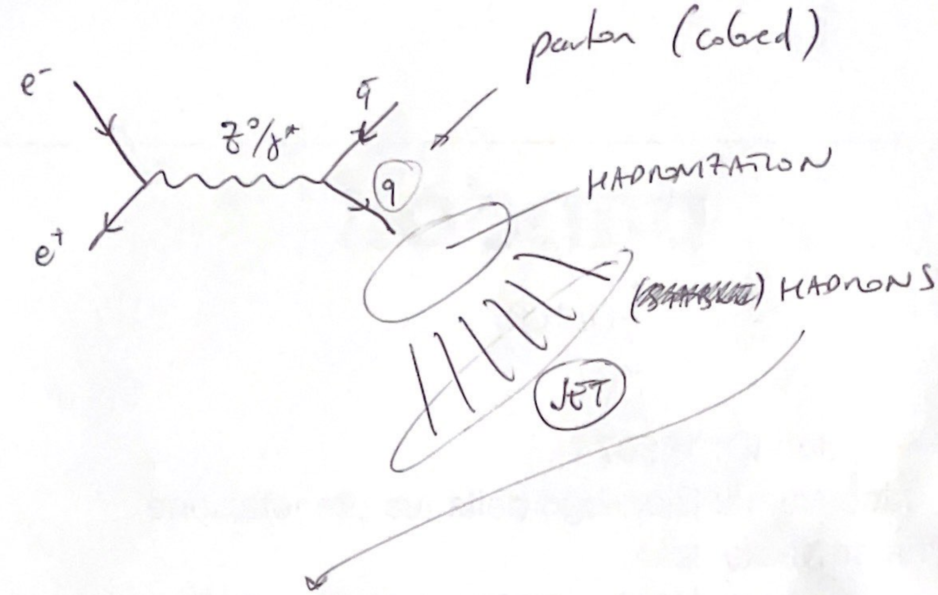
QUICK RECAP



IF WE COULD GROUP THEM ALL TOGETHER

$$\Rightarrow \underbrace{\sum_i^{\text{all}} \vec{p}_i(\text{hadron}_i)}\; = \vec{P}(\text{quark}) = \vec{P}_{\text{parton}}$$

<u>ALMOST</u>! BECAUSE TWO JETS ($q/\bar{q}$) ARE CORRELATED

IN PRACTICE NEED JET CLUSTERING ALGORITHM TO DEFINE JET

$$\sum_i^{\text{clustered}} \vec{p}_i(\text{hadrons}) \equiv \vec{P}_{\text{jet}}$$

$$\neq \sum_i^{\text{all}} \vec{p}_i(\text{hadrons}) \equiv \vec{P}_{\text{parton}}$$

IN DETECTOR WE HAVE <u>RECONSTRUCTED</u> QUANTITIES

tracks, calo deposits...

→ reco particle candidates

→ group them in a jet with clustering algo

reco jet

AIM: USE reco jet to get best estimate of $\vec{p}_{parton}$

TWO QUESTIONS:

JET ENERGY SCALE → (1) AM I RECONSTRUCTING CORRECTLY CLUSTERED PARTICLES?

&

JET CLUSTERING EFFICIENCY → (2) HOW MANY PARTICLES HAVE NOT BEEN CLUSTERED?

jet response: $R = \dfrac{|\vec{p}\,(jet, reco)|}{|\vec{p}\,(parton)|}$ ← want this to be $\underline{\underline{=1}}$

$$R = \frac{|\vec{p}\,(jet, reco)|}{|\vec{p}\,(parton)|} = \frac{\left|\sum_i^{clustered} \vec{p}_i(hadron_i, reco)\right|}{|\vec{p}\,(parton)|} =$$

$$= \underbrace{\frac{\left|\sum_i^{clust.} \vec{p}_i\,(hadron_i, reco)\right|}{\left|\sum_i^{clust} \vec{p}_i\,(hadron_i, true)\right|}}_{(1)} \; \underbrace{\frac{\left|\sum_i \vec{p}_i\,(hadron_i, true)\right|}{|\vec{p}\,(parton)|}}_{(2)}$$

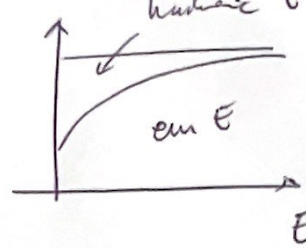
$$① = \frac{\left|\sum_i^{\text{clust.}} \vec{p}_i(\text{hadron}_i, \text{reco})\right|}{\left|\sum_i^{\text{clust}} p_i(\text{hadron}_i, \text{true})\right|} = 1$$

↑ if detector <u>calibrated</u>

HOWEVER: for hadrons detector needs to be calibrated at all different energies

hadronic E ⇒ 30-40% invisible

because f_{em}



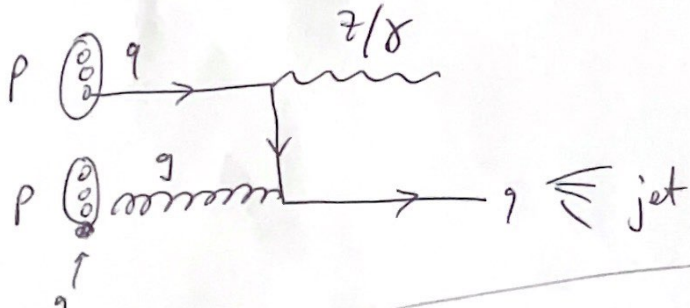
$R = ① \cdot ②$

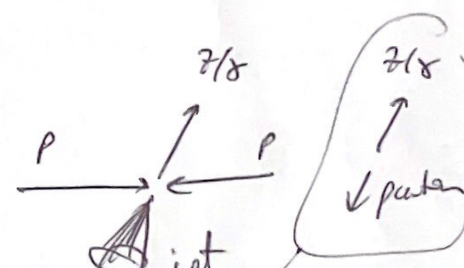
↑ conceptual distinction

in reality we have $R = \frac{|\vec{p}(\text{jet})|}{|\vec{p}(\text{parton})|}$

How?

Z + jets or γ + jets





$Z \to e^+e^- / \mu^+\mu^-$ or γ } very high resolution

before hadronisation

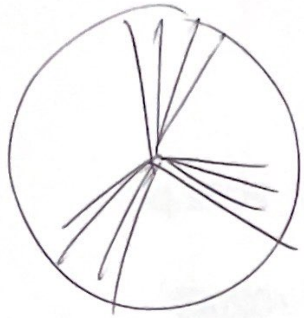
$|\vec{p}(Z/\gamma)| \overset{!}{=} |\vec{p}(\text{parton})|$ back to back

$\Rightarrow$ use $\vec{p}(Z/\gamma)$ as proxy for $p(\text{parton})$

$\Rightarrow R = \dfrac{|\vec{p}(\text{jet})|}{|\vec{p}(Z/\gamma)|}$ measure R at all θ

$\Rightarrow$ calibrate with R^{-1}

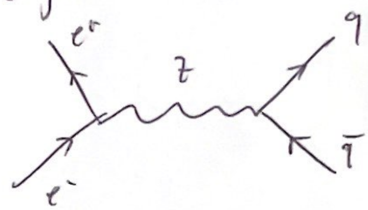
THEN WE SAW 3-jet EVENTS



as evidence of gluons $e^+e^- \to q\bar{q}g$

extra vertex $\to \alpha_s$

whereas 2-jet events are



analogous of BREM in QED

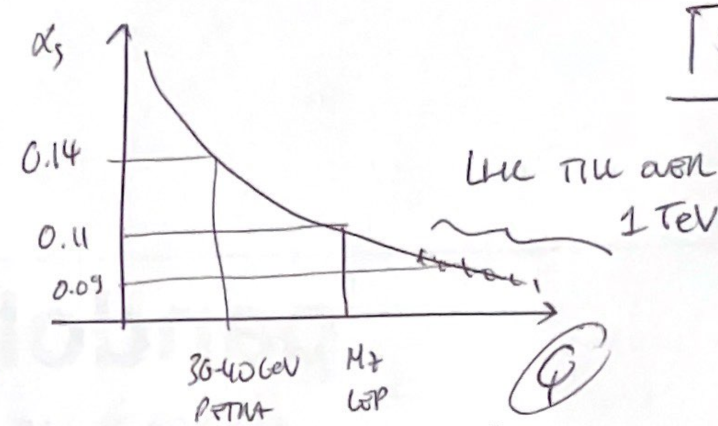
DIFFERENCE: in QED $\alpha_{em} \sim \frac{1}{137}$ small

QCD $\alpha_s \gtrsim 0.1$ large

$\Rightarrow$ emission of gluons more frequent than photons

also $\alpha_s = \dfrac{\sigma(e^+e^- \to 3\,\text{jets})}{\sigma(e^+e^- \to 2\,\text{jets})}$

α_s MEASUREMENT



ENERGY SCALE

$\sqrt{s}$ @ ~~PETRA~~ e^+e^- (PETRA, LEP)

$M_{inv}(jet_1, jet_2)$ @ LHC

"RUNNING" of α_s

DECREASES WITH INCREASING E

→ ASYMPTOTIC FREEDOM

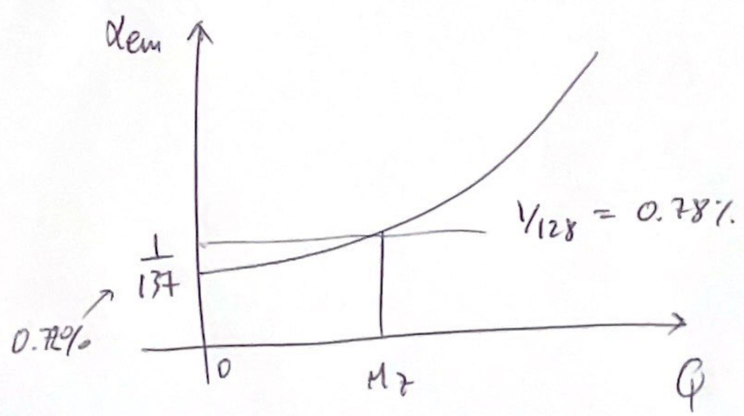
coloured particles feel no strong force ~~[illegible]~~ for

$E \to +\infty$

$\Leftrightarrow$ $\lambda \to 0$ ← the closer the quarks → 0 force

$\Leftrightarrow$ inside nucleon they are almost free

QED is opposite!



OK so 3 jets are $q\bar{q}g$

$\uparrow\uparrow\uparrow$

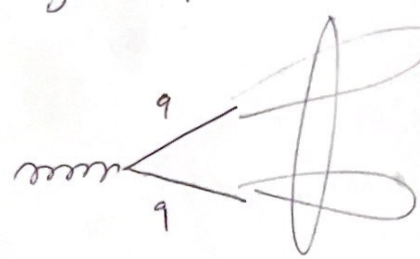
are these all the same?

quark hadronization = gluon hadronization?

SHORT ANSWER: NOT REALLY

reason: first step of gluon hadronization is

gluon splitting

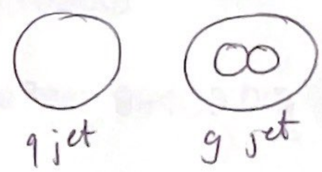


gluon jets have two cores

Also:

gluons have higher color charge → ~~wtaeg~~ wider

2 colors vs 1 color



⇒ hadronize "more"

higher particle multiplicities (at same E)

$\boxed{\text{Q-G discriminant}}$

at a hadron collider, typically

gluon jets are BG (always)

q jets are (sometimes) signal

e.g. $Z \to q\bar{q}$

$W \to q\bar{q}'$

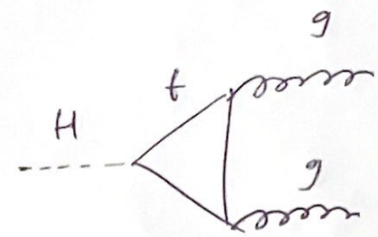
$H \to qq$

$t \to W\, b$

$\hookrightarrow qq$

NO KNOWN gg resonances

(EXCEPT HIGGS!)



$BR(H \to gg) \simeq 10\%$

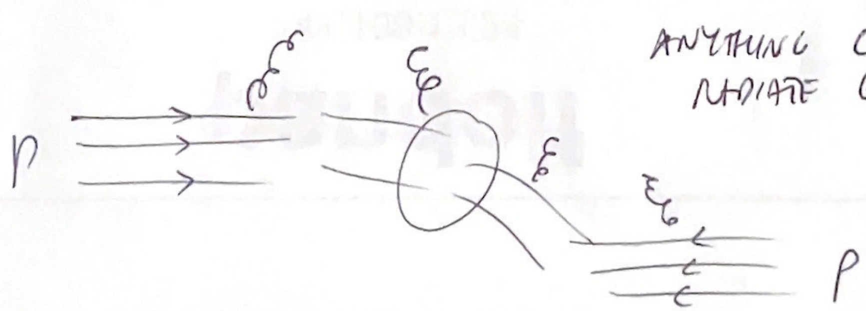
compared to $H \to \gamma\gamma \simeq 2‰$

$H \to ZZ \to 4\ell \simeq 1‰$

NEVER SEEN (YET)!

BG TOO HIGH

ANYTHING CAN RADIATE GLUONS



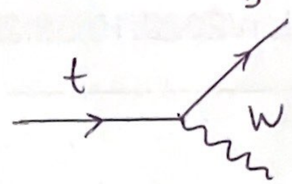
what about quarks

u	c	t
d	s	b

do they all hadronize the same?

top? $m_t \simeq 173$ GeV

DOES NOT HADRONIZE!



real W!

$m_W < m_t$

$\tau(t) \sim 5 \cdot 10^{-25}$ s

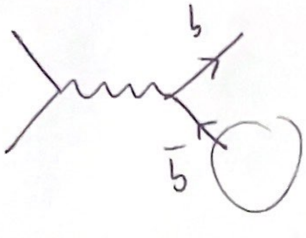
no propagator!

no hadron with t

u	c	X
d	s	b

uds light quarks $\longrightarrow$ similar

c and b ?



b quark hadronization is special

a meson with b will be formed

$|B^+\rangle = u\bar{b}$

$B^0 \quad d\bar{b} \qquad B^0_s \quad s\bar{b}$

$\bar{B}^0 \quad \bar{d}b \qquad \bar{B}^0_s \quad \bar{s}b$

$B^- \quad \bar{u}b$

B meson decays <u>WEAK</u> (b quantum number conserved by strong) and these are lightest mesons with b

480–490

$\Rightarrow \quad c\tau \simeq$ ~~450~~ $-500\ \mu m$

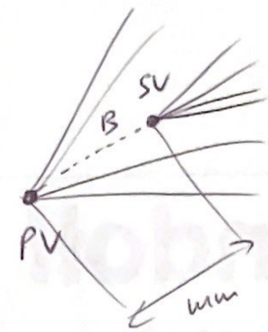
$\Rightarrow \quad \beta\gamma c\tau \sim mm - cm$

$$\text{CKM}: \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \cancel{V_{tb}} \end{pmatrix} \begin{array}{l} \sim 0.003 \\ \sim 0.04 \\ \sim 0.99 \end{array}$$

takes a lot of time to make transition

$b \to t$ NO

b-tagging



CMS TRACKER vertexing resolution ~ 50 μm

b-jets :

- Secondary vertex
- B decay : can produce leptons

  eg $B^+ \to l^+ \nu + X$

  leptons not present in uds jets

- B decay : in general not many hadrons

  eg. $B^0 \to K^+ \pi^-$

  $B^0 \to D^- \pi^+$

  $\hookrightarrow \bar{K}^0 e^- \bar{\nu}_e$

  $\hookrightarrow K^0 \mu^- \bar{\nu}_e$

  $\hookrightarrow \bar{K}^0 \pi^-$

  $\hookrightarrow \bar{K}^0 K^-$

NOT MANY HADRONS!

b-tagging and ML

CUTS → NN → BDT → Deep NN

WHAT ABOUT c jets?

similar idea to b-jets

"c-tagging"

$D^+, D^-, D^0, \bar{D}^0$ mesons

$c\tau \sim 100\text{-}300\,\mu m$

shorter lifetime → harder to tag

b-tagging crucial for top discovery

also for observation of $H \to b\bar{b}$

$$H \to ZZ \to ee/\mu\mu, \quad q\bar{q}$$

$\rightarrow$ 6.8% ee+μμ

$BR(Z \to ee/\mu\mu) \sim 3.4\%$ or

$BR(Z \to q\bar{q}) \sim 70\%$ $\times 20$

why?

$Z \to q\bar{q}$ with $q = \underbrace{udscb}$

5 × 3 colors!

~ 15

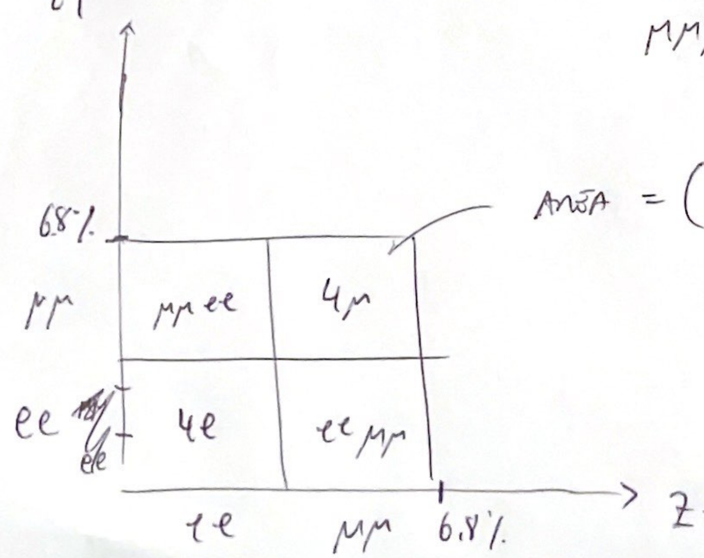
(+ slightly different couplings)

GOLDEN CHANNEL

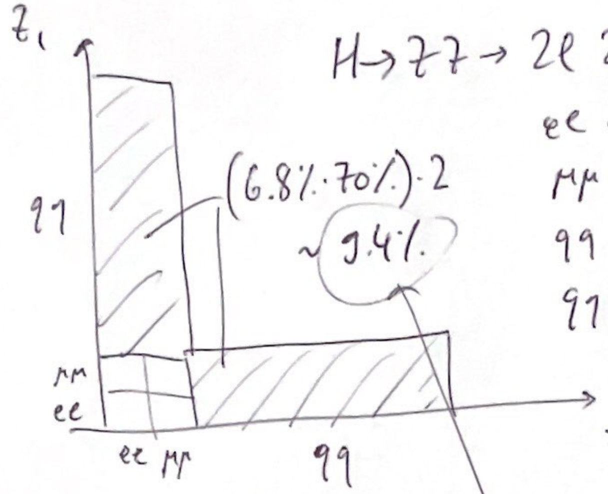
$H \to ZZ \to 4\ell$ ←

ee ee ✓ very good resolution
ee μμ
μμ ee
μμμμ ⊗ very low rate

$\text{AREA} = (6.8\%)^2 \sim 4.6‰$

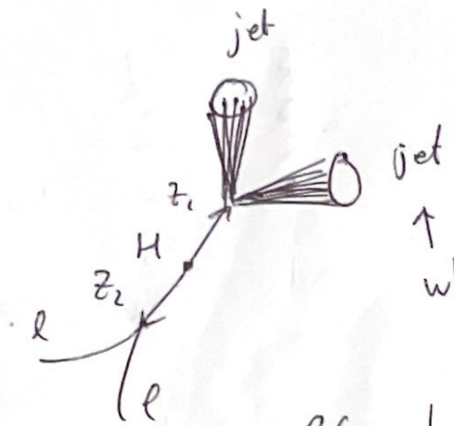


$H \to ZZ \to 2\ell\, 2j$



ee qq
μμ qq
qq ee
qq μμ

×20 wrt 4ℓ !



↑ what jets ?

$Z \to u\bar{u}$, $d\bar{d}$, $c\bar{c}$, $s\bar{s}$, $b\bar{b}$ "democratically"

NO GLUONS

BG: gluons (and quarks)

~~categories:~~

2 discriminators $\begin{cases} \text{quark vs gluons} \\ \text{b-tagging} \end{cases}$

~~gluons~~	light jets	1 btag	2 btags

removed

lower BG →

jets in BG:

(A) lots of gluons

(B) no b-jets

(C) NON resonant ! (No Z)

$\Rightarrow M(jj) \sim M_Z$