Q&A session

QuarkNet 2017

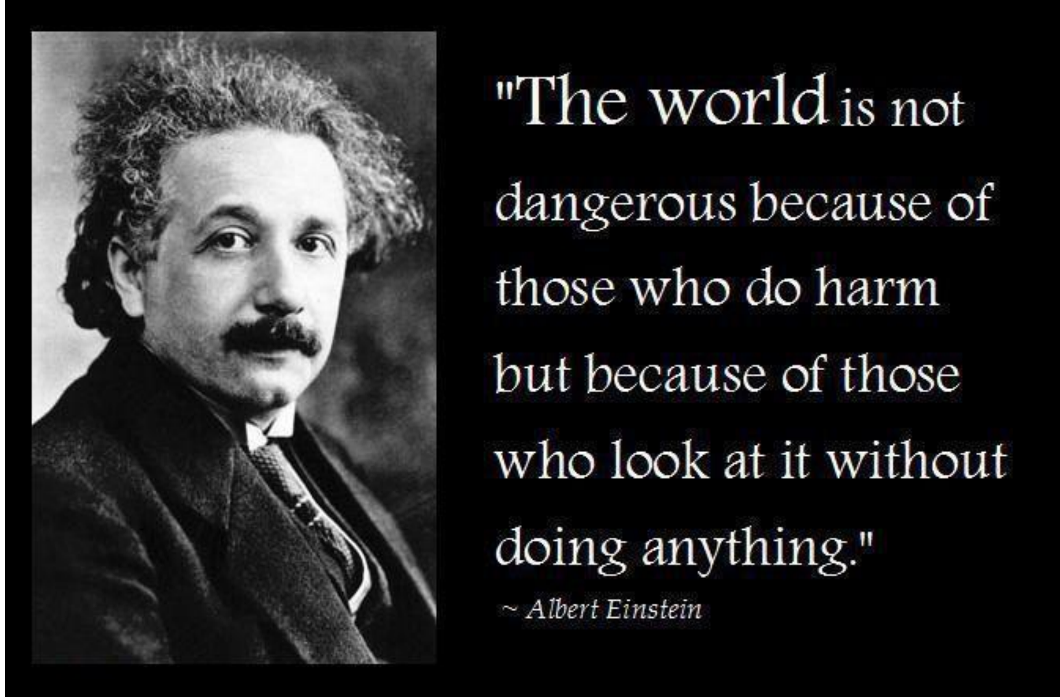
Prof. Steven Blusk

Anything on relativity would work for me.

Special relativity

Special relativity based on 2 postulates

- Speed of light is same, **regardless of the observers state of motion**
- Laws of physics have the same form in all inertial reference frames (IRF).

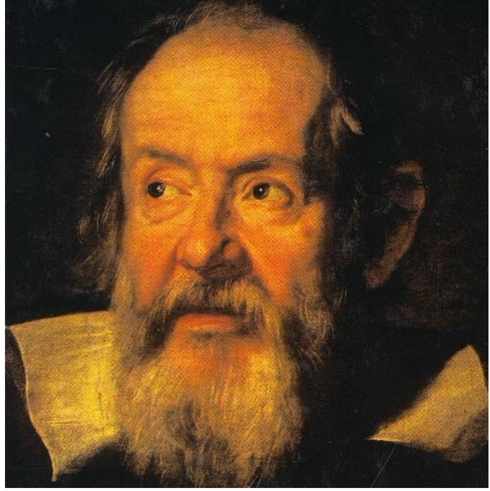


From just these 2 postulates, one predicts:

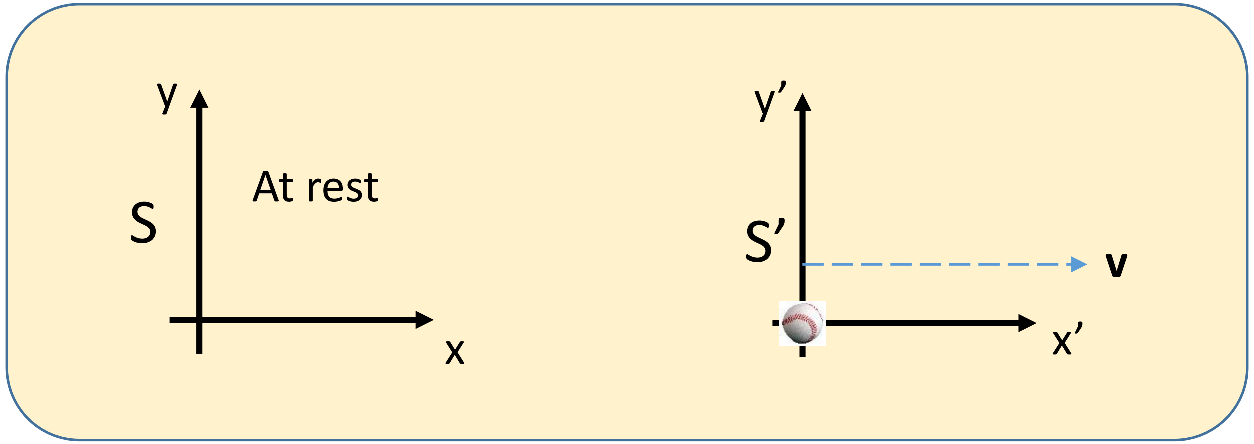
- Simultaneity: What is simultaneous to one observer is NOT necessarily simultaneous to another.
- Time dilation: Moving clocks run slow compared to stationary clocks.
- Length contraction: Lengths contracted along the direction of motion.
- $E = mc^2$

All of these become significant as $v \rightarrow c$ (even 0.1 c is close enough)

Galilean transformations



- How do space & time "transform" between two IRFs, S and S'.



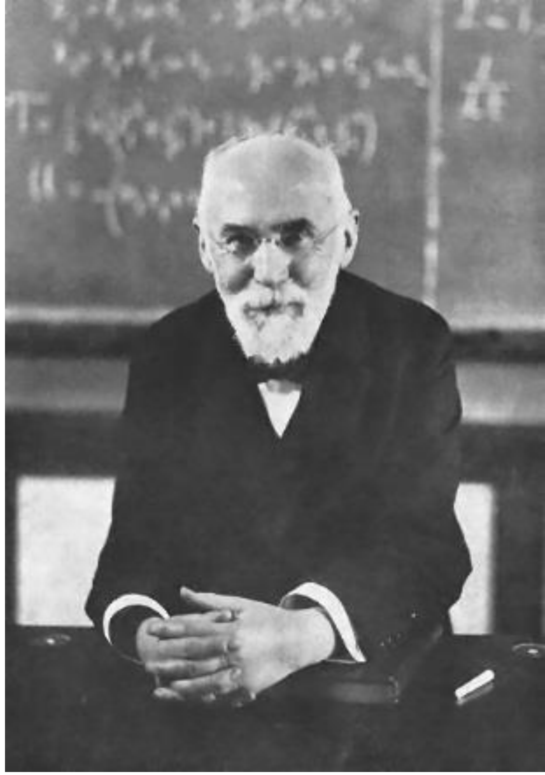
- For *Galilean* ("normal") transformations, easy-peasy. Assume clock starts just when S and S' coincide.

$$x' = x - vt \qquad x = x' + vt$$

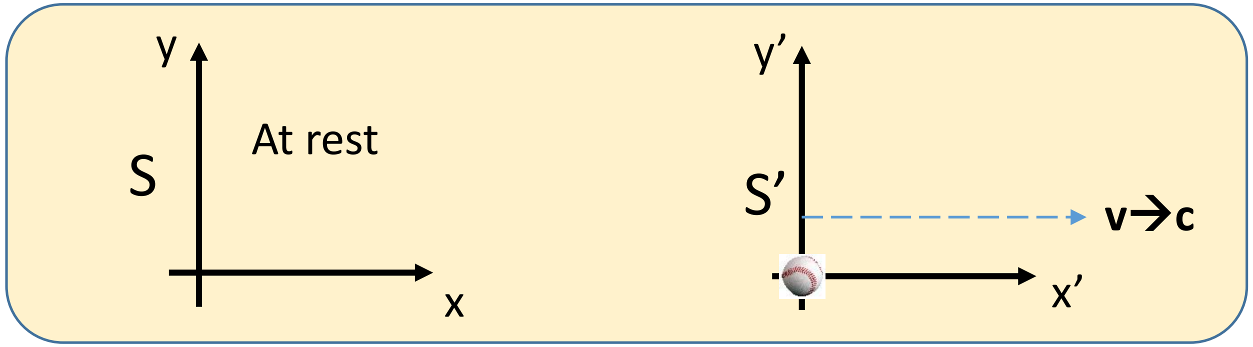
$$y' = y \qquad y = y'$$

$$t' = t \qquad t = t'$$

Lorentz transformations



- **What happens when v → c, according to Einstein ?**



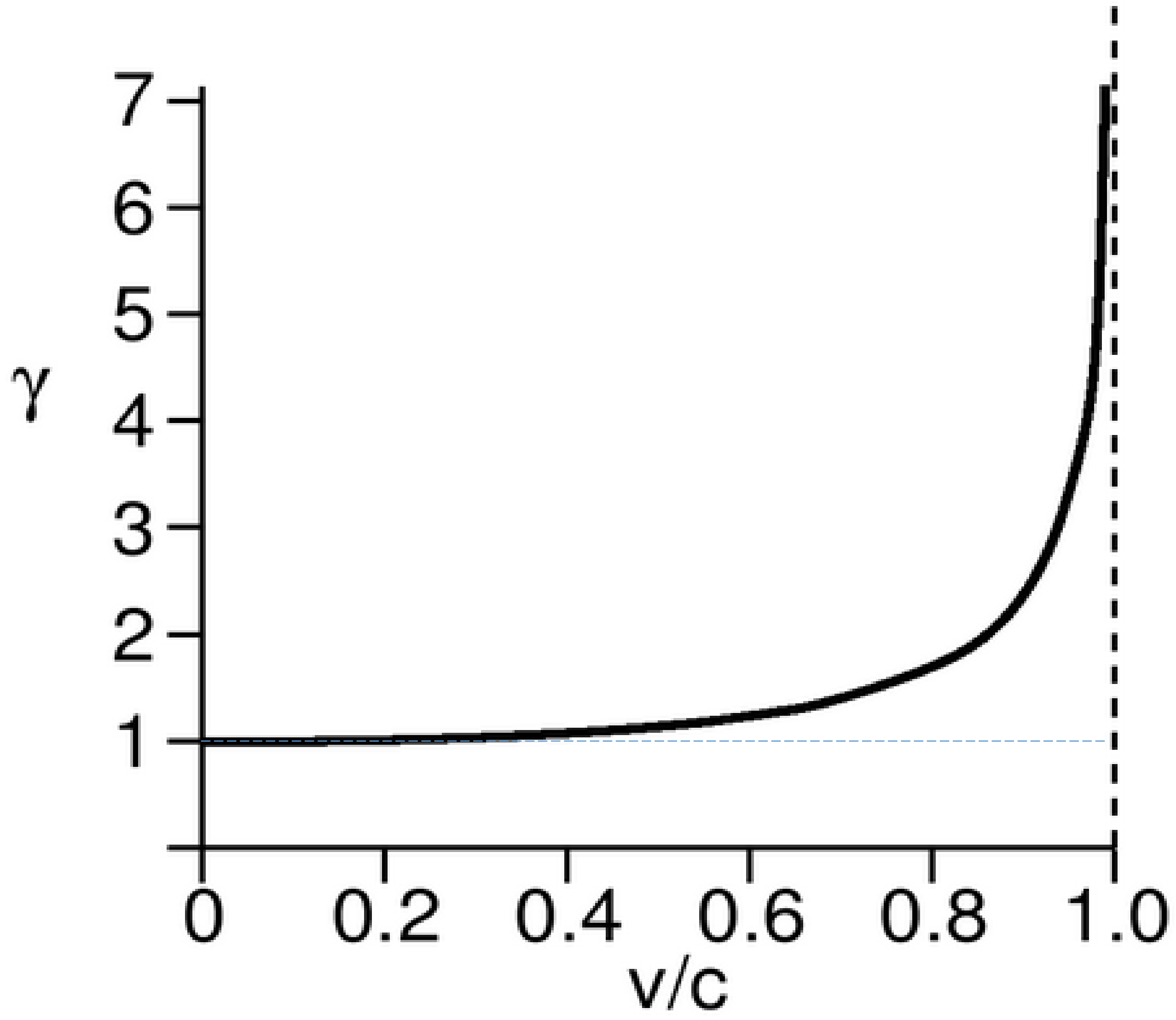
- Just assume:
  - Constant speed in S → constant speed in S'
  - Speed of light same in all IRF (Einstein's postulate)

$$x' = \gamma(x - vt) \qquad x = \gamma(x' + vt') \qquad \gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

$$t' = \gamma(t - (v/c^2)x) \qquad t = \gamma(t' + (v/c^2)x')$$

- Easy to see, if v/c → 0, γ→1 → Recover "normal" ☺ , as you'd expect!

Gamma factor



$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

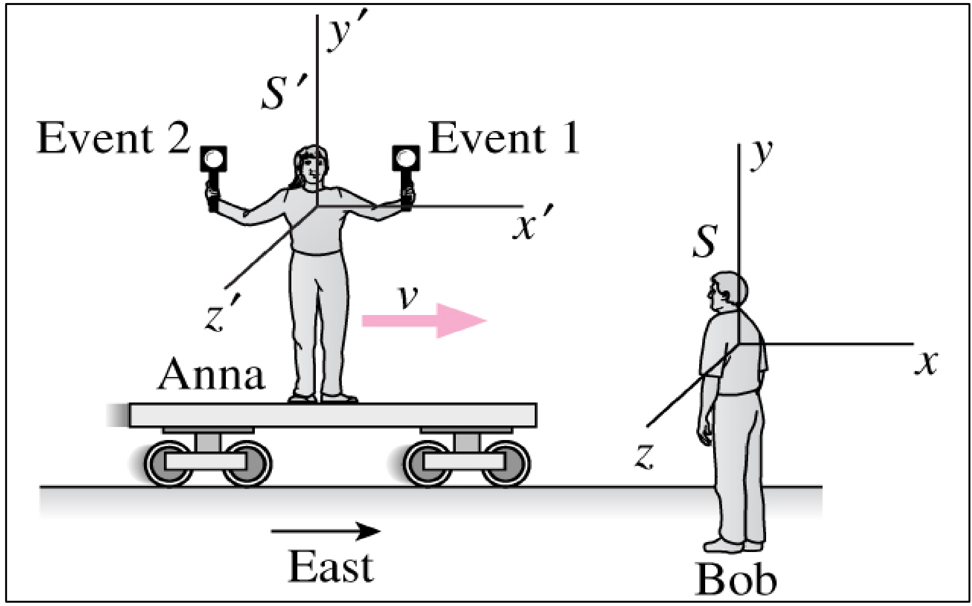
- ❑ Highly non-linear, as v→c!
- ❑ In fact, $\gamma \to \infty$ as v→c

Time and spatial **intervals**

- Consider 2 **events** seen by two observers, Bob & Anna.

	Position	**Time**
Event 1	$x_1' = \gamma(x_1 - vt_1)$	$t_1' = \gamma(t_1 - (v/c^2)x_1)$
Event 2	$x_2' = \gamma(x_2 - vt_2)$	$t_2' = \gamma(t_2 - (v/c^2)x_2)$

- Subtract to get: $\Delta x' = x_2' - x_1'$, $\Delta t' = t_2' - t_1'$



$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

$$\Delta x' = \gamma(\Delta x - v\Delta t) \qquad \Delta x = \gamma(\Delta x' + v\Delta t')$$

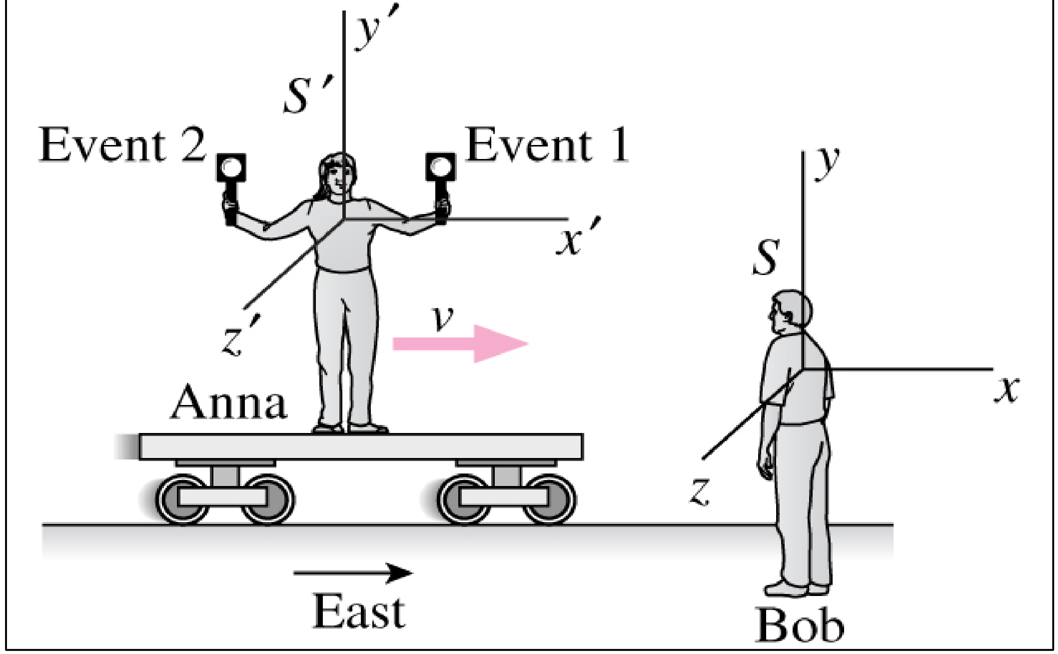
$$\Delta t' = \gamma(\Delta t - (v/c^2)\Delta x) \qquad \Delta t = \gamma(\Delta t' + (v/c^2)\Delta x')$$

That’s it ! That’s all we need to show at least some of the crazy predictions of special relativity!

Simultaneity

$$\Delta x' = \gamma(\Delta x - v\Delta t) \qquad \Delta x = \gamma(\Delta x' + v\Delta t')$$

$$\Delta t' = \gamma(\Delta t - (v/c^2)\Delta x) \qquad \Delta t = \gamma(\Delta t' + (v/c^2)\Delta x')$$



- Suppose Anna holds to two lights 1 m from one another.
  - $\Delta x' = x_2' - x_1' = -1$ m, and
  - She flashes the 2 bulbs at EXACTLY the same time.

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

- **What does Bob observe?**
  - From second bullet: $\Delta t' = 0$

$$\Rightarrow \quad \Delta t = \gamma(\Delta t' + (v/c^2)\Delta x') = \gamma(v/c^2)\Delta x' \neq 0$$

$\Rightarrow$ The 2 events are **NOT simultaneous** according to Bob

Which happens first according to Bob ?

If $\Delta x' = -1$, and $v > 0 \;\Rightarrow\; \Delta t = t_2 - t_1 < 0 \;\Rightarrow\; t_2 < t_1 \;\Rightarrow$ Event 2 happens first according to Bob!

- You'd get the same answer if Anna was to the right of Bob.
- **Not a "perception" issue. For Bob, the 2 events do not happen at the same time, period!**

Time dilation

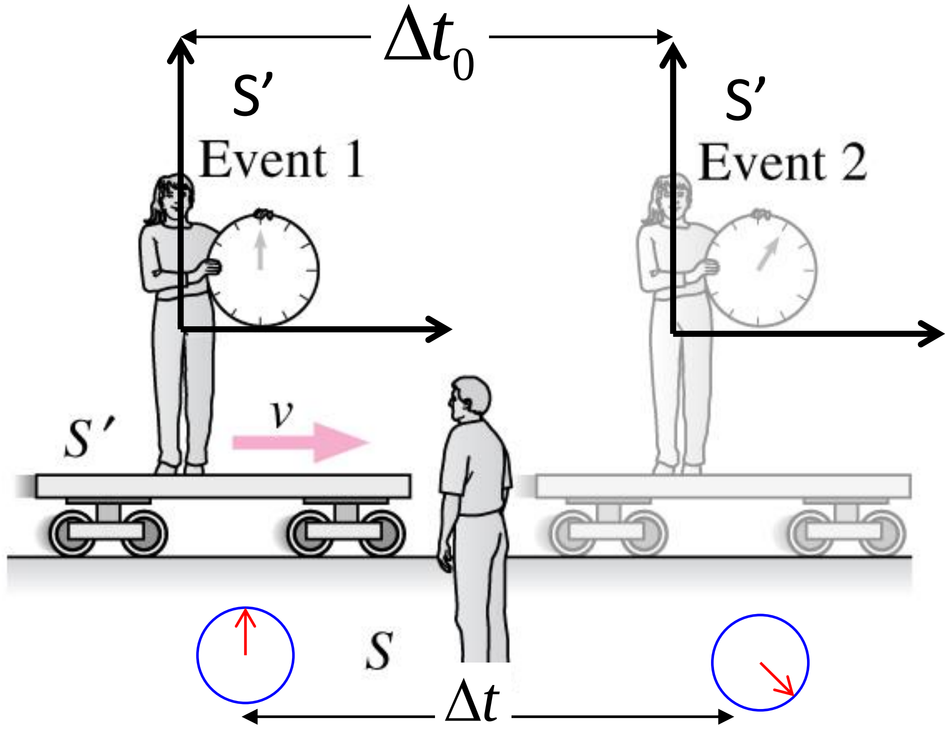
$$\Delta x' = \gamma(\Delta x - v\Delta t) \qquad \Delta x = \gamma(\Delta x' + v\Delta t')$$

$$\Delta t' = \gamma(\Delta t - (v/c^2)\Delta x) \qquad \Delta t = \gamma(\Delta t' + (v/c^2)\Delta x')$$

- Consider 2 events that happen at the **same position** in S'.

$\Rightarrow \Delta x' = 0 \qquad \boxed{\Delta t = \gamma \Delta t'}$

- ❖ Δt' = "Proper time": time interval as measured by an observer (**Anna**) who is at rest relative to the object (clock).
- ❖ Almost universal, to use Δt_0 for "proper time"



$$\boxed{\Delta t = \gamma \Delta t_0}$$

- ❖ Since $\gamma \geq 1$, $\Delta t_{Bob} \geq \Delta t_{Anna}$
- ❖ For Bob, the 2 events are separated by a longer time than what Anna claims.
- ❖ Bob claims that Anna's clock is running slow !

Time dilation – cosmic ray muons

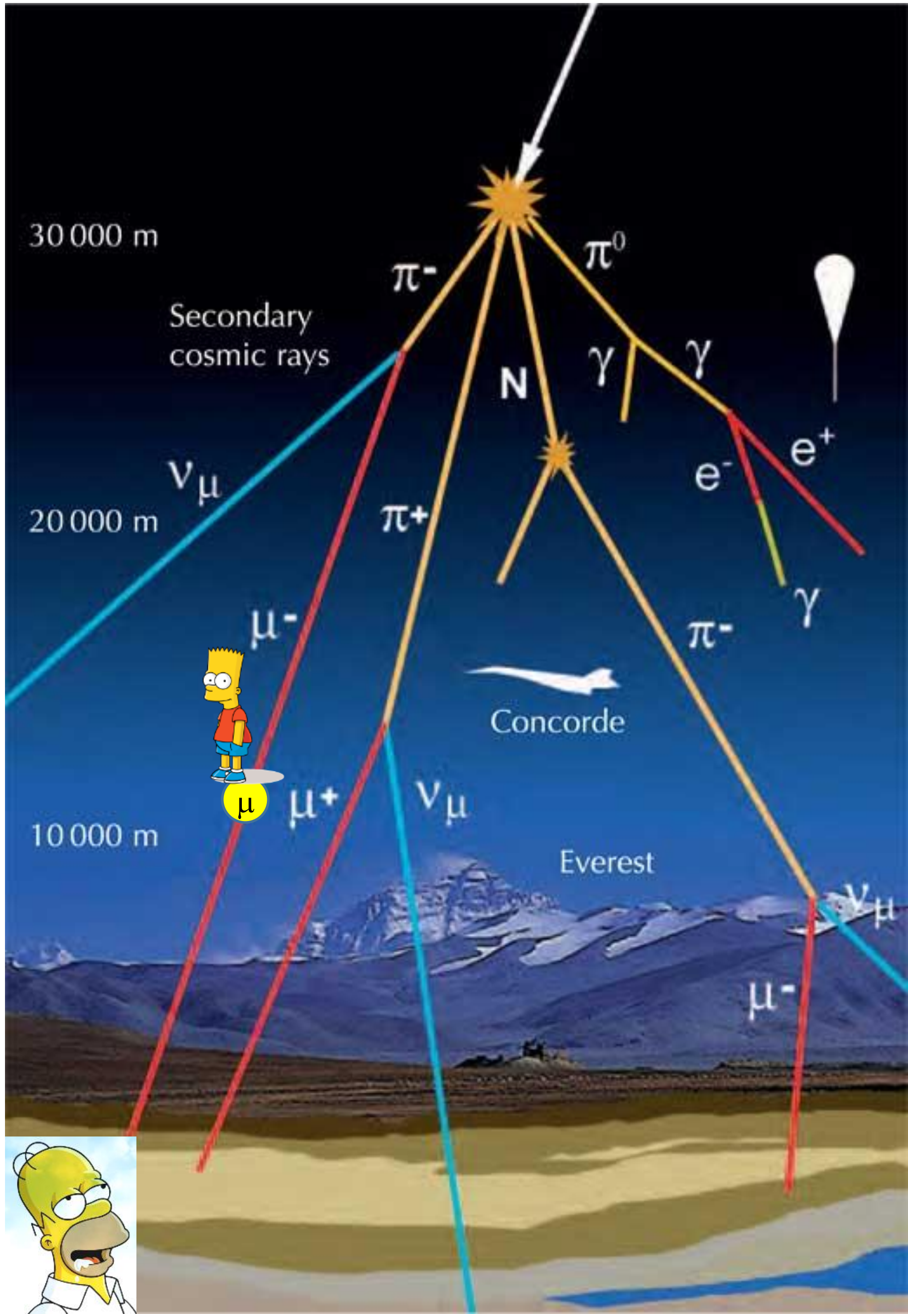
- Energetic muons produced in upper atmosphere from high energy collisions of primary cosmic rays.
- Muon lifetime known: t_0 = 2.2 us.
- Can they make it to Earth from **20,000 m**?

$$d_{muon} = vt_0 \approx ct_0 = (3\times10^{8} m/s)(2.2\times10^{-6} s) = 660 \text{ m}$$

- **Oops, forgot that:**
  - Must use relativity if v→c.
  - Particle **lifetime** refers to the **proper time**!
  - Distance traveled is in Earth (rest) frame.
    - ➔ Muon's clock runs slow relative to one in Earth frame.
- What minimal speed must the muon have to reach the Earth's surface?

$$\frac{d_{Earth}}{d_{muon}} = \frac{v(\gamma_{\min} t_0)}{vt_0} = \frac{20000 \text{ m}}{660 \text{ m}} = 30.3 = \gamma_{\min} = \frac{1}{\sqrt{1-(v_{\min}/c)^2}}$$

$$v_{\min} = 0.99956c$$



Length contraction

$$\Delta x' = \gamma(\Delta x - v\Delta t) \qquad \Delta x = \gamma(\Delta x' + v\Delta t')$$
$$\Delta t' = \gamma(\Delta t - (v/c^2)\Delta x) \qquad \Delta t = \gamma(\Delta t' + (v/c^2)\Delta x')$$

- ❑ Consider now, Anna zipping past Bob, holding a ruler horizontally.
- ❑ Bob wants to know the length of the ruler in his frame (S).
- ❑ He waits, and **at precisely the same time in his frame**, he measures the position of the front & back edge ➔ **$\Delta t = 0$** $\Rightarrow \Delta x' = \gamma \Delta x$

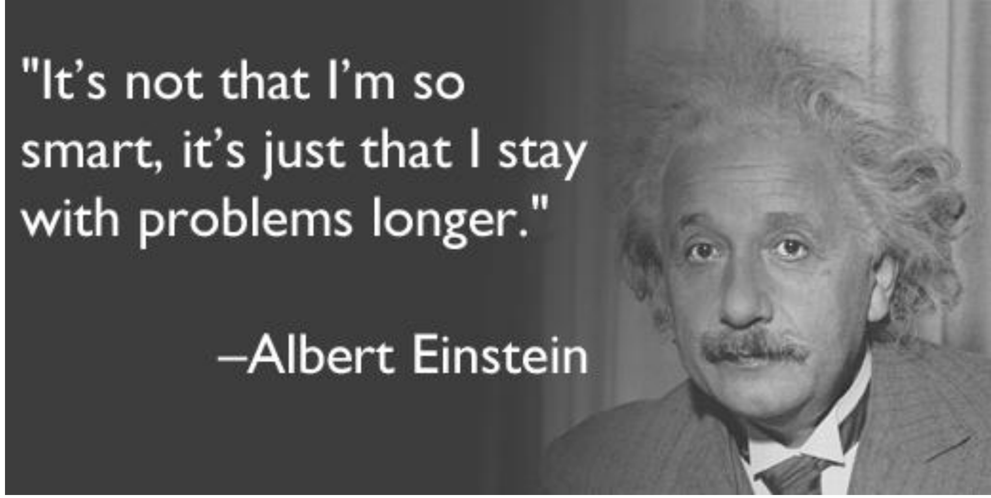
- ❑ Δx is the length according to Bob (L)
- ❑ $\Delta x'$ is the length according to Anna. Denoted as L_0, to mean **proper length**, since ruler is at rest in her frame.

$$\boxed{L = L_0 / \gamma}$$

- ❑ Since $\gamma \geq 1$, Bob will measure the length to be smaller than Anna!

This is not an optical illusion!
In Bob's frame, the ruler IS shorter.

Invariants



- You may hear ALOT the words "invariant mass".
  - Sometimes we're lazy, and just say "mass" ☺
- What do we mean by this phrase?
- **What is an invariant?**
  - Usually means: A quantity whose magnitude is unchanged under some transformation.
  - Example: Length of a vector is invariant under rotations.
- **So what is an "invariant" when it comes to relativity?**
  - A quantity whose magnitude does not change under Lorentz transformations.

$$\Delta x' = \gamma(\Delta x - v\Delta t)$$

$$\Delta t' = \gamma(\Delta t - (v/c^2)\Delta x)$$

  - You can easily see that $|\Delta x| \neq |\Delta x'|$ and $|\Delta t| \neq |\Delta t'|$ in general.

- **Space and time intervals not invariant, depend on your state of motion!**

Relativistic invariants

- It turns out that the following combination

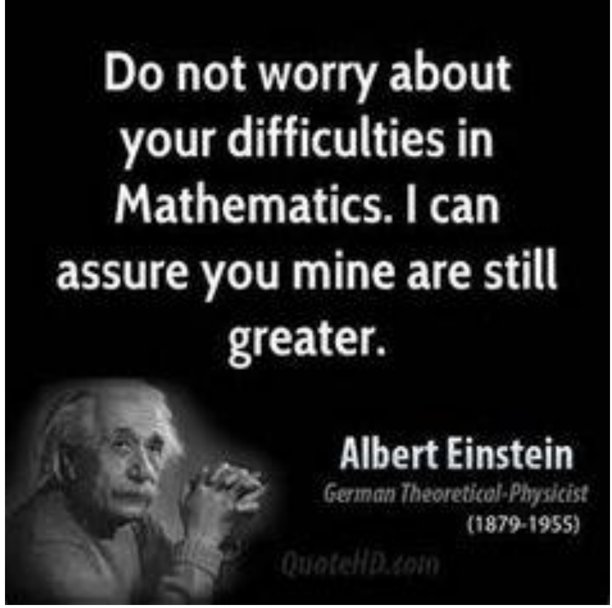
$$(c\Delta t')^2 - \Delta x'^2 \quad = \quad (c\Delta t)^2 - \Delta x^2$$

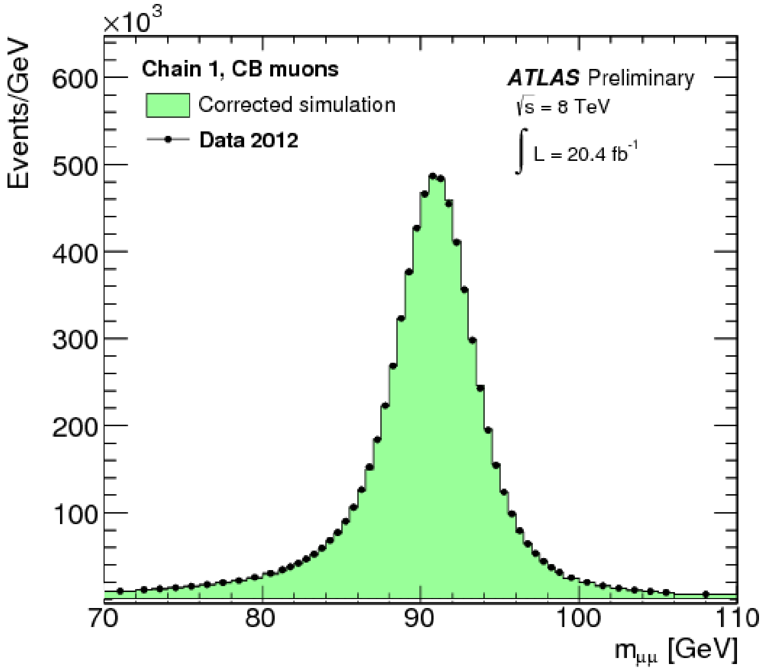
- "$(c\Delta t)^2 - \Delta x^2$" is a <u>relativistic invariant</u>!
- **More generally**, in 3D: $c\Delta t^2 - \Delta x^2 - \Delta y^2 - \Delta z^2$ is a relativistic invariant
  - Space-time forms a *4-component vector*, or "*four-vector*" **s = (ct, x, y, z).**
  - **Rule:** Magnitude of 4-vector: $\mathbf{|s|^2 = s_0^2 - s_1^2 - s_2^2 - s_3^2}$
- **Another very important four-vector**
  - $(E/c^2,\ p_x/c,\ p_y/c,\ p_z/c)$

$$Magnitude:\ m = \sqrt{(E/c^2)^2 - (p_x/c)^2 - (p_y/c)^2 - (p_z/c)^2} = \frac{1}{c^2}\sqrt{E^2 - p^2c^2}$$

  - Not hard to see that "*m*", has units of mass (E/c^2)
  - It is a relativistic invariant (get same value in any/all IRFs!)
  - We use this formula **<u>all the time</u>** to get the mass of a decaying particle!
  - **E.g. $Z^0 \rightarrow \mu^+\mu^-$.**

$$m(\mu^+\mu^-) = \frac{1}{c^2}\sqrt{\left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left(\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right)c^2}$$

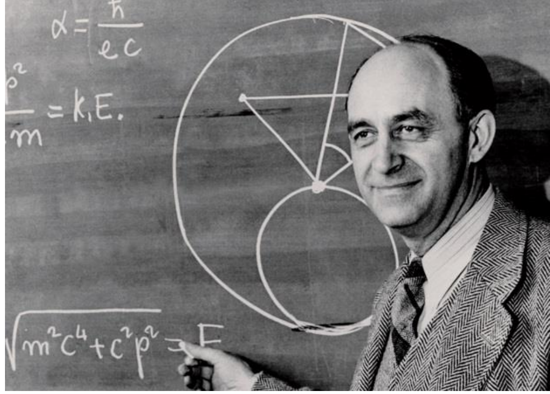


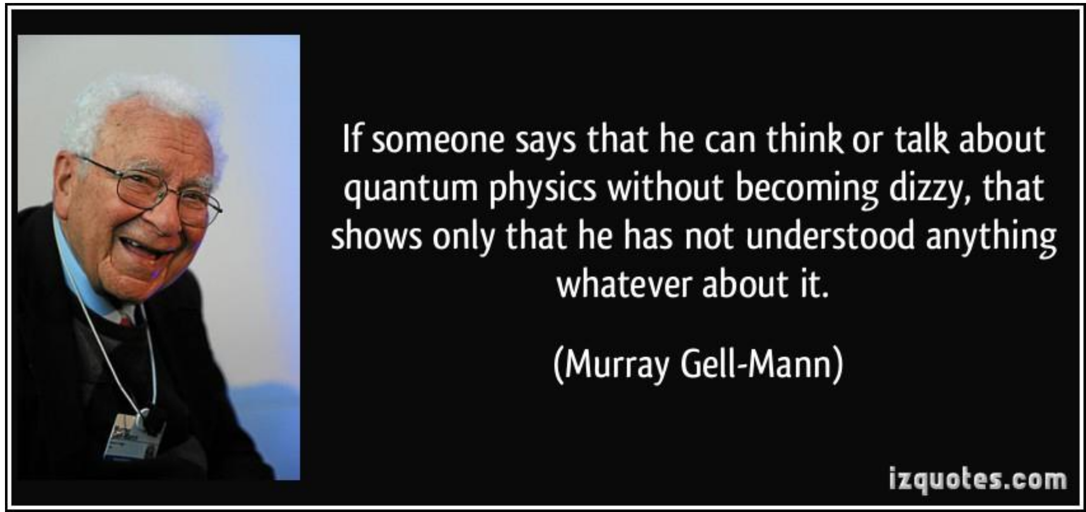


Most of Regents Physics involves simply the names of the quarks. I know uud is a proton and udd is a neutron but if there could be some "fun facts" on the names associated with other combinations (or a general overview of the names of things within boson, meson, baryon, lepton categories), I'd appreciate it. I have very little understanding of strangeness or color of quarks. I know they are characteristic differences but have little understanding of the concept.

Various names

- Quarks: **Gell-mann**, from James Joyce's book Finnegans Wake: “Three quarks for Muster Mark”
- Fermions: Enrico **Fermi**
- Bosons: Satyendra Nath **Bose**
- Hadrons: “Hadro”, Greek for **strong**
- Leptons: “Leptos”, Greek for “fine, small, thin” .
- Neutrino: 1930, postulated by **W. Pauli** to account for apparent violation of energy conservation in neutron decay. He actually referred to it as “neutron”! Later, became “neutrino”, or “little neutral one”.
- Higgs boson: Well, you know that, right?





The J/ψ particle

- Why does it have 2 letters associated with it?
  - Discovered independently by 2 groups in 1974.
  - SLAC: Burton Richter's group, $e^+ e^- \rightarrow X$, : ψ
  - BNL: Sam Ting's group, $p + Be \rightarrow e^+e^- X$: **J**
  - Shared 1976 Nobel prize
- Soonafter discovery, understood to be bound state of a $c\bar{c}$ "atom"

Discovery of a Narrow Resonance in $e^+ e^-$ Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee

Brookhaven National Laboratory, Upton, New York 11973

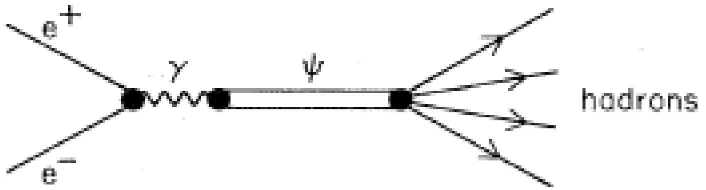
(Received 12 November 1974)

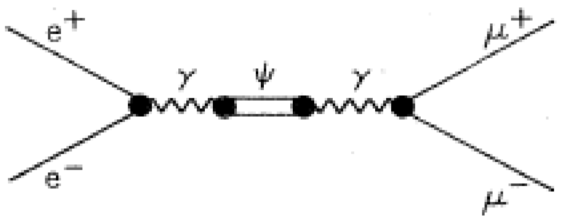
We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

The experimental results

Richter's SLAC expt

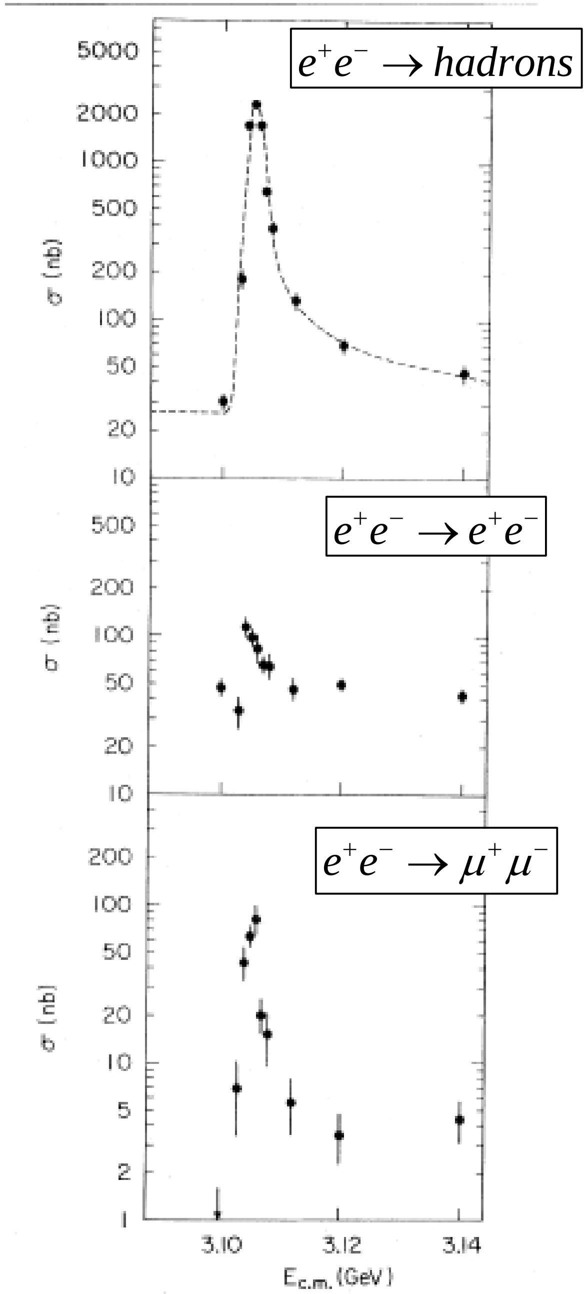
$e^+e^- \rightarrow X$





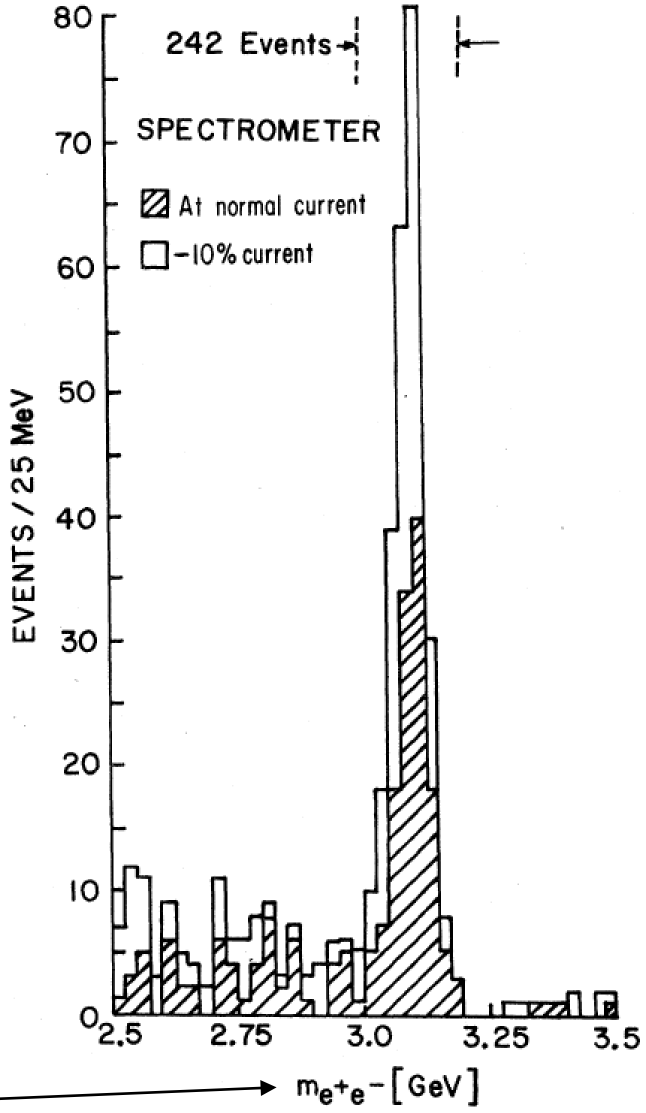
(e⁺)

(e⁻)



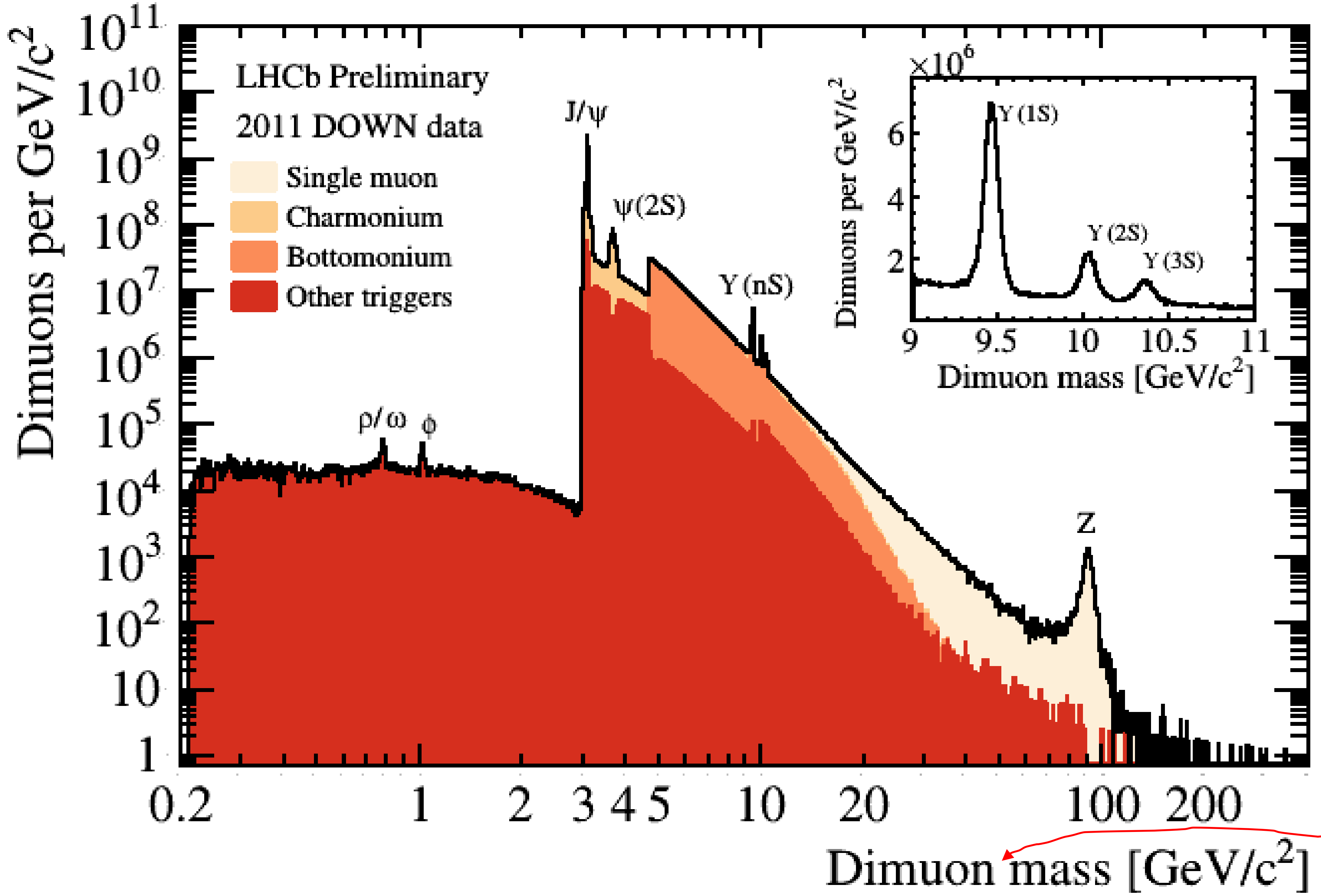
Ting's BNL experiment

$p + Be \rightarrow e^+e^- X$ @ BNL



Invariant mass

Dimuons galore!



invariant

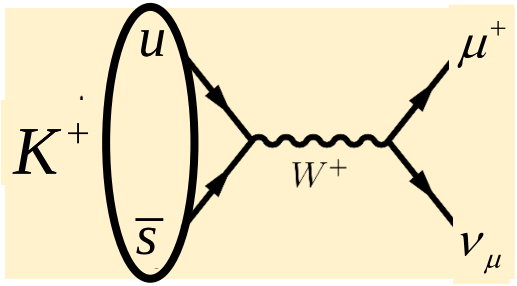
"Strangeness vs color" – What's that all about?

- You're well aware that particles have **properties**:
  - Mass, charge: allows one to distinguish particles from one another.
- Many other "quantum numbers", to account for intrinsic properties, symmetries, or conserved quantities in nature.
  - **Spin:** "intrinsic" angular momentum of particles (not related to its motion)
  - **First "strange" particles discovered in 1947:**
    - Why "strange": were easily produced, but had **MUCH longer lifetimes** than expected.
    - Later found strange particles always produced in pairs.
    - Introduce "*strangeness*" quantum number, as the **net number of s quarks in a particle**.

$$S = -(n_s - n_{\bar{s}})$$

- ❑ Strong interactions conserve S! (also EM as well)

$$\begin{array}{ccccccccc} p & + & p & \rightarrow & K^+ & + & \Lambda^0 & + & p \\ (uud) & & (uud) & & (u\bar{s}) & & (sdu) & & (uud) \end{array}$$



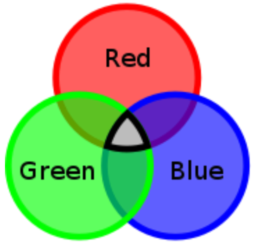
- ❑ However, particles with s-quarks decay via the weak force!
  - ❑ W-boson → Weak interaction.
  - ❑ Weak decays are associated with large lifetimes
  - ❑ Strangeness NOT conserved in weak decays!

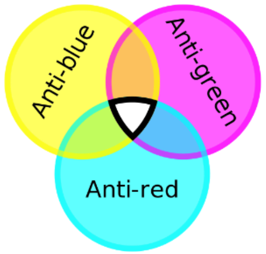
What is this “color” business?

- Color (**color charge)** is an intrinsic property that quarks have (also electric charge, spin, ...)
- Conceptually similar to electric charge.

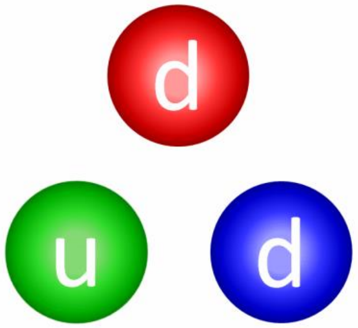
	Electric charge	Color charge
Charges	$+, -$	red, green, blue
Associated force	Electromagnetic	Strong
Theory name	Quantum **Electro**dynamics (QED)	Quantum **Chromo**dynamics (QCD)
Force carrier	photon	gluon
Particles that carry “charge”	Leptons, quarks	Quarks*, gluons
Directly observable?	Yes	No

* Antiquarks carry “anti-color”: antired, antiblue, antigreen





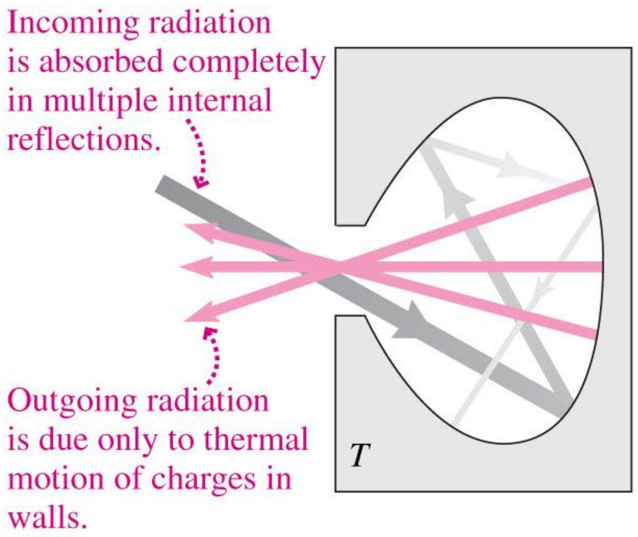
- **Color is just a convenient scheme / name for this new property**.
  - 3 allowed values
  - We only observe “color neutral” hadrons in nature.
    - Baryon: rgb
    - Meson: color-anticolor
    - Could also have 4 & 5-quark (or more) colorless combinations!
- Color charge is conserved (like electric charge)

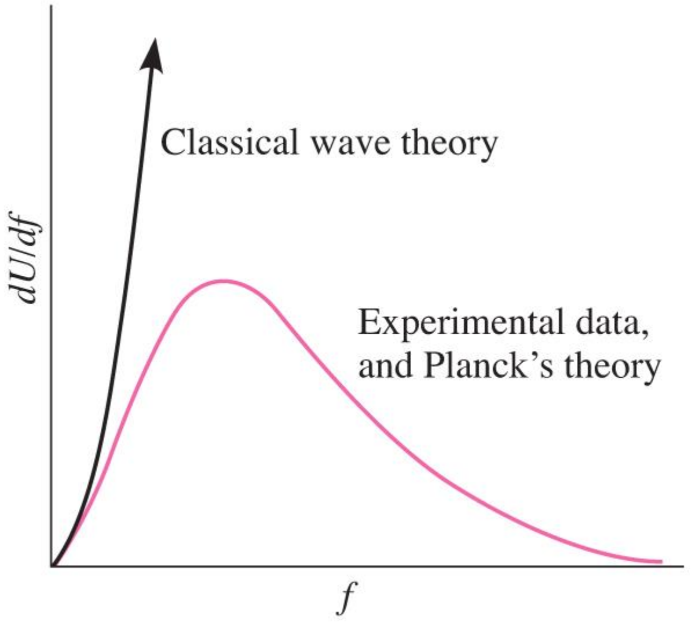


I have a difficult time explaining blackbody radiation to my students. I show the curves and say the words, but I am not sure if I really understand it, so I would like to hear how I should be teaching the concept.

What is a blackbody?

- A blackbody is a body that absorbs ALL EM radiation incident on it.
  - No reflection → body generally appears black.
  - To stay in thermal equilibrium, it must also radiate energy.
  - Can calculate using **classical EM theory** and classical statistical mechanics.





$$\frac{dU}{df} = k_B T \frac{8\pi V}{c^3} f^2$$

$$U_{tot} = \int_0^\infty k_B T \frac{8\pi V}{c^3} f^2 df = \infty!$$

Classical EM theory must be wrong!
Astounding statement of the time.
How to "fix it" ?

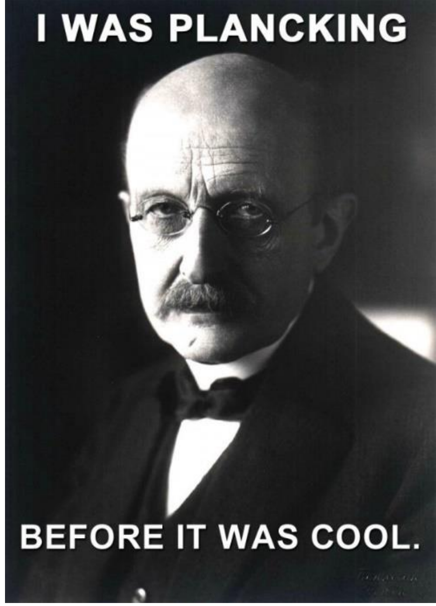
Along comes Plank

Along comes Planck

- Planck proposes that the energy emitted at frequency f is quantized, and can only be:

$$E = nhf$$

where n is an integer and
h is a constant (fitted to data)

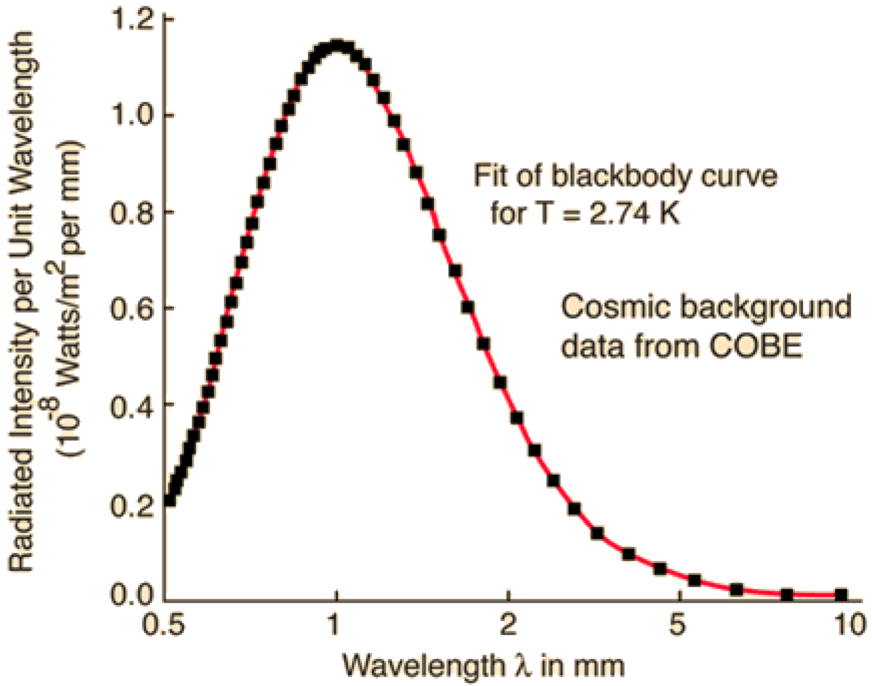


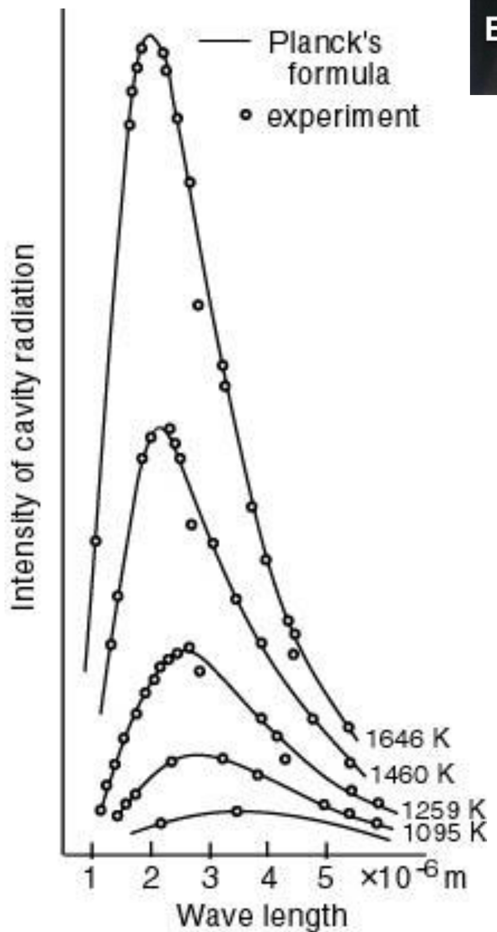
- Because allowed energies are discrete and not continuous, one must **SUM**, **not INTEGRATE**.
- This gives a very different result for the energy density.

$$\boxed{\frac{dU}{df} = k_B T \frac{8\pi V}{c^3} f^2}$$

$$\Downarrow$$

$$\boxed{\frac{dU}{df} = \left(\frac{hf}{e^{hf/k_B T} - 1}\right) \frac{8\pi V}{c^3} f^2}$$





Relevance to quantum physics?

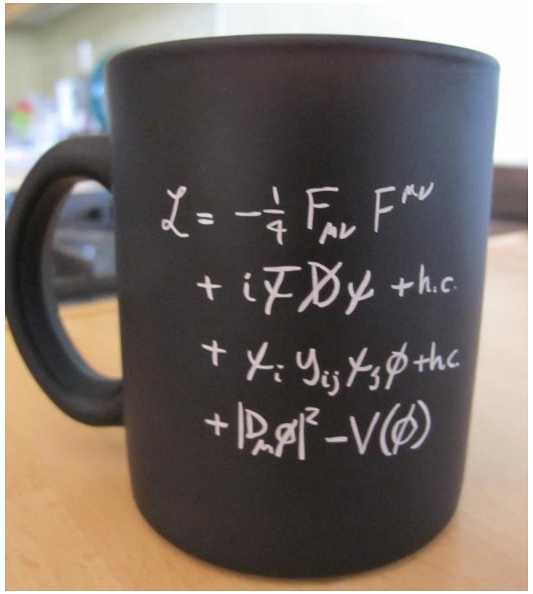
- First indication of a **clear failure of classical laws of physics**.
- While there was no “quantum theory” when first proposed by Planck in 1900, it was the first proposition of **energy quantization**.
- It wasn’t until Einstein’s photoelectric effect demonstrated that light behaves like a particle with energy E = hf, that the “quantum idea” really started to take hold. Einstein got the Nobel prize in 1921 for this (not relativity).

- Other effects that support(ed) particle nature of light
  - Compton effect
  - $e^+e^- \rightarrow \gamma\gamma$.
  - Many others..

How does relativity connect to quantum theory ?

Relativity & quantum theory

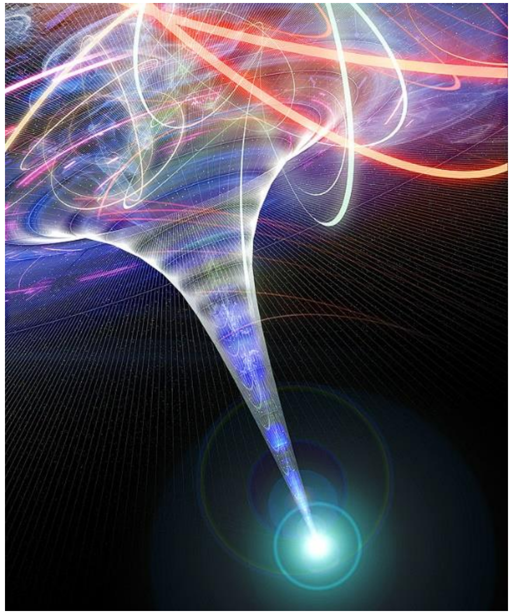
Classical Physics (big & slow)	**Special Relativity** (fast)
Quantum Mechanics (very small)	**Particle Physics** (small & fast) [**QM + special relativity**]



- ❑ Theory of tiny stuff: Quantum physics
- ❑ Theory of very fast: Special relativity
- ❑ Quantum field theory brings both of these together.
  - ❑ **QED** (Quantum Electrodynamics) is a quantum field theory of electromagnetic interactions.
  - ❑ **QCD** (Quantum Chromodynamics) is a quantum field theory of the strong interaction.
- ❑ **Too complicated to go into details on the guts.**

A huge theoretical challenge:

- ❑ Theory of tiny stuff: Quantum physics
- ❑ Theory of gravity: General relativity
- ❑ Both of these must be relevant at the core of a black hole!
- ❑ Currently, no successful theory that brings these two together.




That's all Folks!
kalilak

Backup

$c\bar{c}$ atoms

- cc bound states are like atoms, analogous to positronium.
- Today, a workhorse in HEP: $J/\psi \rightarrow \mu^+\mu^-$ "easy" to detect, and J/ψ often a product of b-hadron decays.