Uvod v analizo podatkov v eksperimentalni fiziki osnovnih delcev

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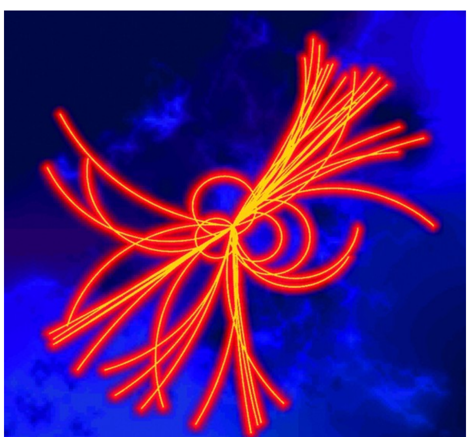
in

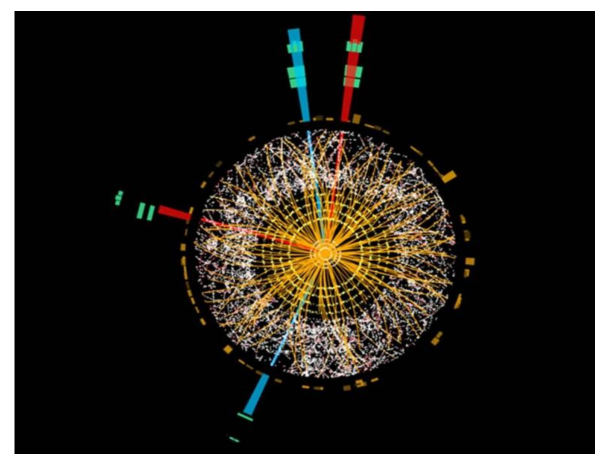
Institut Jožef Stefan

F9 – Odsek za eksperimentalno fiziko osnovnih delcev

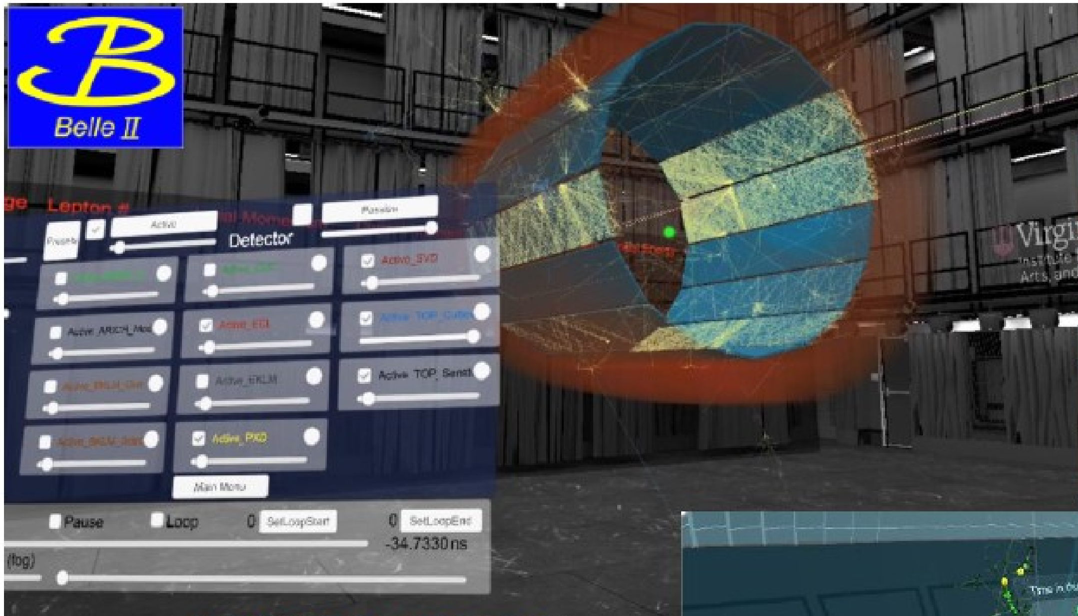
IMC2025 – Belle II, IJS, Ljubljana

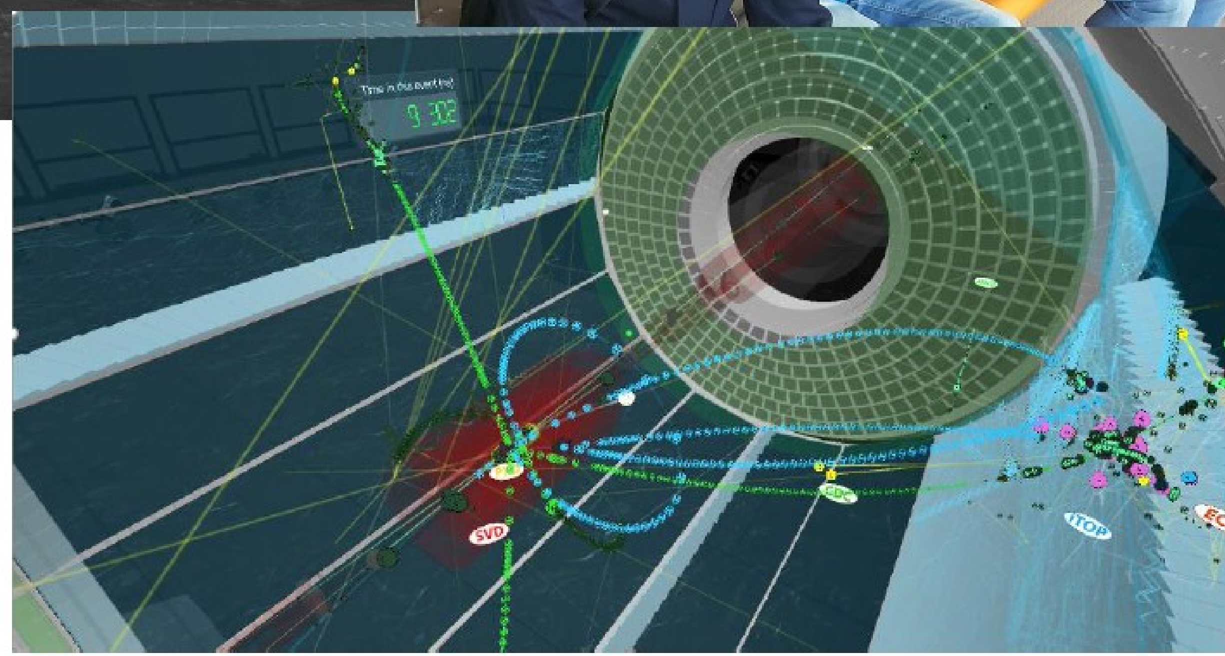
19. marca 2025





Izmerjeni signali (količine) → vizualizacija





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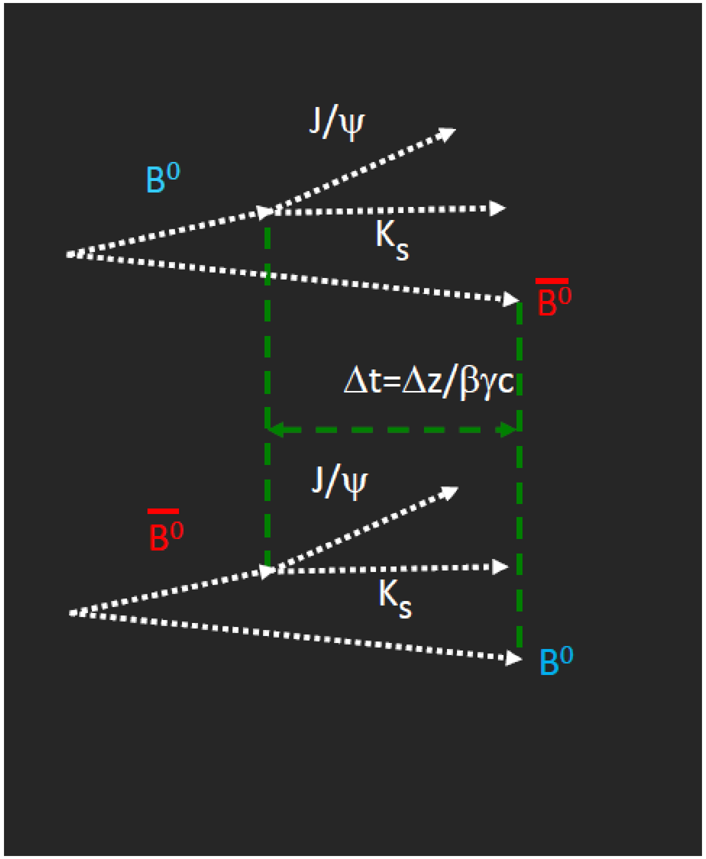
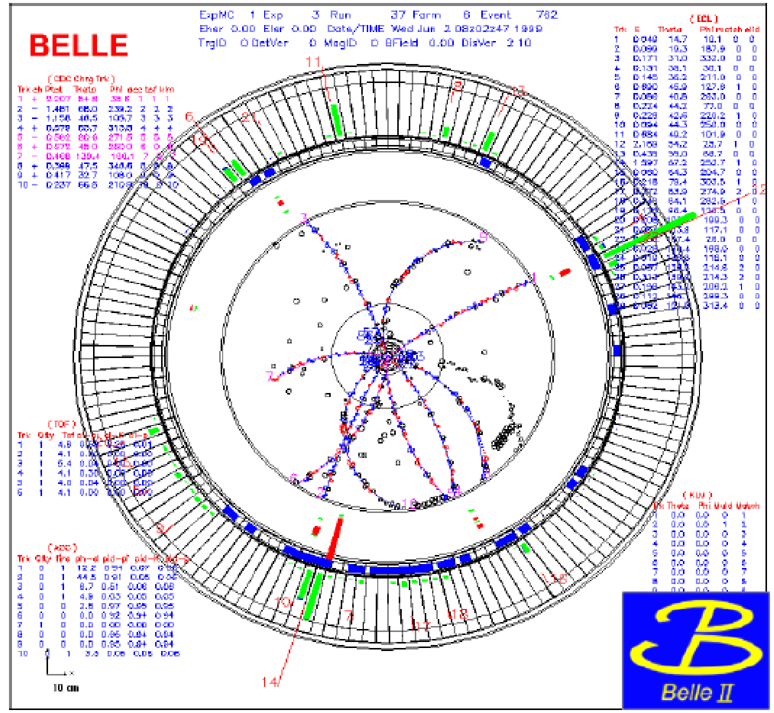
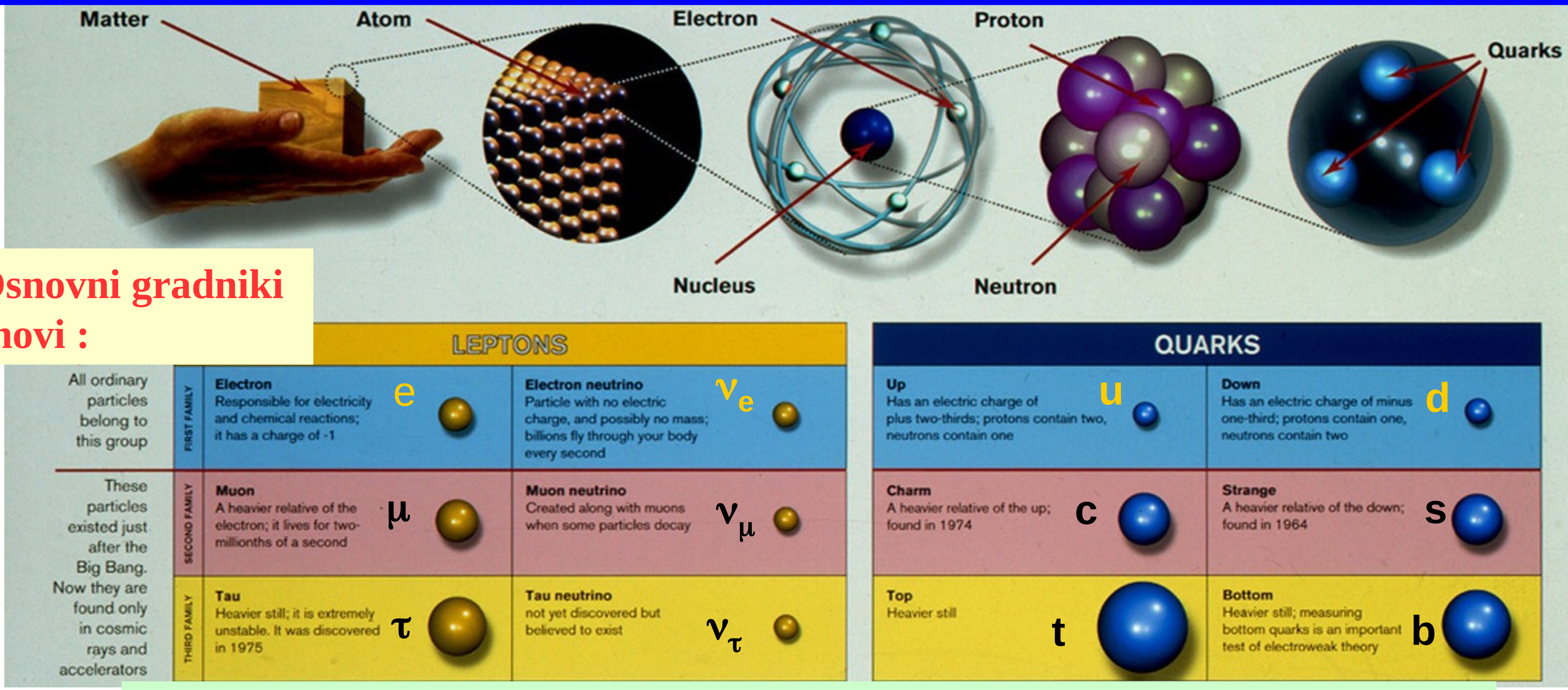




- Za (ročno) pregledovanje je podatkov preprosto preveč ...
- Želimo določiti lastnosti delcev, izmeriti razne vrednosti, konstante, ...

→ Potrebujemo izračunane količine, statistične metode, ...

... in kako snov vidimo/razumemo danes?



Osnovni gradniki snovi :

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

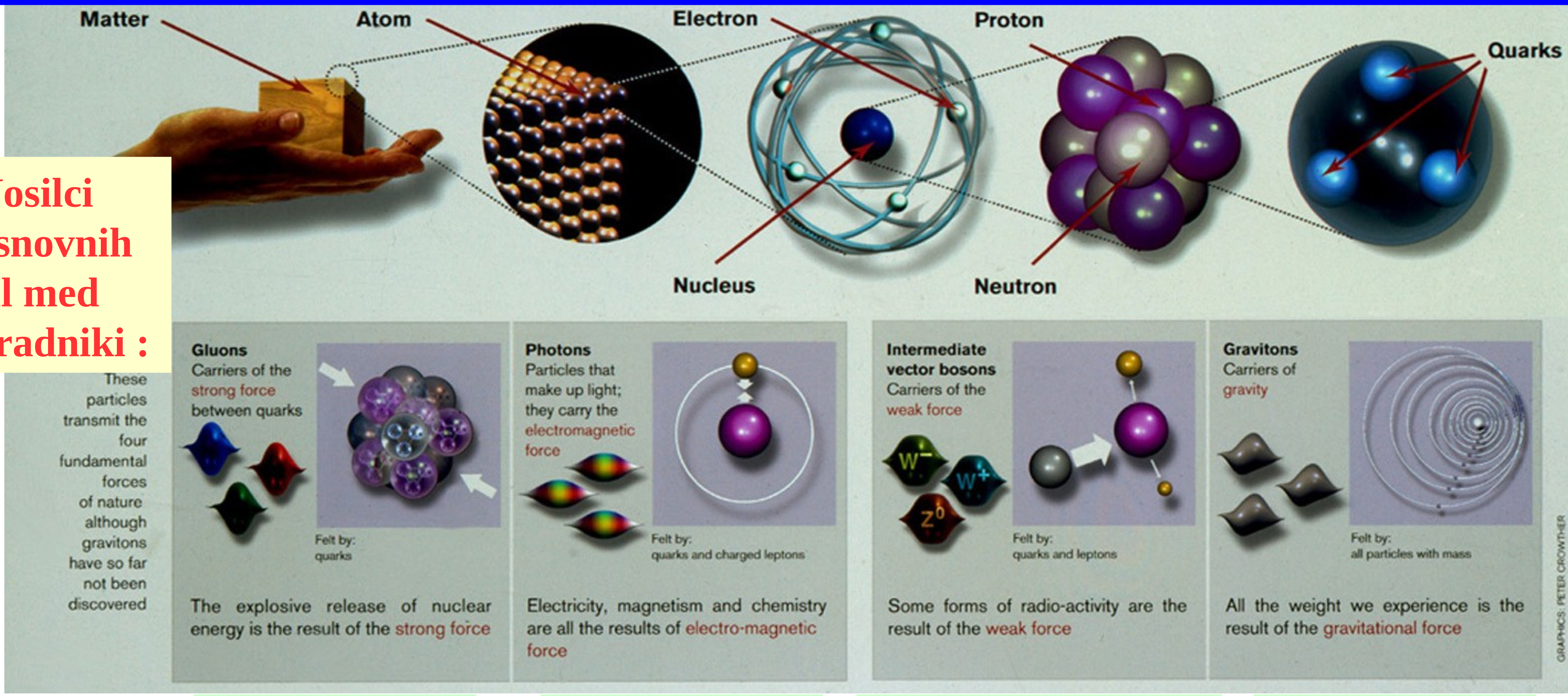
→ **leptoni so nesestavljeni**

→ **kvarki sestavljajo težje delce - hadrone, npr.**

p = uud ($+2/3e_0$ $+2/3e_0$ $-1/3e_0$) **{e_0 je osnovni naboj:**

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

... in kako snov vidimo/razumemo danes?



Nosilci osnovnih sil med gradniki :

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	~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

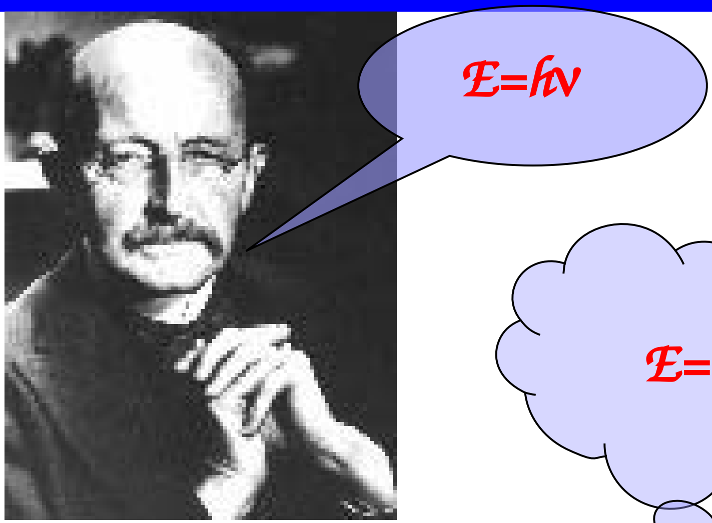
In seveda še mnogi drugi delci …

Kako opazujemo majhne delce?

Kvantna mehanika:
delci se obnašajo kot valovanje
Max Planck

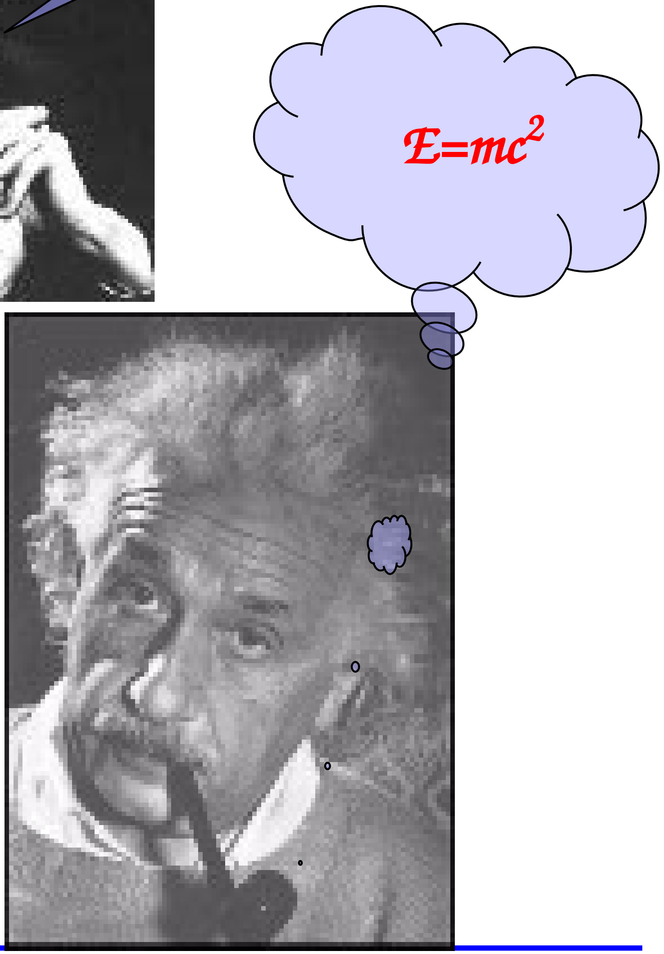
$$E = h\nu = h\,(c\,/\,\lambda)$$

velika energija → velika frekvenca
→ majhna valovna dolžina

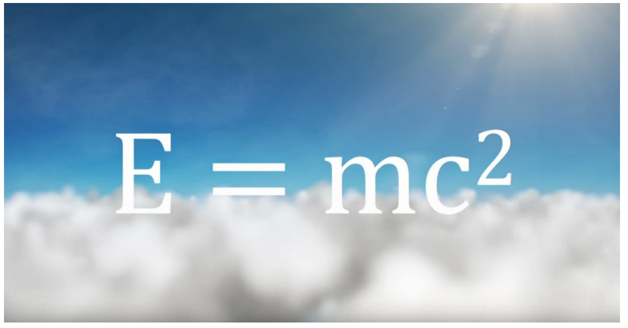


Posebna teorija relativnosti:
energija in masa sta izmenljivi
Albert Einstein

$$E=mc^2$$



Sedaj pa še nekaj enačb:



To je seveda samo poseben primer splošnejše enačbe...

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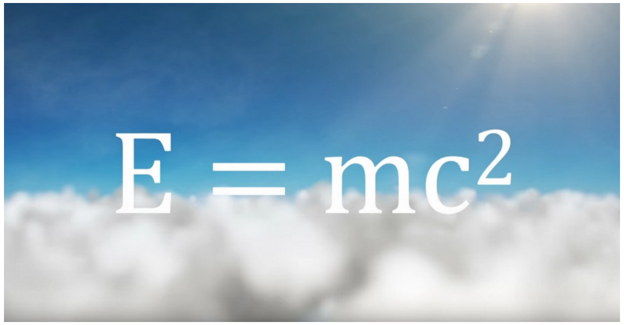
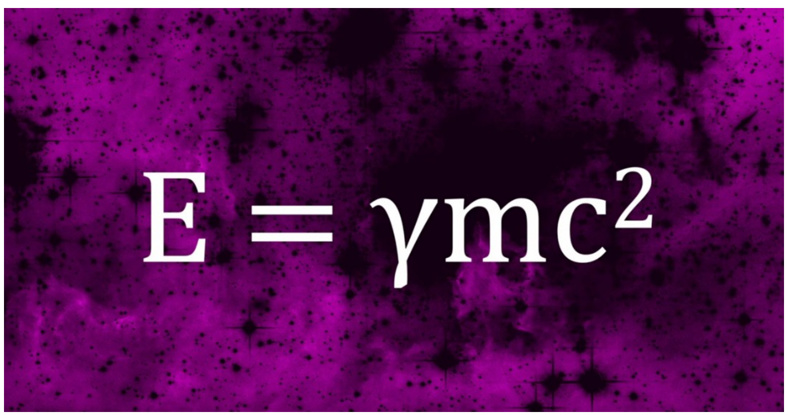
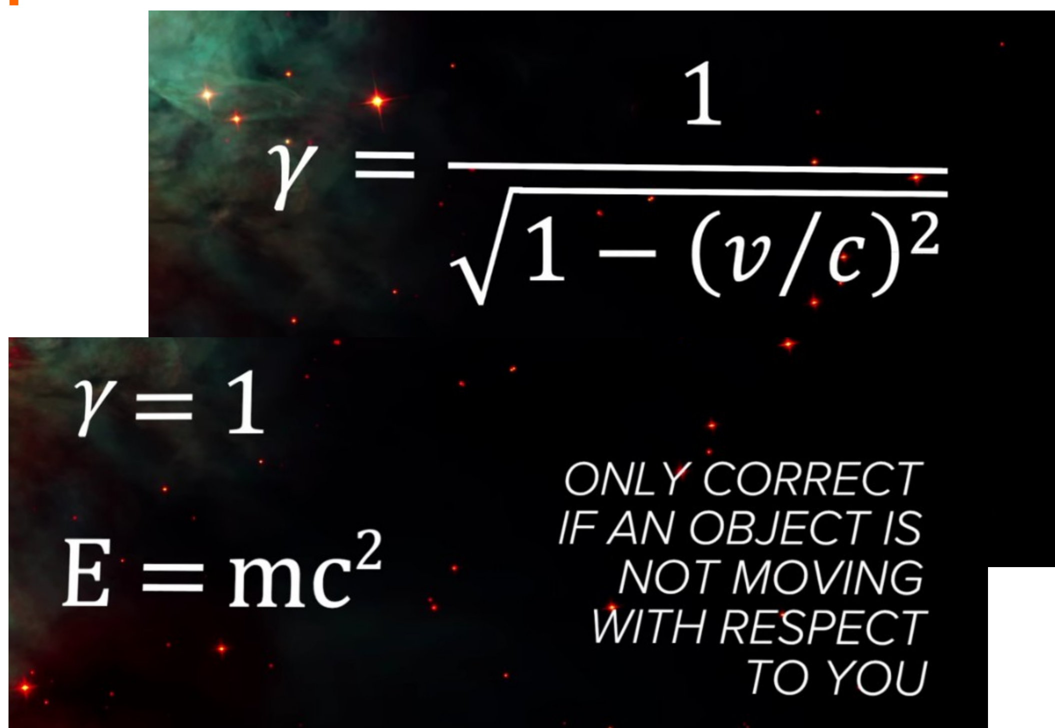


To je seveda samo poseben primer splošnejše enačbe...

zato bi morali v resnici zapisati tole:





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:

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

$$m_{relativistic} = \gamma m$$

$$p = m_{relativistic} v$$

S faktorjem γ lahko tudi predefiniramo maso delca.

Prave (relativistične) enačbe :

$$E = \gamma m c^2$$

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

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

E - *energy*
m - *mass*
c - *speed of light*
p - *momentum*

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

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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 ≈ 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 :

Observation of $Z^+(4430)$ state

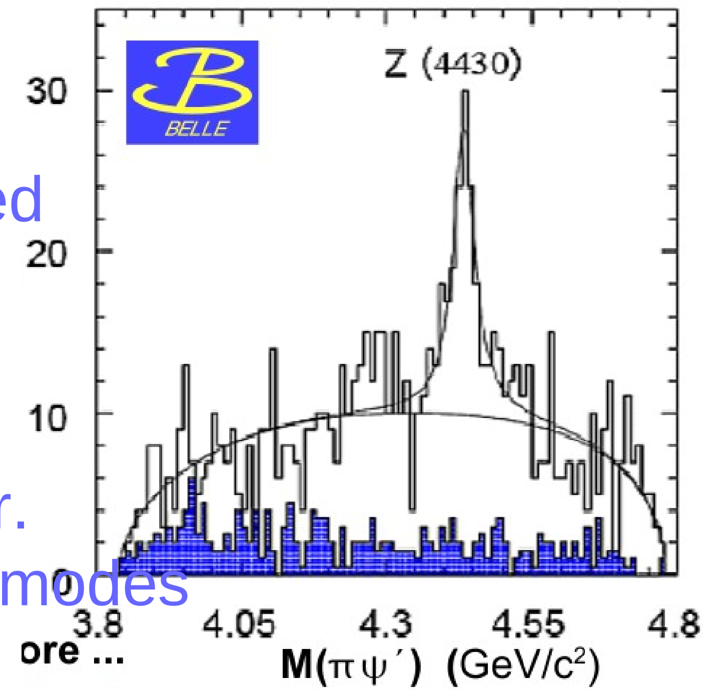
PRL 100, 142001(2008
657 $B\bar{B}$

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

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

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

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



➡ First serious tetraquark candidate

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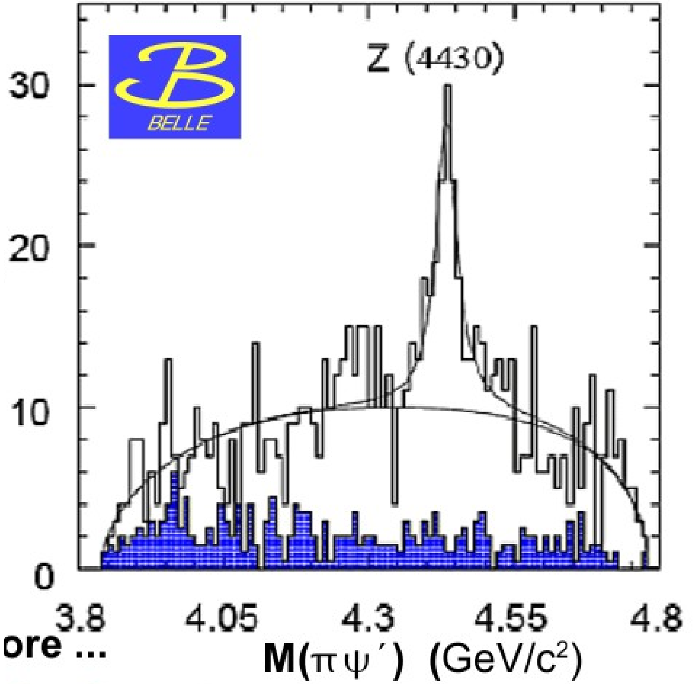

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Necessary ingredients:

- Histogram → bins of m_{invar}
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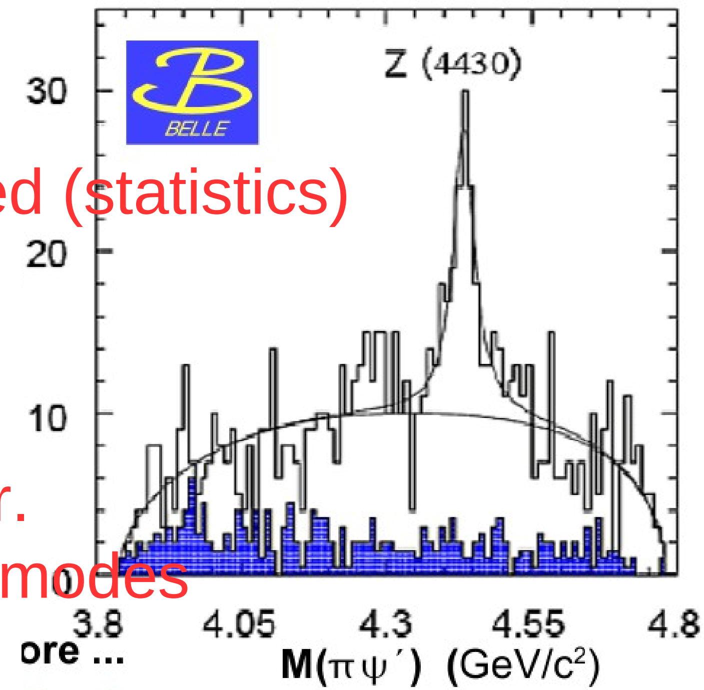


- Extract the parameters: fitting the data distribution with functions

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	½	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	½	0^-	1	0	0	[a]	[a]
K-Short[3]	K^0_S	Self	$\frac{d\bar{s}+s\bar{d}}{\sqrt{2}}$ [b]	497.611 ±0.013[c]	½	0^-	(*)	0	0	$(8.954 \pm 0.004) \times 10^{-11}$	$\pi^+ + \pi^-$ or $\pi^0 + \pi^0$
K-Long[4]	K^0_L	Self	$\frac{d\bar{s}-s\bar{d}}{\sqrt{2}}$ [b]	497.611 ±0.013[c]	½	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 $\pi^+ + \pi^0 + \pi^-$

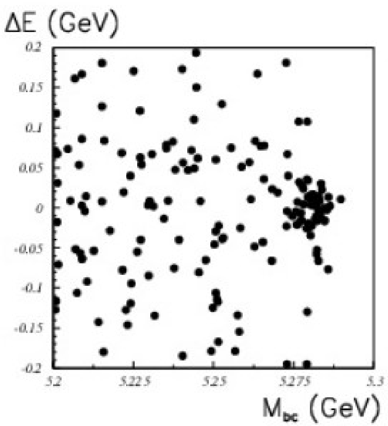
Razpadi mezonov D:

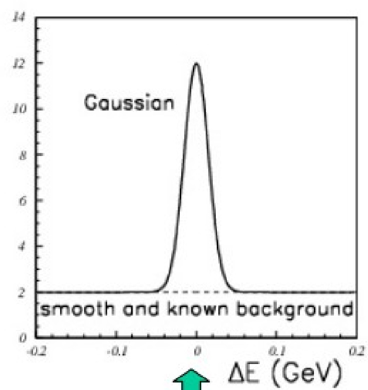
$D^{*+} \rightarrow D^0 \pi^+$ in $D^{*-} \rightarrow \bar{D}^0 \pi^-$

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

Možne izboljšave :

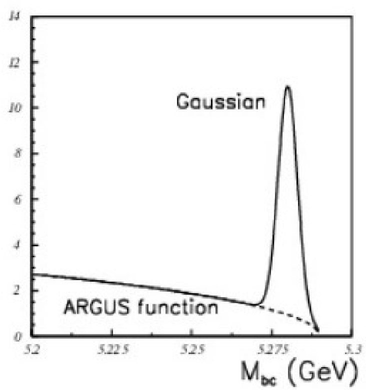
Analysis tools: B-meson selection





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

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



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

Zaključek :

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

Srečno!