Introduction to Hadron Collider Physics

Part 2. Particles and Forces

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Heavily drawing from lectures written in collaboration with
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Note on references: all the images from experiments are taken from the experiment websites unless otherwise noted

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

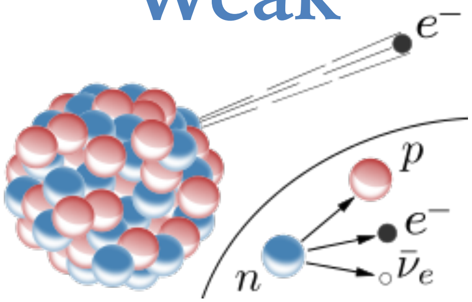
The Four Forces

Electromagnetic

Wikipedia - by ThorstenS

Wikipedia - by Oguraclutch

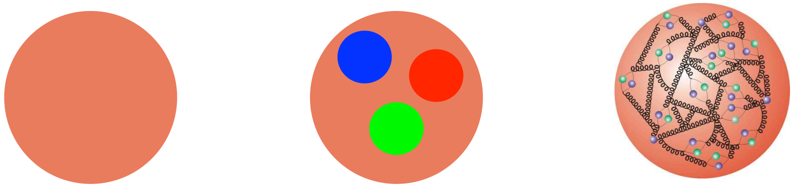
Weak



Wikipedia - By Inductiveload

Strong

proton

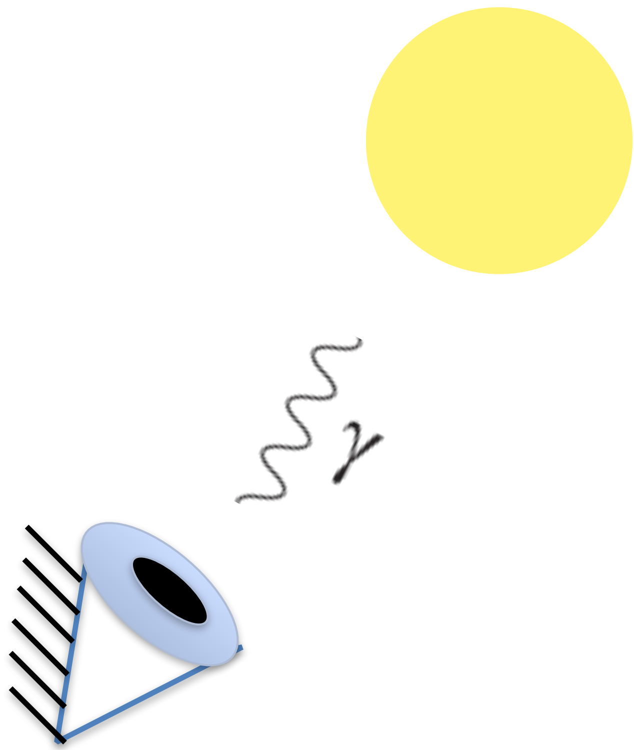


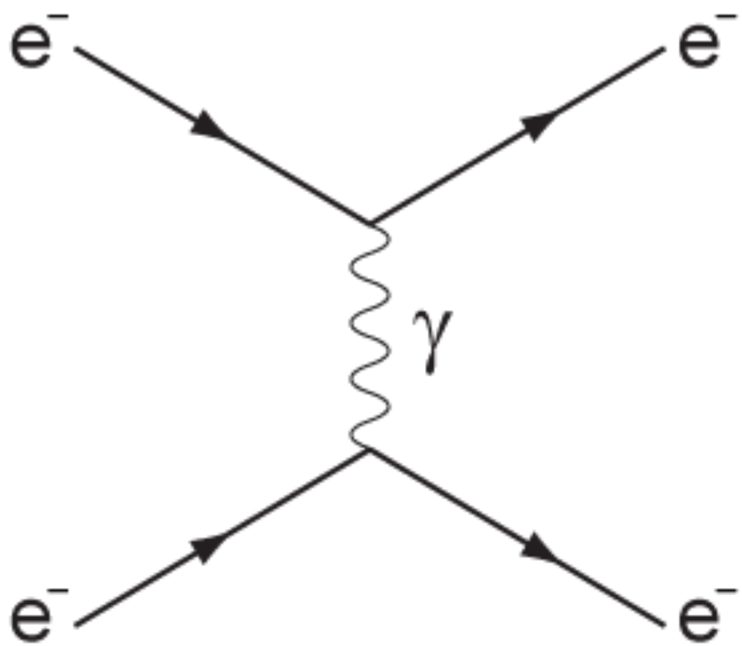
Hyperphysics

Gravitational

Not in Standard Model

How do forces act on particles?



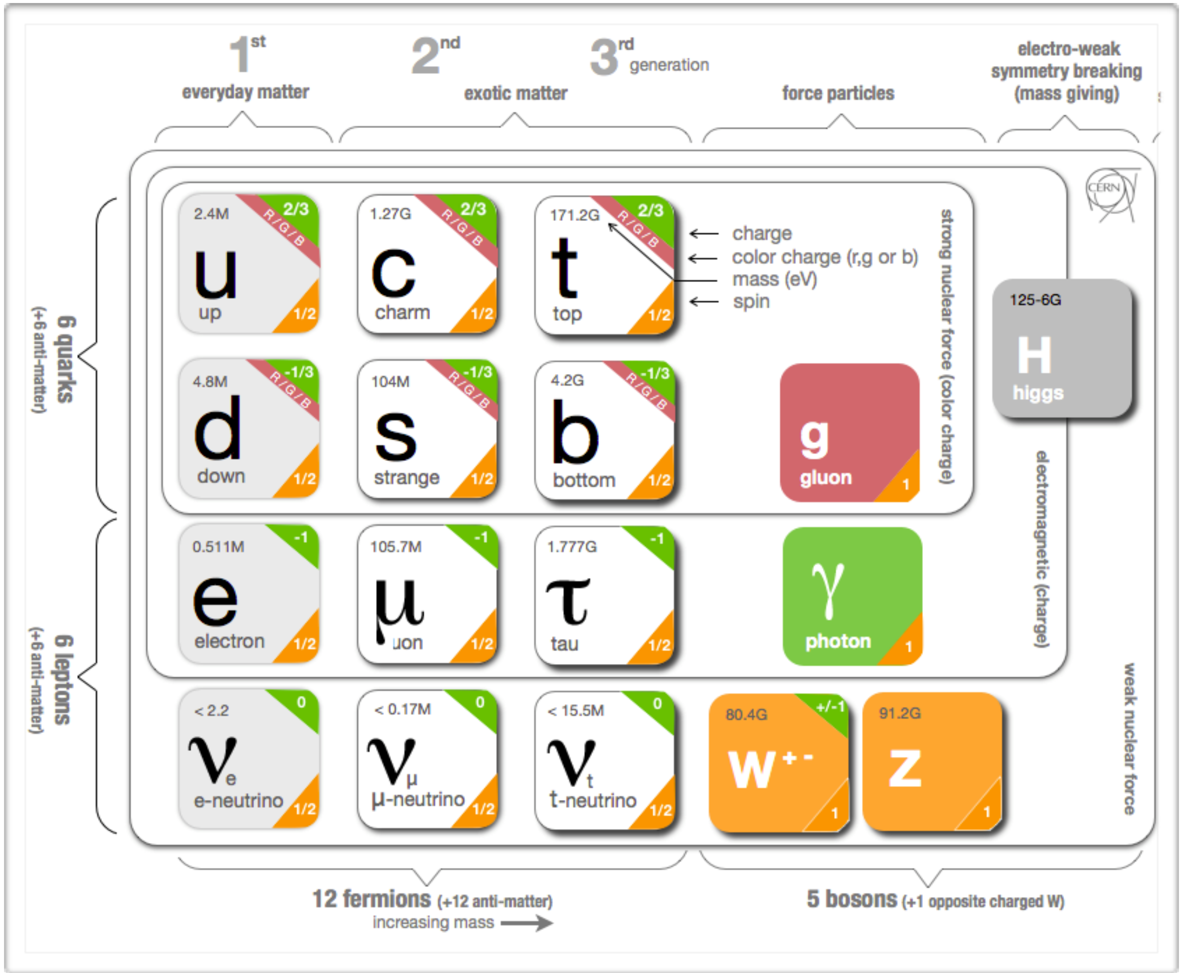


By [[:en:User:{{{1}}}|{{{1}}}]] at Wikipedia

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**!

The electromagnetic force

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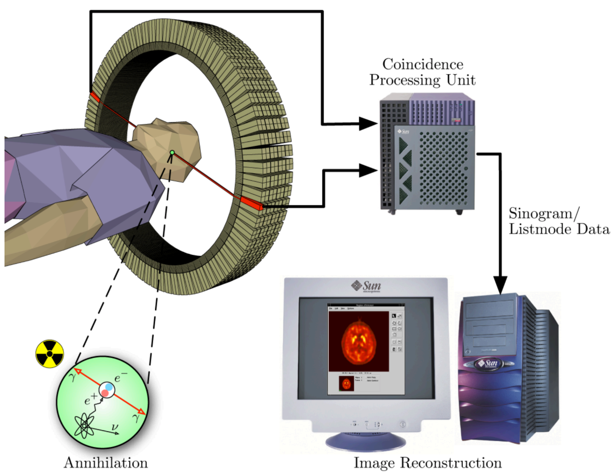
Electromagnetic force in 30 seconds

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)

The weak force

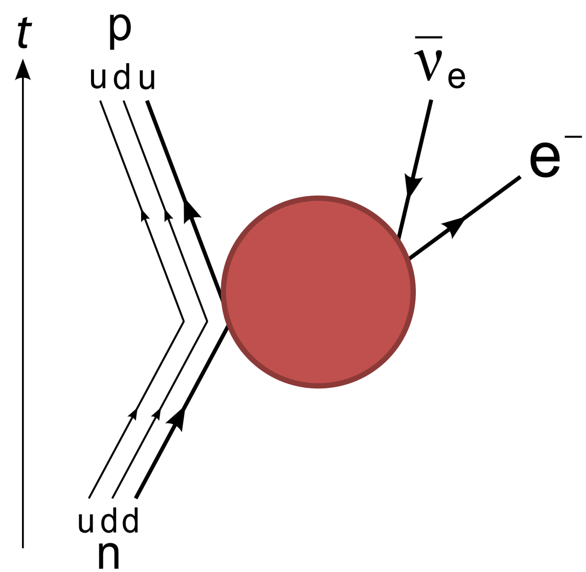
Weak interactions vs EM interaction

Force	*Charge*	*Mediator*	*Range*
EM	*Electric charge*	*photon*	*Long*
Weak	Weak isospin	*weak bosons*	*Short*

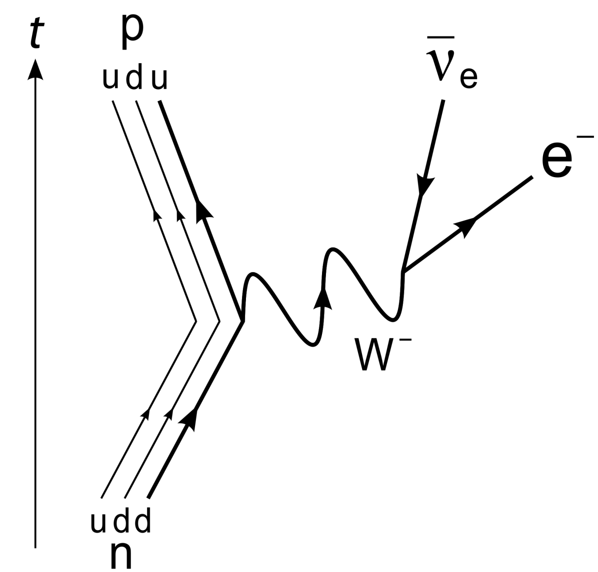
Why?

From Fermi theory to Electroweak theory

1934 **Electroweak theory (1960s)**

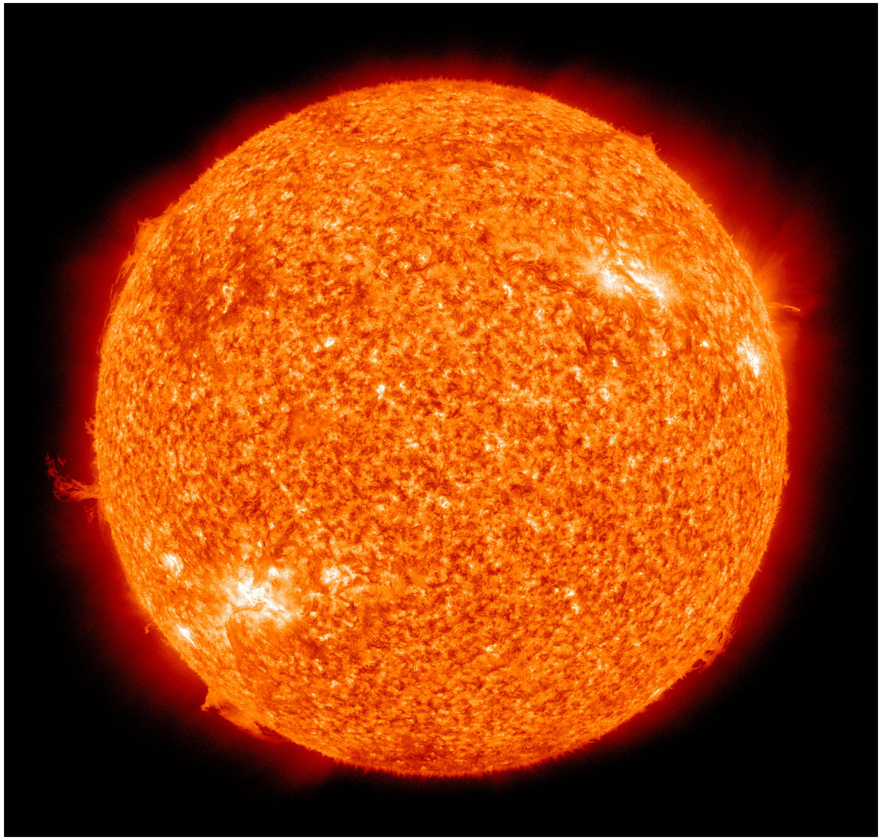


Fermi theory fails at higher energies, therefore…

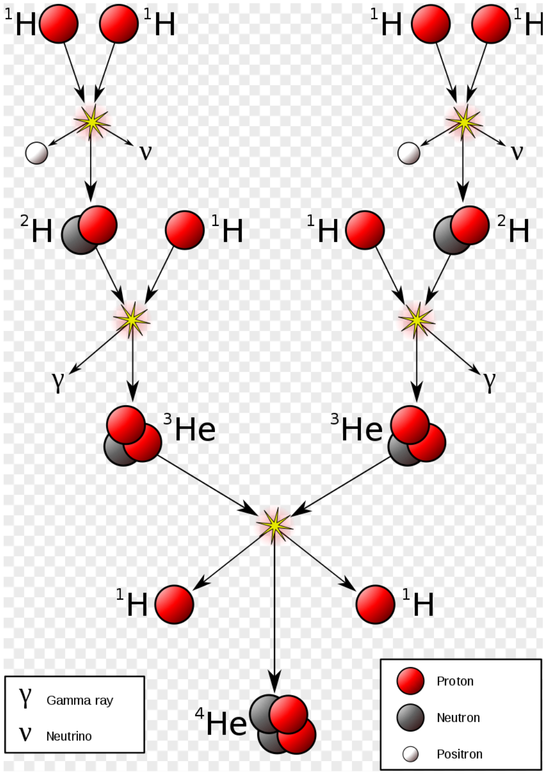


Problems: the W
- has not been discovered
- should be massive, but this “breaks” the SM

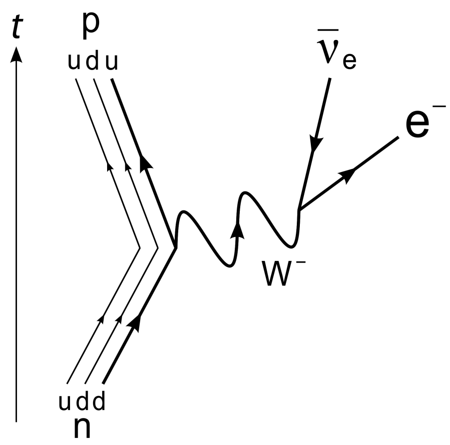
The sun and weak interactions



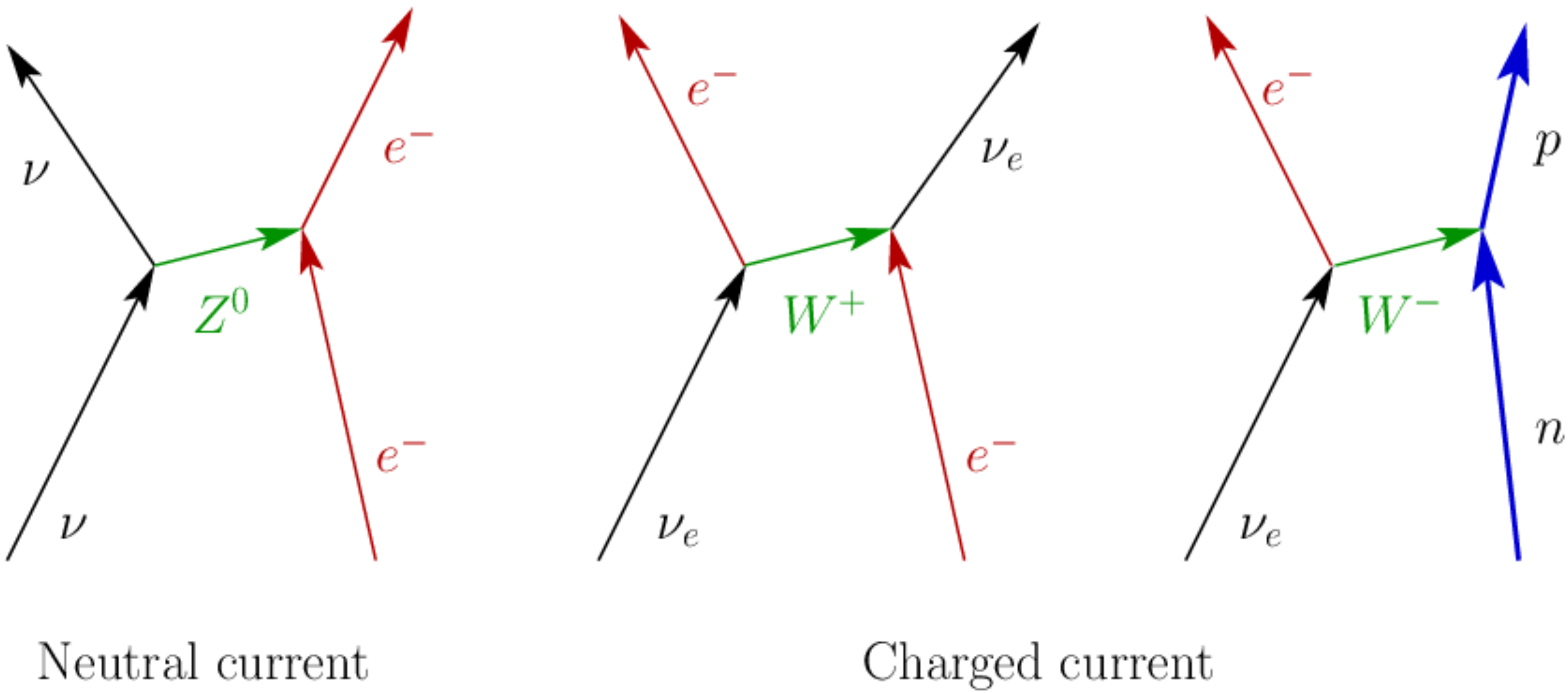
NASA



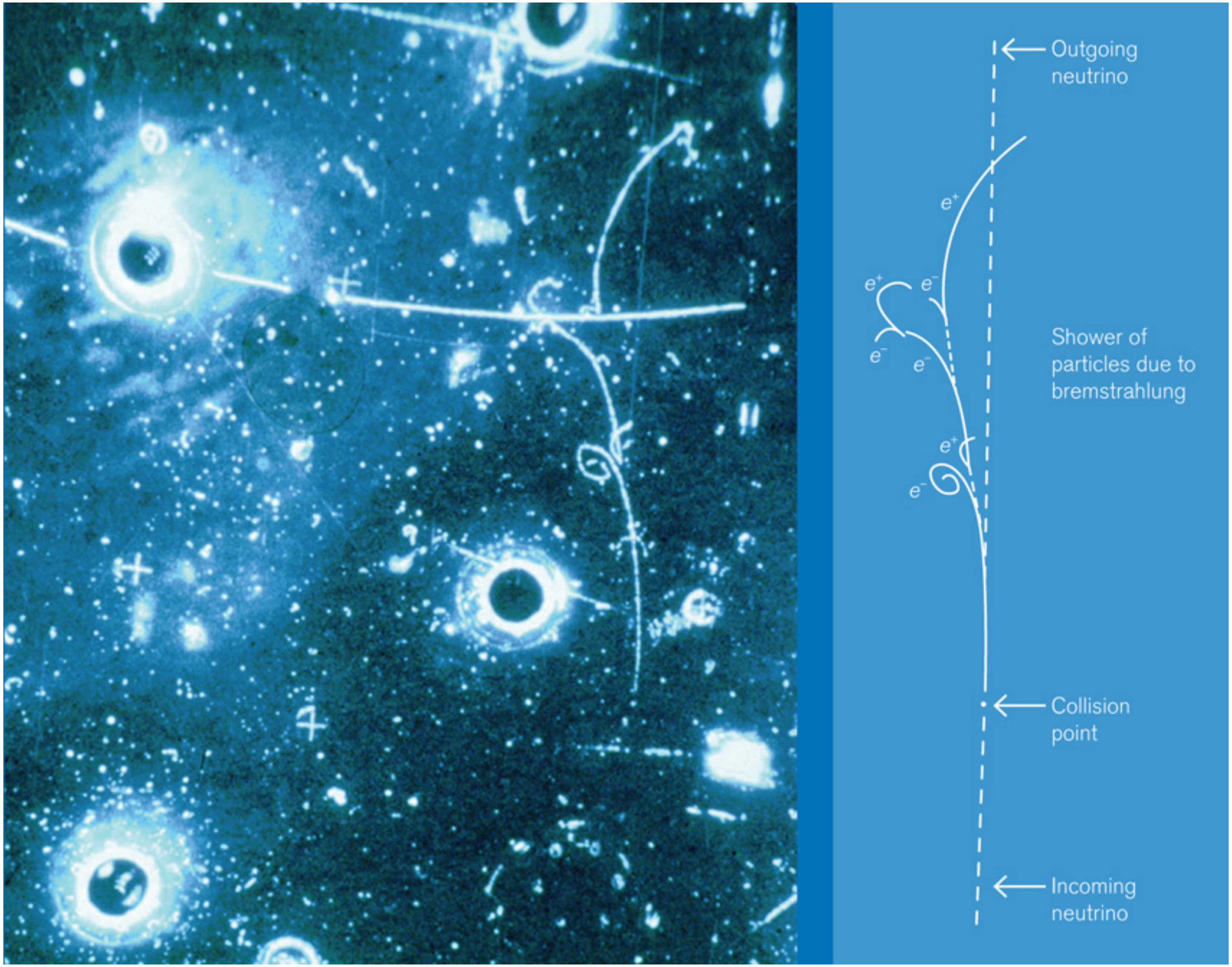
proton-proton chain reaction



Charged (CC) and neutral (NC) currents



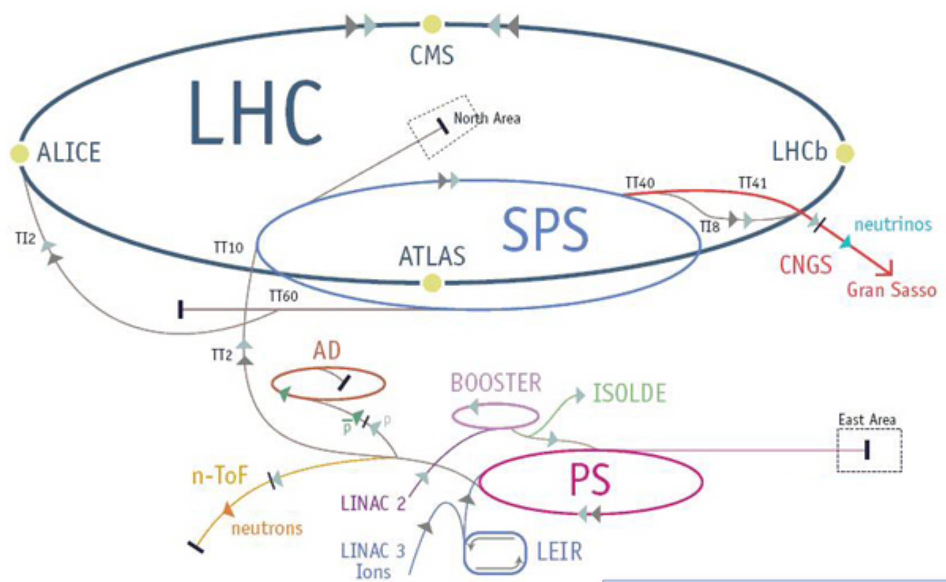
The indirect discovery of the Z



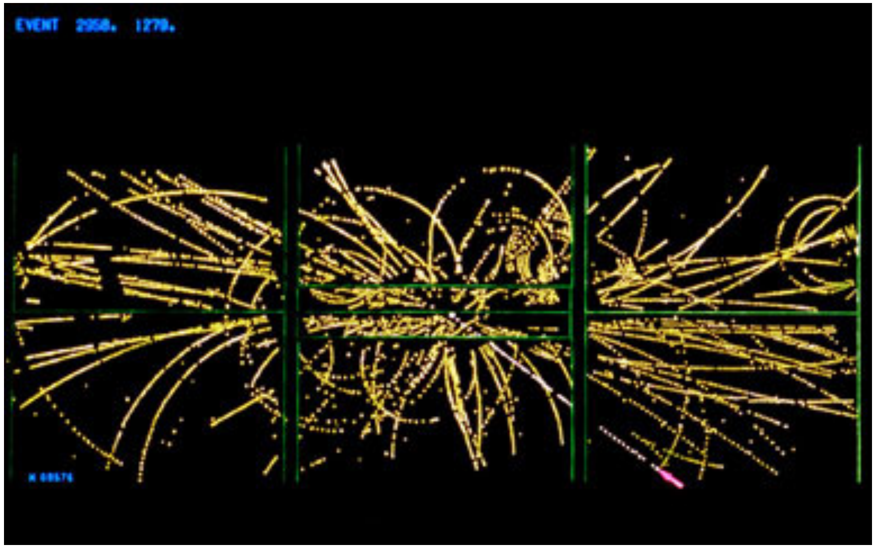
http://www.symmetrymagazine.org/article/august-2009/weak-neutral-current

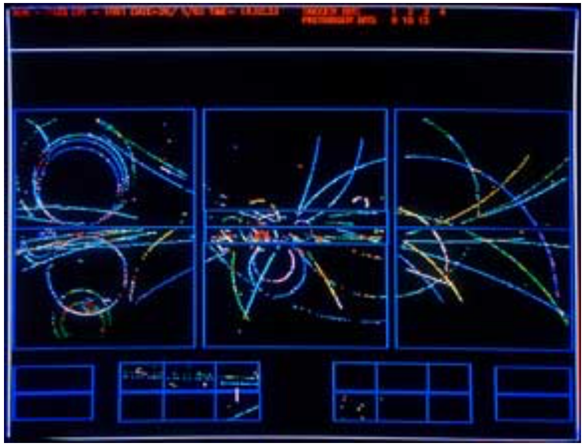
The discovery of the W/Z (1980s)

Mass of W and Z: ~ 100 GeV
→ need a new accelerator (SppS)



More in Part 3





"They look like W's, they feel like W's, they smell like W's, they must be W's!" (Carlo Rubbia)

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Electro+weak theory by Weinberg

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

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

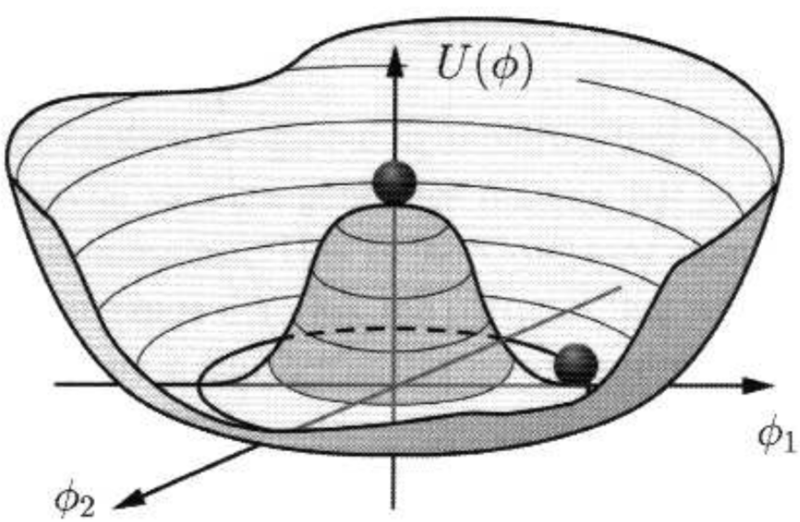
Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon 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.[3] 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!

$$\gamma = \sin\theta_W \cdot W^o + \cos\theta_W \cdot B$$ massless

$$Z^o = \cos\theta_W \cdot W^o - \sin\theta_W \cdot B$$ massive



Symmetry is broken (in 1-dimension):
~not rotationally invariant

More in Part 3

The strong force

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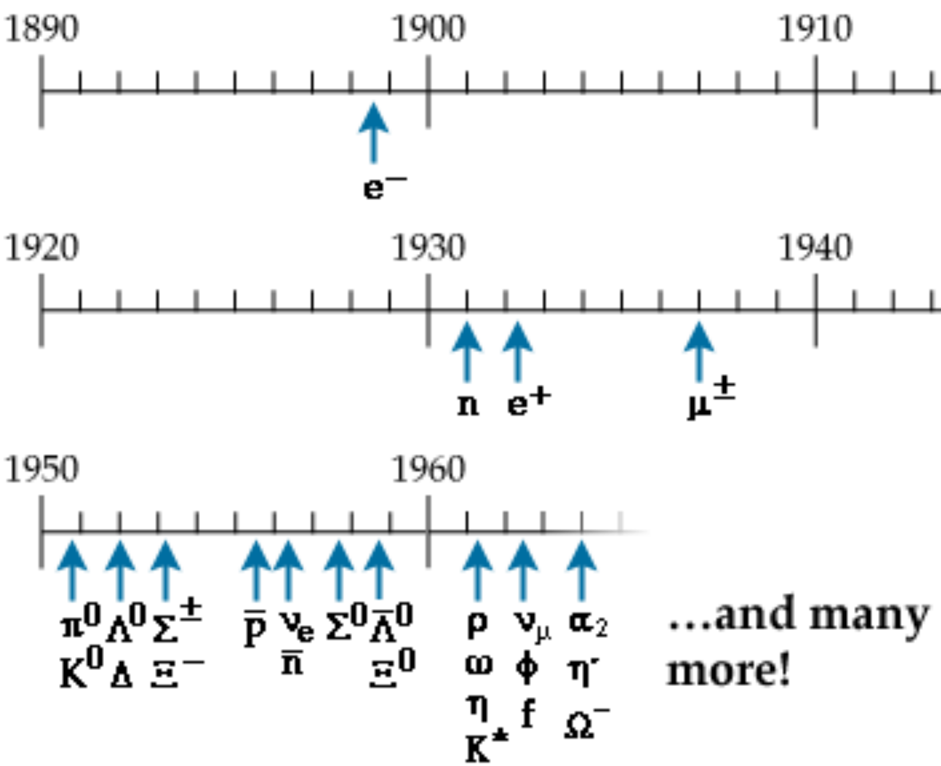
Particle situation as of the 1960s

[Particle Adventure website](#)



WILLIS E. LAMB, JR.

Fine structure of the hydrogen atom

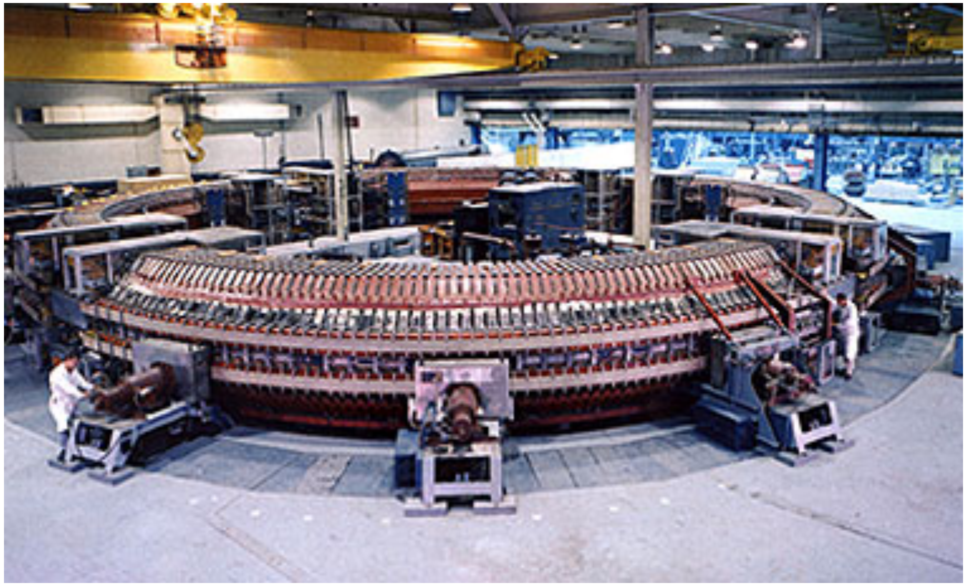
Nobel Lecture, December 12, 1955

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, μ meson, π 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

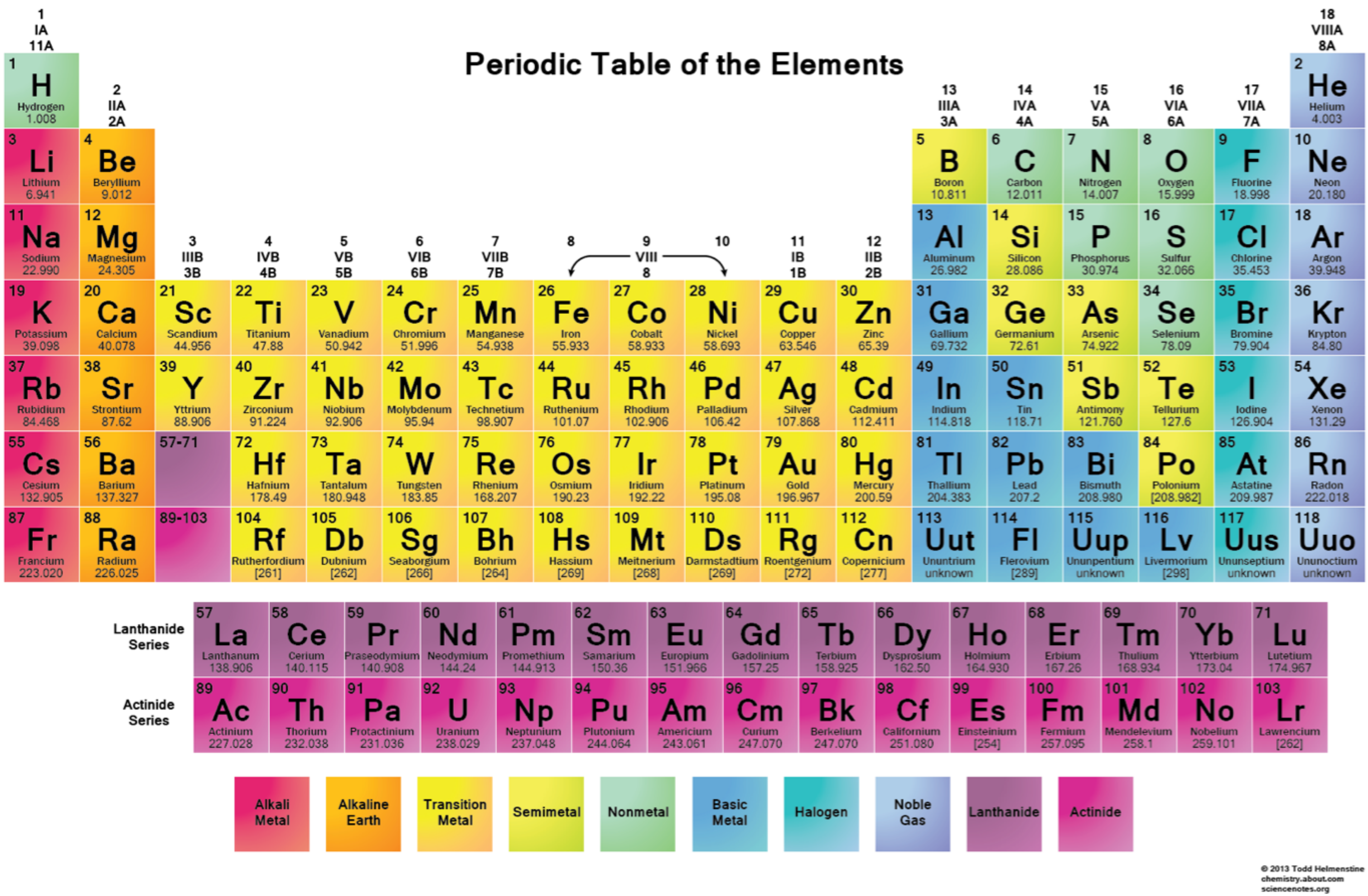
Bevatron - LBNL - 1954-1993
Billions of electron volts (6.5 GeV/beam)

interactions.org

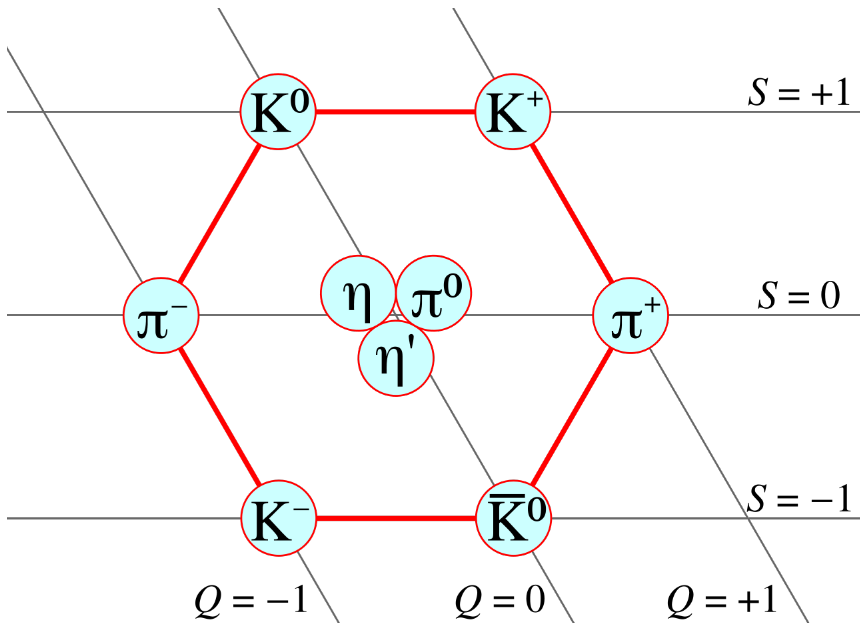
Experimental study of the *spectroscopy* of zoo of composite particles!

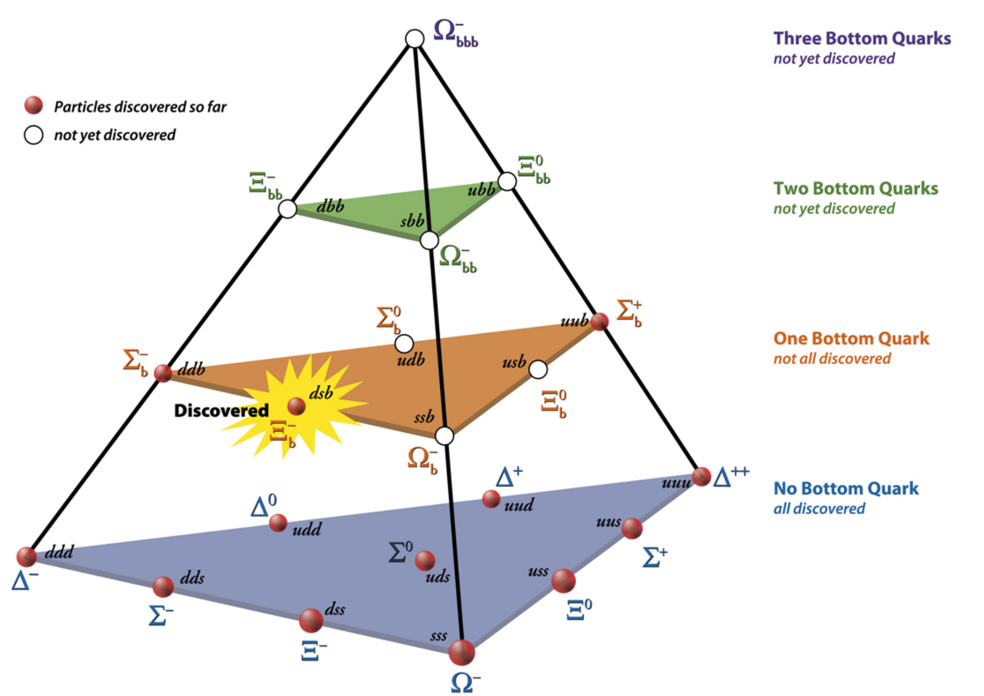
Electromagnetic force   Weak force   Strong force

Our initial analogy…



Categorize hadrons according to spin & charge

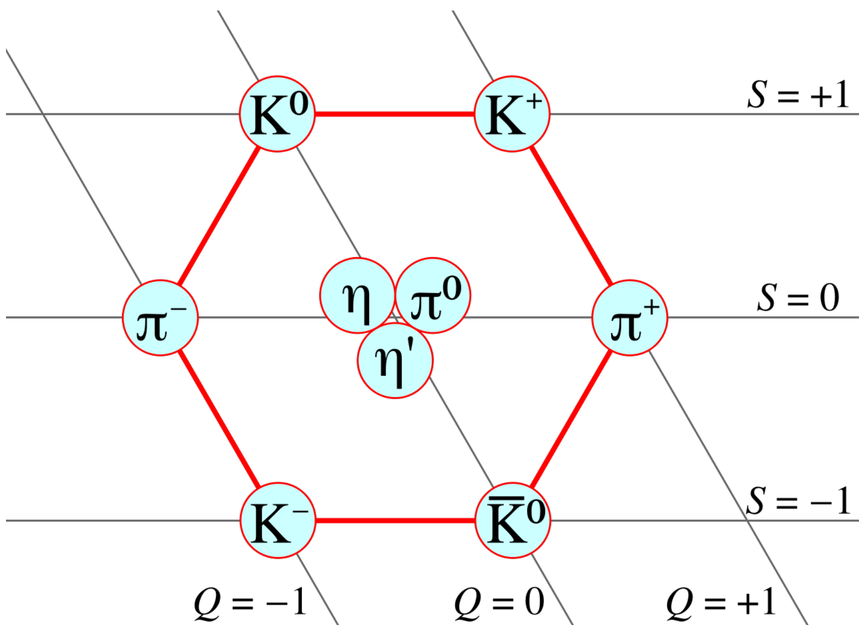


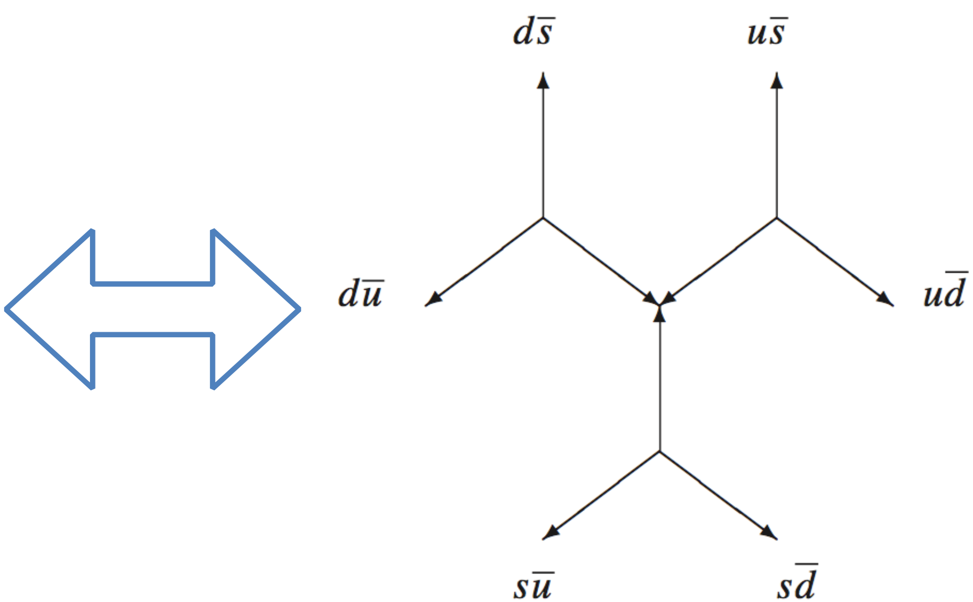


Particle groupings and and quarks

Gell-Mann / Zweig: *"Three quarks for muster Mark" (J. Joyce, Finnegans Wake)*

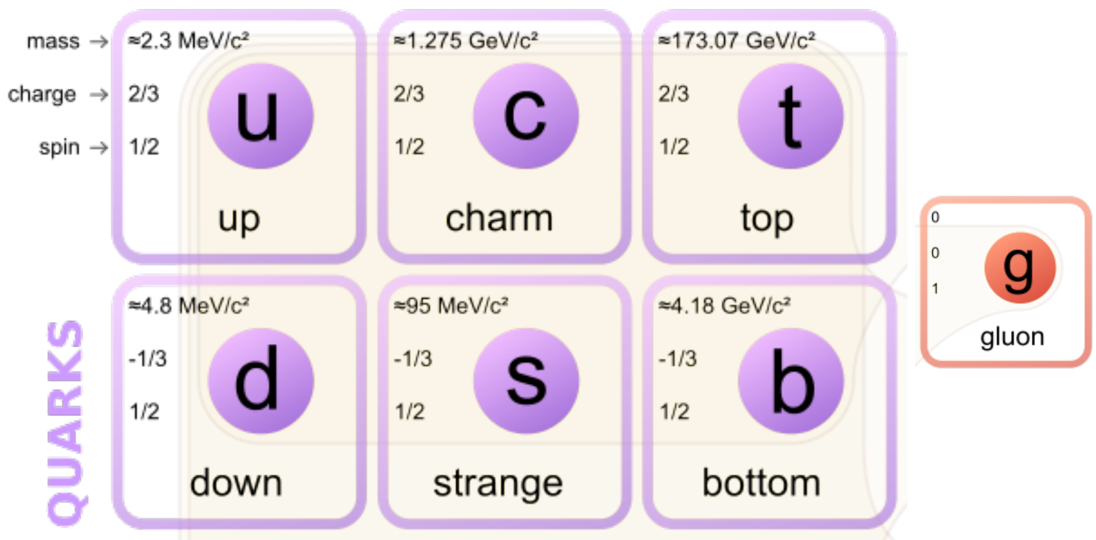
- hadrons are built by three constituent quarks, **u d** and ***s***
- *mesons are composed by **quark/antiquark** pairs*



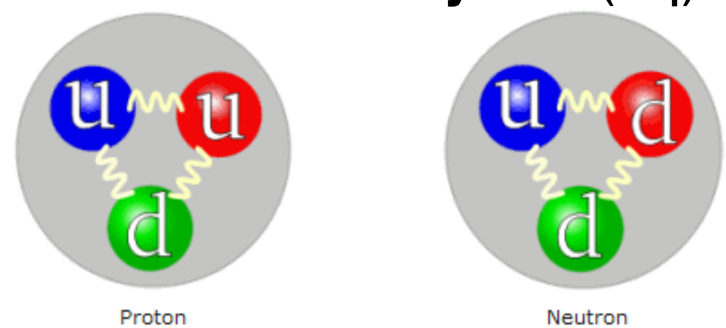


Introducing the quarks and the gluon

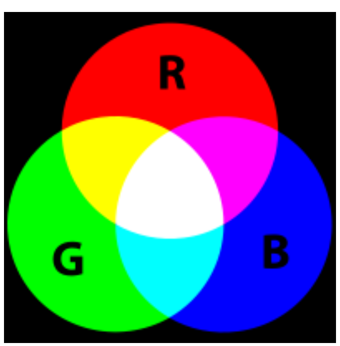
Hadrons = particles made of quarks & gluons, interacting via the strong force



Protons are **baryons** (3q)



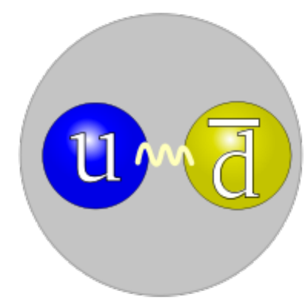
Quark composition of a proton and a neutron (diagrams from *Wikipedia*)



Quarks have **color**
Hadrons are **colorless**

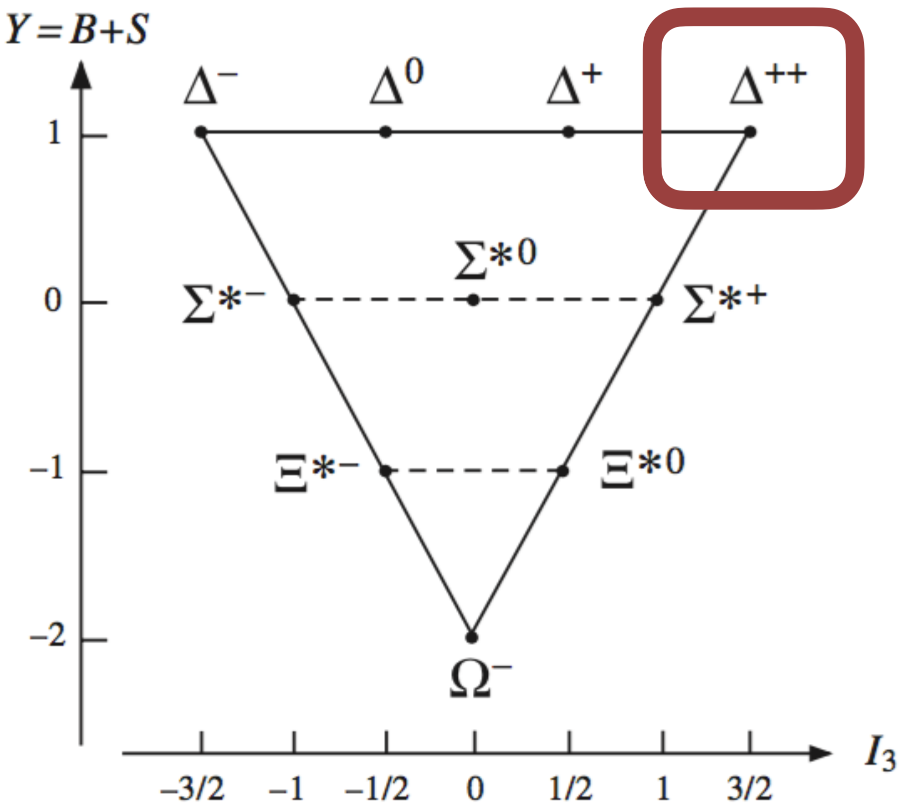
Pions are **mesons** (q-qbar)

π^+: $u\bar{d}$
π^0: $u\bar{u}$ or $d\bar{d}$
π^-: $d\bar{u}$



Images: Wikipedia

Color: what about the Δ and Pauli's principle?



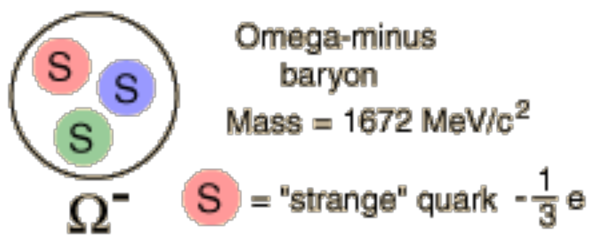
Quarks: uuu
Parity: +
Charge: 2
Spin: 3/2 -> spins are aligned
Isospin: Q+Y/2 = 3/2

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



Hyperphysics

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':

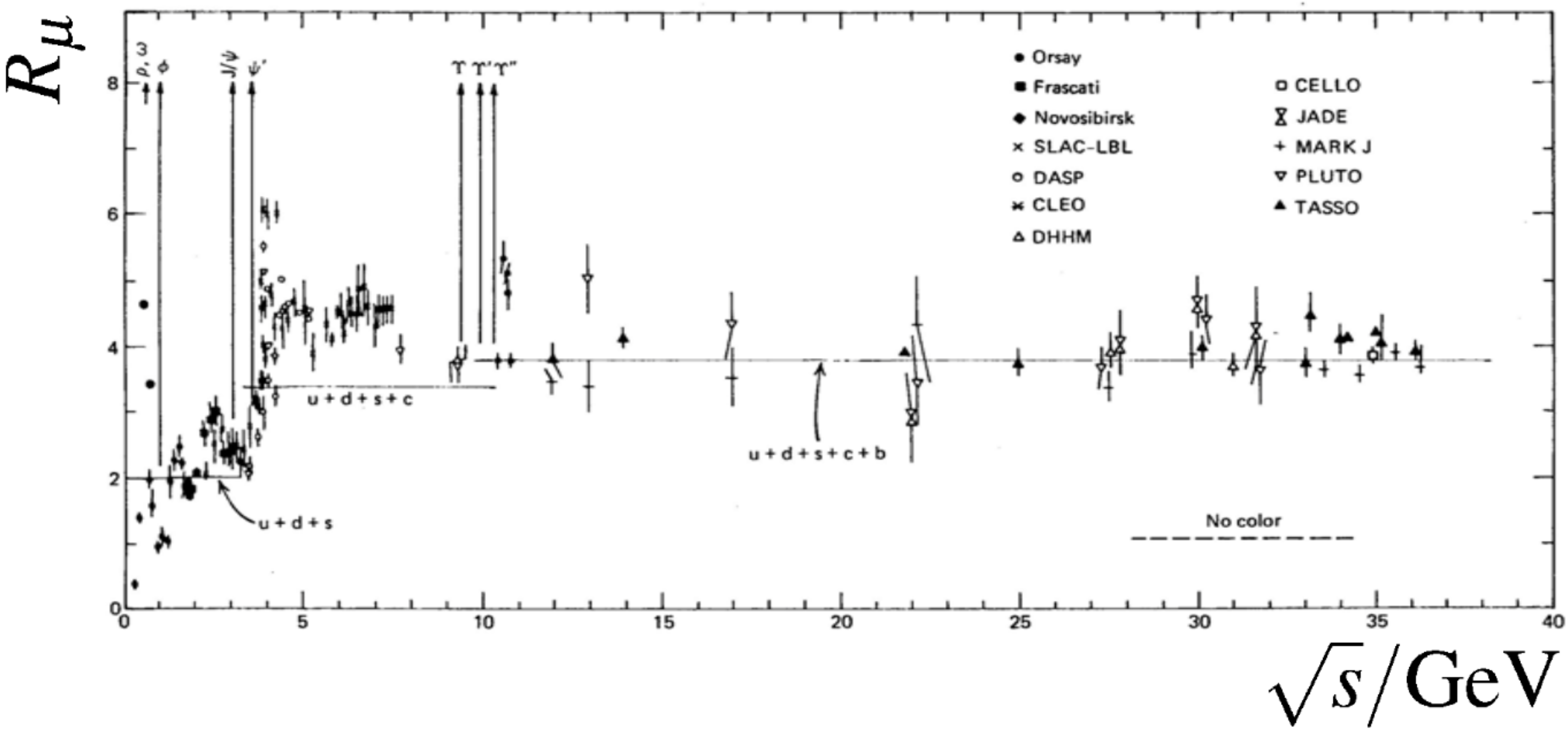
$$I_3^C = Y^C = 0,$$

Baryons and mesons are colourless

Evidence of color

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

= 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

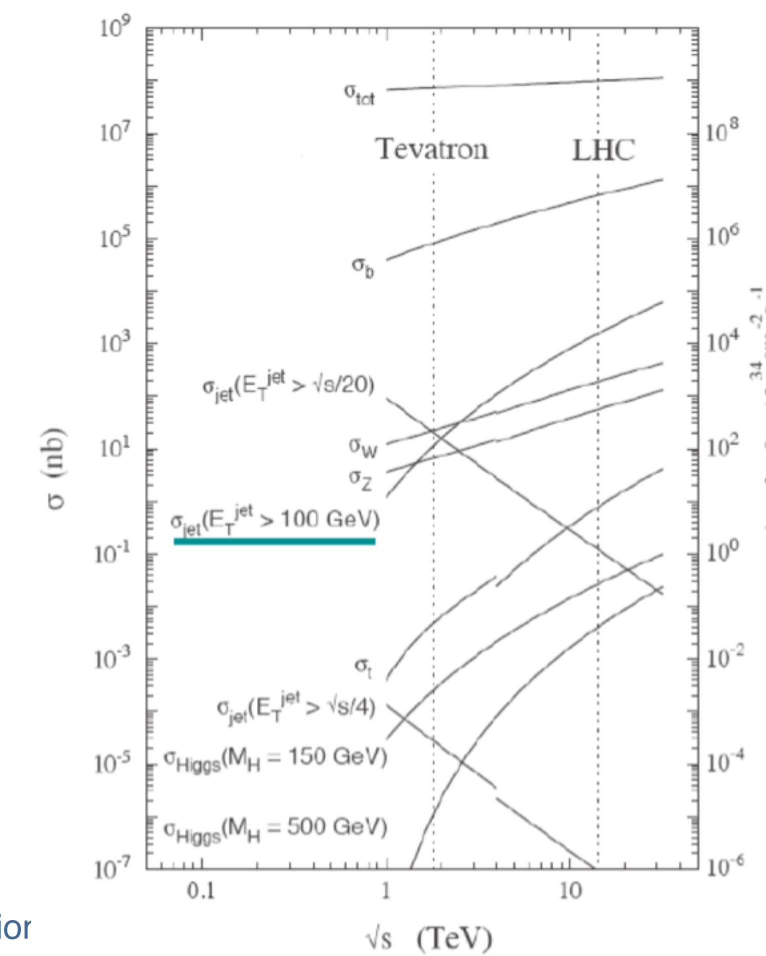
Large **Hadron** Collider: Quark and gluon (→ jet) factory
Force describing interactions of quarks and gluons: **QCD**

Measure QCD processes:

Precision measurements of the Standard Model

Search for deviations from QCD:

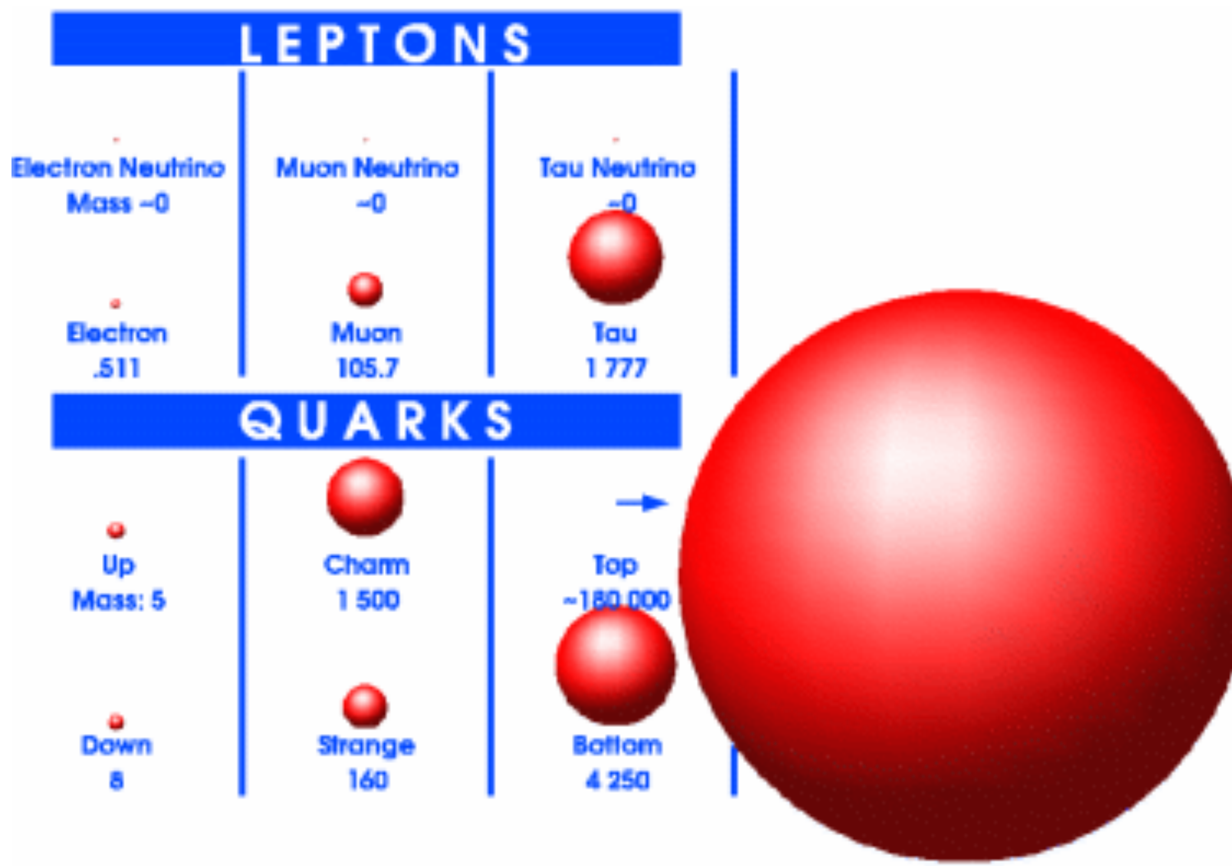
look for new particles decaying into quarks and gluons



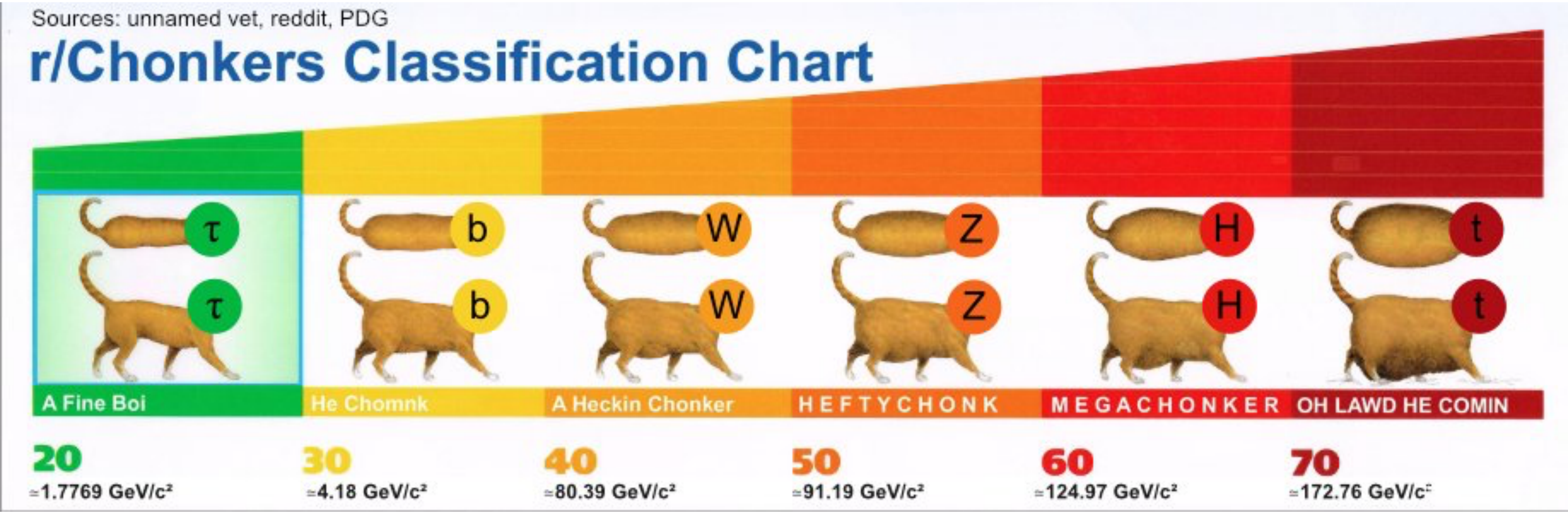
Three generations of quarks

<1971	1974	1995
u up	c charm	t top
d down	s strange	b bottom
<1971	<1971	1977
<1971	<1971	1975
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
e electron	μ muon	τ tau
<1971	<1971	1975

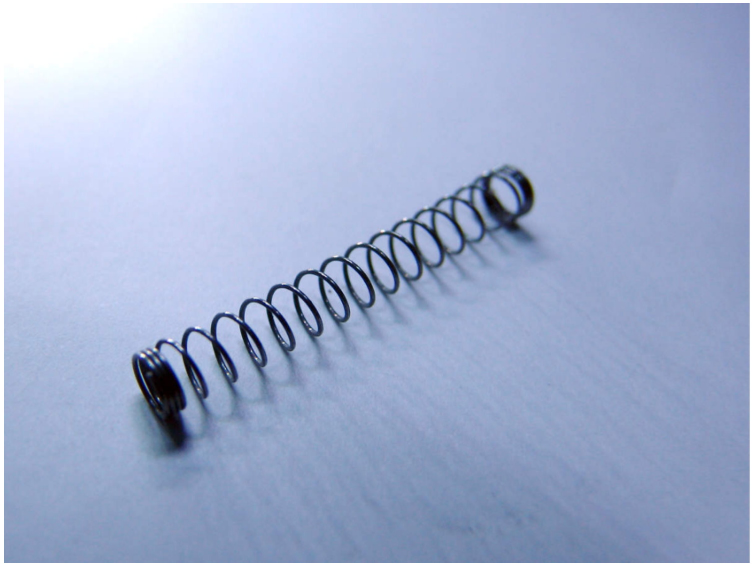
Not covered here: quarks can turn into each other via the W boson (Cabibbo-Kobayashi-Maskawa mechanism)



The inevitable cat meme



QCD (color) force as a spring

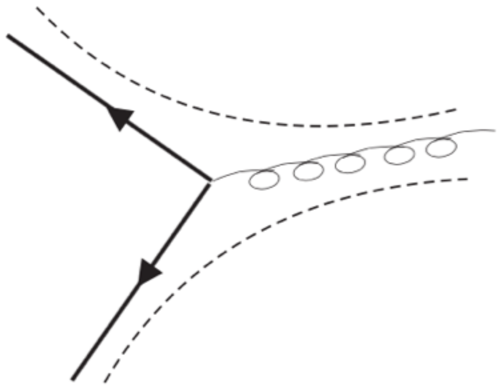


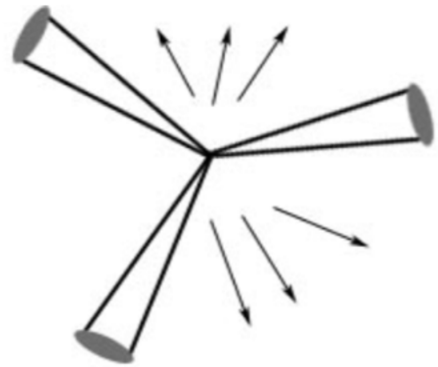
Intuitively:
energy needed to pull quarks apart > energy needed to create a new hadron

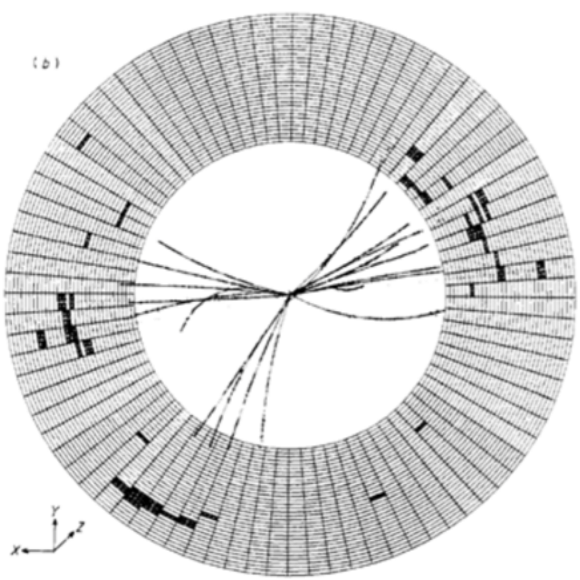
QCD: *confinement and asymptotic freedom*

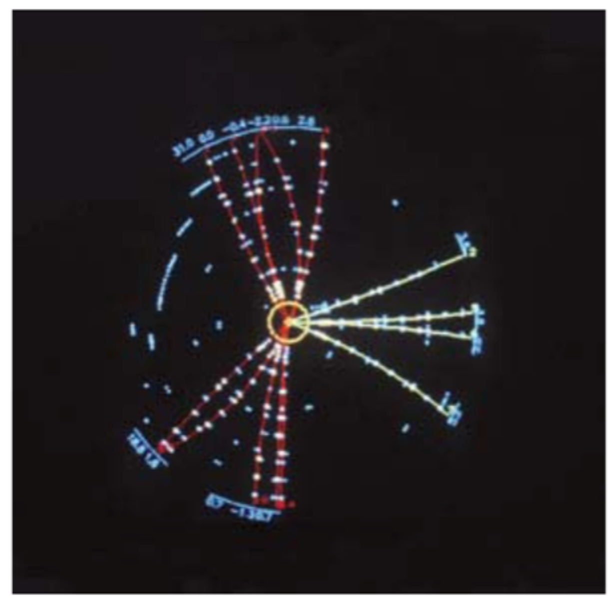
Consequence: since quarks can't be observed alone, hadron interactions (like at the LHC) create **showers of hadrons** (*parton showers*)

The discovery of the gluon







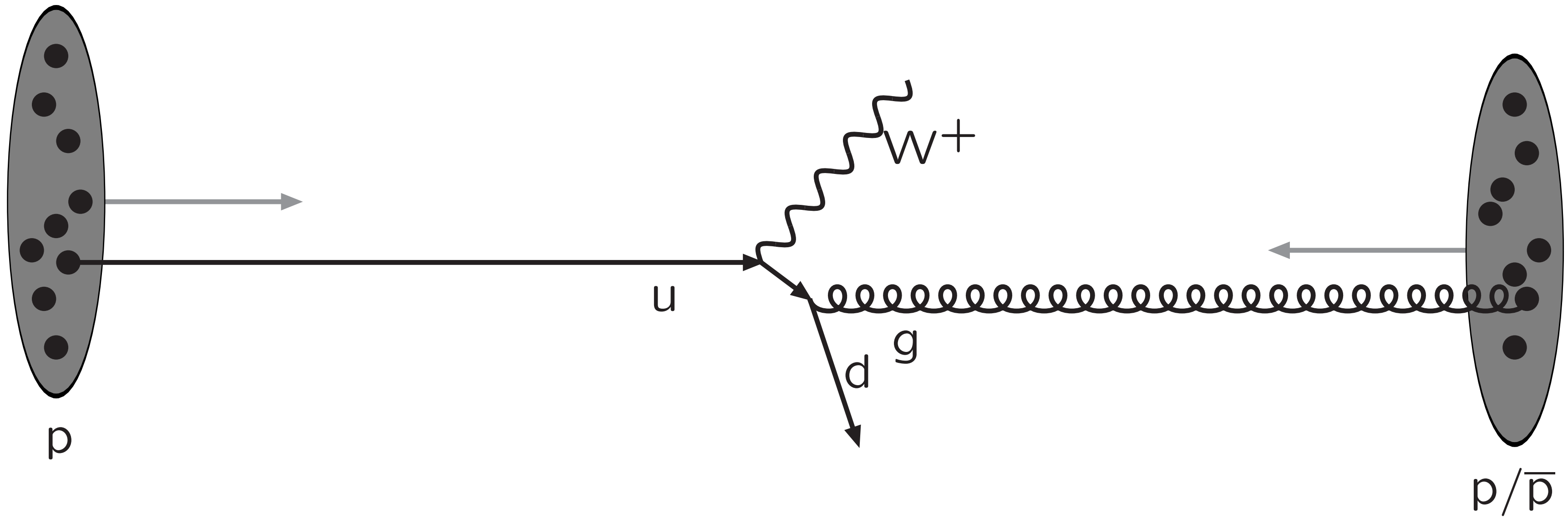


The structure of an event

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

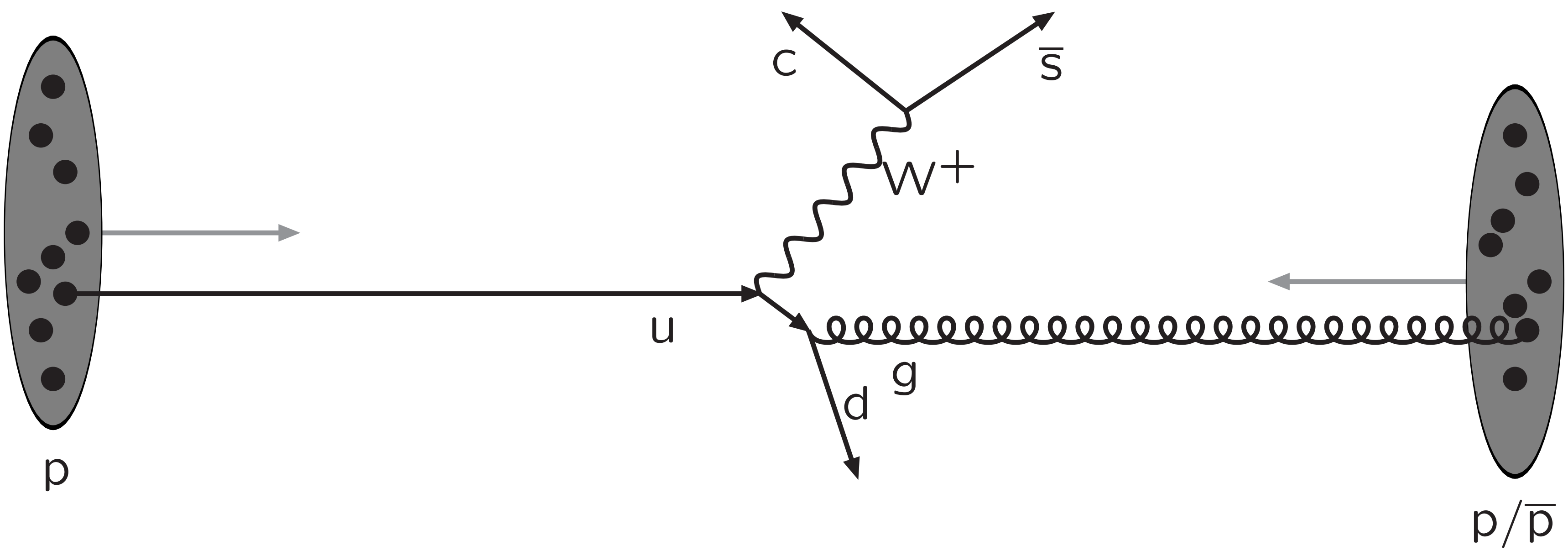
Incoming beams: parton densities

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf

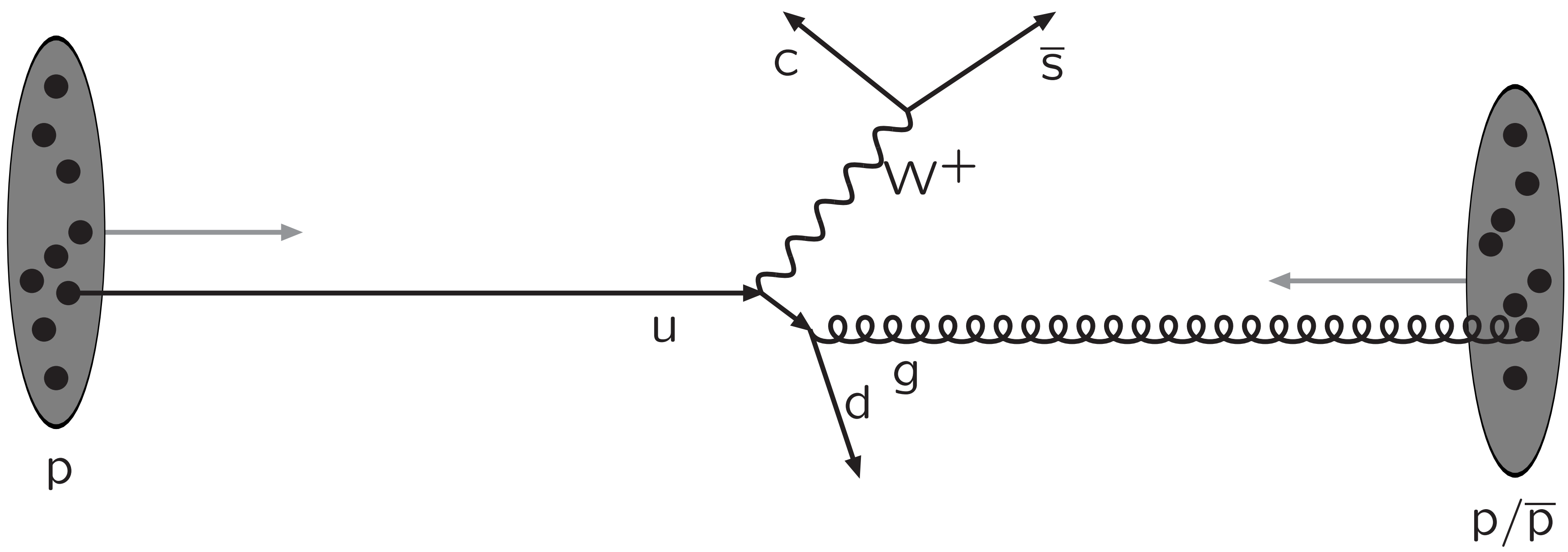


Hard subprocess: described by matrix elements

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



Resonance decays: correlated with hard subprocess



Resonance decays: correlated with hard subprocess

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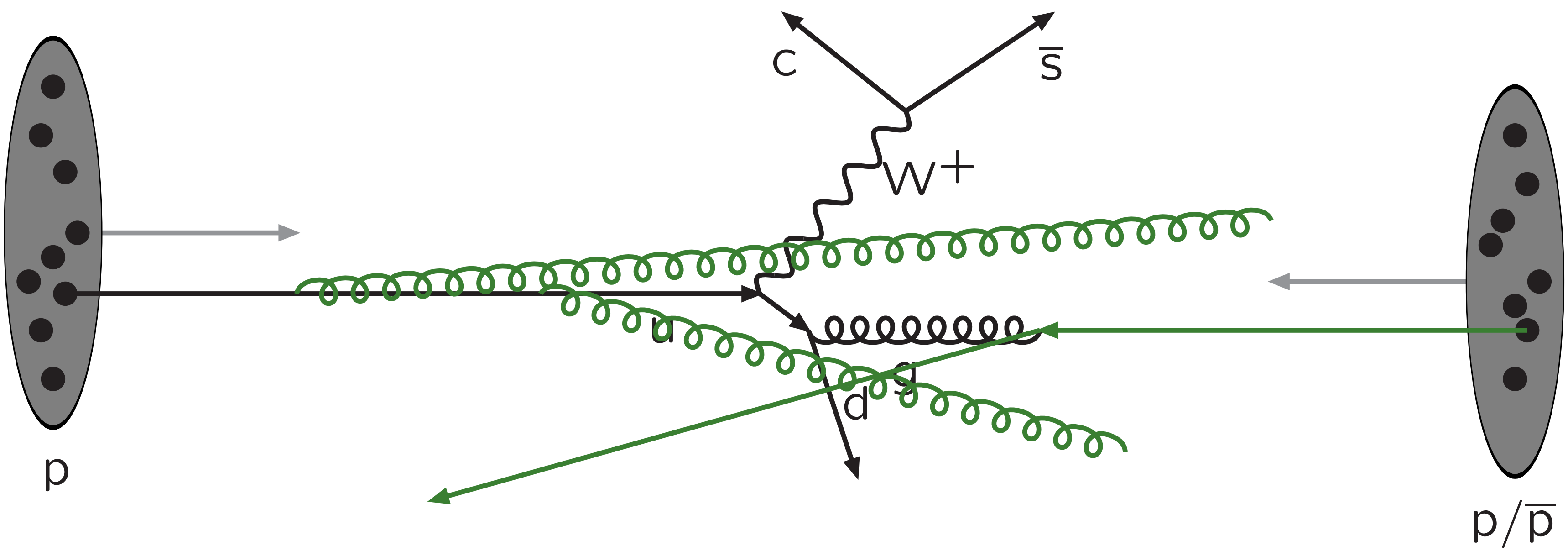
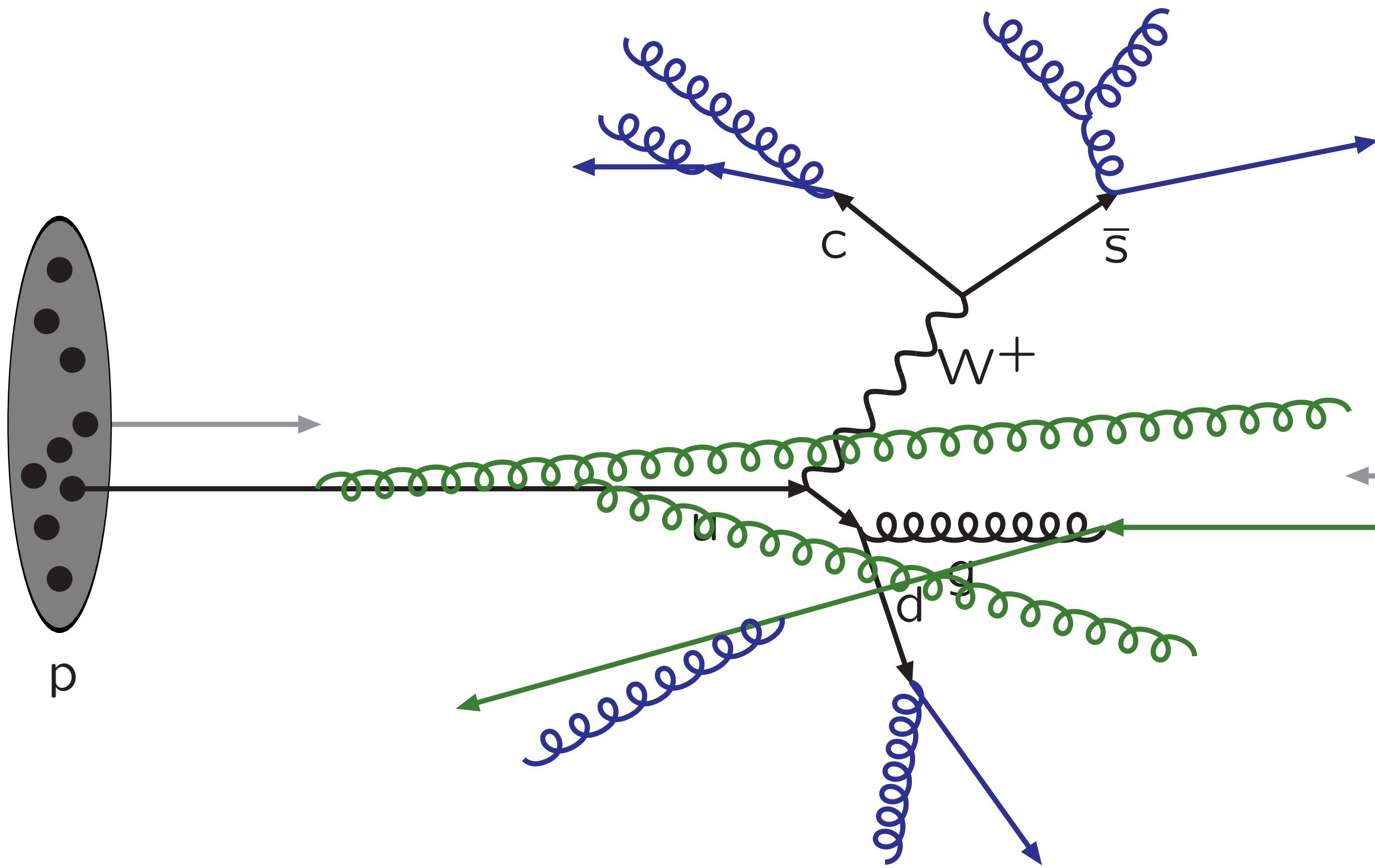


Initial-state radiation: spacelike parton showers

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



Final-state radiation: timelike parton showers

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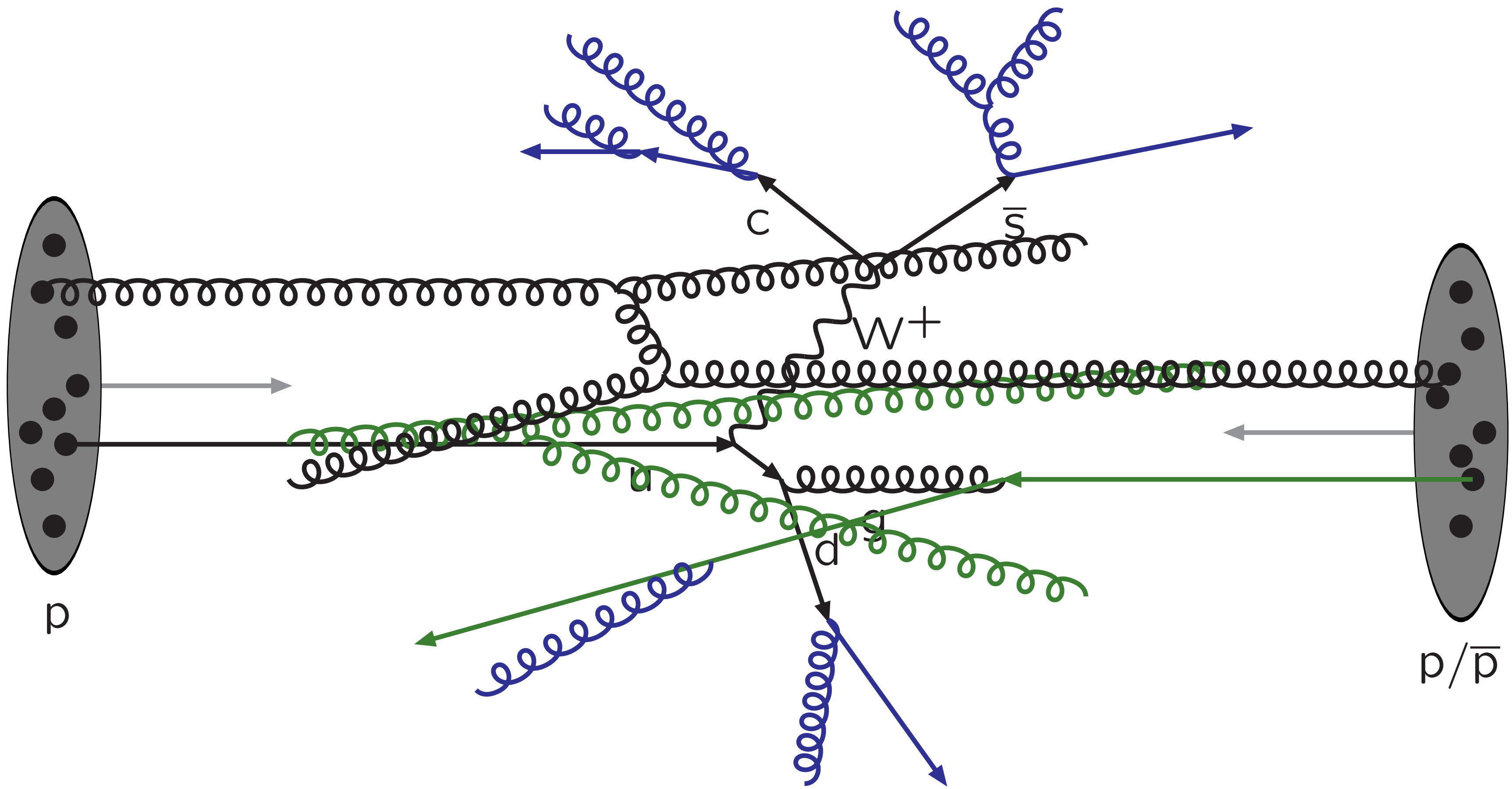
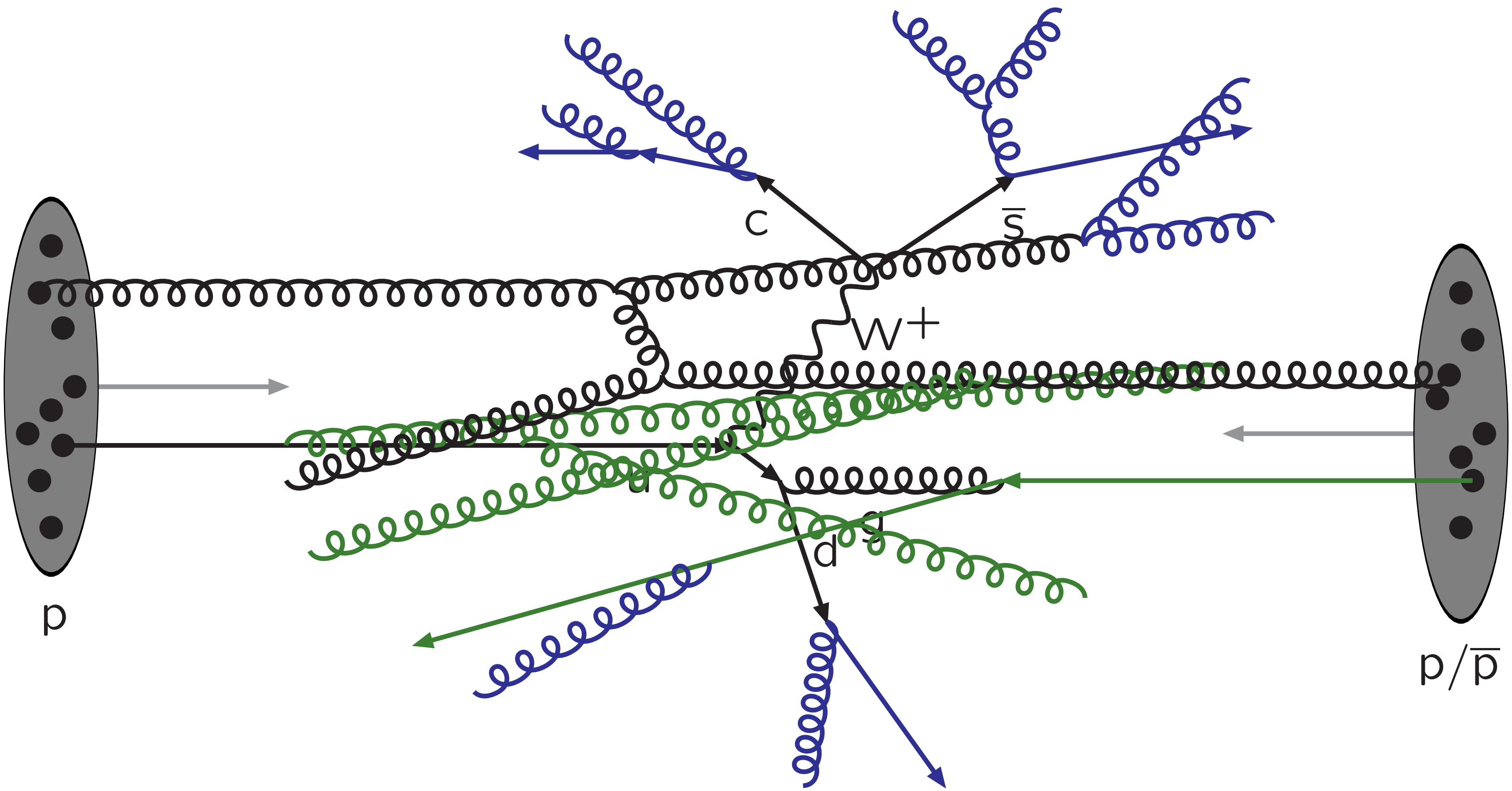


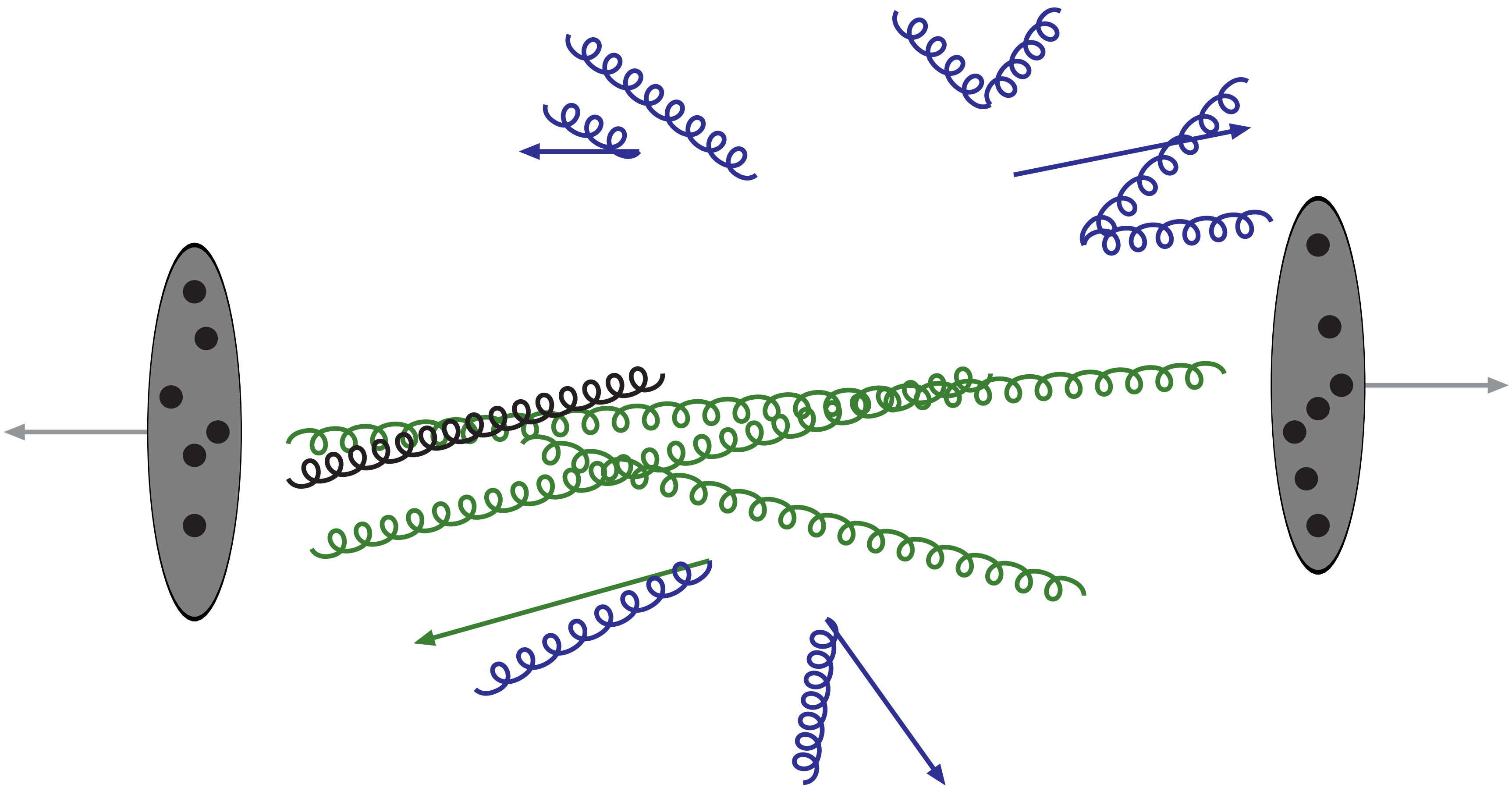
Multiple parton–parton interactions . . .

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



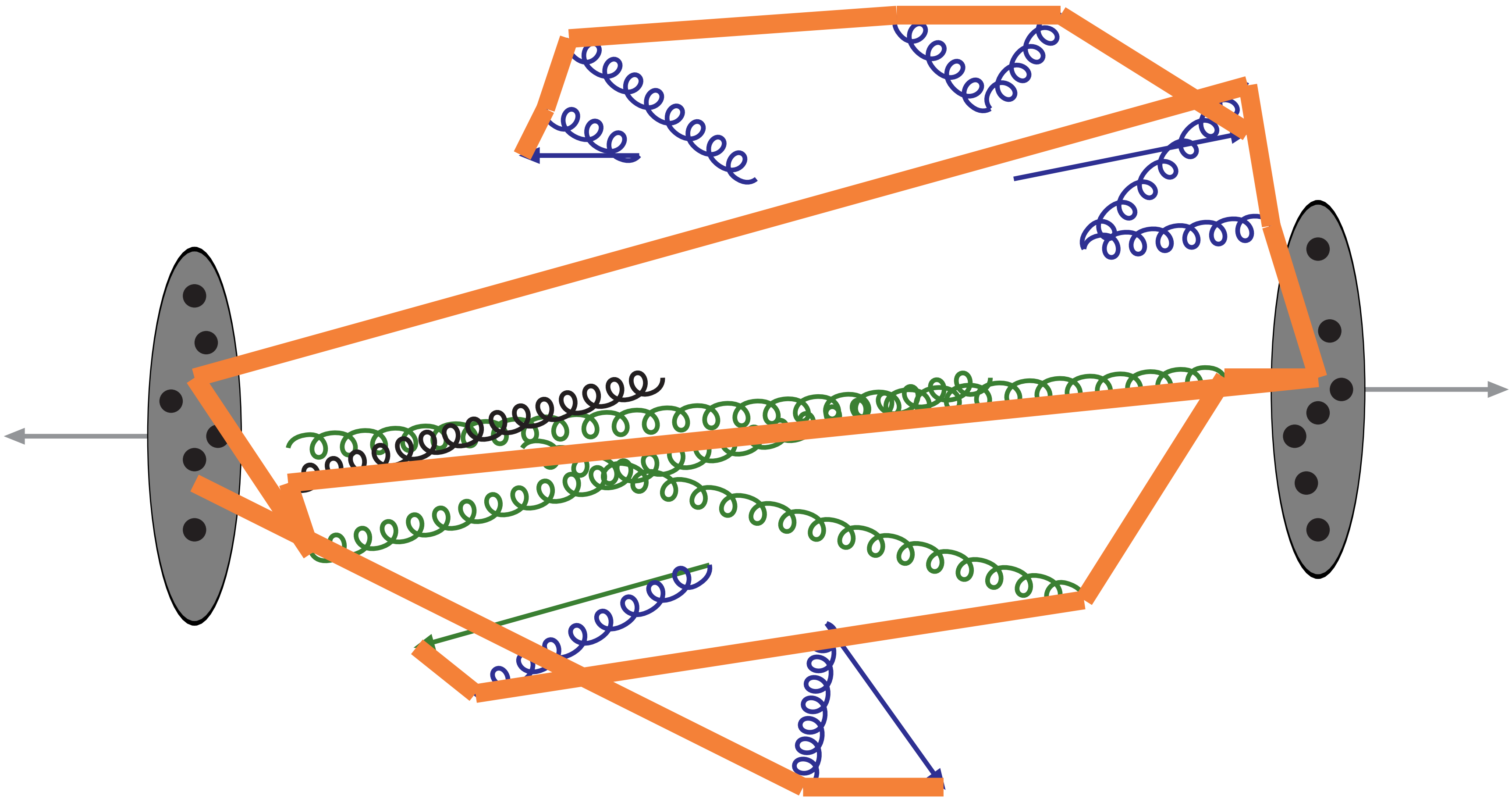
... with its initial- and final-state radiation

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



Beam remnants and other outgoing partons

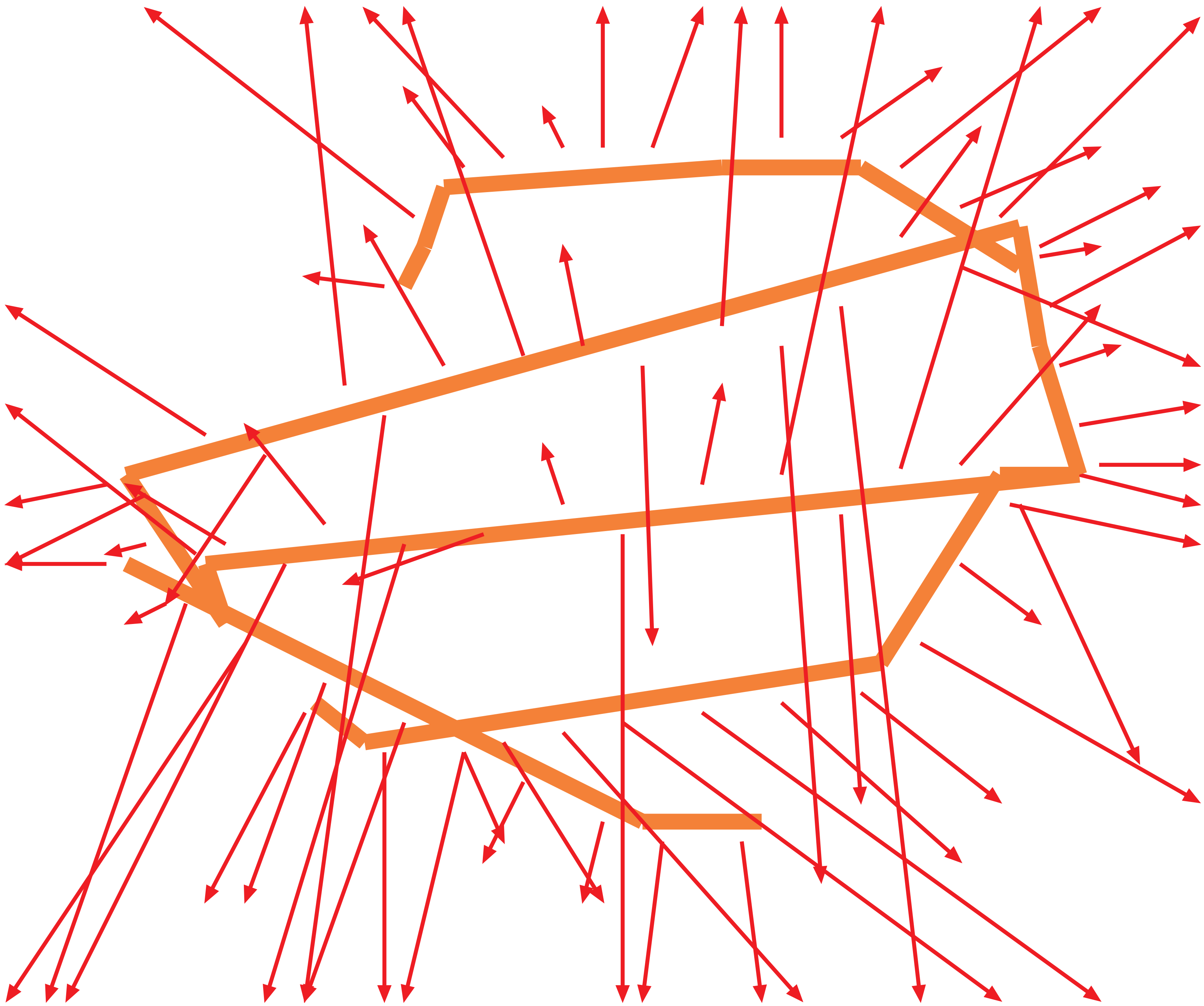
T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



Everything is connected by colour confinement strings

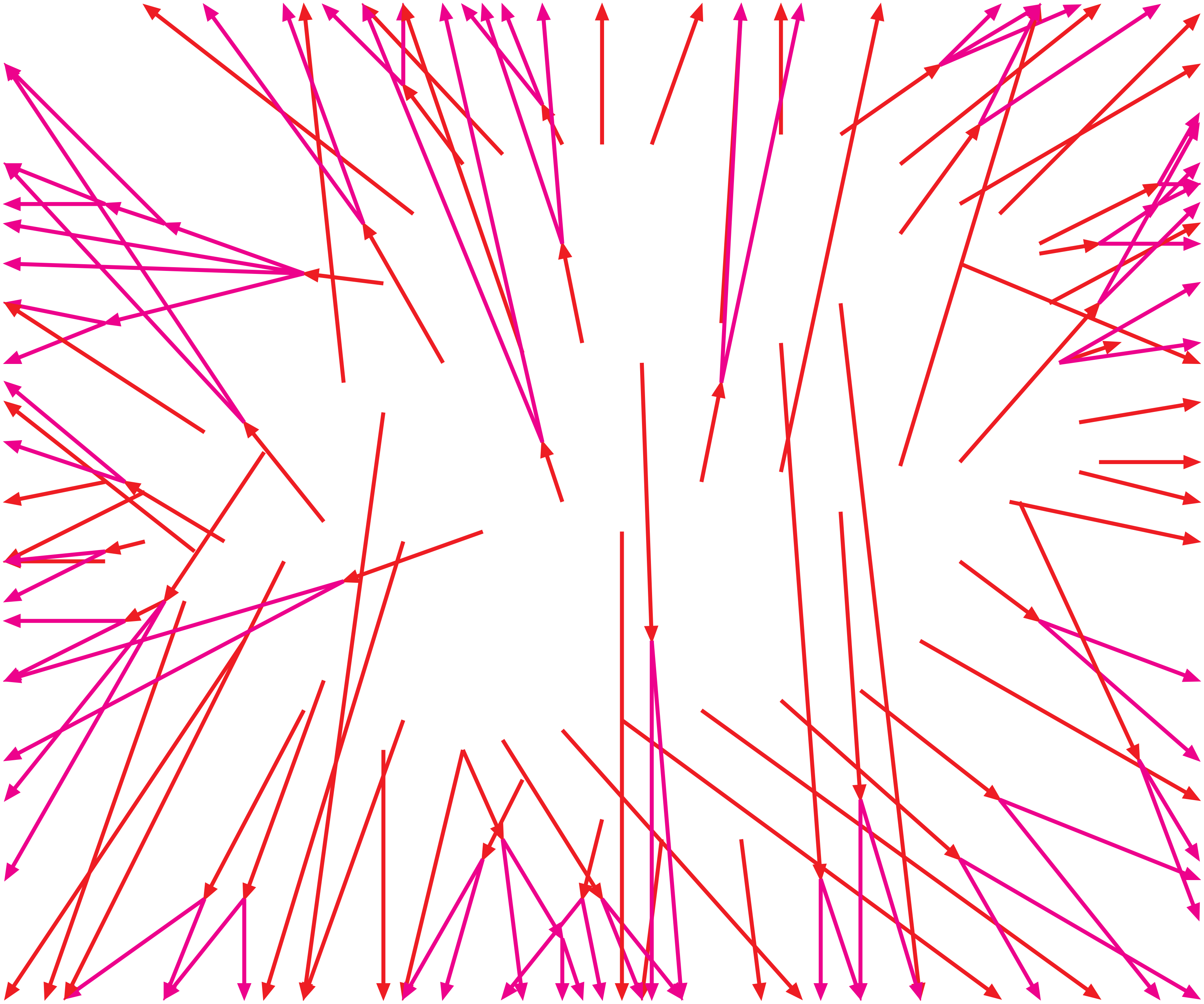
Recall! Not to scale: strings are of hadronic widths

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



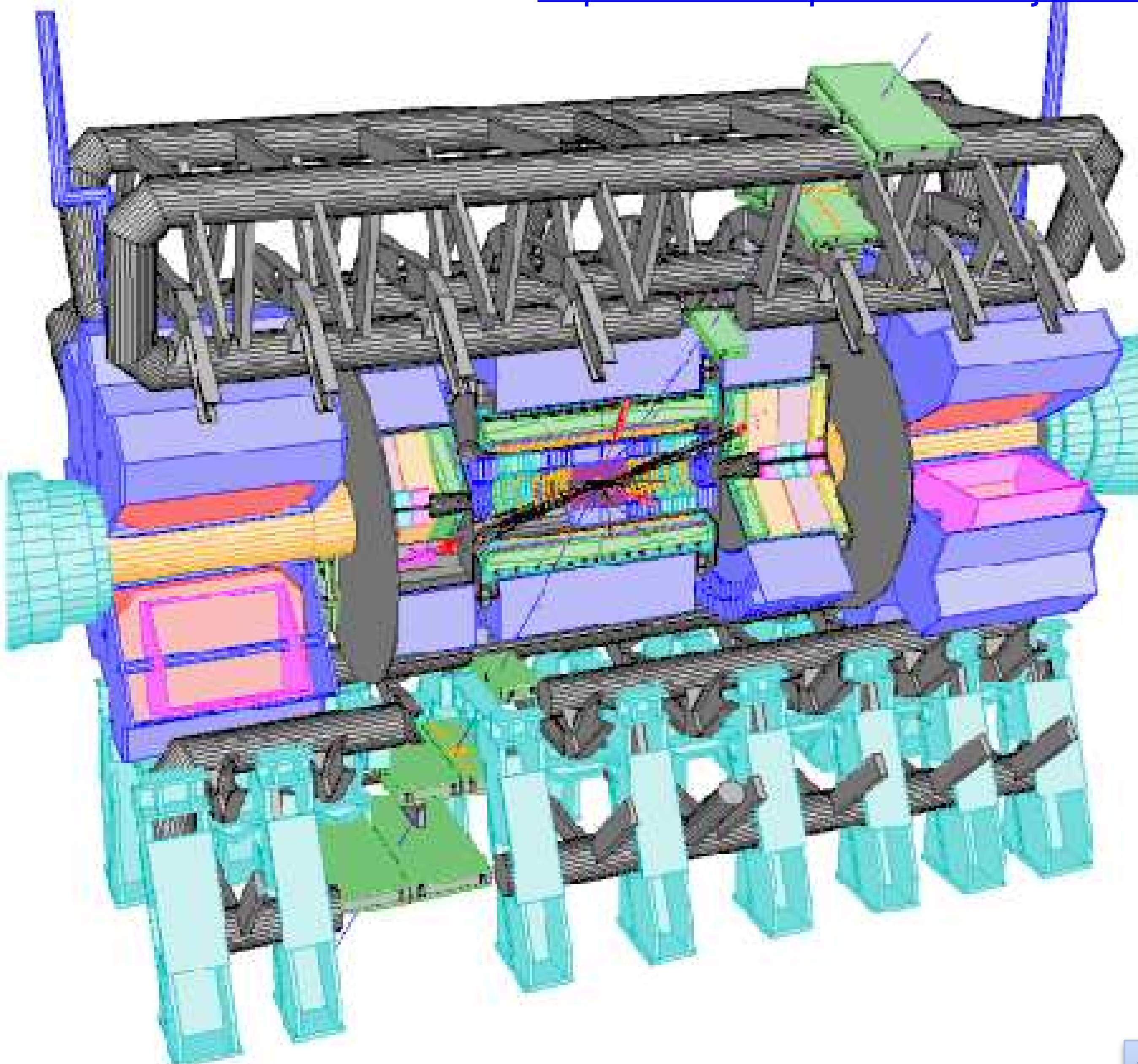
The strings fragment to produce primary hadrons

T. Sjostrand’s lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



Many hadrons are unstable and decay further

T. Sjostrand's lectures at SUSSP 2009: http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf



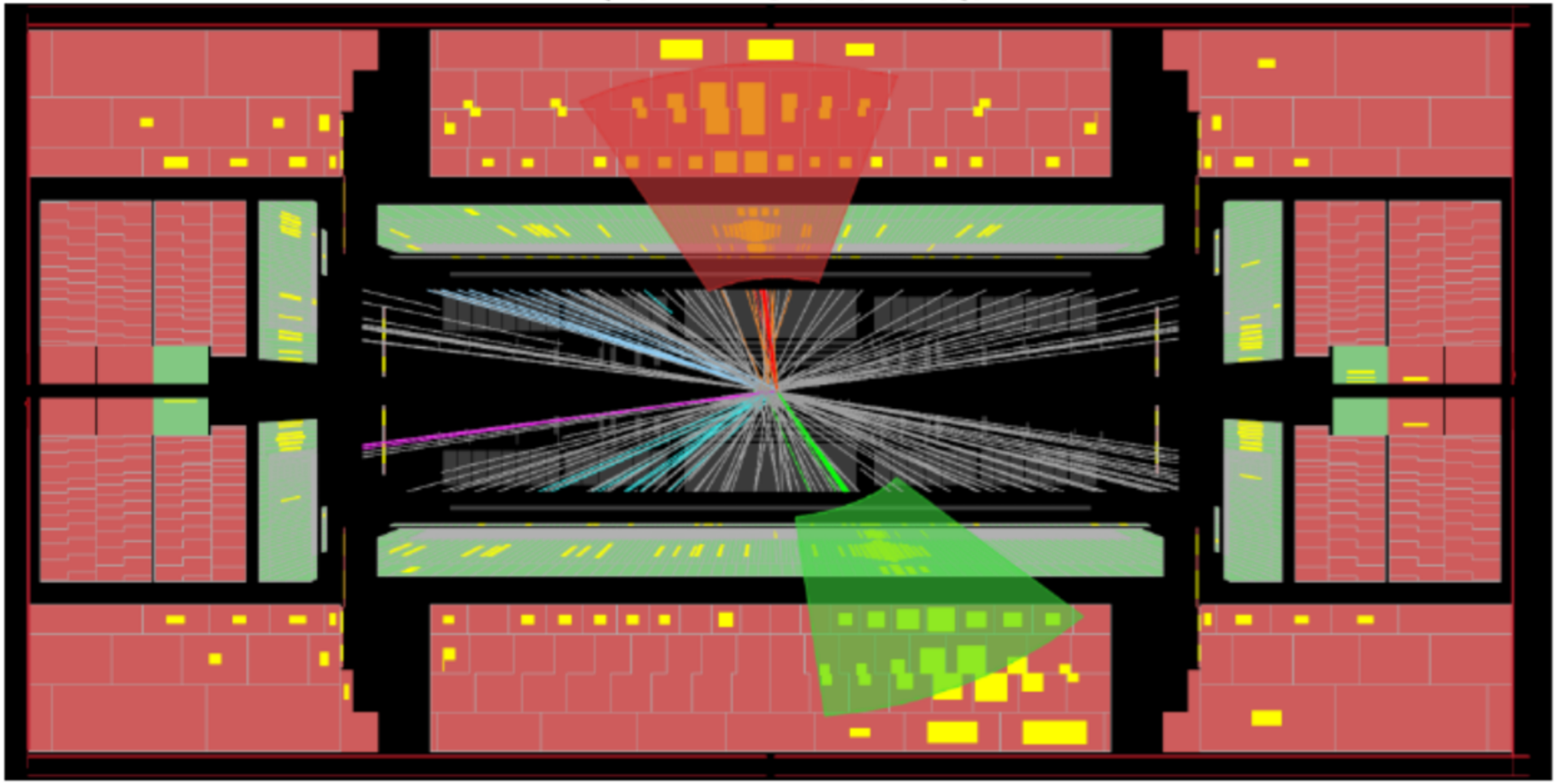
More in Part 3

These are the particles that hit the detector

What is a jet?

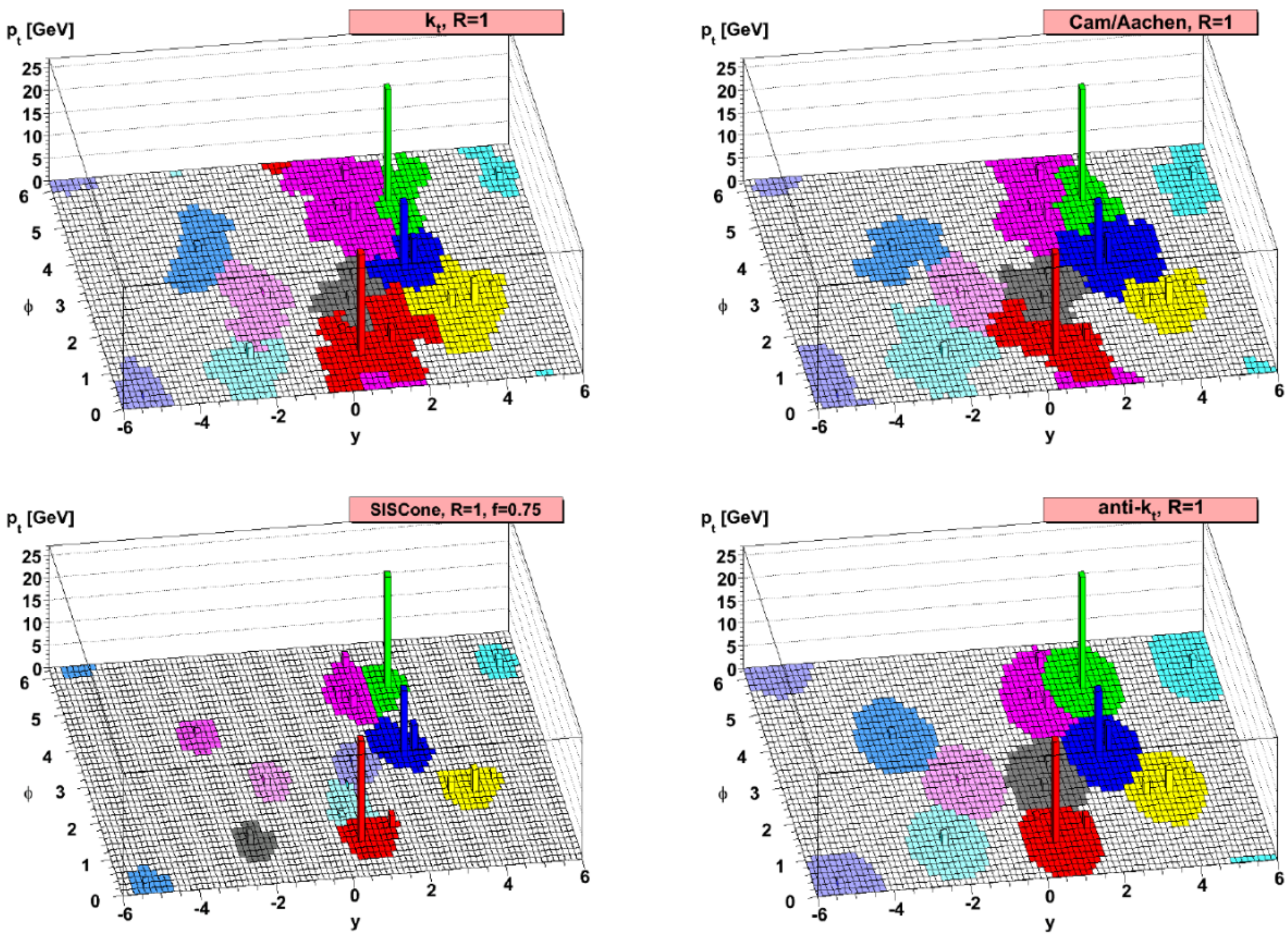
A high-p_T dijet event: how we see it

...in the ATLAS calorimeter...



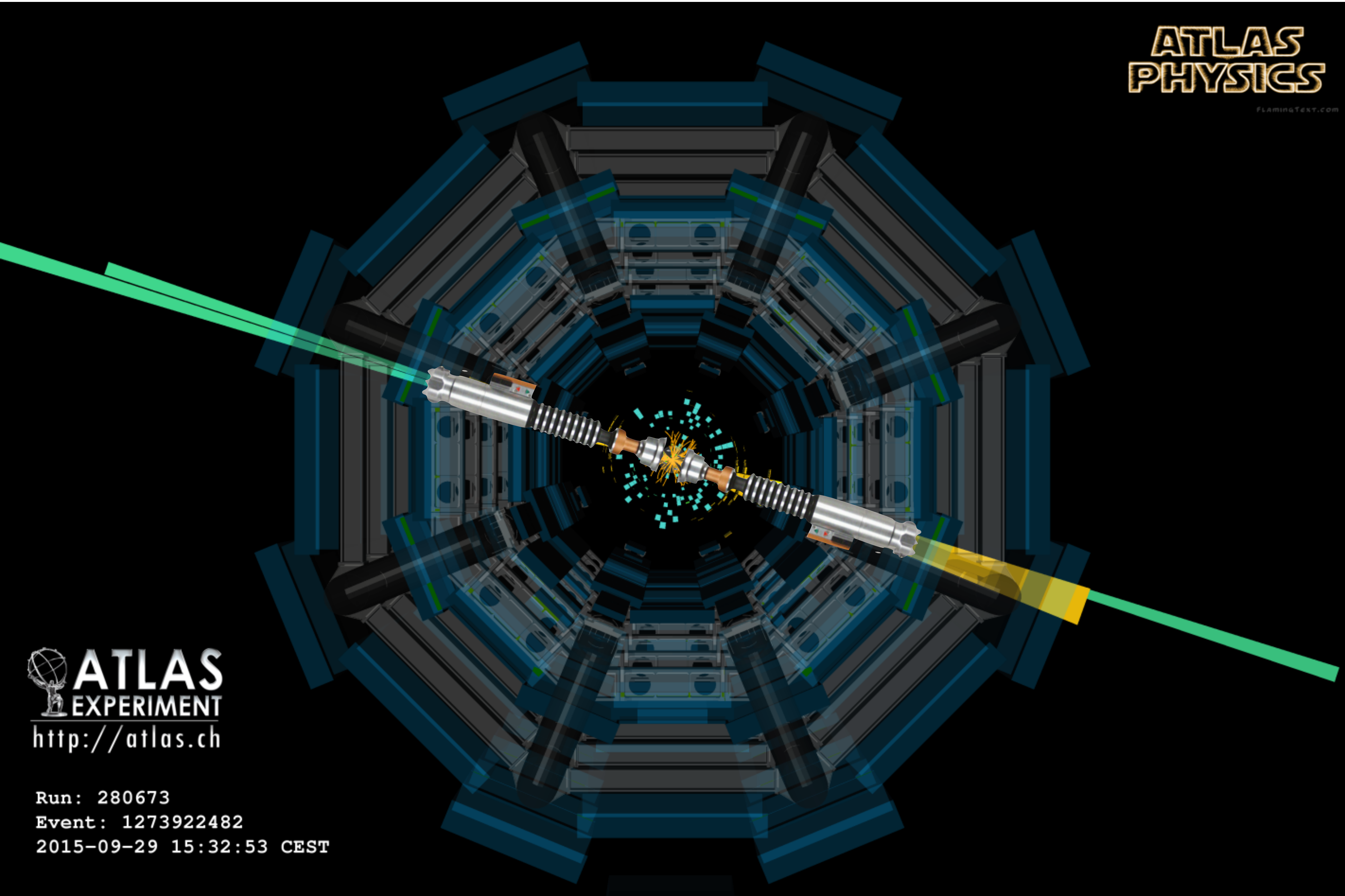
Note: some 'cleaning' already performed: ATLAS topological clustering algorithm

Different jet algorithms



http://arxiv.org/abs/0802.1189

Electromagnetic force Weak force Strong force

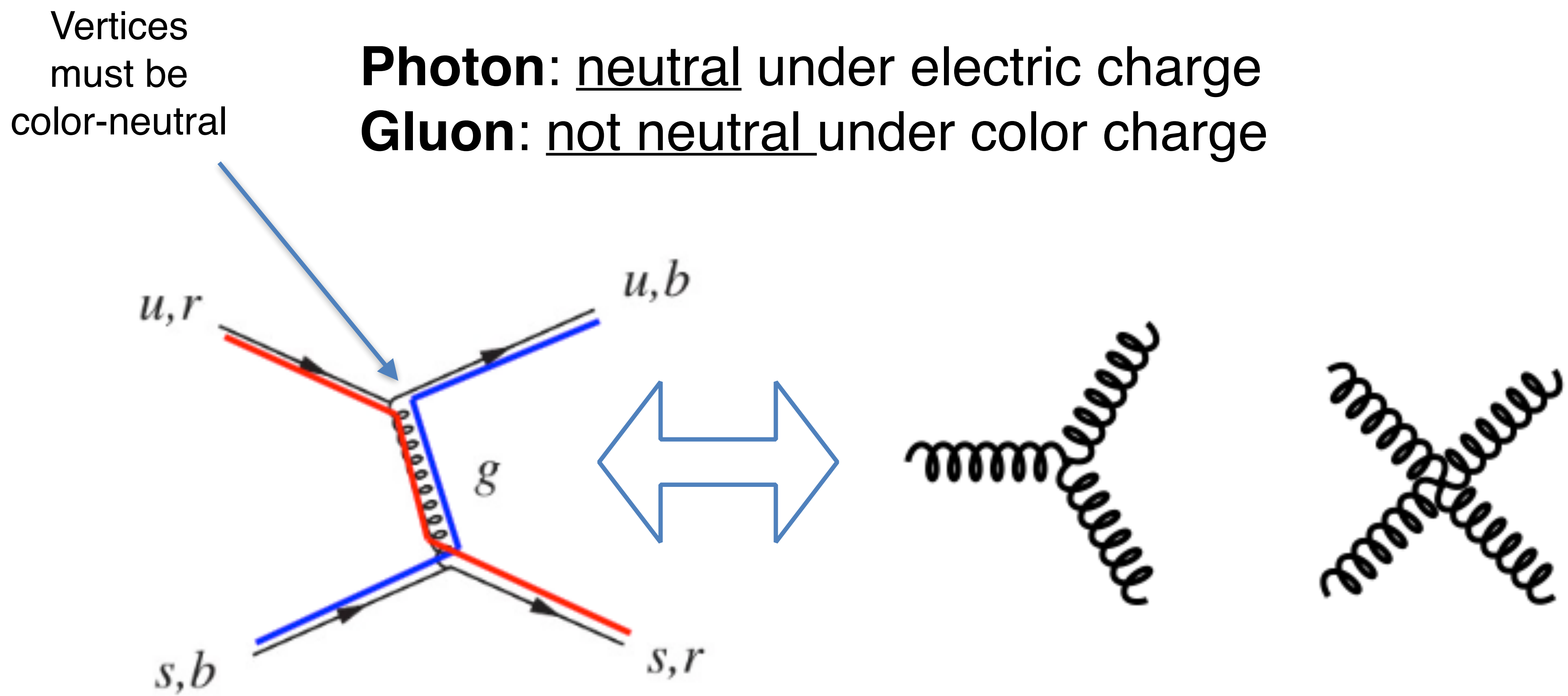


5-10’ for a break (or questions)

Backup

Difference with EM force

Photon: neutral under electric charge
Gluon: not neutral under color charge



Consequence: gluons self-interact!

Further consequences: confinement and asymptotic freedom

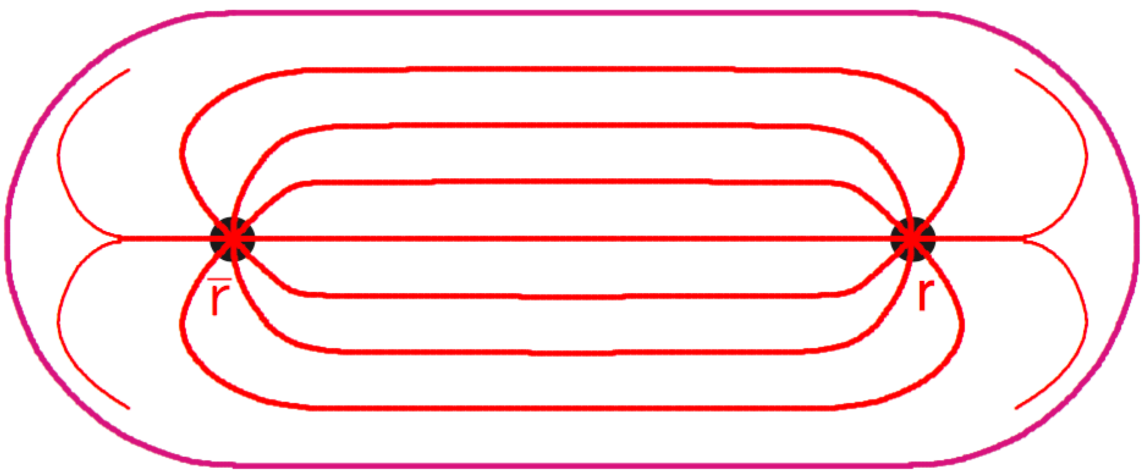
See F. Tanedo's post: http://www.quantumdiaries.org/author/flip-tanedo/page/5/

LUNDS UNIVERSITET

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) ⇒ **string(s)**

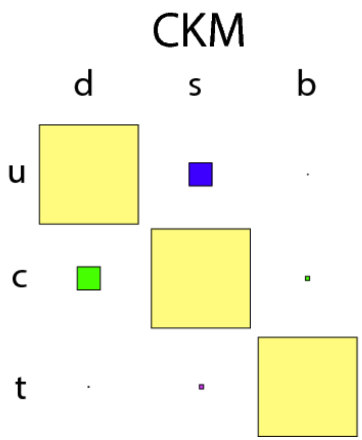


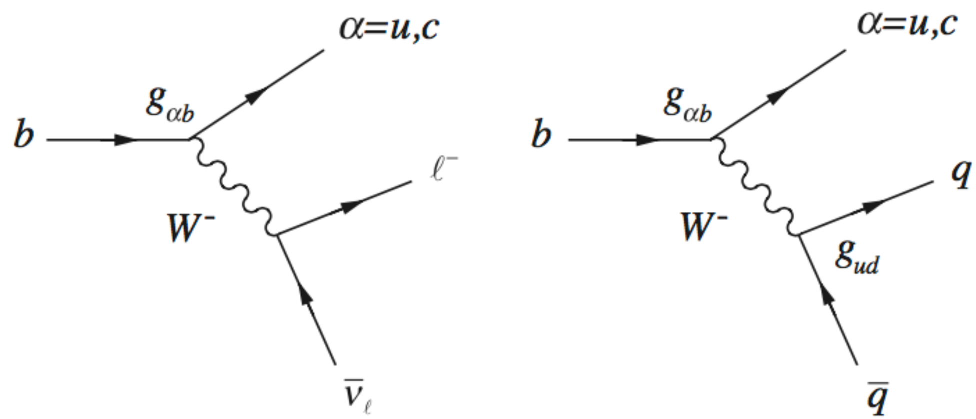
Gives linear confinement with string tension:

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

http://home.thep.lu.se/~torbjorn/talks/durham09.pdf

Long lifetime of B-hadrons

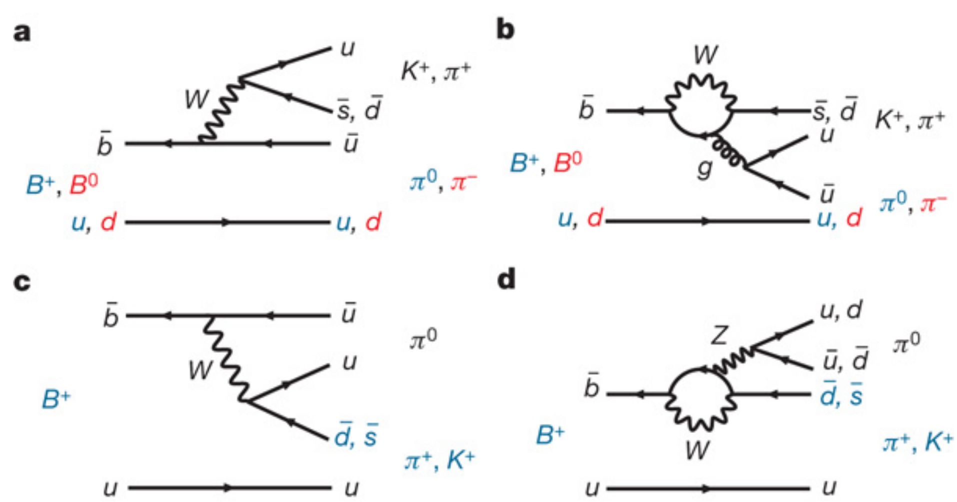




1) b->t forbidden
2) b->anything else: disfavoured

Long lifetime for B hadrons!

$\tau b \approx 10^{-12}$ s



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

A jet algorithm in action

Algorithm specification: Anti-k_t

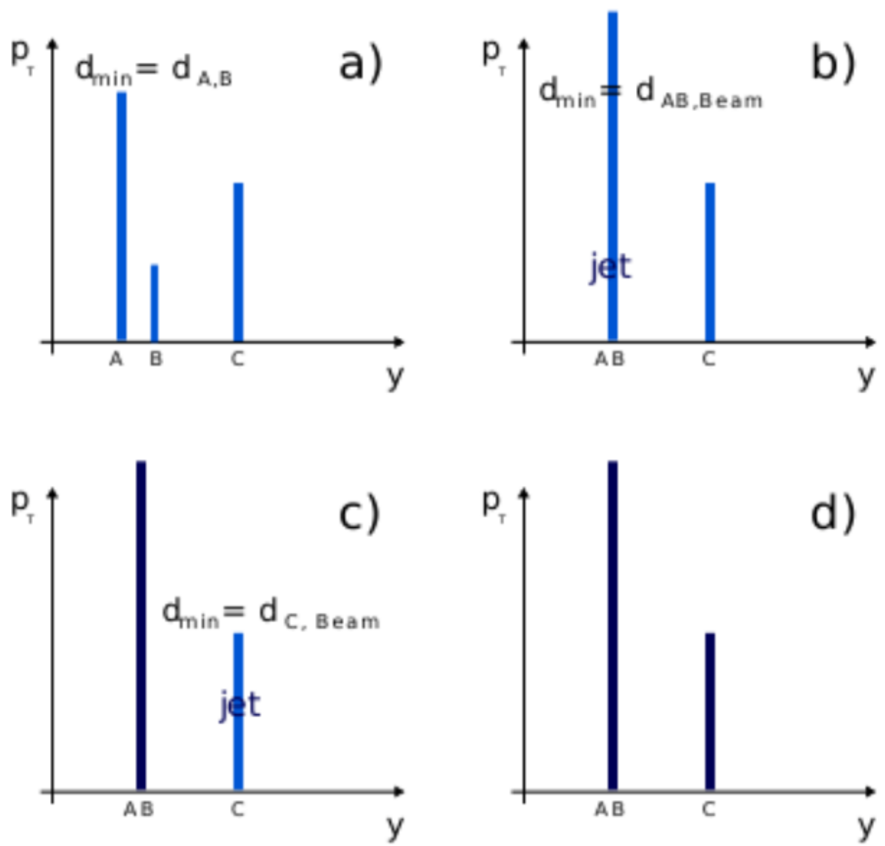
- $$d_{i,j} = min(\frac{1}{p^2_{T,i}}, \frac{1}{p^2_{T,j}})\frac{\Delta R^2}{D^2};$$
  $$d_{i,Beam} = \frac{1}{p^2_{T,i}}$$
- D : algorithm parameter
- Iterate:

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 [a]

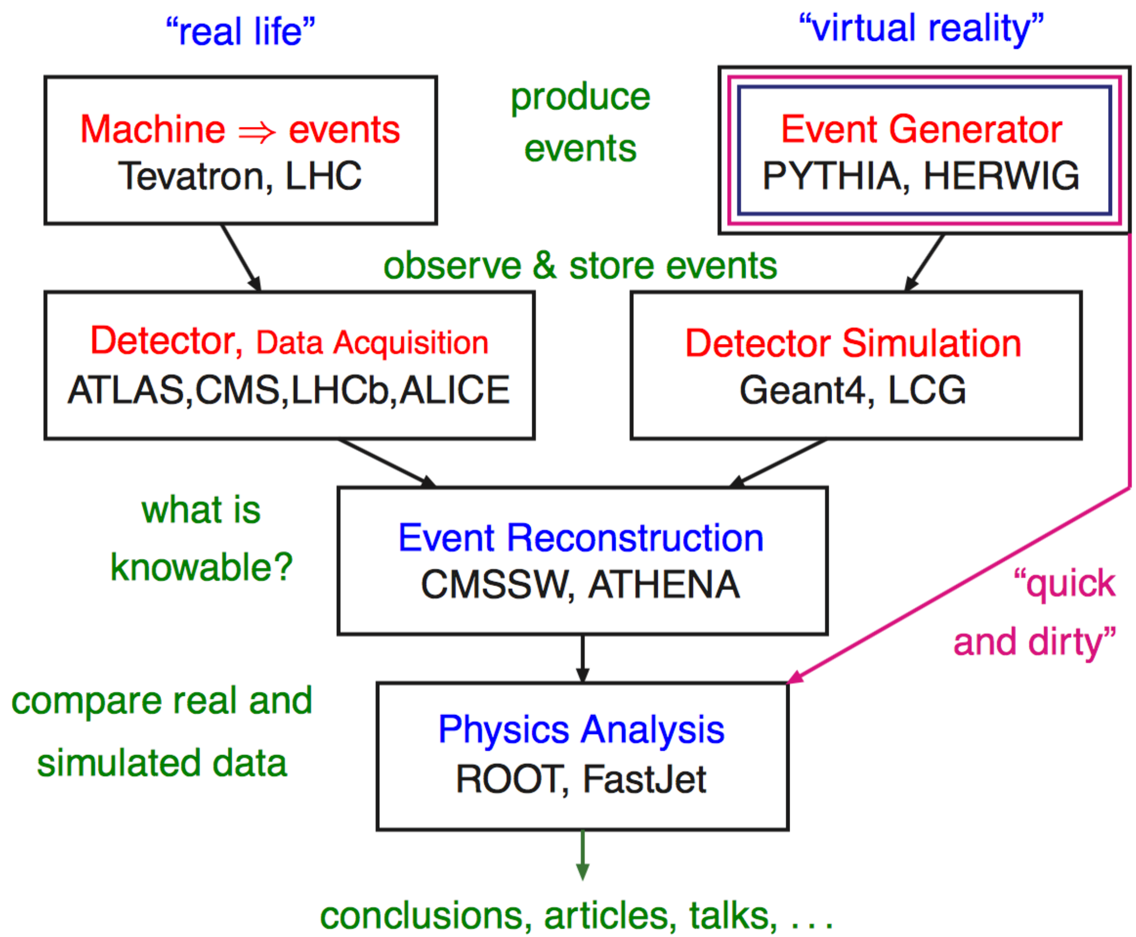
- Recombination starts from hard objects

[a] ATLAS default: inclusive algorithm

Idea:



Monte Carlo generators



http://home.thep.lu.se/~torbjorn/talks/standrews09a.pdf