Experimental Overview

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ATLAS Masterclass

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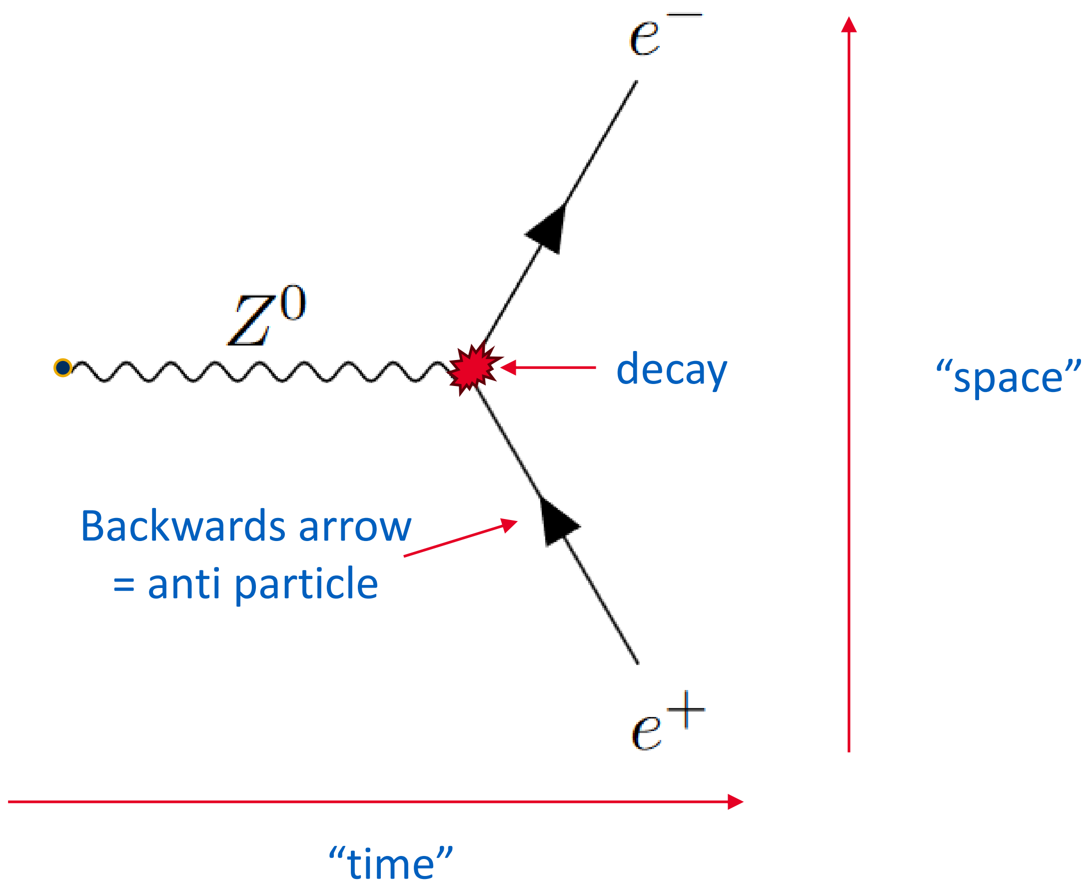
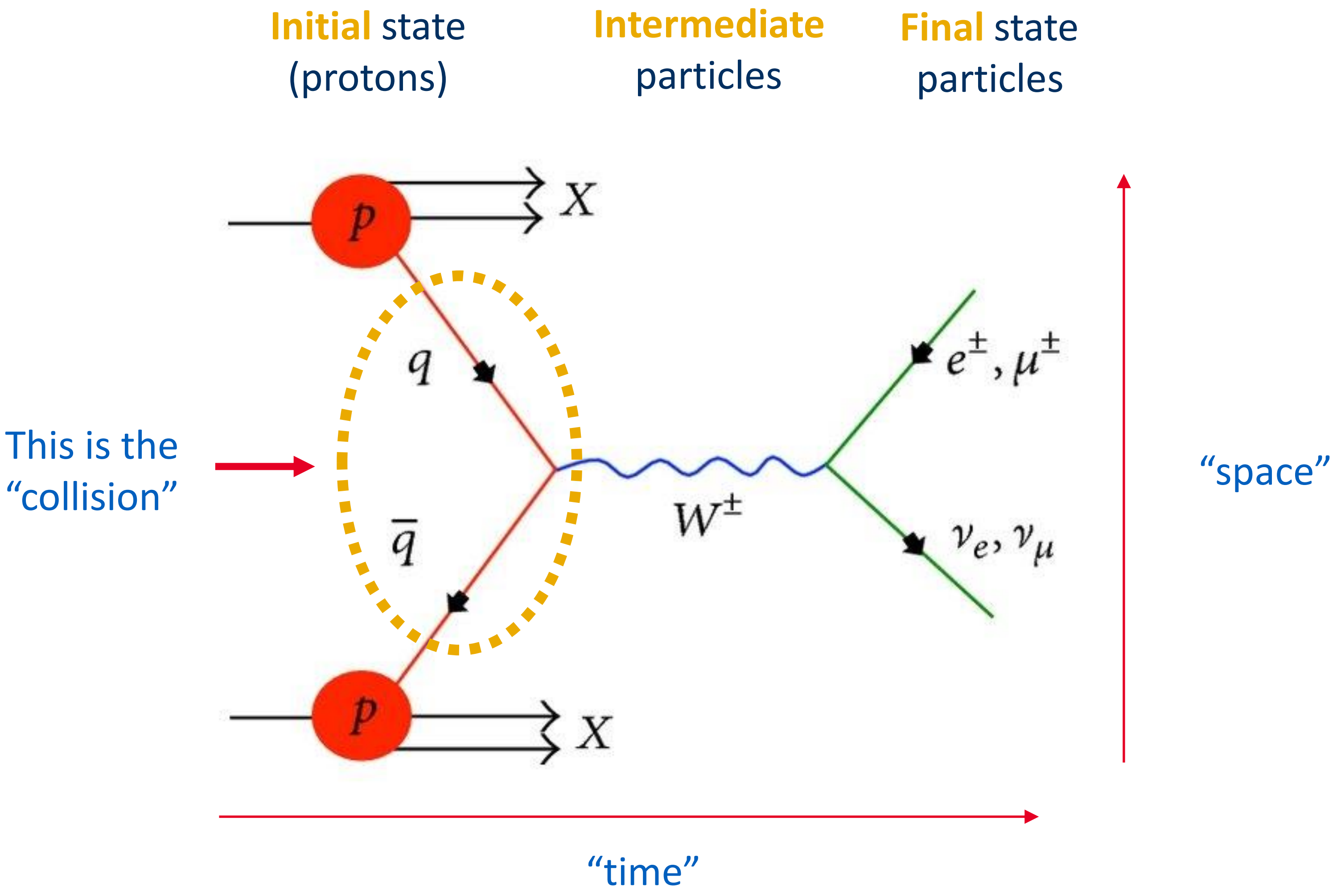
How to Read A Feynman Diagram

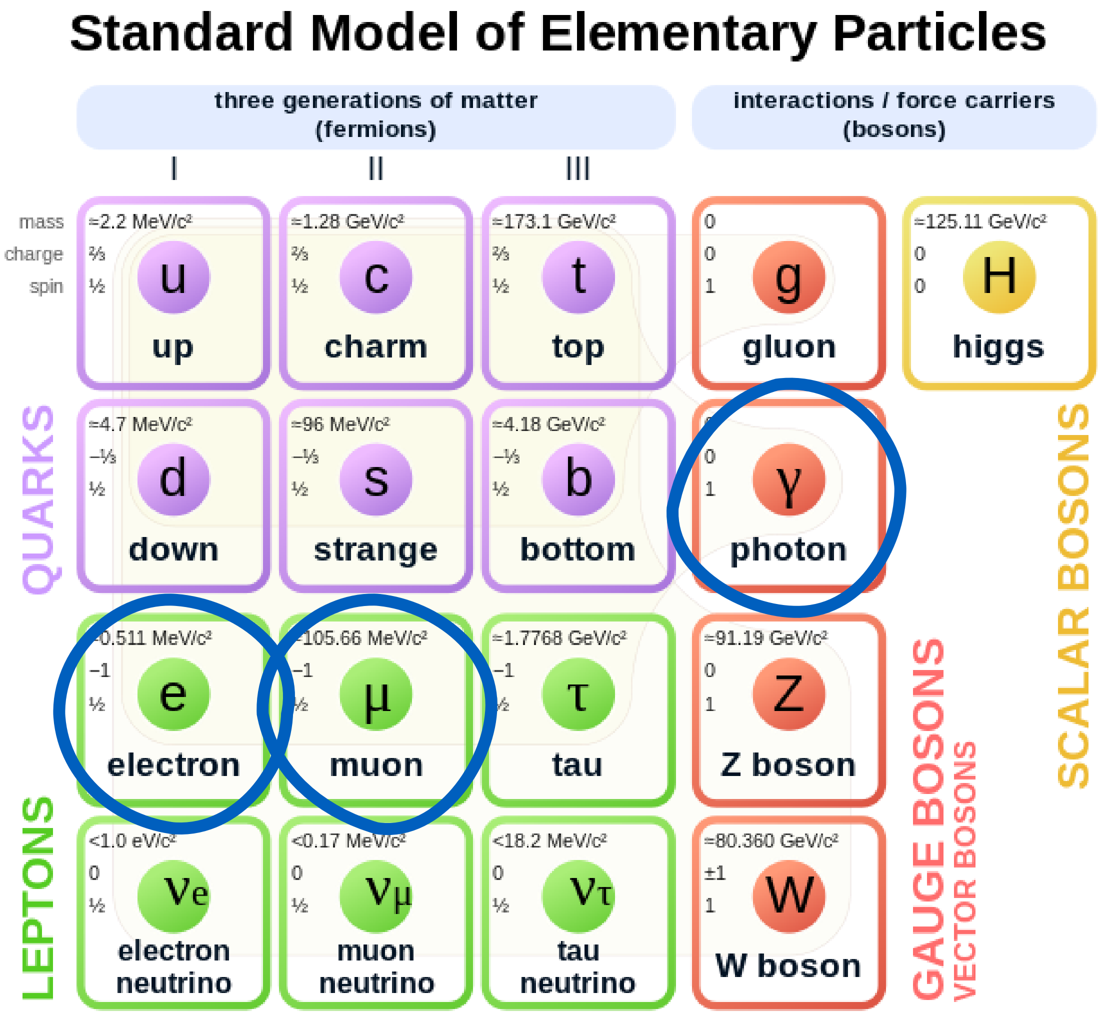
Particles are short-lived, they will decay



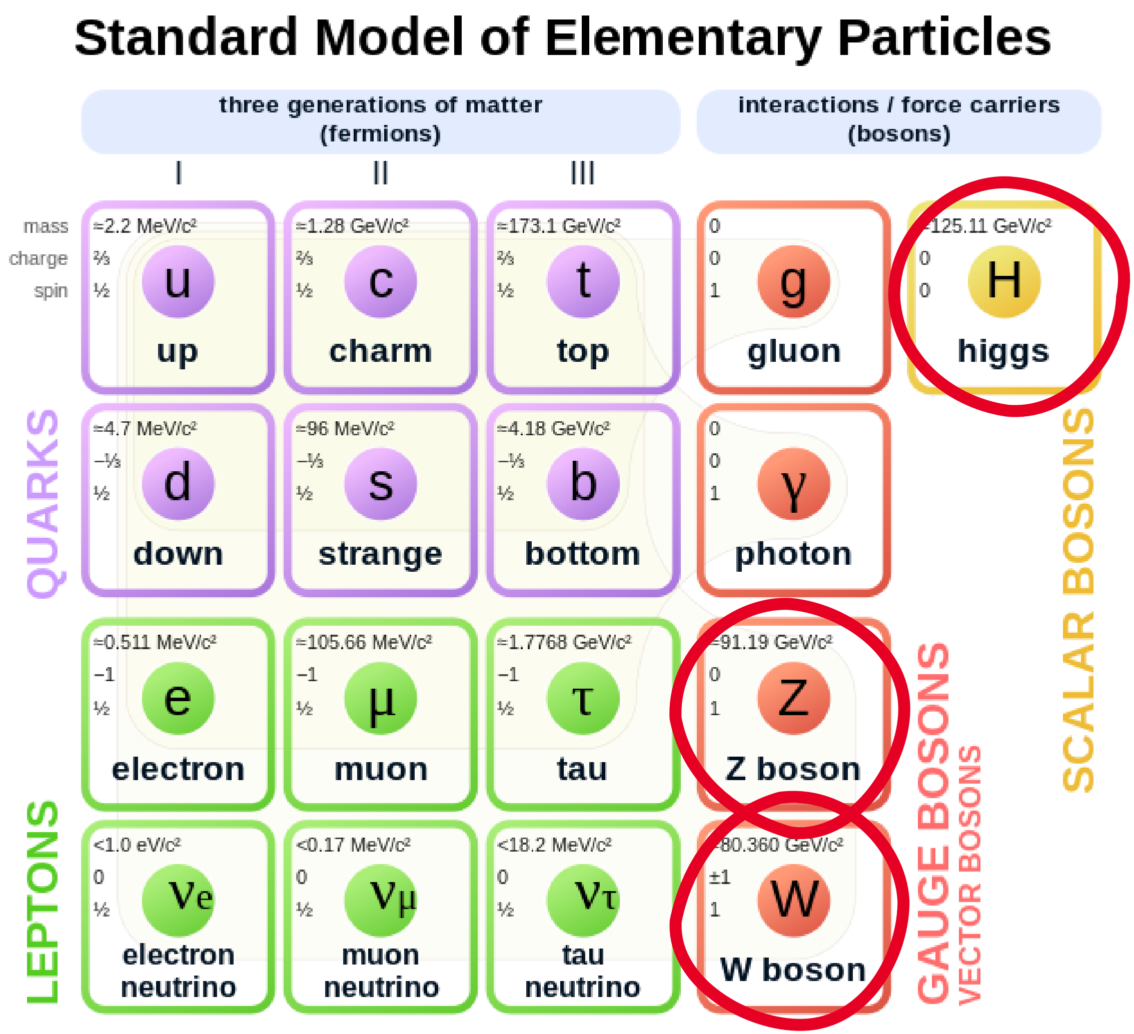
A Typical Collision



Final State Particles

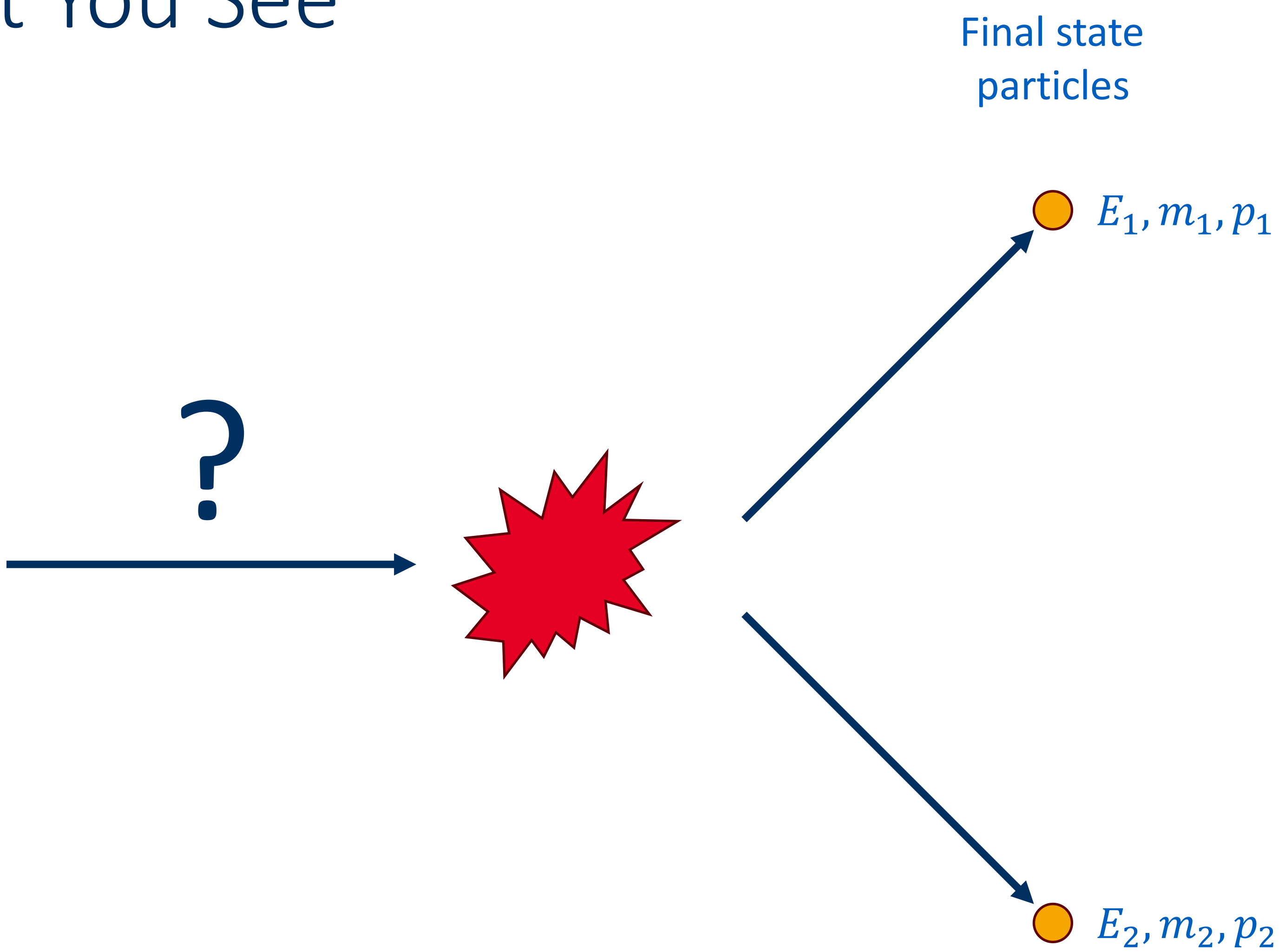


Intermediate Particles

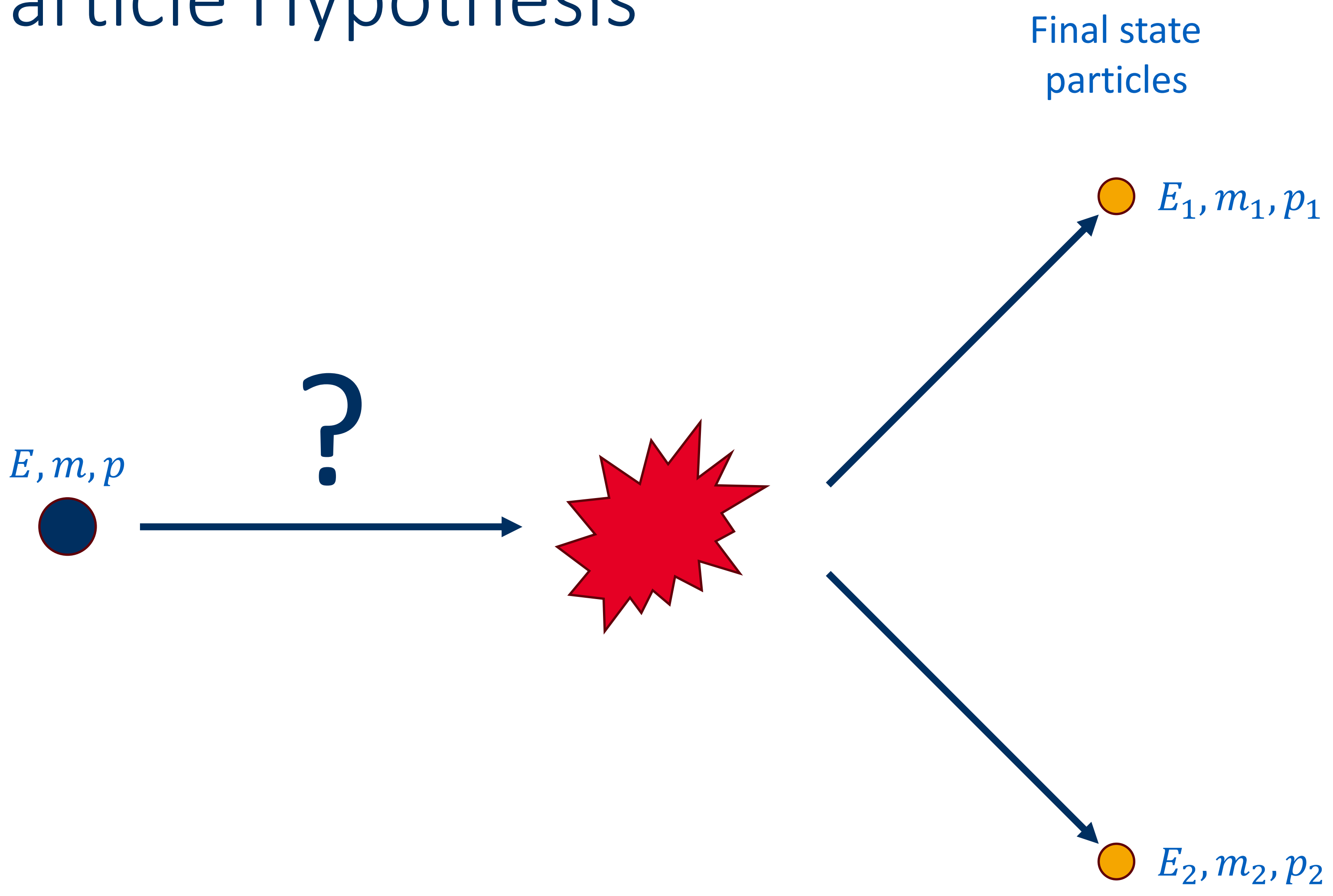


Reconstructing Intermediate Particles

What You See

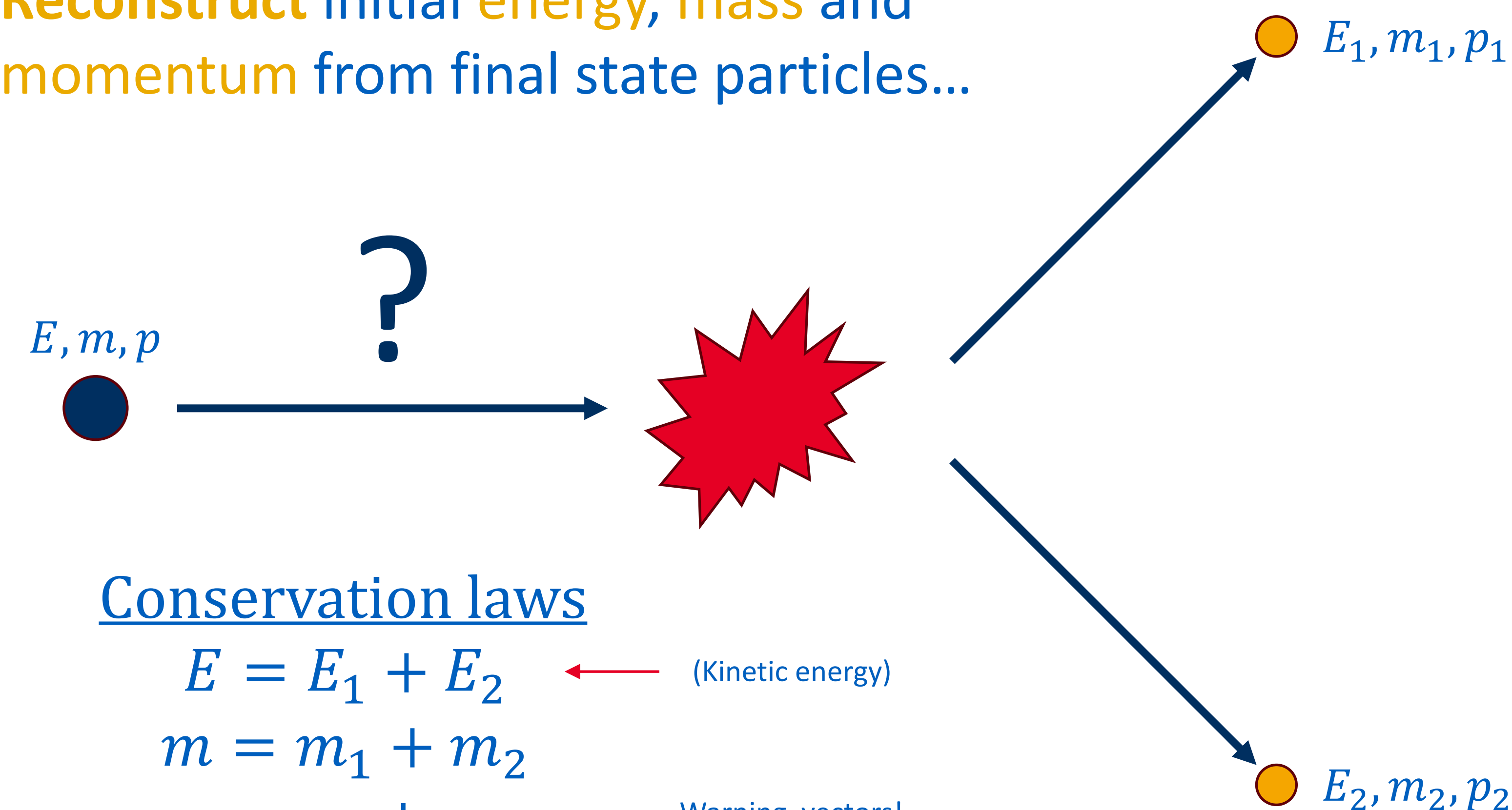


Particle Hypothesis



Classical Kinematics

Reconstruct initial energy, mass and momentum from final state particles…



Conservation laws

$$E = E_1 + E_2$$ ← (Kinetic energy)

$$m = m_1 + m_2$$

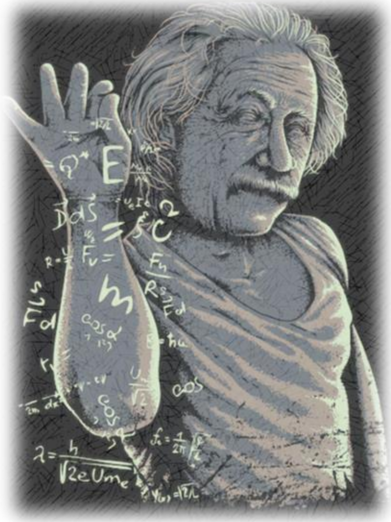
$$p = p_1 + p_2$$ ← Warning, vectors! $p = (p_x, p_y, p_z)$

Relativity

When things are going very fast…

$$E = mc^2$$

Mass can become energy!



(Thank you, Einstein)

Relativity

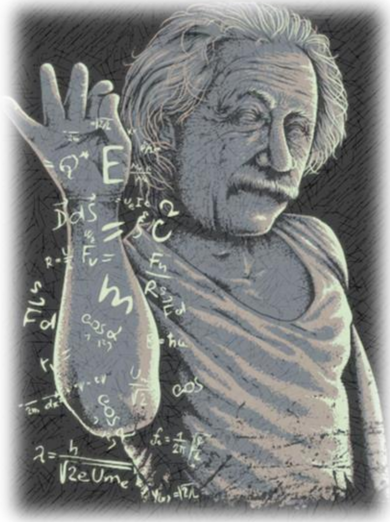
When things are going very fast…

$$E = mc^2$$

Mass can become energy!

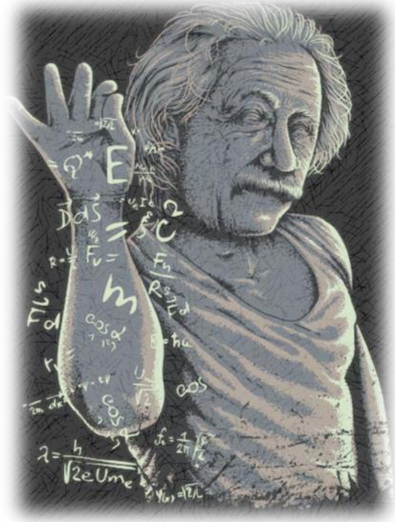
$$E^2 = (mc^2)^2 + (pc)^2$$

or momentum…



(Thank you, Einstein)

Relativity



(Thank you, Einstein)

When things are going very fast…

$$E = mc^2$$

Mass can become energy!

$$E^2 = (mc^2)^2 + (pc)^2$$

or momentum…

<u>Conservation laws</u>

$$E \stackrel{?}{=} E_1 + E_2$$
$$m \stackrel{?}{=} m_1 + m_2$$
$$p \stackrel{?}{=} p_1 + p_2$$

Energy is still conserved.
Momentum is still conserved
But mass? NOT conserved

Invariant Mass

What if nothing is moving?

$$E = mc^2$$

No momentum, all energy is mass.

Invariant Mass

What if nothing is moving?

$$E = mc^2$$

No momentum, all energy is mass.

Now add momentum:

$$E^2 = (mc^2)^2 + (pc)^2$$

m is still the same value! It doesn't change with momentum.

We call this the *Invariant Mass.*

Invariant Mass

$$E^2 = (mc^2)^2 + (pc)^2$$

For 1 particle, *Invariant Mass* = mass

Re-arrange

E, m, p

$$M_{inv} = m = \frac{1}{c^2}\sqrt{E^2 - (pc)^2}$$

Invariant Mass

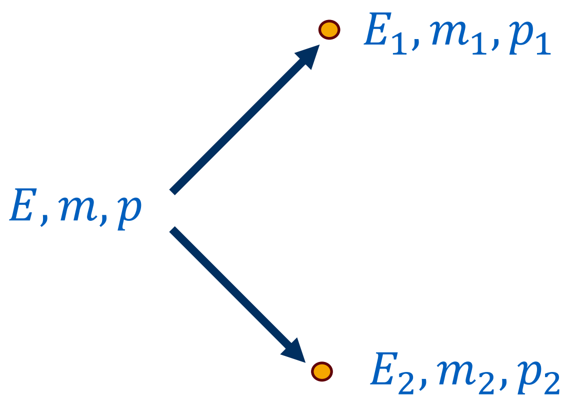
$$E^2 = (mc^2)^2 + (pc)^2$$

Re-arrange

For 1 particle, *Invariant Mass* = mass

$$M_{inv} = m = \frac{1}{c^2}\sqrt{E^2 - (pc)^2}$$

For 2 particles, *Invariant Mass* = mass of the initial conditions



Using: $E = E_1 + E_2$
$p = p_1 + p_2$

$$M_{inv} = m = \frac{1}{c^2}\sqrt{[E_1 + E_2]^2 - [p_1 + p_2]^2 c^2}$$

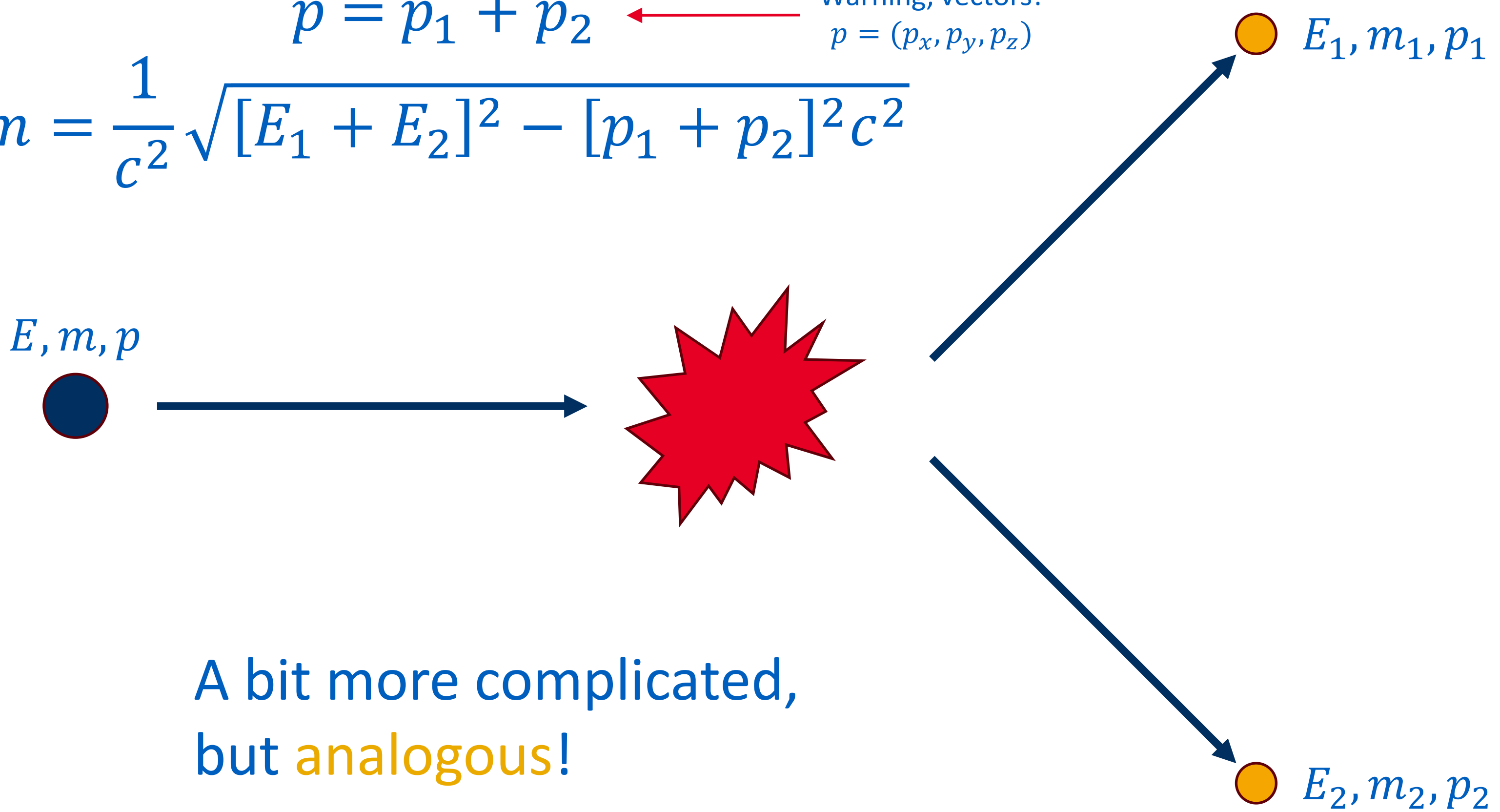
Relativistic Kinematics — Interpretation

Conservation laws

$$E = E_1 + E_2$$ ← (NOT JUST Kinetic energy)

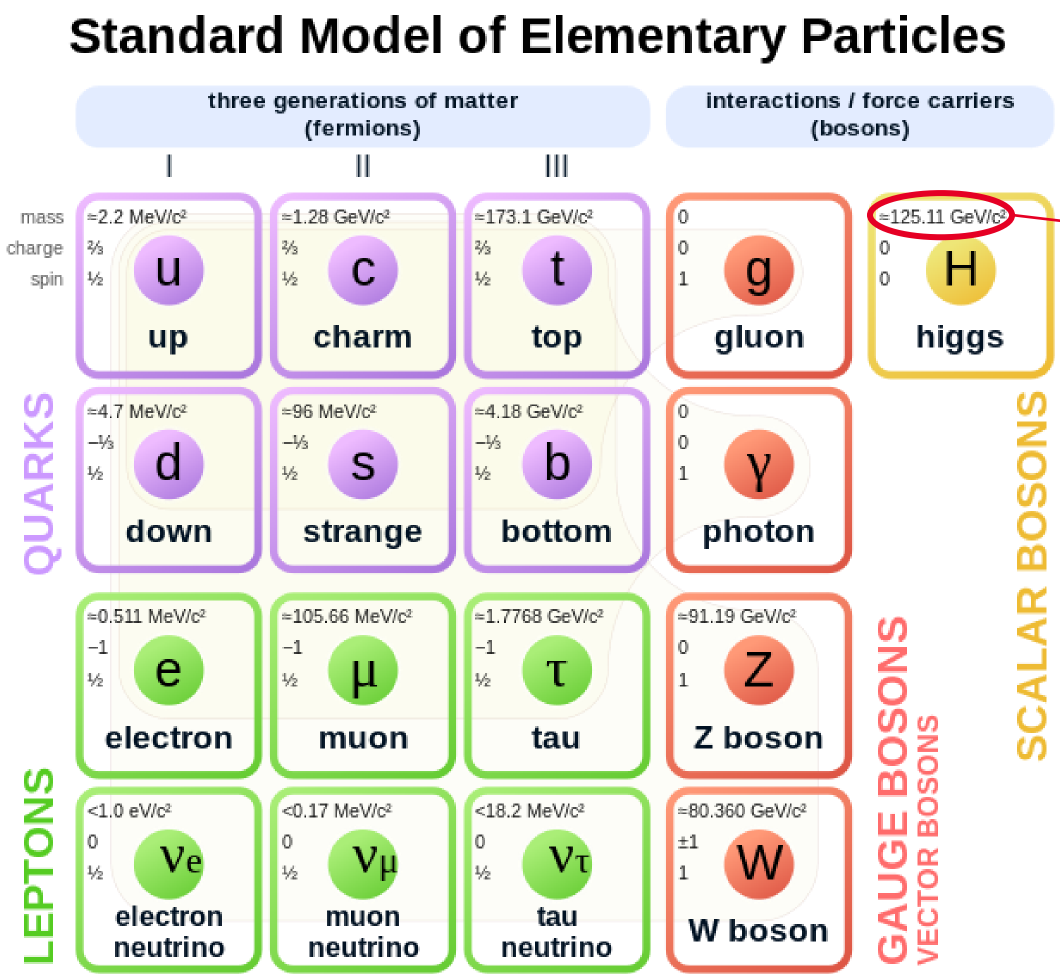
$$p = p_1 + p_2$$ ← Warning, vectors! $p = (p_x, p_y, p_z)$

$$m = \frac{1}{c^2}\sqrt{[E_1 + E_2]^2 - [p_1 + p_2]^2 c^2}$$



A bit more complicated,
but analogous!

Unique Masses!



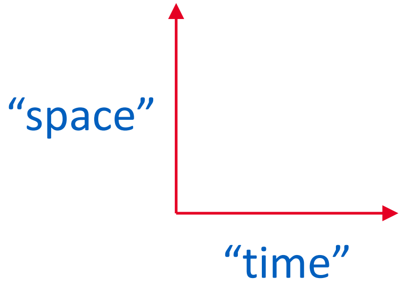
Mass:
$125.11\ GeV/c^2$

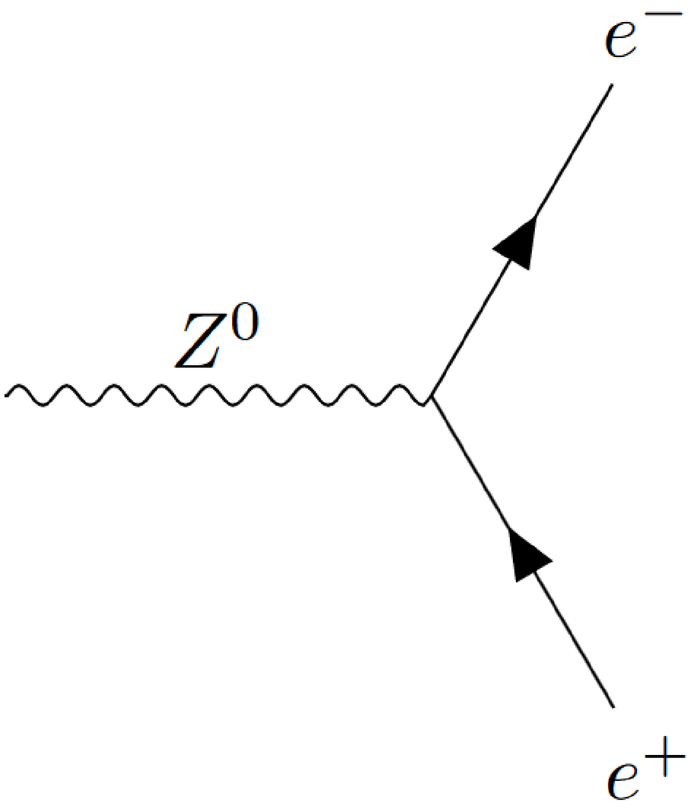
Mass is usually given in units of **Energy**

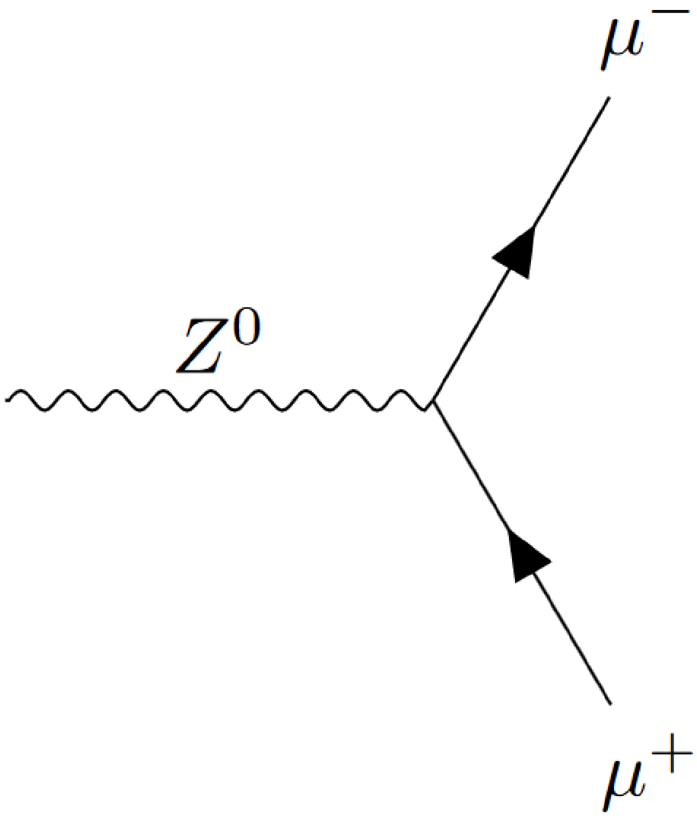
(Because of $E = mc^2$)

$1\ GeV = 10^9 eV$
$\approx 1.6 \times 10^{-10} J$

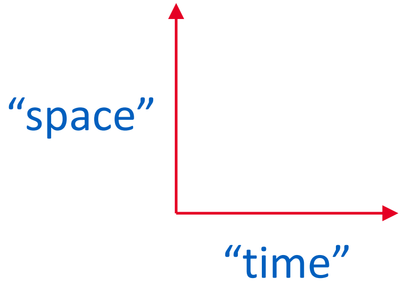
Z Examples

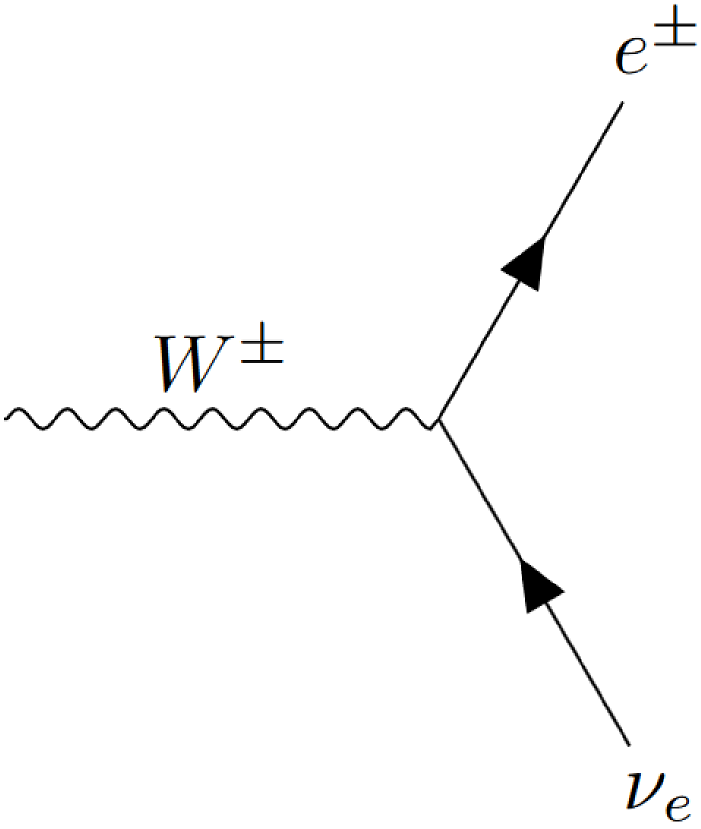


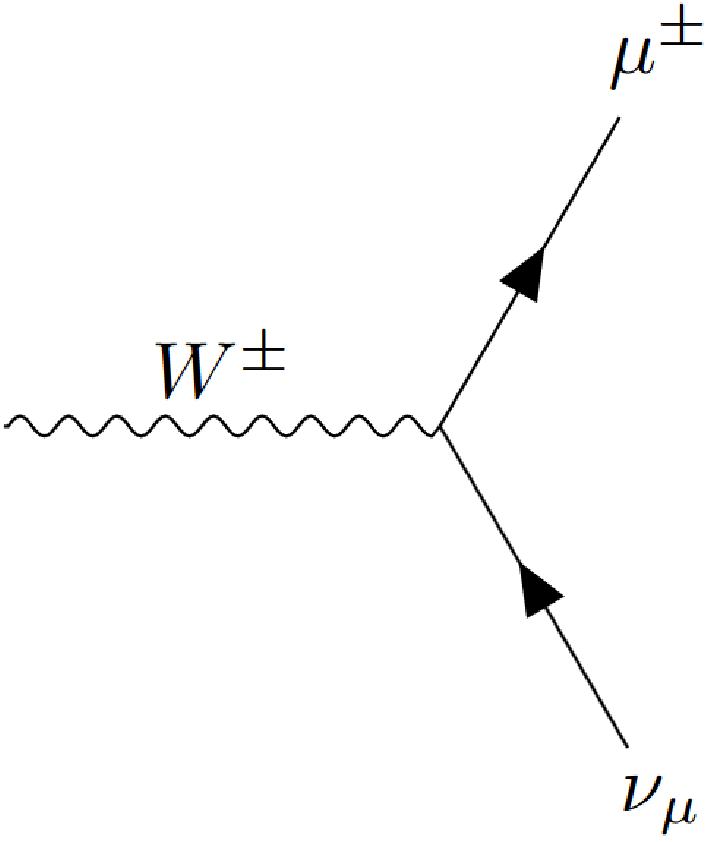




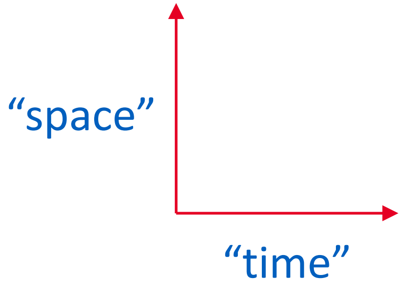
W Examples

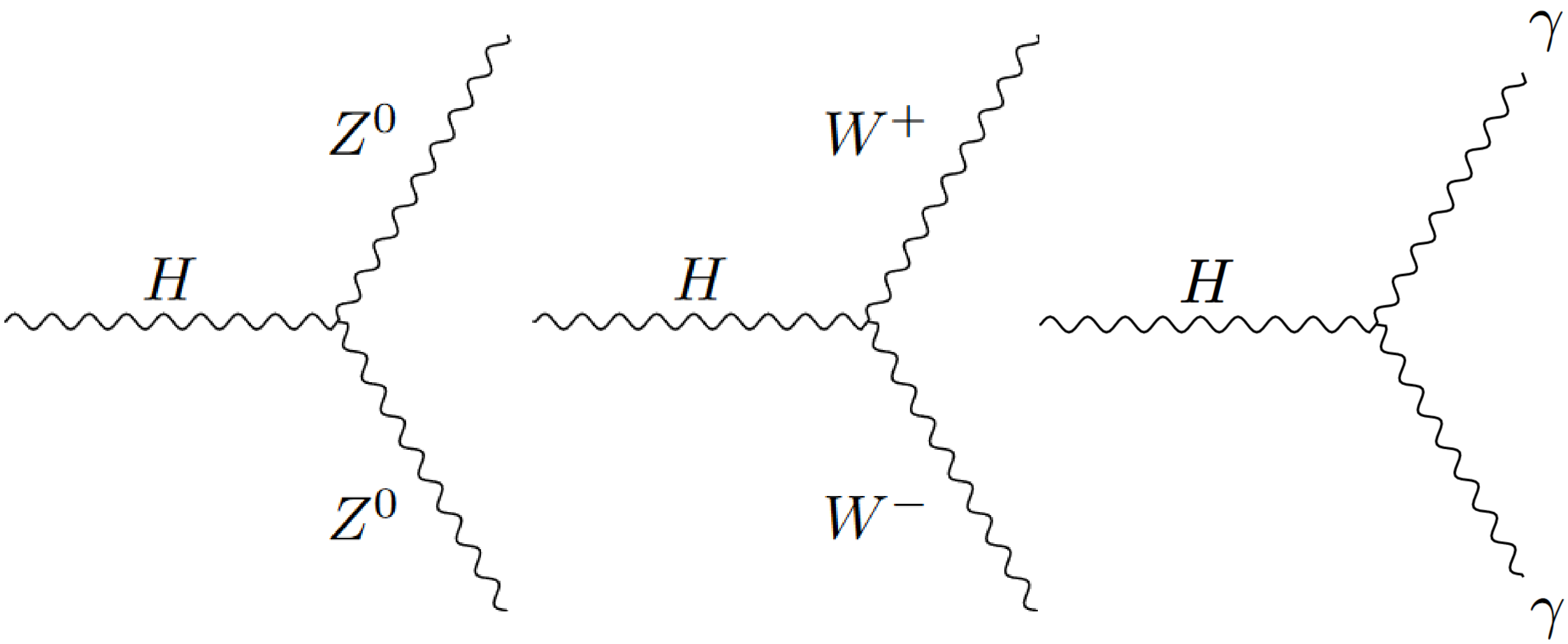




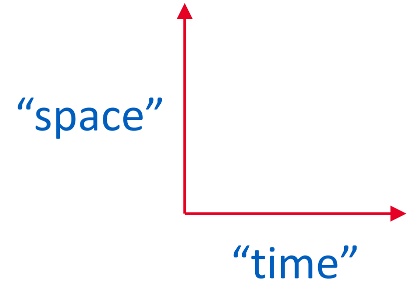


H Examples

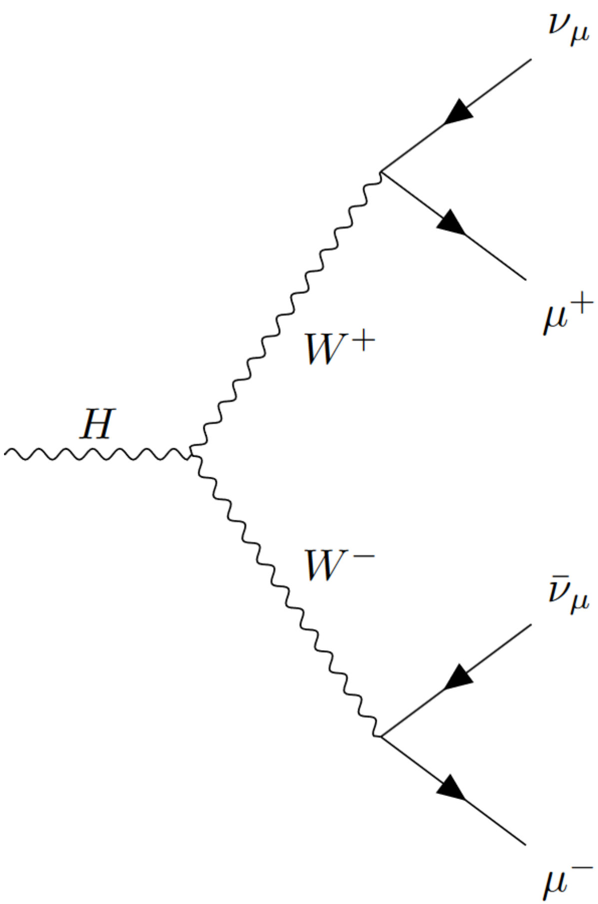




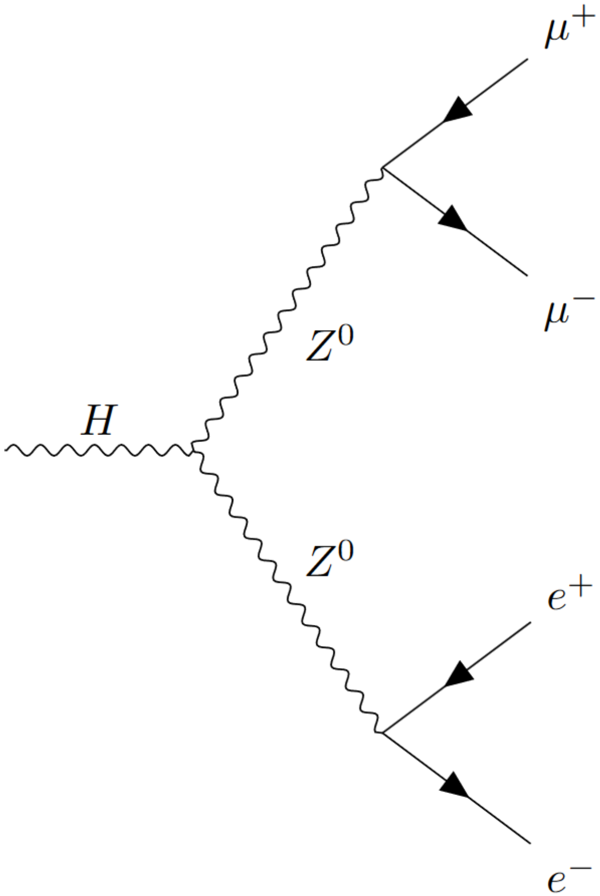
More H



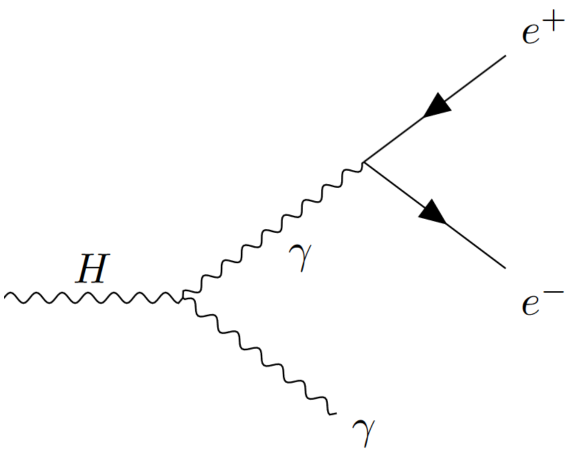
“space”
“time”



ν_μ
μ^+
W^+
H
W^-
$\bar{\nu}_\mu$
μ^-

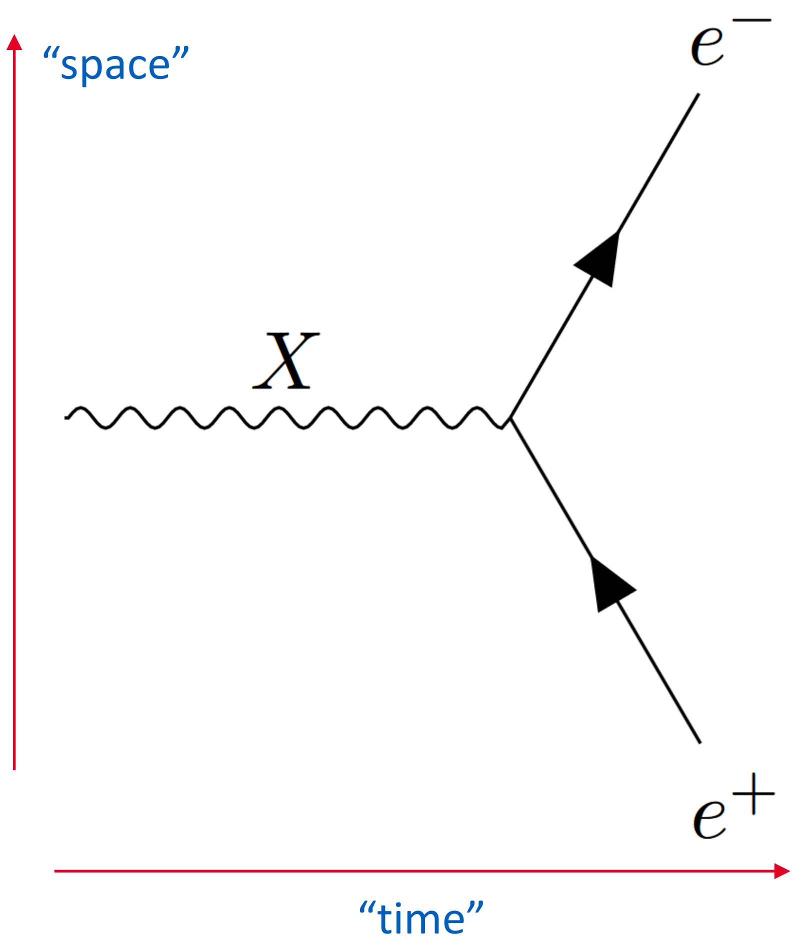


μ^+
μ^-
Z^0
H
Z^0
e^+
e^-



e^+
e^-
H
γ
γ

Example



$m_{e^-}, p_{e^-} = (p^x_{e^-}, p^y_{e^-}, p^z_{e^-})$

$m_{e^+}, p_{e^+} = (p^x_{e^+}, p^y_{e^+}, p^z_{e^+})$

Given m_{e^-}, p_{e^-} and m_{e^+}, p_{e^+}

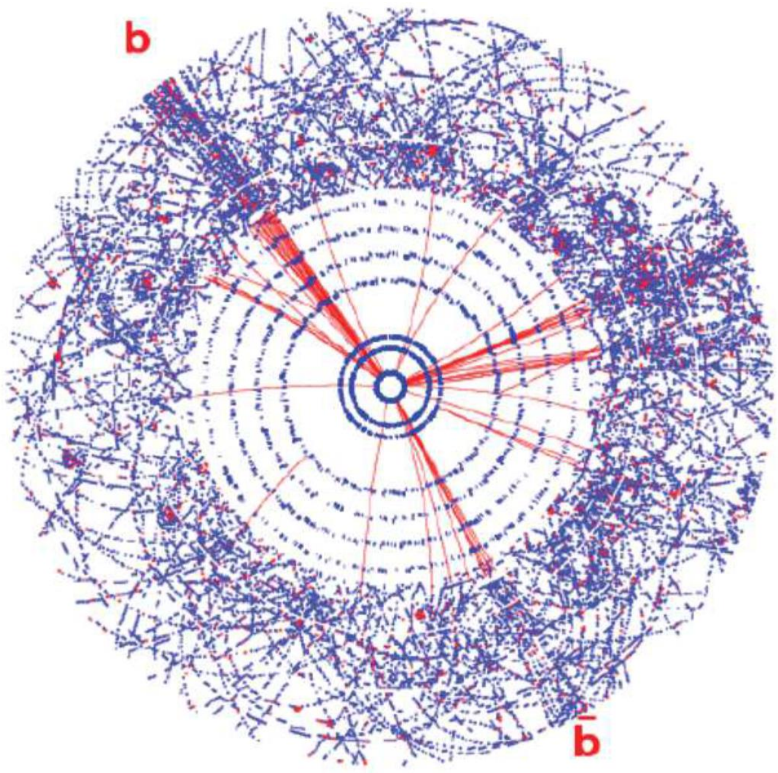
Can you find m_X?

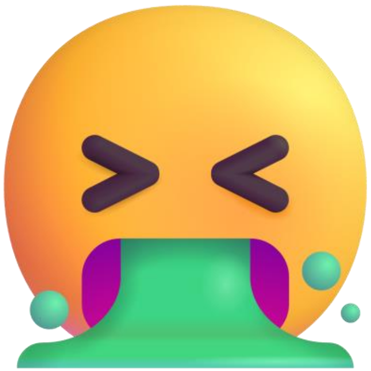
Can you find p_X?

X could be new Physics.

Which Final State Particles to Select?

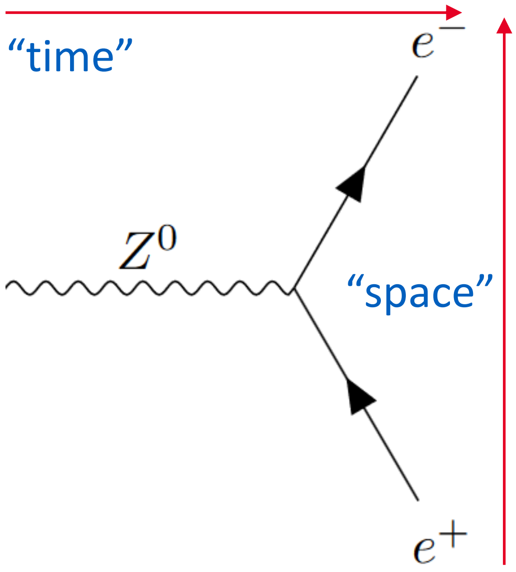
Which tracks should we use to calculate *invariant mass*?



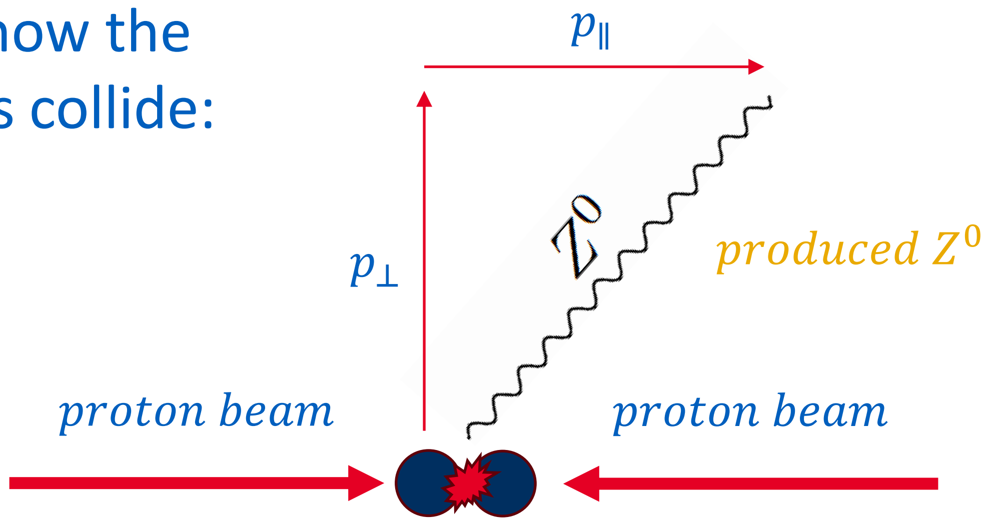


Combinatorics!!

Particle Directions



Notice how the particles collide:



Produced particles will have perpendicular momentum ($p_{\perp}$)

We call it *transverse momentum* p_t ($p_t = p_{\perp}$)

Selections

Require that final state particles have high $\boldsymbol{p_t}$.

Then, confident that they are Physics Events!

Stayed tuned for HYPATIA tutorial next on how to do this!

Conclusion

1. Identify *Final* Particles
2. Reconstruct Intermediate States & *Invariant Masses*
3. Identify *Intermediate* Particles

Fin

Z

Z DECAY MODES

	Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	e^+e^-	[1]	$(3.3632 \pm 0.0042)\%$		45594
Γ_2	$\mu^+\mu^-$	[1]	$(3.3662 \pm 0.0066)\%$		45594
Γ_3	$\tau^+\tau^-$	[1]	$(3.3696 \pm 0.0083)\%$		45559
Γ_4	$\ell^+\ell^-$	[2][1]	$(3.3658 \pm 0.0023)\%$		
Γ_5	$\mu^+\mu^-\mu^+\mu^-$				45593
Γ_6	$\ell^+\ell^-\ell^+\ell^-$	[3]	$(4.55 \pm 0.17) \times 10^{-6}$		45594
Γ_7	invisible	[1]	$(20.000 \pm 0.055)\%$		
Γ_8	hadrons	[1]	$(69.911 \pm 0.056)\%$		
Γ_9	$(u\bar{u} + c\bar{c})/2$		$(11.6 \pm 0.6)\%$		
Γ_{10}	$(d\bar{d} + s\bar{s} + b\bar{b})/3$		$(15.6 \pm 0.4)\%$		
Γ_{11}	$c\bar{c}$		$(12.03 \pm 0.21)\%$		
Γ_{12}	$b\bar{b}$		$(15.12 \pm 0.05)\%$		

W

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

Mode			Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\ell^+\nu$	[1]	$(10.86 \pm 0.09)\%$		
Γ_2	$e^+\nu$		$(10.71 \pm 0.16)\%$		40188
Γ_3	$\mu^+\nu$		$(10.63 \pm 0.15)\%$		40188
Γ_4	$\tau^+\nu$		$(11.38 \pm 0.21)\%$		40169
Γ_5	hadrons		$(67.41 \pm 0.27)\%$		
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$	CL=95%	40188
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	CL=95%	40164
Γ_8	c X		$(33.3 \pm 2.6)\%$		
Γ_9	$c\bar{s}$		$(31^{+13}_{-11})\%$		
Γ_{10}	invisible	[2]	$(1.4 \pm 2.9)\%$		

H

H DECAY MODES

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	WW^*	$(25.7 \pm 2.5)\%$		
Γ_2	ZZ^*	$(2.80 \pm 0.30)\%$		
Γ_3	$\gamma\gamma$	$(2.50 \pm 0.20) \times 10^{-3}$		62625
Γ_4	$b\bar{b}$	$(53 \pm 8)\%$		
Γ_5	e^+e^-	$< 3.6 \times 10^{-4}$	CL=95%	62625
Γ_6	$\mu^+\mu^-$	$(2.6 \pm 1.3) \times 10^{-4}$		62625
Γ_7	$\tau^+\tau^-$	$(6.0^{+0.8}_{-0.7})\%$		62600
Γ_8	$Z\gamma$	$(3.2 \pm 1.5) \times 10^{-3}$		29431