Journey to the origins of the universe – what we do in the laboratory

International Particle Physics Outreach Group

INTERNATIONAL MASTERCLASSES
hands on particle physics

POLITECHNIKA WARSZAWSKA
WARSAW UNIVERSITY OF TECHNOLOGY
WUT

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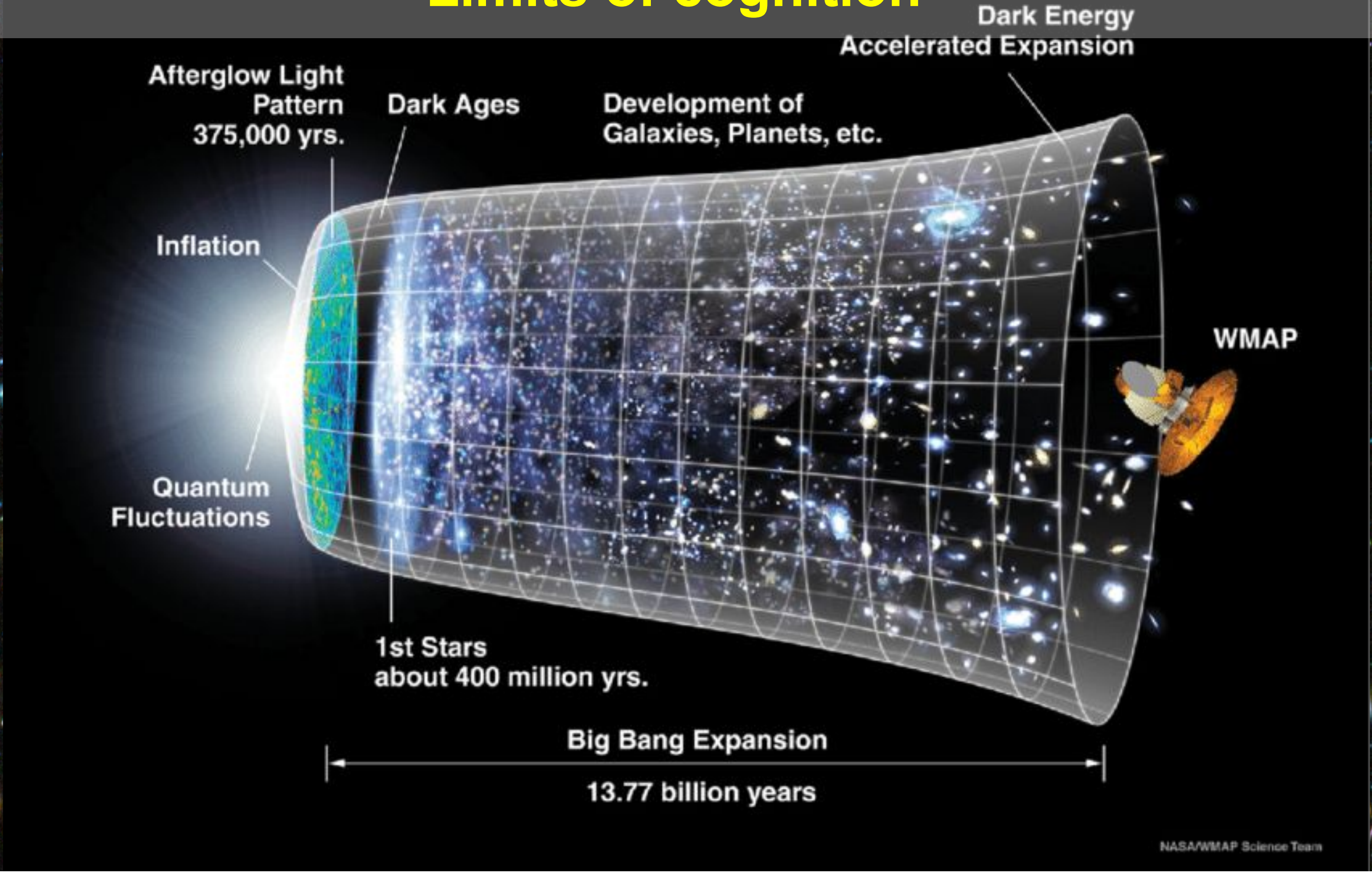
Masterclass Lecture, QCHSC 2024 (Cairns, Australia)
20.08.2024

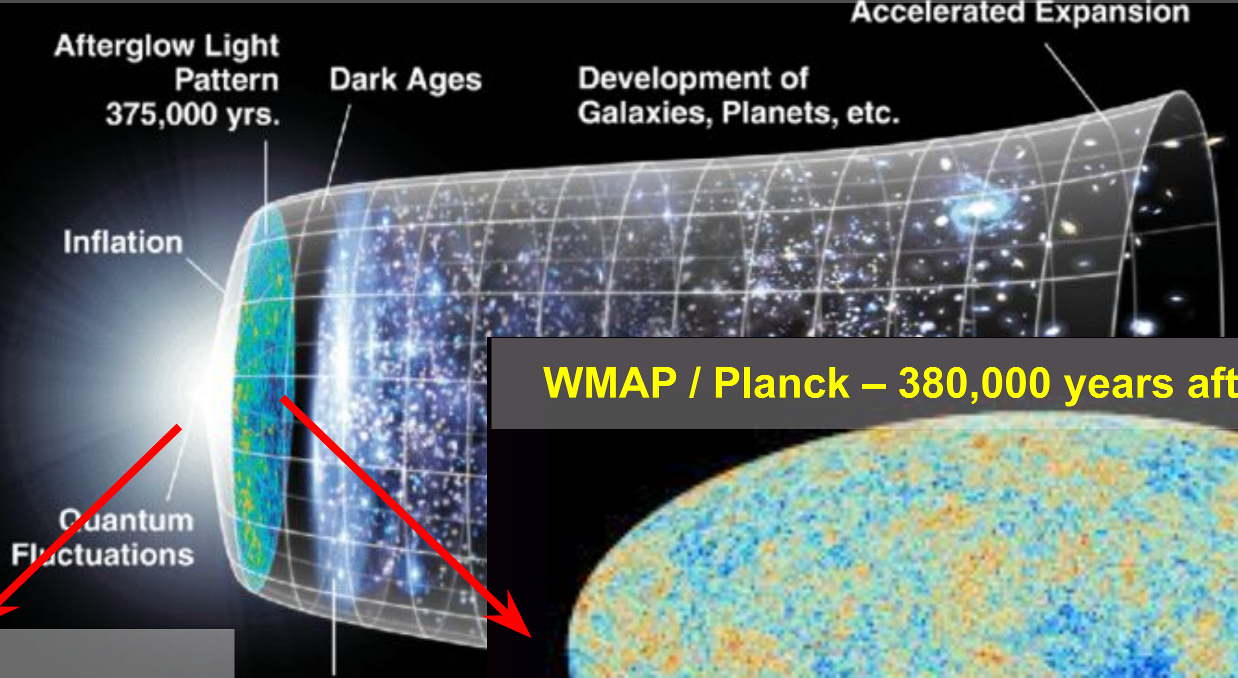
How do we go back to the beginnings?

Hubble Deep Field

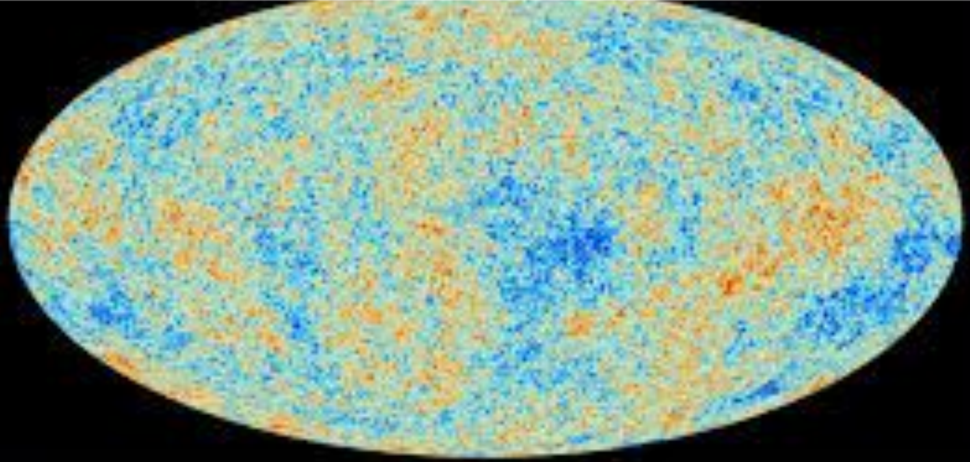
Limits of cognition



Limits of cognition



WMAP / Planck – 380,000 years after the Big Bang



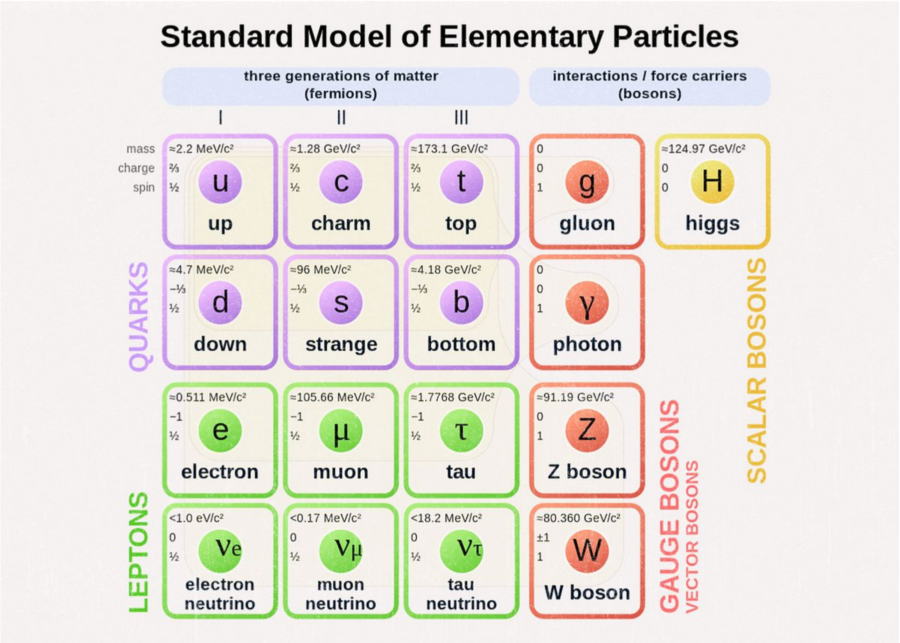
?

But what came before?

How do you check it?

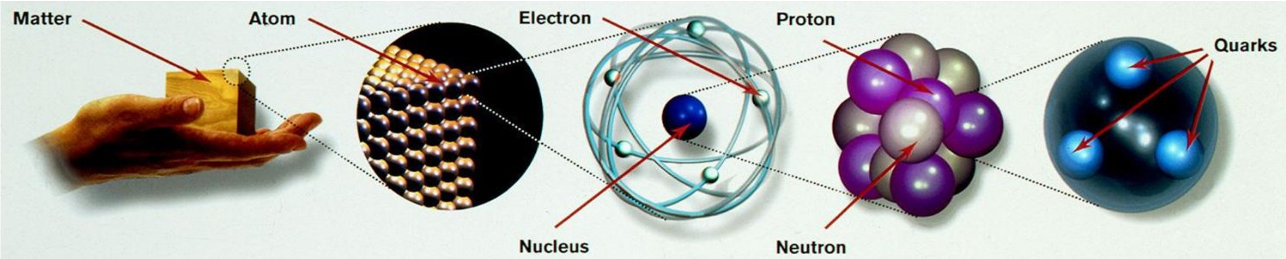
How can we study something we cannot see?

https://vignette.wikia.nocookie.net/walterlantz/images/0/0f/Reckless02.jpg/revision/latest?cb=20110608085154



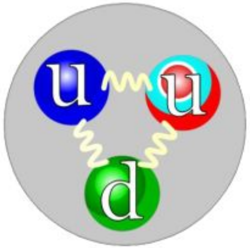
https://en.wikipedia.org/wiki/Standard_Model

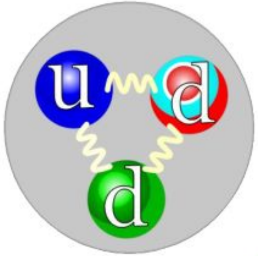
Quarks and gluons



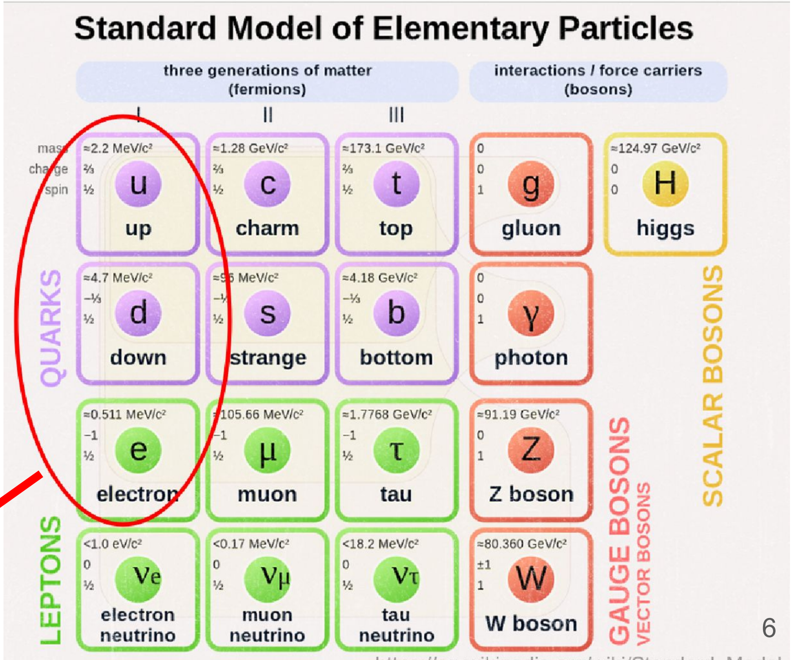
http://www.plasma-physics.com/FusionProglidePower/quark-particles

- Quarks are tightly bound by gluons, forming the components of the atomic nucleus: protons and neutrons.

proton 



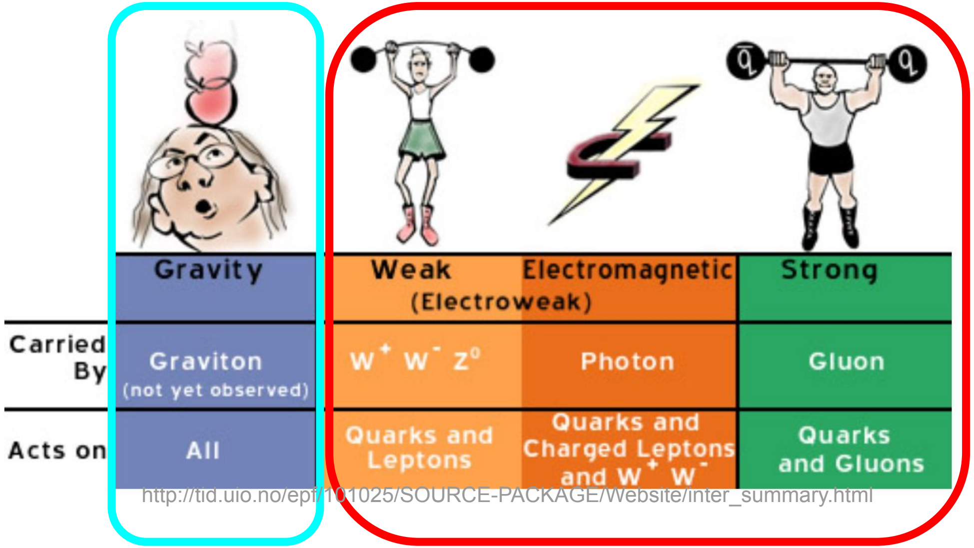
neutron



https://en.wikipedia.org/wiki/Standard_Model

- We and almost all the matter around us are made up of just these 3.

Interactions



http://tid.uio.no/epf/101025/SOURCE-PACKAGE/Website/inter_summary.html

- The Standard Model contains 3 of the 4 interactions (without gravity)
- Gravity is the weakest force in the microworld (it is negligibly small)
- Strong interactions behave differently (increase with distance)

Free the quarks!

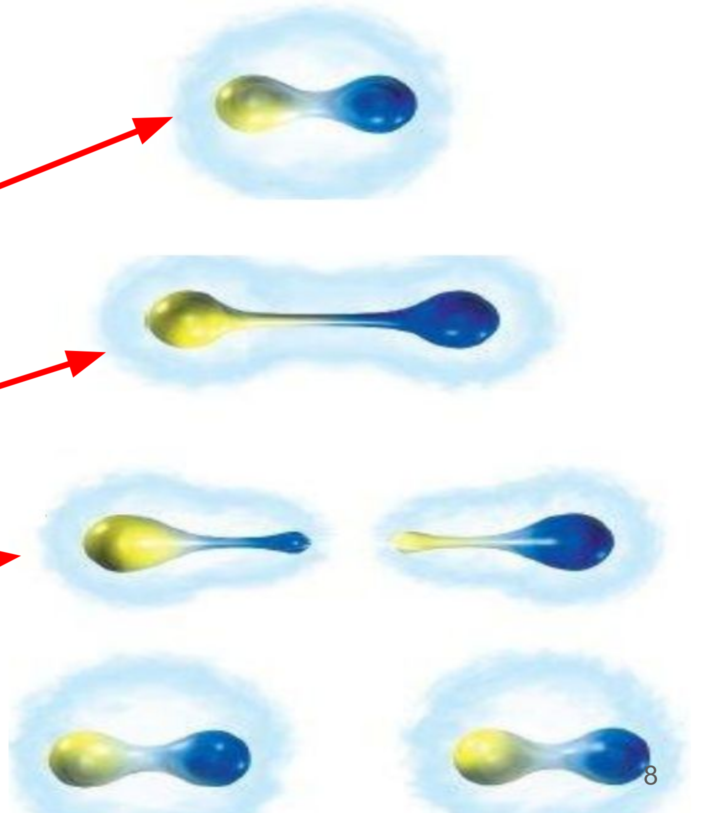
Free quarks could not be observed. But why?

Quark-antiquark pair (meson)

We try to separate them (we add energy)

$E=mc^2$

We get two mesons

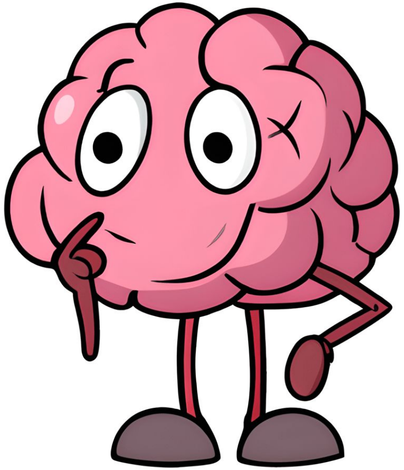


https://slideplayer.com/slide/16818182/

Problem: a free quark cannot be obtained

Question: Do we need to isolate a single quark? Or would it be better to free them all at once? Is this possible?

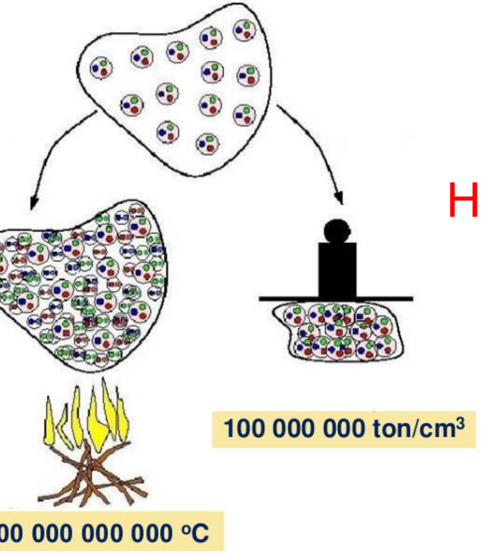
We need to create conditions in which quarks are free. Many quarks at once…



Recipe to free the quarks

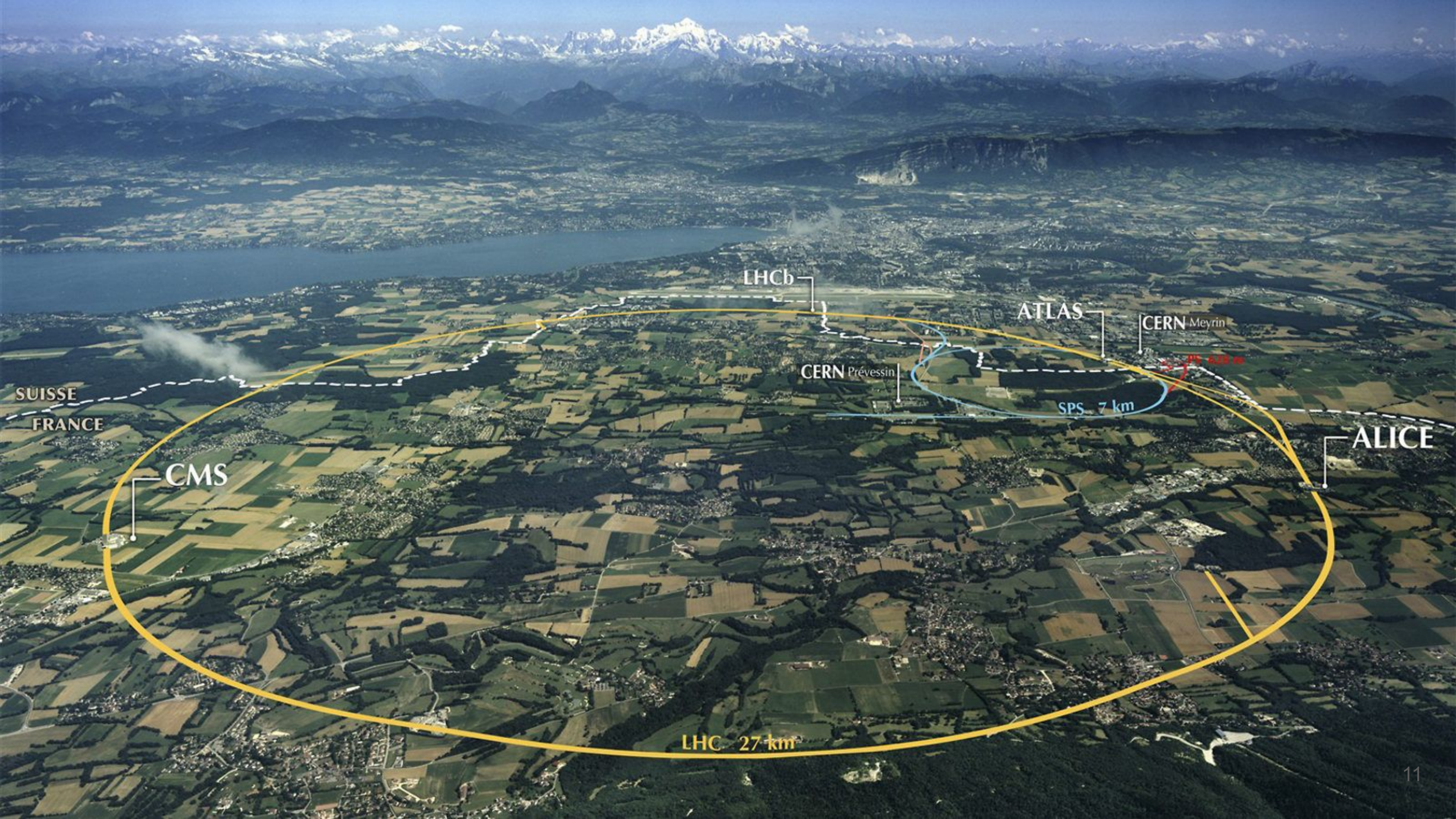
Hadronic matter:
quarks trapped in
protons and neutrons

Quark matter:
quarks are free and
can move



High temperature

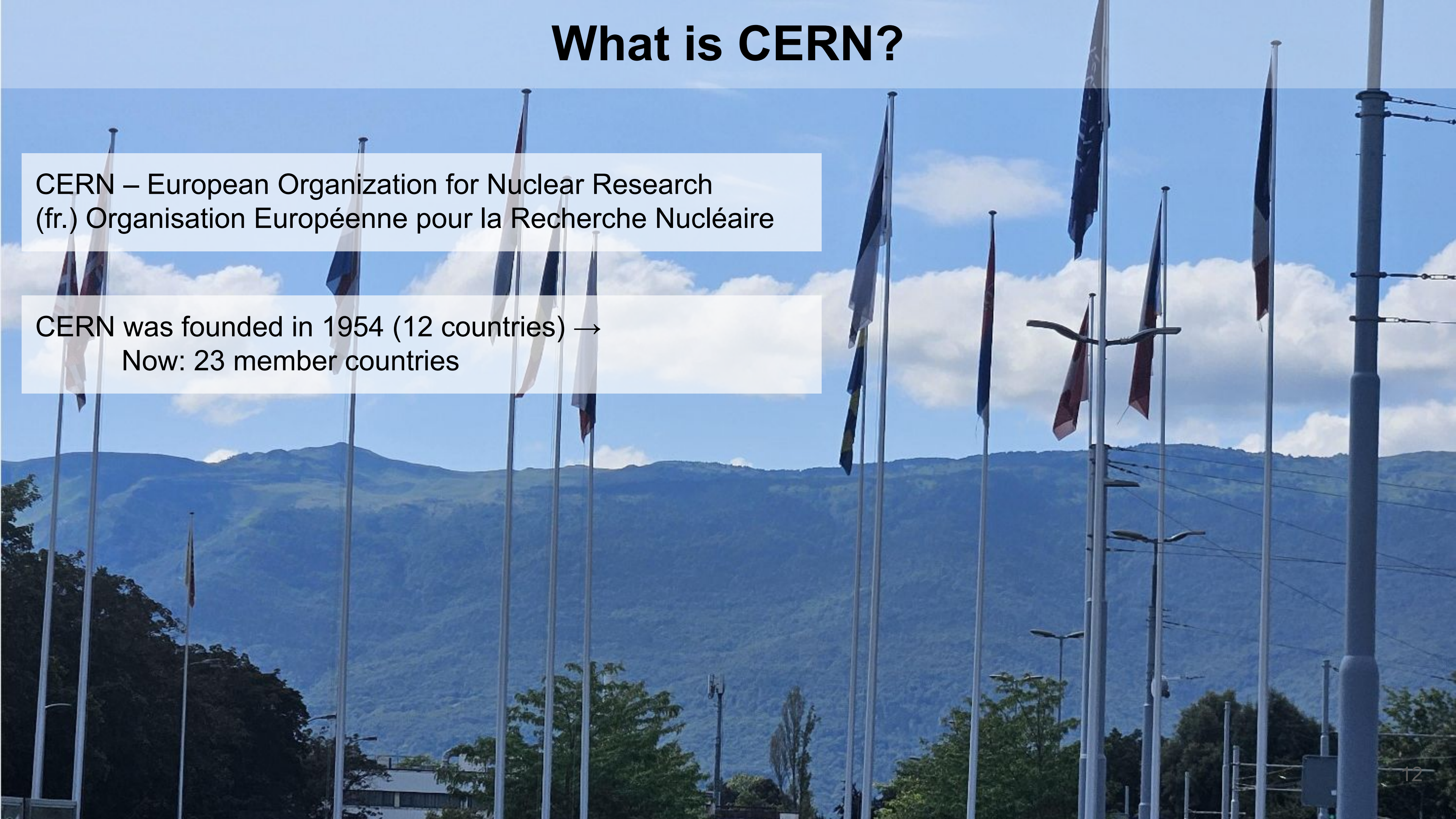
High pressure


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

What is CERN?

CERN – European Organization for Nuclear Research
(fr.) Organisation Européenne pour la Recherche Nucléaire

CERN was founded in 1954 (12 countries) →
Now: 23 member countries



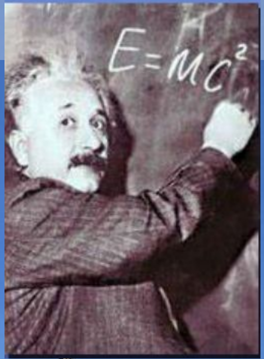
CERN mission

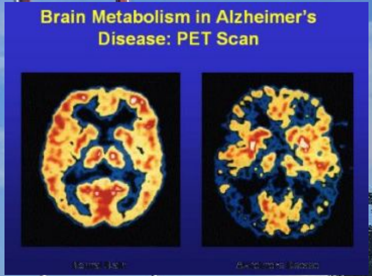
- Pushing the boundaries of science
  e.g., the mystery of the Big Bang - what was our Universe like in the first moments of its existence?

- Development of accelerator and detector technologies, information technology - e.g., World Wide Web, GRID, medicine - diagnosis and treatment (e.g. PET).

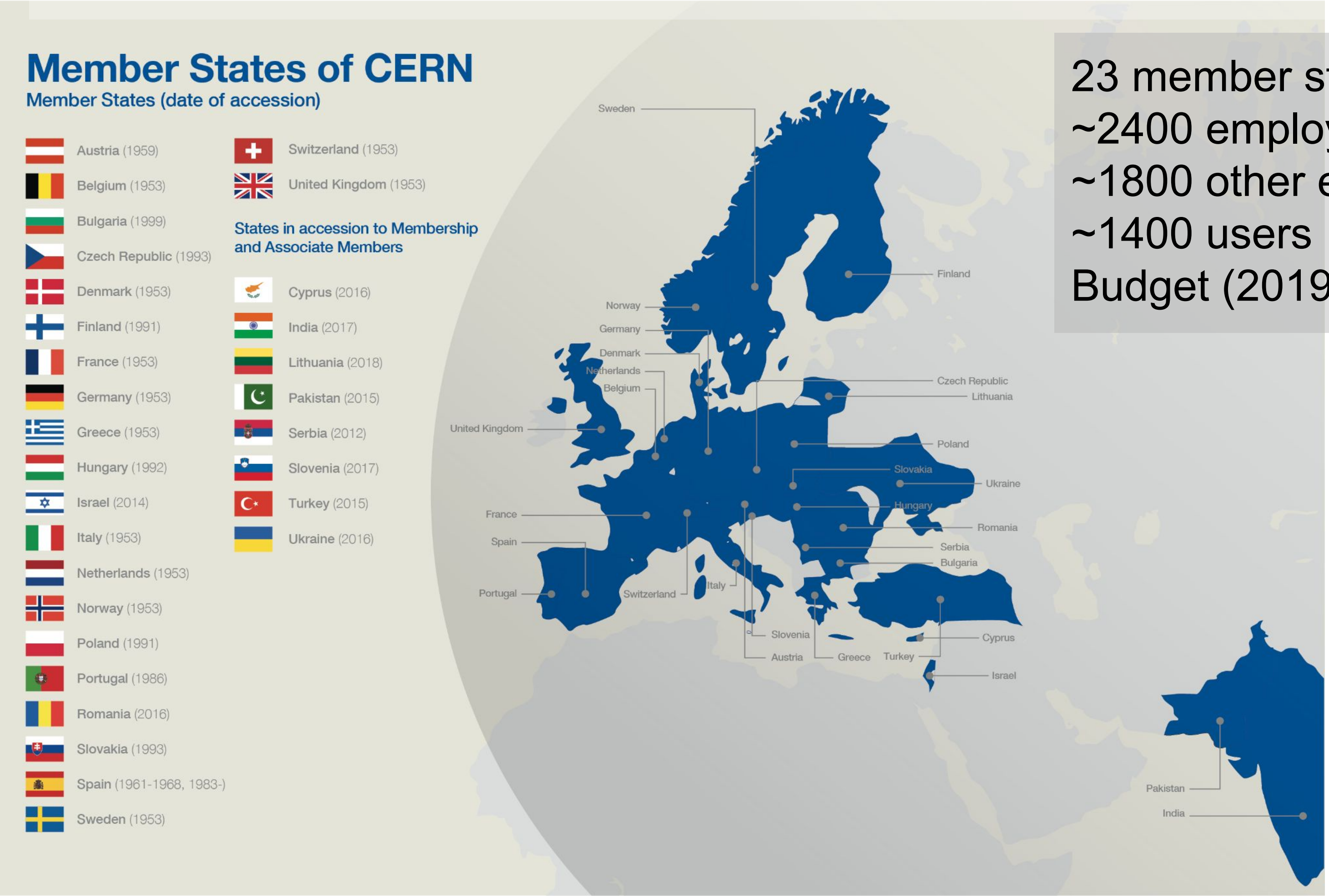
- Training new generations of scientists and engineers.

- Uniting people from different countries and cultures.



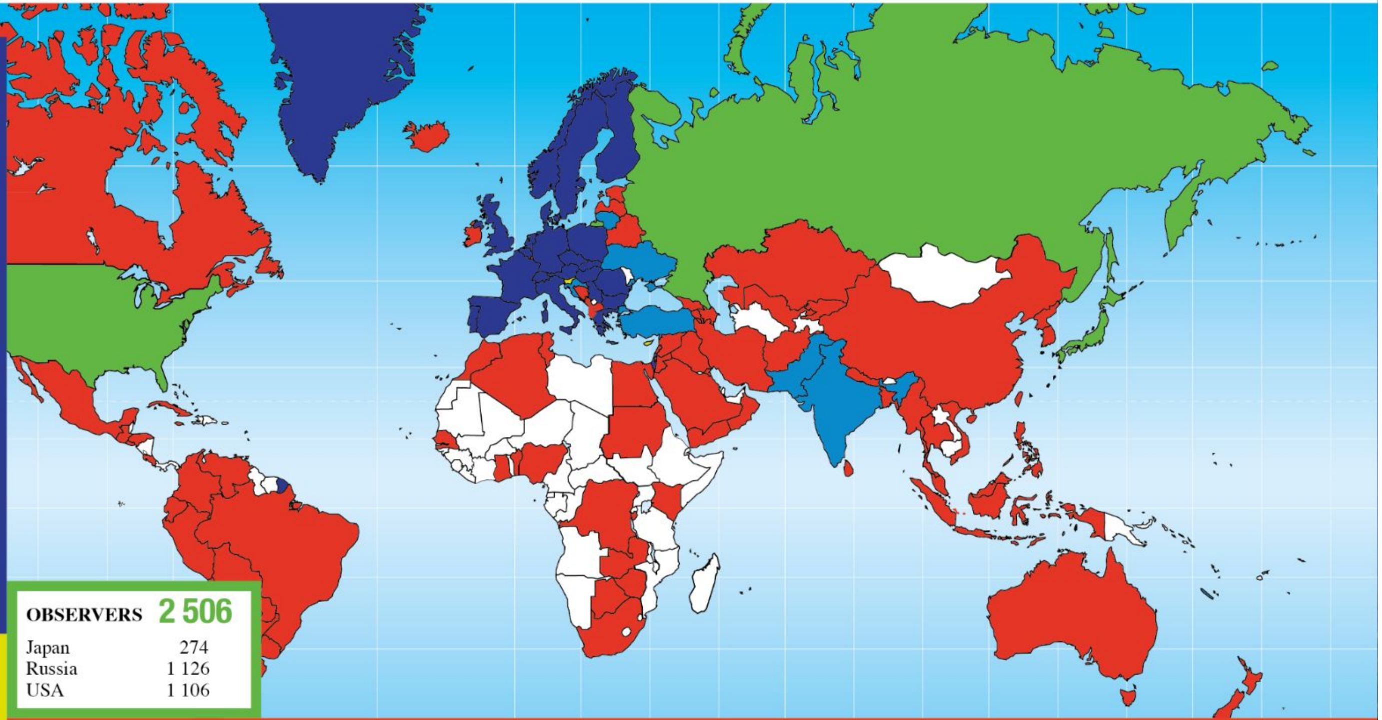


CERN in numbers



23 member states
~2400 employed scientists
~1800 other employes
~1400 users
Budget (2019): ~1200 MCHF

Distribution of All CERN Users by Nationality on 27 January 2020



MEMBER STATES 7 149

Austria	95
Belgium	113
Bulgaria	71
Czech Republic	216
Denmark	52
Finland	72
France	778
Germany	1 177
Greece	216
Hungary	77
Israel	59
Italy	1 856
Netherlands	170
Norway	59
Poland	311
Portugal	94
Romania	144
Serbia	49
Slovakia	128
Spain	405
Sweden	74
Switzerland	204
United Kingdom	729

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP 54

Cyprus	21
Slovenia	33

ASSOCIATE MEMBERS 770

Croatia	47
India	367
Lithuania	31
Pakistan	63
Turkey	162

OBSERVERS 2 506

Japan	274
Russia	1 126
USA	1 106

OTHERS

Albania	4
Algeria	8
Argentina	22
Armenia	18
Australia	28
Azerbaijan	7
Bahrain	3
Bangladesh	5
Belarus	49
Bolivia	2
Bosnia & Herzegovina	2
Bostwana	1
Brazil	121
Burundi	1
Canada	155
Chile	21
China	569
Colombia	35
Congo	1
Costa Rica	1
Cuba	16
Egypt	26
El Salvador	1
Estonia	16
Georgia	54
Ghana	1
Gibraltar	1
Guatemala	1
Hong Kong	1
Honduras	1
Iceland	5
Indonesia	11
Iran	46
Ireland	14
Jamaica	1
Jordan	2
Kazakhstan	12
Kenya	1
Korea	161
Kyrgyzstan	1
Latvia	4
Lebanon	23
Luxembourg	3
Malaysia	19
Malta	5
Montenegro	8
Morocco	26
Myanmar	1
Nepal	8
New Zealand	6
Nigeria	2
North Korea	3
North Macedonia	2
Oman	1
Palestine	7
Paraguay	1
Peru	6
Saint Kitts and Nevis	1
Saudi Arabia	2
Senegal	1
Singapore	4
South Africa	54
Sri Lanka	6
Sudan	2
Syria	2
Taiwan	47
Thailand	24
Tunisia	5
Uzbekistan	3
Venezuela	10
Viet Nam	10
Yemen	1
Zambia	1
Zimbabwe	1

1 822

CERN - Nobel prizes

- 1984 Carlo Rubbia and Simon van der Meer ‘for the work that led to the discovery of the W and Z bosons’
- 1992 George Charpak ‘for the conception and development of particle detectors, in particular the MWPC (multiwire proportional chamber proportional chamber)’

Other Nobel laureates associated with CERN:

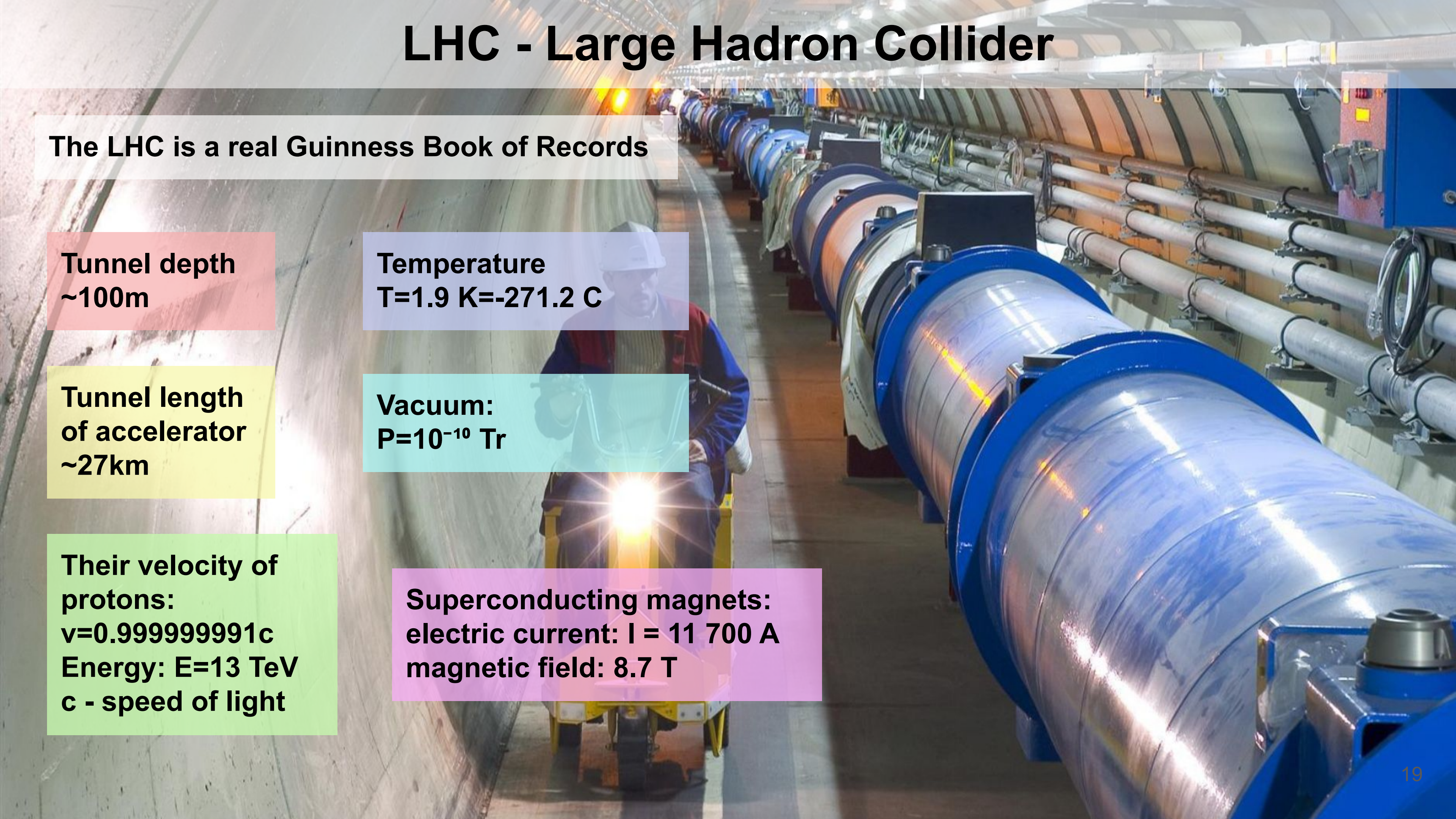
- 1952 Felix Bloch - for precise measurements of the magnetism of atomic nuclei - first Director General of CERN
- 1976 Samuel C. Ting - for the discovery of the J/ψ particle - once head of the L3 experiment at LEP, now head of the AMS experiment on the International Space Station

http://public-archive.web.cern.ch/en/About/Nobels-en.html

1954 70 YEARS / ANS CERN 2024

LHC - Large Hadron Collider

LHC - Large Hadron Collider



The LHC is a real Guinness Book of Records

Tunnel depth
~100m

Temperature
T=1.9 K=-271.2 C

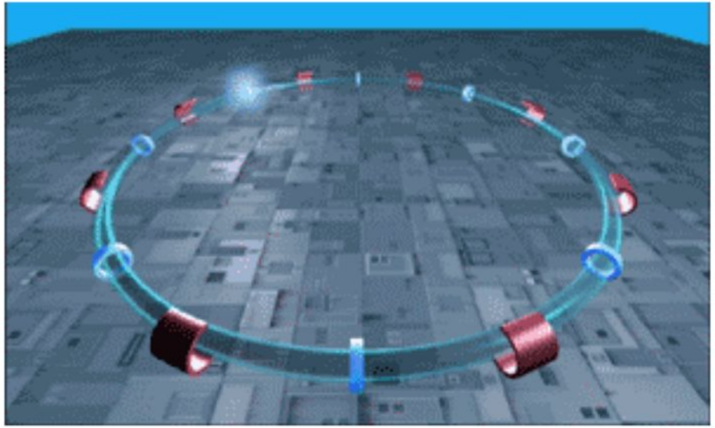
Tunnel length of accelerator
~27km

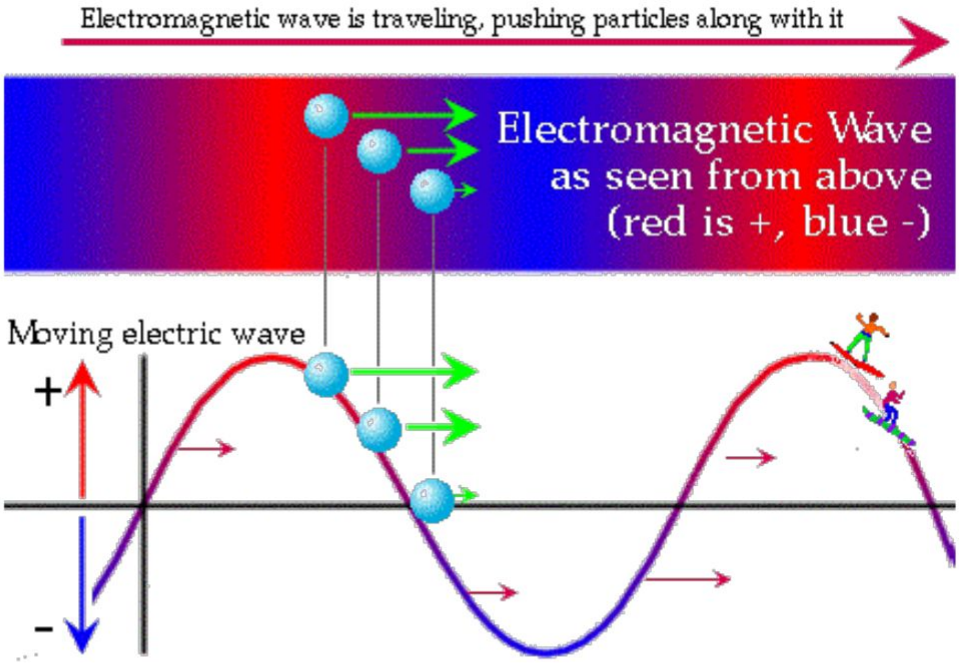
Vacuum:
$P=10^{-10}$ Tr

Their velocity of protons:
v=0.999999991c
Energy: E=13 TeV
c - speed of light

Superconducting magnets:
electric current: I = 11 700 A
magnetic field: 8.7 T

How it works?



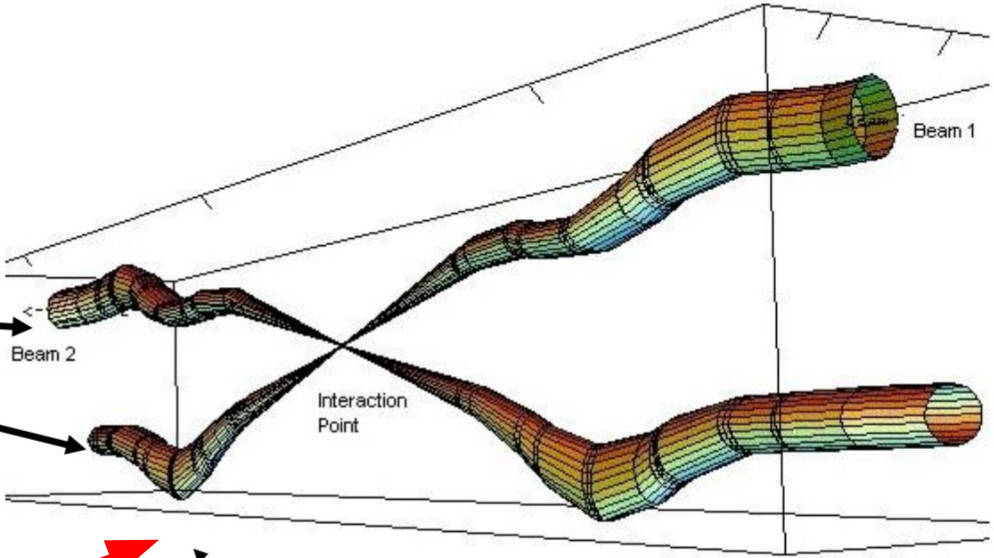


http://fafnir.phyast.pitt.edu/particles/conuni8.html

We can only accelerate charged particles (electrons, protons, atomic nuclei)

- Electric field - accelerates particles
- Magnetic field - bends the beam path - focuses the beam

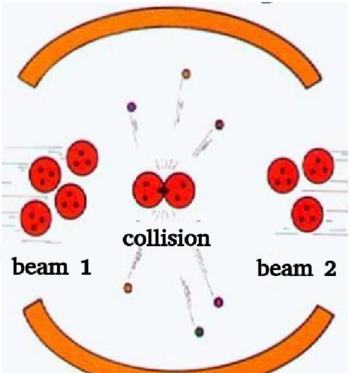
Collision of two beams



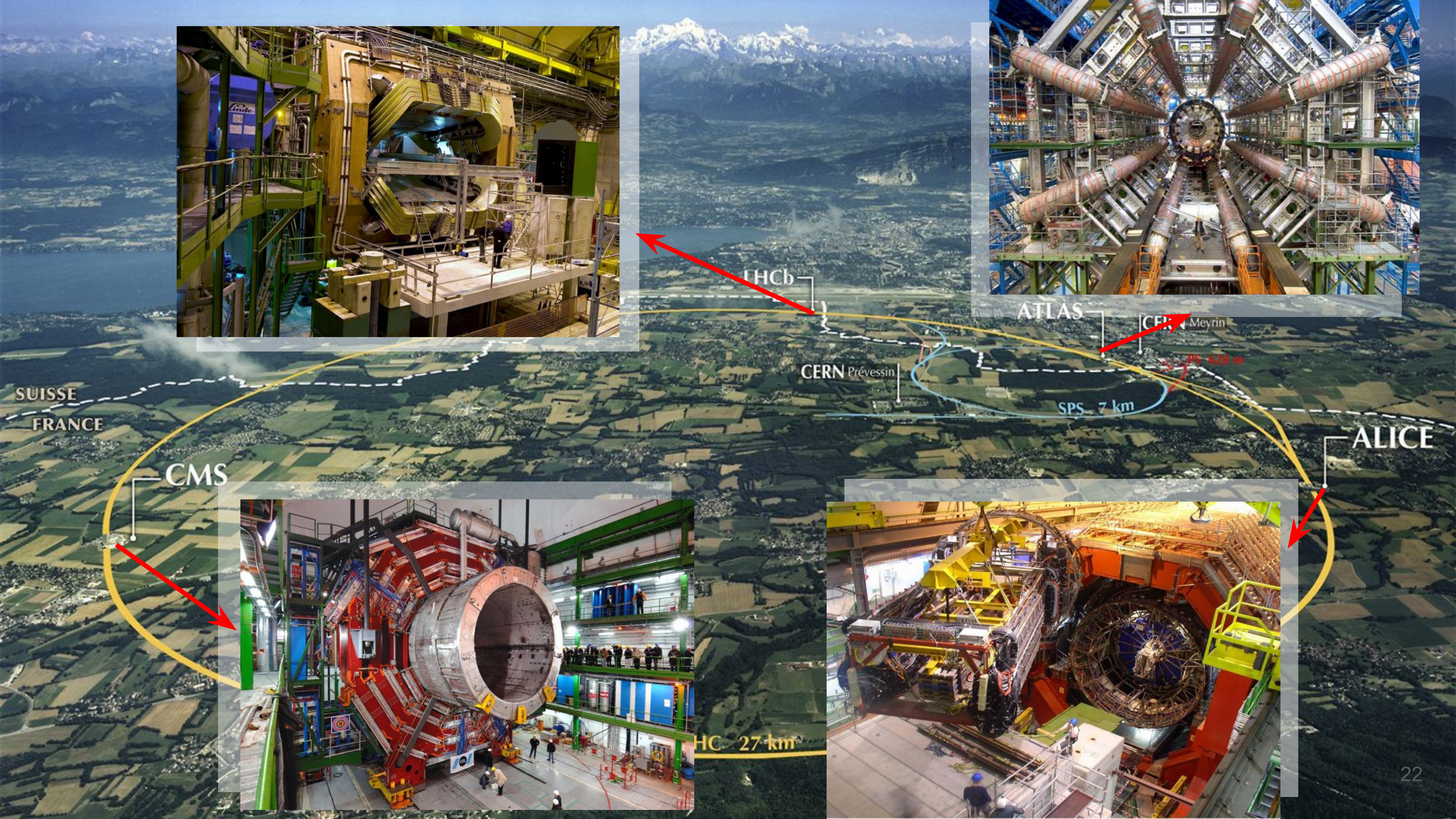
Collission of two beams

https://lhc-machine-outreach.web.cern.ch/collisions.htm

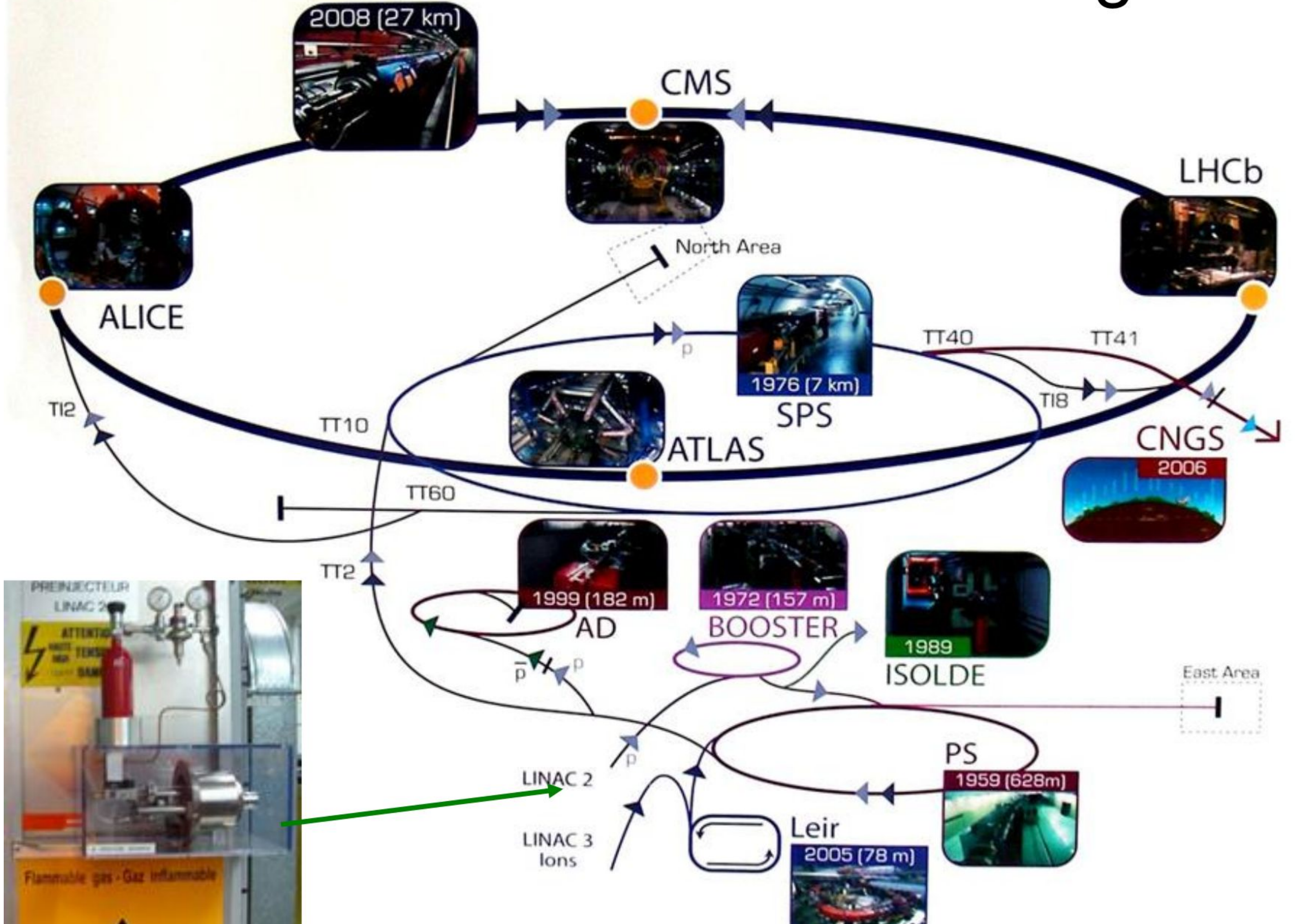
detectors

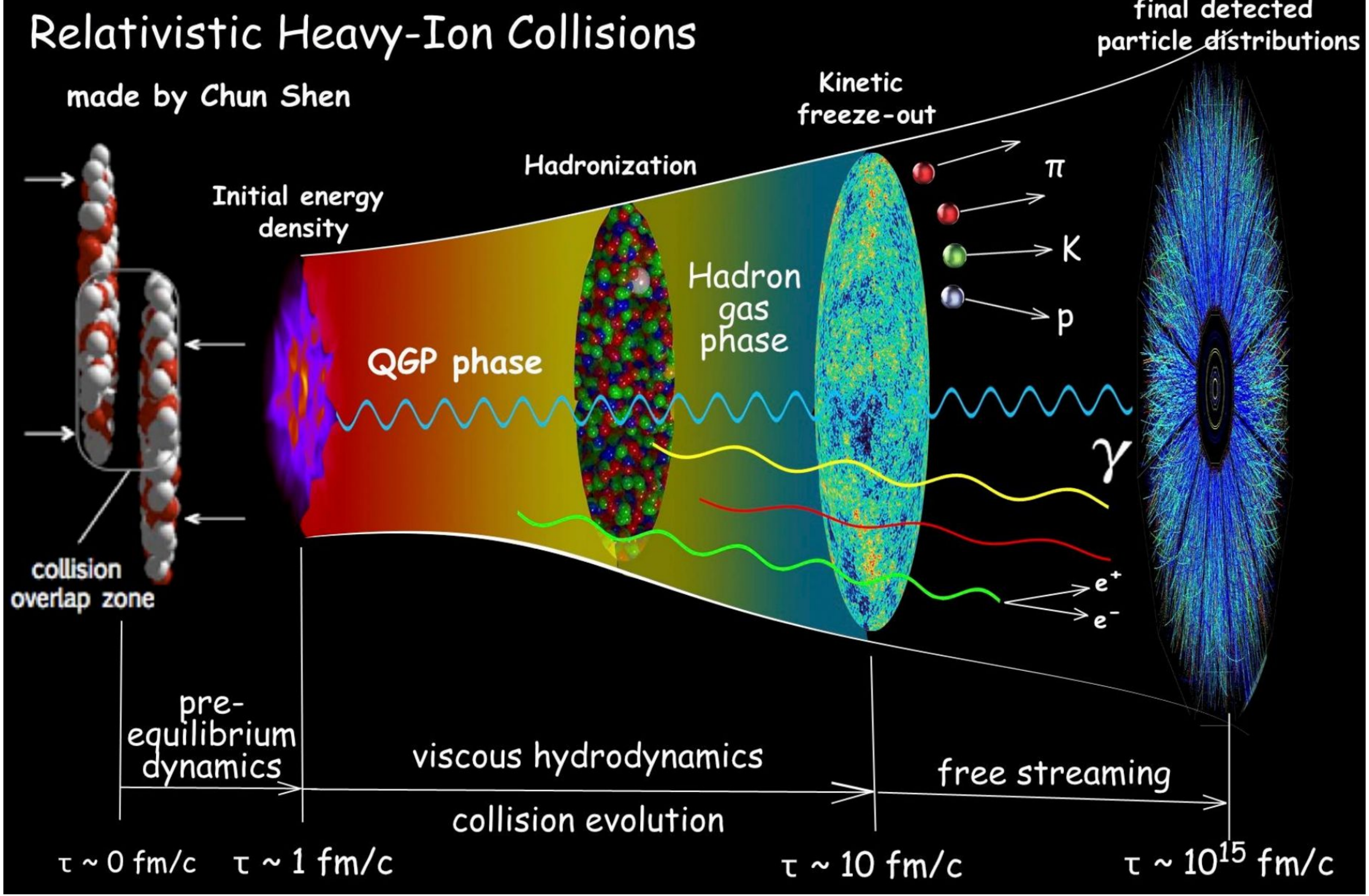


The beam is curved and focused also by magnets.


LHCb
ATLAS
Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
HC 27 km

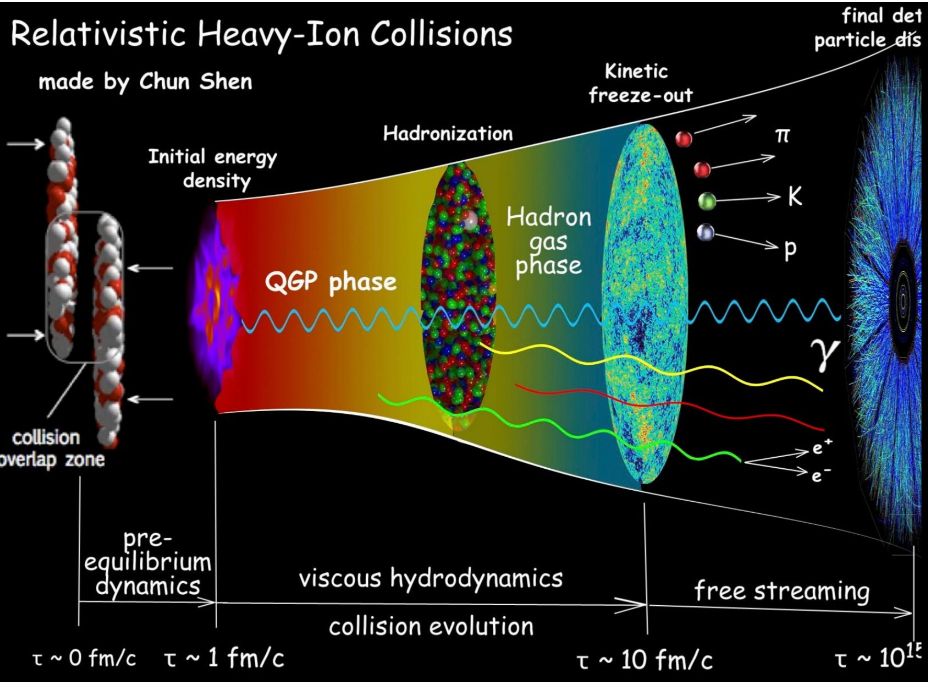
LHC = Lord of the Rings

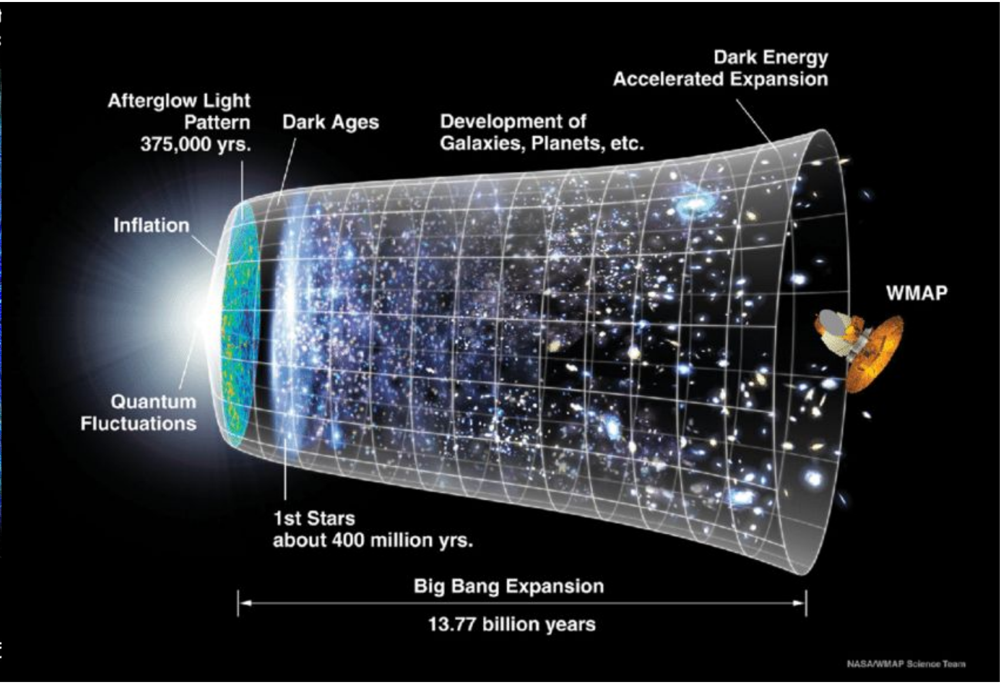




Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

So, we can look at the beginning of the Universe



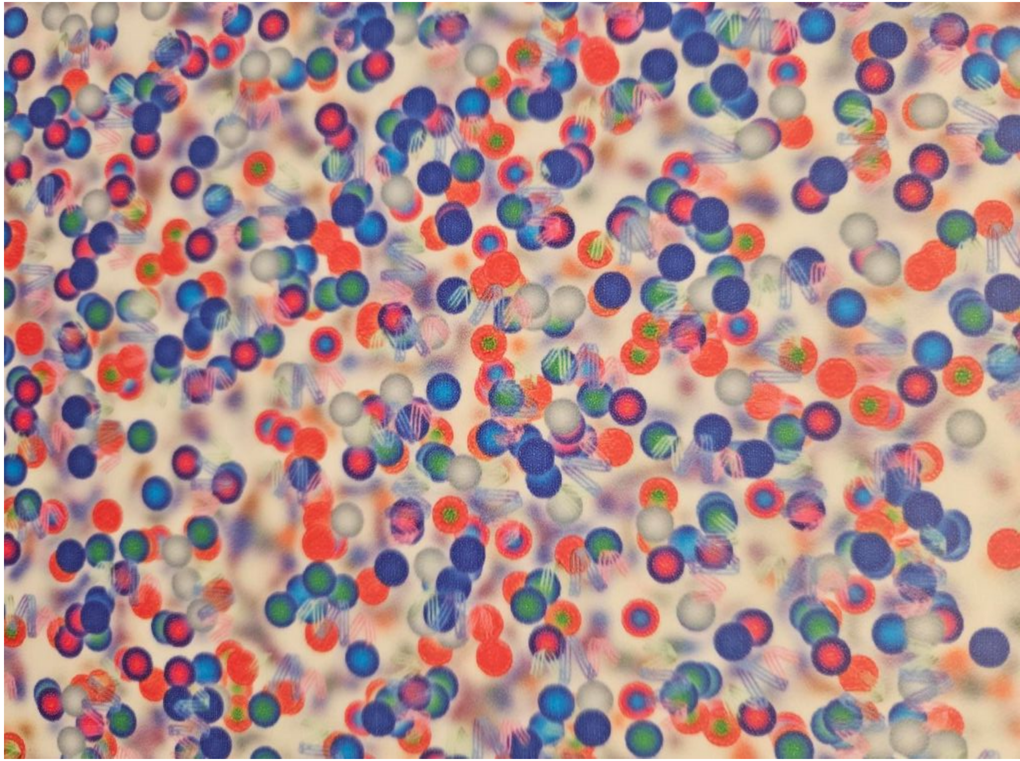


How to study QGP

QGP exists for only ~10^{-23} s

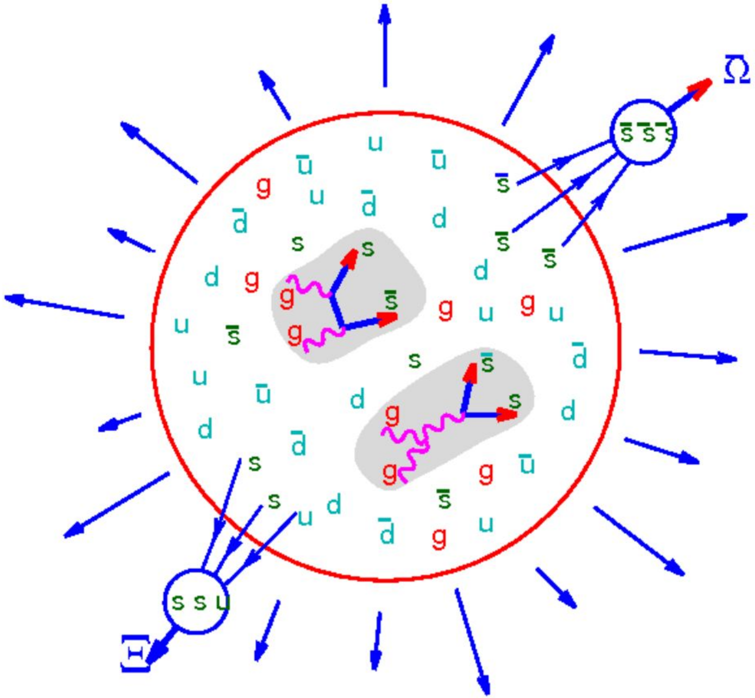
BUT!

We can use processes which are created by the QGP itself ('self-generated QGP probes').



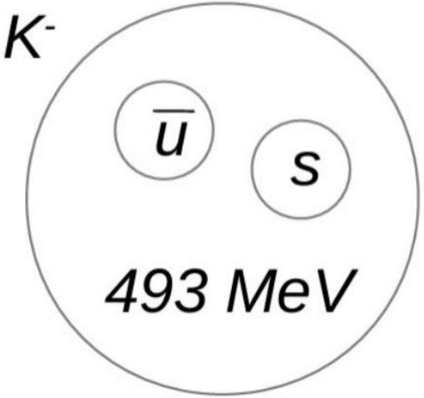
Strangeness enhancement

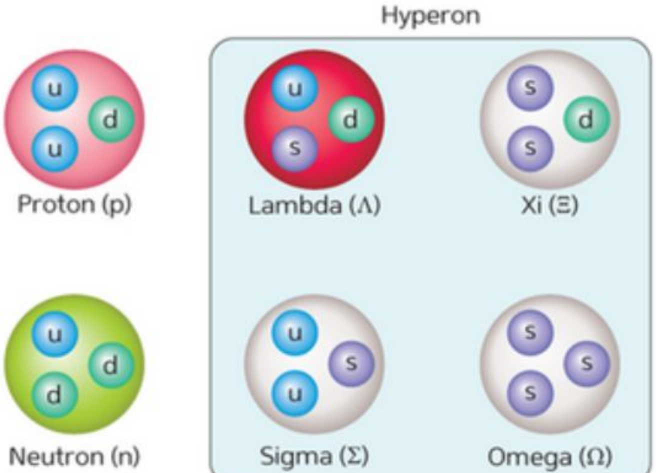
- Strange particles are hadrons containing at least one strange quark
- Strange quarks do not normally exist in the surrounding matter - the ideal probe for QGP research!
- The number of strange quarks produced quarks depends on the conditions and plasma dynamics.



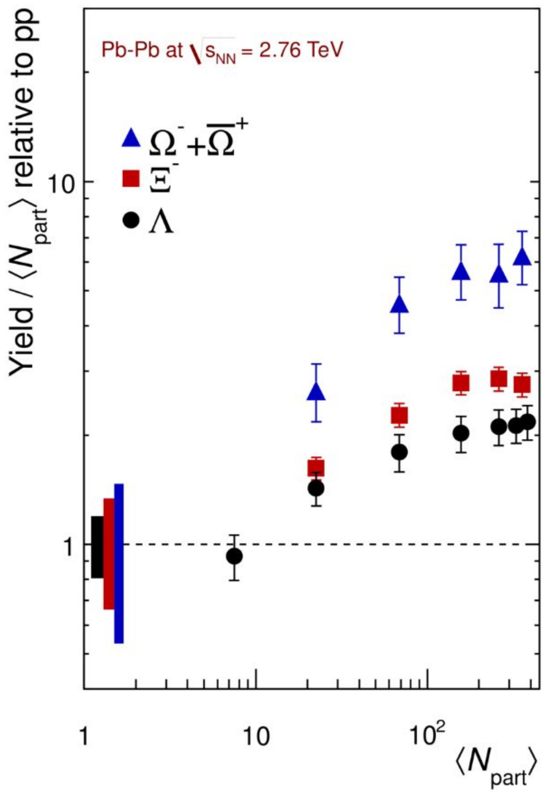
Strangeness enhancement

- Particles are produced from the collision energy $E=mc^2$.
- Under normal conditions (no QGP), the ‘cost’ of producing one strange quark is comparable with the kaon mass.
- When QGP exists, s quarks can exist independently, so the production cost of one quark is less.
- We should observe more strange particles in heavy-ion collisions where QGP is produced in comparison to nucleon-nucleon collisions.





Results



Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
$\Omega^- + \overline{\Omega}^+$
Ξ^-
Λ
Yield / $\langle N_{part} \rangle$ relative to pp
10
1
1
10
10^2
$\langle N_{part} \rangle$

Stability of particles

- Most particles are unstable and each of particle has its own lifetime τ

Stability of particles

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p: $\tau > 10^{31}$ years

n: $\tau = 880{,}1 \pm 1{,}1$ s

π^{+-} : $\tau = (2{,}6033 \pm 0{,}0005) \times 10^{-8}$ s

K^{+-}: $\tau = (1{,}2380 \pm 0{,}0021) \times 10^{-8}$ s

K^0S : $\tau = (0{,}8954 \pm 0{,}0004) \times 10^{-10}$ s

Λ: $\tau = (2{,}632 \pm 0{,}020) \times 10^{-10}$ s

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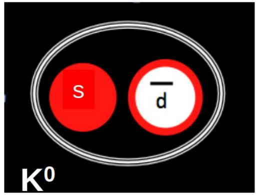
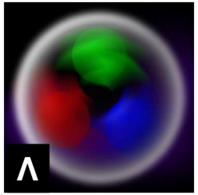
Strange particles

meson



$d\bar{s}$, $\bar{d}s$

baryon



uds

hadrons (baryons or mesons) containing at least one strange (s) quark

We will be looking for neutral strange particles, which travel some distance (mm or cm) from the point of production (collision point) before they decay into two oppositely charged particles

$K^0_s \rightarrow \pi^+\pi^-$

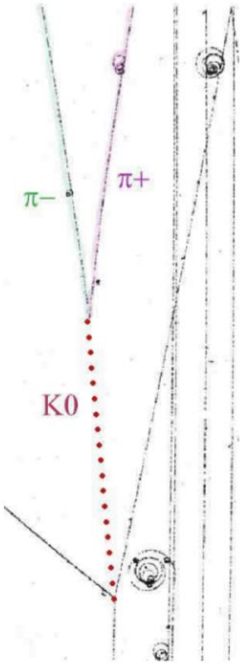
$\tau = 0.89 \times 10^{-10}$ s
$c\tau = 3 \times 10^{10}$ cm $s^{-1} \times 8.9 \times 10^{-11}$ s
2.67 cm from the point of interaction

$\Lambda \rightarrow \pi^- p$

$\bar{\Lambda} \rightarrow \pi^+ \bar{p}$

$\tau = 2.6 \times 10^{-10}$ s
$c\tau = 3 \times 10^{10}$ cm $s^{-1} \times 2.6 \times 10^{-10}$ s
7.2 cm distance from the point of interaction

Weak decays : strangeness is not conserved



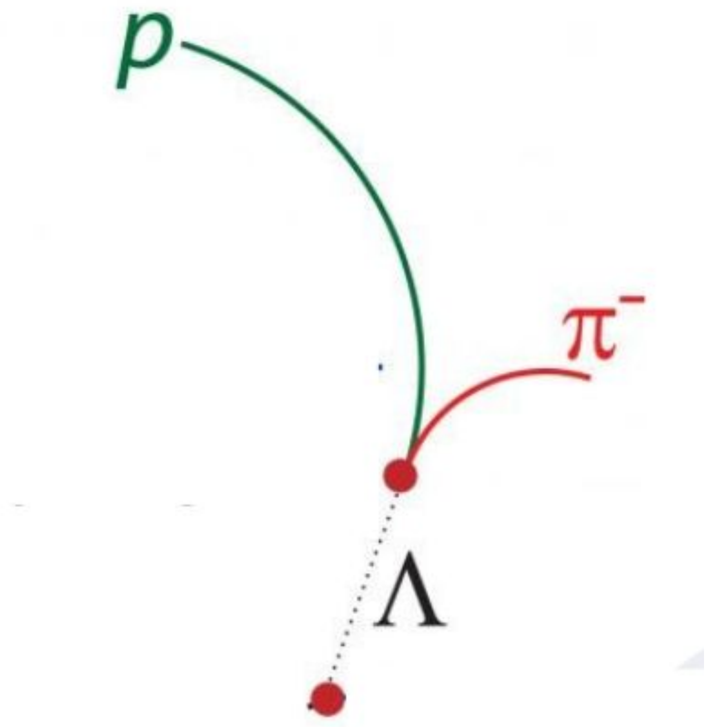
*v = 0,5 c = 1,5 * 10^8 m/s*

*c = 3 * 10^8 m/s*
*t = 2,6 * 10^-10 s*

*s = v * t*
*s = 1,5 * 10^8 * 2,6 * 10^-10 [m/s *s]*
*s = 3,9 * 10^-2 m*
s = 3,9 cm

Particle decay

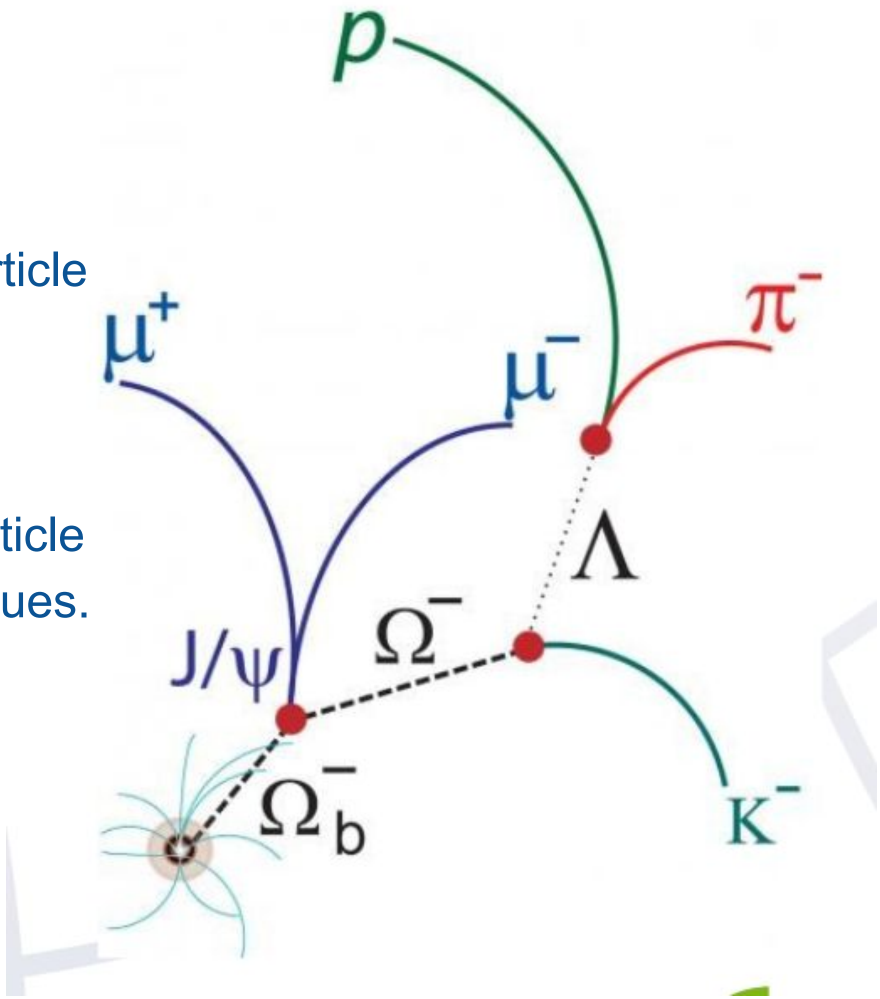
- A spontaneous process in which a particle transforms into other particles.
- Particles with smaller masses are created.



$$\Lambda \rightarrow p + \pi^-$$

Particle decay

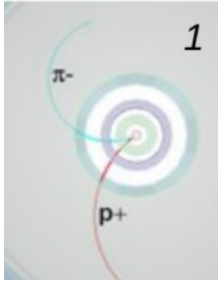
- A spontaneous process in which a particle transforms into other particles.
- Particles with smaller masses are created.
- If, during the process, an unstable particle is produced, the decay process continues.

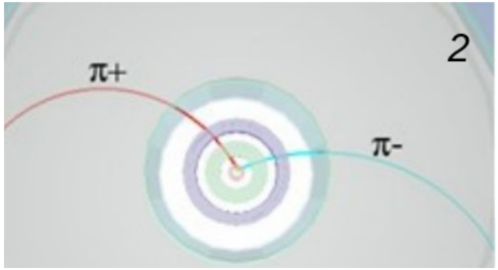


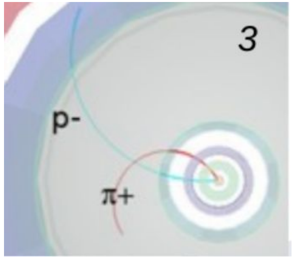
Particle decay

Weak decays - decays caused by weak interactions, average lifetime τ of a decaying particle: 10^{-8} s - 10^{-10} s

1. $\Lambda \rightarrow p + \pi^-$
2. $K_s^0 \rightarrow \pi^+ + \pi^-$
3. $\bar{\Lambda} \rightarrow \pi^+ + \bar{p}$





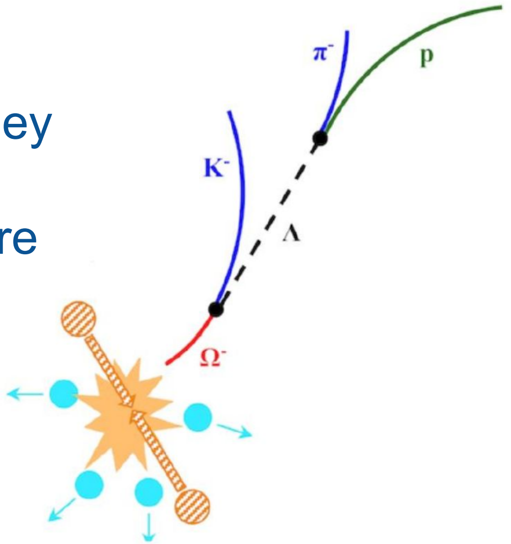


Strong decays - decays caused by the strong interactions, average lifetime τ of a decaying particle: 10^{-23} s

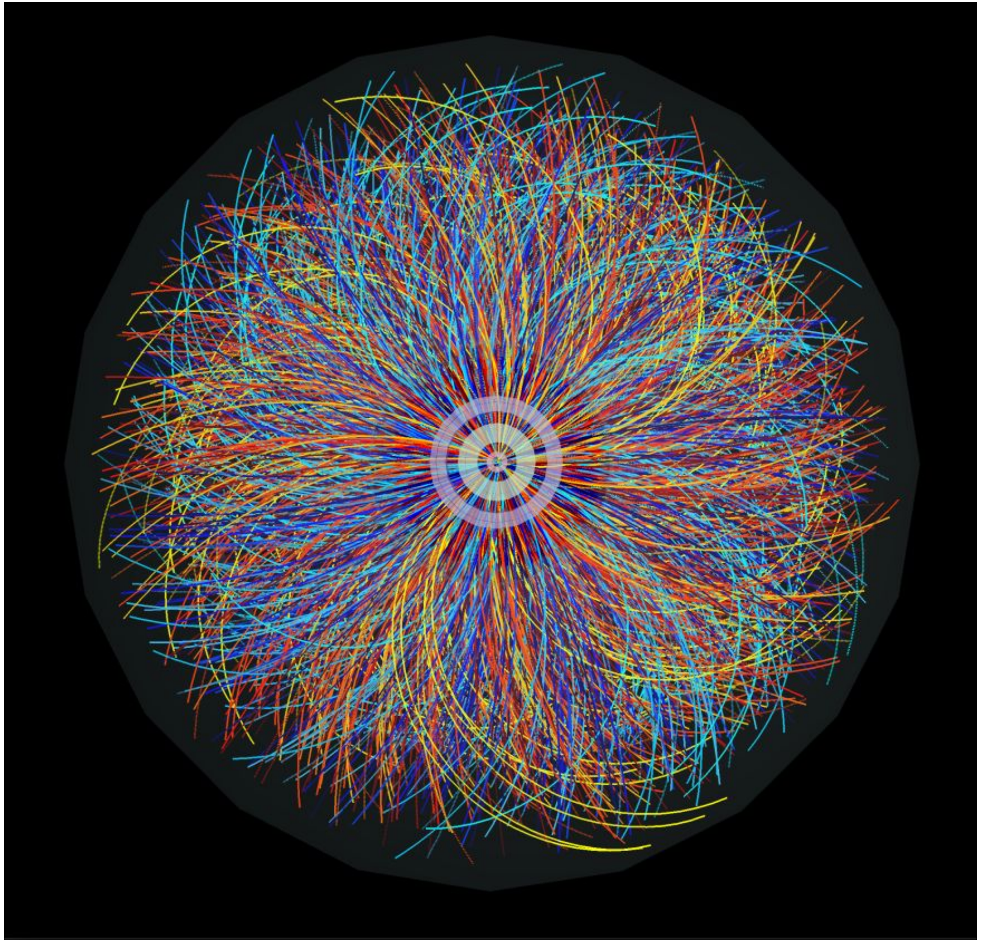
Strange particles

- Contain at least one strange quark or anti-quark.
- They travel a few cm in the detector from the interaction point (IP, or Primary Top).
- In the so-called Secondary Top they decay into more stable particles, which move in the opposite directions and are registered by the detector.
- Such particles have a specific decay topology V, hence they are called V0 (0 - no electric charge).
- For particles with many s quarks, the topology can be more extended.

$$\Lambda \to p\pi^-$$
$$\Xi^- \to \Lambda\pi^-$$
$$\Omega^- \to \Lambda K^-$$



How to find them?



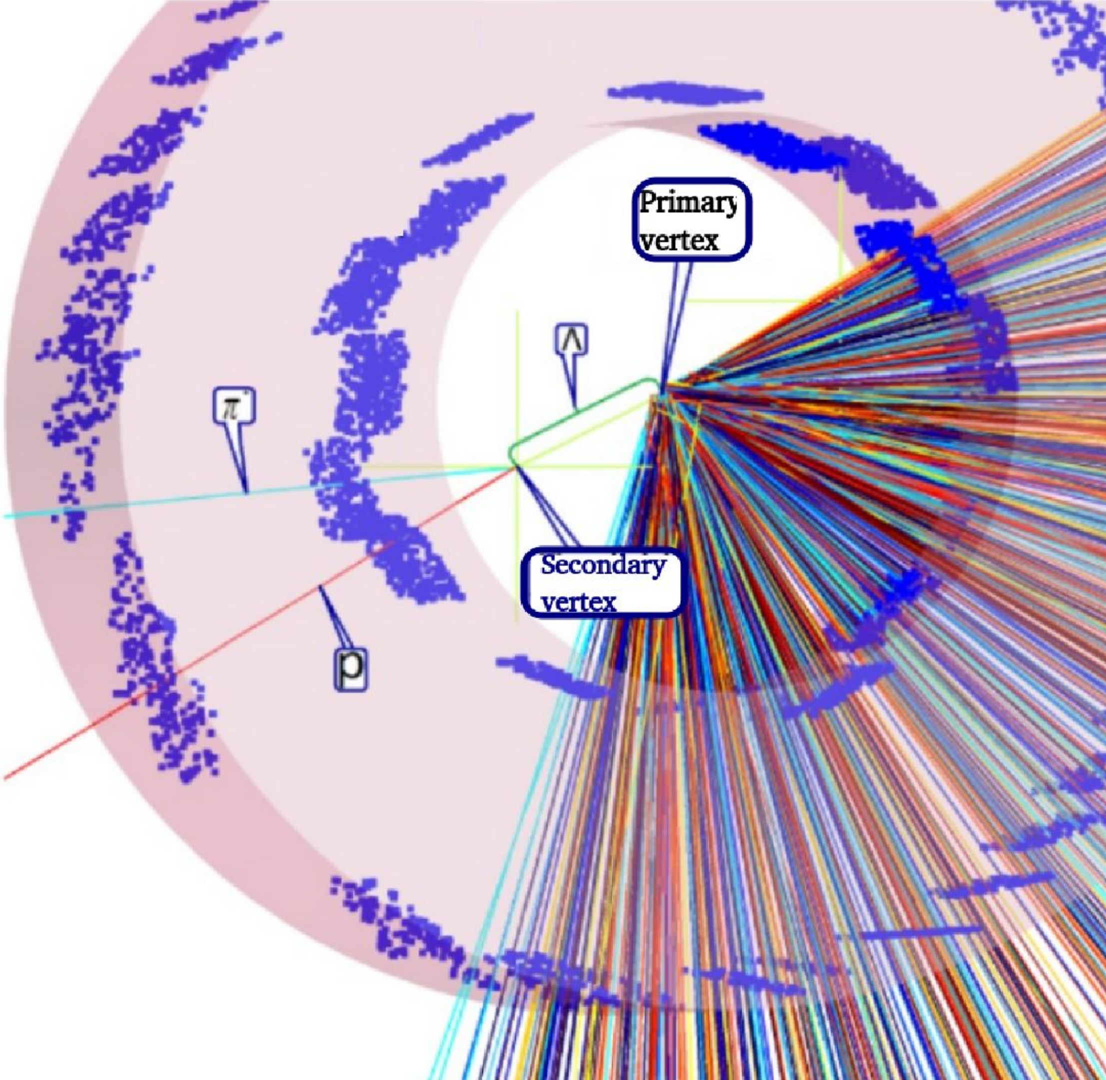
Example:

The decay reconstruction process and identification of a neutral particle that decay into a pair of charged particles:

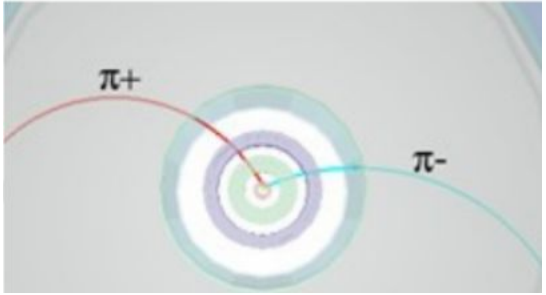
1) Identification of the secondary vertex and determination of its coordinates.

2) Identification of both secondary particles and determination of their momentum.

3) Calculation of invariant mass.



Invariant mass



$$K_0^S \rightarrow \pi^+ \pi^-$$

Each particle can be described with: (p_x, p_y, p_z, E) m

K_0^S: E $\mathbf{p}$ m

π^+: E_1 $\mathbf{p}_1$ m_1

π^-: E_2 $\mathbf{p}_2$ m_2

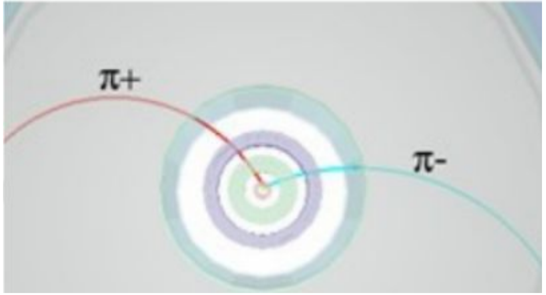
Energy and momentum conservation

$$E = E_1 + E_2$$
$$p = p_1 + p_2$$
$$E^2 = p^2 + m^2$$

and

$$E_1^2 = p_1^2 + m_1^2$$
$$E_2^2 = p_2^2 + m_2^2$$

Invariant mass



$$K_0^S \rightarrow \pi^+ \pi^-$$

Each particle can be described with: (p_x, p_y, p_z, E) m

K_0^S: E $\mathbf{p}$ m

π^+: E_1 $\mathbf{p}_1$ m_1

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Energy and momentum conservation

$$E = E_1 + E_2$$
$$p = p_1 + p_2$$
$$E^2 = p^2 + m^2$$

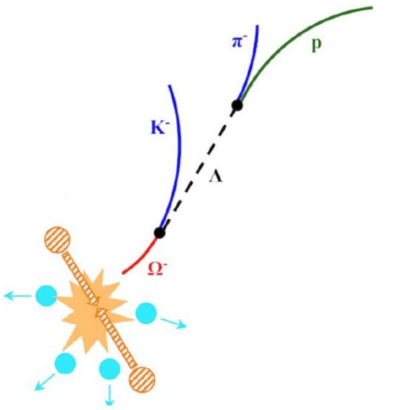
and

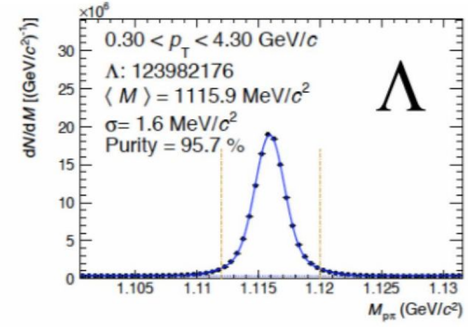
$$E_1^2 = p_1^2 + m_1^2$$
$$E_2^2 = p_2^2 + m_2^2$$

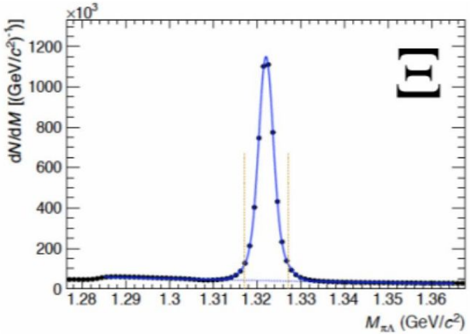
$$m^2 = m_1^2 + m_2^2 + 2E_1E_2 - 2p_1p_2$$

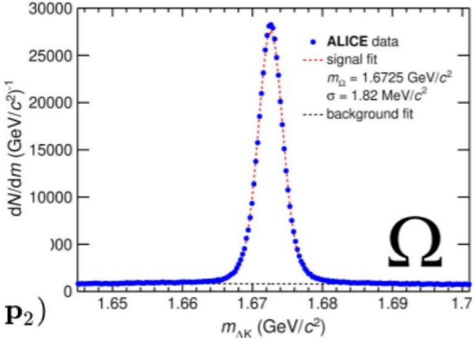
Invariant mass

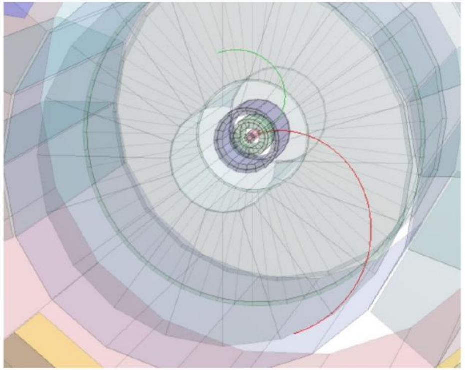
$$\Lambda \to p\pi^-$$
$$\Xi^- \to \Lambda\pi^-$$
$$\Omega^- \to \Lambda K^-$$











$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\,(E_1E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)$$

Strangeness enhancement:

Increased production of strange particles when:

$$\frac{N_s}{N_{\not{s}}} > \frac{N_s}{N_{\not{s}}}$$

with QGP without QGP

N_s number of strange particles produced;

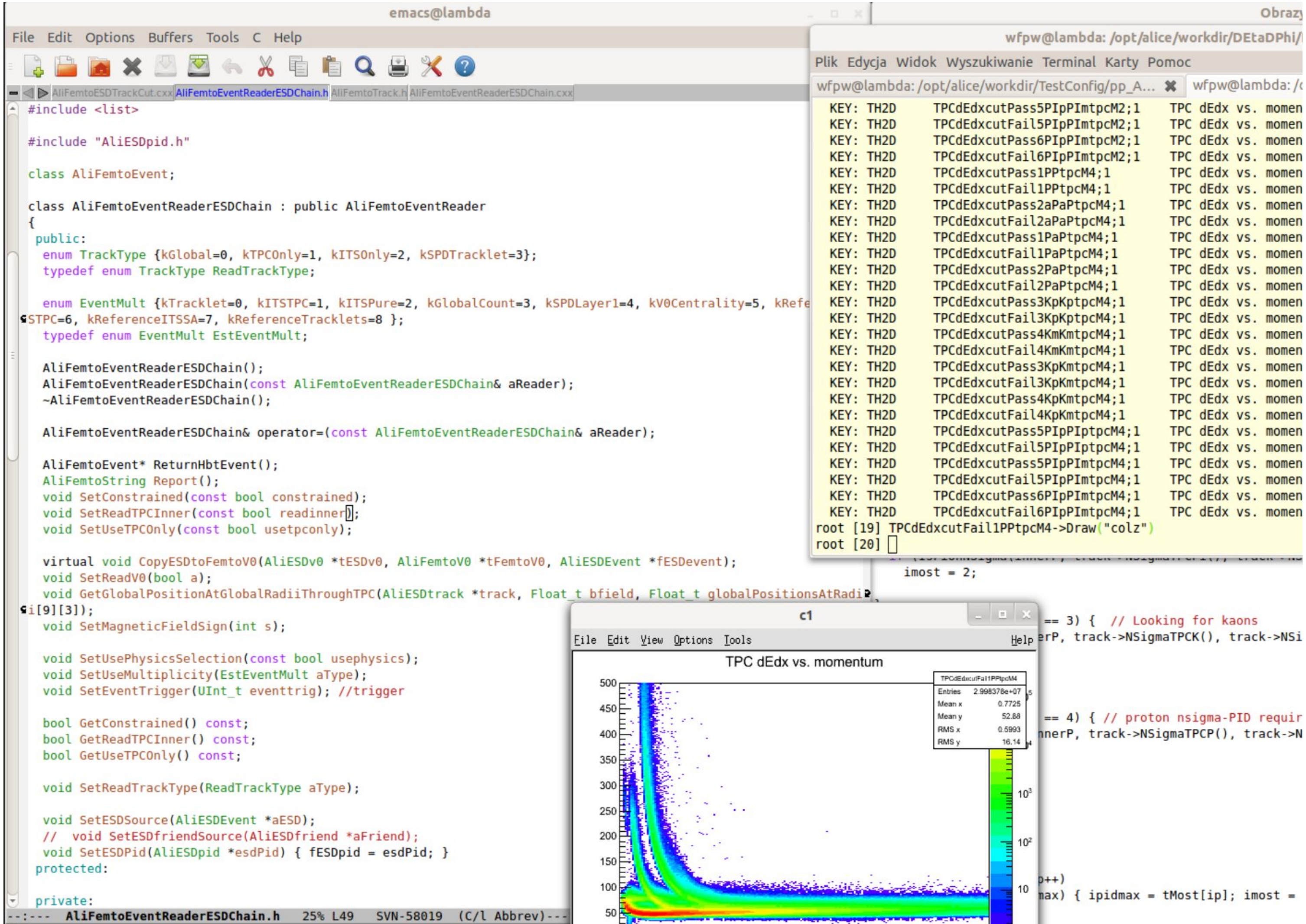
$N_{\not{s}}$ number of particles containing no strange quarks

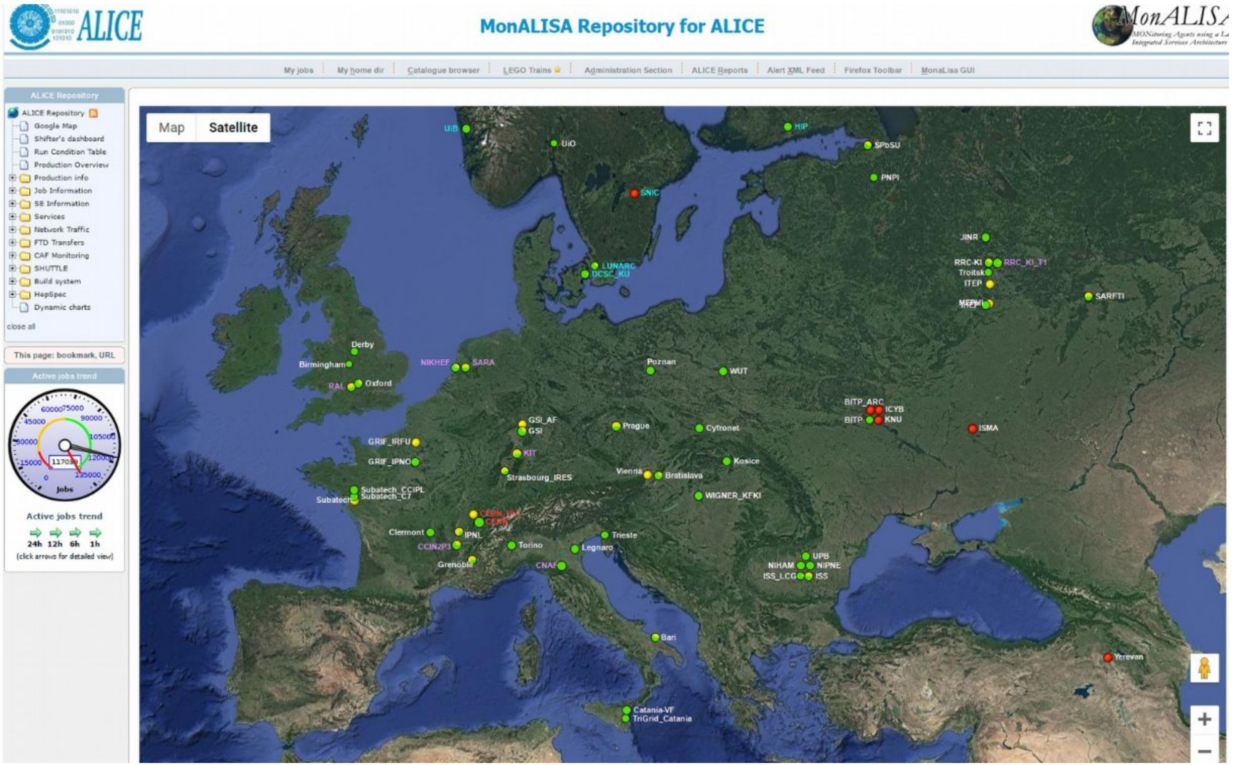

PRIMARY DETECTION CHAMBER


RESONANCE
79.66%


HADRON COLLISION SPECTROMETRY
BOSON CALORIMETER 2


Detector Control System
PROTON PHYSICS: NO BEAM
ALICE
A Large Ion Collider Experiment


emacs@lambda
File Edit Options Buffers Tools C Help
AliFemtoESDTrackCut.cxx AliFemtoEventReaderESDChain.h AliFemtoTrack.h AliFemtoEventReaderESDChain.cxx
#include <list>
#include "AliESDpid.h"
class AliFemtoEvent;
class AliFemtoEventReaderESDChain : public AliFemtoEventReader
{
public:
enum TrackType {kGlobal=0, kTPCOnly=1, kITSOnly=2, kSPDTracklet=3};
typedef enum TrackType ReadTrackType;
enum EventMult {kTracklet=0, kITSTPC=1, kITSPure=2, kGlobalCount=3, kSPDLayer1=4, kV0Centrality=5, kRefe
STPC=6, kReferenceITSSA=7, kReferenceTracklets=8 };
typedef enum EventMult EstEventMult;
AliFemtoEventReaderESDChain();
AliFemtoEventReaderESDChain(const AliFemtoEventReaderESDChain& aReader);
~AliFemtoEventReaderESDChain();
AliFemtoEventReaderESDChain& operator=(const AliFemtoEventReaderESDChain& aReader);
AliFemtoEvent* ReturnHbtEvent();
AliFemtoString Report();
void SetConstrained(const bool constrained);
void SetReadTPCInner(const bool readinner);
void SetUseTPCOnly(const bool usetpconly);
virtual void CopyESDtoFemtoV0(AliESDv0 *tESDv0, AliFemtoV0 *tFemtoV0, AliESDEvent *fESDevent);
void SetReadV0(bool a);
void GetGlobalPositionAtGlobalRadiiThroughTPC(AliESDtrack *track, Float_t bfield, Float_t globalPositionsAtRadi
i[9][3]);
void SetMagneticFieldSign(int s);
void SetUsePhysicsSelection(const bool usephysics);
void SetUseMultiplicity(EstEventMult aType);
void SetEventTrigger(UInt_t eventtrig); //trigger
bool GetConstrained() const;
bool GetReadTPCInner() const;
bool GetUseTPCOnly() const;
void SetReadTrackType(ReadTrackType aType);
void SetESDSource(AliESDEvent *aESD);
// void SetESDfriendSource(AliESDfriend *aFriend);
void SetESDPid(AliESDpid *esdPid) { fESDpid = esdPid; }
protected:
private:
--:--- AliFemtoEventReaderESDChain.h 25% L49 SVN-58019 (C/l Abbrev)---
wfpw@lambda: /opt/alice/workdir/DEtaDPhi/
Plik Edycja Widok Wyszukiwanie Terminal Karty Pomoc
wfpw@lambda: /opt/alice/workdir/TestConfig/pp_A...
KEY: TH2D TPCdEdxcutPass5PIpPImtpcM2;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail5PIpPImtpcM2;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass6PIpPImtpcM2;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail6PIpPImtpcM2;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass1PPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail1PPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass2aPaPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail2aPaPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass1PaPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail1PaPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass2PaPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail2PaPtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass3KpKptpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail3KpKptpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass4KmKmtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail4KmKmtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass3KpKmtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail3KpKmtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass4KpKmtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail4KpKmtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass5PIpPIptpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail5PIpPIptpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass5PIpPImtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail5PIpPImtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutPass6PIpPImtpcM4;1 TPC dEdx vs. momen
KEY: TH2D TPCdEdxcutFail6PIpPImtpcM4;1 TPC dEdx vs. momen
root [19] TPCdEdxcutFail1PPtpcM4->Draw("colz")
root [20]
imost = 2;
== 3) { // Looking for kaons
erP, track->NSigmaTPCK(), track->NSi
== 4) { // proton nsigma-PID requir
nerP, track->NSigmaTPCP(), track->N
p++)
max) { ipidmax = tMost[ip]; imost =
c1
File Edit View Options Tools Help
TPC dEdx vs. momentum
TPCdEdxcutFail1PPtpcM4
Entries 2.998378e+07
Mean x 0.7725
Mean y 52.88
RMS x 0.5993
RMS y 16.14


ALICE
MonALISA Repository for ALICE
MonALISA
My jobs
My home dir
Catalogue browser
LEGO Trains
Administration Section
ALICE Reports
Alert XML Feed
Firefox Toolbar
MonaLisa GUI
ALICE Repository
Google Map
Shifter's dashboard
Run Condition Table
Production Overview
Production info
Job Information
SE Information
Services
Network Traffic
FTD Transfers
CAF Monitoring
SHUTTLE
Build system
HepSpec
Dynamic charts
close all
This page: bookmark, URL
Active jobs trend
Jobs
Active jobs trend
24h 12h 6h 1h
(click arrows for detailed view)
Map
Satellite
UiB
UiO
HIP
SPbSU
PNPI
SNIC
JINR
RRC-KI
RRC_KI_T1
Troitsk
ITEP
SARFTI
LUNARC
DCSC_KU
Derby
Birmingham
NIKHEF
SARA
RAL
Oxford
Poznan
WUT
BITP_ARC
ICYB
BITP
KNU
ISMA
GSI_AF
GSI
Prague
Cyfronet
GRIF_IRFU
GRIF_IPNO
KIT
Kosice
Strasbourg_IRES
Vienna
Bratislava
Subatech_CCIPL
Subatech
WIGNER_KFKI
Clermont
IPNL
Trieste
CCIN2P3
Torino
Legnaro
Grenoble
CNAF
UPB
NIHAM
NIPNE
ISS_LCG
ISS
Bari
Yerevan
Catania-VF
TriGrid_Catania

Vague but exciting ...

CERN DD/OC

Information Management: A Proposal

Tim Berners-Lee, CERN/DD

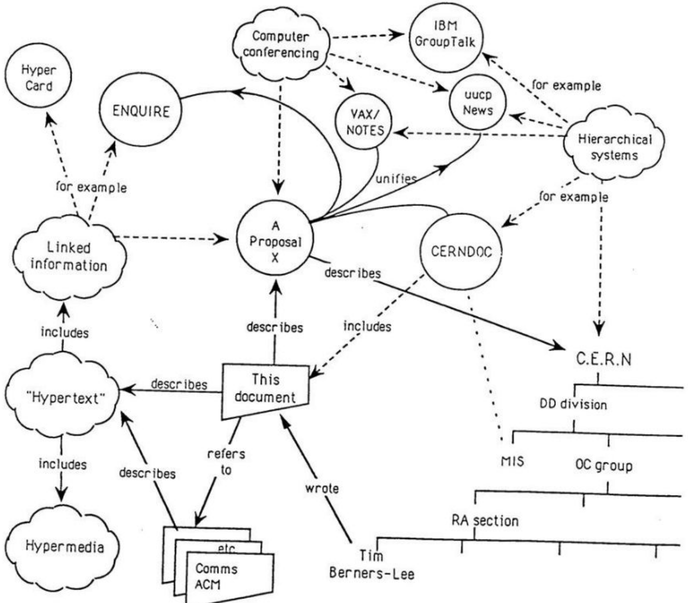
March 1989

Information Management: A Proposal

Abstract

This proposal concerns the management of general information about accelerators and experiments at CERN. It discusses the problems of loss of information about complex evolving systems and derives a solution based on a distributed hypertext sytstem.

Keywords: Hypertext, Computer conferencing, Document retrieval, Information management, Project control



26 years ago….

Tim Berners-Lee writes the famous document that marked the beginning of the World Wide Web (HTML). In its opening paragraphs he writes:

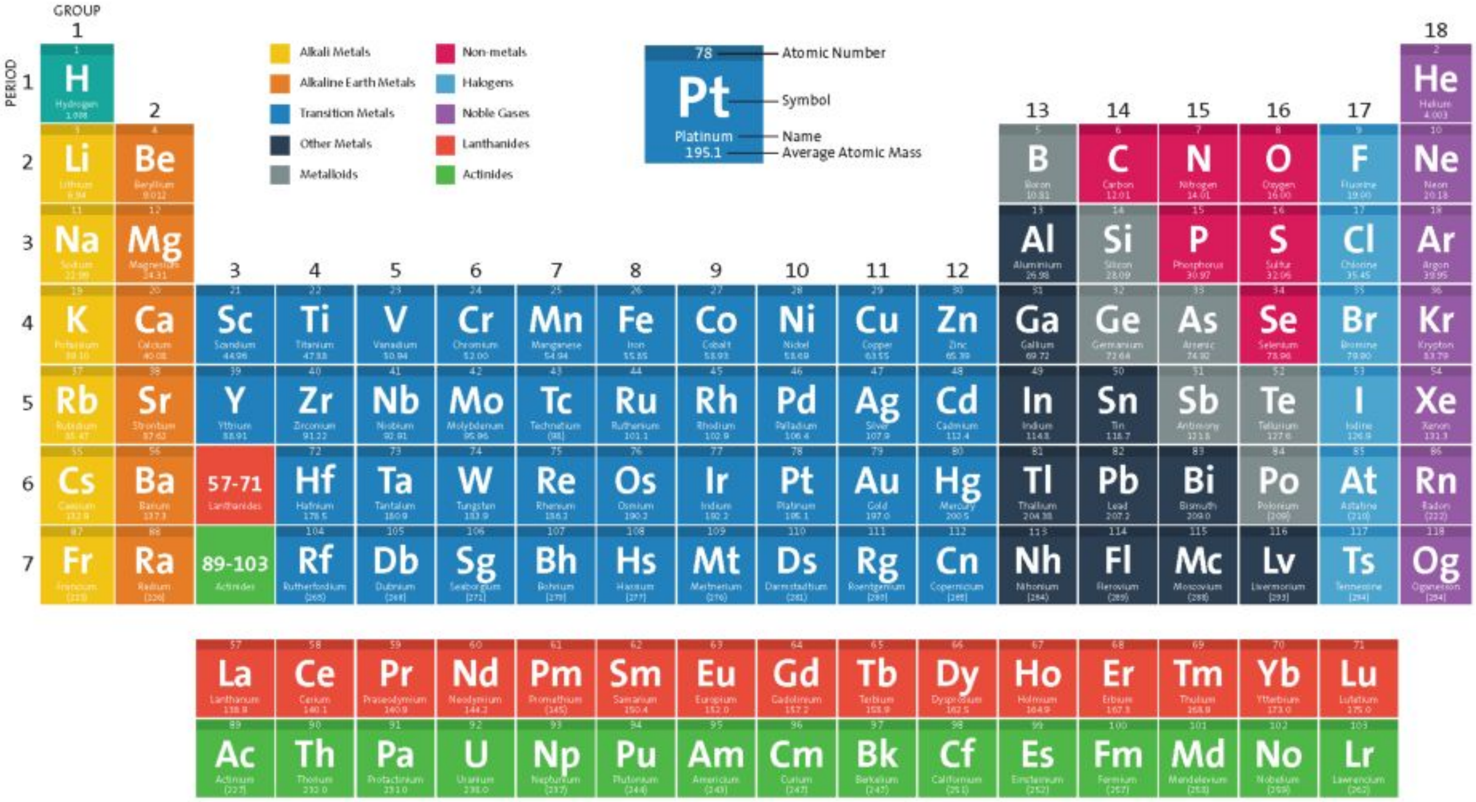
"Many of the discussions of the future at CERN **and the LHC era** end with the question - ªYes, but how will we ever keep track of such a large project?º This proposal provides an answer to such questions. Firstly, it discusses the problem of information access at CERN. Then, it introduces the idea of linked information systems, and compares them with less flexible ways of finding information."

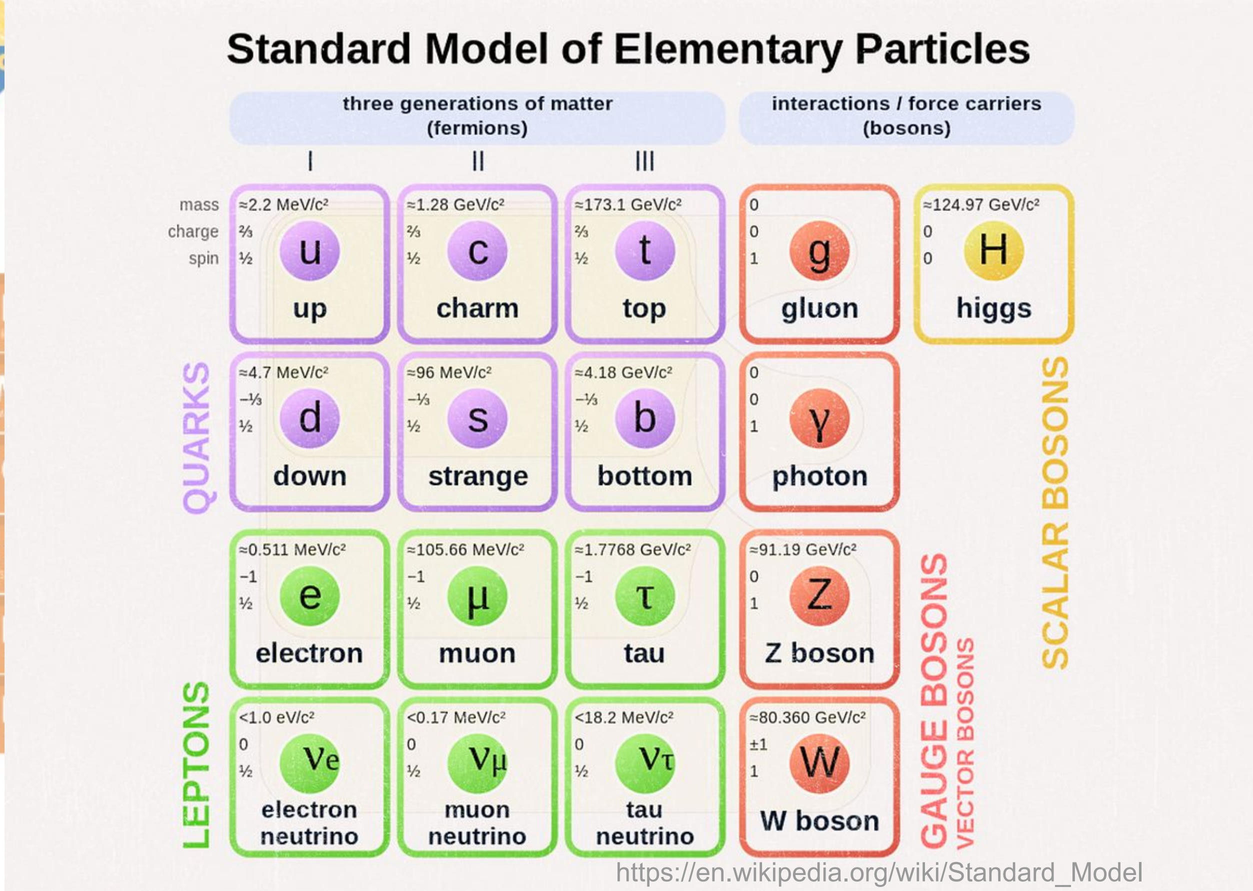
Thank you for your attention!

Backup

ACS
Chemistry for Life®

PERIODIC TABLE OF ELEMENTS




Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
charge
spin
≈2.2 MeV/c²
⅔
½
u
up
≈1.28 GeV/c²
⅔
½
c
charm
≈173.1 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≈124.97 GeV/c²
0
0
H
higgs
≈4.7 MeV/c²
−⅓
½
d
down
≈96 MeV/c²
−⅓
½
s
strange
≈4.18 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
≈0.511 MeV/c²
−1
½
e
electron
≈105.66 MeV/c²
−1
½
μ
muon
≈1.7768 GeV/c²
−1
½
τ
tau
≈91.19 GeV/c²
0
1
Z
Z boson
<1.0 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≈80.360 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS
https://en.wikipedia.org/wiki/Standard_Model

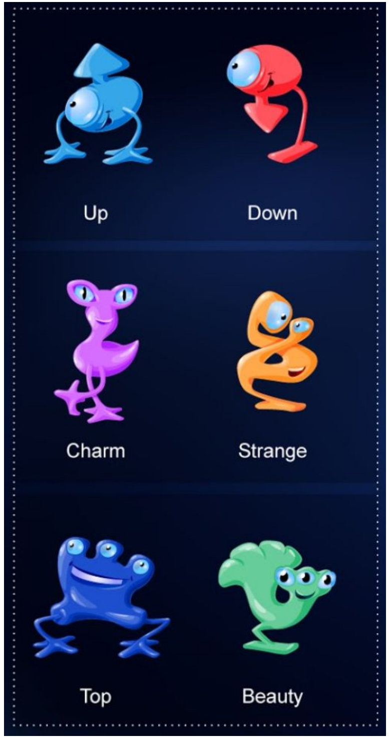
Standard model

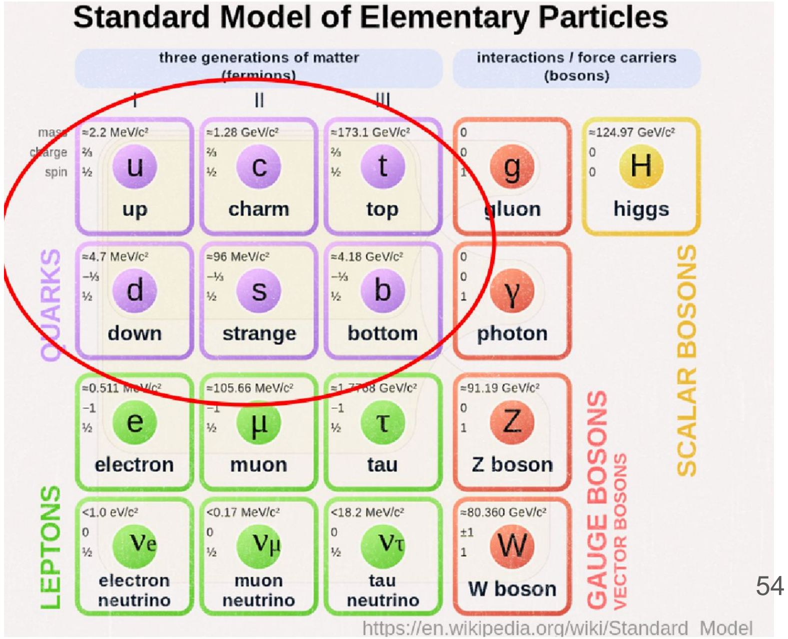
QUARKS

I

II

III





Credit: CERN

Standard model

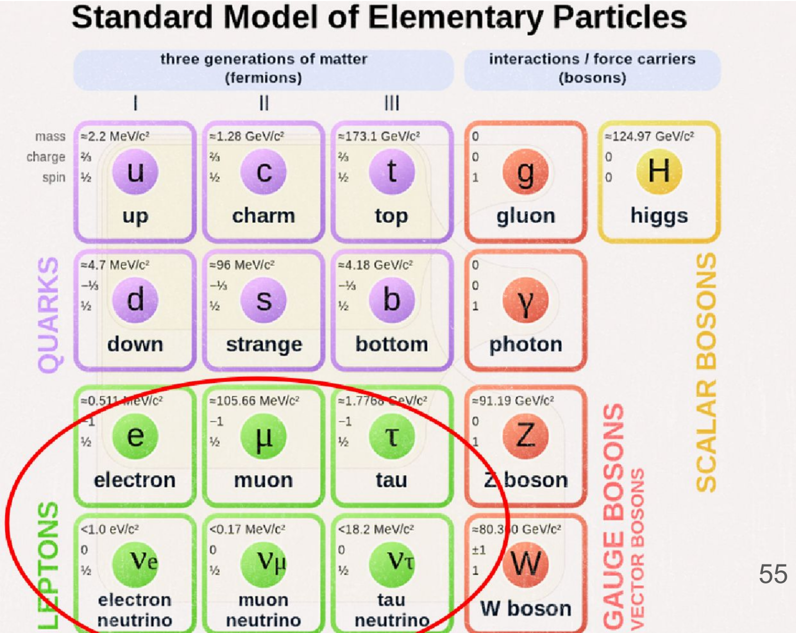
LEPTONS

I

II

III

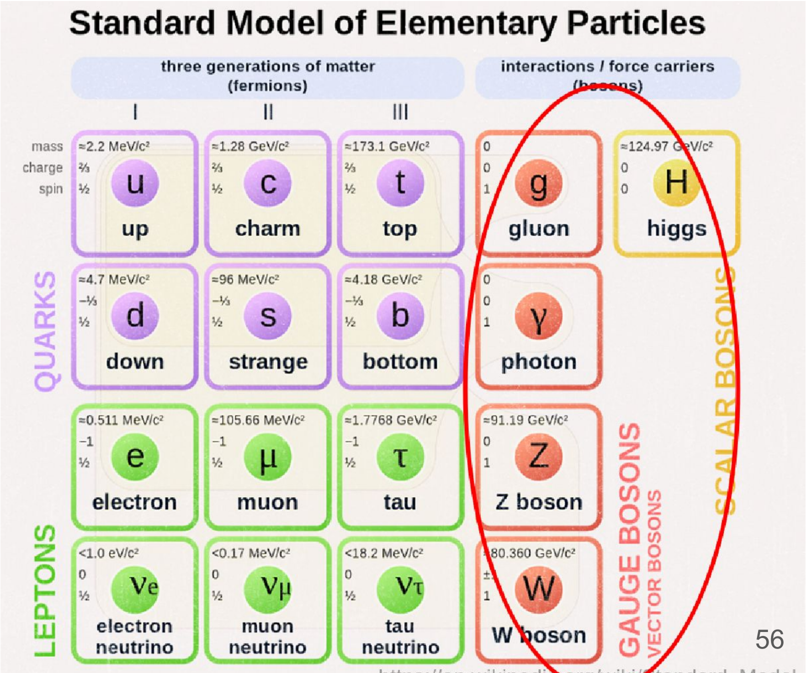
Credit: CERN



Interactions

BOSONS

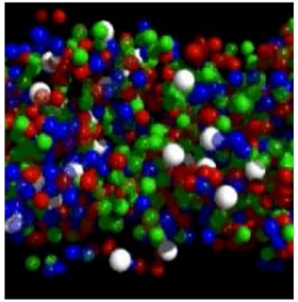
Credit: CERN

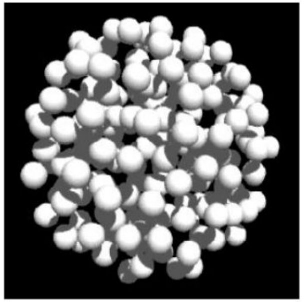


https://en.wikipedia.org/wiki/Standard_Model

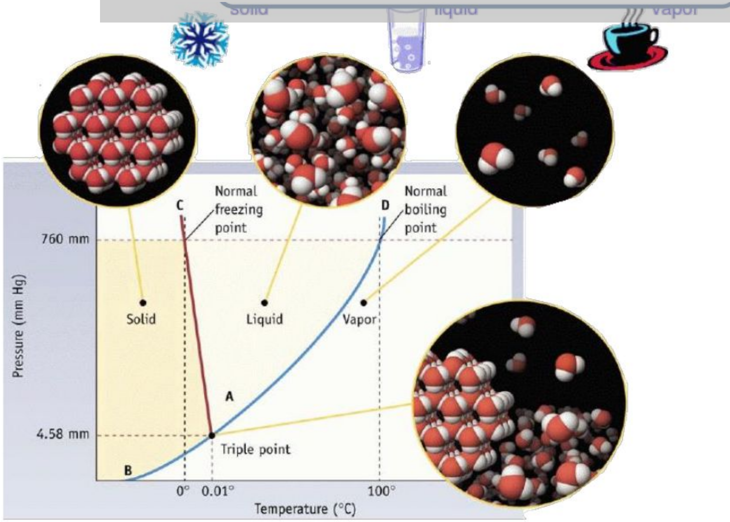
The critical temperature below which the phase transition occurs.

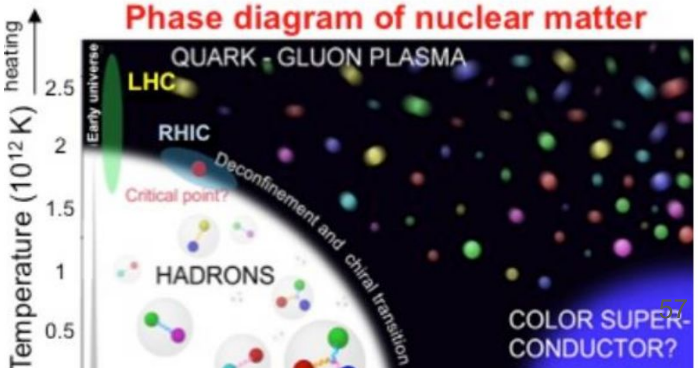
Below a certain temperature, quarks combine to form protons, neutrons, and other particles.

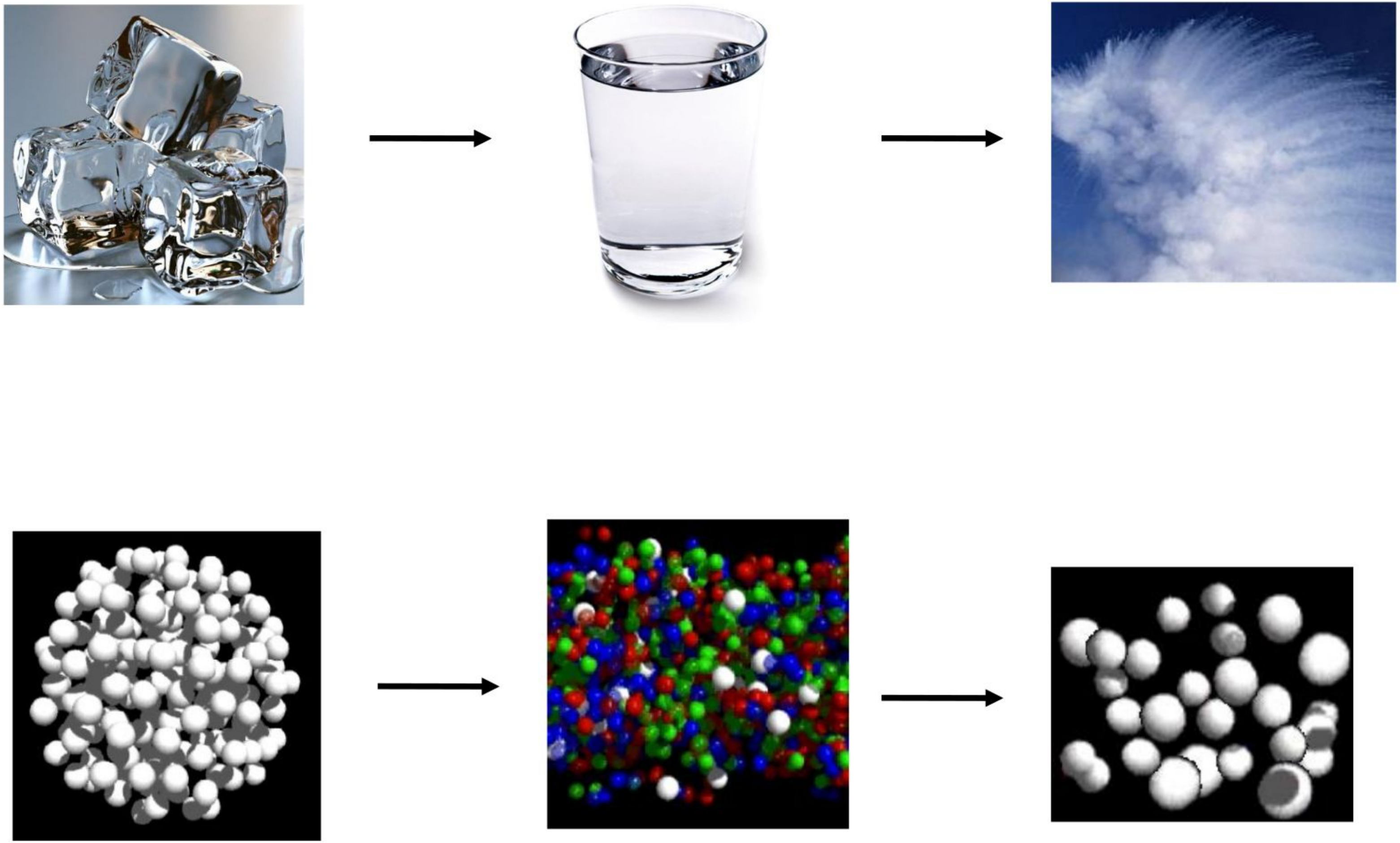




Phase diagram of water

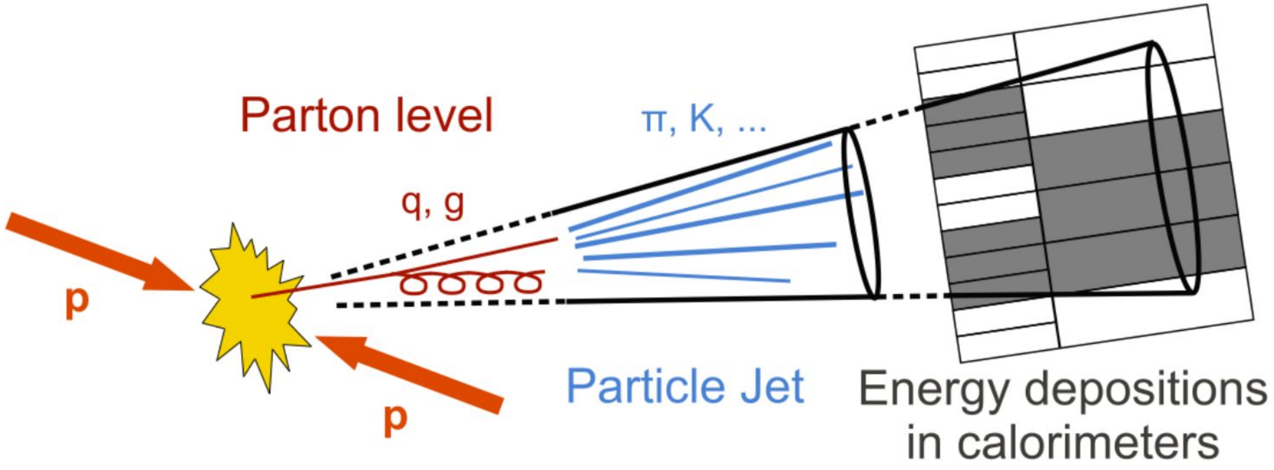






Jets

Initial partons (quarks or gluons) with high shoots give rise to so-called jets:

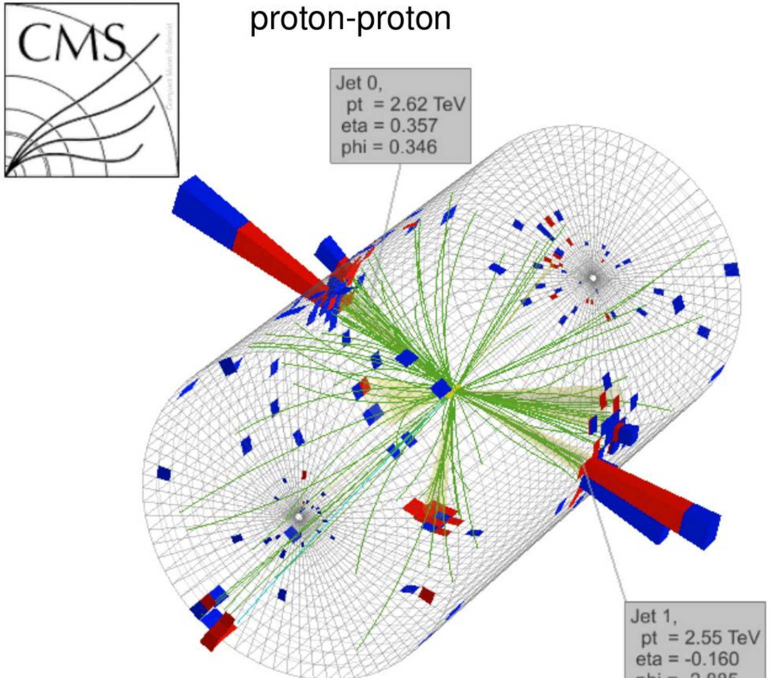


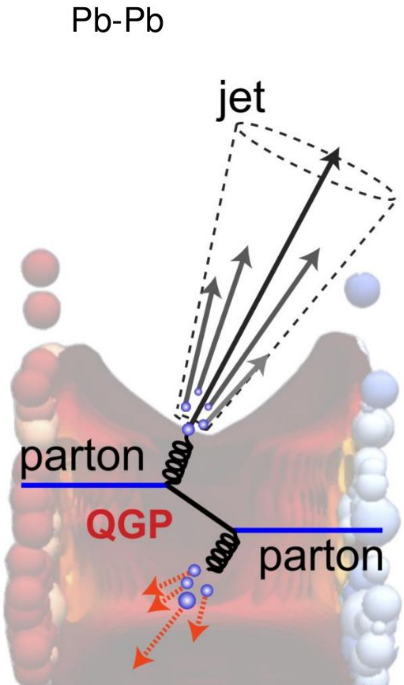
- “jet” is a collimated stream of particles (hadrons) of high momentum (energy), which reach the detectors

- In practice (conservation of energy-momentum principle) in a collision we have two (or sometimes more) such jets

Jets

In heavy ion collisions, one of the two jets should be suppressed on passage through the plasma

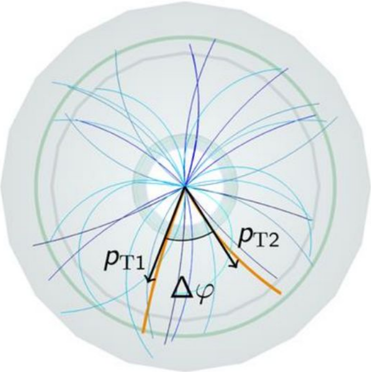




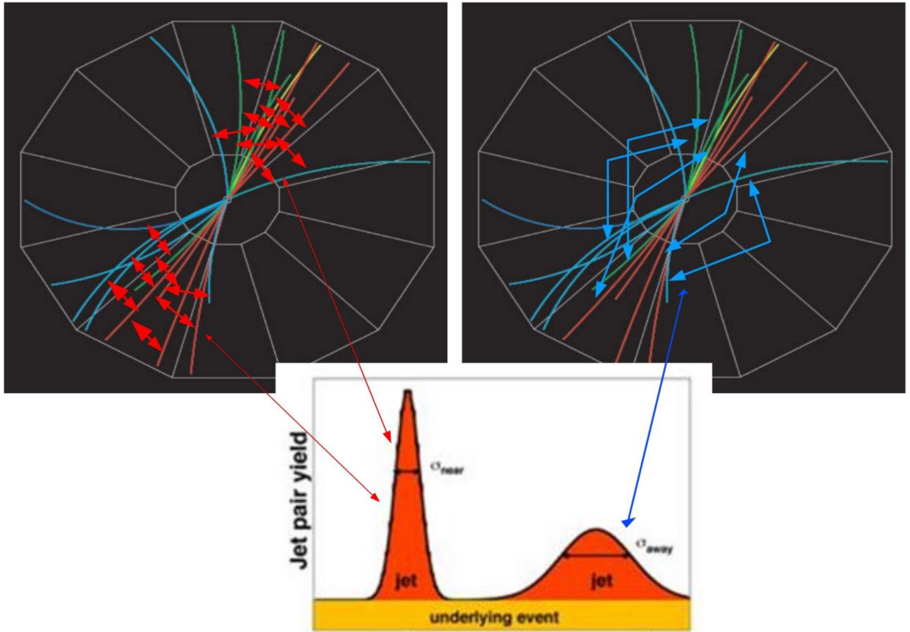
Jet quenching

- How can we experimentally measure the suppression of the second jet?

- We can look at the collision in a plane perpendicular to the beam axis and count the difference in azimuthal angle for a pair of particles:



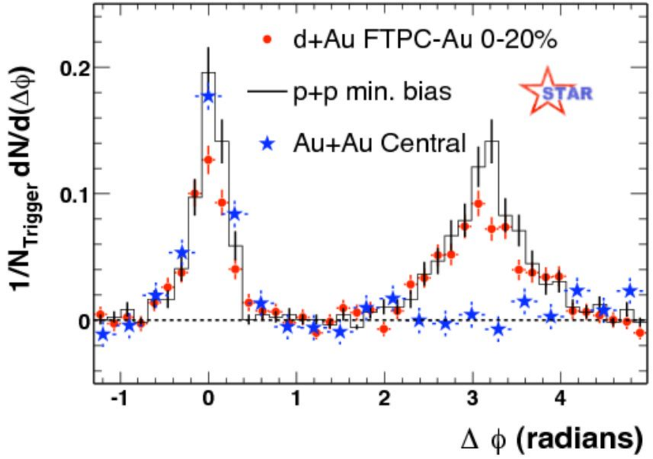
p_T - transverse momentum;
φ - azimuthal angle;

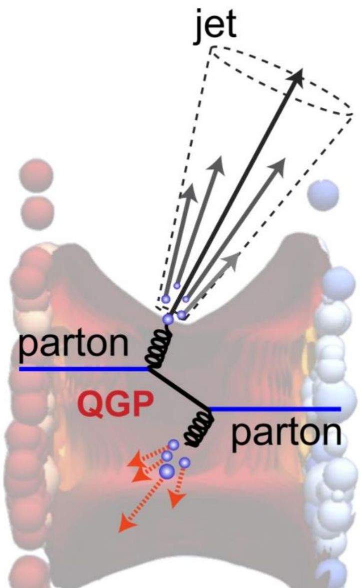


Jet quenching

And if we carry out such an analysis separately for collisions between protons and heavy ions, we obtain:

here an example from the STAR experiment at the RHIC accelerator in the USA





- This result indicates that there is indeed suppression of the second jet (jet quenching) - we have different