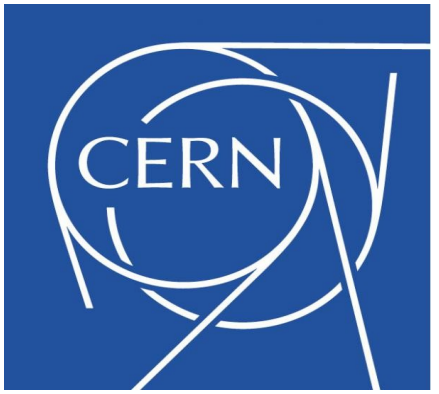
Higgs Story
aneb
Jak se dělají částice

Jiří Kvita, PřF UP



Higgs Story
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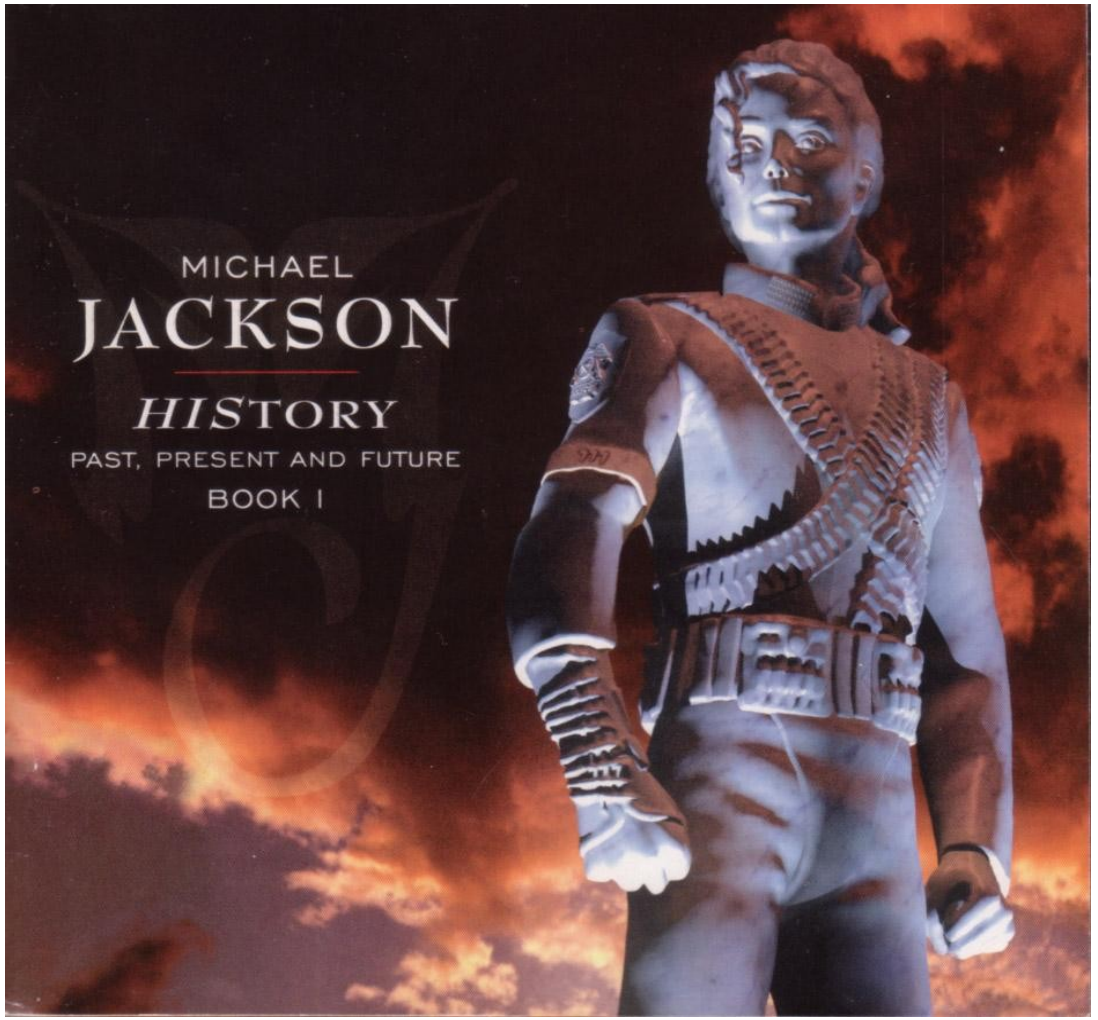
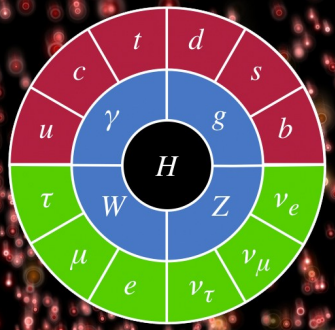
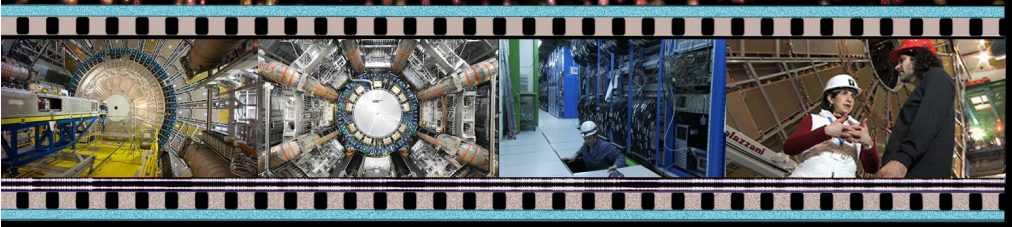


Physicists are on the cusp of the greatest scientific discovery of all time -- or perhaps their greatest failure.





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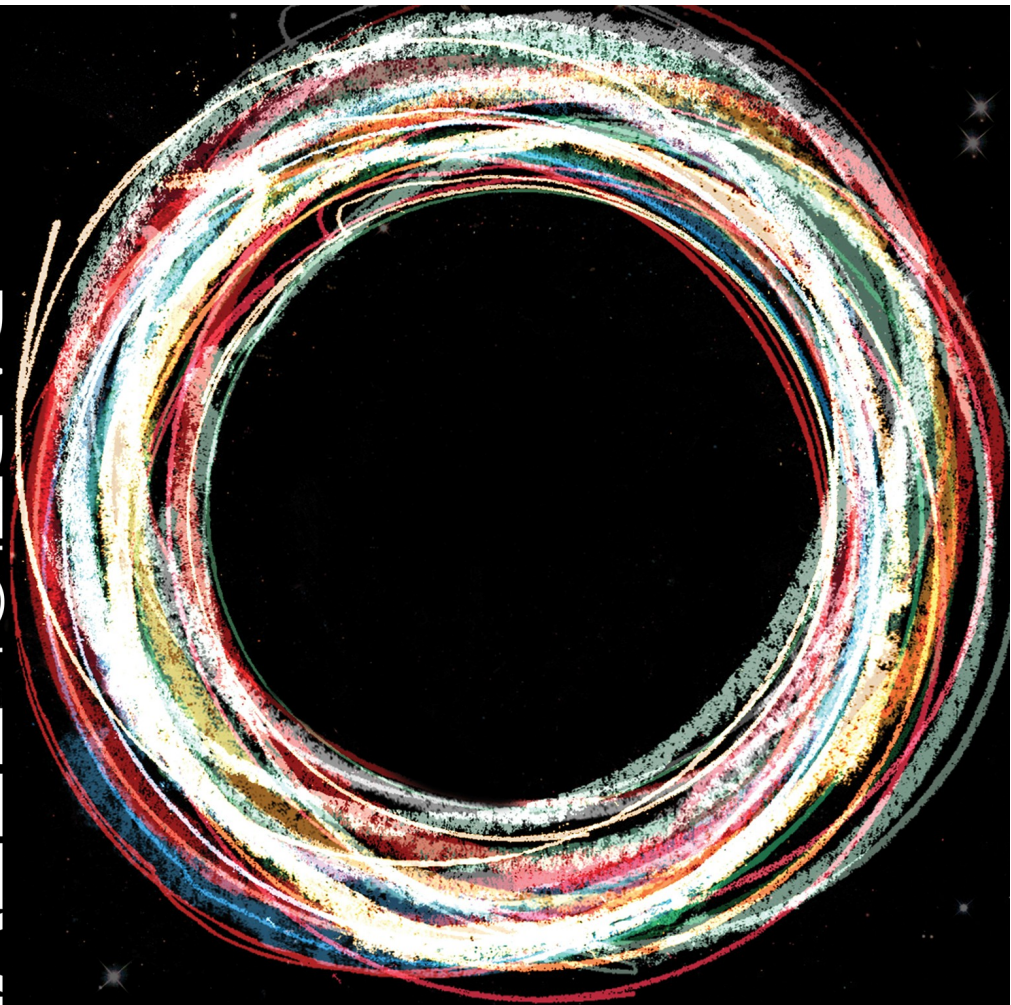

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WITH ONE SWITCH, EVERYTHING CHANGES

DVD VIDEO


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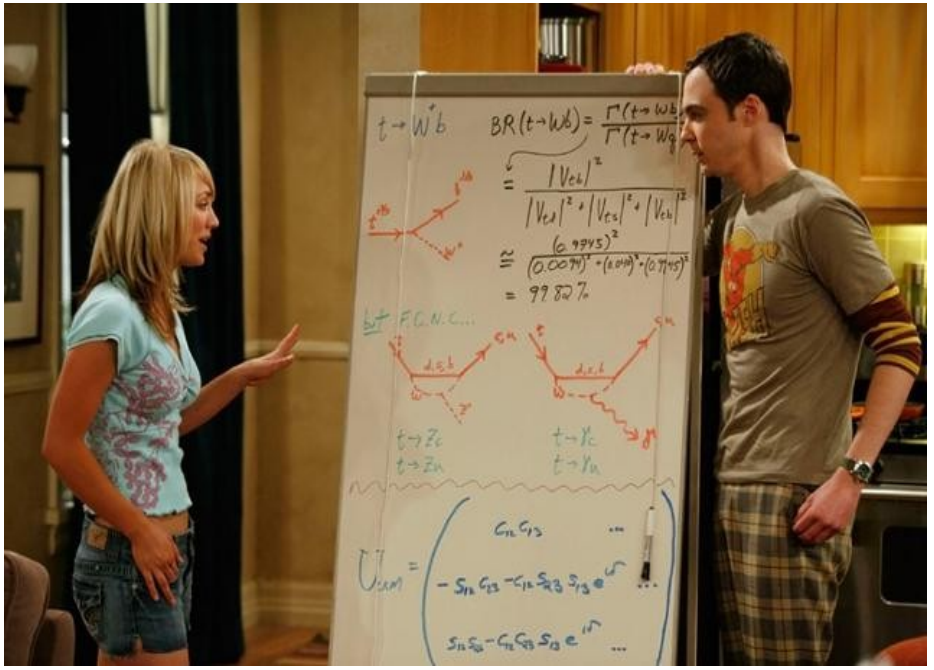
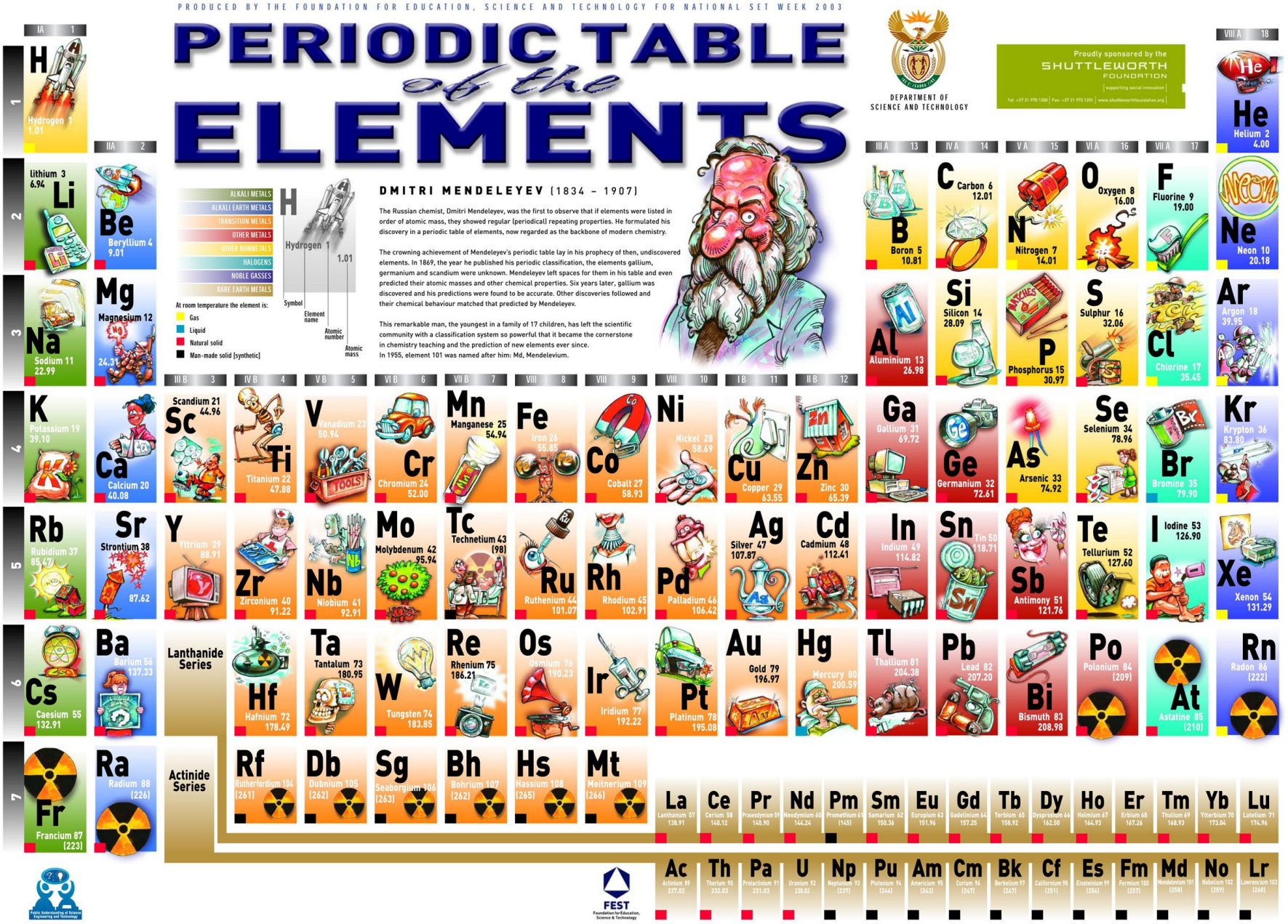
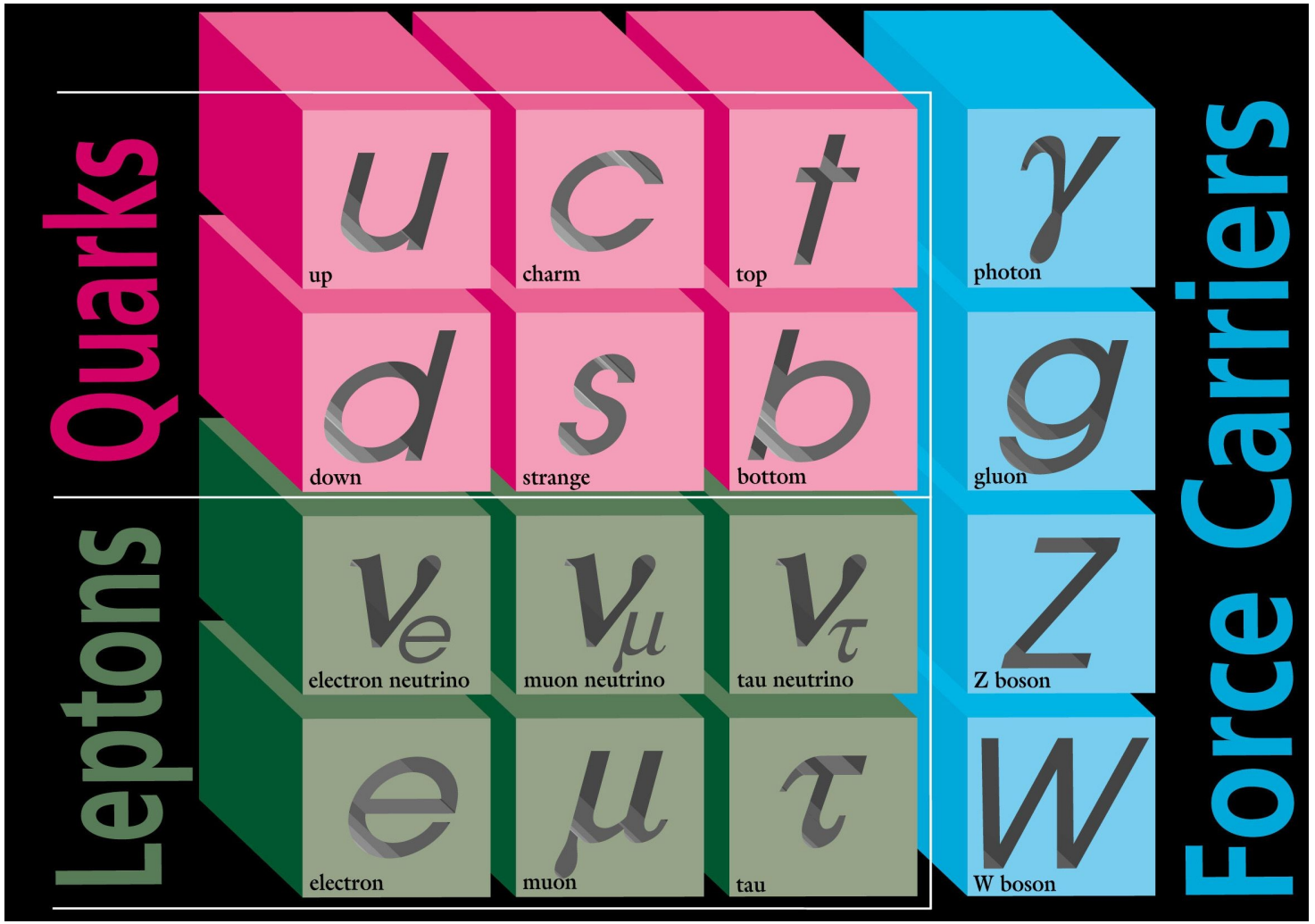

t → W b
BR(t → Wb) = Γ(t → Wb) / Γ(t → Wq)
= |Vtb|² / (|Vtd|² + |Vts|² + |Vtb|²)
≅ (0.9995)² / (0.0074)² + (0.0008)² + (0.9995)²
= 99.82 %
but F.C.N.C...
t → Zc
t → Zu
t → γc
t → γu

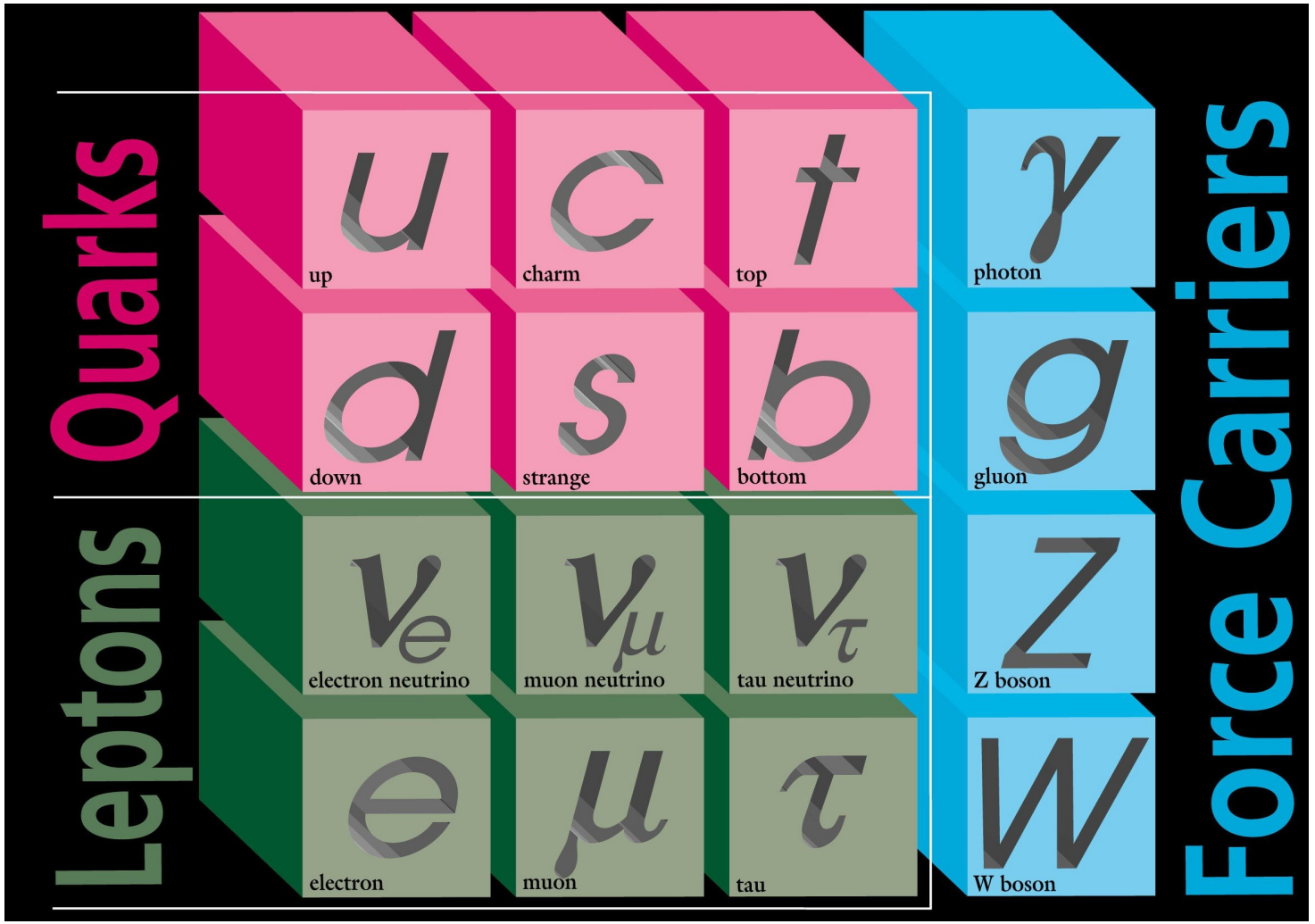
Stavební kameny chemie



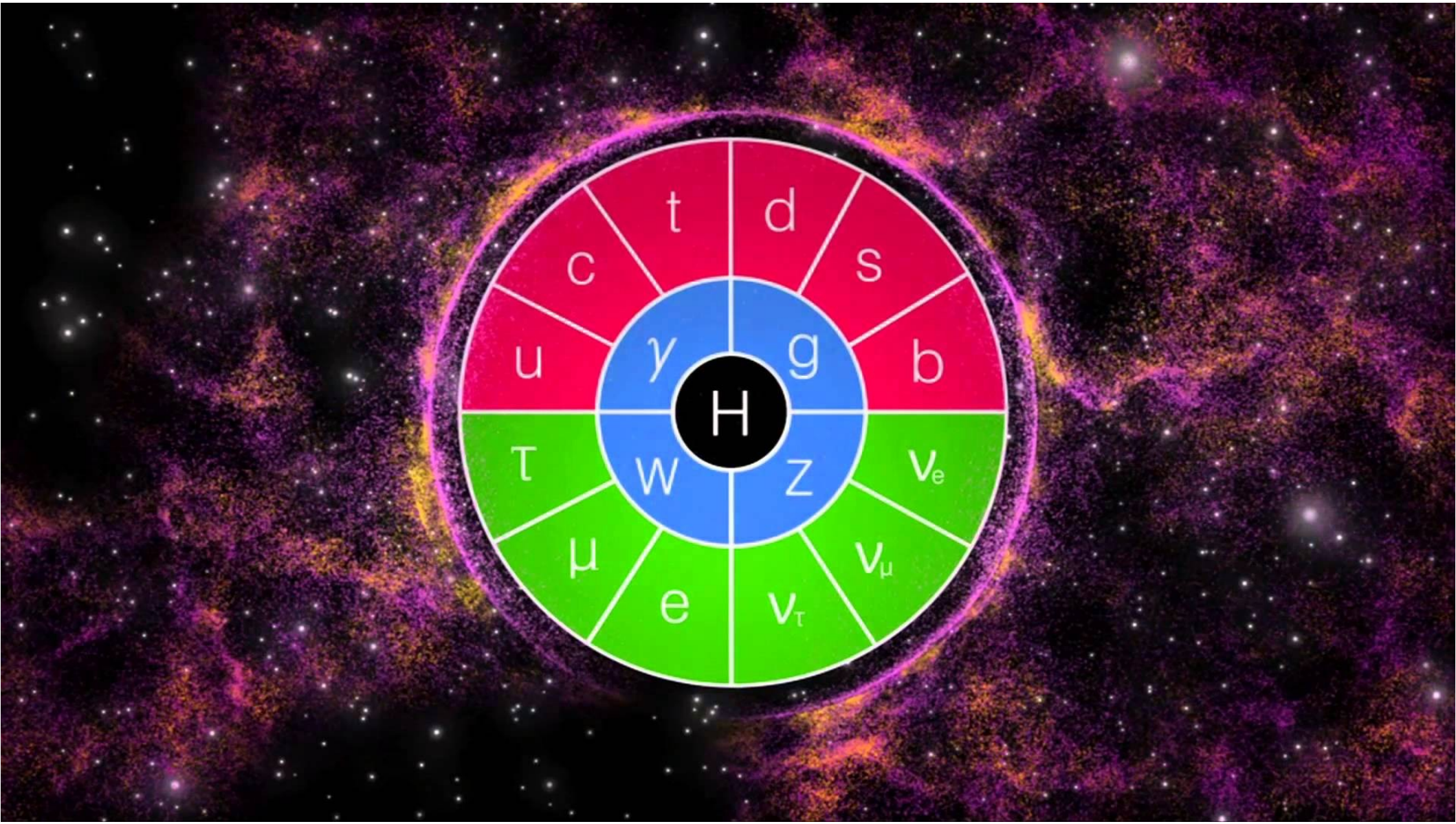
Stavební kameny fyziky



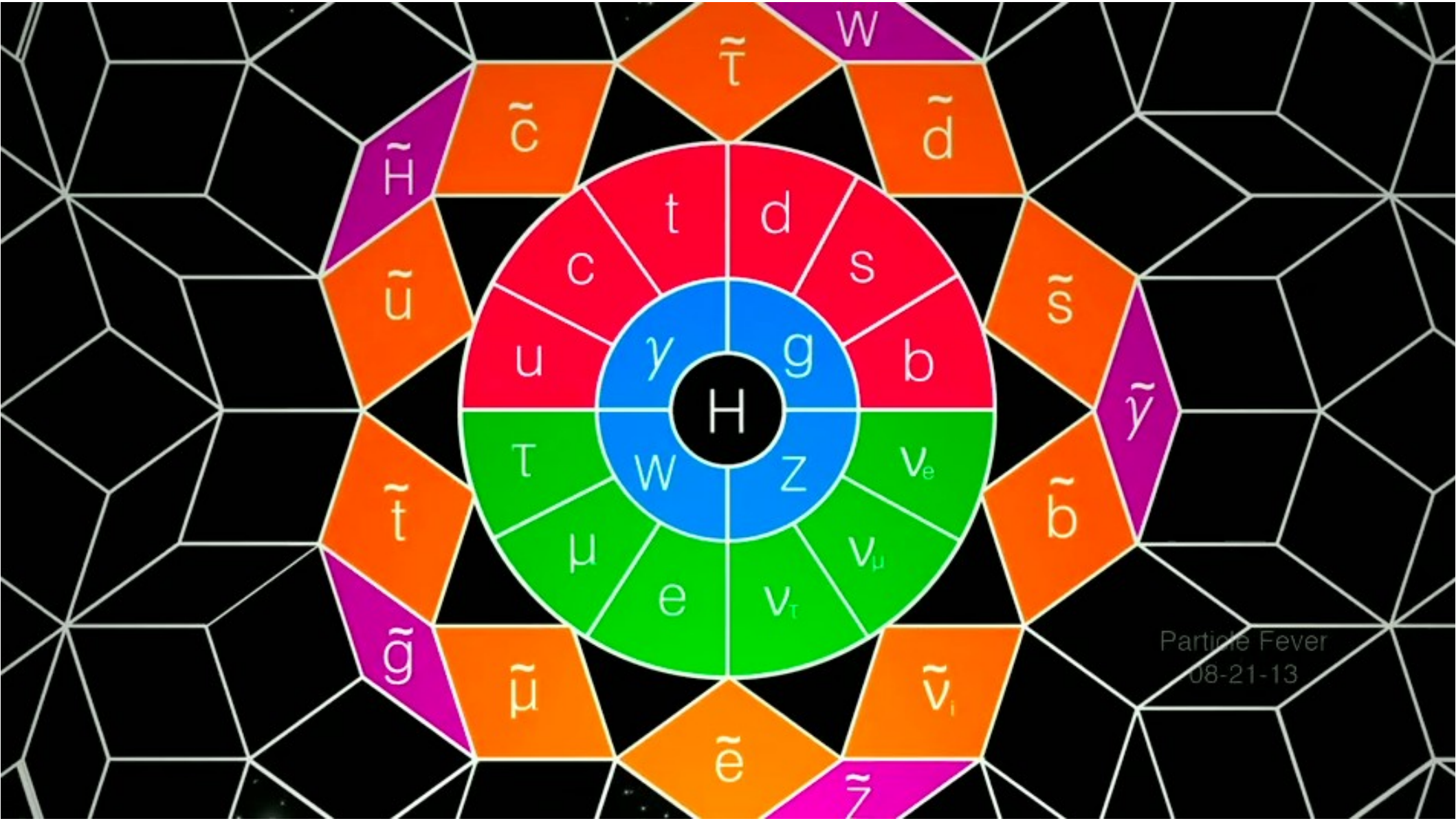
Stavební kameny fyziky



Stavební kameny fyziky



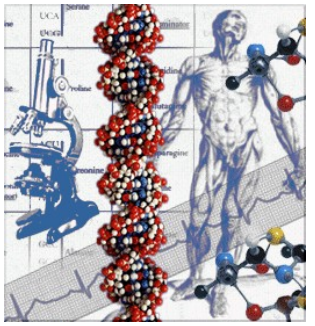
Stavební kameny fyziky



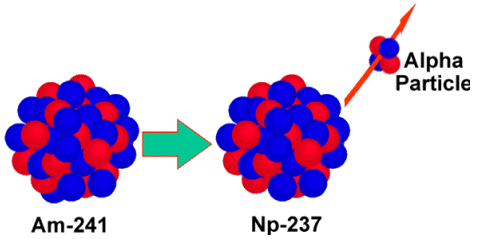
Síly (interakce) v přírodě

- **Gravitační** – makroskopická tělesa, Vesmír.

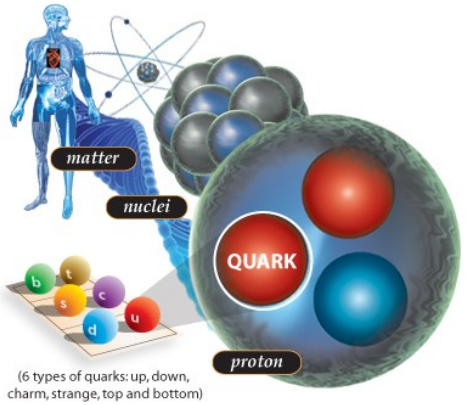
- **Elektromagnetická** – stavba atomu, chemie, život.



- **Slabá** – radioaktivita, procesy hoření ve Slunci.

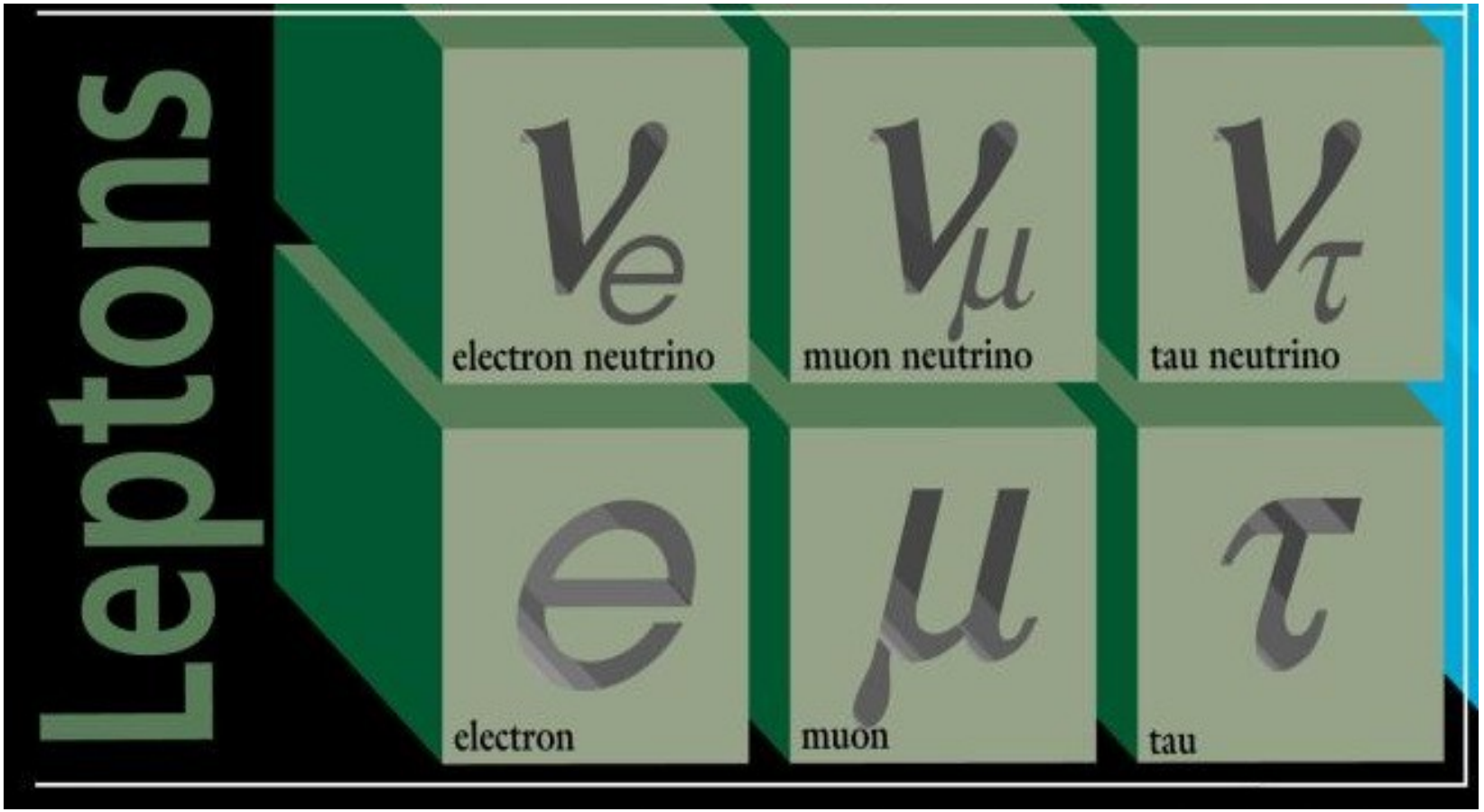


- **Silná** – stavba atomového jádra, interakce mezi nukleony, hlouběji mezi kvarky.



Leptony

- řecky $\lambda\varepsilon\pi\tau\acute{o}\varsigma$ - drobný

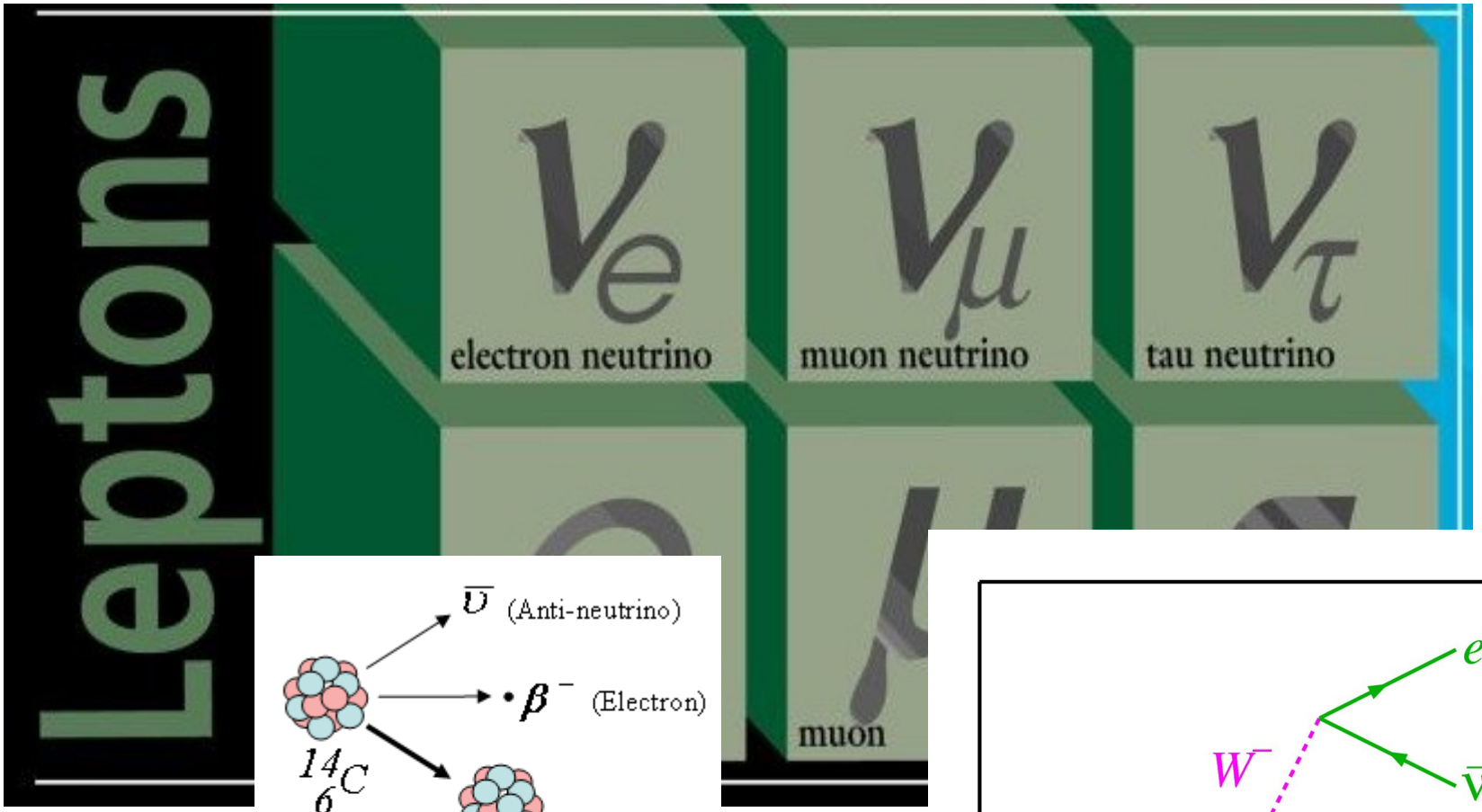


Q = 0

Q = - |e|

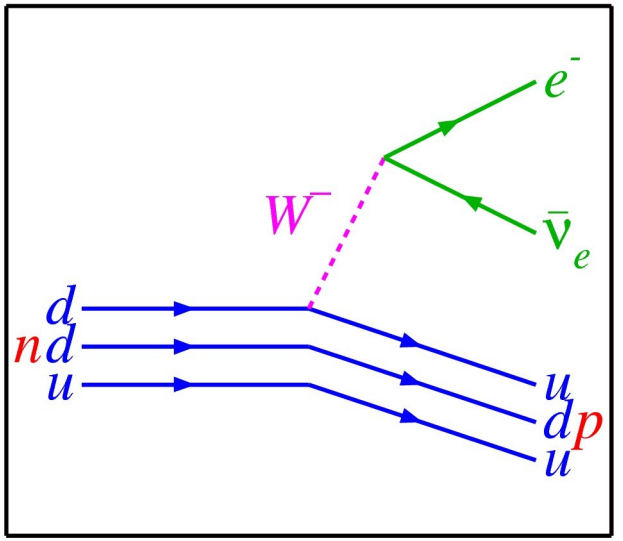
Leptony

- řecky $\lambda\varepsilon\pi\tau\acute{o}\varsigma$ - drobný

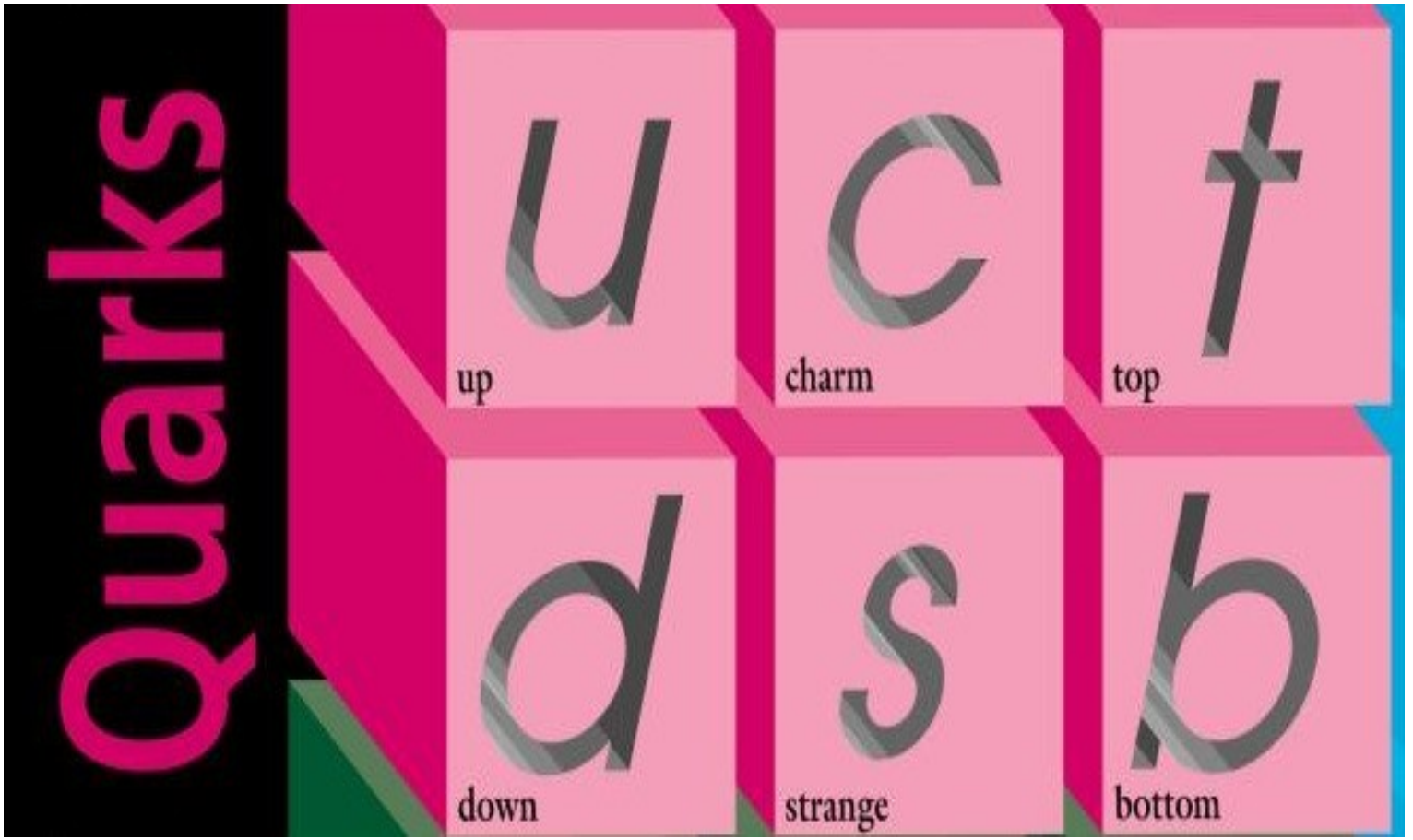


Q = 0

Q = - |e|



Hadrony: částice z kvarků



Q = +2/3 |e|

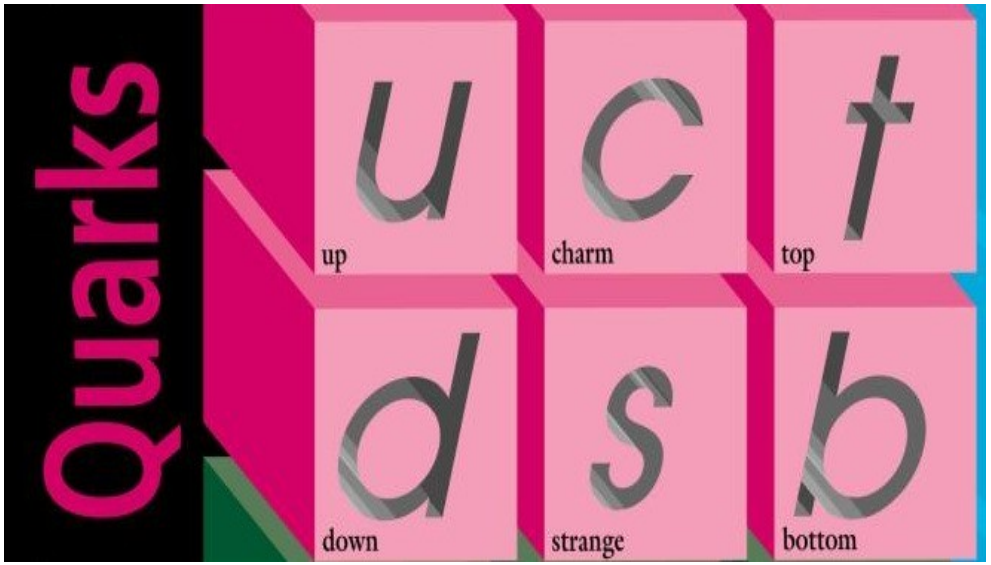
Q = -1/3 |e|

Hadrony: částice z kvarků

- Hadrony -- částice složené z kvarků.
- Účastní se silné interakce – drží pohromadě atomové jádro.

- Proton či neutron jsou příkladem **baryonů** (řecky $\beta\alpha\rho\acute{\upsilon}\varsigma$ - těžký), částic složených ze tří kvarků, které mají polocelý spin (fermiony).

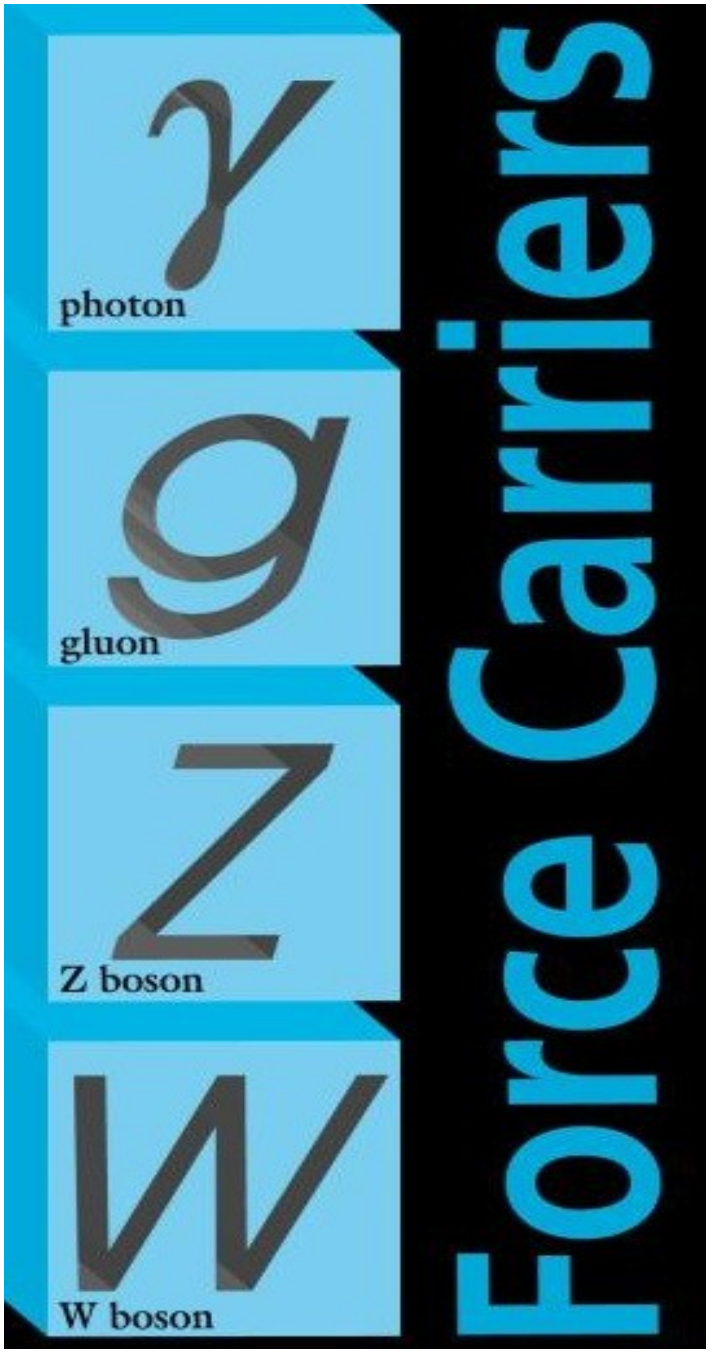
- Piony patří mezi **mezony** (řecky $\mu\acute{\varepsilon}\sigma o\varsigma$ - střední), skládajíce se z páru kvark-antikvark, které mají celočíselný spin (bosony).



Q = +2/3 |e|

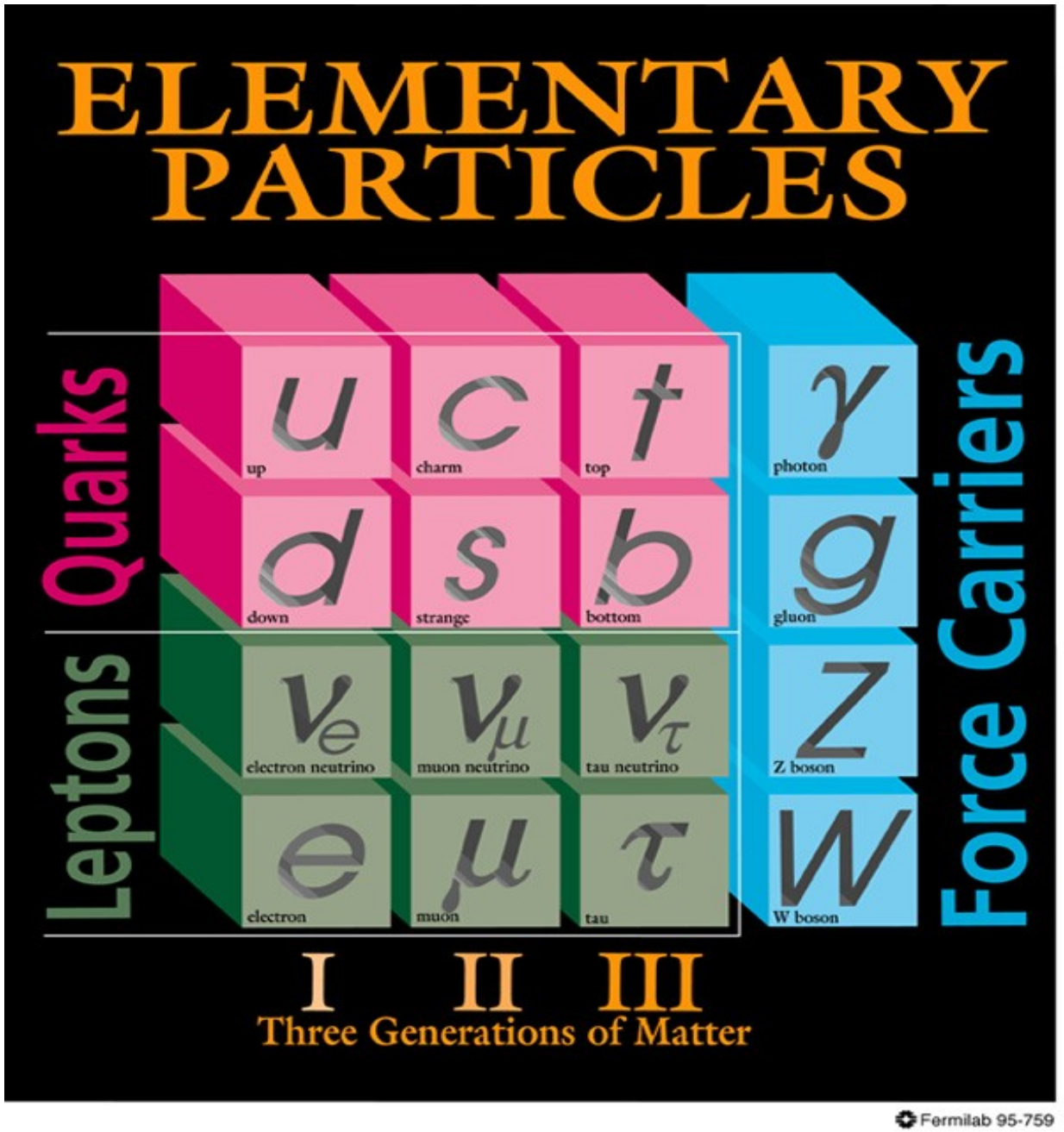
Q = -1/3 |e|

Výměnné částice sil



Higgsův boson

Leptony, Kvarky, Kvanta polí



Leptony, Kvarky, Kvanta polí

Částice:

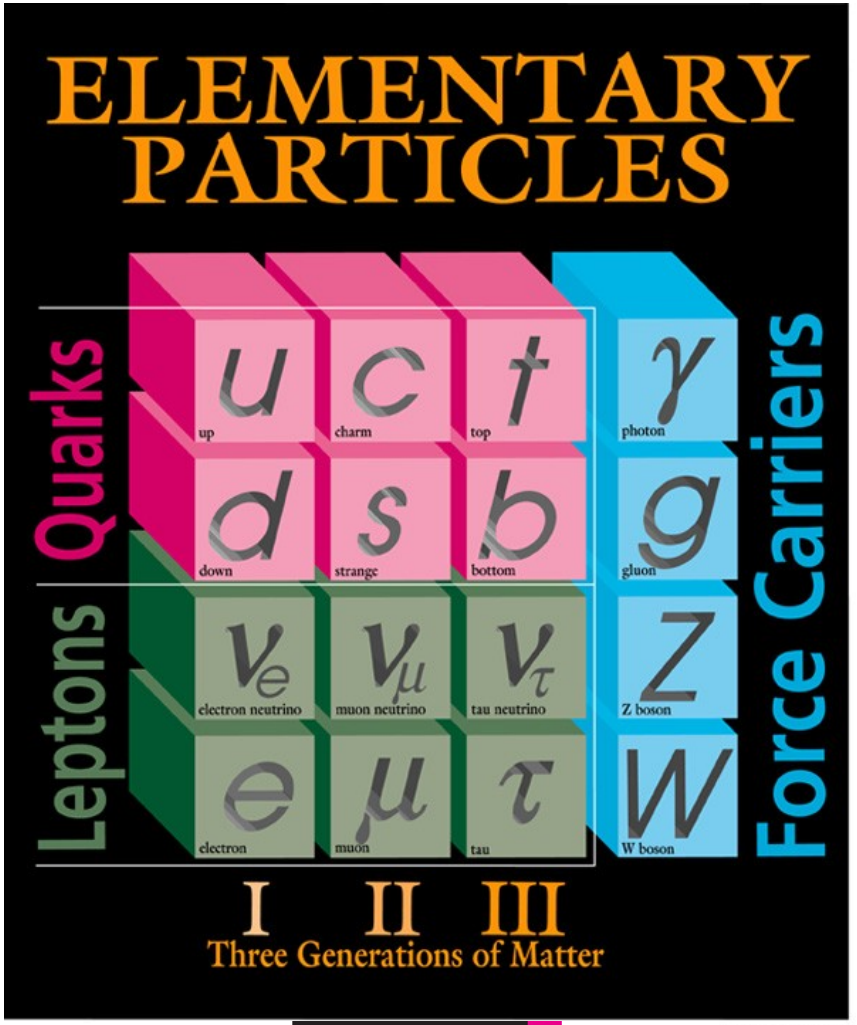
- **Leptony**: elektron a neutrino + dvě další rodiny
- **Kvarky**: tvoří hadrony
  - mezony: kvark+antikvark (piony)
  - baryony: 3 kvarky (proton, neutron)

- **Intermediální bosony** – $W^{\pm}$, Z, γ, 8 gluonů.

Higgsův boson: zodpovědný za hmotnosti částic.

Síly (interakce):

- Gravitační
- Slabá + Elektromagnetická = Elektroslabá
- Silná
- Interakce s Higgsovým bosonem.



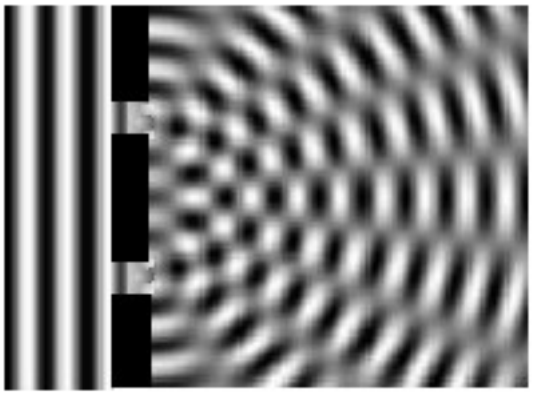
Částice

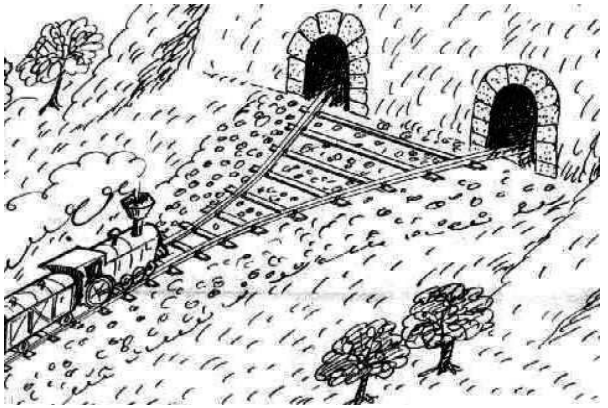
- **Elementární částice**: bez vnitřní struktury, bodové: elektron, foton, neutrino…

- **Částicové ZOO je plné částic složených**:
  proton a neutron tvořeny kvarky.

Kuličky, ale i vlny: umějí interferovat, ale také třeba z obalu atomu vyrazit elektron či způsobit zčernání zrna na fotopapíře.

Mikrosvět je popsán **kvantovou mechanikou.**
Běžnému životu podivuhodné věci: elektron v atomu může mít jen určité hodnoty energie, nelze přesně současně říci, kde elektron je a jakou má rychlost (relace neurčitosti).

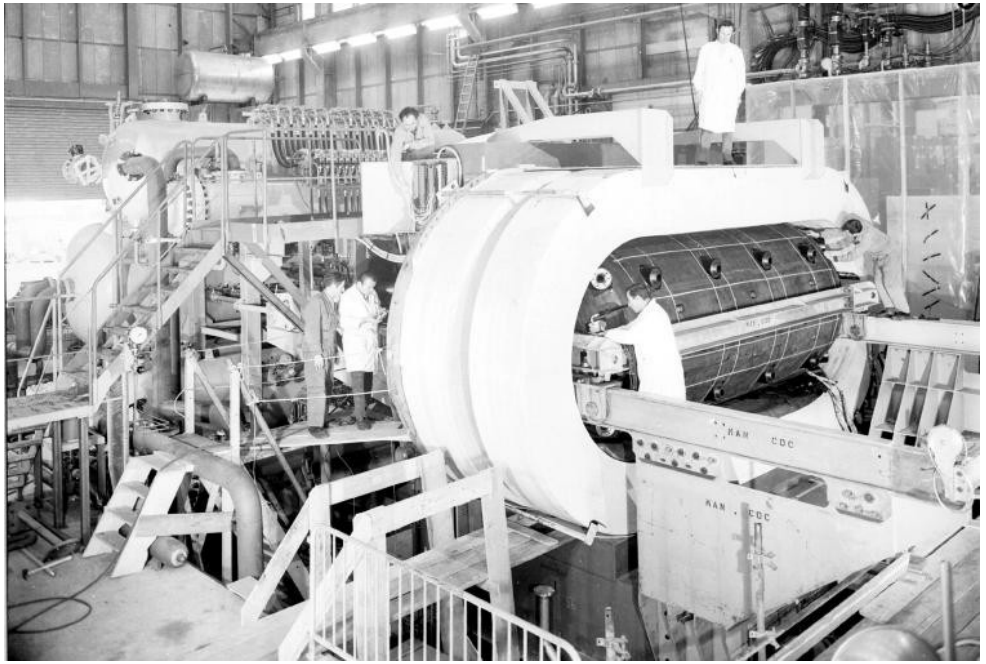


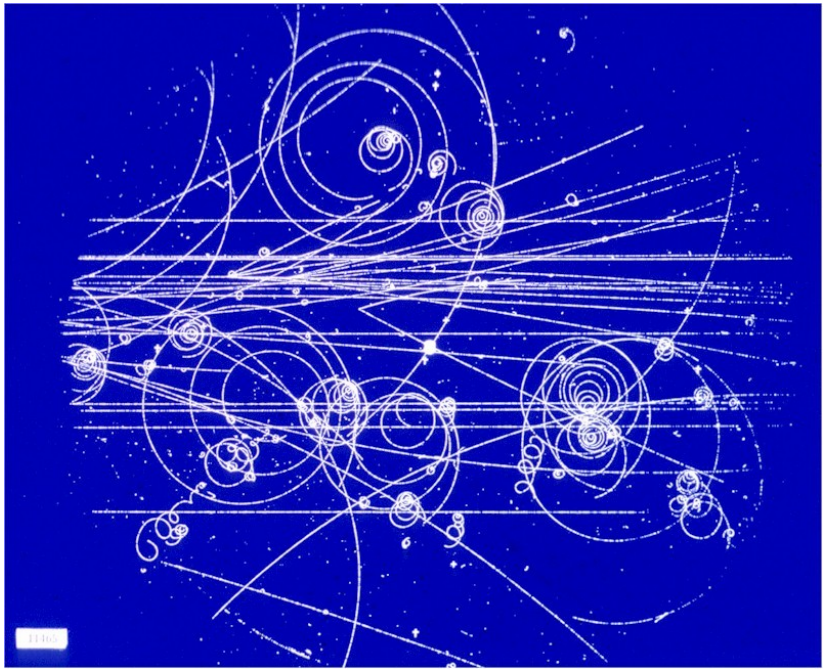


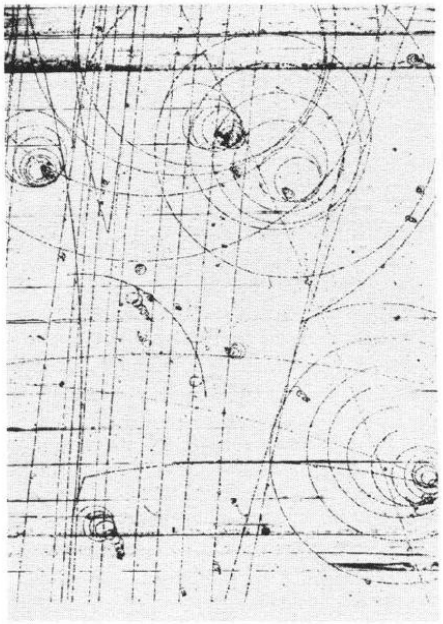
Jak částice vypadají?

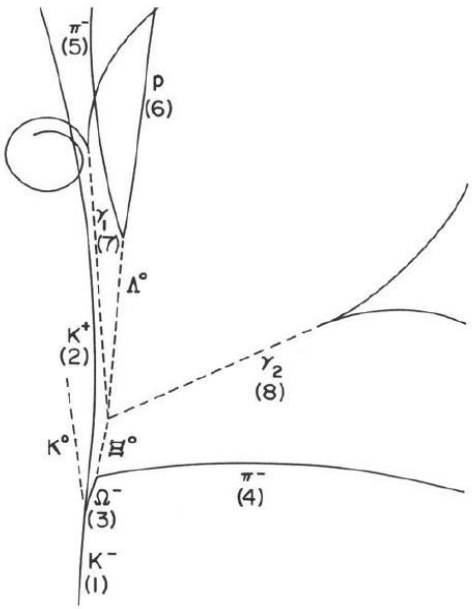
Bublinová komora

Bublinová komora





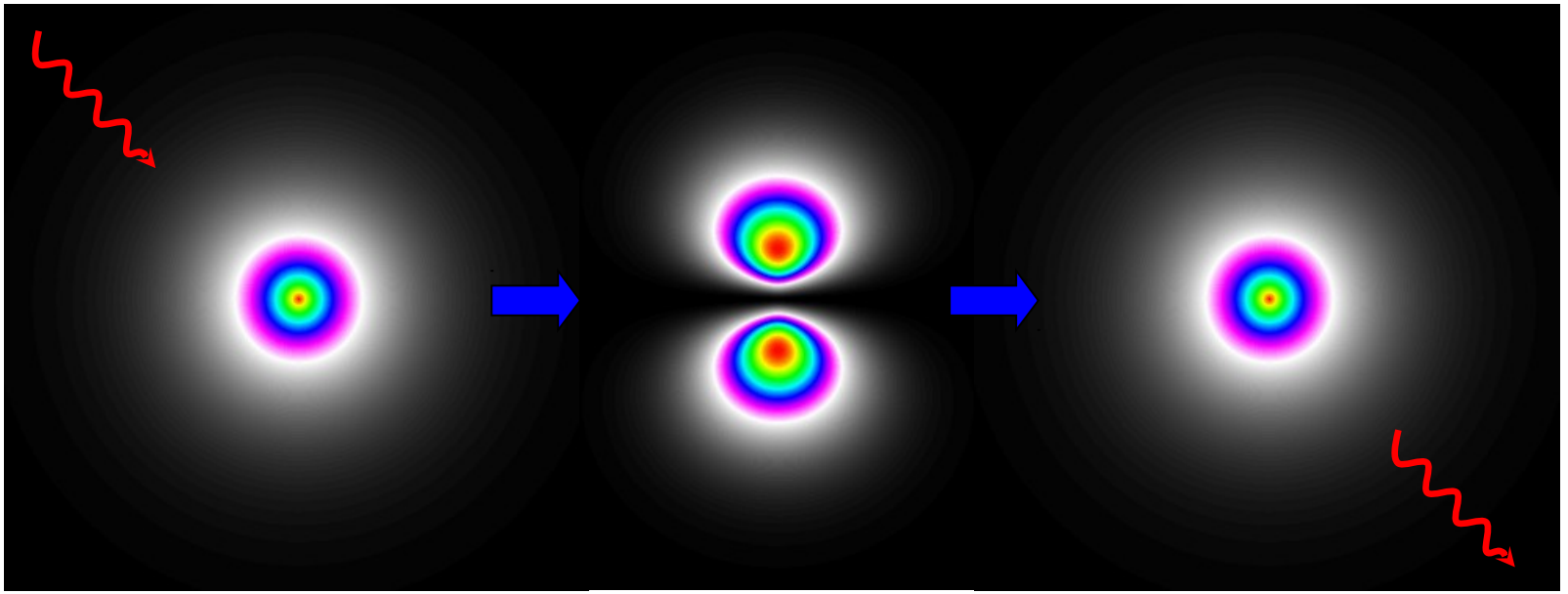


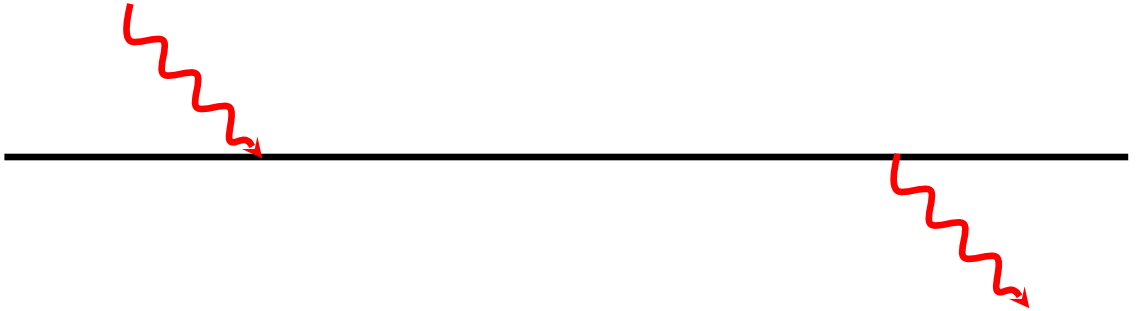


Takto by to ale dále dlouho nešlo…
(ruční prohlížení fotografií)

Interakce I

- Excitace atomu fotonem a opětovná emise.
- Částice vznikají a zase zanikají – na rozdíl od objektů v běžném světě!





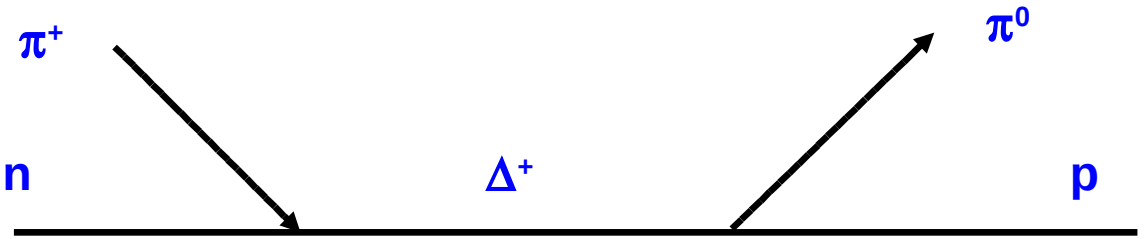
Interakce II

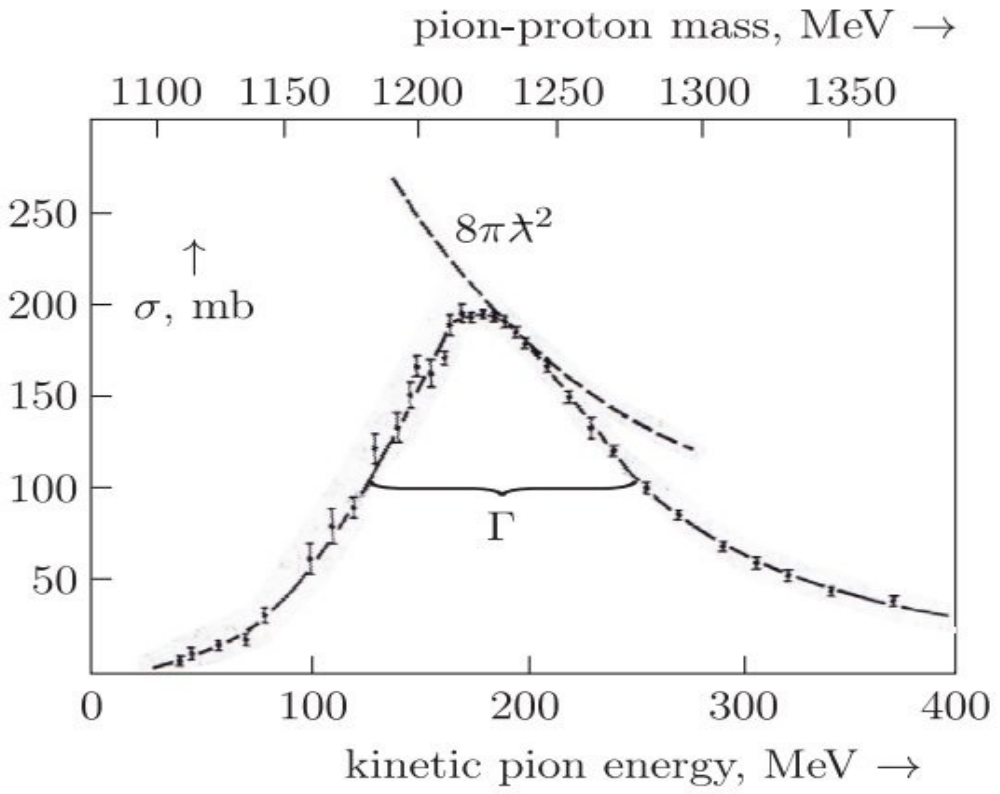
- Částice zvané **piony** lze připravit jednoduše ostřelováním terče:

  $p + p \rightarrow p\ n\ \pi^+\ \pi^- \cdots$

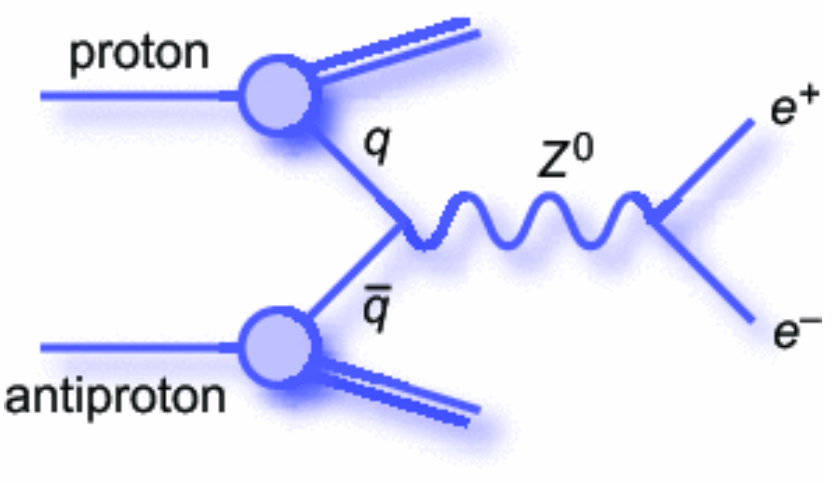
- Svazkem pionů pak můžeme zase střílet na další terč, může vzniknout krátce žijící částice (rezonance) zvaná **Delta**: **$\pi^+ n \rightarrow \Delta^+ \rightarrow \pi^+ n$**

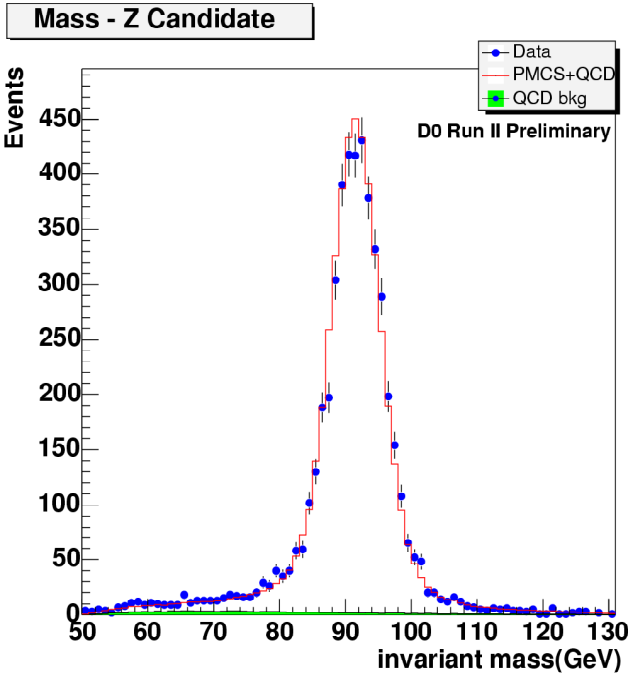
  Delta se může rozpadnou i na něco jiného: **$\pi^+ n \rightarrow \Delta^+ \rightarrow \pi^0 p$**

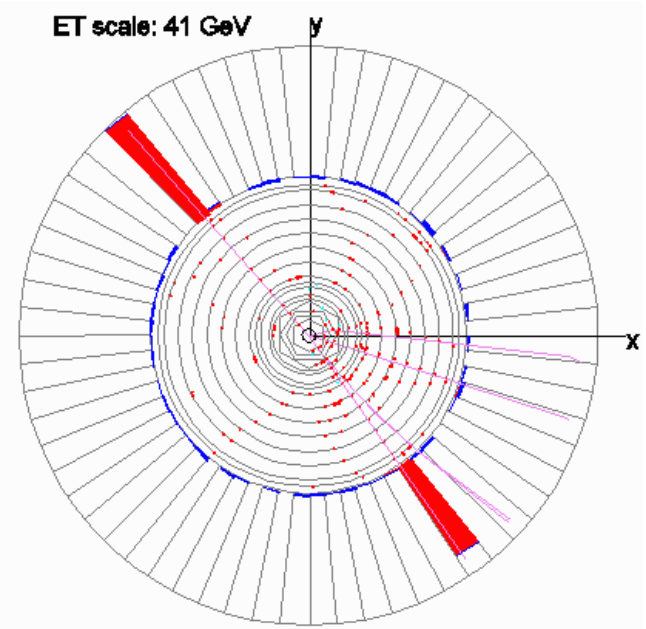


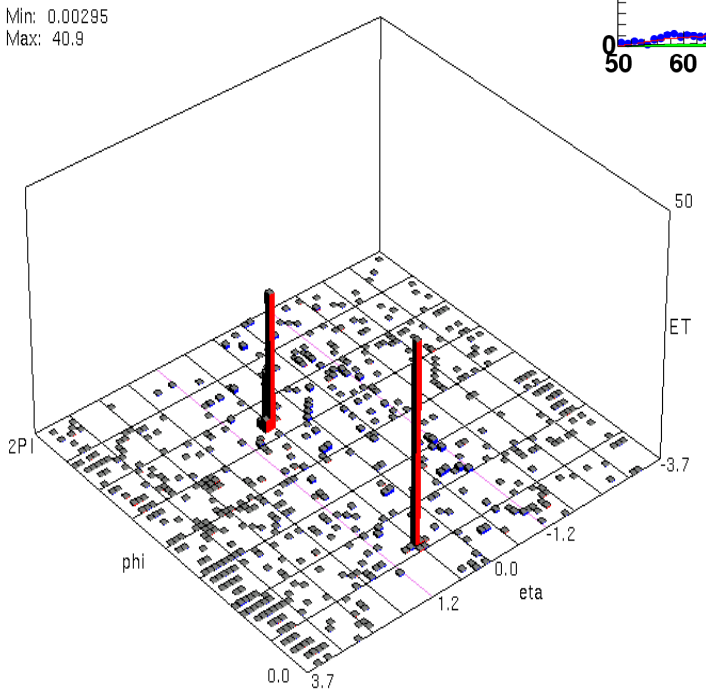


Interakce I: $qq \rightarrow Z \rightarrow e^+e^-$

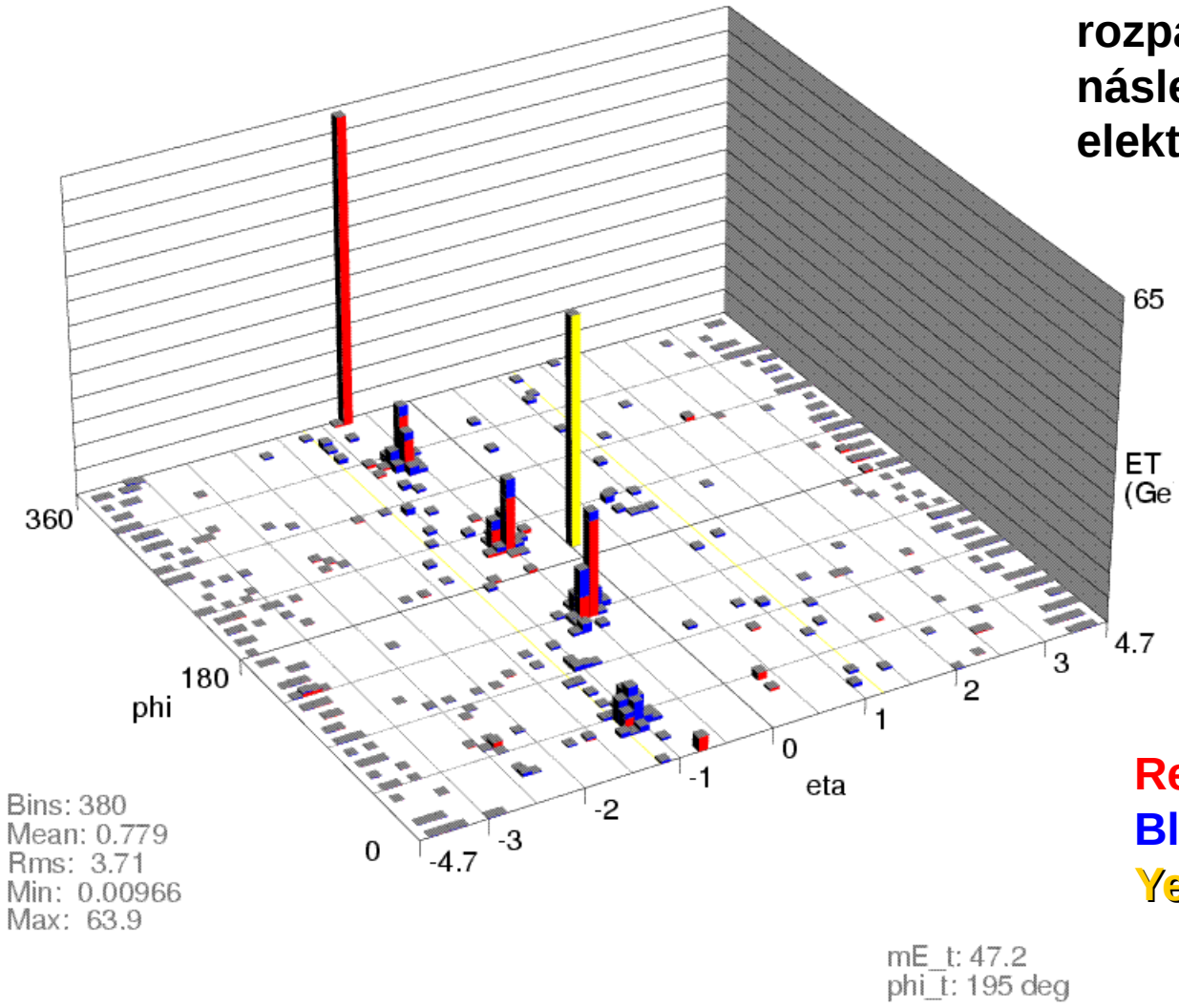




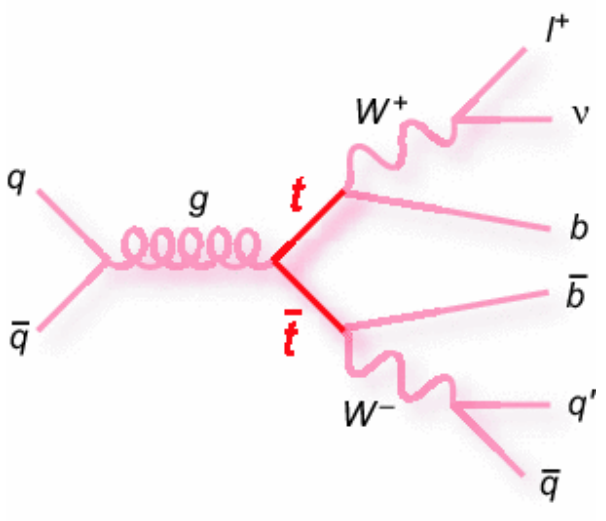




Interakce II
Top-antitop pár, jak viděno DØ Detektorem

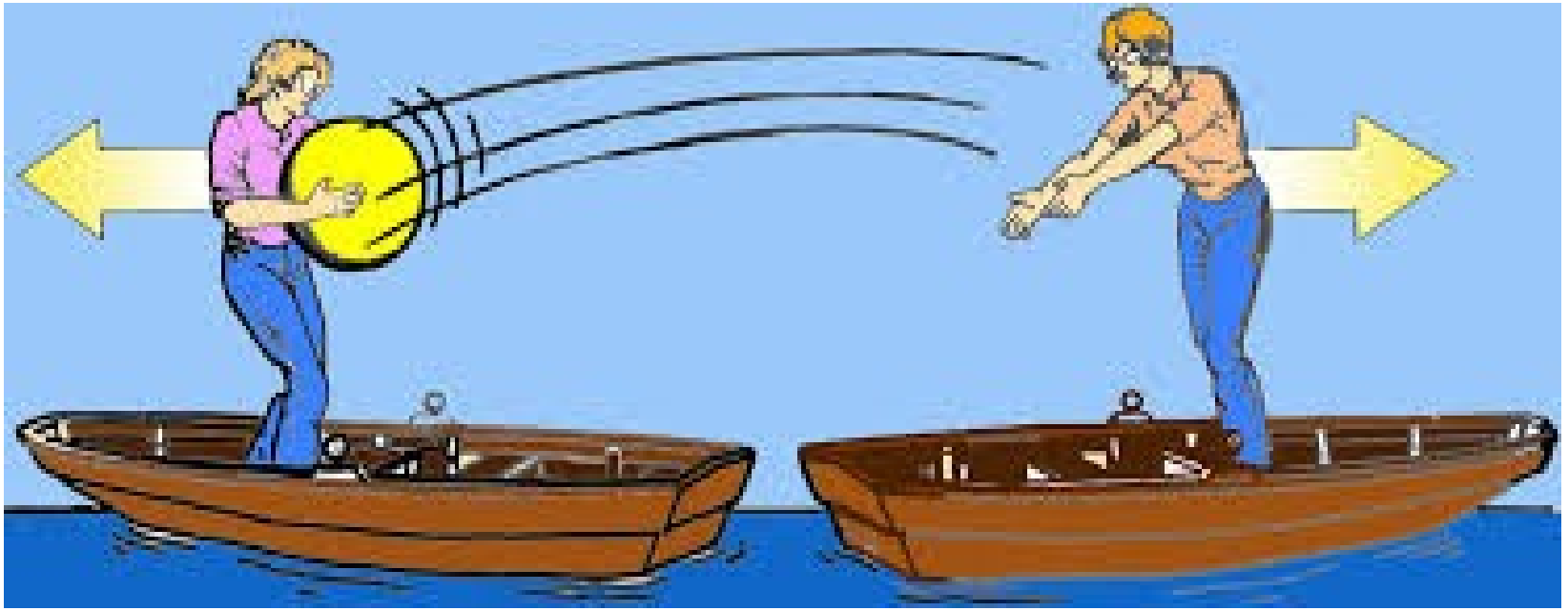


Pár top-anti top rozpadající se na *WbWb* a následně na 4 jety, elektron a neutrino.

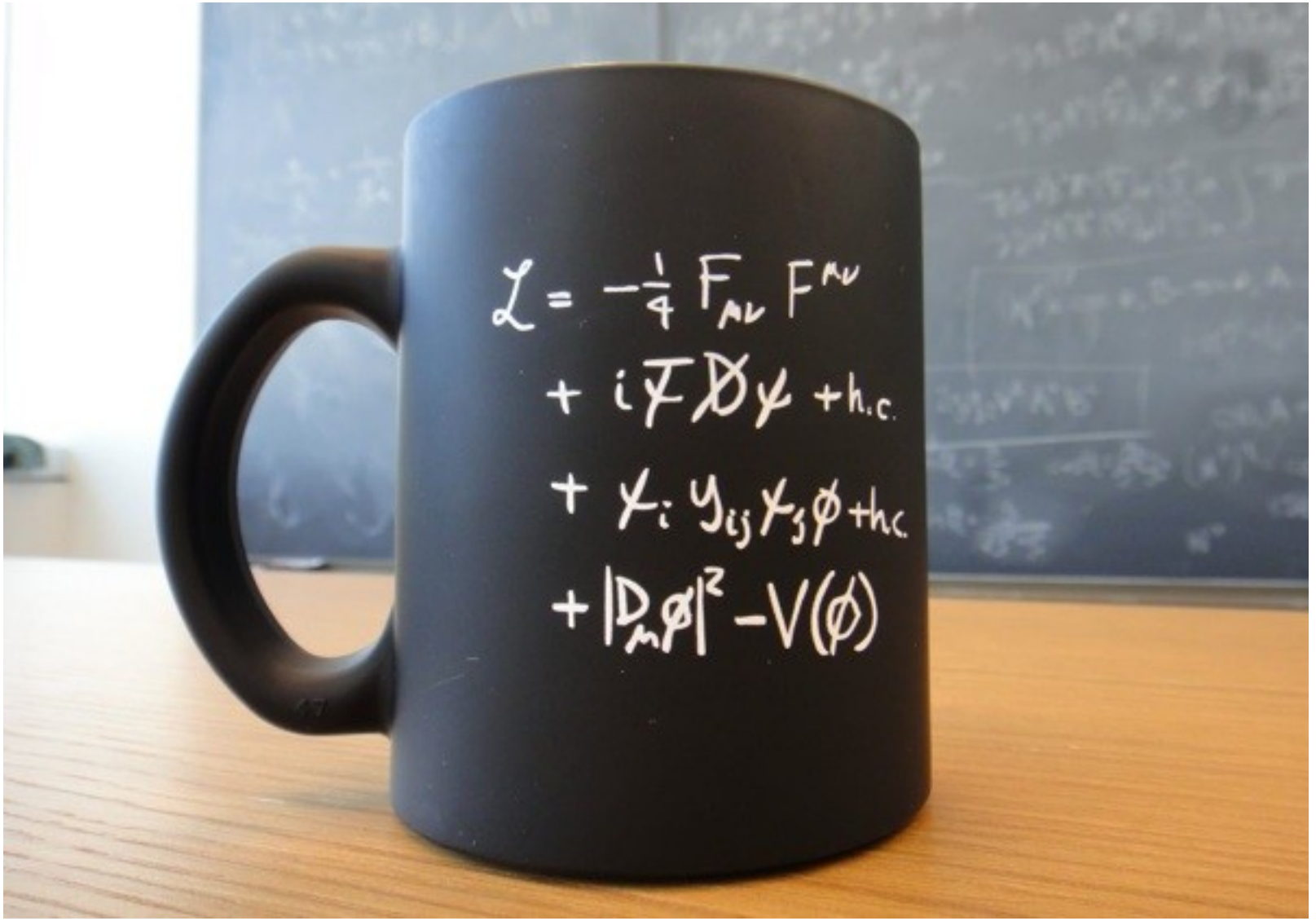


Red: EM Calorimeter
Blue: Hadronic Calorimeter
Yellow: Missing Energy (neutrino signature)

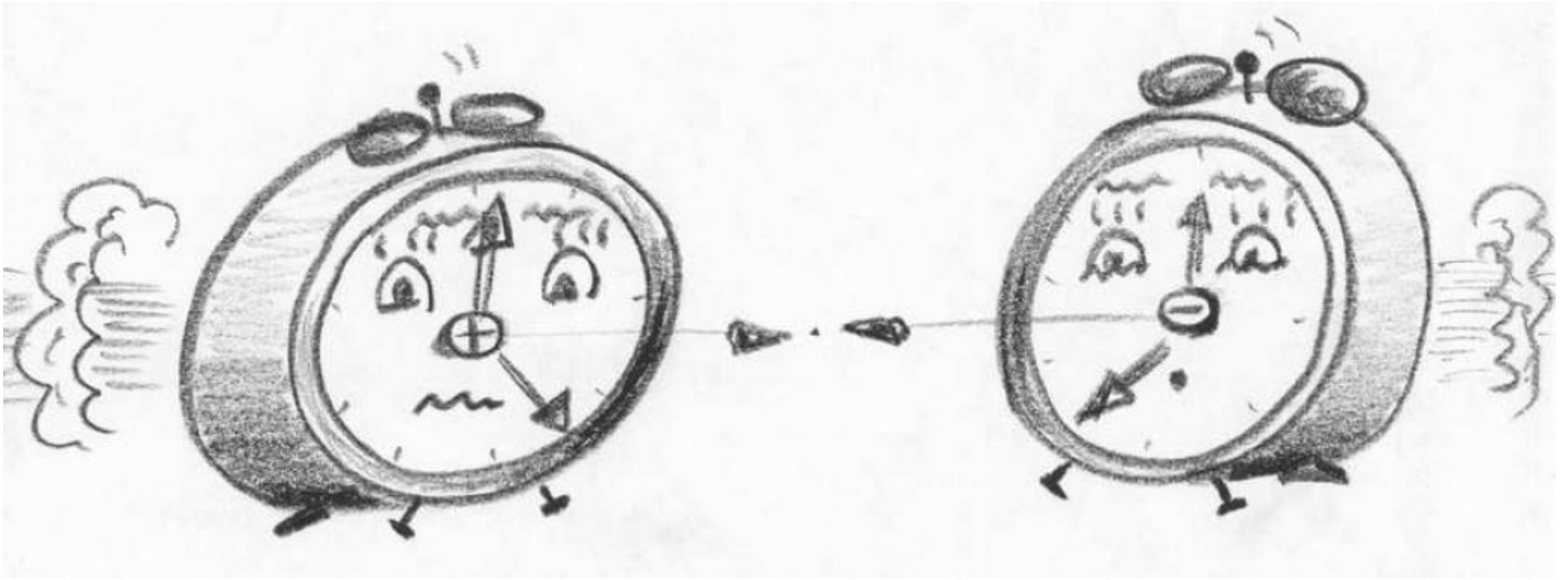
Interakce částic

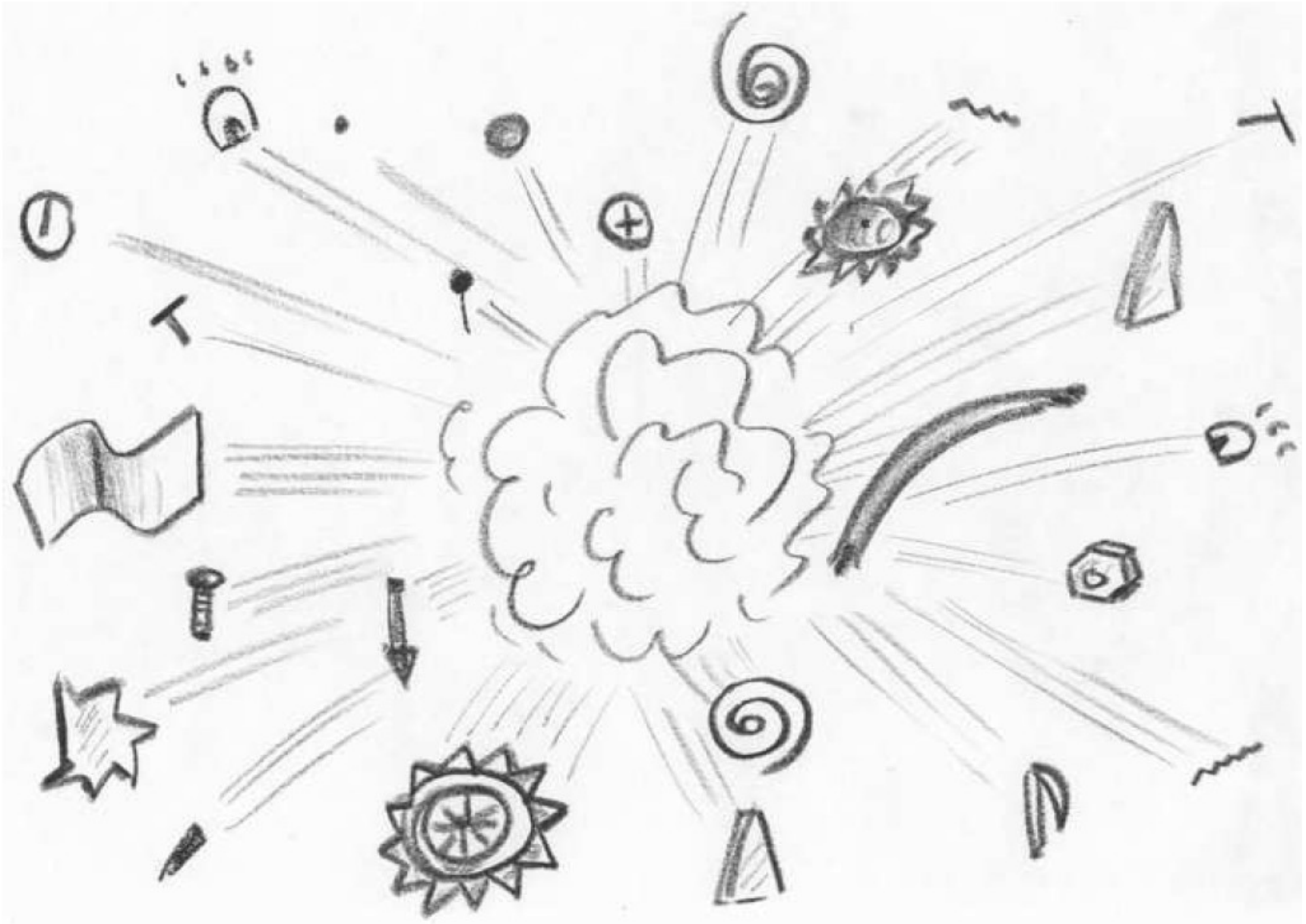


Interakce částic

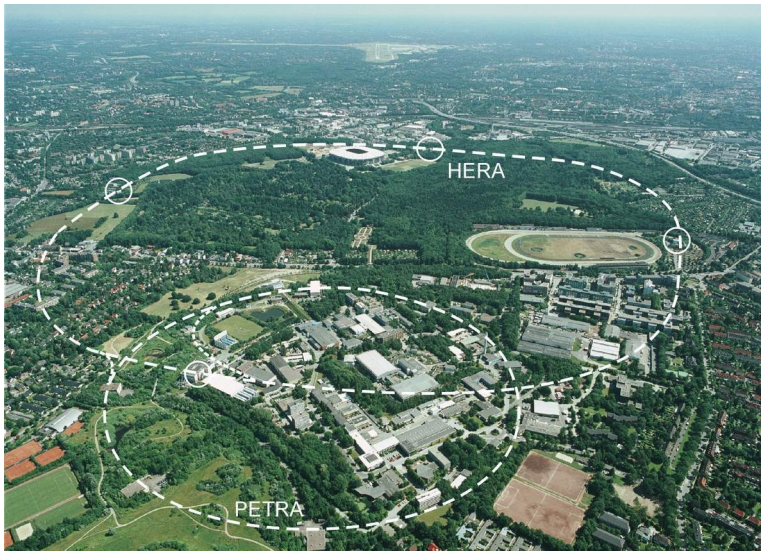


$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_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)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}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)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

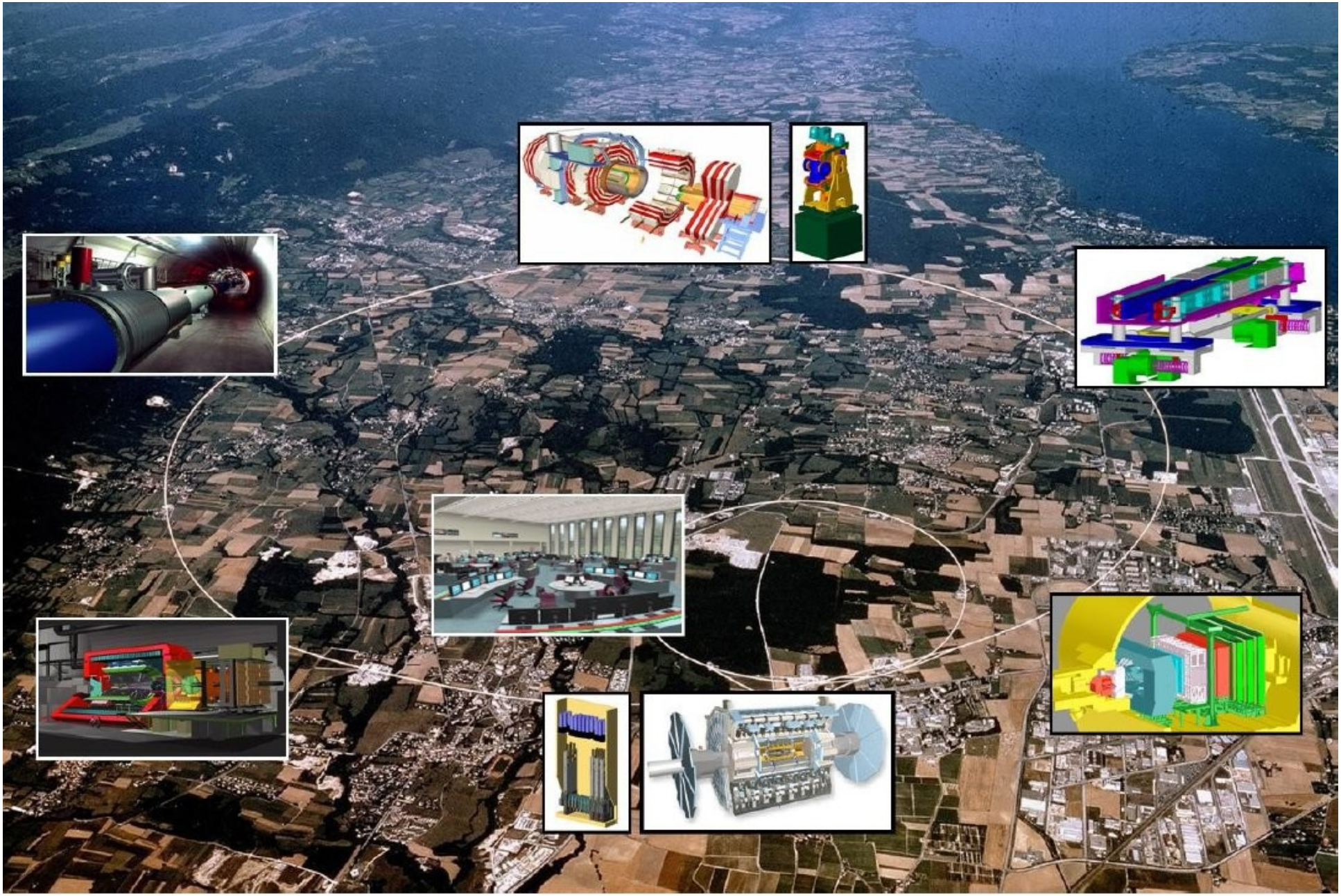




CERN, Fermilab, Brookhaven, DESY



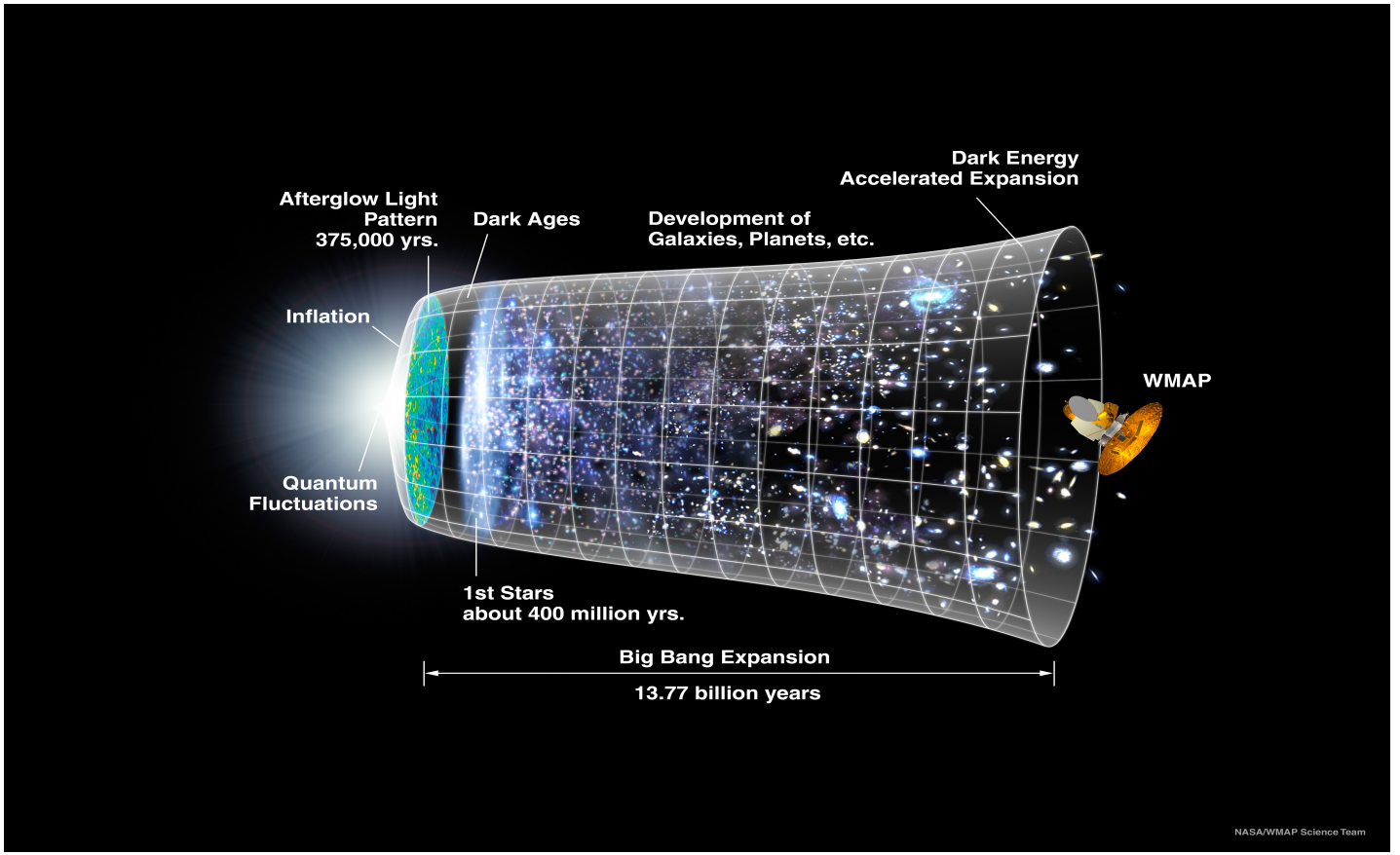
CERN



Co se v CERNu studuje?

- **Jaké jsou síly v přírodě?**
- **Kolik máme rodin částic?**
- **Proč tady jsme?**

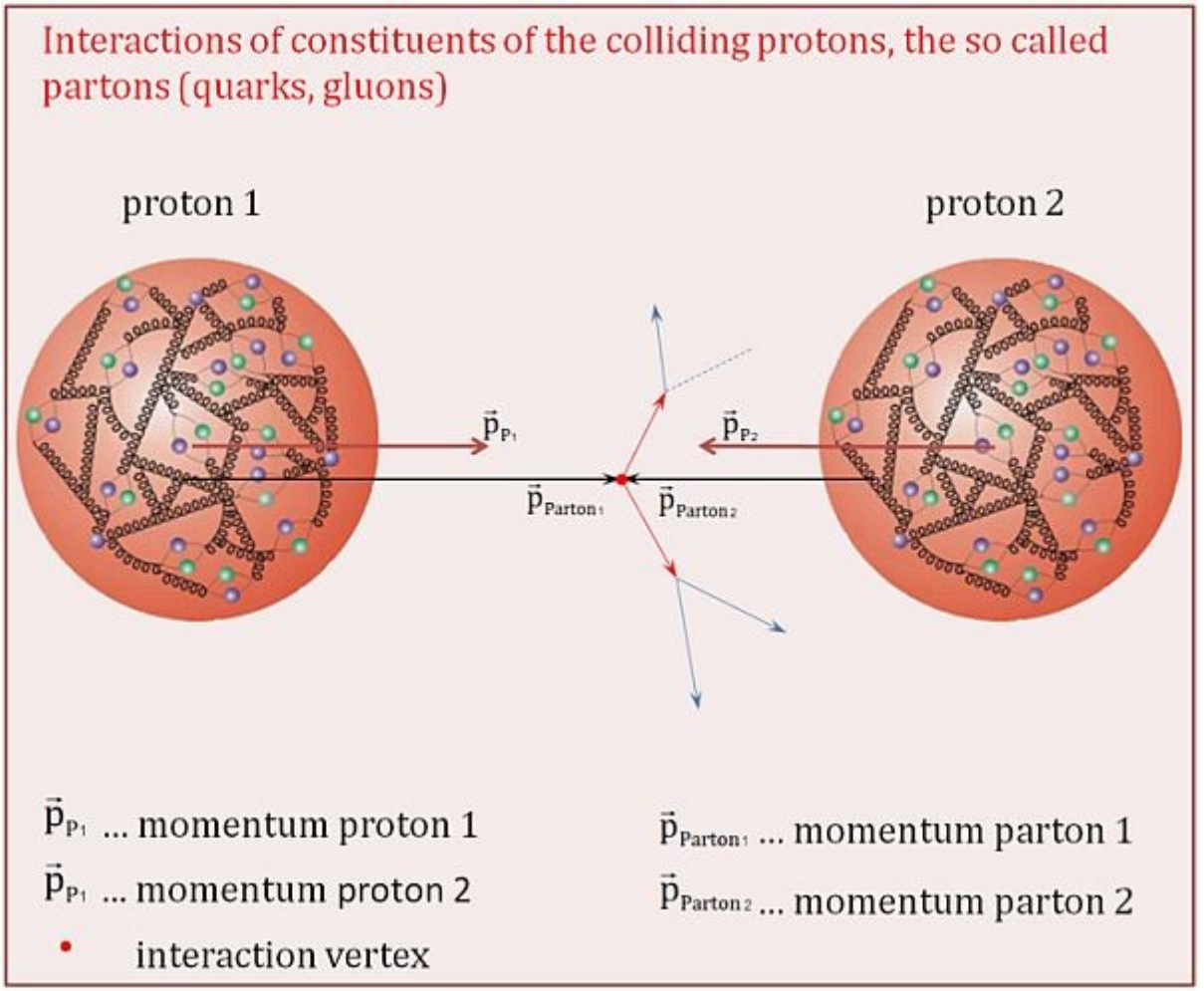
- **Proč je Vesmír z hmoty a ne z antihmoty?**
- **Co je to temná hmota a temná energie?**
- **Jsou další síly či částice v přírodě?**



LHC

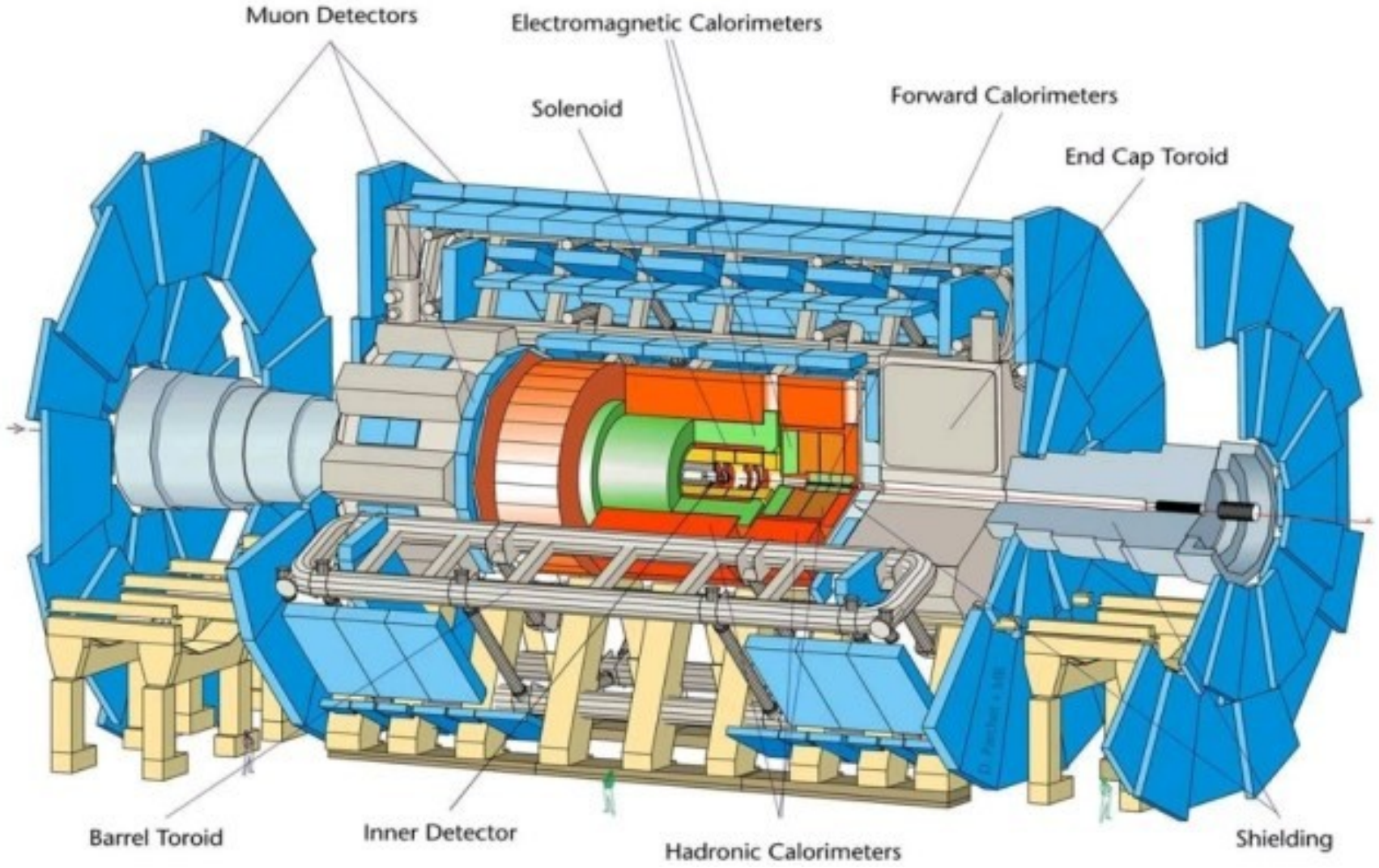
- Sráží protony při velkých energiích s frekvencí 40MHz pro hledání vzácných procesů, zatím neznámých částic, a vytváří podmínky jako těsně po Velkém třesku.

LHC

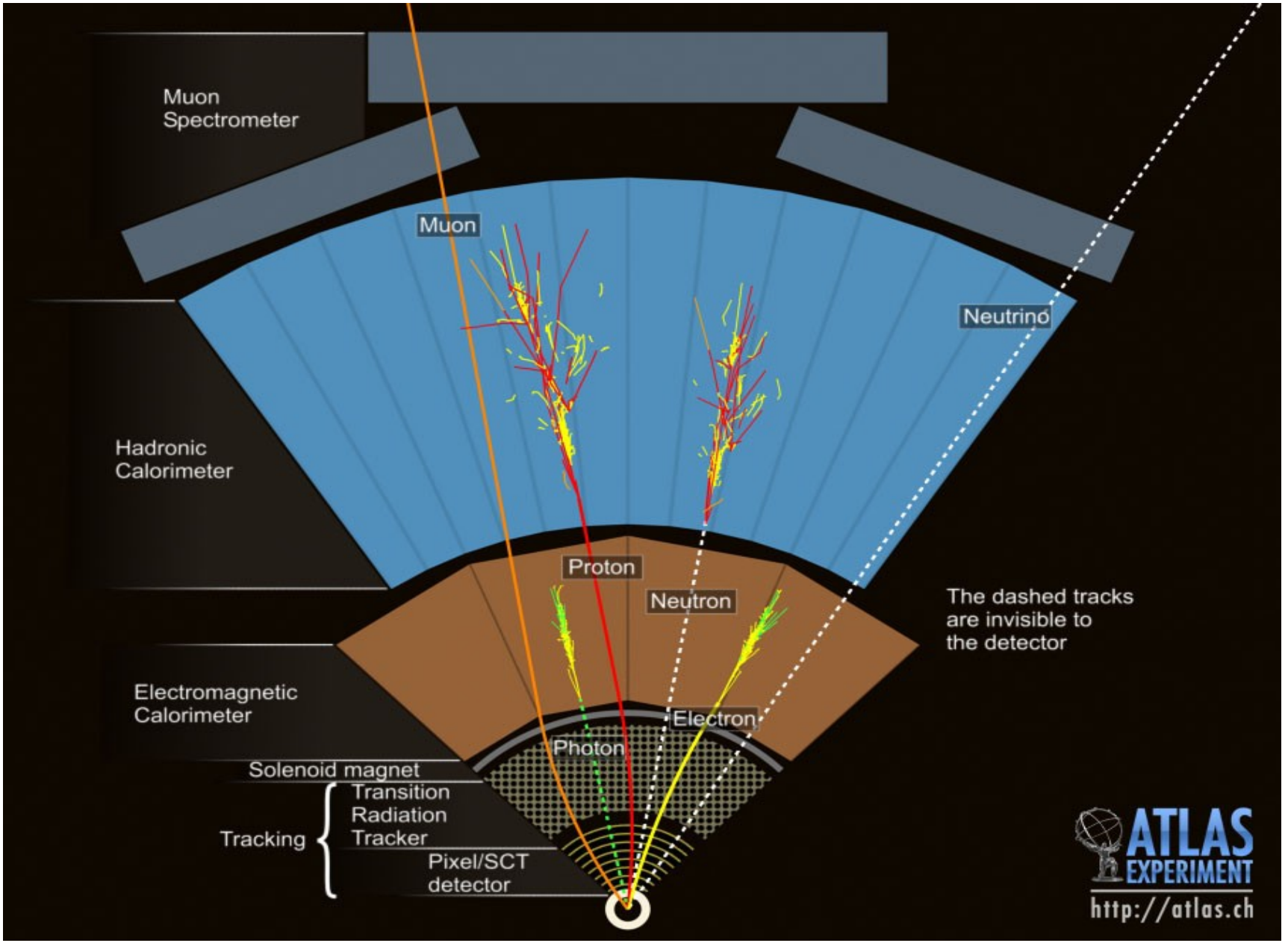

Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)
proton 1
proton 2
$\vec{p}_{P_1}$
$\vec{p}_{P_2}$
$\vec{p}_{Parton_1}$
$\vec{p}_{Parton_2}$
$\vec{p}_{P_1}$ ... momentum proton 1
$\vec{p}_{P_1}$ ... momentum proton 2
interaction vertex
$\vec{p}_{Parton_1}$ ... momentum parton 1
$\vec{p}_{Parton_2}$ ... momentum parton 2

ATLAS Experiment

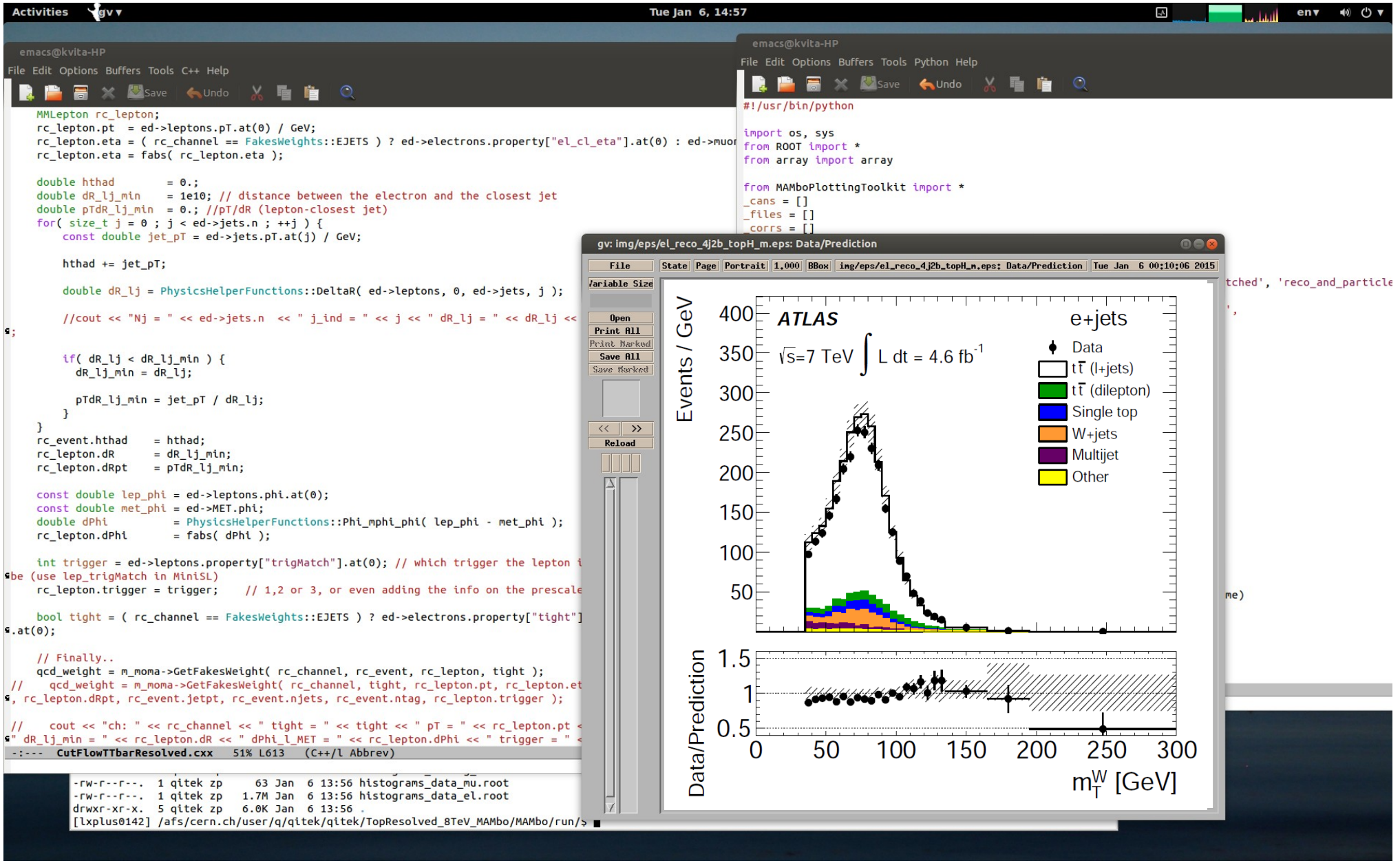
- Jeden ze dvou víceúčelových experimentů na urychlovači LHC



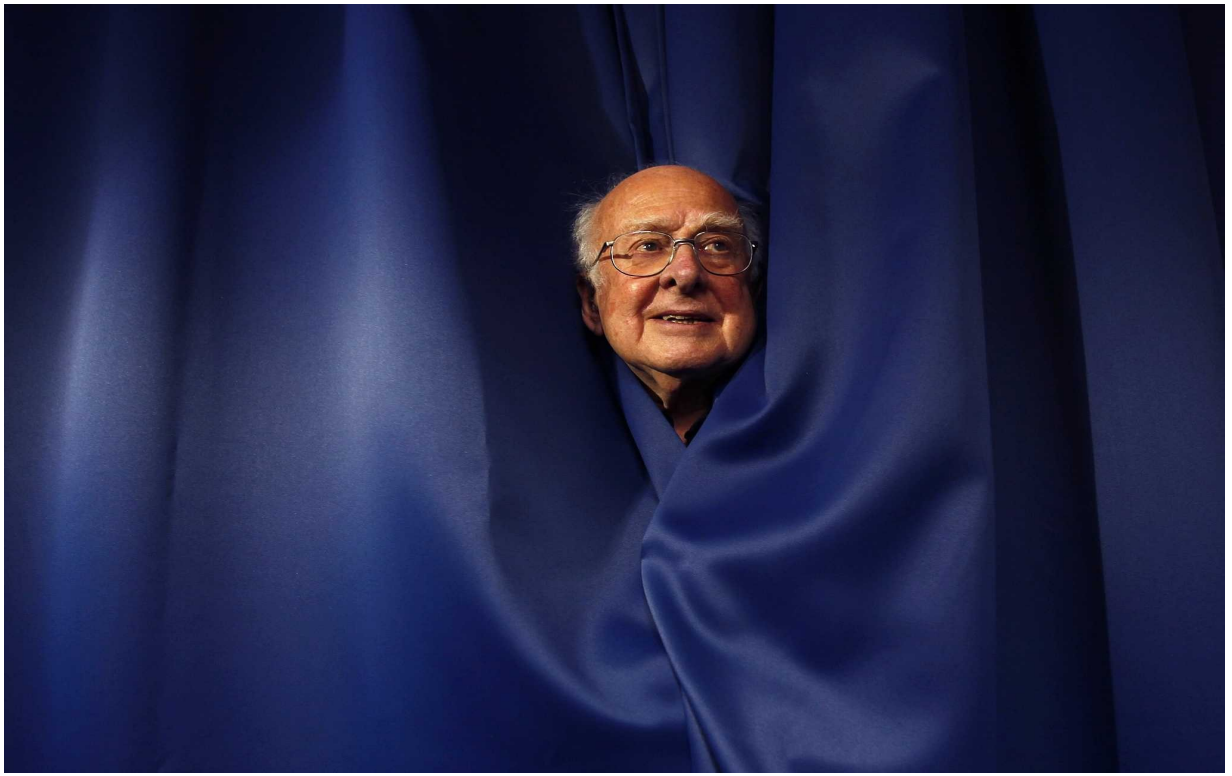
Průchod částic detektorem ATLAS

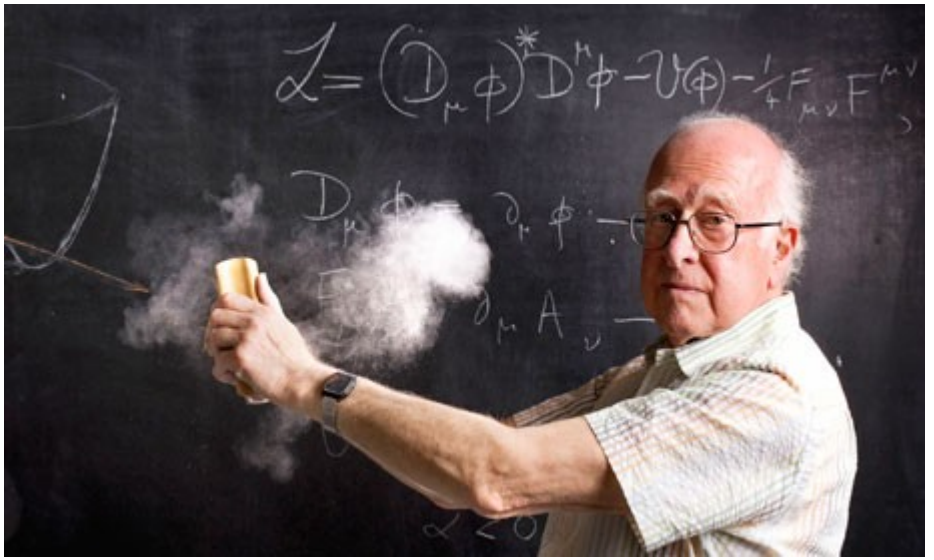


Každodenní realita

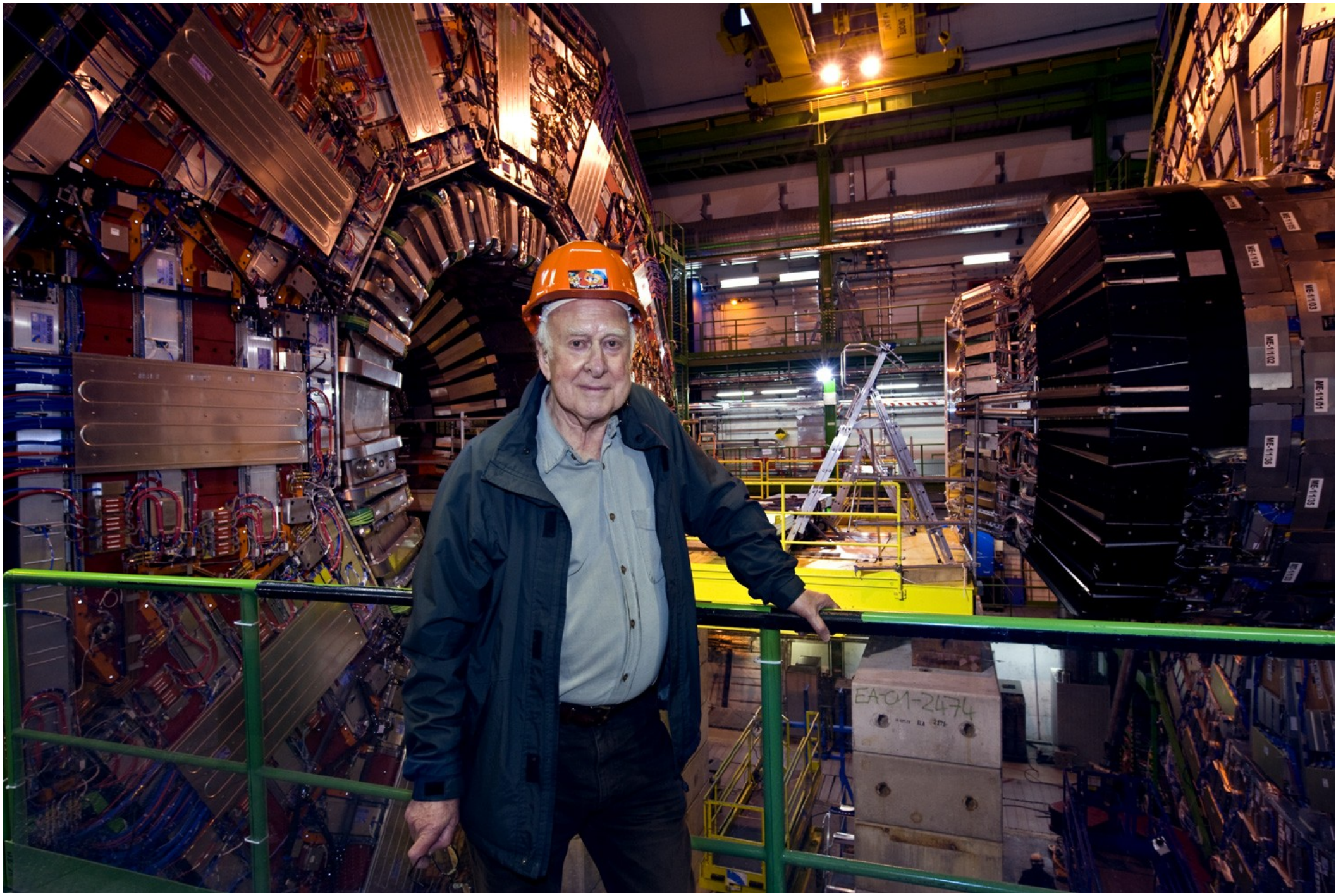


Higgs

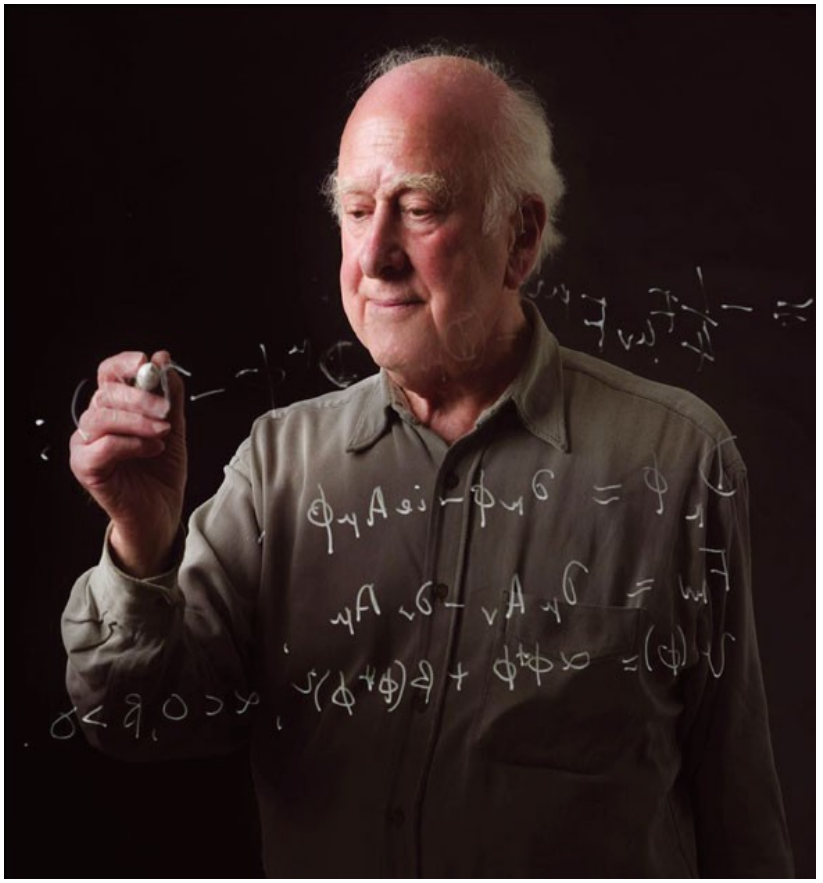




Higgs



Higgs



THEOLOGY VS. PHYSICS

Higgs – Proč?

- Standardní model funguje pro **nehmotné částice**.
- Ale náš svět je evidentně hmotný:)

- Bylo třeba najít mechanizmus, který “dodá” částicím hmotu, a přitom nerozbije dosavadní teorii a interakce.

- Higgsův boson byl dokonce nutný i pro “záchranu” předpovědí teorie na vysokých energiích.

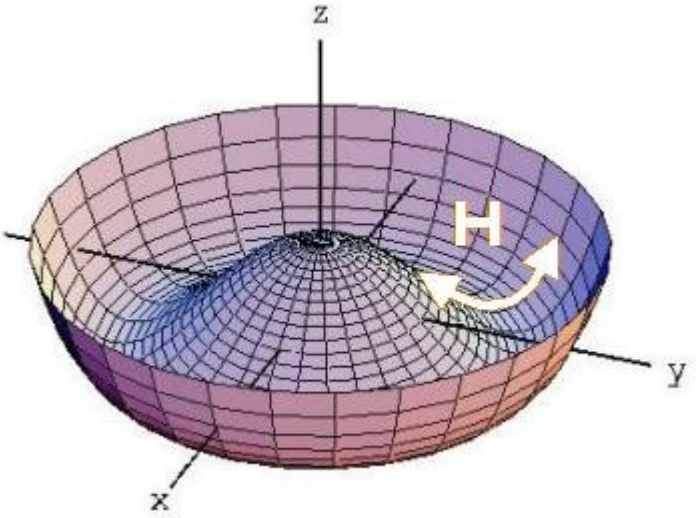
- Teorie nepředpovídala, jakou má mít hmotnost.

- Exotičtější teorie předpovídají více Higgsových bosonů (stále ve hře).

Higgs – Jak?

$$\mathscr{L}_{Higgs} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (\partial_\mu - igA_\mu)\varphi(\partial^\mu + igA^\mu)\varphi^* - \lambda(\varphi\varphi^* - \frac{v^2}{2})^2$$

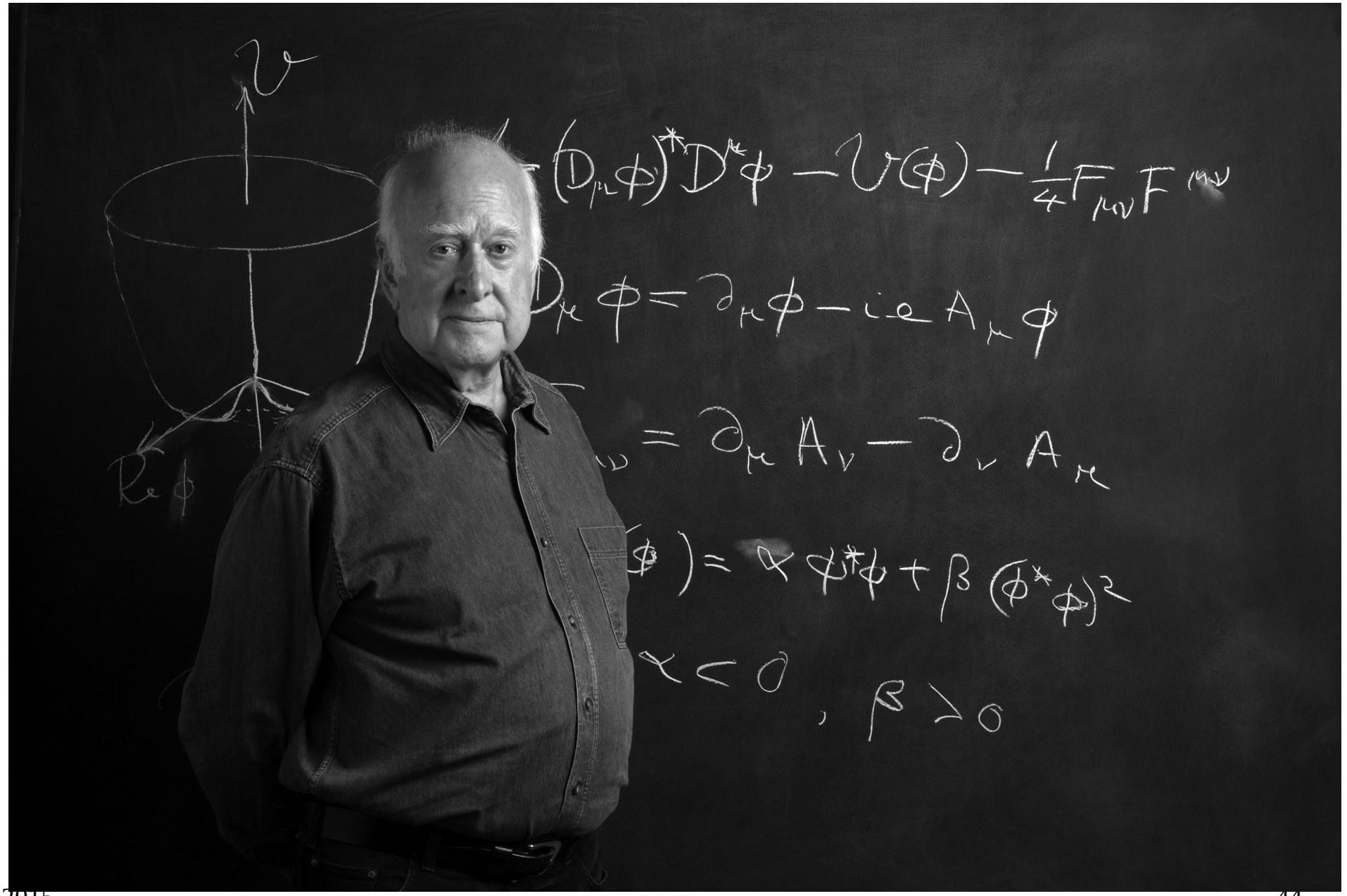
$$\varphi(x) = \rho(x)\exp\left(i\frac{\pi(x)}{v}\right) \qquad \rho = \frac{1}{\sqrt{2}}(\sigma + v)$$



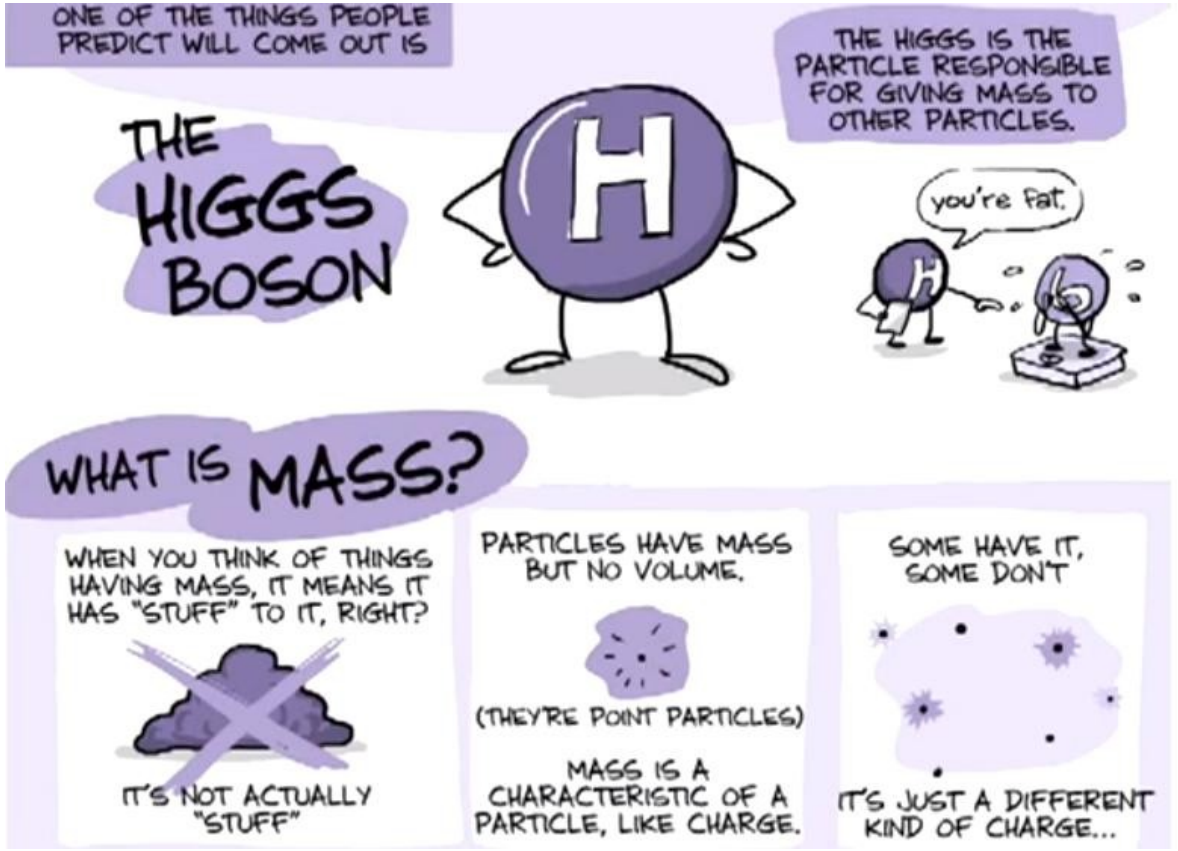
$$\mathscr{L}^{(U)}_{Higgs} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \lambda v^2\sigma^2 - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \frac{1}{2}g^2v^2B_\mu B^\mu + g^2v\sigma B_\mu B^\mu + \frac{1}{2}g^2\sigma^2 B_\mu B^\mu - \lambda v\sigma^3 - \frac{1}{4}\lambda\sigma^4$$

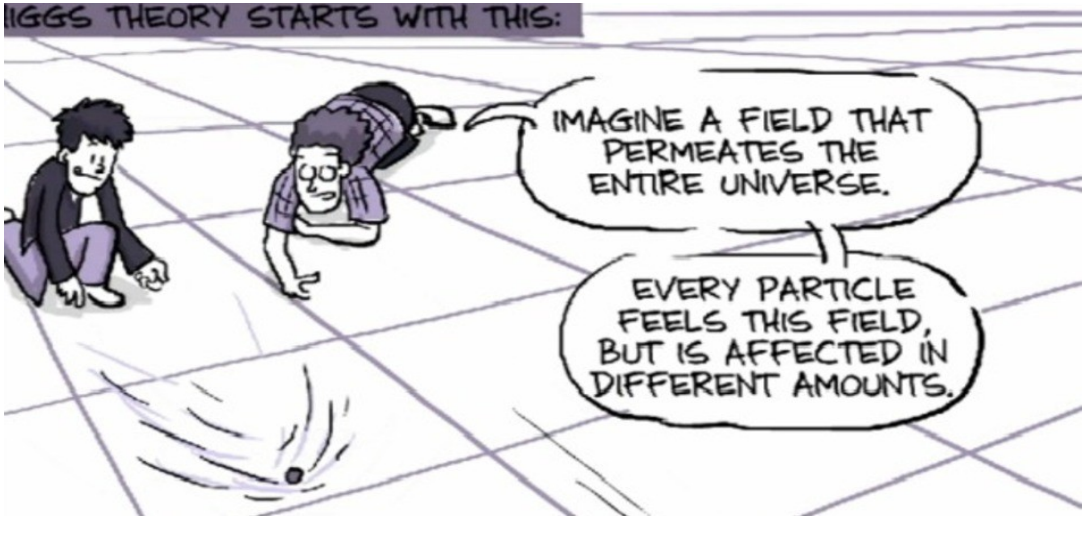
Hmotový člen pro pole B

Higgs – Jak?

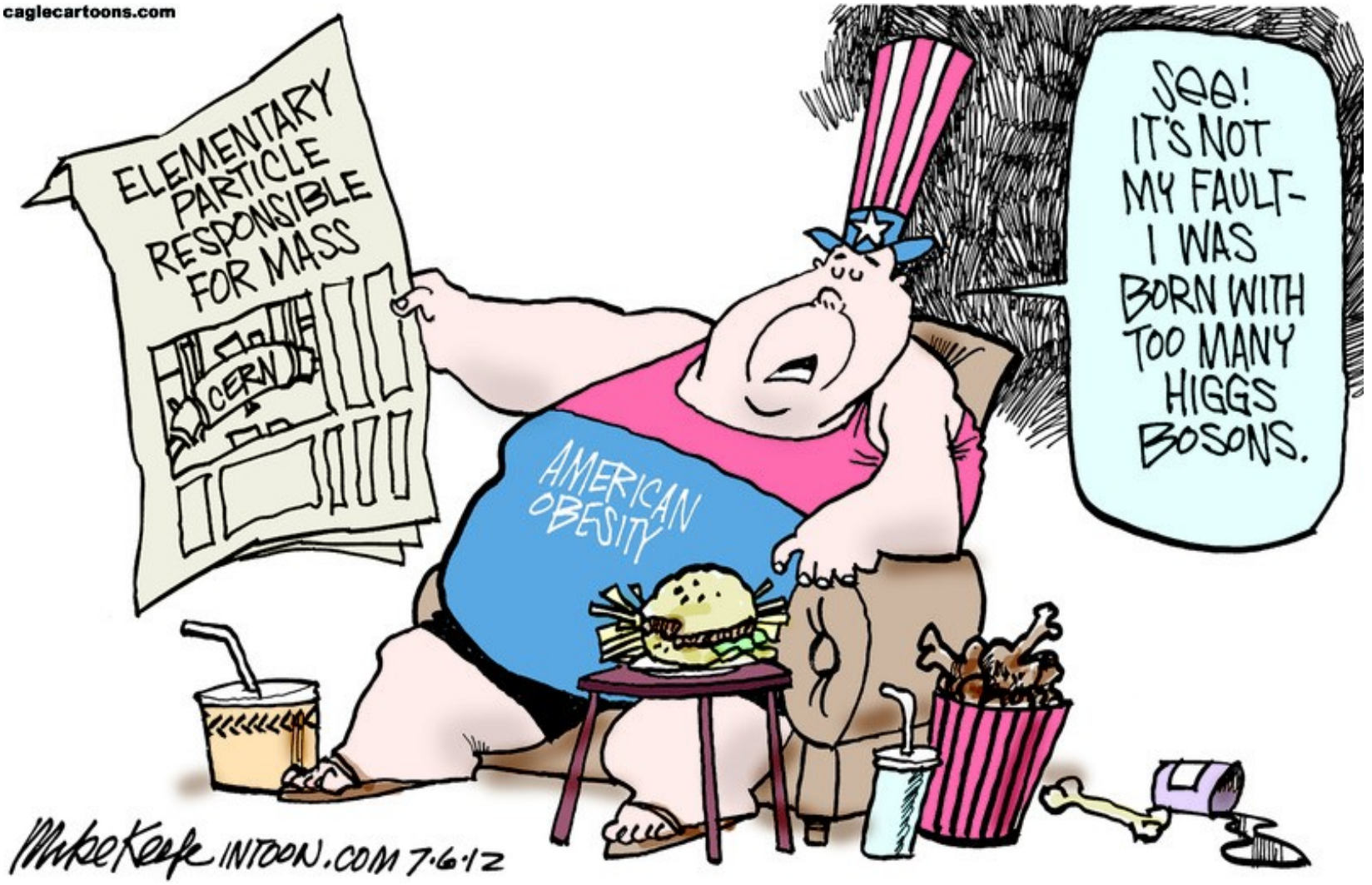

$(D_\mu\phi)^* D^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
$D_\mu\phi = \partial_\mu\phi - ie A_\mu\phi$
$= \partial_\mu A_\nu - \partial_\nu A_\mu$
$\phi) = \alpha\phi^*\phi + \beta(\phi^*\phi)^2$
$\alpha < 0$, $\beta > 0$
Re ϕ

Higgs – Co?


ONE OF THE THINGS PEOPLE PREDICT WILL COME OUT IS
THE HIGGS BOSON
H
THE HIGGS IS THE PARTICLE RESPONSIBLE FOR GIVING MASS TO OTHER PARTICLES.
you're fat.
WHAT IS MASS?
WHEN YOU THINK OF THINGS HAVING MASS, IT MEANS IT HAS "STUFF" TO IT, RIGHT?
IT'S NOT ACTUALLY "STUFF"
PARTICLES HAVE MASS BUT NO VOLUME.
(THEY'RE POINT PARTICLES)
MASS IS A CHARACTERISTIC OF A PARTICLE, LIKE CHARGE.
SOME HAVE IT, SOME DON'T
IT'S JUST A DIFFERENT KIND OF CHARGE...


IGGS THEORY STARTS WITH THIS:
IMAGINE A FIELD THAT PERMEATES THE ENTIRE UNIVERSE.
EVERY PARTICLE FEELS THIS FIELD, BUT IS AFFECTED IN DIFFERENT AMOUNTS.

Higgs

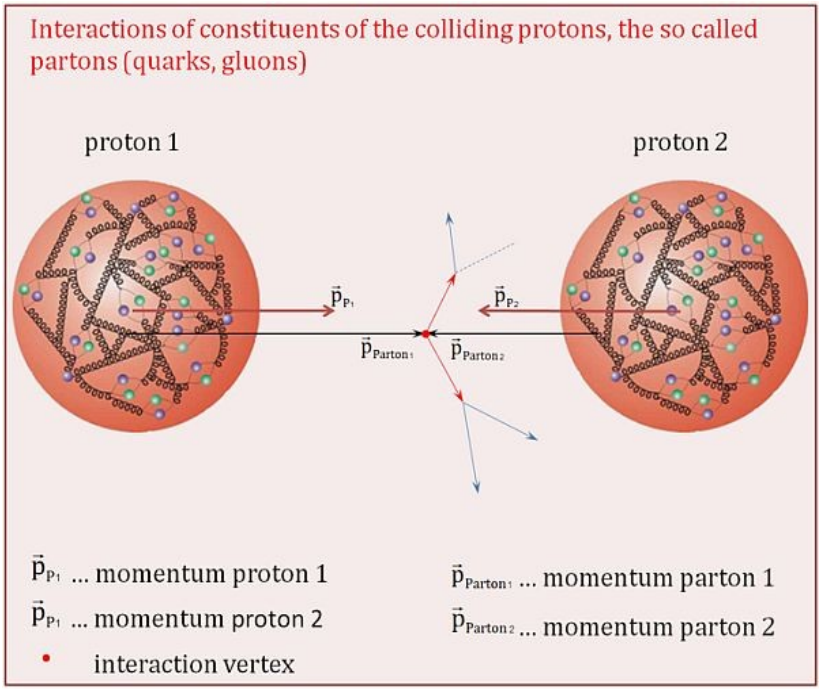

caglecartoons.com
ELEMENTARY PARTICLE RESPONSIBLE FOR MASS
CERN
AMERICAN OBESITY
SEE! IT'S NOT MY FAULT- I WAS BORN WITH TOO MANY HIGGS BOSONS.
MikeKeefe INTOON.COM 7·6·12

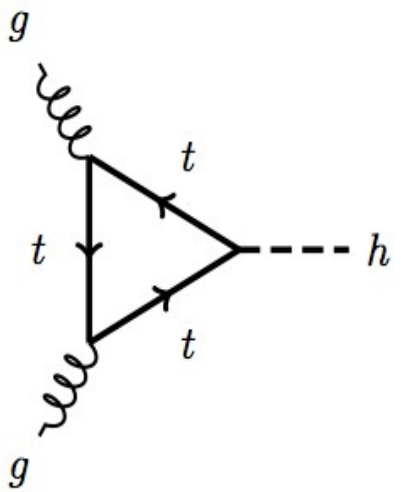
Higgs – Jak?

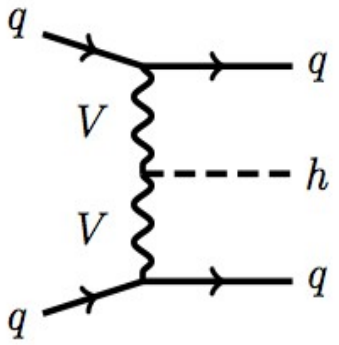
- Coctail party analogy:
- Hosté: Higgsovo pole.
- Osobnost: částice, obalením obdivovateli se pohybuje pomaleji: získala hmotnost.

Higgs – Jak objevit?

- Srážet a čekat:)
- A hledat všude – teorie nepředpovídá jeho hmotnost.
- Higgs interaguje s částicemi “silou” úměrnou jejich hmotnosti.
- Neváže se tedy přímo na foton ani gluon.
- “Rád” se rozpadá na těžké částice.

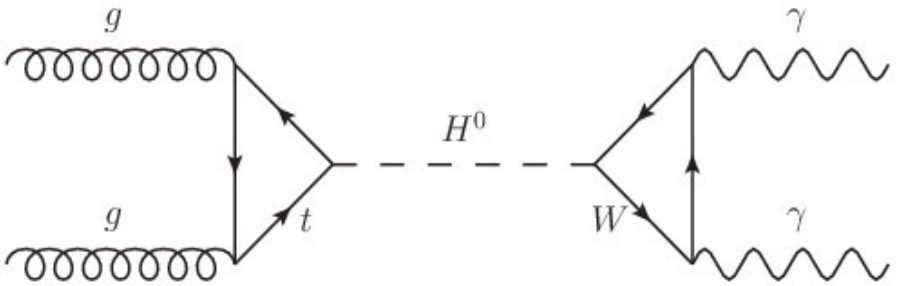


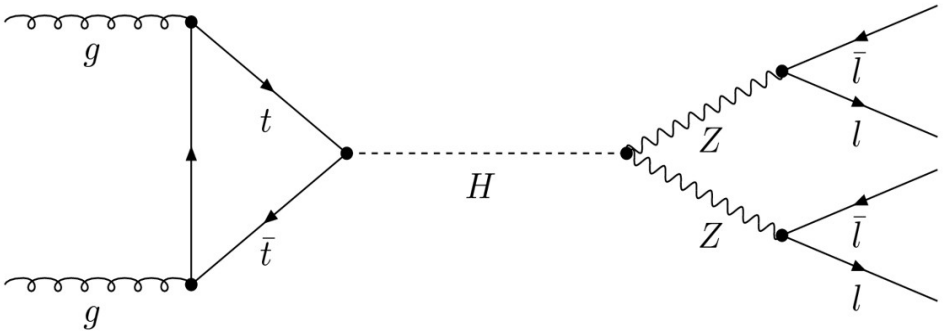


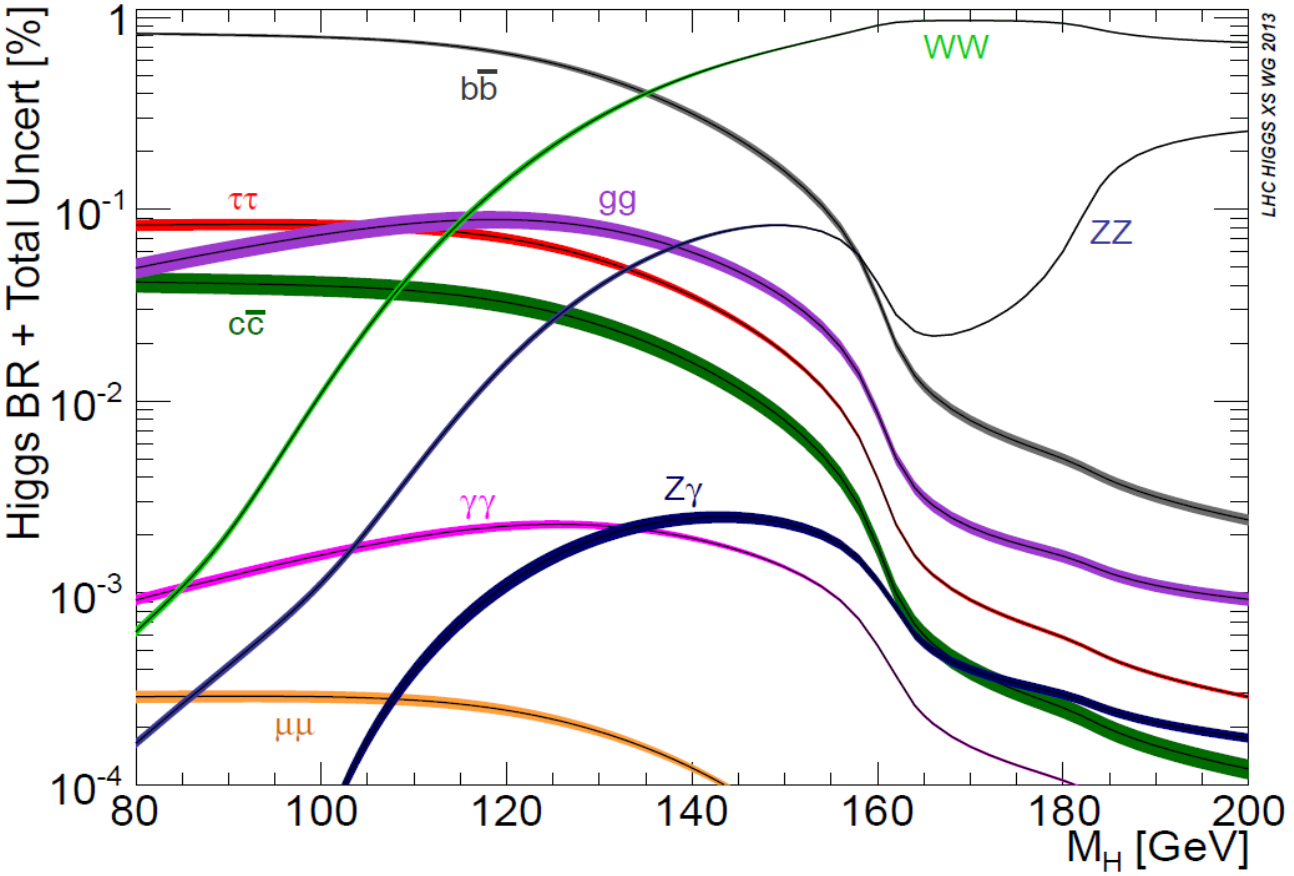


Higgs – Jak uvidět?

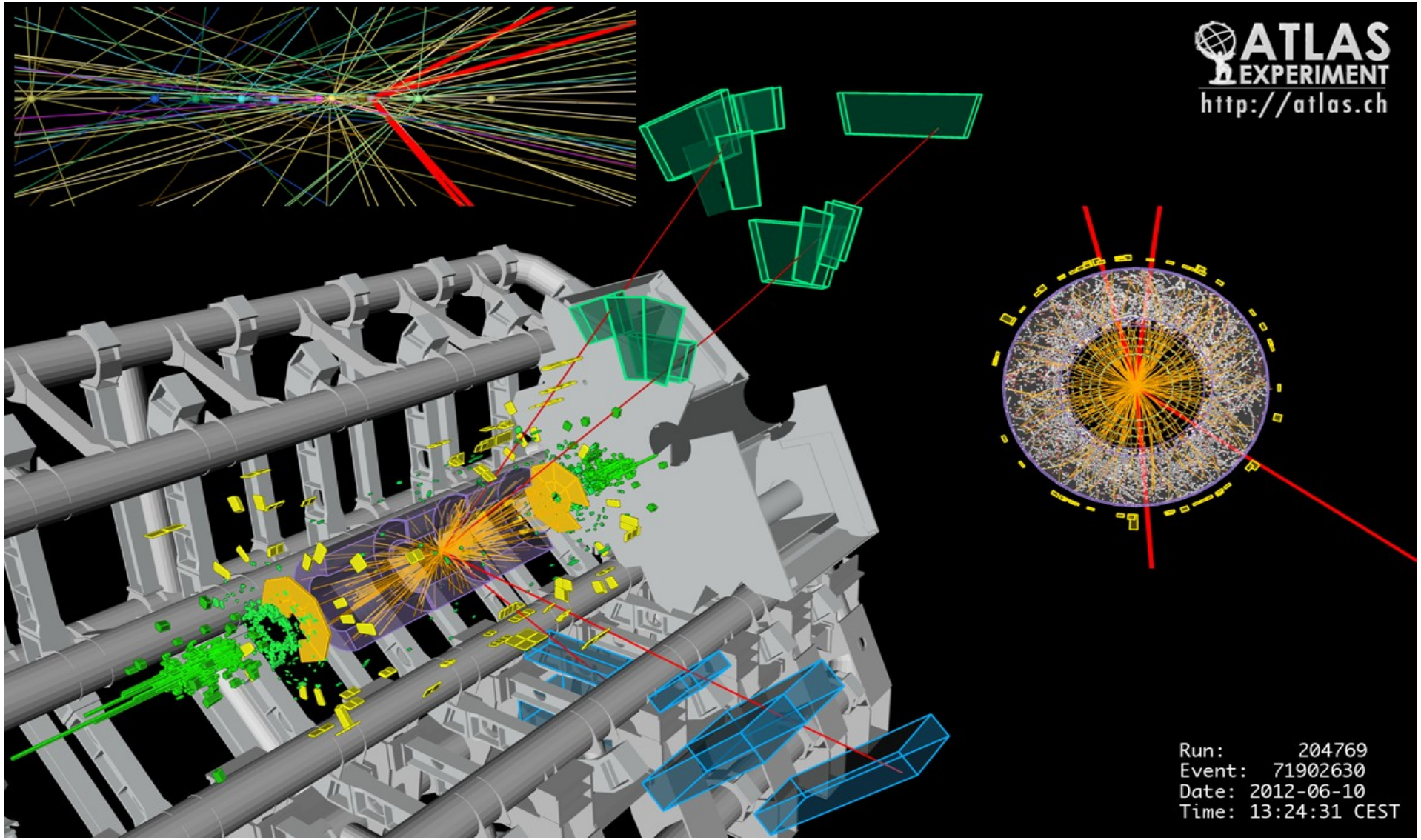
- Dle toho, na co se rozpadá: a to už teorie předpovídá!





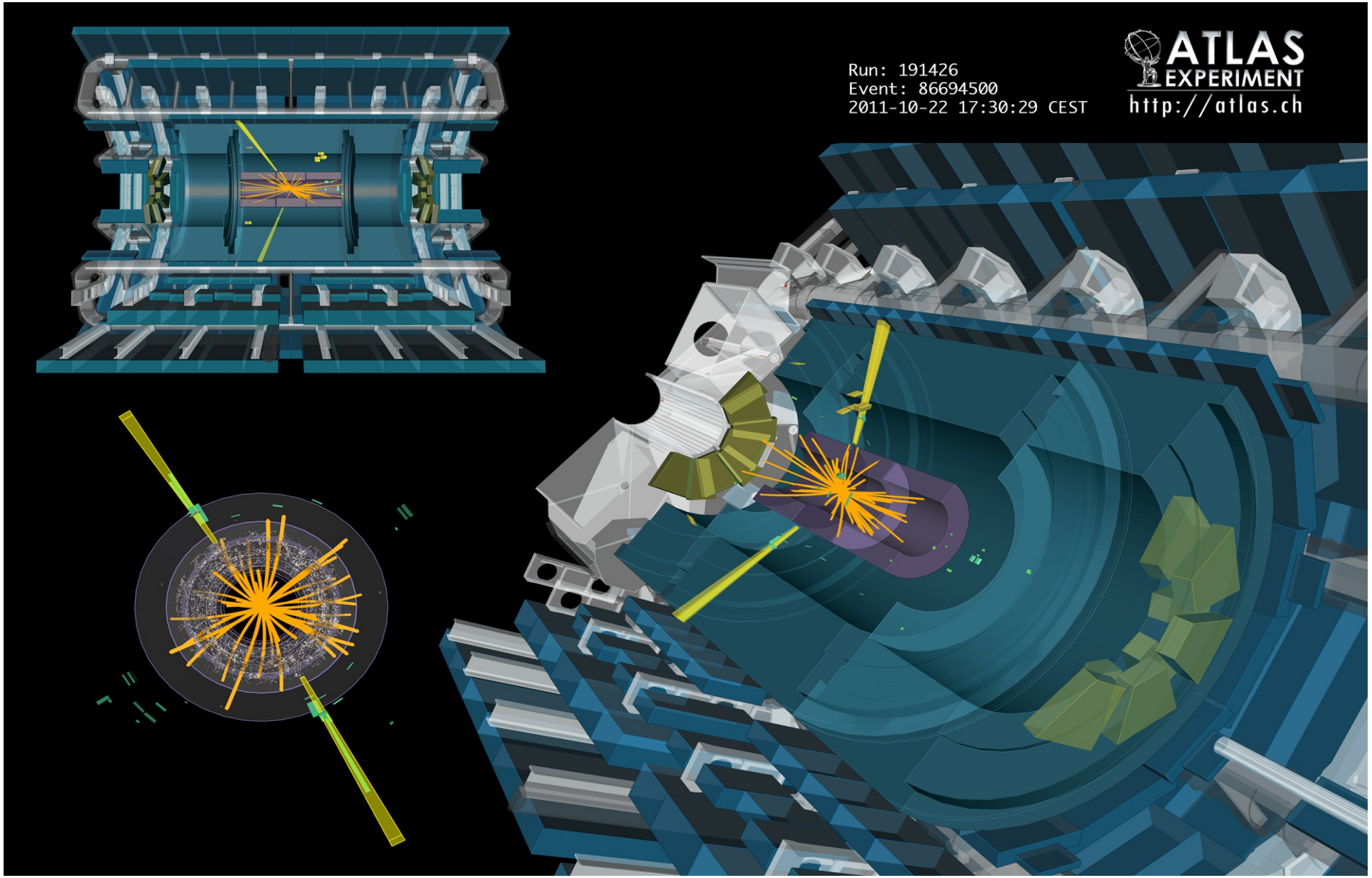


Higgs – Jak vypadá?

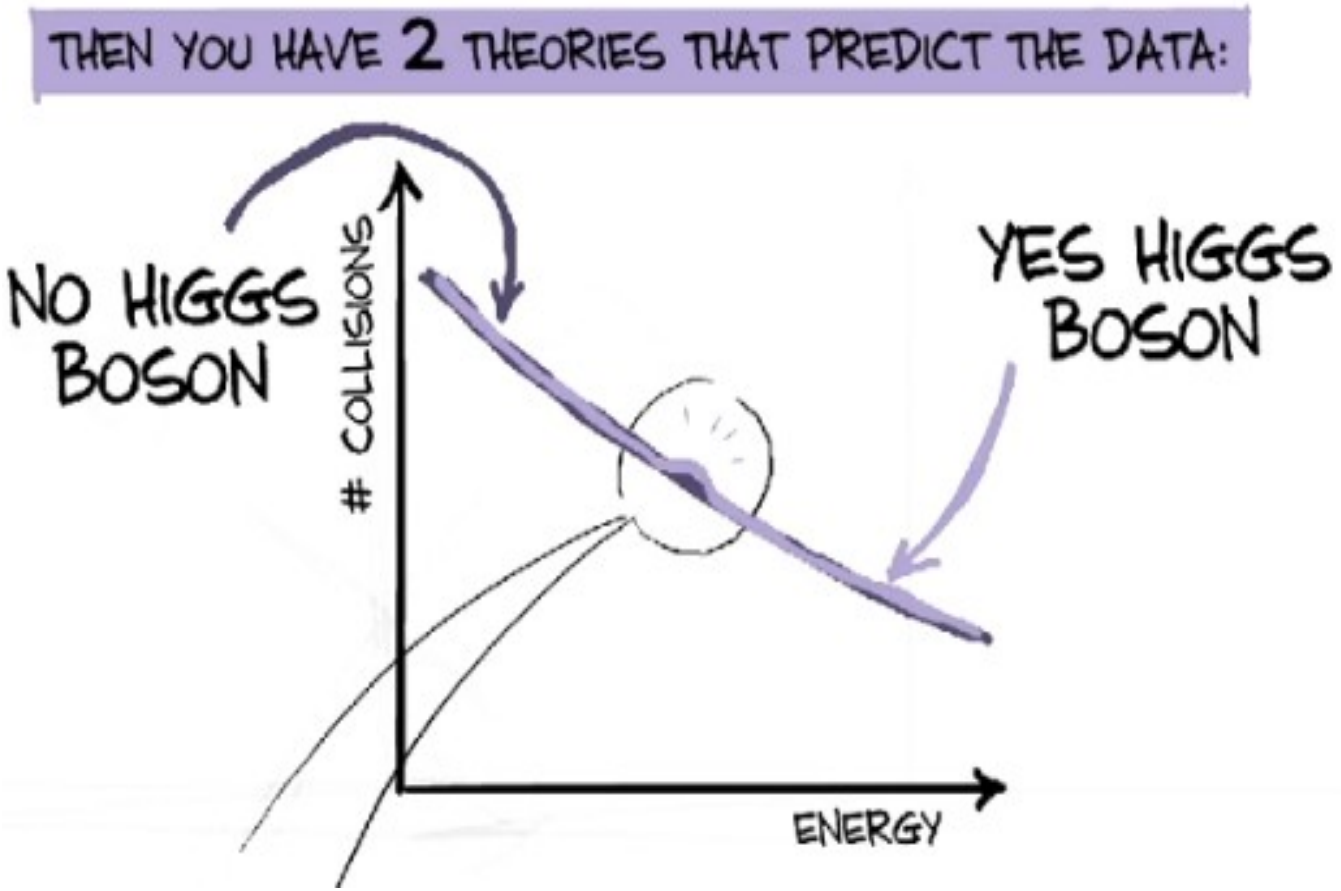


H → ZZ → 4 leptony

Higgs – Jak vypadá?

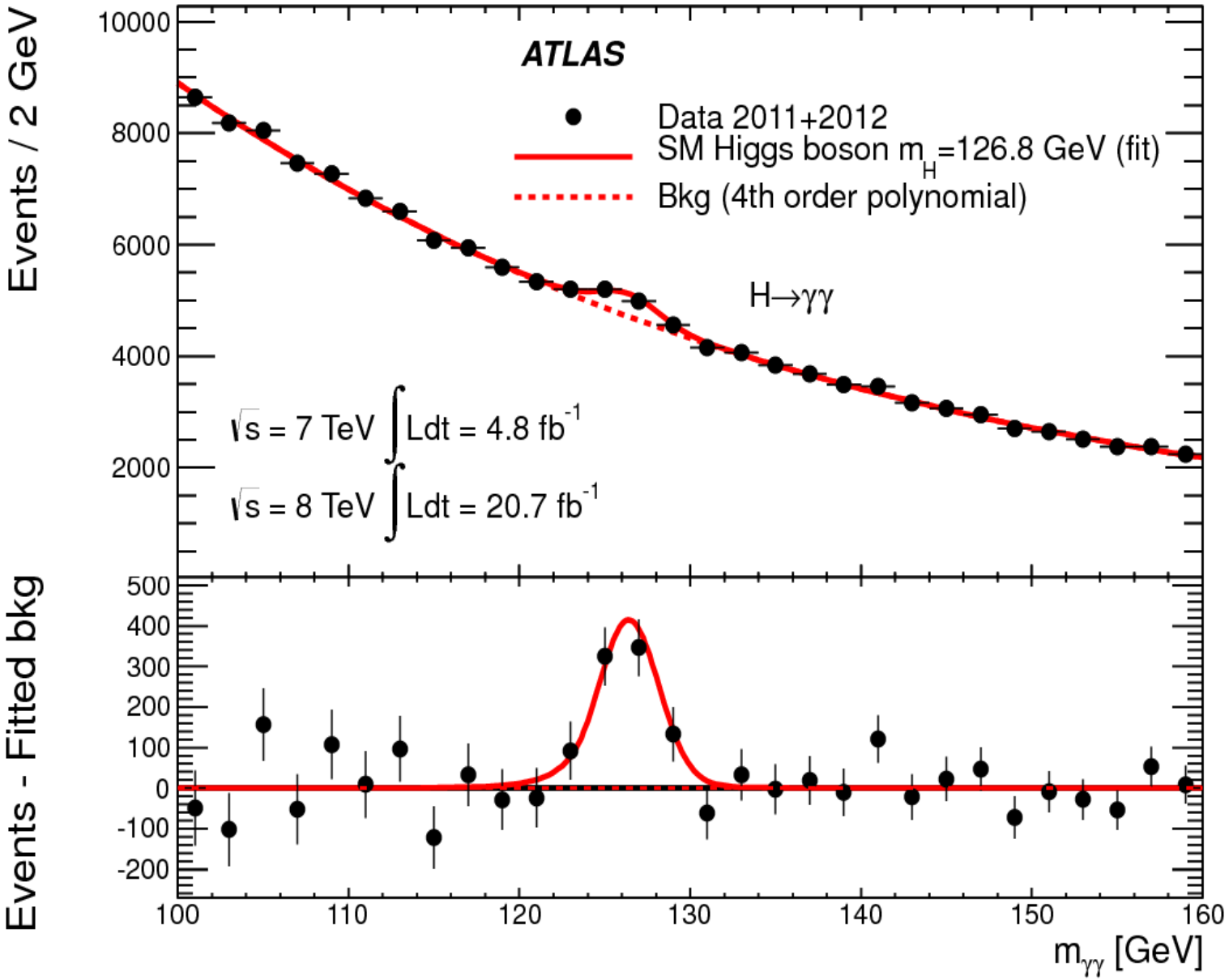


Higgs – Jak byl objeven?



Higgs – Jak byl objeven?

- Data z roku 2011 (energie srážek 7TeV) a 2012 (8TeV).



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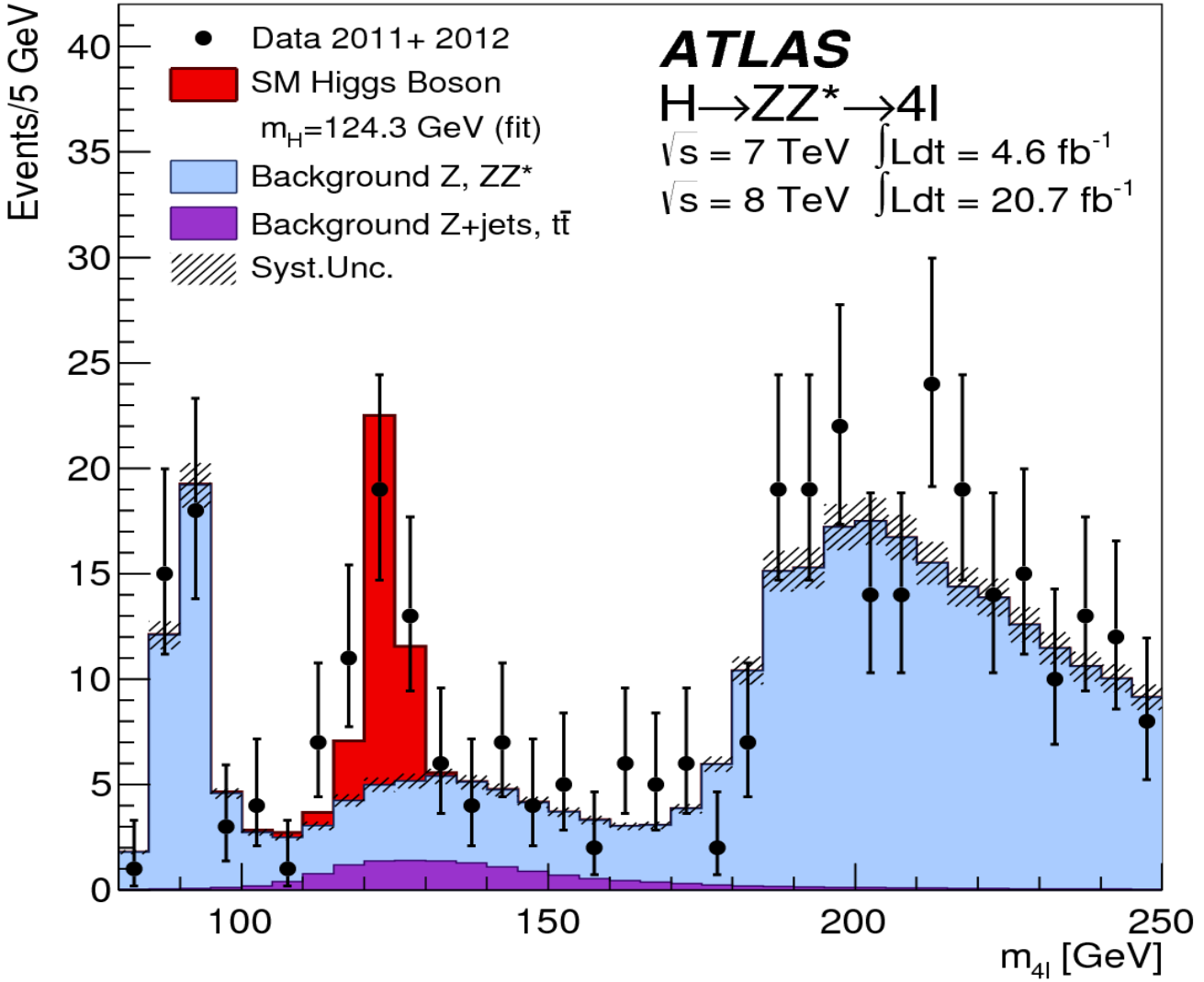


Higgs – objev

- Oznámen 4.7.2012 (ale náznaky již prosinec 2011).
- Poslední chybějící kousek Standardního modelu.
- Triumf teorie staré 50 let.
- http://www.atlas.ch/HiggsResources/

The Nobel Prize in Physics 2013

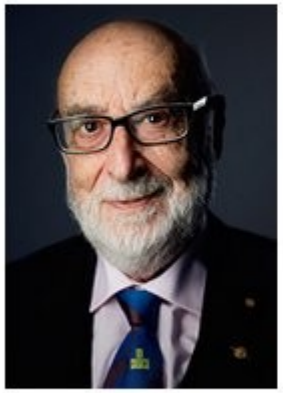


Photo: A. Mahmoud

François Englert

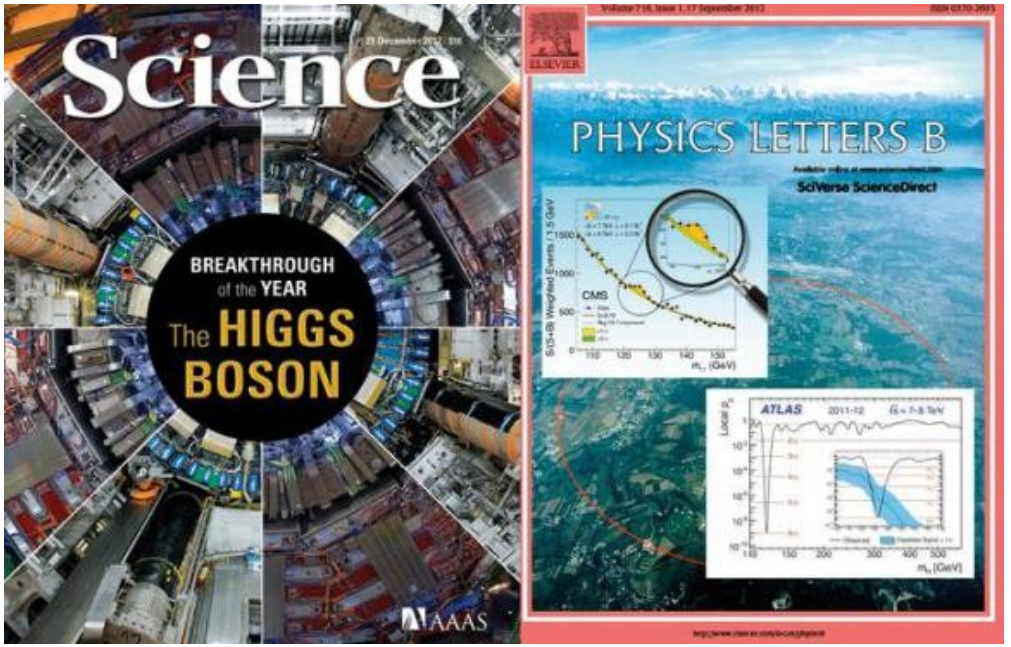
Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

9.1.2015



Higgs – objev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