Teilchenspuk am LHC

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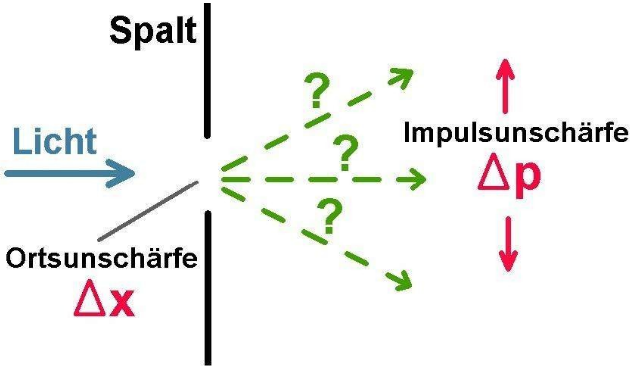
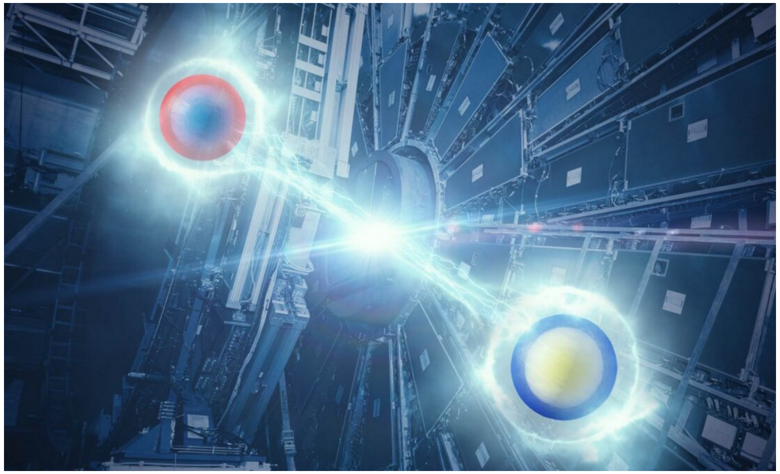
3. Dezember 2024

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

EXZELLENZCLUSTER
QUANTUM UNIVERSE

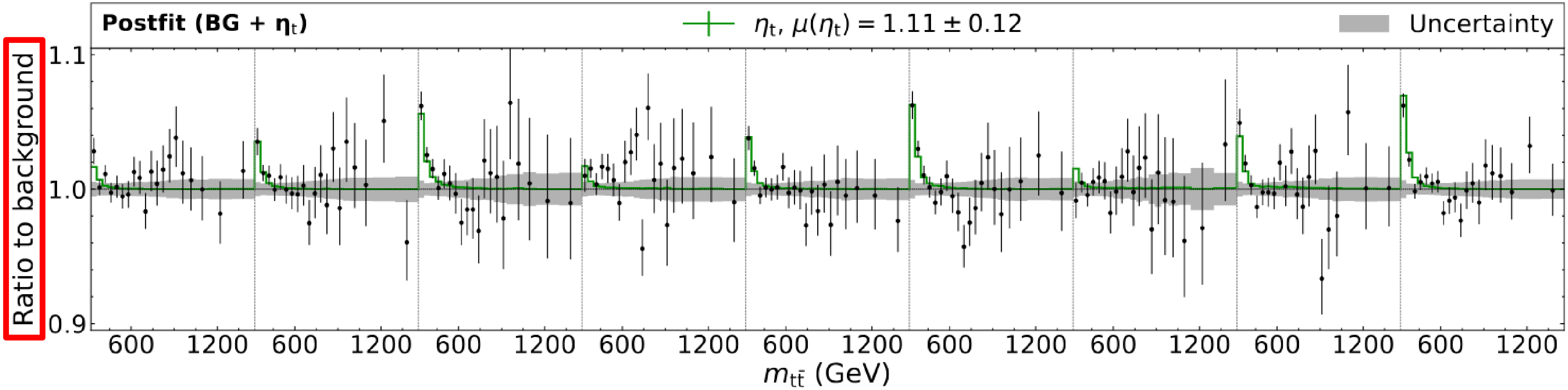
Eigentlich ...





CERN's CMS detector observes quantum entanglement at highest energy ever

… dann kam der Zufall ...



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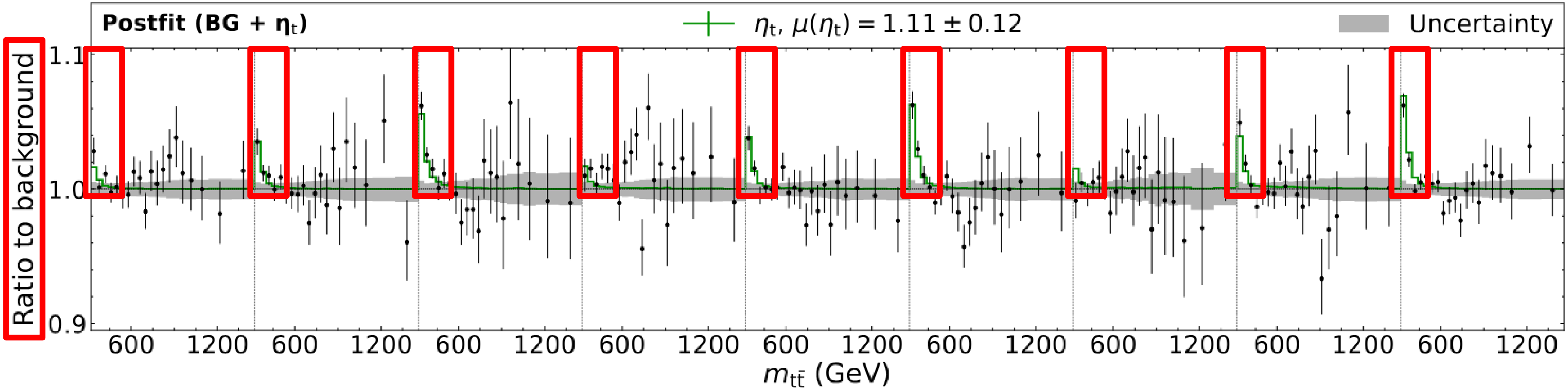
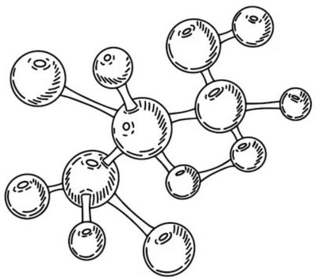


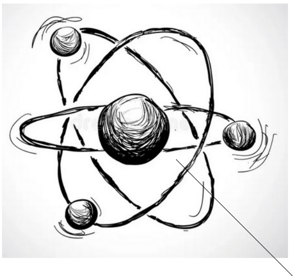
Ein erster Blick auf noch unerforschte Physik am LHC?

Vom Brot zum Quark und Elektron

Brot:
~ 0.3 m



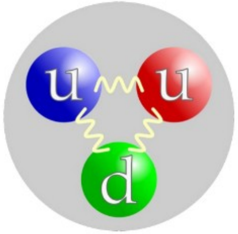
Molekül:
10^{-9} m



Atom:
10^{-10} m

Elektron:
$<10^{-19}$ m

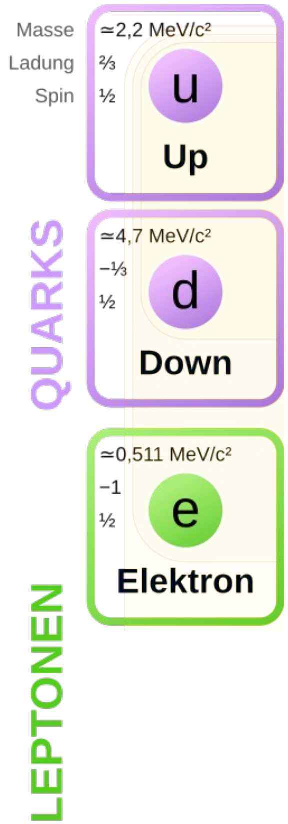
Atomkern:
10^{-14} m



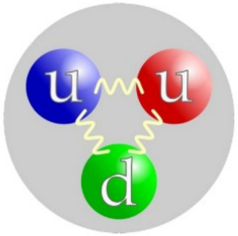
Proton:
10^{-15} m

Vom Brot zum Quark und Elektron

Standardmodell der Elementarteilchen

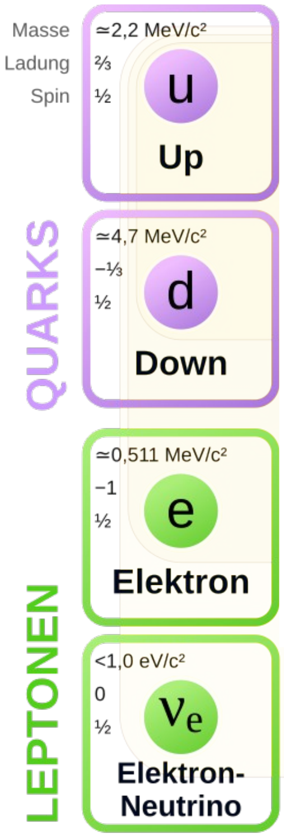


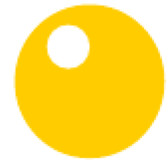
Elektron:
$<10^{-18}$ m



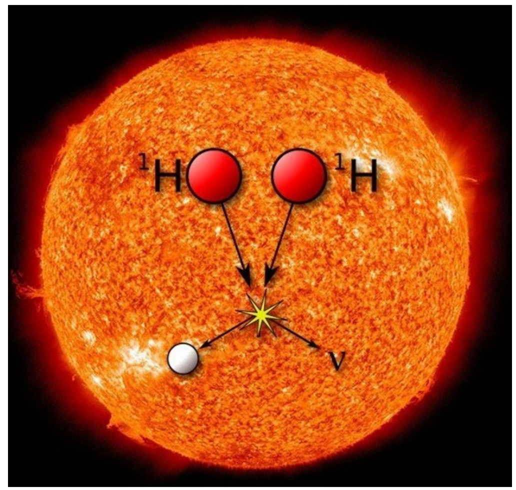
Proton:
10^{-15} m

Standardmodell der Elementarteilchen



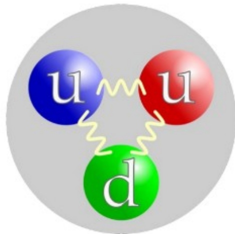


Elektron:
<10^{-18} m



Elektron-Neutrino

- z. Bsp. aus der Sonne
- 1956 entdeckt
- Hunderte von Milliarden pro Sekunde durch unseren Körper



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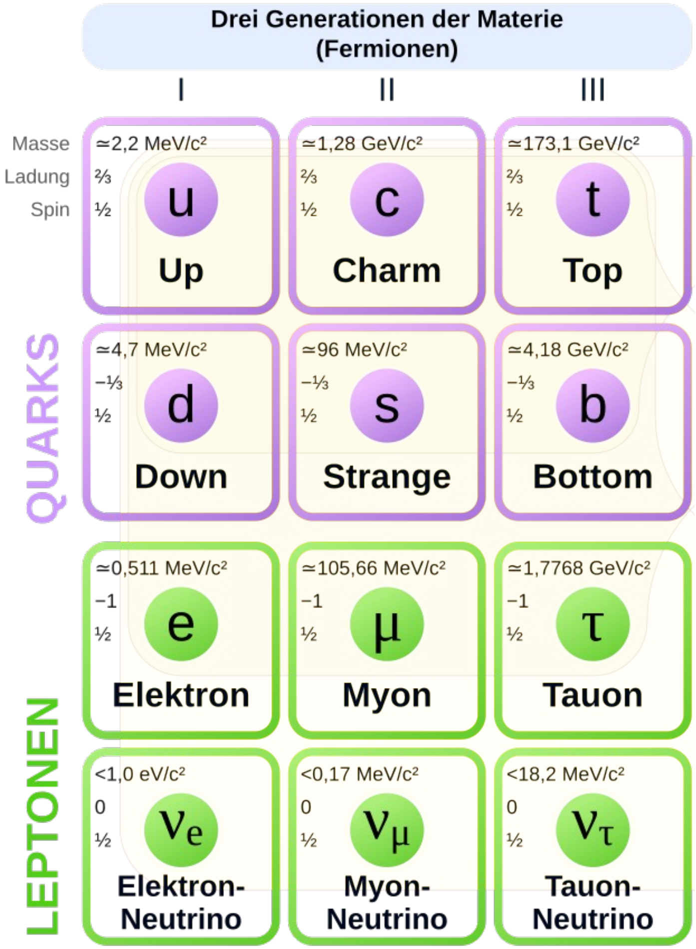

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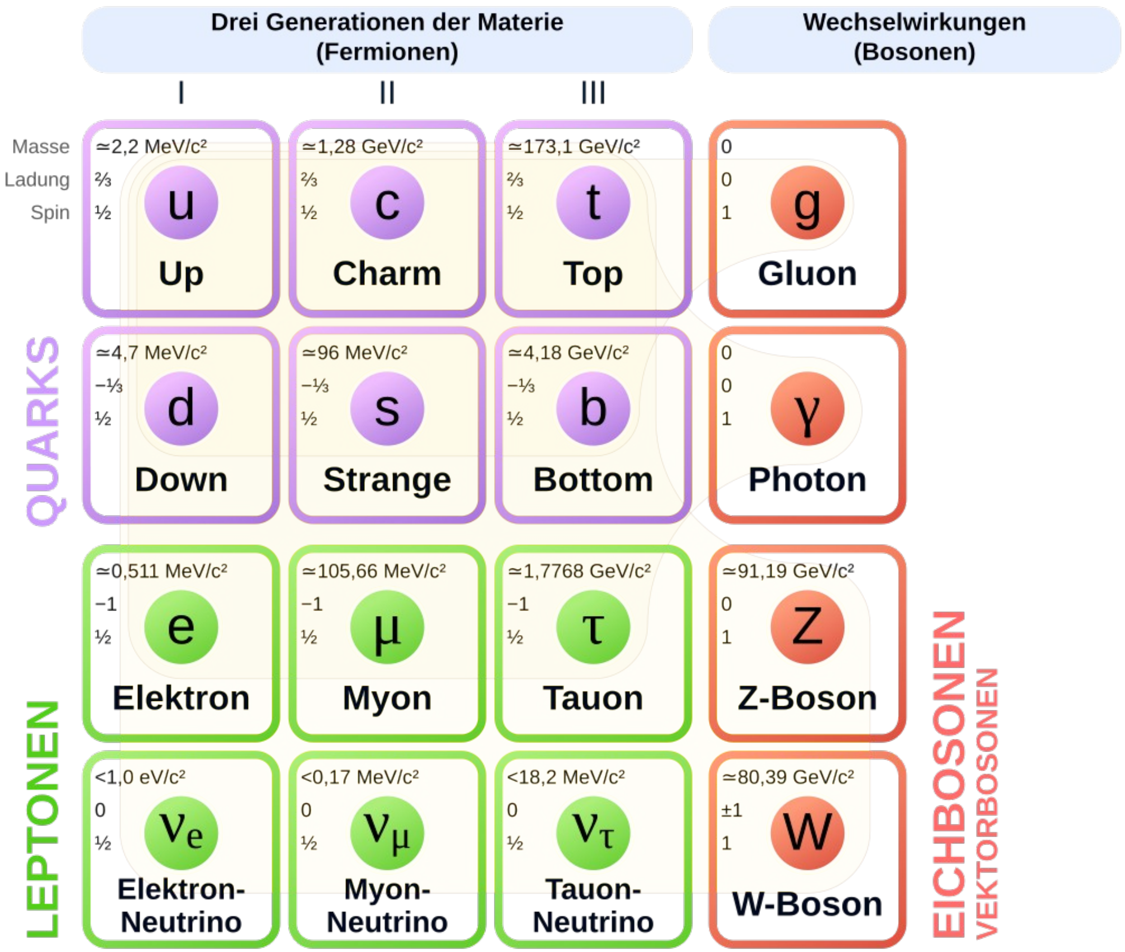
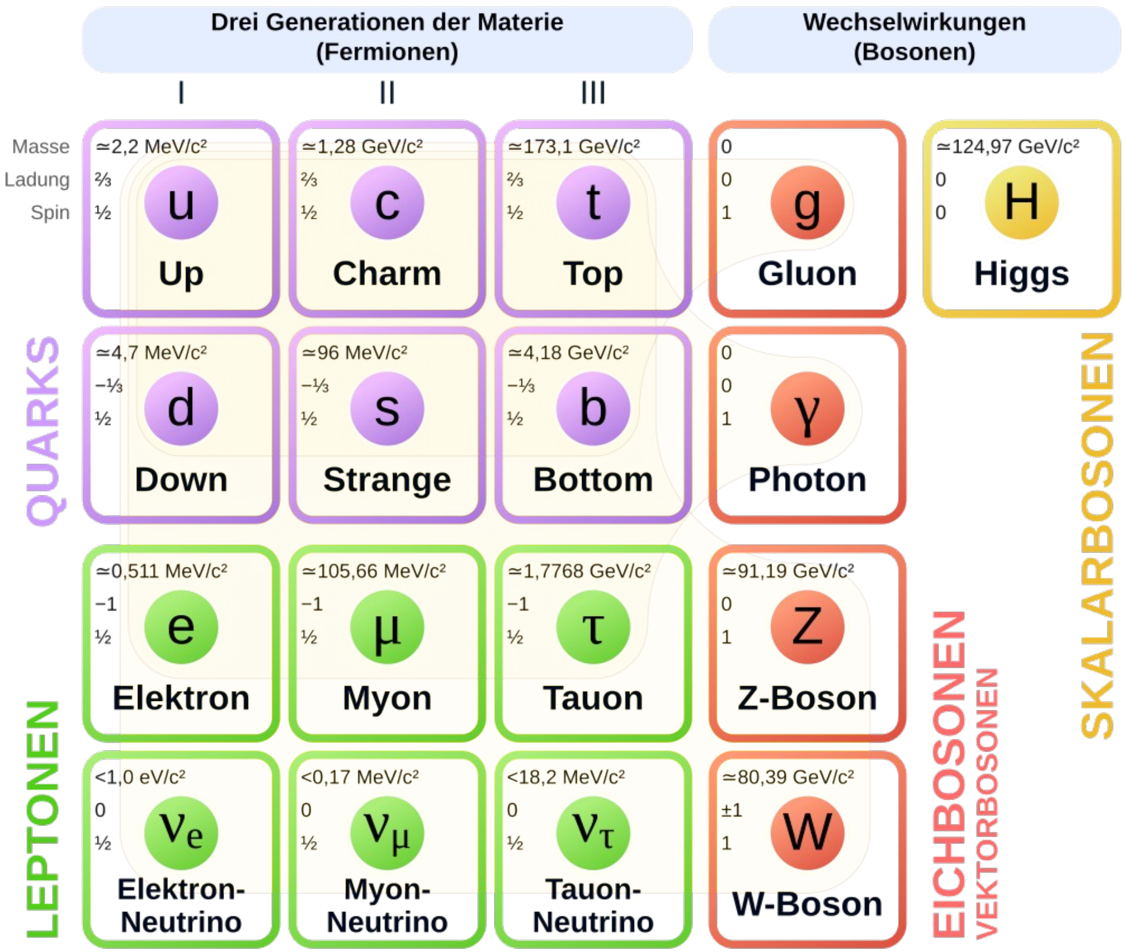


Vom Brot zum Quark und Elektron

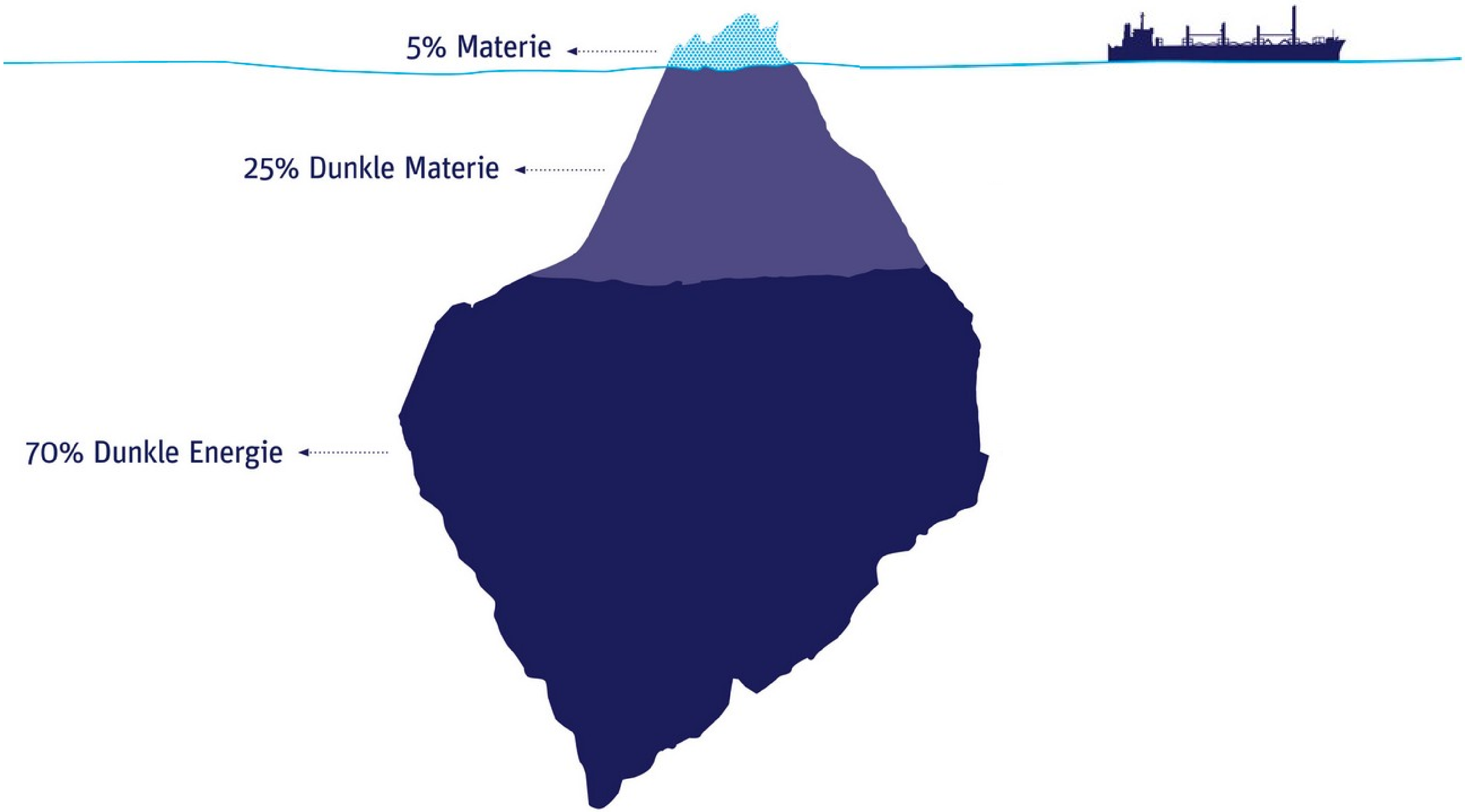
Standardmodell der Elementarteilchen

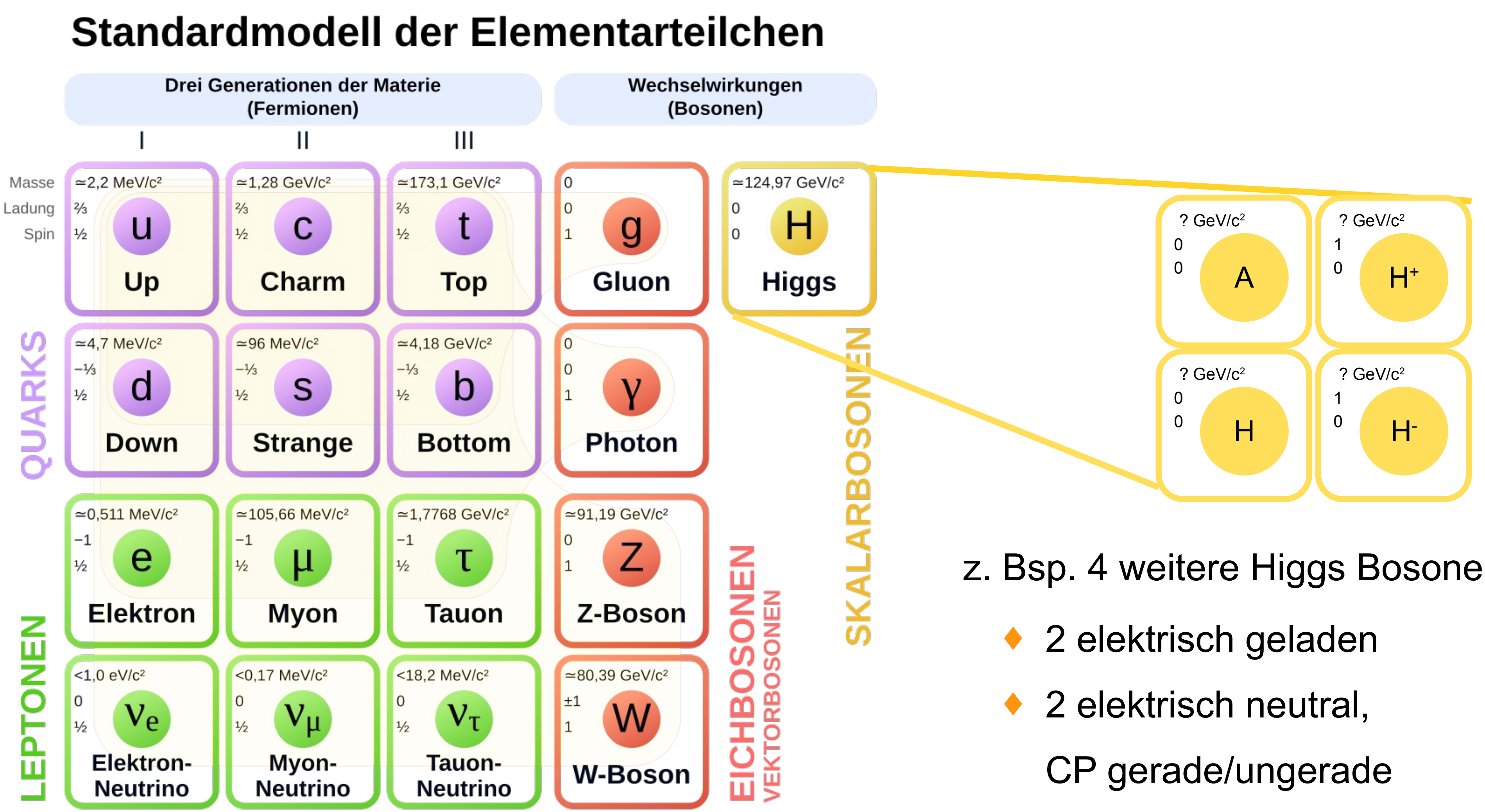


- vorantwortlich fuer die Masse von Elementarteilchen
- 2012 am CERN entdeckt

- Ringvorlesung von Matthias Schroeder am 22.10.2024

Und doch nur die Spitze des Eisberges

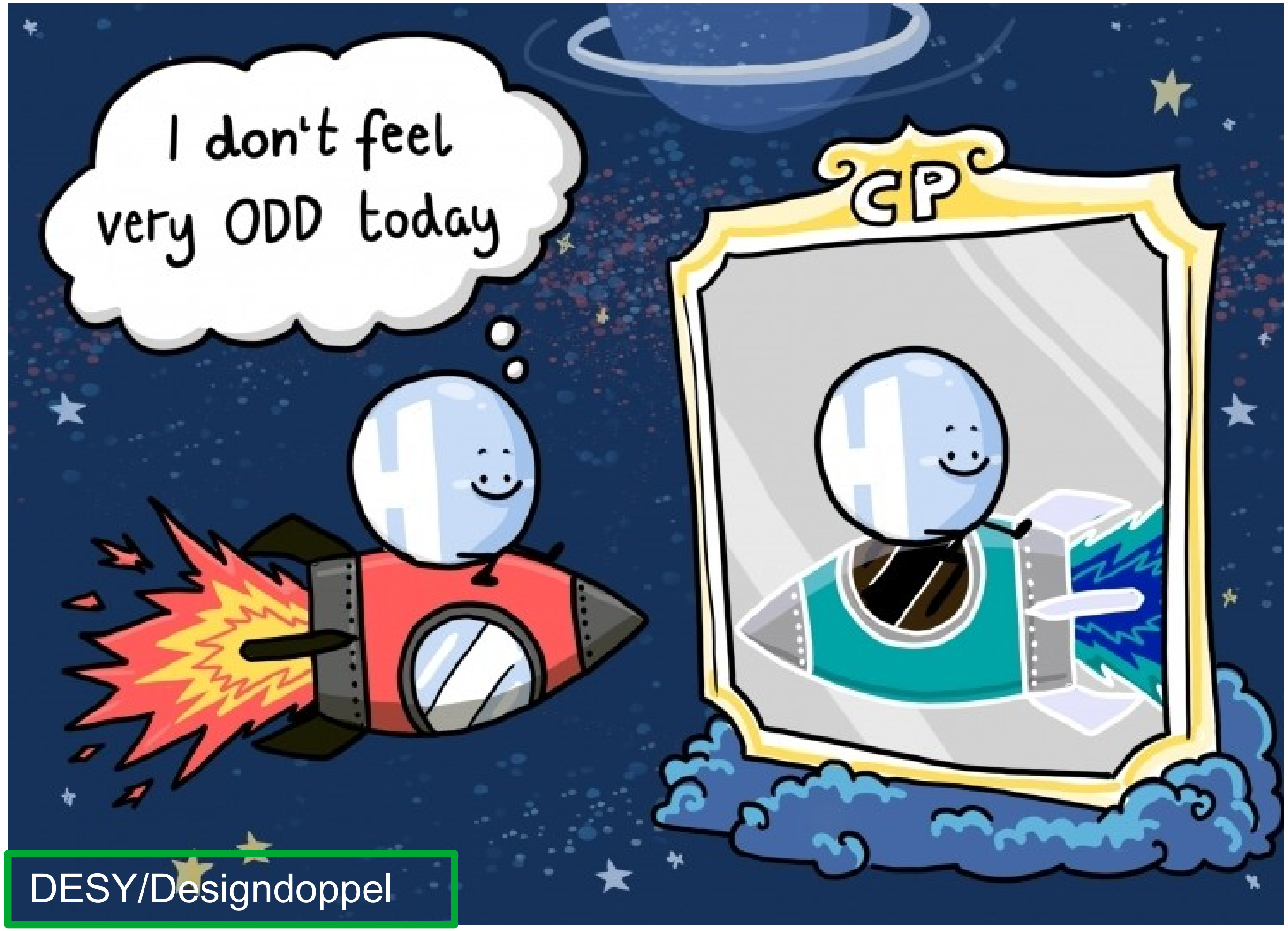




z. Bsp. 4 weitere Higgs Bosonen

- 2 elektrisch geladen
- 2 elektrisch neutral,
  CP gerade/ungerade

Was meint CP-gerade?

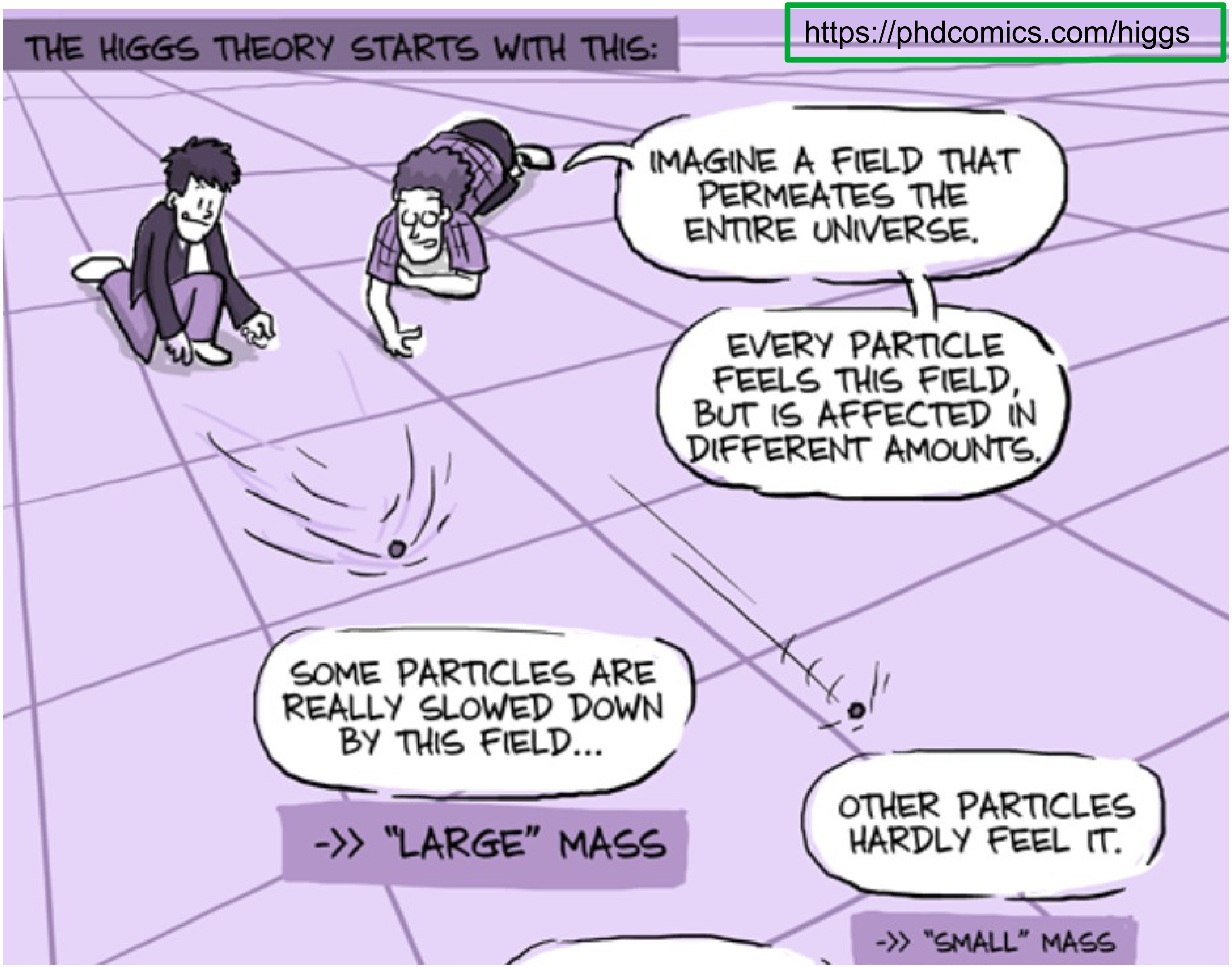


DESY/Designdoppel

C: Ladung
P: Parität

Higgs Bosonen und Top Quarks

https://phdcomics.com/higgs



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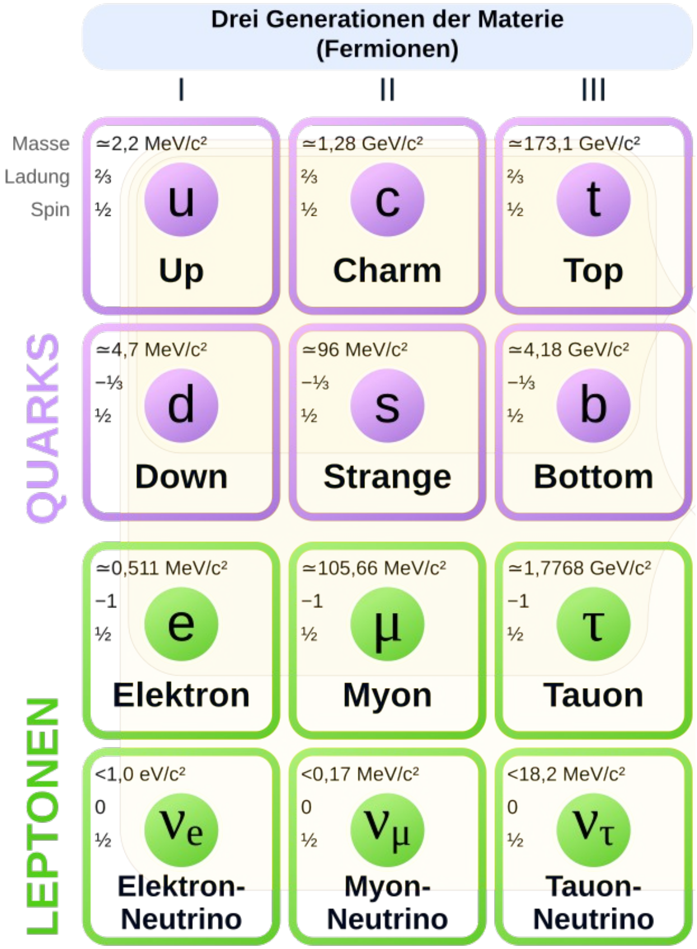
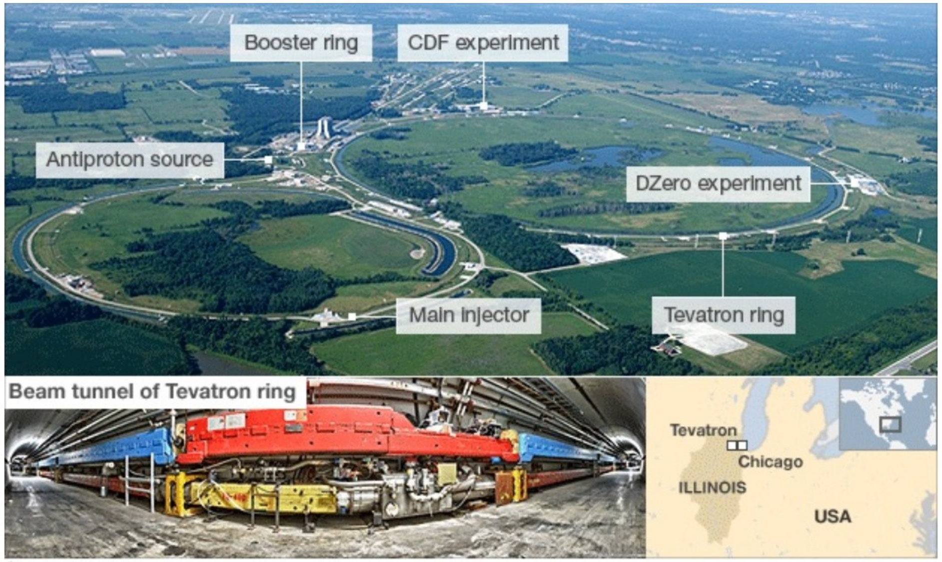
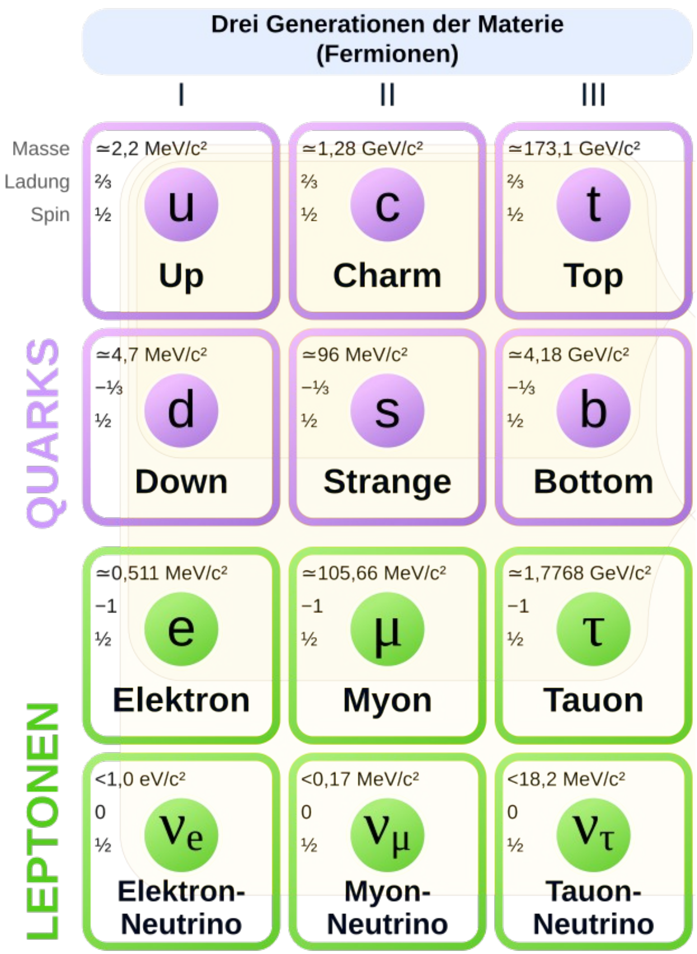


- 1995 am Tevatron $p\bar{p}$ Beschleuniger entdeckt



Source: Fermilab

Standardmodell der Elementarteilchen

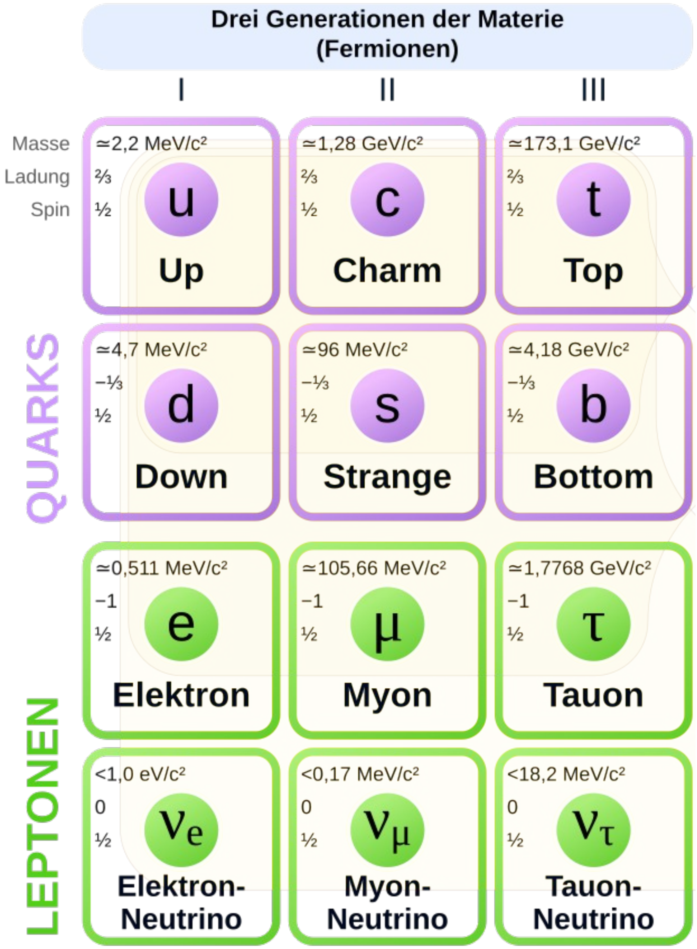


- 1995 am Tevatron $p\bar{p}$ Beschleuniger entdeckt
- das schwerste aller bekannten Elementarteilchen

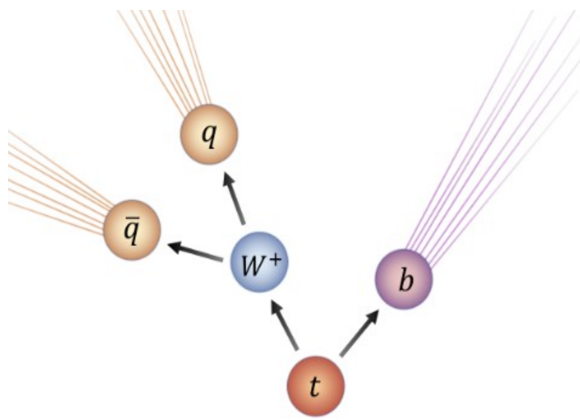
ICE mit 7 Waggons

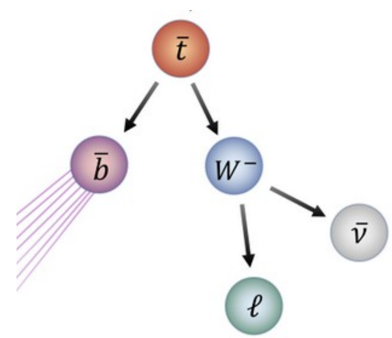
Das Top Quark

Standardmodell der Elementarteilchen

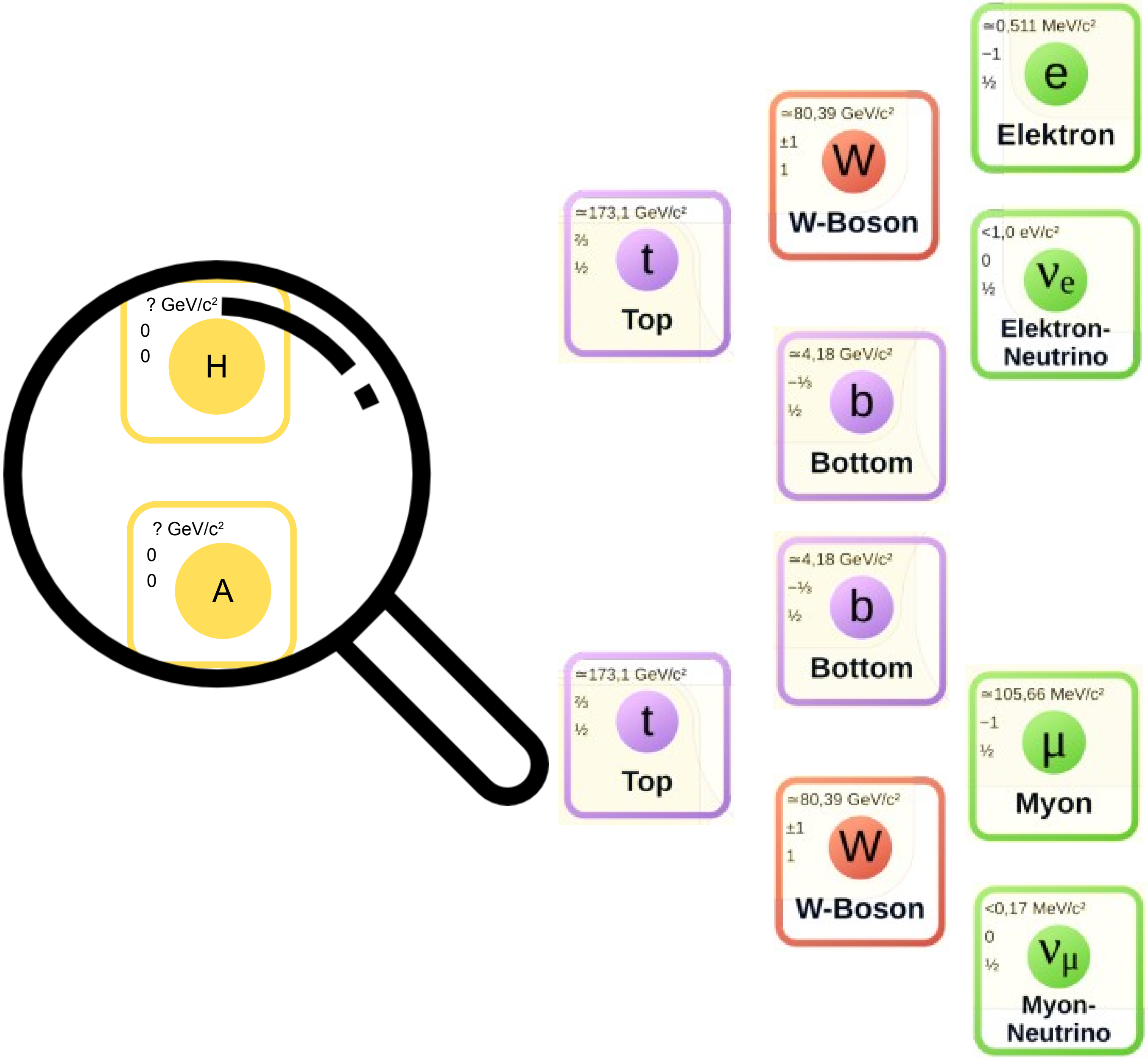


- 1995 am Tevatron $p\bar{p}$ Beschleuniger entdeckt
- das schwerste aller bekannten Elementarteilchen
- Zerfall in W boson und b Quark nach $O(10^{-25})$ s

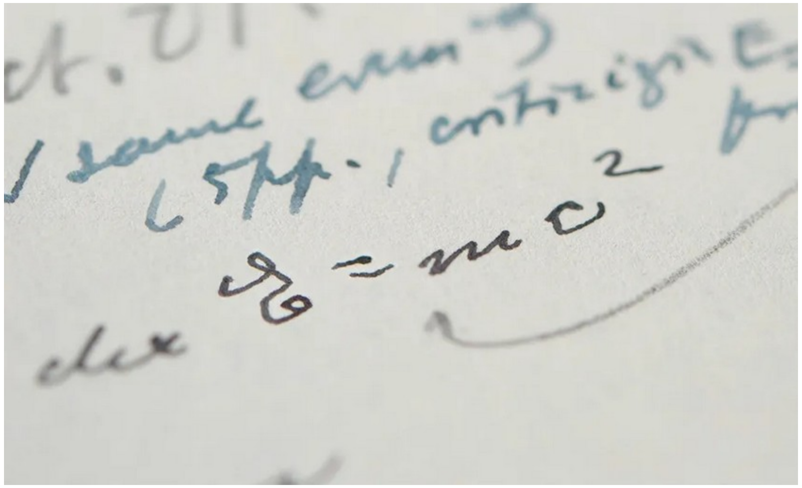


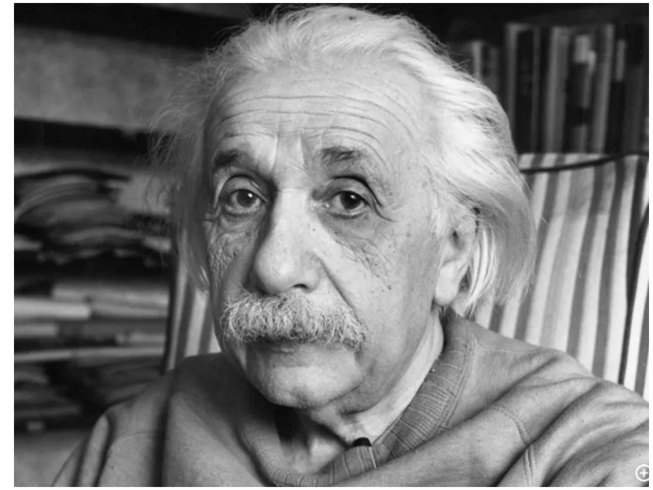


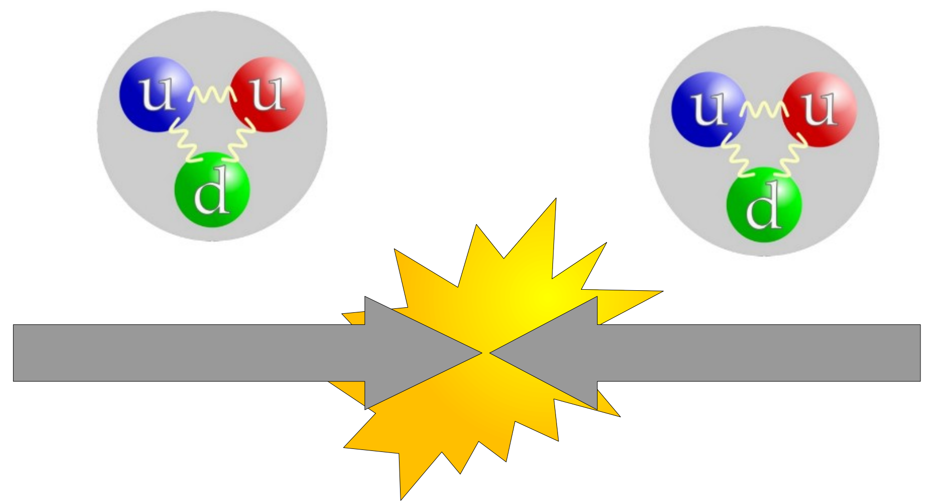
Zwischenbilanz



Wie erzeugt man schwere Teilchen?







Erzeugung neuer Teilchen bis zur Masse $2 \cdot E/c^2$

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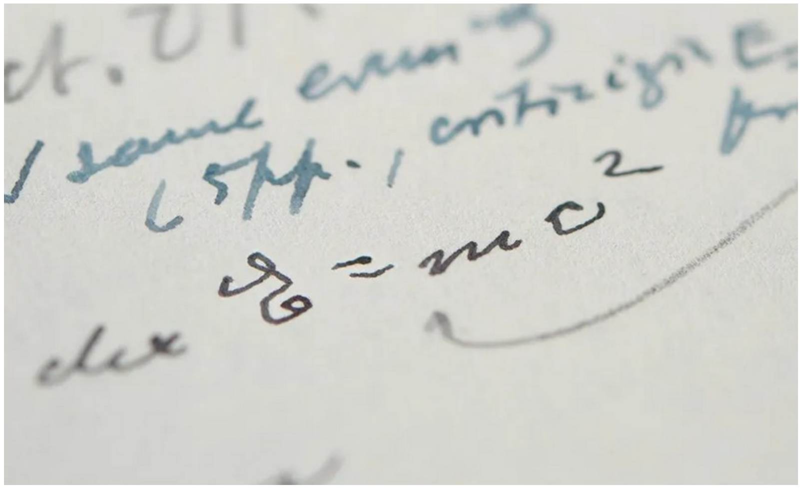
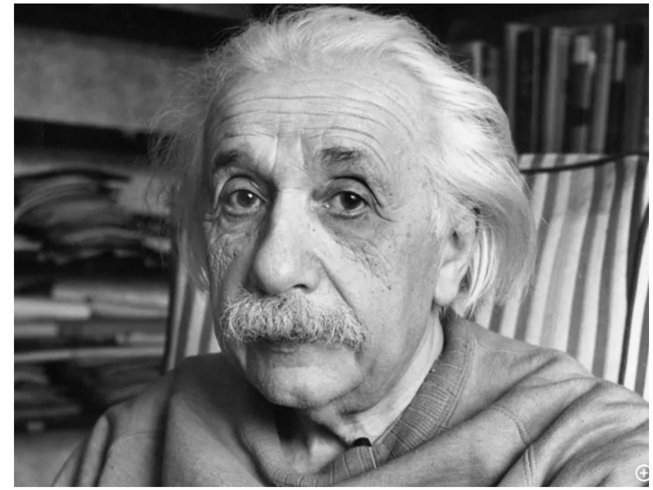
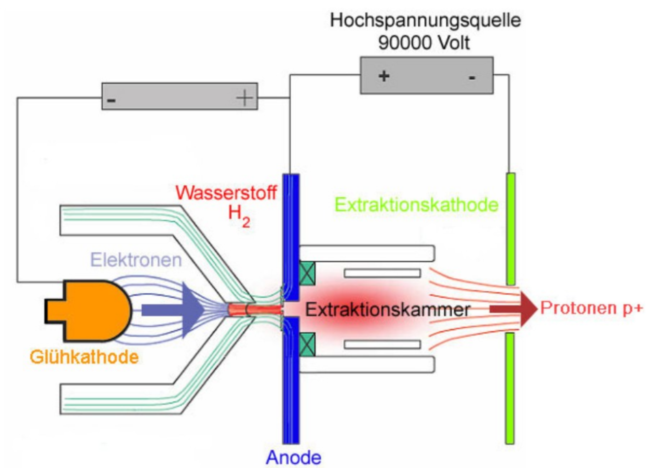
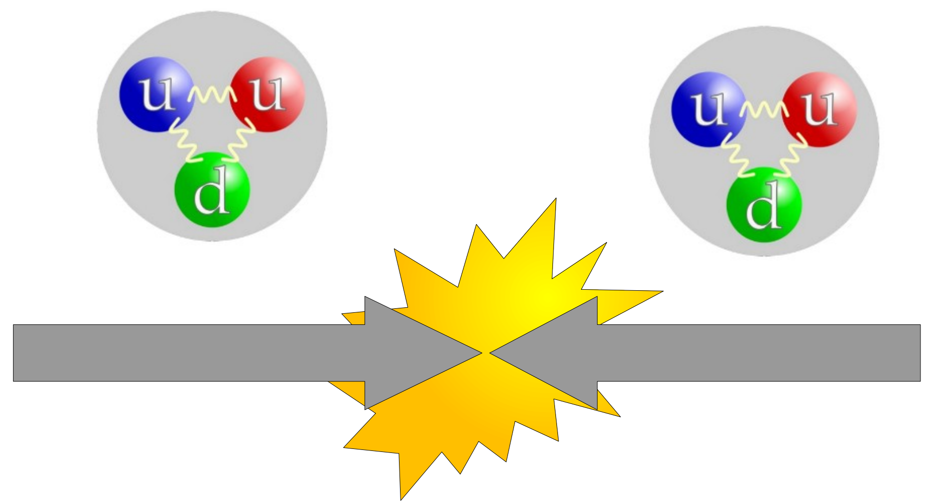






Schema einer Protonenquelle



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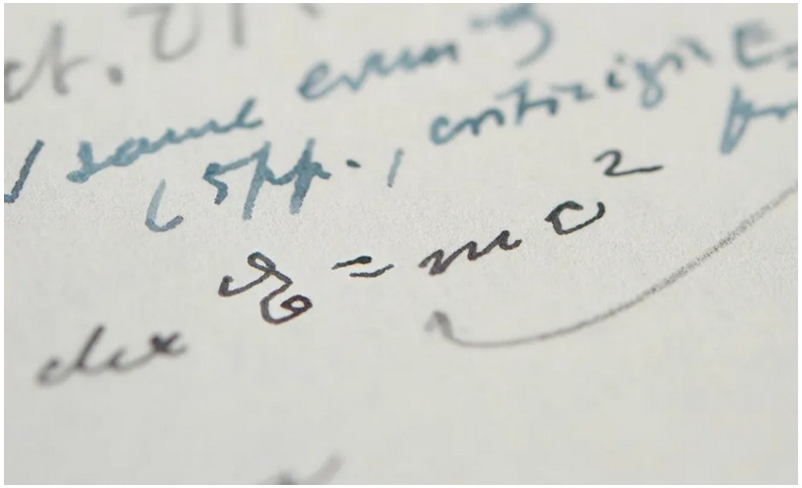
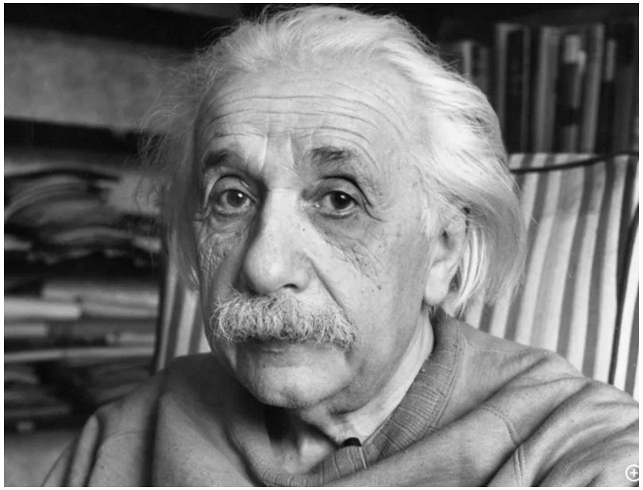
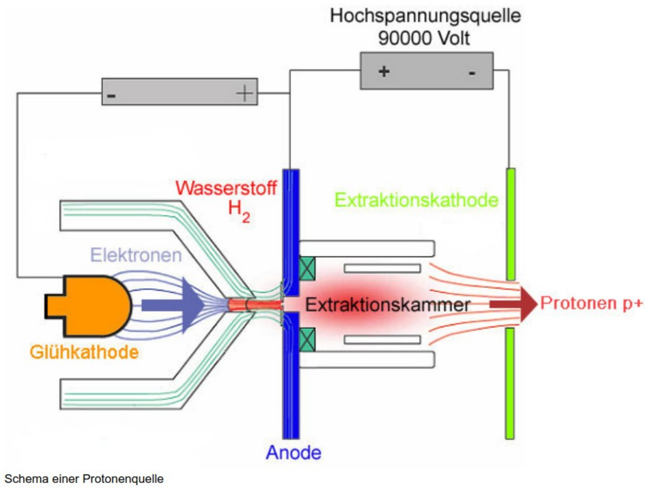
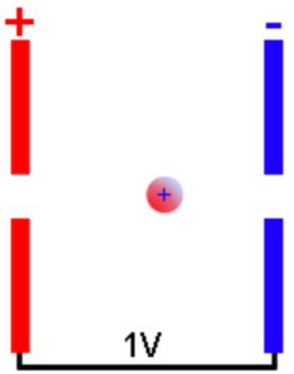
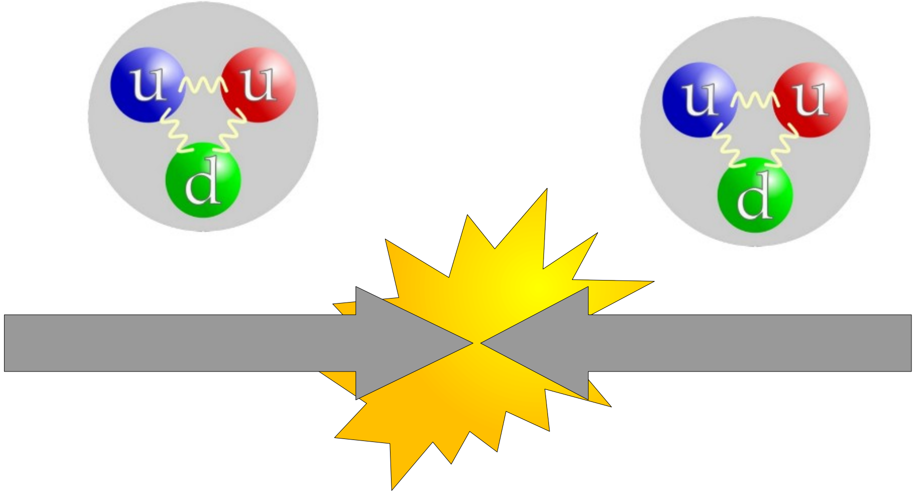






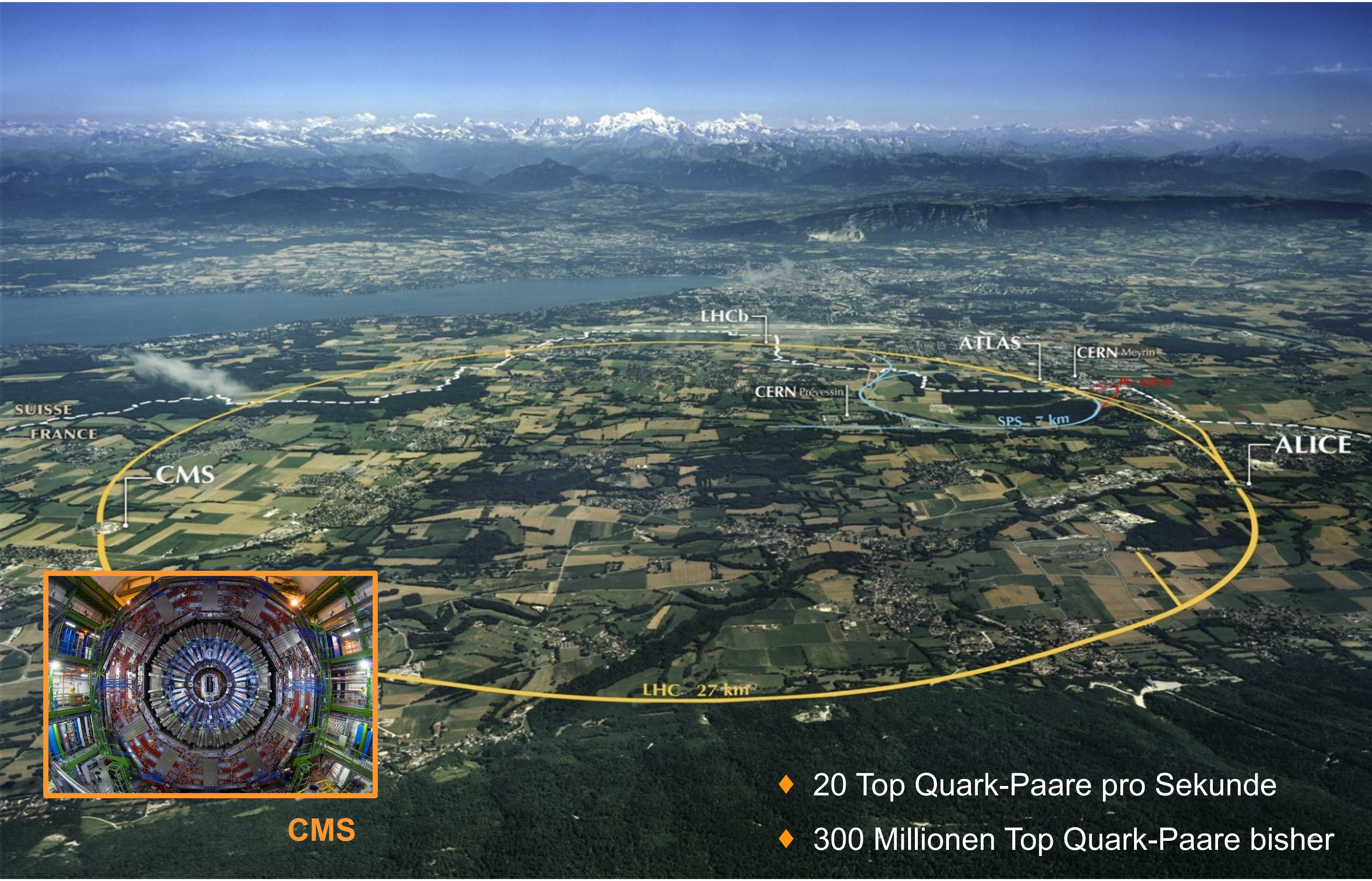


Beschleunigung auf 1 eV



Etwas Wasserstoff und 250 Milliarden 1,5 V Batterien → Erzeugung von zwei Top Quarks

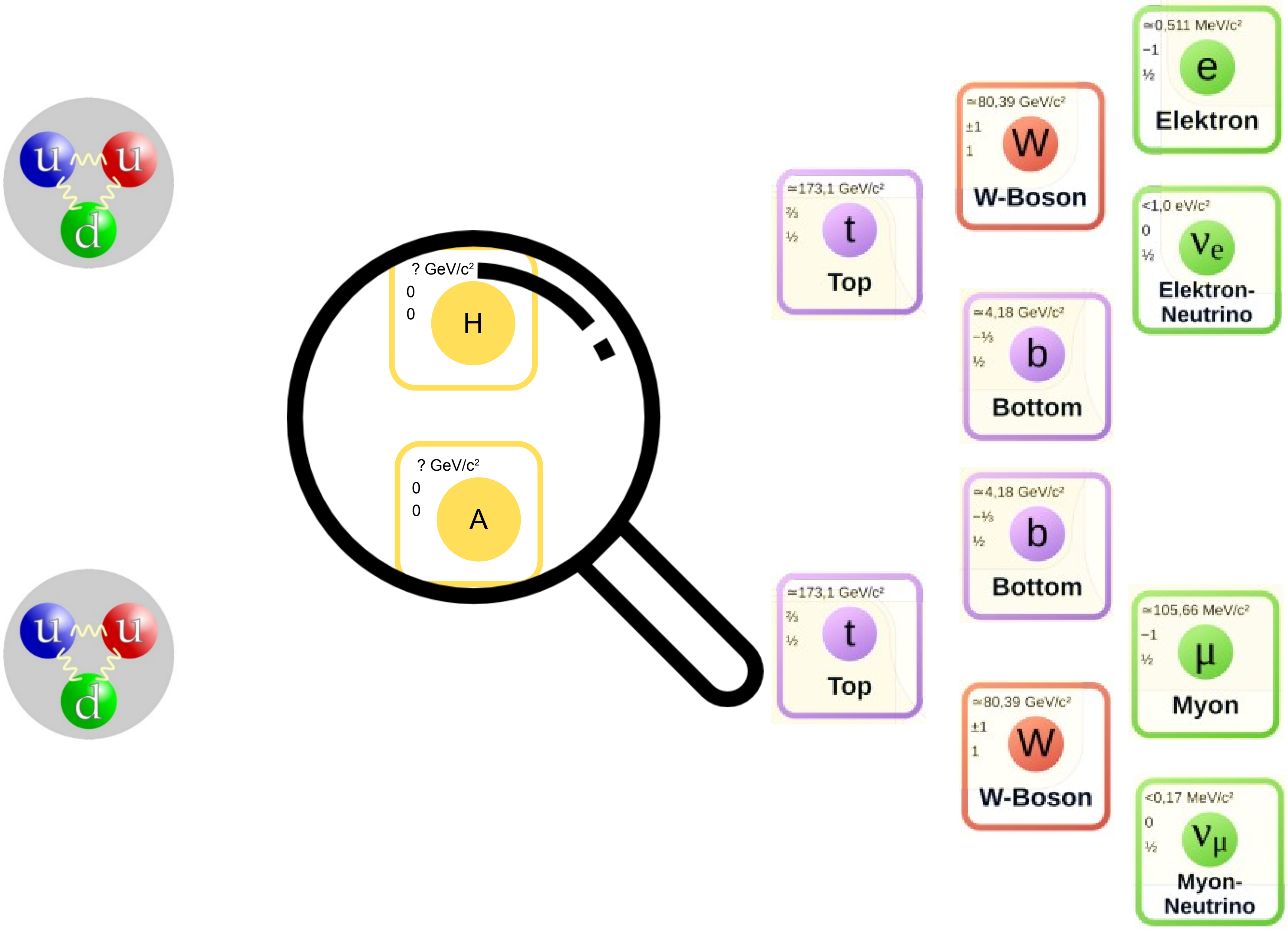
Top Quarks am Fließband

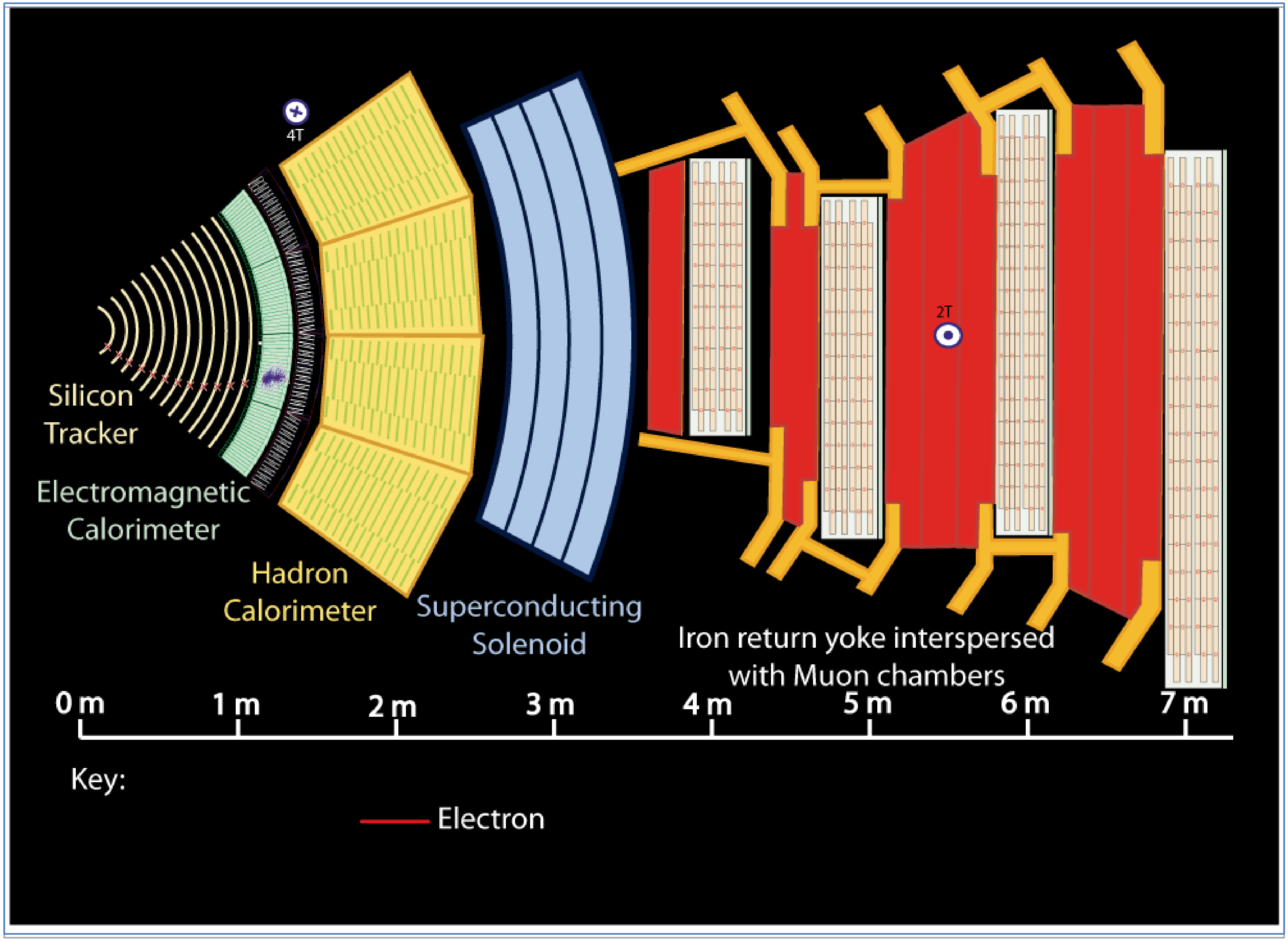


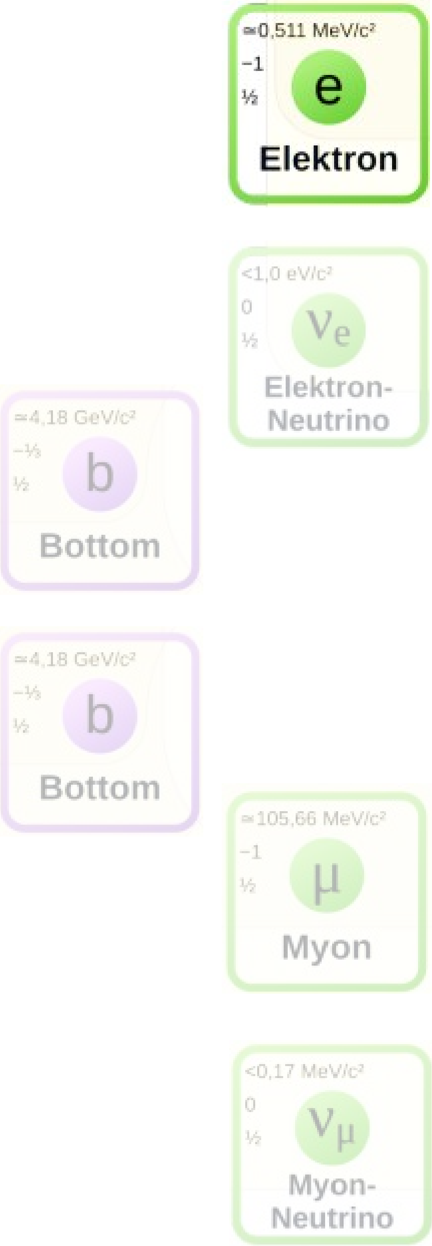
CMS

- 20 Top Quark-Paare pro Sekunde
- 300 Millionen Top Quark-Paare bisher

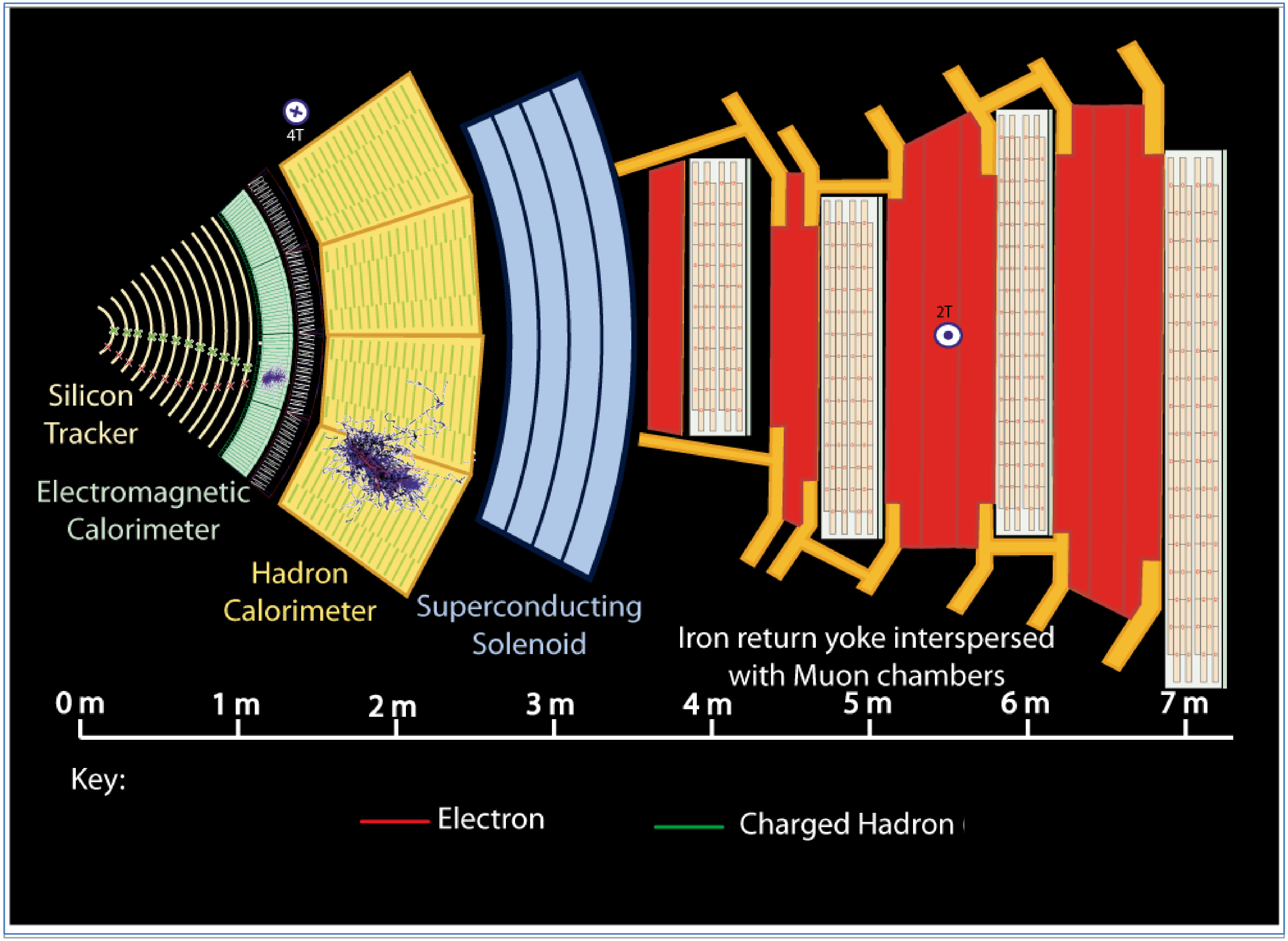
Zwischenbilanz

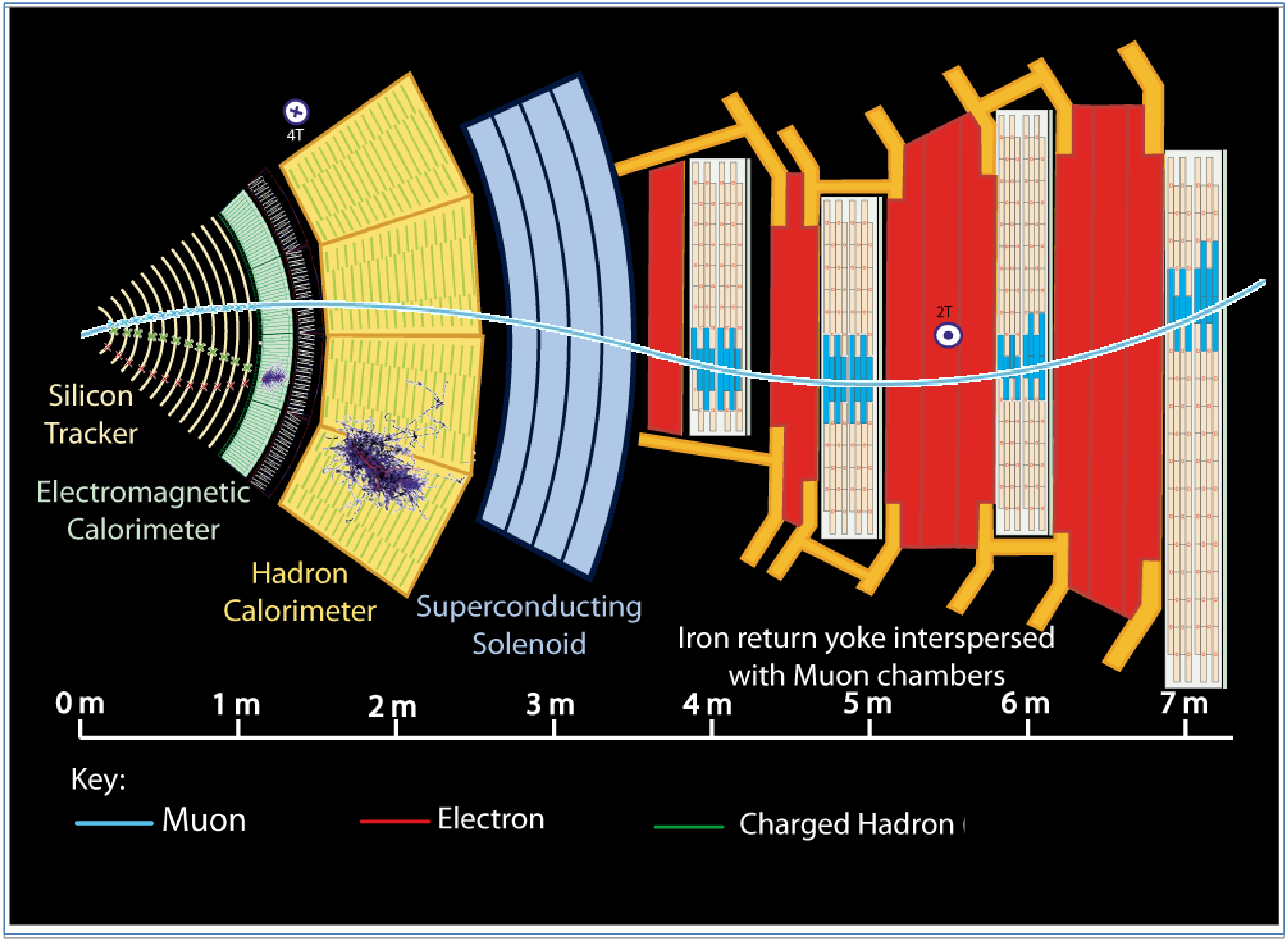



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Electron


≈0,511 MeV/c²
−1
½
e
Elektron
<1,0 eV/c²
0
½
Elektron-Neutrino
≈4,18 GeV/c²
−⅓
½
b
Bottom
≈4,18 GeV/c²
−⅓
½
b
Bottom
≈105,66 MeV/c²
−1
½
μ
Myon
<0,17 MeV/c²
0
½
Myon-Neutrino

Teilchen im CMS Detektor

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Key:
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≈0,511 MeV/c²
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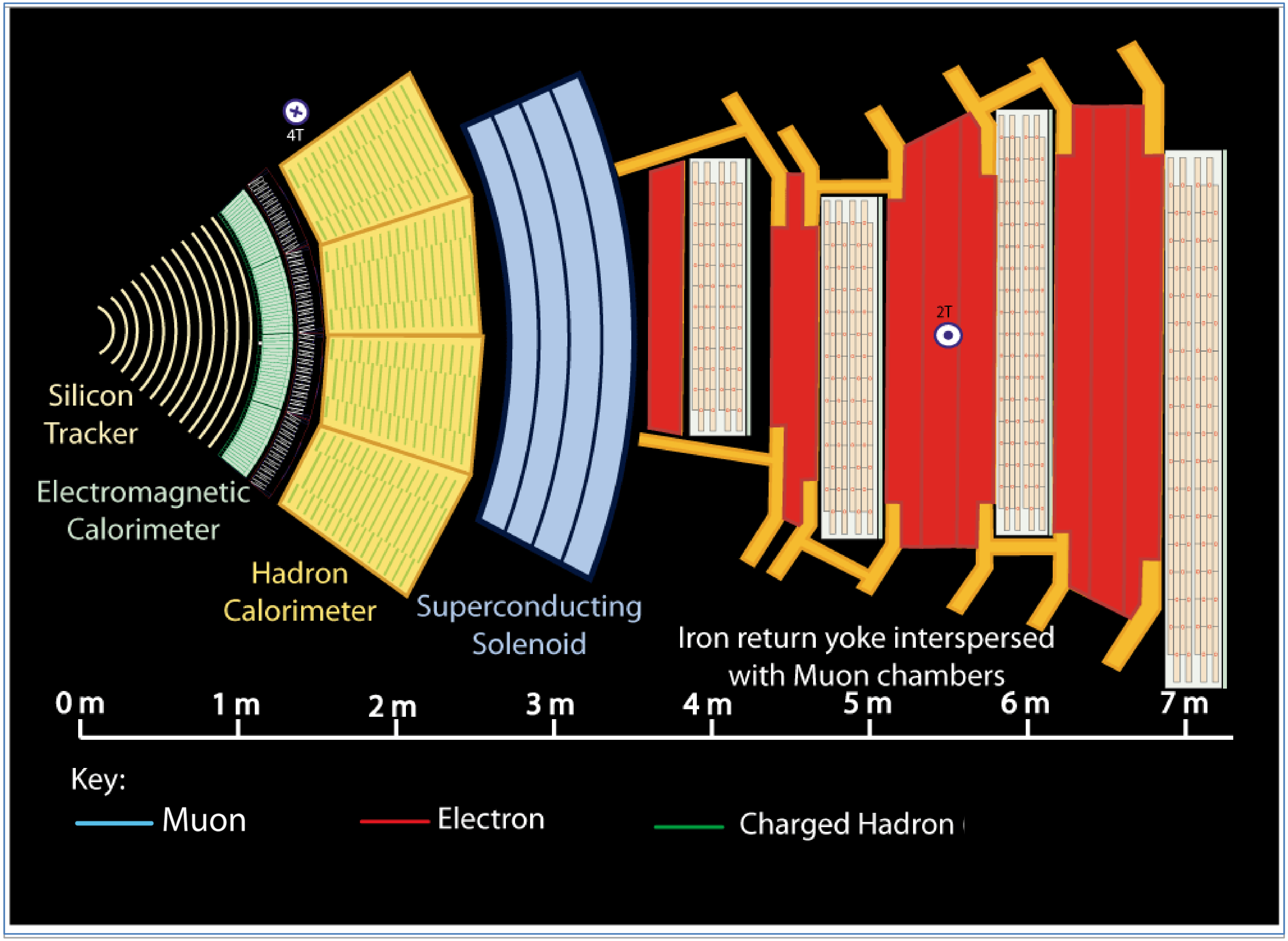
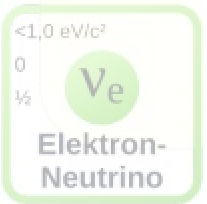
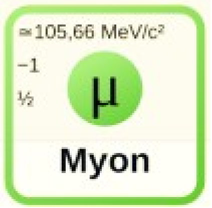
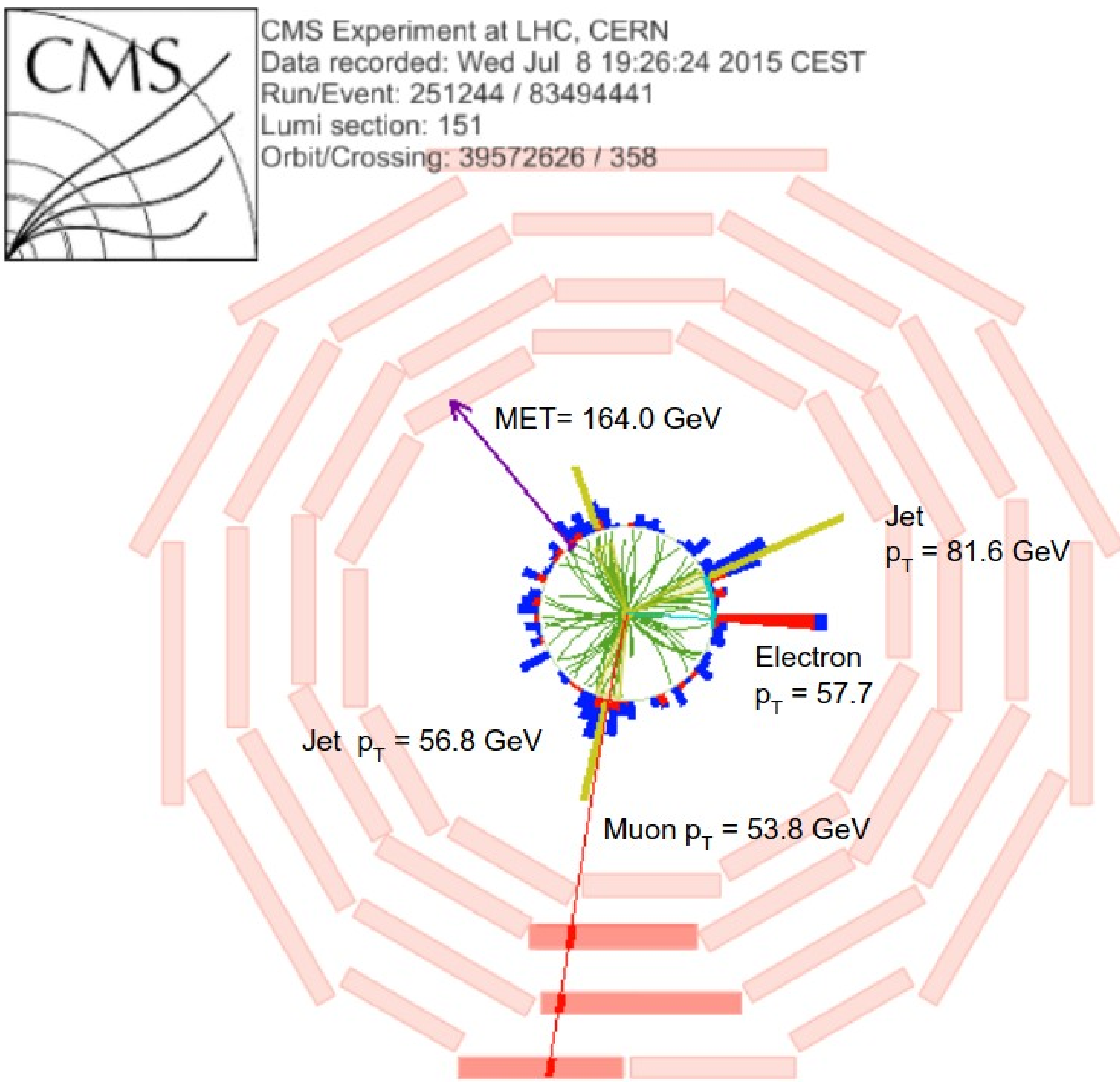
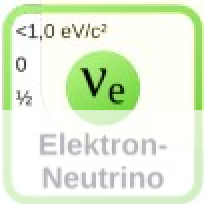







CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 19:26:24 2015 CEST
Run/Event: 251244 / 83494441
Lumi section: 151
Orbit/Crossing: 39572626 / 358
MET= 164.0 GeV
Jet
p_T = 81.6 GeV
Electron
p_T = 57.7
Jet p_T = 56.8 GeV
Muon p_T = 53.8 GeV


≈0,511 MeV/c²
−1
½
e
Elektron


<1,0 eV/c²
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½
ν_e
Elektron-
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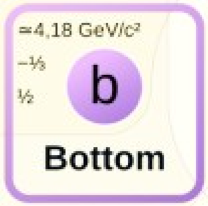
≈4,18 GeV/c²
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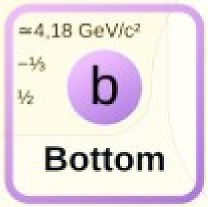
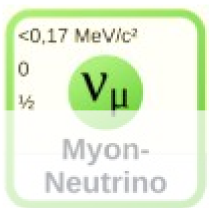
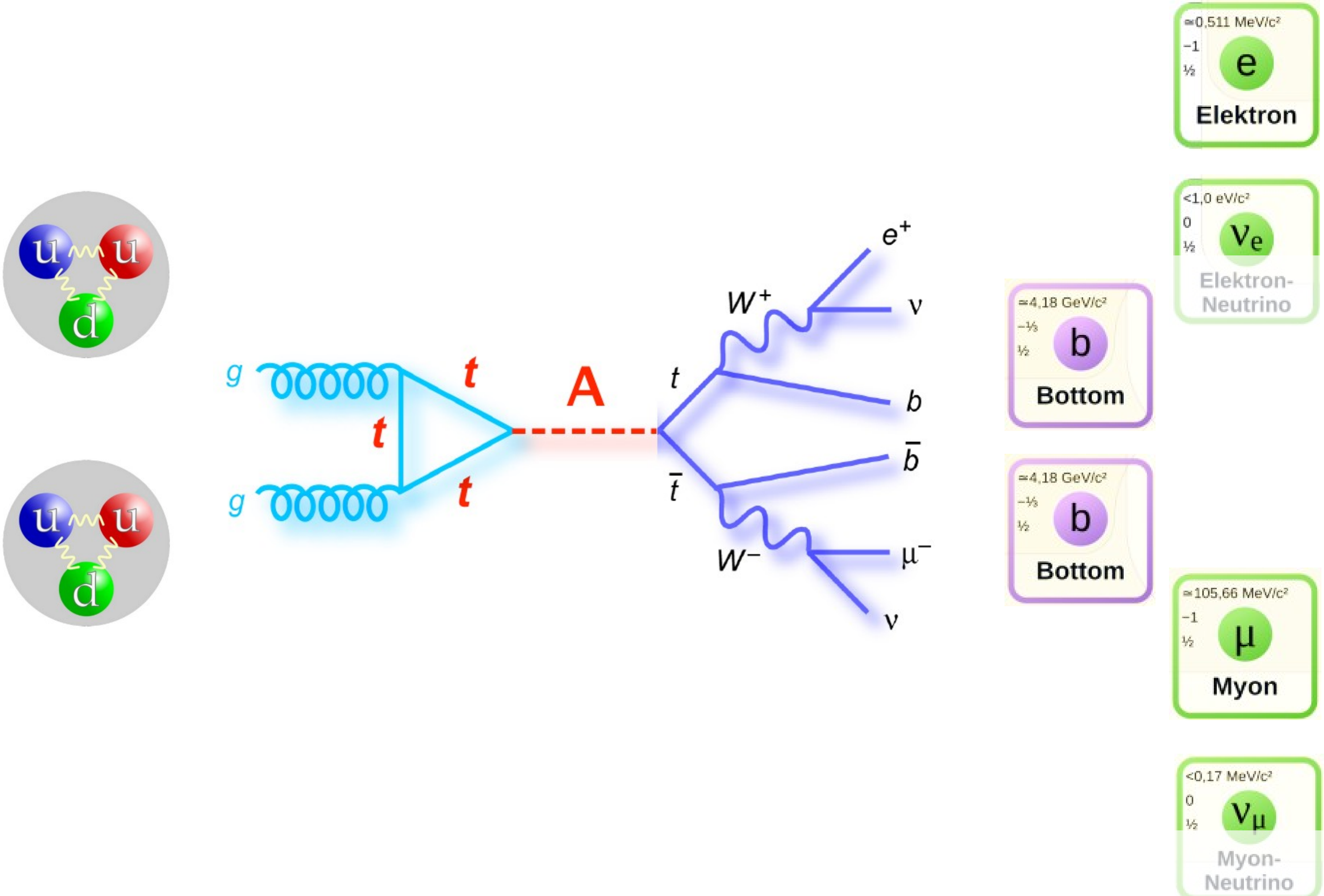

≈4,18 GeV/c²
−⅓
½
b
Bottom

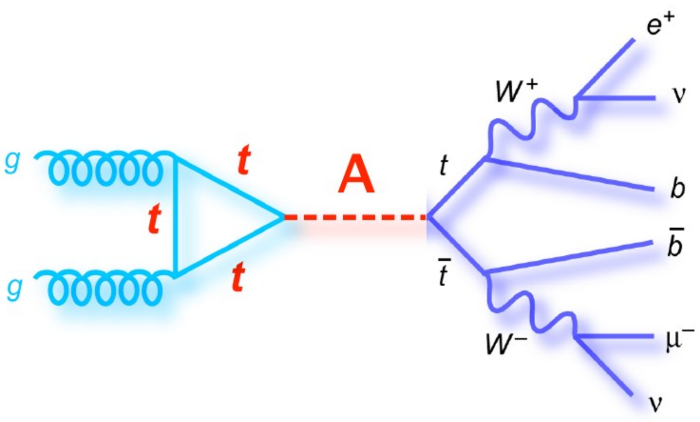

≈105,66 MeV/c²
−1
½
μ
Myon

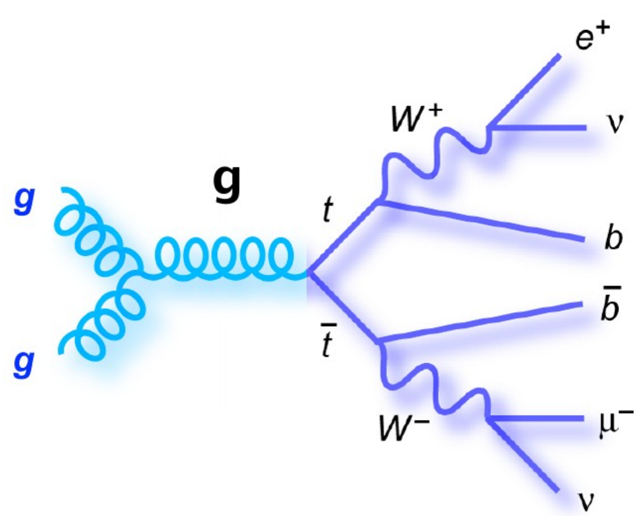

<0,17 MeV/c²
0
½
ν_μ
Myon-
Neutrino

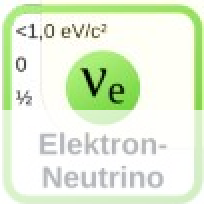
Zwischenbilanz

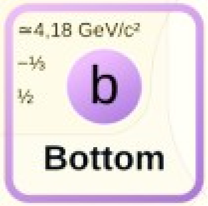


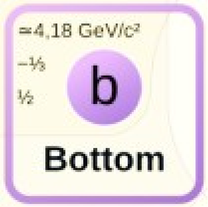
“Ratio to Background: Untergrund

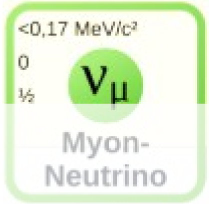




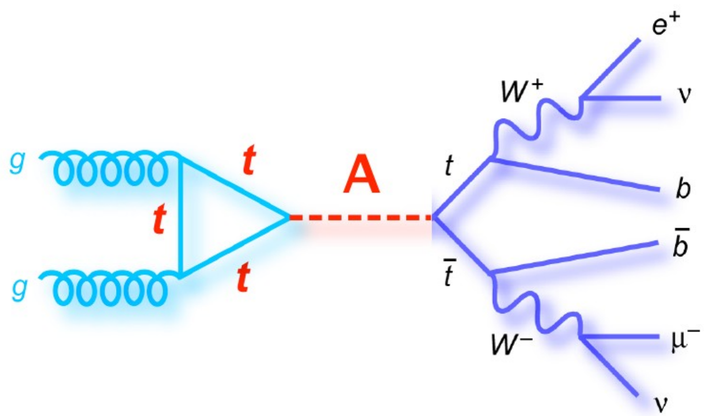


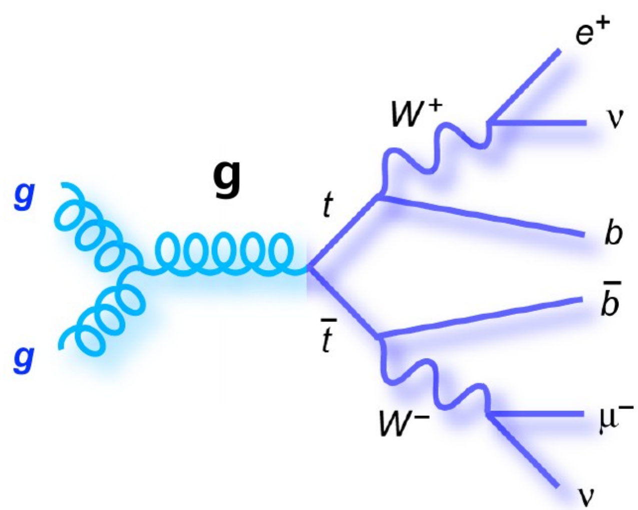


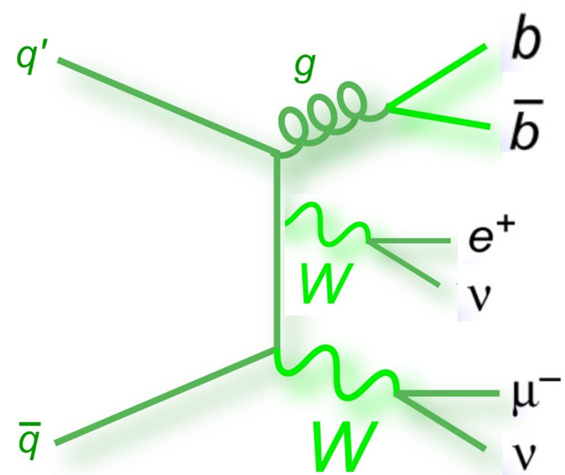


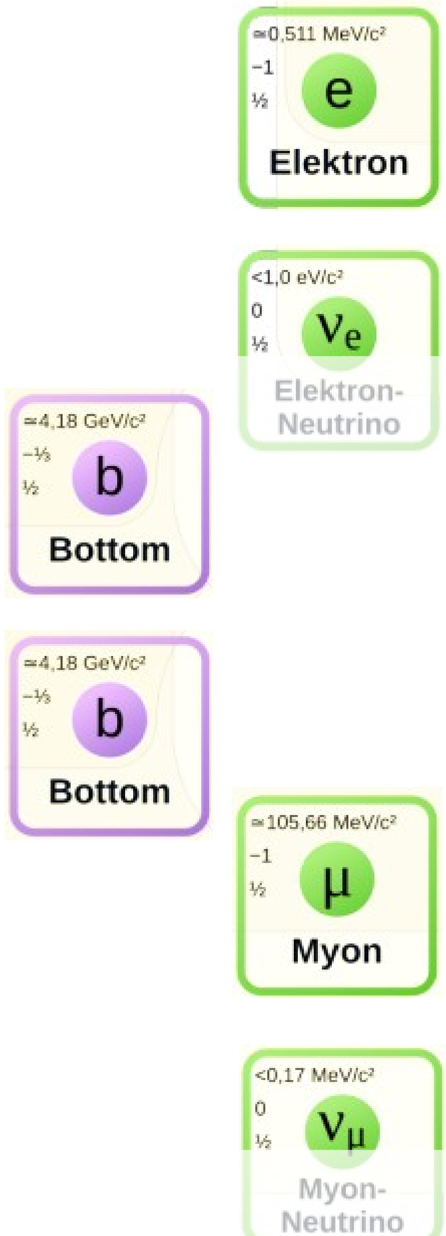


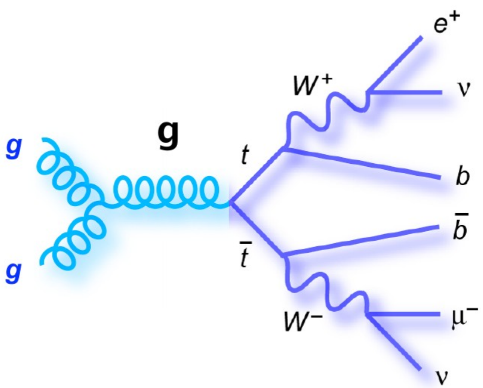
“Ratio to Background: Untergrund







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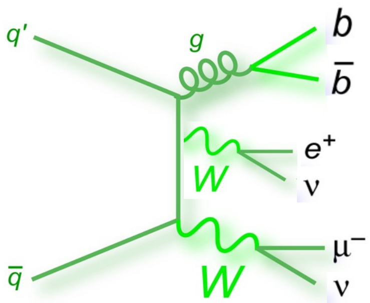
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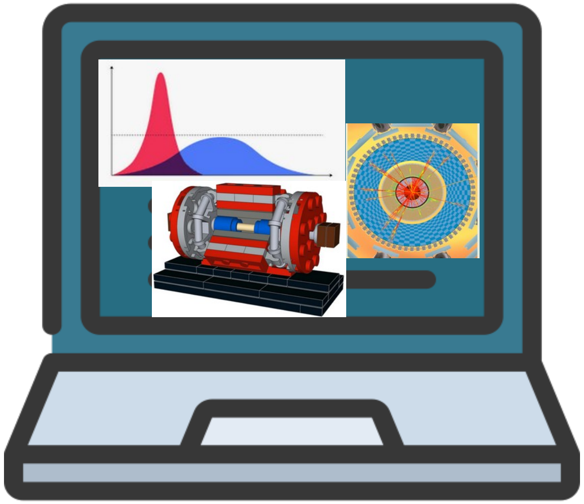

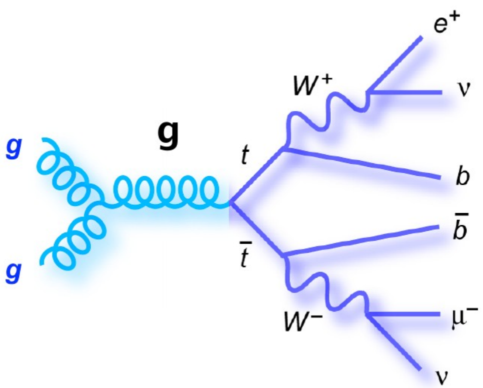
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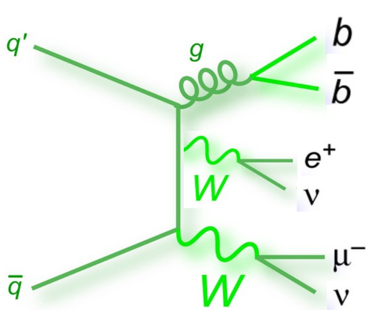
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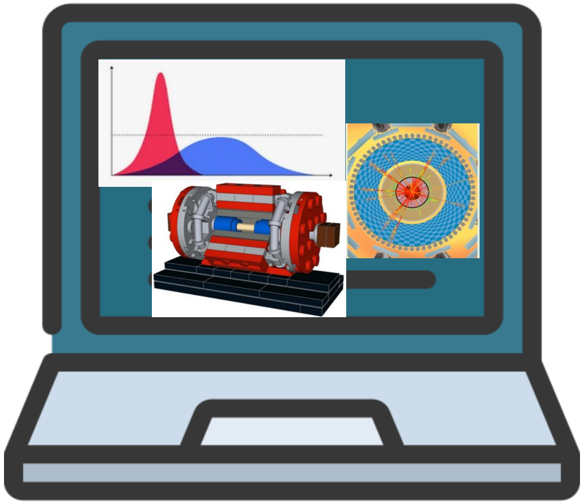

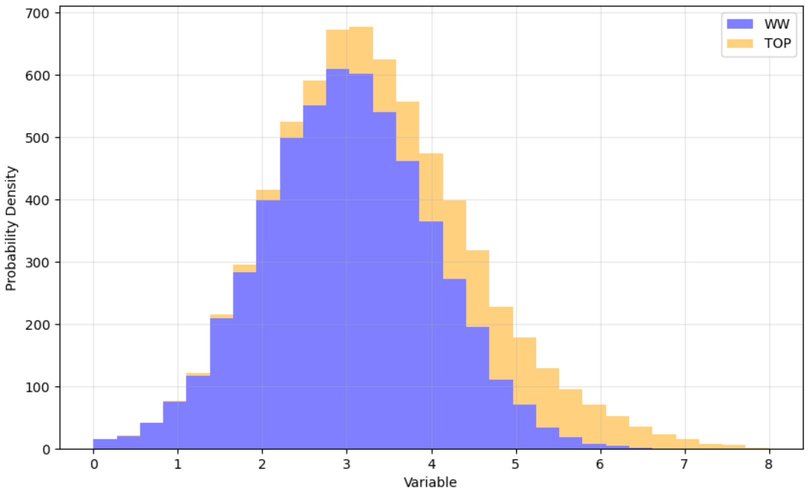
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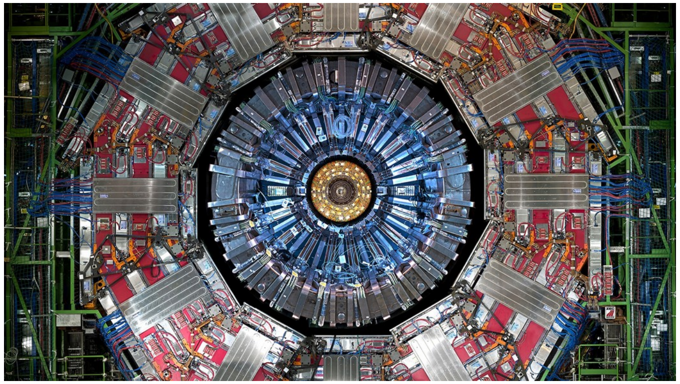
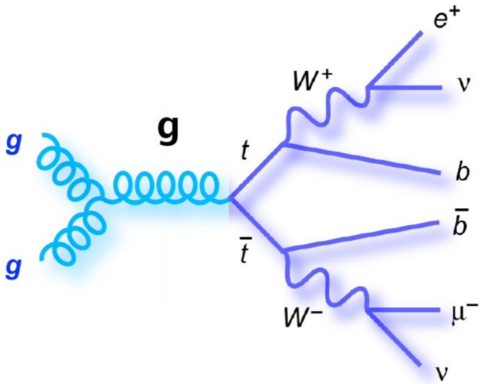
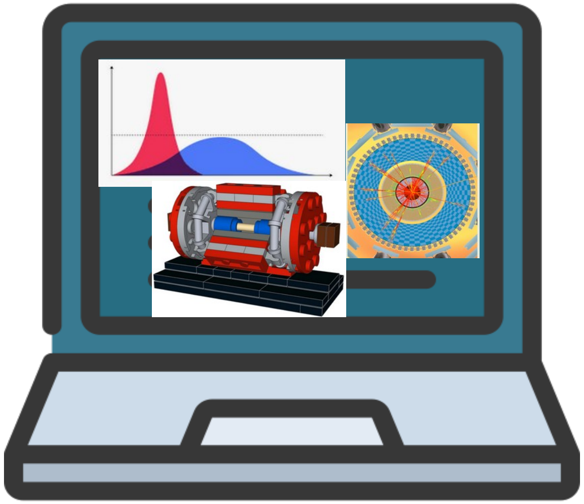
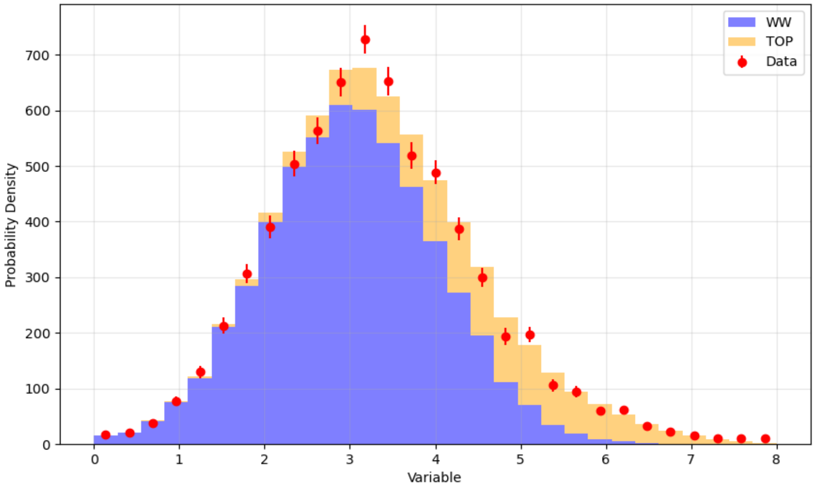
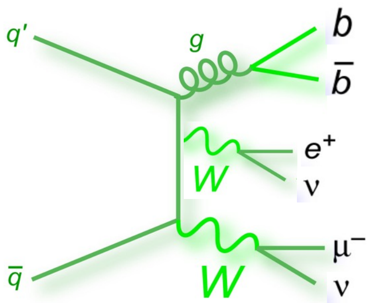
LHC Analyse Rezept

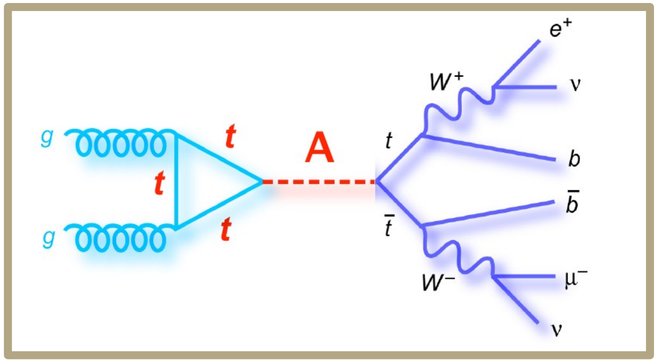












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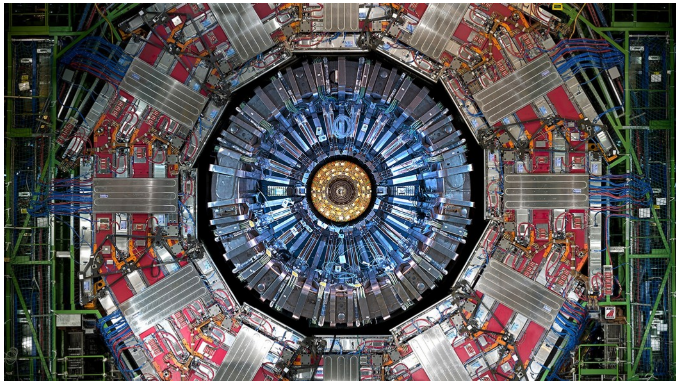

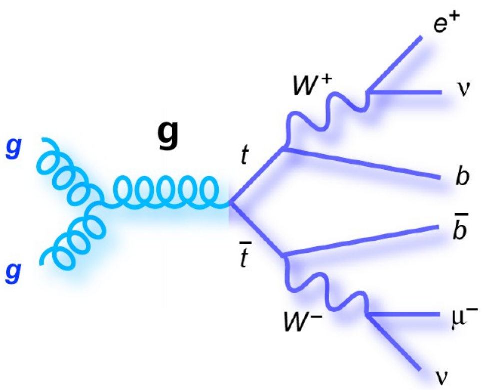

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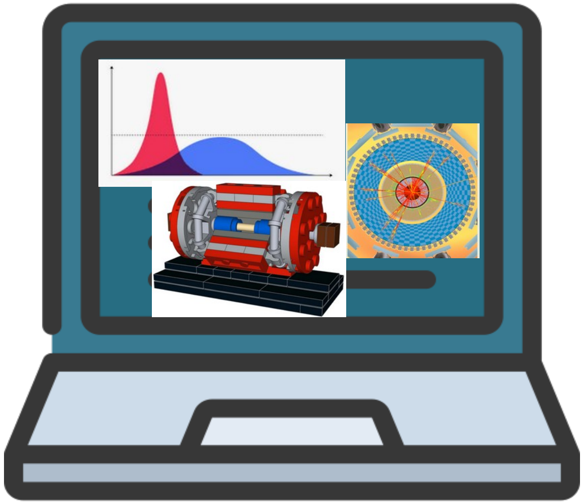

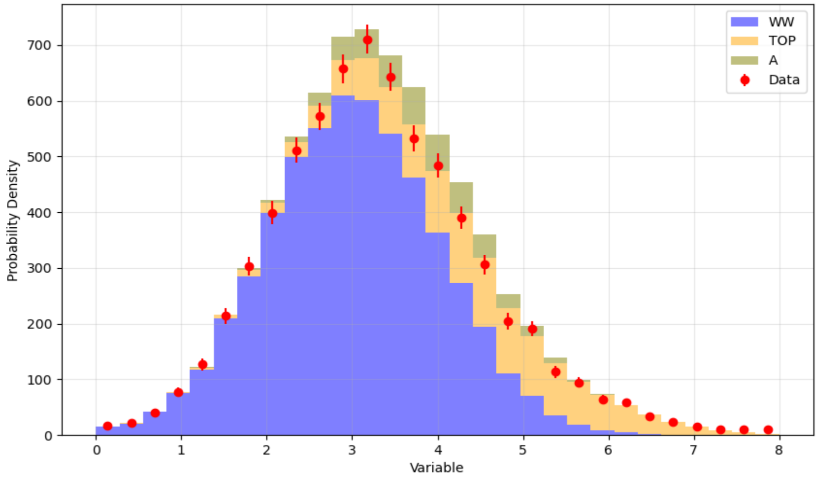

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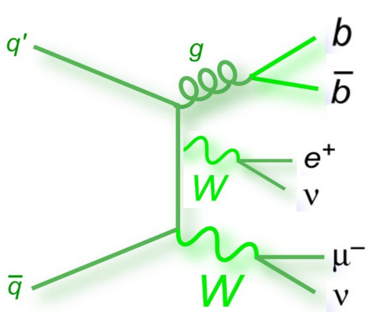

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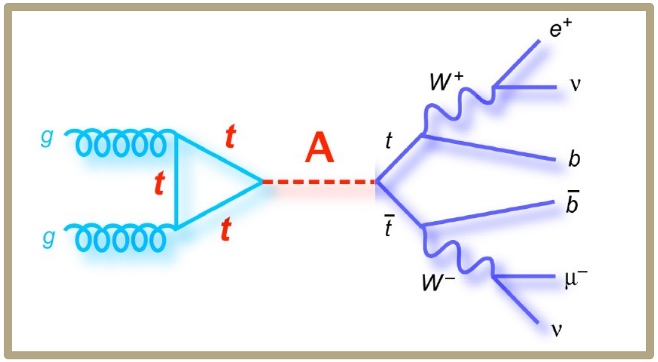

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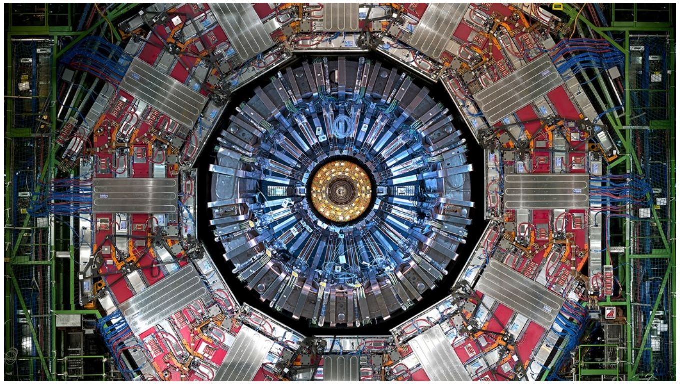

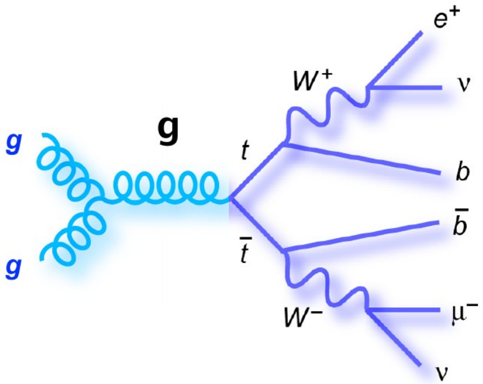

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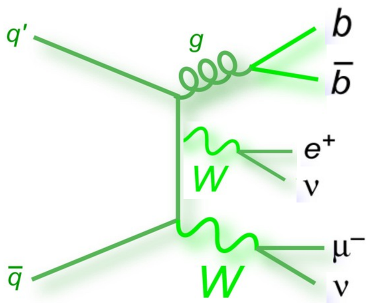

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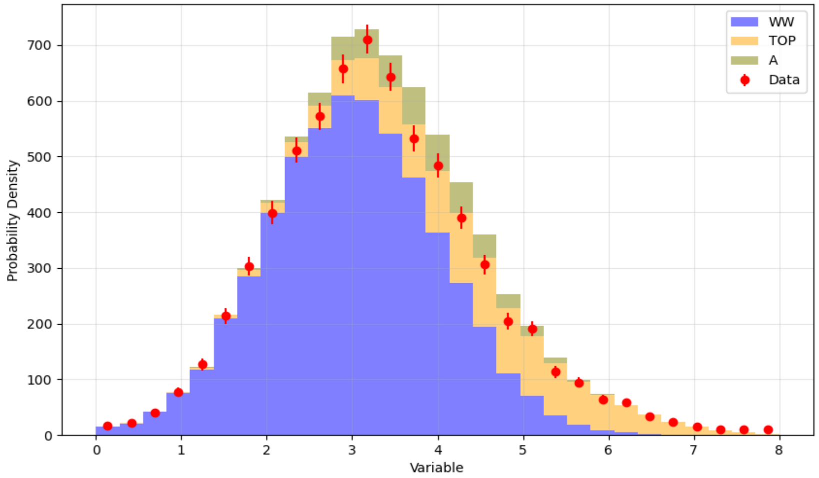
Burj Khalifa



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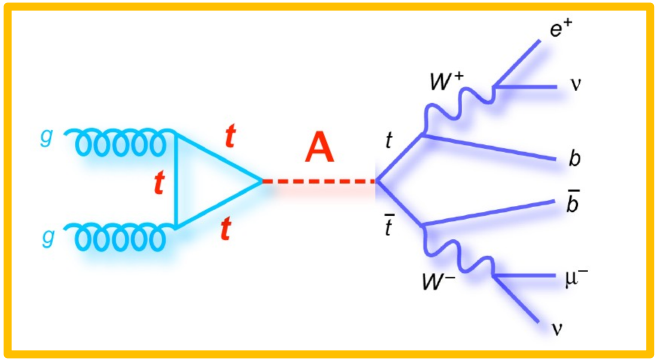
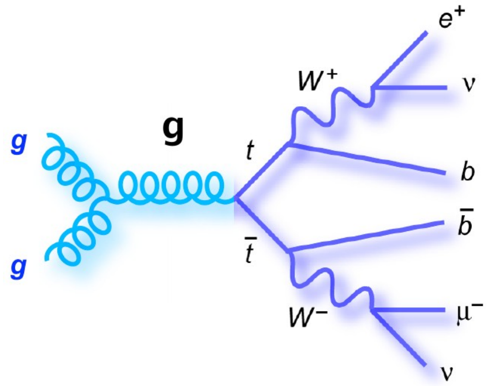
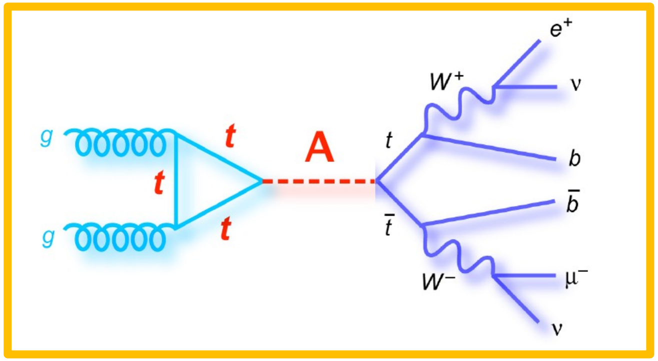
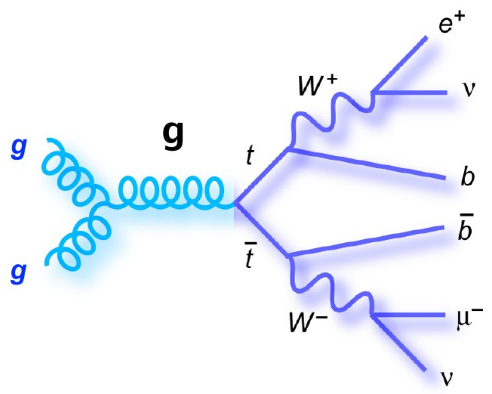
Wie kann man Signal von Untergrund unterscheiden ?





- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks
  - Teilchen durch Energie und Impuls beschrieben $(E,p_x,p_y,p_z) \rightarrow E^2 = p^2 + m^2$
  - 2 (fast) masselose Neutrinos → 6 Unbekannte





- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks
  - Teilchen durch Energie und Impuls beschrieben $(E, p_x, p_y, p_z) \rightarrow E^2 = p^2 + m^2$
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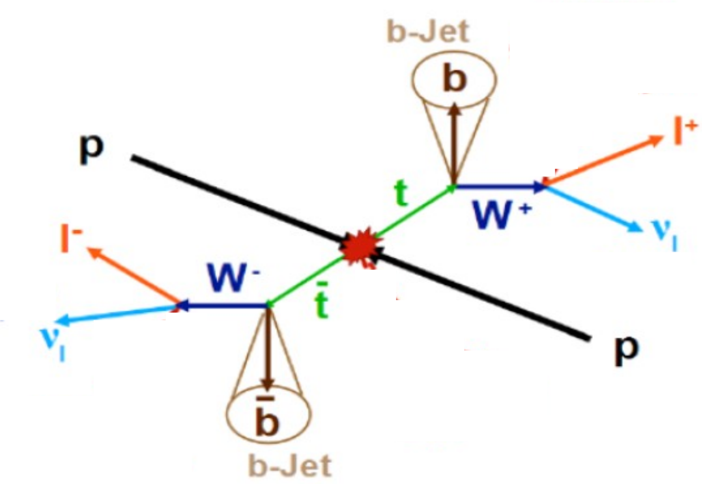

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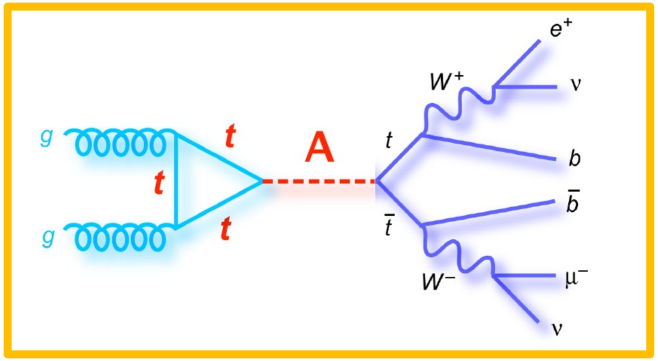
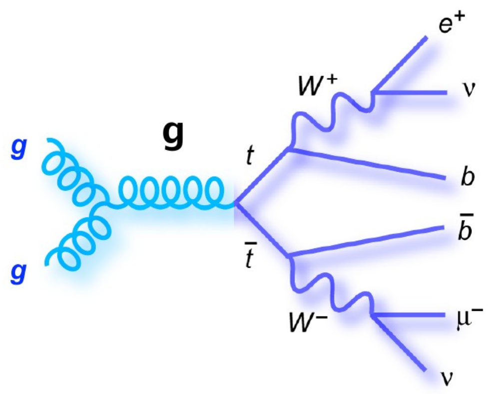
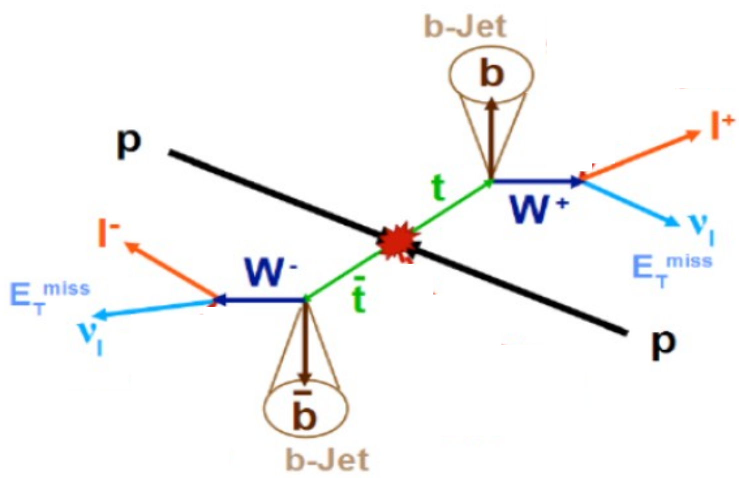
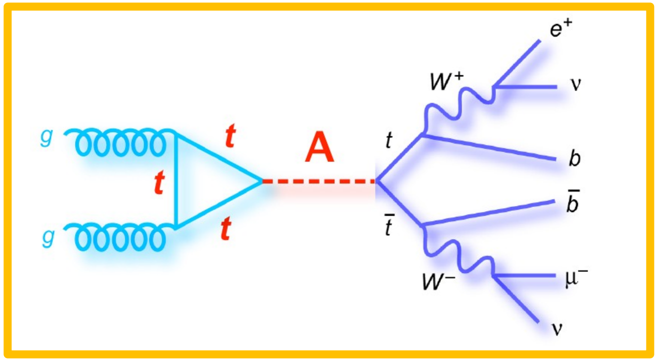
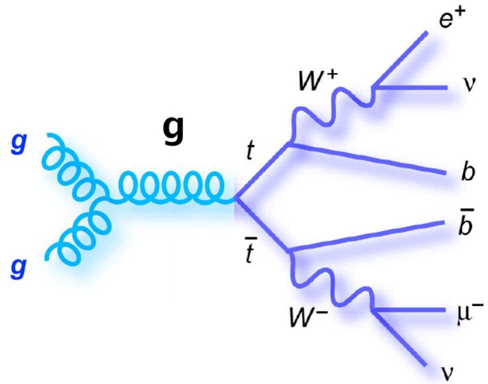




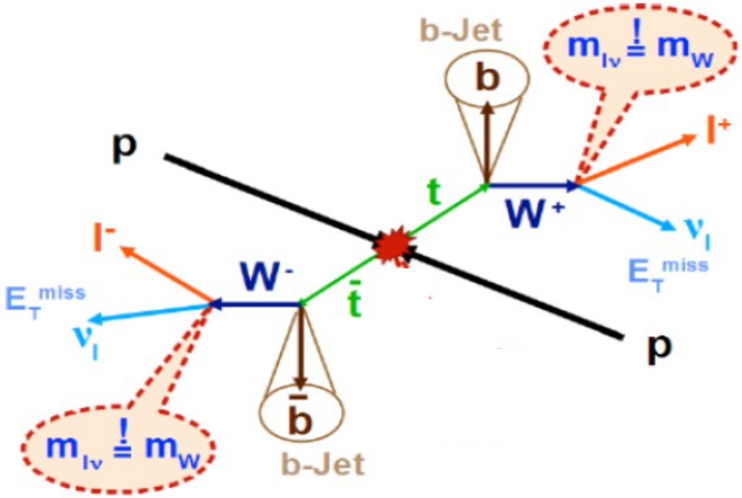
- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks
  - Teilchen durch Energie und Impuls beschrieben (E,p_x,p_y,p_z) $\rightarrow$ $E^2 = p^2 + m^2$
  - 2 (fast) masselose Neutrinos + $E_{T,x}^{miss}$ + $E_{T,y}^{miss}$ $\rightarrow$ 4 Unbekannte



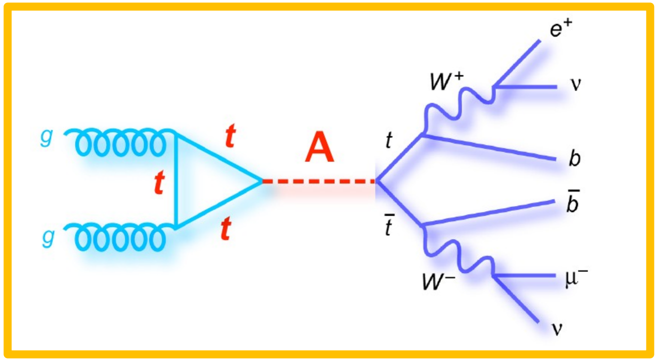


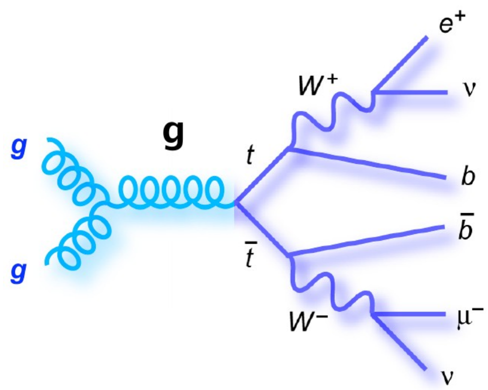


- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks
  - Teilchen durch Energie und Impuls beschrieben $(E,p_x,p_y,p_z) \rightarrow E^2 = p^2 + m^2$
  - 2 (fast) masselose Neutrinos + $E_{T,x}^{miss}$ + $E_{T,y}^{miss}$ + $m_W \rightarrow$ 2 Unbekannte

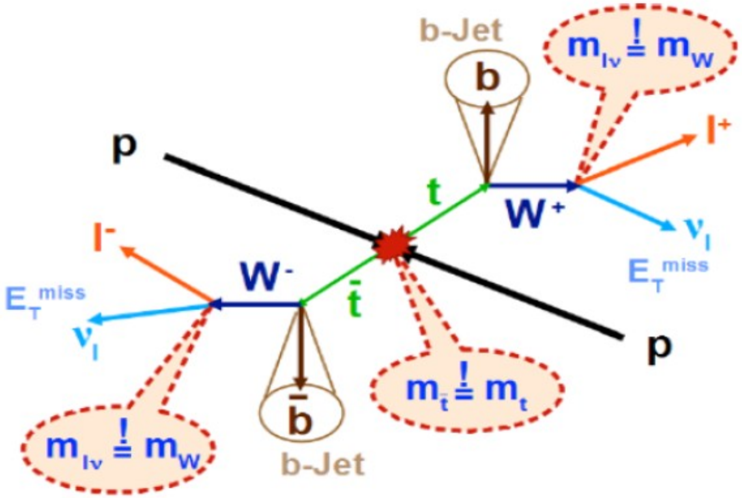


Wie kann man Signal von Untergrund unterscheiden ?

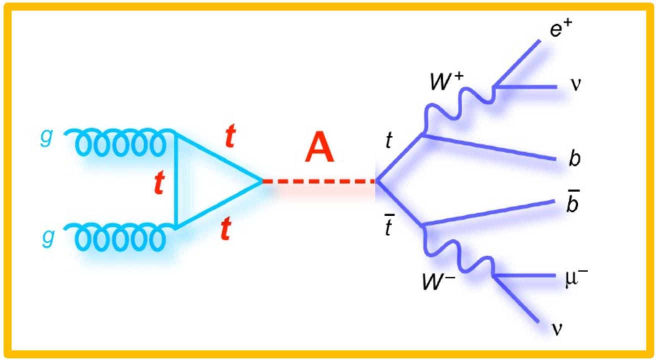


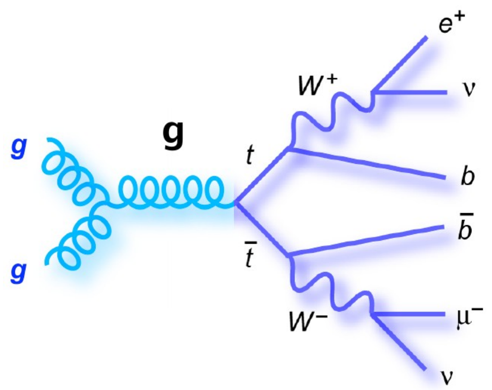


- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks
  - Teilchen durch Energie und Impuls beschrieben $(E,p_x,p_y,p_z) \rightarrow E^2 = p^2 + m^2$
  - 2 (fast) masselose Neutrinos + $E_{T,x}^{miss}$ + $E_{T,y}^{miss}$ + m_W + m_{top} $\rightarrow$ 0 Unbekannte

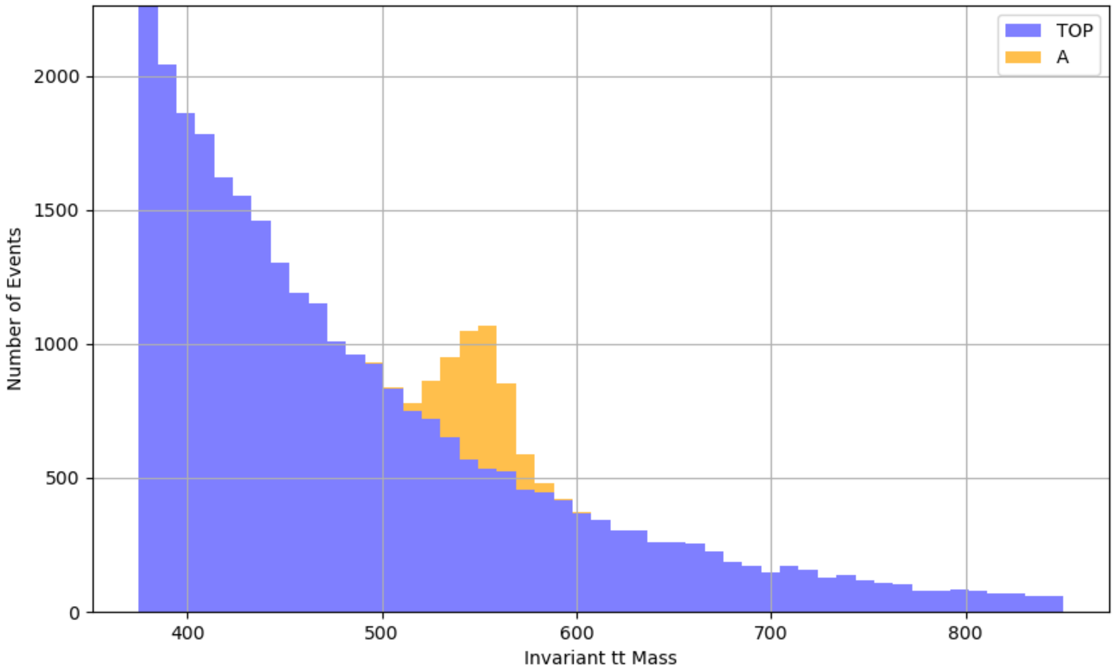


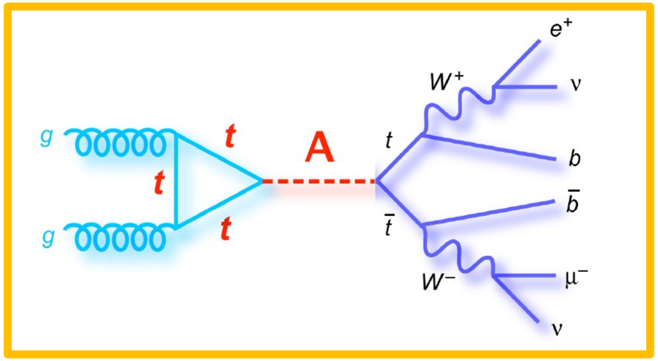
Wie kann man Signal von Untergrund unterscheiden ?

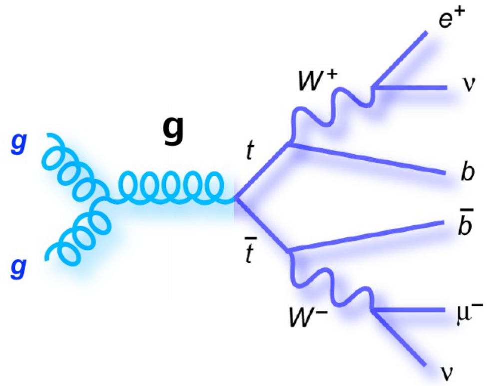




- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks

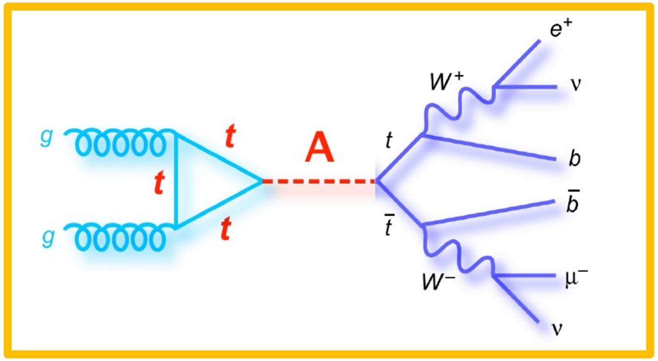


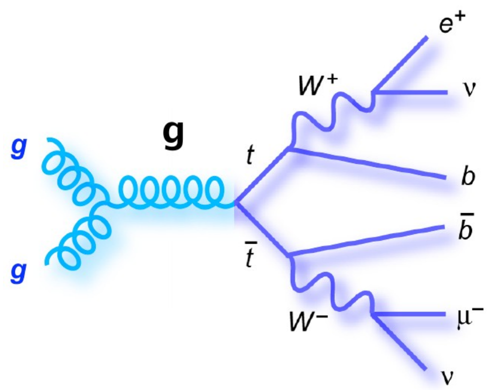




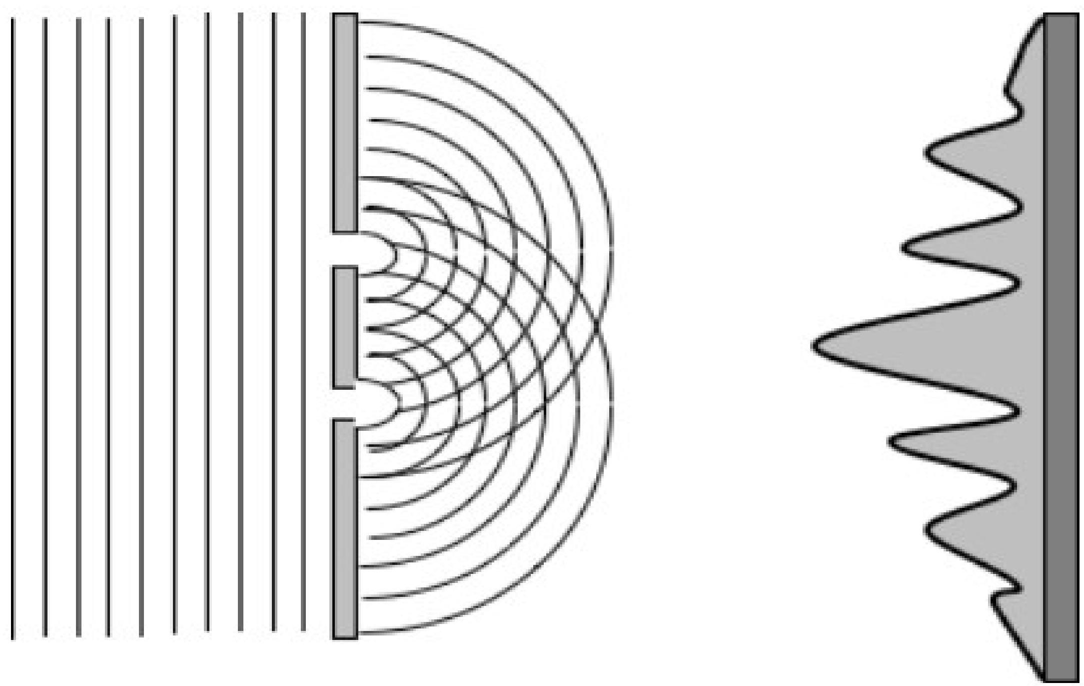
- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks

Wie kann man Signal von Untergrund unterscheiden ?

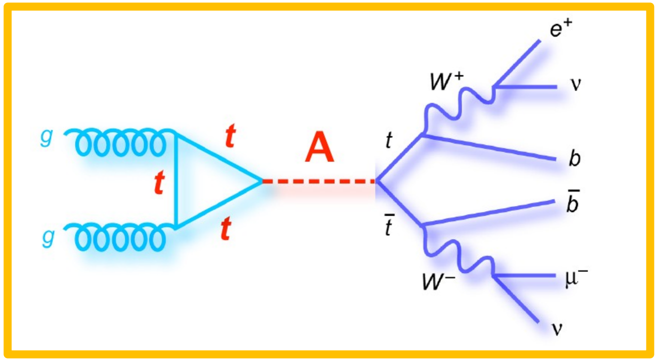


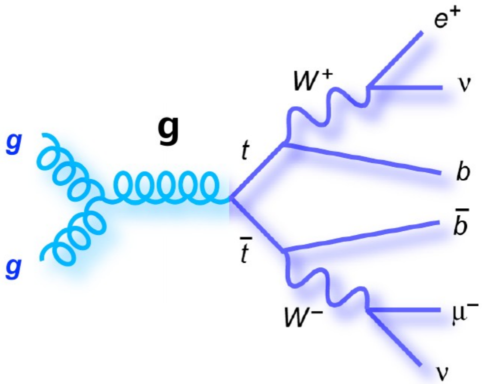


- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks

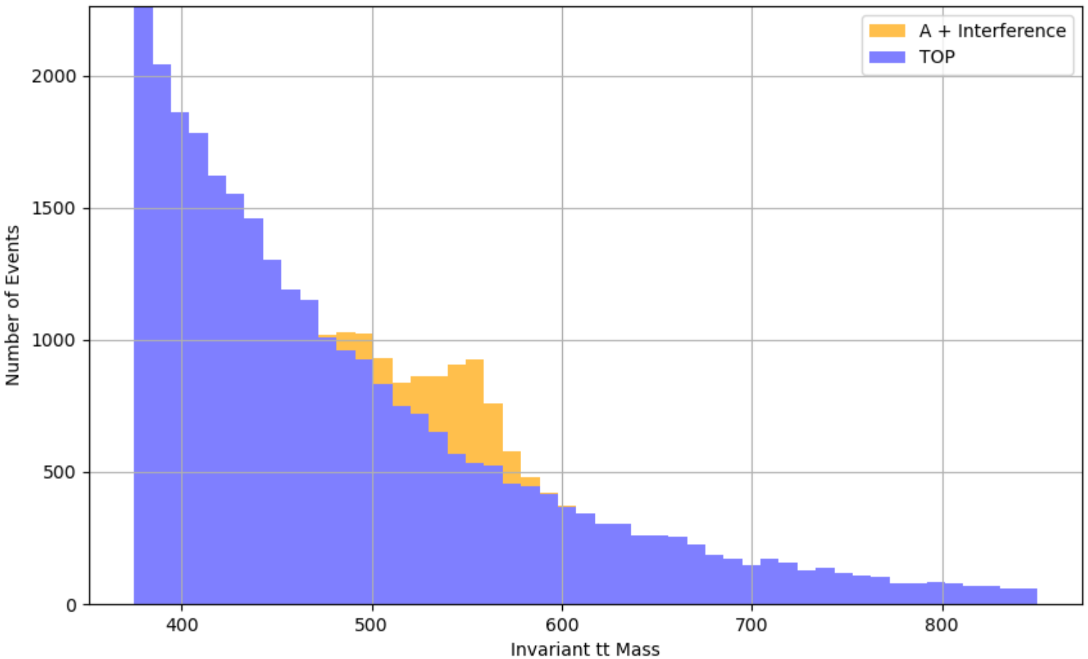


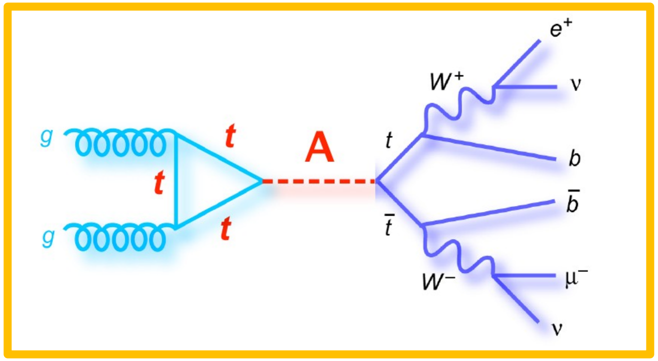
Wie kann man Signal von Untergrund unterscheiden ?

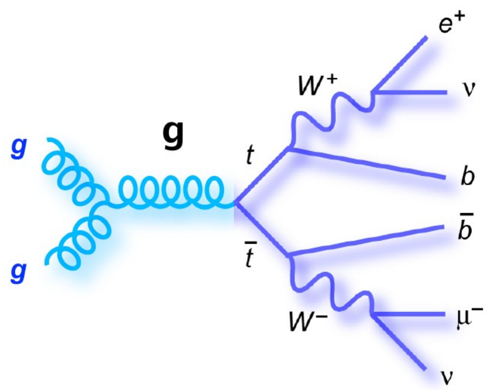




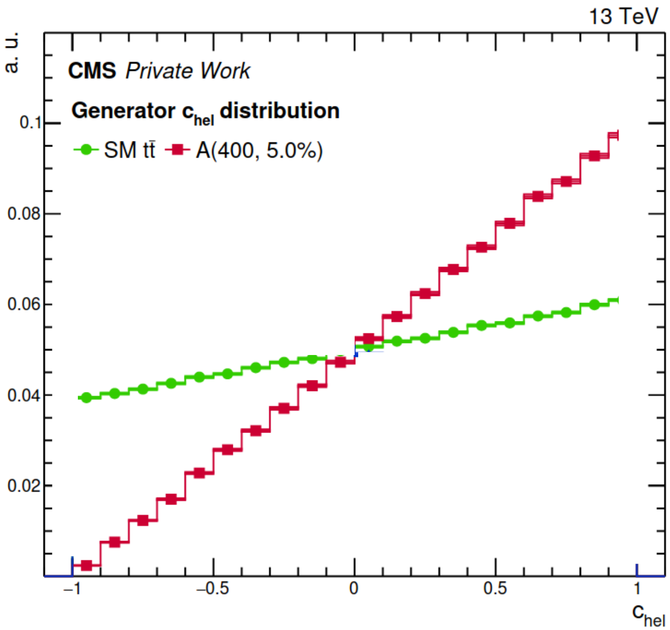
- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks



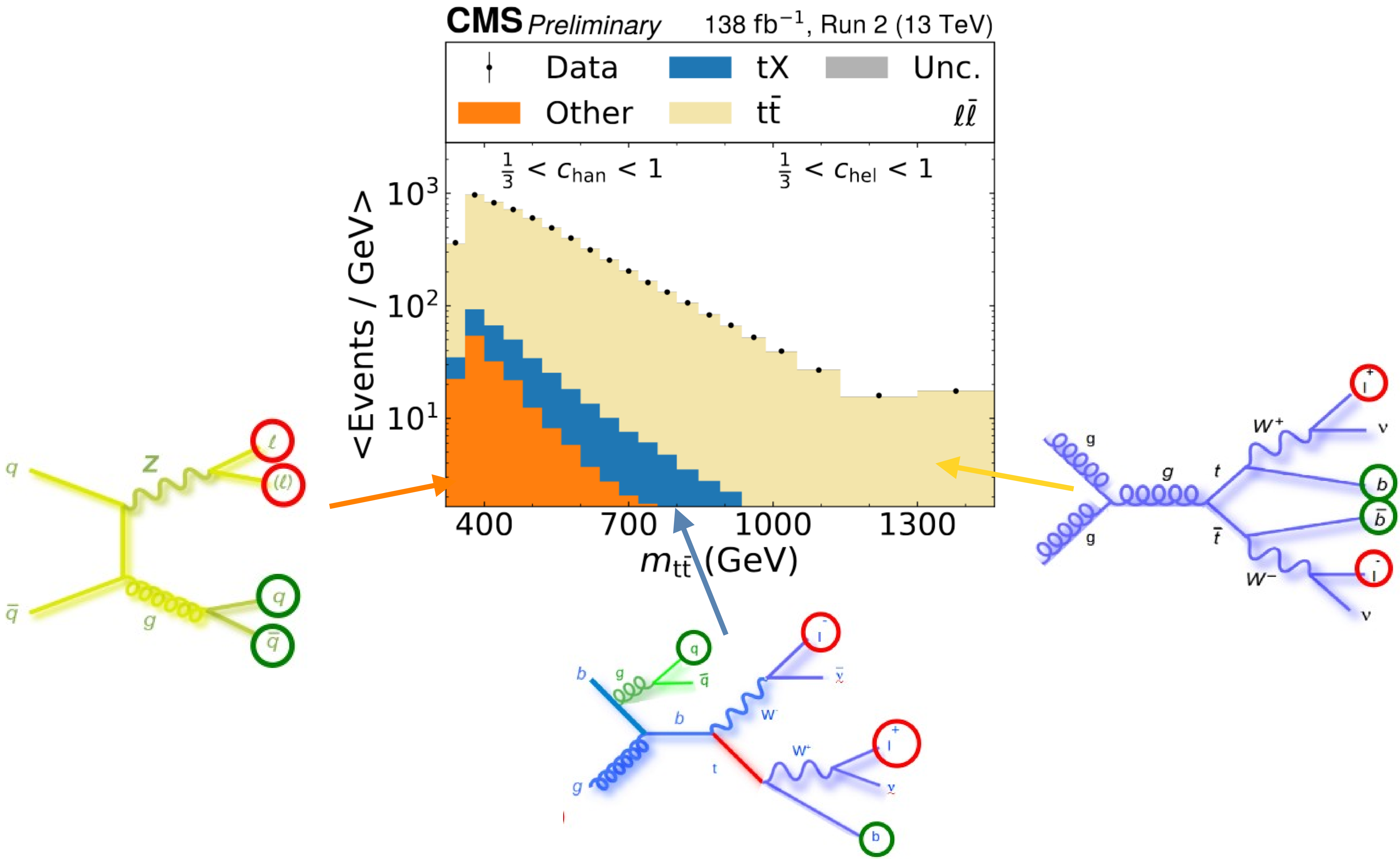




- Hilfsmittel: Kinematische Rekonstruktion von Top Quarks
- Spins der produzierten Top Quarks:
  - A: ↑↓ oder ↓↑
  - SM: ↑↓ oder ↓↑ oder ↑↑ oder ↓↓



Was haben wir am CMS Experiment gesehen?



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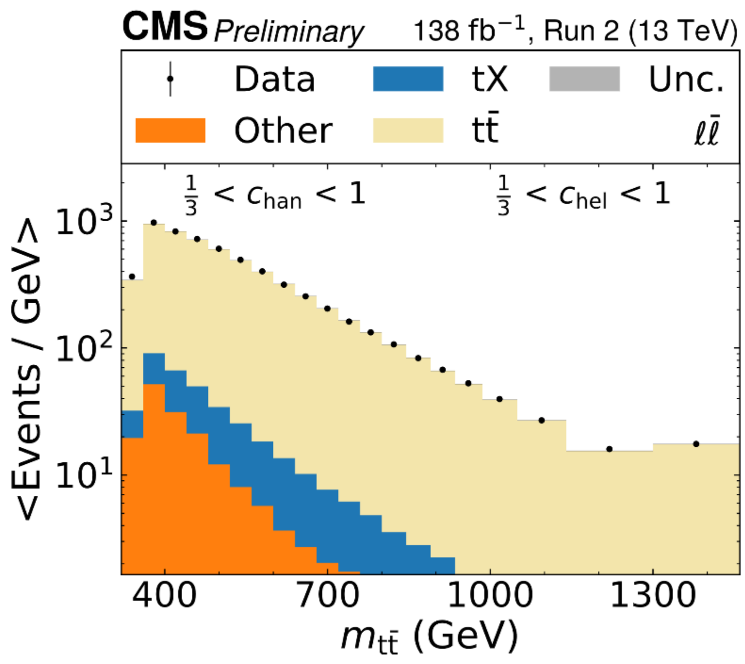
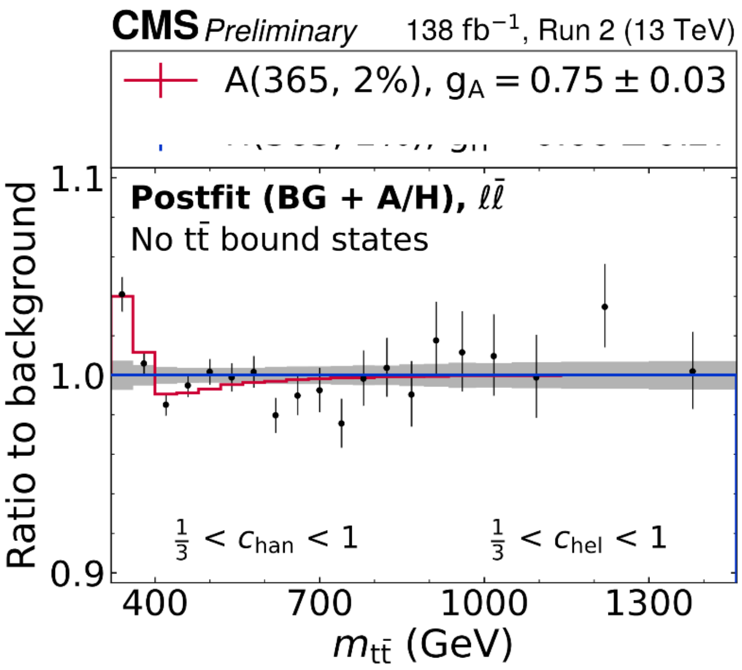
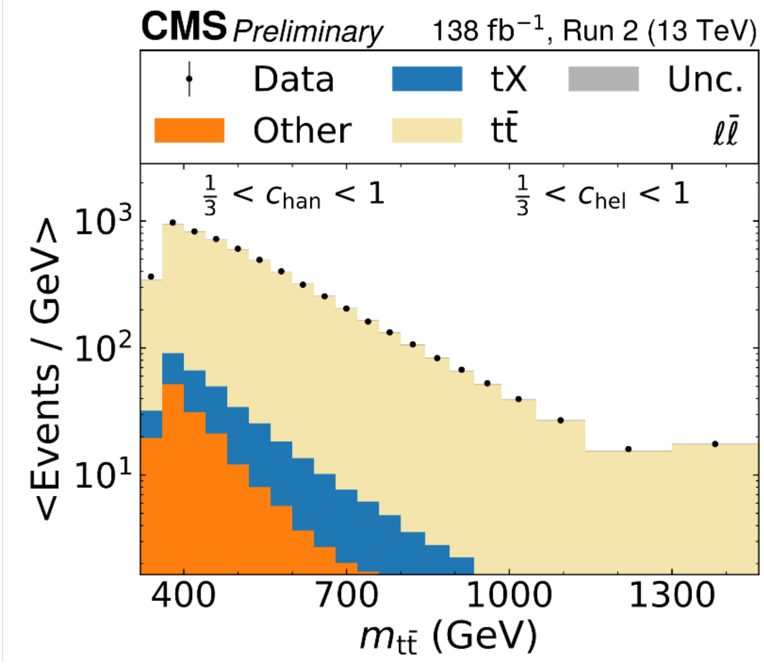
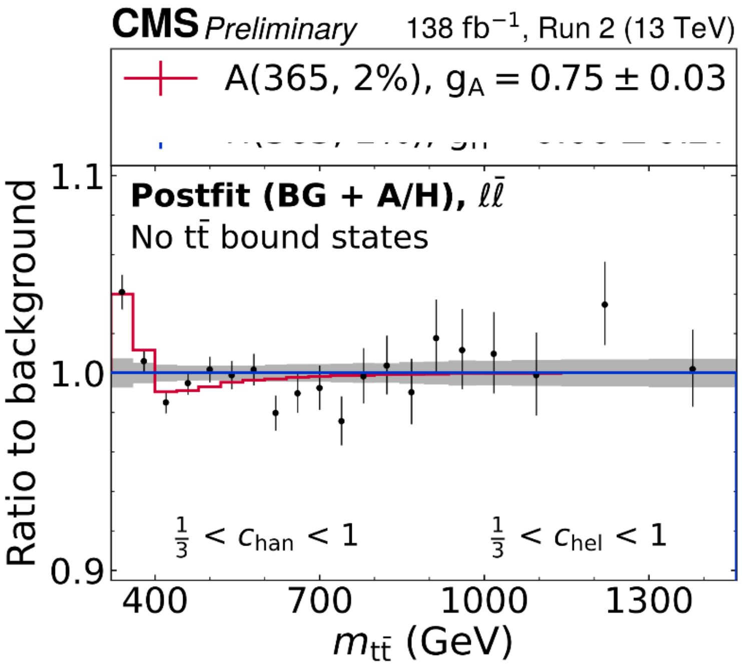
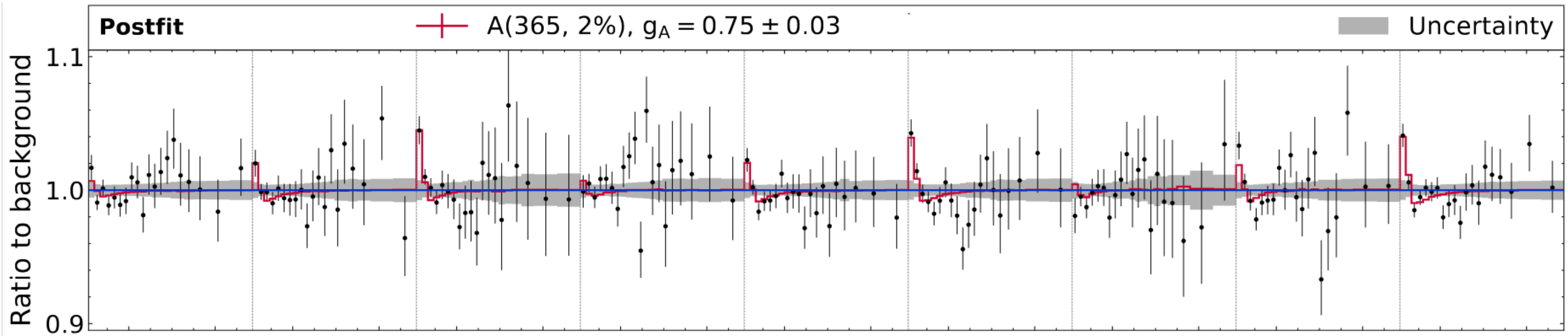




Was haben wir am CMS Experiment gesehen?







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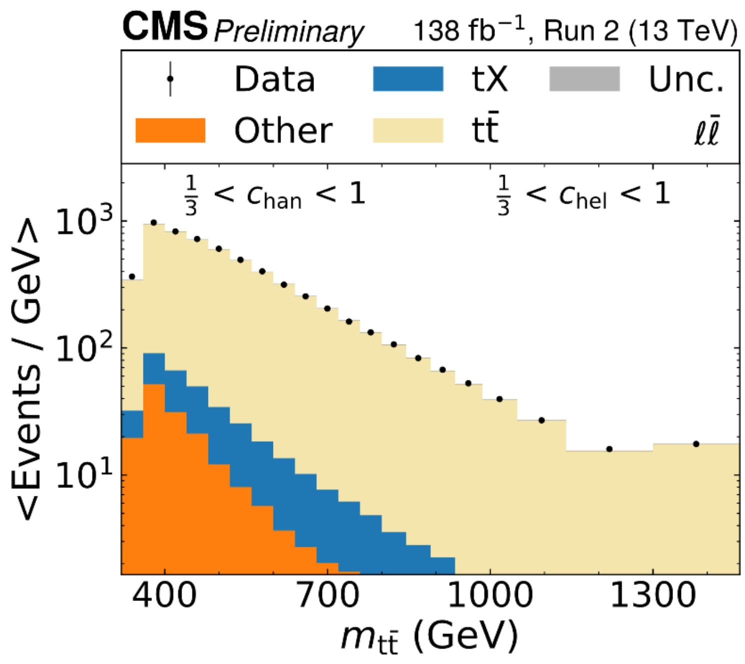
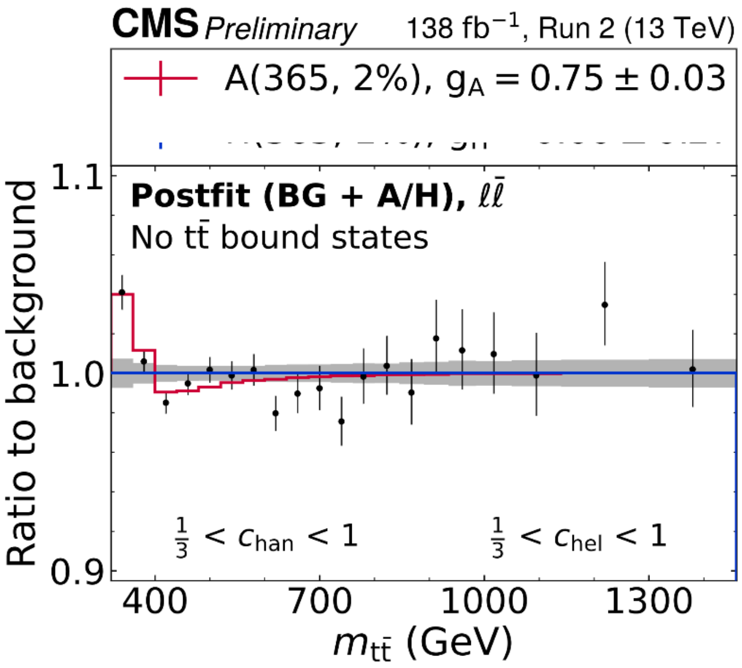
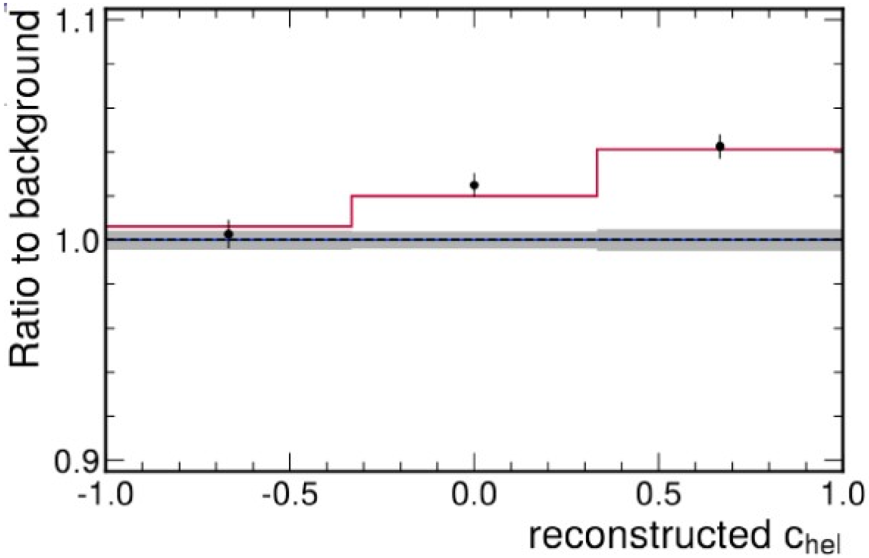
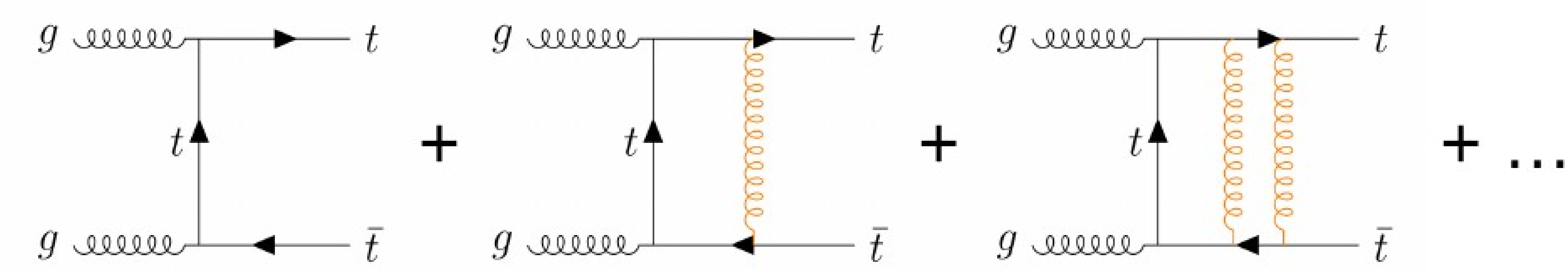




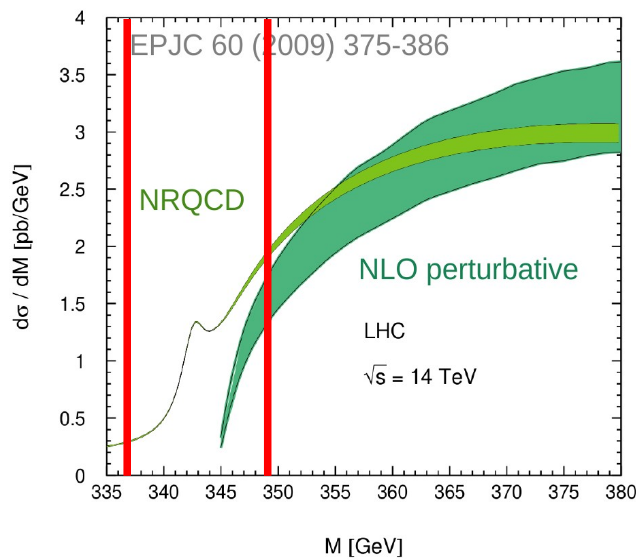


Alternative Unbekannte – Gebundene Top Zustände

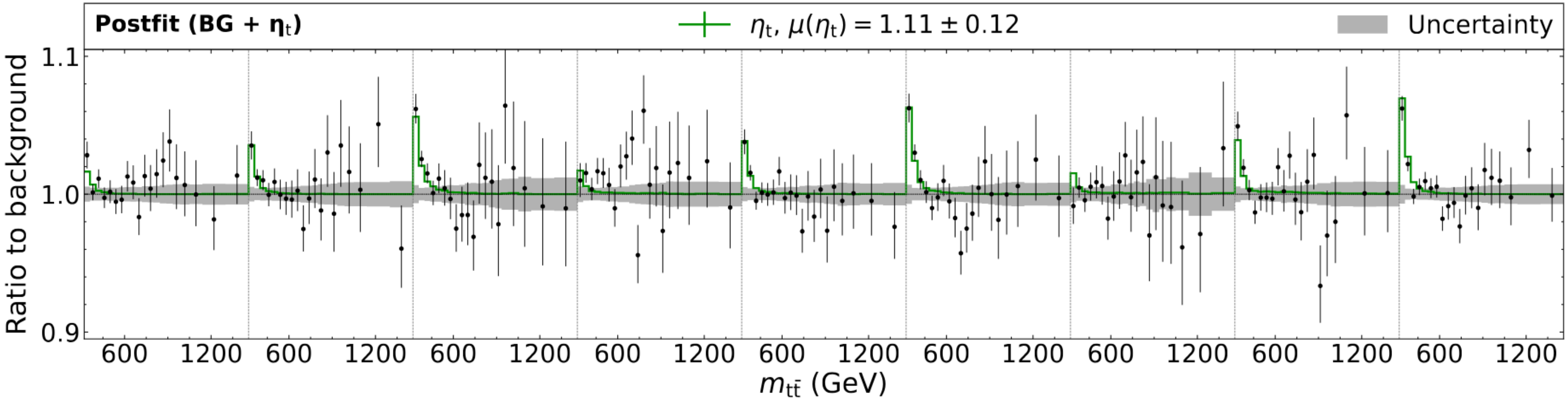
- Tops zerfallen zu schnell, um stabile, gebundene Zustände zu bilden $\mathcal{O}(10^{-25})$ s

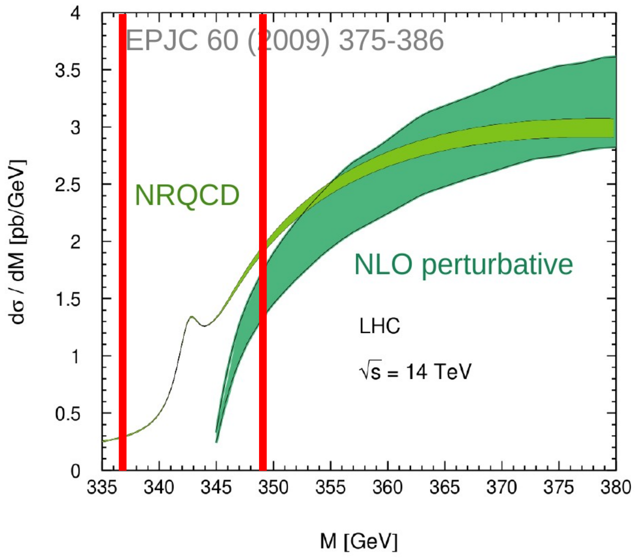


- aber: nicht relativistische Top Quarks tauschen Gluonen aus und wirken wie gebundene Zustände

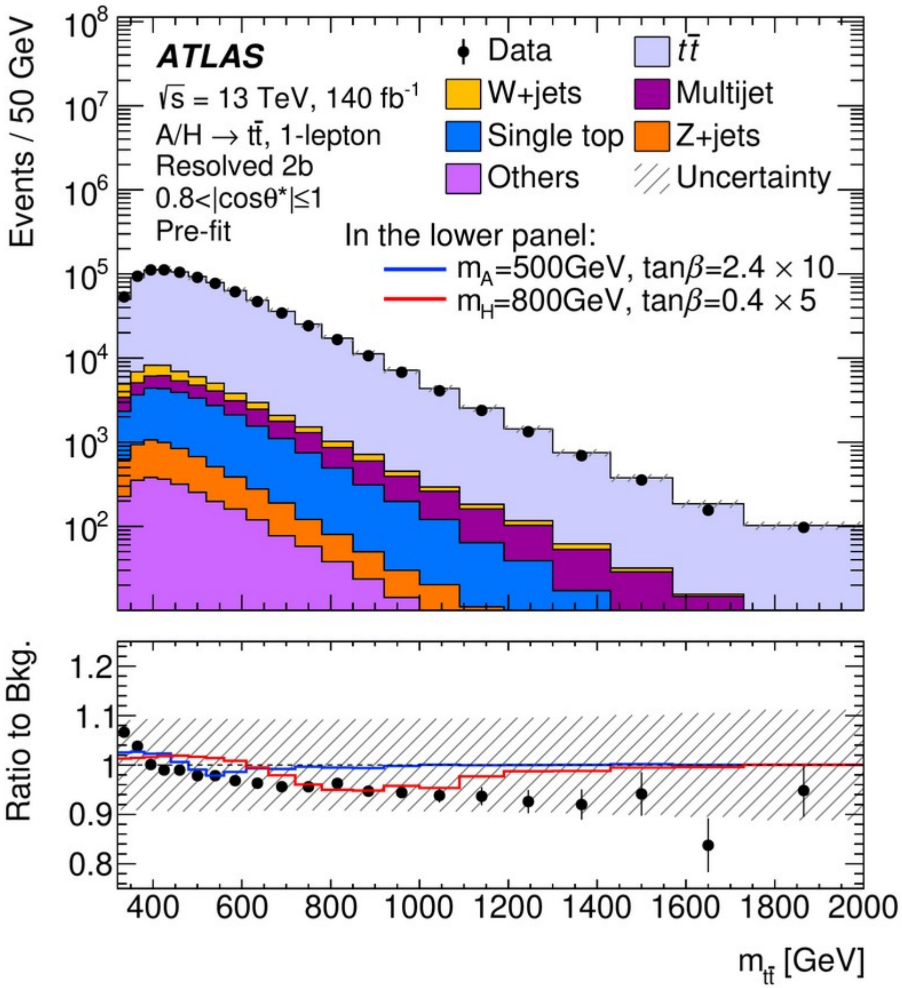


Alternative Unbekannte – Gebundene Top Zustände





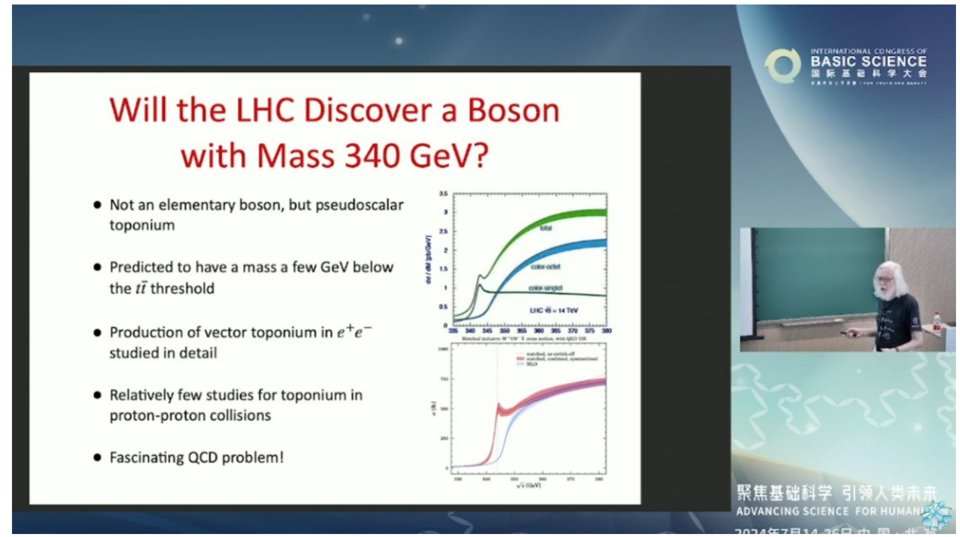
ATLAS EXPERIMENT



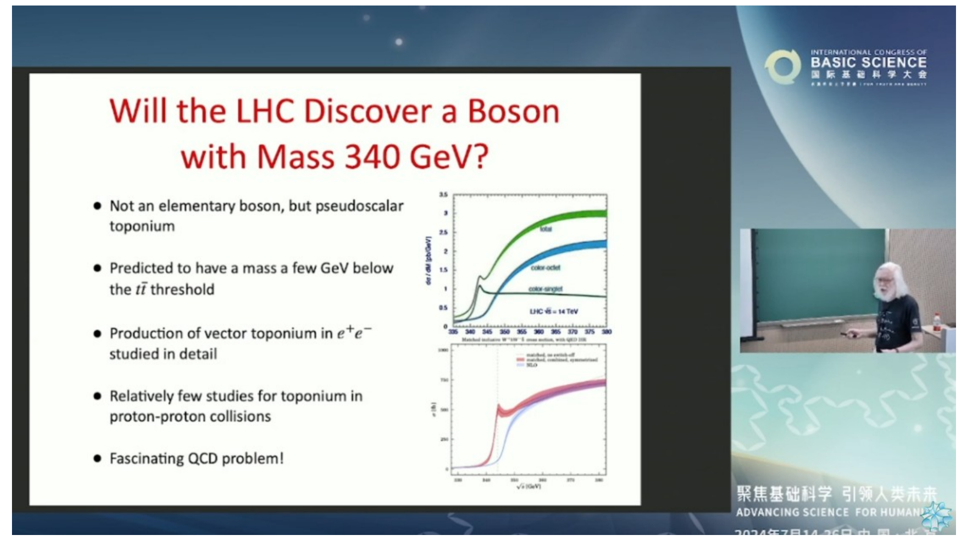
Abweichungen bei kleinen Massen – aber große systematische Fehler

Ein Blick in die Zukunft

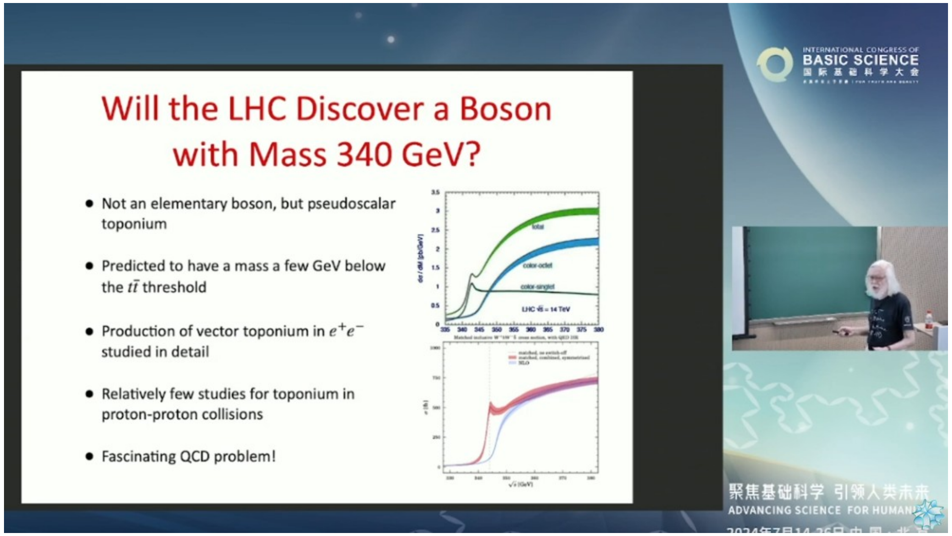
Ein Blick in die Zukunft



Ein Blick in die Zukunft



Ein Blick in die Zukunft

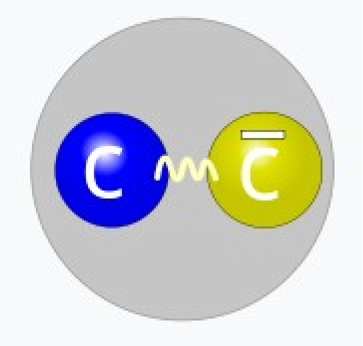


Back-Up

Gebundene Zustaende: J/Psi

mean lifetime of 7.2×10^{-21} s

$c\bar{c} \to 3\,g$	64.1% ± 1.0%
$c\bar{c} \to \gamma + 2\,g$	8.8% ± 1.1%
$c\bar{c} \to \gamma$	~25.5%
$\gamma \to$ hadrons	13.5% ± 0.3%
$\gamma \to e^+ + e^-$	5.971% ± 0.032%
$\gamma \to \mu^+ + \mu^-$	5.961% ± 0.033%



"**November Revolution**".

1976 Nobel Prize in Physics.

CMS/LHC

CMS Experiment (Compact Muon Solenoid)

1. **Weight:**
   The CMS detector weighs approximately **14,000 tonnes**, equivalent to the weight of **2,000 elephants**.
2. **Size:**
   It is **21 meters long**, **15 meters wide**, and **15 meters high**, about the size of a **five-story building**.
3. **Magnet Strength:**
   The solenoid magnet in CMS produces a magnetic field of **4 Tesla**, about **100,000 times stronger** than Earth's magnetic field.
4. **Data Generation:**
   During collisions, CMS generates around **40 million events per second**, which is reduced to **1,000 events per second** for detailed analysis after filtering.
5. **Silicon Tracker:**
   The CMS silicon tracker has **75 million detection elements**, making it one of the most sophisticated trackers in the world.
6. **Number of Contributors:**
   CMS involves over **4,000 scientists, engineers, and students** from **more than 200 instituti** across **over 50 countries**.
7. **Material Usage:**
   The detector uses **12,000 tonnes of steel**, enough to construct about **30 Eiffel Towers**!
8. **Cooling System:**
   The detector is kept at **-20°C** to ensure ↓ silicon sensors operate correctly.

Large Hadron Collider (LHC)

1. **Circumference:**
   The LHC is a circular particle accelerator with a circumference of **27 kilometers (17 miles)**, located **100 meters underground** at the France-Switzerland border.
2. **Energy:**
   It accelerates protons to an energy of **6.5 TeV (teraelectronvolts)** per beam, resulting in collision energies of **13 TeV**, making it the world's most powerful collider.
3. **Speed of Particles:**
   Protons in the LHC travel at **99.9999991%** of the speed of light, completing over **11,000 laps per second**.
4. **Dipole Magnets:**
   The LHC uses **1,232 dipole magnets**, each **15 meters long**, to bend the beams around its circular path.
5. **Cooling System:**
   The LHC operates at **-271.3°C**, colder than outer space, using **120 tonnes of liquid helium** to maintain superconductivity in its magnets.
6. **Vacuum Pressure:**
   The beam pipes are maintained at a vacuum pressure of **10^-13 atmospheres**, lower than the pressure on the Moon's surface.
7. **Data Production:**
   The LHC generates about **30 petabytes of data** annually, enough to fill around **43,000 standard DVDs every year**.
8. **Protons Per Beam:**
   Each beam contains **~2,800 bunches**, with each bunch holding **~100 billion protons**, resulting in nearly **600 million collisions per second**.
9. **Electric Power Usage:**
   The LHC consumes approximately **120 megawatts** of electricity, roughly the same as **120,000 households**.
10. **Budget:**
    The total construction cost of the LHC was approximately **€4.6 billion**, spread over a decade.