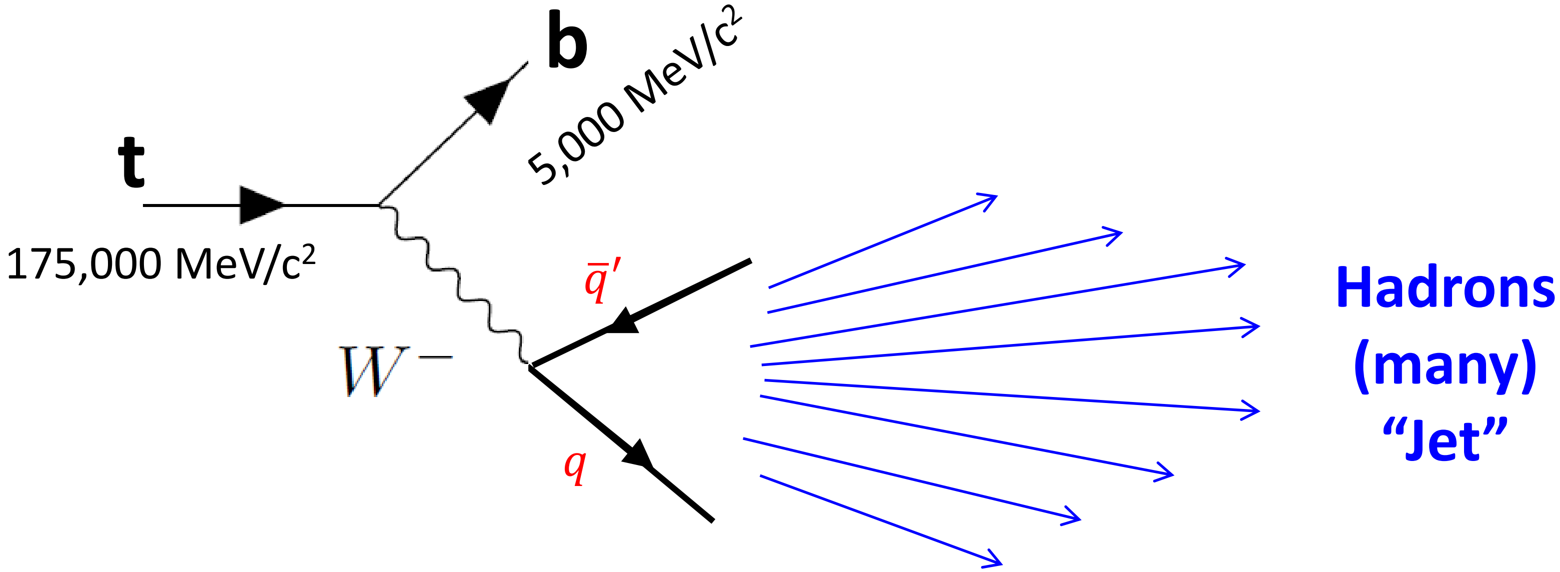
Particle	Quarks	Mass (MeV/c²)
π^-	$(\bar{u}d)$	139.5
D_s^-	$(\bar{c}s)$	1968
K^-	$(\bar{u}s)$	493.7
D^-, D^+	$(\bar{c}d), (c\bar{d})$	1869
$\bar{D}^0$	$(c\bar{u})$	1865
D_s^-, D_s^+	$(\bar{c}s), (c\bar{s})$	1968

	Parent		Dau		$\overbrace{}^{W^-}$	
	n	$\rightarrow$	p	$+$	π^-	NO
Mass (MeV /c²)	939.6		938.3		139.5	
	$\bar{D}^0$	$\rightarrow$	K^+	$+$	K^-	YES
Mass (MeV/c²)	1865		493.7		493.7	
	D_s^+	$\rightarrow$	K^+	$+$	D^0	NO
Mass (MeV/c²)	1968		493.7		1865	
	$\bar{B}^0$	$\rightarrow$	D^+	$+$	D_s^-	YES
Mass (MeV /c²)	5279		1869		1777	

Top quark decay



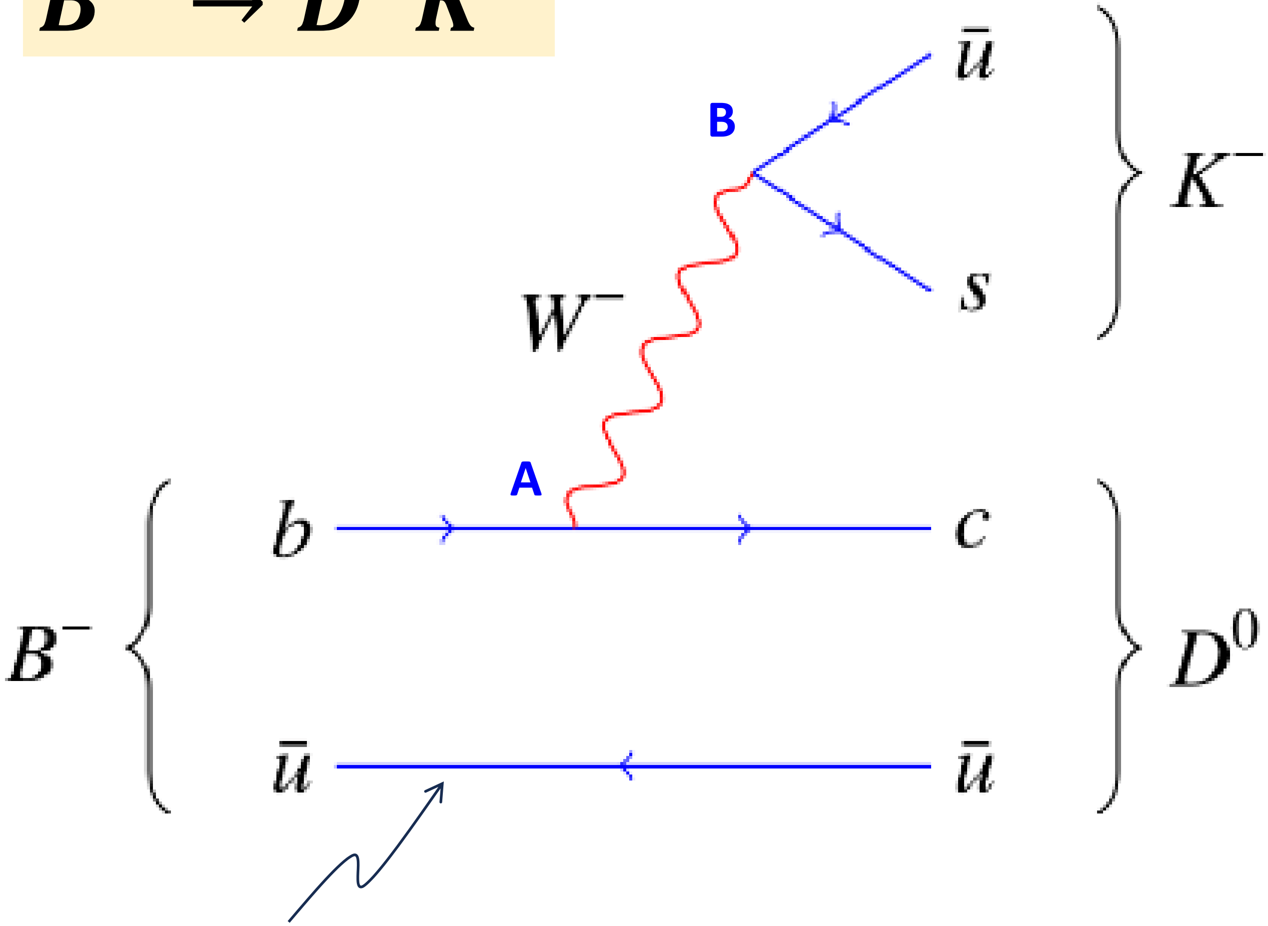
Any of these 3 can occur



Any $q\bar{q}'$ pair that has Q_{tot}=1, except t quark

Example Weak decay (1)

$B^- \rightarrow D^0 K^-$

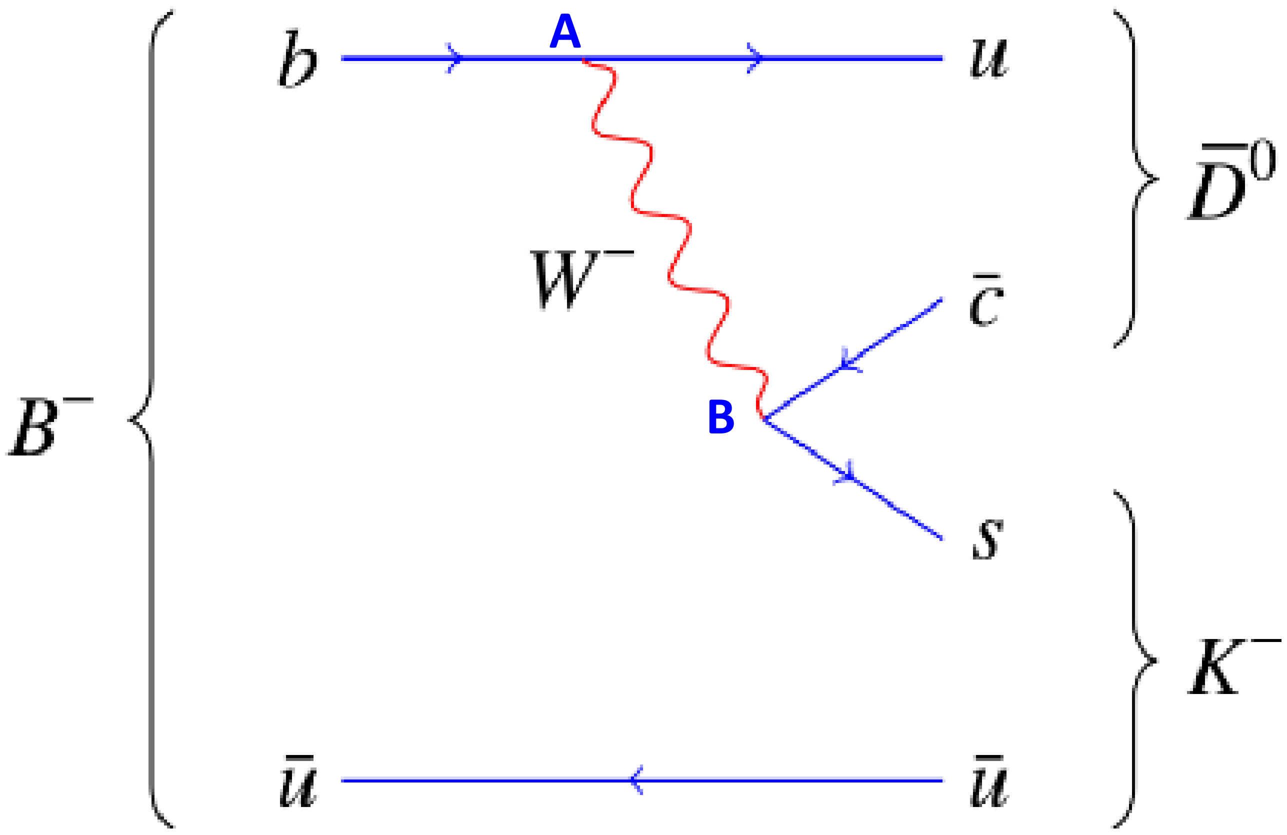


Jargon we sometime use:
"The $\bar{u}$ (from the B⁻) is a spectator"
(Speculations as to why?)

- What tells us this is a weak decay?
- Weak decay is a **2-step process**
  - At **A**: $b \rightarrow c + W^-$
  - At **B**: $W^- \rightarrow \bar{u} + s$
- But, there is an additional part!
- The $\bar{u}s$ have to "stick together" and form a K^-.
- The $c\bar{u}$ have to "stick together" and form a D^0.
- What interaction do you think is responsible for this "binding"?

Example Weak decay (2)

$\boldsymbol{B^- \rightarrow \bar{D}^0 K^-}$

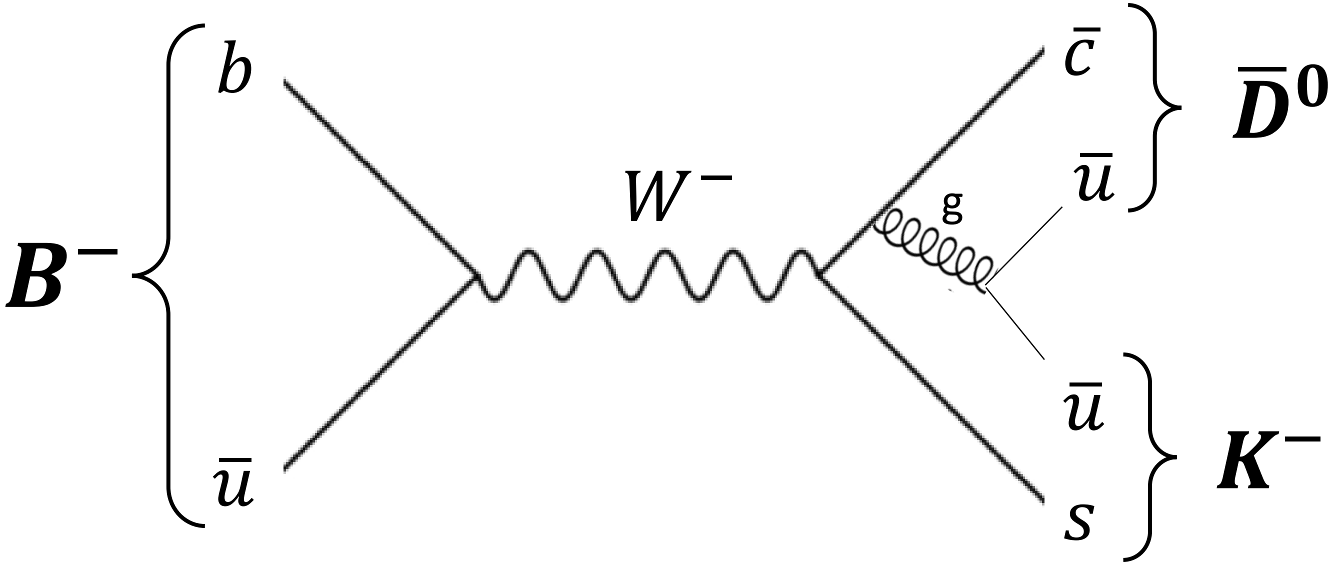


- Here the W^- goes "internal"
- Weak decay is a **2-step process**
  - At **A**: $b \rightarrow u + W^-$
  - At **B**: $W^- \rightarrow \bar{c} + s$
- The $\bar{u}c$ bind "to form a $\bar{D}^0$.
- The $s\bar{u}$ bind to form a K^-.

Both this "internal W" or "external W" (prev slide) are possible

Are there other diagrams ?

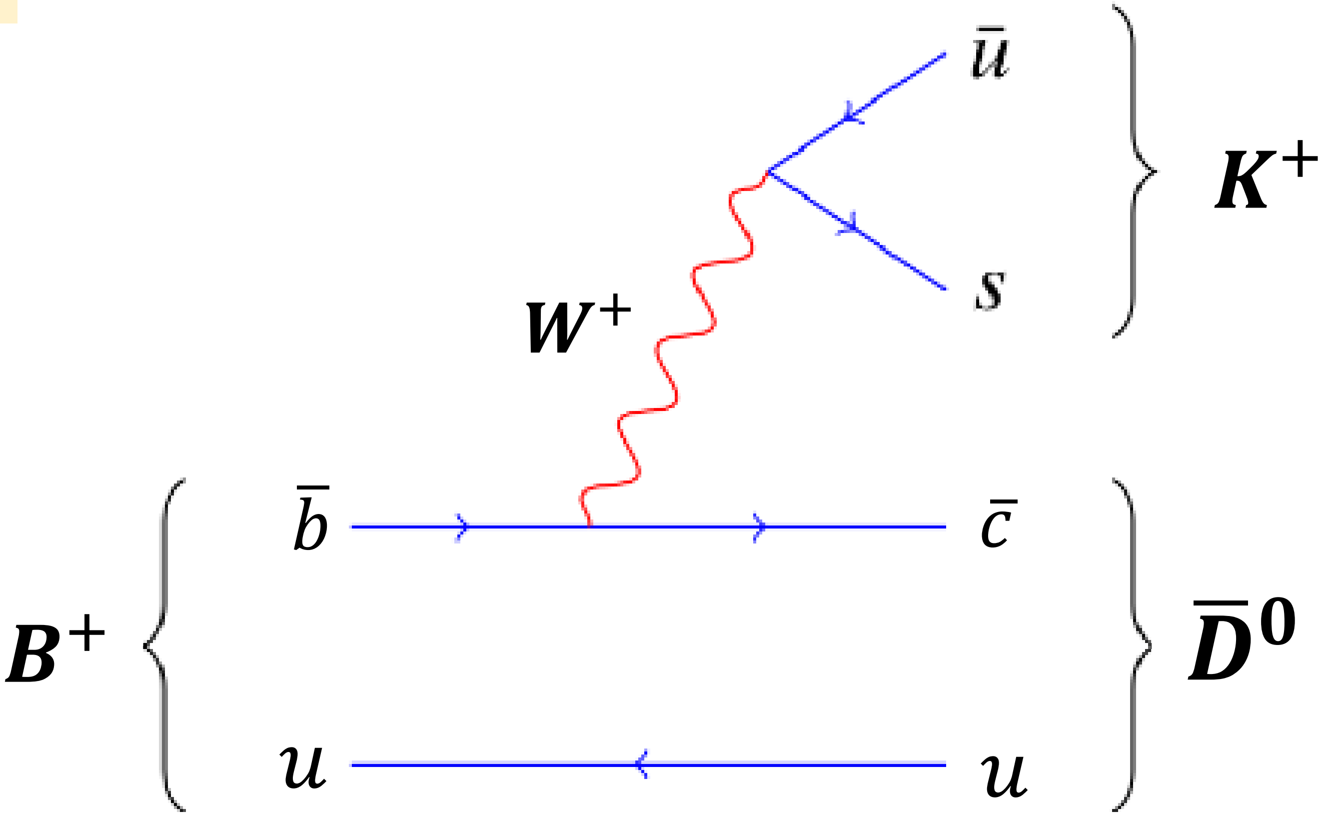
$B^- \to \overline{D}^0 K^-$



Here, the initial b and $\bar{u}$ annihilate into a W^-, and then the W^- decays into $\bar{c}$ + s

Could also have W+

$B^+ \rightarrow \bar{D}^0 K^+$



You must conserve electric charge at each vertex. In weak decays of heavy quarks, the charge must change by +1 unit or -1 unit! **Here: $\bar{b}$(+1/3) → $\bar{c}$ (-2/3), so the W MUST be +1 charge.**

Computing weak decay rates (Γ)

- This is very hard for most particles, because you have to consider **ALL** possible ways it can decay!
- Suppose a particle can decay 100 ways, then what is Γ ?

$$\Gamma = \Gamma_1 + \Gamma_2 + \Gamma_3 + \ \dots + \ \Gamma_{100}$$

- Moreover, part of each Γ_i calculation is:
  "How likely is it that the quarks will bind (via the strong force)?"

- Very hard to compute this. (in practice, not feasible in almost all cases)

- Instead, we can measure the lifetime, which is related to the width, $\tau = 1/\Gamma$

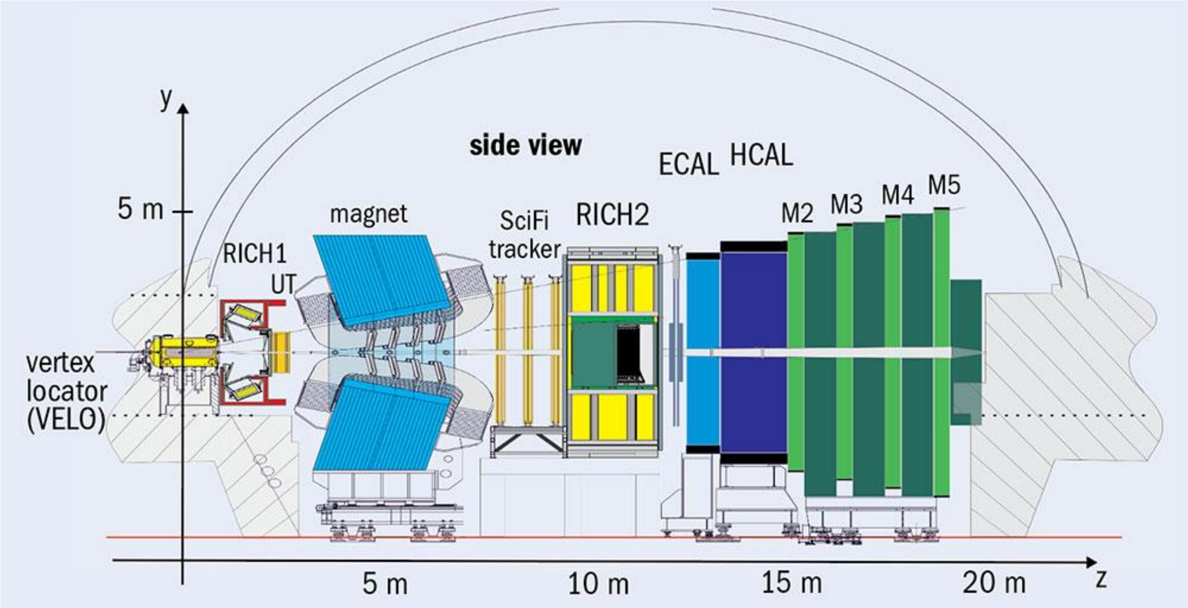
Some particle lifetimes (Weak decays)

Particle	Quarks	Lifetime
μ^+		22 μs
π^+	$(u\bar{d})$	26 ns
K^+	$(u\bar{s})$	12.4 ns
K_S^0	$(s\bar{d})$	90 ps
Λ	sud	263 ps
D^0	$(c\bar{u})$	0.41 ps
D^+	$(c\bar{d})$	1.03 ps
Λ_c^+	cud	0.2 ps
B^+	$(\bar{b}u)$	1.64 ps
Λ_b^0	bud	1.5 ps

- Micro (10^{-6}), nano (10^{-9}) and pico (10^{-12}) second lifetimes may not seem very long, but they are **directly measurable**!

Particle	τ	$\langle d\rangle \cong c\tau$	$\langle d\rangle \cong \gamma c\tau$
K^+	12.4 ns	3.7 m	74 m
B^+	1.64 ps	0.5 mm	10 mm

Special Relativity ➔ "*fast moving clocks run slow*!" (time dilation!)
The time dilation factor (γ) depends on the particle's energy, but in LHCb, $\gamma \approx 20$ is typical.



Unstable particles like K^+, π^+, μ^+ usually traverse the entire LHCb detector before decaying!

Some particle lifetimes (Weak decays)

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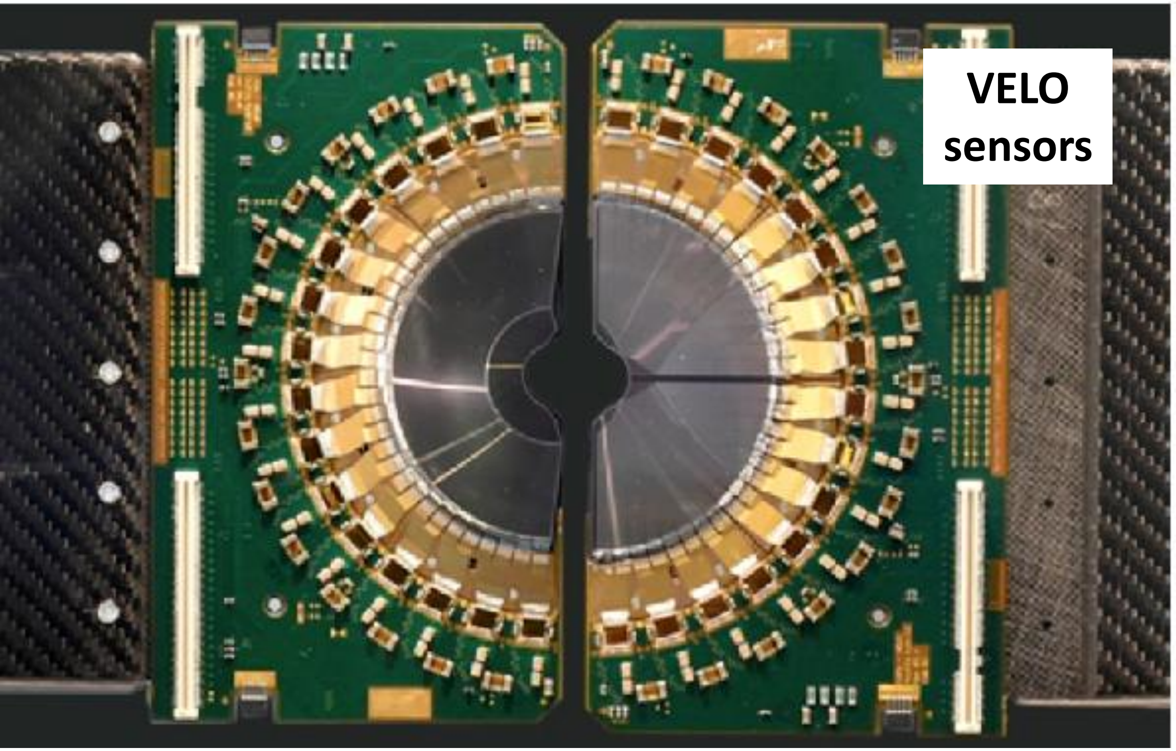
- **For comparison:**
  - EM decay: Lifetimes ~10^{-17} to 10^{-20} sec
  - Strong decay: Lifetimes ~10^{-23} sec
  - These lifetimes are too short for us to measure.

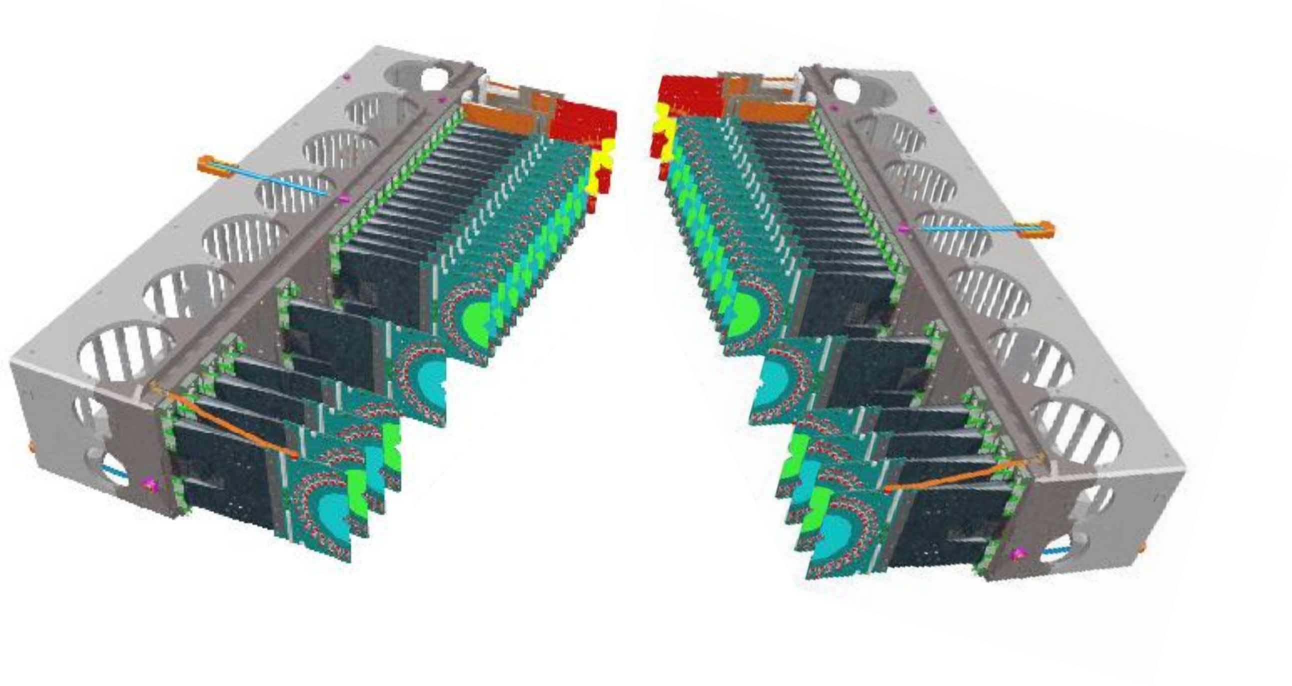
Measuring lifetimes of particles that decay weakly



Build detectors with hair-thin (~50 μm) active detection elements.

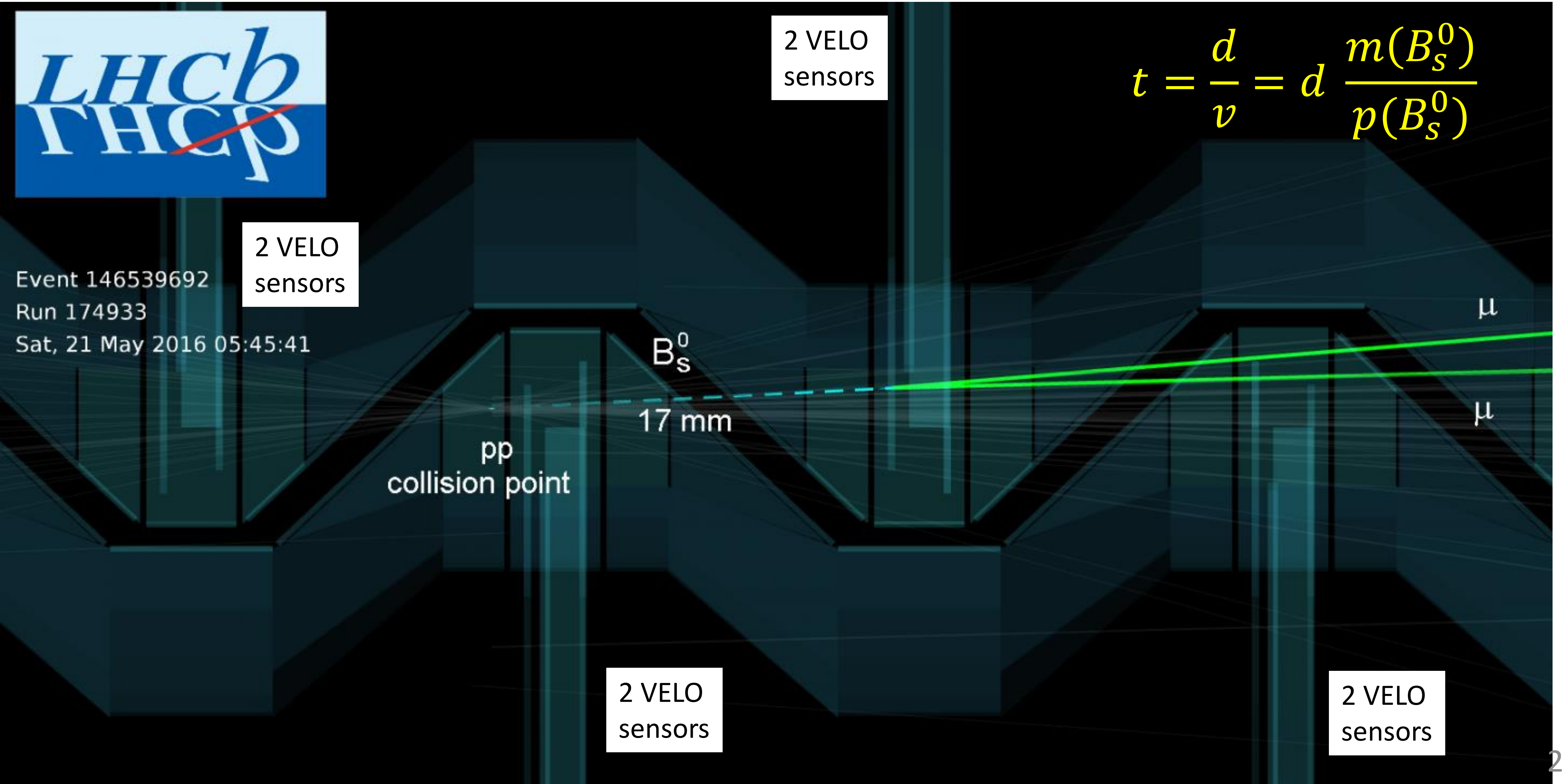
1000's of such detection elements in this "module"

Measuring lifetimes of particles that decay weakly



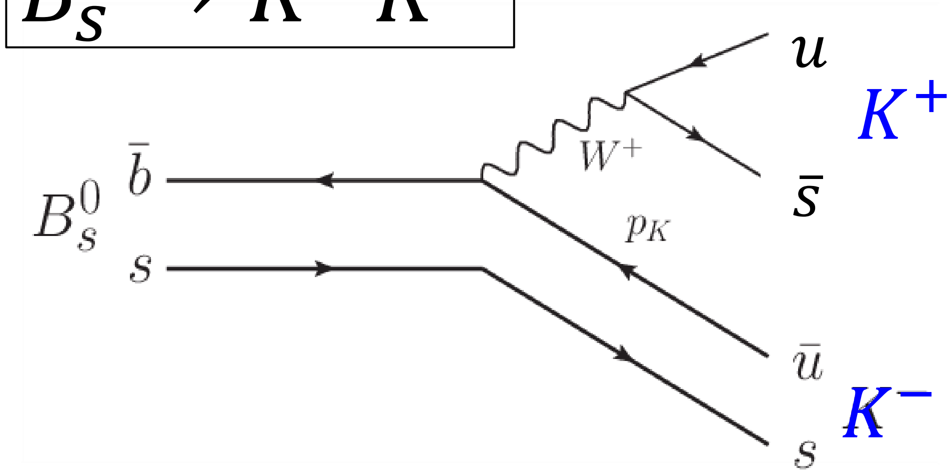
Put many of them in a row so that charged particles pass through many of them.
➔ VELO detector

A candidate $B_s \to \mu^+\mu^-$ decay



A real (early) measurement

$B_s \rightarrow K^+K^-$

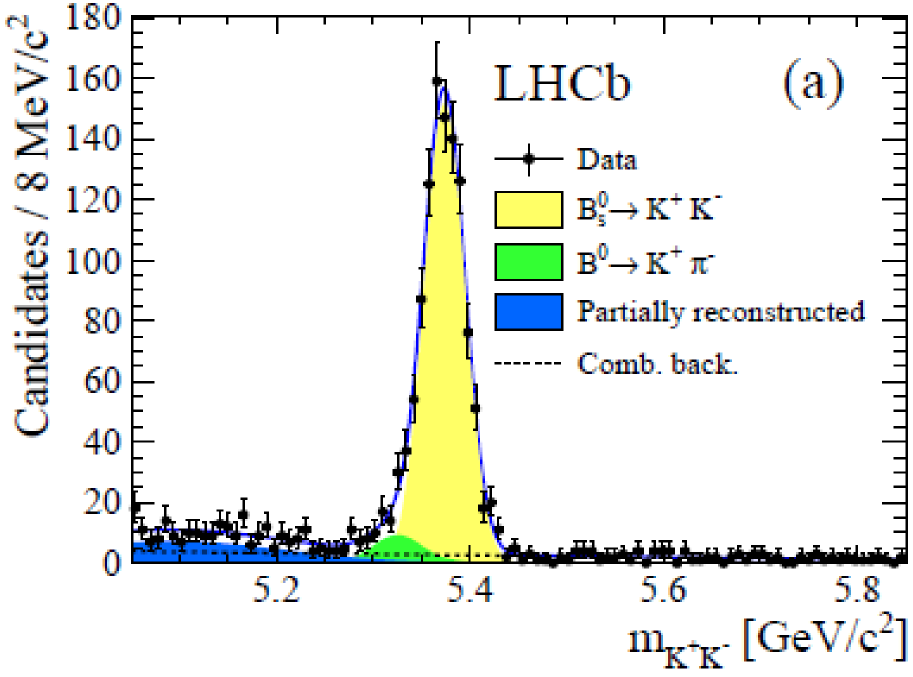


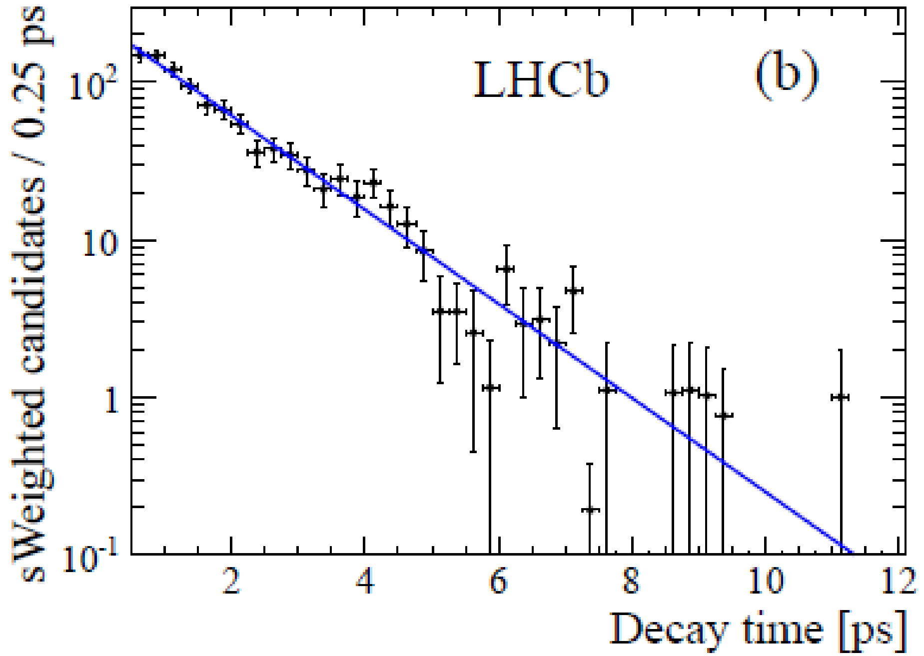
$$N = N_0 e^{-t/\tau}$$

$$\ln N = \ln N_0 - \left(\frac{1}{\tau}\right) t$$

Fitting the logN plot versus time
→ Slope = 1/τ !

$\boldsymbol{\tau = 1.455 \pm 0.046(stat) \pm 0.006(syst)}$ **ps**





Backup

Some particle lifetimes (Weak decays)

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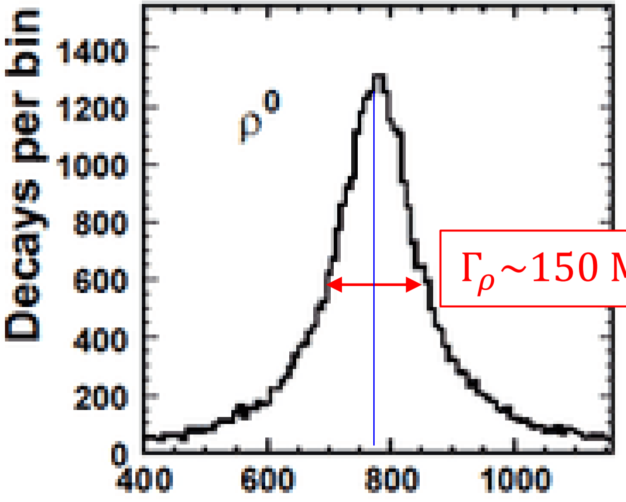
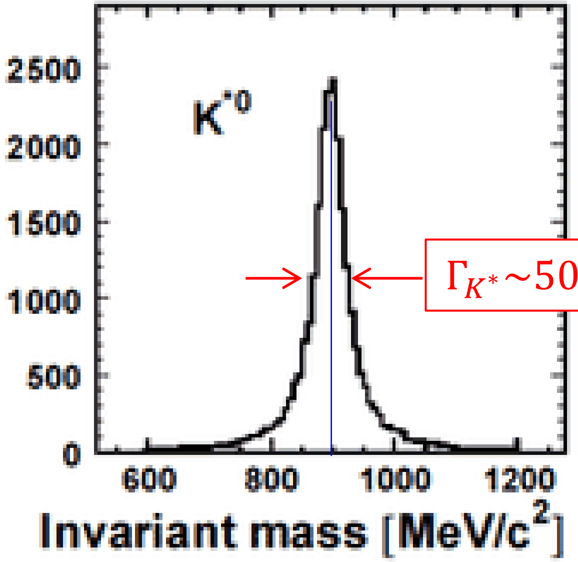
- **For comparison:**
  - EM decay: Lifetimes ~10^{-17} to 10^{-20} sec
  - Strong decay: Lifetimes ~10^{-23} sec
  - These lifetimes are too short for us to measure.
  - Often, we can measure the particle's decay "width"
    - $\Gamma_E = \hbar\Gamma = \hbar\ /\ \tau$
  - Two examples below of strong decays



$\Gamma_\rho \sim 150\ \mathrm{MeV/c^2}$

$M_\rho \sim 770\ \mathrm{MeV/c^2}$



$\Gamma_{K^*} \sim 50\ \mathrm{MeV/c^2}$

$M_{K^*} \sim 892\ \mathrm{MeV/c^2}$