1.2 reality checks

- <u>hadron spectrum</u>

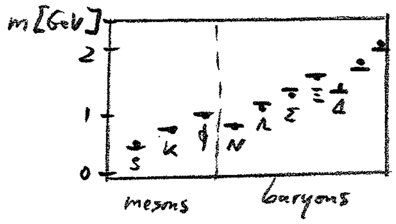
↳ (bound states of quarks; eg $K = s\bar{d}$, $p = uud$, $\Lambda = uds$, ...)

in "our" world, at long distances, observe not quarks + gluons, but hadrons (mesons $q\bar{q}$, baryons qqq)

→ "solve" QCD eqs by computer: Lattice QCD — powerful: presently $O(10)$ TFlops

⇒ what one gets are just the observed particles + masses (no gluons; no fractional charges)

upshot: QCD postdicts the low-lying hadron masses



← plot online [Aoki et al, PACS-CS 2008]

((discretise eg. $V \sim (3\,\mathrm{fm})^4 \to 48^3 \times 64$ points; Euclidean time $t \to -it_E$; physics may differ))

- <u>experimental checks of QCD</u>

collider physics

eg. LEP (@ CERN, 1989-2000): $e^+e^- \to X$ — stuff hitting the detectors

→ asymptotic freedom enables us to compute interactions of quarks + gluons at <u>short</u> distances; detectors are a <u>long</u> distance away, see hadrons (not free partons)

⇒ for comparison of theory ⇔ experiment, need also

<u>infrared safety</u>: classes of quantities which are independent of long-distance physics, hence pQCD calculable

<u>factorization</u>: even wider class of processes, can be factorized into <u>universal</u> long-distance piece and <u>process-dependent</u> (but pQCD calculable) short-distance pc.

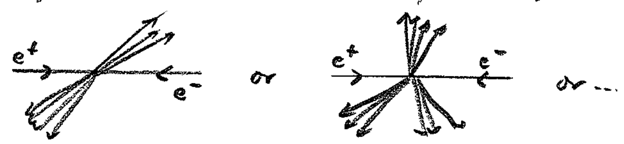
(more later!)

get (QFT!) (1) $X = e^+e^-$ or $\tau^+\tau^-$ or ... ⇒ detailed QED check

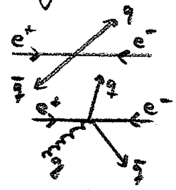
(2) $X >$ 10 particles: π, S, p, $\bar{p}$, ... ⇒ QCD "<u>Jets</u>"

case (1) : no color charge → mainly QED interactions
simple final state: coupling $\alpha_{em} \approx \frac{1}{137}$ small
→ most of the time (99%) <u>nothing</u> happens
→ $e^+e^-\gamma$ ~ 1% ⇒ check QED details
→ $e^+e^-\gamma\gamma$ ~ 0.01% ⇒ ...

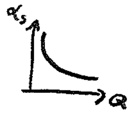
case (2) : $X \in$ {"greek & latin soup" constructed from quarks + gluons
observed pattern:



flow of energy + momentum in "jets"
$\alpha_s \gtrsim \frac{1}{10}$ → 2 jets 90%
→ 3 jets 9%
→ 4 jets 0.9%



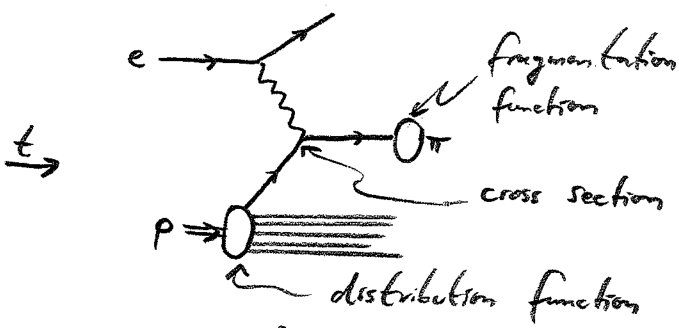
• perturbative QCD and hard physics

we have seen (pg 4) ((and will calculate later)) that $\alpha_s(Q^2) =$ 

⇒ for large enough 4-momentum squared Q^2 coupling should be small enough for perturbation theory to converge
((more precisely: one gets asymptotic expansions which converge only when "higher twist" and genuine non-perturbative contributions such as "instantons" are also accounted for))

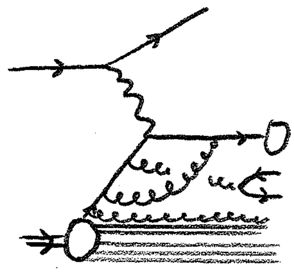
→ perturbative QCD is the basis for interpreting most experiments.
⇒ so pQCD is the most important topic to learn here.

e.g. deep inelastic scattering:



(LO)

vs.



(real life)

- QCD and search for "New Physics"

Specific example: anomalous magnetic moment of muon a_μ

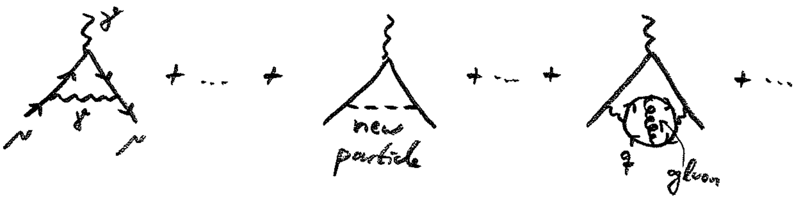
→ determined experimentally and theoretically (within the SM) with such high precision that it became a very sensitive test for many ideas for "physics beyond the SM"

$$a_\mu(\text{exp}) = 11659208\,(\pm 6) \cdot 10^{-10}$$
$$a_\mu(\text{theor}) = 11659186\,(\pm 8) \cdot 10^{-10}$$

deviation: 2-3 σ
not "significant" yet

↳ dominated by uncertainty of QCD contributions

→ strategy for "New Physics" search:

$a_\mu \sim$ 

typically get rather stringent limits on e.g. the minimal allowed mass of hypothetical new particles; obviously, any deviation between $a_\mu(\text{exp})$ and $a_\mu(\text{theor})$ could be a signal for new physics.

⇒ does the lack of precision in our QCD calculations keep us from clearly "seeing" signals of exciting new physics?

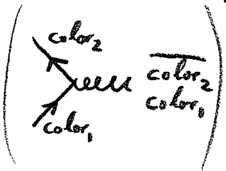
1.3 Color charge in QCD

- in addition to its electric charge $\left(\left(\begin{matrix} u & c & t & \leftarrow +\frac{2}{3} \\ d & s & b & \leftarrow -\frac{1}{3} \end{matrix}\;;\; \bar{q} \text{ neg.}\right)\right)$ each quark carries a <u>color</u> charge.

  3 possible values, e.g. r = red, g = green, b = blue

  ((experimentally determined, more later; often we generalize $3 \to N_c$))

- if a quark emits a gluon, its color may or may not change



$\rightarrow$ 9 ways of coupling a gluon between initial + final quark

e.g. $g_1 = r\bar{g}$, $g_2 = r\bar{b}$, $g_3 = g\bar{r}$, $g_4 = g\bar{b}$, $g_5 = b\bar{r}$, $g_6 = b\bar{g}$, $g_7 = \frac{1}{\sqrt{2}}(r\bar{r} - g\bar{g})$, $g_8 = \frac{1}{\sqrt{6}}(r\bar{r} + g\bar{g} - 2b\bar{b})$, $\Big\}$ SU(3) color "octet"

$g_0 = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$ $\Big\}$ SU(3) "singlet"

- experimental evidence: from scattering expt's we know that matter (mesons = $q\bar{q}$, baryons = qqq) is composed of quarks, yet those hadrons must be neutral to the strong force.

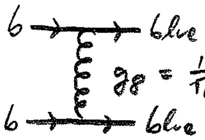
  $\Rightarrow$ stable particles (hadrons) are "colorless";
  more precisely: they are in "color singlet state"

  $\Rightarrow$ color singlet gluon state g_0 is not needed / observed.

- strength of coupling between 2 quarks ~ color factors:

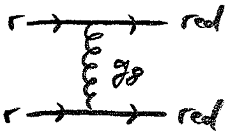
((QED:  $\sim e_1 e_2 \alpha_{em}$ where e.g. $e_{u,c,t} = +\frac{2}{3}$, $e_{d,s,b} = -\frac{1}{3}$ etc.))

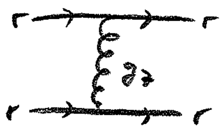
QCD:  $\sim \frac{c_1}{\sqrt{2}} \frac{c_2}{\sqrt{2}} \alpha_s$ where $\frac{1}{\sqrt{2}}$ are historical; c_i from g_i above

example: 

$g_8 = \frac{1}{\sqrt{6}}(r\bar{r} + g\bar{g} - 2b\bar{b}) \sim \frac{1}{2}\left(-\frac{2}{\sqrt{6}}\right)\left(-\frac{2}{\sqrt{6}}\right) = \frac{1}{3}$ $\left(\times \alpha_s\right)$

same result due to color symmetry

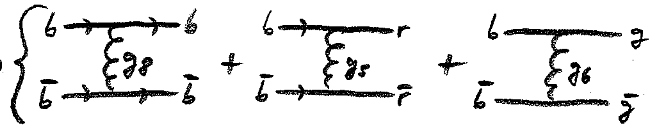
vs 

$+$ 

$\sim \frac{1}{2}\frac{1}{\sqrt{6}}\frac{1}{\sqrt{6}} + \frac{1}{2}\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}} = \frac{1}{12} + \frac{1}{4} = \frac{1}{3}$

example: single gluon exchange between q and $\bar{q}$ in color singlet state

$(q\bar{q})_{singlet} = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$ $\Rightarrow$ consider e.g. $b\bar{b}$, mult. $\times 3$

$3\Big\{$ 

$\Big\} \sim 3\,\frac{1}{2}\,\frac{1}{\sqrt{3}}\,\frac{1}{\sqrt{3}}\left\{-\frac{2}{\sqrt{6}}\frac{2}{\sqrt{6}} - 1\cdot 1 - 1\cdot 1\right\} = -\frac{4}{3}$

(($\bar{q}$ opposite charge to q $\Rightarrow$ $-$ sign for $\bar{q}$ vertex))

$\Rightarrow$ color force can be both repulsive and attractive.