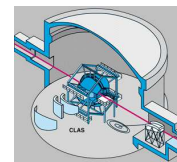


Three Quarks for Muster Mark, and Five for Me

Keith Griffioen

email: `griff@physics.wm.edu`, tel: 757-221-3537

College of William & Mary, Williamsburg, VA



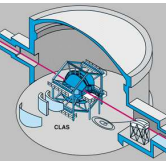
THREE QUARKS FOR MUSTER
MARK, BUT FIVE FOR ME

Keith Griffioen
Monroe Lecture
15 Nov. 2004

Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.
But O, wreneagle Almighty, wouldn't un be a sky of a lark
To see that old buzzard whooping about for uns shirt in the dark
And he hunting round for uns speckled trousers around by Palmerstown Park?

etc ...

James Joyce Finnegans Wake
Book 2 Episode 4



THE LEGO UNIVERSE

How to make a universe

- Building blocks
 - Rules of combination
- ⇒ infinite possibilities

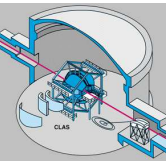
but not everything is possible

In the LEGO universe limits come from

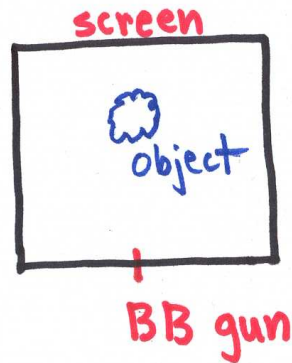
- block size
- only 2 perpendicular orientations

Yet in LEGO Land there are

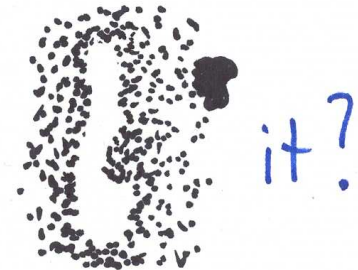
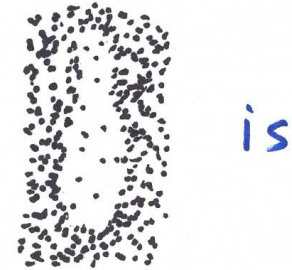
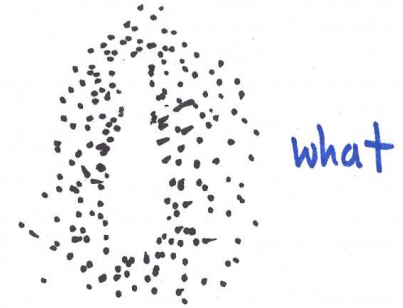
- houses
- creatures
- roller coasters



GEDANKEN EXPERIMENT



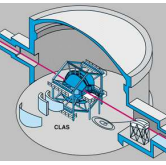
- object in a box
- can't see it
- can shoot BBs at it



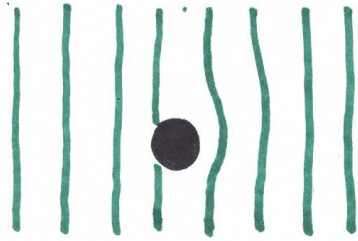
Better experiments



- shoot at random
- measure direction of shot
- measure initial and final speed



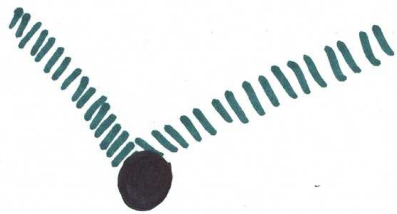
WAVES ARE ALL THAT MATTER



long wavelength
diffraction

waves bend
around objects

↓
can't get a sharp
image



short wavelength
just like BBs

De Broglie wavelength

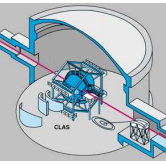
wavelength →

$$\lambda = \frac{h}{p}$$

← Planck's
constant

← particle
momentum

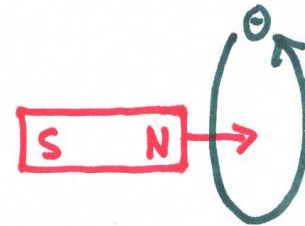
MATTER WAVES



ELECTROMAGNETISM

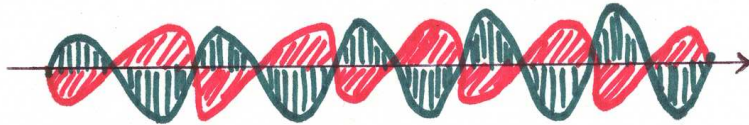


Circulating
charge
creates a
magnet



Moving
magnet
moves a
charge

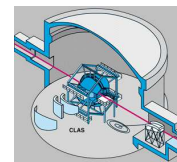
- charge fills space with an electric field
- magnet fills space with a magnetic field



light is a wave
of electric and
magnetic fields

light comes in bundles of

$$\text{energy} \rightarrow E = h\nu \leftarrow \begin{array}{l} \text{frequency} \\ \rightarrow \text{Planck's constant} \end{array}$$



RELATIVITY

- Light travels at speed

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

strength of
magnetism

strength of
electricity

- Our universe has a
speed limit : c

- Consequence : $E = \sqrt{(mc^2)^2 + (pc)^2}$

$$E = mc^2 \\ \text{if } p = 0$$

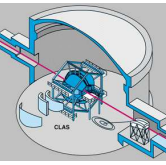
total energy

mass

momentum

How to "weigh" a subatomic particle:

$$m = \frac{1}{c^2} \sqrt{E^2 - (pc)^2}$$



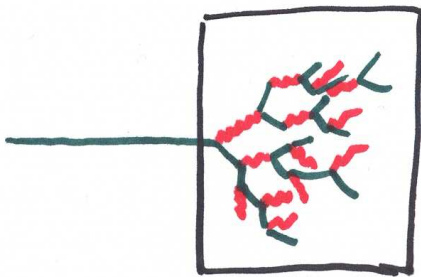
MEASURING E AND P



In a magnetic field a moving charge travels in a circle

$$P = qBr$$

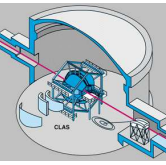
momentum → charge → magnetic field strength ← radius



particles traveling through matter lose their energy to the surrounding medium

This can be measured

⇒ calorimetry

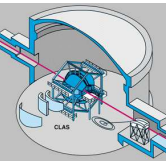


SPIN AND MAGNETISM

- Subatomic particles have intrinsic spin
- Spinning charges produce magnetic fields
- Subatomic particles are tiny magnets

Weirdness

- some particles have spin but no charge
neutron, neutrino, photon
- some particles have charge but no spin
 π^+ , π^- , ${}^4\text{He}$ nucleus
- some particles have both.
proton, electron



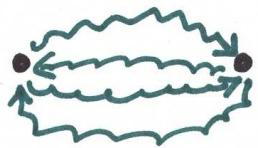
ACTION AT A DISTANCE

How does the moon know the Earth is there?

This is a problem Newton could not solve even though he could predict precisely the moon's motion.

20th c. Two objects have to communicate to feel each other's presence.

— Messenger particles are the force carriers —



E&M

Gravity

strong nuclear force

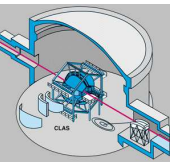
weak nuclear force

photon

graviton

gluon

W, Z boson



Quarks

'64	u	$\frac{1}{2}$	$\frac{2}{3}$	"up"	.002-.004
8		$\frac{1}{2}$	$-\frac{1}{3}$	"down"	.004-.008
'69	d	$\frac{1}{2}$	$-\frac{1}{3}$	"strange"	.080-.130
'74		$\frac{1}{2}$	$\frac{2}{3}$	"charm"	1.2-1.4
'77	c	$\frac{1}{2}$	$-\frac{1}{3}$	"bottom"	4-5
'95		$\frac{1}{2}$	$\frac{2}{3}$	"top"	190
		$\frac{1}{2}$	$\frac{2}{3}$		

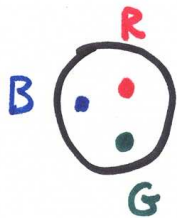
$\frac{1}{2}$ Spin $\times \frac{h}{2\pi}$
 $\frac{2}{3}$ charge $\times e$
 190 mass \times proton mass

atoms are neutral: +, - charge balances exactly

quarks have "color charge"

RGB

neutral
 $\equiv RGB$ or
 $RR\bar{R}$ or
 $GG\bar{G}$ or
 $BB\bar{B}$

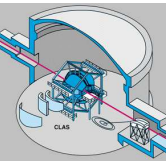


baryon



meson

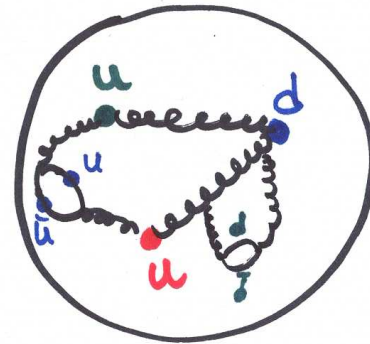
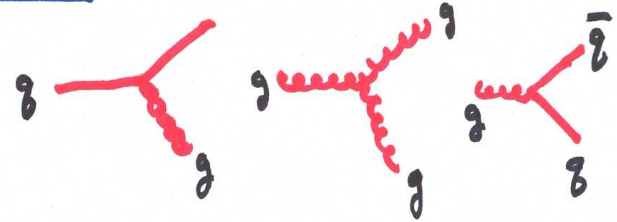
together = hadrons



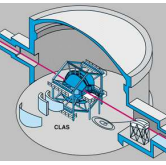
THE REAL UNIVERSE

proton	uud
neutron	udd
π^+	$u\bar{d}$
π^-	$d\bar{u}$
K^+	$u\bar{s}$
K^0	$d\bar{s}$
\bar{K}^0	$\bar{d}s$
K^-	$\bar{u}s$

etc.

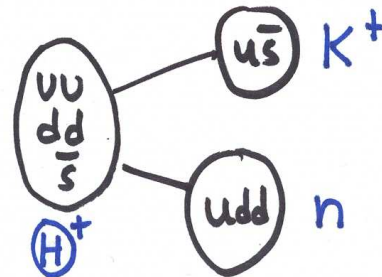
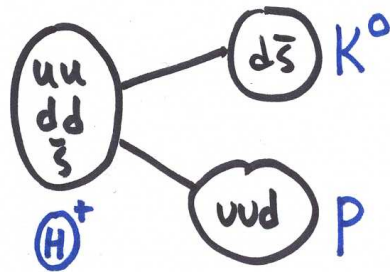


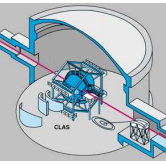
- gluons carry color charge from one quark to another
- quark-antiquark pairs are frequently created



PENTA QUARKS

- Why not 5 quarks? $RGB R\bar{R}$ is color neutral
- Pentaguarks never seen (until last year)
- What to look for
 - $uud u\bar{u}$ can't tell apart from the proton
 - $uud d\bar{s}$ could see this





SMOKING GUN

$$E_{\text{tot}} = E_p + E_{K^0}$$
$$\vec{p}_{\text{tot}} = \vec{p}_p + \vec{p}_{K^0}$$

each decay particle is measured in our detector

$$m = \sqrt{(E_{\text{tot}})^2 + (\vec{p}_{\text{tot}}c)^2}$$

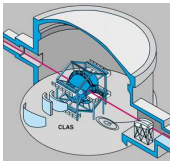
↳ mass of parent

If we see a peak \Rightarrow new particle

... or detector problems
"ghost peaks"



CLAS, Jefferson Lab



V. Kubarovsky *et al.*,

hep-ex/0311046

$\gamma p \rightarrow \pi^+ K^- (K^+ n)$

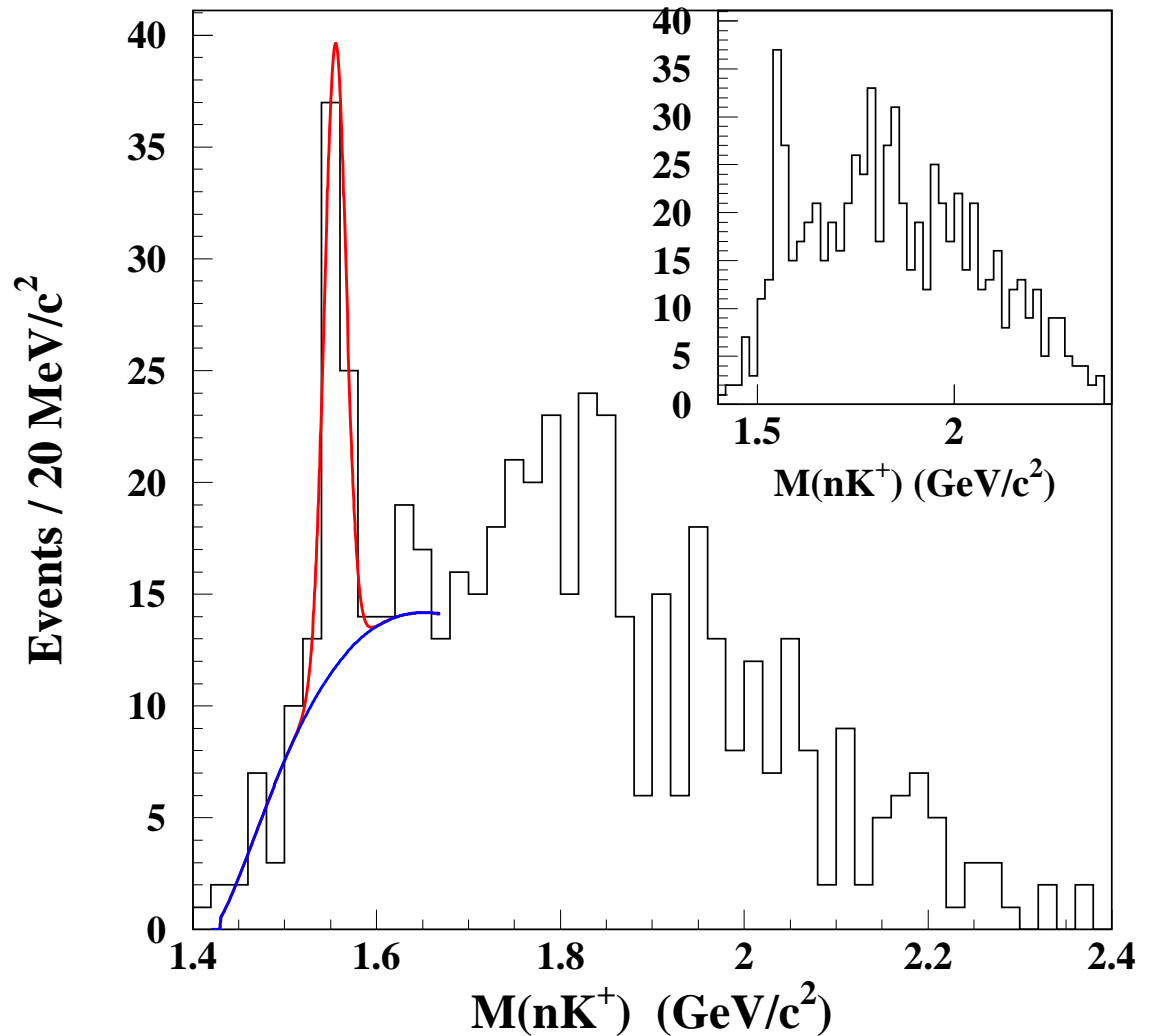
$M_{\Theta^+} = 1555 \pm 10 \text{ MeV}$

$\Gamma < 26 \text{ MeV}$

$N_s / \sqrt{N_b} = 7.8$

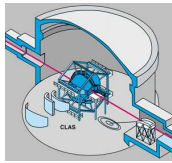
inset: less strict

forward-angle cuts





BEBC, CERN & 15' Bub. Ch., FNAL



A. Asratyan *et al.*,

hep-ex/0309042

$$\nu(\bar{\nu})A \rightarrow K_s^0 p X$$

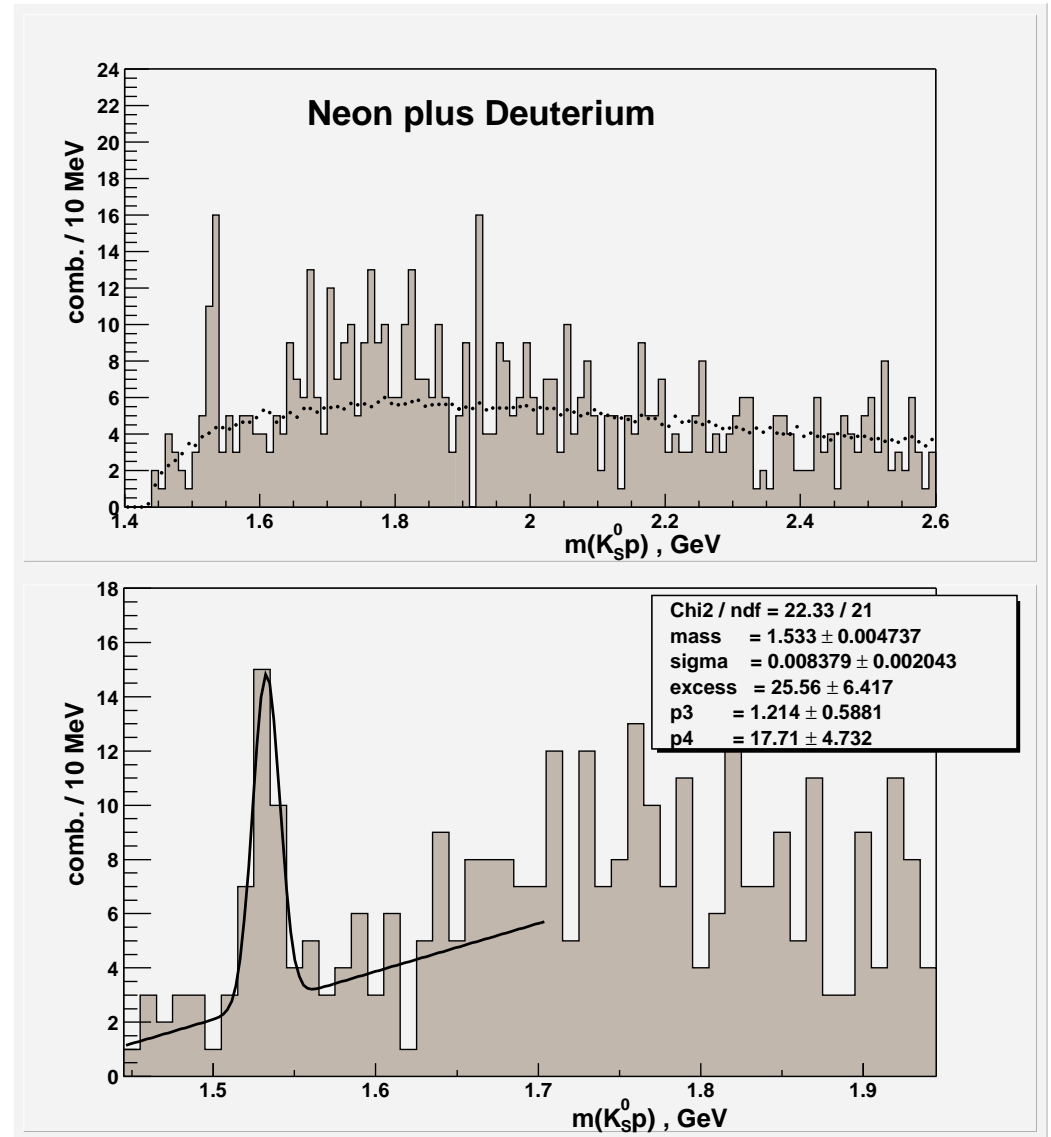
$$M_{\Theta^+} = 1533 \pm 5 \text{ MeV}$$

$$\Gamma < 20 \text{ MeV}$$

$$N_s / \sqrt{N_b} = 6.7$$

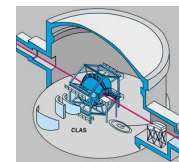
Upper: full spectrum

Lower: expanded scale
around the peak





HERMES, DESY



hepex/0312044

$$\gamma d \rightarrow K_s^0 p X$$

$$M_{\Theta^+} = 1528 \pm 3 \text{ MeV}$$

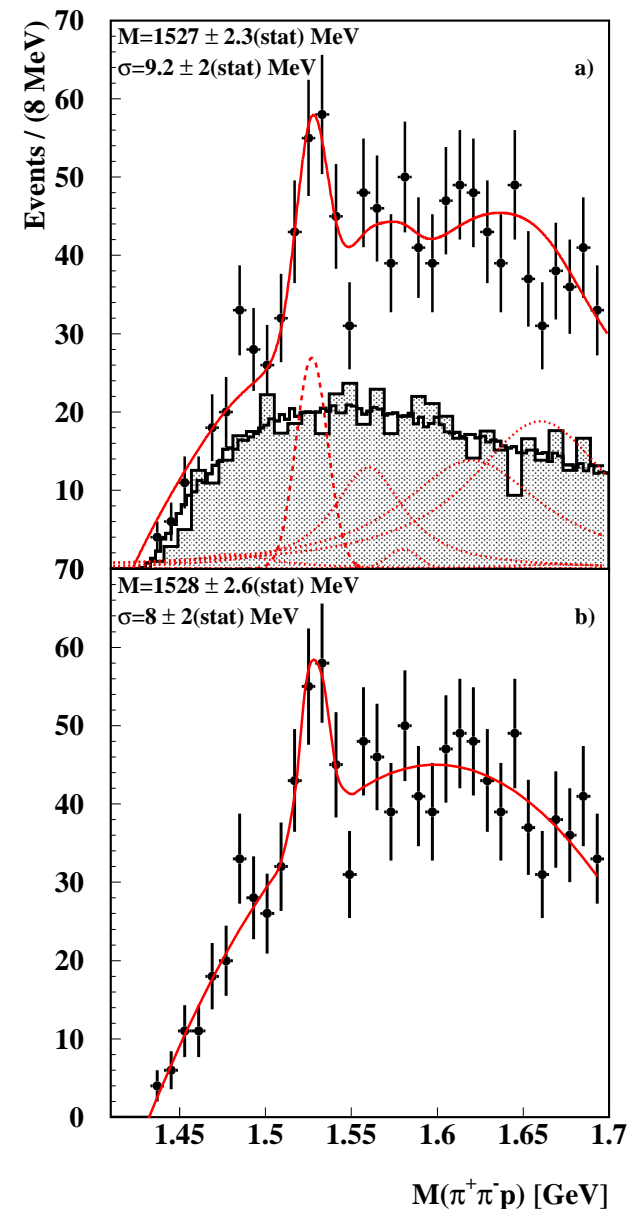
$$\Gamma < 17 \text{ MeV}$$

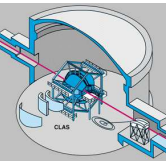
$$N_s / \sqrt{N_b} = 4.7$$

shaded: mixed events / full MC

peaks: known Σ resonances

with fitted heights





WHERE ARE WE NOW?

- Dozen experiments see Θ^+
- No other combinations have been found.

Why not $ddss\bar{u}$ the Ξ^{--} ?

- We don't know
 - perhaps quark pairs (diquarks) insure that only the Θ^+ is bound
 - perhaps there are no pentaquarks at all and a dozen experiments are seeing the same ghost peak
- All of this is happening right now!

We still live in the age of discovery!