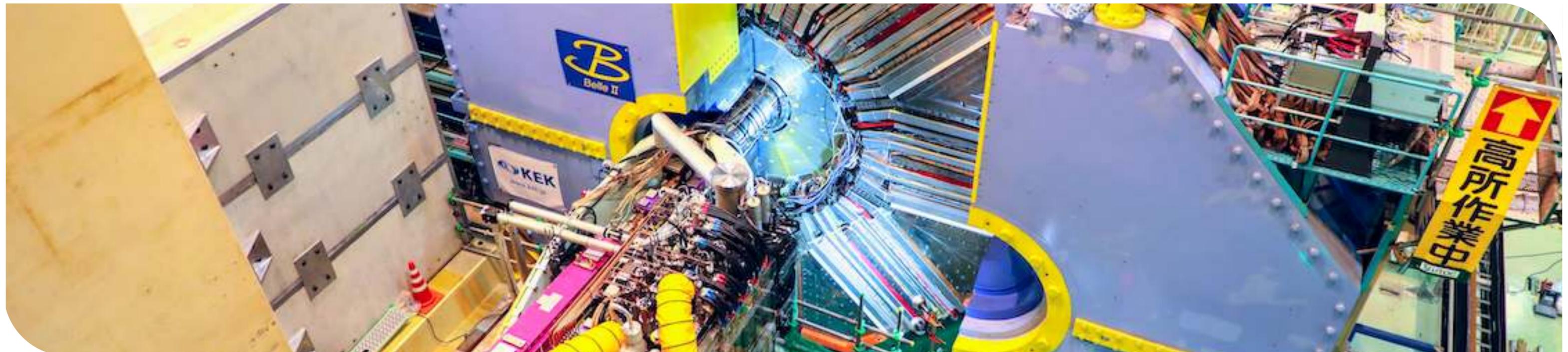


Das Universum im Labor: Forschung an Teilchenbeschleunigern

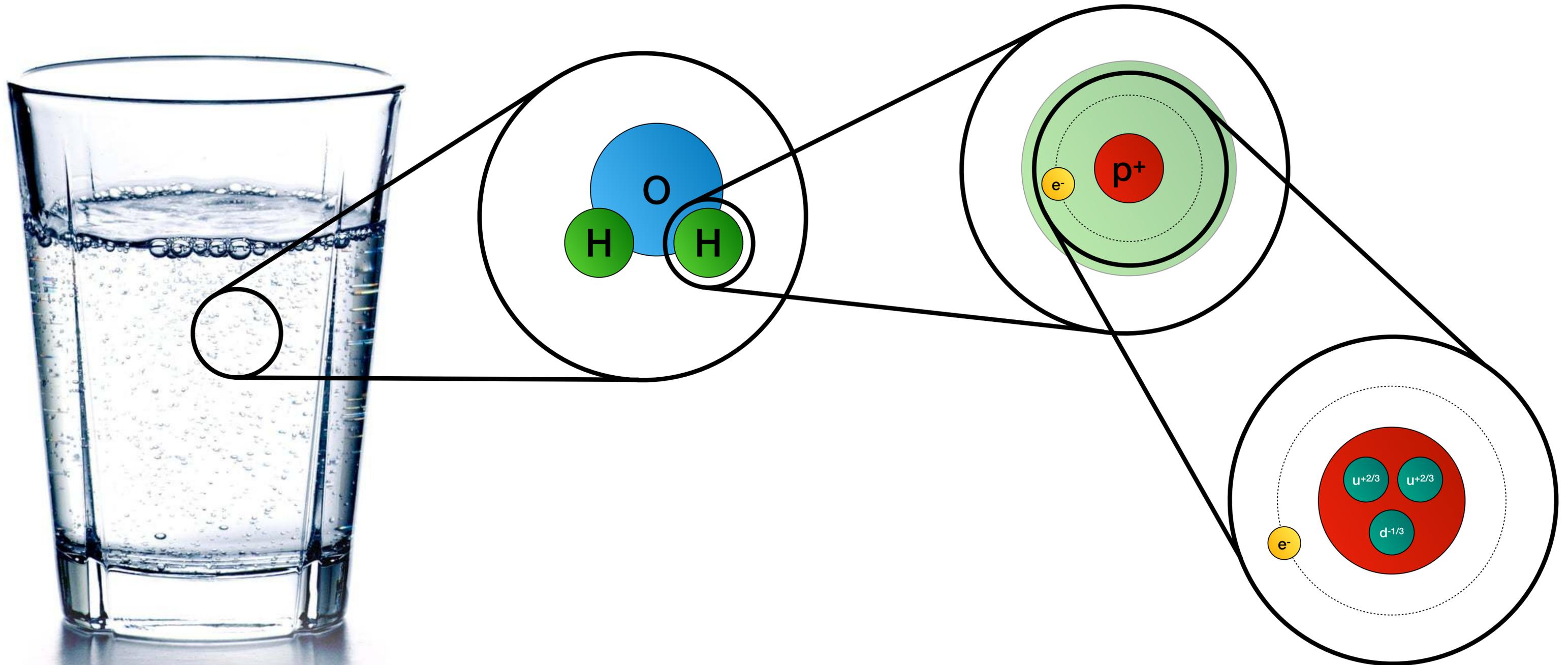
Lehrerfortbildung der KIT-Fakultät für Physik, 17.05.2023

Prof. Dr. Torben Ferber (torben.ferber@kit.edu)
Institut für Experimentelle Teilchenphysik (ETP)



(Image: S. Takahashi)

Materie als elementare Teilchen



		Elektrische Ladung
Quarks	Up	$+2/3$
	Down	$-1/3$
Leptonen	Elektron	-1



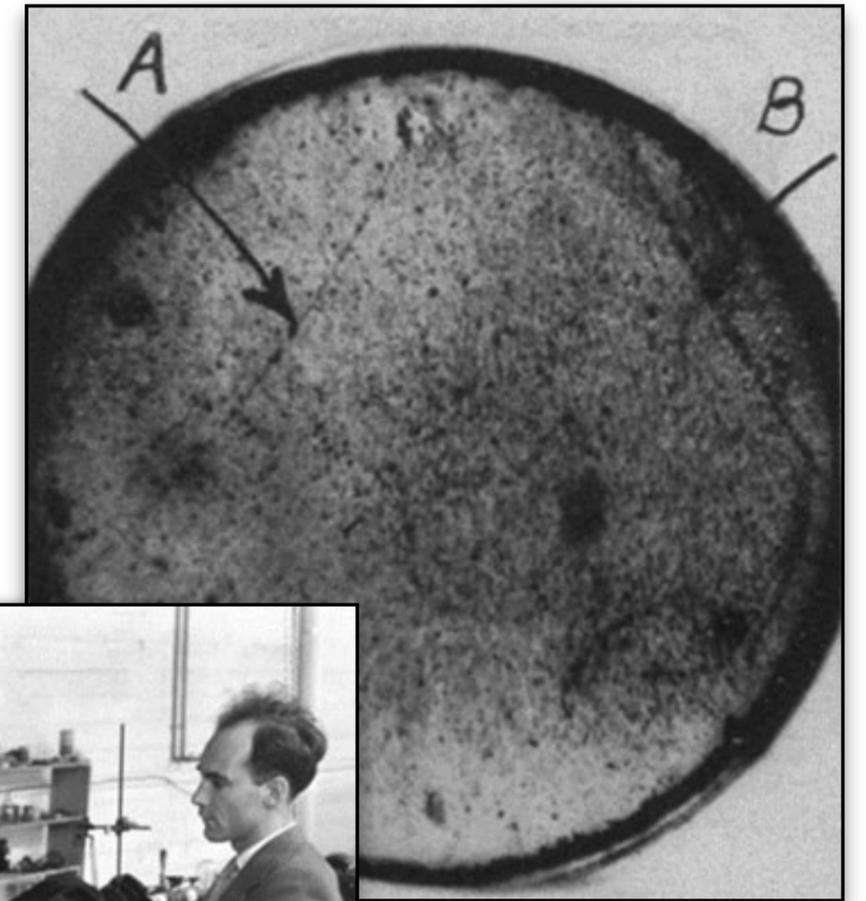
Credit: <https://www.nobelprize.org/prizes/physics/1933/dirac/facts/>

- Dirac (Nobelpreis 1933) erkennt um 1930, dass seine Gleichung zum Verhalten von Elektronen zwei Lösungen hat - eine für Teilchen mit positiver Energie und eine für Teilchen mit negativer (???) Energie

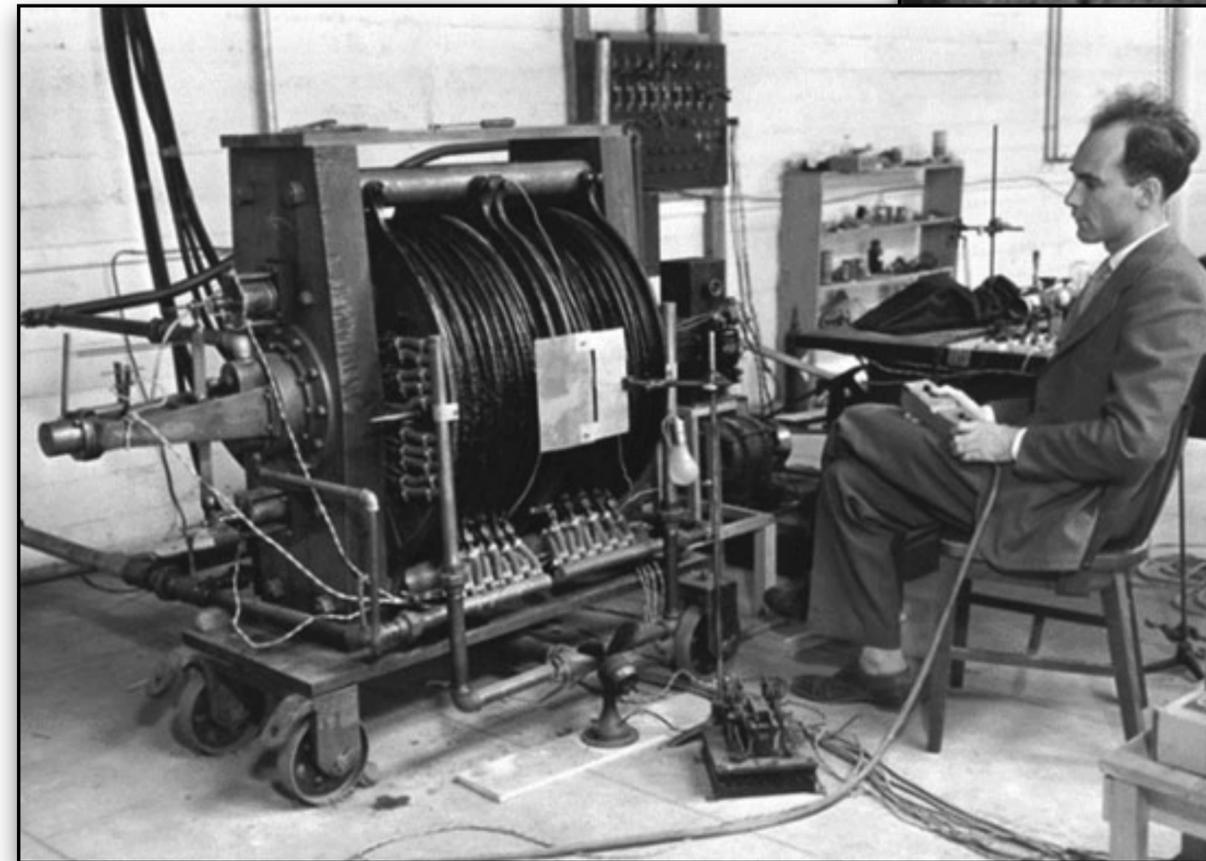
$$\left(i\gamma^\mu \partial_\mu - m \right) \psi = 0$$

Entdeckung von Antimaterie: Experiment

- C. Anderson (Nobelpreis 1936) beobachtet um 1931 Teilchenspuren aus kosmischer Strahlung, die sich in einem Magnetfeld unterschiedlich krümmen
- Protonen (positiv geladen) als Erklärung konnten schnell ausgeschlossen werden...



Credit: Caltech Archives



Credit: Caltech Archives

	Elektrische Ladung
Quarks	Up $+2/3$
	Down $-1/3$
Leptonen	Elektron -1

	Elektrische Ladung
Anti-Leptonen	Anti-Elektron $+1$

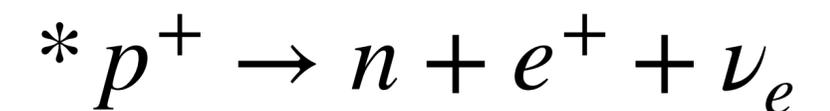
		Elektrische Ladung
Quarks	Up	$+2/3$
	Down	$-1/3$
Leptonen	Elektron	-1

		Elektrische Ladung
Anti-Leptonen	Positron	$+1$

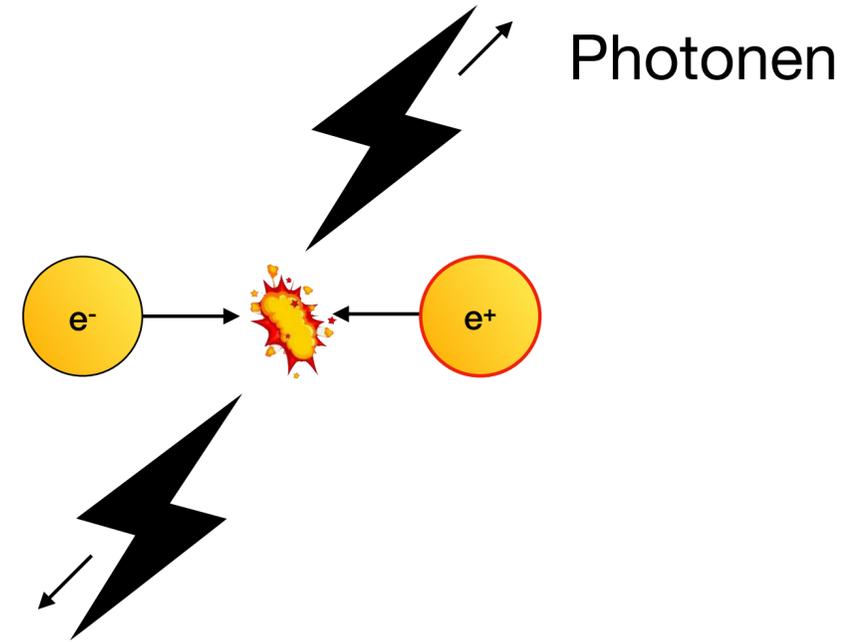
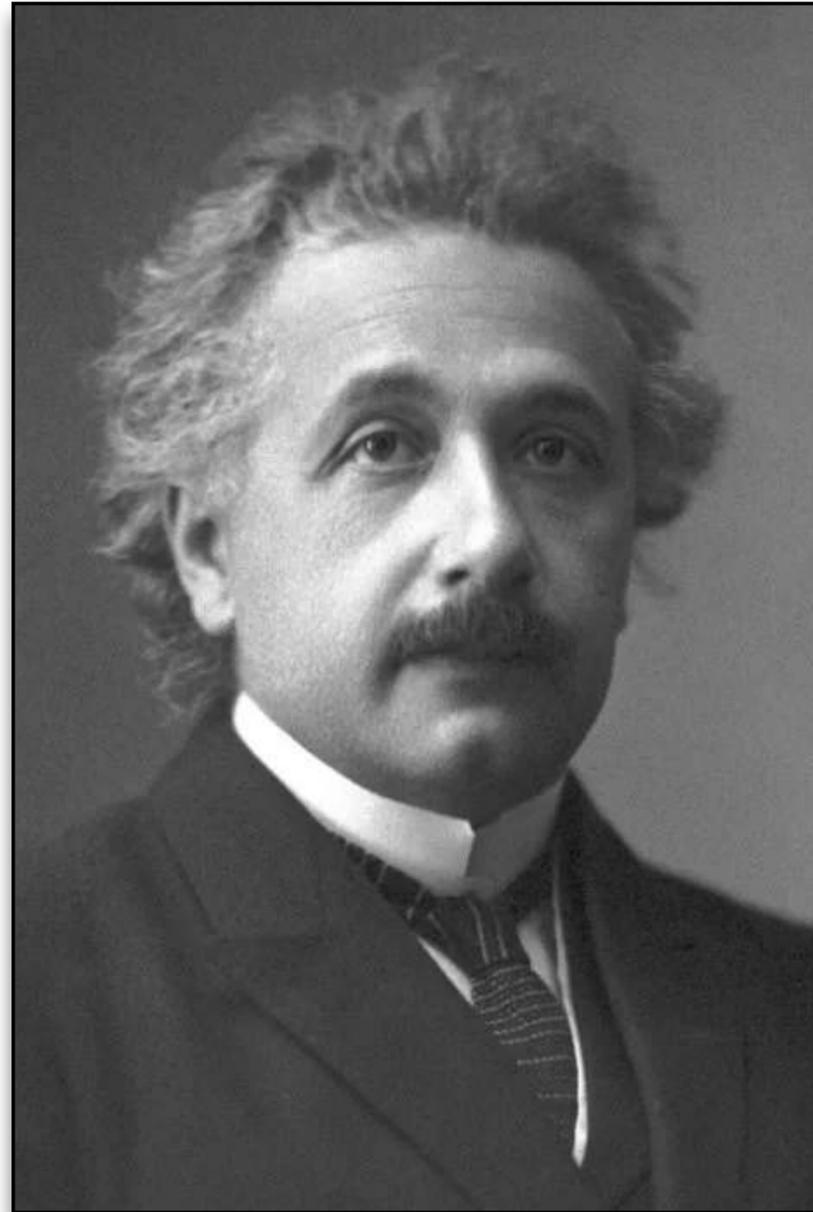


Antimaterie im Alltag

- Eine Banane emittiert etwa 15 Anti-Elektronen pro Tag, die aus dem radioaktiven Zerfall* von Kalium-40 stammen



Credit <https://www.nobelprize.org/prizes/physics/1921/einstein/facts/>



$$E = mc^2$$

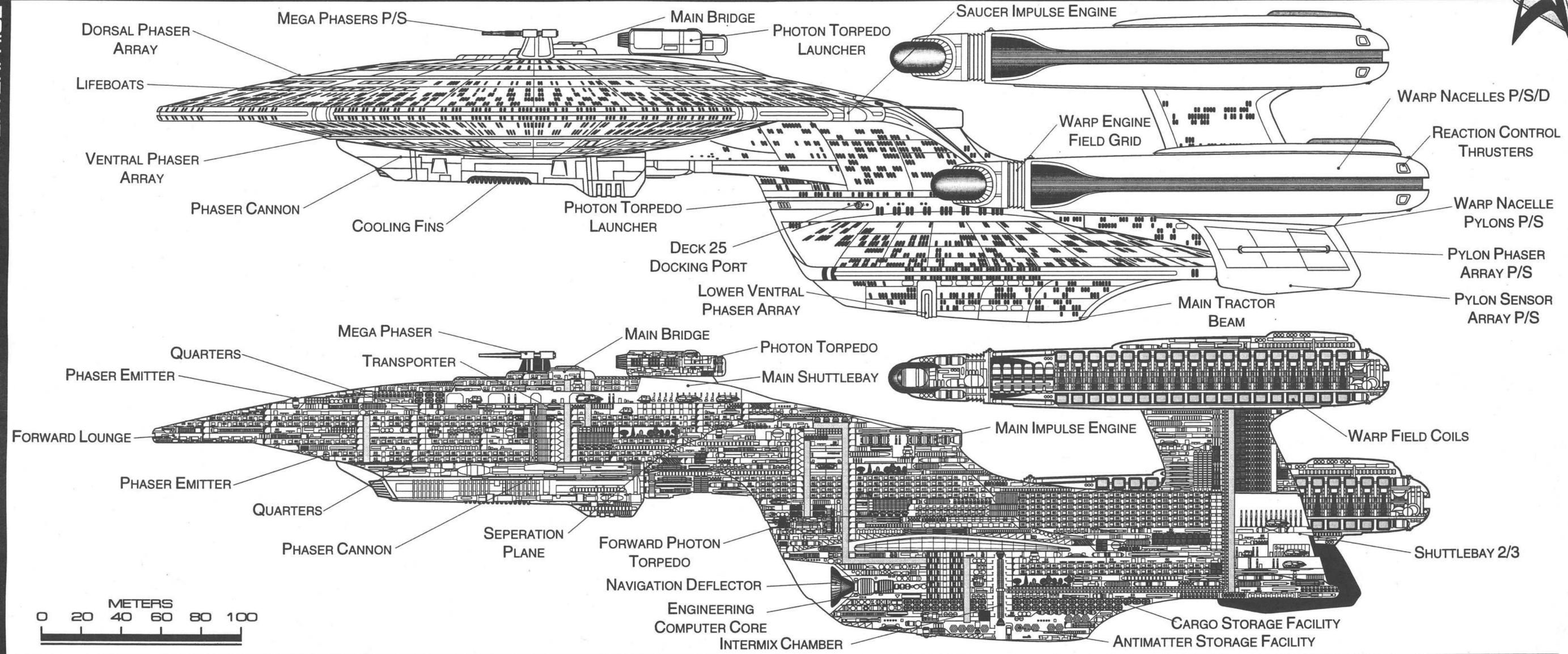
Wenn Teilchen und Antiteilchen mit Massen m kollidieren, annihilieren sie sich und setzen dabei ihre gesamte Masse als Energie $E = 2m$ frei.



HEAVY CRUISER REFIT



U.S.S. ENTERPRISE



Statistics	
Classification: Heavy Cruiser	Ship Complement: 940
Class: Galaxy refit	Duration: 5/20
Naval Construction Contract: 70637	Speed:
Dimensions:	Optimum Speed: N/A
Overall Dimensions	Max. Safe Cruising: N/A
Length: 641.20 m	Emergency Speed: N/A
Width: 467.12 m	Maximum Speed: N/A
Height: 152.33 m	Destructive Speed: N/A
Primary Hull	Weapons:
Length: N/A	Phasers: N/A
Width: 467.12	Phaser Output: N/A
Height: N/A	Megaphasers: N/A
Secondary Hull	MegaPhaser Output: N/A
Length: N/A	Photon Torpedo Tubes: 4
Width: N/A	Defense:
Height: N/A	Shield Holdoff: N/A
Nacelle Dimensions	Shield Refresh: N/A
Length: N/A	Tractor Beams: 2
Width: N/A	Tow Capacity: 4.25x10 ⁸ mt
Height: N/A	Max Range: 1.06x10 ⁶ km
Displacement: 5,250,000mt	

Ship Silhouettes

Total Target Area 289082.31 m²

Top Silhouette
Area 200344.35 m²

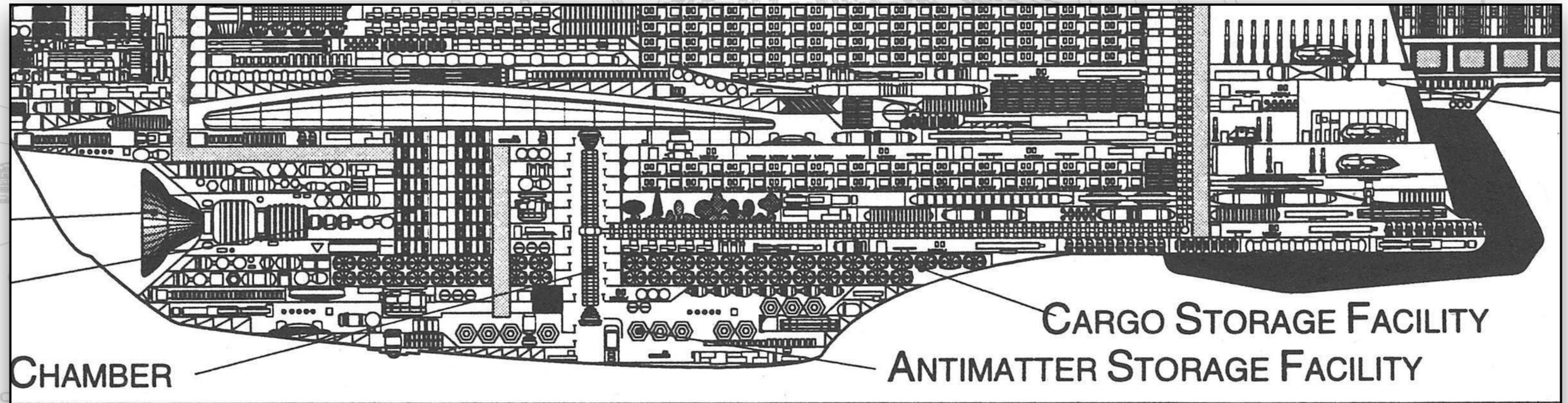
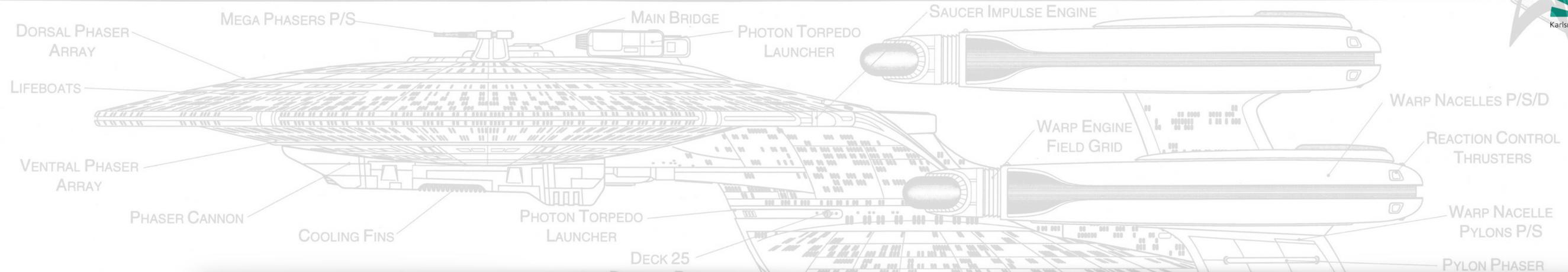
Port Silhouette
Area 50314.63 m²

Front Silhouette
Area 36423.13 m²

© (Eric Kristiansen 1996)

HEAVY CRUISER REFIT

U.S.S. ENTERPRISE



Statistics

Classification: Heavy Cruiser	Ship Complement: 940
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Width: 467.12	Phaser Output: N/A
Height: N/A	Megaphasers: N/A
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Length: N/A	Photon Torpedo Tubes: 4
Width: N/A	Defense:
Height: N/A	Shield Holdoff: N/A
Nacelle Dimensions	Shield Refresh: N/A
Length: N/A	Tractor Beams: 2
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Height: N/A	Max Range: 1.06x10 ⁶ km
Displacement: 5,250,000mt	

Ship Silhouettes



© (Eric Kristiansen 1996)

Source: NCC-1701 Technical

Antimaterie als Energiequelle?

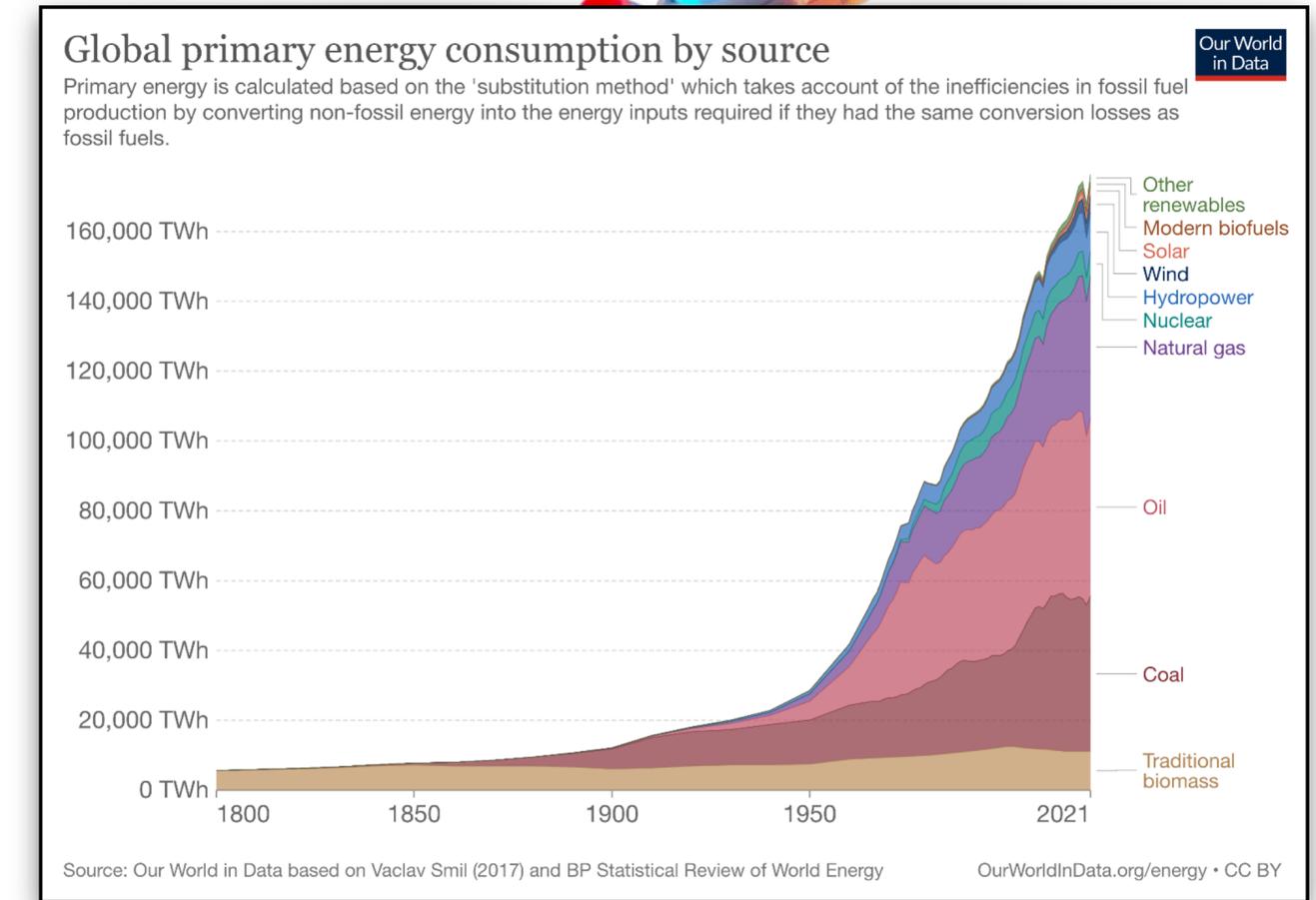
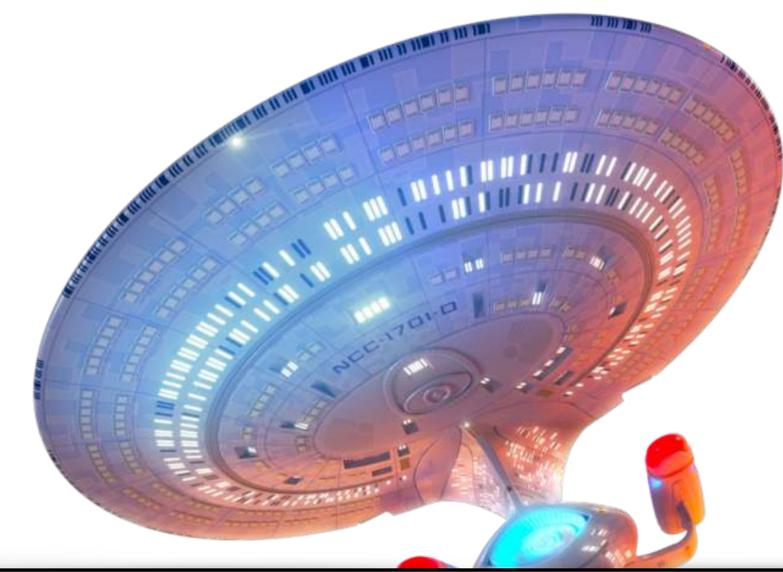
- Gewicht der Enterprise NCC-1701-D (“Next Generation”), sehr optimistische Schätzung: etwa 500 Millionen kg

- Energiedichte von Antimaterie: etwa zweimal 100 MJ/μg

- zum Vergleich:
 - Deuterium Kernfusion: ~ 0.5 MJ/μg
 - Uran Kernspaltung: ~0.07 MJ/μg
 - (flüssiger) Wasserstoff: ~1.2×10⁻⁷ MJ/μg
 - Schokolade: ~ 0.3×10⁻⁷ MJ/μg

- Beschleunigung auf 25% Lichtgeschwindigkeit benötigt etwa dann etwa 1.3 × 10²⁴J

→ Benötigte Antimaterie: etwa 7.3t (100% Effizienz)
→ Gesamte bislang auf der Erde produzierte Antimaterie: etwa 15 Nanogram



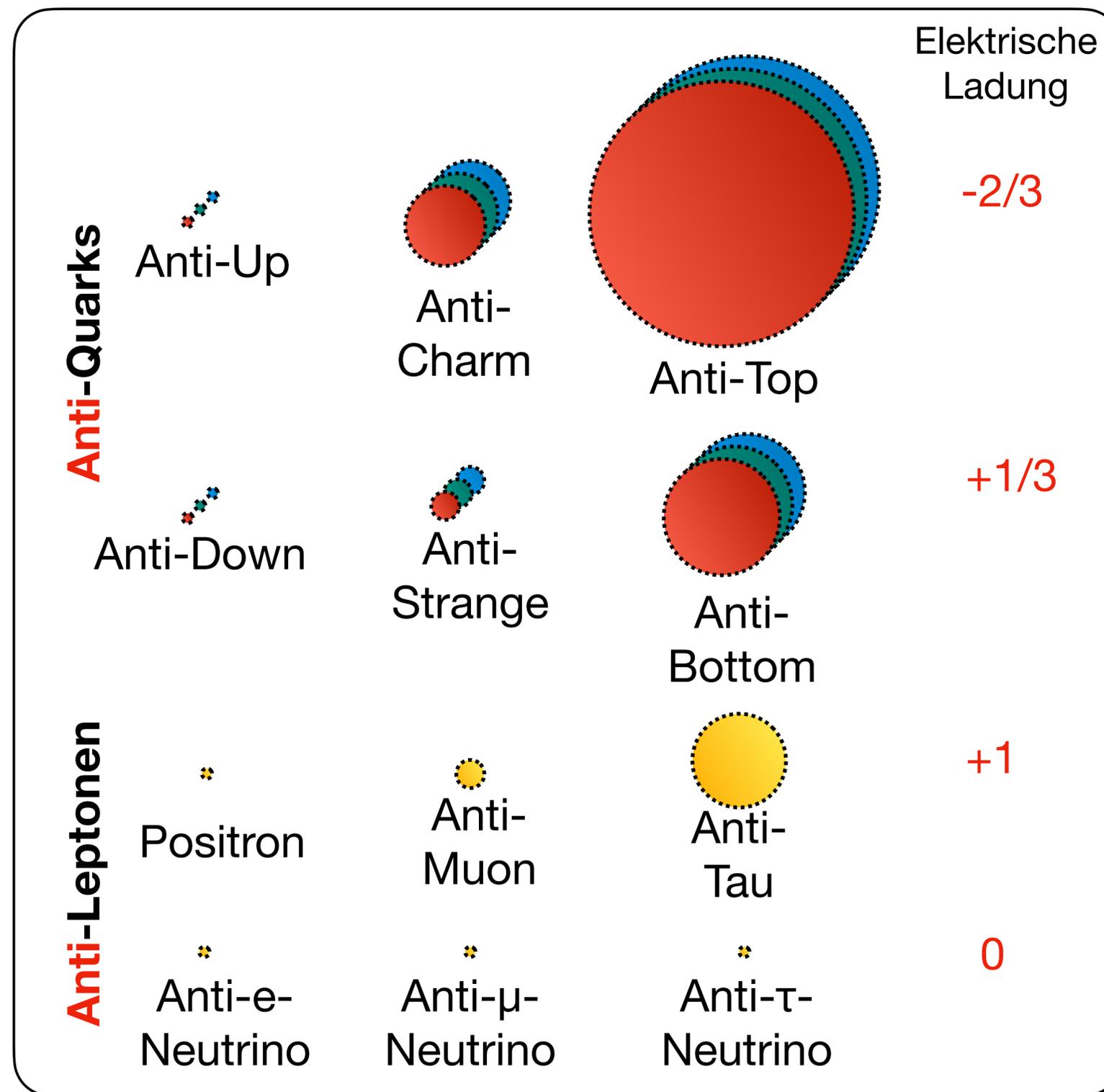
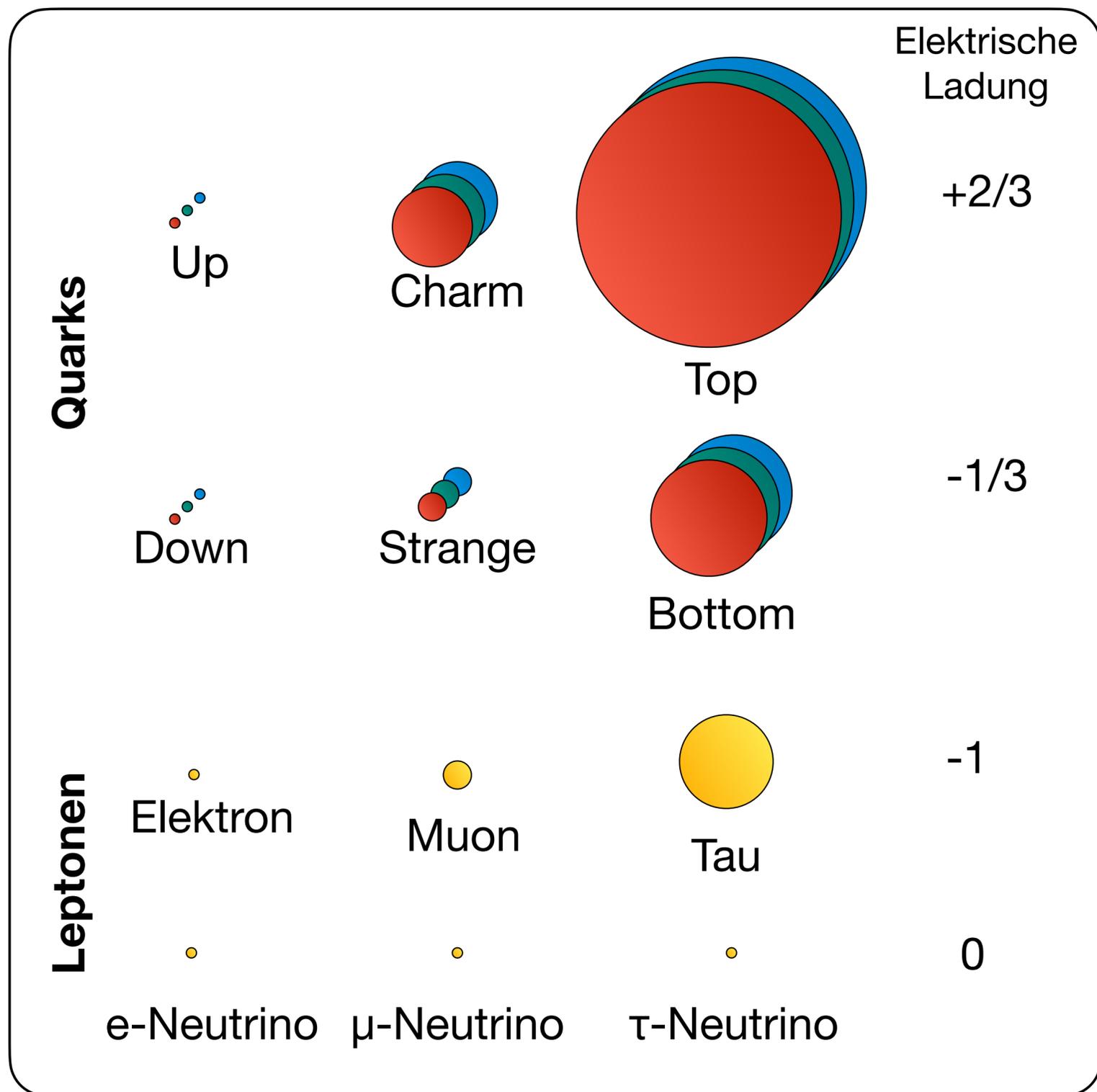
Energieweltjahresproduktion 2022: etwa 1.3 × 10²⁰J

		Elektrische Ladung
Quarks	Up	$+2/3$
	Down	$-1/3$
Leptonen	Elektron	-1

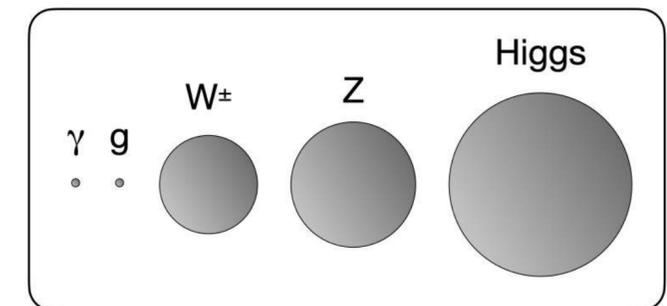
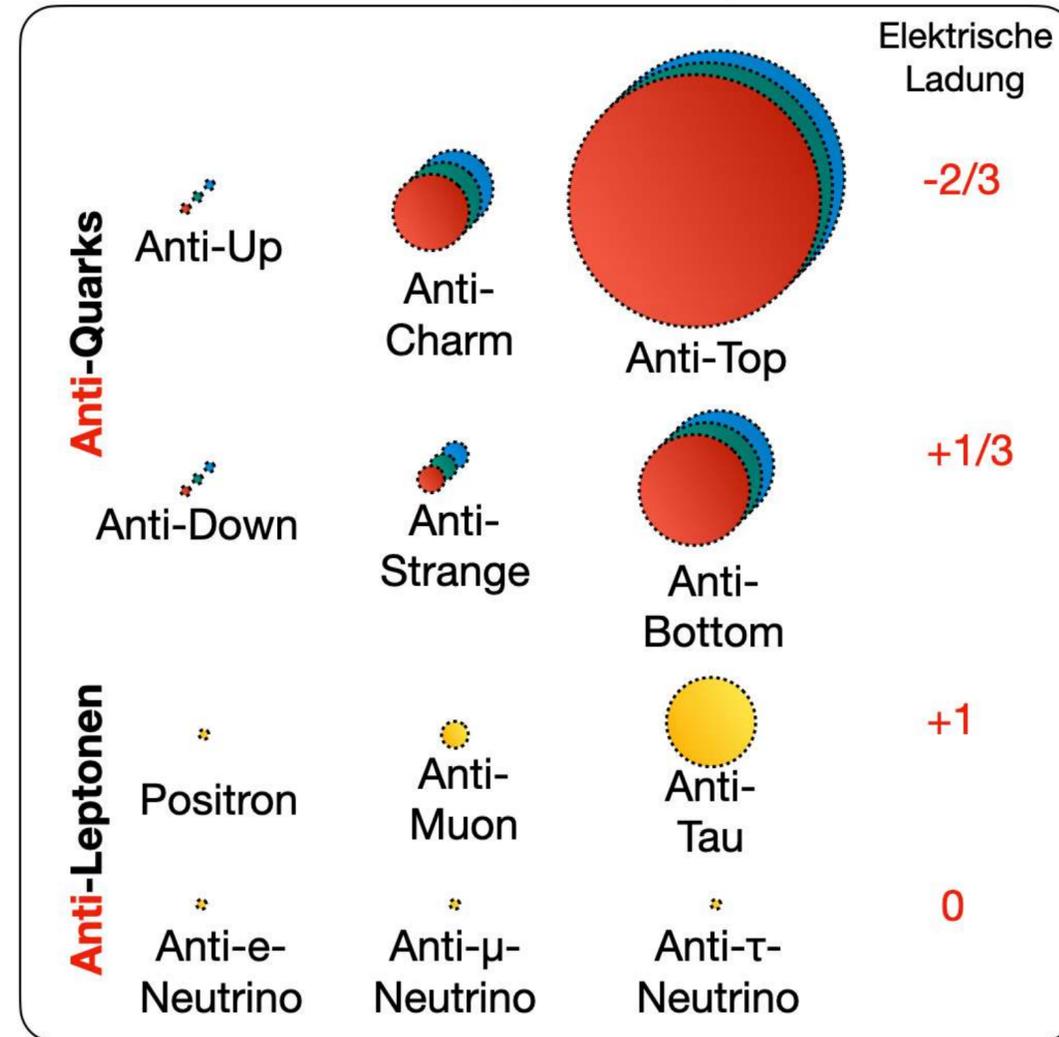
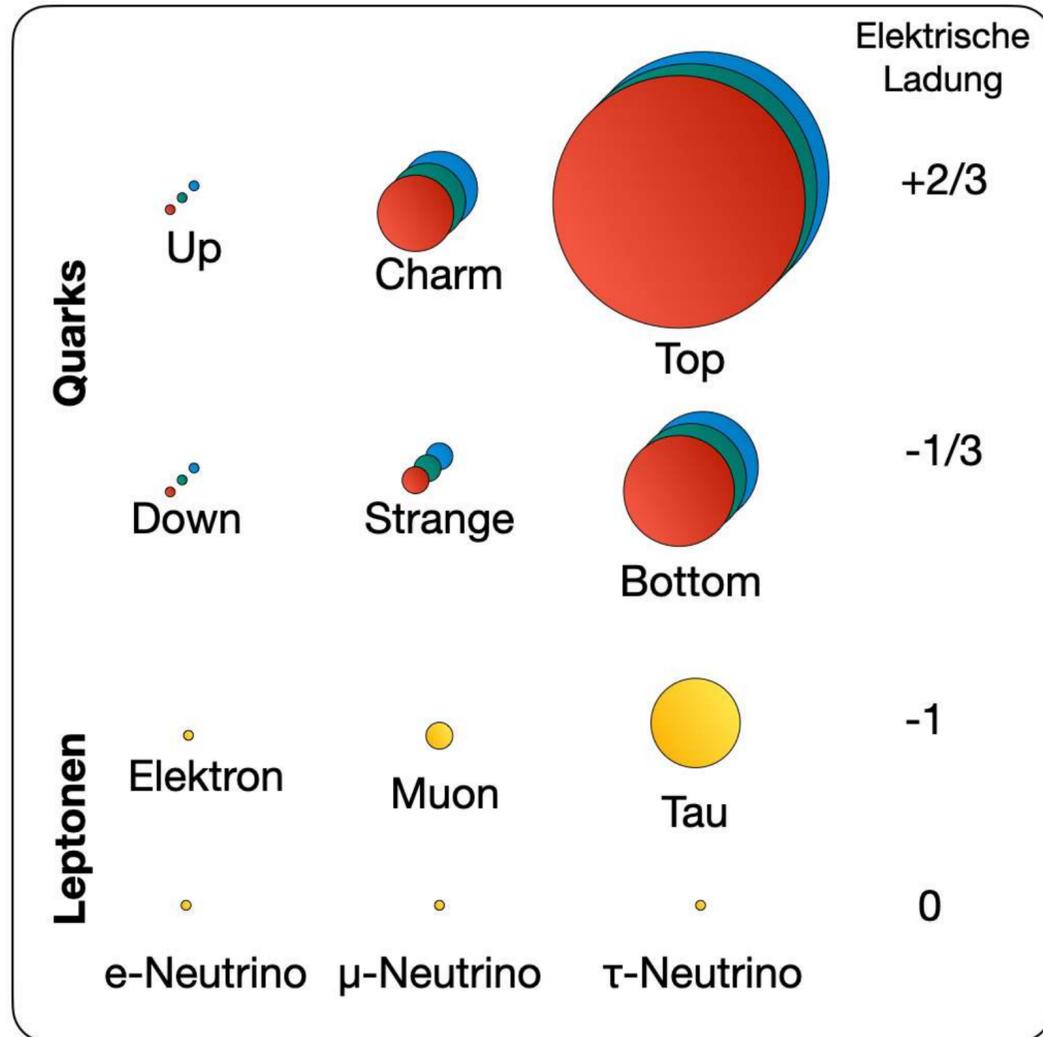
		Elektrische Ladung
Anti-Leptonen	Positron	$+1$

Elementare Teilchen und Antiteilchen

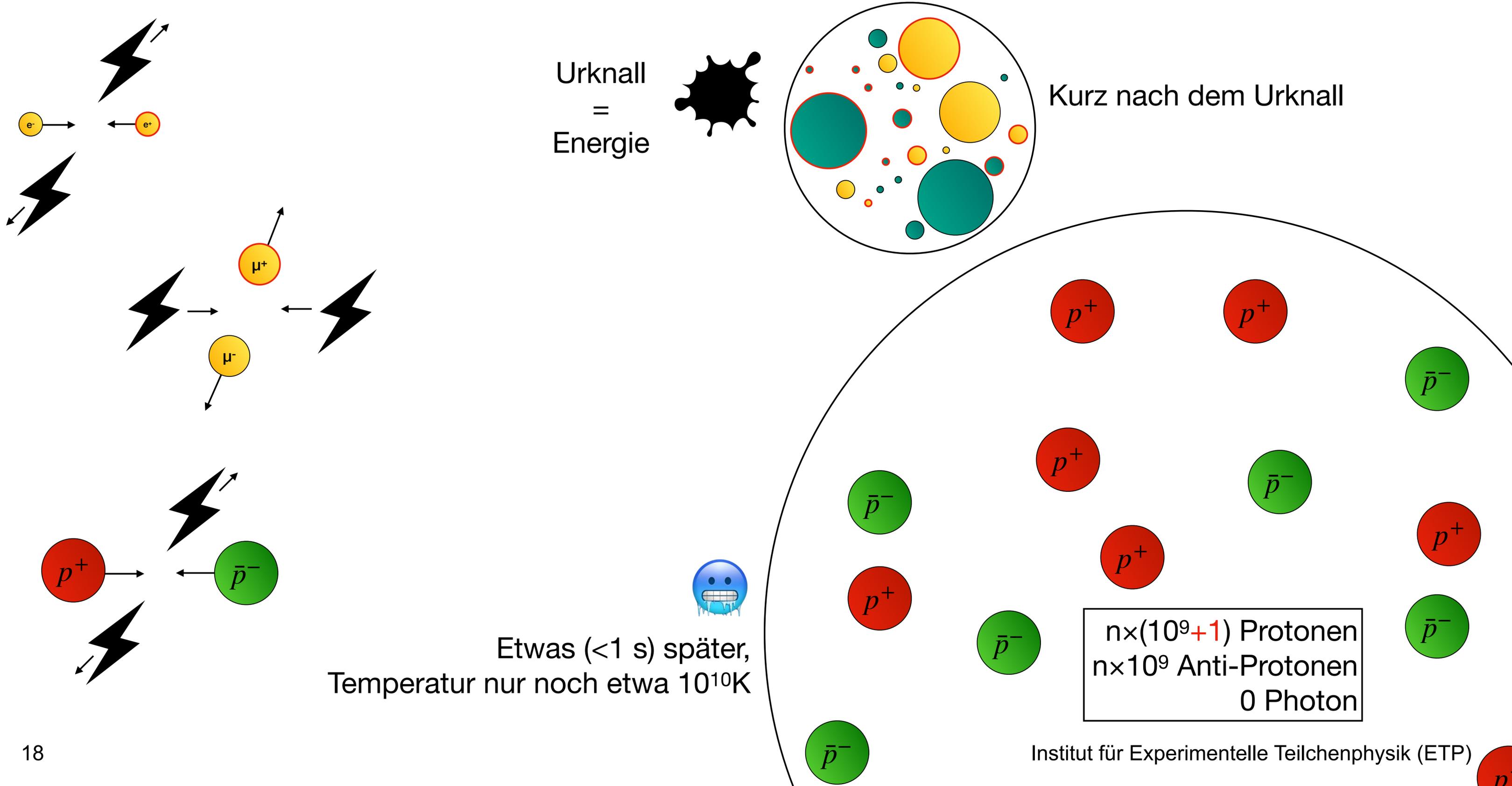
Anti-Farben: **Anti-Rot**, **Anti-Grün**, **Anti-Blau**



Elementare Teilchen und Antiteilchen



Wo ist denn die Antimaterie?



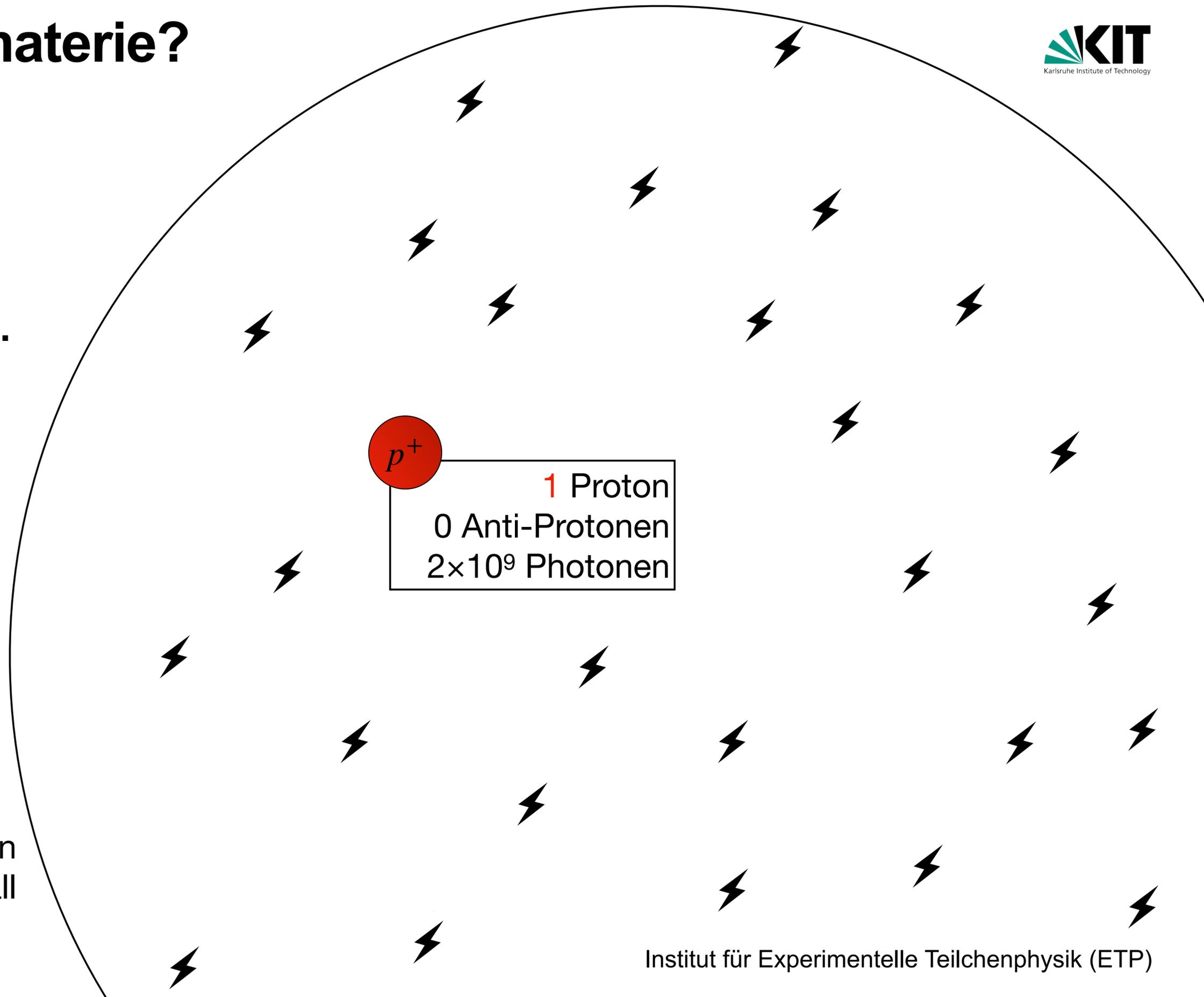
Wo ist denn die Antimaterie?

- Unsere Daten zeigen:
Es wurde fast alle
Materie und
Antimaterie vernichtet.
Aber 0.0000001%
Materie ist übrig
geblieben.

Niemand weiß
warum!

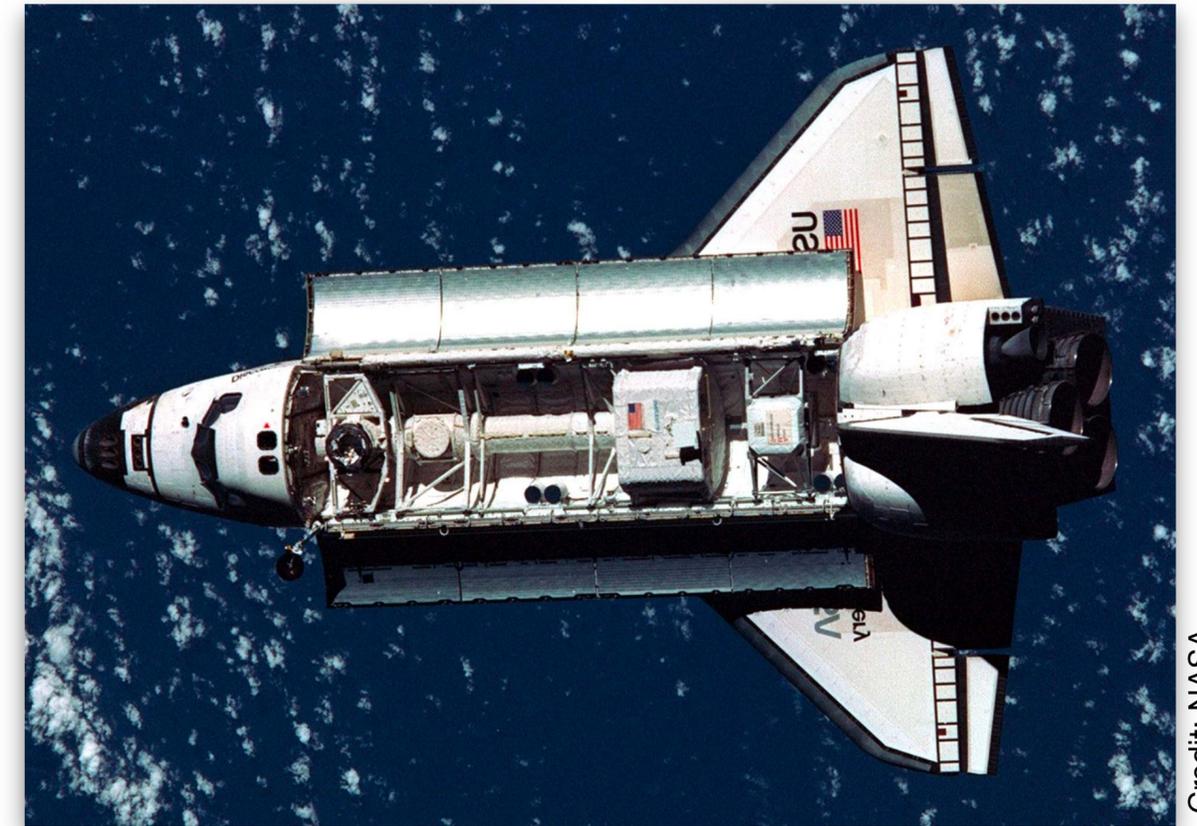
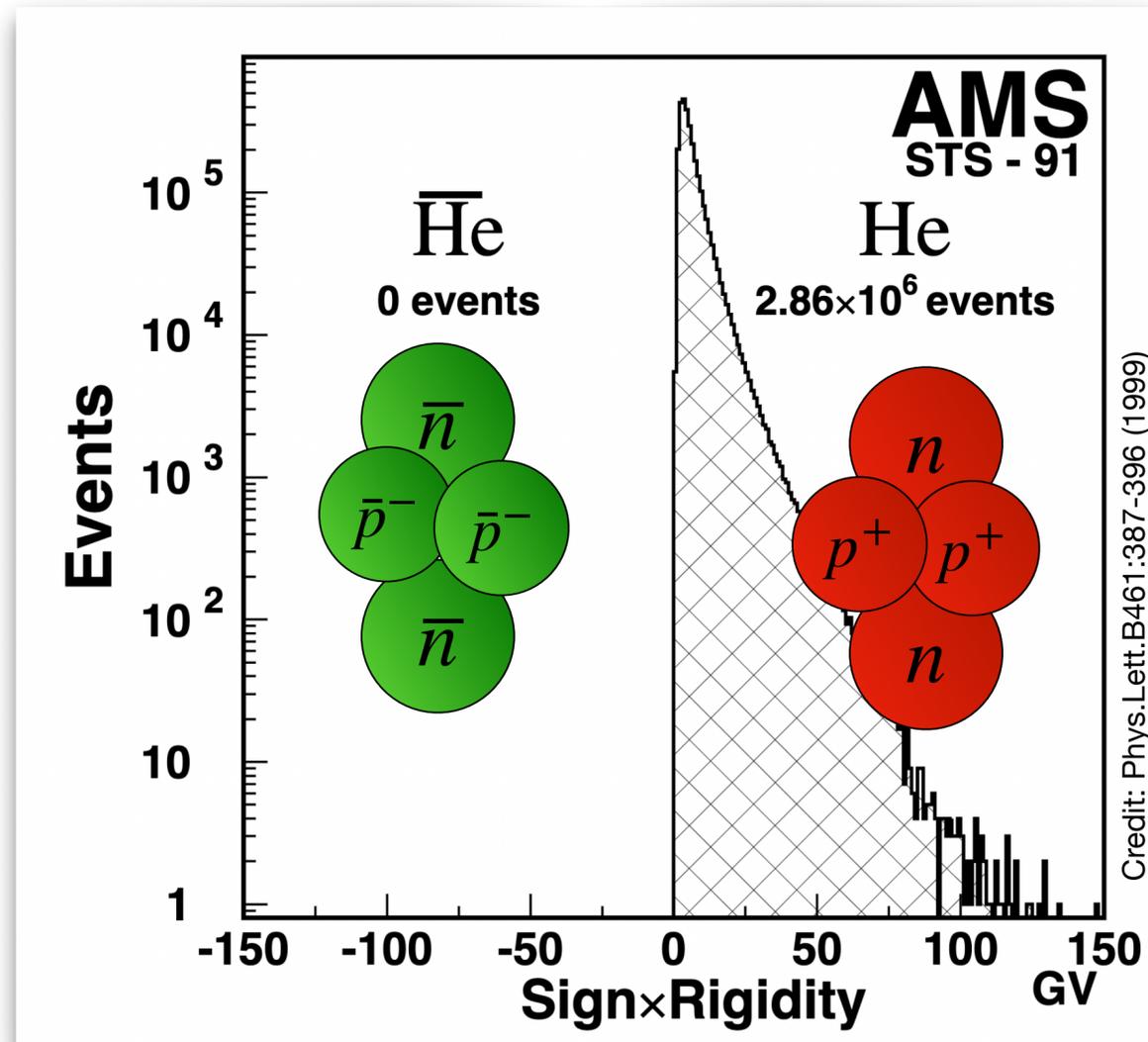


Noch viel später... 13.7 Milliarden
Jahre nach dem Urknall

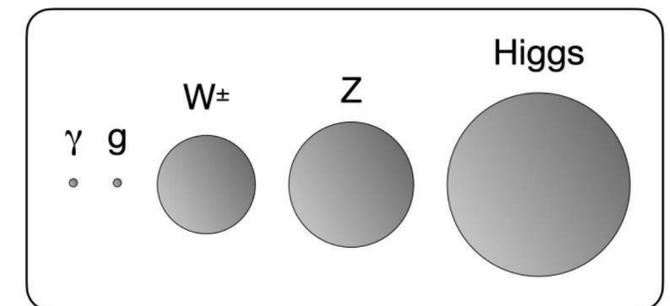
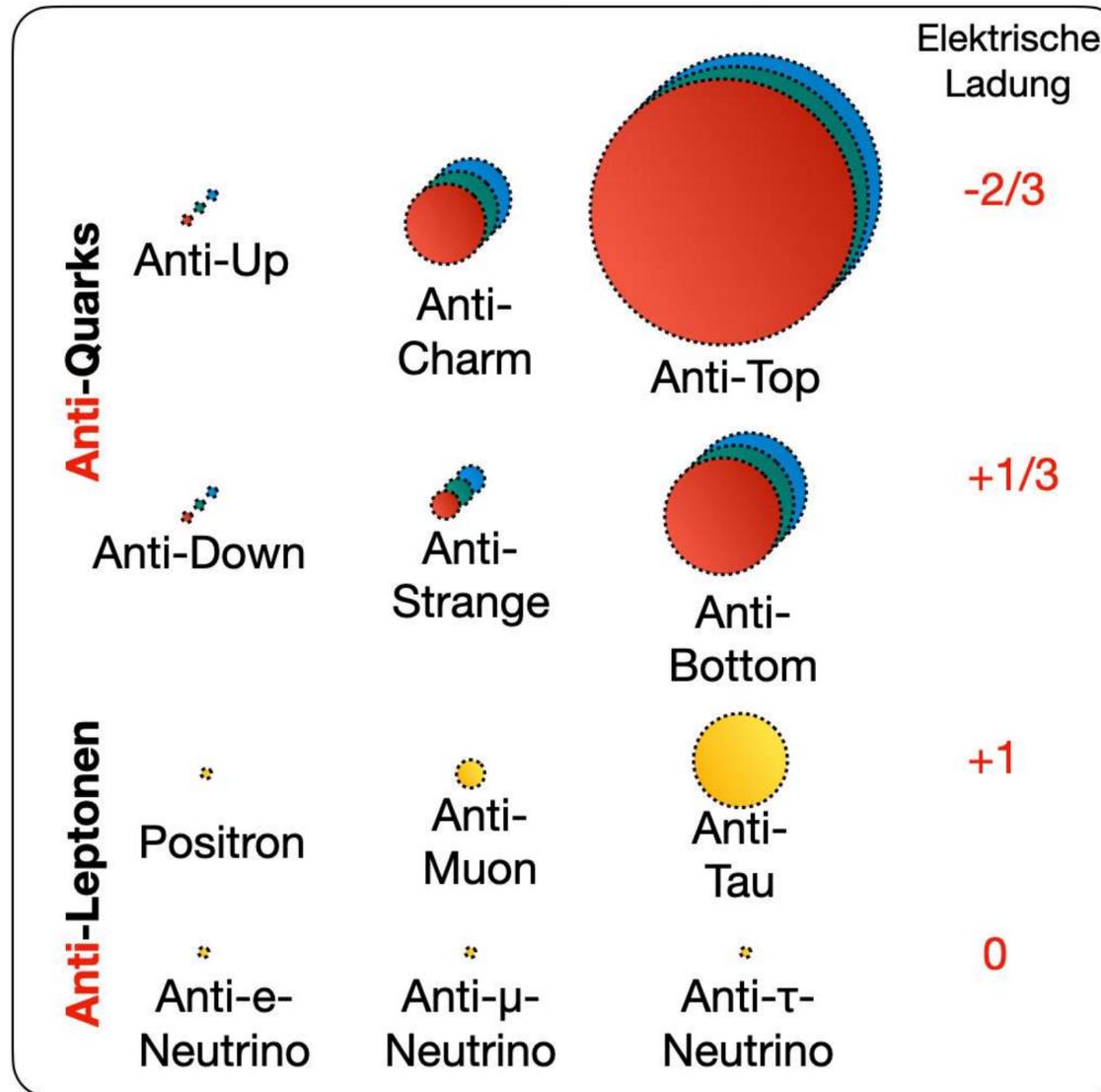
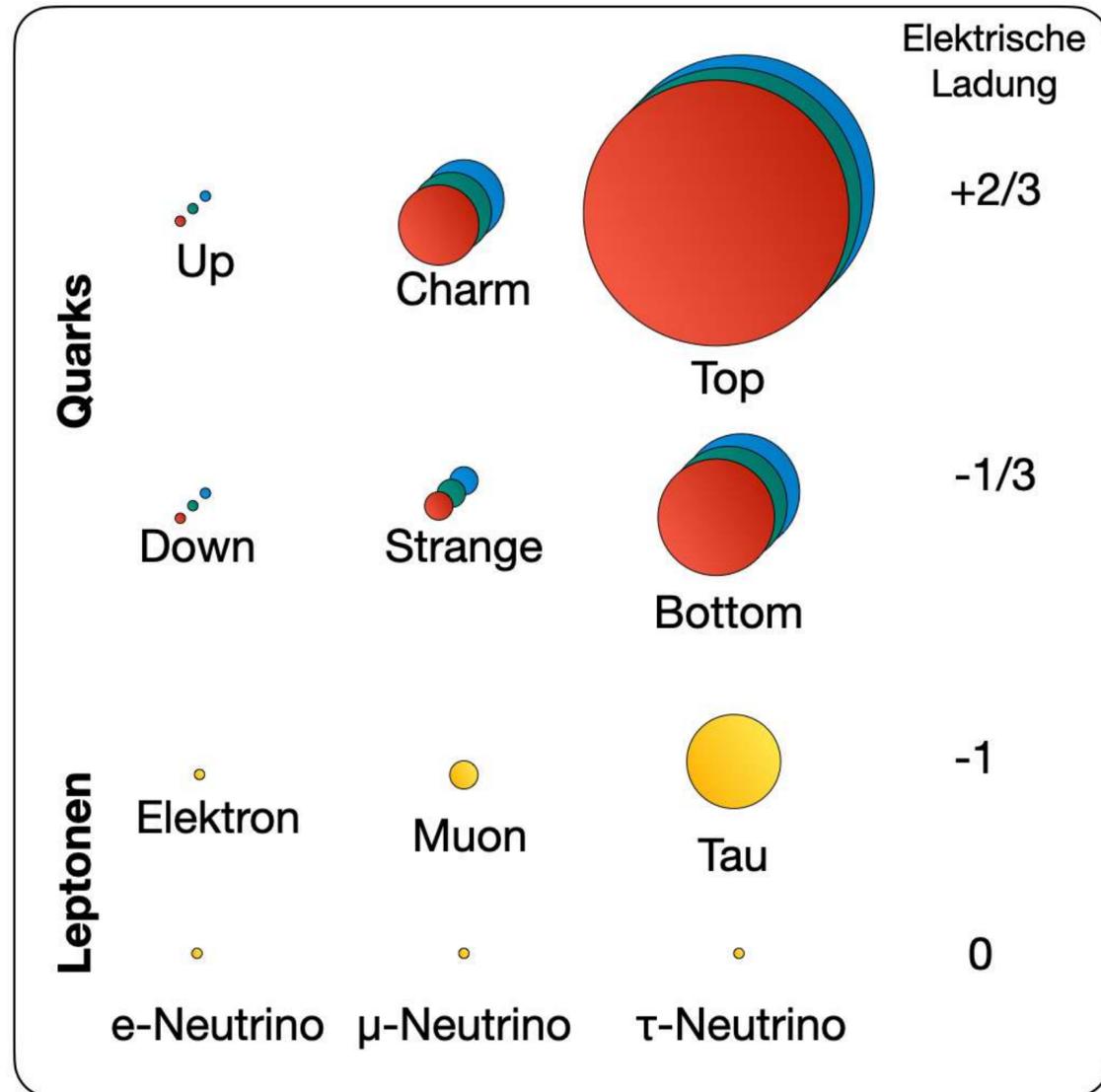


Wo ist denn die Antimaterie?

- Schwerere Anti-Atomkerne wären ein klares Zeichen für die Existenz von Antimaterie im Universum...



Elementare Teilchen und Antiteilchen



Das Universum im Labor

(Image: S. Takahashi)

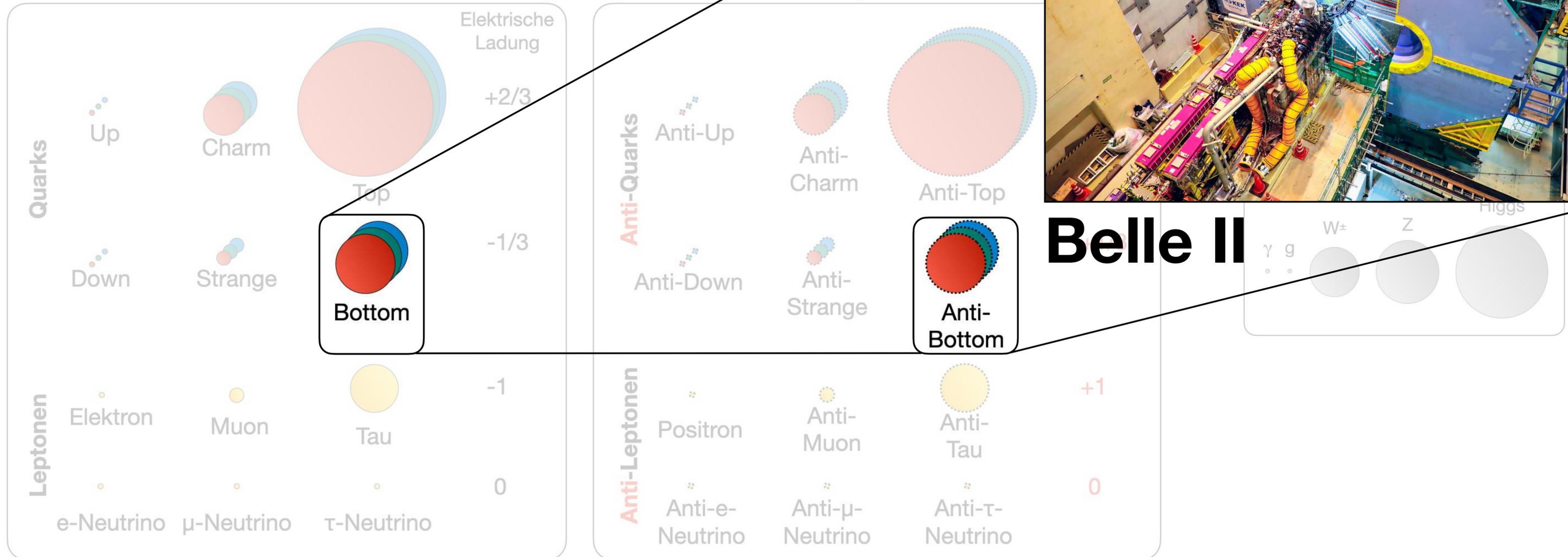
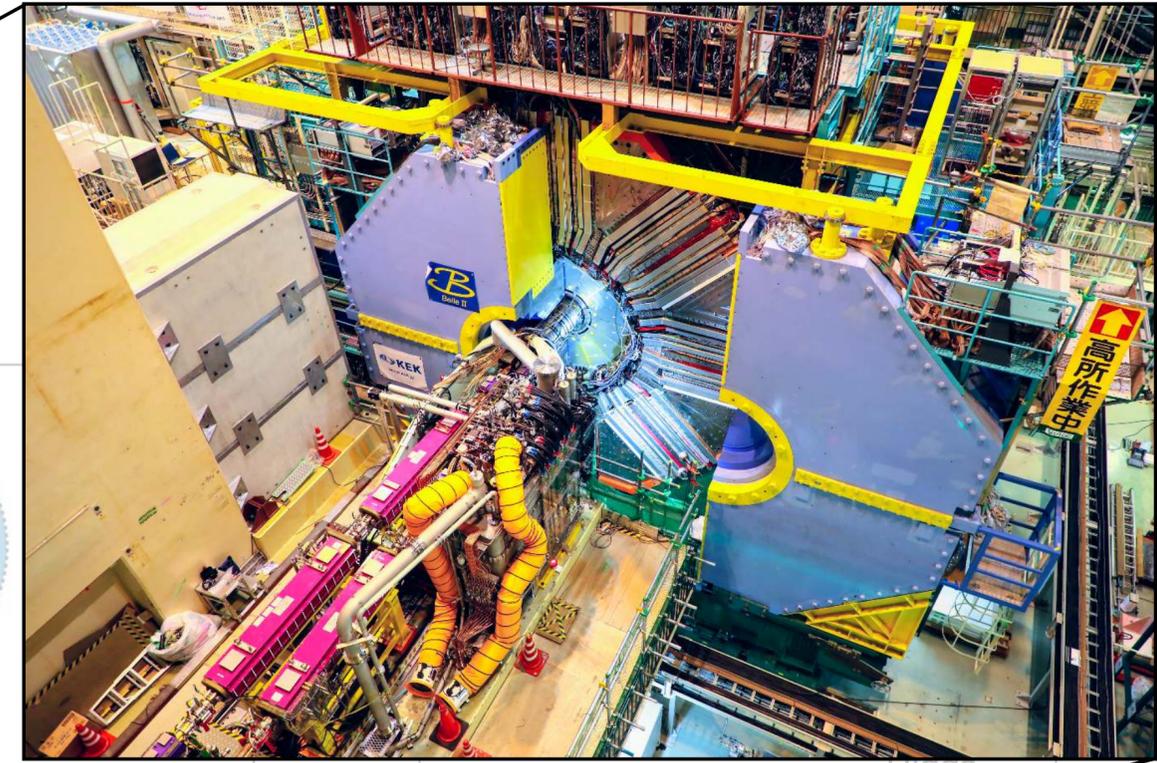
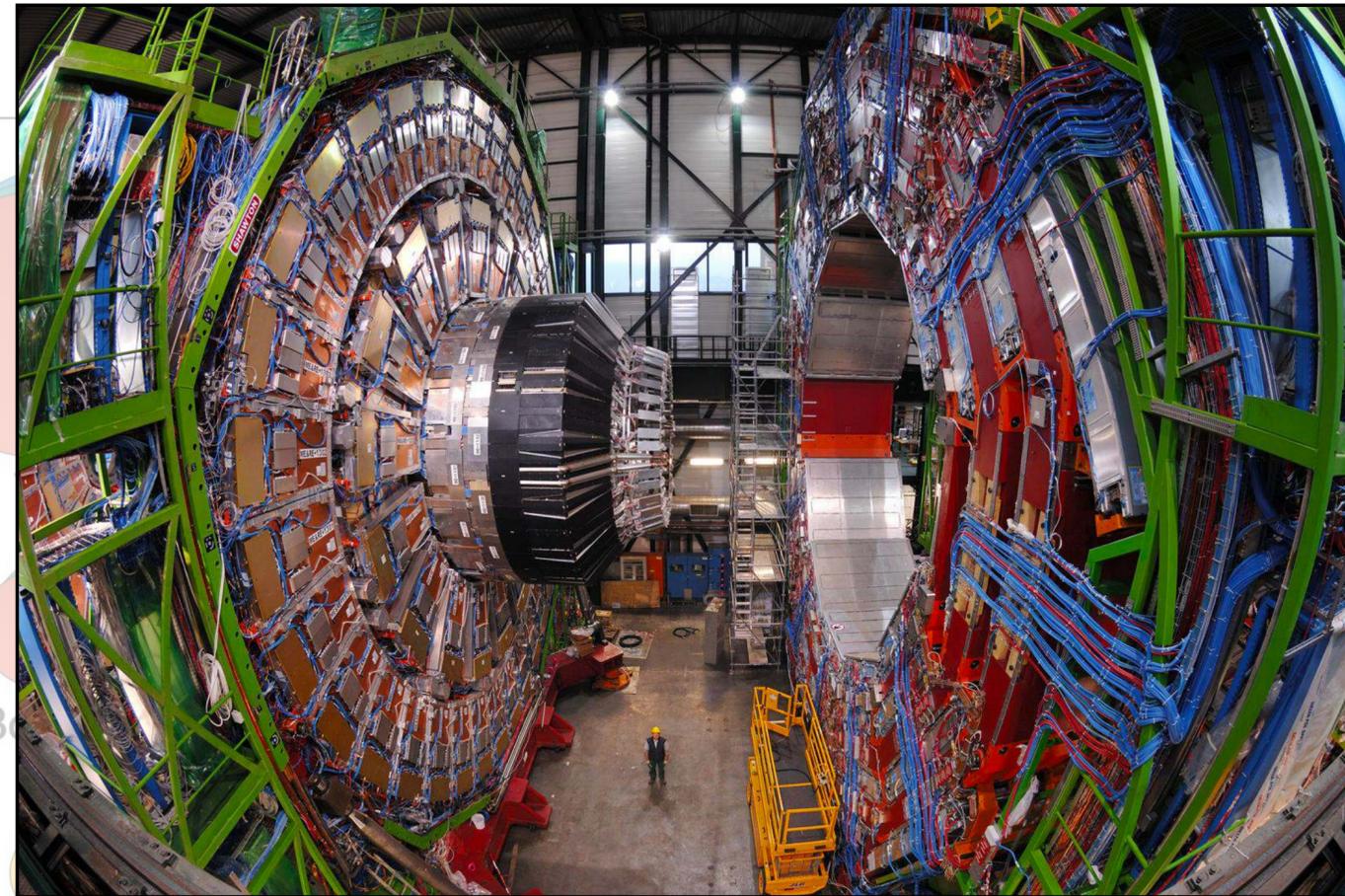


Foto: Maximilien Brice

Foto: Maximilien Brice



CMS

Quarks

Up Charm

Down Strange

Leptonen

Elektron Muon

e-Neutrino μ -Neutrino τ -Neutrino

Anti-Leptonen

Positron Anti-Muon Anti-Tau

Anti-e-Neutrino Anti- μ -Neutrino Anti- τ -Neutrino

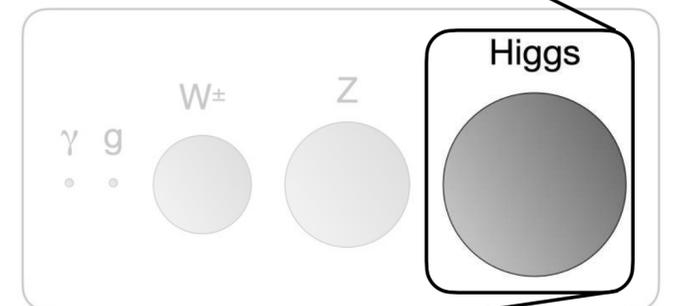
Elektrische Ladung

-2/3

+1/3

+1

0



KATRIN



Foto: Rake Hora

Elektrische Ladung $+2/3$

Leptonen

e-Neutrino μ -Neutrino τ -Neutrino

Elektrische Ladung $-2/3$

Anti-Quarks

Anti-Up
Anti-Down
Anti-Charin
Anti-Strange
Anti-Top
Anti-Bottom

Elektrische Ladung $+1/3$

Anti-Leptonen

Positron
Anti-Muon
Anti-Tau

Elektrische Ladung $+1$

Anti-e-Neutrino
Anti- μ -Neutrino
Anti- τ -Neutrino

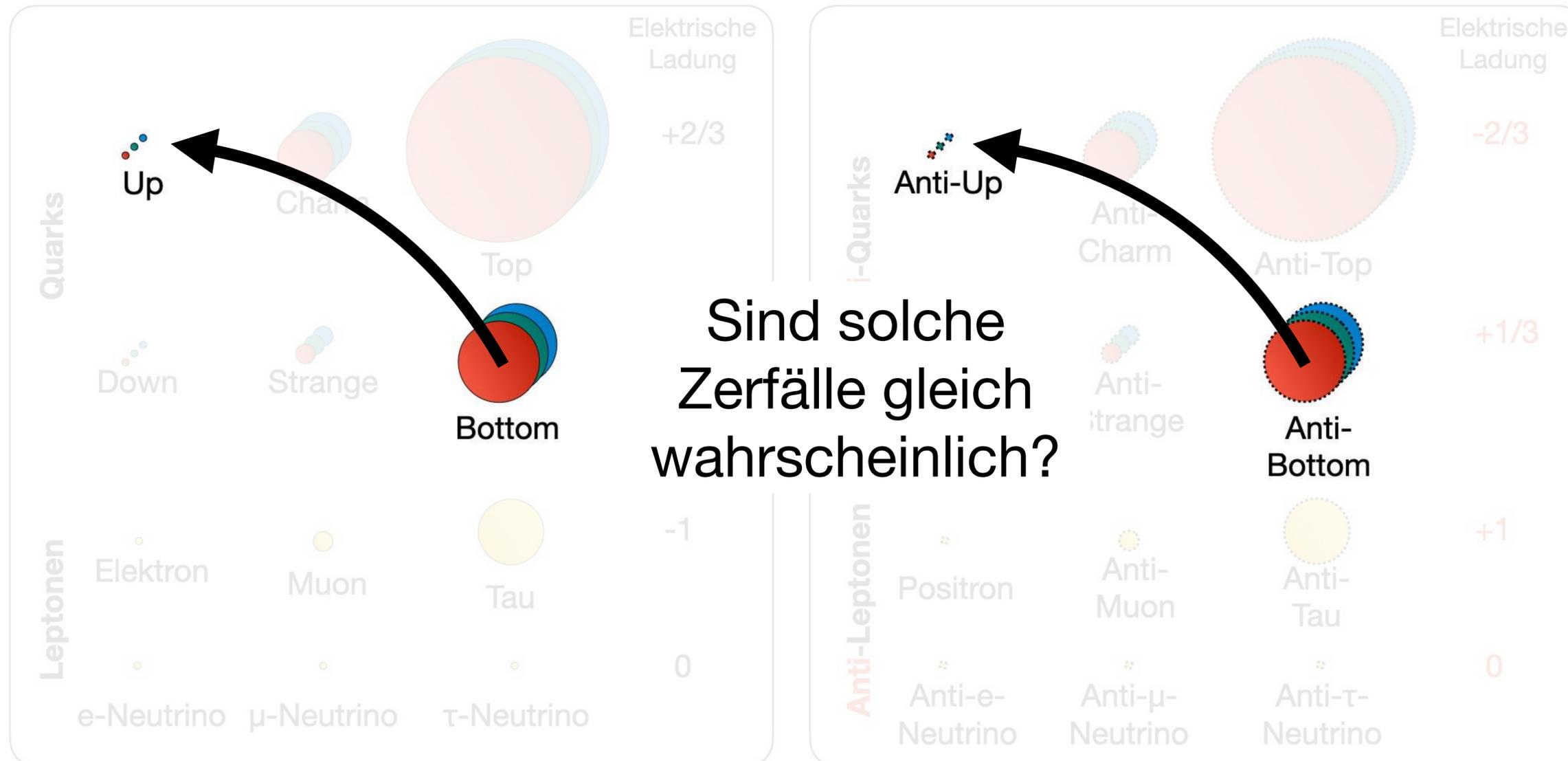
Elektrische Ladung 0

Elektrische Ladung 0

γ g
W \pm Z Higgs

$$\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^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{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 \left[\frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{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_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & 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}{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)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^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{s_w^2}{c_w} M 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}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{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^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma^\lambda \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma^\lambda \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma^\lambda \partial + m_u^\lambda) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma^\lambda \partial + m_d^\lambda) d_j^\lambda + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{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) + (\bar{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) + (\bar{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^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{i g}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_e^\lambda}{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_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{i g}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \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^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Elementare Teilchen und Antiteilchen

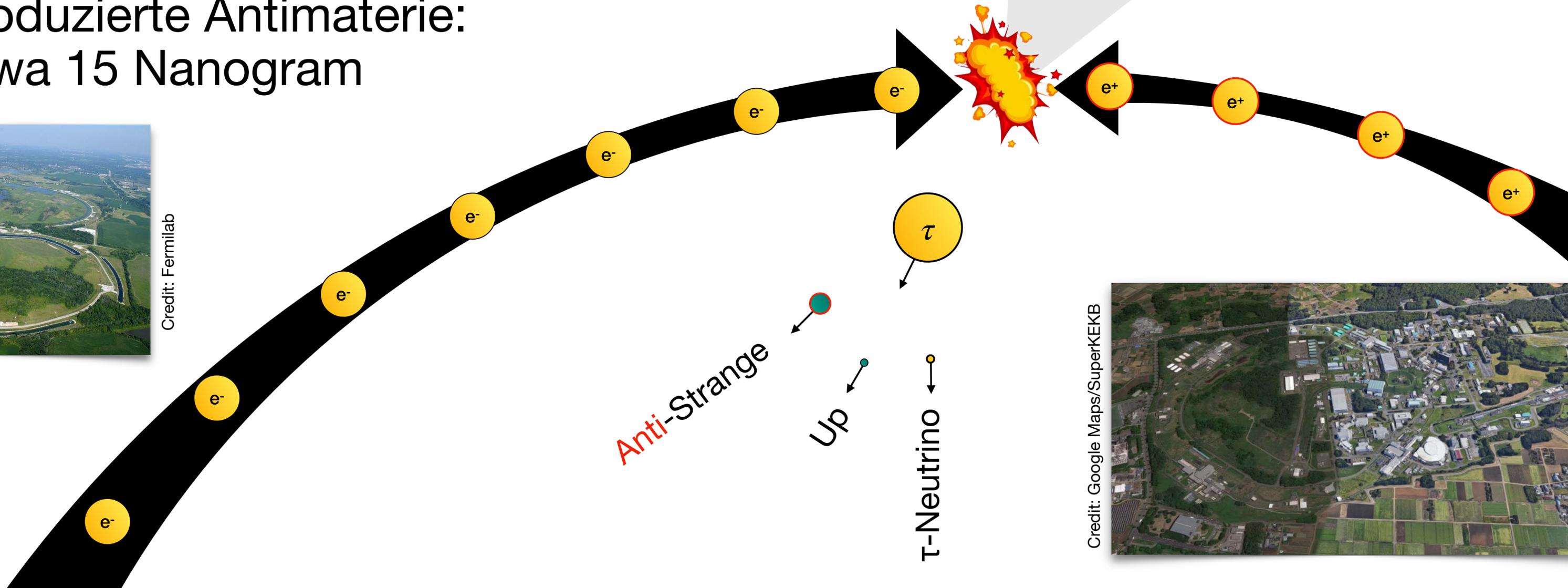


Woher bekommen wir die Antimaterie?

- Bisher einzige Methode um Antimaterie in signifikanteren Mengen herzustellen: **Teilchenbeschleuniger**
- Bislang auf der gesamten Welt produzierte Antimaterie: Etwa 15 Nanogramm

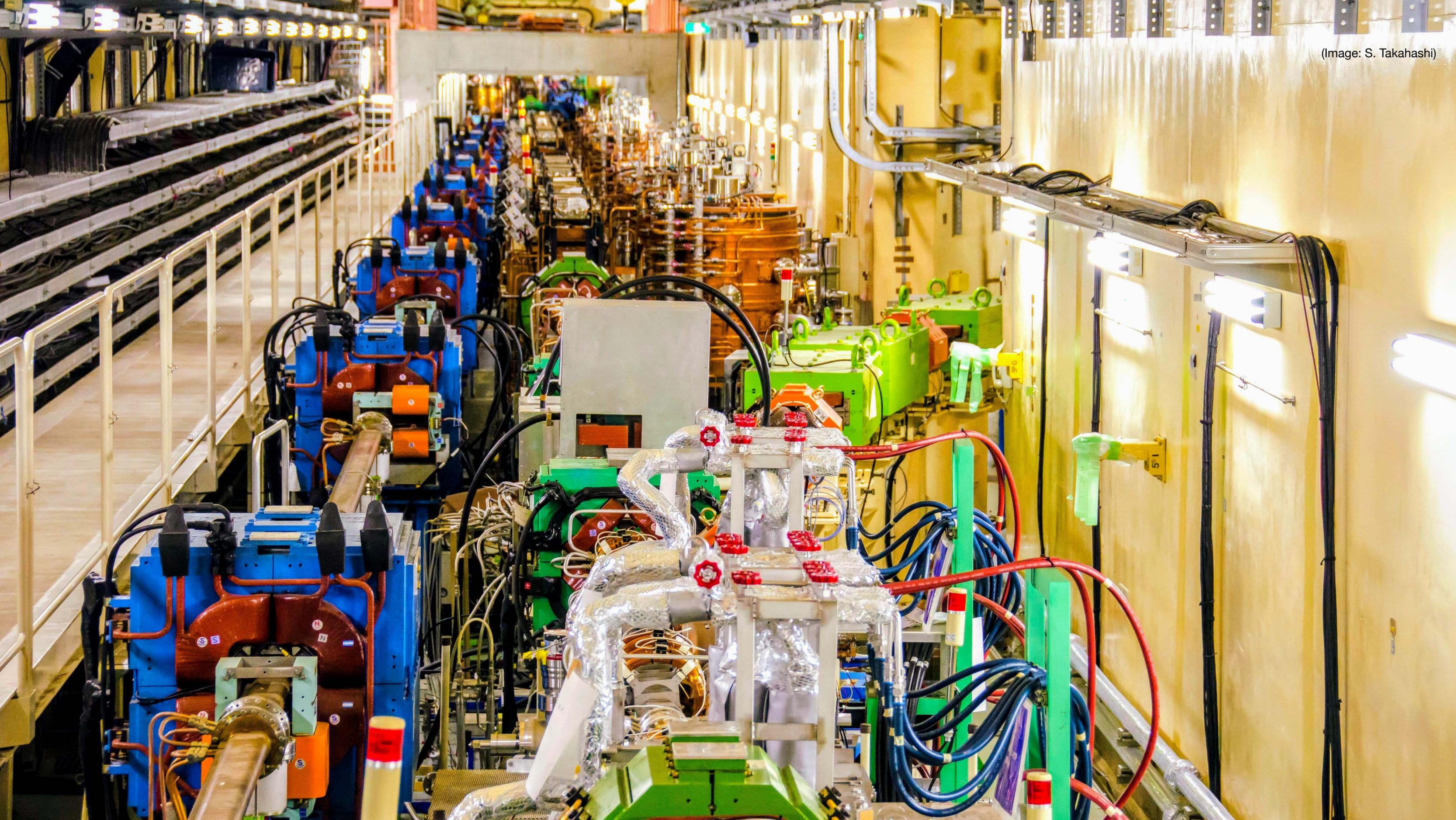


Credit: Fermilab

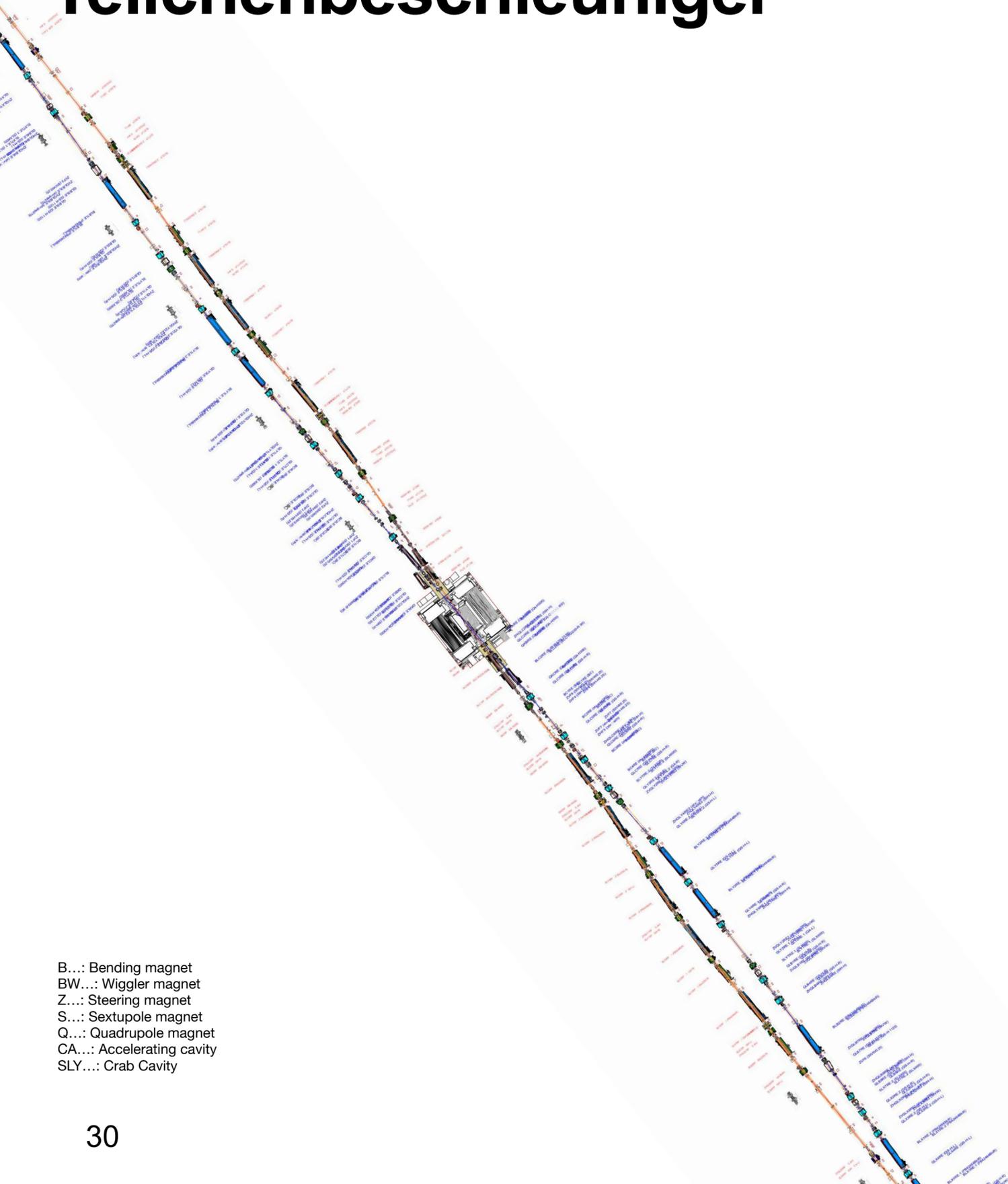


Credit: Google Maps/SuperKEKB

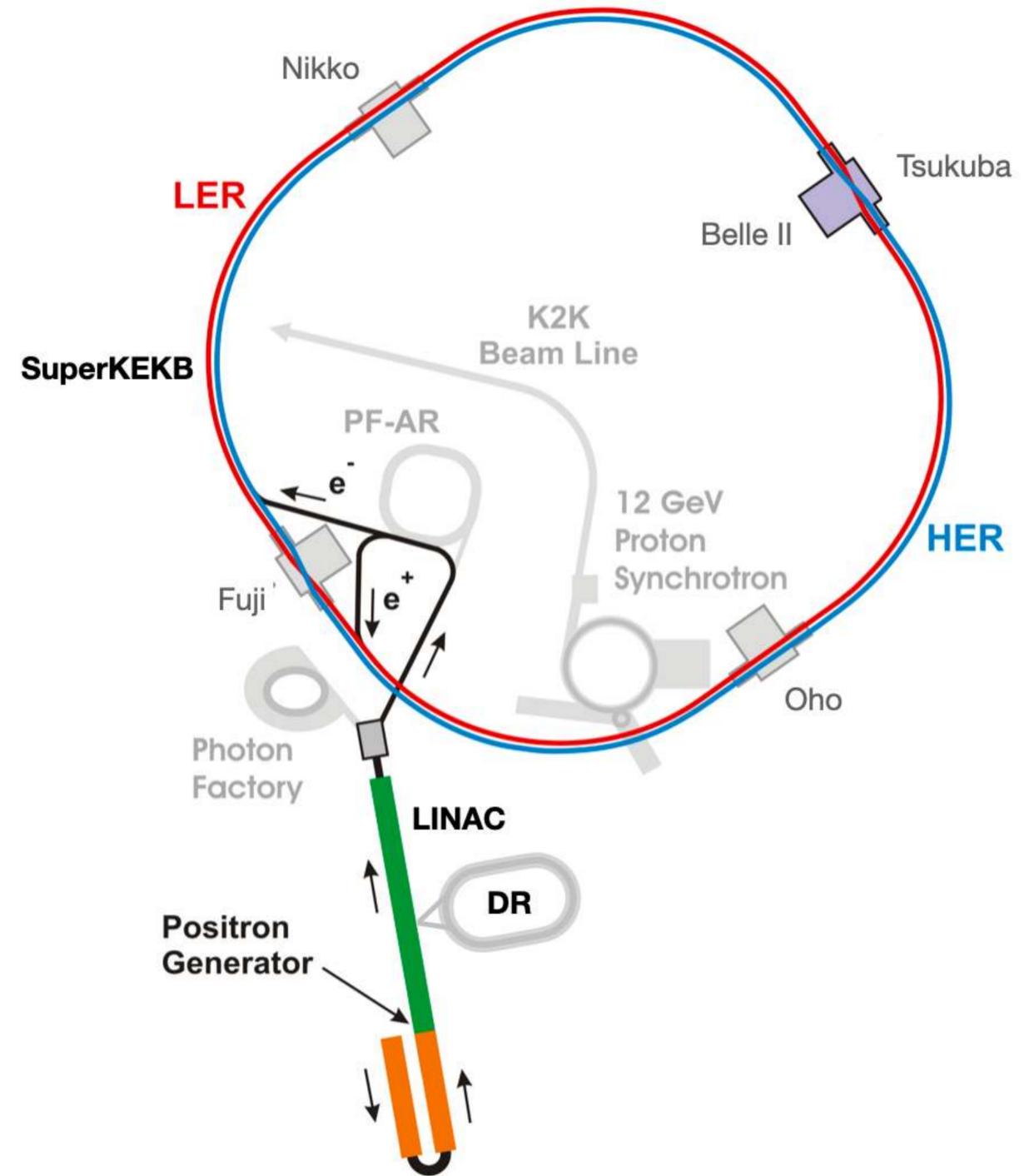




Teilchenbeschleuniger



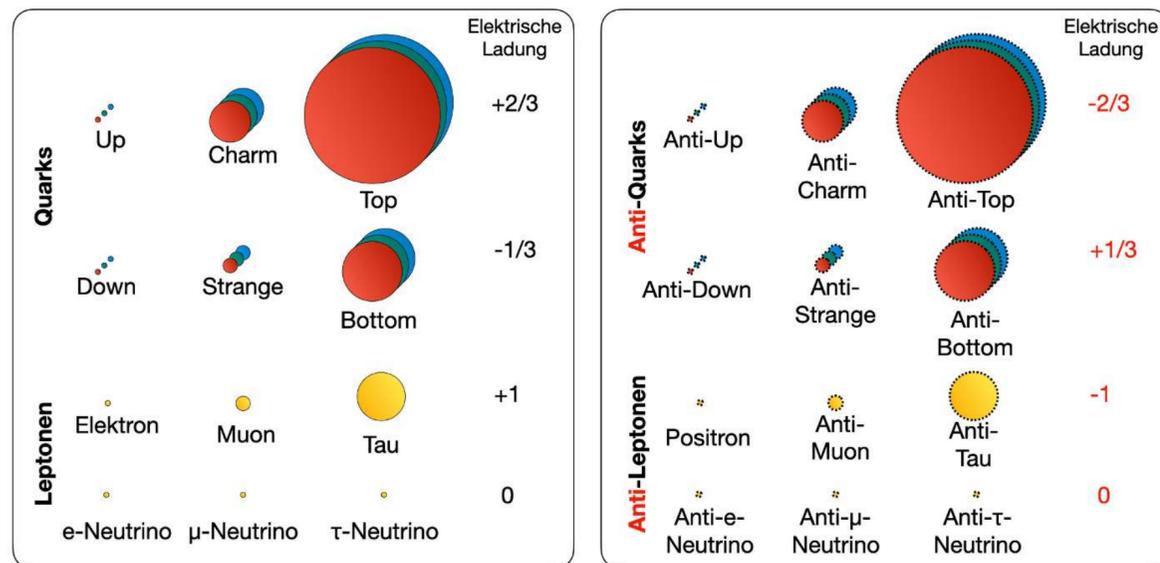
B...: Bending magnet
 BW...: Wiggler magnet
 Z...: Steering magnet
 S...: Sextupole magnet
 Q...: Quadrupole magnet
 CA...: Accelerating cavity
 SLY...: Crab Cavity



Antimaterie an Teilchenbeschleunigern

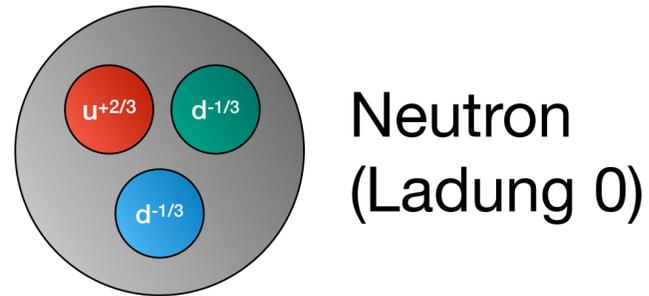
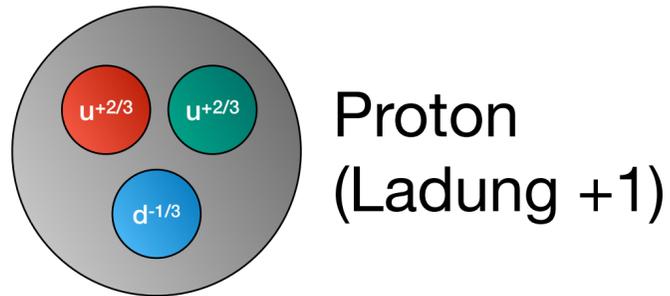
- Fundamentale Eigenschaften von Quarks sind schwierig zu beobachten:

Quarks kommen nur in gebundenen Zuständen mit anderen Quarks vor

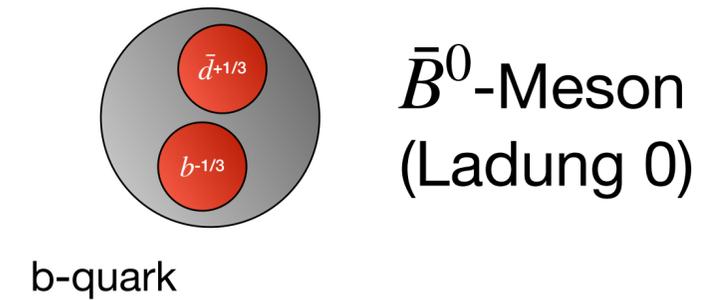
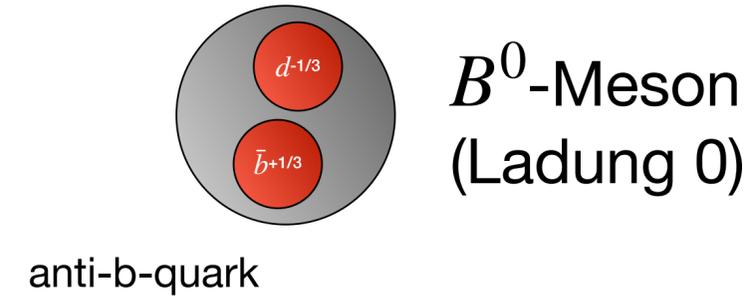


Antimaterie an Teilchenbeschleunigern

Baryonen, z.B.



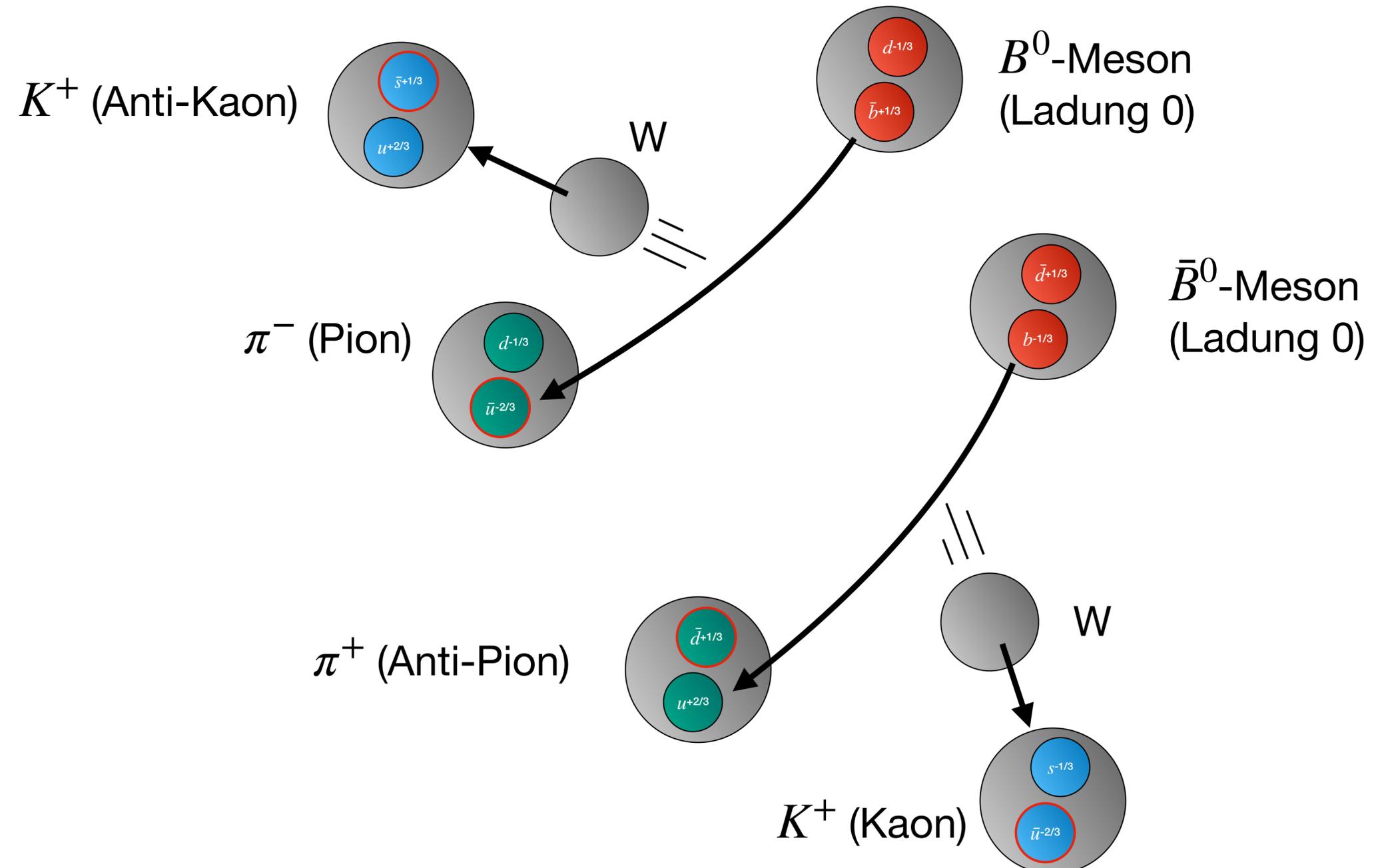
Mesonen, z.B.



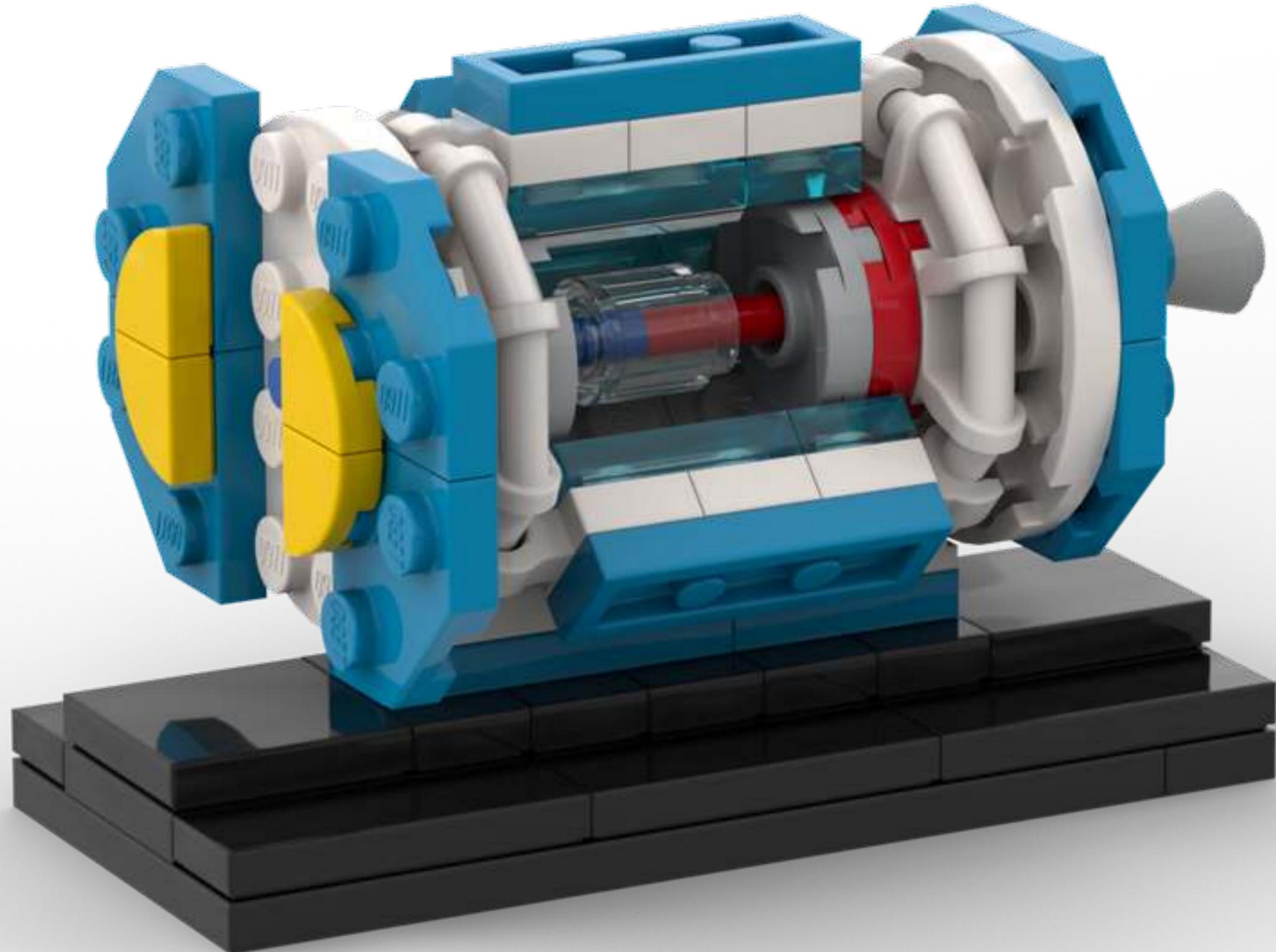
Quarks		Elektrische Ladung
Up	Charm	+2/3
Down	Strange	-1/3
	Bottom	-1/3
Leptonen		
Elektron	Muon	+1
e-Neutrino	μ -Neutrino	0
	τ -Neutrino	0

Anti-Quarks		Elektrische Ladung
Anti-Up	Anti-Charm	-2/3
Anti-Down	Anti-Strange	+1/3
	Anti-Bottom	+1/3
Anti-Leptonen		
Positron	Anti-Muon	-1
Anti-e-Neutrino	Anti- μ -Neutrino	0
	Anti- τ -Neutrino	0

Antimaterie an Teilchenbeschleunigern

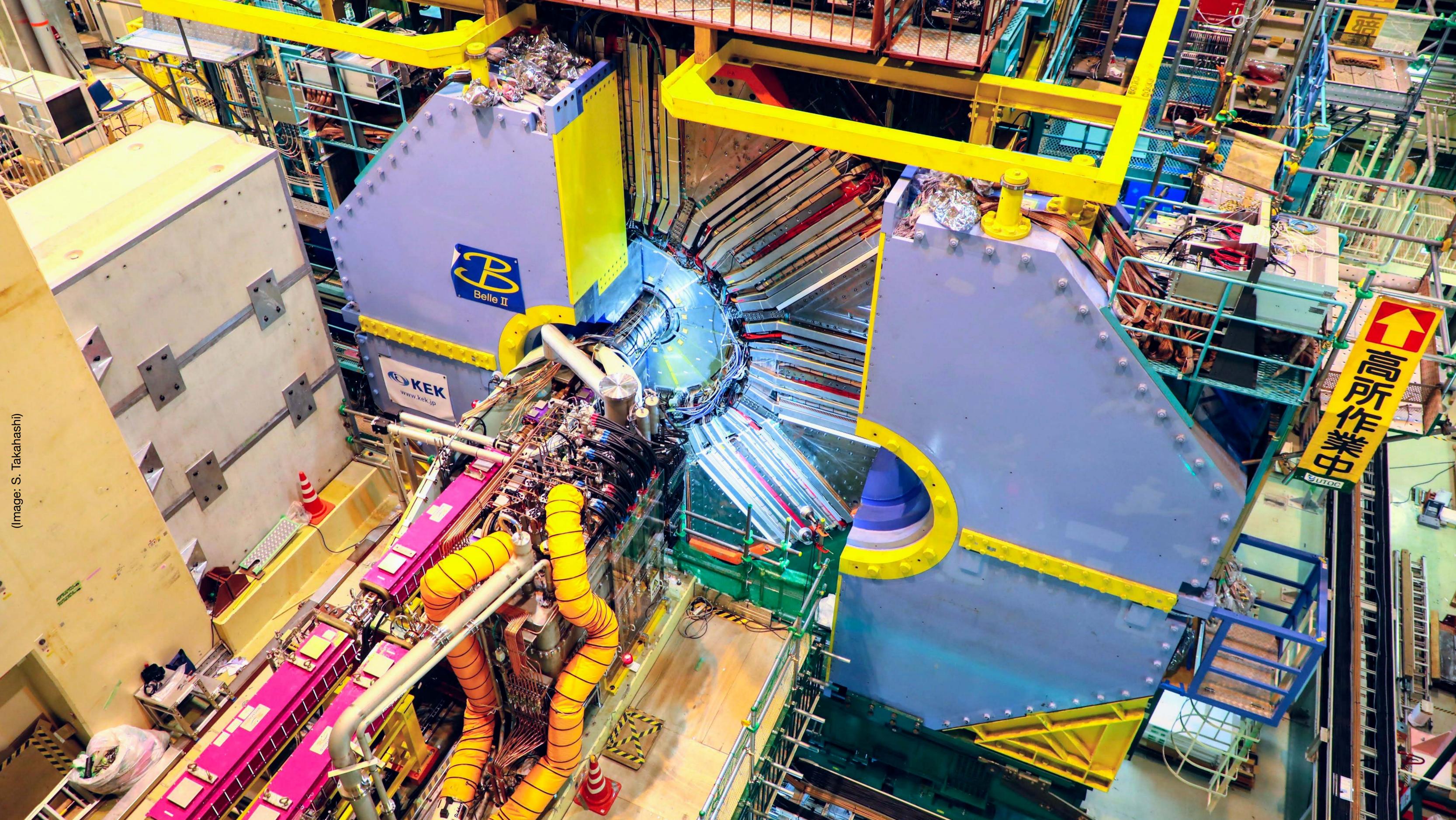


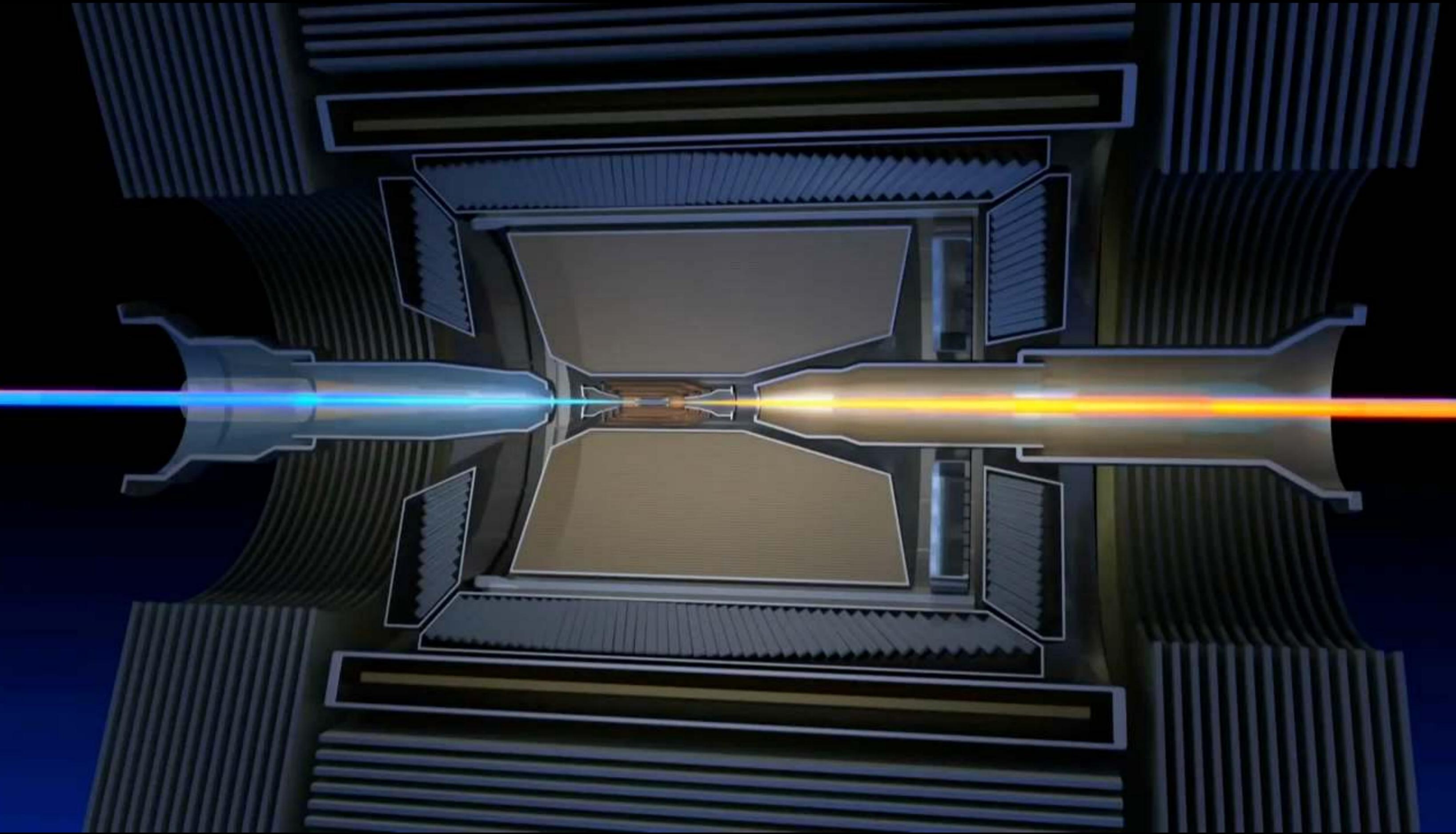
Teilchendetektoren aus LEGO



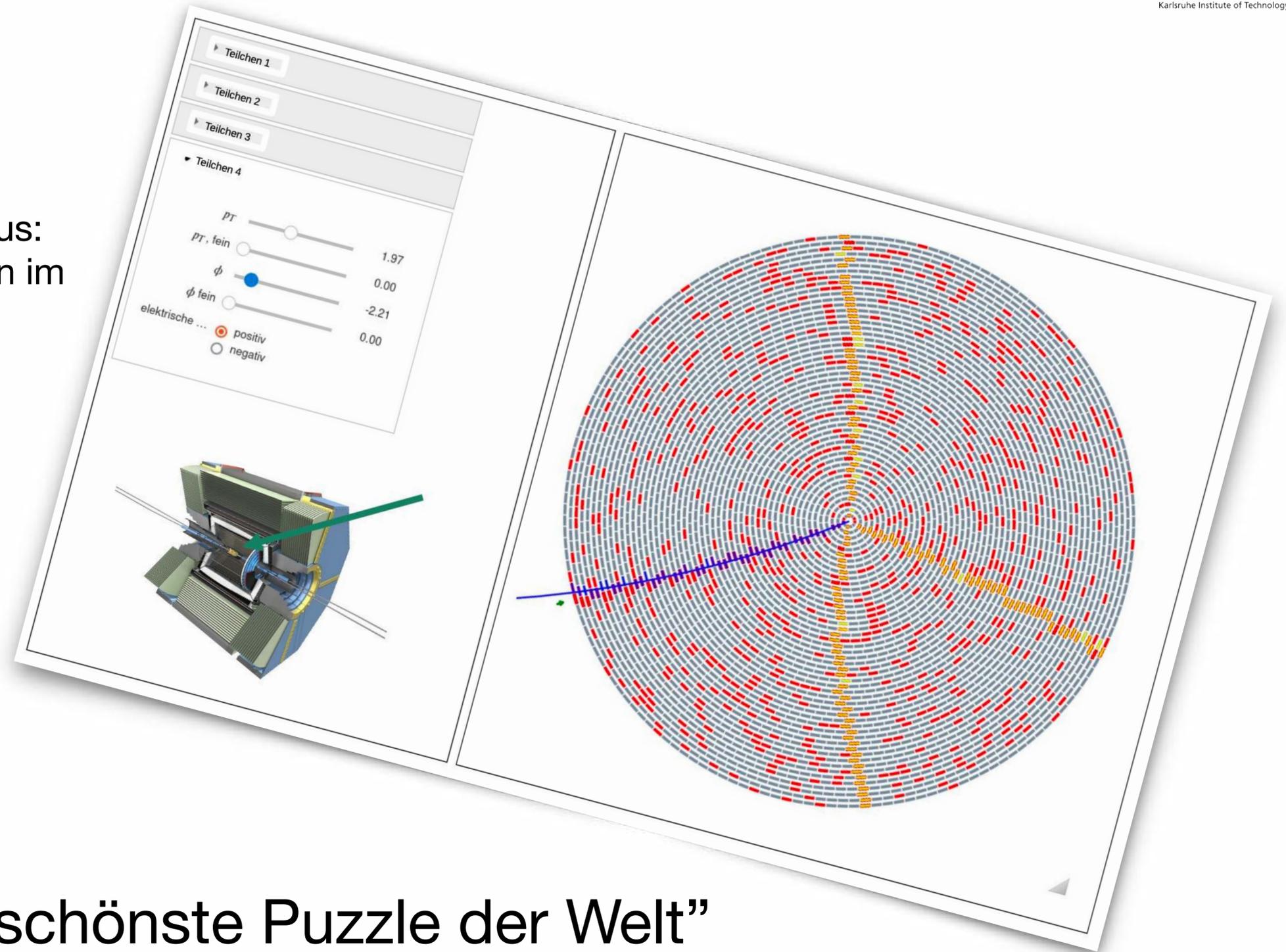
Credit: ETP Ferber

(Image: S. Takahashi)



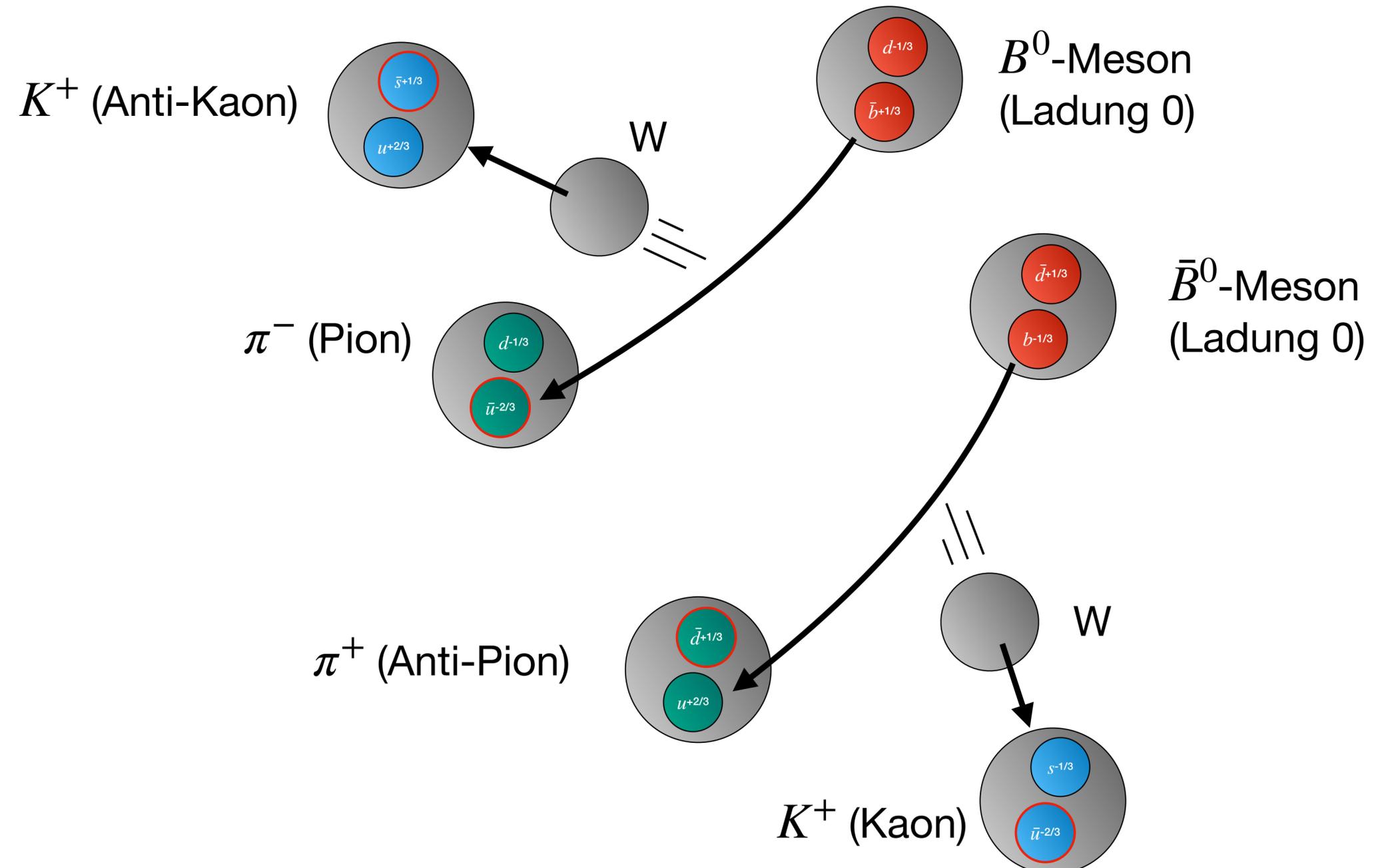


Probieren sie es selbst aus:
Können Sie Teilchenspuren im
Detektor finden?

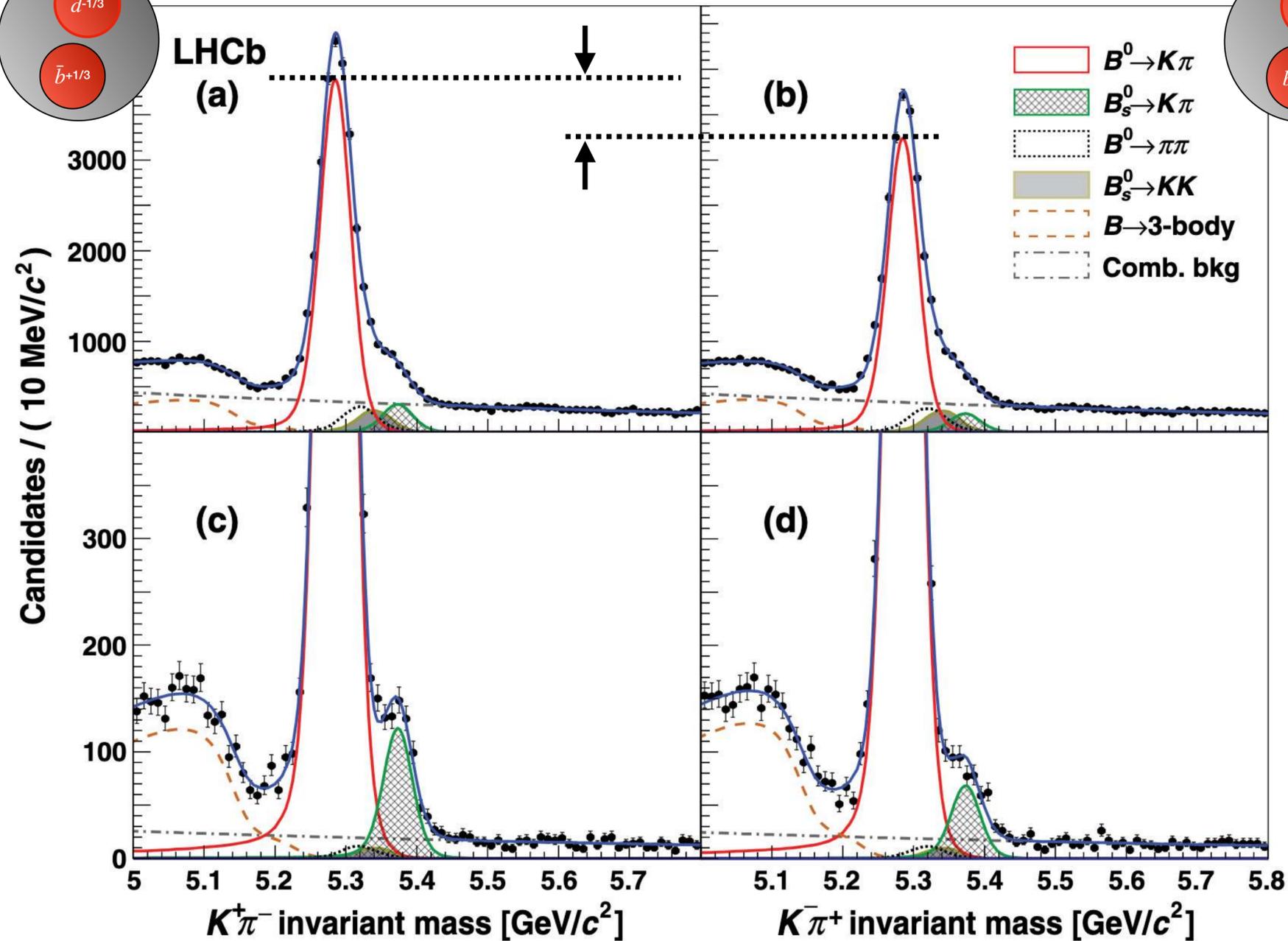
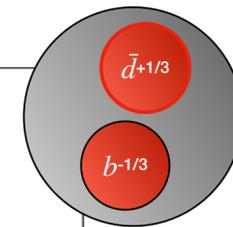
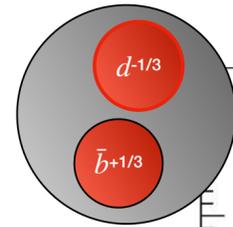
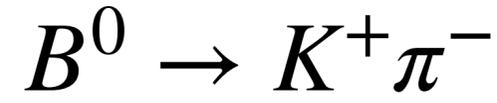


- Belle II Masterclass “Das schönste Puzzle der Welt”

Antimaterie an Teilchenbeschleunigern



B-Meson Zerfälle



Das Universum im Labor

- Unser Universum besteht (fast) nur aus Materie
- An Teilchenbeschleunigern im Labor konnten wir kleinste “Verletzungen” der ansonsten perfekten Symmetrie zwischen Materie und Antimaterie bei Quarks beobachten
- Diese “Verletzungen” ist jedoch viel zu klein um den Überschuss an Materie im Universum zu erklären...
- Neutrinos könnten eine wichtige Rolle spielen: Verhalten sich Neutrinos und Antineutrinos fundamental unterschiedlich? Sind es überhaupt unterschiedliche Teilchen?

Und im Gegensatz zu allen anderen Teilchen gibt es noch eine andere Frage: Wie schwer ist so ein Neutrino eigentlich?