# The ALICE Experiment

## ALICE = A Large Ion Collider Experiment


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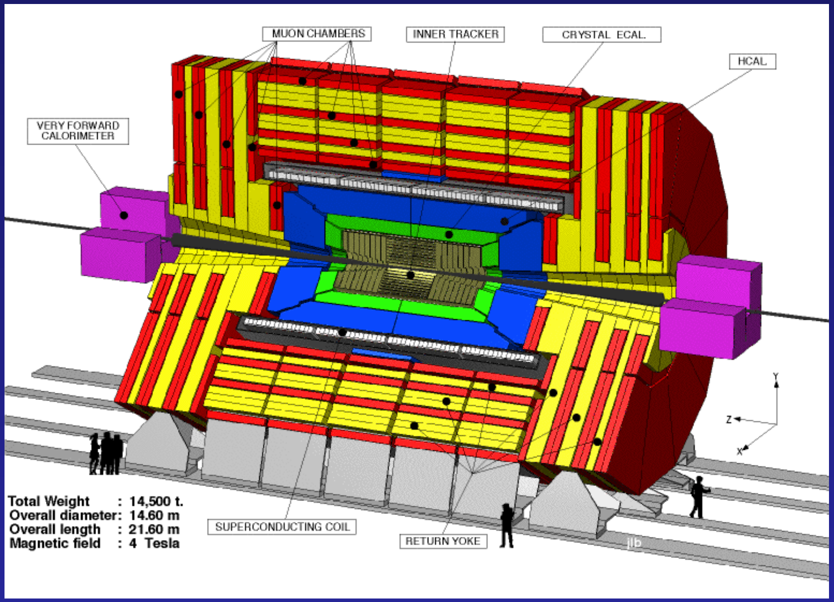
# The ALICE Experiment

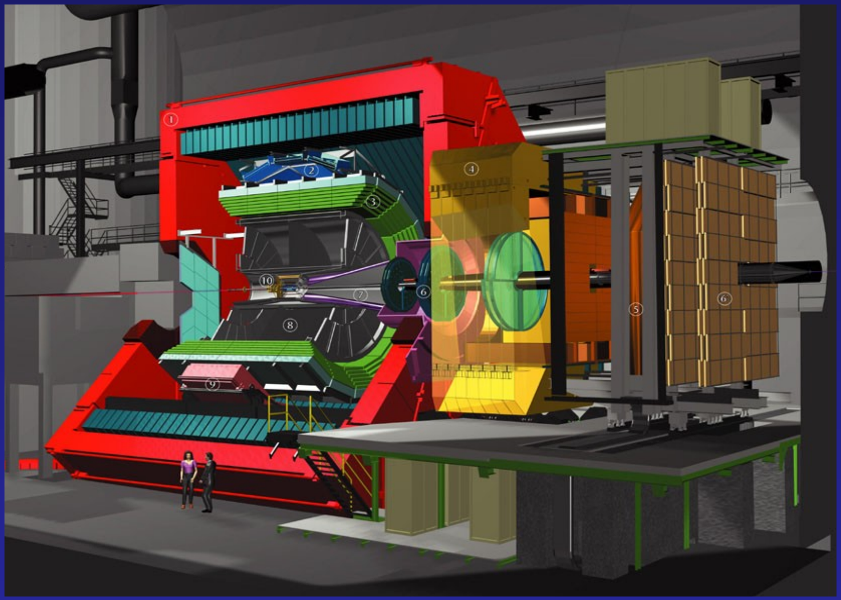
## ALICE = A Large Ion Collider Experiment

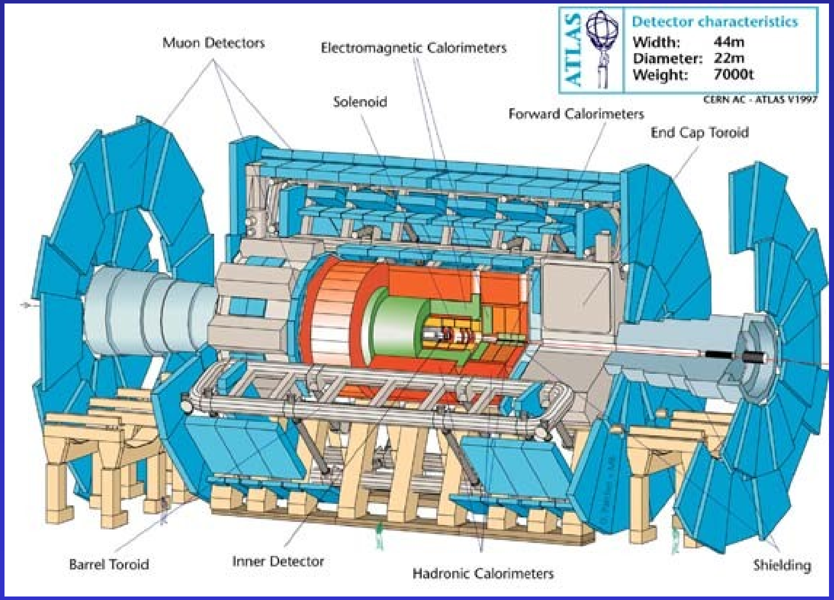
- The primary purpose of ALICE is to study Pb+Pb and p+Pb interactions.

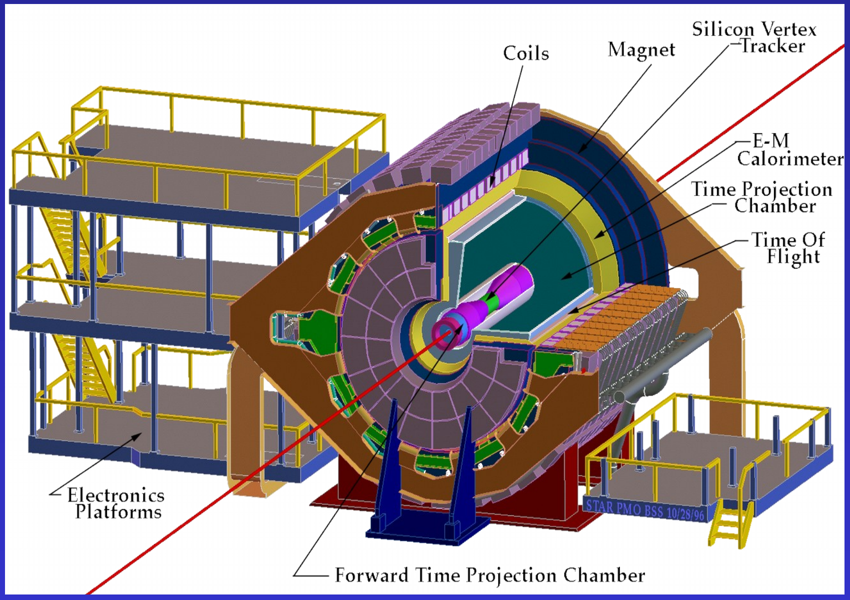
- 45 mins from now we will go to ALICE and you will see the exhibition and the Control Room.

# Some High Energy Physics Detectors

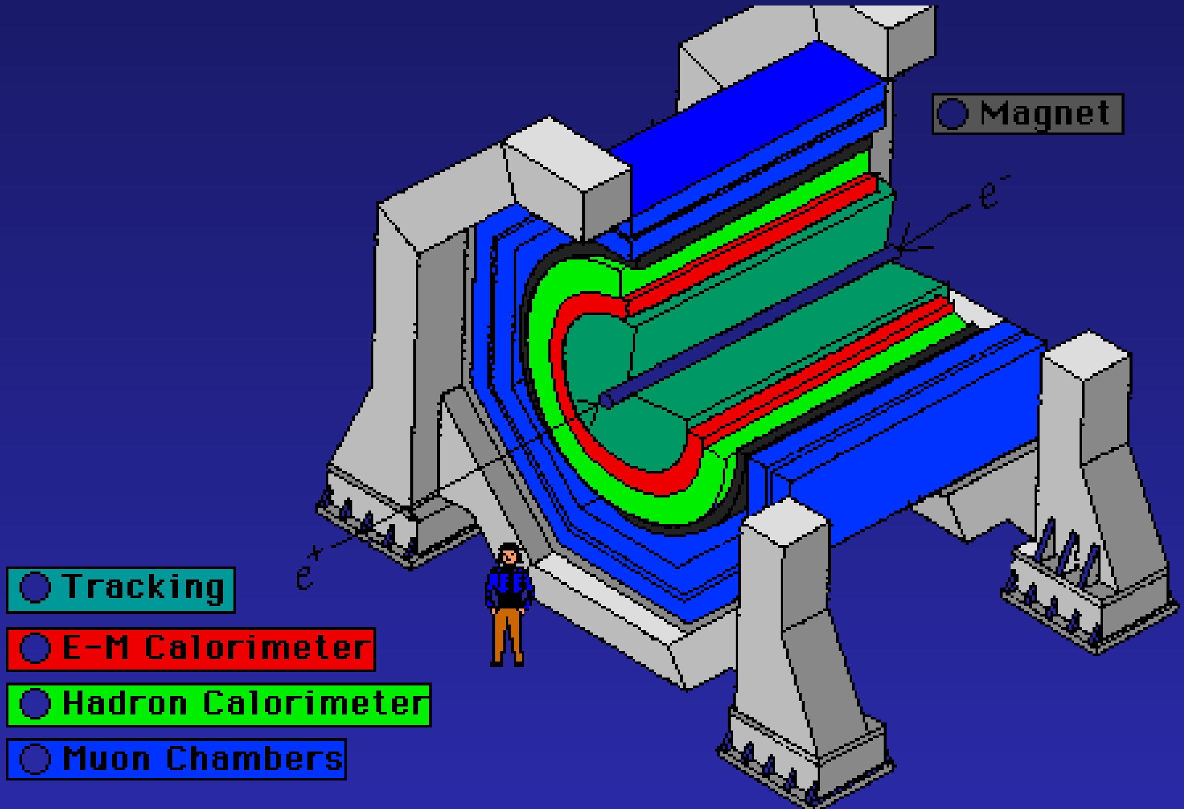




# There is a common structure or ordering of the subdetectors



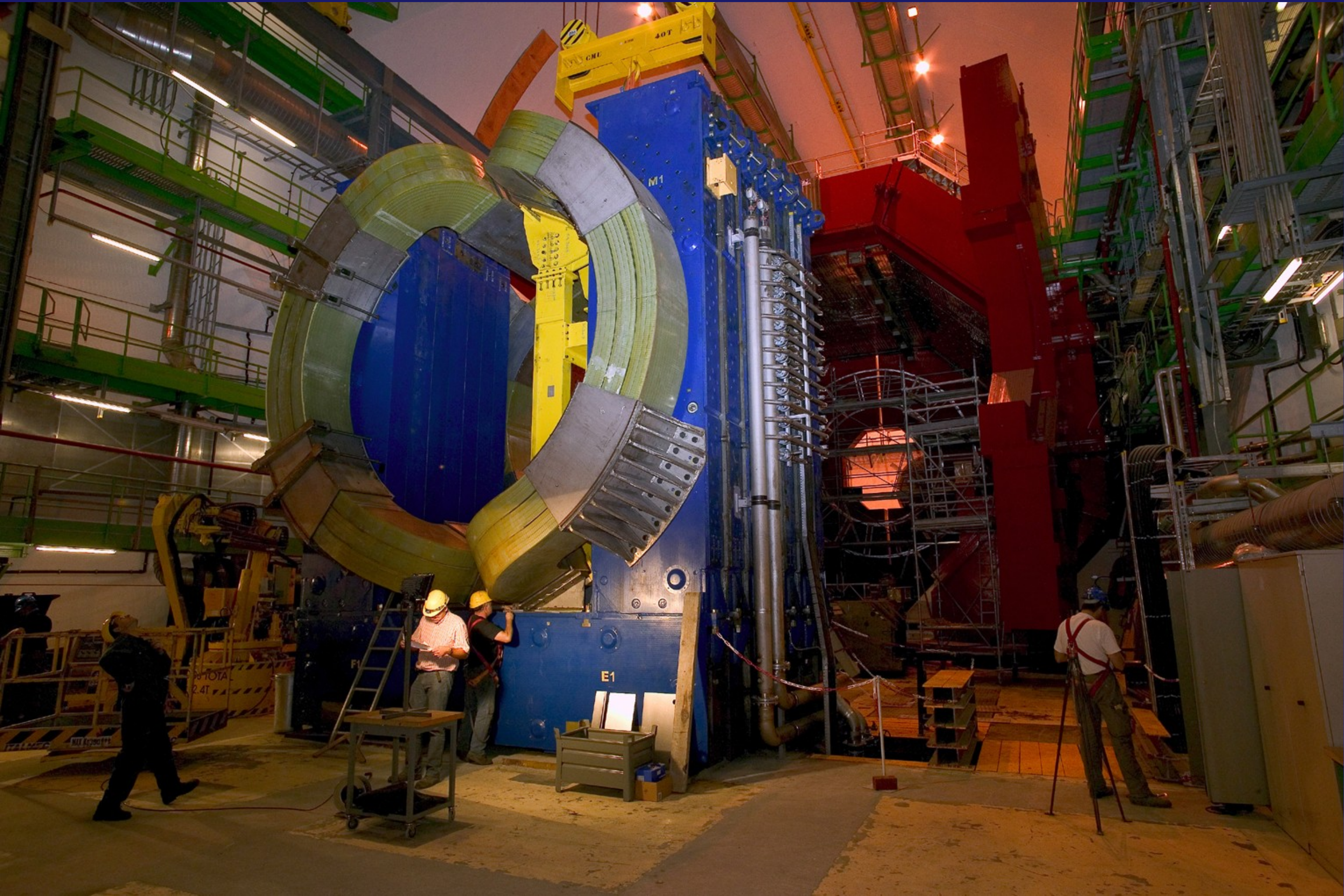

- Most detectors in the central barrel of ALICE are there to track and identify charged particles.
- There are also three ElectroMagnetic Calorimeters covering about 2/3 in $\phi$.
- Muons are identified in a separate muon arm.


1
2
3
4
5
6
7
8
9
10

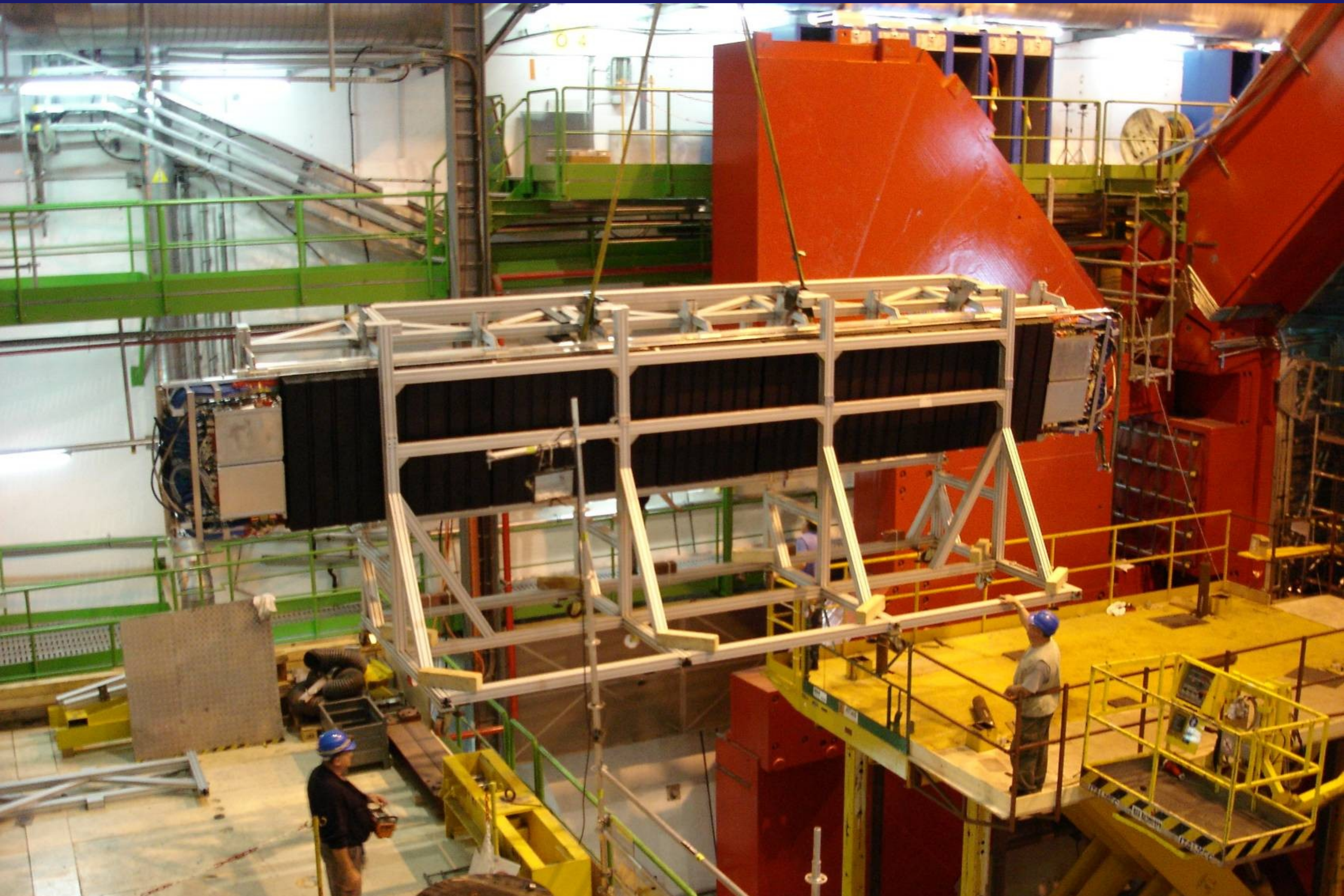

Eiffel tower
~ 7300 tons
ALICE magnet
~ 8000 tons

# In the beginning...

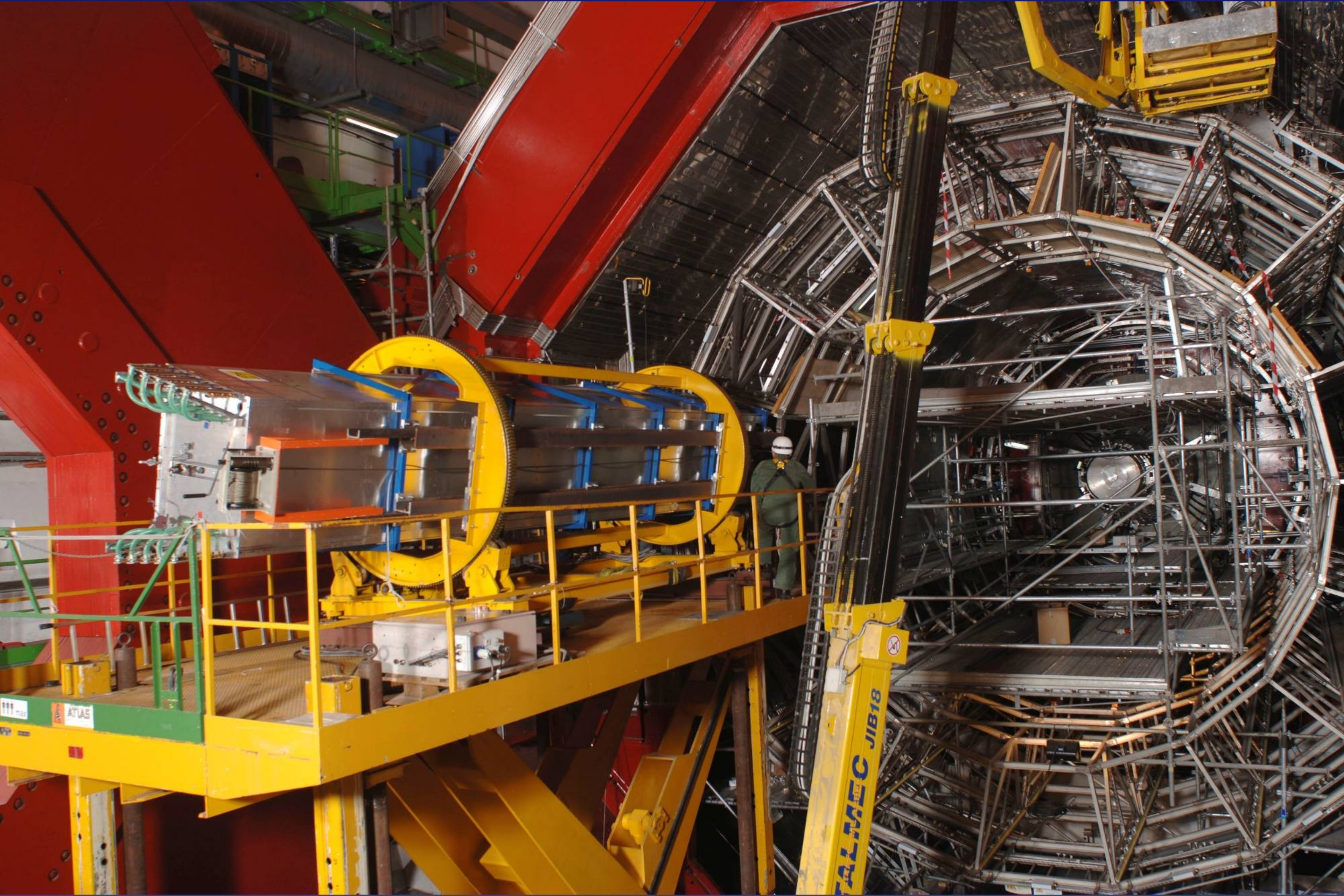
# January 2005 (Muon magnet)



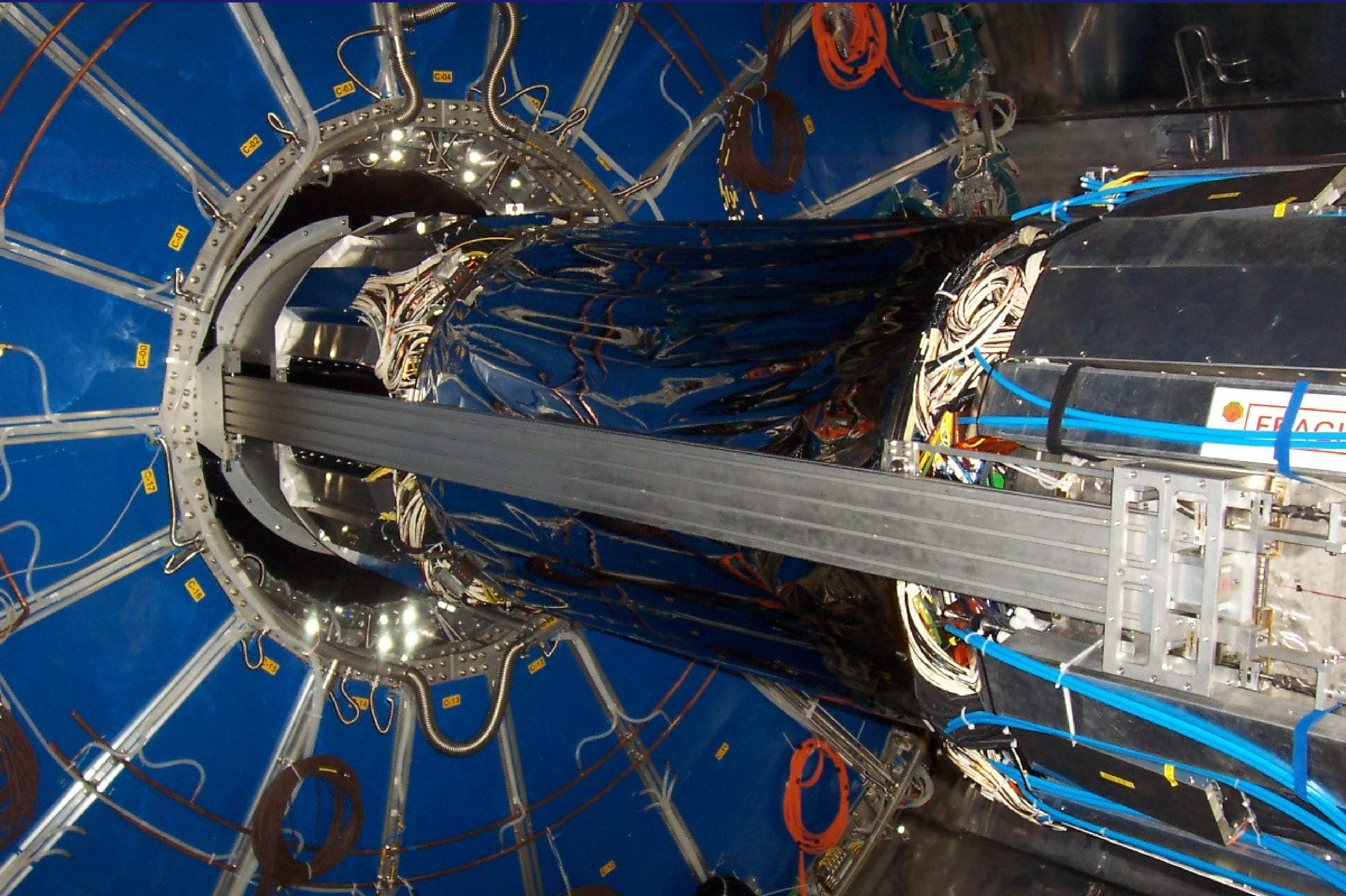
# October 2006 (TOF Module)



# October 2006 (TRD Module)

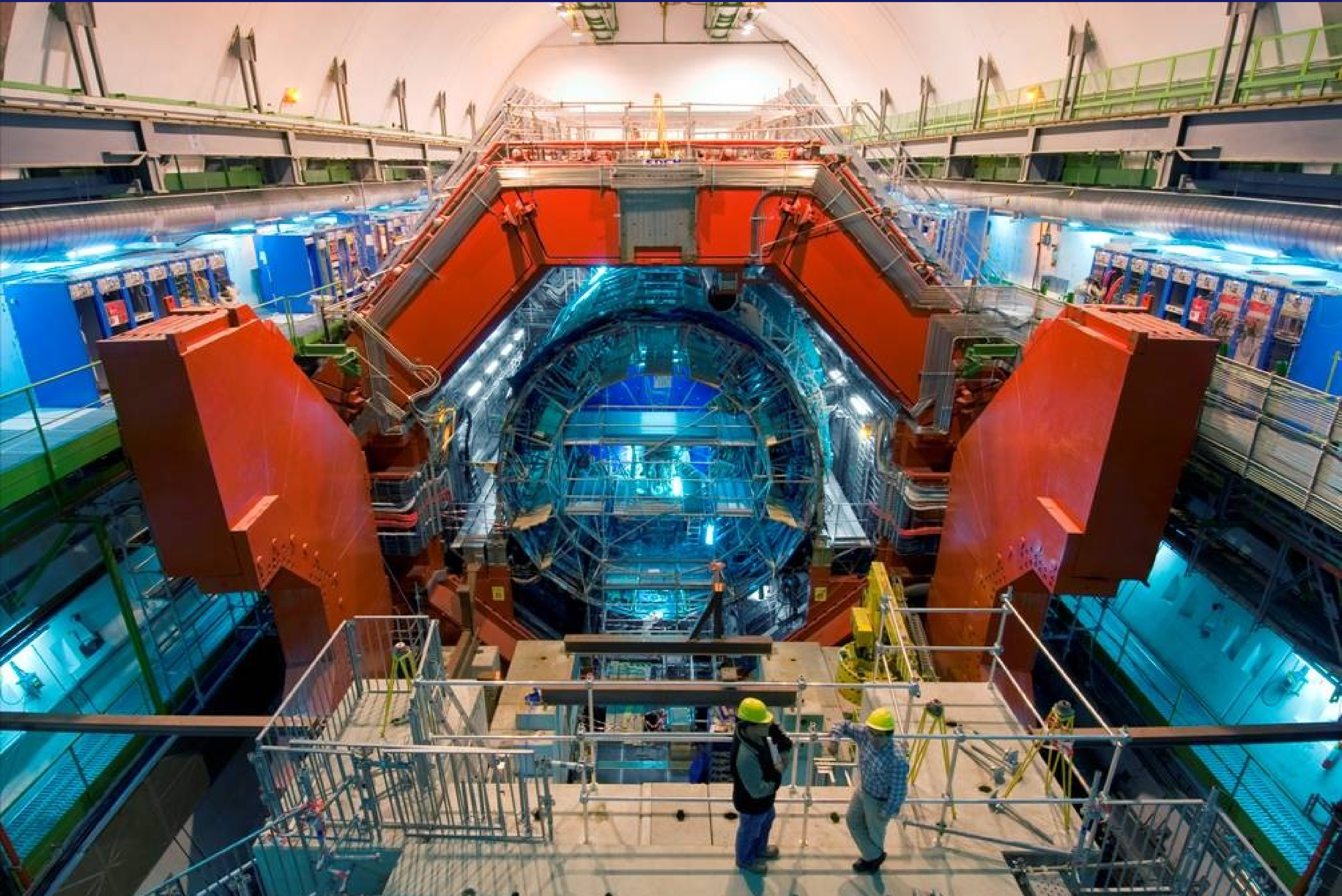


# September 2007 (ITS/TPC)



# April 2008 (PHOS Module)

# and when it was ready...



# time to close the doors!

# and take a picture! (July 2008)

# and take a picture! (July 2008)

# and wait for first collisions (23 November 2009)

- The first LHC Run lasted from November 2009 – January 2013.

- Proton-proton collisions 90% of the time; two runs with Pb+Pb (2010, 2011) and one run with p+Pb (2013).

- 2013 – 2015 was the first Long Shutdown. Collision energy upgraded 8 TeV --> 13 TeV. Proton-proton collisions from the beginning of this year until now.

- Pb+Pb run will start in 2 weeks (23 November) and last until Christmas.

# Why collide heavy ions?

# Why collide heavy ions?

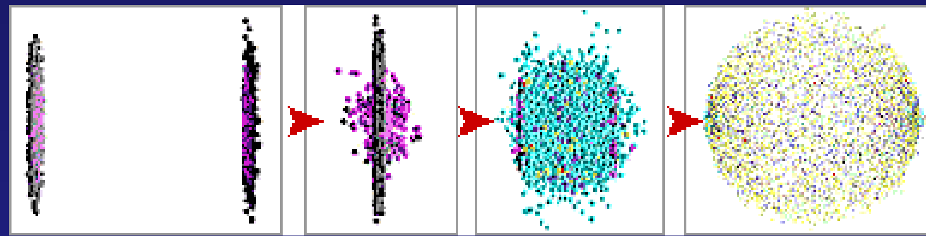
We want to study nuclear matter.

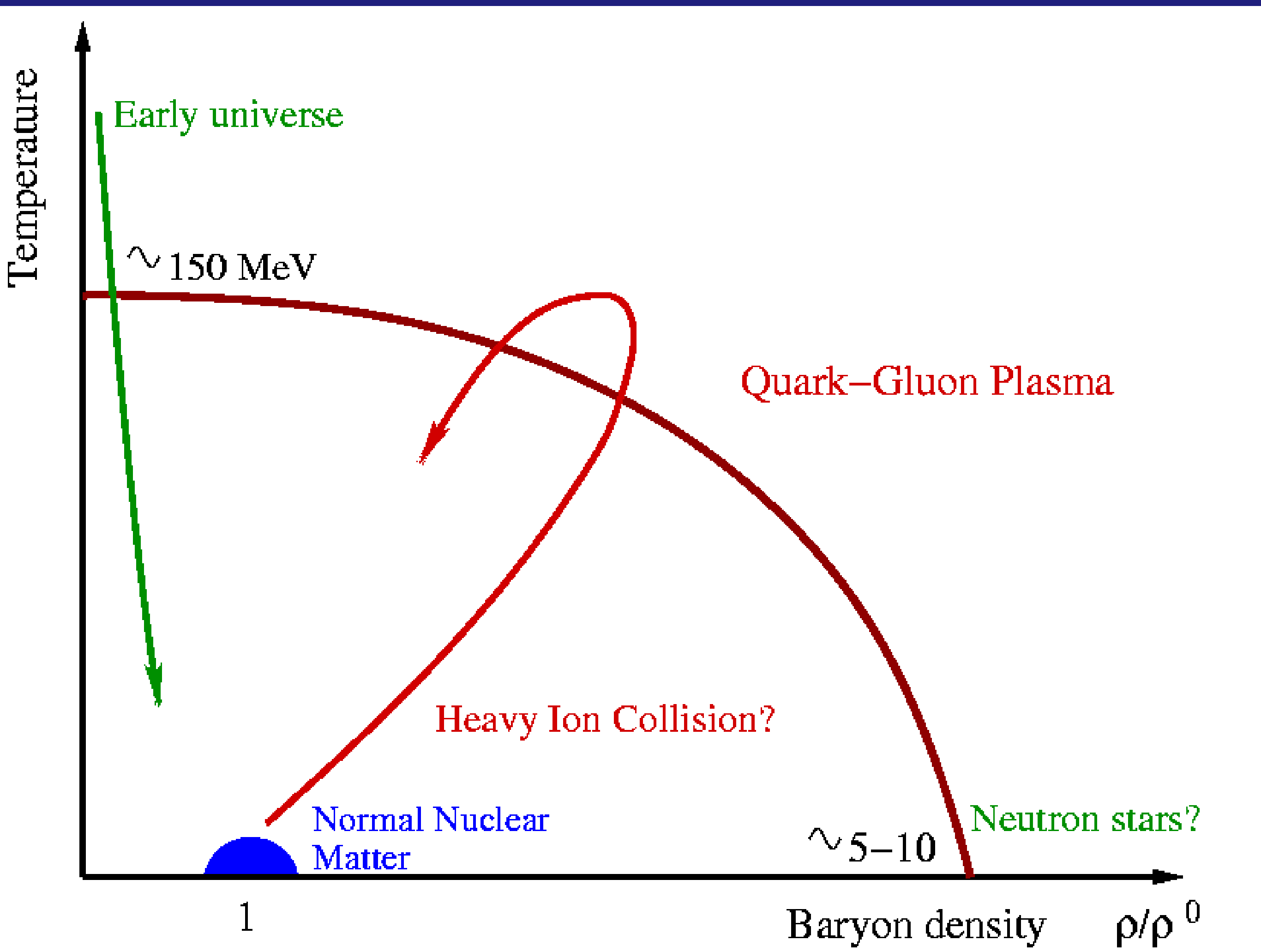
Quantum Chromodynamics (QCD) works fine if one treats one particle at a time and when the ”scale” is high enough (above several GeV/c).

We want to understand how QCD works for large systems, systems containing 1000’s of particles occupying ”large” volumes.

We want to understand how (nuclear) matter behaves under extreme conditions, under extreme temperatures and densities.

# The goal of relativistic heavy-ion collisions is to study hot and dense nuclear matter



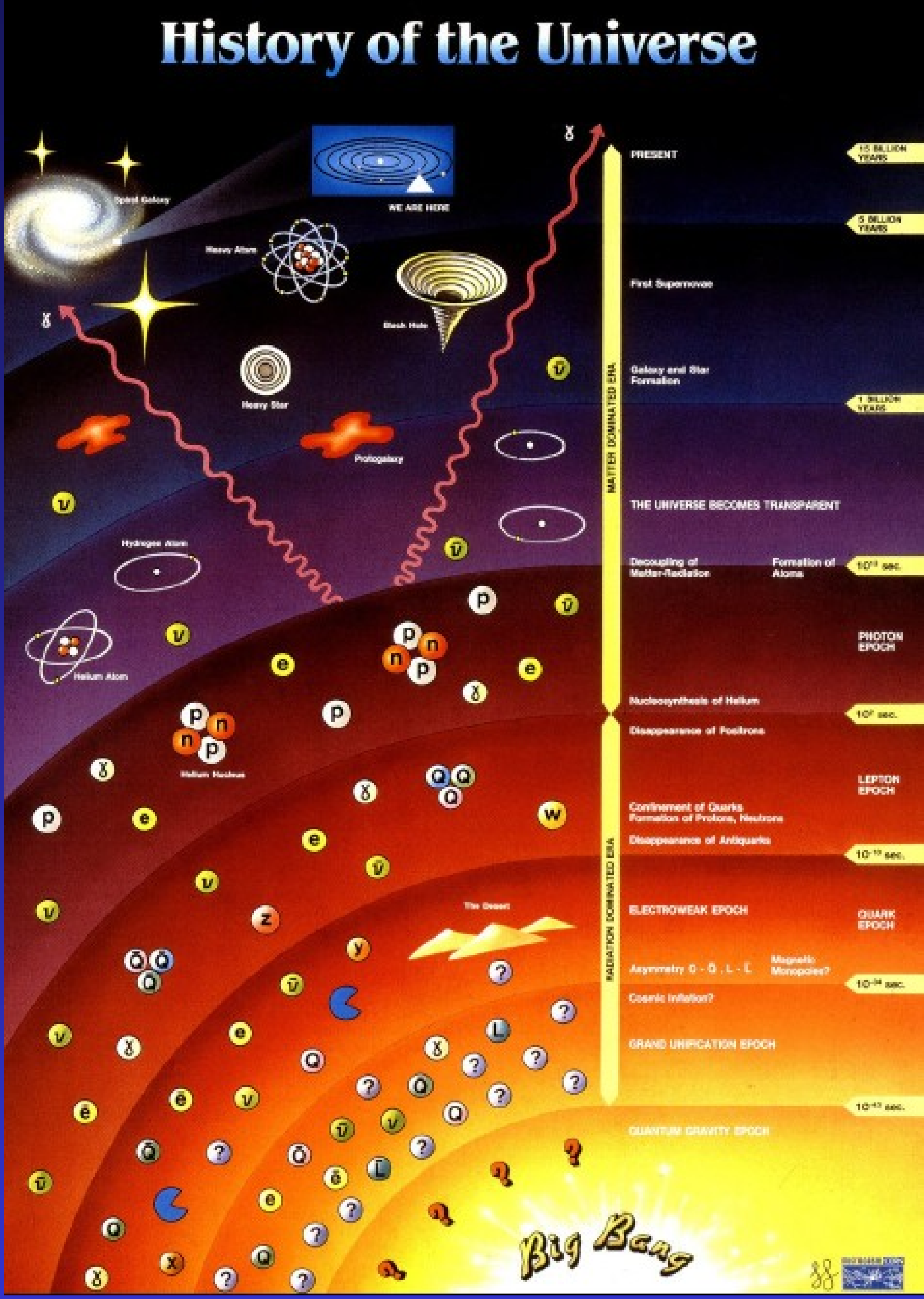



## The nuclear phase diagram

The age and temperature of the universe today, $13.7 \cdot 10^9$ years and 2.7 K, respectively. ⇒

T = 150 MeV ≈100µs after Big Bang.

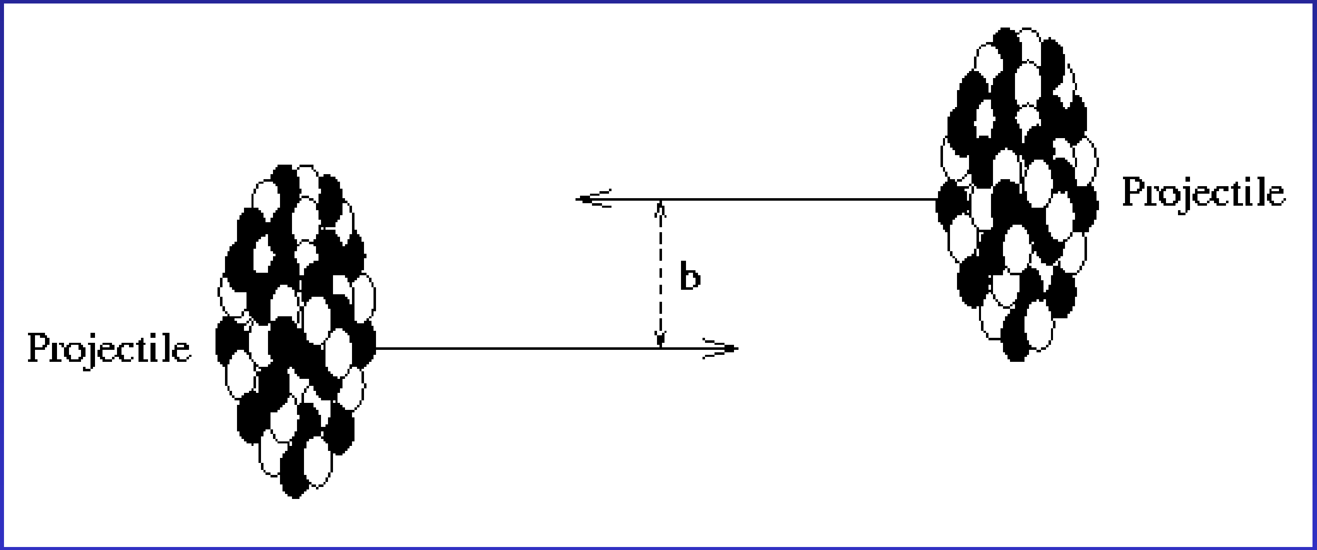
One goal of heavy-ion interactions is to understand what happened in the early universe.



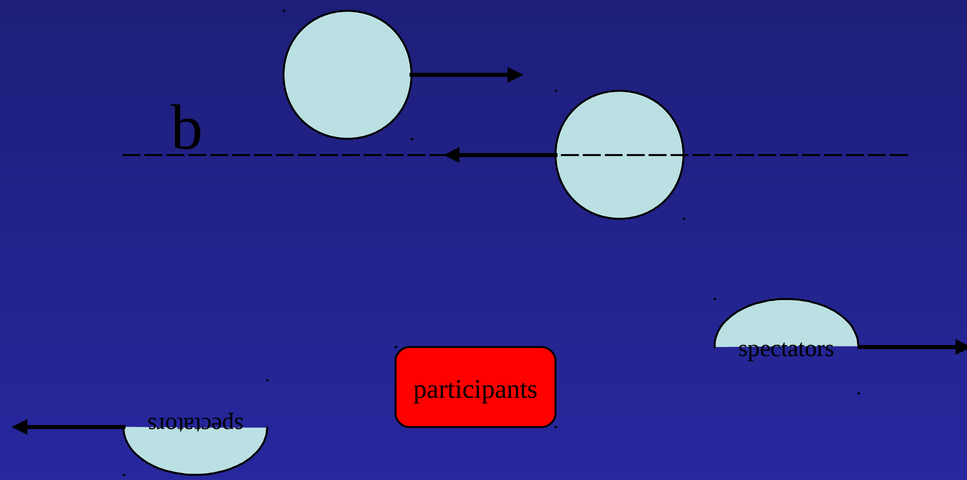
# What is a "heavy ion"?

Accelerator terminology: Any ion with A>4,
⇒ Anything heavier than α-particle

This talk: *truly heavy ions* –
ions with A ≈ 200 ($^{197}$Au, $^{208}$Pb)



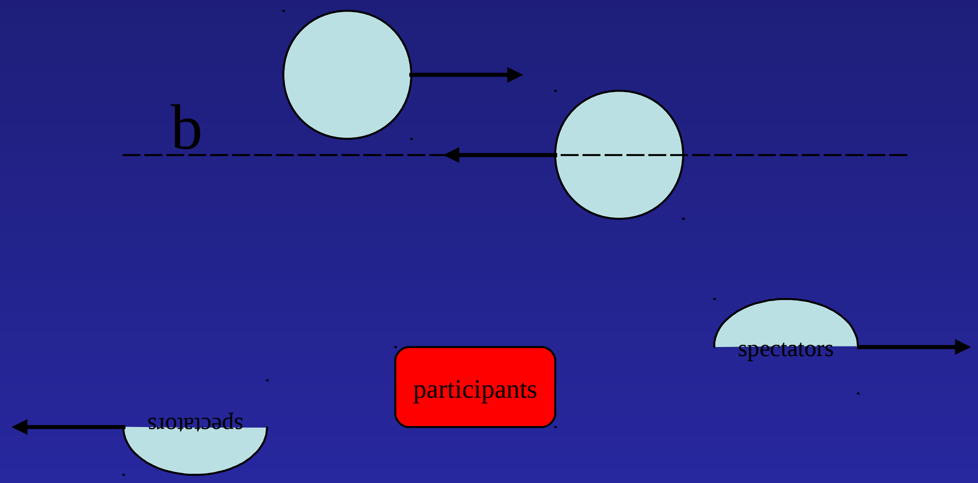
In heavy-ion collisions, the impact parameter (b) is usually a well-defined quantity. ⇒ Classify collisions based on centrality, from central (b=0) to peripheral ($b \approx 2R$):




Total inelastic cross section: $\sim \pi(R_A + R_B)^2$

The number of produced particles (dominated by soft process): $\propto N_{part}$

In heavy-ion collisions, the impact parameter (b) is usually a well-defined quantity. ⇒ Classify collisions based on centrality, from central (b=0) to peripheral (b≈2R):

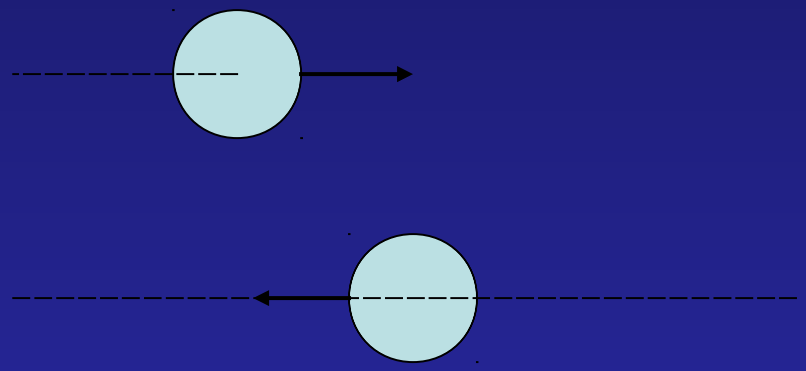



Total inelastic cross section: $\sim \pi(R_A + R_B)^2$

The number of produced particles (dominated by soft process): $\propto N_{part}$

But the rest of this talk will be about Ultra-Peripheral Collisions.

Ultraperipheral collisions are defined as collisions where $b > R_A + R_B$ and in which no strong, hadronic interactions occur.



$b > 2R$

Range of strong nuclear force: ~1-2 fm ⇒ The interaction must be mediated by the electromagnetic field.

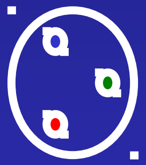
Is there any idea to study interactions where the nuclei miss each other?

What is inside a nucleus ?

==> Protons and neutrons (nucleons)

What is inside a nucleon ?

==> 3 Quarks



How do we know this ?

# Probing the interiors of nucleons and nuclei

Shine light on the proton with a wave length << its size.

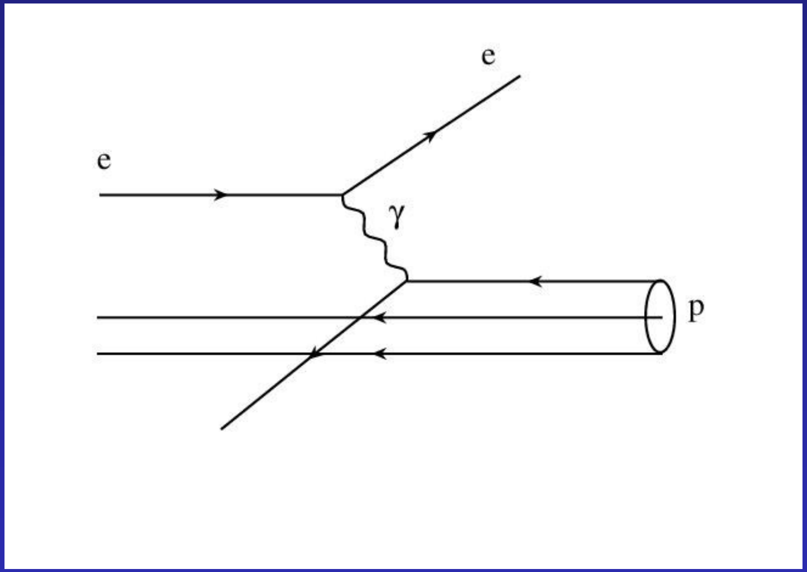
Size of proton r $\approx$ 0.7 fm ==>

Wave length $\lambda$<0.7 fm <==> $E_\gamma = \hbar c/\lambda$ > 280 MeV

To probe deep inside the proton, down to $10^{-18}$ m, we need even higher photon energies, typically several 100 GeV.

# Probing the interiors of nucleons and nuclei

So high photon energies can only be obtained from virtual photons emitted from, for example, an electron in a scattering experiment.

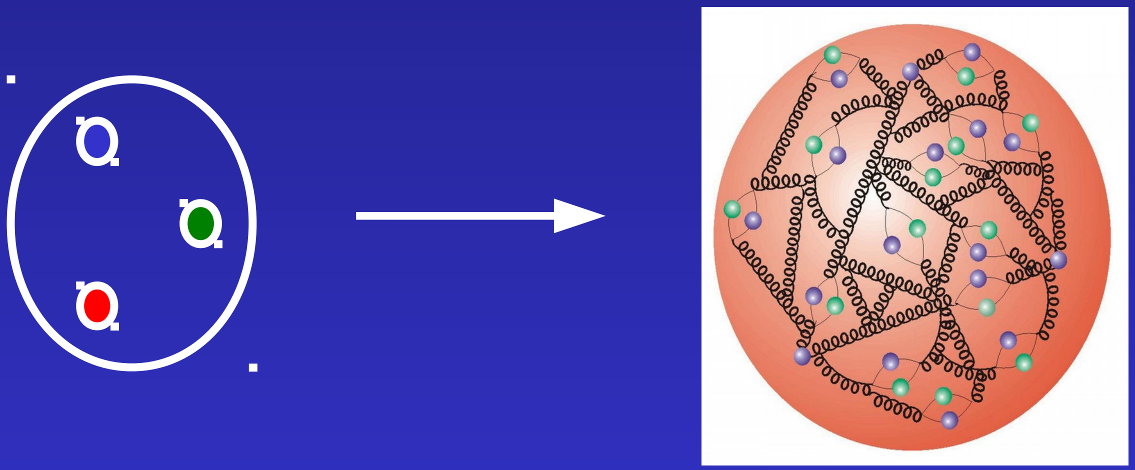



Such experiments were done at the electron-proton Collider HERA (at DESY in Hamburg). A 28 GeV electron was collided with a 920 GeV proton.

# Probing the interiors of nucleons and nuclei

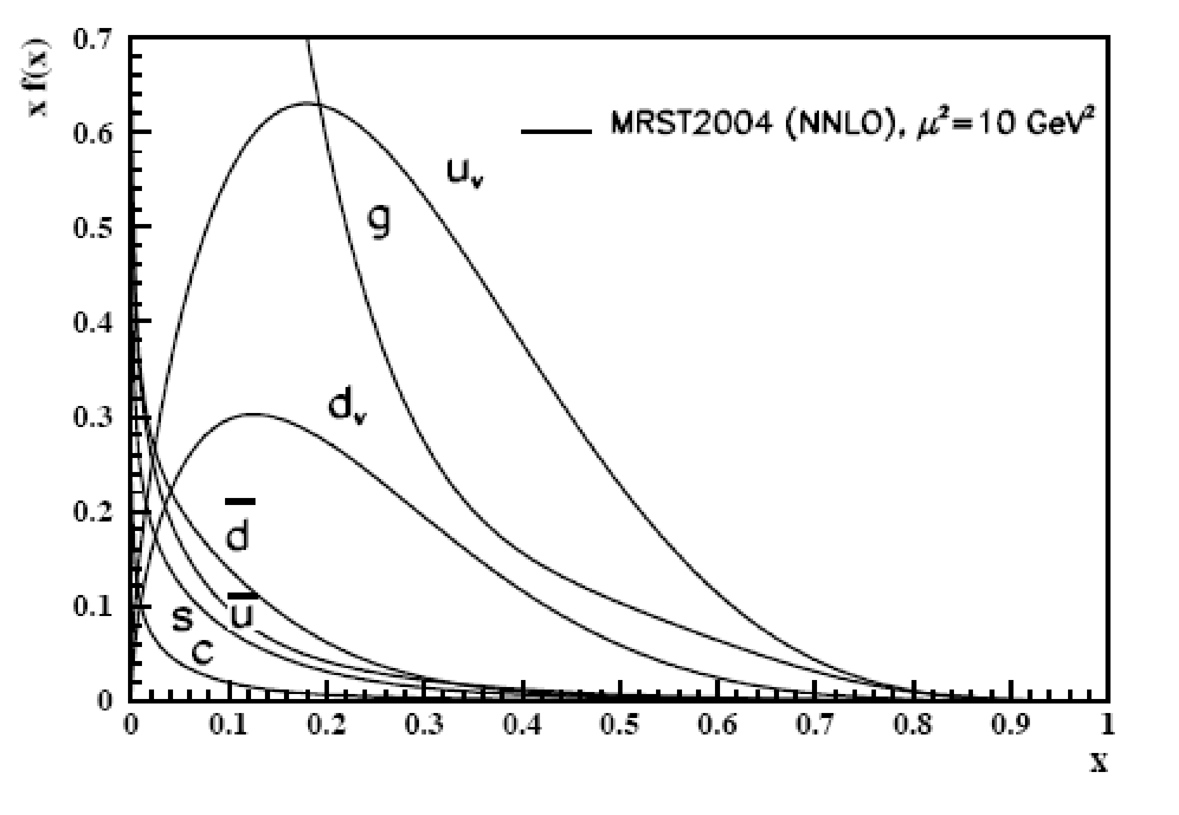
These experiments revealed a much more complicated structure than just 3 quarks.

In addition to the 3 quarks (called valence quarks) there are short-lived fluctutation of quark-antiquark pairs (sea quarks) and gluons (the charge carrier of the strong force).



# Probing the interiors of nucleons and nuclei

The *Parton Distribution Functions* tell us how the "partons" (that is quarks and gluons) are distributed inside the proton.




Bjorken x is the fraction of the proton energy carried by the quark/gluon.

# Probing the interiors of nucleons and nuclei

Determining the *Parton Distribution Functions* is of interest to understand the basic properties of the proton and neutron.

The PDFs are also necessary to be able to calculate any fundamental cross section in proton-proton collisions.

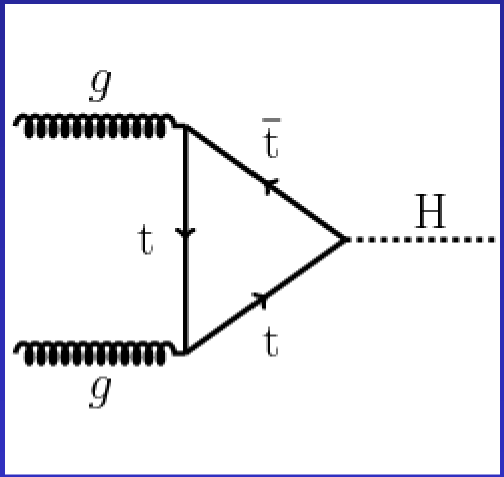
There are even ideas that the strong density of gluons at low x would correspond to a new state of matter - A Color Glass Condensate.

The nuclear PDFs are different from the ones of the nucleon.

# How do we use pQCD to calculate cross sections at the LHC ?

Take Higgs as an example. What is the cross section for $\sigma(p+p \rightarrow H+X)$?

Using the Standard Model pQCD we can only calculate cross sections for elementary particles, like gluon+gluon --> H.




The cross section $\sigma(g+g \rightarrow H)$ can be calculated from the Feynman diagram to the left.

# How do we use pQCD to calculate cross sections at the LHC ?

To get the cross section in a pp collisions we have to convolute this basic cross section, $\sigma(g+g \rightarrow H)$, with the gluon distributions in the two protons:

$$\sigma(p+p \rightarrow H+X) = \int g_1(x_1) g_2(x_2) \sigma(g+g \rightarrow H) dx_1 dx_2$$

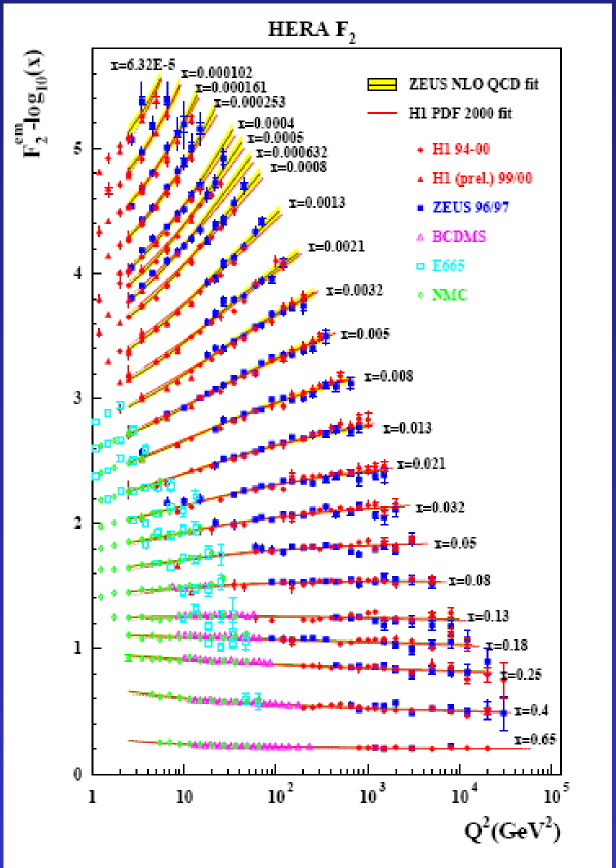
Gluons in proton 1

Gluons in proton 2

To do accurate cross section calculation we need the PDFs!

# Parton Distribution Functions

The PDFs have been mapped out in detail over a wide range of x and $Q^2$, at the electron-proton collider HERA and in fixed target experiments with electron and muon beams.



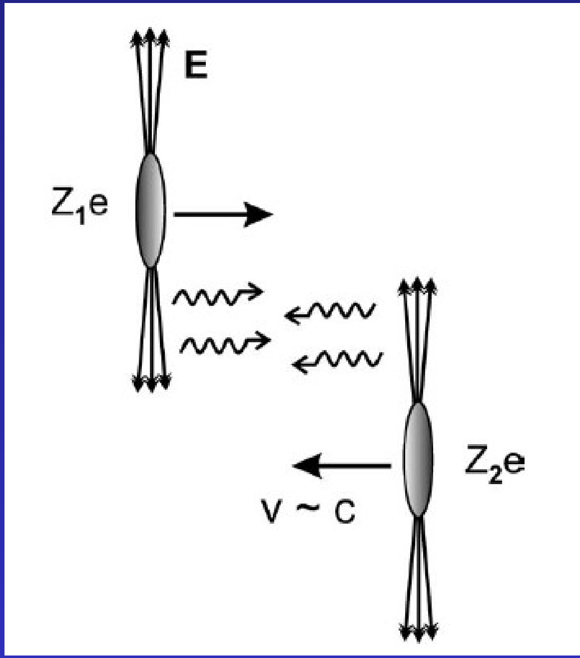

But there is a limit to the range HERA could cover because of the finite beam energies.

==> Enter Ultra-Peripheral Collisions. Use the strong electromagnetic fields of heavy ions in LHC to study γ-p and γ-nucleus interactions!

# What are Ultra-peripheral Collisions?

Collisions between nuclei and protons with impact parameters larger than the sum of the radii.

Strong interactions suppressed. Interactions instead mediated by the electromagnetic field.




The EM fields correspond to an equivalent flux of photons (Fermi/ Weizsäcker-Williams).

Two-photon and photonuclear/photon-proton interactions can be studied at unprecedented energies in UPC at the LHC.

# Electromagnetic fields of a moving charged particle

The 4-vector potential

$$A^{\mu} = (\phi, \overline{A})$$

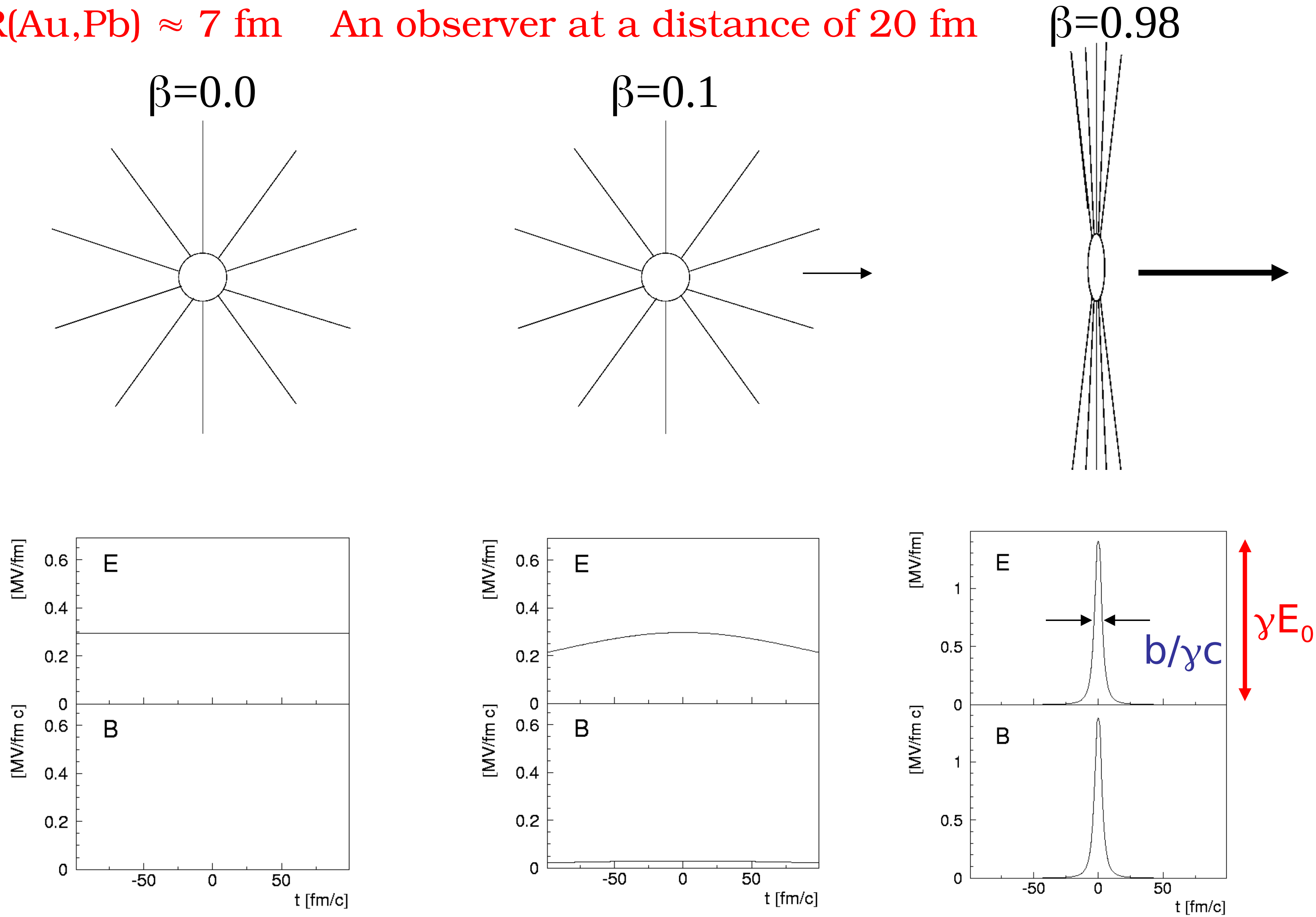
Transforms as a 4-vector under Lorentz transformations

From $A^{\mu}$ we get **E** and **B**

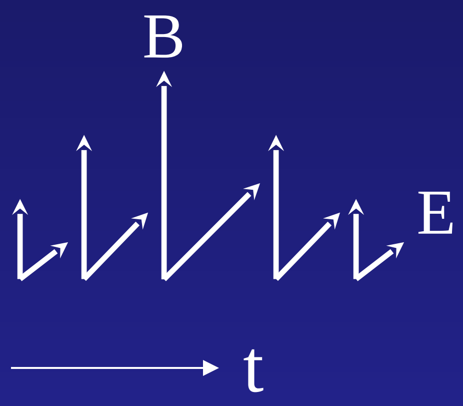
$$\overline{E} = \overline{\nabla}\phi \quad \text{and} \quad \overline{B} = \overline{\nabla} \times \overline{A}$$

# Electromagnetic fields of a moving charged particle

R(Au,Pb) ≈ 7 fm    An observer at a distance of 20 fm

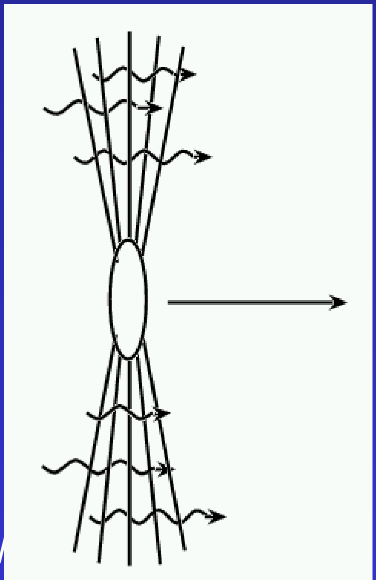


# Electromagnetic fields of a moving charged particle




1) $|E| \approx |B|$ 2) $(E \perp B)$ 3) $\Delta t \sim b/\gamma c$

Fermi 1924: The effect of the fields is equivalent to a flux of of photons with a continous energy spectrum.



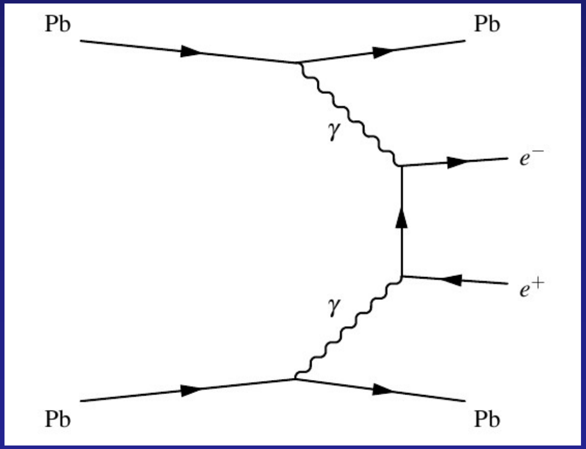
Pulse width $b/\gamma c$ $\leftrightarrow$ the spectrum contains photons w/ $\omega < \gamma c/b$

Quantum Mechanical derivation 1935 by Weizsäcker,Williams. $\Rightarrow$ *Weizsäcker-Williams method*

We can calculate $n(\omega)$ through a Fourier transform.

The quantum of the electromagnetic field is the photon ==> two-photon interactions are possible, for example

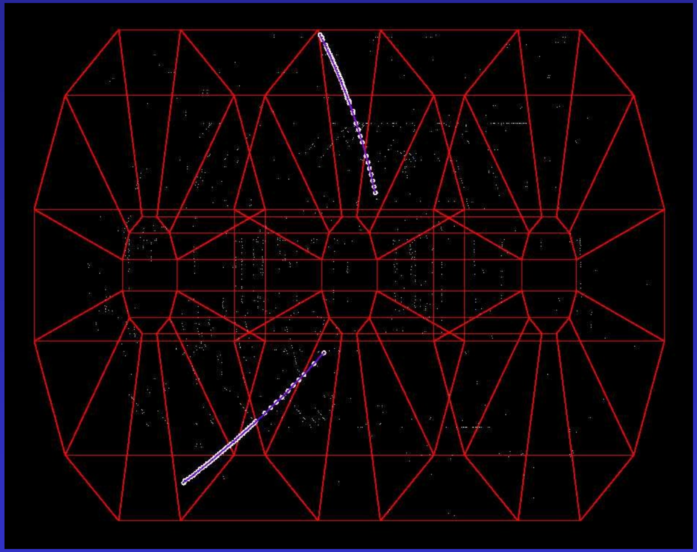
$Pb + Pb \rightarrow Pb + Pb + \mu^+ + \mu^-$



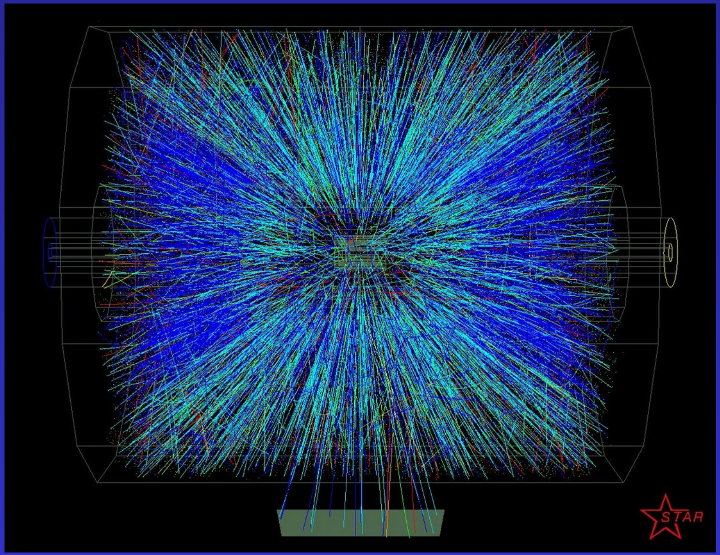

The Pb-nuclei just sweep past each other and a $\mu^+\mu^-$ pair appears in the middle!

Compare the event topologies

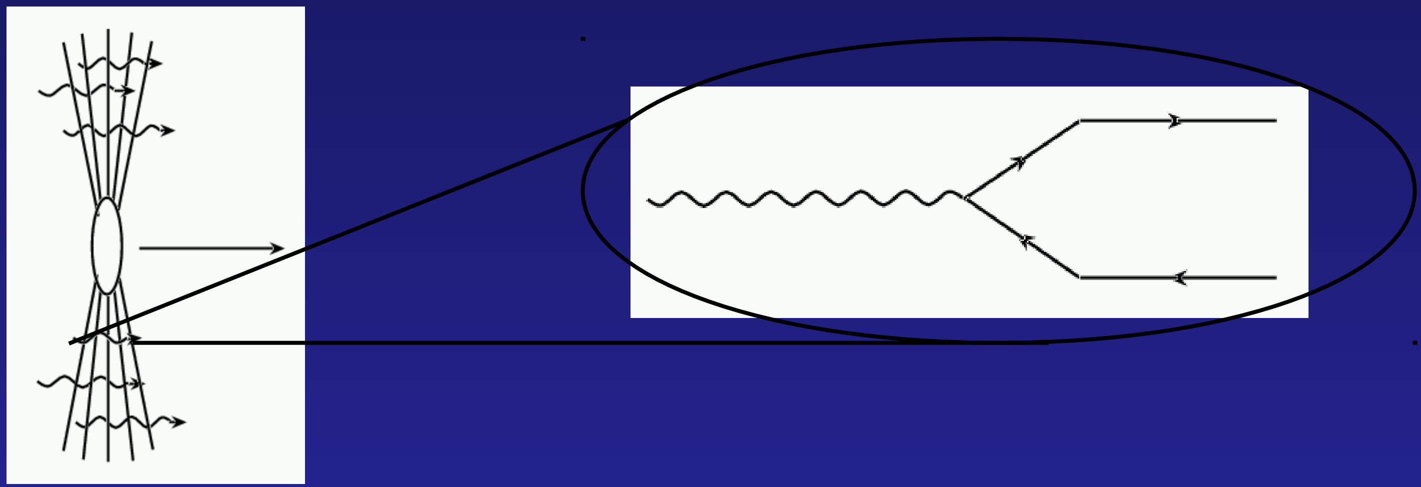
UPC



CENTRAL



But this is not the only possibility …



The photon is not always a photon. With some probability one can find it in a hadronic state (Vector Meson, spin=1).

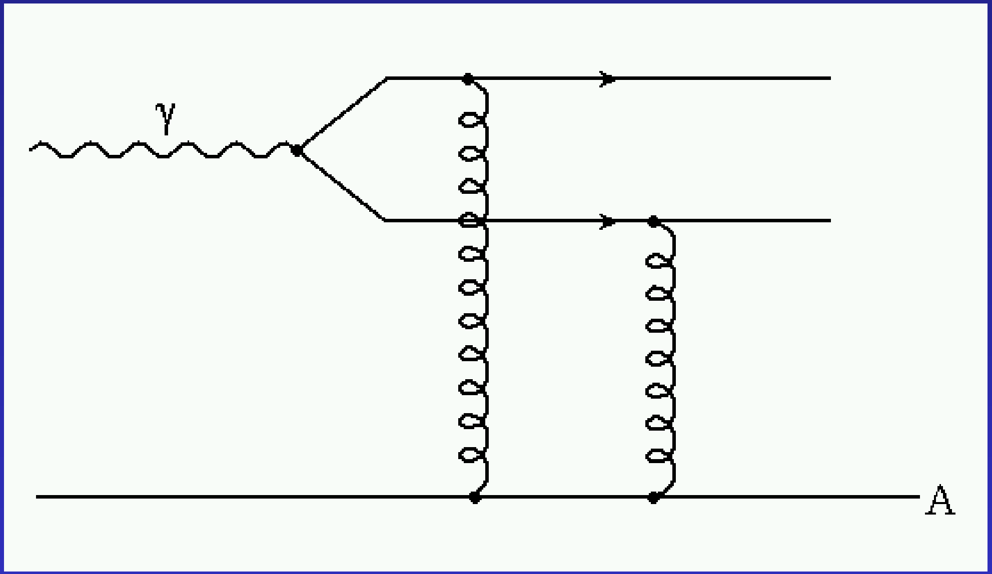
The virtual vector meson can materialize by scattering elastically off the other nucleus.

So reactions Pb+Pb → Pb+Pb+J/ψ are possible.
The J/ψ decays, J/ψ → $\mu^+ + \mu^-$ so the final state is
Pb + Pb → Pb + Pb + $\mu^+ + \mu^-$, same as for a two-photon interaction.

# Exclusive Vector Meson Production

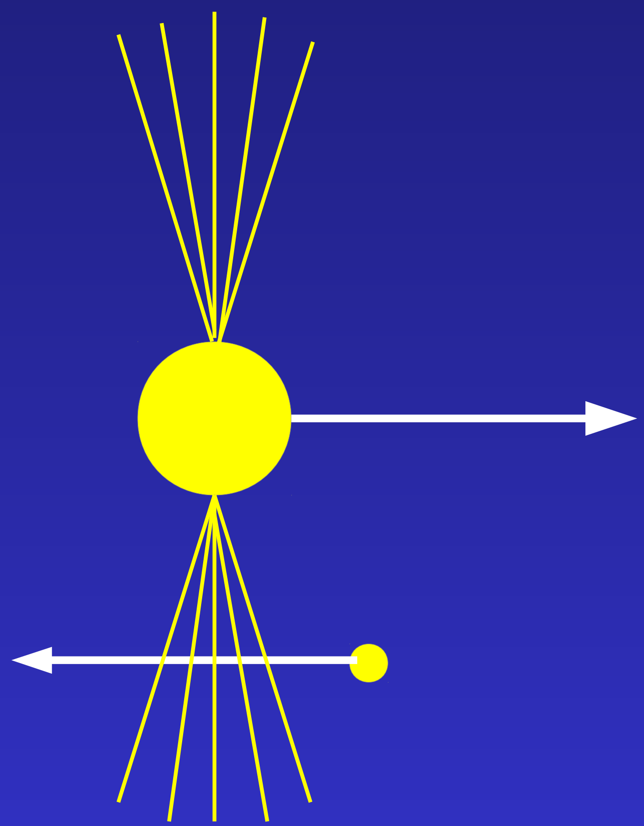
The mechanism responsible for producing the vector meson is the exchange of two gluons.

==> The reaction can be used to probe the proton and nuclear gluon distributions.



# Exclusive Vector Meson Production

The reaction $\gamma$+p $\rightarrow$ J/$\psi$+p can be studied in p+Pb collisions at the LHC.

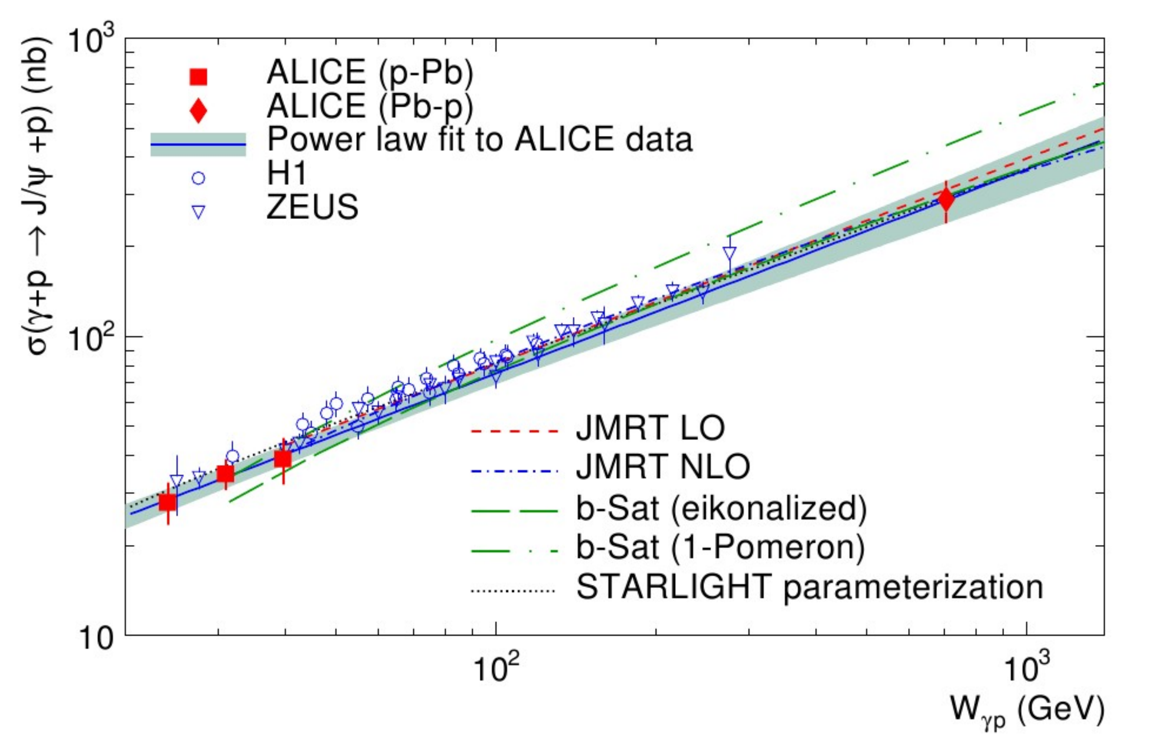


Photon flux $\propto Z^2$ so the Pb-nucleus provides a strong source of photons which hit the proton.

The high beam energies at the LHC means that $\gamma$+p interactions can be studied at higher energies than ever before.

# Exclusive Vector Meson Production

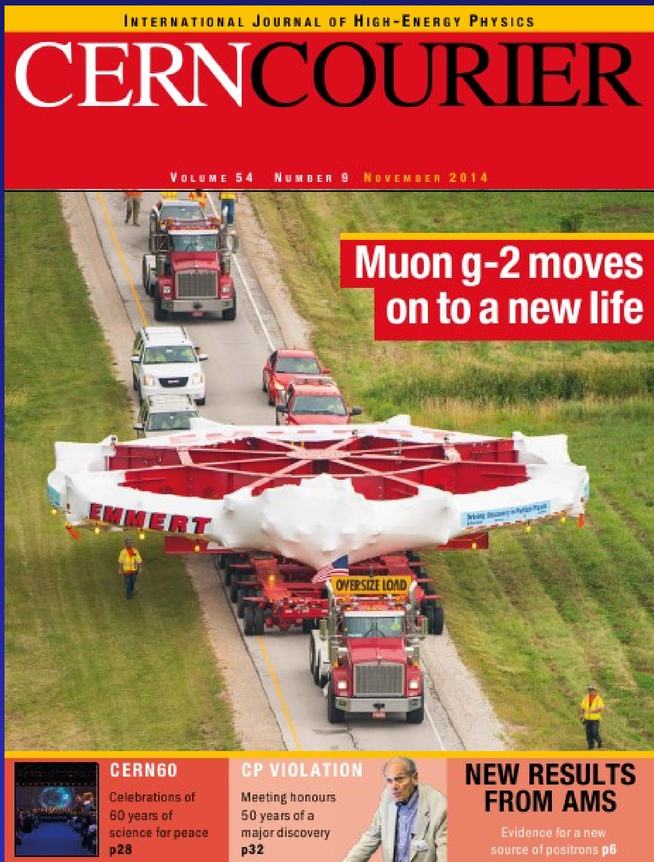
## Results from ALICE on $\gamma$+p $\rightarrow$ J/$\psi$+p




Energy range extended by factor ~3. Range in x extended from $10^{-4}$ to $2 \cdot 10^{-5}$.

*A natural explanation is that no change in the behaviour of the gluon PDF in the proton is observed between HERA and LHC energies*

# Exclusive Vector Meson Production




November 2014

## Producing charm with light

ALICE

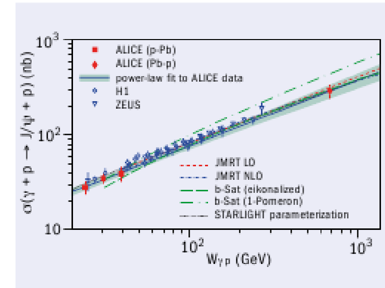
The electric charge of lead ions, when accelerated to ultra-relativistic velocities, is the source of an intense flux of high-energy quasi-real photons. Ultra-peripheral collisions – the interaction of a photon with a target at impact parameters larger than the sum of the radii of the incoming particles, where hadronic interactions are suppressed – provide a clean tool to study photon-induced production processes at the LHC (*CERN Courier* November 2012 p9).

ALICE has performed the first measurement of exclusive photoproduction of J/ψ mesons off protons in proton–lead collisions at the LHC, using data collected in early 2013 (Abelev *et al.* 2014). These data cover a range of photon–proton centre-of-mass energies that were not accessible previously. Such interactions have been studied at the electron–proton collider HERA, and are proposed as a key measurement at a future electron–hadron collider, to probe the gluon distribution in the proton.

The J/ψ mesons were reconstructed from their decay into a $\mu^+\mu^-$ pair, where the muons were measured by the ALICE muon spectrometer. Requiring no other activity to be present in the detector enforced the exclusivity condition. Around the middle of the data-taking period, the beam direction was inverted, allowing ALICE to take data first when protons, and later lead ions, were travelling towards the muon spectrometer, providing proton–lead and lead–proton collisions, respectively. The rapidity of the J/ψ, measured with respect to the direction of the proton beam, determines the photon–proton centre of mass energy ($W_{\gamma p}$). In lead–proton collisions, the acceptance of ALICE corresponds to values of $W_{\gamma p}$ more than twice as large as was reached at HERA by the H1 and ZEUS experiments, while the proton–lead collisions correspond to values of $W_{\gamma p}$ studied previously at HERA and in fixed-target experiments.

According to leading-order calculations in perturbative QCD, this process depends on the square of the gluon distribution in the proton evaluated at a scale close to the J/ψ mass ($M_{J/\psi}$) and at x-Bjorken $x = (M_{J/\psi}/W_{\gamma p})^2$. The range in x covered by ALICE therefore extends from about $2 \times 10^{-2}$ (proton–lead) to $2 \times 10^{-5}$ (lead–proton). It is then possible to study the evolution of the gluon density in the proton at a perturbative scale along three orders of magnitude in x, and probe into the region where the gluon density increases, possibly leading to a saturation regime, in which the proton wave-function is described by a coherent colour field created by the many overlapping gluons.

The cross-section measured by ALICE (see figure) has been compared with the predictions of models based on (i) perturbative QCD calculations at leading order (ii) and including the main next-to-leading order contributions, (iii) a saturation prescription including impact parameter dependence and (iv) a parameterization of HERA and fixed-target results. All models were fitted to HERA measurements, and are able to describe the current ALICE data.




*The cross-section measured by ALICE for exclusive photoproduction of J/ψ mesons off protons in proton–lead collisions.*

ALICE has found that a power law in $W_{\gamma p}$ can describe the measured cross-section. The value of the power-law exponent is compatible with those found by H1 and by ZEUS. Therefore, no deviation from the same power law is observed up to about 700 GeV, or in a leading-order perturbative QCD context, down to $x = 2 \times 10^{-5}$, extending by a factor five the maximum x value explored previously.

In conclusion, within the current precision, ALICE has observed no change of regime with respect to what was measured at HERA. Data to be collected during LHC Run 2 at beam energies increased by a factor of two will allow ALICE both to improve the precision of the measurement and to access larger values of $W_{\gamma p}$. Lowering the x value to values never reached before will open new opportunities to search for saturation phenomena.

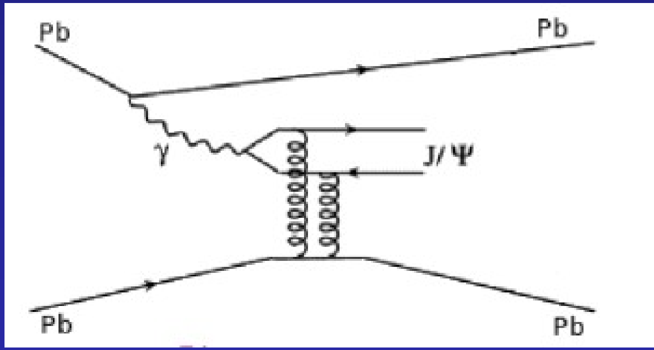
**Further reading**

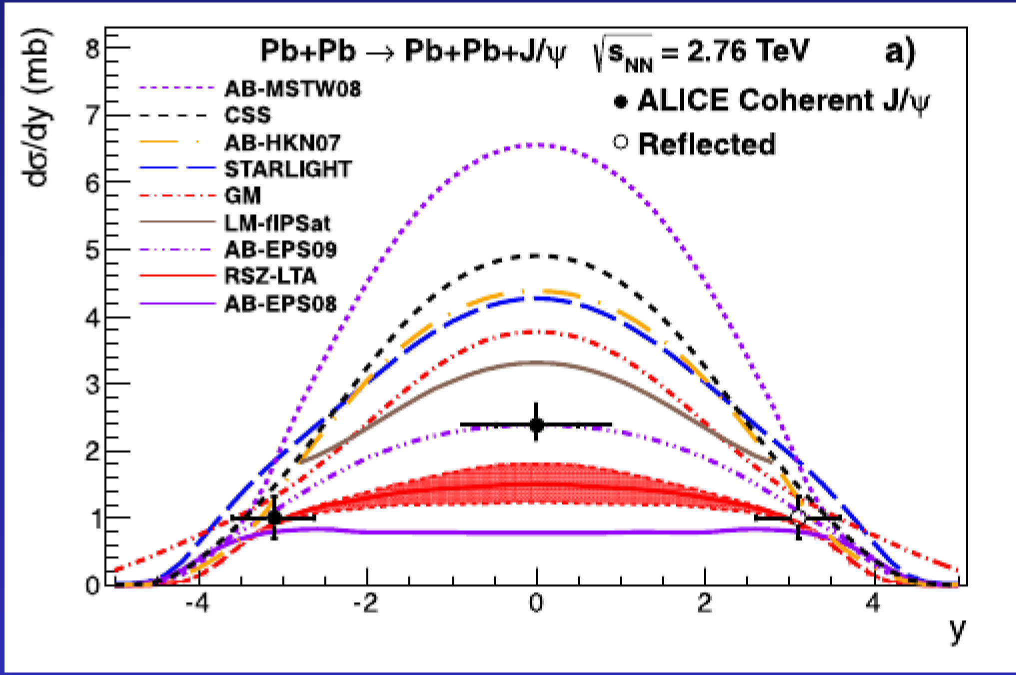

B B Abelev *et al.* (ALICE Collaboration) 2014 arXiv:1406.7819 [nucl-ex].


http://cerncourier.com/cws/article/cern/58915

# Exclusive Vector Meson Production

This process can be studied also in Pb+Pb collisions. Then both nuclei can be either photon emitter or target.




The results (2013) show that the gluon distribution in a Pb nucleus is different (reduced) from that in a proton.

# Physics with the ALICE Detector

- The main goal of ALICE is to study a new state of matter – The Quark Gluon Plasma – formed in central (head on) Pb+Pb Collisions.

- But at the same time as being the most powerful p-p and Pb-Pb collider in the world, LHC is also the most powerful photon collider!

- ALICE has taken advantage of this by studying $\gamma$-p, $\gamma$-Pb as well as $\gamma$-$\gamma$ interactions in novel energy ranges.

# How is it to work in a collaboration with >1000 participants?

A small cog in a big wheel?

Physics Letters B 718 (2013) 1273–1283

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# Coherent J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV ☆

ALICE Collaboration

ARTICLE INFO

*Article history:*
Received 17 September 2012
Received in revised form 16 November 2012
Accepted 26 November 2012
Available online 5 December 2012
Editor: V. Metag

ABSTRACT

The ALICE Collaboration has made the first measurement at the LHC of J/ψ photoproduction in ultra-peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The J/ψ is identified via its dimuon decay in the forward rapidity region with the muon spectrometer for events where the hadronic activity is required to be minimal. The analysis is based on an event sample corresponding to an integrated luminosity of about 55 $\mu b^{-1}$. The cross section for coherent J/ψ production in the rapidity interval $-3.6 < y < -2.6$ is measured to be $d\sigma^{coh}_{J/\psi}/dy = 1.00 \pm 0.18(stat)^{+0.24}_{-0.26}(syst)$ mb. The result is compared to theoretical models for coherent J/ψ production and found to be in good agreement with those models which include nuclear gluon shadowing.

## References

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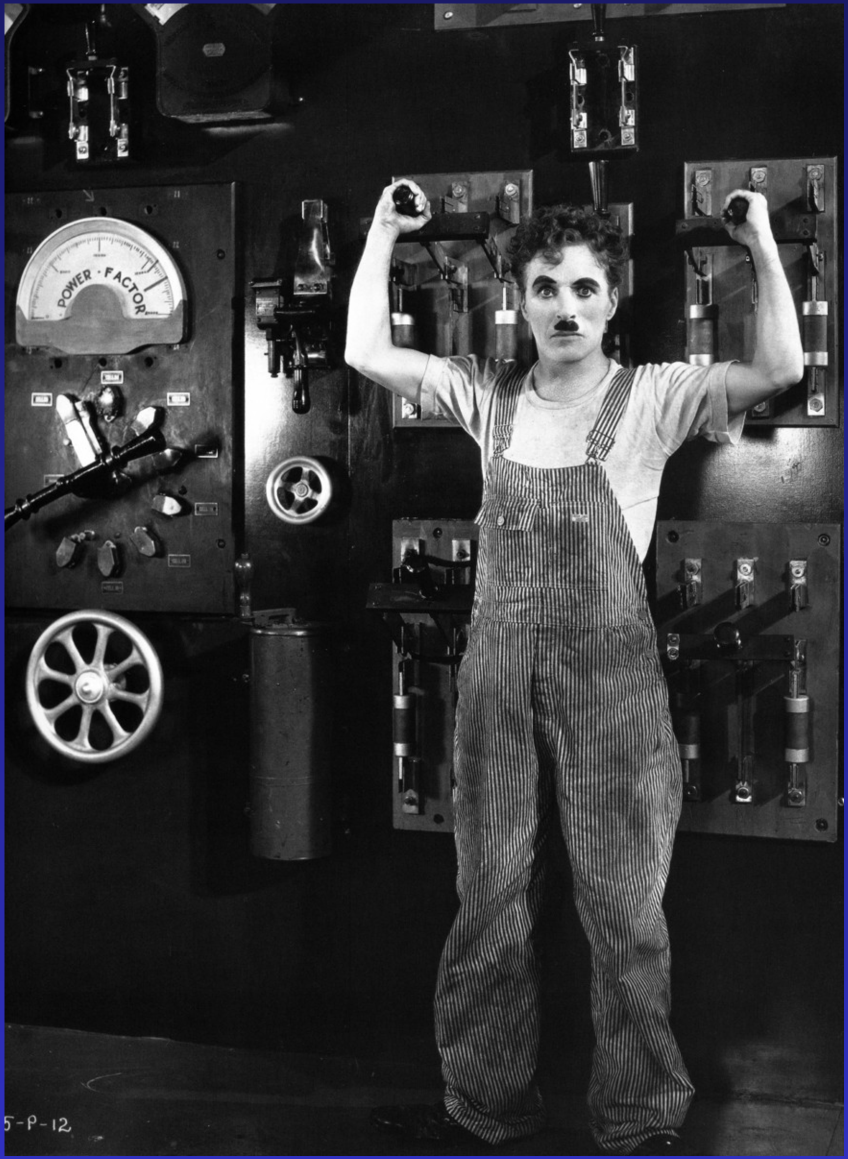


It *is* possible to have an impact at the LHC, even from a small university on the periphery of Europe!