COLOR AND JETS

MEASUREMENT OF

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \cdot \sum_{(i)} Q_i^2$$

3 colors!

(i): available quarks (energetically)

CONVENTIONALLY: RED, GREEN, BLUE

r g b

=> three versions of every quark

$u \longrightarrow u_r, u_g, u_b$ three copies

same mass, charge, spin

different color

$\bar{q} \to \bar{q}_{\bar{r}}, \bar{q}_{\bar{g}}, \bar{q}_{\bar{b}}$ anticolor for antiquarks

WHAT ABOUT THE PION?

$$|\pi^+\rangle = |u\bar{d}\rangle \xrightarrow{?} |u_r d_{\bar{r}}\rangle + |u_g d_{\bar{g}}\rangle + |u_r d_{\bar{g}}\rangle + |u_b d_{\bar{r}}\rangle \text{ etc?}$$

YET WE SEE ONLY ONE PION

QCD POSTULATES THAT ONLY COLOR-NEUTRAL ("WHITE") COMBINATIONS ARE PHYSICAL PARTICLES

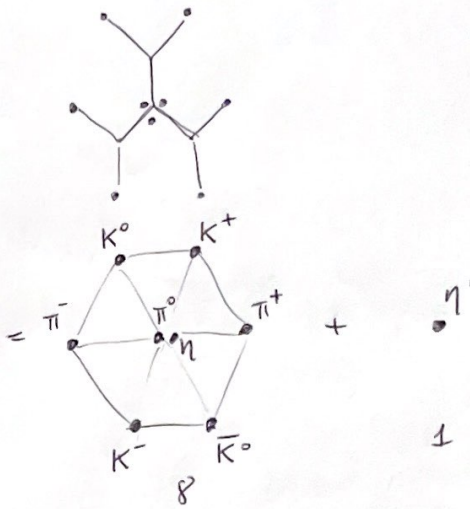
REMEMBER uds ? THREE BUILDING BLOCKS

MESONS ARE $q\bar{q} \rightarrow \begin{pmatrix} u \\ d \\ s \end{pmatrix} \times \begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{s} \end{pmatrix}$

$SU(3): \quad 3 \otimes \bar{3} = 8 \oplus 1$

OCTET SINGLET

3: 

$3 \times \bar{3}$: 

SAME WITH COLOR

$\Rightarrow$ 8 states form an octet ← Here constituents have color ≠0

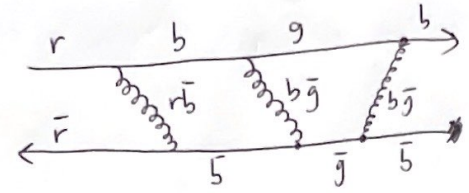
+ 1 singlet ← The singlet is colorless

This is the only color combination physical mesons can have $\Rightarrow$ there is only one pion

the singlet is a combination of $r\bar{r}$, $g\bar{g}$, $b\bar{b}$

color ↑↓ anticolor = 0

$\pi^+ = \begin{pmatrix} u \\ \bar{d} \end{pmatrix}$ {



by excluding gluons → mix of $q\bar{q}$

(*) other consequence: gluons are colored force mediators

↗

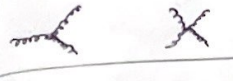
$c\bar{c}'$ they are the octet

⇒ there are 8 gluons, one per colored $c\bar{c}'$ combination

DIFFERENCE FROM QED!

in QED photon is electrically neutral (but interacts with charges)

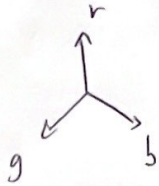
in QCD gluon is colored ⇒ GLUONS INTERACT WITH THEMSELVES!



BARYONS? same idea but to neutralize color need rgb

$|qqq\rangle$

$c_1 c_2 c_3$



$r\bar{r}$ ↑↓

mesons

baryons

⇒ $|p\rangle = |uud\rangle \longrightarrow |u_b u_r d_g\rangle + |u_r u_b d_g\rangle + \dots$

DIFFERENCE BETWEEN uds SU(3) and COLOR SU(3)

approximate symmetry

$m_u \neq m_d \neq m_s$

EXACT symmetry

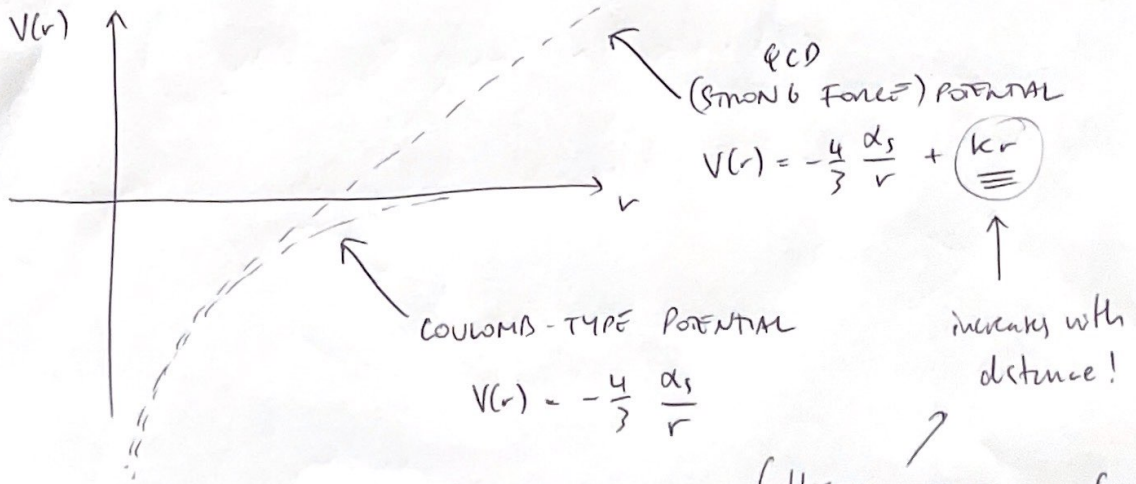
OTHER CONSEQUENCE: if you have a proton say $u_r d_{\bar{r}}$

you CANNOT extract a quark

because it would create two colored states

$\Rightarrow$ quark CONFINEMENT: they exist only bound in color-less states

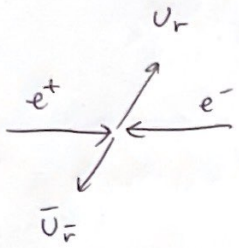
by the strong force potential

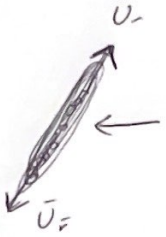


So let's look at ~~e^+e^-~~

$e^+e^- \to (u\bar{u})$

↳ $u_r \bar{u}_{\bar{r}}$ need a colorless combo

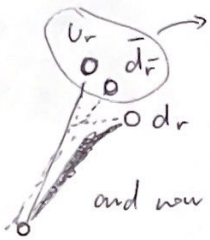




← as they drift apart potential energy between them increases

→ to the point it's energetically favored to create a new $q\bar{q}$ pair from vacuum

eg.:



and now energy build up between $\bar{u}_{\bar{r}}$ and $\bar{d}_r$

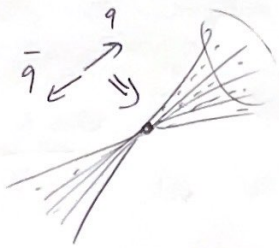
→ new $q\bar{q}$ pair

and so on .. until all quarks are "confined" in colorless configurations

→ stable hadrons (HADRONIZATION)

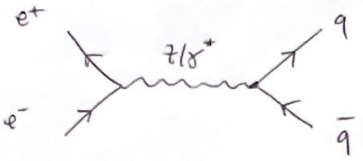
(can be lots of them!)

→ hadronic JETS

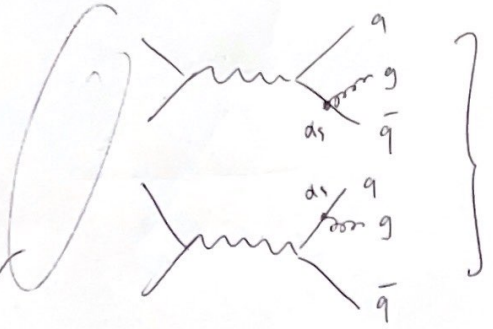


HADRONIZATION

OTHER CONSEQUENCE : three-jet events



2 jets $e^+e^- \to q\bar{q}$



emission of hard gluon FSR

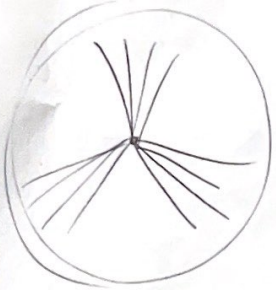
$e^+e^- \to q\bar{q}g$ 3 jets

FIRST OBSERVATION AT PETRA COLLIDER @ DESY

↑

e^+e^- with $\sqrt{s} > 30$ GeV

1981



3 jet events

$$\frac{\sigma(e^+e^- \to 3\,\text{jets})}{\sigma(e^+e^- \to 2\,\text{jets})} \sim \alpha_s$$

JADE

$\alpha_s(\sim 35\,\text{GeV}) \sim 0.14$

$\alpha_s(M_Z) \sim 0.11$ ↑ ALEPH

FIRST EVIDENCE OF GLUONS EXISTENCE

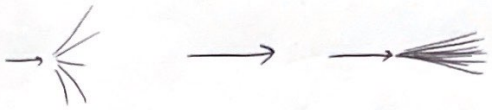
ALSO : if this model is correct → energy accumulated in the plane between q and $\bar{q}$

⇒ 3rd jet (gluon) should be emitted in same plane as $q\bar{q}$ ⇒ 3 jets all on same plane ⇒ observed ! (TASSO, JADE, ETC)

JETS

higher initial energy $\Rightarrow$ (1) more particles in jet

(2) particles are more collimated



IDEALLY if all particles of a jet are grouped together

$$\Rightarrow \quad P_{q/g} = \sum_{i}^{jet} P_i$$

HOWEVER jets are never completely independent!

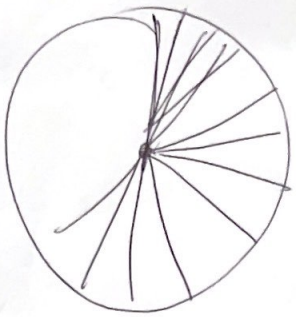
$e^+e^- \rightarrow (q\bar{q}) \rightarrow$ 2 jets

↑ there is color connection between $q\bar{q}$

$\Rightarrow$ the particle content of 2 jets is correlated

to close color string

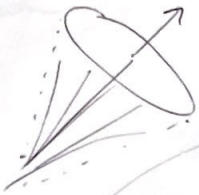
BUT YOU SEE THIS



HOW MANY JETS?

⇒ 1st PROBLEM: NEED JET CLUSTERING ALGORITHM

SIMPLE EXAMPLE: CMS ITERATIVE CONE



1. OPEN CONE AROUND HIGH ENERGY "SEED"
   ↳ FIXED RADIUS
2. SUM ALL MOMENTA OF PARTICLES IN CONE
3. COMPUTE NEW AXIS
4. OPEN NEW CONE
5. ITERATE TILL CONE AXIS DOESN'T CHANGE MUCH

HOW LARGE?

× TOO SMALL → YOU MISS PARTICLES FROM JET

× TOO LARGE → YOU HAVE PROBLEMS SEPARATING CLOSE-BY JETS
(ALSO YOU COLLECT NOISE IN CONE)

WILL NEVER BE 100% EFFICIENT IN CLUSTERING PARTICLES

⇒ EVEN IF YOU RECONSTRUCT ALL HADRONS PERFECTLY, SMALL INEFFICIENCY DUE TO CLUSTERING (LEFT-OUTS)

JET RESPONSE

$$R_{jet} = \frac{|\vec{p}(jet, reco)|}{|\vec{p}(parton, true)|} = \frac{\left|\sum_{i}^{(in\ jet)} \vec{p}_i(hadron_i, reco)\right|}{|\vec{p}(parton, true)|}$$

↑ quark or gluon that started hadronization

$$= \frac{\left|\sum_{i \in jet} \vec{p}_i(hadron_i, reco)\right|}{\left|\sum_{i \in jet} \vec{p}_i(hadron_i, true)\right|} \cdot \frac{\left|\sum_{i \in jet} \vec{p}_i(hadron_i, true)\right|}{|\vec{p}(parton, true)|}$$

↑ detector response to hadrons

↑ jet clustering efficiency ($\varepsilon \sim 95\text{-}99\%$)

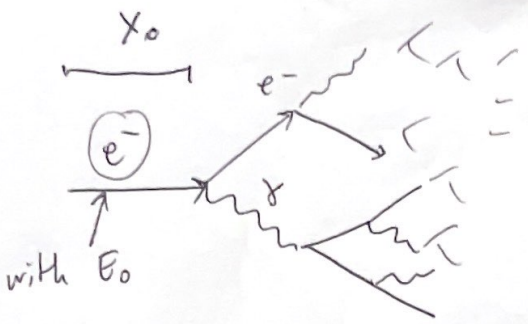
some particles are not clustered

AKA JET ENERGY SCALE

↑ in general:
- difficult to get very close to 1
- depends on energy

LET'S SEE WHY

REMEMBER EM SHOWERS



ALL ENERGY IS POTENTIALLY DETECTABLE

ALL ENERGY TRANSFORMED INTO LOW-ENERGY $e^\pm$ OR γ

⇒ IN HOMOGENEOUS ECAL ALL E "STORED" IN EXCITATION OF ELECTRONS → DE-EXCITATION PRODUCES SCINTILLATION LIGHT → $N_\gamma \propto E_0$

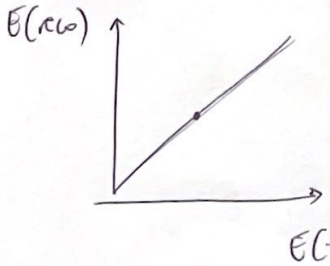
$\forall E_0$!

⇒ with a properly designed ECAL

- NO HOLES
- DEEP ENOUGH TO CONTAIN FULL SHOWER

ECAL RESPONSE IS LINEAR

⇒ you need to calibrate it in principle only ONCE $E(reco) = k \cdot N_\gamma$



WHAT ABOUT HADRONS

π^+ entering the detector

charged → will ionize (like a μ)

then eventually encounter a nucleus → strong int.

dramatic effect

many possible outcomes

eg: turn into (15 new hadrons)

[these will continue and might have other strong int.

A STRONG. INT. ON AVERAGE EVERY λ_{int} (like X_0 for EM)

⇒ multiplication

⇒ hadronic shower

IN PRINCIPLE CONCEPTUALLY SIMILAR TO EM SHOWER

BUT: ① INVISIBLE ENERGY

part of the energy of the hadronic shower is fundamentally undetectable

② particle composition of shower changes with energy

⇒ hadron calorimeters are intrinsically non-linear

③ size: $\lambda_{int} > X_0$ eg. for (Pb) $X_0 = 0.89$ cm, $\lambda_{int} > 20$ cm

① INVISIBLE ENERGY

When a hadron hits a nucleus it can release nucleons from the nucleus

REMEMBER NUCLEAR STARS FROM EMULSION EXPERIMENTS?

Spallation: incoming hadron collides with nucleons, nucleons collide with other nucleons (cascade effect), some pions might be created in the process (if enough E), some nucleons might escape the nucleus

to be able to escape the nucleus (bound state) enough E must be transferred to overcome nuclear binding energy

TYPICALLY 30-40% OF HADRONIC INTERACTIONS ARE INVISIBLE

THIS ENERGY IS LOST FOR CALORIMETRIC PURPOSES → INVISIBLE ENERGY

DØ CALORIMETER: URANIUM ABSORBER

→ NUCLEAR INTERACTION INDUCED RADIOACTIVITY

→ MC TO REDUCE INVISIBLE ENERGY

OTHER SOURCE OF INVISIBLE ENERGY IN JETS:

$\pi^{\pm} \rightarrow \mu^{\pm} (\nu)$ PION DECAYS IN FLIGHT

$c\tau \sim$ & m

→ SO CONCEPTUALLY IMPOSSIBLE TO DETECT 100% OF ENERGY OF HADRONIC SHOWERS

(2) PARTICLE COMPOSITION

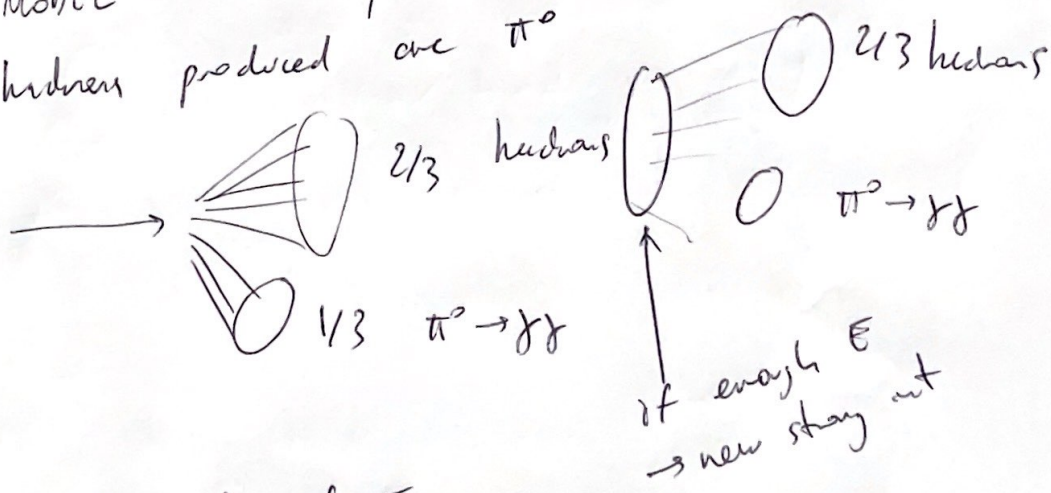
AT EVERY NUCLEAR INTERACTION → NEW HADRONS PRODUCED

Some of these decay to photons: $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$

→ hadronic showers have EM component

(EM component has NO invisible E)

SIMPLE MODEL: at every interaction 1/3 of the hadrons produced are π^0



So at every step 1/3 of E is STORED IN PHOTONS → IRREVERSIBLE PROCESS

"A ONE-WAY STREET"

In this simple model at every step for which there's still enough E to produce new hadrons → 1/3 of energy goes to EM sector

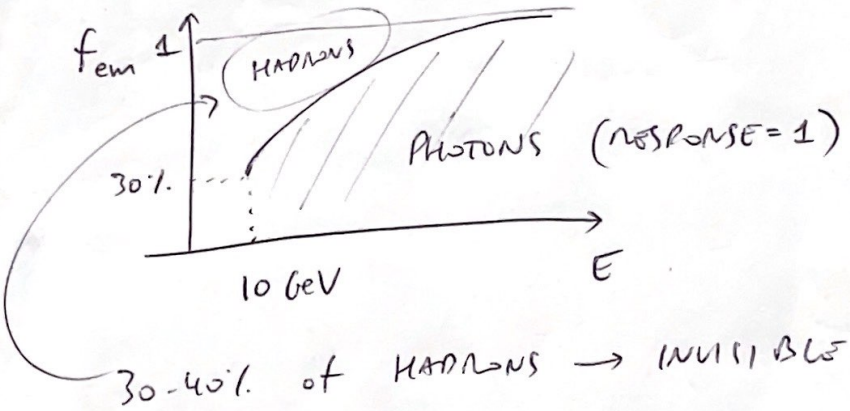
$$\Rightarrow f_{em} = 1 - \left(1 - \frac{1}{3}\right)^{n}$$

n: number of steps, $n \propto E_0$

THIS IS A SIMPLE MODEL

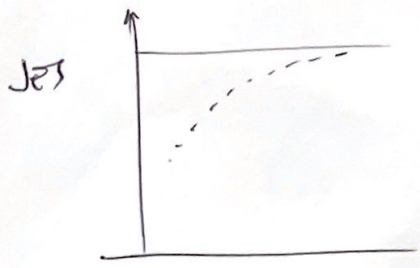
In reality $f_{e0} < \frac{1}{3}$ (other particles can be produced)

BUT NOT TOO FAR OFF

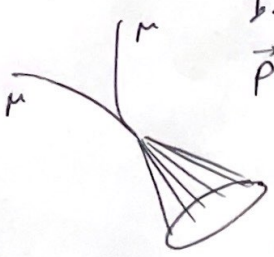


30-40% of HADRONS → INVISIBLE E

→ JET ENERGY SCALE: NEED TO CALIBRATE AT ALL ENERGIES



$Z \to \mu\mu$ + jet events



back-to-back

$\vec{P}(Z \to \mu\mu) - \vec{P}(\text{jet})$

FLUCTUATIONS! JER ~ 5-10% AT BEST (e/γ noise < 1% @ CMS)