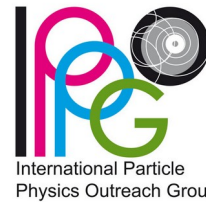




Univerza v Ljubljani



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INTERNATIONAL



hands on particle physics

Uvod v analizo podatkov v eksperimentalni fiziki osnovnih delcev

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Univerza v Mariboru, FKKT

in

Institut Jožef Stefan



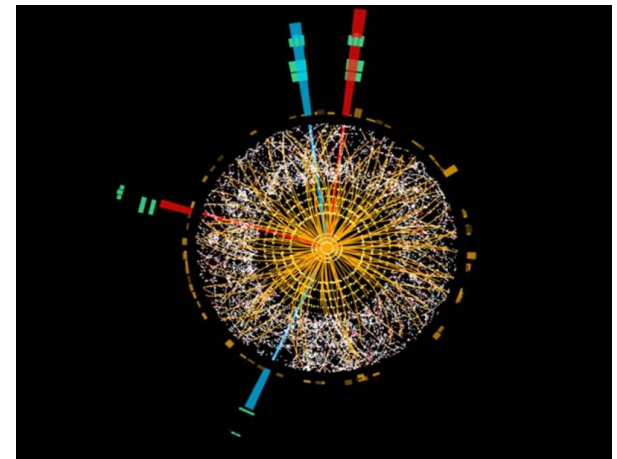
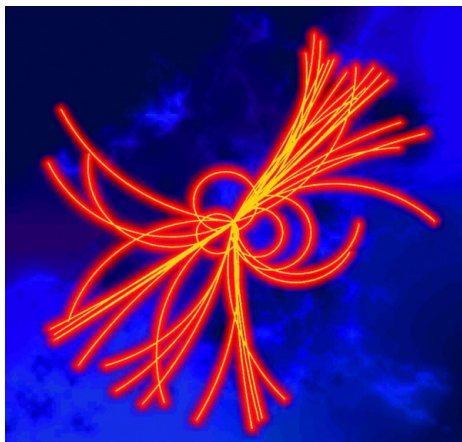
F9 – Odsek za eksperimentalno fiziko osnovnih delcev

IMC2025 – Belle II, IJS, Ljubljana

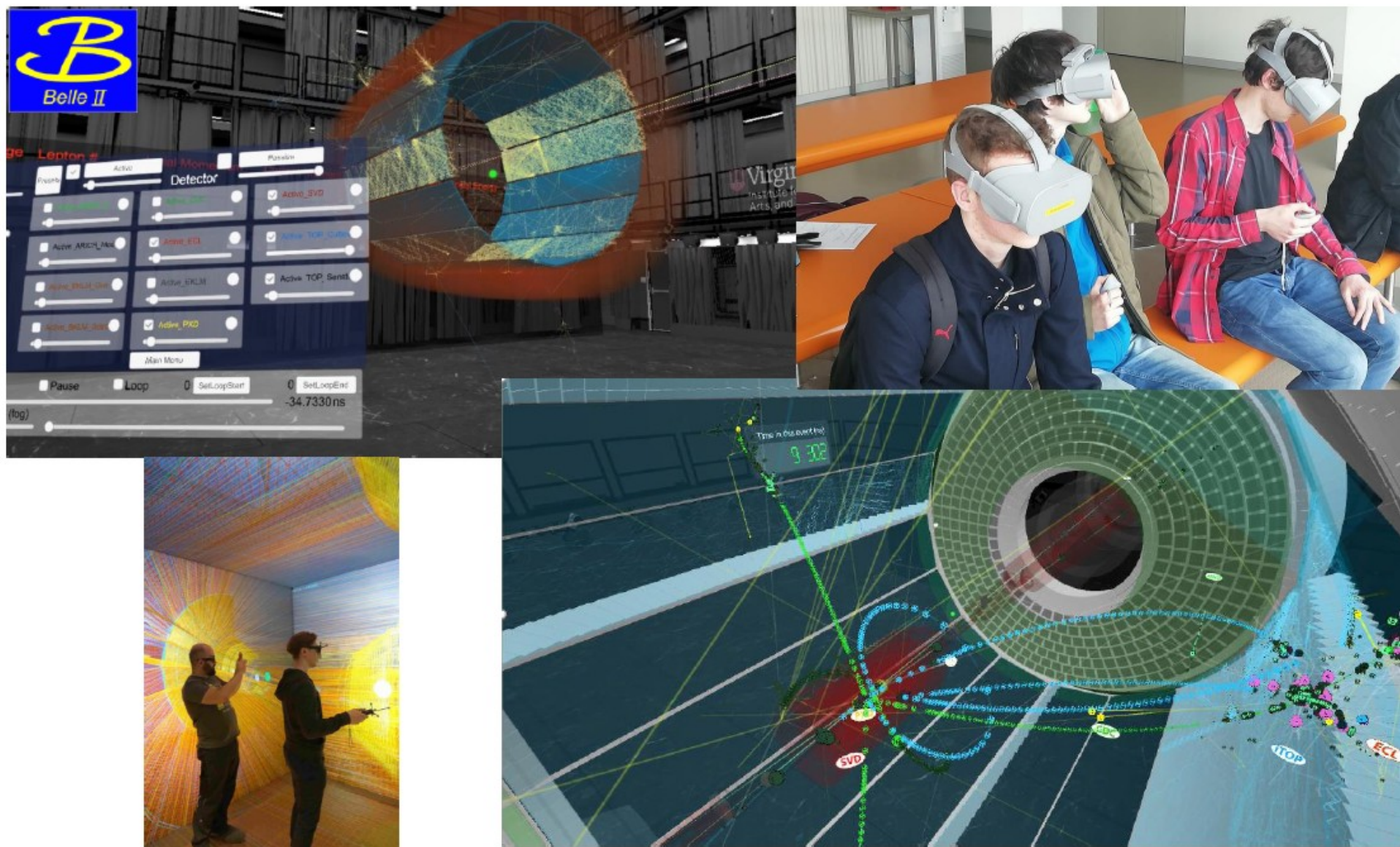
19. marca 2025



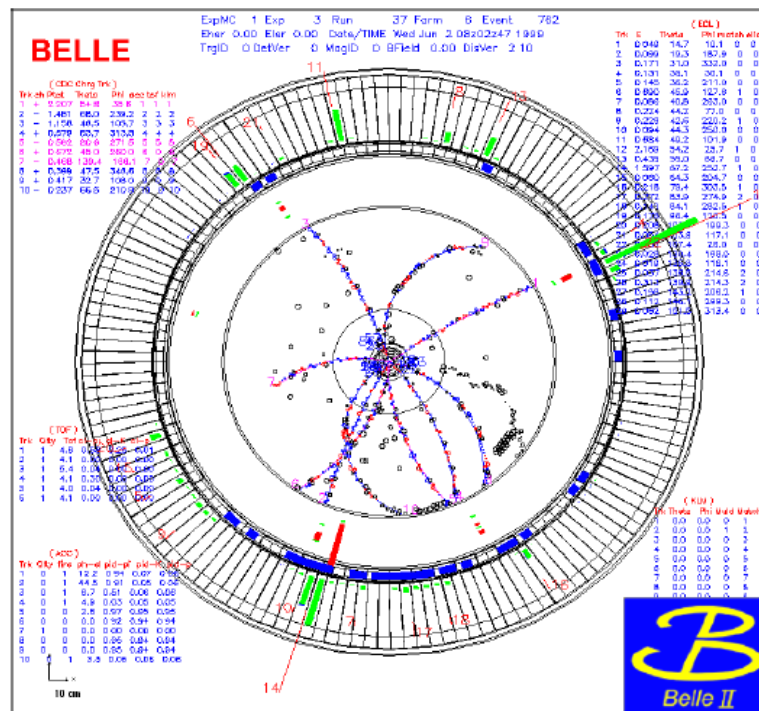
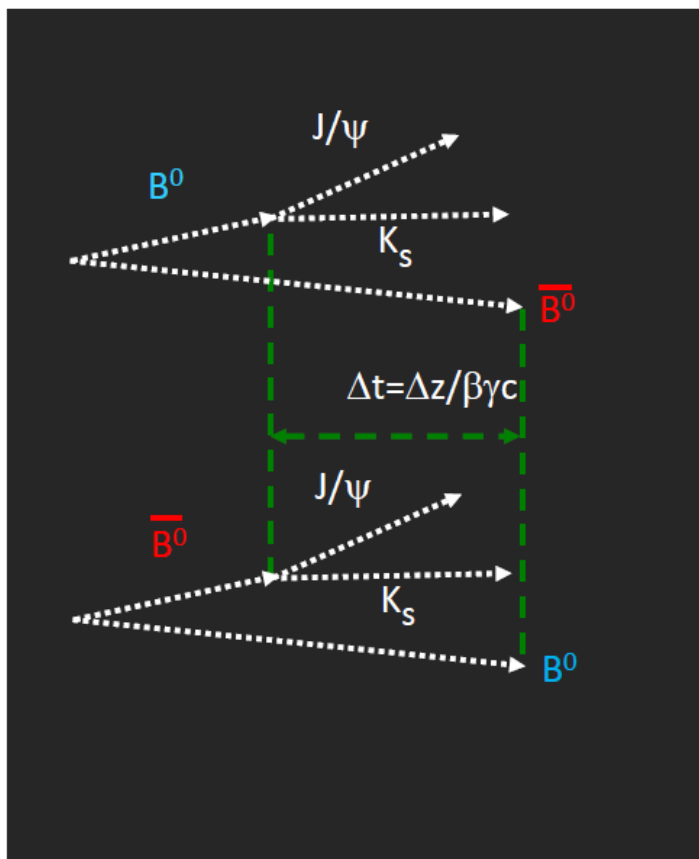
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Izmerjeni signali (količine) → vizualizacija

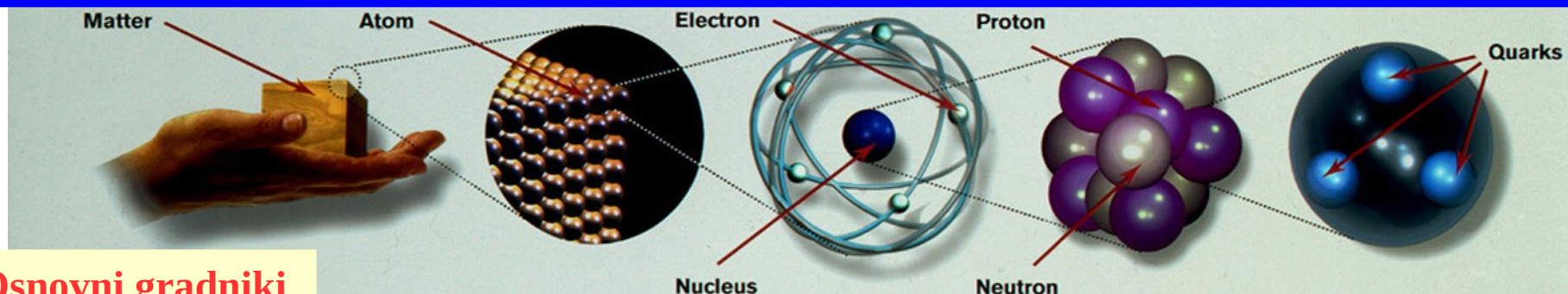


Izmerjeni signali (količine) → vizualizacija



- Za (ročno) pregledovanje je podatkov preprosto preveč ...
- Želimo določiti lastnosti delcev, izmeriti razne vrednosti, konstante, ...
- Potrebujemo izračunane količine, statistične metode, ...

... in kako snov vidimo/razumemo danes?



Osnovni gradniki snovi :

		LEPTONS		QUARKS	
All ordinary particles belong to this group These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators	FIRST FAMILY	Electron Responsible for electricity and chemical reactions; it has a charge of -1 e	Electron neutrino Particle with no electric charge, and possibly no mass; billions fly through your body every second ν_e	Up Has an electric charge of plus two-thirds; protons contain two, neutrons contain one u	Down Has an electric charge of minus one-third; protons contain one, neutrons contain two d
	SECOND FAMILY	Muon A heavier relative of the electron; it lives for two-millionths of a second μ	Muon neutrino Created along with muons when some particles decay ν_μ	Charm A heavier relative of the up; found in 1974 c	Strange A heavier relative of the down; found in 1964 s
	THIRD FAMILY	Tau Heavier still; it is extremely unstable. It was discovered in 1975 τ	Tau neutrino not yet discovered but believed to exist ν_τ	Top Heavier still t	Bottom Heavier still; measuring bottom quarks is an important test of electroweak theory b

→ vsak delec iz tabele ima svoj anti-delec, npr. e^- in e^+

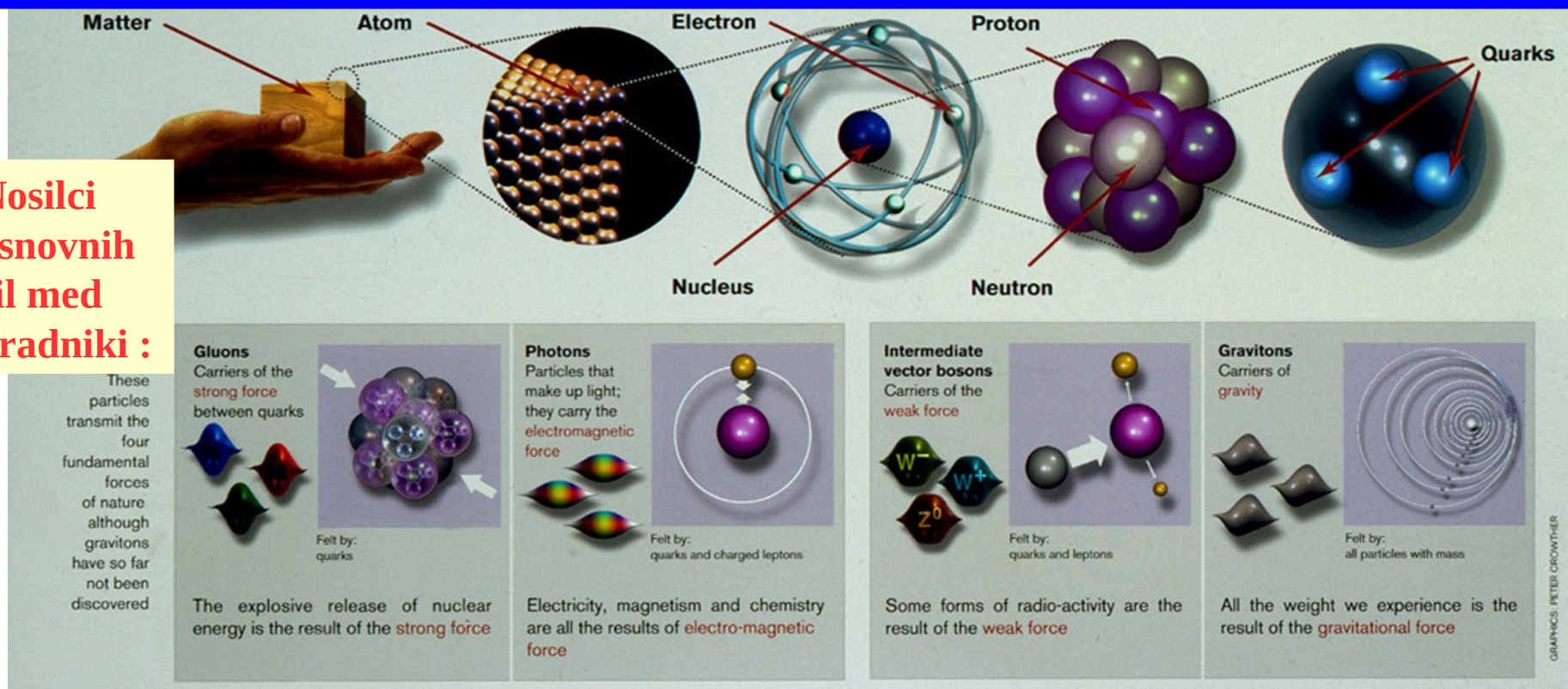
→ leptoni so nesestavljeni

→ kvarki sestavljajo težje delce - hadrone, npr.

$$p = uud \quad (+2/3e_0 + 2/3e_0 - 1/3e_0) \quad \{e_0 \text{ je osnovni naboj:}$$

$$n = udd \quad (+2/3e_0 - 1/3e_0 - 1/3e_0) \quad \sim 1,6 \cdot 10^{-19} \text{ As}\}$$

... in kako snov vidimo/razumemo danes?



**gluoni
(močna sila)**

**fotoni
(EM sila)**

**bozoni W^+ , W^- , Z^0
(šibka sila)**

**gravitoni
(gravitacija)**

**Higgsovo polje
(masa delcev) :**

**Higgsov
bozon**

Barioni in mezoni: vezana stanja kvarkov in antikvarkov

Barioni

masa

proton: uud

$1 m_p$

nevtron: udd

$\sim 1 m_p$

Λ : uds

$1.2 m_p$

Mezoni

masa

π^+ : kvark u + antikvark $\bar{d}$

$1/7 m_p$

K_S : kvark d + antikvark $\bar{s}$

$1/2 m_p$

J/ψ : kvark c + antikvark $\bar{c}$

$3 m_p$

B^0 : kvark d + antikvark $\bar{b}$

$5.5 m_p$

In seveda še mnogi drugi delci ...

Kako opazujemo majhne delce?

Kvantna mehanika:

delci se obnašajo kot valovanje

Max Planck

$$E = h\nu = h (c / \lambda)$$

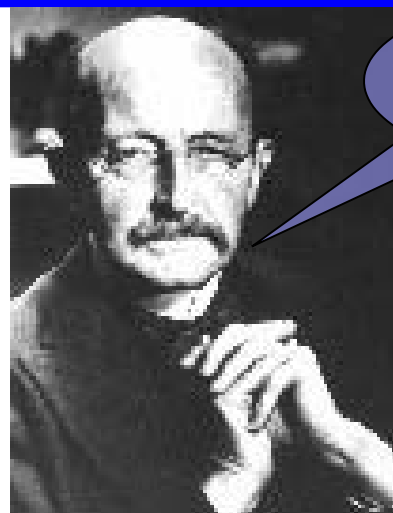
velika energija → velika frekvenca
→ majhna valovna dolžina

Posebna teorija relativnosti:

energija in masa sta izmenljivi

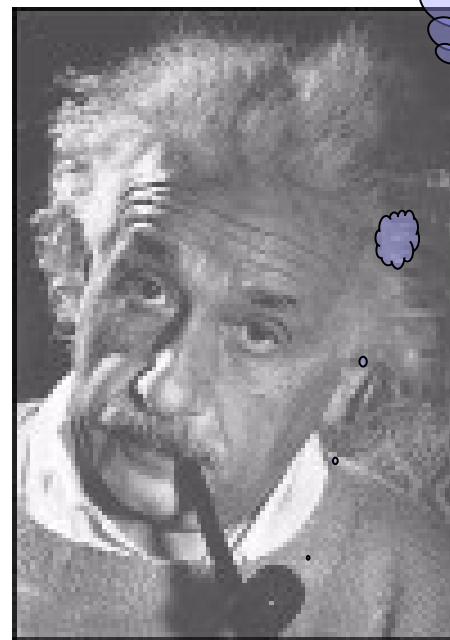
Albert Einstein

$$E=mc^2$$

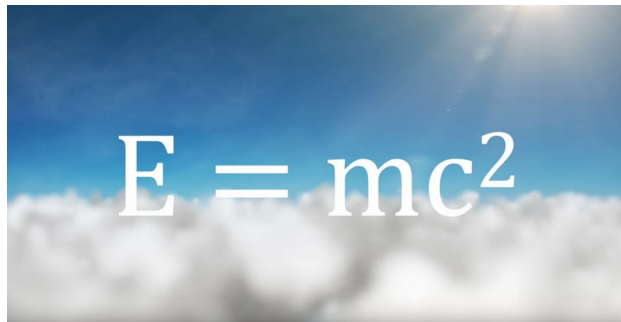


$$E=h\nu$$

$$E=mc^2$$

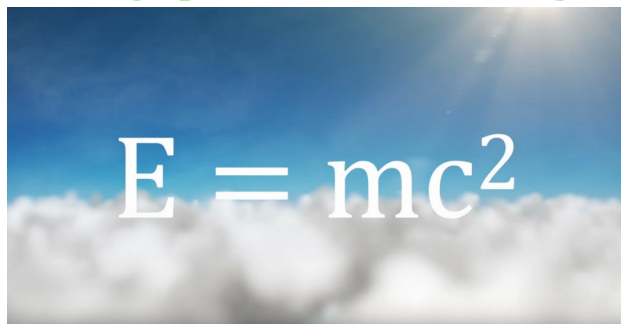


Sedaj pa še nekaj enačb:


$$E = mc^2$$

To je seveda samo poseben primer splošnejše enačbe...

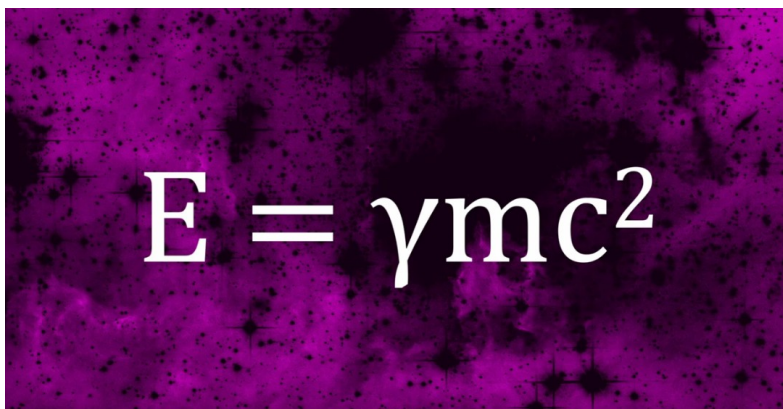
Sedaj pa še nekaj enačb:



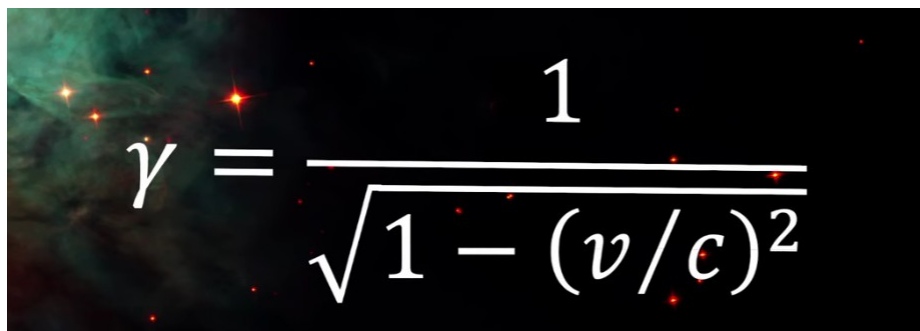
The equation $E = mc^2$ is displayed in white text against a background of a blue sky with white clouds.

To je seveda samo poseben primer splošnejše enačbe...

zato bi morali v resnici zapisati tole:

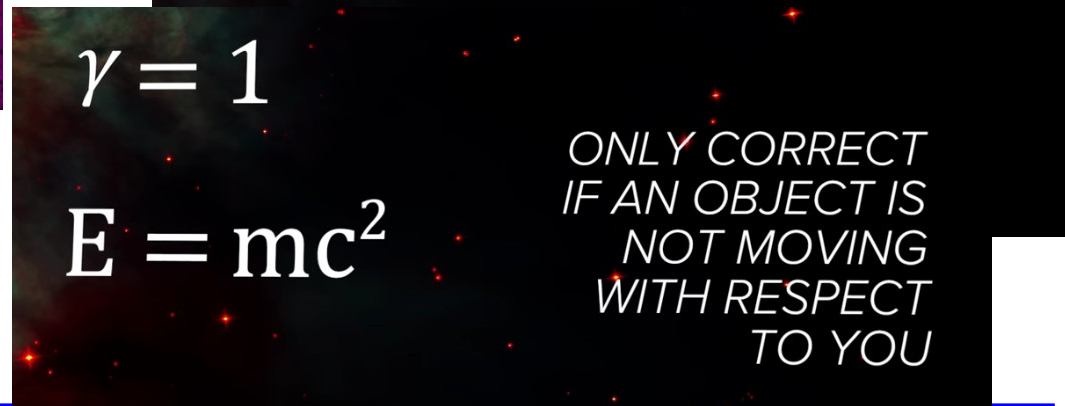


The equation $E = \gamma mc^2$ is displayed in white text against a background of a purple and black nebula.



The formula for the Lorentz factor γ is displayed in white text against a background of a starry space with green and blue nebulae.

$$\gamma = \frac{1}{\sqrt{1 - (v/c)^2}}$$



The equation $E = mc^2$ is displayed in white text against a background of a starry space. To the right of the equation, the following text is written in white capital letters:

ONLY CORRECT
IF AN OBJECT IS
NOT MOVING
WITH RESPECT
TO YOU

Sedaj pa še nekaj enačb: faktor gama (γ)

$$\gamma = \frac{E}{mc^2}$$



$$\gamma = \frac{E \text{ (moving)}}{E \text{ (not moving)}}$$

Ta faktor se torej povečuje,
ko pospešujemo delce.

Isti faktor nastopa tudi v definiciji gibalne količine:

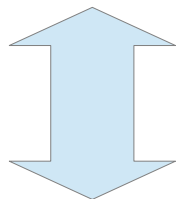
$$p = \gamma \times m \times v$$
$$m_{\text{relativistic}} = \gamma m$$
$$p = m_{\text{relativistic}} v$$

S faktorjem γ lahko tudi
predefiniramo maso delca.

Prave (relativistične) enačbe :

$$E = \gamma mc^2$$

$$p = \gamma \times m \times v$$



$$E^2 = (pc)^2 + (mc^2)^2$$

E - energy

m - mass

c - speed of light

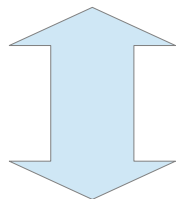
p - momentum

Z definicijo faktorja γ lahko to enačbo preverite sami...

Prave (relativistične) enačbe :

$$E = \gamma mc^2$$

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$$E^2 = (pc)^2 + (mc^2)^2$$

E - energy

m - mass

c - speed of light

p - momentum

Dva posebna primera :

Za $p = 0$ (delec, ki miruje) :

$$E = mc^2$$

Za $m = 0$ (foton – γ) :

$$E = pc$$

Invariantna masa – eksperimentalna količina :

$$m c^2 = \sqrt{E^2 - p^2 c^2} \quad (1)$$

Maso delca lahko izrazimo (preverite!) iz prejšnje enačbe... in v idealnem primeru bi bila masa (1) natanko enaka masi delca

Neidealni primer - komplikacije :

- Delci razpadajo → uporabiti moramo razpadne produkte;
- Tudi če zaznamo/izmerimo vse razpadne produkte, povsem natančne meritve niso mogoče → masa (1) je torej $\approx$ enaka masi delca
- Ozadje (npr. podobni razpadi) → še več razlik med maso (1) in maso delca ...

→ Invariantna masa delca :

$$m c^2 = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i c\right)^2}$$

$$E_i = \sqrt{\left(\sum_i m_i c^2\right)^2 + \left(\sum_i \vec{p}_i c\right)^2}$$

Indeks i teče po razpadnih produktih delca!

Primer (prave) meritve z detektorjem Belle :

$\mathcal{B}$ Observation of $Z^+(4430)$ state

PRL 100, 142001(2008)
657 $B\bar{B}$

$$Z(4430)^+ \rightarrow \psi(2S)\pi^+ :$$

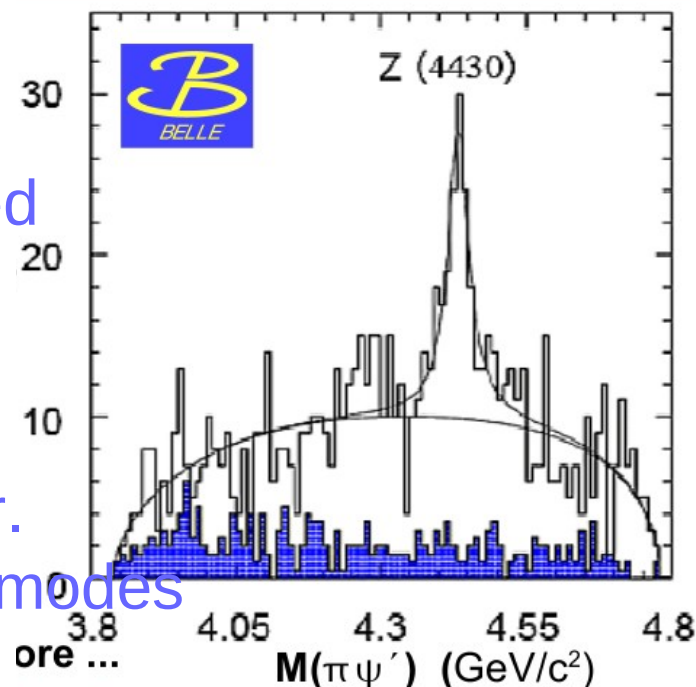
Charged state that decays like charmonium (= charged charmonium-like state)

$$\text{Br}(\bar{B}^0 \rightarrow K^- Z^+(4430)) \times \text{Br}(Z^+(4430) \rightarrow \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

Necessary ingredients:

- Histogram $\rightarrow$ bins of $m_{\text{invariant}}$
- Just specific decay modes are used
- Errors from measurements ...
- Background:
 - wrong part. identification
 - missing particles in reconstr.
 - wrong combinations/decay modes
 - ...

$\rightarrow$ First serious tetraquark candidate



Primer (prave) meritve z detektorjem Belle :

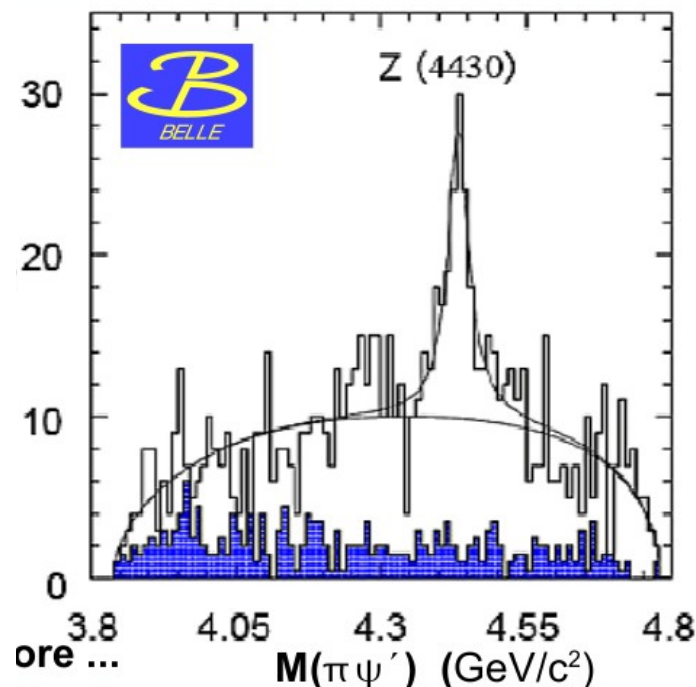
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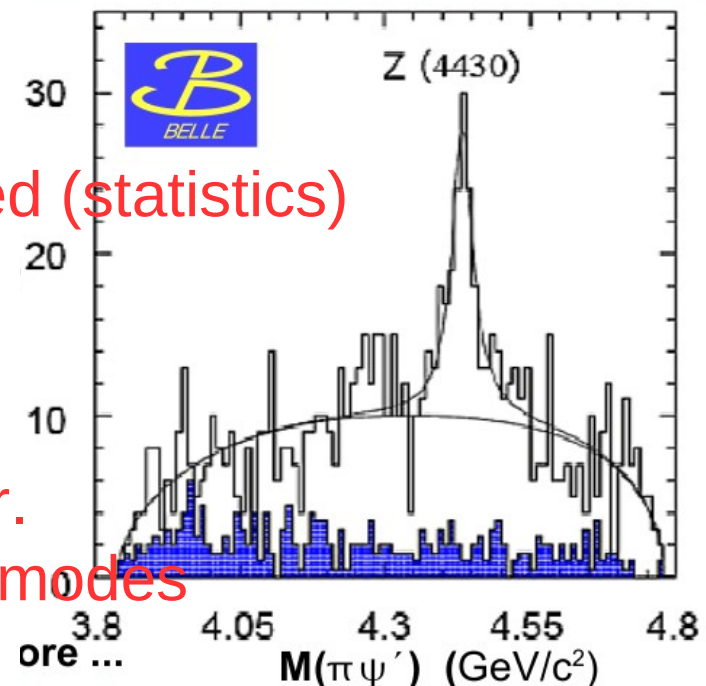
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Necessary ingredients:

- Histogram $\rightarrow$ bins of m_{invar}
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- Errors from measurements ...
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 - wrong part. identification
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 - ...



- Extract the parameters: fitting the data distribution with functions

Primer komplikacij : različni razpadni načini delcev

Properties of kaons

Particle name	Particle symbol ⇄	Antiparticle symbol ⇄	Quark content	Rest mass (MeV/c ²) ⇄	I ^G ⇄	J ^{PC} ⇄	S ⇄	C ⇄	B' ⇄	Mean lifetime (s) ⇄	Commonly decays to (>5% of decays)
Kaon ^[1]	K^+	K^-	$u\bar{s}$	493.677 ± 0.016	$\frac{1}{2}$	0^-	1	0	0	$(1.2380 \pm 0.0021) \times 10^{-8}$	$\mu^+ + \nu_\mu$ or $\pi^+ + \pi^0$ or $\pi^+ + \pi^+ + \pi^-$ or $\pi^0 + e^+ + \nu_e$
Kaon ^[2]	K^0	$\bar{K}^0$	$d\bar{s}$	497.611 ± 0.013	$\frac{1}{2}$	0^-	1	0	0	[a]	[a]
K-Short ^[3]	K_S^0	Self	$\frac{d\bar{s} + s\bar{d}}{\sqrt{2}}$ [b]	$497.611 \pm 0.013^{[c]}$	$\frac{1}{2}$	0^-	(*)	0	0	$(8.954 \pm 0.004) \times 10^{-11}$	$\pi^+ + \pi^-$ or $\pi^0 + \pi^0$
K-Long ^[4]	K_L^0	Self	$\frac{d\bar{s} - s\bar{d}}{\sqrt{2}}$ [b]	$497.611 \pm 0.013^{[c]}$	$\frac{1}{2}$	0^-	(*)	0	0	$(5.116 \pm 0.021) \times 10^{-8}$	$\pi^\pm + e^\mp + \nu_e$ or $\pi^\pm + \mu^\mp + \nu_\mu$ or $\pi^0 + \pi^0 + \pi^0$ or $\pi^+ + \pi^0 + \pi^-$

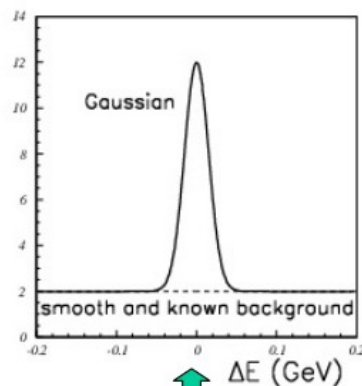
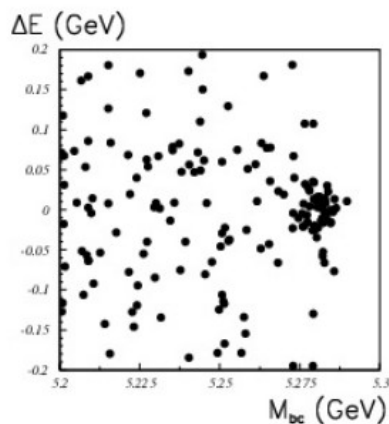
Razpadi mezonov D:

$$D^{*+} \rightarrow D^0 \pi^+ \quad \text{in} \quad D^{*-} \rightarrow \bar{D}^0 \pi^-$$

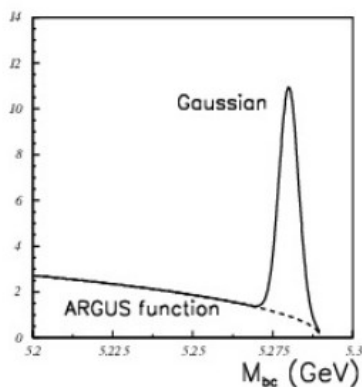
$$\bar{D}^0 \rightarrow K^+ \pi^- \quad / \quad D^0 \rightarrow K^- \pi^+$$

Možne izboljšave :

Analysis tools: B-meson selection



Reconstructing B meson decays at Y(4S):
use two variables,
beam-constrained mass M_{bc}
(energy-substituted mass m_{ES})
and
energy difference ΔE



$$\Delta E \equiv \sum E_i^{CMS} - E_{beam}^{CMS}$$

$$M_{bc} = \sqrt{(E_{beam}^{CMS})^2 - (\sum \vec{p}_i^{CMS})^2}$$



Zaključek :

Sedaj ste (vsaj v grobem) pripravljeni, da tudi sami poskusite priti do rezultatov ...

Srečno!

