

Mikrosvět aneb Od E. Rutherforda k laboratoři CERN a urychlovači LHC



Jiří Kvita

15.3.2024

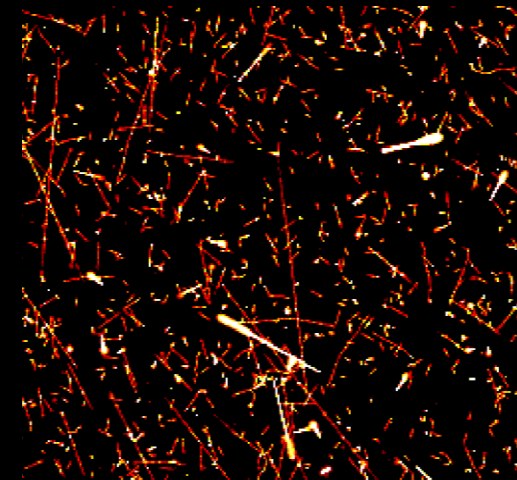
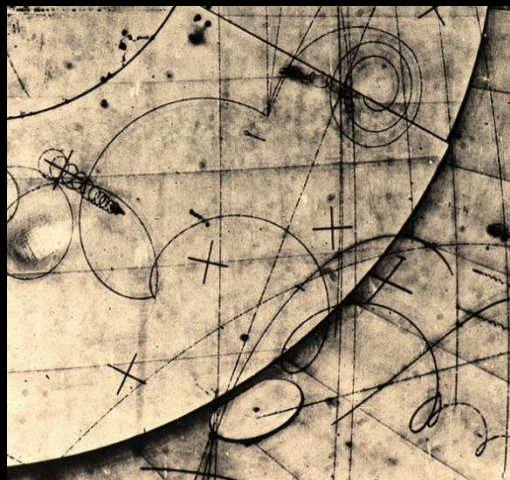
Jiri.Kvita@upol.cz

Společná laboratoř optiky UP a AVČR

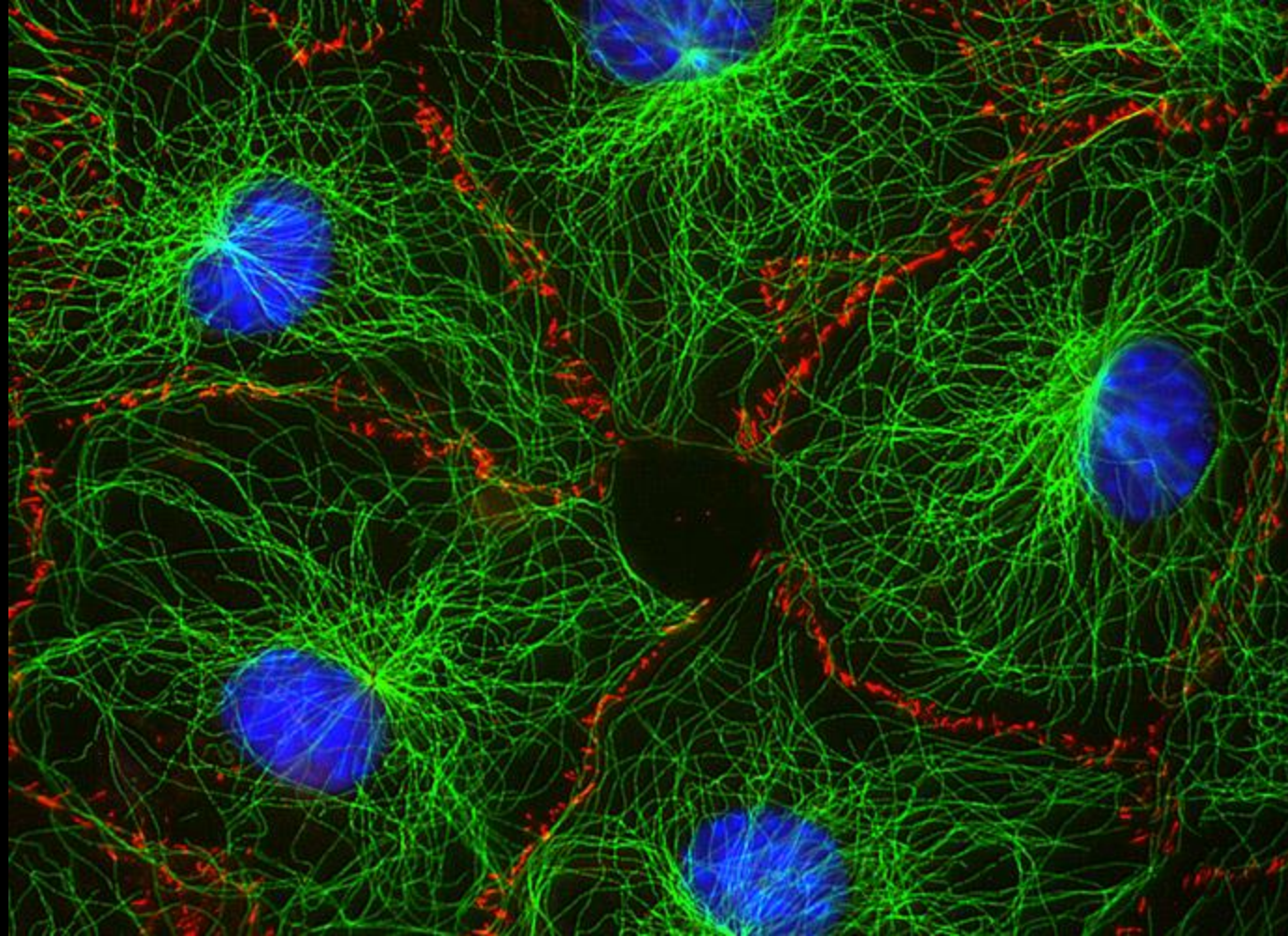
Přírodovědecká fakulta

Univerzity Palackého

Olomouc

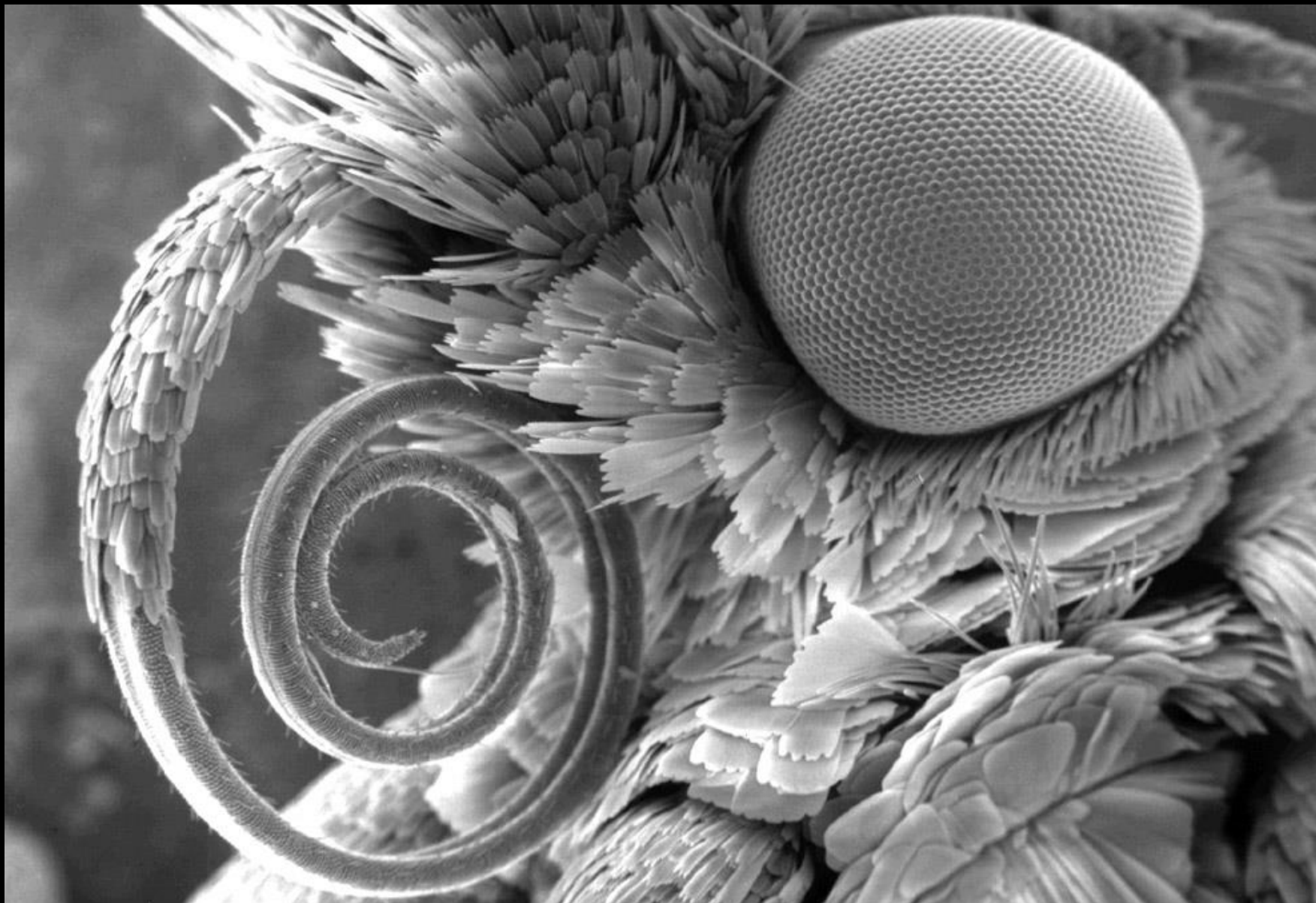


Buňka



10^{-5} m

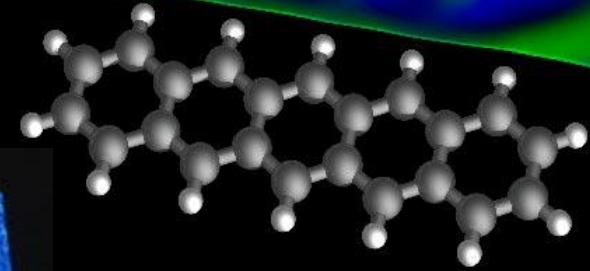
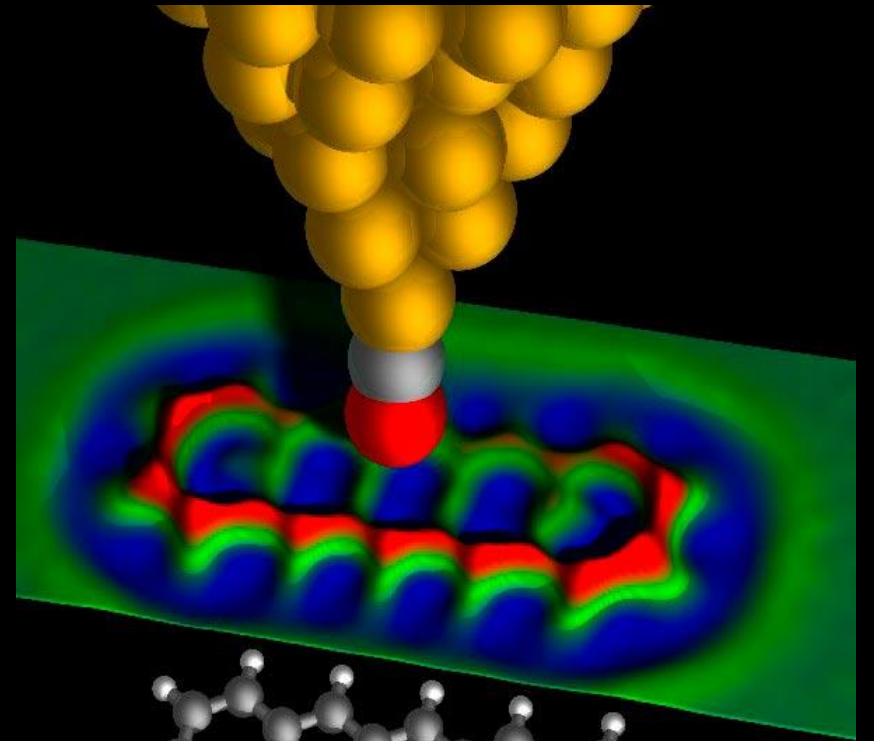
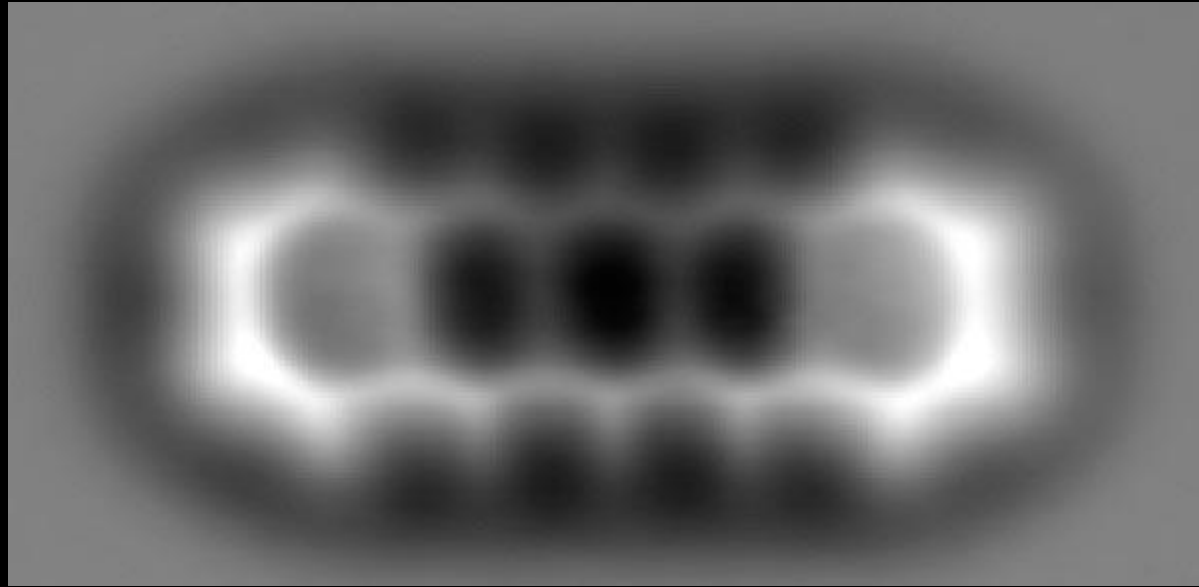
myší vazivová buňka, Jan Schmoranzer



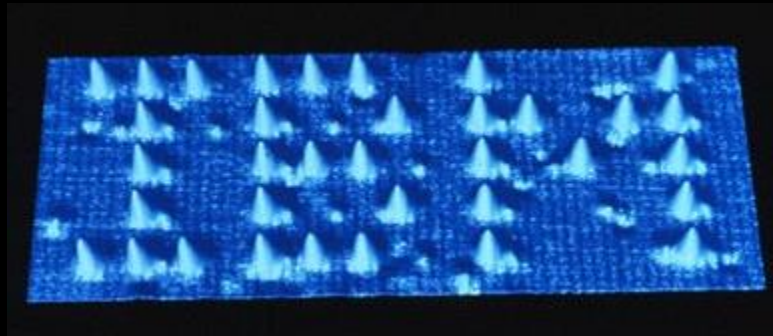
10^{-3} m

Motýl elektronovým mikroskopem na Dartmouth College

Molekula pentacenu – obláčky elektronů

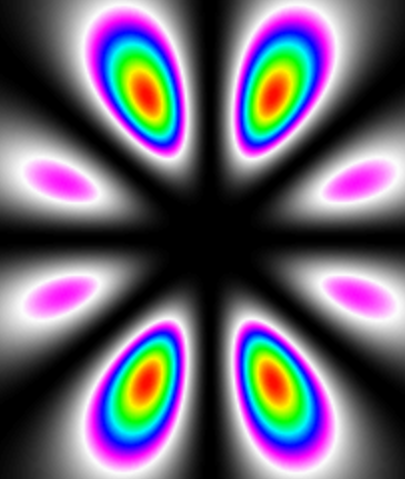
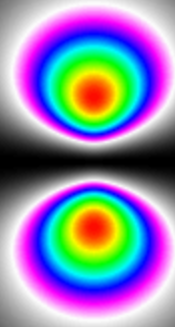
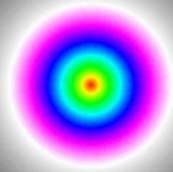


10^{-9} m



IBM, Zurich

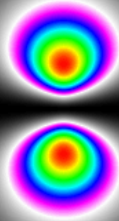
Atom – stojaté vlny elektronů kolem jádra



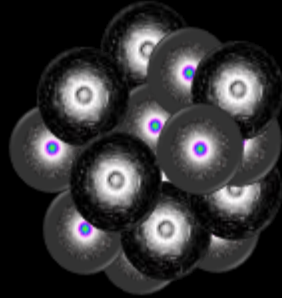
10^{-10} m

Škály délek a energií

- Atomový obal
 - 10 nm = 10^{-8} m
 - 10 eV -- keV



- Atomové jádro
 - 100 fm = 10^{-13} m
 - 10 keV -- 1 MeV




- Struktura protonu
 - 1 fm = 10^{-15} m
 - 1 GeV

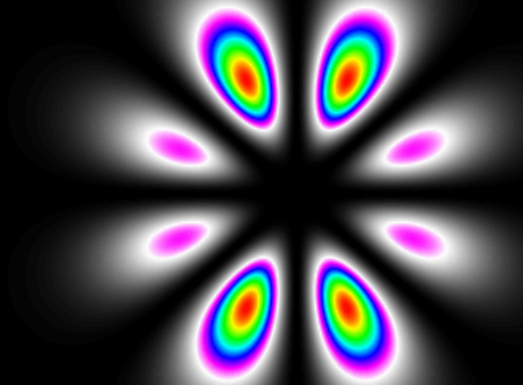
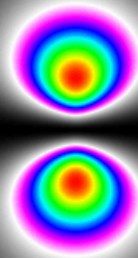
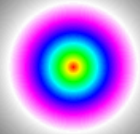


1 elektronvolt: kinetická energie, kterou získá částice s náboje elektronu po urychlení napětím 1 V.

$$1\text{eV} = 1,602 \cdot 10^{-19} \text{ J}$$

Elektron

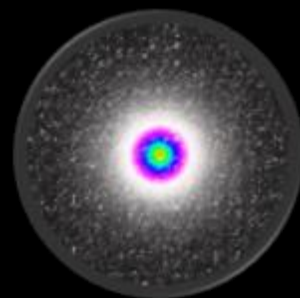
- Elektron: 
 - Náboj -1 v jednotkách elementárního náboje.
 - Klidová energie 0,511 MeV.
 - Bodová částice bez vnitřní struktury!
 - „Necítí“ silnou (jadernou) interakci.
 - Spin $\frac{1}{2}$.



Proton a neutron

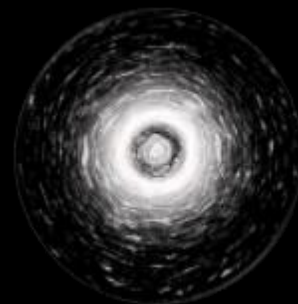
- Proton:

- Náboj +1 v jednotkách elementárního náboje.
- Střední poloměr okolo 1 fm.
- Klidová energie 938 MeV.
- Spin $\frac{1}{2}$.
- Kvarkový obsah *uud*.



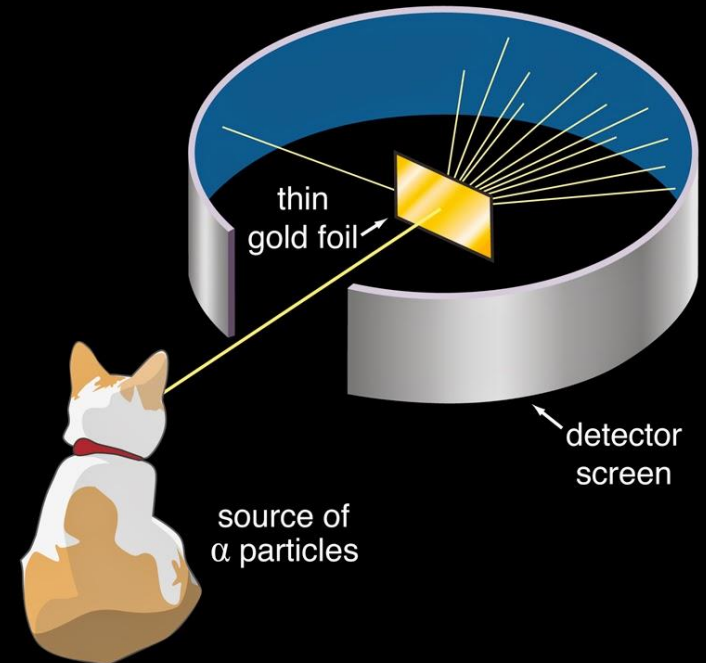
- Neutron:

- Nulový náboj.
- Střední poloměr okolo 1 fm.
- Klidová energie 939 MeV.
- Spin $\frac{1}{2}$.
- Kvarkový obsah *udd*.



Rutherfordův experiment 1918

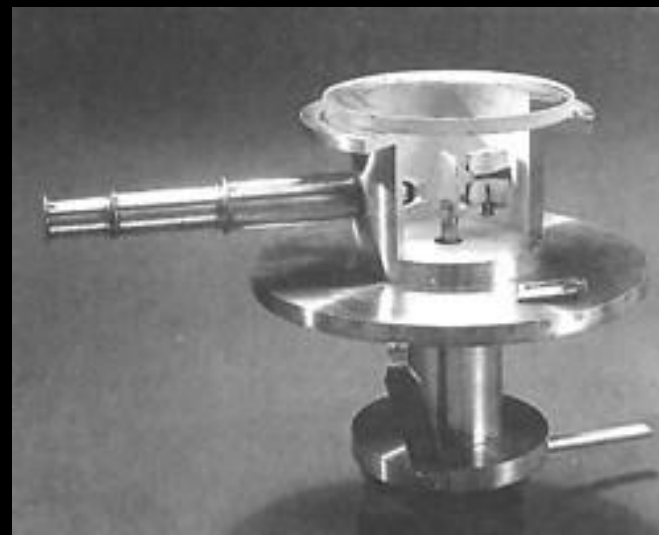
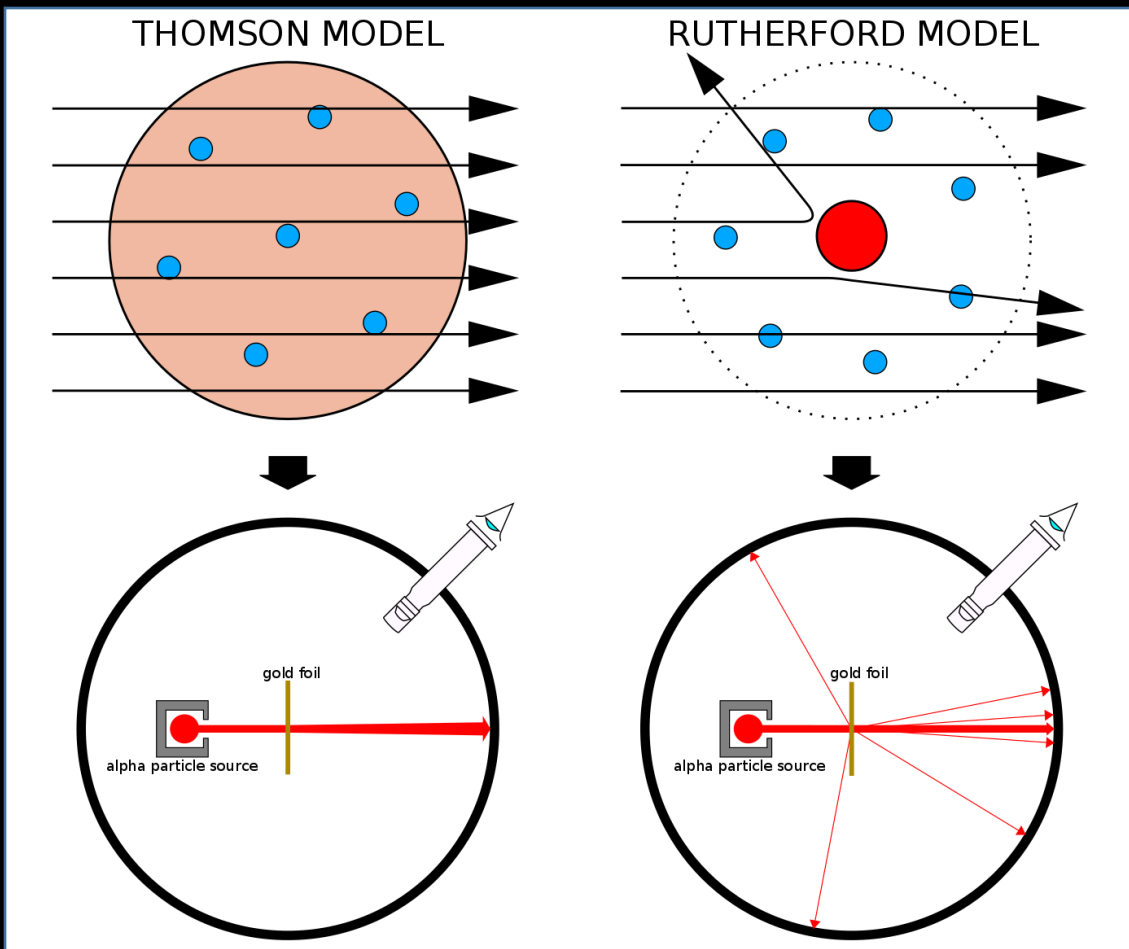
- **Alfa částice:** jádra hélia, která vyletují z jiných těžkých jader, čímž vznikají stabilnější jádra.
- Alfa částice ve vzduchu uletí jen několik cm.
- Alfa rozpadem se přeměňují velmi těžké prvky, např. uran, radon, polonium, rádium...
- Bombardováním zlaté fólie alfa částicemi objevil Ernest Rutherford atomové jádro!
 - Alfa částice se občas odrazily zpět, což nešlo vysvětlit jinak, než že většina hmotnosti atomu je v nějakém velmi malém hmotném centru.



Rutherford's experiment 1918

- Ernest Rutherford led and designed the experiment
- Measured Hans Geiger and Ernest Marsden

https://en.wikipedia.org/wiki/Geiger%E2%80%93Marsden_experiment



Rutherfordův experiment 1918

- Bombardování zlaté fólie částicemi alfa.
- Energie alfa částic z rádia okolo 5 MeV.
- Pravděpodobnost rozptylu alfa částice bodovým těžkým objektem do úhlu vzhledem k původnímu směru je úměrná
- Rutherfordův vztah

$$\frac{1}{\sin^4 \phi/2}$$

$$y = \frac{Qdm}{2\pi r^2 \sin \phi \cdot d\phi} = \frac{ntb^2 \cdot Q \cdot \operatorname{cosec}^4 \phi/2}{16r^2}$$

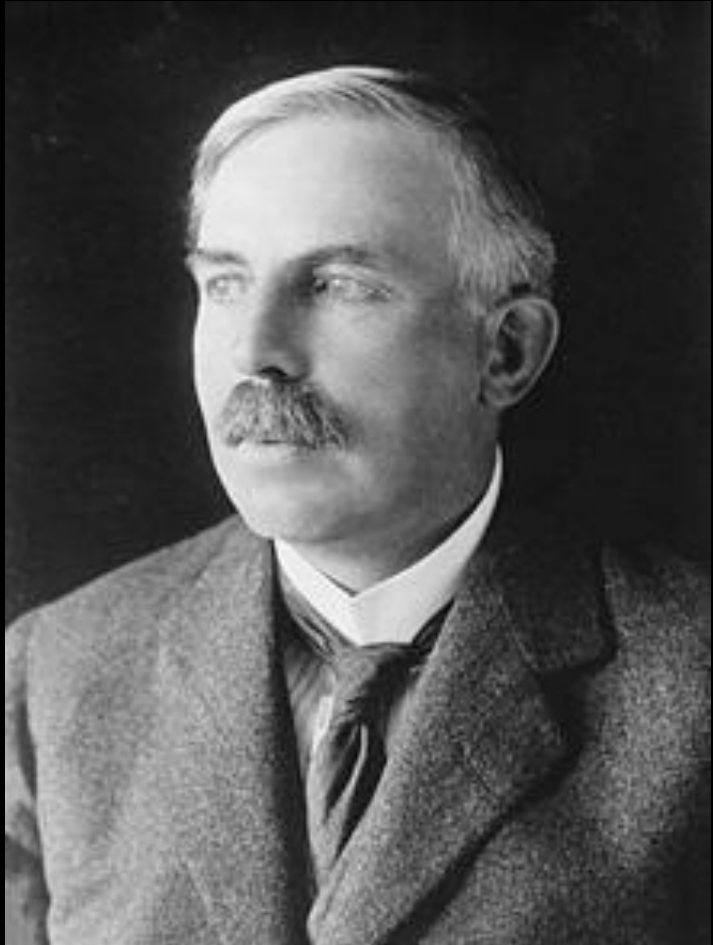
- **Důkaz existence velmi hmotného a malého atomového jádra!**
- "It was quite the most incredible event that ever happened to me in my life. It was as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

Table II.
Variation of Scattering with Angle. (Collected results)

I. Angle of deflexion, ϕ	II. $\frac{1}{\sin^4 \phi/2}$	III. SILVER		V. GOLD	
		Number of scintillations, N	$\frac{N}{\sin^4 \phi/2}$	Number of scintillations, N	$\frac{N}{\sin^4 \phi/2}$
150	1.15	22.2	19.3	33.1	28.8
135	1.38	27.4	19.8	43.0	31.2
120	1.79	33.0	18.4	51.9	29.0
105	2.53	47.3	18.7	69.5	27.5
75	7.25	136	18.8	211	29.1
60	16.0	320	20.0	477	29.8
45	46.6	989	21.2	1435	30.8
37.5	93.7	1760	18.8	3300	35.3
30	223	5260	23.6	7800	35.0
22.5	690	20300	29.4	27300	39.6
15	3445	105400	30.6	13200	38.4
30	223	5.3	0.024	3.1	0.014
22.5	690	16.6	0.024	8.4	0.012
15	3445	93.0	0.027	48.2	0.014
10	17330	508	0.029	200	0.0115
7.5	54650	1710	0.031	607	0.011
5	276300			3320	0.012

Rutherfordův experiment 1918

- Ernest Rutherford vedl a navrhoval experimenty
- Měřili Hans Geiger a Ernest Marsden



Velikost protonu

- Jak si posvítit na proton? – elektrony z urychlovače!
- Energie: 188 MeV!
- Robert Hofstadter, 1956, laboratoř SLAC, USA.

PHYSICAL REVIEW

VOLUME 102, NUMBER 3

MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§||¶

R. W. McALLISTER AND R. HOFSTADTER

Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California

(Received January 25, 1956)

The elastic scattering of 188-Mev electrons from gaseous targets of hydrogen and helium has been studied. Elastic profiles have been obtained at laboratory angles between 35° and 138° . The areas under such curves, within energy limits of ± 1.5 Mev of the peak, have been measured and the results plotted against angle. In the case of hydrogen, a comparison has been made with the theoretical predictions of the Mott formula for elastic scattering and also with a modified Mott formula (due to Rosenbluth) taking into account both the anomalous magnetic moment of the proton and a finite size effect. The comparison shows that a finite size of the proton will account for the results and the present experiment fixes this size. The root-mean-square radii of charge and magnetic moment are each $(0.74 \pm 0.24) \times 10^{-13}$ cm. In obtaining these results it is assumed that the usual laws of electromagnetic interaction and the Coulomb law are valid at distances less than 10^{-13} cm and that the charge and moment radii are equal. In helium, large effects of the finite size of the alpha-particle are observed and the rms radius of the alpha particle is found to be $(1.6 \pm 0.1) \times 10^{-13}$ cm.

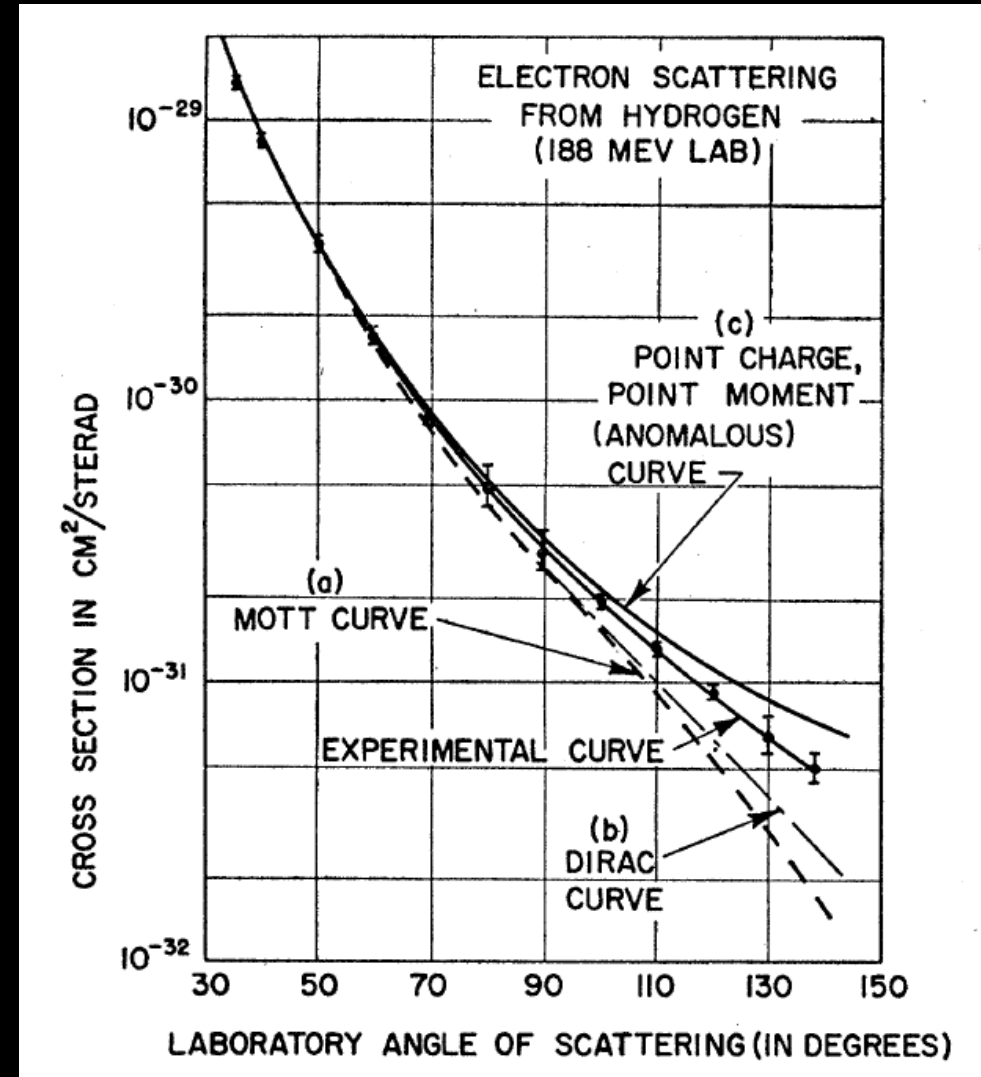
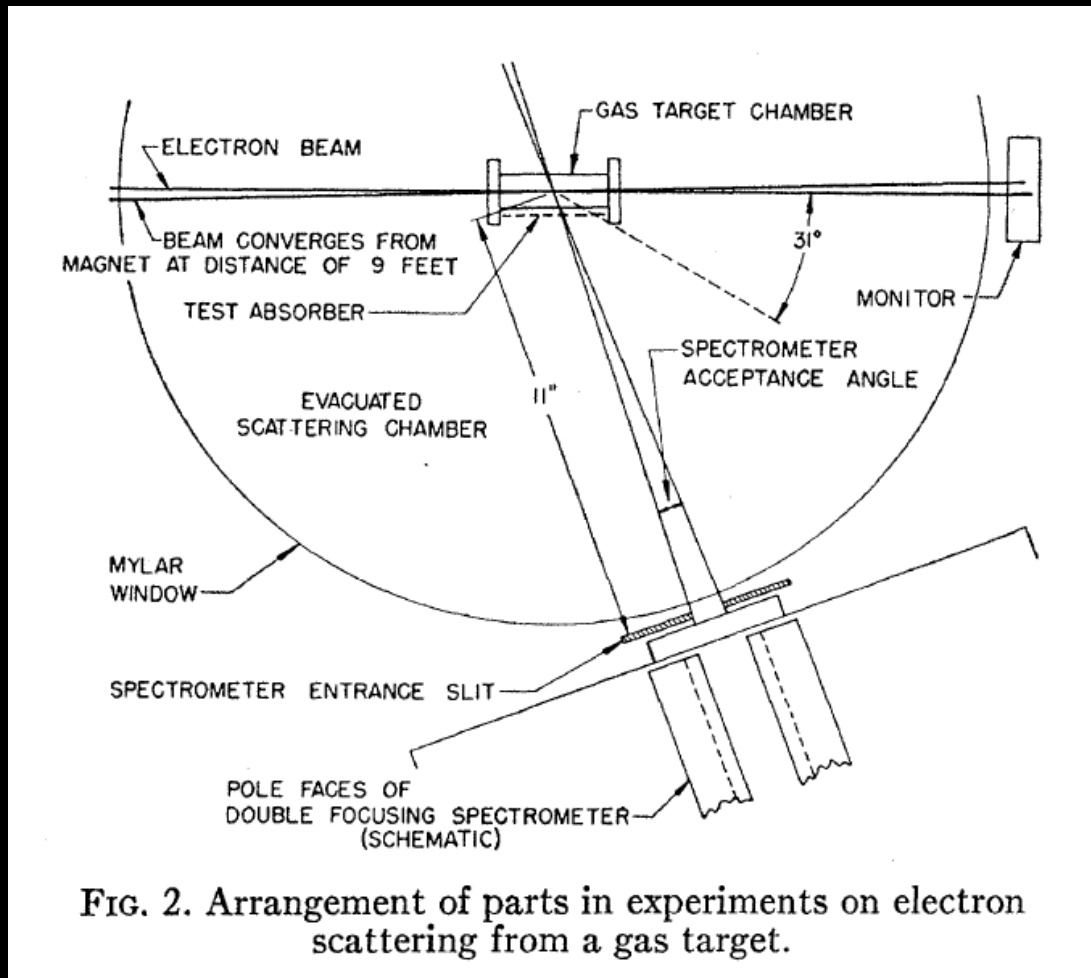
I. INTRODUCTION

II. EXPERIMENTAL METHODS



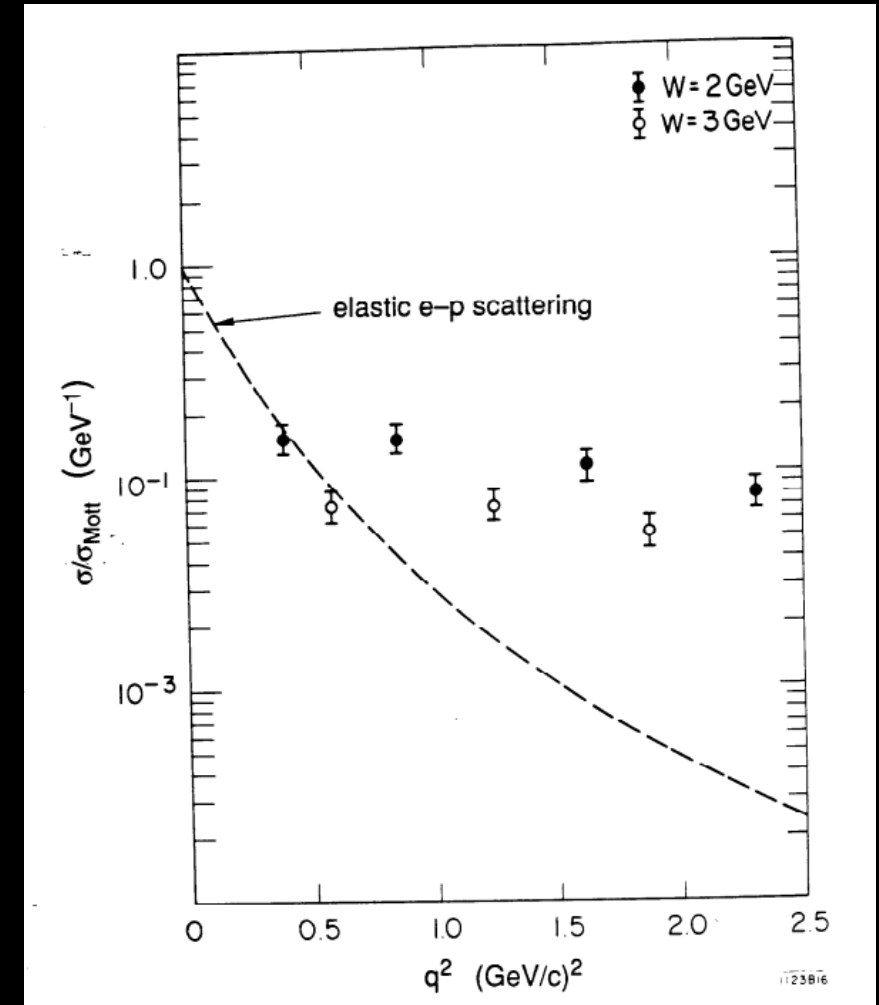
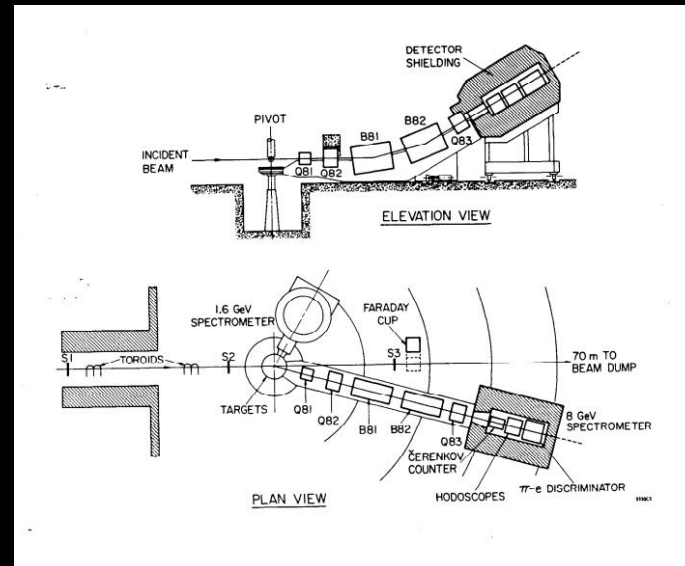
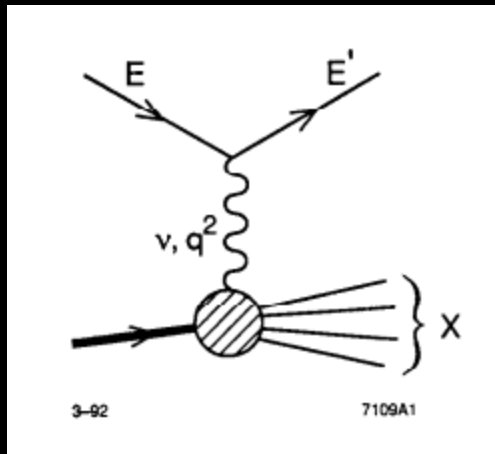
Velikost protonu, 1956

- Robert Hofstadter, 1956, laboratoř SLAC, USA.

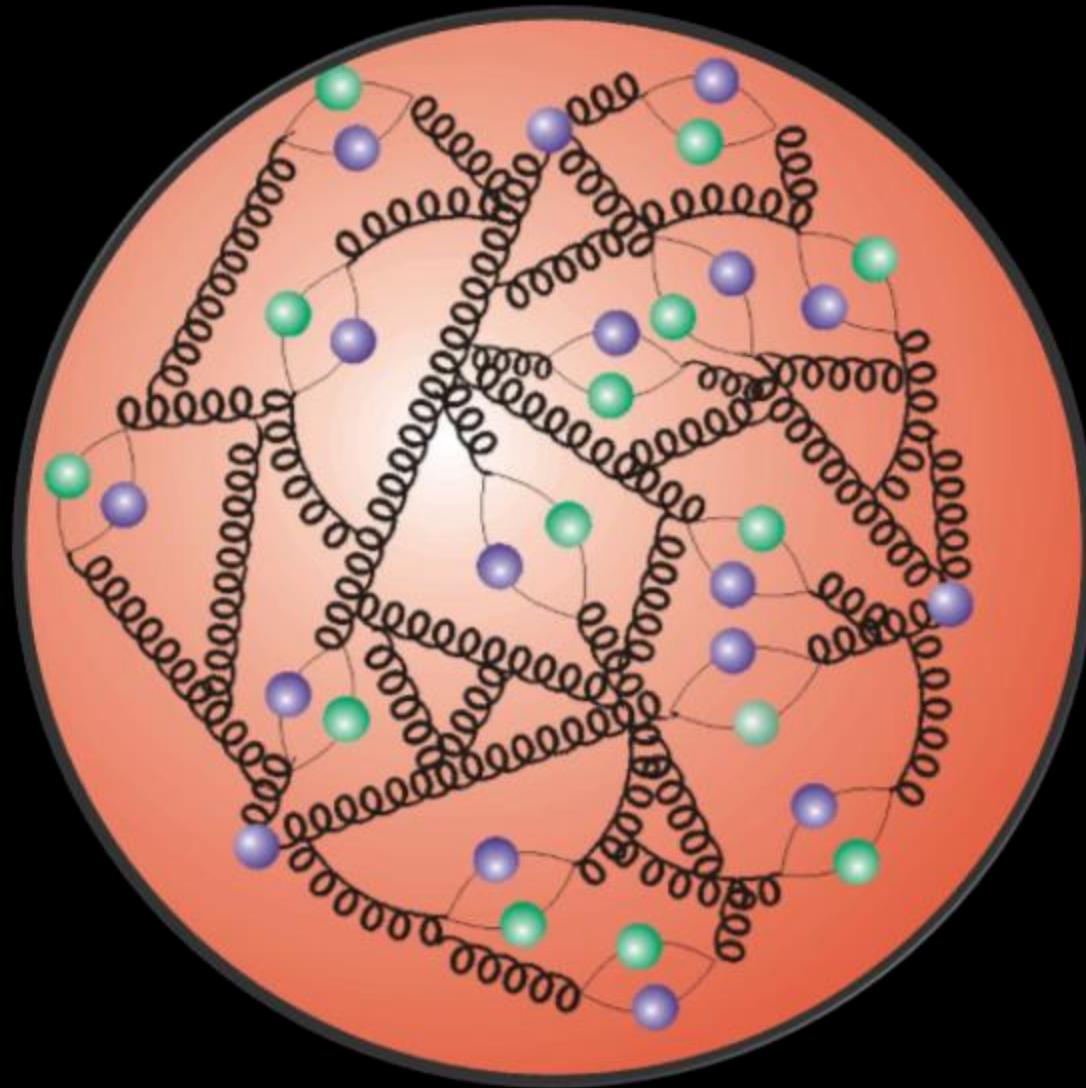


Struktura protonu

- Friedman, Kendall, Taylor, Bjorken, Feynman, SLAC, 1967 -- 1973.
- Elektrony o vyšší energii (20 GeV) už proton rozbijeme.
- Neelastické srážky, Deep inelastic scattering.
- Feynman nazval částičky v protonu partony.

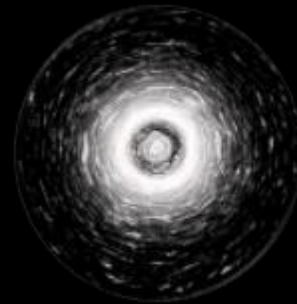
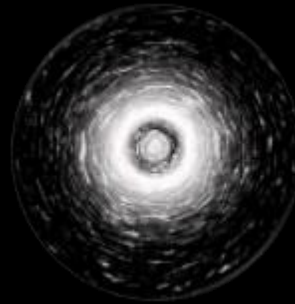
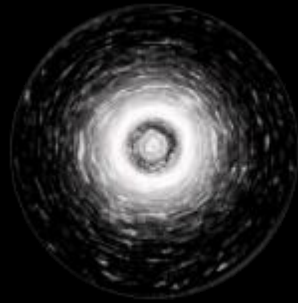
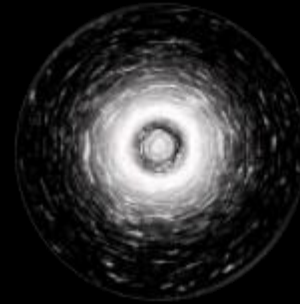
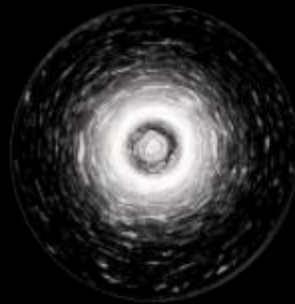
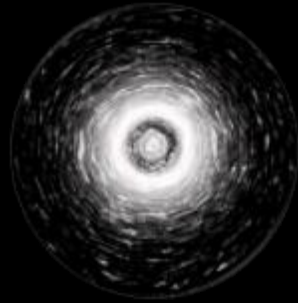


Proton – silná „polévka“ kvarků a gluonů



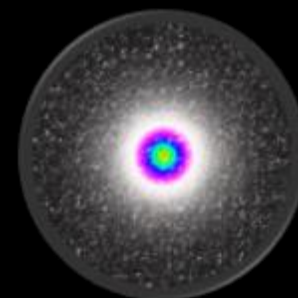
10^{-15} m

Můj neutron?



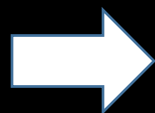
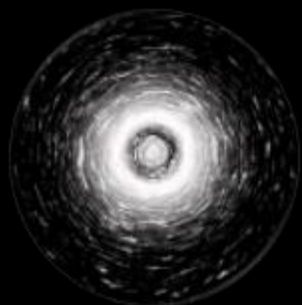
Rozpad volného neutronu

- Neutron je trochu těžší než proton.
- S poločasem rozpadu asi 15min se volný neutron rozpadá na proton, elektron a elektricky neutrální elektronové antineutrino.



Proton

Neutron



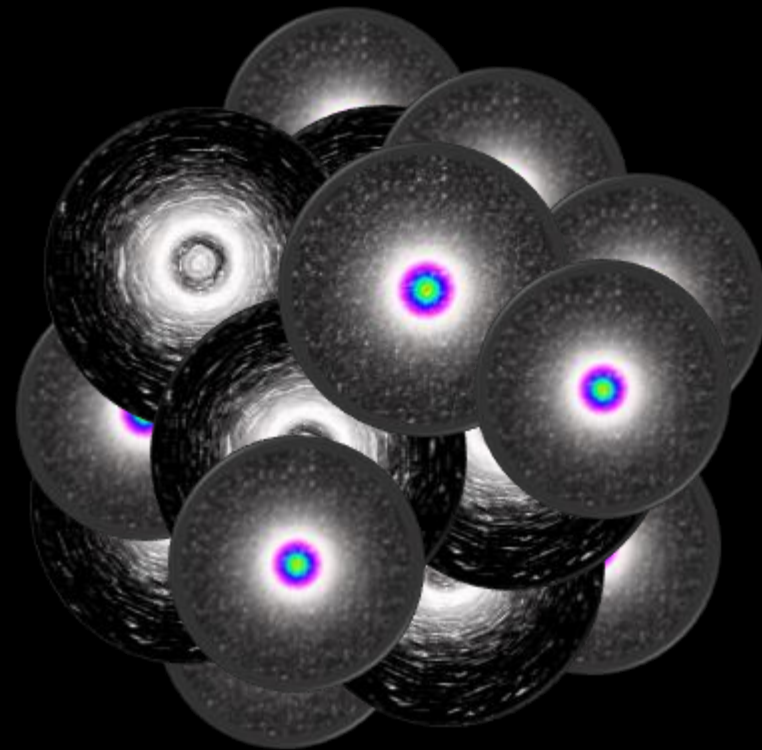
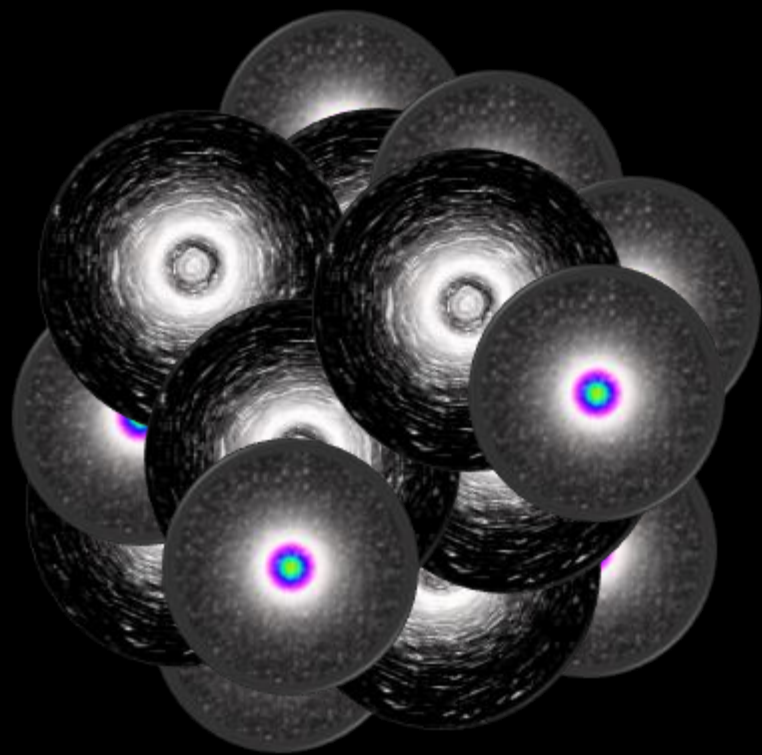
Elektron

- Průměrně žije volný neutron ~15min.
- Ale pro jeden konkrétní neutron nemůžeme čas, kdy se rozpadne, předpovědět (náhodnost kvantové mechaniky).



**Elektronové
antineutrino**

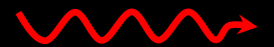
Rozpad atomového jádra



Elektron



Gama



Foton



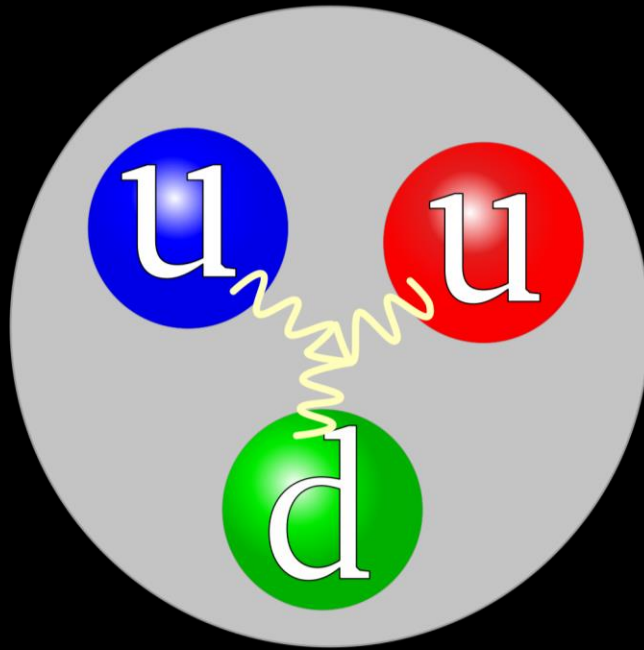
**Elektronové
antineutrino**

Elektron v jádře předtím nebyl. Prostě vznikl. Částice vznikají a zanikají.

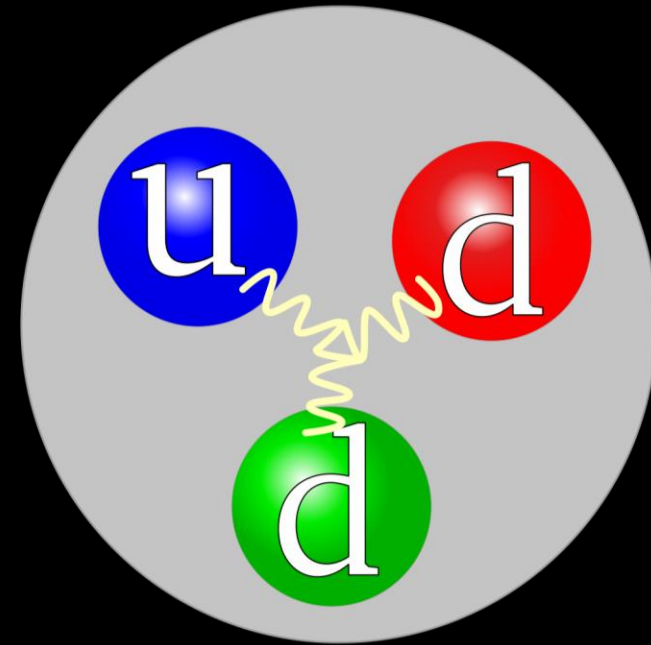
10^{-14} m

Proton a neutron

Proton



Neutron



- Kvark u (up, nahoru): náboj $+2/3 |e|$
- Kvark d (down, dolů): náboj $-1/3 |e|$

Elementární částice

Quarks



Leptons



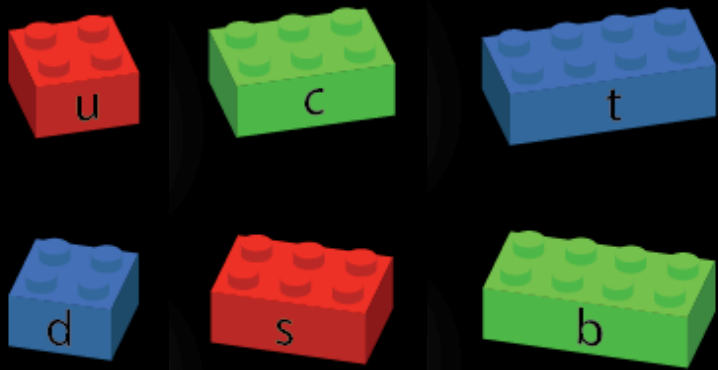
Force Carriers



H
Higgs boson

Částice složené z kvarků -- baryony

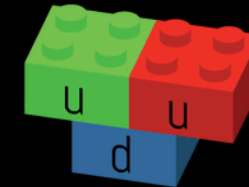
Kvarky



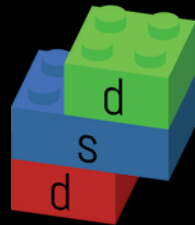
Neutron



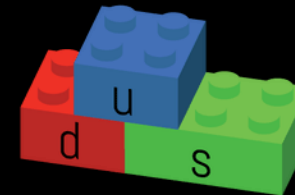
Proton



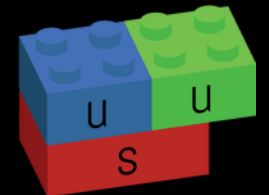
Σ^-



Λ^0

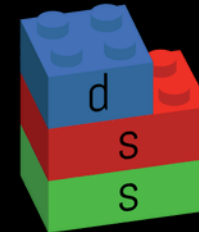


Σ^0

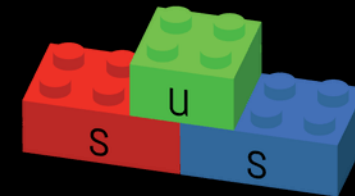


Σ^+

Ξ^-



Ξ^0

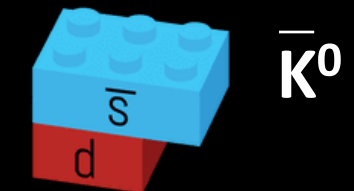
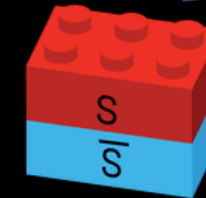
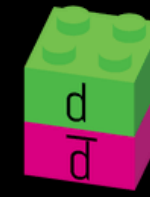
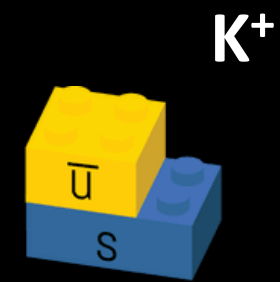
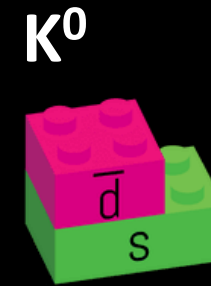
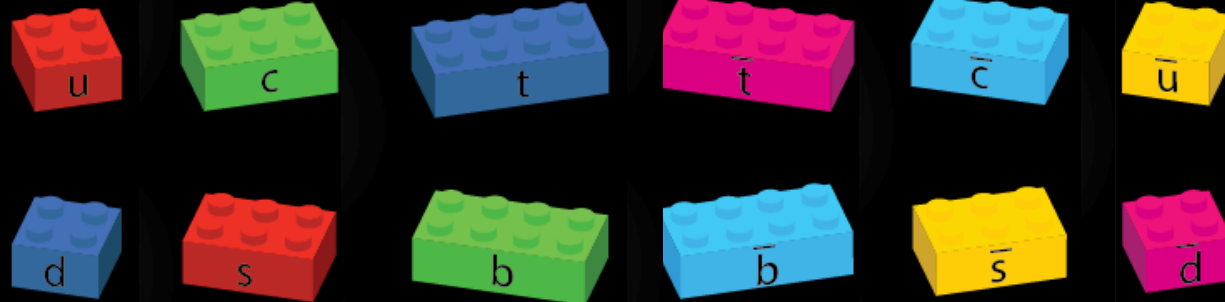


Z antikvarků jsou složeny antibaryony (antiproton, antineutron).

Částice složené z kvarku a antikvarku -- mezony

Kvarky

Antikvarky



Mezony zahrnují částice i antičástice

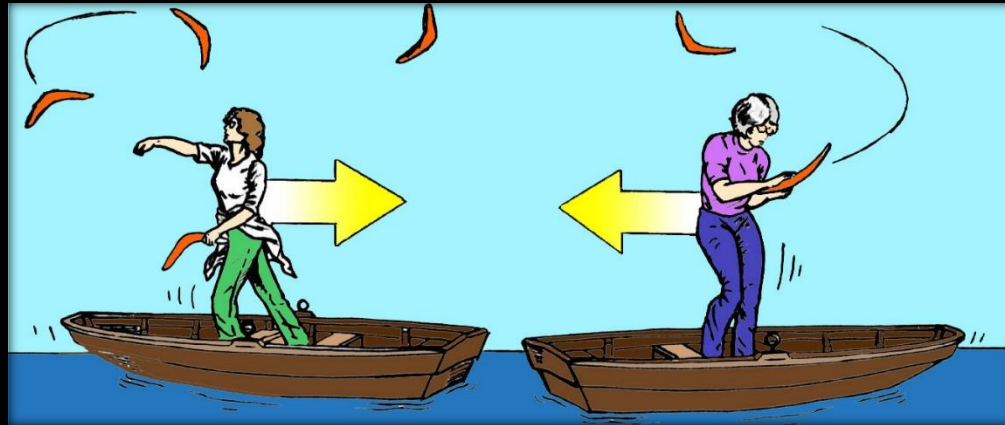
K^- je antičástice ke K^+

Interakce jako výměna částic

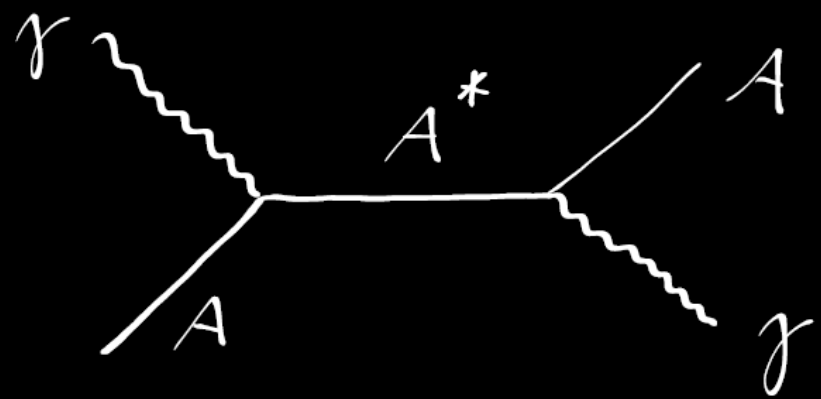
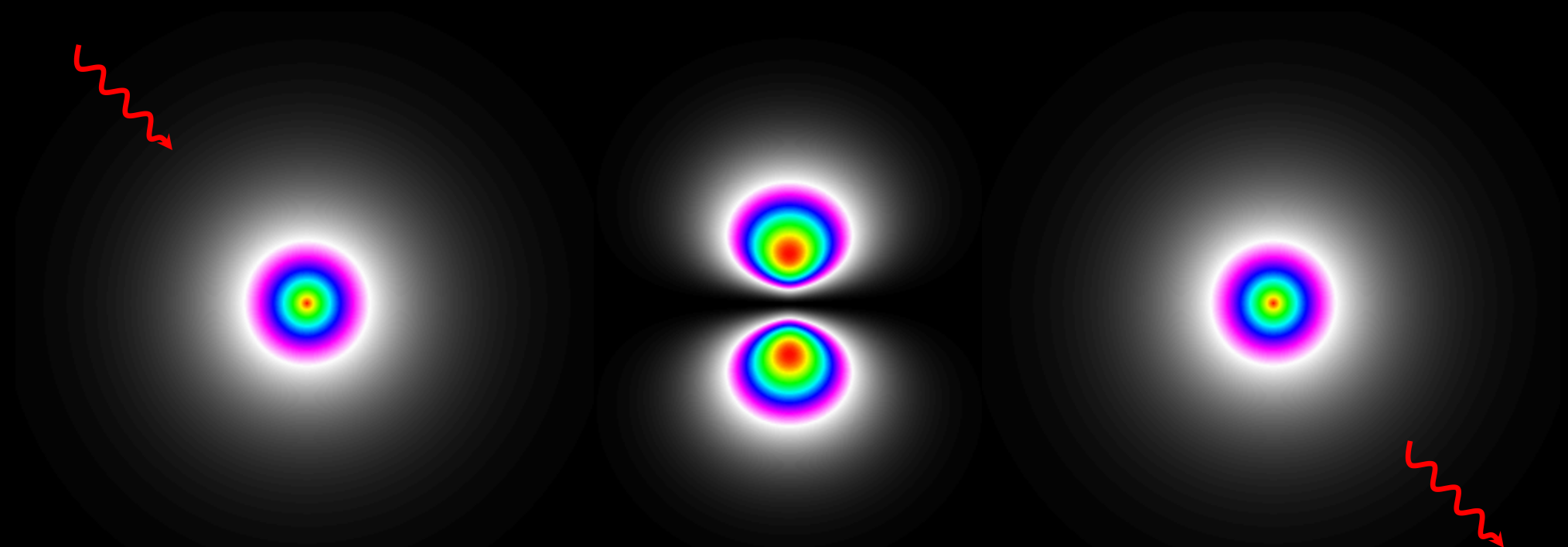
- Odpuzování



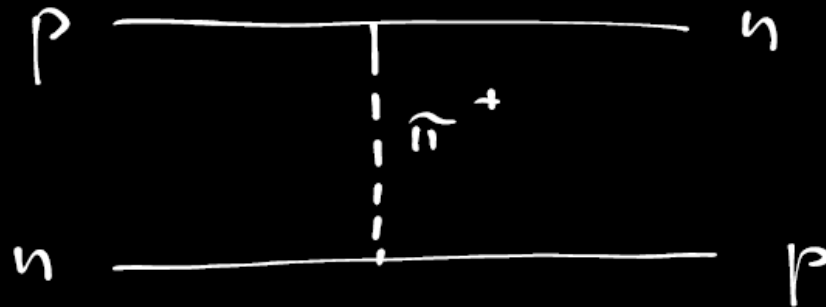
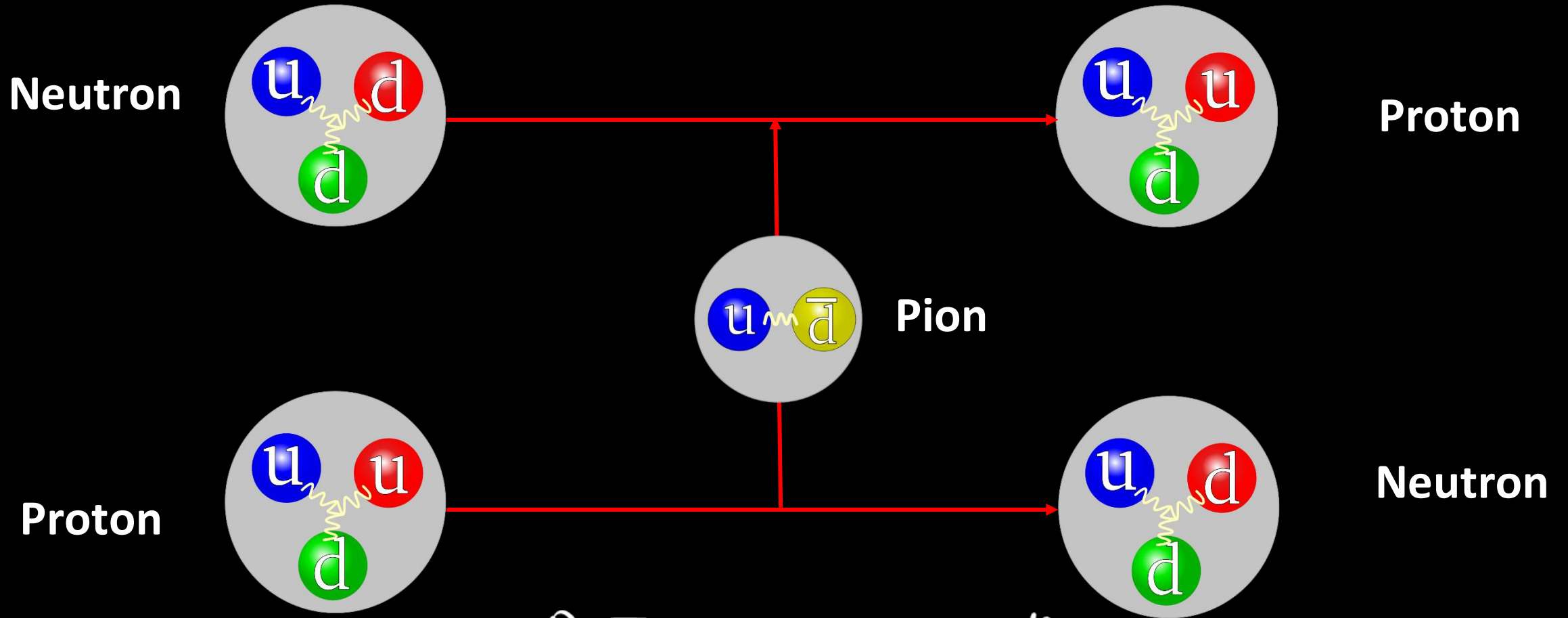
- Přitahování



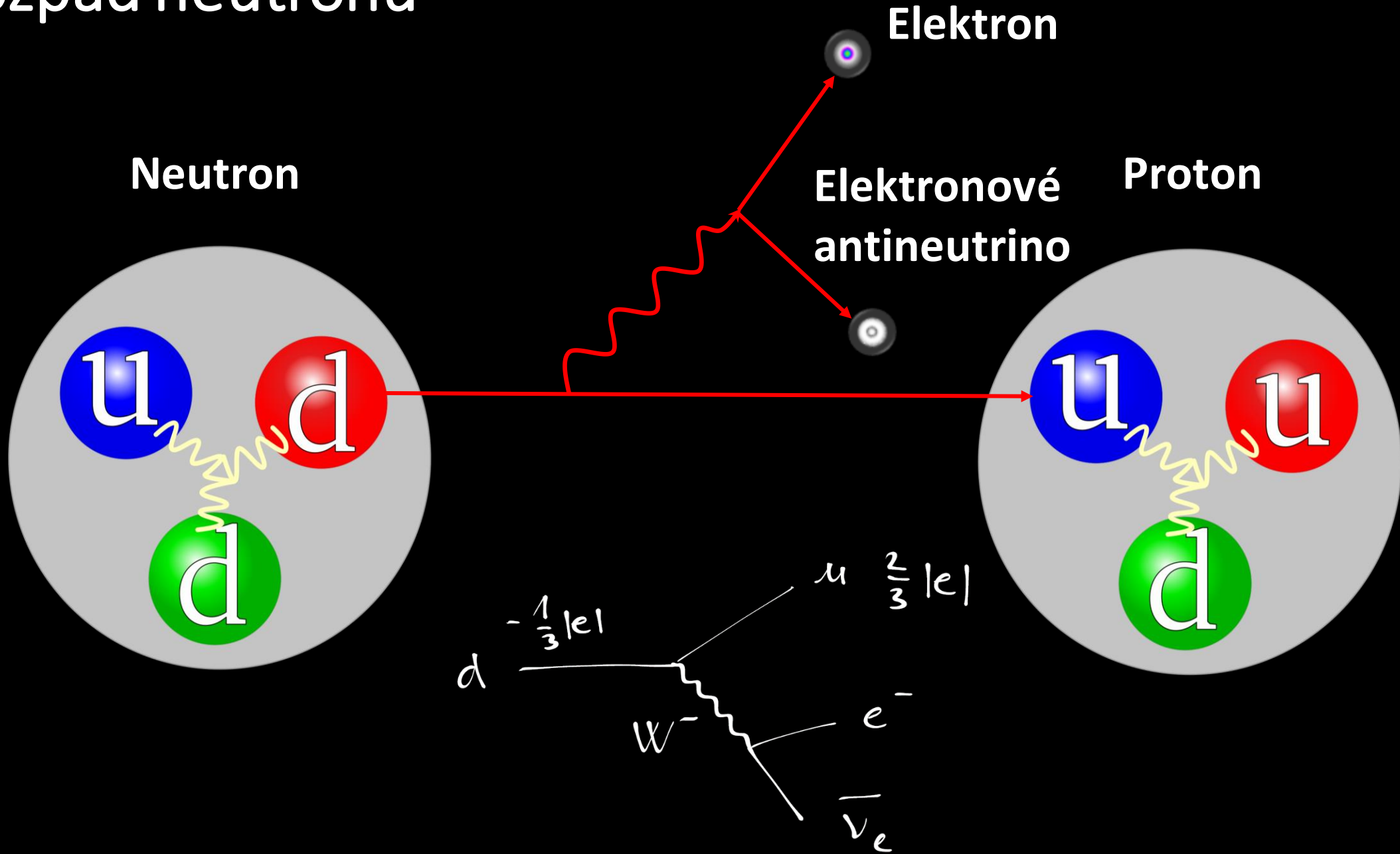
Posviťme si na atom!



Proton a neutron

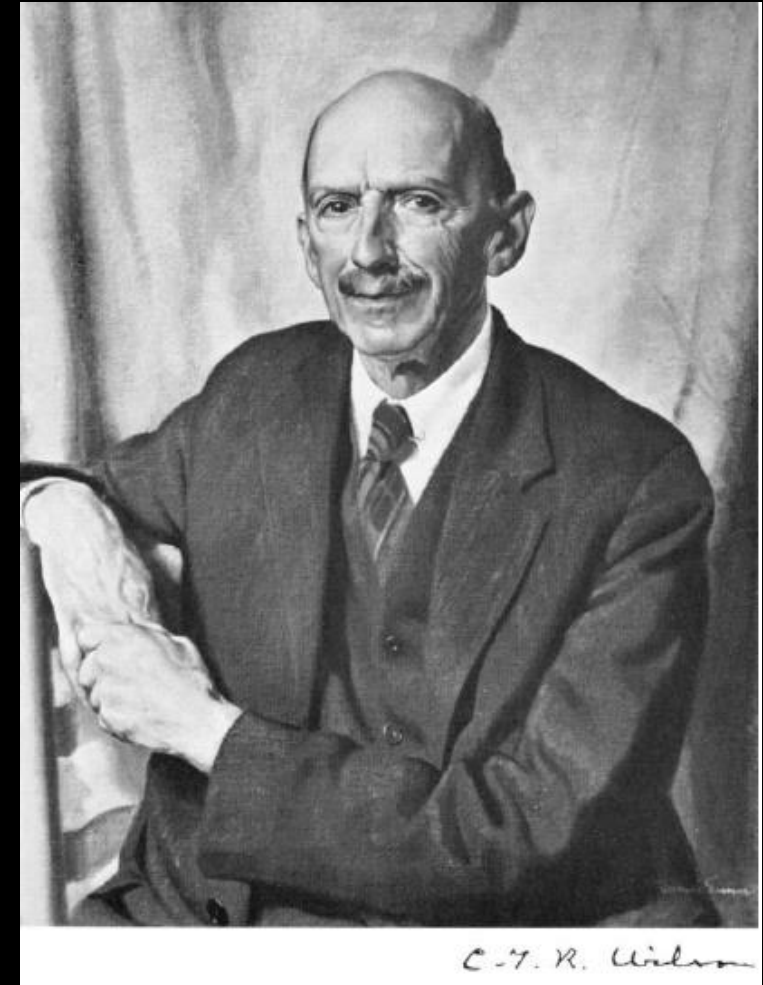
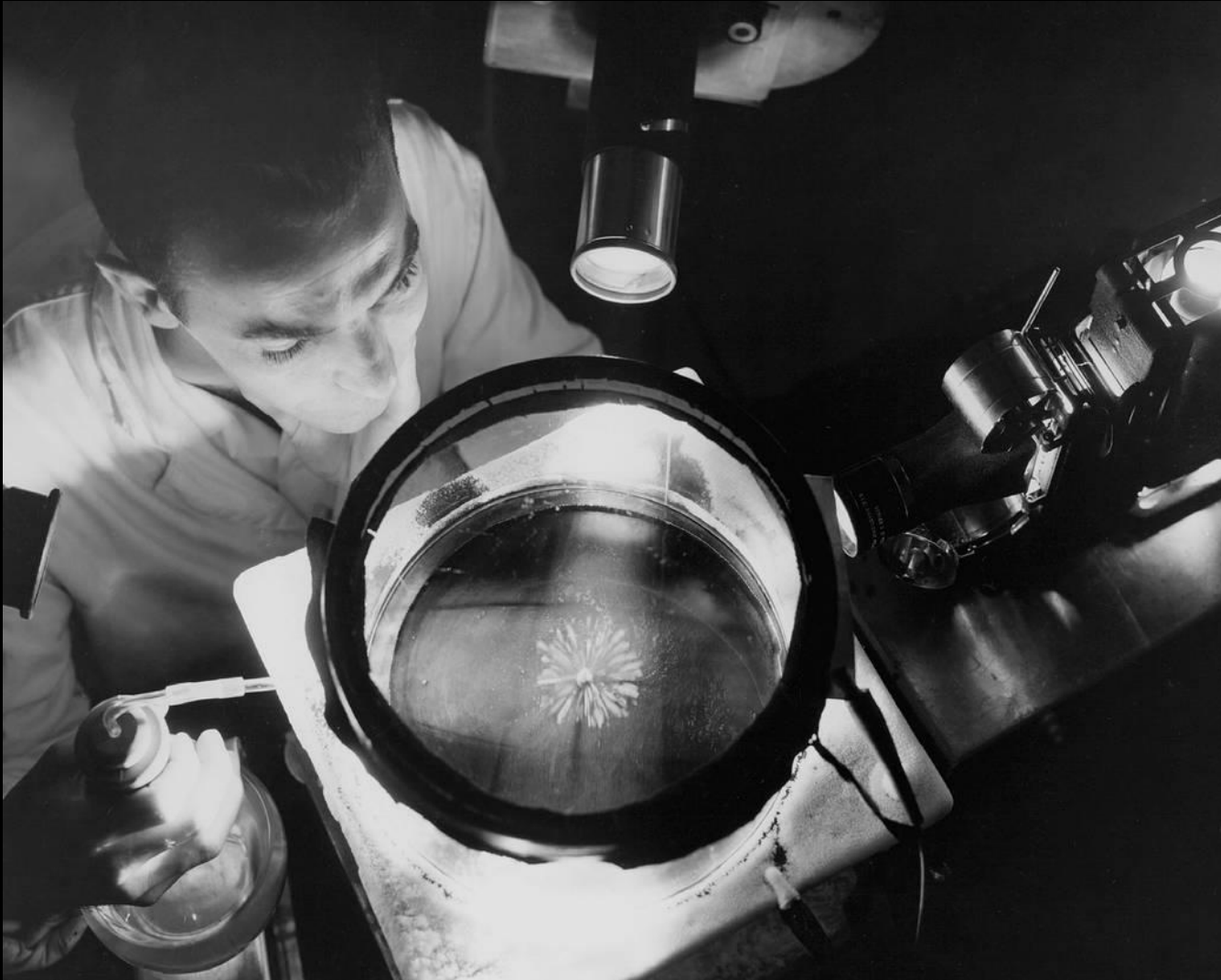


Rozpad neutronu



Jak vidíme částice

- Mlžná komora



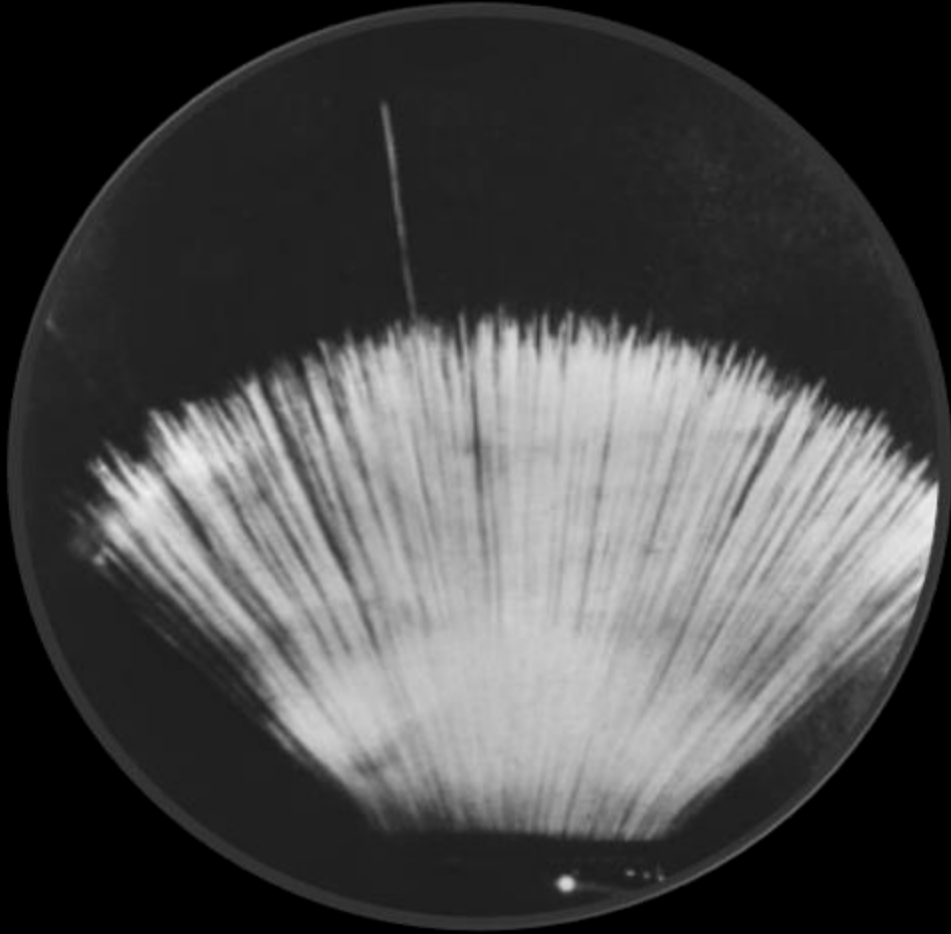
CHARLES T. R. WILSON

On the cloud method of making visible ions and the tracks of ionizing particles

Nobel Lecture, December 12, 1927

Jak vidíme částice

- Mlžná komora

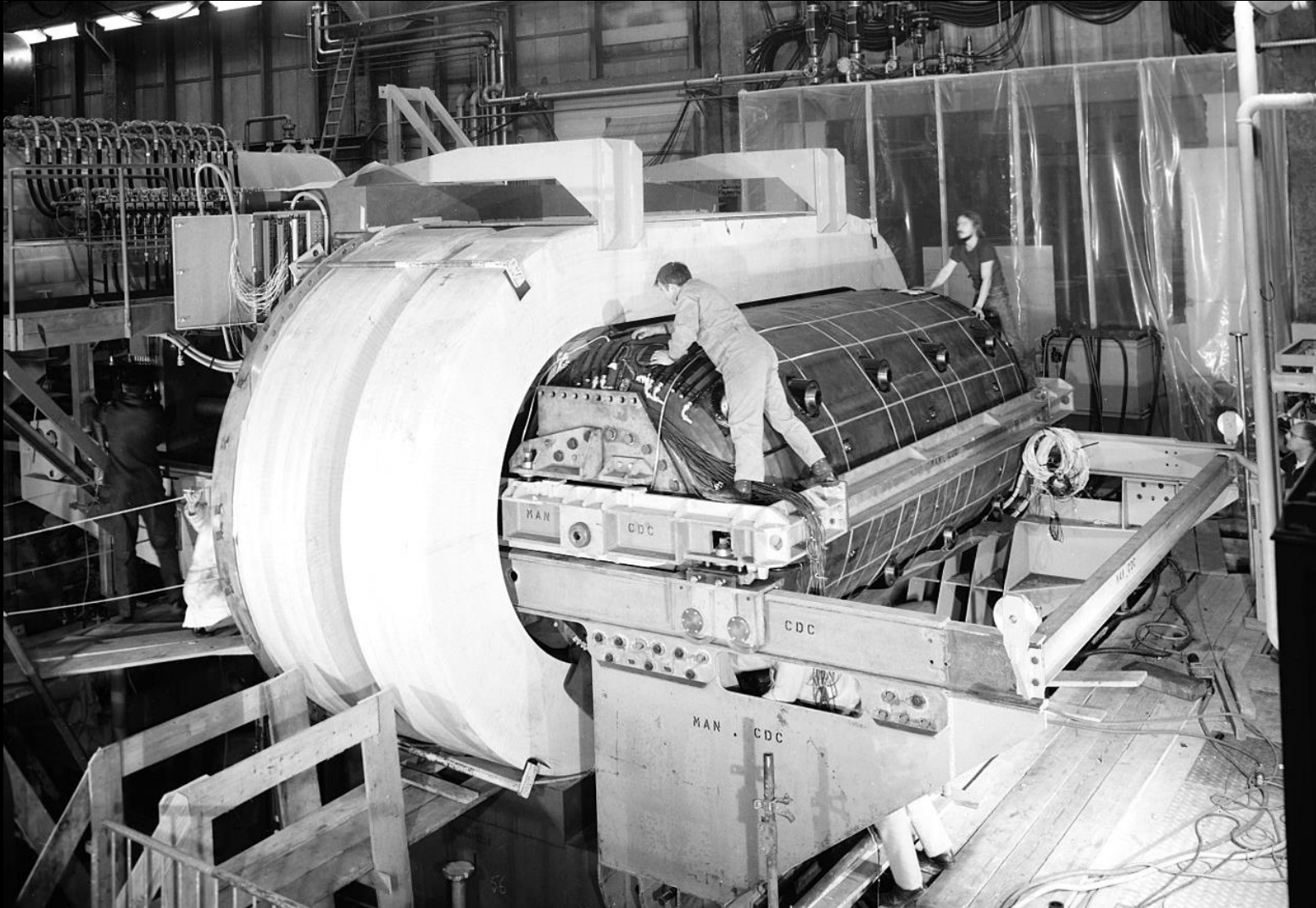


Alfa částice



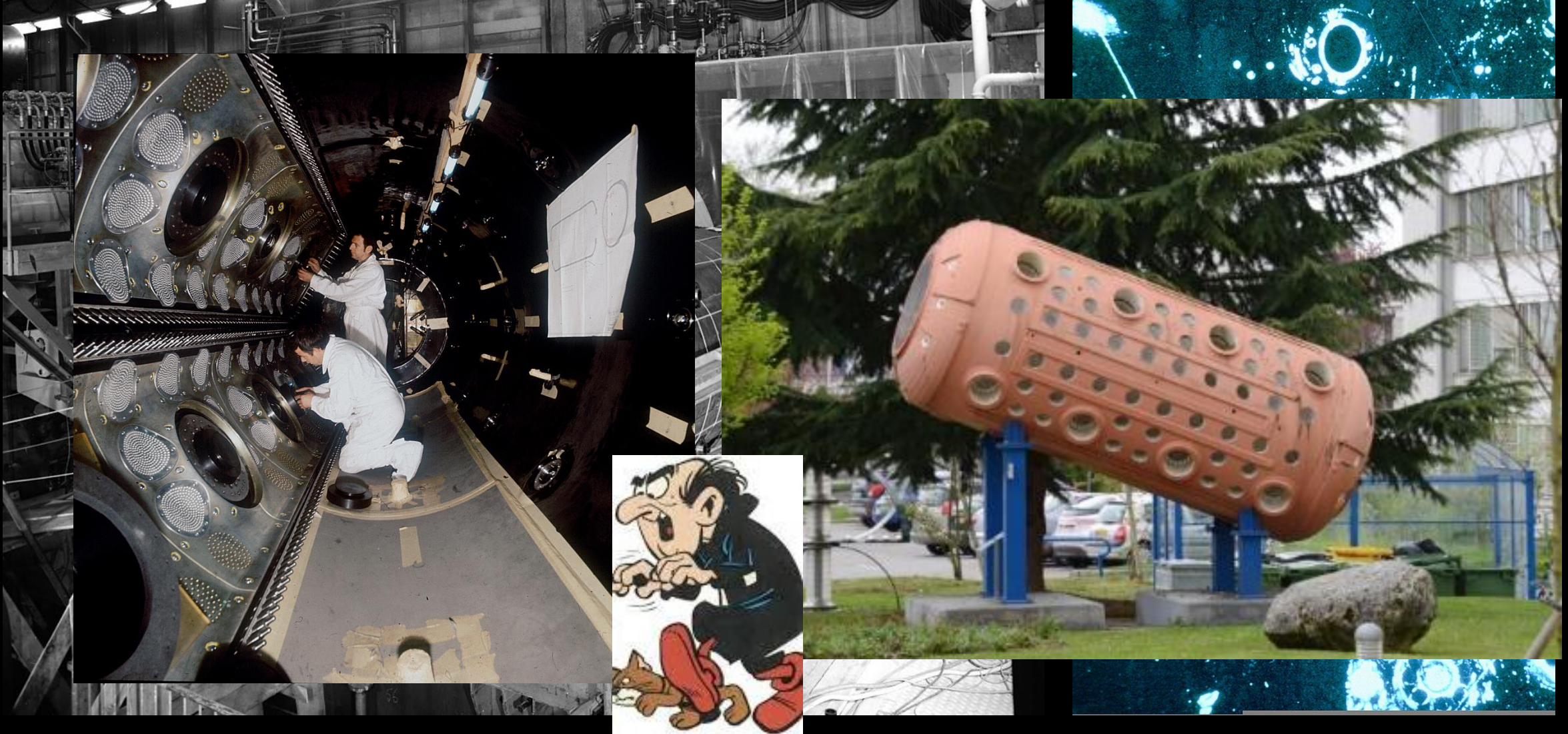
Jak vidíme částice

- Bublinová komora Gargamelle 1970-1979



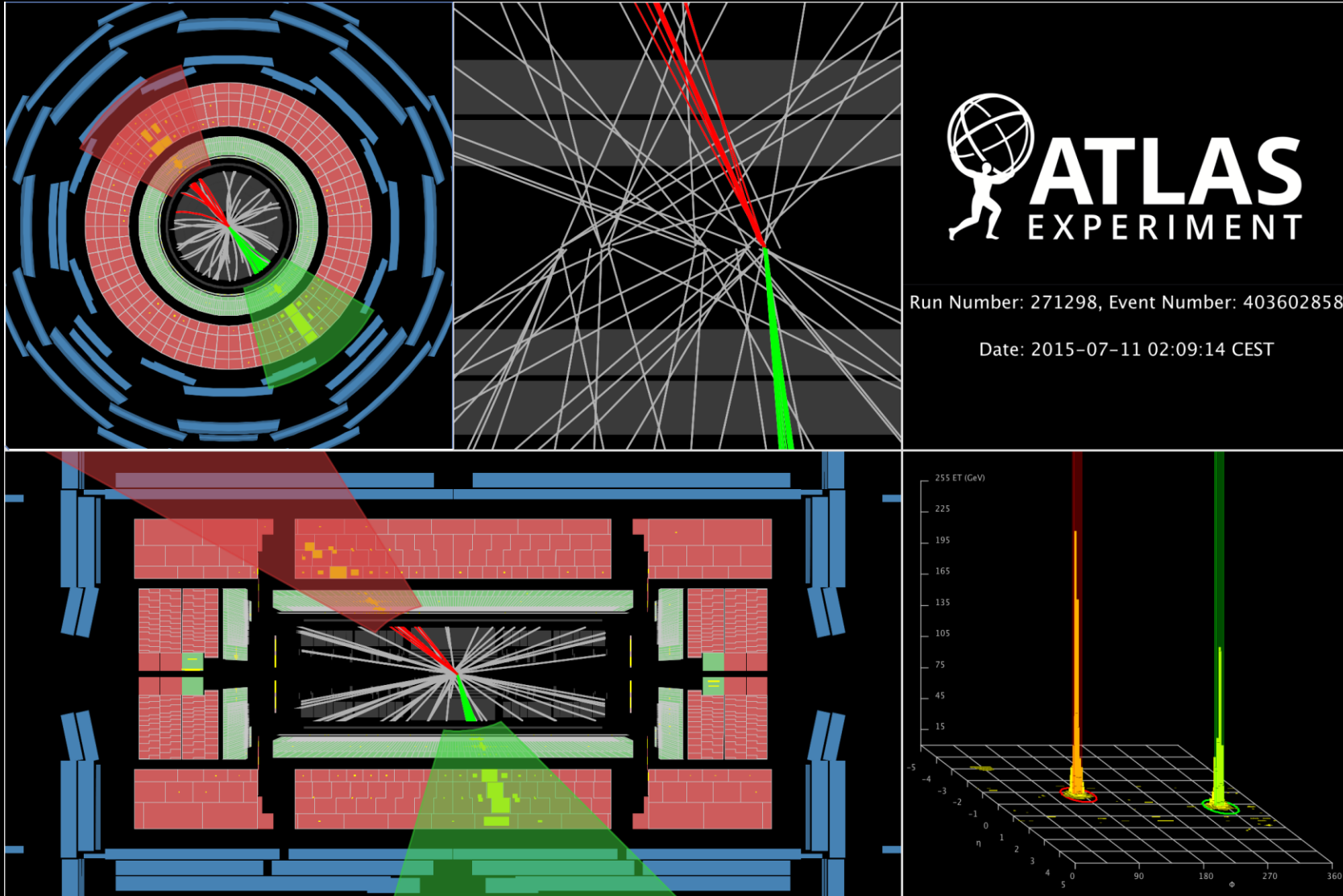
Jak vidíme částice

- Bublinová komora Gargamelle 1970-1979



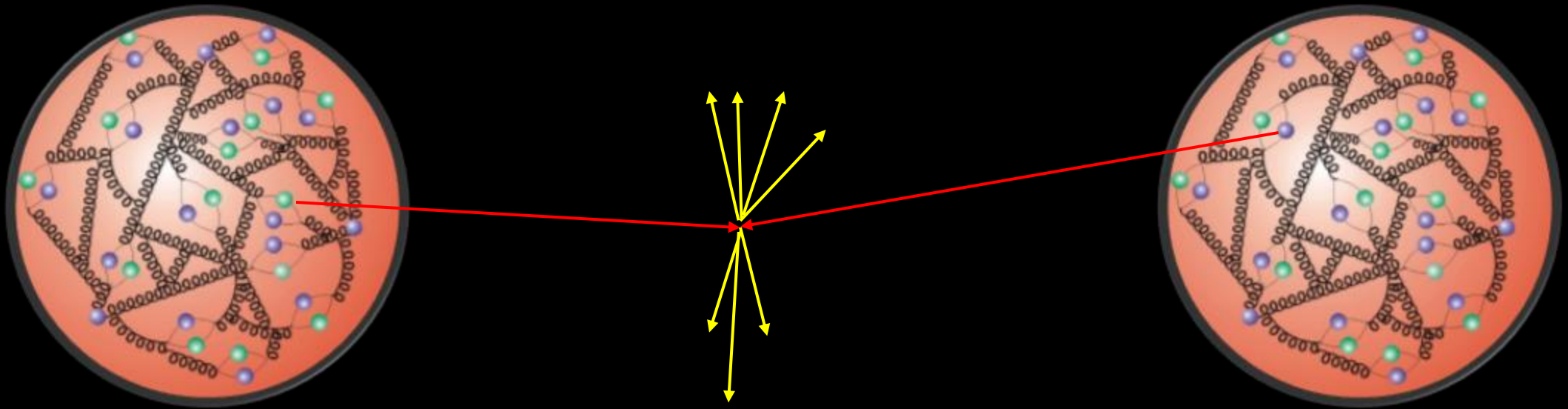
Jak vidíme částice

- Současnost



Srážky částic

- Chceme-li něco nového vytvořit, musíme nejprve něco rozbít ☺
- Srážka dvou protonů: při velkých energiích nejčastěji srážka dvou částiček protonu (partonů: kvarků a gluonů), protony se sebe rozbijí.

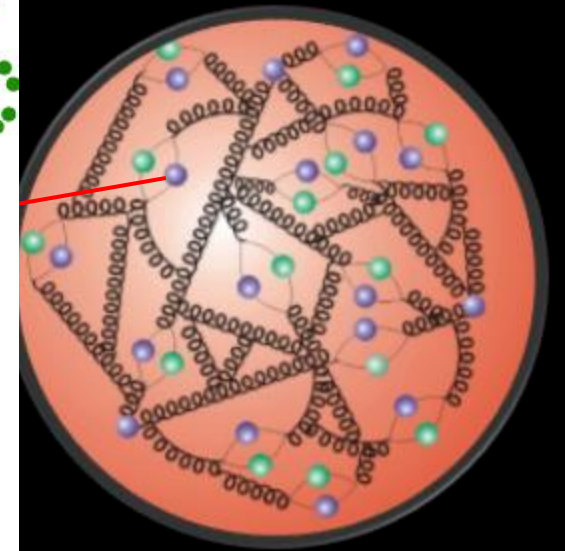
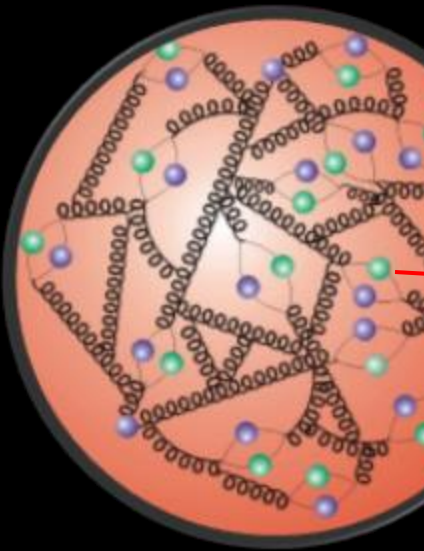
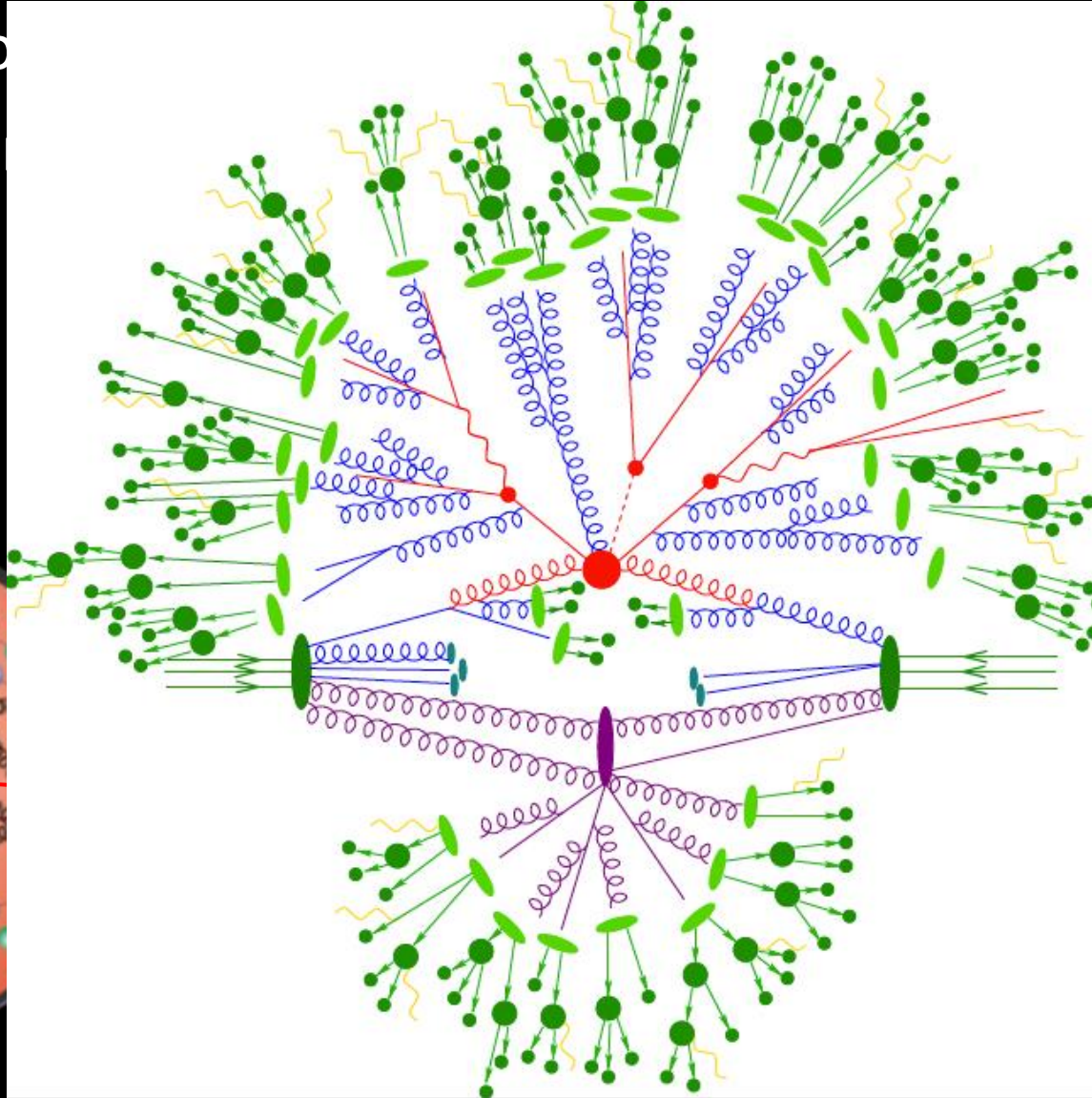


Srážky částic

- Chceme-li něco nového objevit
- Srážka dvou protonů (partonů: kvarků a leptonů)

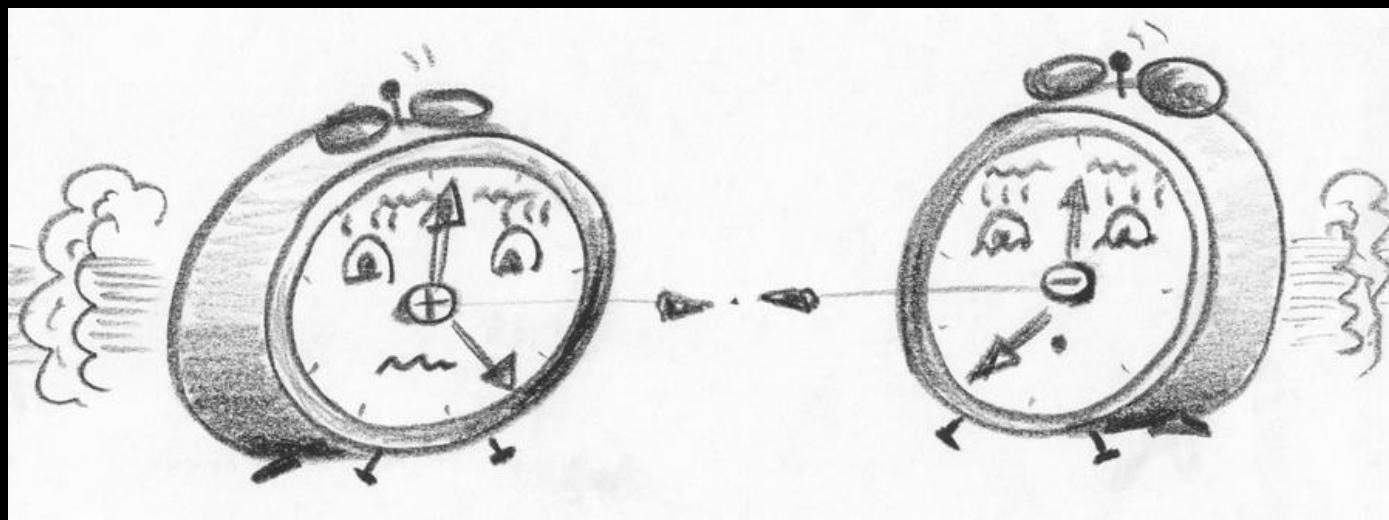
rozbit ☺

Srážka dvou částic
se rozbijí.



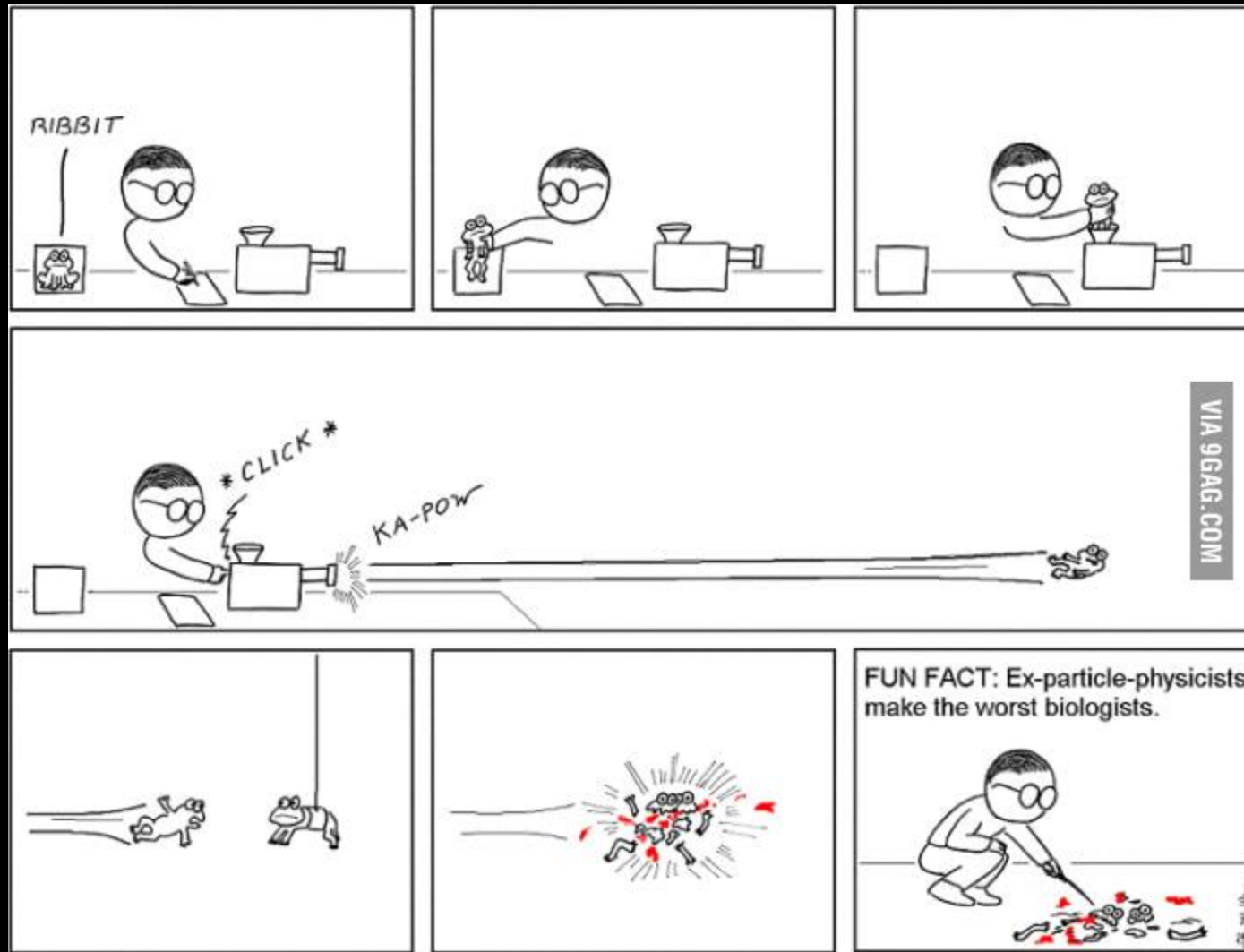
Srážky částic

- Aneb je to jako srážet dva budíky...



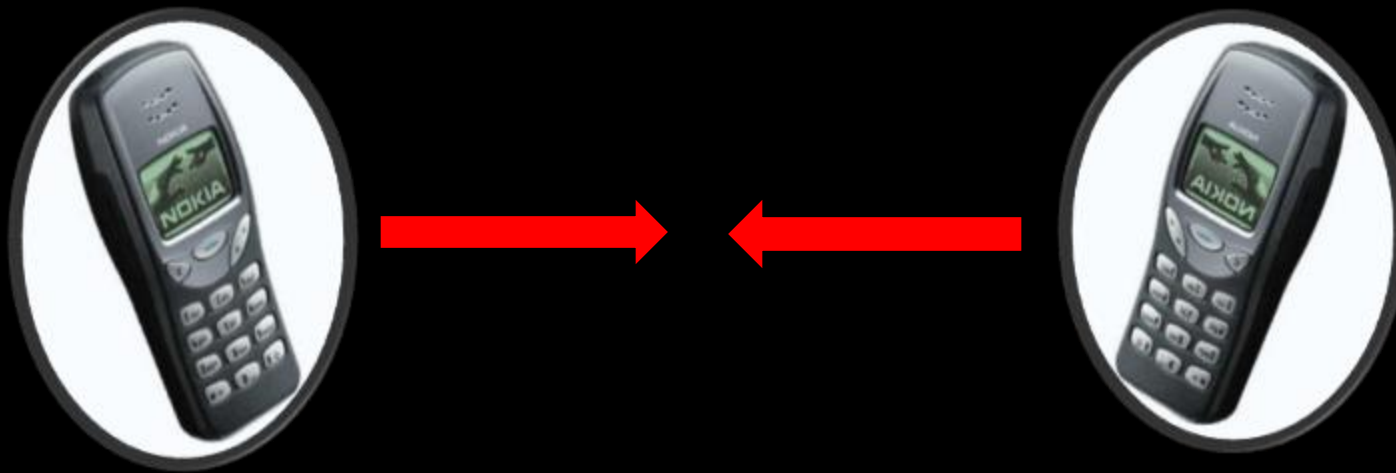
Srážky částic

- Neaplikovat v biologii...



Srážky částic

- Chceme-li něco nového vytvořit, musíme nejprve něco rozbít.



Srážky částic

- Chceme-li něco nového vytvořit, musíme nejprve něco rozbít.
- Často se ale nestane skoro nic...



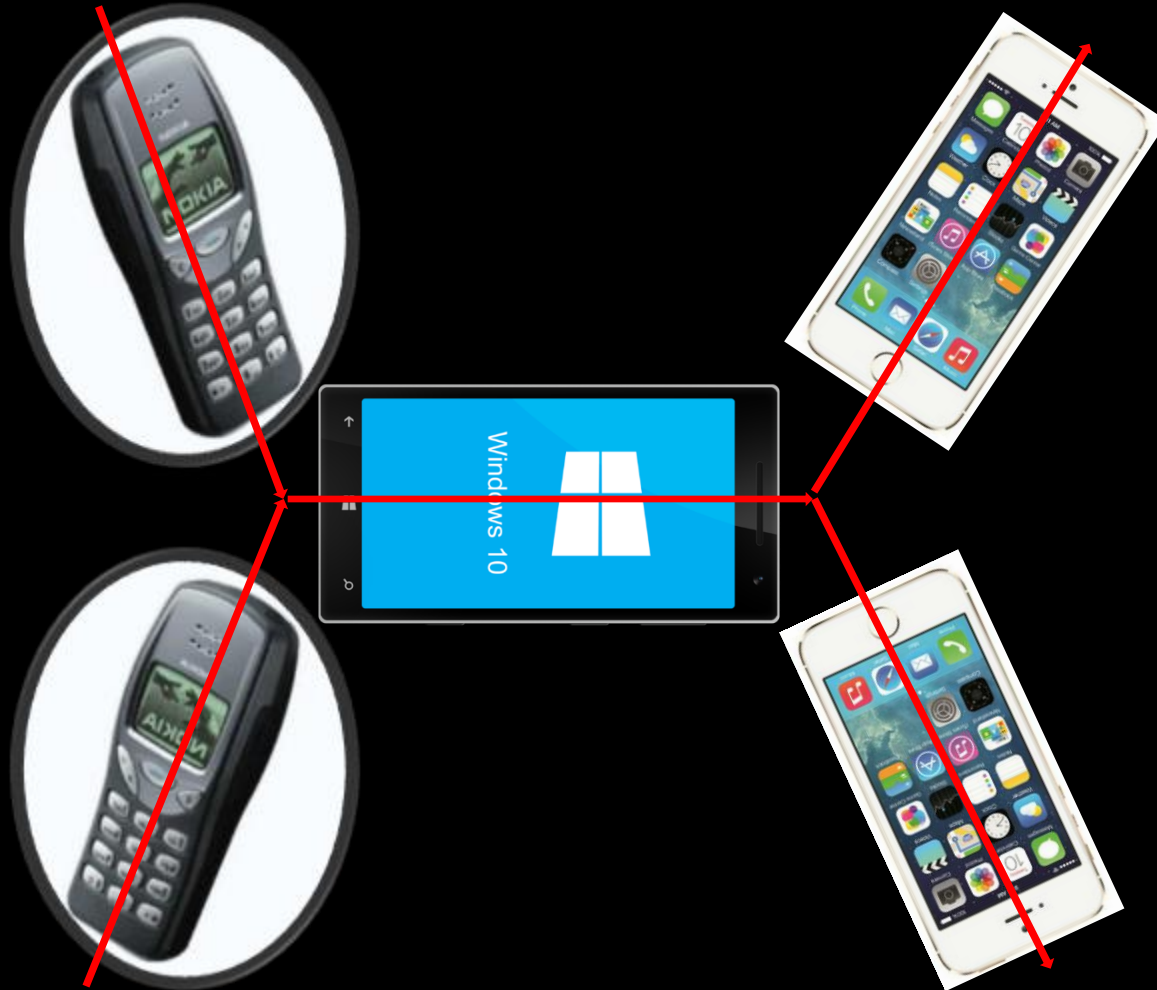
Srážky částic

- Chceme-li něco nového vytvořit, musíme nejprve něco rozbít.
- Ve srážkách ale mohou vznikat částice nové!
- $E = mc^2$



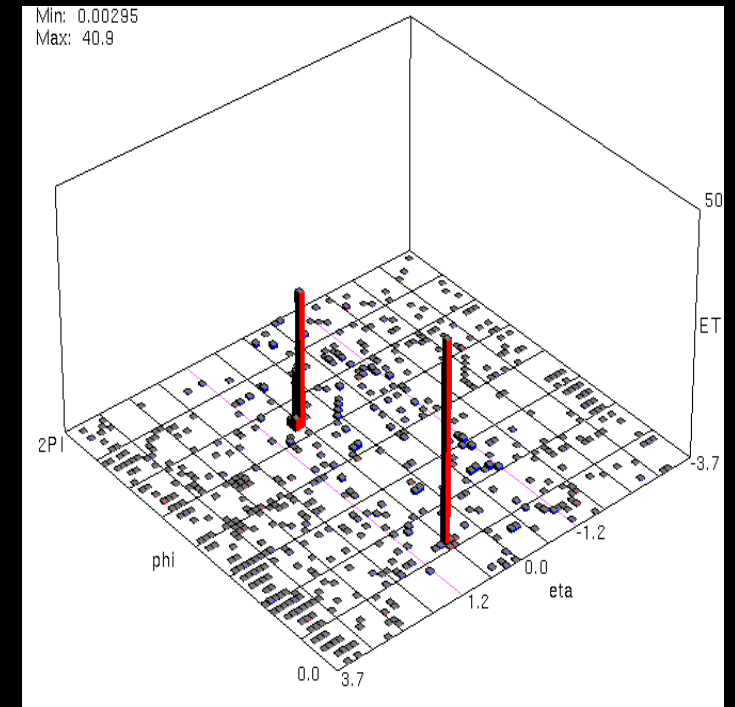
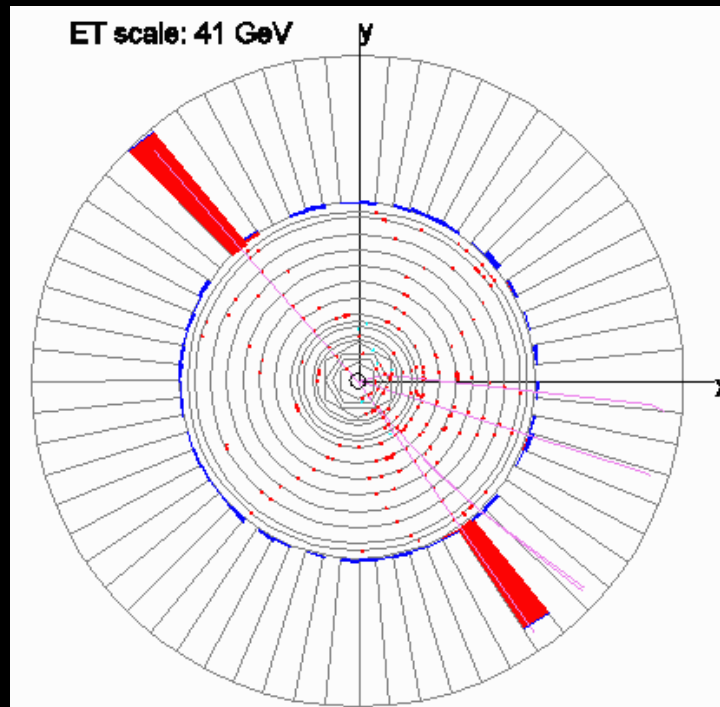
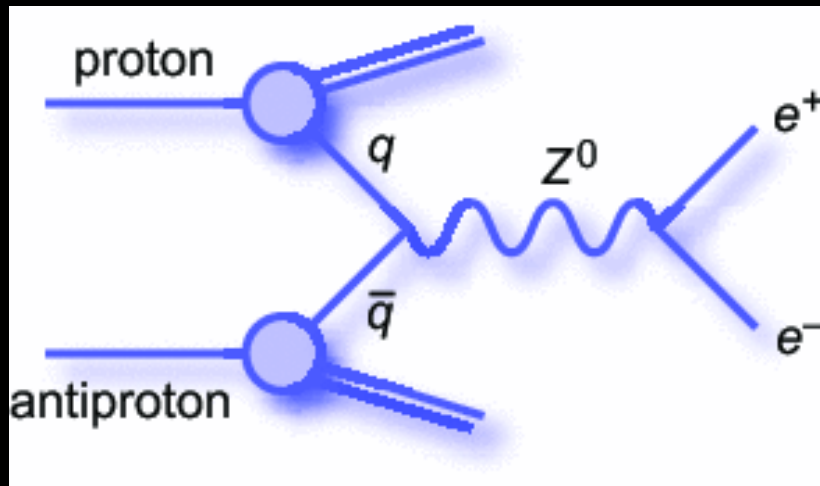
Srážky částic

- Chceme-li něco nového vytvořit, musíme nejprve něco rozbít.
- Ve srážkách ale mohou vznikat částice nové!
- $E = mc^2$



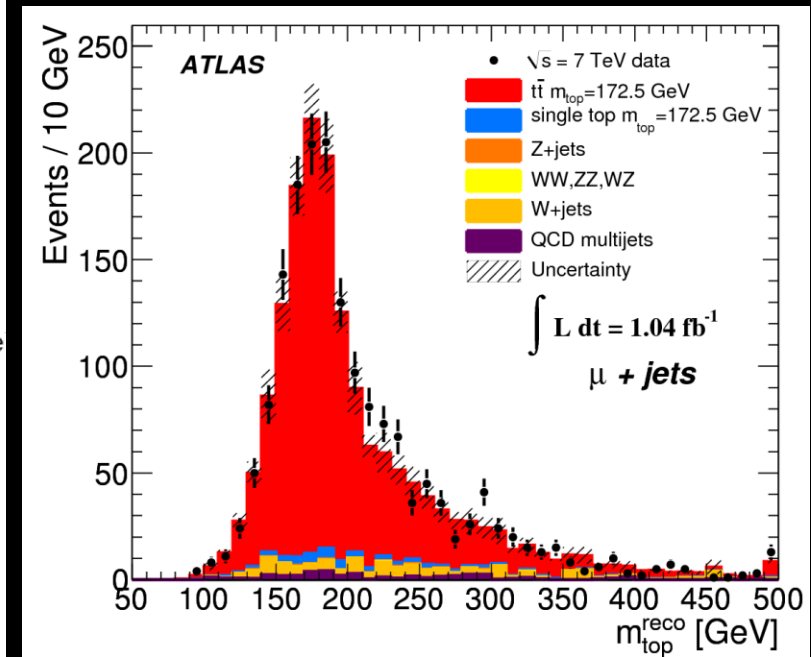
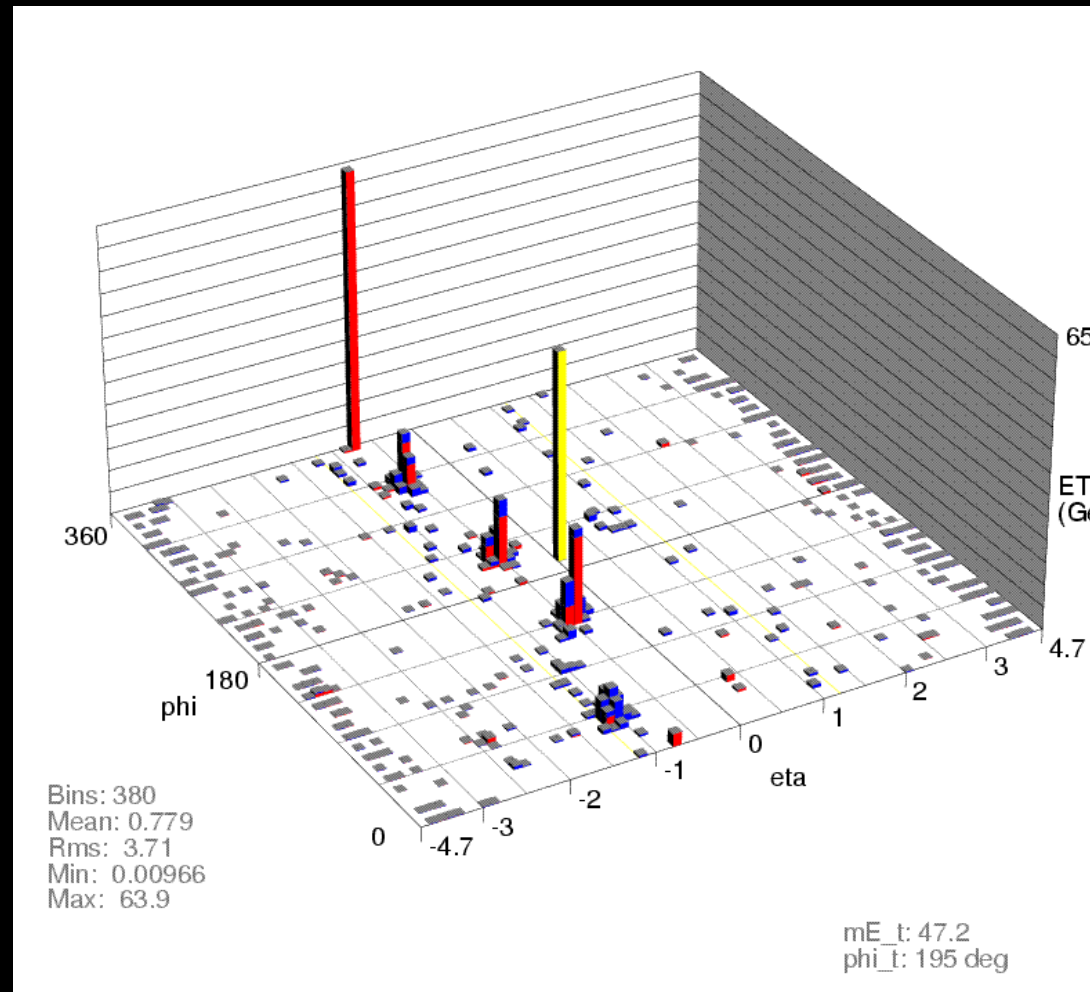
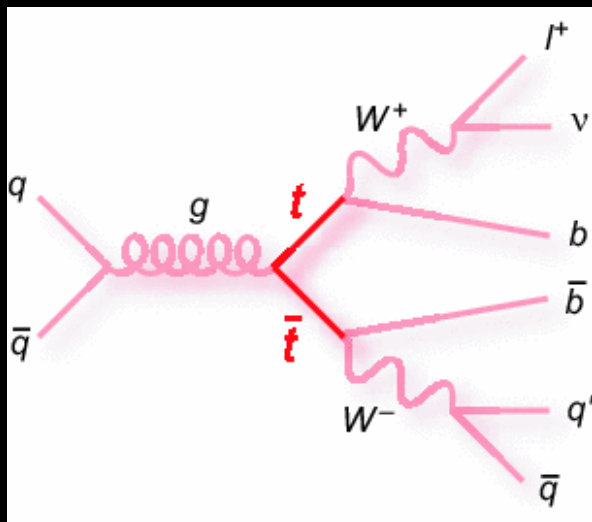
Interakce

- Energie se může přeměnit v hmotu nové těžké částice.
- Zde Z boson \sim těžký foton, nestabilní a rychle se rozpadá.
- Jak změřit hmotnost Z bosonu? Jak vlastně víme, že existuje?



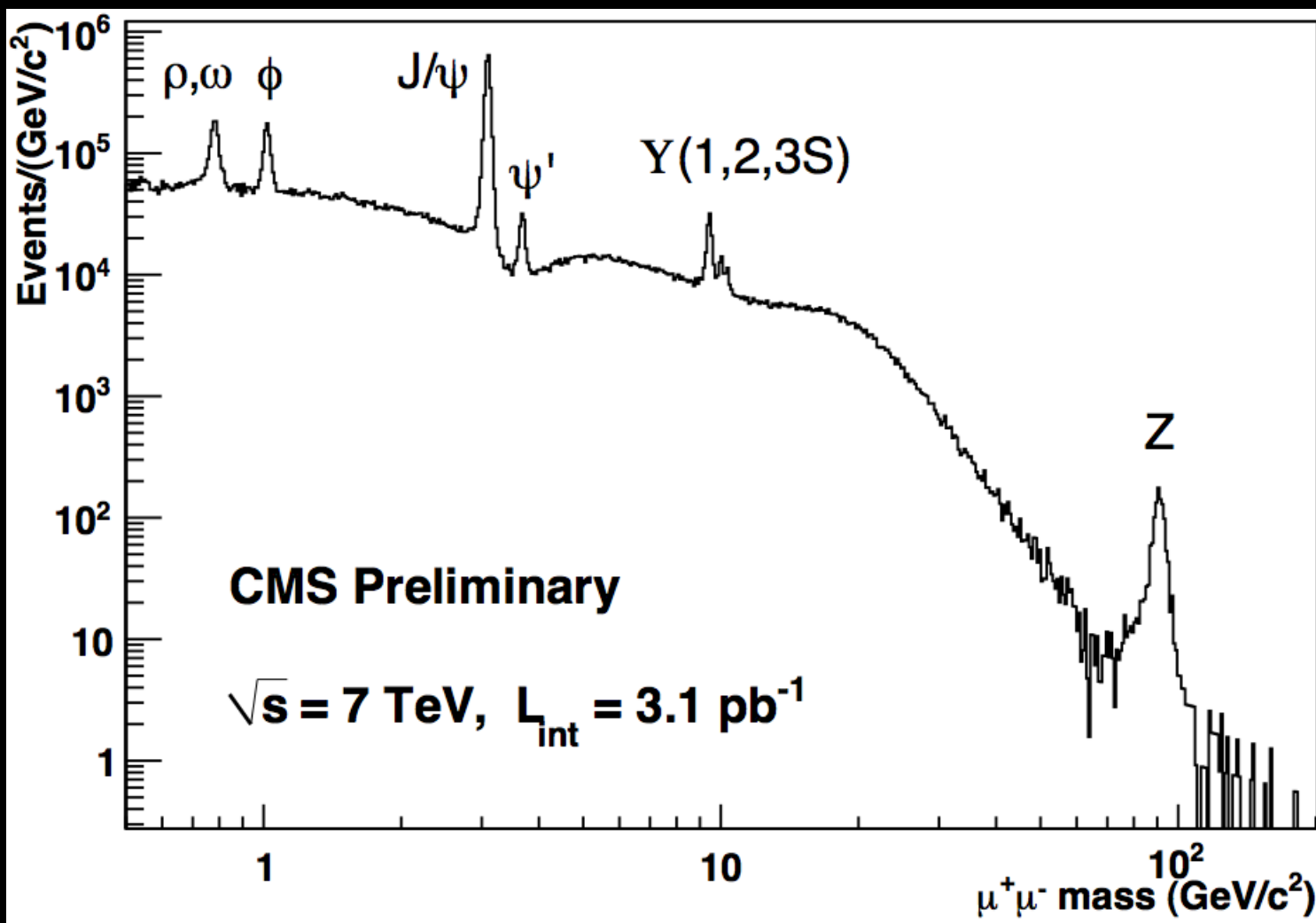
Interakce

- Složitější případ vzniku párů top kvarků.

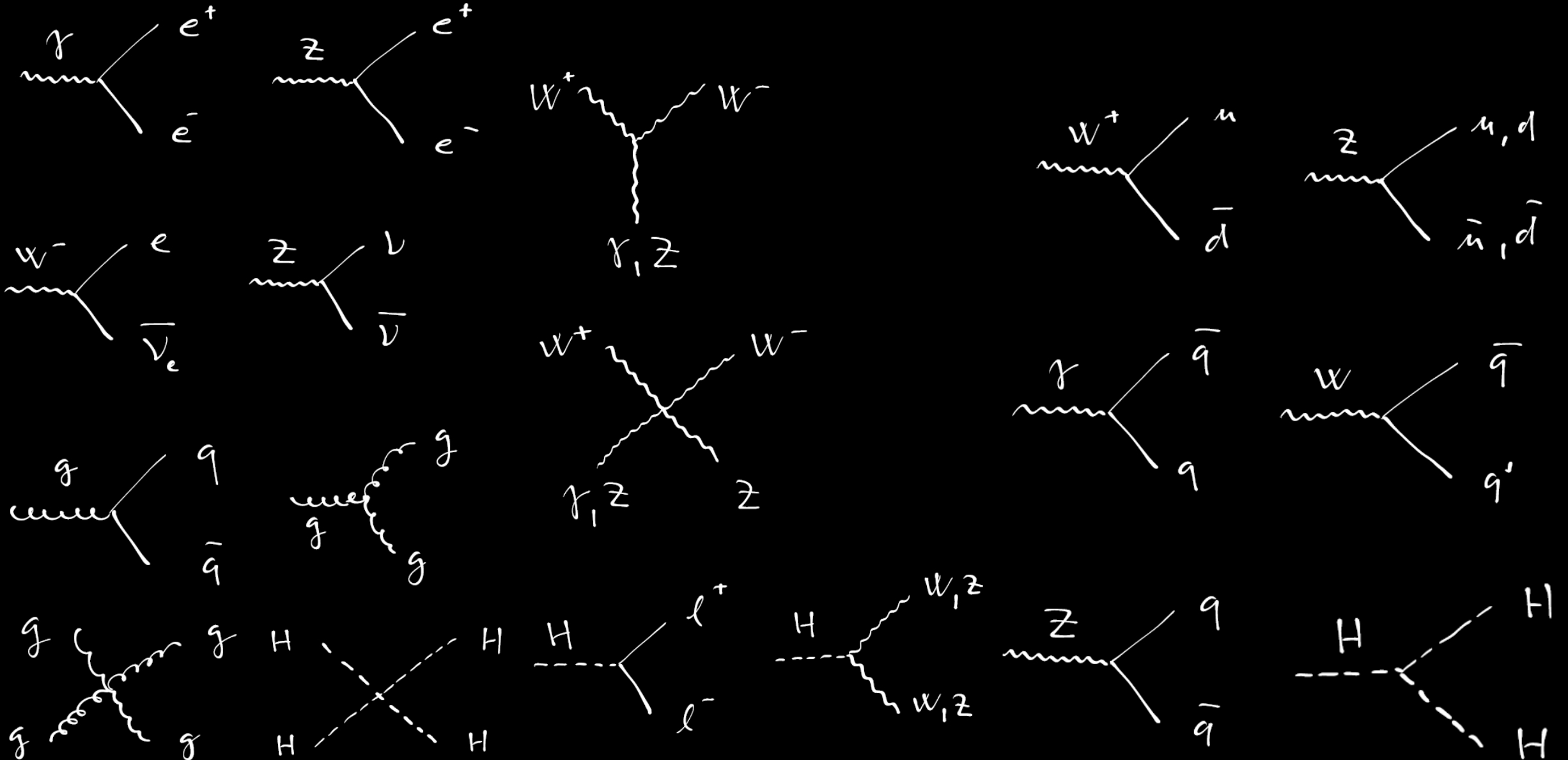


„Částice je kopeček!“

- ...když zkoumáme, jak často se něco děje při různé energii.



Všecky interakce světa

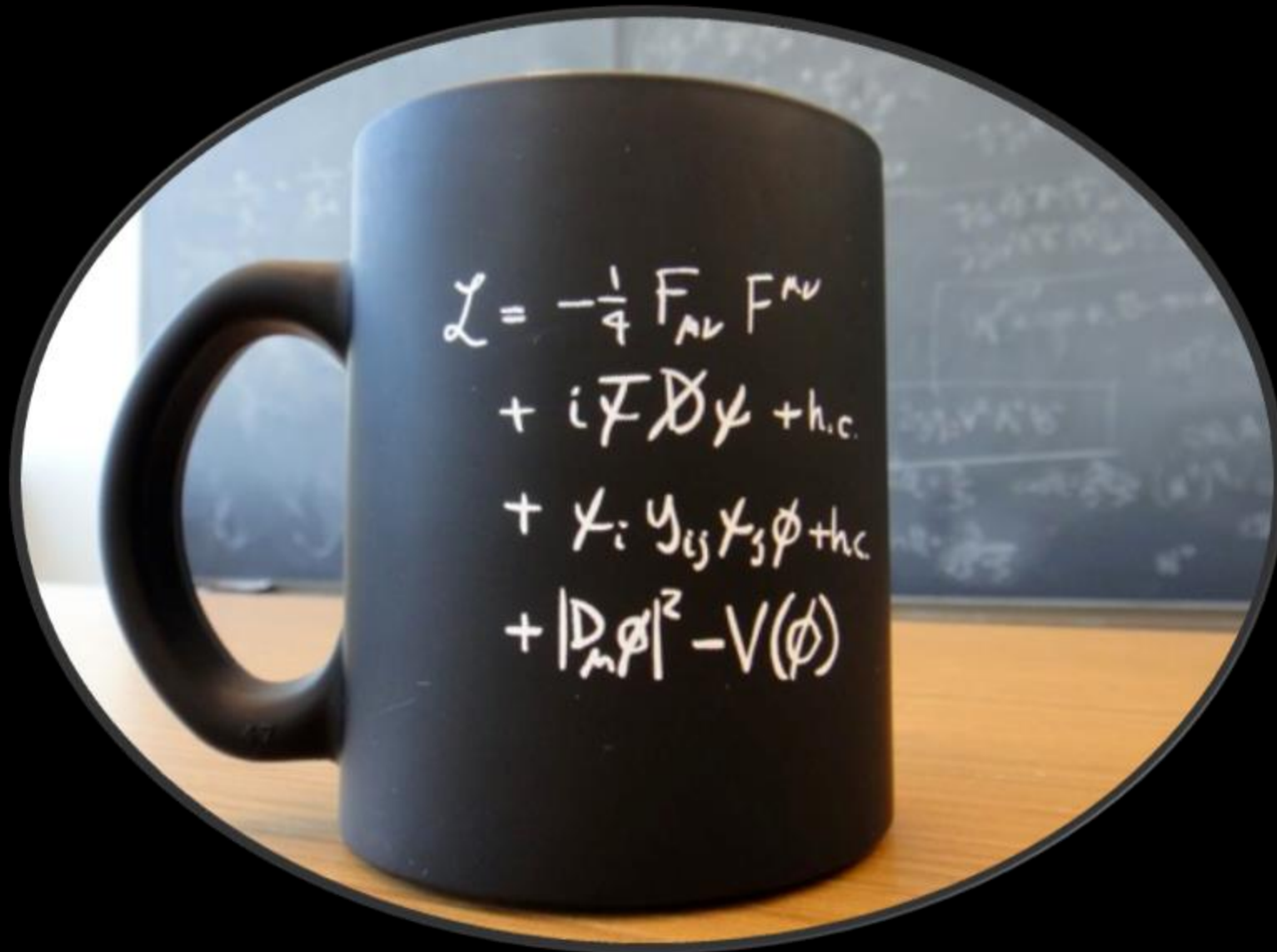


Všecky interakce světa

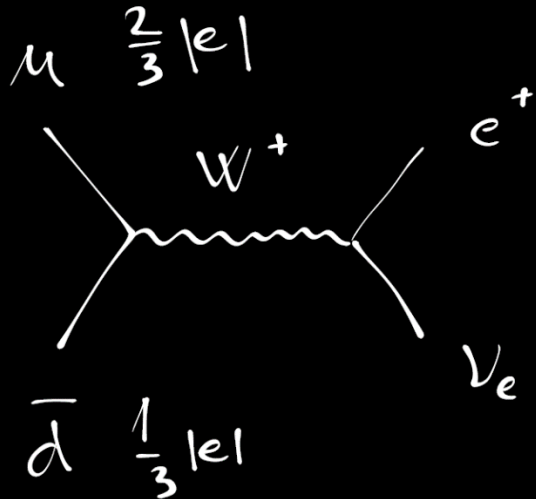
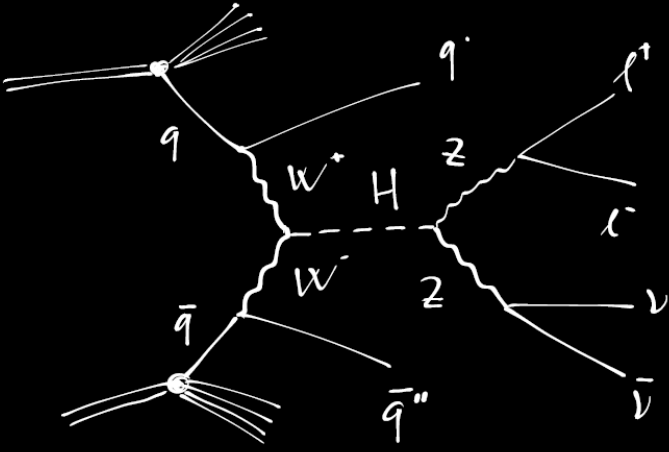
$$\begin{aligned}\mathcal{L}_{SM} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\Psi} \not{D} \Psi + h.c. \\ & + \bar{\Psi}_i \gamma_{ij} \Psi_j \phi + h.c. \\ & + (D_\mu \phi)^\dagger D^\mu \phi - V(\phi)\end{aligned}$$

- Významnou roli hrají symetrie.
- Má-li být teorie neměnná vůči nějaké symetrii/změně, vede to na interakci.
- Analogie kalibrace potenciálů elmag. pole: „Kalibrační interakce, kalibrační bosony.“

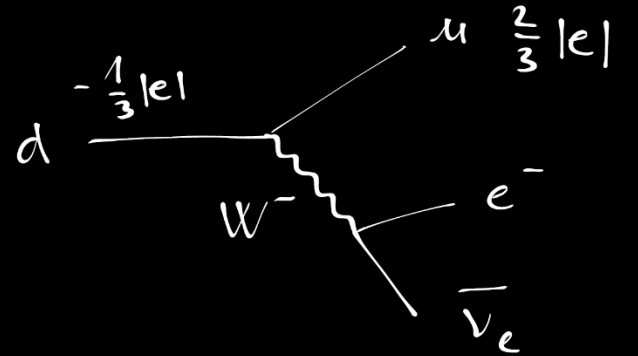
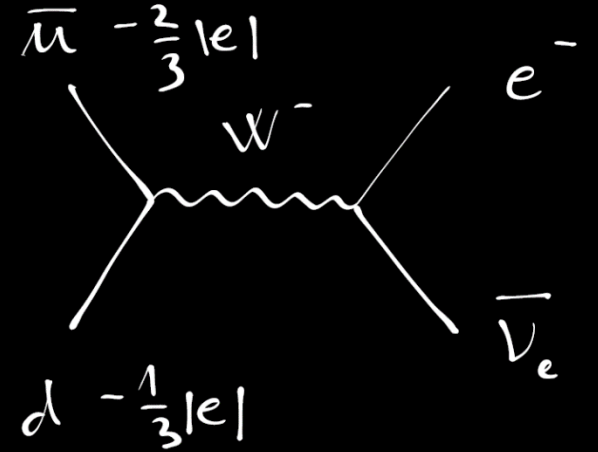
Všecky interakce světa kompaktně



WHAT PART OF



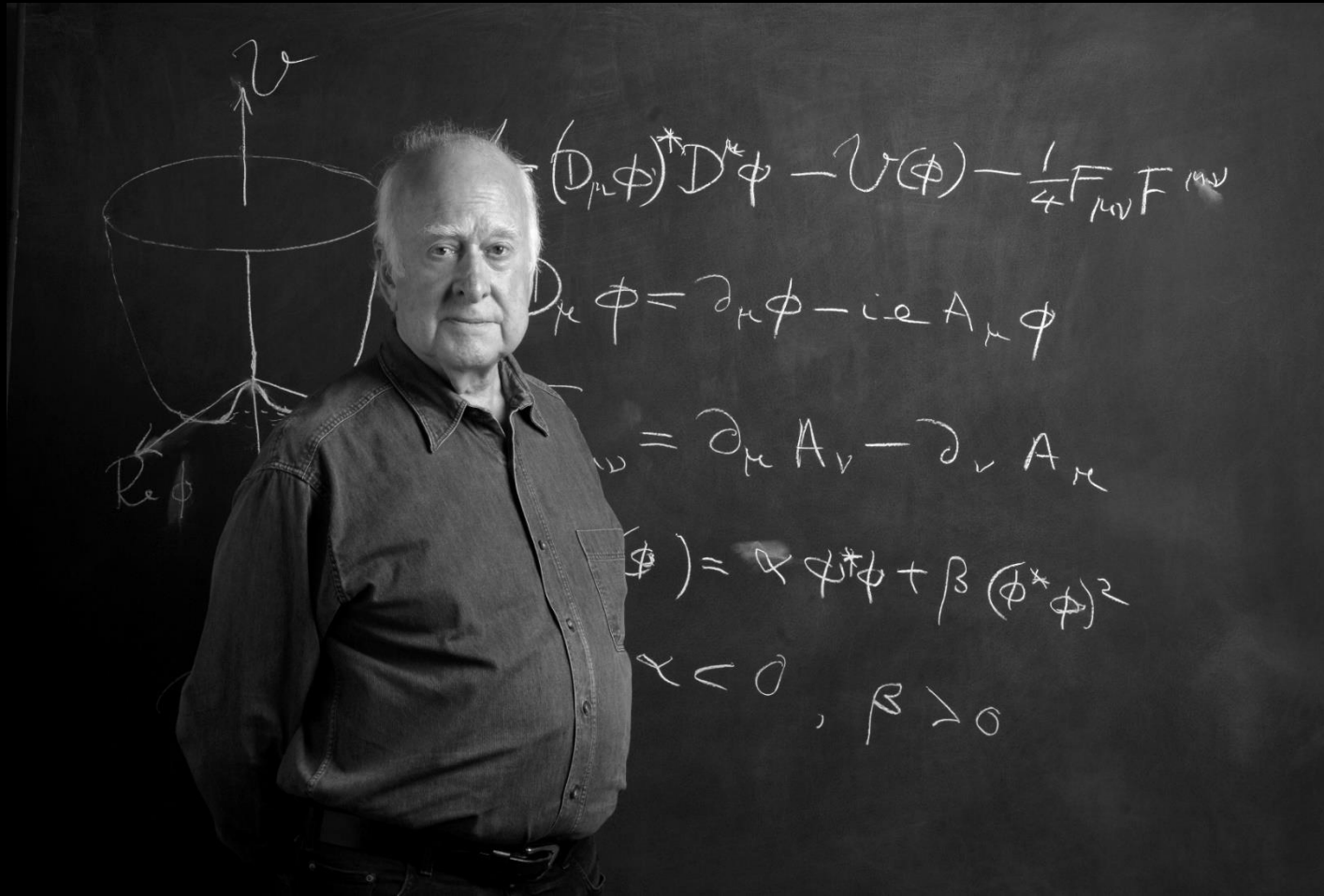
$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}i g_s^2 (\bar{q}_i \gamma^\mu q^i) g_\mu \\
 & \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \\
 & \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_H^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - i g s_w \partial_\nu A_\mu (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\nu^0 Z_\mu^0 W_\nu^+ W_\mu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - \\
 & A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^- W_\mu^+) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^- - g\alpha [H^3 + \\
 & H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \frac{1}{2}g^2 \alpha_h H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + \\
 & 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \\
 & \phi^0 \partial_\mu H) + i g \frac{M}{c_w} Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \\
 & \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 [H^2 + (\phi^0)^2 + 2(2c_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \\
 & \frac{1}{2}i g^2 \frac{s_w}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}i g^2 s_w A_\mu H (W_\mu^+ \phi^- \\
 & W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^4 s_w^2 A_\mu A_\nu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \theta + m_e^2) e^\lambda - \\
 & \bar{\nu}^\lambda \gamma \theta \nu^\lambda - \bar{u}_j^\lambda (\gamma \theta + m_u^2) u_j^\lambda - d_j^\lambda (\gamma \theta + m_d^2) d_j^\lambda + i g s_w A_\mu [- (e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \\
 & \frac{1}{3} (d_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{i g}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) - (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (d_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^+ [(\nu^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) - (u_j^\lambda \gamma^\mu (1 + \\
 & \gamma^5) C_{\lambda k} d_j^\lambda)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(e^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (d_j^\lambda \gamma^\mu C_{\lambda k} (1 + \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} M [- \phi^+ (\bar{\nu}^\lambda (1 - \\
 & \gamma^5) e^\lambda) + \phi^- (e^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^2}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^+ [- m_e^2 (\bar{u}_j^\lambda C_{\lambda k} (1 - \\
 & \gamma^5) d_j^\lambda) + m_e^2 (\bar{u}_j^\lambda C_{\lambda k} (1 + \gamma^5) d_j^\lambda)] + \frac{i g}{2M\sqrt{2}} \phi^- [m_e^2 (\bar{d}_j^\lambda C_{\lambda k}^1 (1 + \gamma^5) u_j^\lambda) - m_e^2 (\bar{d}_j^\lambda C_{\lambda k}^1 (1 - \\
 & \gamma^5) u_j^\lambda) - \frac{g}{2} \frac{m_u^2}{M} H (u_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^2}{M} H (d_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{i g}{2} \frac{m_d^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
 & X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + Y \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu X^0 X^- - \\
 & \partial_\nu X^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\nu X^+ \bar{Y}) + i g c_w W_\mu^- (\partial_\mu X^- X^0 - \partial_\nu \bar{X}^0 X^+) + \\
 & i g s_w W_\mu^- (\partial_\mu X^- Y - \partial_\nu Y X^+) + i g c_w Z_\mu^0 (\partial_\mu X^+ X^+ - \partial_\nu X^- X^-) + i g s_w A_\mu (\partial_\mu X^+ X^+ - \\
 & \partial_\nu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
 & X^- X^0 \phi^-] + \frac{1}{2c_w} i g M [X^0 X^- \phi^+ - X^0 X^+ \phi^-] + i g M s_w [X^0 X^- \phi^+ - X^0 X^+ \phi^-] + \\
 & \frac{1}{2}i g M \bar{X}^+ X^+ \phi^0 - X^- X^- \phi^0]
 \end{aligned}$$



DO YOU NOT UNDERSTAND?

Higgs :: Peter Higgs

- Problém: interakce zavedené kalibračním principem fungují jen pro nehmotné částice...
- Jak částicím v teorii dodat hmotnost, a zachovat symetrii teorie?



1964

We'll be back soon...

Laboratoř CERN

Science for peace

CERN's convention states: "The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available."

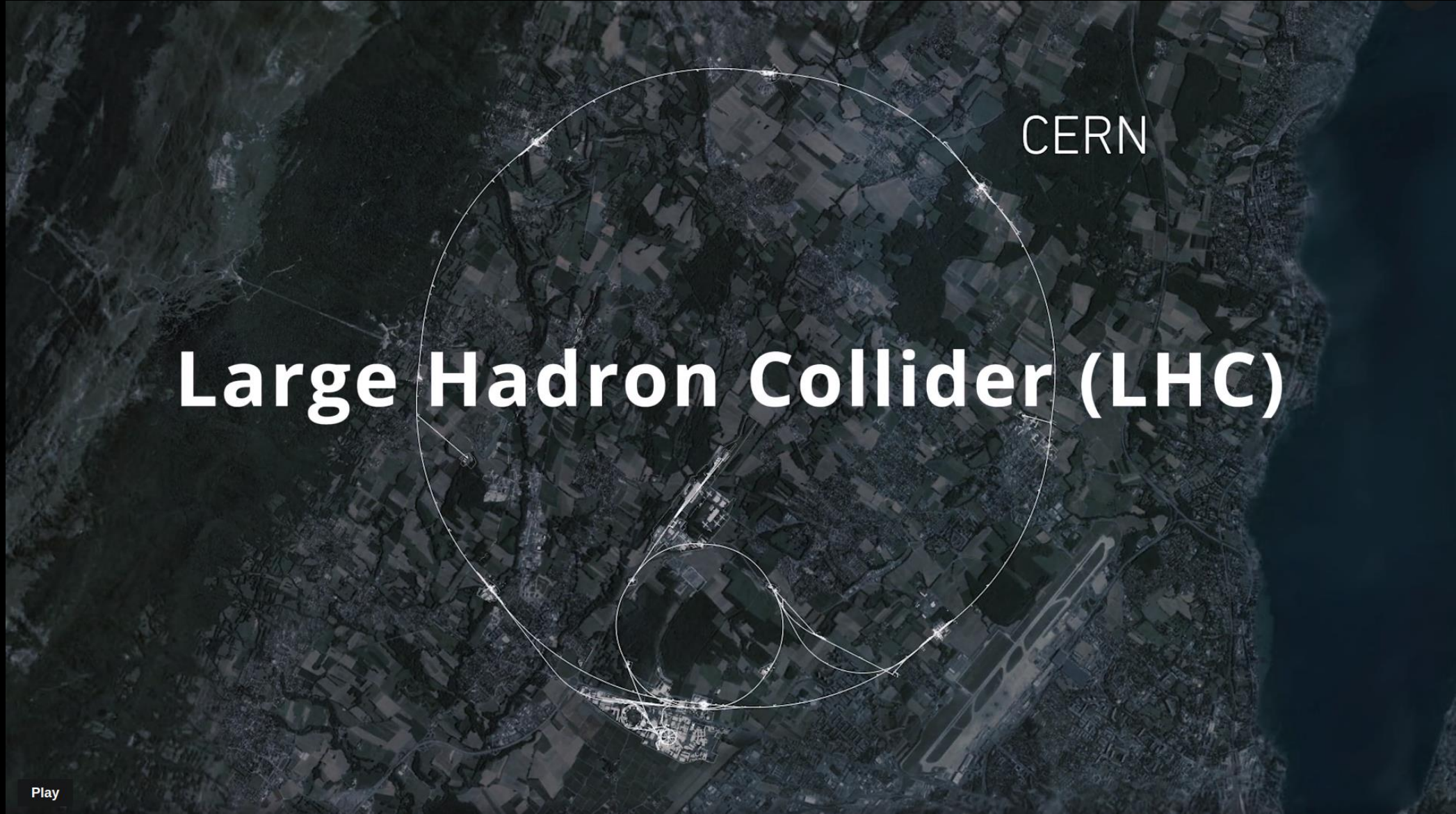


Play

Laboratoř CERN



Laboratoř CERN

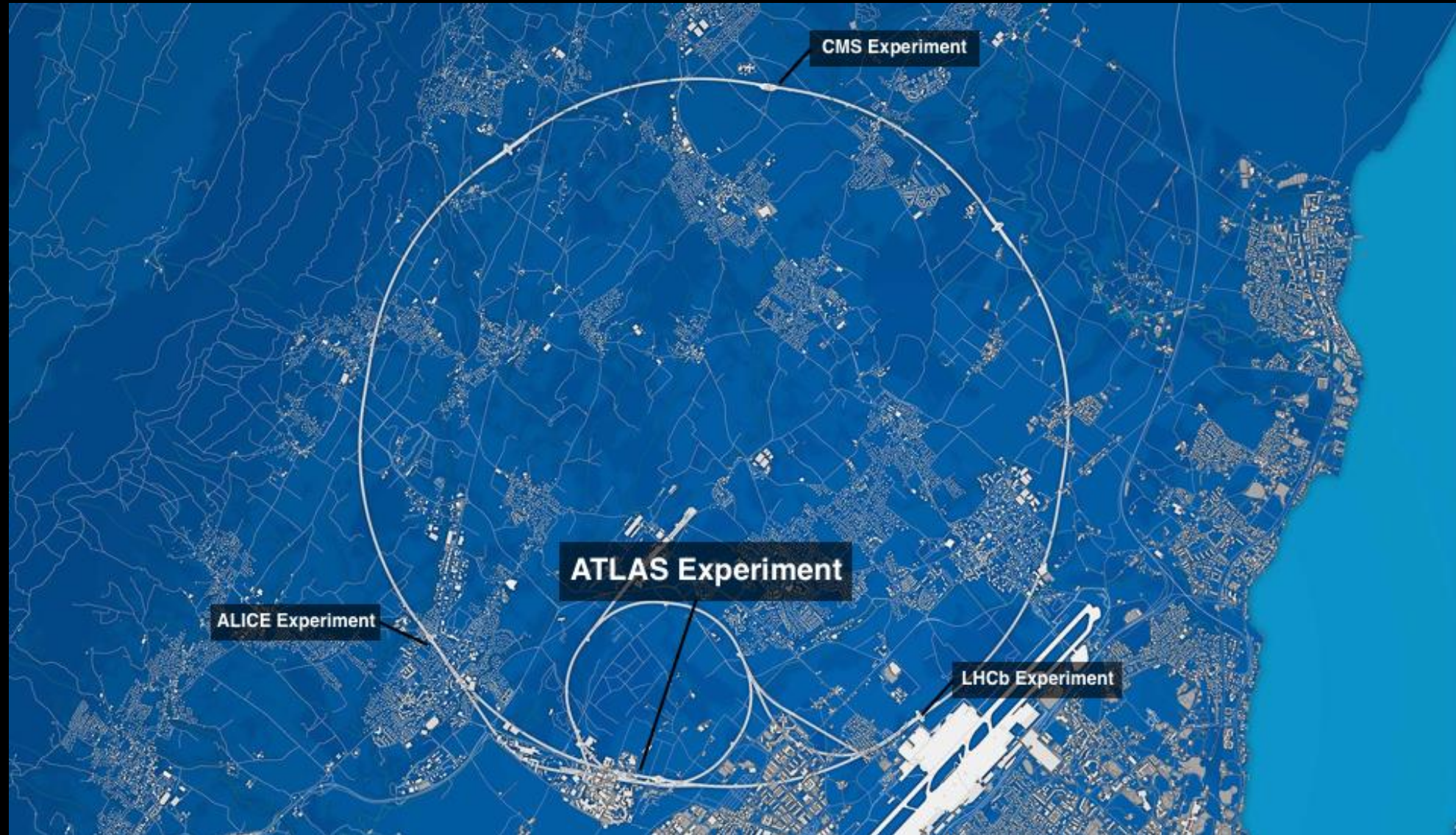


CERN

Large Hadron Collider (LHC)

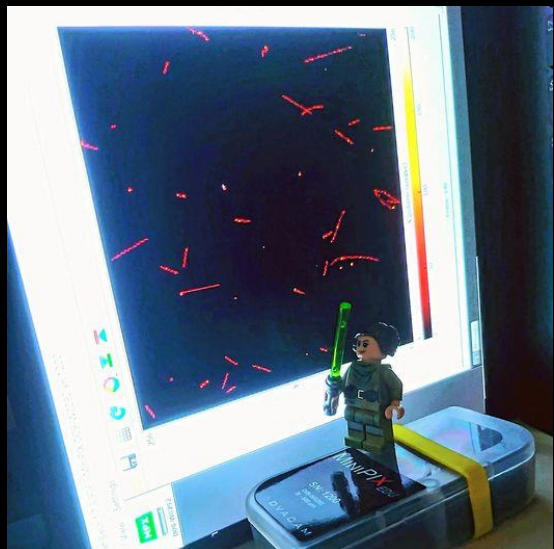
Play

Laboratoř CERN

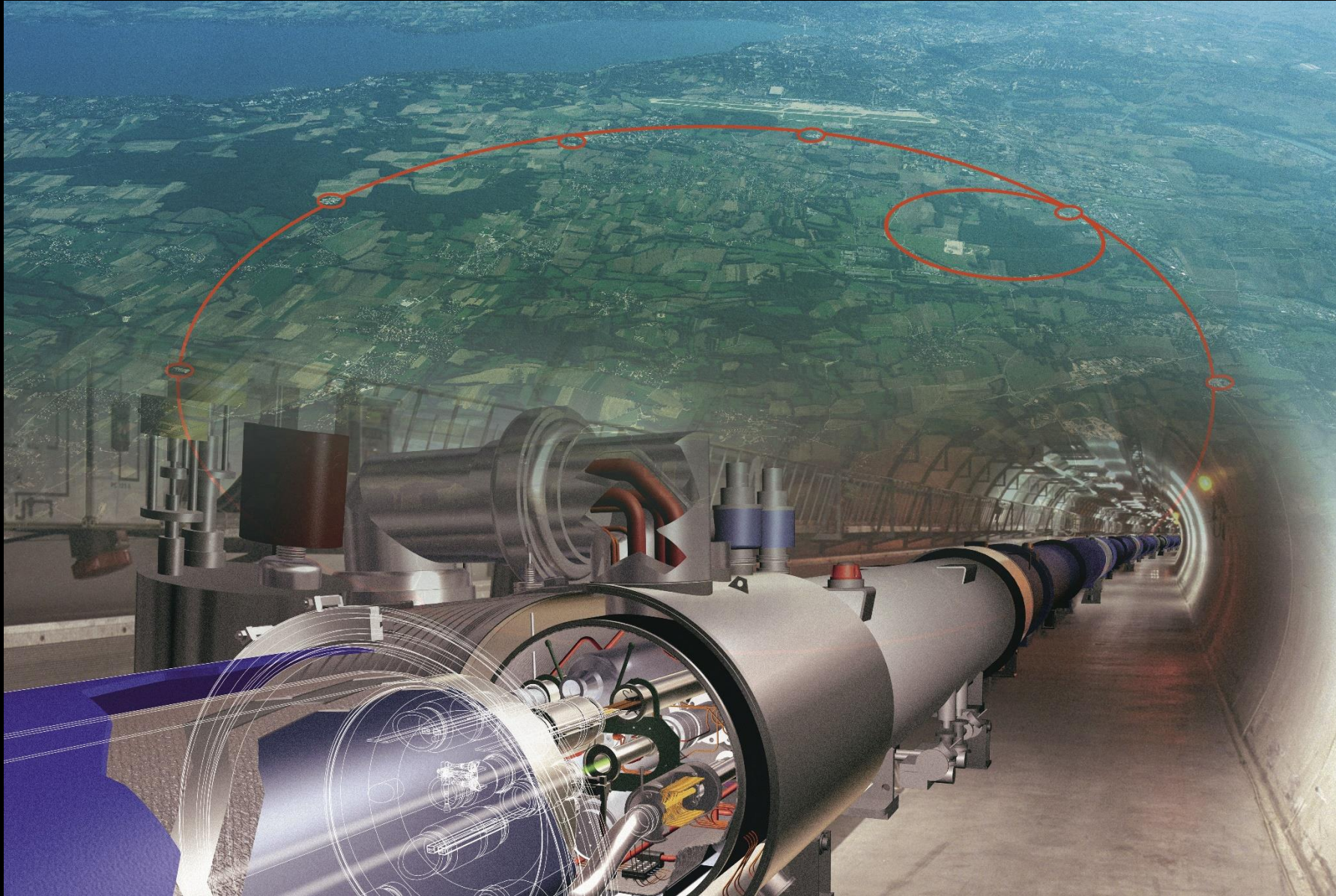


Laboratoř CERN

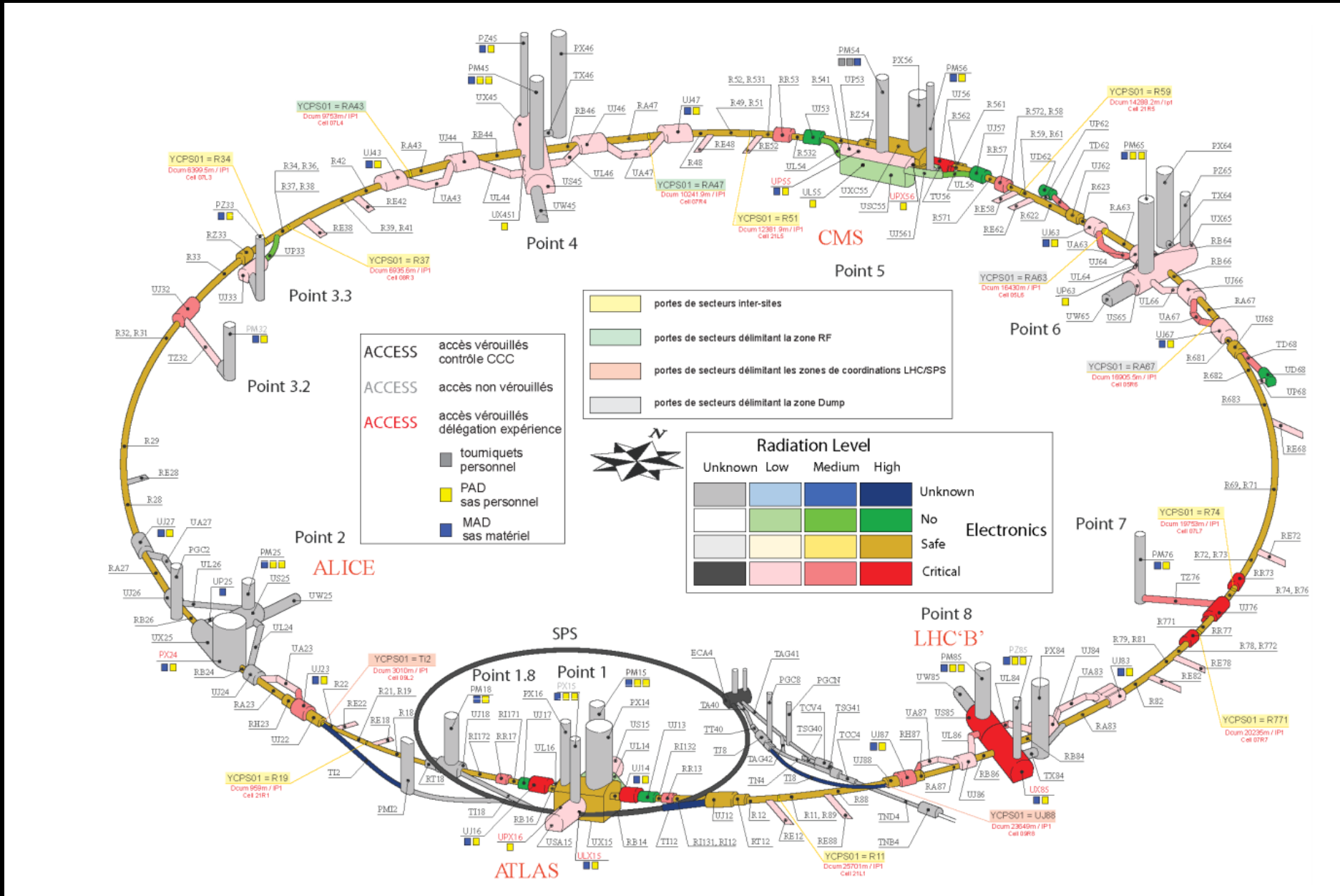




Mezitím v laboratoři CERN, kde „ $E = mc^2$ “



Mezitím v laboratoři CERN, kde „ $E = mc^2$ “



CERN: laboratoř „ $E = mc^2$ “

- Urychlovač LHC (Large Hadron Collider): 27 km obvod.
- Supravodivé dipólové magnety chlazeny na 1,9 K.
 - Studenější než Vesmír.
 - Elektrický proud v supravodiči je 13 kA.
- Mikroskop s rozlišením 0,01 fm.
- Srážky protonů: lokální teplota 10^{16} Kelvinů.
 - Místo s nejvyšší teplotou ve Sluneční soustavě.
- Protony o energii 6,5 TeV oběhnou za 90 μ s.
- Protony jsou ve shlucích po 10^{10} částic.
- Shluků je 2000.
- Frekvence srážek je 40 MHz, tj. každých 25 ns.
- Spotřeba energie jako kanton Ženeva.

Urychlovač LHC

LHC Page1 Fill: 7547 E: 450 GeV 25-04-22 10:21:44

BEAM SETUP: PREPARE RAMP

Energy: 450 GeV I B1: 8.20e+09 I B2: 6.68e+09

Beta* IP1: 11.00 m Beta* IP5: 11.00 m Beta* IP2: 10.00 m Beta* IP8: 9.95 m

FBCT Intensity and Beam Energy Updated: 10:21:44

Comments (25-Apr-2022 10:13:34)
 Beam commissioning
 First ramp to 6.8 TeV with pilots

BIS status and SMP flags		B1	B2
Link Status of Beam Permits		false	false
Global Beam Permit		true	true
Setup Beam		true	true
Beam Presence		true	true
Moveable Devices Allowed In		false	false
Stable Beams		false	false
PM Status B1	ENABLED		
PM Status B2	ENABLED		

AFS: MD_MKI_13inj_both

<https://jointlab.upol.cz/kvita/LHC.html>

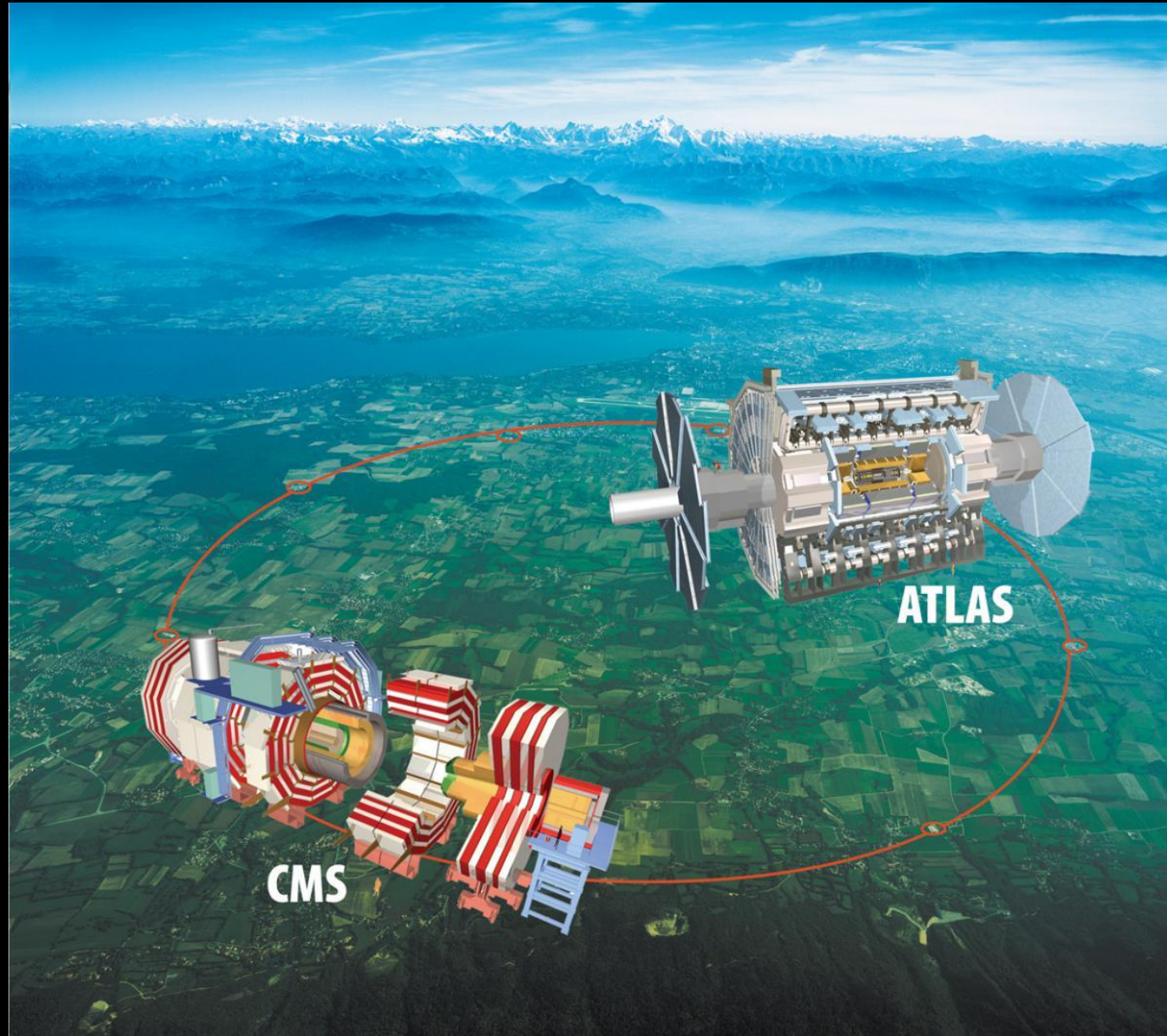
CERN Control Centre

- Hlavní kontrolní místnost všech urychlovačů v CERN
- 24/7

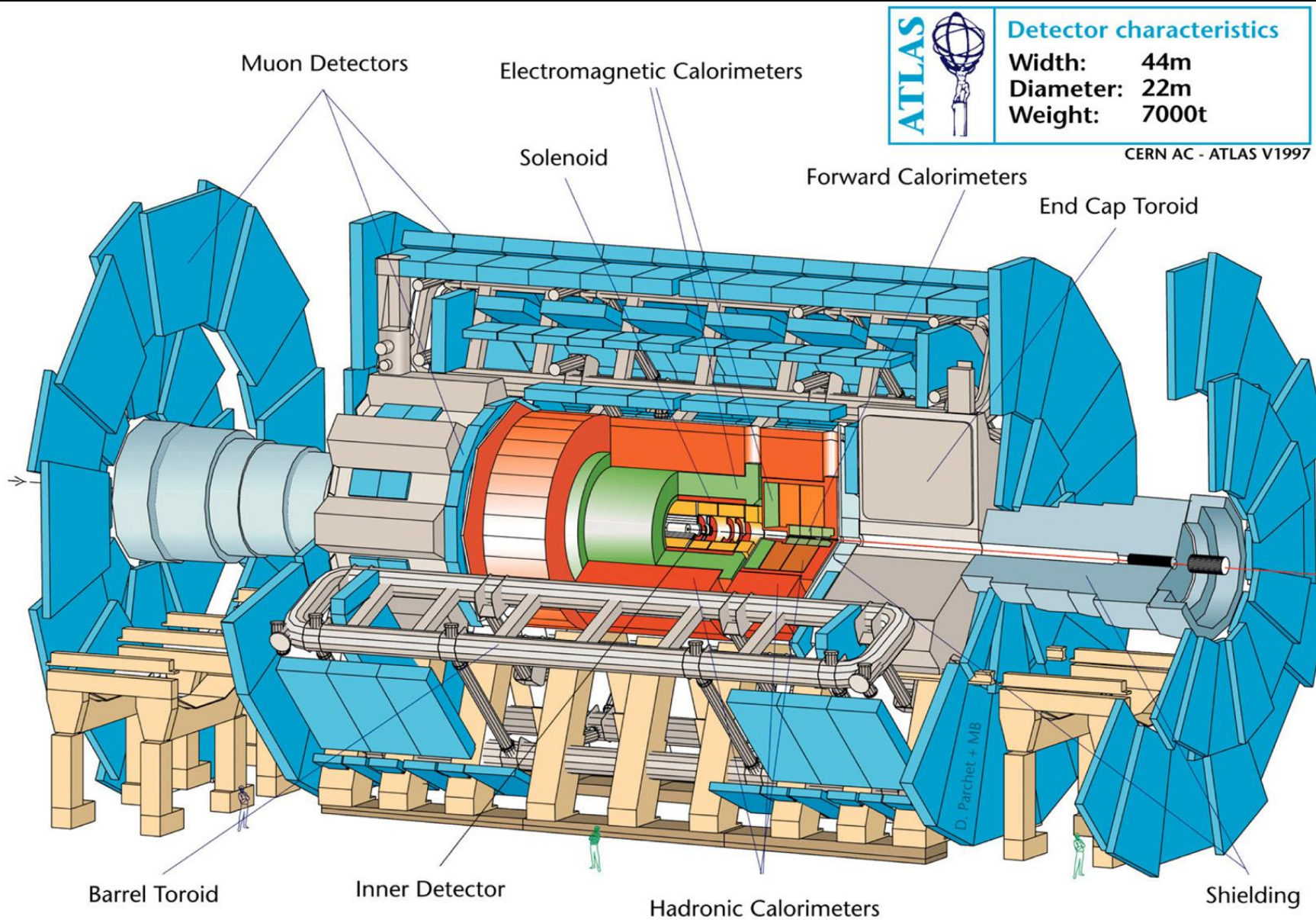


<https://home.cern/resources/image/accelerators/cern-control-centre-images-gallery>

CERN – Evropské centrum (sub)jaderného výzkumu



Experiment ATLAS



Experiment ATLAS



Detector characteristics

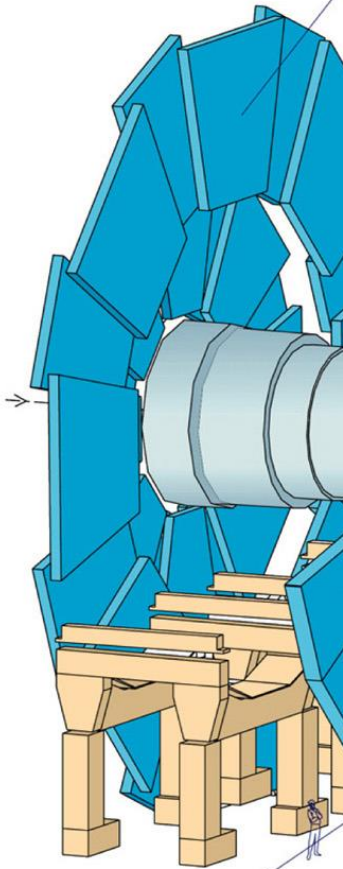
Width: 44m
Diameter: 22m
Weight: 7000t

CERN AC - ATLAS V1997

Muon Detectors

Electromagnetic Calorimeters

Solenoid

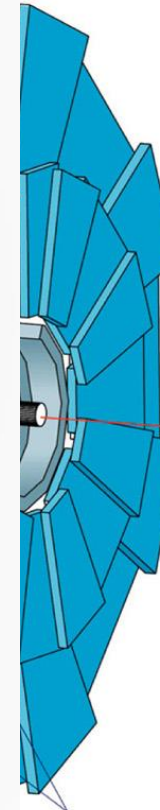


Barrel Toroid



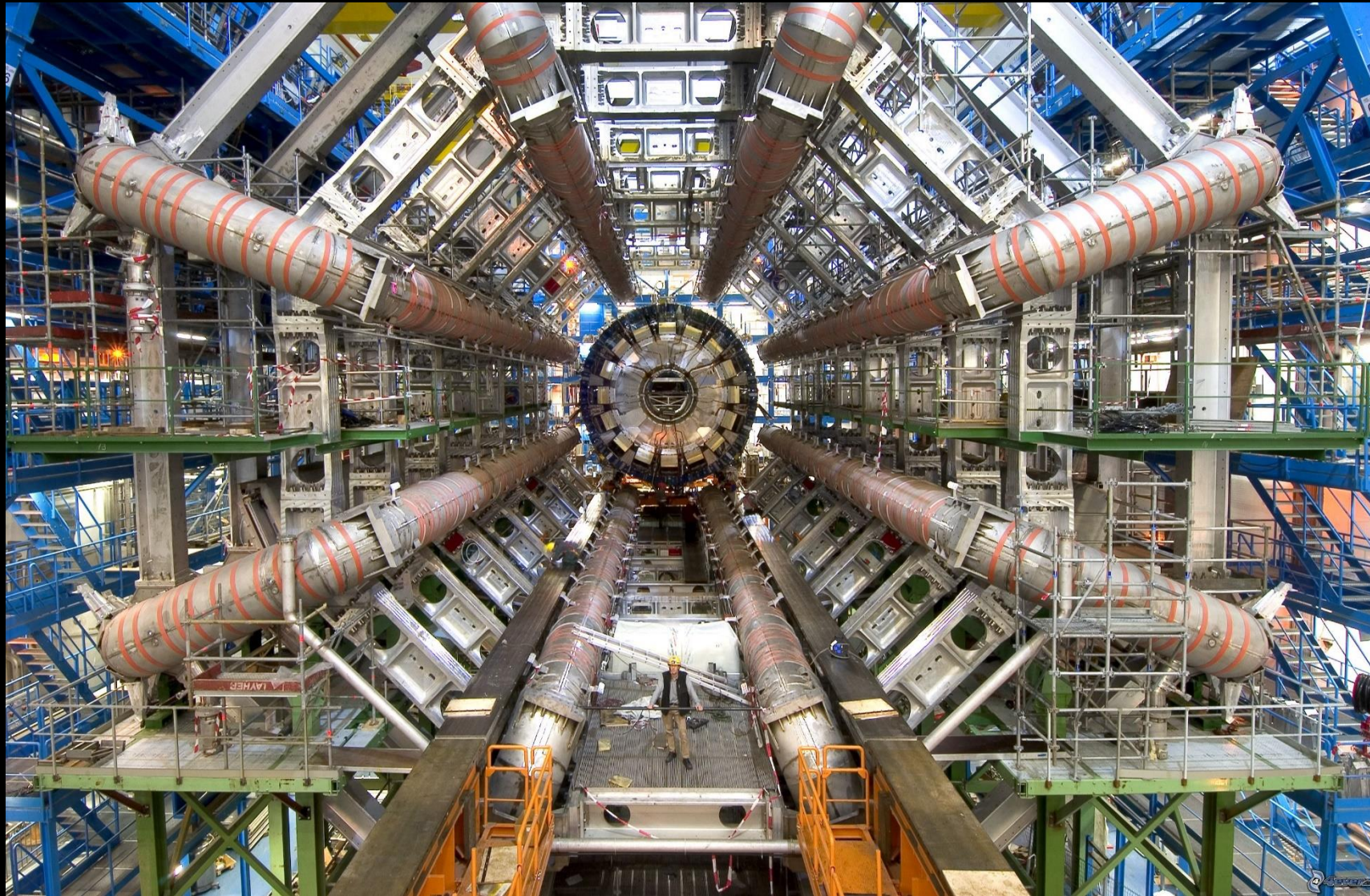
Inner Detector

Hadronic Calorimeters



Shielding

Experiment ATLAS

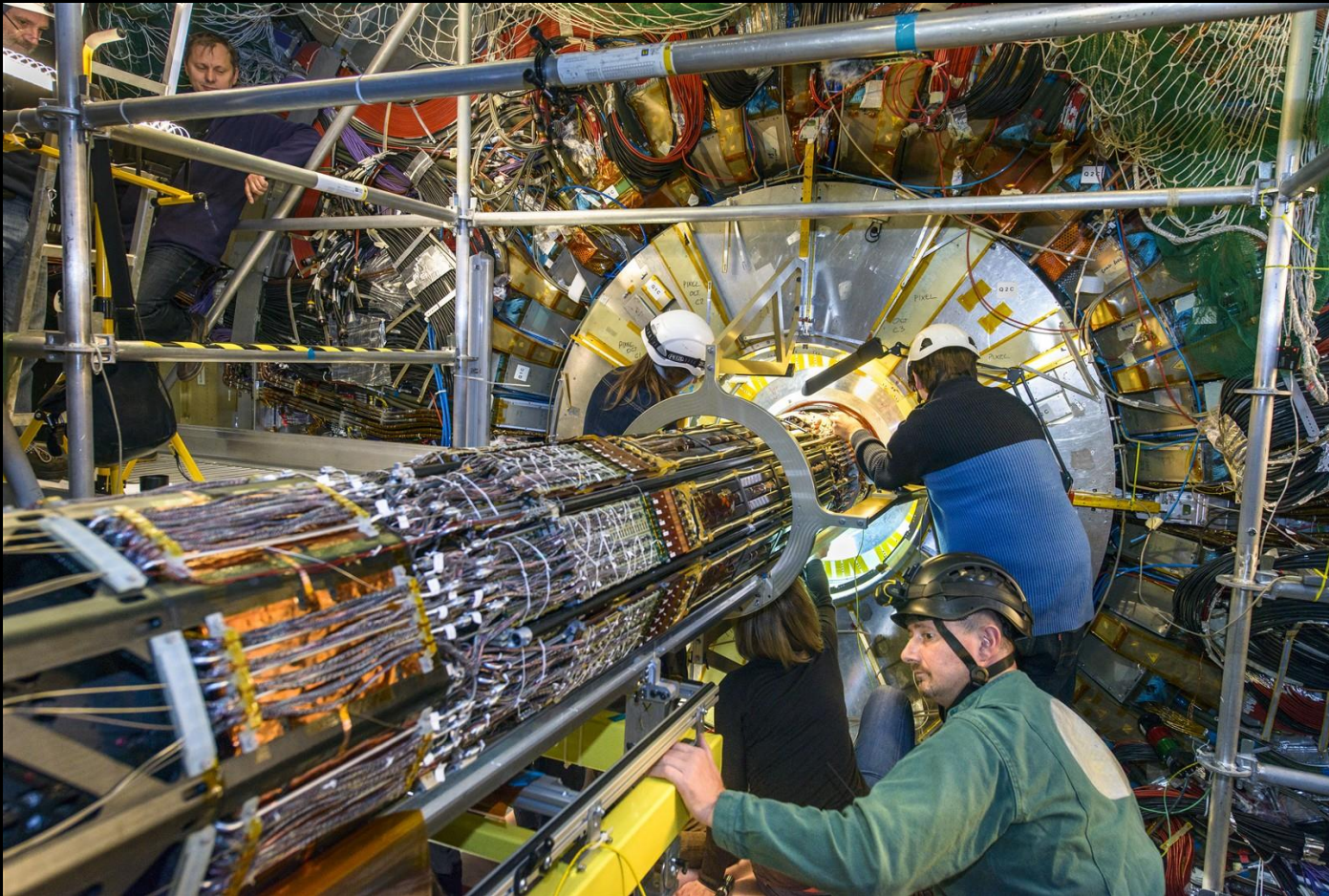


Experiment ATLAS

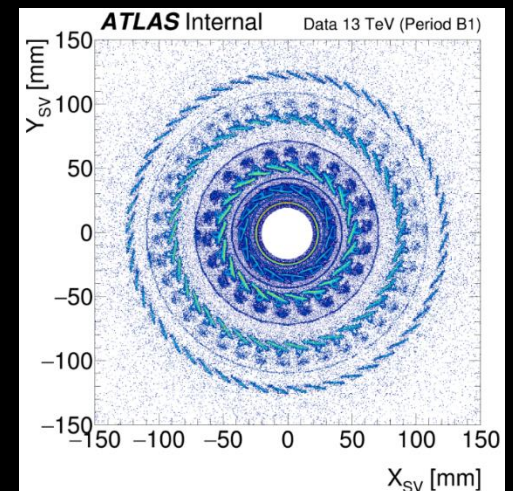
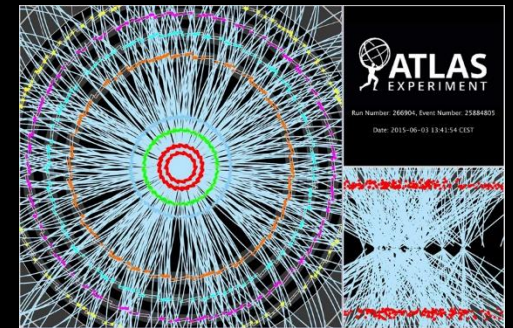
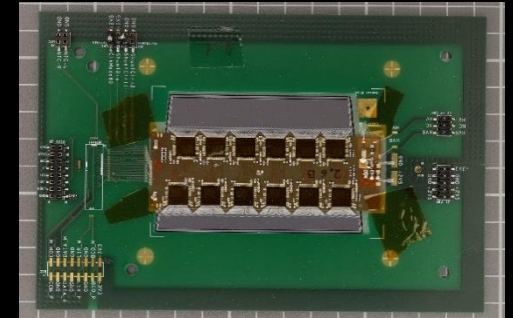


Polovodičové dráhové detektory

- Měření polohy a hybnosti částic
- Smysl zakřivení drah v magnetickém poli: náboj.



<https://atlas.cern/Discover/Detector/Inner-Detector>

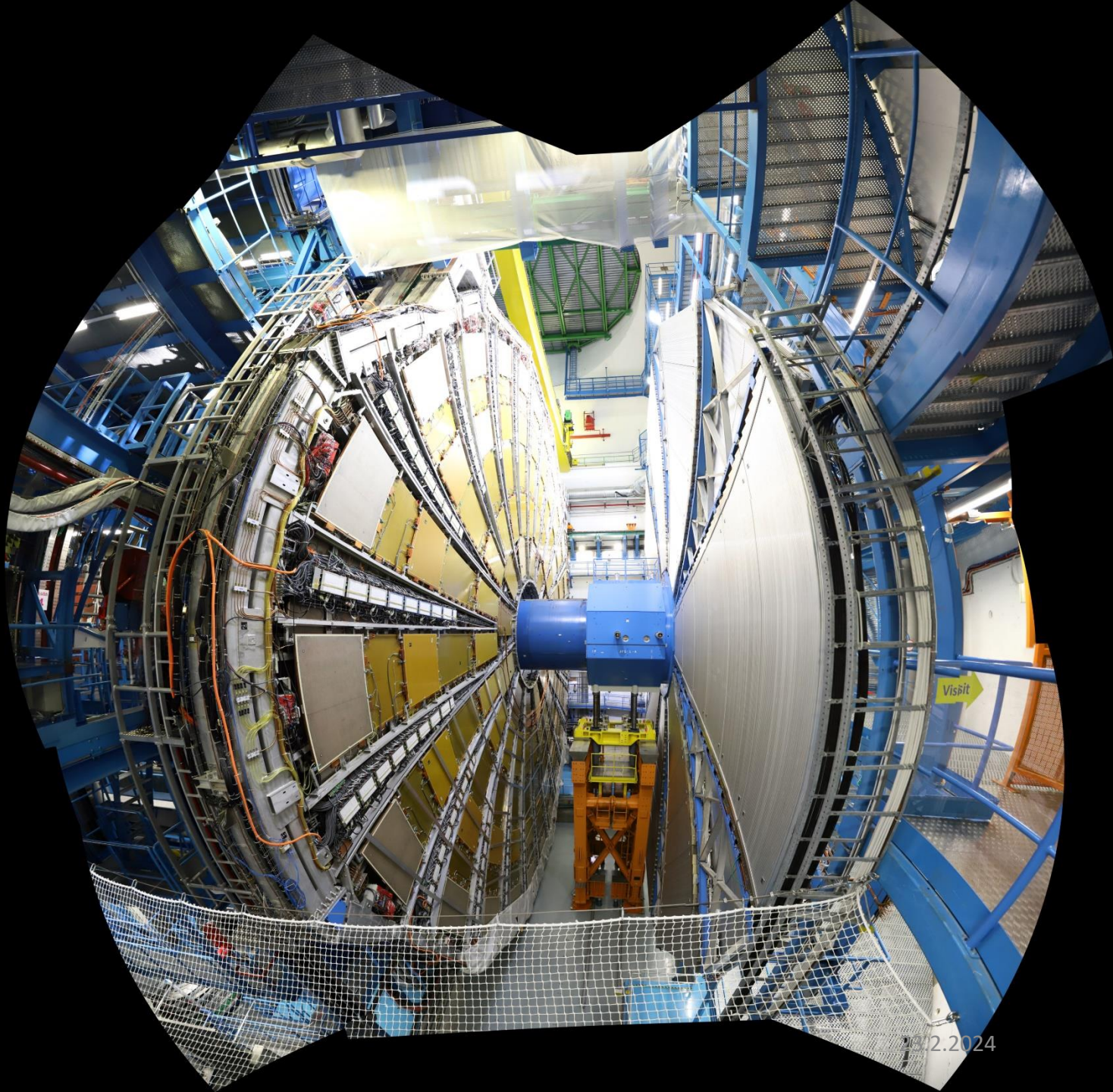


Experiment ATLAS



Experiment ATLAS

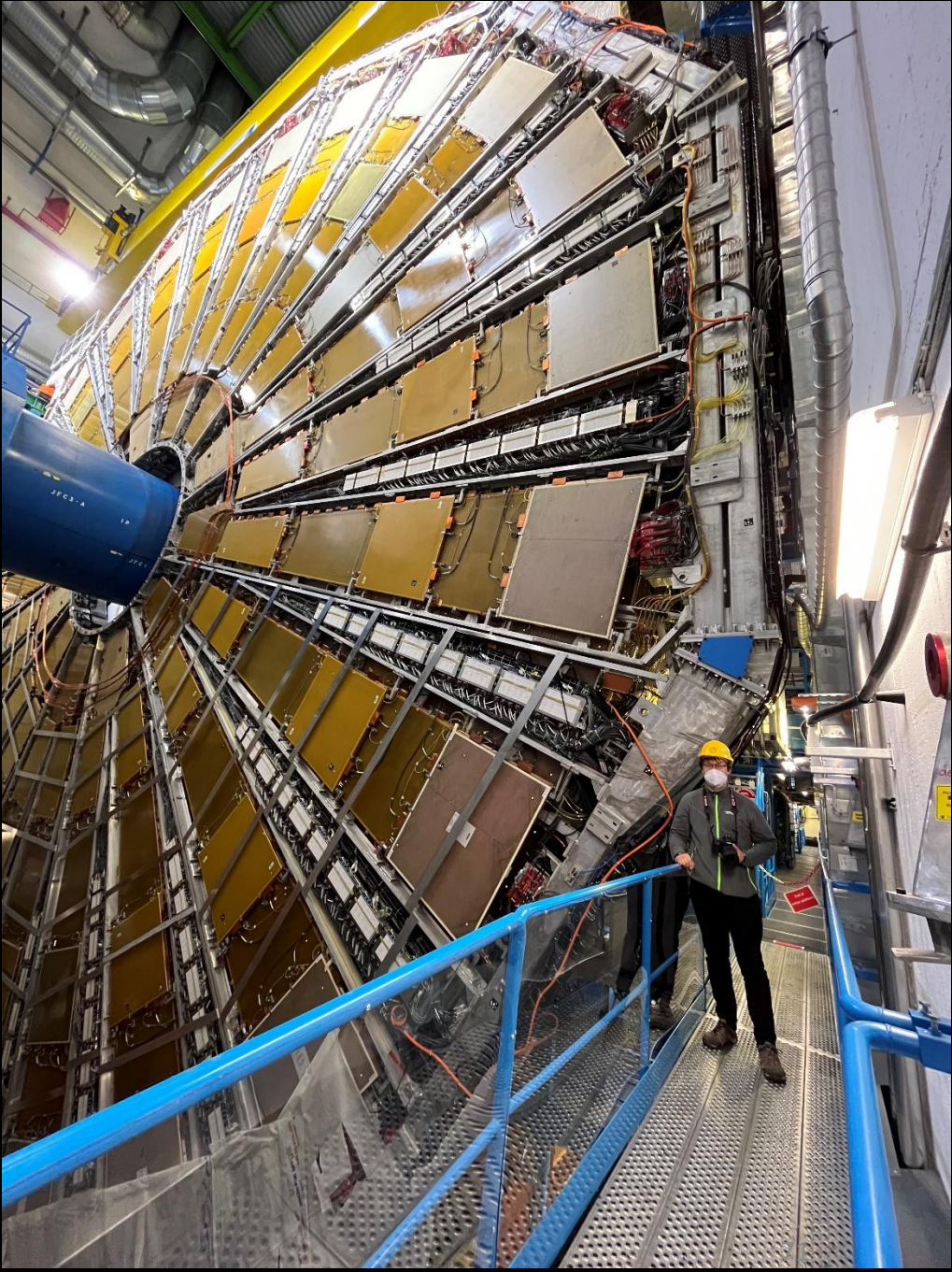
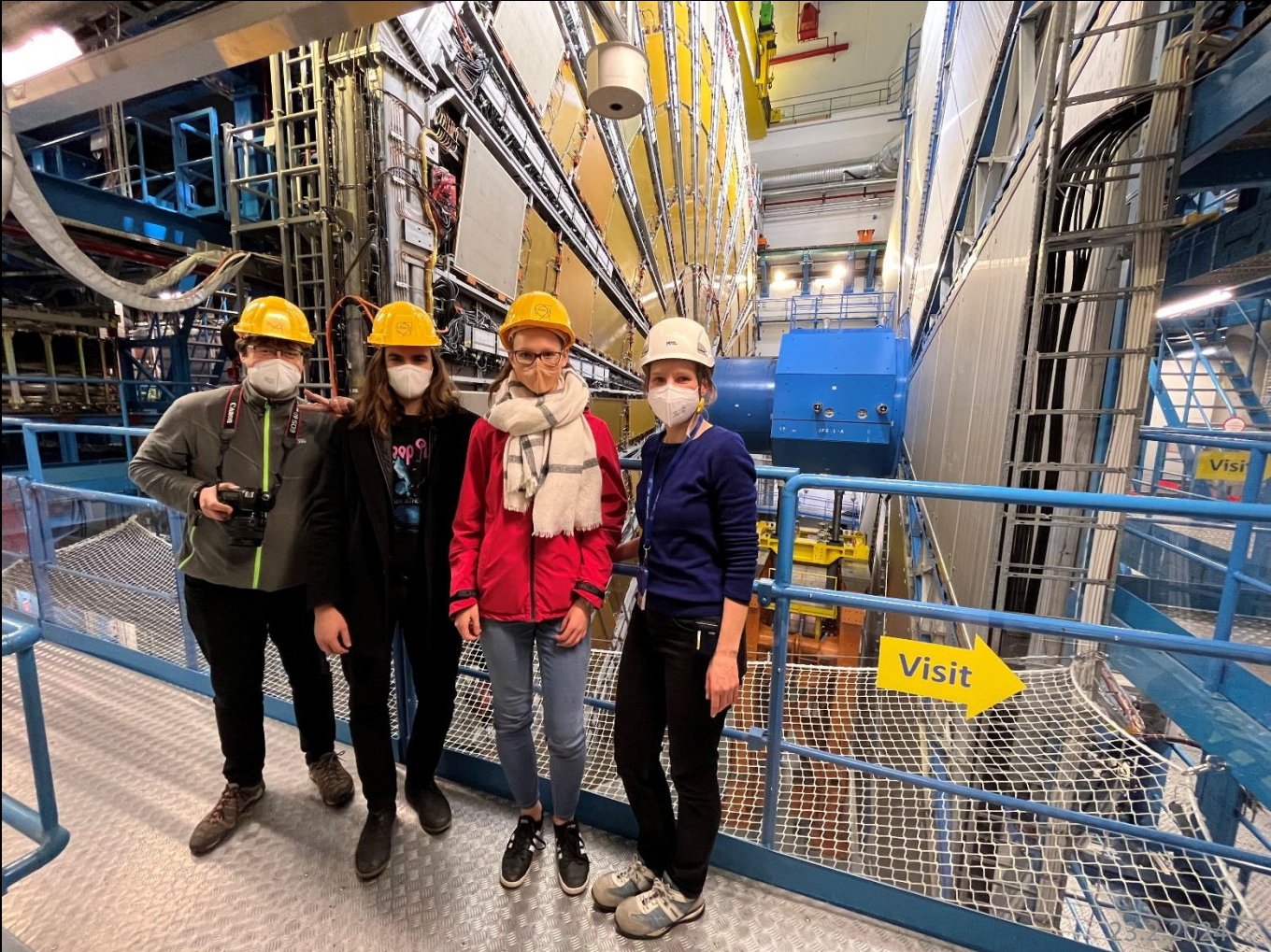




20.12.2024

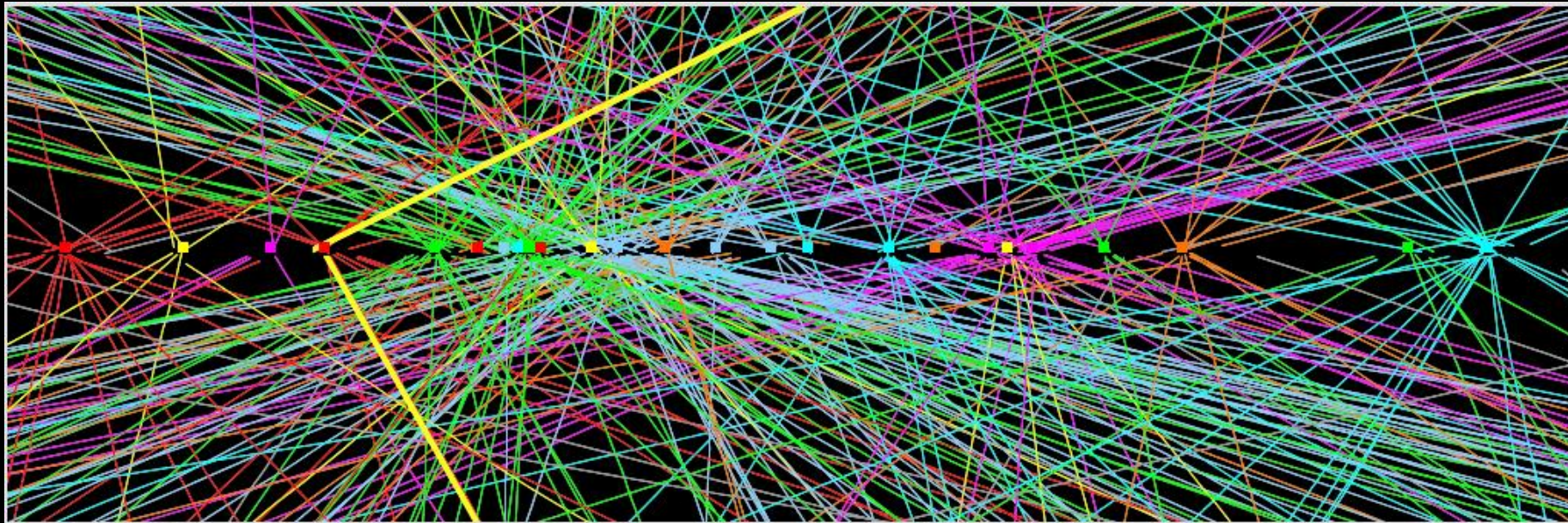


Experiment ATLAS

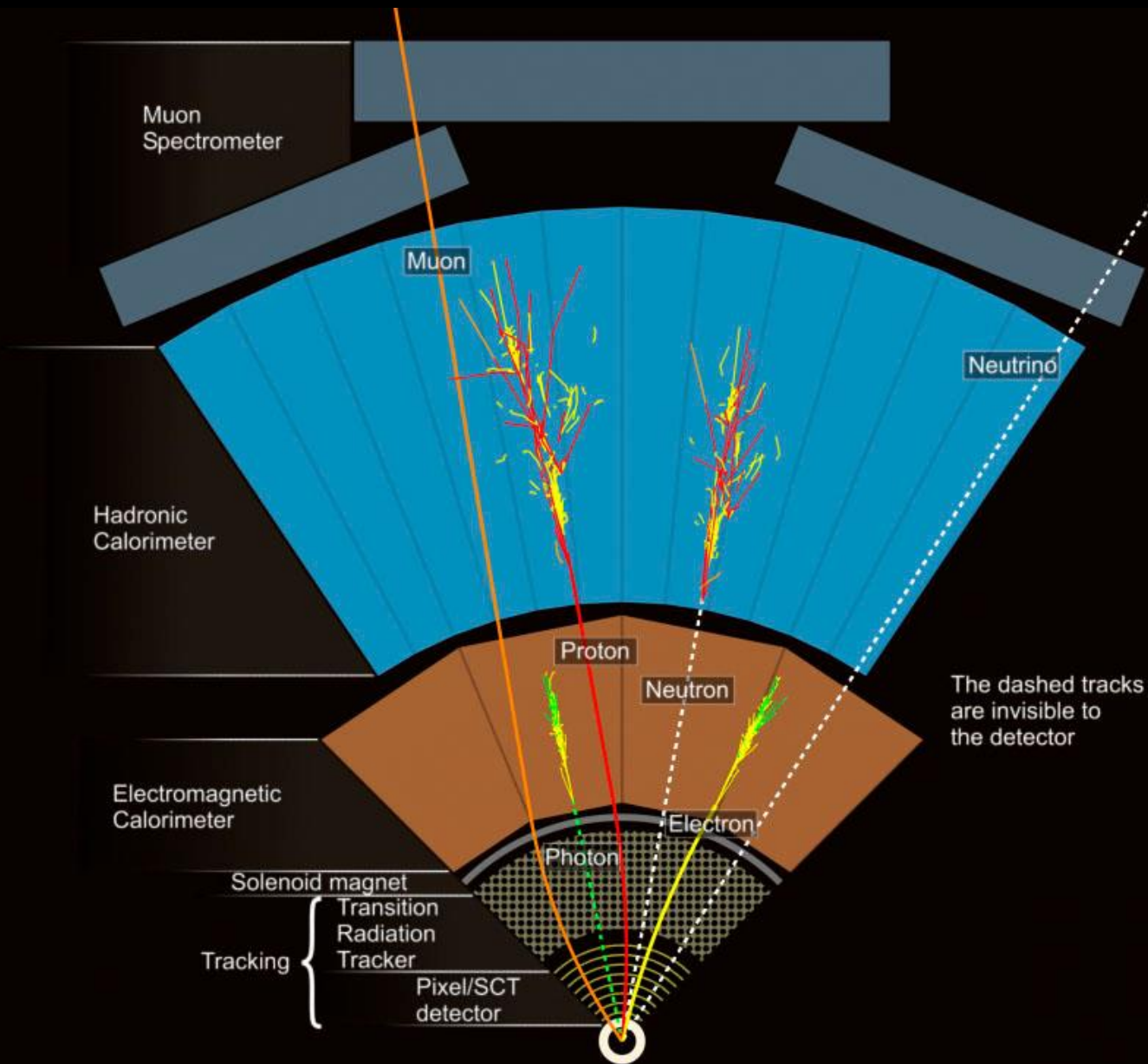


Interakce v srdci experimentu ATLAS

- Až 100 interakcí na jednom snímku z detektoru při jednom průchodu sluků částic (tzv. pile-up).
- Higgsův boson produkován cca v jedné srážce z 10 miliard, tj cca každých 5 min.
 - (někde v atmosféře každých 8s:)



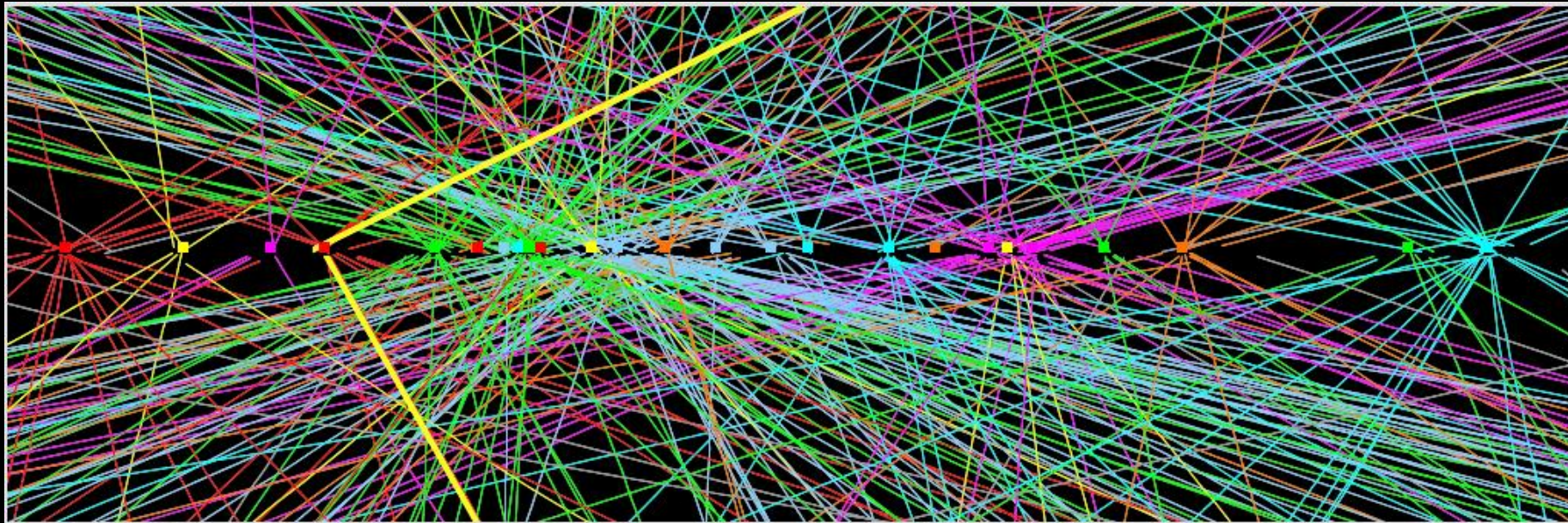
Jak ATLAS vidí částice



- Částice většinou nejsou takto ideálně izolované.
- V praxi se definuje jejich „ID“ či kvalita např. na základě toho, jak moc dalších drah či energie je okolo mionu či elektronu.

Jak ATLAS vidí částice

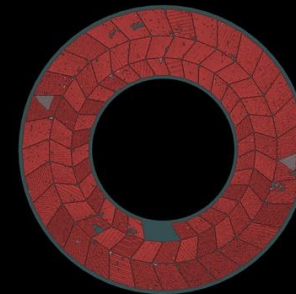
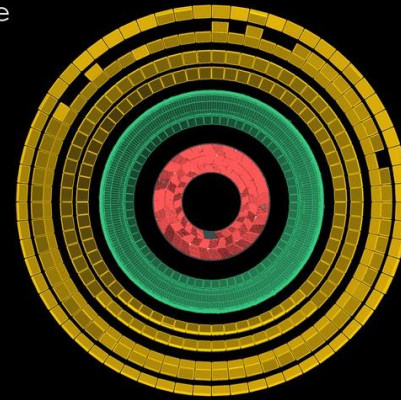
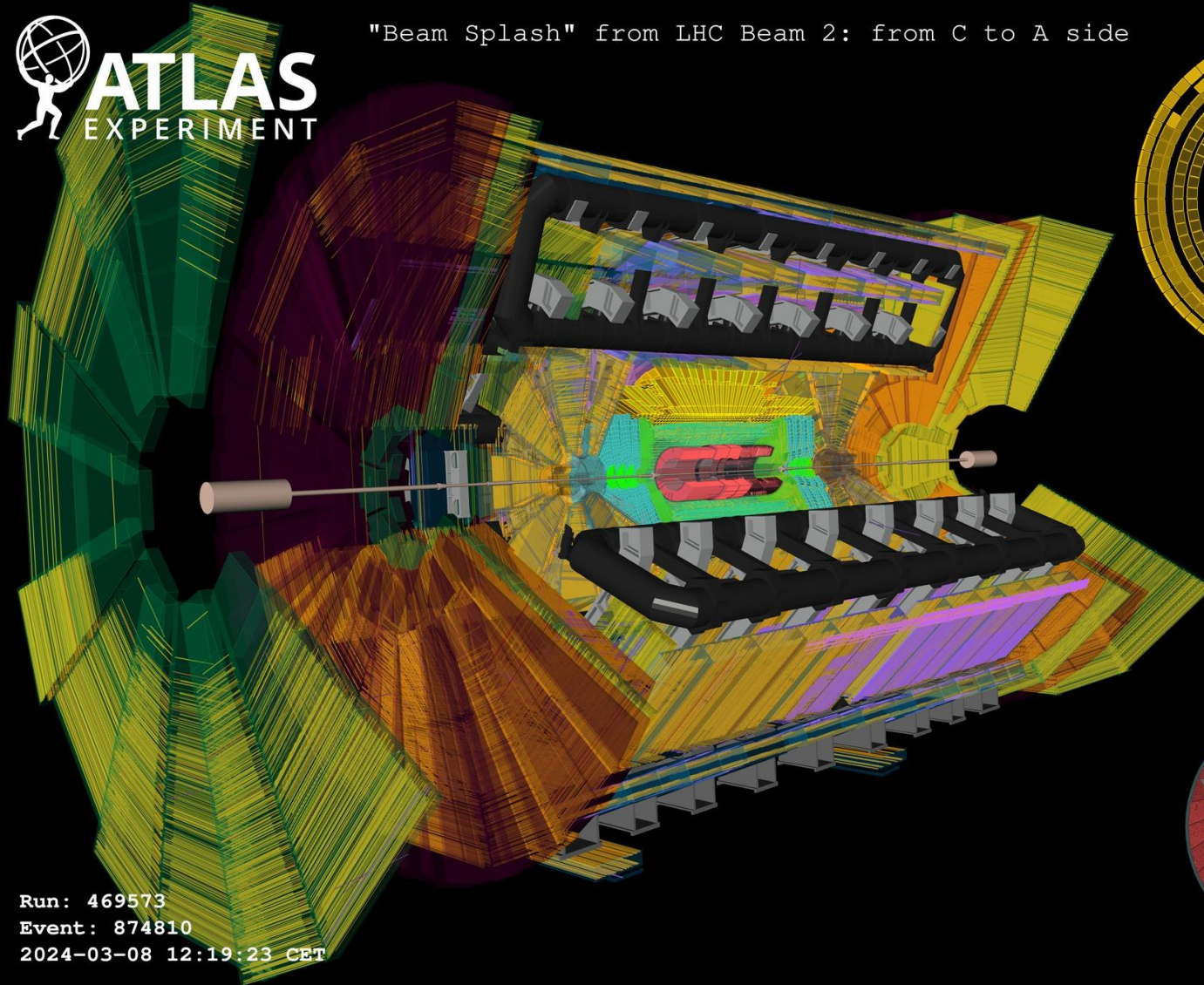
- Až 100 interakcí na jednom snímku z detektoru při jednom průchodu sluků částic (tzv. pile-up).
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Jak ATLAS vidí částice



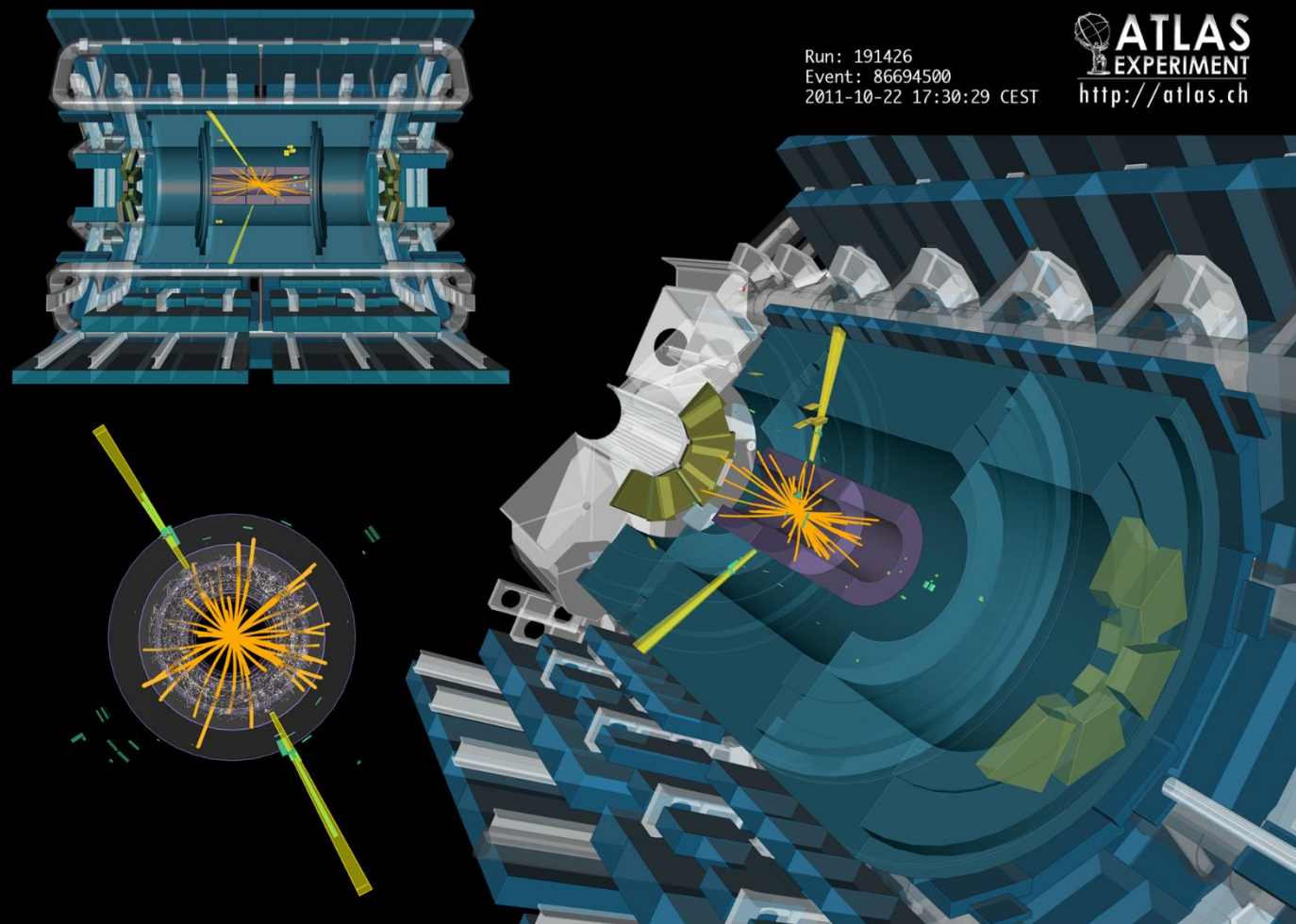
"Beam Splash" from LHC Beam 2: from C to A side



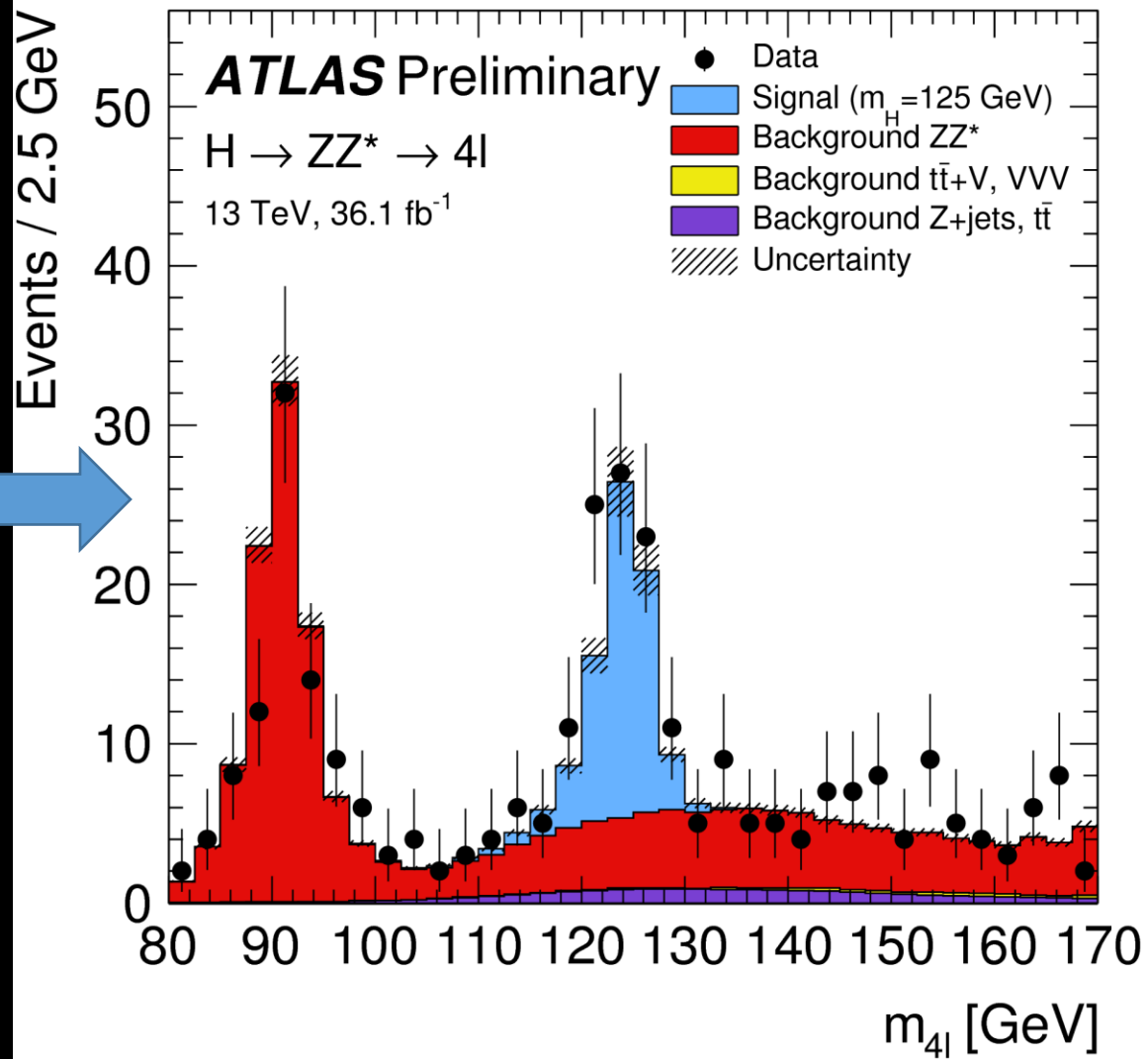
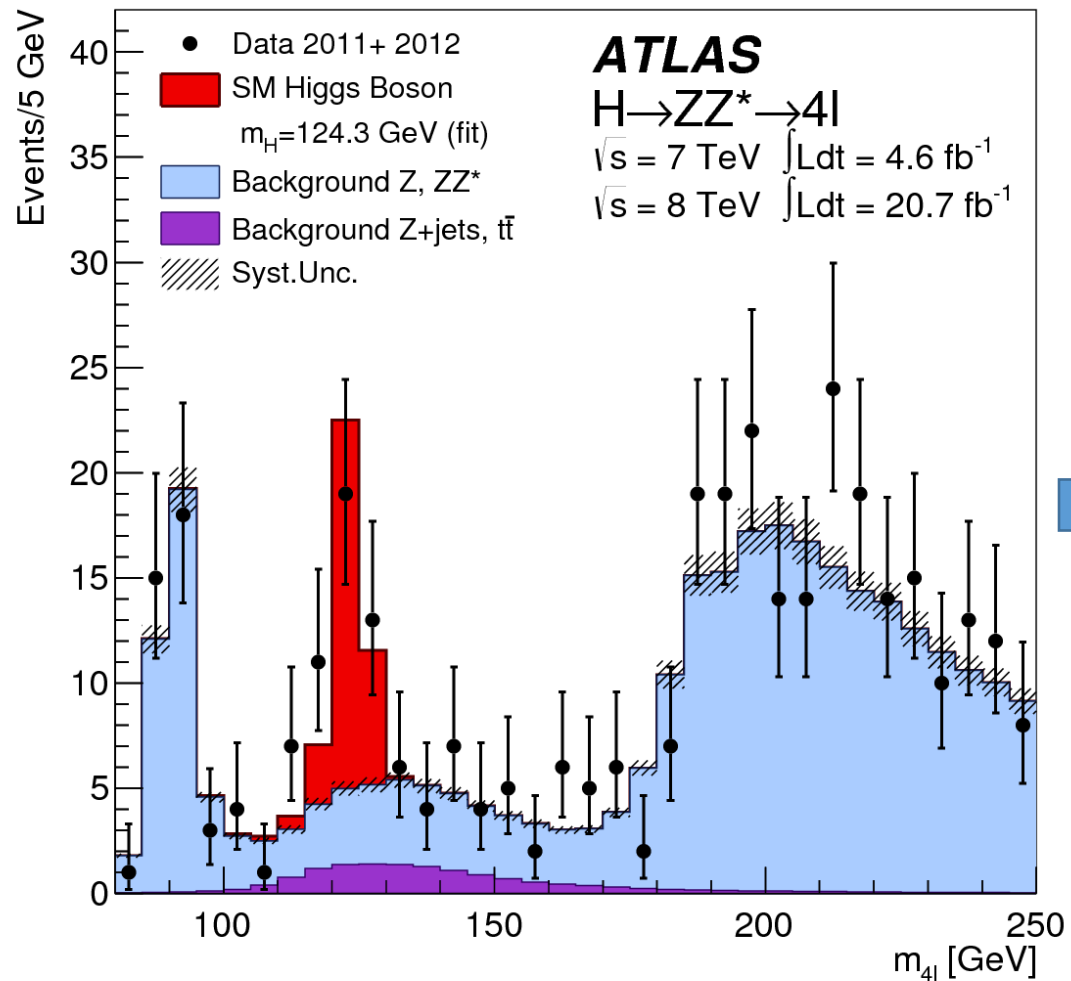
Run: 469573
Event: 874810
2024-03-08 12:19:23 CET

Higgsův boson

- Rozpad Higgsova bosonu na dva fotony.

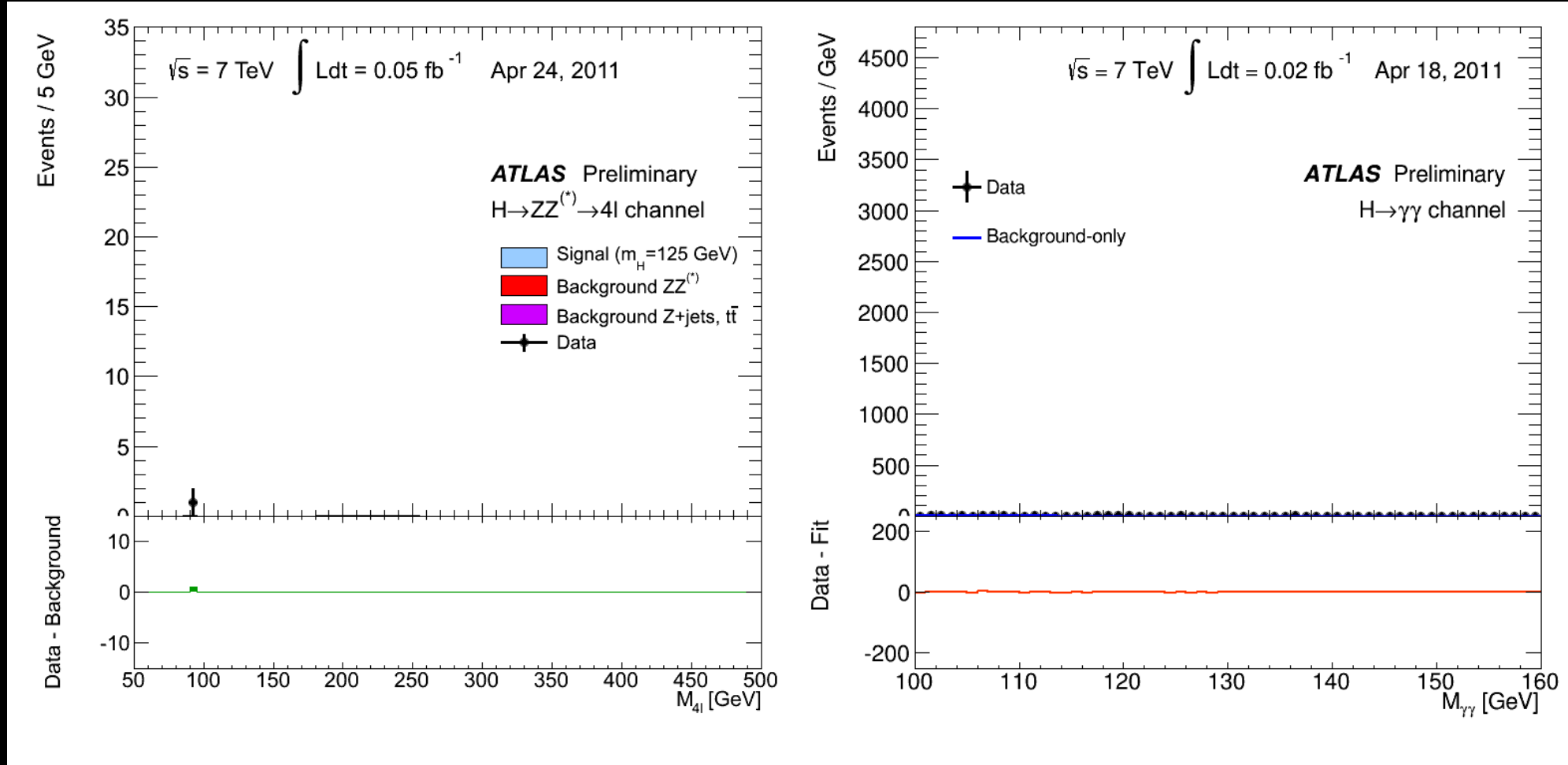


Higgs boson



Higgsův boson

- Čekání na Higgse.



Higgsův boson

- BEH boson (Brout, Englert, Higgs).
(a také Gerald Guralnik, C. R. Hagen, a Tom Kibble)

Fabiola Gianotti a Peter Higgs, 2012



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013




Photo: A. Mahmoud
François Englert
Prize share: 1/2




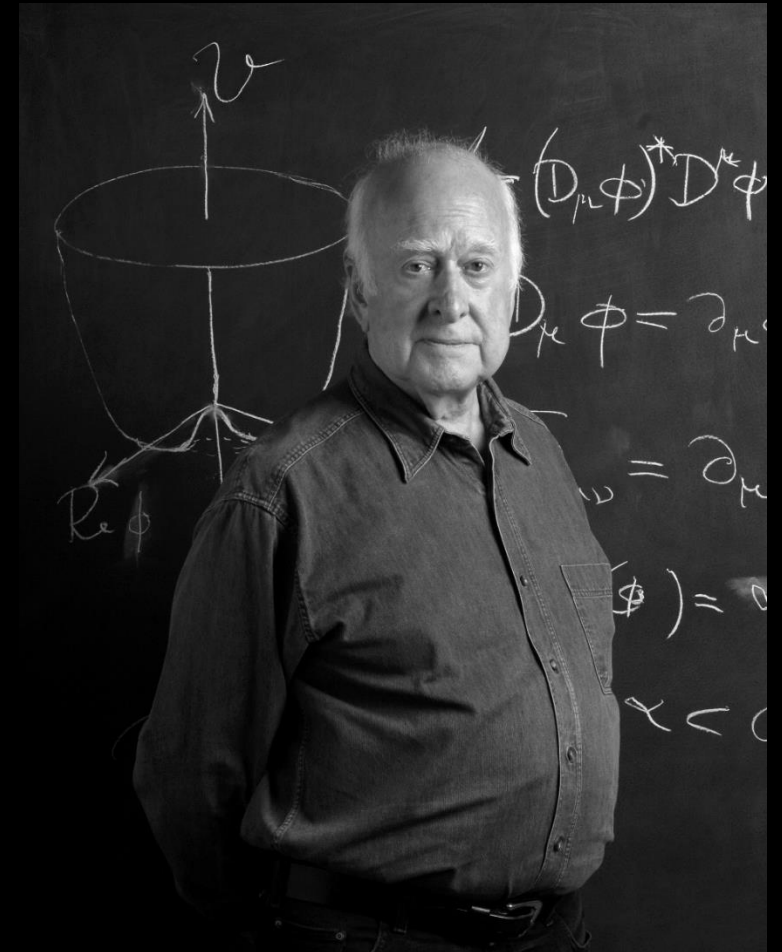
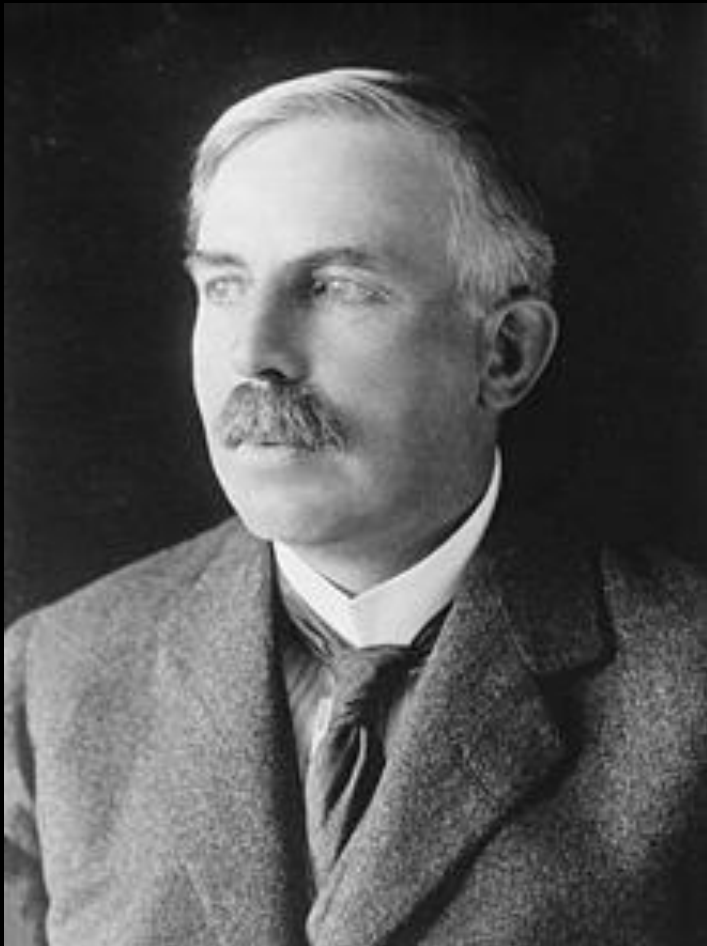
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2



Robert Brout
(1928 -- 2011)

Rozptylový experiment

- Aneb od E. Rutherforda k R. Hofstadterovi a P. Higgsovi.
- Od alfa částic a elektronů ke srážkám protonů na urychlovači LHC.



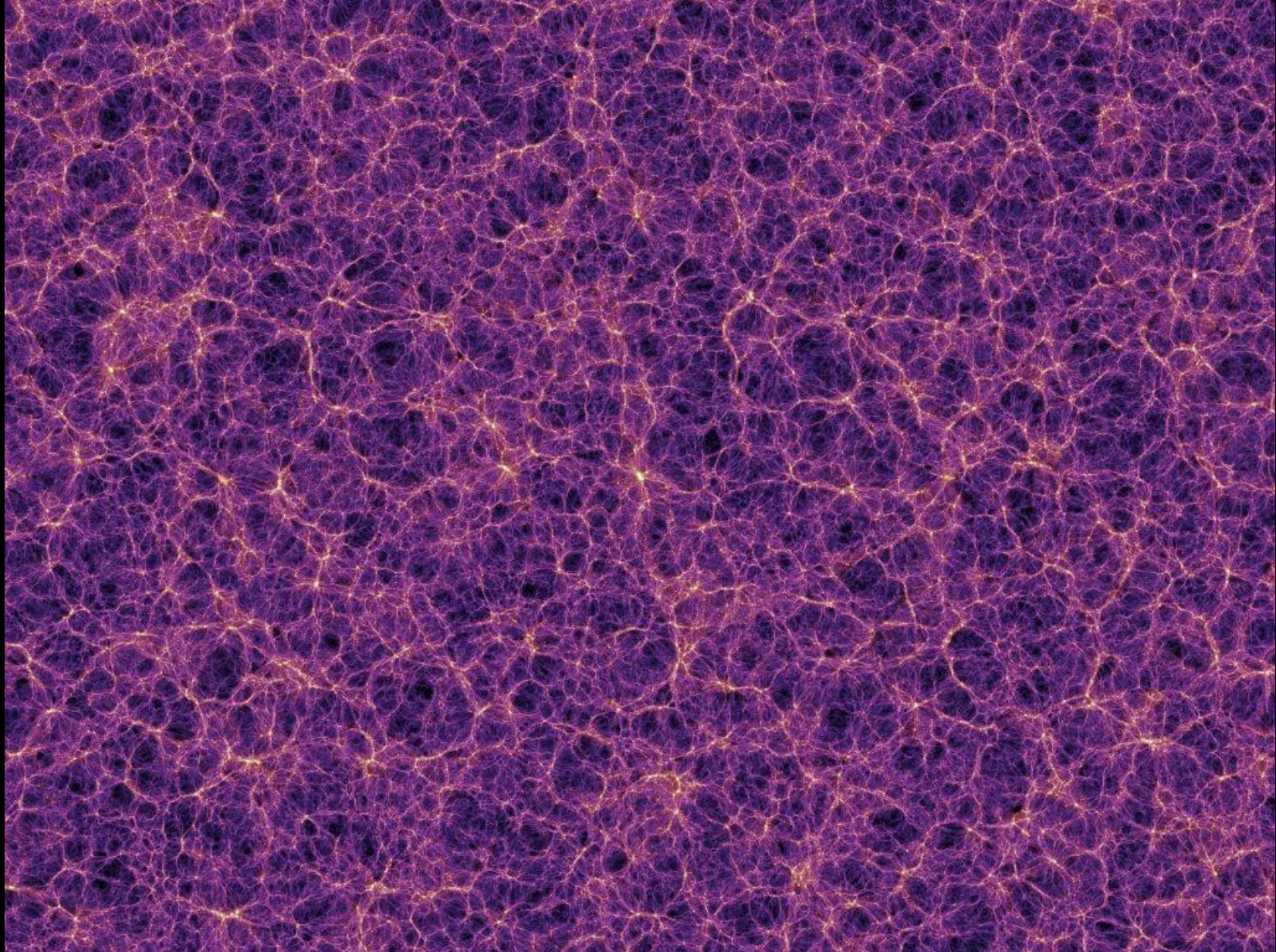
Nebojte se bádát!

- Projekty pro vás!
- <https://badatel.upol.cz>



Badatel

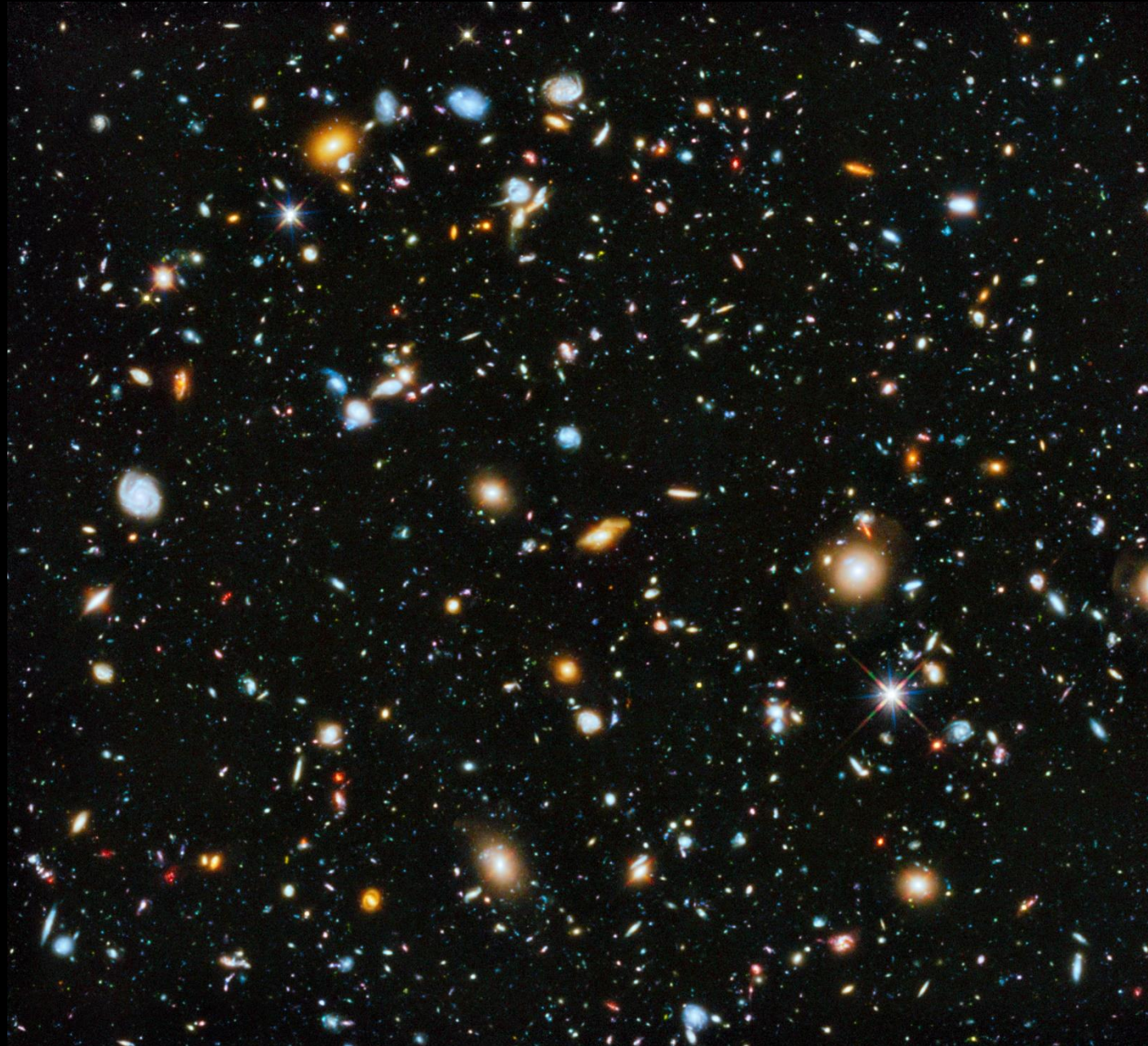
Vesmír



10^{26} m, 10 Gly

Millenium Simulation

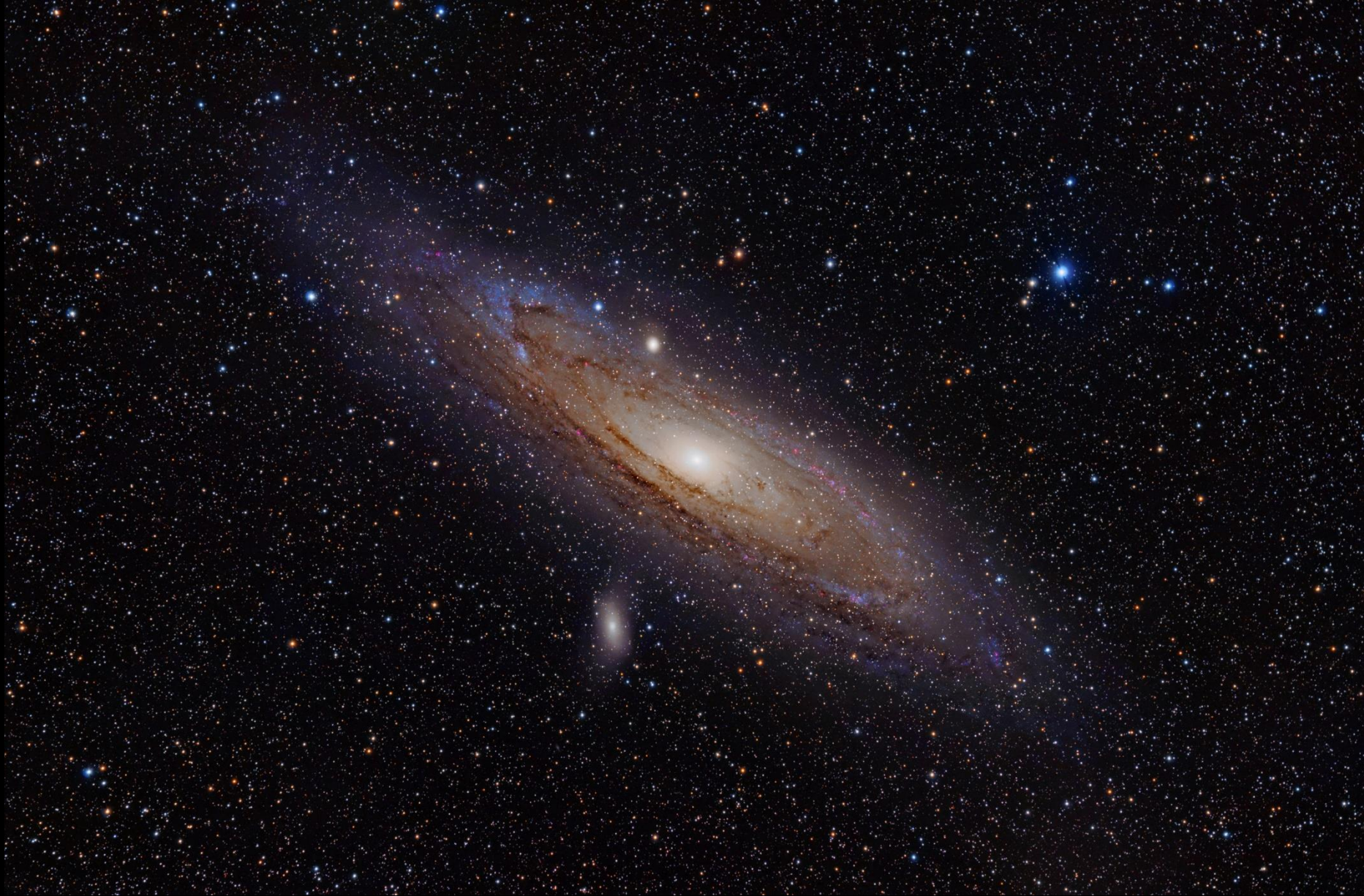
Kupy galaxií



10^{23} m, 10 Mly

Hubble Space Telescope

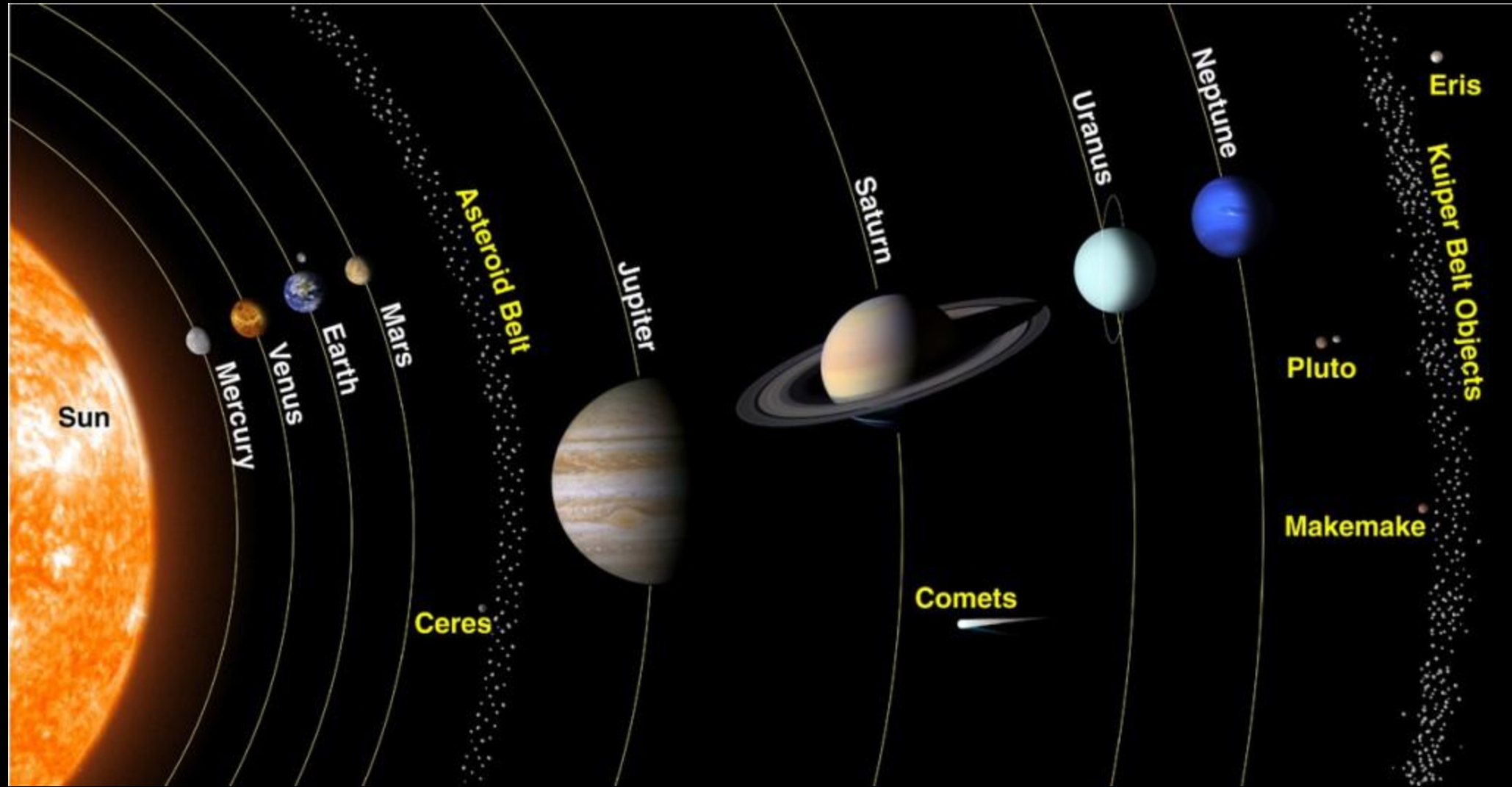
Galaxie



10^{21} m, 100 kly

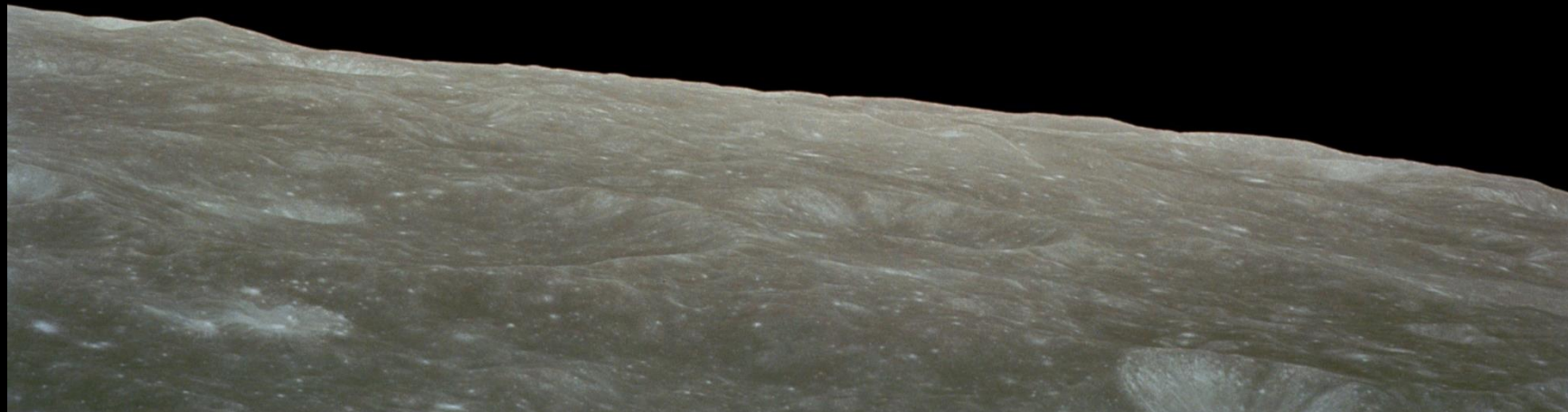
Adam Evans

Sluneční soustava



10^{11} m, 10 lh

Ze Země na Měsíc



10^8 m, 1 ls

Země



10^7 m

by Apollo 17

Tvor



10^{-2} m

Optická fotografie listovnice nádherné, ifauna.cz