FAIR Facility for Antiproton and Ion Research

An European laboratory for studies of particles and nuclear physics

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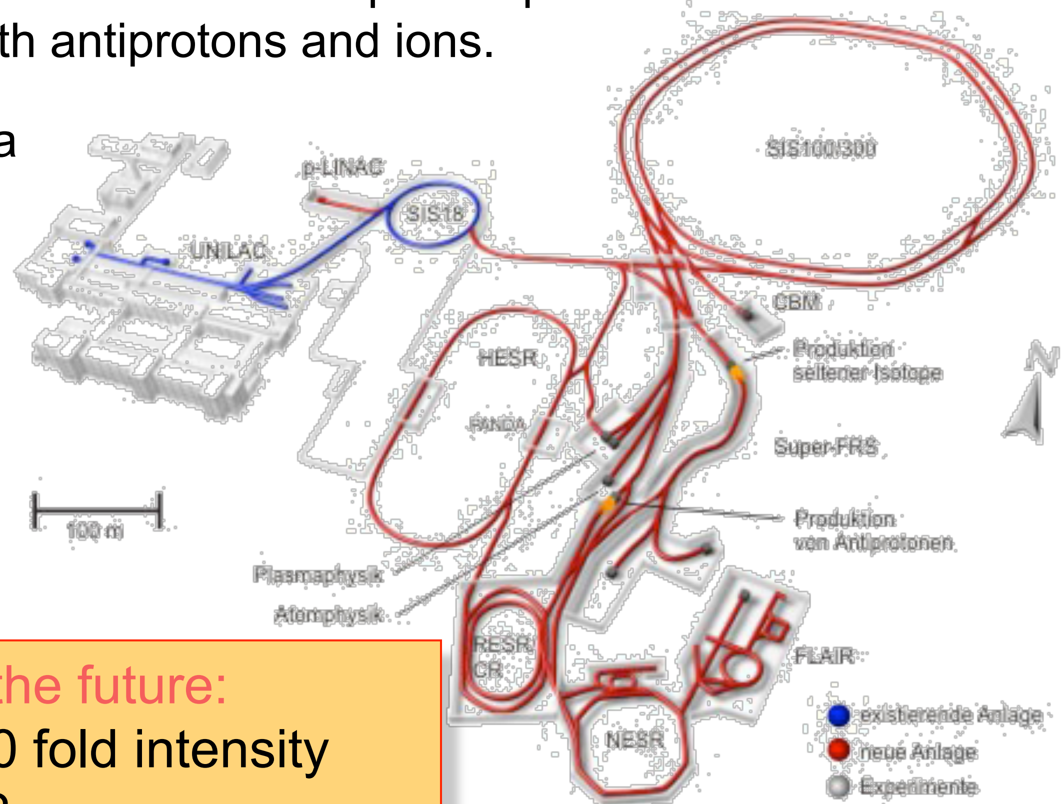
Where is FAIR ?

FAIR

Facility for Antiproton
and Ion Research
in Europe GmbH

FAIR, **F**acility for **A**ntiproton and **I**on **R**esearch, is a new international accelerator complex to perform fundamental research with antiprotons and ions.

It is under construction in Germany as a cooperation of an international community of countries and scientists.



Beams now:

Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon

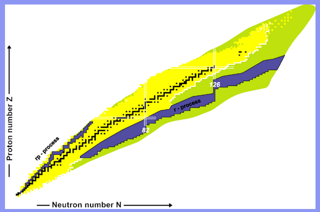
Beams in the future:
...00 fold intensity
...2
...o uranium plus
...er, i.e. anti-protons)
up to 35 - 45 GeV/nucleon

Antiproton production
Linac: 50MeV H-
SIS18: $5\cdot10^{12}$ protons / cycle
SIS100: $2\text{-}2.5\cdot10^{13}$ protons / cycle
Production target: 29 GeV protons
bunch compressed to 50nsec
$2\cdot10^{7}$/s ($7\cdot10^{10}$/h) antiprotons

Summary of Research Areas at FAIR

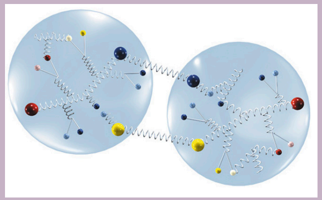
Structure and Dynamics of Nuclei - Radioactive Beams

Nucleonic matter
Nuclear astrophysics
Fundamental symmetries



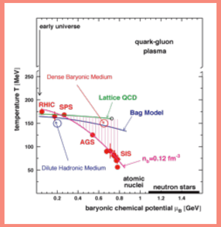
Hadron Structure and Quark-Gluon Dynamics - Antiprotons

Non-pertubative QCD
Quark-gluon degrees of freedom
Confinement and chiral symmetry



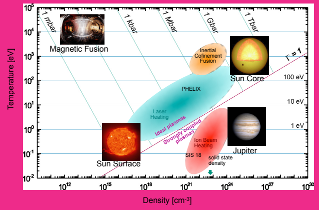
Nuclear Matter and the Quark-Gluon Plasma - Relativistic HI - Beams

Nuclear phase diagram
Compressed nuclear/strange matter
Deconfinement and chiral symmetry



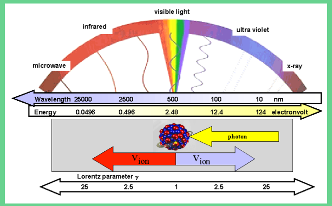
Physics of Dense Plasmas and Bulk Matter - Bunch Compression

Properties of high density plasmas
Phase transitions and equation of state
Laser - ion interaction with and in plasmas



Ultra High EM-Fields and Applications - Ions & Petawatt Laser

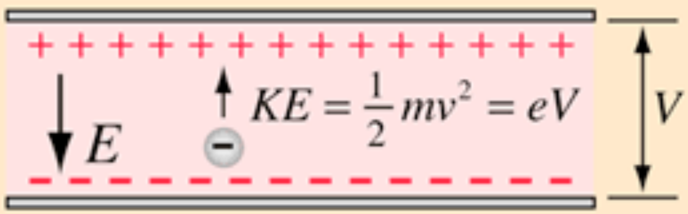
QED and critical fields
Ion - laser interaction
Ion - matter interaction



...Let's open a parenthesis [

The **electron volt** (symbol **eV**) is a unit for energy. It is equal to 1.6×10^{-19} joule.

It is defined as the amount of energy gained by an electron moved across an electric potential difference of one volt.



Work done on electron W:

$W = qV = (1.6x10^{-19}C)(1\frac{J}{C})$

$W =$ 1 electron volt $= 1.6x10^{-19}J$

e = electron charge $= 1.6x10^{-19}C$

V = voltage E = electric field

If an electron starts from rest at the negative plate, then the electric field will do work eV on it, giving it that amount of kinetic energy when it strikes the positive plate.

1 MeV = 10^6 eV, 1 GeV = 10^9 eV, 1 TeV = 10^{12} eV

Basic Concepts

$$\boxed{E^2 = \vec{p}^2 c^2 + m_0^2 c^4}$$

• Energy E measured in eV • momentum p measured in eV/c • mass m_0 measured in eV/c^2

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad E = m_0 \gamma c^2 \qquad p = m_0 \gamma \beta c \qquad \beta = \frac{p\,c}{E}$$

How much energy is 1 eV? $1\ eV = 1.6 \cdot 10^{-19}\ J$ $\quad 1eV/c^2 = 1.8 \cdot 10^{-36}\ Kg$

$m_{bee} = 1\ \text{g} = 5.8 \cdot 10^{32}\ \text{eV}/c^2$

$v_{bee} = 1\ \text{m/s} \rightarrow E_{ape} = 10^{-3}\ \text{J} = 6.25 \cdot 10^{15}\ \text{eV}$

$$\boxed{E_{LHC} = 14 \cdot 10^{12}\ \text{eV}}$$

After all LHC is not so bad...

Total LHC energy:

10^{14} protons $*$ $14 \cdot 10^{12}$ eV $\approx 10^8$ J this is as a big truck

$m_{truck} = 100$ T

$v_{truck} = 120$ Km/h

Some values of mass and energy

1 MeV — 1 GeV — 1 TeV

M_e = 0.5 MeV

M_μ = 105 MeV

M_π = 140 MeV

$M_{n,p}$ = 1 GeV

M_Z = 91 GeV

M_{LEP} = 200 GeV

M_{LHC} = 14 TeV

Length typical values

1 μm (10^{-6} m) detector spatial resolution

1 nm (10^{-9} m) wave length of green light 500 nm

1 A (10^{-10} m) atom dimension

1 fm (10^{-15} m) proton dimension

Time typical values

1 ms (10^{-6} s) drift time of an electron in 5 cm di Ar

1 ns (10^{-9} s) time of a relativistic electron to travel 30 cm

1 ps (10^{-12} s) mean life-time of a B meson

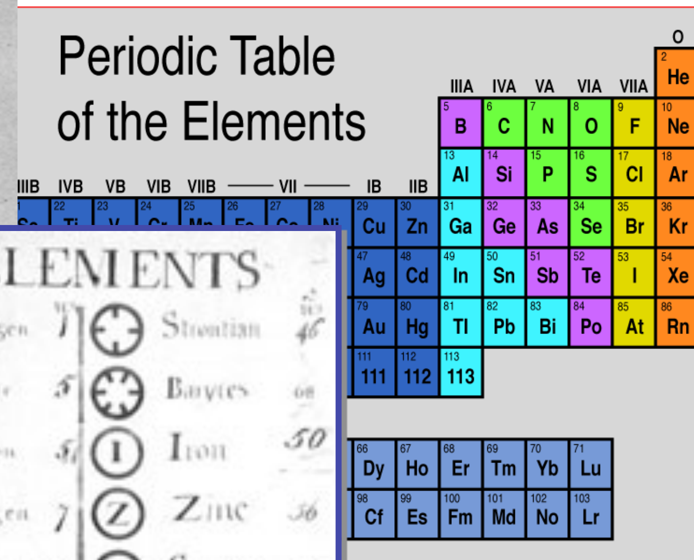
To simplify formulae we put $\hbar = c = 1$ ➡ $E^2 = \vec{p}^2 + m_0^2$ ➡ $[E] = [m] = [p] = \text{eV}$

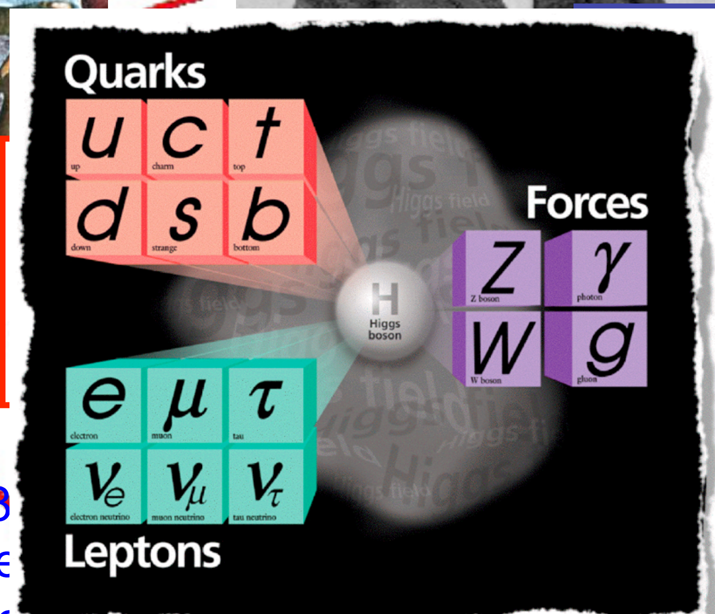
...we can close the parenthesis]

what is matter made of?

Our present knowledge of matter is the result of centuries of studies…

Phil
belie
elem





9 introduced the
f elements

18
we
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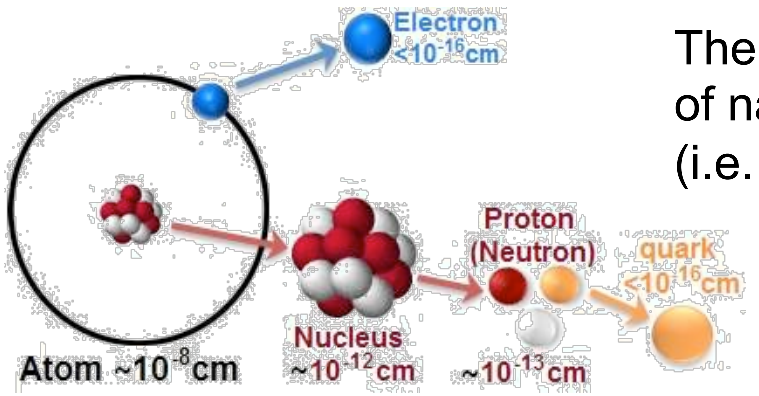
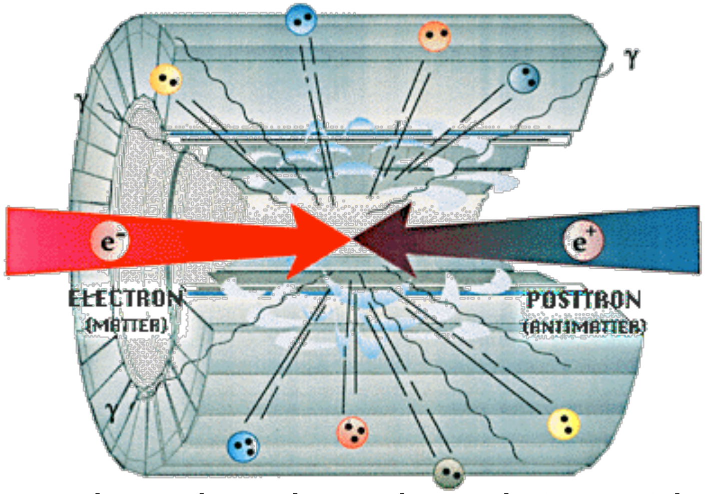
1963 Murray, Gell-Mann, and Zweig laid the foundation of the quark model

what particle physics does ...



The elementary particles are the simplest systems of nature, they are basic elements or bound states (i.e. the proton) of quarks, antiquarks and gluons.



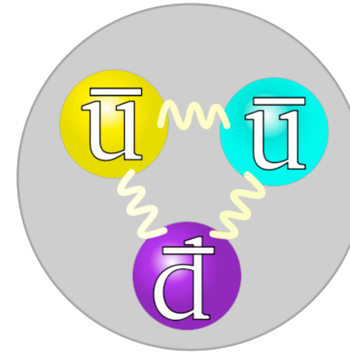
Particle physics studies their interactions by observing scattering and decay processes (and some bound states like antimatter atoms, positronium, . . .).

Elementary particles (protons, electrons, ions) are produced and made to interact in accelerators/colliders (pp , $p\bar{p}$, e^+e^-). Beams of secondary particles can also be obtained from nuclear reactors (neutrons and neutrinos), cosmic rays, solar neutrinos.

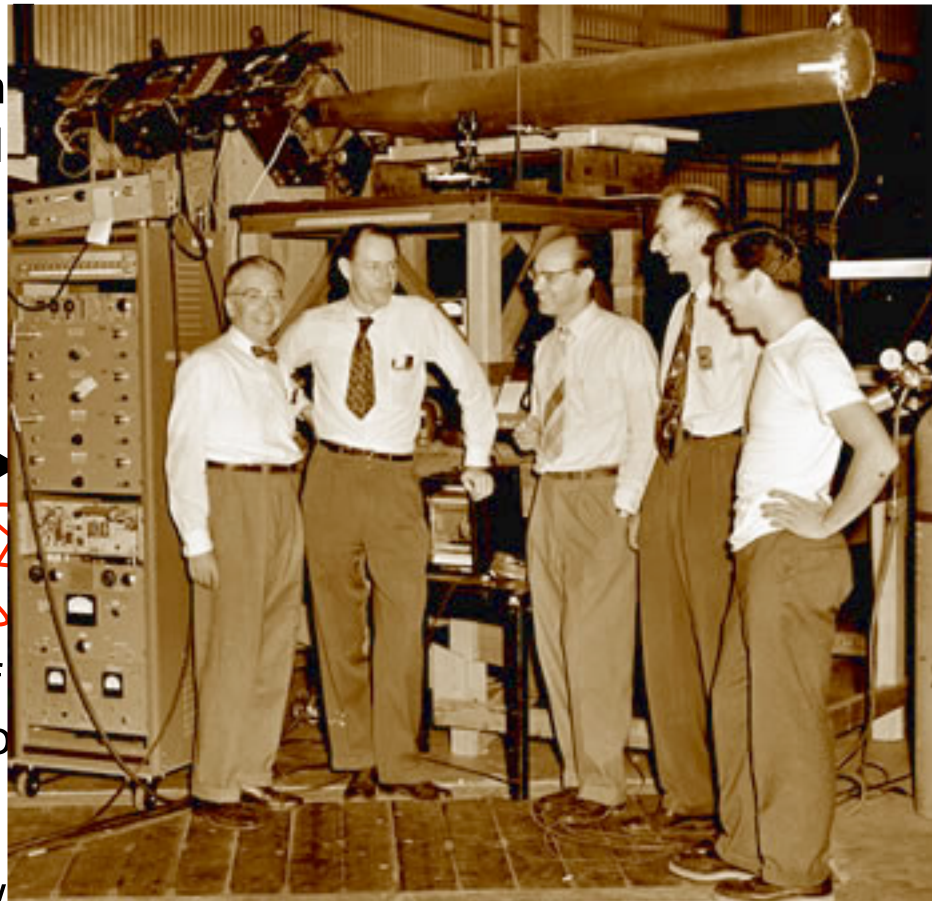
The physical processes are studied using ad-hoc detectors whose information is collected and studied by means of sophisticated analyses. The comparison of data with existing/new theories is then the key to describe new phenomena.

Antiprotons powerful tool

The **antiproton**, ns
are stable, but th n
with a proton will urst
of energy.



$\bar{p}^-$ E



The existence of site to the +1 electric
charge of the pro Nobel Prize lecture.

The antiproton w ersity of California,
Berkeley physicists Emilio Segrè and Owen Chamberlain, for which they were
awarded the 1959 Nobel Prize in Physics.

Physics with antiprotons had a great past

High Energy:

- $\bar{p}p$-Colliders (CERN, Fermilab)
  - Discovery of Z^0, $W^{\pm}$
  - Discovery of t-quark

Medium Energy:

- Conventional $\bar{p}$-beams (LBL, BNL, CERN, Fermilab, KEK, ...)
- $\bar{p}$-Storage Rings (LEAR (CERN); Antiproton Accumulator (Fermilab))
  - Meson Spectroscopy (u, d, s, c)
  - $\bar{p}$-nucleus interaction
  - Hypernuclei
  - Antihydrogen first production
  - CP-violation

Low Energy (Stopped $\bar{p}$'s):

- Conventional $\bar{p}$-beams
- $\bar{p}$-Storage Rings (LEAR, AD (CERN))
  - $\bar{p}$-Atoms ($\bar{p}$He)
  - $\bar{p}$/p-mass ratio
  - Antihydrogen

Physics with antiprotons have a great future

High Energy:

$\bar{p}p$-Collider (Fermilab, CERN??)

- B physics, Top, Electroweak, QCD, Higgs

Medium Energy:

Conventional $\bar{p}$-beams (Fermilab??, JPARC??, ...)

$\bar{p}$-Storage Rings (HESR)

- Charmonium spectroscopy
- Exotic search
- D physics
- Baryon spectroscopy
- Hypernuclei
- CP-violation

Low Energy (Stopped $\bar{p}$'s):

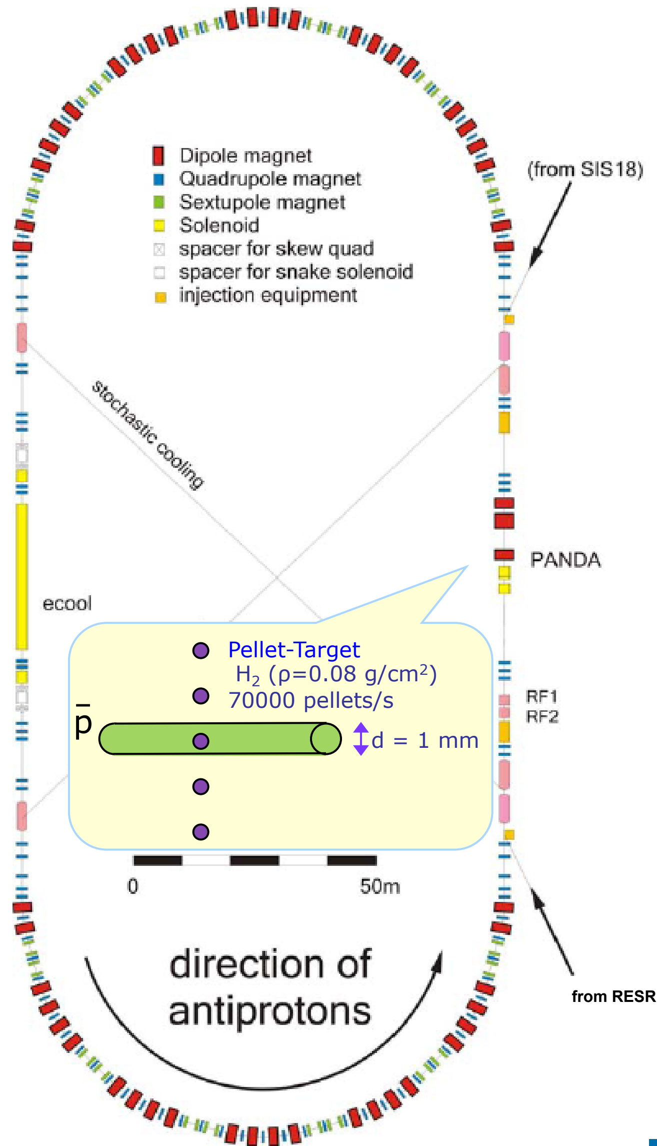
Conventional $\bar{p}$-beams

$\bar{p}$-Storage Rings (FLAIR, AD (CERN))

- $\bar{p}$-Atoms
- Antihydrogen spectroscopy

HESR - High Energy Storage Ring

- Production rate 2x10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5x10^{10} $\bar{p}$
- Internal Target



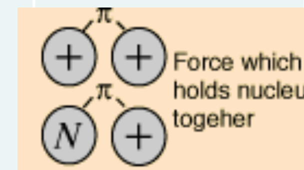
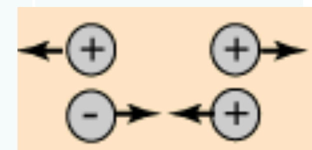
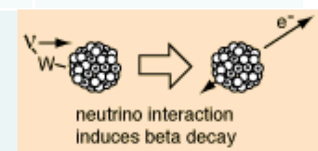
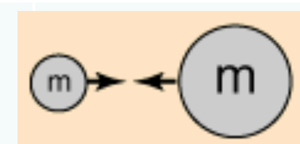
High resolution mode

- $\delta p/p$ ~ 10^{-5} (electron cooling)
- Luminosity = 10^{31} cm^{-2} s^{-1}

High luminosity mode

- Luminosity = 2 x 10^{32} cm^{-2} s^{-1}
- $\delta p/p$ ~ 10^{-4} (stochastic cooling)

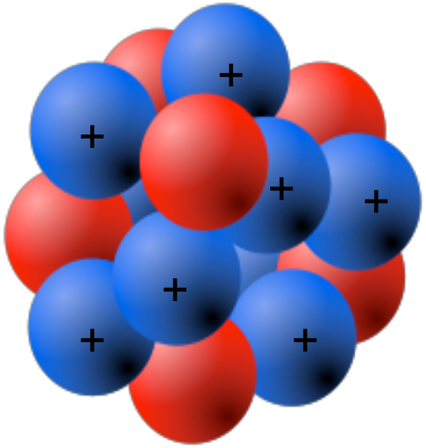
Fundamental interactions

Interaction	Current theory	Mediators	Relative strength	Long-distance behavior	Range (m)	Particles
Strong	Quantum Chromo Dynamics (QCD)	gluons	10^{38}	1	10^{-15}	
Electro-magnetic	Quantum Electro Dynamics (QED)	photons	10^{36}	$1/r^2$	∞	
Weak	Electroweak Theory (EWT)	W and Z bosons	10^{25}	$1/r\ e^{-mw,Z}\ r$	10^{-18}	
Gravitation	General Relativity (GR)	gravitons (hypothetical)	1	$1/r^2$	∞	

Strong Interaction

The strong interaction is responsible:

- at large scale (about 1 to 3 fm), it is the force that binds protons and neutrons (nucleons) together to form the nucleus of an atom.
- At small scale (less than about 0.8 fm, the radius of a nucleon), it is the force (carried by gluons) that holds quarks together to form protons, neutrons, and other hadron particles.

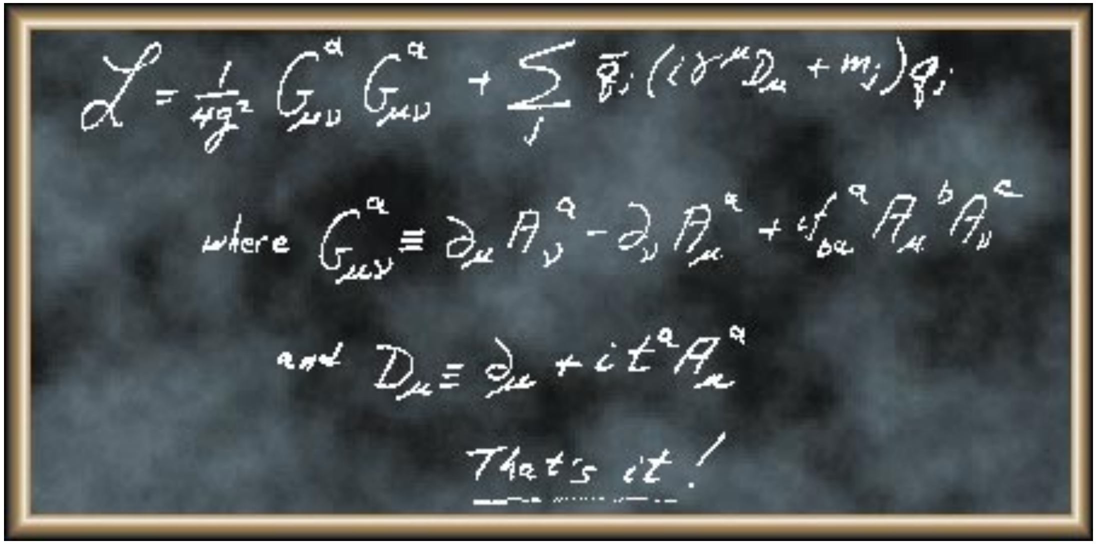


The strong force has so high strength that the energy of an object bound by the strong force (a hadron) is high enough to produce new massive particles.

Thus, if hadrons are struck by high-energy particles, they give rise to new hadrons instead of emitting freely moving radiation (gluons).

This property of the strong force is called color confinement, and it prevents the free "emission" of strong force: instead jets of massive particles are observed.

Quantum Chromodynamics



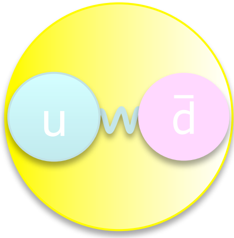
Frank Wilczeck Nobel Prize for Physics 2004

The QCD Lagrangian is, in principle, a complete description of the strong interaction.
There is just one overall coupling constant g , and six quark-mass parameters m_j for the six quark flavors

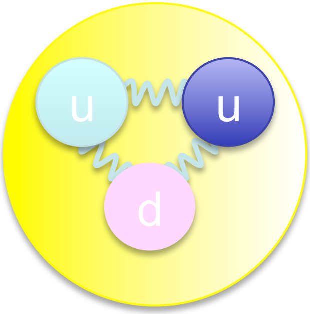
But,
it leads to equations that we cannot solve

Theoretical Framework

In the QCD framework hadrons are basically $q\bar{q}$ or qqq *SU(3)* color singlets (neutral in color), but within the theory nothing prevents to have other color singlet combinations, these are called exotic hadrons.

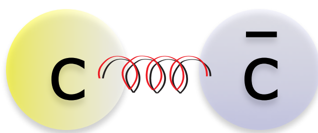


In the low energy domain (below 2 GeV) a considerable experimental effort has been made to search for "exotics" without any firm conclusion.

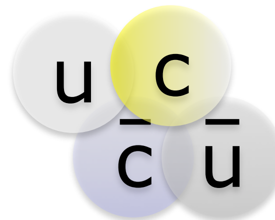


Recently, the advent of high-energy and high-luminosity factories allowed the discovery of states that cannot be ascribed to the ordinary categories.

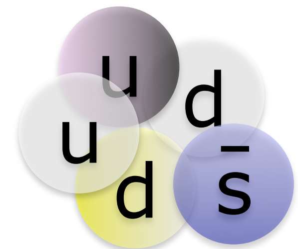
Non conventional charmonium



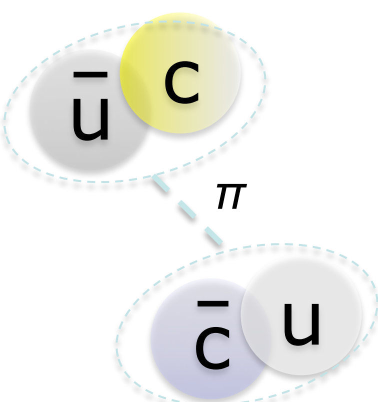
$q\bar{q}g$ hybrid



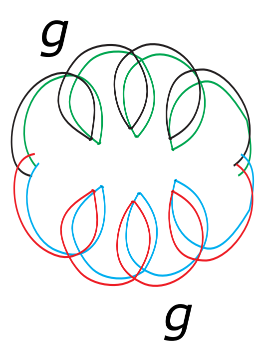
diquark + anti-diquark



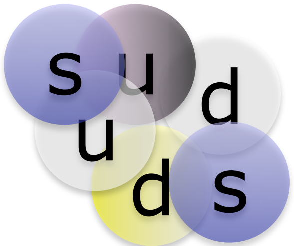
pentaquark



dimeson molecule



glueball



dibaryon

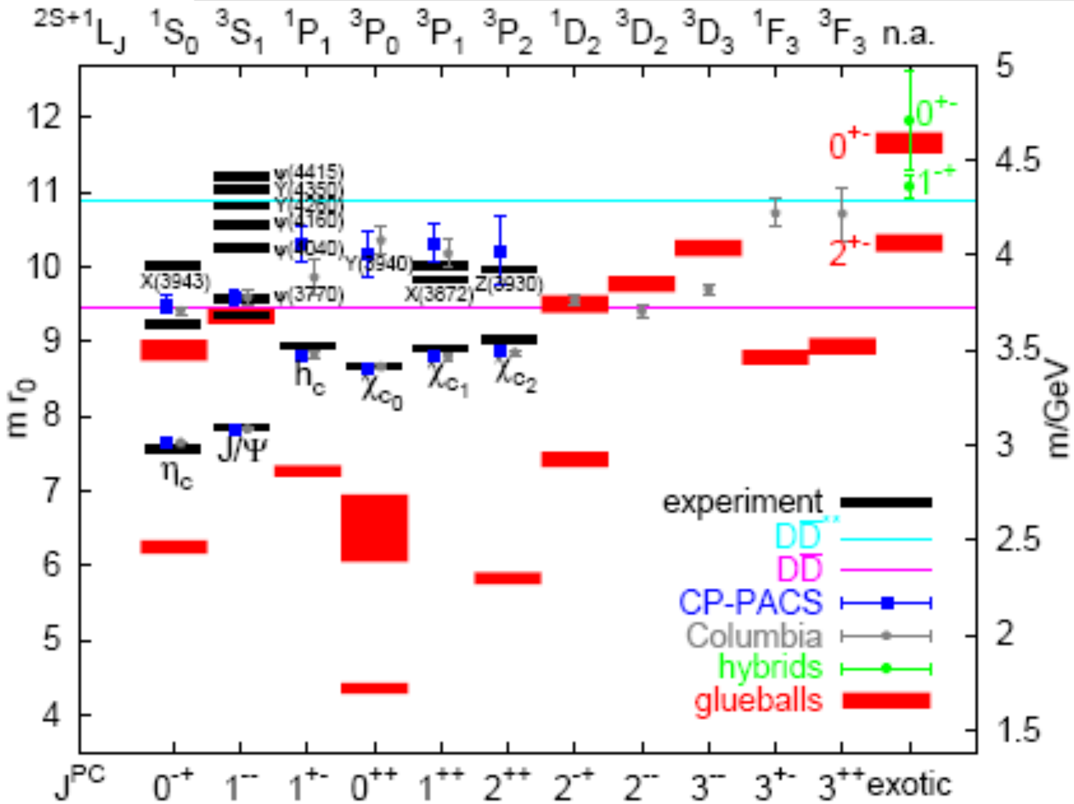
Exotic hadrons

In the light meson region, about 10 states have been classified as "Exotics". Almost all of them have been seen in $p\bar{p}$...

Main non-$q\bar{q}$ candidates	
$f_0(980)$	4q state - molecule
$f_0(1500)$	0^{++} glueball candidate
$f_0(1370)$	0^{++} glueball candidate
$f_0(1710)$	0^{++} glueball candidate
$\eta(1410)$; $\eta(1460)$	0^{-+} glueball candidate
$f_1(1420)$	hybrid, 4q state
$\pi_1(1400)$	hybrid candidate 1^{-+}
$\pi_1(1600)$	hybrid candidate 1^{-+}
π (1800)	hibrid candidate 0^{-+}
$\pi_2(1900)$	hybrid candidate 2^{-+}
$\pi_1(2000)$	hybrid candidate 1^{-+}
$a_2'(2100)$	hybrid candidate 1^{++}

Charmonium region

Charmonium spectrum, glueballs, spin-exotics $c\bar{c}$-glue hybrids with experimental results



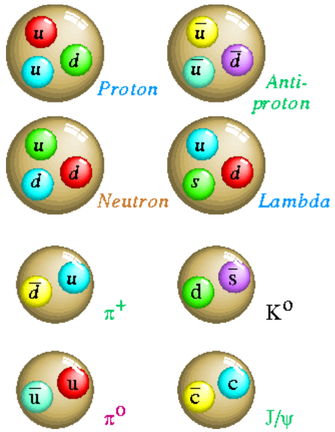
From G. S. Bali, Int.J.Mod.Phys. A21 (2006) 5610-5617

arXiv:hep-lat/0608004

Quantum numbers assignments become clear only with high statistics and different final states

The Confinement

None of the particles that we've actually seen appear in the formula and none of the particles that appear in the formula has ever been observed.



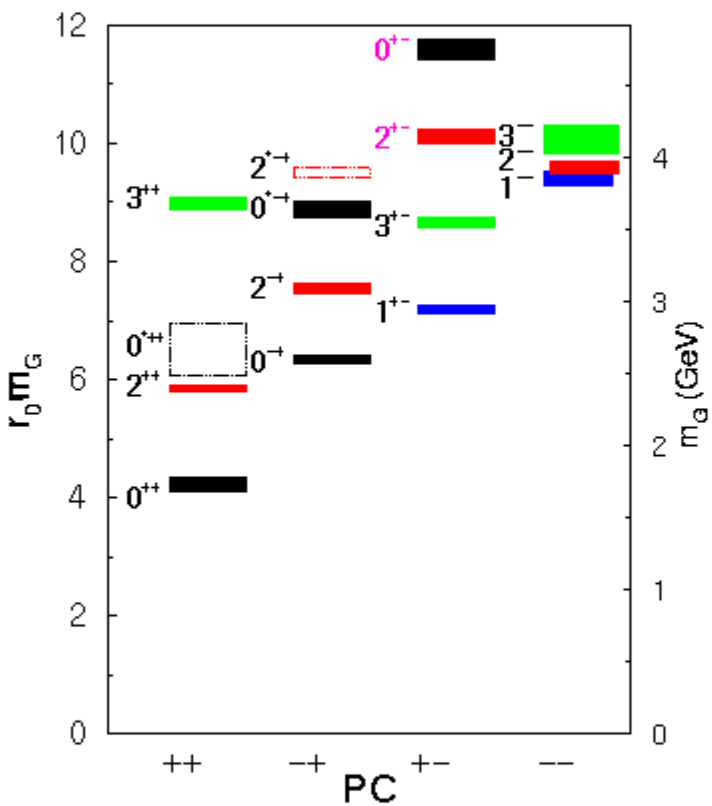
Furthermore, we've ... ional electric charge, which we nonetheles

And certainly we haven't seen anything like gluons--massless particles mediating long-range strong forces.

So if QCD is to describe the world, it must explain why quarks and gluons cannot exist as isolated particles. That is the so-called confinement problem.

Hadron masses

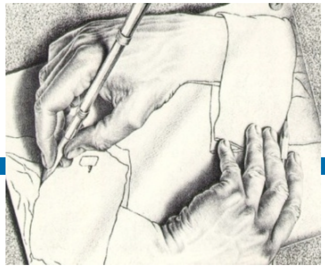
The elementary particles of the Standard Model gain their mass through the Higgs mechanism.
However, only a few percent of the mass of the proton is due to the Higgs mechanism. The rest is created in an unknown way by the strong interaction.



Glueballs would be massless without the strong interaction and their predicted masses arise solely from the strong interaction.

The possibility to study a whole spectrum of glueballs might therefore be the key of understanding the mechanism of mass creation by the strong interaction.

C. Morningstar and M. Peardon, Phys. Rev. D 60, 034509 (1999)



The chiral symmetry

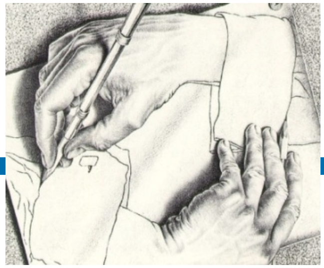
There is another qualitative difference between the observed reality and the world of quarks and gluons.

The phenomenology indicates that if QCD is to describe the world, then the u and d quarks must have very small masses.

But if u and d quarks have very small masses, then the equations of QCD possess some additional symmetry, called chiral symmetry.

There is no such symmetry among the observed strongly interacting particles; they do not come in opposite-parity pairs. So if QCD is to describe the real world, the chiral symmetry must be spontaneously broken.

and this mechanism is playing an important role in the process of mass generation



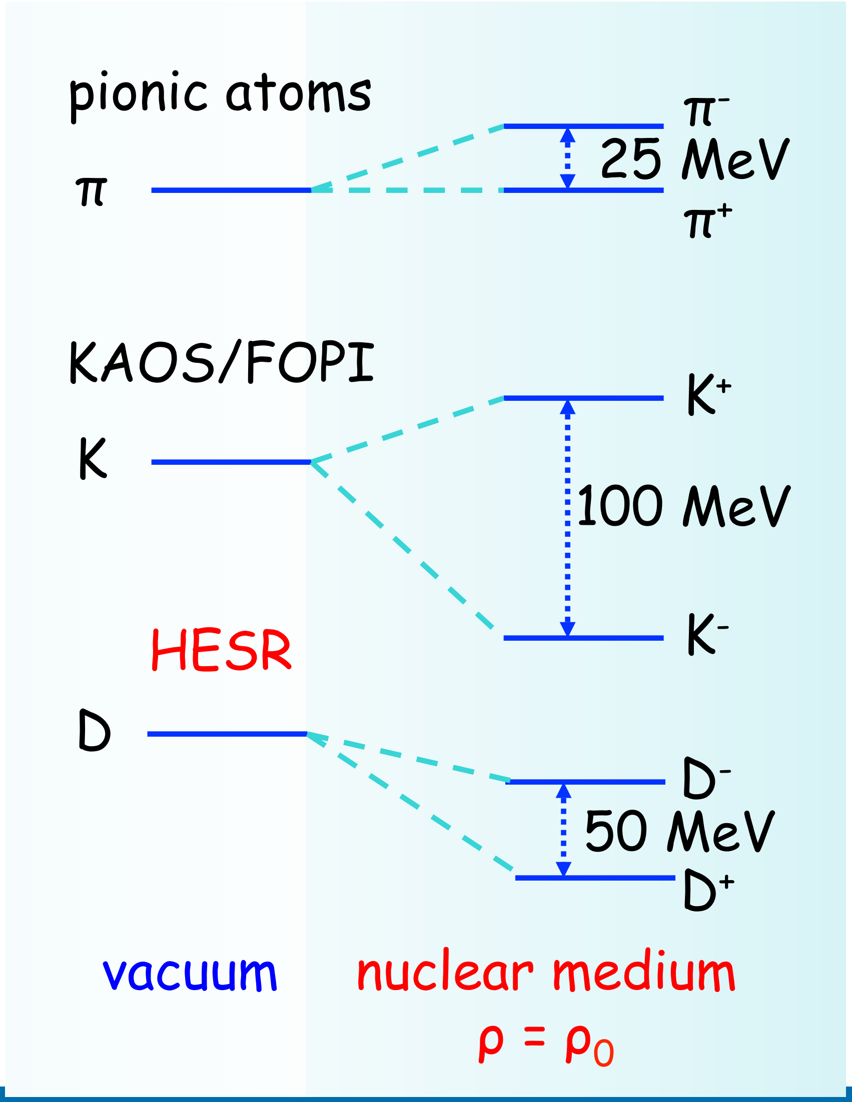
Chiral symmetry restoration

The mass of light hadrons (u,d,(s)) is dominated by spontaneous chiral symmetry breaking.

In the nuclear medium (ρ>0) we can restore this symmetry at least partially.

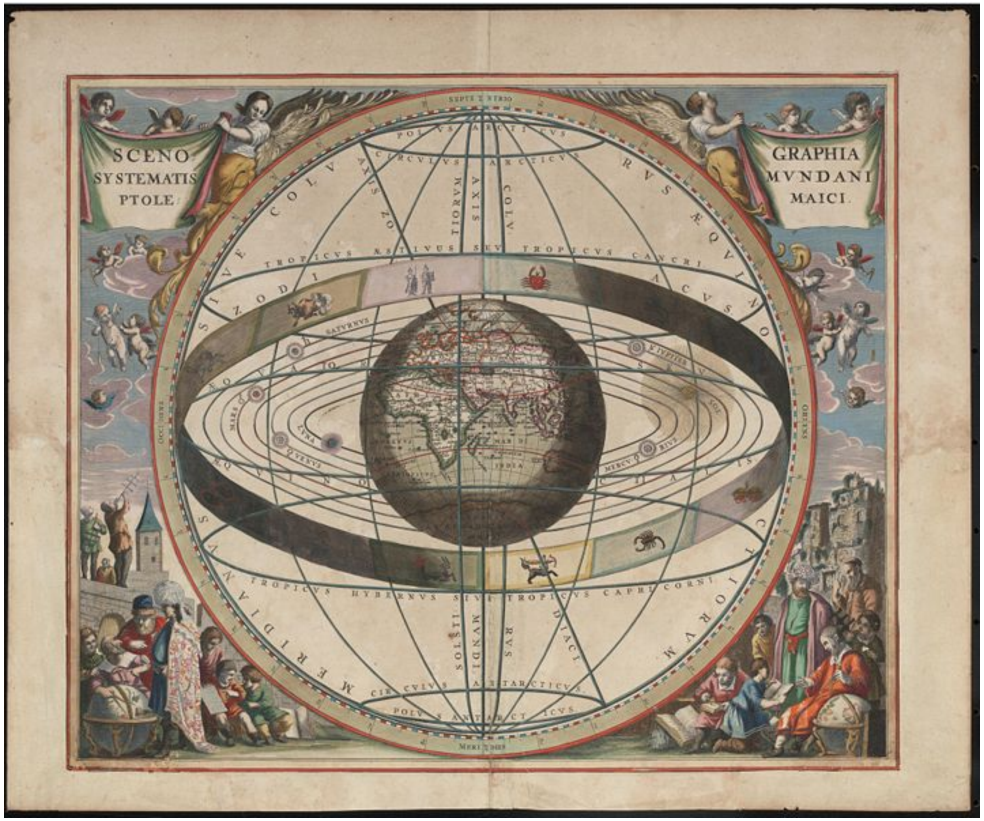
Hints of this effect have been already observed. We wants to extend these studies to charmed mesons.

Mass modifications of mesons



Can we be satisfied?

Today QCD predictions can reach a precision of about 10% at the GeV scale, and also the phenomenological models are not doing better!
Can we be satisfied of this accuracy?

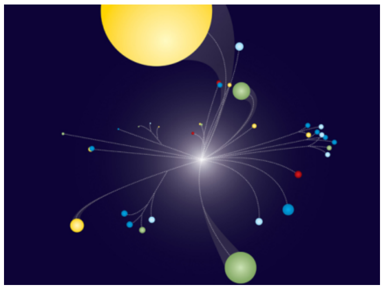


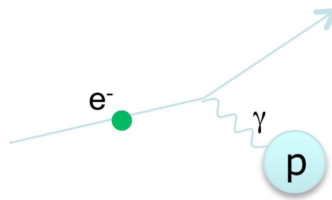
Just a note: the Ptolemaic system allowed to predict the positions of the planets with the same level of accuracy…..

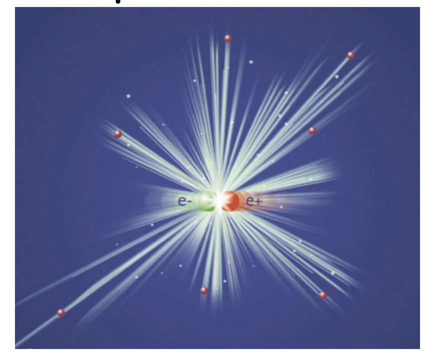
but it was wrong!

Experimental tests are needed…

High statistics and high quality data are necessary to help constrain the models

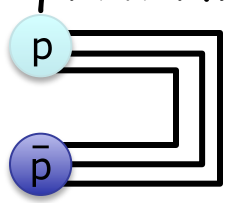






Different experimental techniques can be used to focus on different aspects:

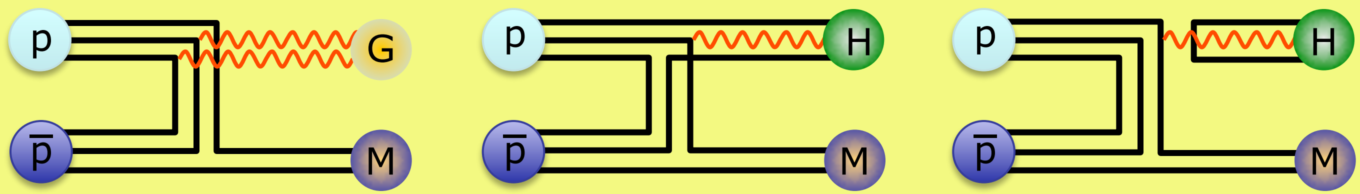
- The selection of special working conditions or of final states helps filtering initial/final state quantum numbers;



- In proton-antiproton annihilations complex objects collide
- The interaction occurs between two beams of (anti)quarks and gluons

Spectroscopic studies

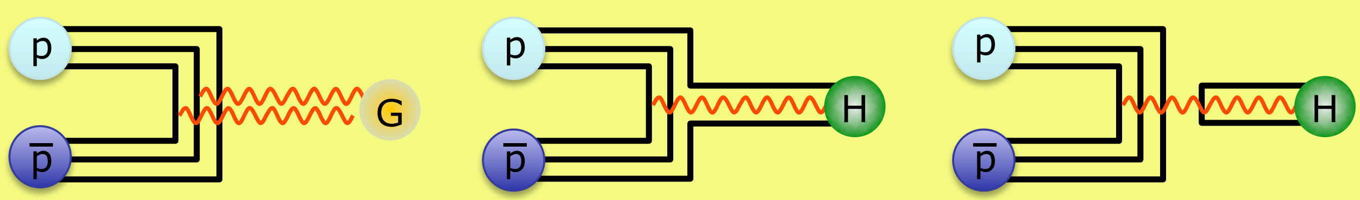
Two are two mechanisms to access particular final states:



Even exotic quantum numbers can be reached σ ~100 pb

Exotic states are produced with rates similar to conventional $q\bar{q}$ systems

All ordinary quantum numbers can be reached σ ~1 μb

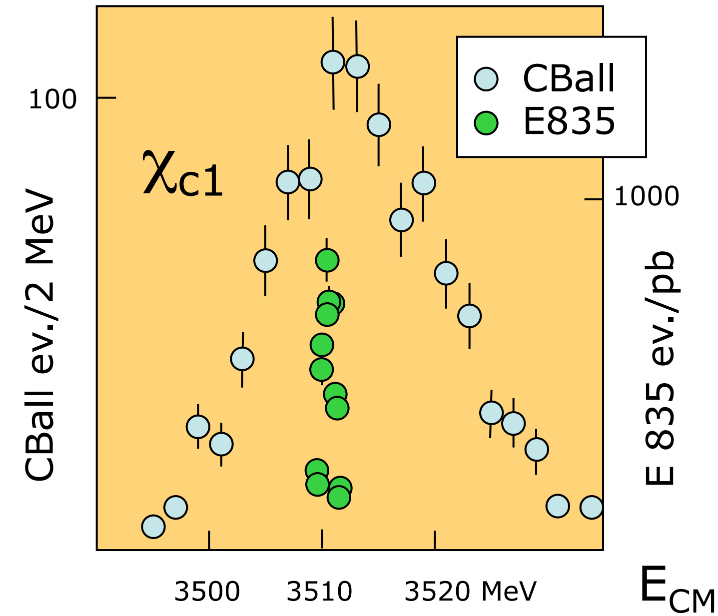


Antiproton's power

$e^+e^- \rightarrow \Psi'$
$\rightarrow \boxed{\gamma\chi_{1,2}}$
$\rightarrow \gamma\gamma J/\psi$
$\rightarrow \gamma\gamma e^+e^-$

$\bar{p}\,p \rightarrow \boxed{\chi_{1,2}}$
$\rightarrow \gamma J/\psi$
$\rightarrow \gamma e^+e^-$

- e^+e^- interactions:
  - Only 1^{--} states are formed
  - Other states only by secondary decays (moderate mass resolution)



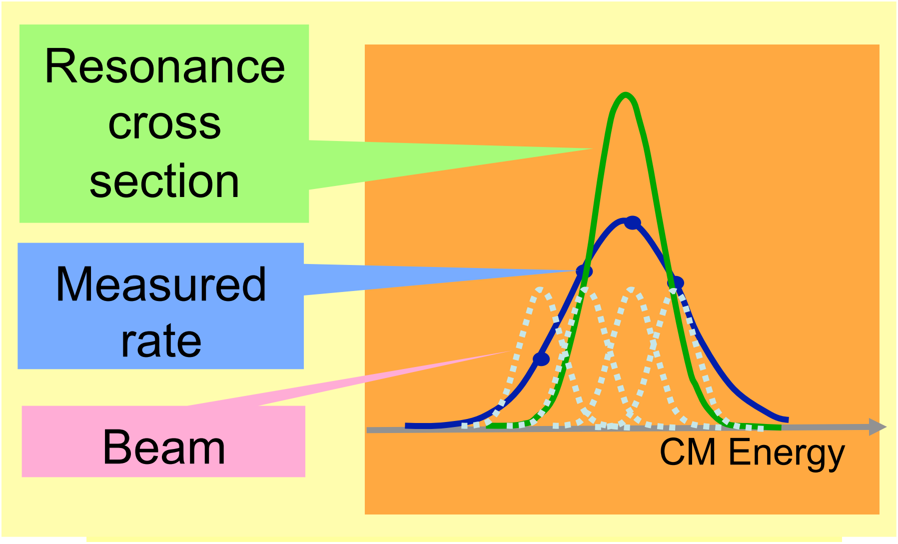
- $p\bar{p}$ reactions:
  - All states directly formed (very good mass resolution)

$Br(\bar{p}p \rightarrow \eta_c) \approx 1.2\ 10^{-3}$

$Br(e^+e^- \rightarrow \psi) \cdot Br(\psi \rightarrow \gamma\eta_c) = 2.5\ 10^{-5}$

Antiproton's power

$\bar{p}$-beams can be cooled → Excellent resonance resolution



- e^+e^-: typical mass res. ~ 10 MeV
- Fermilab: 240 keV
- HESR: ~30 keV

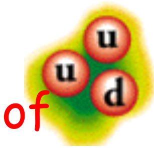
The production rate of a certain final state ν is a convolution of the BW cross section and

$$\nu = L_0 \left\{ \varepsilon \int dE f(E, \Delta E) \sigma_{BW}(E) + \sigma_b \right\}$$

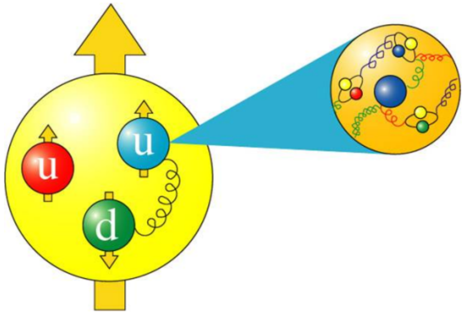
The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

The hadron's structure

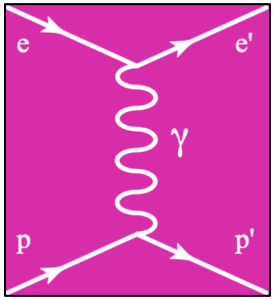
Properties of hadrons are only determined to a small degree by the constituent quarks.

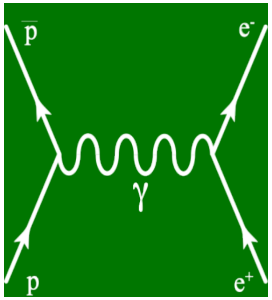


Quarks and gluons dynamics plays a fundamental role in the definitions of hadron's properties: mass, spin, etc…



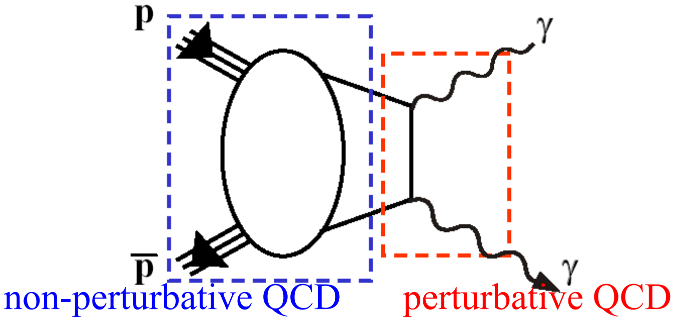
Generalized Parton Distributions (GPDs) contain both the usual form factors and structure functions, but in addition they include correlations between states of different longitudinal and transverse momenta. GPDs give a three-dimensional picture of the nucleon.





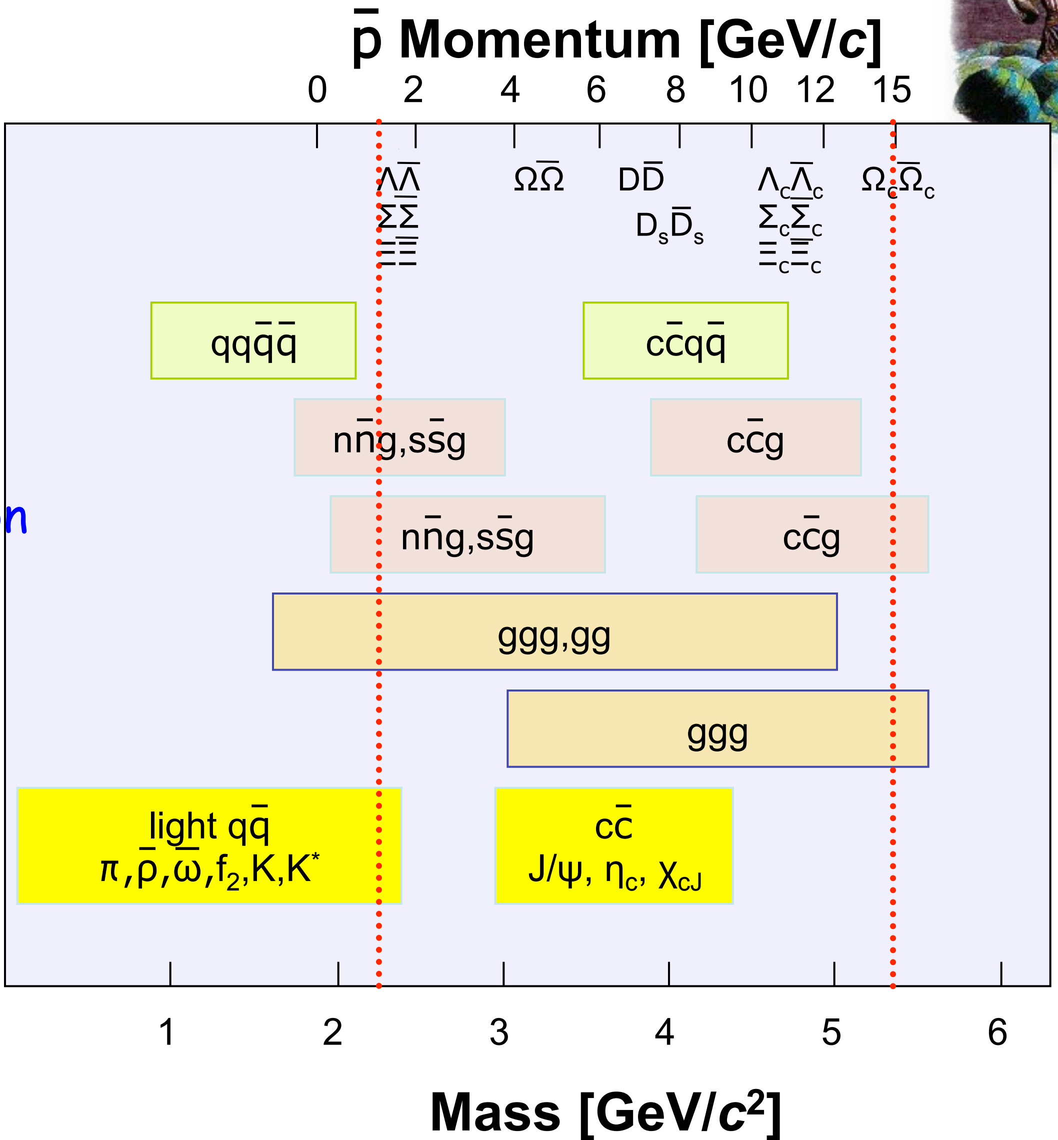
Nucleon Form Factors have been mainly studied using electromagnetic probes, but the physical diagrams can be inverted… and a complementary approach can be used

In a similar way Deeply Virtual Compton Scattering (DVCS) can be crossed-studied



Our Playground

- Meson spectroscopy
  - light mesons
  - charmonium
  - exotic states
    - ✓glueballs
    - ✓ hybrids
    - ✓molecules/multiquarks
  - open charm
- Baryon/antibaryon production
- Charm in nuclei
- Hypernuclei
- Em. form factors of the proton
- Generalized Parton Distributions

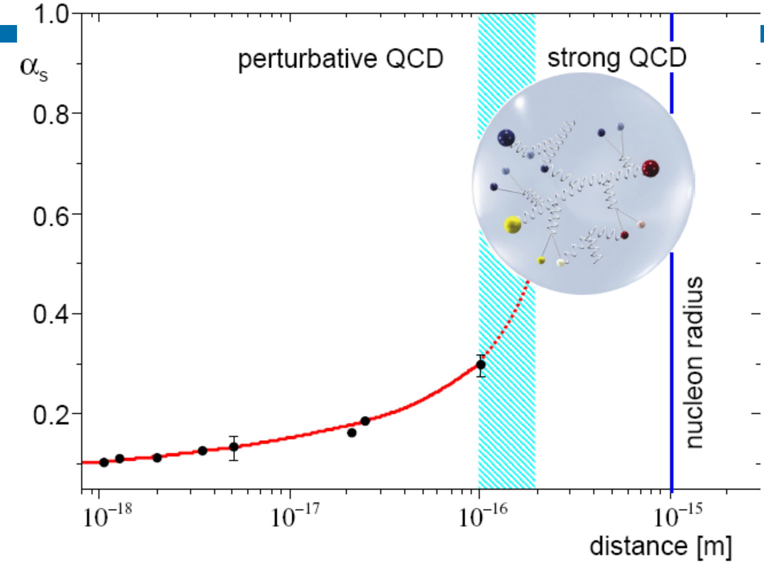


Production Rates (1-2 fb^{-1}/y)

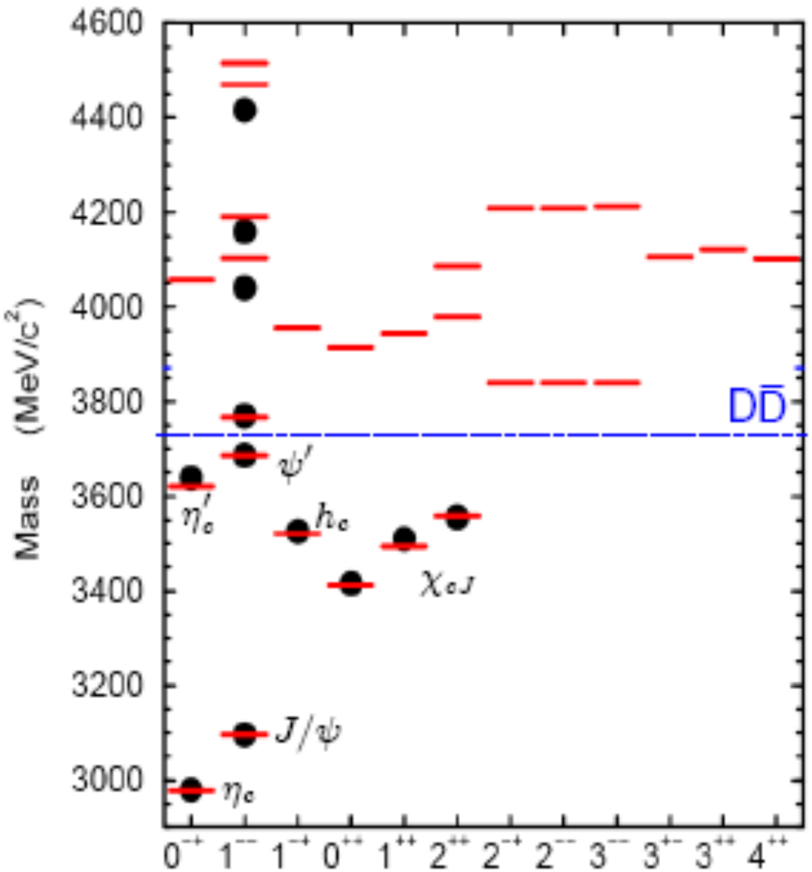
Final State	cross section	# rec. events/y
$\eta_c \to K_S^0 K^{\pm} \pi^{\mp}$	$10\,nb$	10^7
$\Lambda\bar{\Lambda}$	$50\,\mu b$	10^{10}
$\Xi\bar{\Xi}(\to_{\Lambda\Lambda} A)$	$2\,\mu b$	$10^8 (10^5)$
$\psi(3770) \to D\bar{D}$	$3\,nb$	10^7
$J/\psi(\to e^+e^-, \mu^+\mu^-)$	$630\,nb$	10^9
$\chi_2(\to J/\psi + \gamma)$	$3.7\,nb$	10^7
$\Lambda_c\bar{\Lambda}_c$	$20\,nb$	10^7
$\Omega_c\bar{\Omega}_c$	$0.1\,nb$	10^5
$\boxed{\sigma_T(p\bar{p})}$	$70\,mb$	

Key elements : Low multiplicity events
Possibility to trigger on defined final states

Charmonium spectroscopy



Charmonium energy is the transition range between the perturbative and the non-perturbative regimes. It is the energy range where models are tuned



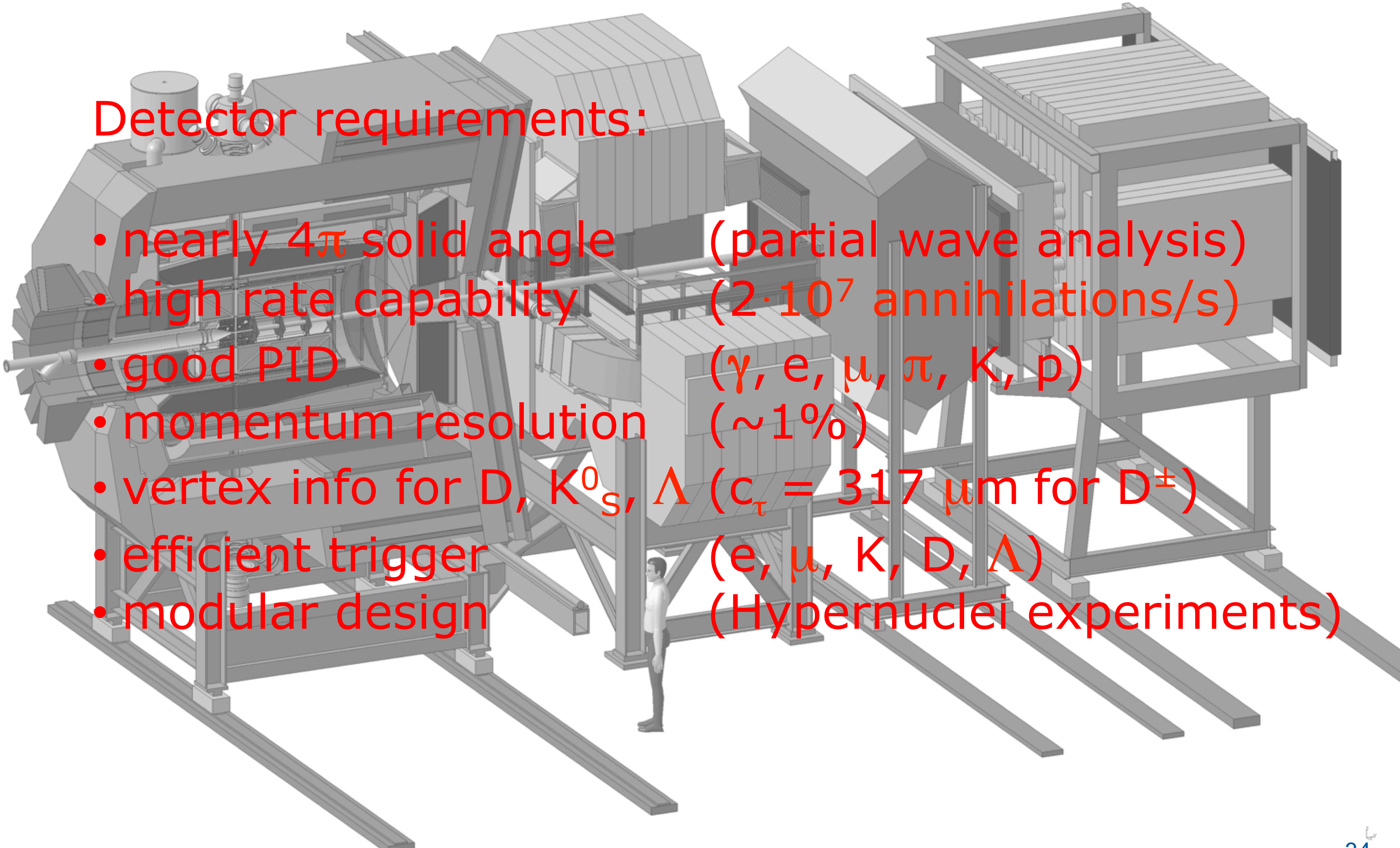
below $\overline{DD}$ threshold

- all the predicted states have been detected,

  but
- there is lack of precise measurements of masses, widths and branching ratios

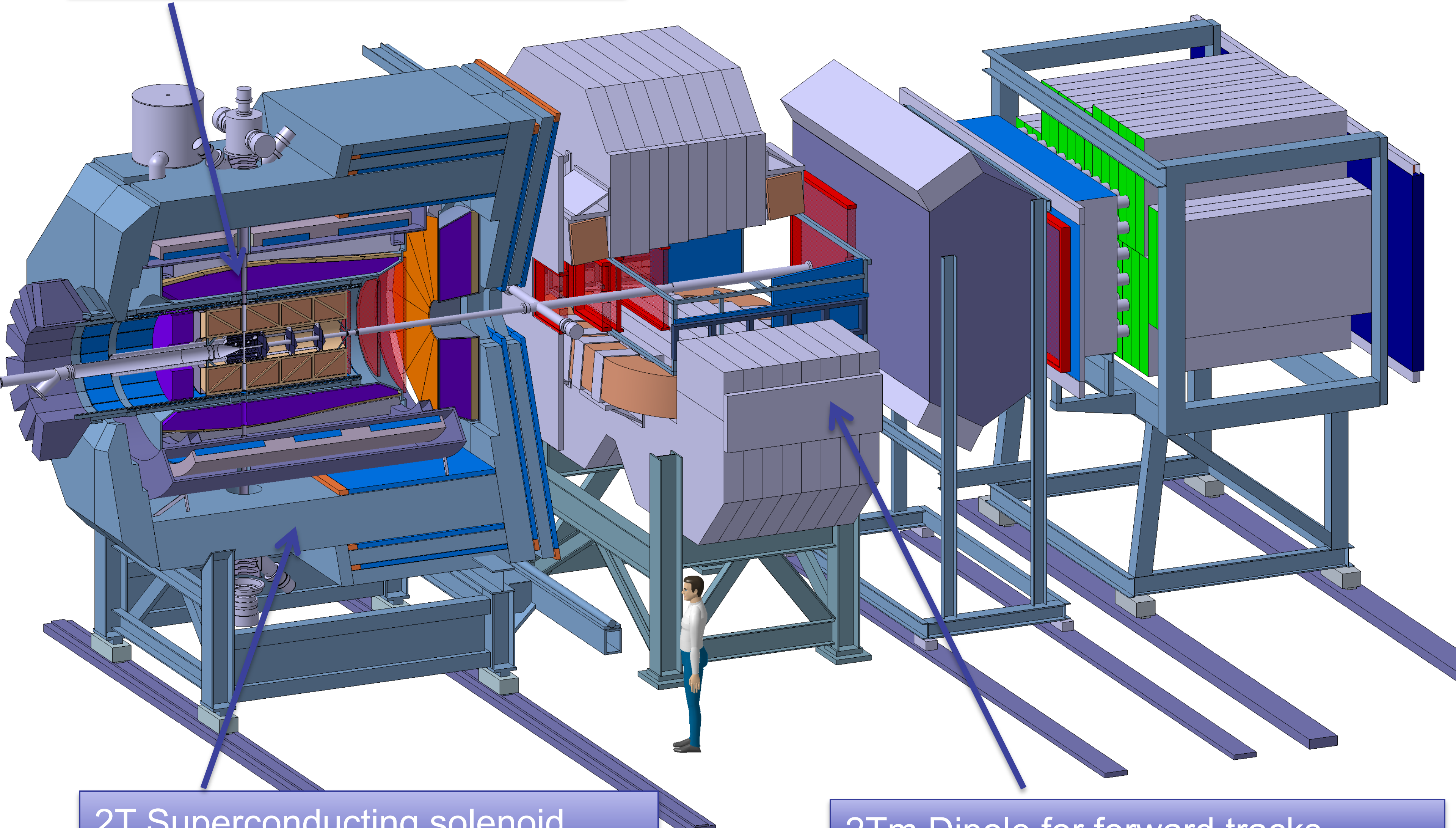
(i.e. η_c, $\eta_c(2S)$, h_c)

PANDA General Purpose Detector



Detector requirements:

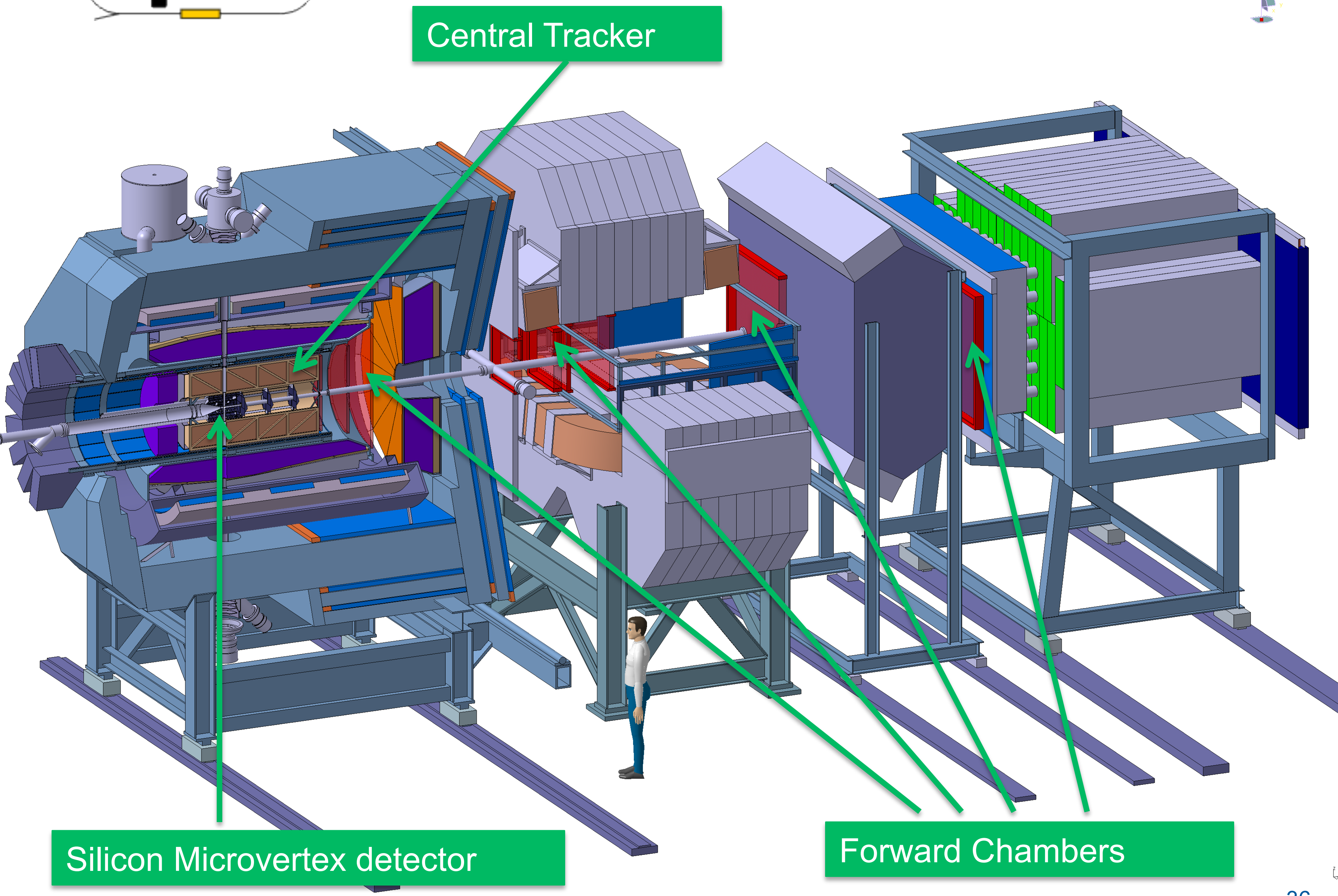
- nearly 4π solid angle (partial wave analysis)
- high rate capability ($2 \cdot 10^7$ annihilations/s)
- good PID (γ, e, μ, π, K, p)
- momentum resolution (~1%)
- vertex info for D, K^0_S, Λ (c_τ = 317 μm for $D^\pm$)
- efficient trigger (e, μ, K, D, Λ)
- modular design (Hypernuclei experiments)



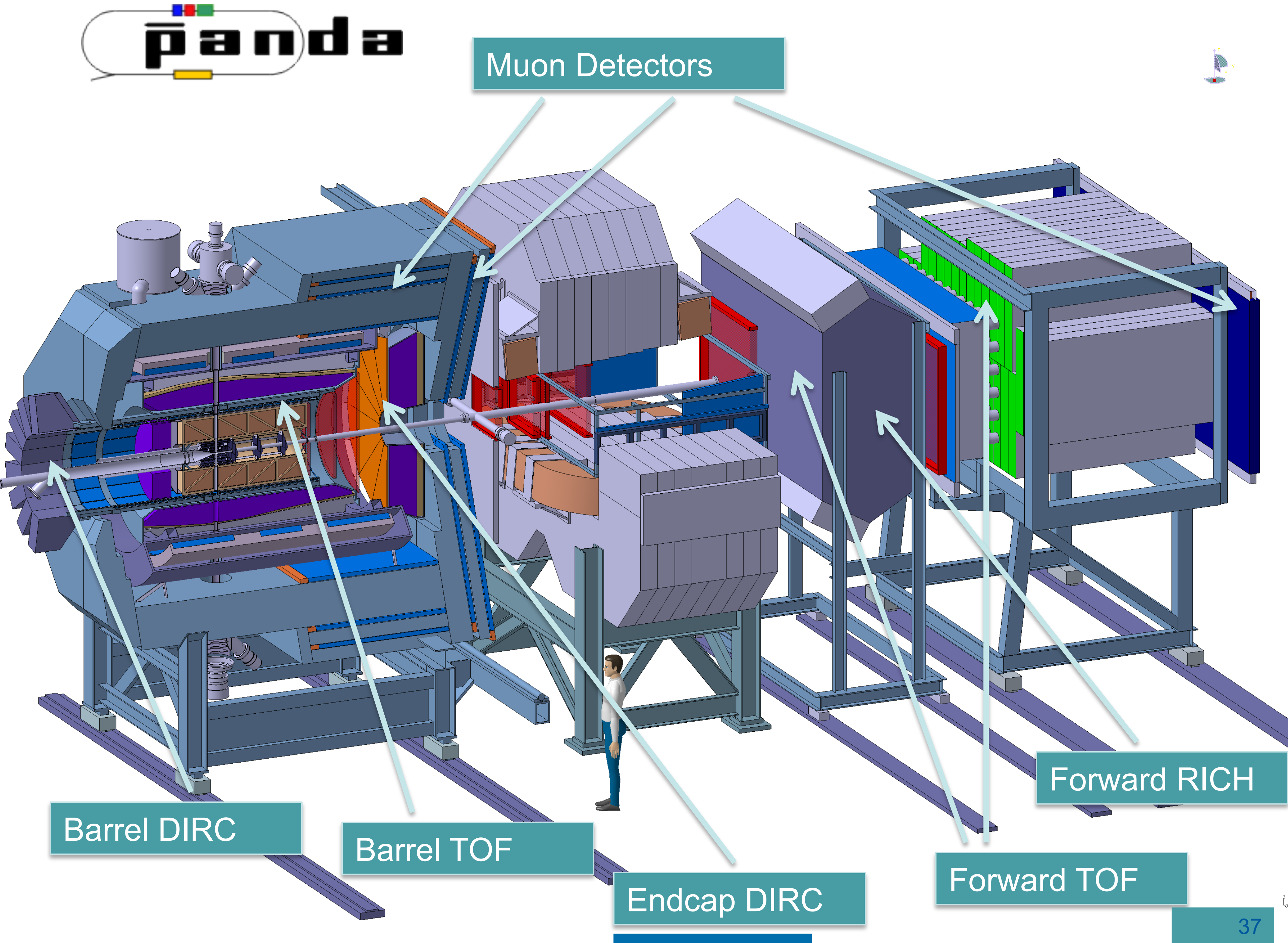
Pellet or cluster-jet target

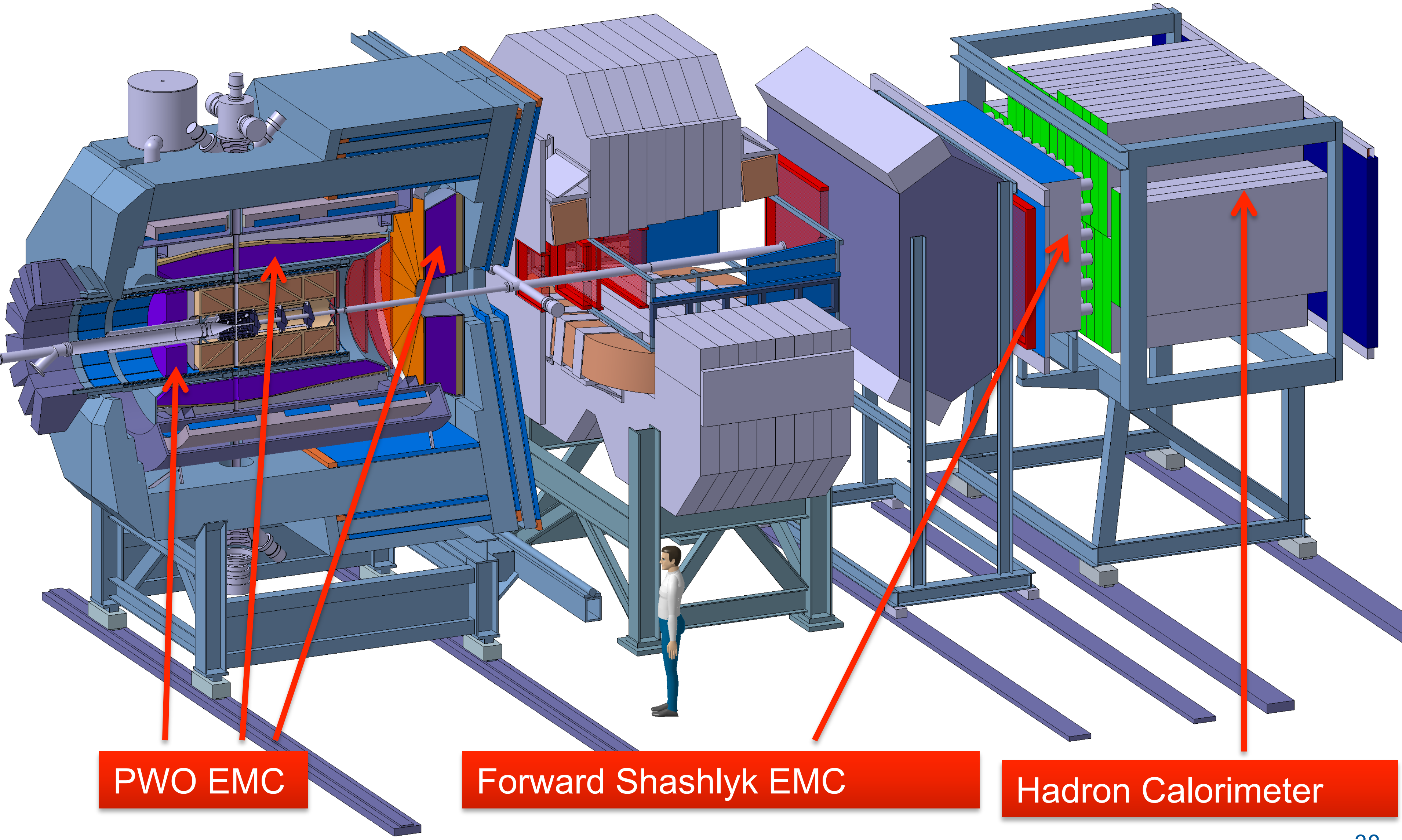
2T Superconducting solenoid
for high p_t particles

2Tm Dipole for forward tracks



Central Tracker
Silicon Microvertex detector
Forward Chambers


Muon Detectors
Barrel DIRC
Barrel TOF
Endcap DIRC
Forward TOF
Forward RICH


PWO EMC
Forward Shashlyk EMC
Hadron Calorimeter

The P̄ANDA Collaboration

At present 500 physicists from 67 institutions in 18 countries

Aligarh, Basel, BARC, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, IIT Chicago, AGH Cracow, Cracow, Jag Cracow, IFJ PAN Cracow, Cracow UT, Edinburgh, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, Goa, GSI, FAIR, IIT Indore, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Gujart, Lanzhou, LNF, LNL, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow,TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, IHEP Protvino, PNPI St.Petersburg, KTH Stockholm, Stockholm, Suranaree Univ Tech, Surat, FH Südwestfalen, Sydney, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, Tübingen, TSL Uppsala, Uppsala, Valencia, SINS Warsaw, TU Warsaw, SMI Wien

Summary

A new International Facility for fundamental research is under construction in Europe.
FAIR aims to provide scientists in the world with an outstanding accelerator and experimental facility for studying matter at the level of

- atoms;
- atomic nuclei;
- protons and neutrons.

The aim is to study the building blocks of matter a wider group of particles called hadrons which are made of constituents called quarks and gluons.

The heart of the new facility is a superconducting synchrotron with a circumference of about 1,1 km.
A system of other rings and various experimental halls will be complete the facility.
The accelerators will yield ion beams with highest beam intensity and also higher beam energies. Moreover, the facility offers the possibility to provide high quality beams of antiprotons for the experimental program.

http://www.fair-center.eu/en/public/information-material.html

Space: The final frontier…

In the Star Trek universe, spaceships use the enormous energy of matter-antimatter annihilation to leap across the universe.

This is science fiction, but antiproton-proton annihilation is not


A new challenging Enterprise is started!
PANDA