Instructor: Kaustubh Agashe

Research area: theoretical particle physics; beyond standard model (BSM) ... discuss some of it in part III

- Today: Logistics of course; outline of topics; details next...
- Course webpage contains (links to) most information: bookmark it
- Annoucements link at top (e.g., incoming survey & 1st HW assigned) ... keep eye on it
- Course email will be used for communication (e.g., HW due; solutions posted); sorry for flooding!
- Coordinates: lectures on Mon. & Wed. 11 am. to 12.15 pm
- Office hours: right after lecture or by

appointment (same zoom link as lecture)

- Grade break-up: 75% HW (~10 total) + 25% term paper (including presentation (some topics already suggested)
- HW assigned at link (same PDF will be updated with #2 ...); solutions & notes links
- feedback welcome (don't wait for official course evaluations at end!), e.g., lectures too slow/fast; HW difficult / long (I can modify accordingly)
  - build new topic on top of previous, so keep up ...
- Feel free to ask questions (interrupt me if needed): I will also pose questions to you (make it interactive)

- Onto (slowly) physics/content of course
- Goal: develop theory of SM; then study phenomenology (experimental consequences / testing predictions) ... followed by BSM: motivation and one example, likely grand unified theories (GUTs)

- Background:
  - required: introductory quantum field theory (QFT) course, e.g., Phys 624, since QFT is "language" of SM
  - recommended: survey-level course (e.g., advanced UG) on phenomenlogy of SM; moving parts/actors, e.g., matter types: leptons & quarks (spin-1/2)

forces: EM; strong; weak (no gravity)
(spin-1 gauge bosons)

"last" ingredient: Higgs boson (spin-0)

(Now, "back it up" by detailed theory)

- Fill out incoming survey (see email or announcements part of course webpage) to give me an idea of your course background & research interests

- Textbooks:

- required: Lahiri & Pal (LP): some HW problems assigned from it + (roughly) follow outline/notation from it for SM part of course

- Recommended: Peskin & Schroeder (PS) ... Cheng & Li (CL)

- Above 3 for learning theory of SM (including QFT topics) and basic phenomenlogy

- Donoghue, Golowich & Holstein (DGH): assuming SM theory background, develops phenomenlogy in more detail (+ good summary of theory of SM in beginning chapters)
- BSM: chapter 14 of CL for GUT's (other lecture notes for supersymmetry; extra dimensions; dark matter...)
- (Rough) Outline of course topics (technical terms used will be explained later) [more detailed outline just before starting each topic
- To develop theory of SM, need to study a few more QFT topics beyond Phys 624 (QED, mostly tree-level): will be clear soon
- So, cover QFT topics first: Phys 851 (Advanced QFT) will also develop them,

that too more systematically/generally
⇒ some repetition with Phys 851, but that's good! So, I won't "coordinate" with Phys 851 (also, some of students might not be taking Phys 851)

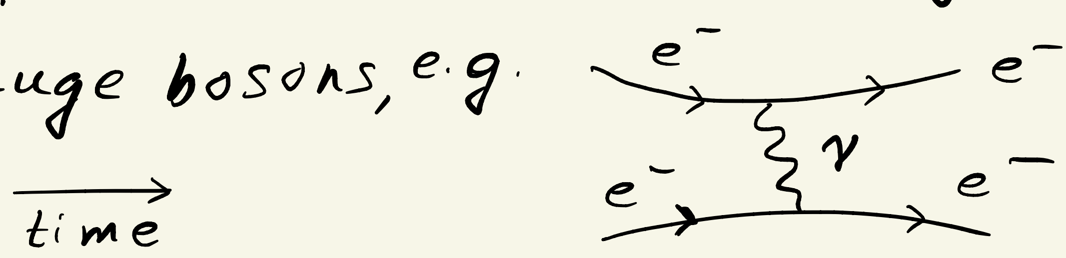
– So, three "parts" of course:
(I). QFT topics; (II). Theory & Phenomenlogy of SM and (III). BSM (GUT's)

Part (I) (QFT topics)

(A). Renormalizabity of QED (chapter 12 of LP)

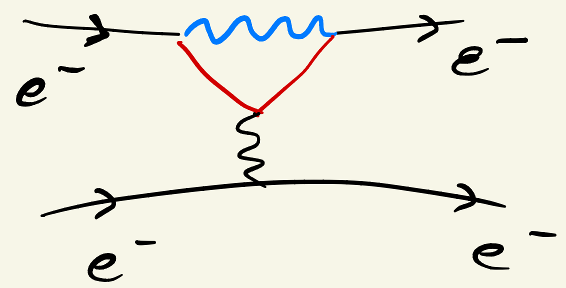
– QED is "1st" force of SM, "basic model" for SM (other forces are copies/extensions of QED) ⇒ need to really understand all features of QED

– QED is gauge theory: forces between matter particles due to exchange of spin-1 gauge bosons, e.g.



– Summary:

(i) loop diagrams (higher order corrections):



result in divergences: naively a disaster!
Good news: can be "tamed" ⇒ predictions (agree with experiments) (so, "all's well that ends well", but after lot of work!)

(ii) Coupling constant (e) evolves with characteristic energy of process ("running"): in case of QED, grows as we go to higher energy: "free" in infra-red (IR)

(B) Renormalizable theory for massive gauge bosons (LP chapter 13)

— weak (nuclear) force, e.g., radioactive decay has short range (empirically)

... vs. long range for QED, due to photon being massless

- So, if model weak force as gauge theory (based on success of QED), need massive gauge bosons (W, Z)
- However, adding "bare" mass terms for gauge bosons, then (at least naively) lose renormalizability (divergences "out of control": cannot make predictions / lose nice feature)
- Instead, gauge bosons acquire masses via spontaneous symmetry breaking (SSB) called Higgs mechanism
  - maintains renormalizability of gauge theory ("like" QED)

... what's left? strong (nuclear) force

(c). Non-abelian gauge theory

(chapter 14 of LP)

- Nuclei made up of protons (p) and neutrons (n)

- In turn, p/n (lots of hadrons in general) conjectured to be built out of constituents ("quarks") which are weakly-coupled at higher energies ($\gg$ GeV), but tightly bound at low energies ($\lesssim$ GeV) (empirically) $\Rightarrow$ if strong force modeled as gauge theory, then need coupling constant to be ultra-violet (UV) or "asymptotically" free (AF) ...unlike QED

$\Rightarrow$ Non-abelian gauge theory: "generalization" of QED (abelian): self-interactions of gauge bosons

(weak gauge theory also non-abelian, since $W^\pm$ is charged)

... part (I) could take half semester, but needed to develop SM...

Onto part (II): theory / phenomenology of SM (chapter 15 of LP + PS, CL)

- with above QFT concepts / ingredients, (and data) straightforward to build SM
- Particle (matter) content & gauge symmetries

electron in QED → leptons (electron, muon, tau) & quarks

photon in QED → photon (EM); gluon (strong) & W/Z (weak)

- To give masses to W/Z in a renormalizable way, add Higgs field / boson
- comes with "unification" of EM & weak

forces: electro-weak symmetry

⇒ "re-organization" of gauge bosons after Higgs mechanism: photon remains massless, W/Z massive

— Phenomenology of SM (following from above theory) of various kinds: high and low (collider) energy; involving (or not) "flavor" (multiple generations – including mixings – of quarks & leptons) ...

... SM predictions agree with data, but still incomplete: no neutrino mass or dark matter (data); also theoretical/aesthetic issues, e.g., hierarchy between weak & Planck (gravity) scales or too many parameters

... motivates

part (III) Beyond SM (BSM), e.g., grand unified theories (reduce number of parameters) in course lectures + supersymmetry, extra dimensions (addressing Planck-weak hierarchy problem); dark matter; seesaw mechanism for neutrino mass ... in term papers