

# Introduction to Hadron Collider Physics

## Part 2. Particles and Forces

---

Caterina Doglioni - Lund University

Heavily drawing from lectures written in collaboration with  
Peter Christiansen & Alice Ohlson - Lund University

# Outline of these introductory lectures

## \* Part 1: Introduction

- Fundamental components of matter
- Drawing particles and interactions: Feynman diagrams

*10' Q&A + break*

## \* Part 2: Standard Model forces and interactions

- Electromagnetism
- Weak interactions
- Quantum Chromodynamics

## \* Part 3: Tools

- CERN and particle physics collaborations
- Particle accelerators: the LHC
- Detectors for particle physics
- Discovering the Higgs

*10' Q&A + break*

## \* Part 4: Beyond the Standard Model

- Problems of the Standard Model
- Solutions beyond the Standard Model
- Dark Matter
  - My research and its interdisciplinary connections

*10' Q&A + break*

# The Four Forces

## Electromagnetic

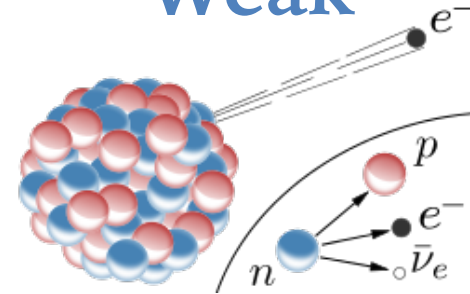


Wikipedia - by ThorstenS



Wikipedia - by Oguraclutch

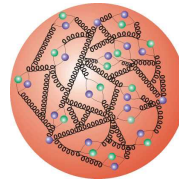
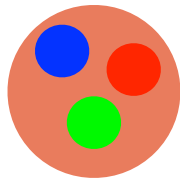
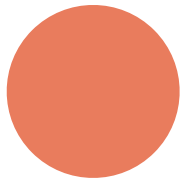
## Weak



Wikipedia - By Inductiveload

## Strong

proton



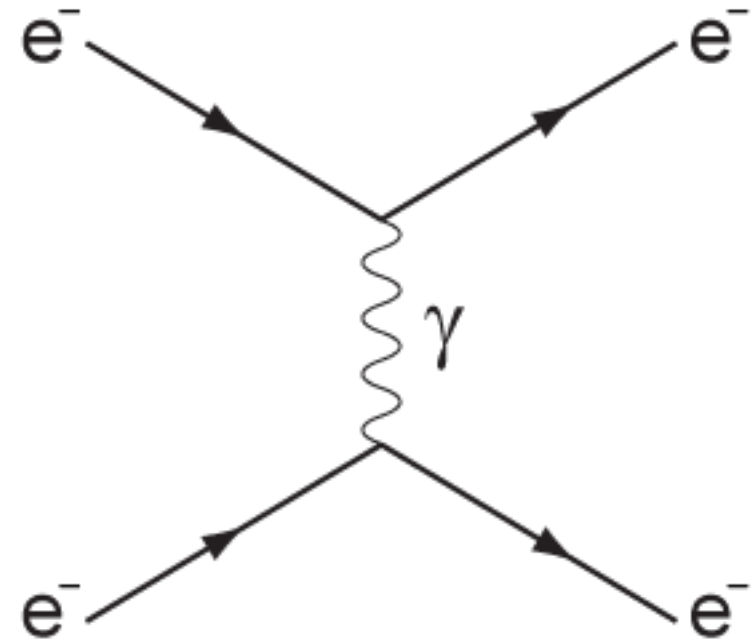
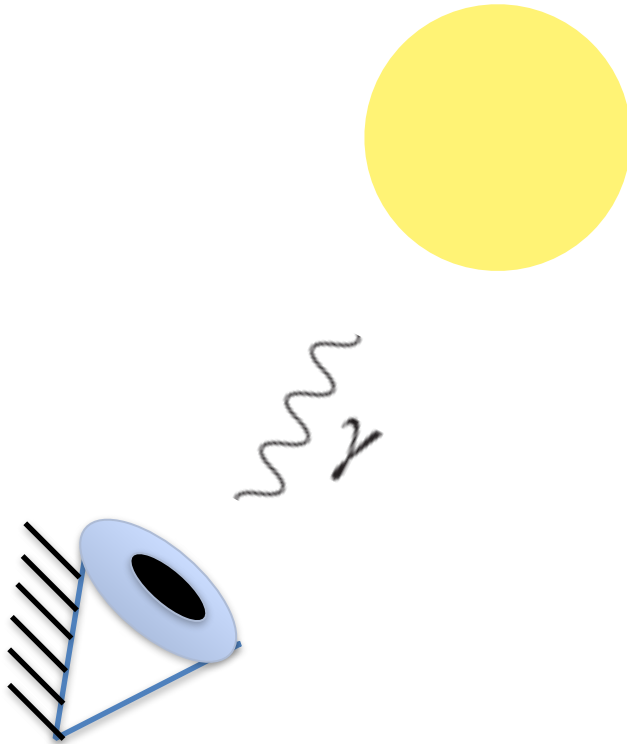
Hyperphysics

## Gravitational



Not in Standard Model

# How do forces act on particles?

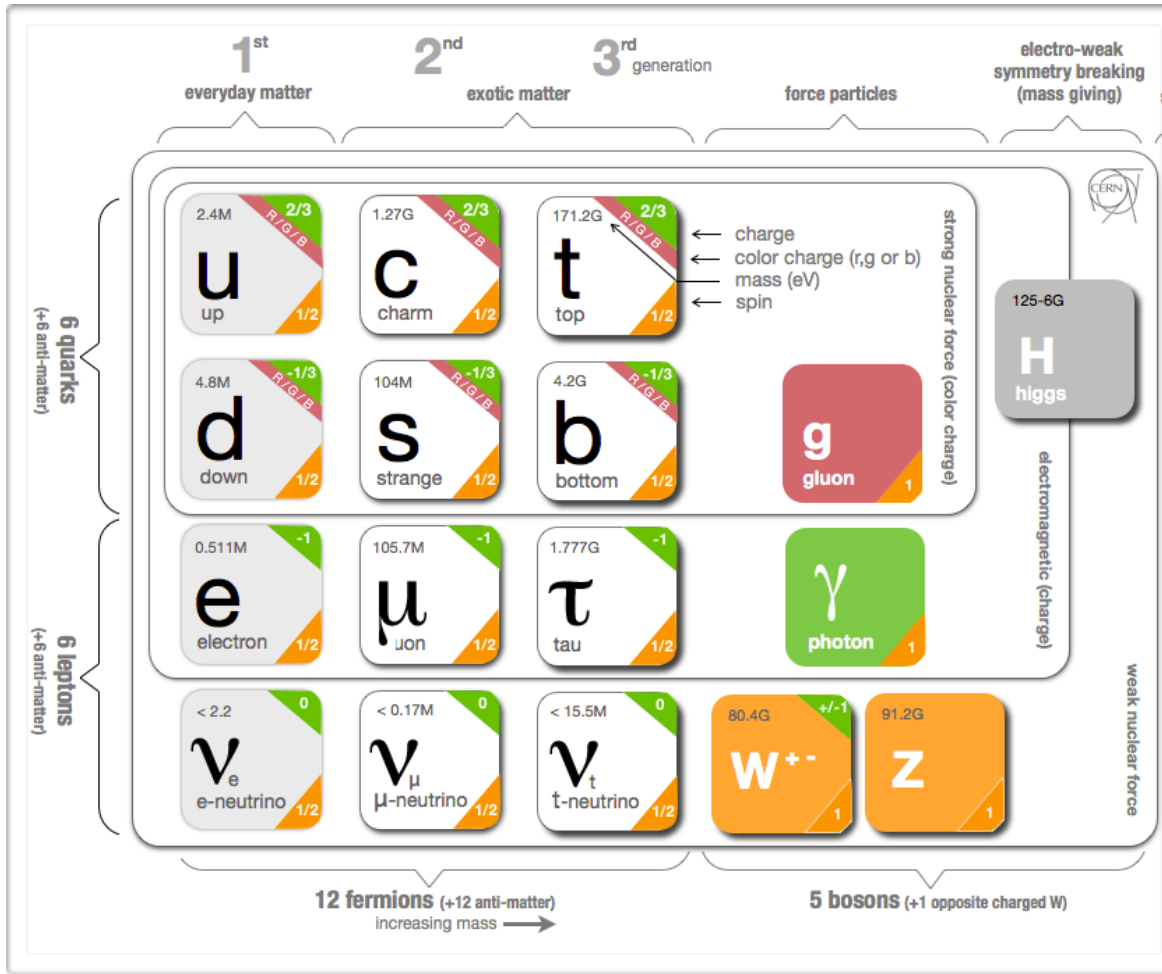


By [\[:en:User:{{1}}\]{{1}}](#) at Wikipedia

Every force needs particles  
that act as mediators: gluons, photon, W and Z bosons



# What forces act on which particles?



**Electromagnetic force:**  
anything with electric charge  
+ **photons** (force mediators)

**Weak force (mediated by W/Z bosons):**

Anything except the the gluon

**Note:** electromagnetic and weak forces are two sides of the same force

**Strong force:**  
quarks and **gluons** (mediators)

This forms the basis of how we can see particles in particle detectors: particles **interact!**



LUNDS  
UNIVERSITET

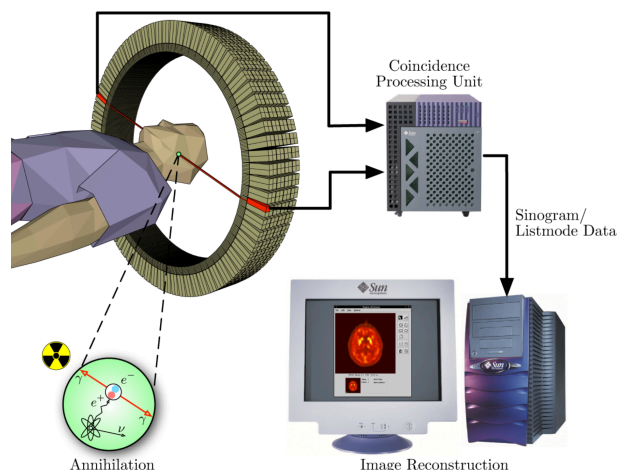
# The electromagnetic force

---

# Electromagnetic force in 30 seconds

*I assume you all had an electromagnetism course at your home university*

- Electromagnetic **charge**
- **Mediated** by photon
- One application out of many:
  - Positron Emission Tomography



- See also: cancer therapy and particle detectors (see tomorrow's lecture)



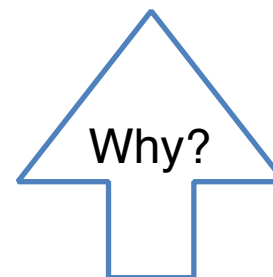
LUNDS  
UNIVERSITET

# The weak force

---

# Weak interactions vs EM interaction

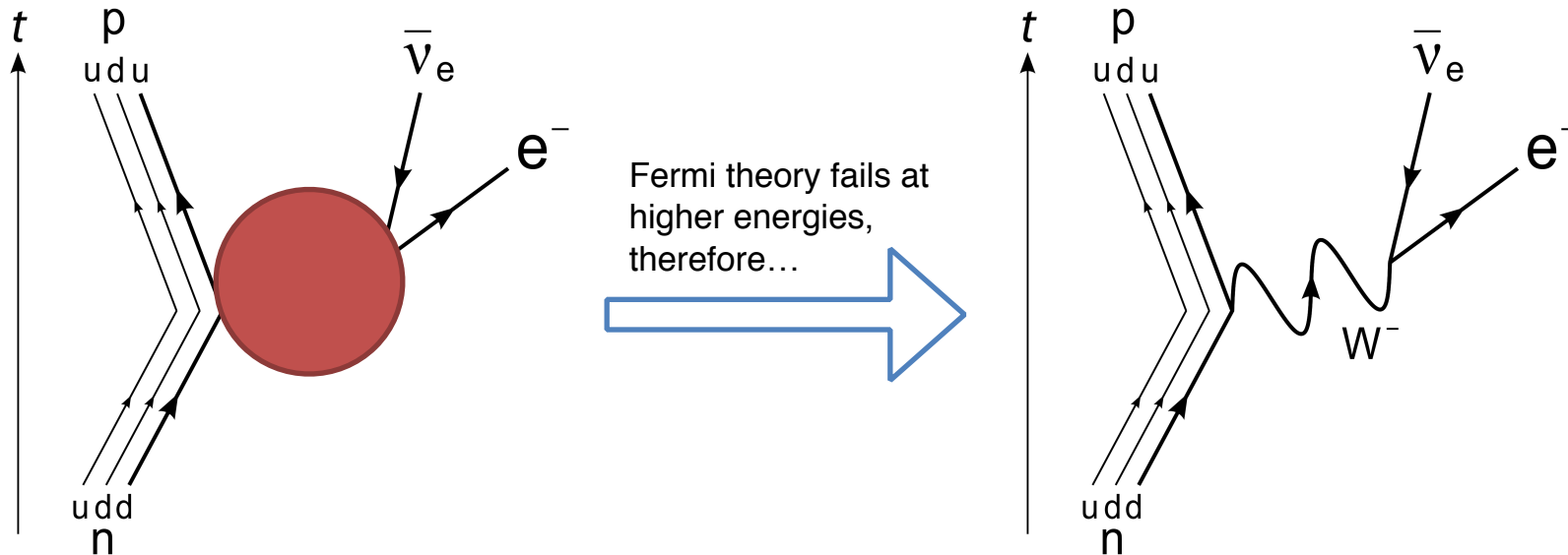
<i>Force</i>	<i>Charge</i>	<i>Mediator</i>	<i>Range</i>
<i>EM</i>	<i>Electric charge</i>	<i>photon</i>	<i>Long</i>
<i>Weak</i>	<i>Weak isospin</i>	<i>weak bosons</i>	<i>Short</i>



# From Fermi theory to Electroweak theory

1934

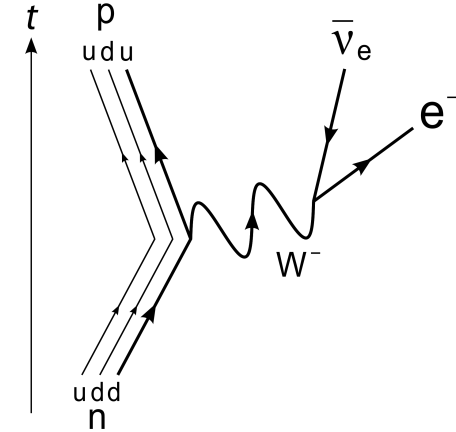
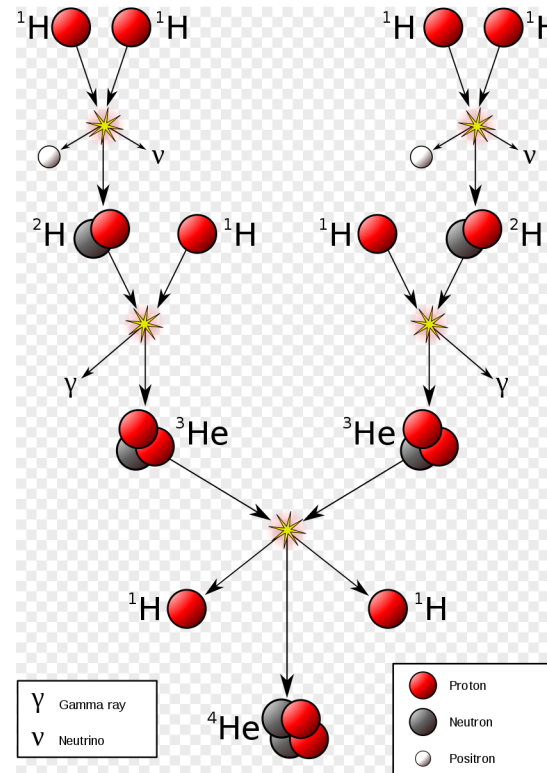
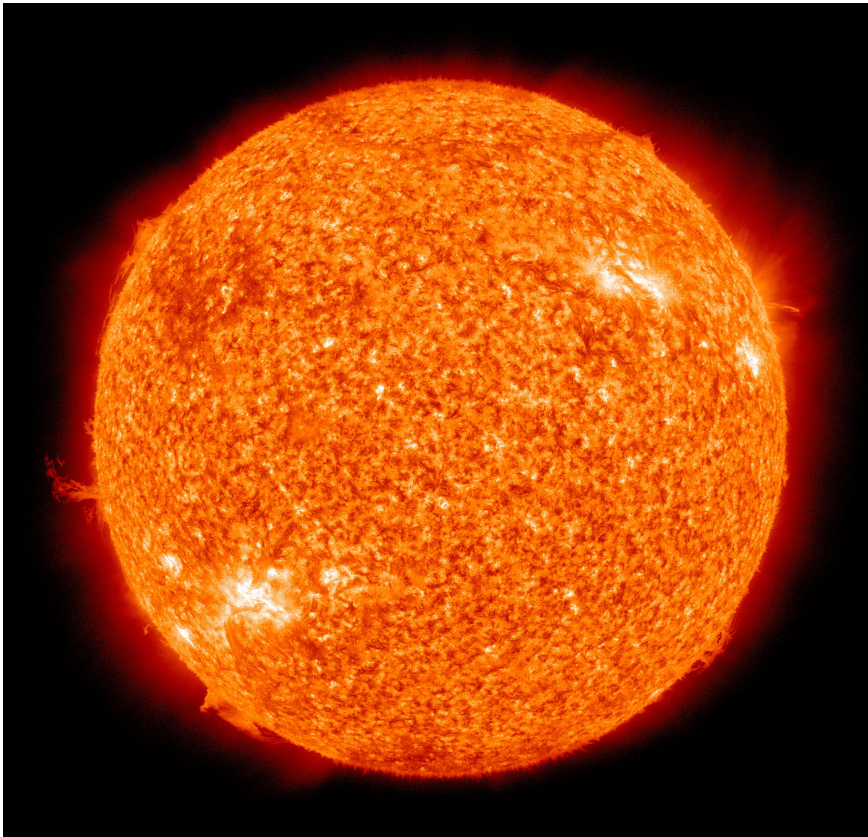
Electroweak theory (1960s)



Problems: the  $W$

- has not been discovered
- should be massive, but this “breaks” the SM

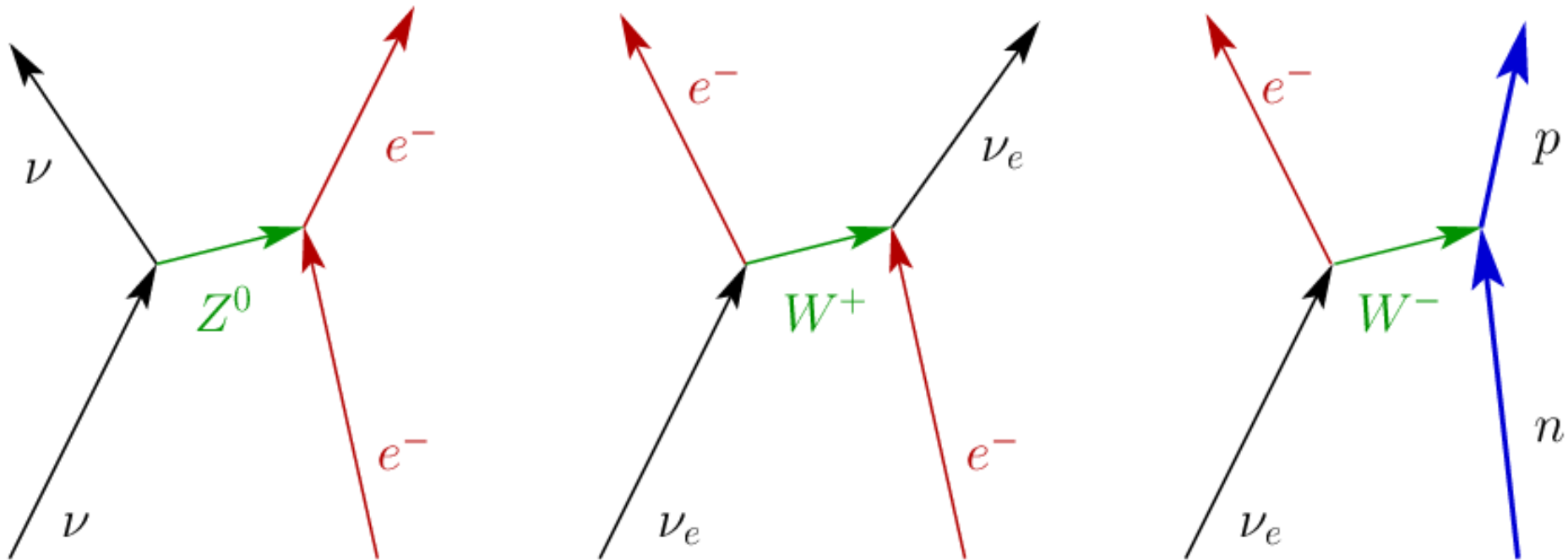
# The sun and weak interactions



proton-proton chain reaction



# Charged (CC) and neutral (NC) currents

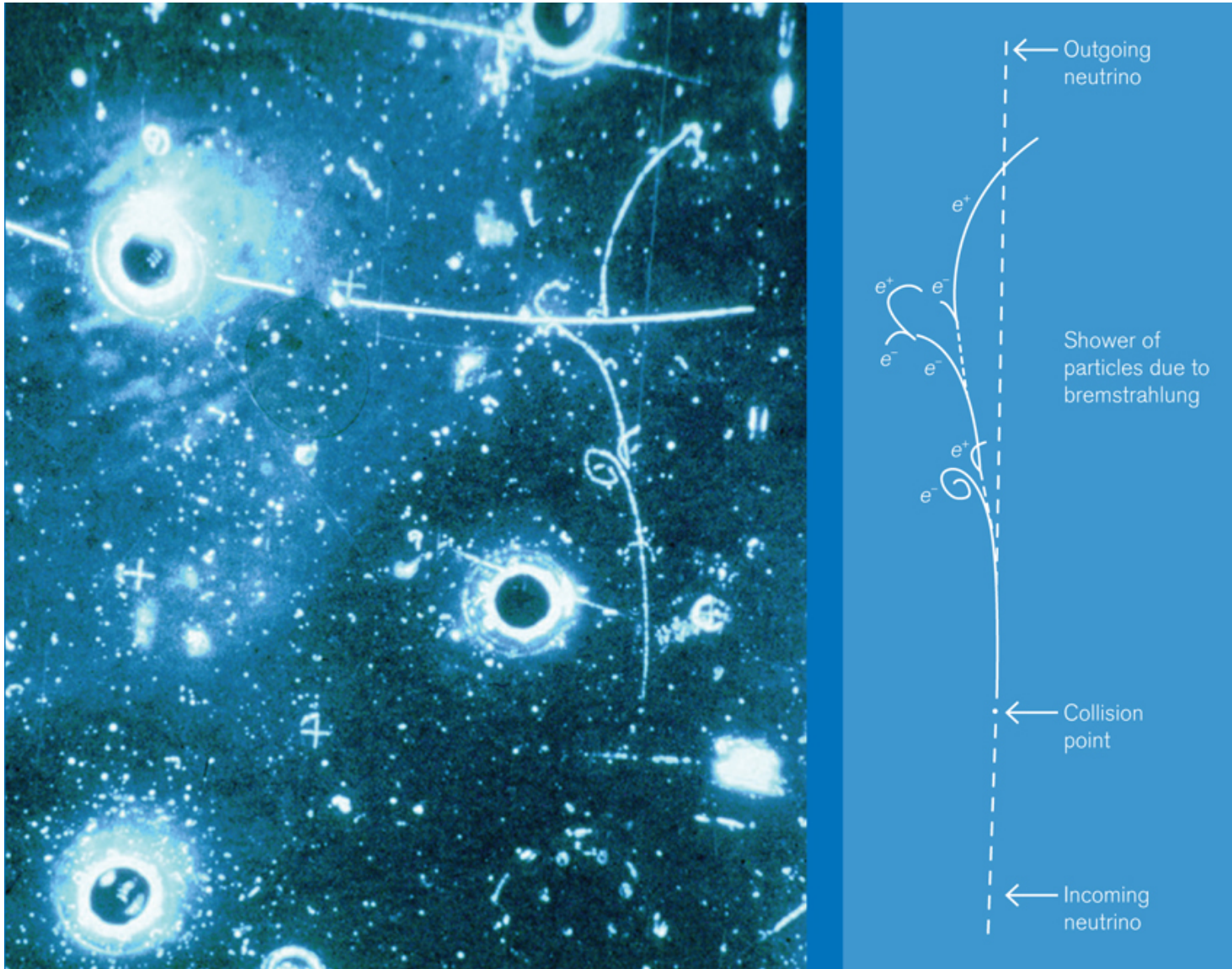


Neutral current

Charged current



# The indirect discovery of the Z







# Electro+weak theory by Weinberg

## A MODEL OF LEPTONS\*

Steven Weinberg<sup>†</sup>

Laboratory for Nuclear Science and Physics Department,  
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

<sup>1</sup>The history of attempts to unify weak and electromagnetic interactions is very long, and will not be reviewed here. Possibly the earliest reference is E. Fer-

mi, Z. Physik 88, 161 (1934). A model similar to ours was discussed by S. Glashow, Nucl. Phys. 22, 579

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite<sup>1</sup> these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons. This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.<sup>3</sup> The model may be renormalizable.

# Gauge bosons and their masses

## **Problem (II):**

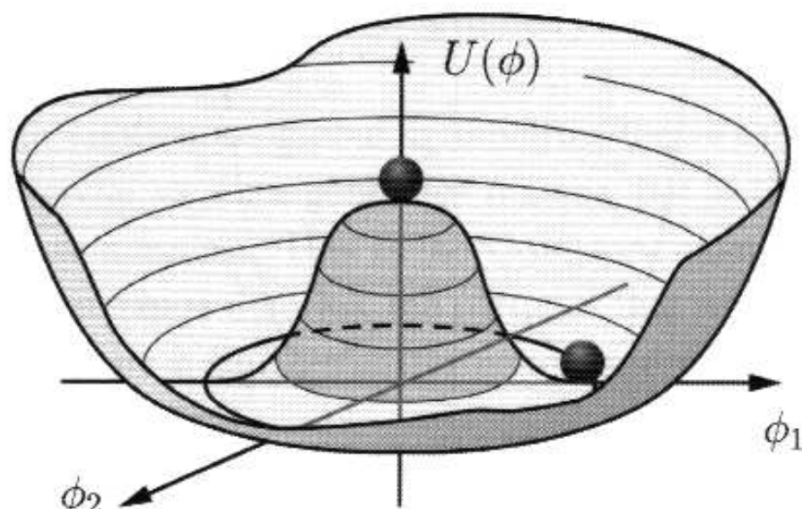
all bosons are massless, adding masses by hand spoils theory

## **Solution (II):**

Higgs mechanism!

$$\gamma = \sin \theta_W \cdot W^0 + \cos \theta_W \cdot B \quad \text{massless}$$

$$Z^0 = \cos \theta_W \cdot W^0 - \sin \theta_W \cdot B \quad \text{massive}$$



**Symmetry is broken (in 1-dimension):**

~not rotationally invariant

More in Part 3

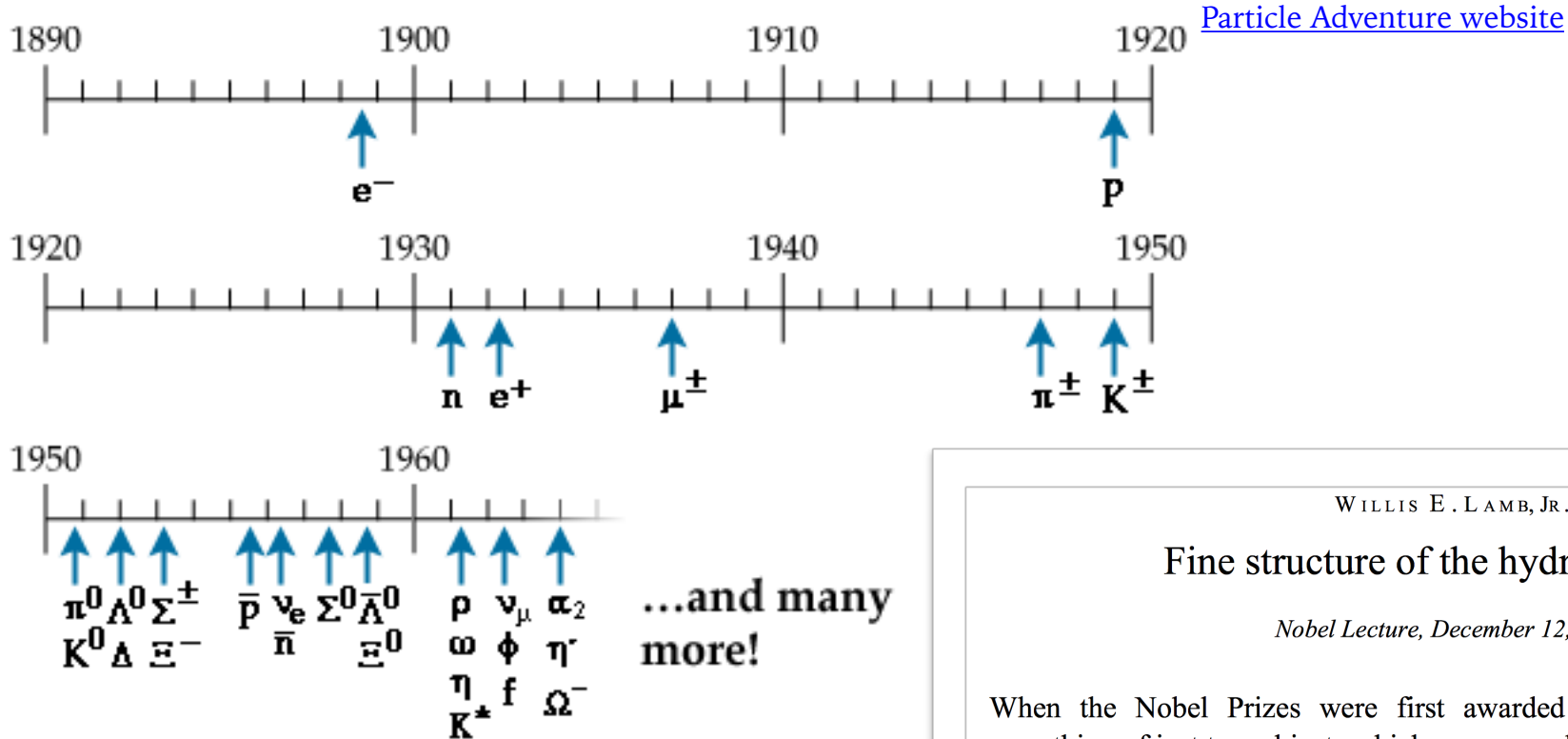


LUNDS  
UNIVERSITET

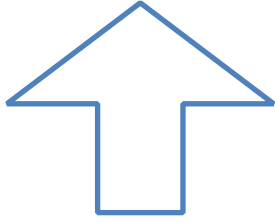
# The strong force

---

# Particle situation as of the 1960s



...and many more!



WILLIS E. LAMB, JR.

**Fine structure of the hydrogen atom**

*Nobel Lecture, December 12, 1955*

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino,  $\mu$  meson,  $\pi$  meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a \$10,000 fine ».

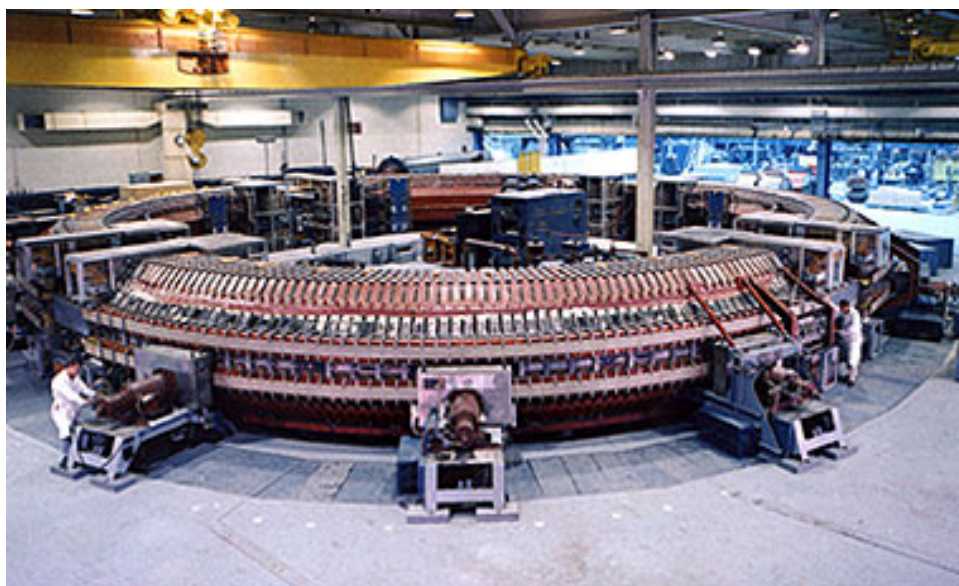
Is there an order in this apparent chaos?  
 This is how the Standard Model was born!



# A necessity: better microscopes

Cosmotron - BNL - 1952-1966

First accelerator beyond the GeV scale



<https://www.bnl.gov/about/history/accelerators.php>

Bevatron - LBNL - 1954-1993

Billions of electron volts (6.5 GeV/beam)



[interactions.org](https://interactions.org)

Experimental study of the *spectroscopy* of zoo of composite particles!

# Our initial analogy...

**Periodic Table of the Elements**

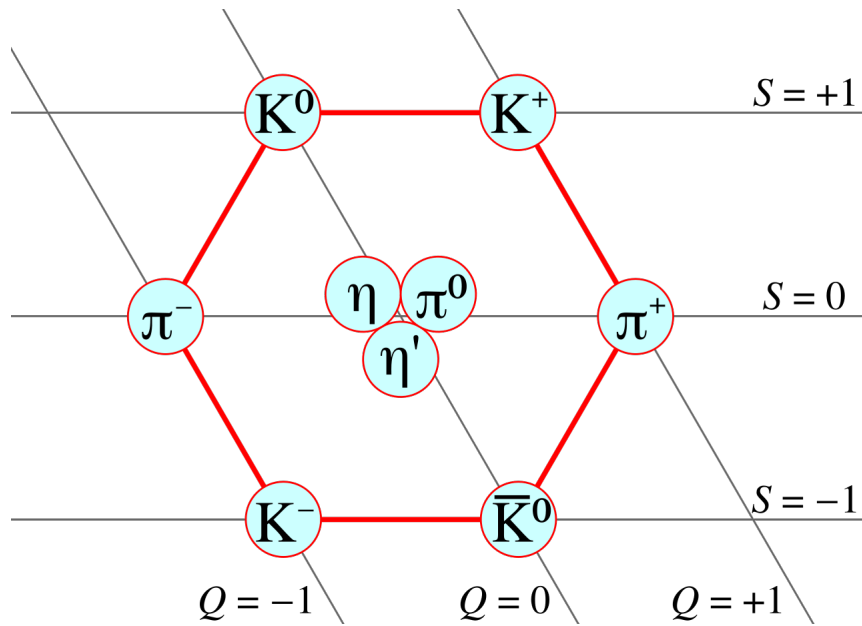
1 1A 11A <b>H</b> Hydrogen 1.008																	18 VIII A 8A <b>He</b> Helium 4.003
3 <b>Li</b> Lithium 6.941	4 2A <b>Be</b> Beryllium 9.012											5 <b>B</b> Boron 10.811	6 4A <b>C</b> Carbon 12.011	7 5A <b>N</b> Nitrogen 14.007	8 6A <b>O</b> Oxygen 15.999	9 7A <b>F</b> Fluorine 18.998	10 <b>Ne</b> Neon 20.180
11 <b>Na</b> Sodium 22.990	12 2A <b>Mg</b> Magnesium 24.305	3 IIIB 3B <b>Sc</b> Scandium 44.956	4 IVB 4B <b>Ti</b> Titanium 47.88	5 VB 5B <b>V</b> Vanadium 50.942	6 VIB 6B <b>Cr</b> Chromium 51.996	7 VIIB 7B <b>Mn</b> Manganese 54.938	8 <b>Fe</b> Iron 55.933	9 VIII 8 <b>Co</b> Cobalt 58.933	10 <b>Ni</b> Nickel 58.693	11 IB 1B <b>Cu</b> Copper 63.546	12 IIB 2B <b>Zn</b> Zinc 65.39	13 <b>Al</b> Aluminum 26.982	14 <b>Si</b> Silicon 28.086	15 <b>P</b> Phosphorus 30.974	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.098	20 2A <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.933	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.732	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.09	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 84.80
37 <b>Rb</b> Rubidium 84.468	38 2A <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.905	56 2A <b>Ba</b> Barium 137.327	57-71 Lanthanide Series	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.948	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 168.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.980	84 <b>Po</b> Polonium [208.982]	85 <b>At</b> Astatine 209.987	86 <b>Rn</b> Radon 222.018
87 <b>Fr</b> Francium 223.020	88 2A <b>Ra</b> Radium 226.025	89-103 Actinide Series	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>F1</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [298]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown

Lanthanide Series	57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.115	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.966	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.930	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967
Actinide Series	89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium 244.064	95 <b>Am</b> Americium 243.061	96 <b>Cm</b> Curium 247.070	97 <b>Bk</b> Berkelium 247.070	98 <b>Cf</b> Californium 251.080	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.095	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.101	103 <b>Lr</b> Lawrencium [262]

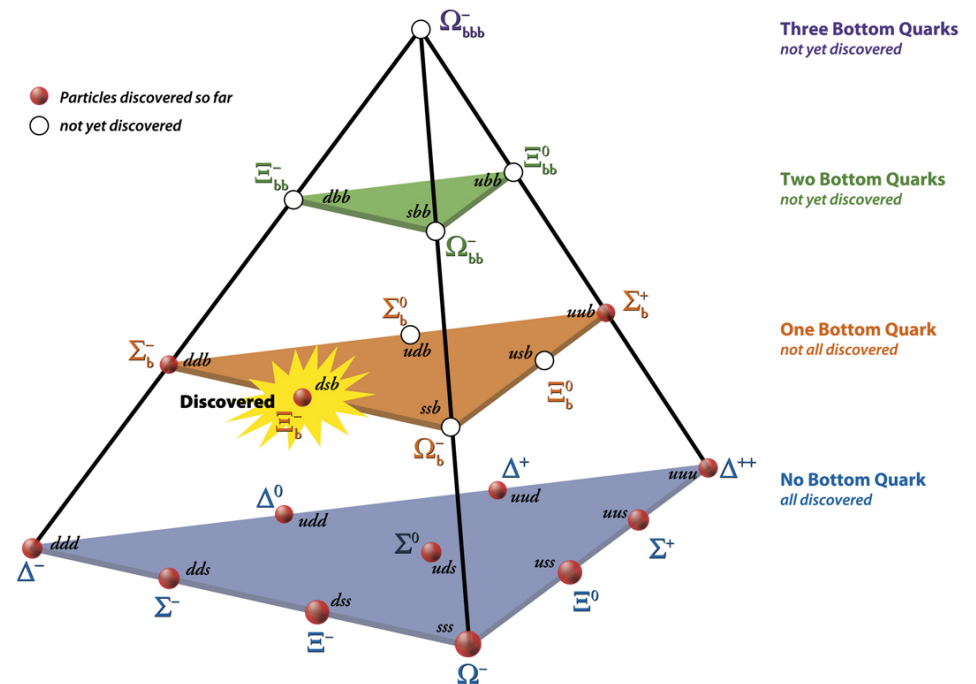
Alkali Metal	Alkaline Earth	Transition Metal	Semimetal	Nonmetal	Basic Metal	Halogen	Noble Gas	Lanthanide	Actinide
--------------	----------------	------------------	-----------	----------	-------------	---------	-----------	------------	----------



# Categorize hadrons according to spin & charge



Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin ( $J = 3/2$ )

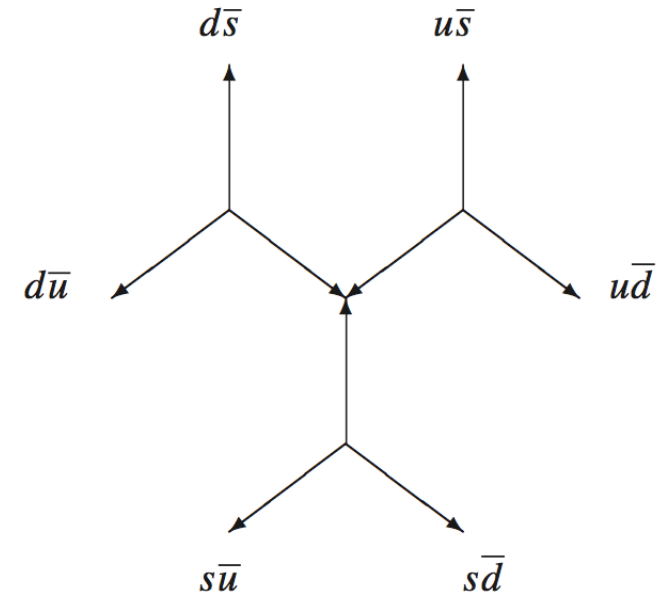
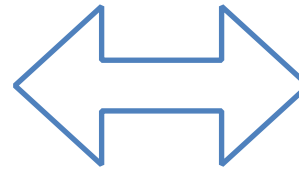
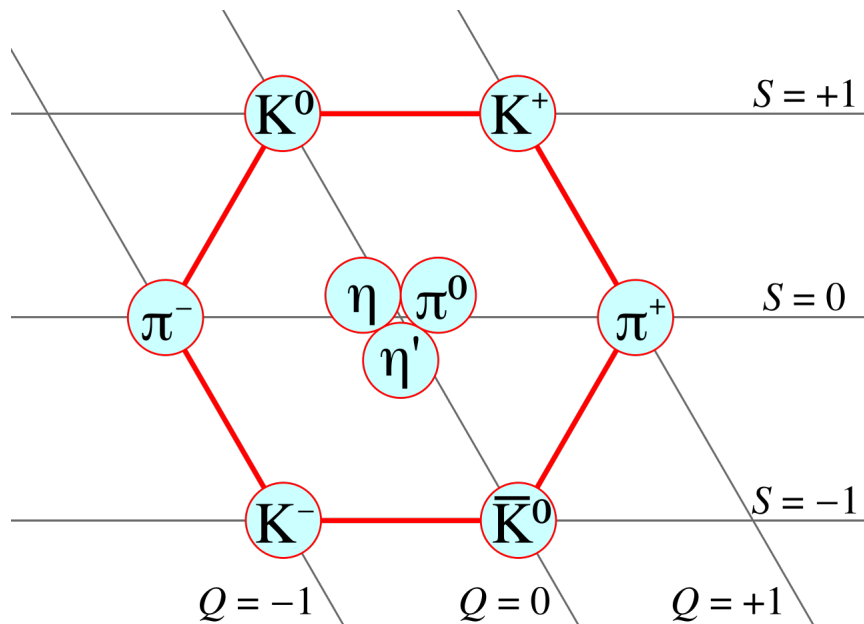


# Particle groupings and quarks

Gell-Mann / Zweig:

*“Three quarks for muster Mark” (J. Joyce, Finnegans Wake)*

- hadrons are built by three constituent quarks, **u** **d** and **s**
- *mesons are composed by **quark/antiquark** pairs*



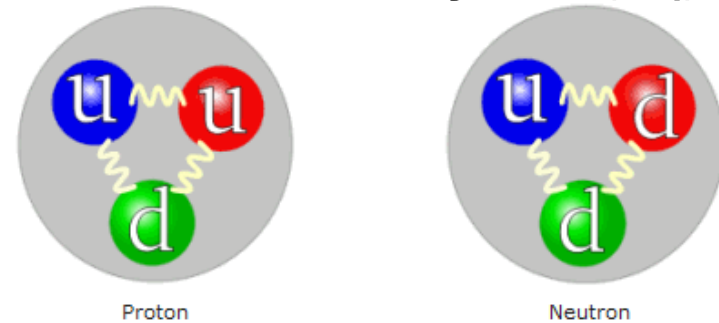
# Introducing the quarks and the gluon

**Hadrons** = particles made of quarks & gluons, interacting via the strong force

QUARKS	mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$
	charge →	$2/3$	$2/3$	$2/3$
	spin →	$1/2$	$1/2$	$1/2$
		<b>u</b> up	<b>c</b> charm	<b>t</b> top
		$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
		$-1/3$	$-1/3$	$-1/3$
	$1/2$	$1/2$	$1/2$	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	

0	<b>g</b>
0	gluon
1	

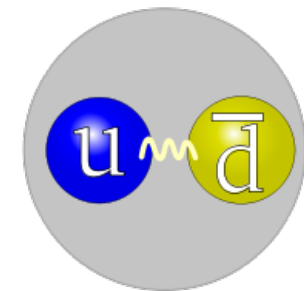
Protons are **baryons** (3q)



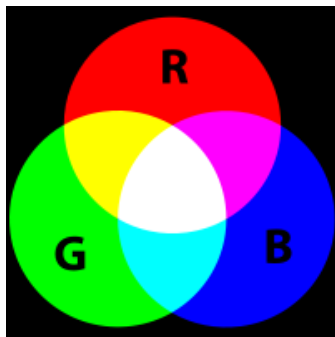
Quark composition of a proton and a neutron (diagrams from Wikipedia)

Pions are **mesons** (q-qbar)

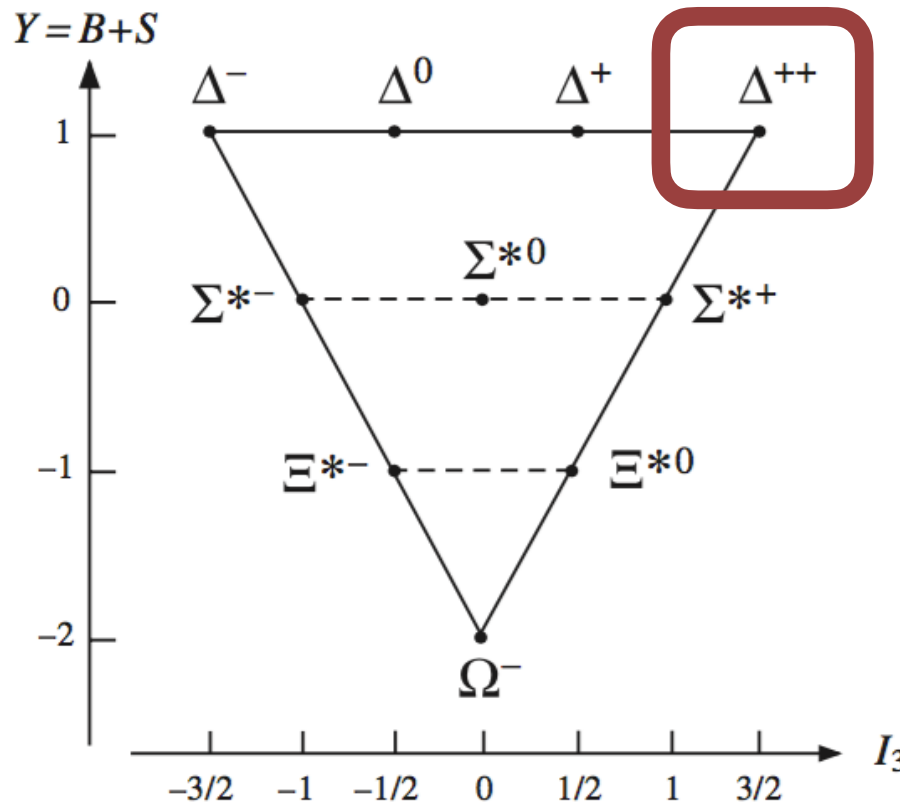
$$\begin{aligned} \pi^+ &: u\bar{d} \\ \pi^0 &: u\bar{u} \text{ or } d\bar{d} \\ \pi^- &: d\bar{u} \end{aligned}$$



Images: Wikipedia



# Color: what about the $\Delta$ and Pauli's principle?



Quarks:  $uuu$

Parity: +

Charge: 2

Spin:  $3/2 \rightarrow$  spins are aligned

Isospin:  $Q + Y/2 = 3/2$

**Completely symmetric wavefunction!**

**But:** three fermions should not all have the same state, according to Pauli's principle!

# Everyone needs more color

Solution to the  $\Delta$  puzzle:

add another **degree of freedom** that can be anti-symmetric  
color is the **charge** of quantum chromodynamics

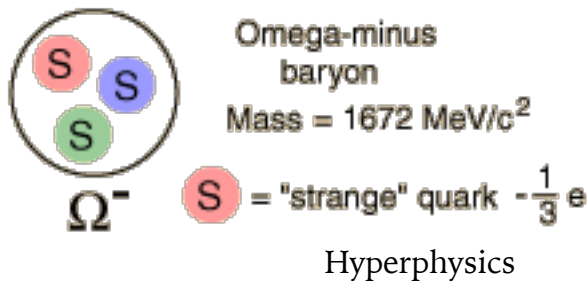


TABLE 6.8 Values of the colour charges  $I_3^C$  and  $Y^C$  for the colour states of quarks and antiquarks.

	(a) Quarks		(b) Antiquarks		
	$I_3^C$	$Y^C$	$I_3^C$	$Y^C$	
$r$	$1/2$	$1/3$	$\bar{r}$	$-1/2$	$-1/3$
$g$	$-1/2$	$1/3$	$\bar{g}$	$1/2$	$-1/3$
$b$	$0$	$-2/3$	$\bar{b}$	$0$	$2/3$

Confinement 'rule':

$$I_3^C = Y^C = 0,$$

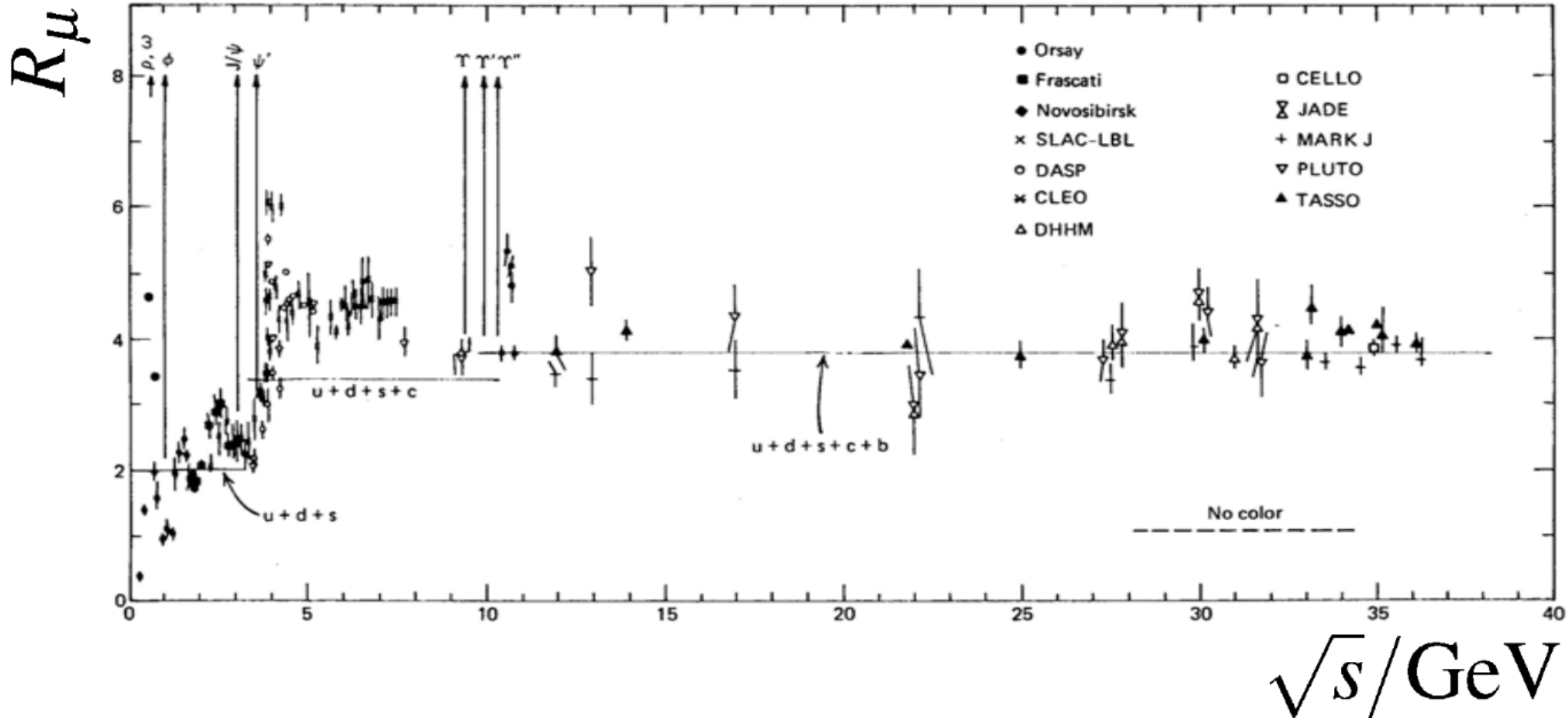
Baryons and mesons are colourless



# Evidence of color

$$\frac{\sigma(e^+e^- \rightarrow \text{hadrons}, Q)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-, Q)}$$

= measured to be 3 times wrt theory w/o color  
 → means each quark comes in 3 versions/colors!



# The theory of the strong force: Quantum ChromoDynamics

Large **Hadron** Collider: Quark and gluon ( $\rightarrow$  jet) factory  
Force describing interactions of quarks and gluons: **QCD**

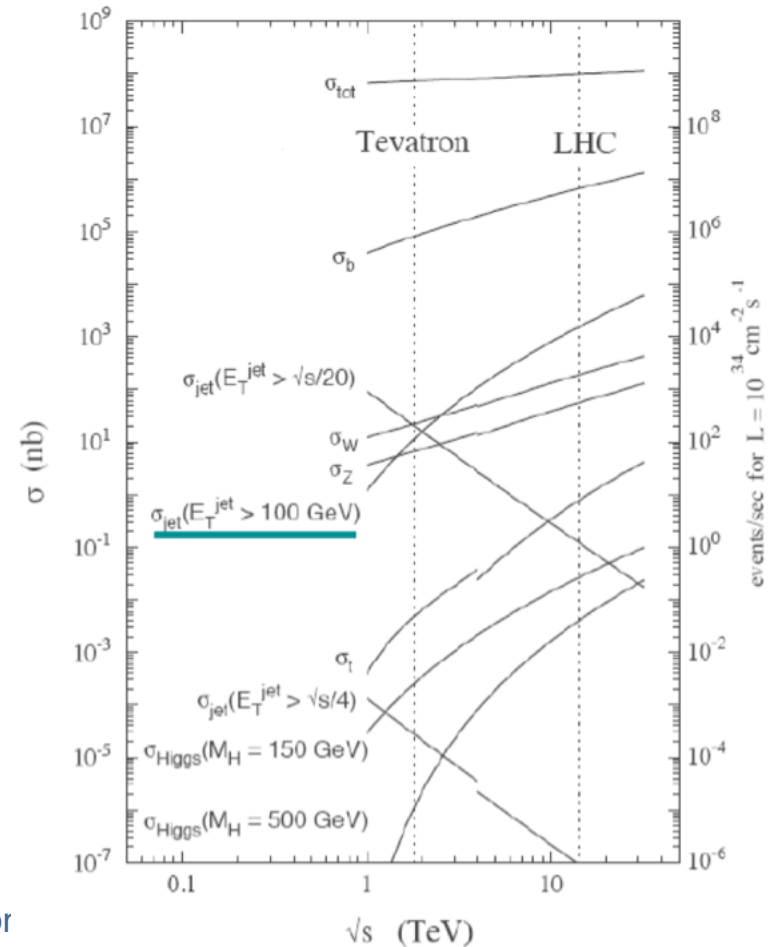
Measure QCD processes:



Precision measurements of the  
Standard Model

Search for deviations from  
QCD:

look for new particles decaying  
into quarks and gluons



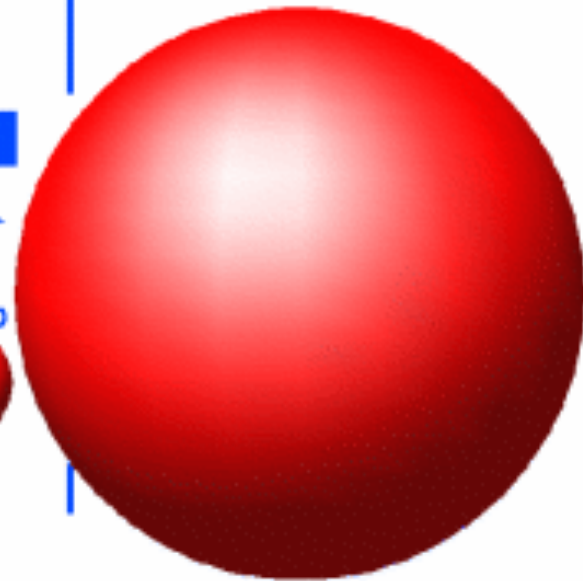




# Three generations of quarks

*Not covered here: quarks can turn into each other via the W boson (Cabibbo-Kobayashi-Maskawa mechanism)*

<1971	1974	1995
<b>u</b> up	<b>c</b> charm	<b>t</b> top
<b>d</b> down	<b>s</b> strange	<b>b</b> bottom
<1971	<1971	1977
<1971	<1971	1975
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino
<b>e</b> electron	$\mu$ muon	$\tau$ tau

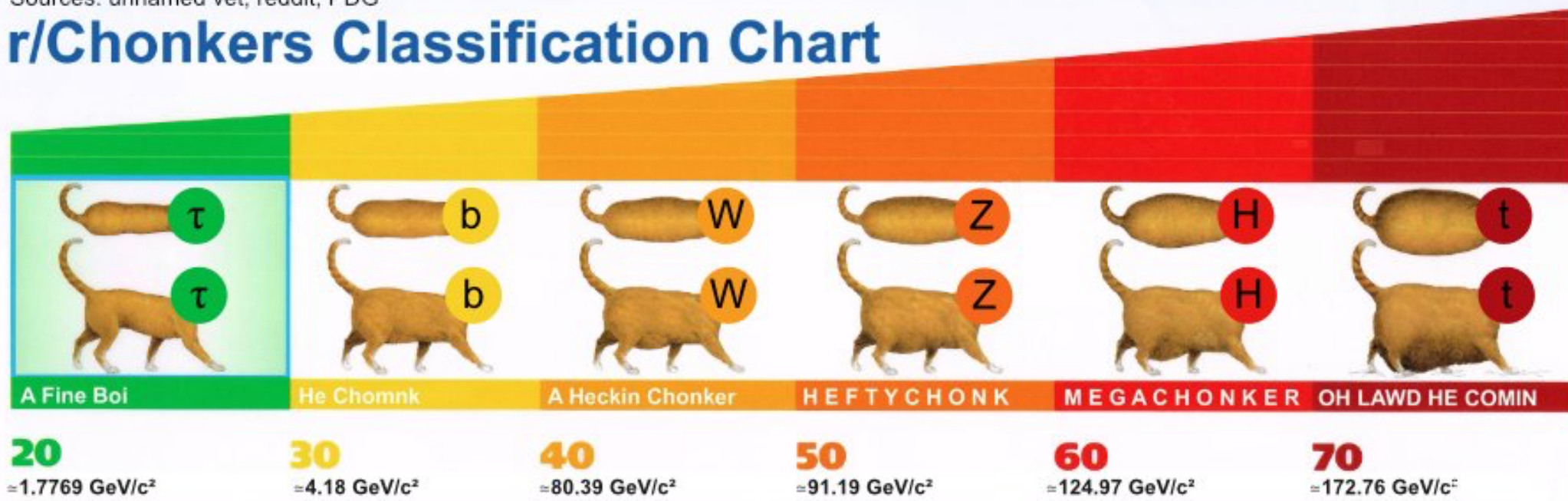




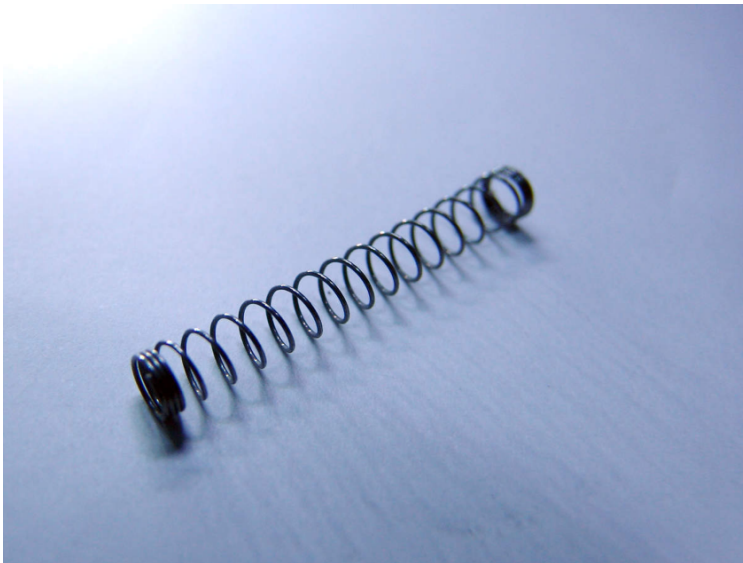
# The inevitable cat meme

Sources: unnamed vet, reddit, PDG

## r/Chonkers Classification Chart



# QCD (color) force as a spring



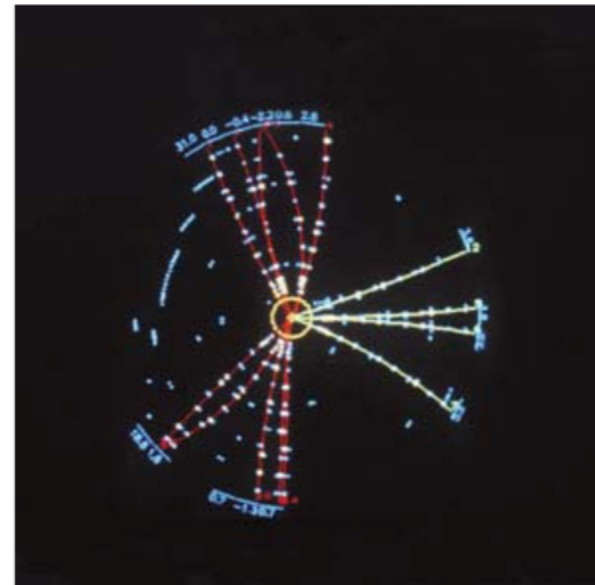
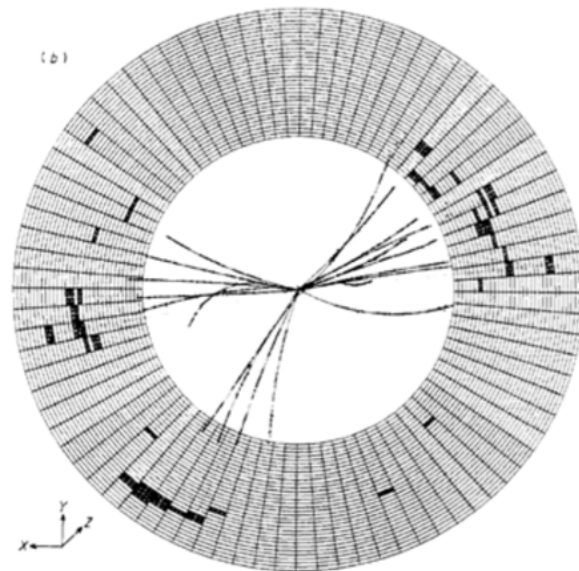
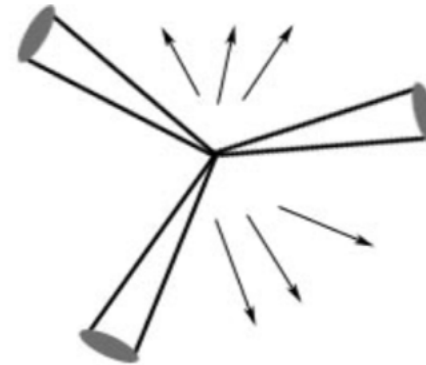
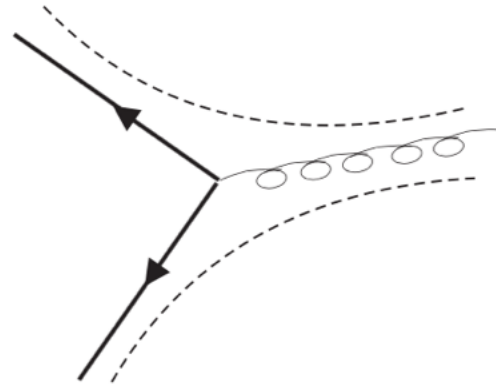
## Intuitively:

energy needed to pull quarks  
apart  $>$  energy needed to  
create a new hadron

**QCD:** *confinement and asymptotic freedom*

**Consequence:** since quarks can't be observed alone,  
hadron interactions (like at the LHC)  
create **showers of hadrons** (*parton showers*)

# The discovery of the gluon

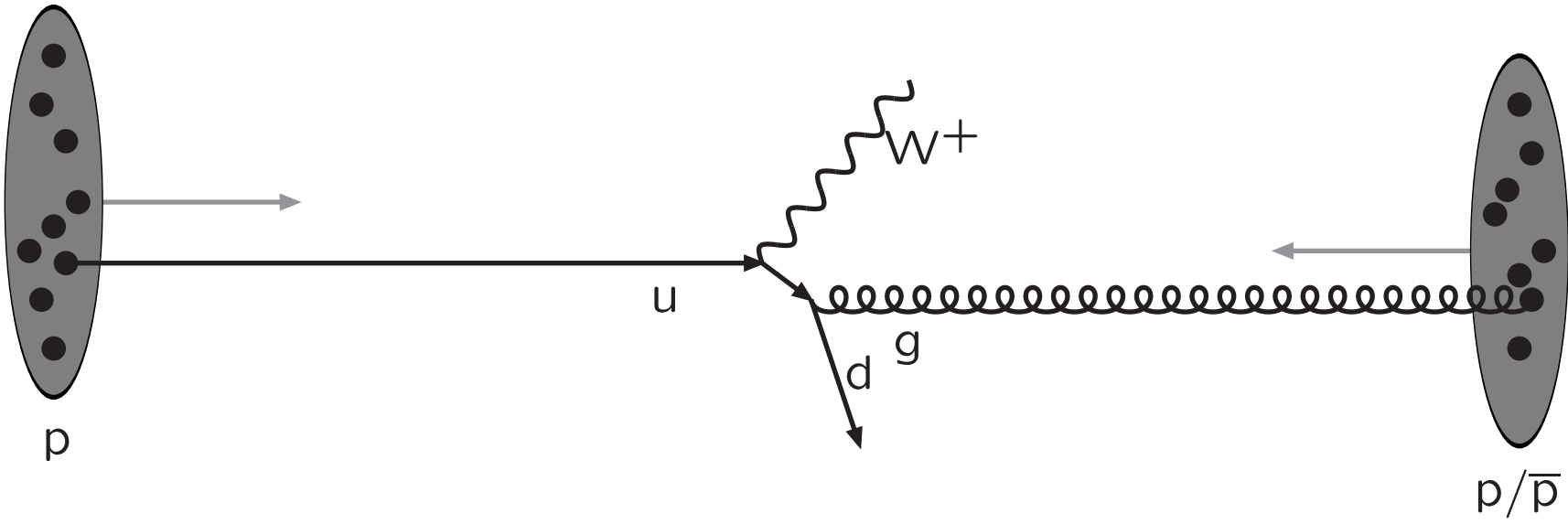


## The structure of an event

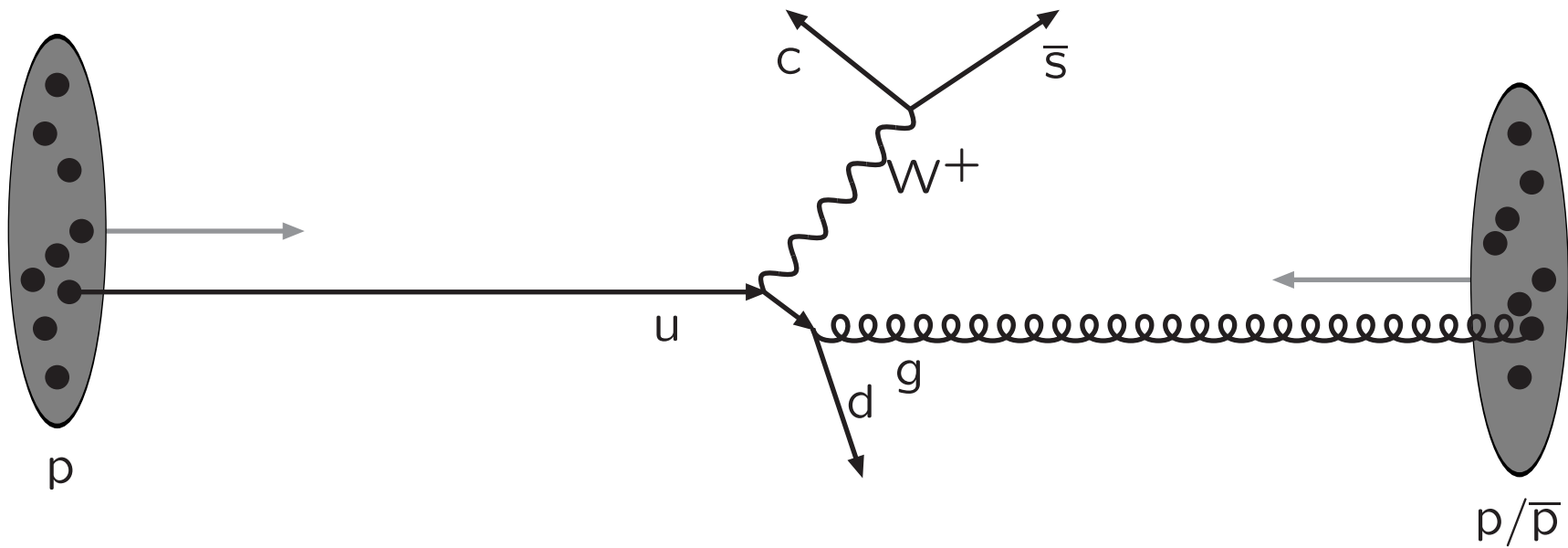
Warning: schematic only, everything simplified, nothing to scale, . . .

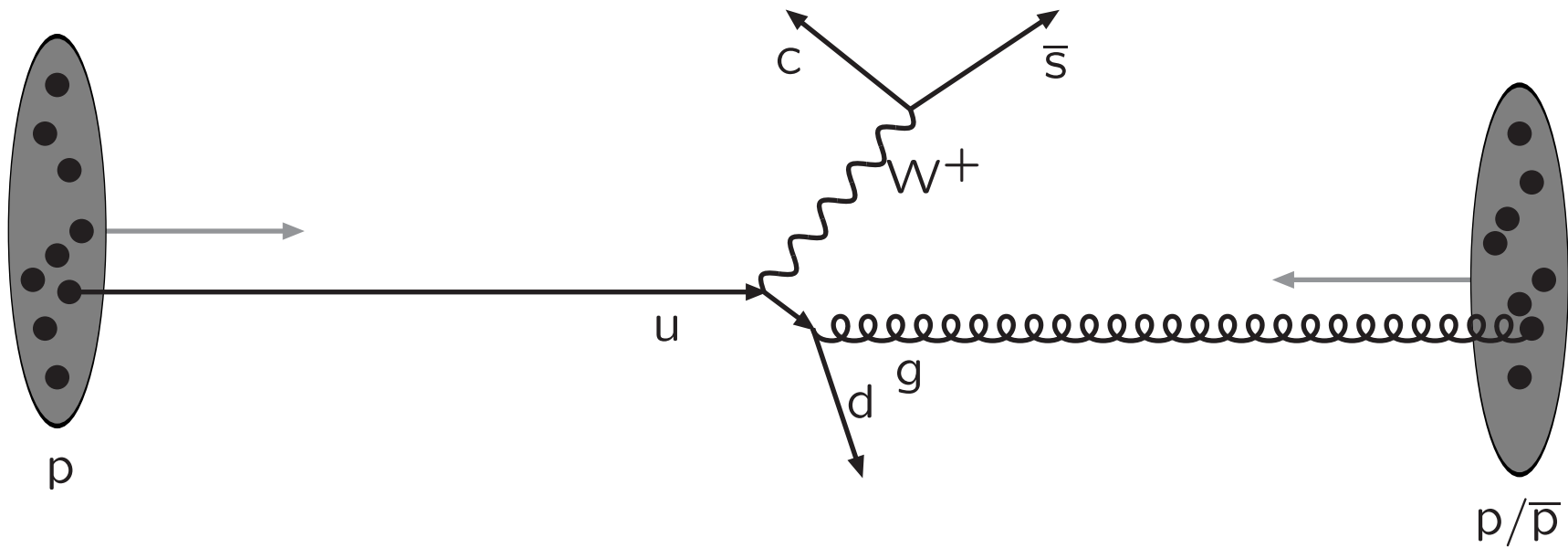


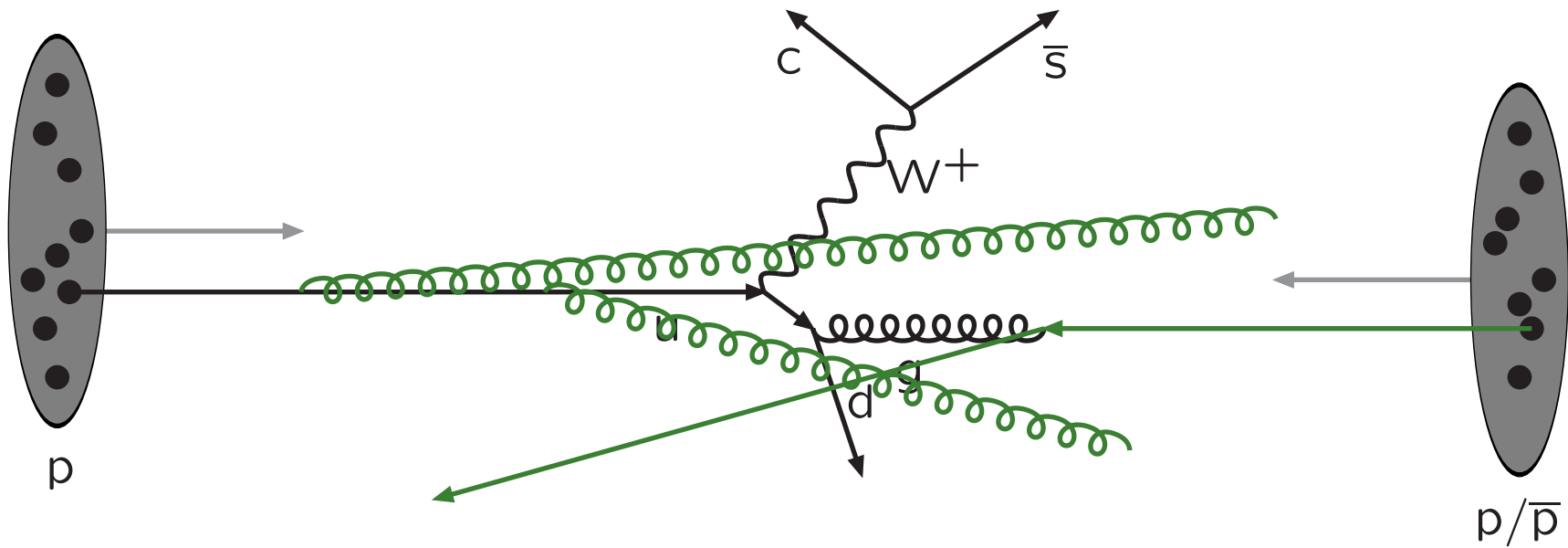
Incoming beams: parton densities



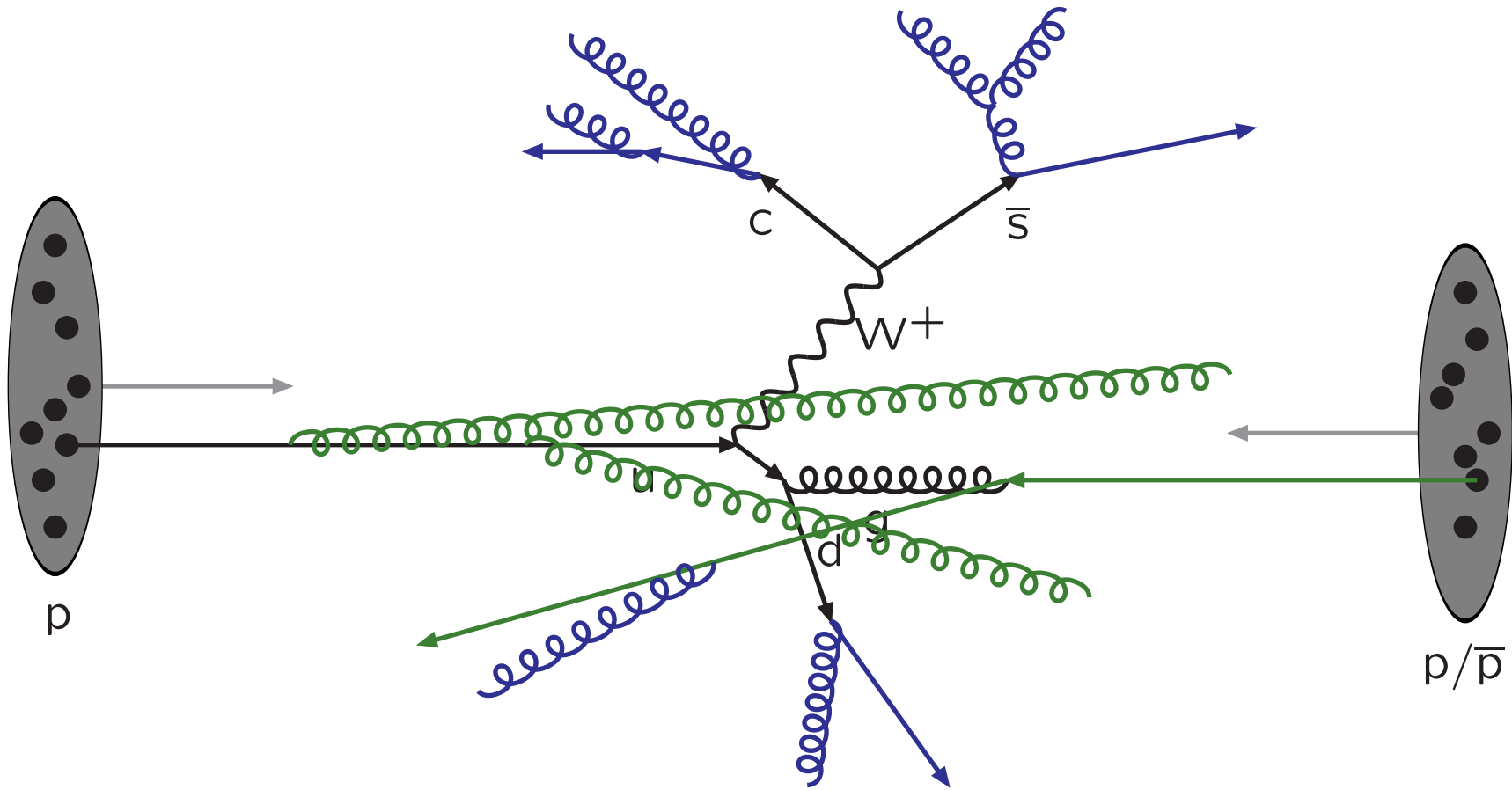
Hard subprocess: described by matrix elements

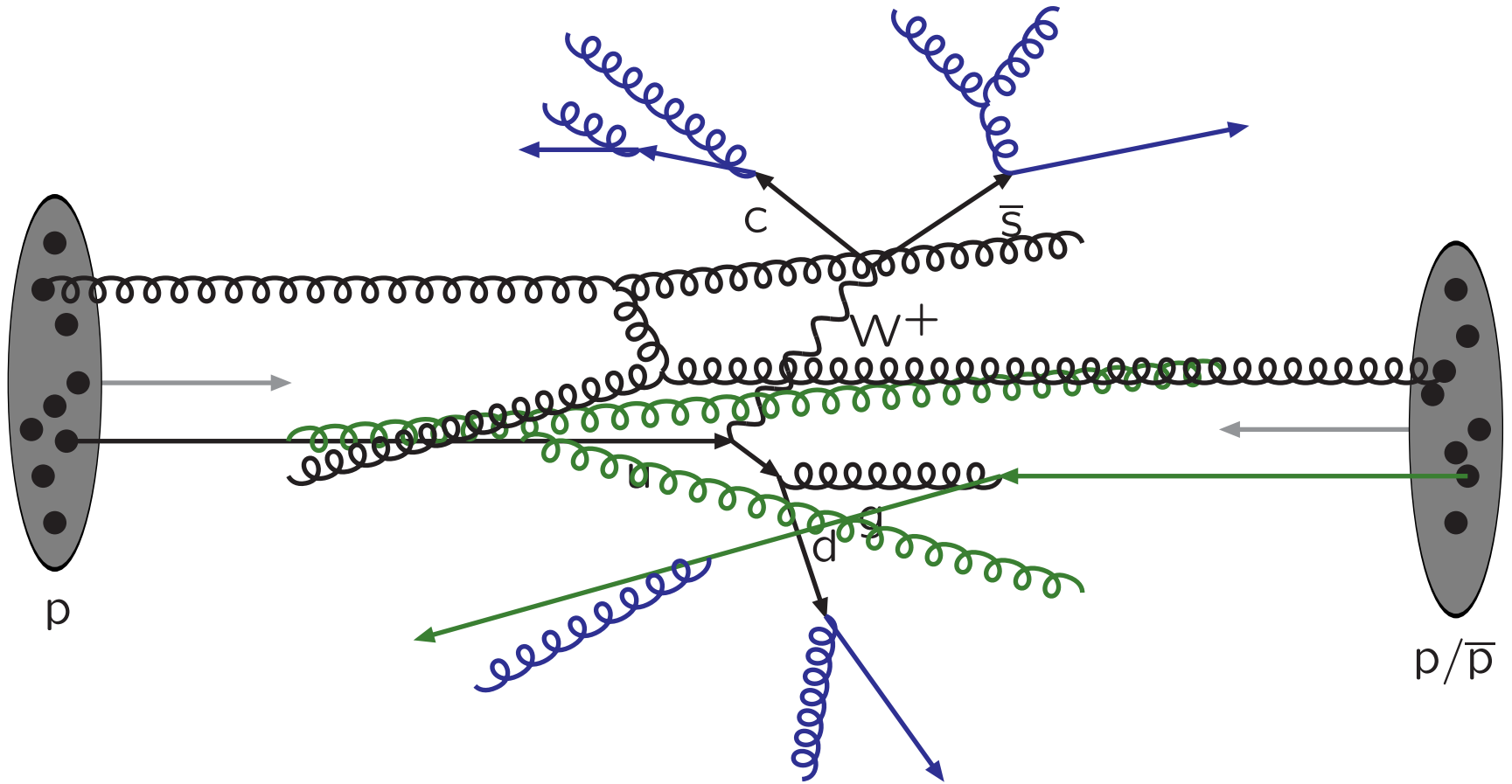


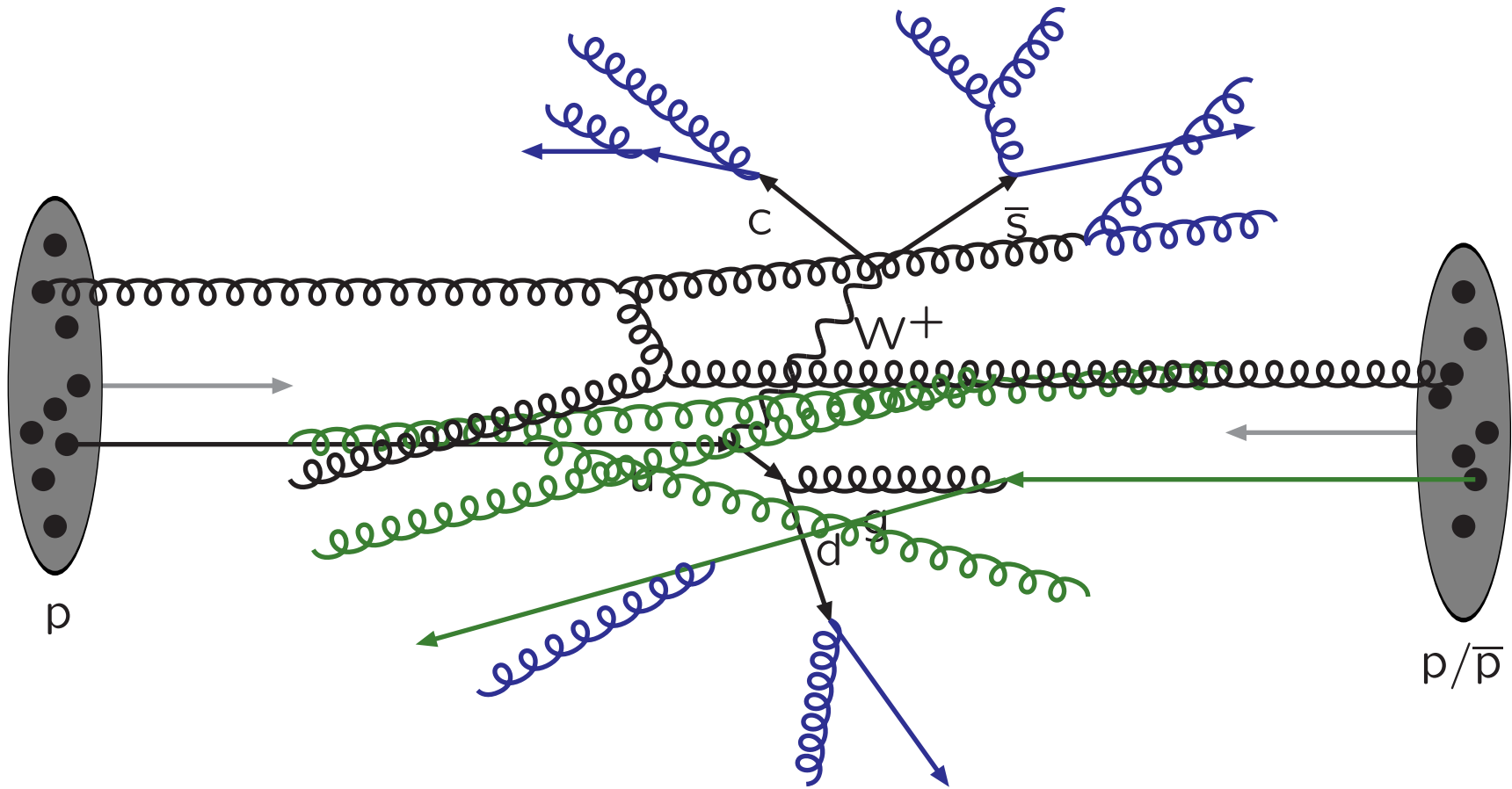




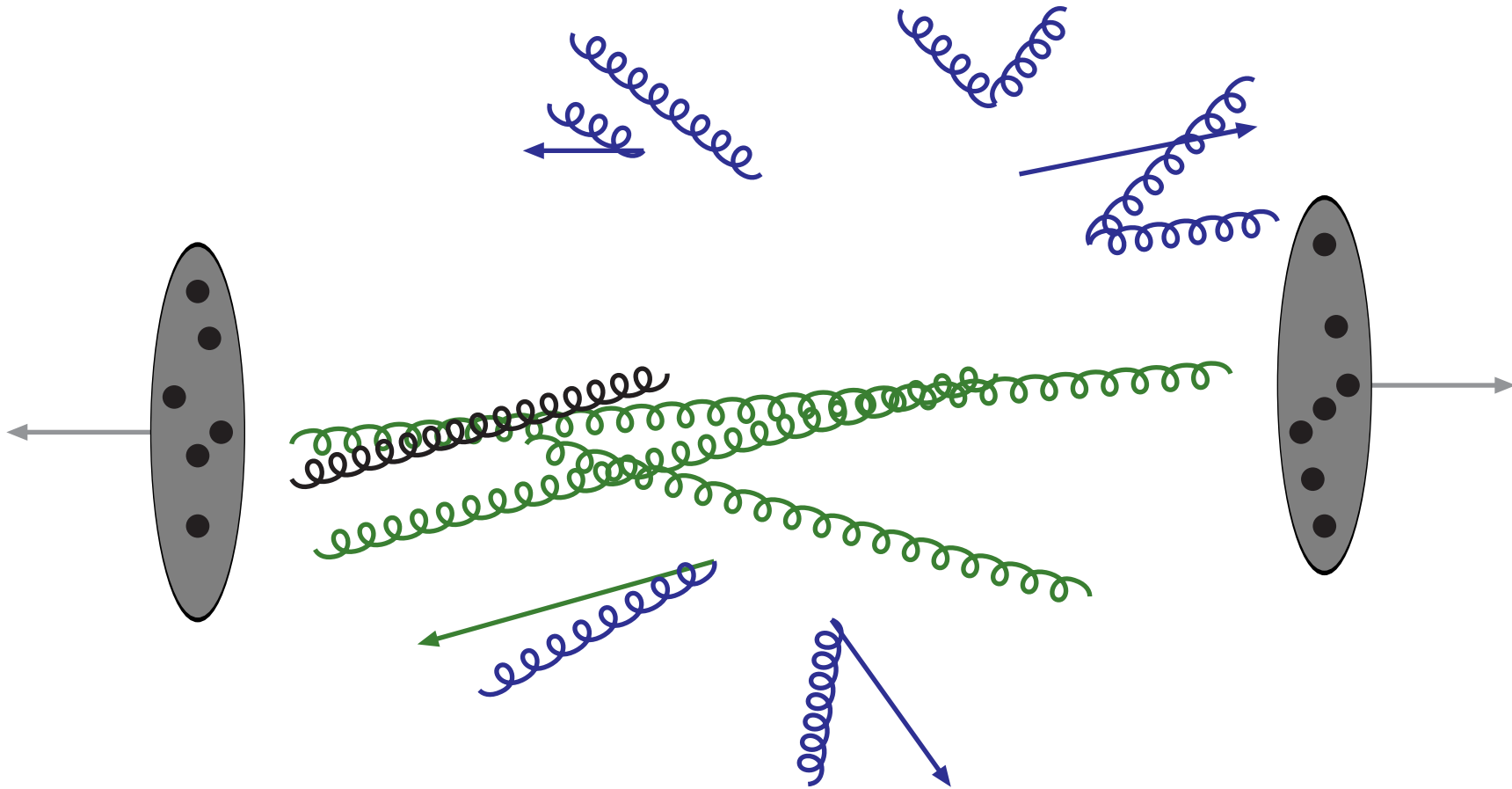




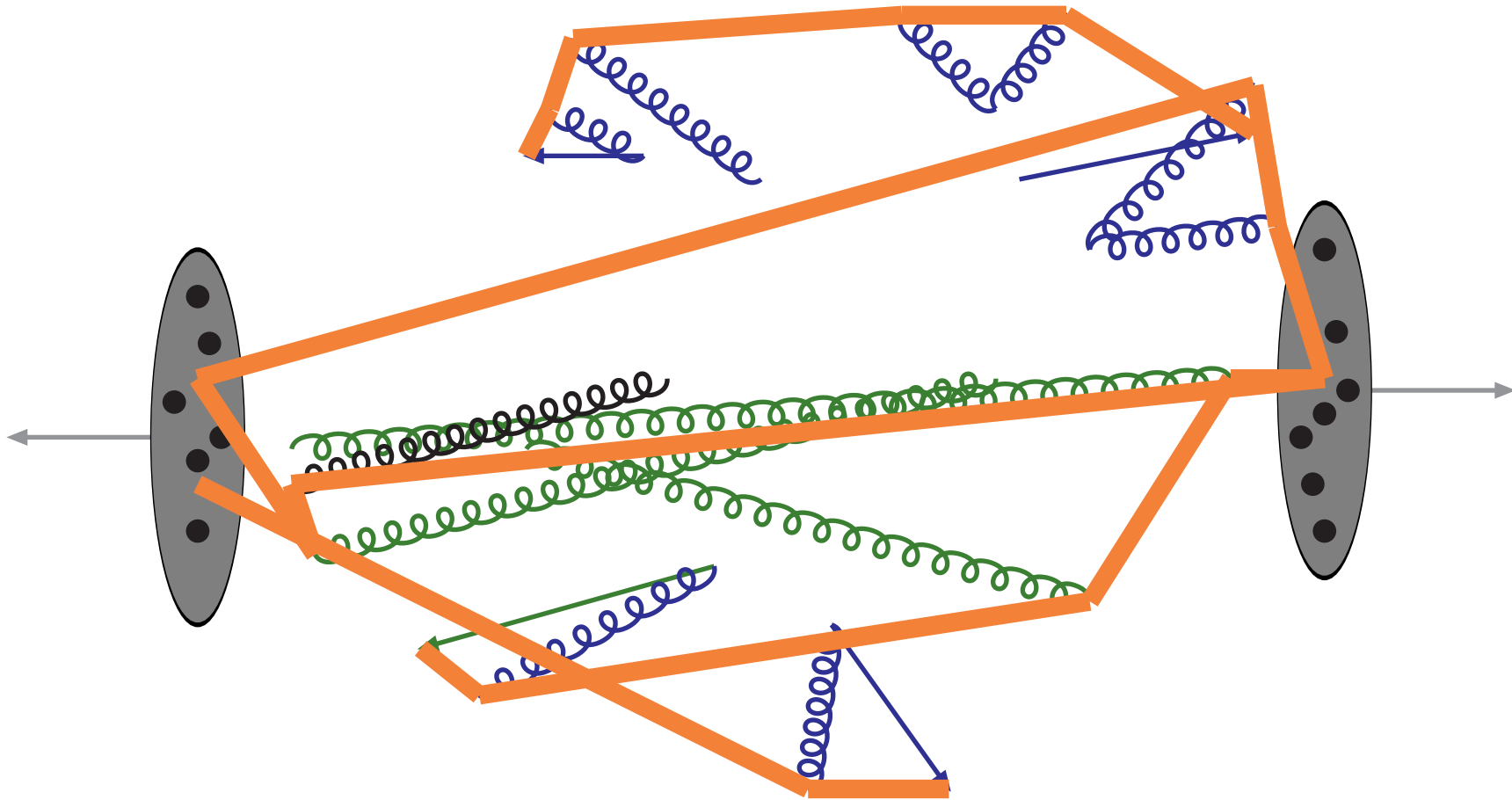




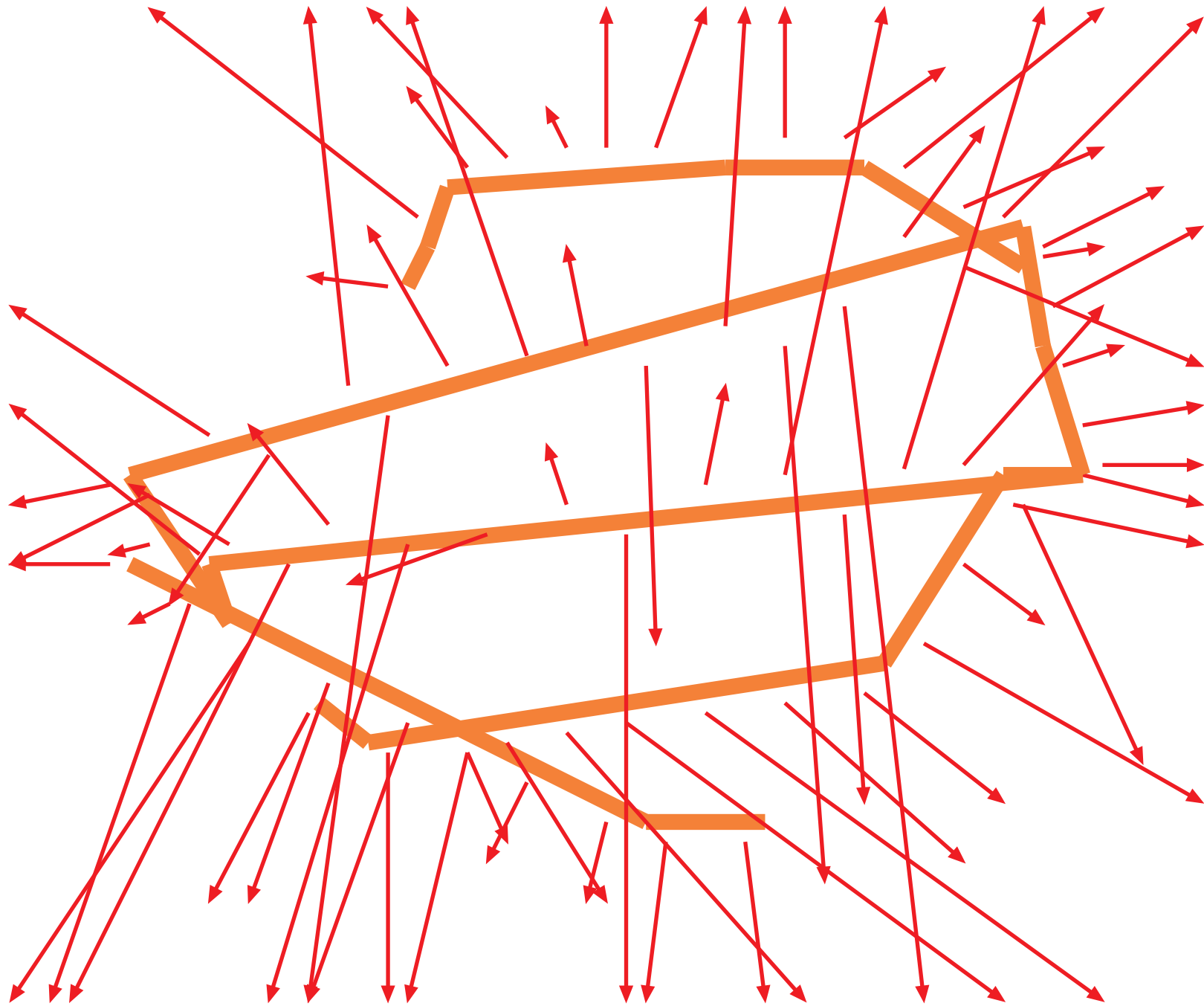
... with its **initial-** and **final-**state radiation



Beam remnants and other outgoing partons

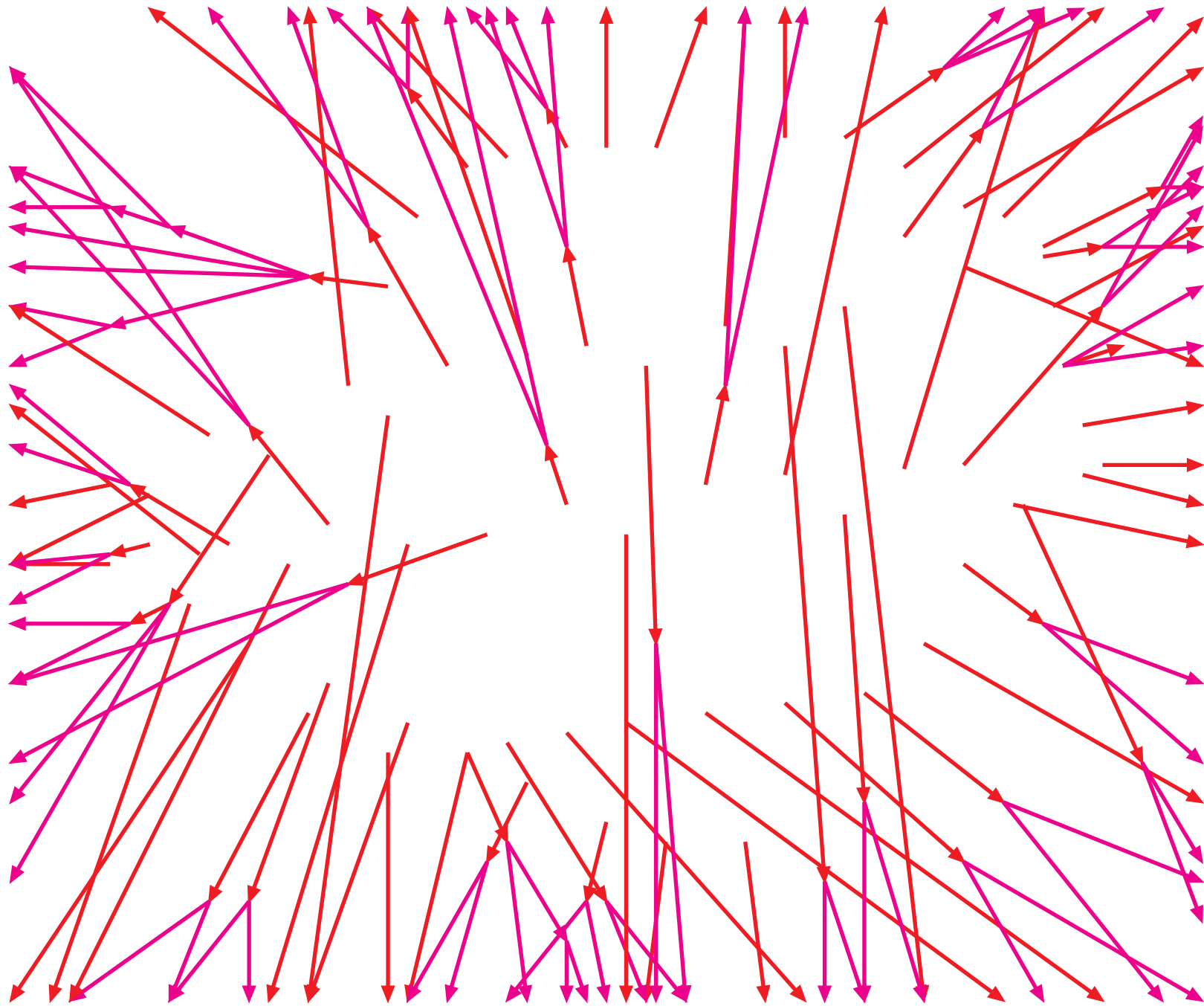


Everything is connected by colour confinement strings  
Recall! Not to scale: strings are of hadronic widths

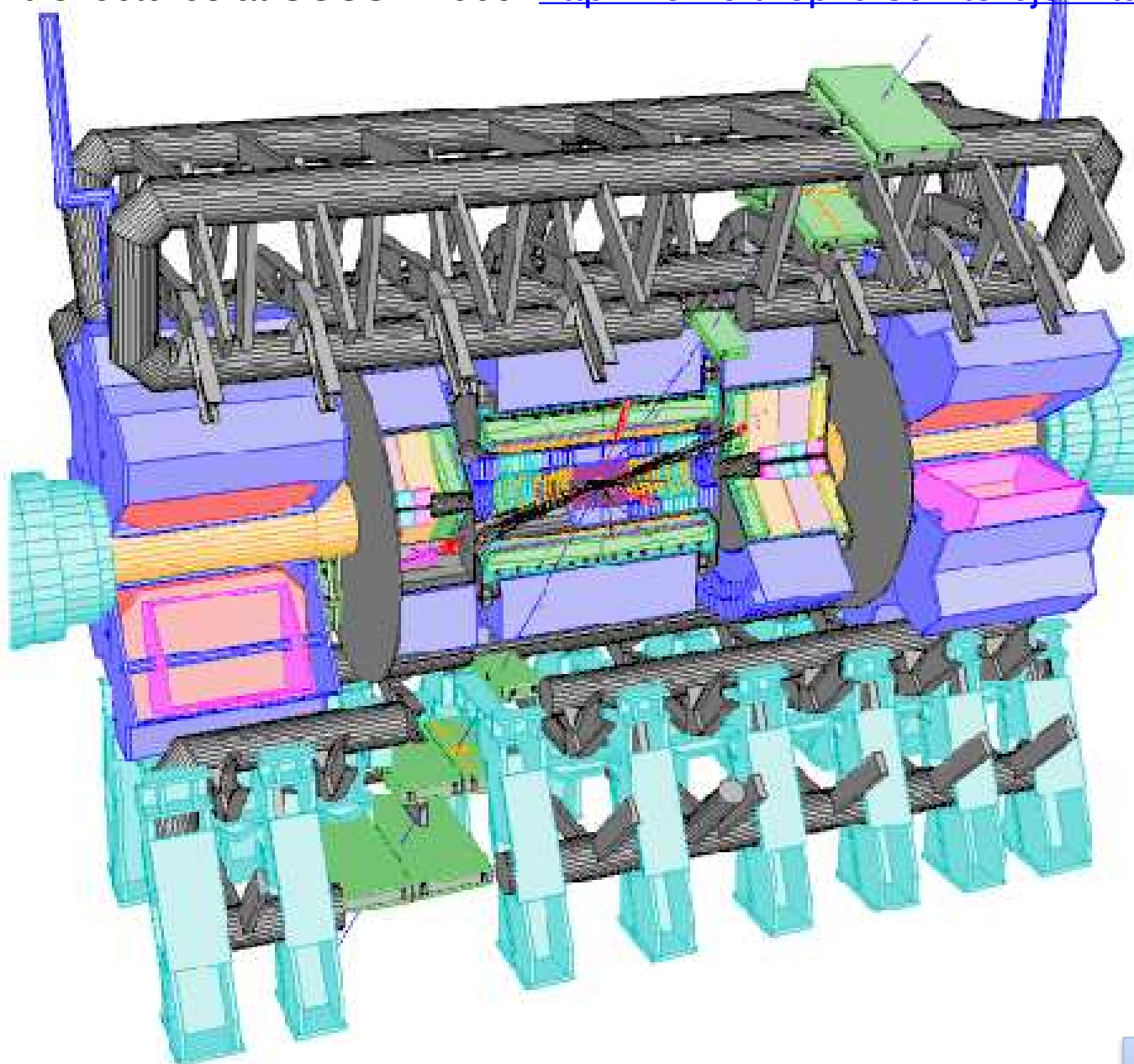


The strings fragment to produce primary hadrons





Many hadrons are unstable and decay further



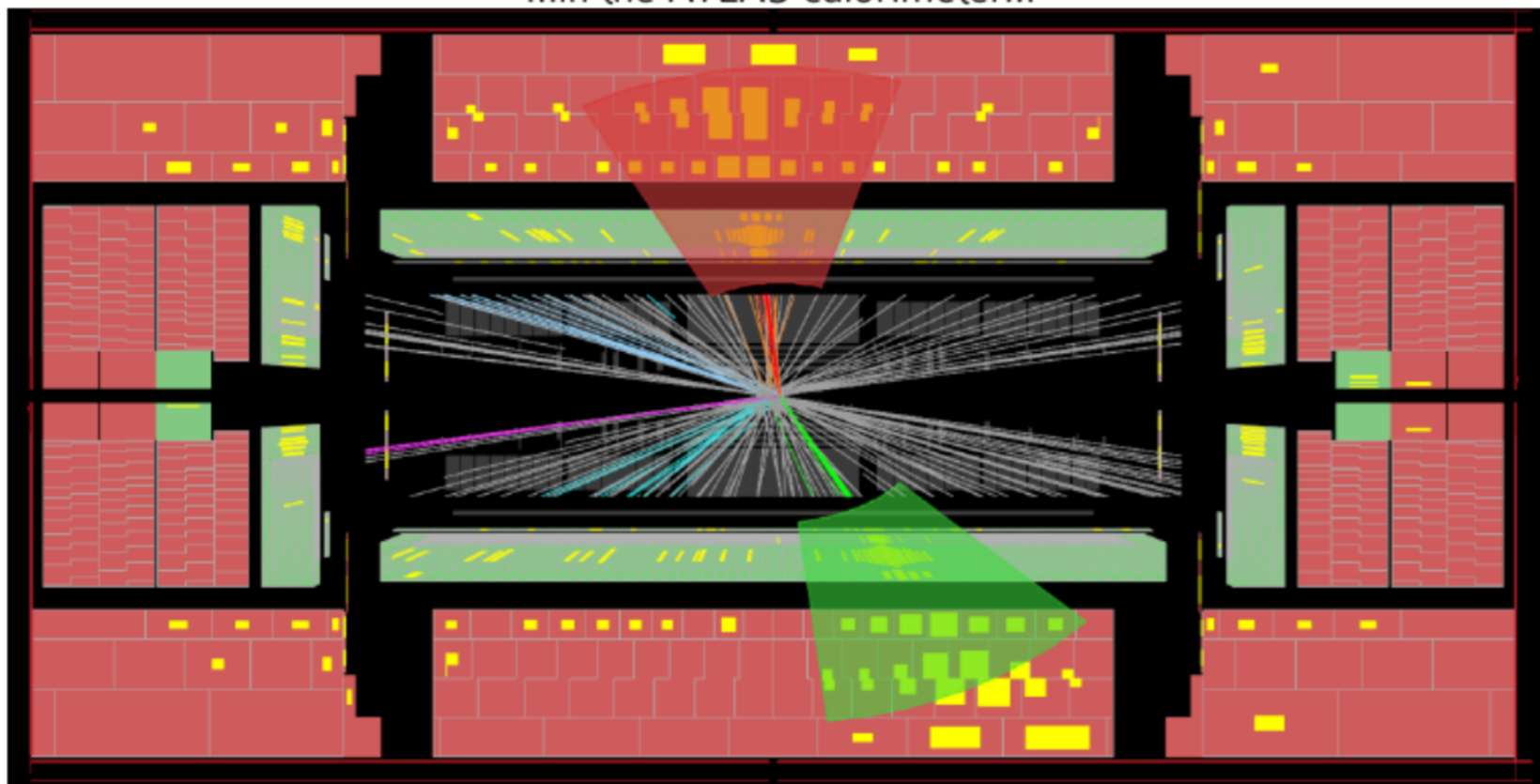
More in Part 3

These are the particles that hit the detector

# What is a jet?

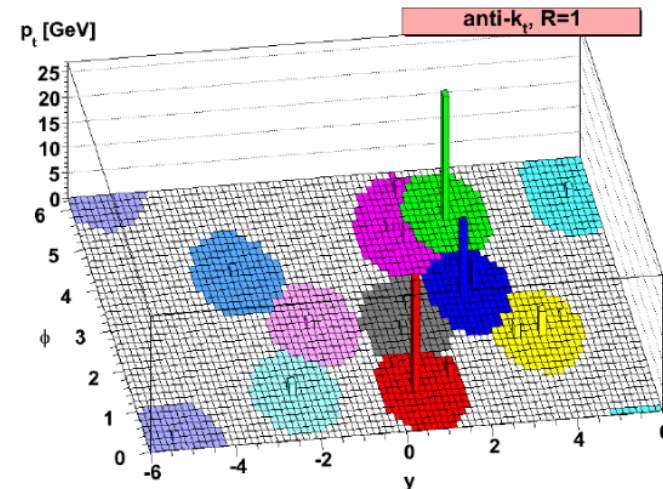
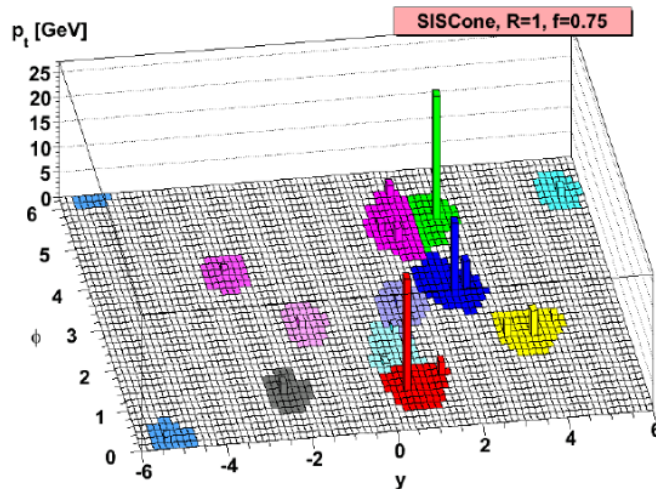
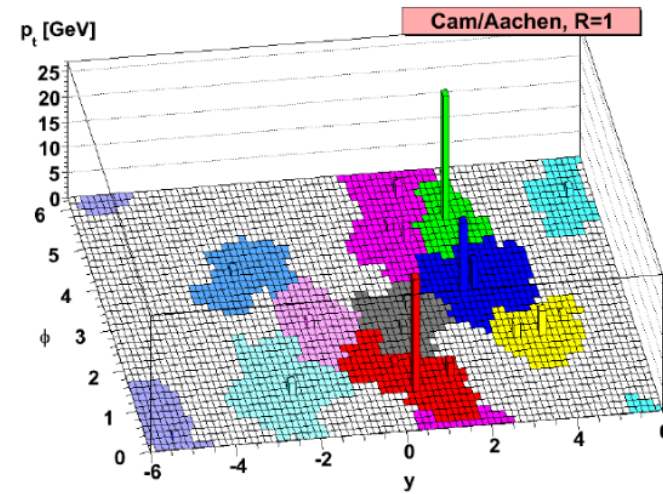
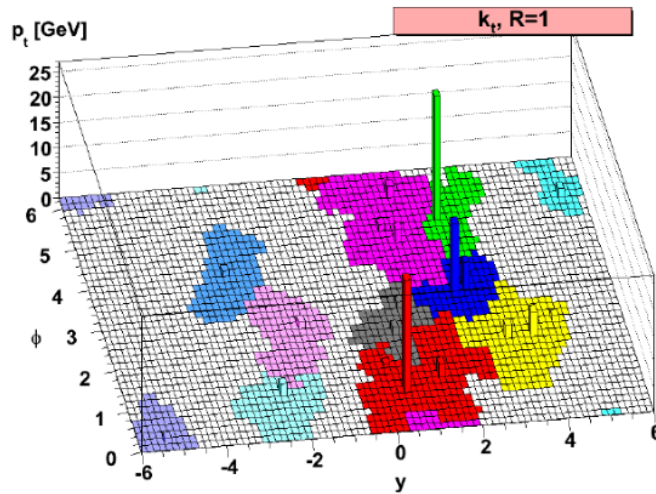
A high- $p_T$  dijet event: how we see it

...in the ATLAS calorimeter...



Note: some 'cleaning' already performed: ATLAS topological clustering algorithm

# Different jet algorithms



<http://arxiv.org/abs/0802.1189>



Electromagnetic force

Weak force

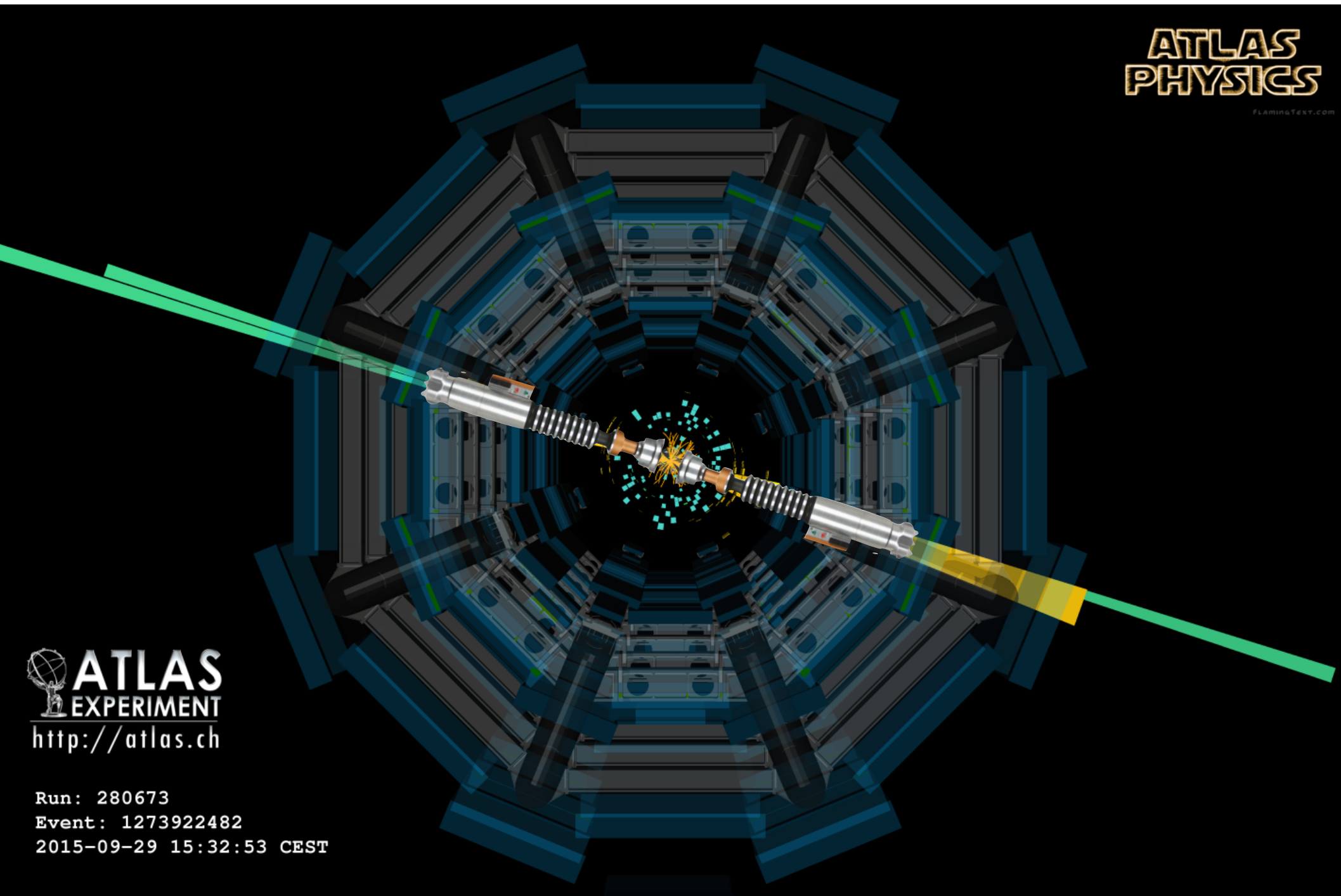
Strong force



LUNDS  
UNIVERSITET

ATLAS  
PHYSICS

FLAMINGTEXT.COM



 **ATLAS**  
EXPERIMENT  
<http://atlas.ch>

Run: 280673

Event: 1273922482

2015-09-29 15:32:53 CEST

# 5-10' for a break (or questions)

---







LUNDS  
UNIVERSITET

# Backup

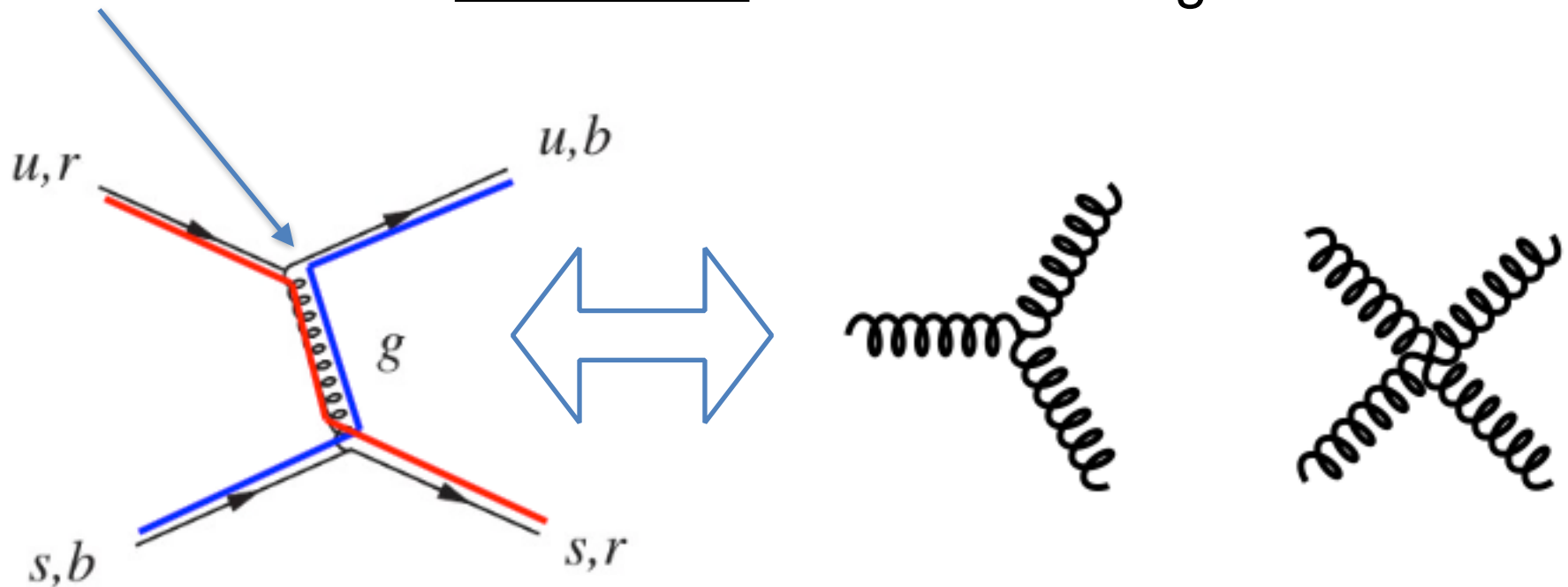
---

# Difference with EM force

Vertices  
must be  
color-neutral

**Photon:** neutral under electric charge

**Gluon:** not neutral under color charge



**Consequence:** gluons self-interact!

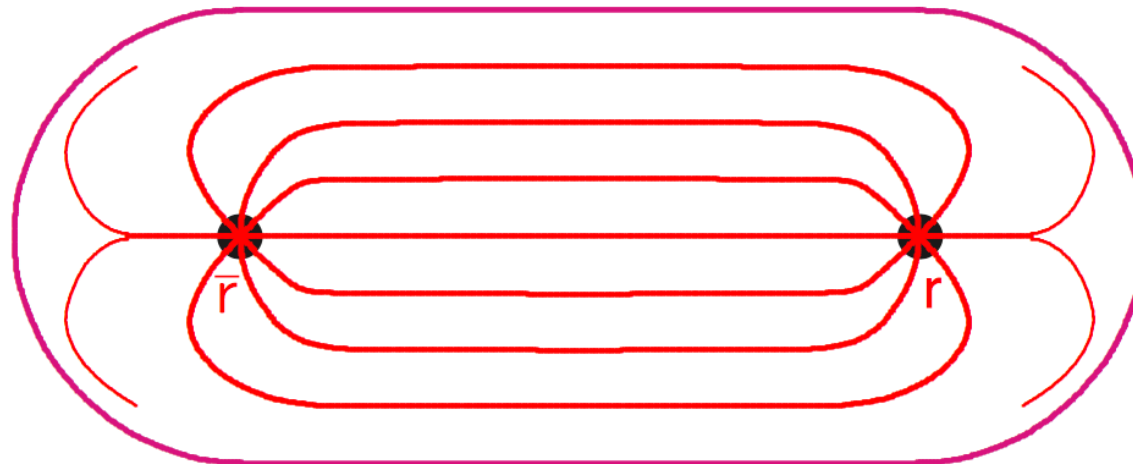
**Further consequences:** confinement and asymptotic freedom

See F. Tanedo's post: <http://www.quantumdiaries.org/author/flip-tanedo/page/5/>

# How Lund deals with parton showers

## The Lund String Model (1977 - )

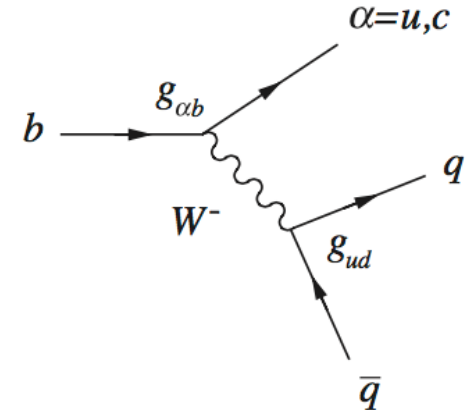
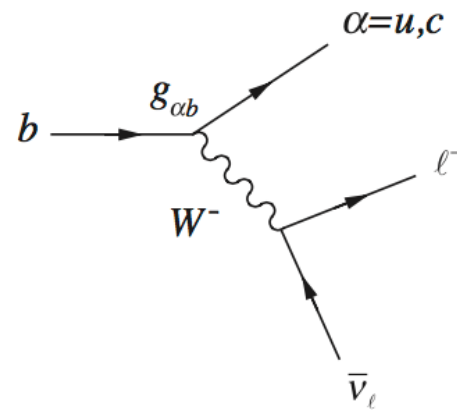
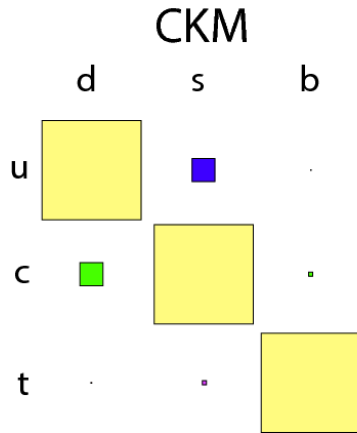
In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s)  $\Rightarrow$  **string(s)**



Gives linear confinement with string tension:

$$F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$$

# Long lifetime of B-hadrons

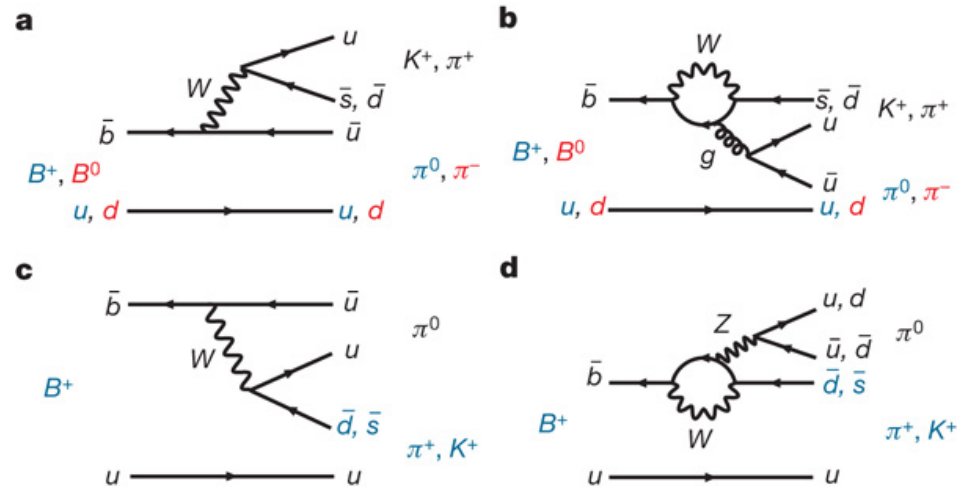


- 1) b->t forbidden
- 2) b->anything else: disfavoured



Long lifetime for B hadrons!

$$\tau_b \approx 10^{-12} \text{ s}$$



**Question:** how long does a relativistic b-hadron walk in a detector?

# A jet algorithm in action

## Algorithm specification: Anti- $k_t$

- $d_{i,j} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right) \frac{\Delta R^2}{D^2}$  ;
- $d_{i,Beam} = \frac{1}{p_{T,i}^2}$

- $D$  : algorithm parameter

- Iterate:

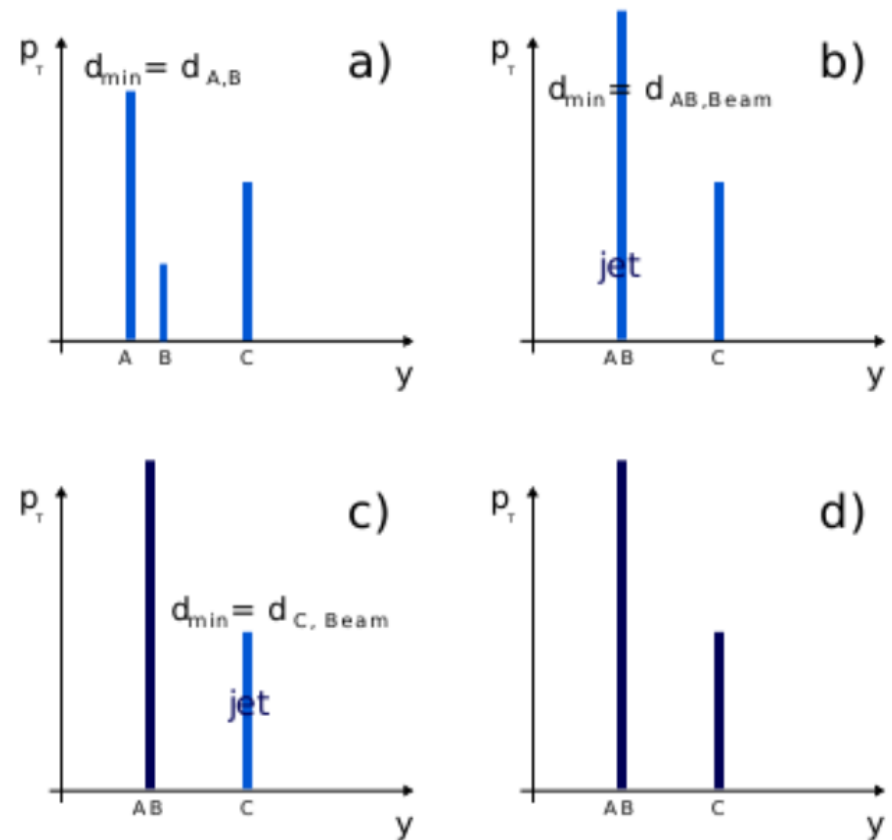
- 1 For every pair of objects  $i, j$  calculate  $d_{min} = \min(d_{i,j}, d_{i,beam})$

- 2 If  $d_{min} = d_{i,j}$  recombine objects  
Else  $i$  is a jet, remove it from list <sup>a</sup>

- Recombination starts from hard objects

<sup>a</sup>ATLAS default: inclusive algorithm

Idea:



# Monte Carlo generators

