Introduction to Nuclear and Particle Physics

Lesson 8

hadrons and strong interaction

Warm-up question 1

At an e+ e- collider we want to study the nature of hadrons.

Which statements are correct?

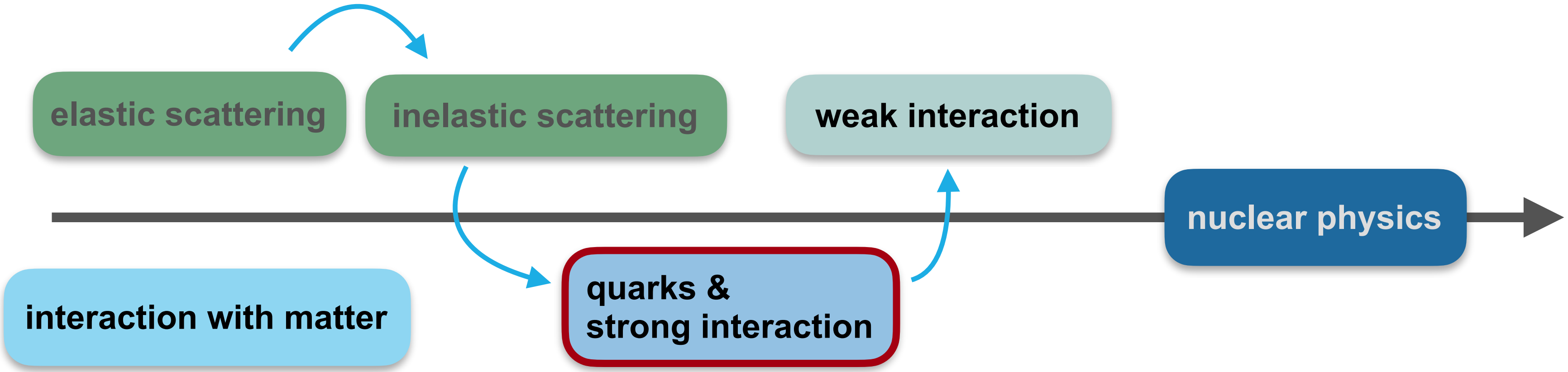
A) We will not observe any jets because leptons do not interact strongly.

B) If we chose a clever combination of detectors and magnetic fields, we can measure the isospin of particles

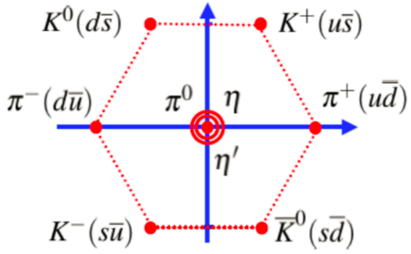
C) The standard model assumes an SU(3) flavour symmetry for the strong interaction.

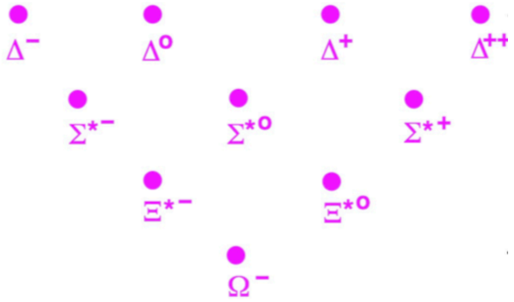
D) The SU(3) flavour symmetry is an approximate symmetry only since the masses of Kaons are different from those of pions.

Where are we now?



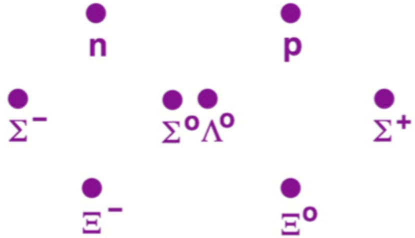
From hadrons to multiplets

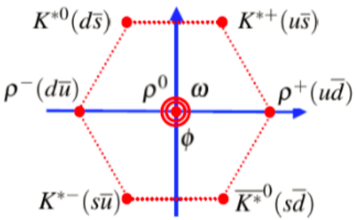




… what is this about?

we approach it (semi-) historically





Recommendation for group theorists:

Extra chapter in script (<u>not mandatory</u> for exam)

How it started: Isospin symmetry

Observation 1:

Apart from electric charge,
p+ and n are very similar

$\Rightarrow$ invent isospin doublet

$$|p\rangle = \left|\frac{1}{2}, \frac{1}{2}\right\rangle \qquad |n\rangle = \left|\frac{1}{2}, -\frac{1}{2}\right\rangle$$

Observation 2: π^- π^0 π^+

Found 3 light mesons with similar masses!

$\Rightarrow$ Isospin triplet !?

But lighter than nucleons.
So fewer quarks?

Historic approach:

Try to classify all new strongly interacting particles might help to see the order behind this zoo.

First hints about quarks!

$$|p\rangle = |uud\rangle \qquad |\pi^+\rangle = |u\bar{d}\rangle$$

$$|u\rangle = \left|\frac{1}{2}, \frac{1}{2}\right\rangle \qquad |d\rangle = \left|\frac{1}{2}, -\frac{1}{2}\right\rangle$$

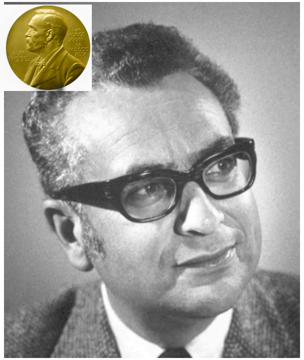
$\Rightarrow$ fits also to the four Δ baryons!

(isospin-quartet with isospin 3/2)

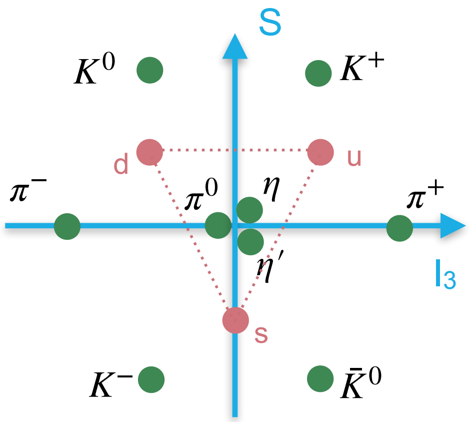
Next Problem: New hadrons found, with higher mass and “untypical” behaviour

Complete the quark flavour symmetry

Murray Gell-Mann -
the master of classification!



Example:
The scalar Meson Octet



- *Invent additional quantum number: "Strangeness"*
- *Striking discovery of u,d,s flavour symmetry and quark model was result of clever combinatorics!*

Meaning today:

- We know even 3 more, heavier quarks
- Flavour symmetry mainly historically important
- **Standard Model**: SU(3) color symmetry for strong interaction

Exam questions

a) **QCD**: QCD has an $SU(3)_C$ symmetry. The 3 stands for a local symmetry between:

A) the 3 colours (r,g,b)

B) the three generations (u, c, t)

C) the 3 lightest quarks (u, d, s)

D) neutrons, protons and electrons

b) **Colour**: Physical gluons form:

A) a colour singlet

B) an anti-colour sextet

C) a colour and anti-colour octet

D) no colour representation - gluons are colourless.

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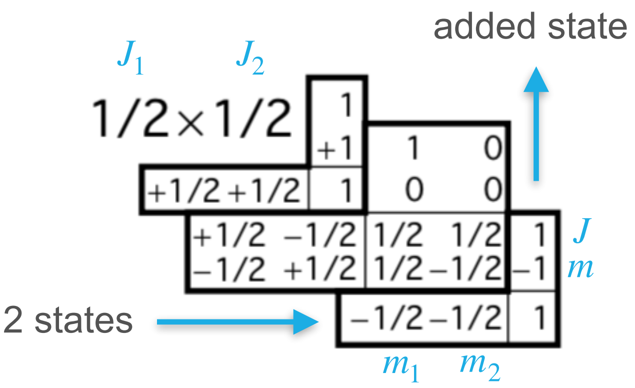
Aspects of Clebsch-Gordan Coefficients



… help us to add two angular momentum states up

Example:

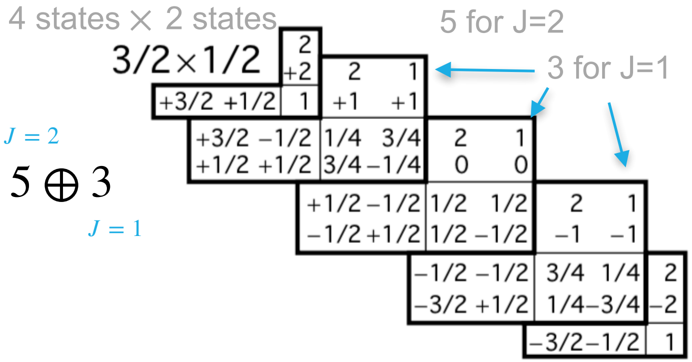
$$|1,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

Secret trick:

We can directly read from CGC, how many multiplets the addition of two states causes.

$$4 \otimes 2 = 5 \oplus 3$$

$J_1 = \frac{3}{2}$, $J_2 = \frac{1}{2}$, $J = 2$, $J = 1$



some hadrons we should know…

		valence quarks	mass (MeV/c2)	I_3	strangeness	main decay channel
Baryons	p^+					
	n	udd				
	Δ^{++}		1232	3/2	0	
	Δ^0					$n + \pi^0$ / $p^+ + \pi^-$
Mesons	π^+				0	
	π^0	$u\bar{u} - d\bar{d}$				$\gamma + \gamma$
	K^+		~ 500			

some hadrons we should know…

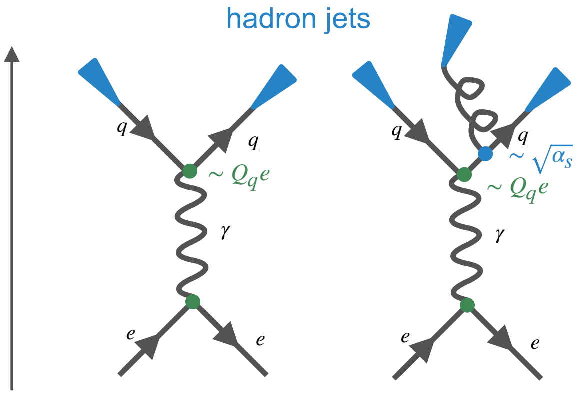
		valence quarks	mass (MeV/c2)	I_3	strangeness	main decay channel
Baryons	p^+	uud	~ 940	$1/2$	0	-
	n	udd		$-1/2$		$p^+ + e^- + \bar{\nu}_e$
	Δ^{++}	uuu	1232	$3/2$	0	$p^+ + \pi^+$
	Δ^0	udd		$-1/2$		$n + \pi^0$ / $p^+ + \pi^-$
Mesons	π^+	$u\bar{d}$	~ 140	1	0	$\mu^+ + \nu_\mu$
	π^0	$u\bar{u} - d\bar{d}$		0		$\gamma + \gamma$
	K^+	$u\bar{s}$	~ 500	$1/2$	1	$\mu^+ + \nu_\mu$

e^+ / e^- colliders

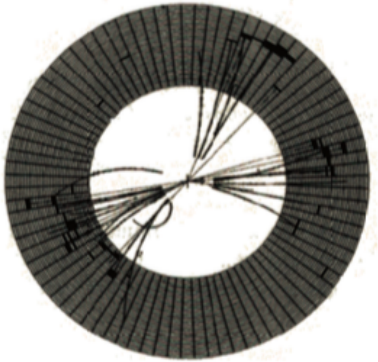
In collisions of e+ and e- new particles / resonances can be directly produced.

First colliders measured

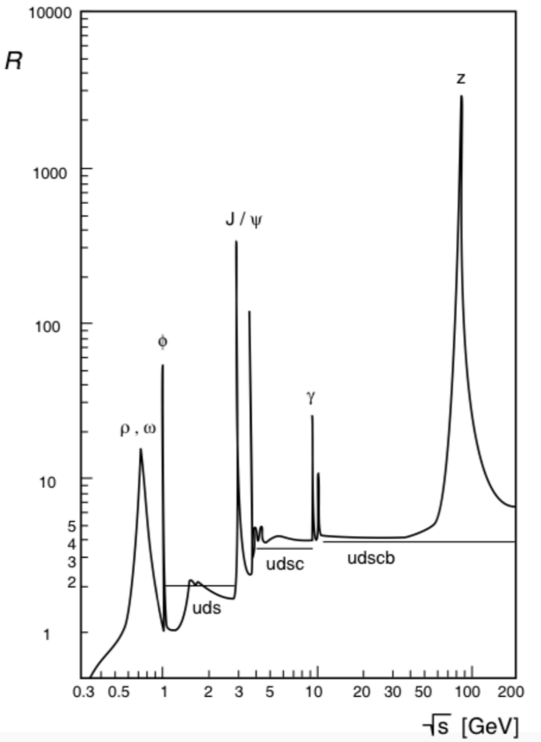
- *new quarks*
- *number of colors (homework)*
- *coupling strength α_s (N_{3jet}/N_{2jet})*



2-jet 3-jet



signature of 3-jet event



Estimate the number of colors:

$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = N_{color}\Sigma_i Q_i^2$$

Exam question

d) **3-jet events**: At an electron-positron collider, the ratio of the 3-jet to 2-jet event rate can be used to measure:

A) the EM coupling $\alpha(q)$

B) the number of neutrino flavours N_ν

C) the strong coupling $\alpha_s(q)$

D) the gluon splitting $g \rightarrow b\bar{b}$ rate

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✓ the strong coupling $\alpha_s(q)$

D) the gluon splitting $\mathrm{g} \rightarrow \mathrm{b}\bar{\mathrm{b}}$ rate

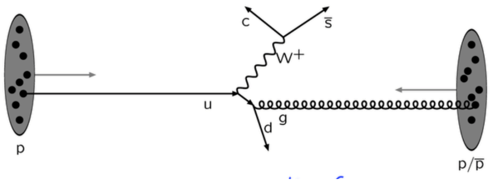
Proton colliders

Proton collisions are far more difficult to analyse:

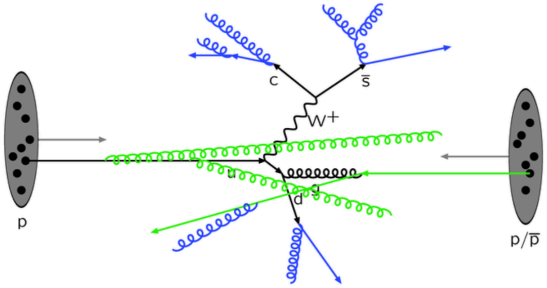
- **various partons can collide at once**
- **lots of gluons in initial and final states**

$\Rightarrow$ Jets everywhere!

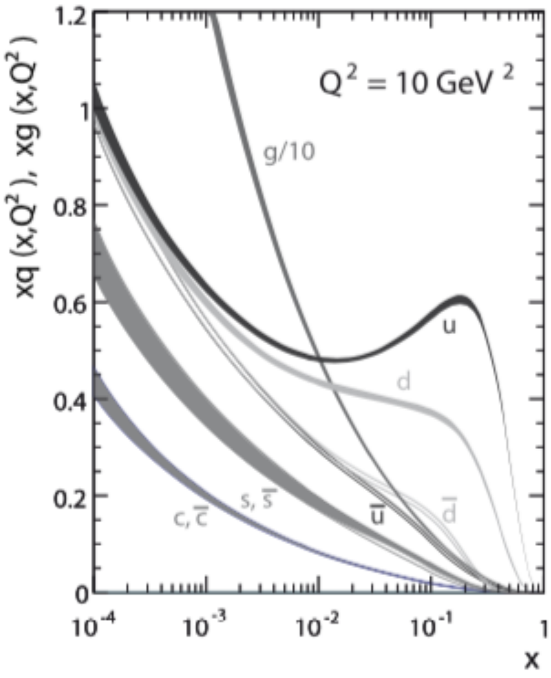
main process



accompanied by additional jets

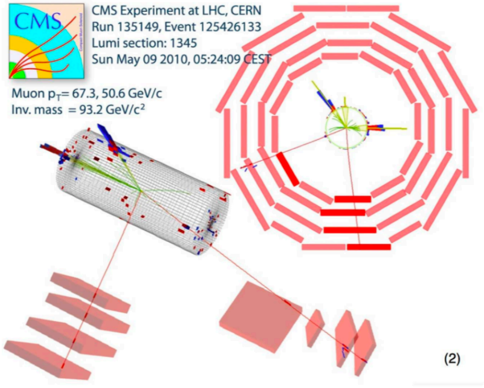


Parton distribution functions

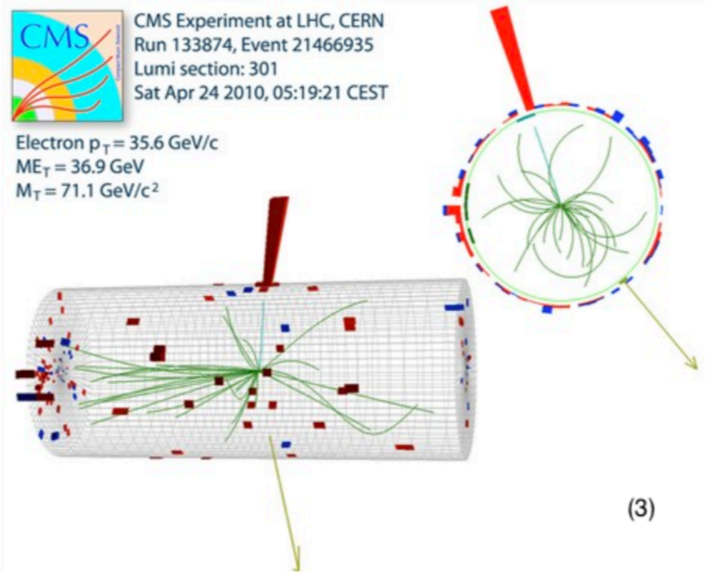


[aus Povh]

Event displays at LHC



event includes 2μ + hadrons



Event includes $e + \nu$

muons: penetrate to outer layers

electrons: bend strongly in trackers + energy in calorimeter

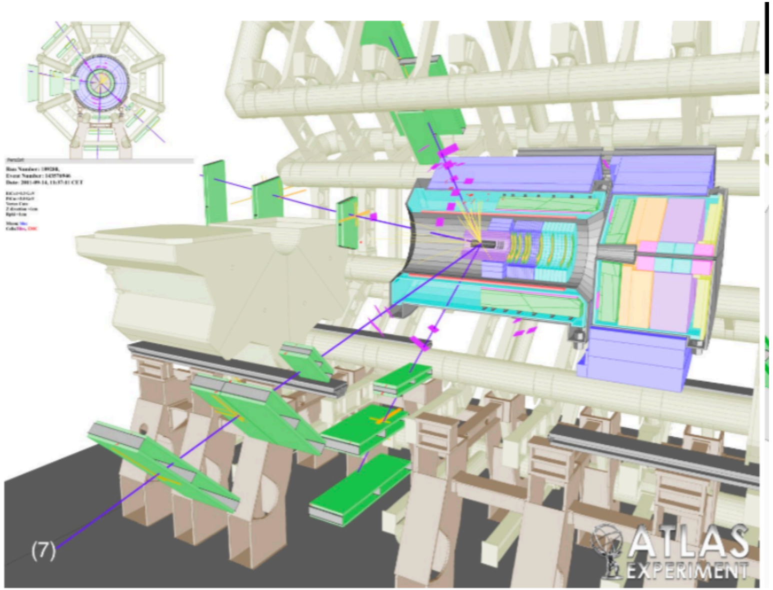
hadrons: particle jets!

neutrinos: missing energy

gammas: energy in calorimeter, no trace in tracker

Event displays - activity

Which process matches the event display on the left?



a) $Z \to ee$

b) $ZZ \to 4\mu$

e) $W \to \tau\nu$

h) Cosmic muon

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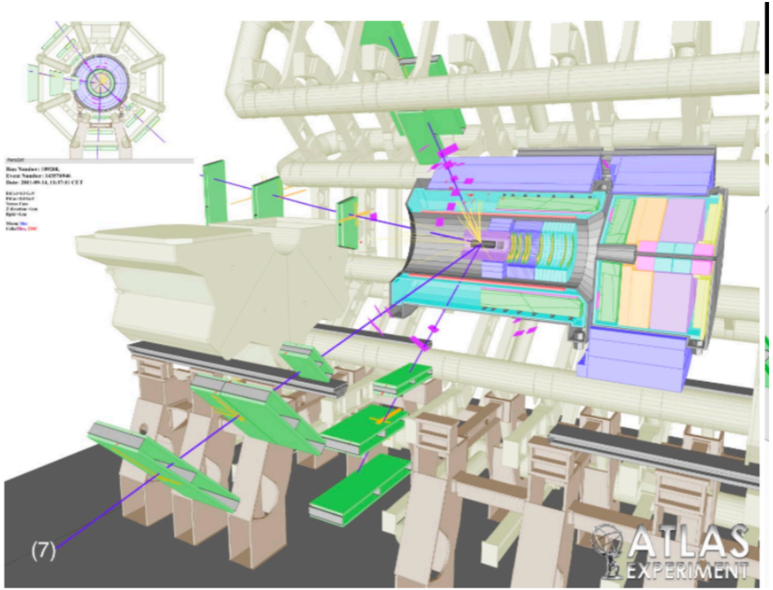

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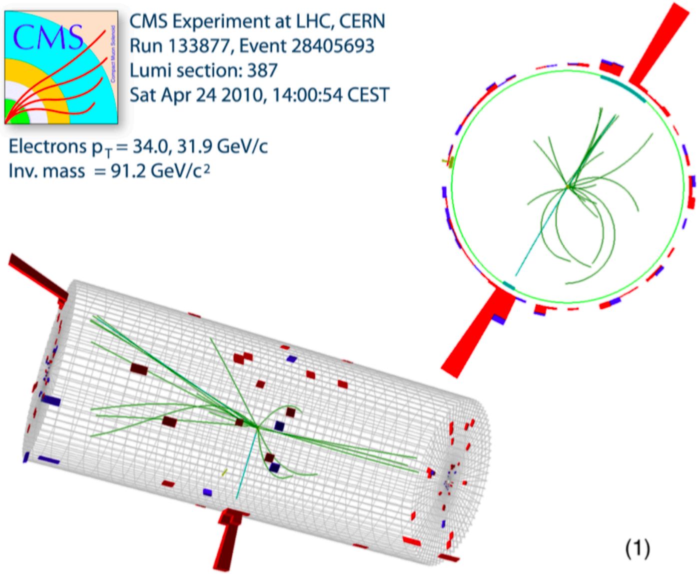

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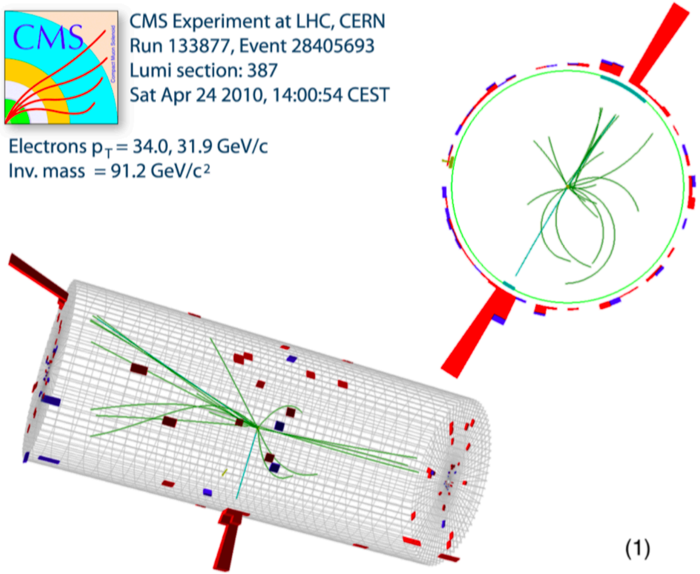

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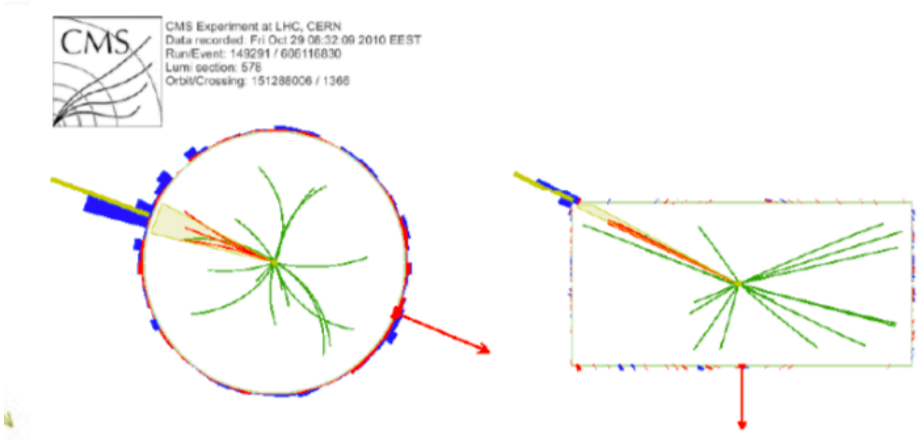

(4)

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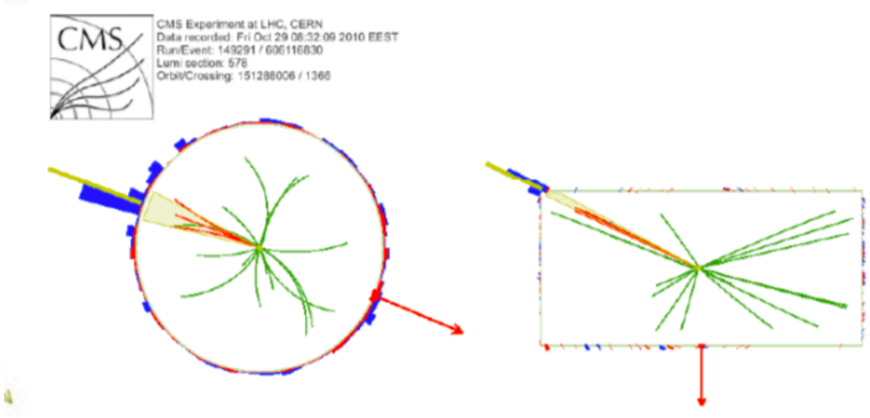

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(4)

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