## HISTORICAL CONTEXT (ASIDE)

→ BTW, CAN CAST E&M IN LAGRANGIAN FORMALISM; WE'LL DO THIS LATER.

BY END OF 1800'S, PHYSICISTS THOUGHT THEY WERE "DONE"
E&M + MECHANICS (i.e. GRAVITY) SEEMED TO EXPLAIN EVERYTHING!
↑ CAN EVEN ADD SPECIAL RELATIVITY!

... EXCEPT:

- WHY DOES THE SUN SHINE? (NUCLEAR PHYS)
- WHY IS THE SKY BLUE? (maybe)
- WHY ARE SOME MATERIALS CONDUCTORS / INSULATORS? (QM)
- WHY DO ALL ELECTRONS HAVE THE SAME CHARGE? (QFT)
- WHAT DETERMINES THE THERMODYNAMIC PROPERTIES OF MATERIALS? (STAT M)
- WHY ARE THERE 3+1 DIMENSIONS? (STRINGY WINGY)

These notes are outside the 121 curriculum!

SO WHY DID SCIENTISTS THINK THEY WERE DONE?
→ CM DESCRIBED THINGS ON SCALES WE UNDERSTOOD
→ THIS IS THE IDEA OF "EFFECTIVE (FIELD) THEORY"
PHYSICS @ DIFFERENT SCALES (ENERGY, LENGTH, etc.) SHOULDN'T SIGNIFICANTLY AFFECT PHYSICS AT THE SCALE ONE IS MEASURING.

i.e. "A CHEF DOES NOT NEED QFT" - SAVAS DIMOPOULOS.

→ THIS IS WHY THE LHC IS EXCITING
IT WILL PROBE NEW ENERGY SCALES THAT MAY HAVE EXCITING NEW PHYSICS

EVEN TODAY IT LOOKS LIKE PHYSICISTS ARE "DONE"
(well, 1970's)
→ THE "STANDARD MODEL" IS SELF CONSISTENT ("RENORMALIZABLE" IF YOU WANT TO BE FANCY-SCHMANCY)
→ BUT STILL LOTS OF QUESTIONS TO BE ASKED & ANSWERED

## HOW THIS CAN BE SEEN IN E&M (HEURISTIC!)

(FROM H. MURAYAMA)

LET US MODEL THE COULOMB SELF-ENERGY OF THE ELECTRON BY

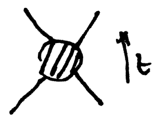
$$E_c = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}$$ WHERE $r_e$ IS AN EFFECTIVE ELECTRON RADIUS

(UP TO SOME NUMERICAL PREFACTOR OF ORDER 1 DEPENDING ON WHETHER WE MODEL THE $e^-$ AS A SOLID BALL OR A SHELL)

NOW, WE "KNOW" THAT THE REST ENERGY OF THE ELECTRON is $(m_e c^2)_{obs.}$
i WILL MARK THIS AS THE OBSERVED ELECTRON REST ENERGY
WHY? TO DISTINGUISH IT FROM THE "BARE" REST ENERGY $(m_e c^2)_B$
THAT WE WRITE IN OUR EQUATIONS.

~> THIS is A WEIRD THING TO SAY
IN QFT, FEYNMAN DIAGRAMS ARE A TAYLOR EXPANSION OF PROBABILITY AMPLITUDES

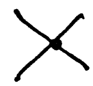
e.g.



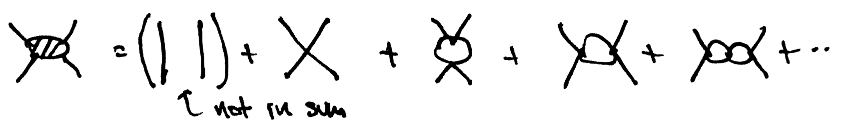
is AN AMPLITUDE FOR 2 PARTICLES GOING iN + 2 PARTICLES GOING OUT

OUR THEORY (LAGRANGIAN) DETERMINES THE KINDS OF VERTICES (INTERACTIONS WE CAN DRAW).

i.e. LET'S SAY 2 PARTICLES CAN HAVE A 4-PT INTERACTION :

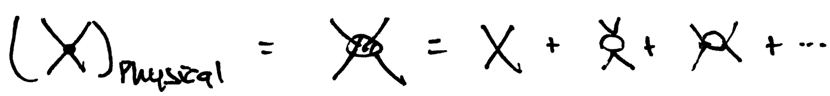


THEN




HOWEVER, THE MASSES/COUPLINGS THAT GO INTO EACH FEYNMAN DIAGRAM ARE DIFF. FROM THE OBSERVABLE MASSES/COUPLINGS iN A PHYSICAL PROCESS, WHICH IS THE SUM OF DIAGRAMS.

i.e.




[if you're confused, don't worry!!]

ANYWAY, THE OBSERVED REST ENERGY SHOULD BE THE SUM OF THE BARE REST ENERGY W/ THE COULOMB SELF ENERGY:

$$(m_e c^2)_{OBS} = (m_e c^2)_B + E_c$$
$$= (m_e c^2)_B + \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

EXPERIMENT TELLS US $r_e \lesssim 10^{-17}$ cm

$\Rightarrow E_c \gtrsim 10$ GeV

BUT $(m_e c^2)_{OBS} = 0.511$ MeV !

Why is this weird? We get a large "fine-tuning"

$$0.511 = -9999.489 + 10000.000$$

↑ OBS — ↑ BARE REST E IS NEGATIVE (it's ok - it's just a mathematical #) — ↑ $\sim E_c$

ISN'T IT ODD THAT NATURE CARES ABOUT 5 DECIMAL POINTS?
WHAT A "MIRACULOUS" CANCELLATION!

## ALTERNATE POINT OF VIEW

FINE TUNING IS A HINT OF NEW PHYSICS
SUPPOSE THERE IS NO FINE TUNING,
THEN

$$E_c = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}$$

MUST BE INVALID ON SCALES SHORTER THAN

$$r \sim \frac{e^2}{4\pi\varepsilon_0 (m_e c^2)} \approx 2.8 \times 10^{-13} \text{ cm}$$

THE RESOLUTION: ∃ POSITRON!
NEVERMIND THE MOTIVATION FOR THE POSITRON,
BUT YOU KNOW FROM PHYS 70 THAT EM FIELD IS
"MADE UP OF" PHOTONS ($\gamma$) THAT CAN PAIR PRODUCE:

$$\gamma \to e^+ e^-$$

ALSO FROM PHYS 70 $\Delta t \Delta E \sim \hbar$
FOR QUANTUM EFFECTS

THUS WE EXPECT PAIR PRODUCTION TO BECOME RELEVANT
AT DISTANCE SCALES OF

$$d \sim c\Delta t \sim \hbar c/(2m_e c^2) \approx 200 \times 10^{-13} \text{ cm}$$

⇒ CLASSICAL E&M BREAKS DOWN AT AROUND THE SCALE
WE PREDICTED!

## EVEN MORE DETAIL

SO OUR PICTURE IS :

ON SCALES $\gg 10^{-11}$ CM : USUAL POTENTIAL
ON SCALES $\lesssim 10^{-11}$ CM : VIRTUAL PAIRS OF $e^+e^-$ MATERIALIZE OUT OF THE EM FIELD TO SCREEN THE $1/r$ POTENTIAL

V. WEISSKOPF (1939) WAS THE 1ST TO CALCULATE THE CONTRIBUTION TO THE $e^-$ SELF-ENERGY FROM PAIR PRODUCTION:

$$E_{PAIR} = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}\Big|_{r \lesssim 10^{-11}\text{cm}}$$

↑ MINUS SIGN! ⇒ <u>CANCELS</u> $E_c$ TO LEADING ORDER

SO $\Delta E = E_c + E_p$
AS $r_e \to 0$ , $\Delta E \to \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$
↑ BARE

$$(m_e c^2)_{OBS} = (m_e c^2)_{BARE}\left[1 + \frac{3\alpha}{4\pi}\log \hbar/m_e c r_e\right]$$