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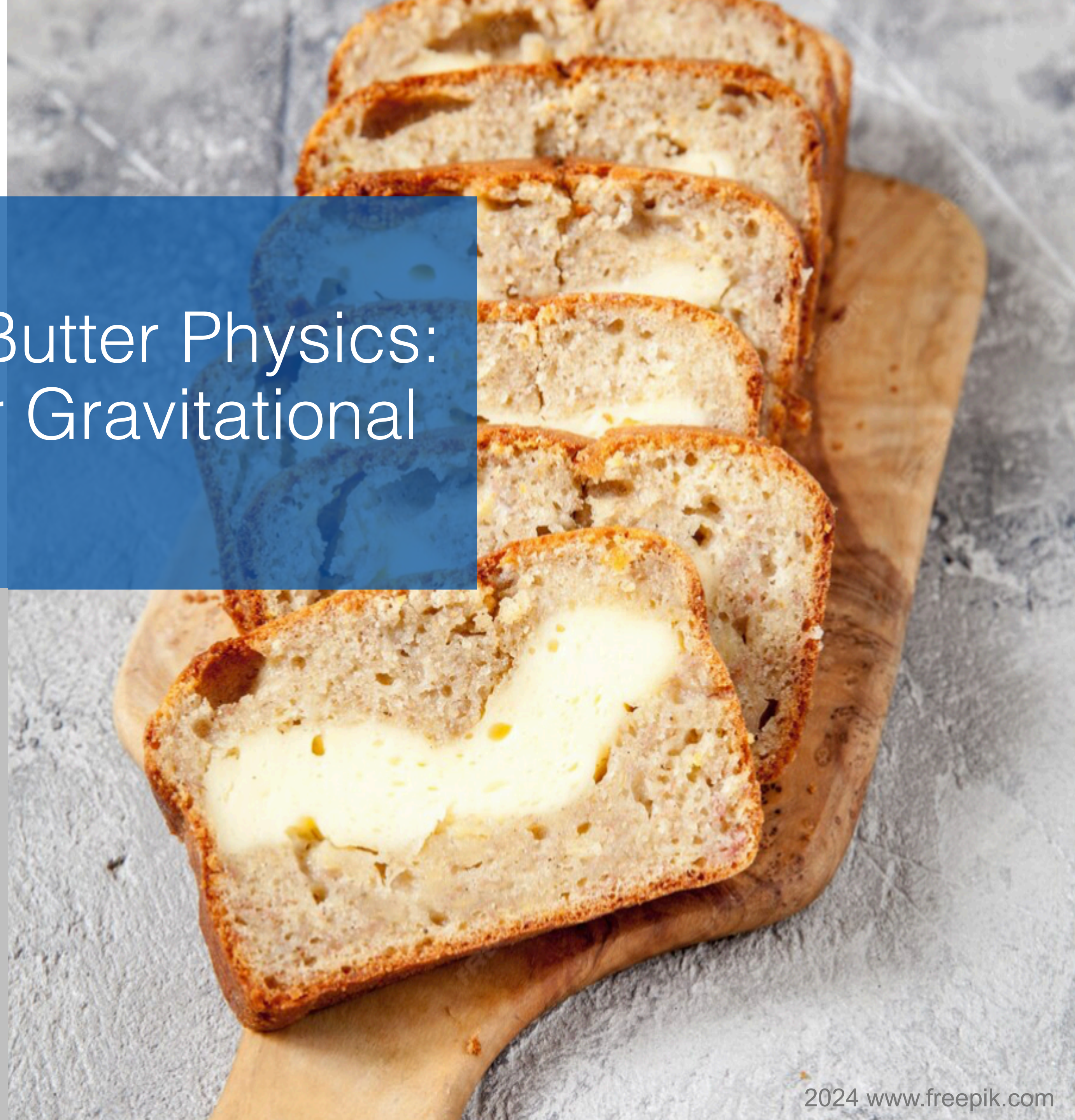
Matthias Schott

Bread and Butter Physics: Neutrinos or Gravitational Waves



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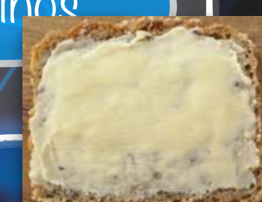
Two Options

Gravitational Waves

- Black Holes
- Axions
- High Frequency GW
- Global Detector Networks

Neutrinos

- What are neutrinos?
- The FASER Experiment
- Dark Photons
- Anti-Tau Neutrinos



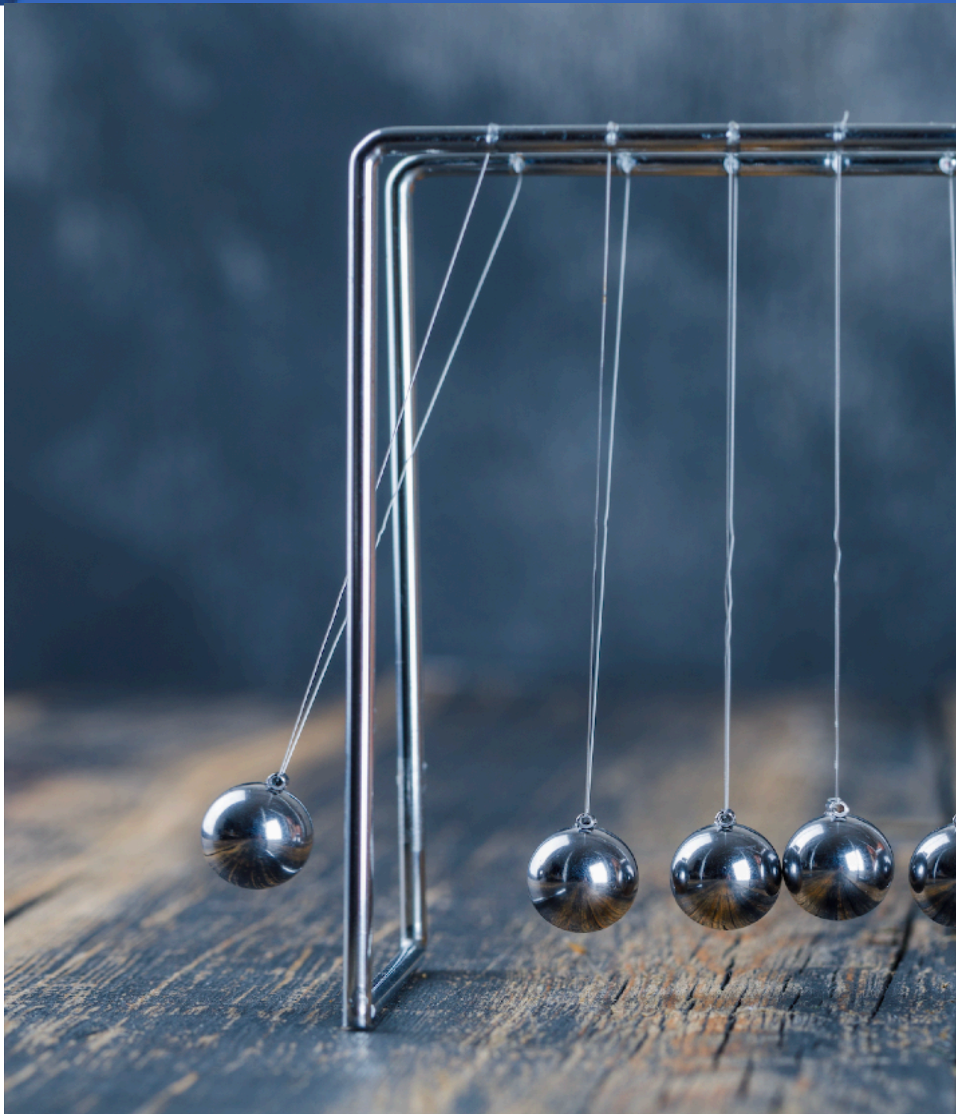
Matthias Schott

Going Forward: Neutrinos at the Large Hadron Collider

Butter bread and Newton

Predictions

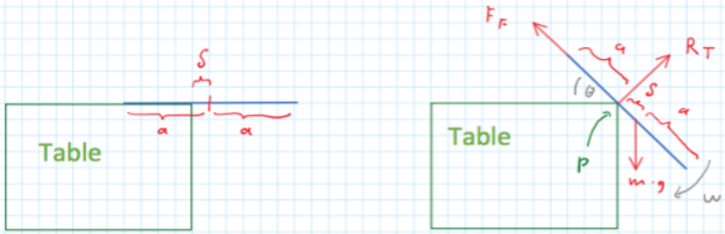
- Newton was the first person to realize that nature can be described by mathematics
- Very few basic assumptions and laws allow a multitude of correct predictions
- Newton's ideas explain not only mechanics, but also gravity
  - (at least until Einstein came on the scene)
  - However, basic considerations of mechanics still apply today



Mechanics of Toast

Toast: homogeneous rectangular lamina with mass m

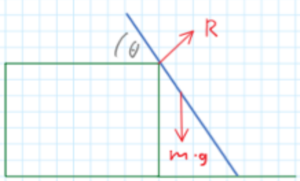
Starting point: Overhanging toast with zero horizontal velocity



Frictional force F_F prevents sliding

- Consider turning lamina around fixed axis

Consider stable position



$$0 = R - m g \cos\theta$$

When toast is falling: additional acceleration in direction of R_T

$$m\cdot a = m\cdot\dot{v} = m\,\delta\,\omega$$

$\llcorner\; v = r\cdot\omega$

$$\Rightarrow \quad (1) \quad m\cdot\delta\cdot\omega = R_T - m\cdot g\cdot\cos\theta$$

Consider centrifugal force (opposite to FF)

$$F_Z = m\frac{v^2}{r} = m\frac{r^2\omega^2}{r} = m\,\delta\,\omega^2$$

Not forget the component of the gravitational force

$$F_G = m\cdot g\cdot\sin\theta$$

$$F_Z + F_G = F_F$$

$$\Rightarrow \quad (2) \quad m\,\delta\,\omega^2 = F_F - m\cdot g\cdot\sin\theta$$

Last missing piece: Torque (Drehmoment)

$$M = J\cdot\dot{\omega} \qquad (\hat{=}\; F = m\cdot a)$$

$\llcorner$ Moment of Inertia

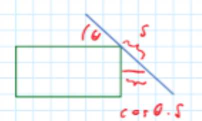
$$J_{Toast} = \int_V r_\perp^2\,\rho(\bar{r})\,dV = \underbrace{\int r^2\,dm}_{\text{for const. mass}} = \int_{-a}^{a} r^2\frac{m}{2a}\,dr = \frac{1}{12}m(2a)^2 = \frac{m a^2}{3}$$

Steiners Theorem: Moment of inertia for parallel shifts of rotation axis

$$J = J_{old} + m d^2$$

$$\Rightarrow \quad J = \frac{m a^2}{3} + m\,\delta^2 = m\,(a^3$$

What is the lever-force?



$$- m g \delta \cos\theta$$

Mechanics of Toast

Torque and lever force

$$m\left(\frac{a^2}{3}+\delta^2\right)\dot{\omega} = -mg\delta\cos\theta \qquad (3)$$

We can derive a relation between ω and θ

$(3)\cdot 2\omega$

$$2\omega\left(\frac{a^2}{3}+\delta^2\right)\dot{\omega} + 2\omega g\delta\cos\theta = 0$$

$$2\dot{\theta}\left(\frac{a^2}{3}+\delta^2\right)\ddot{\theta} + 2\dot{\theta} g\delta\cos\theta = 0 \qquad \Big| \int \text{ with } \theta=\dot{\theta}=0$$

$$\left(\frac{a^2}{3}+\delta^2\right)\dot{\theta}^2 + 2g\delta\sin\theta = 0$$

$$\Rightarrow \omega^2 = \frac{2g\delta}{\frac{a^2}{3}+\delta^2}\sin\theta$$

Introduce overhanging parameter

$$\delta := \eta a \qquad (0<\eta\le 1)$$

Central Toast Formula

$$\omega^2 = \frac{6g}{a}\cdot\frac{\eta}{1+3\eta^2}\sin\theta \qquad (4)$$

(4) gives the angle velocity once the toast is detached. If the velocity is large enough, the toast will rotate more than 3π/2-ϕ, i.e. lands for sure on the jam-side up

↑ angle at detachment $\phi=\theta_0$

$$\Rightarrow \text{jam-up condition: } \omega_0\tau > \frac{3\pi}{2}-\phi \qquad (5)$$

$$\text{with } \tau=\sqrt{\frac{2(h-2a)}{g}} \qquad (6) \qquad \left(g=\ddot{x} \Rightarrow \tfrac{1}{2}gt^2 = x = h-2a\right)$$

What is the angle at which the sliding occurs?

- Force down must be larger than friction force

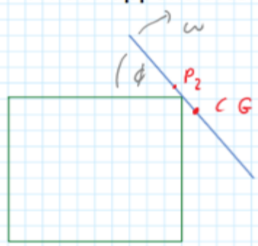
$$F=\mu R$$

From (1), (2), (4) follows

$$\phi > \arctan\left[\frac{\mu}{1+9\eta^2}\right]$$

my own calculation $\phi > \arctan\left(\frac{\mu(1+3\eta^2)}{1+9\eta^2}\right)$

What is the free-falling angular rotation rate ω_0 ?
- What happens after sliding?



$P_2 \hat{=} (G - a(\eta+\varepsilon))$

slightly non overhanging

P_2 has rotationally-induced horizontal velocity component

$a\cdot\varepsilon\cdot\omega\cdot\sin\phi$

Sliding brings this point over the table => detachment

P_2 is essentially unchanged from initial conditions

- Free falling rotation rate is given by

$$\omega_0^2 = \frac{6g}{a}\left[\frac{\eta_0}{1+3\eta_0^2}\right]\sin\phi \qquad (8)$$

Calculate lower limit of η_0 to avoid jam side down - set $\phi=\pi/2$ (highest rotation speed) use (5), (6) and (8)

$$\eta_0 > \frac{1-\sqrt{1-12\alpha^2}}{\alpha^2} \qquad \text{with} \qquad \alpha = \frac{\pi^2}{12\left(\frac{h}{a}-2\right)}$$

Experiments!

- Any theory is worthless if it does not make correct predictions
- Experiments are an integral part of any natural science
- Sandwiches: The above derivation only applies to
  - rectangular sandwiches
  - slow sandwiches
  - in relatively thick slices
  - with relatively soft bread

Why Physics is so cool

- Start with very simple assumptions
- Formulate the most simplest theory that explains observation
- Test it with experiments
- Example: Emmy Noether
  - You want that the physics today is the same as yesterday?
    - You get Energy Conservation
  - You want that physics in Munich is the same as in Bonn?
    - You get Momentum Conservation

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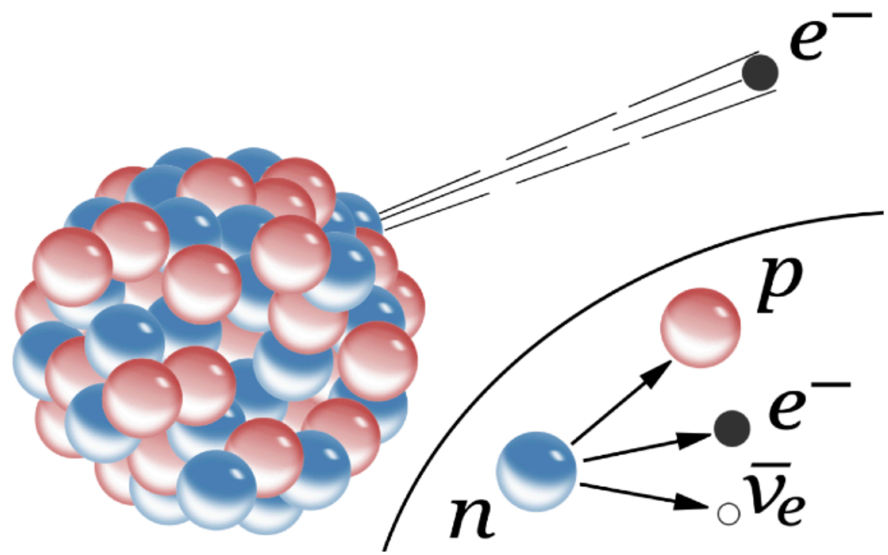
Neutrinos

Pauli's Idea

- Problem: Energy Conservation seems to be violated in the neutron decay



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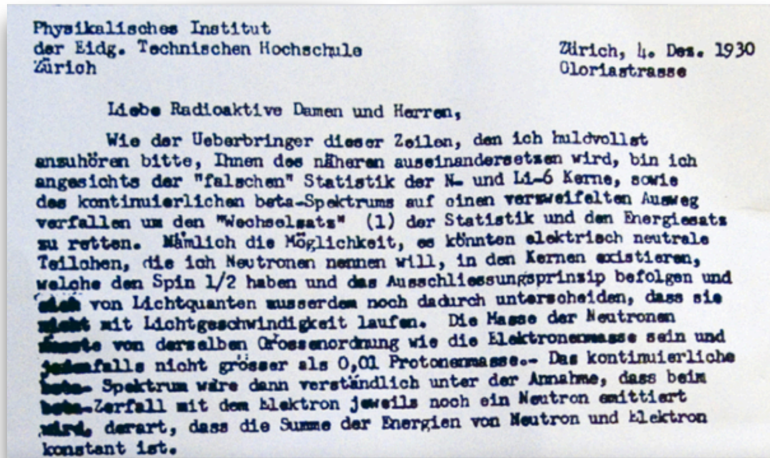


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

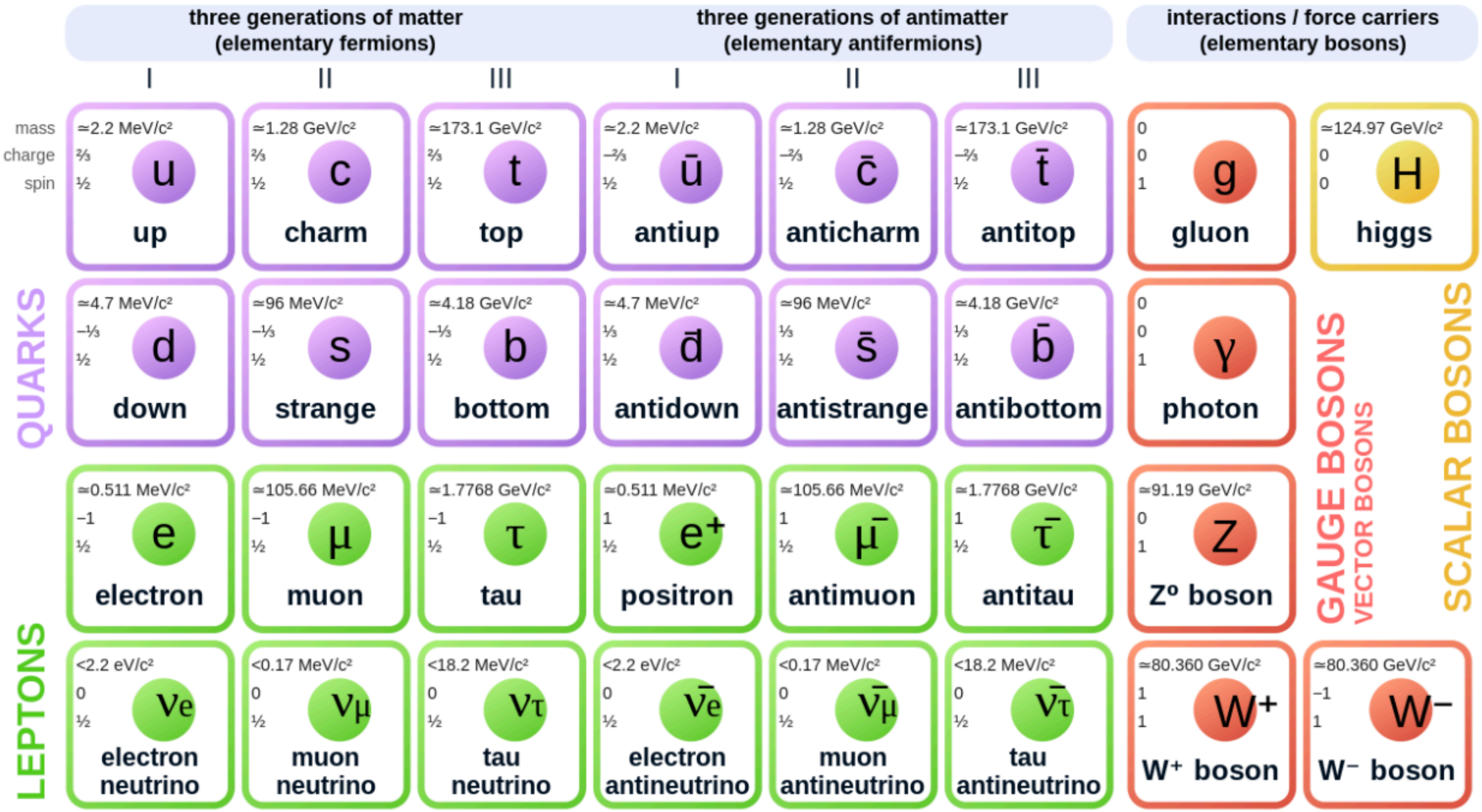
Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

- Pauli's idea: maybe there is a new particle involved, which one (nearly) cannot observe
  - The neutrino!

Particles of the Standard Model



Credit: 2024 Wikimedia

Have we discovered all particles?

- Discovery of the Higgs in 2012 is celebrated as the discovery of the last missing particle of the Standard Model
- So we are done…
- Not so fast: Never observed the reaction of an anti-tau neutrino
- Why?

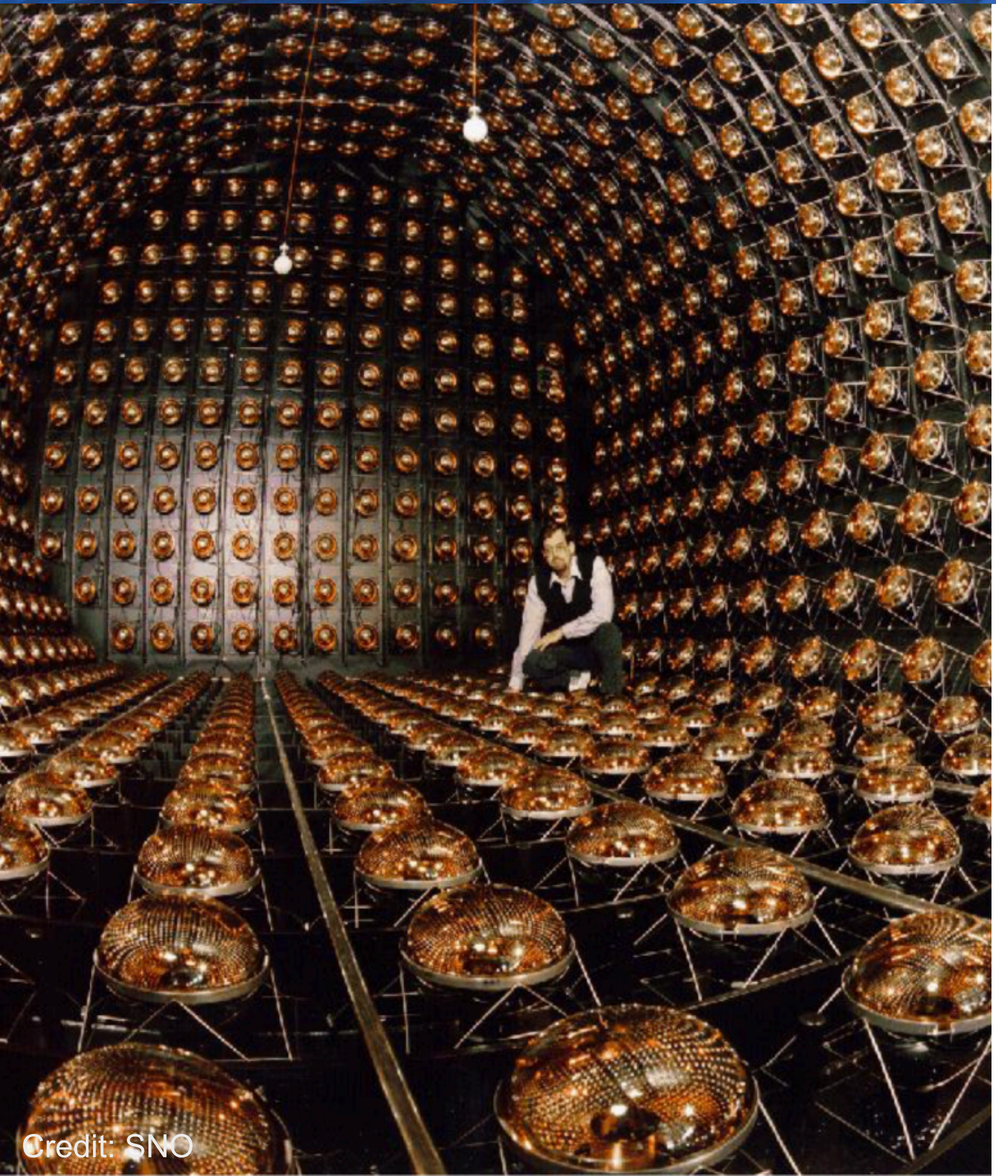
Why are Neutrinos special?

- Only particles which interact with other matter only via the weak interaction

- What does this imply?
  - Being a neutrino is a lonely business
  - Most neutrinos travel through the universe and never ever interact

- 1 out of 100,000,000,000 neutrinos interacts when crossing through earth

But they have a mass!



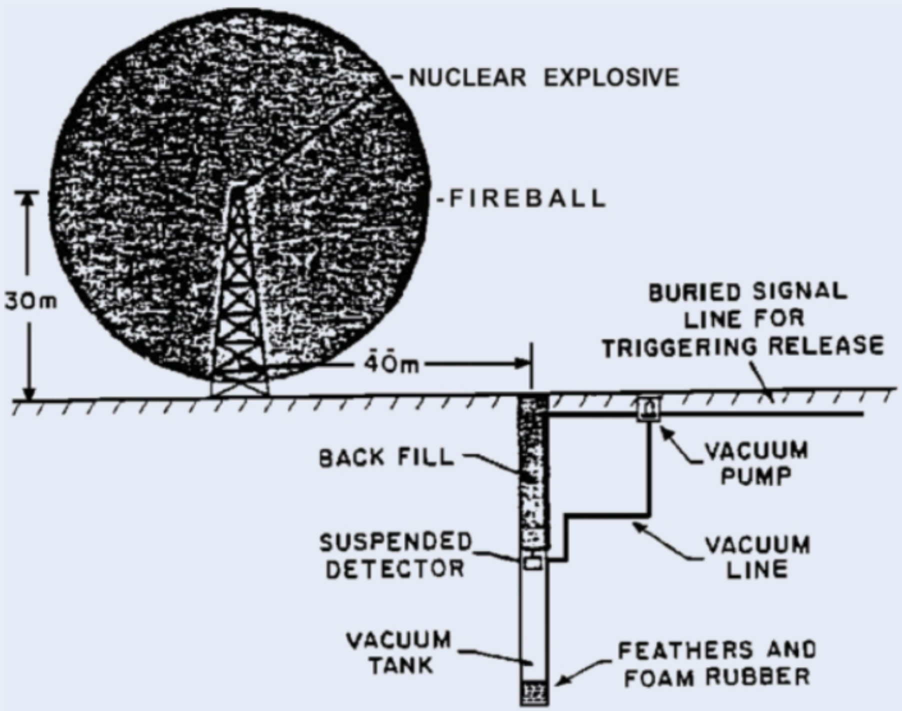
- 2001: Discovery of Neutrino Oszillation by Sudbury Neutrino Observatory
  - Nobelprize in 2015
- Long story short: Neutrino Oszillation can only happen if they have a mass
- Problem: The mathematics behind der Standard Model does not allow them to have a mass
  - There must be physics that we have not found so far

How to discover Neutrinos?

- Neutrinos interact only very little
  - we need many neutrinos to observe only a few

- One idea by Clyde Cowan and Frederick Reines: use a nuclear bomb
  - … was even approved

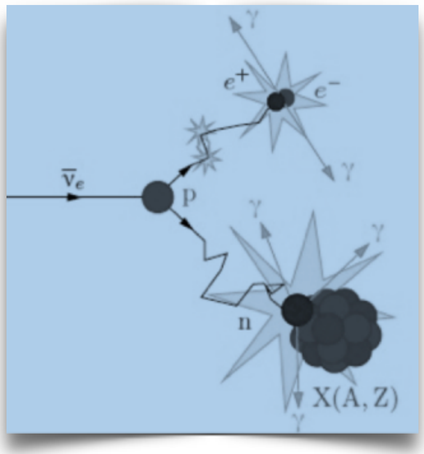
- Maybe there is a better way …



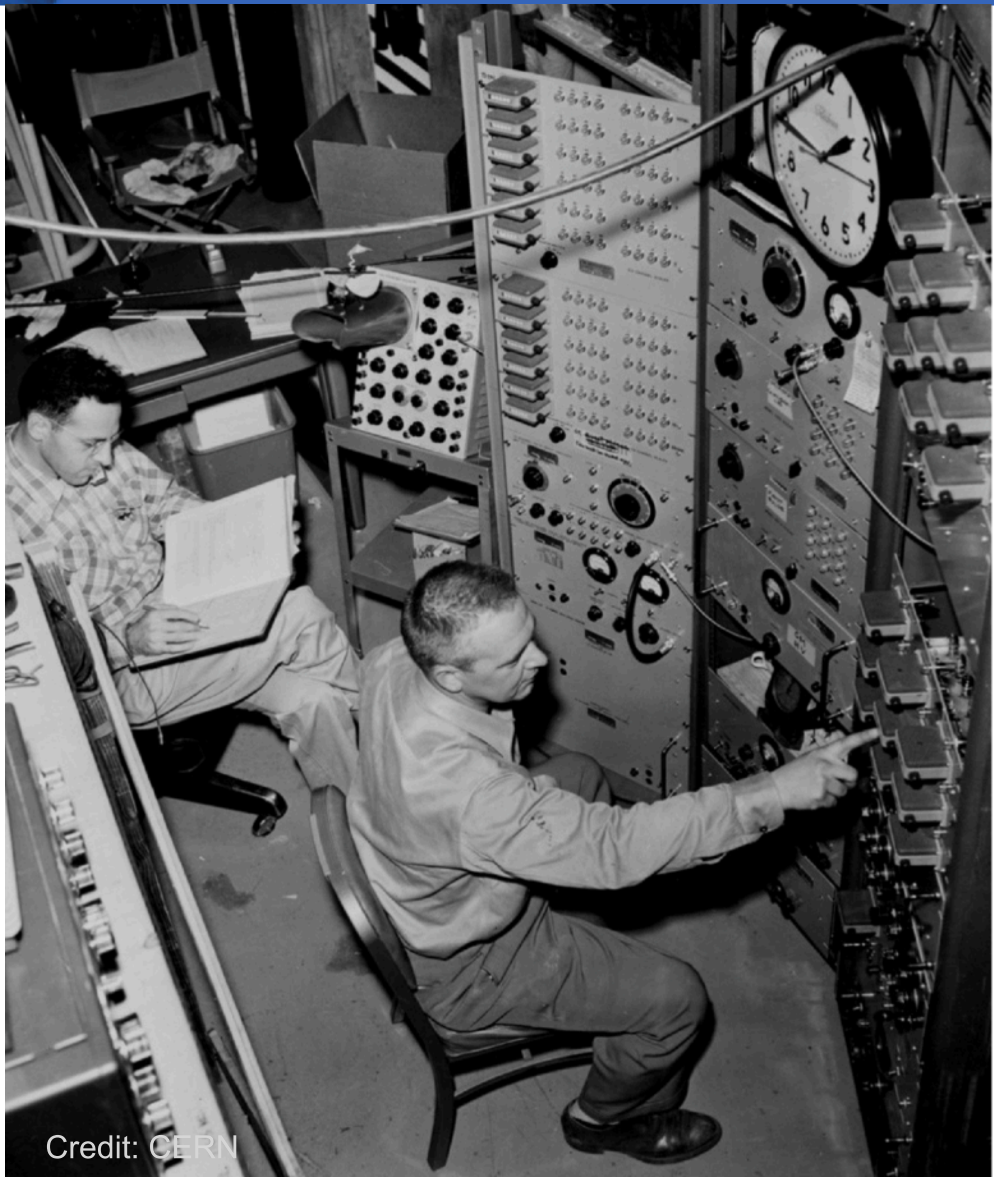
Credit: CERN

… and how was it done?

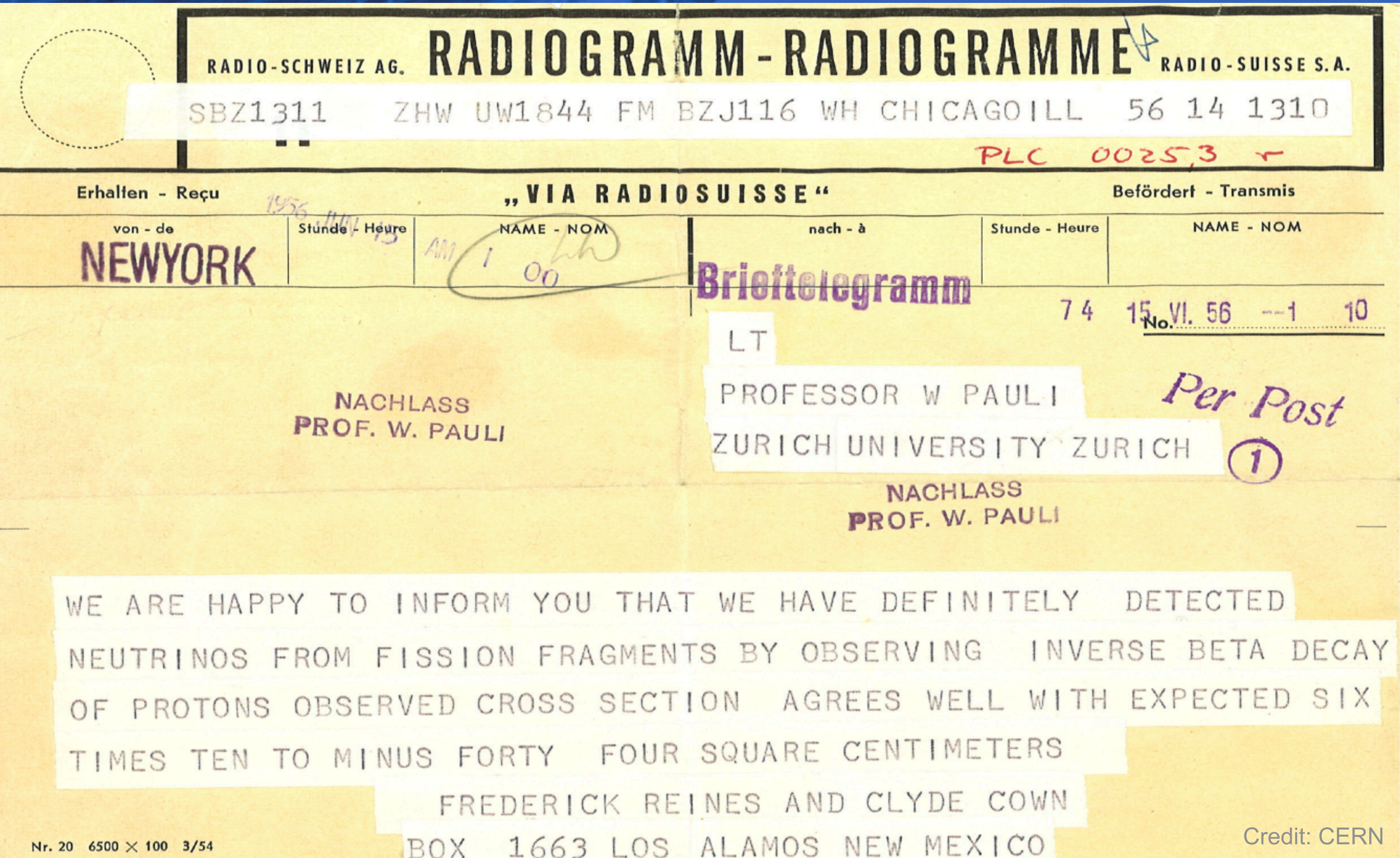
- Project Poltergeist
- Use a nuclear reactor
  - Constant stream of neutrinos



- Essentially look for the annihilation process of the positron and the electron
  - Two photons with a characteristic energy



Telegram to Pauli



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

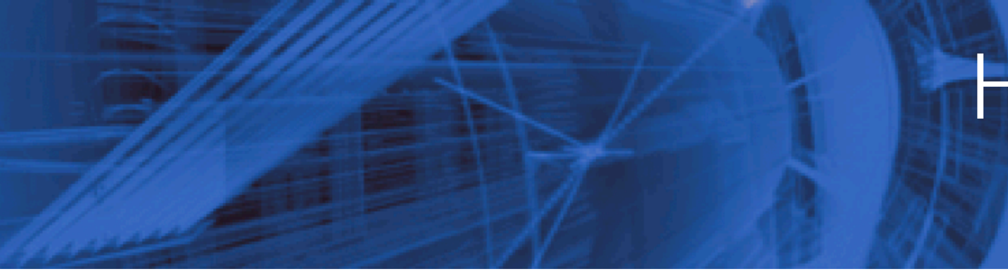
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

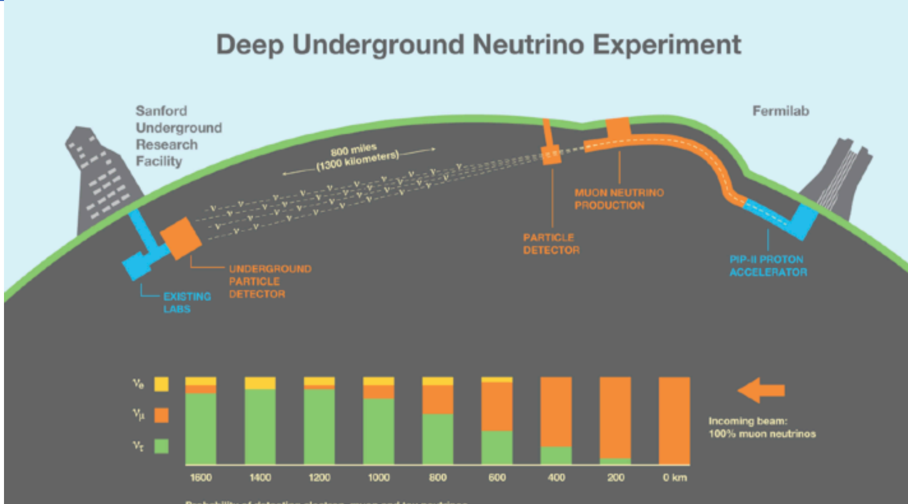
Nr. 20 6500 × 100 3/54

Credit: CERN



How to study neutrinos nowadays?

- Today: Study neutrinos from all kinds of different sources
  - Sun
  - Astrophysical / Cosmic Sources
  - Beam-Dump Experiments
  - Particle Colliders



Credit: Dune Collaboration

Credit: IceCube Collaboration

Credit: JUNO Collaboration

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Collider Physics

Some Coding

```python
import random

def get_random_number():
    return random.randint(0, 1000000)

# Generate a random number
random_number = get_random_number()
print(random_number)
```

```python
import StudentCode

def get_random_number():
    return StudentCode.GetNumber(0, 1000000)

# Generate a random number
random_number = get_random_number()
print(random_number)
```

```
>python3 Random.py

826179
```

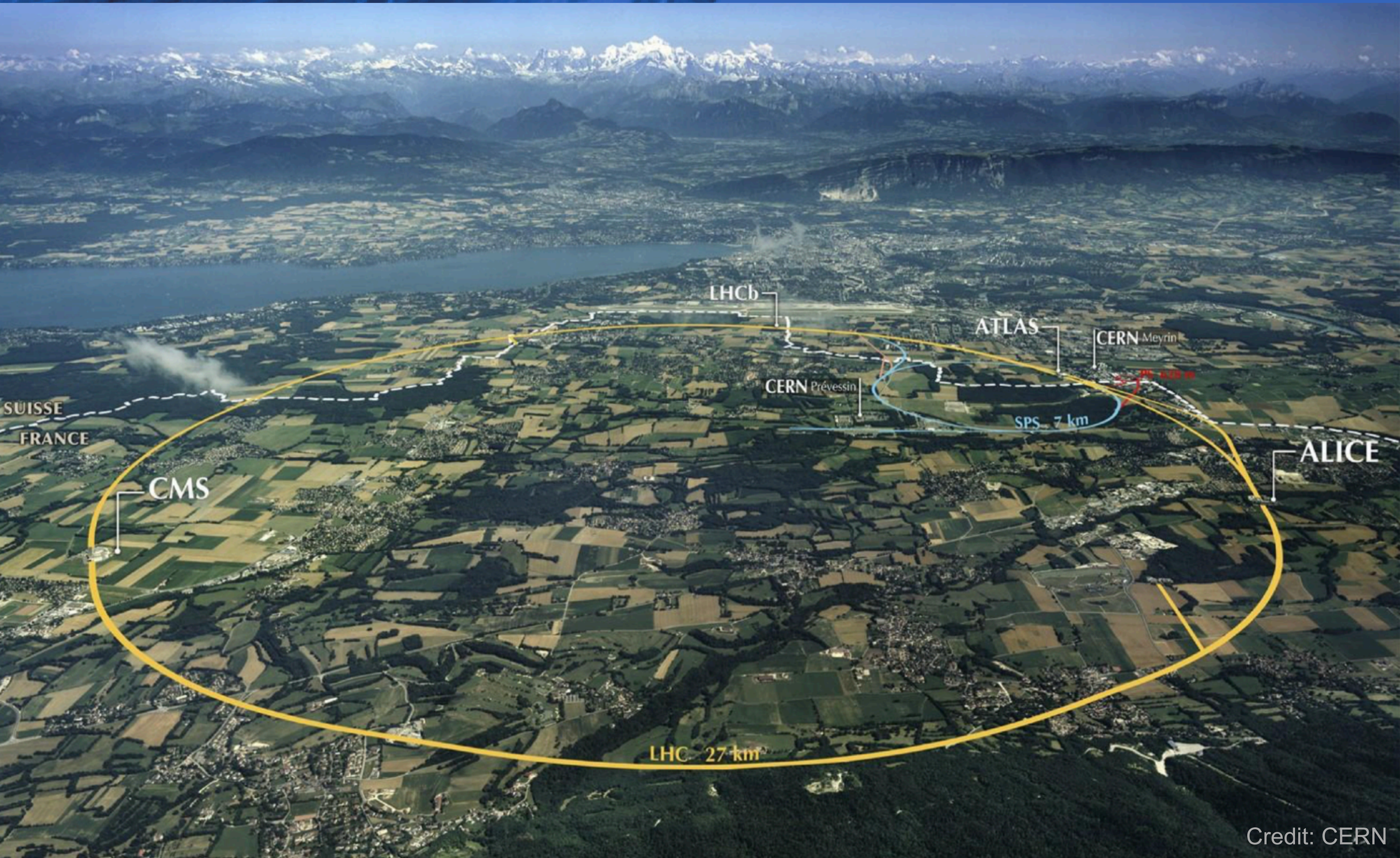
```
>python3 Random.py

0
```

Open Questions and Problems of the Standard Model

- Unanswered Questions
  - Why is there more matter than anti-matter?
  - Why are the particle masses varying over so many orders of magnitudes?
  - …
- Hard Evidences
  - Kinematic behavior of galaxies (Dark Matter?)
  - Expansion of the Universe (Dark Energy?)
- (More than) aesthetic problems
  - Higgs Boson Mass
  - Non-Existing Dipole Moment of the neutron

The Large Hadron Collider



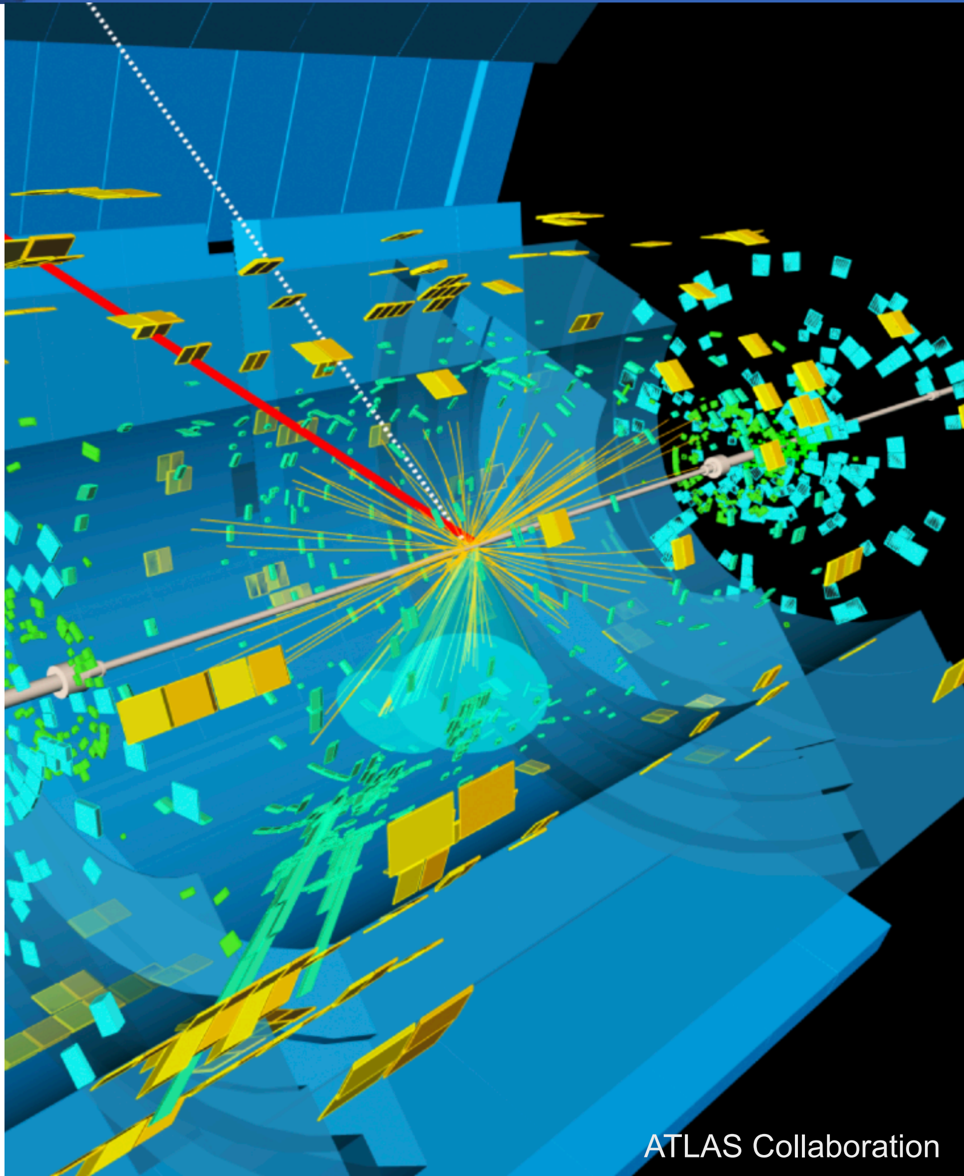
Credit: CERN

Physics Goals at the LHC

- Search for new particles, new interactions and new phenomena

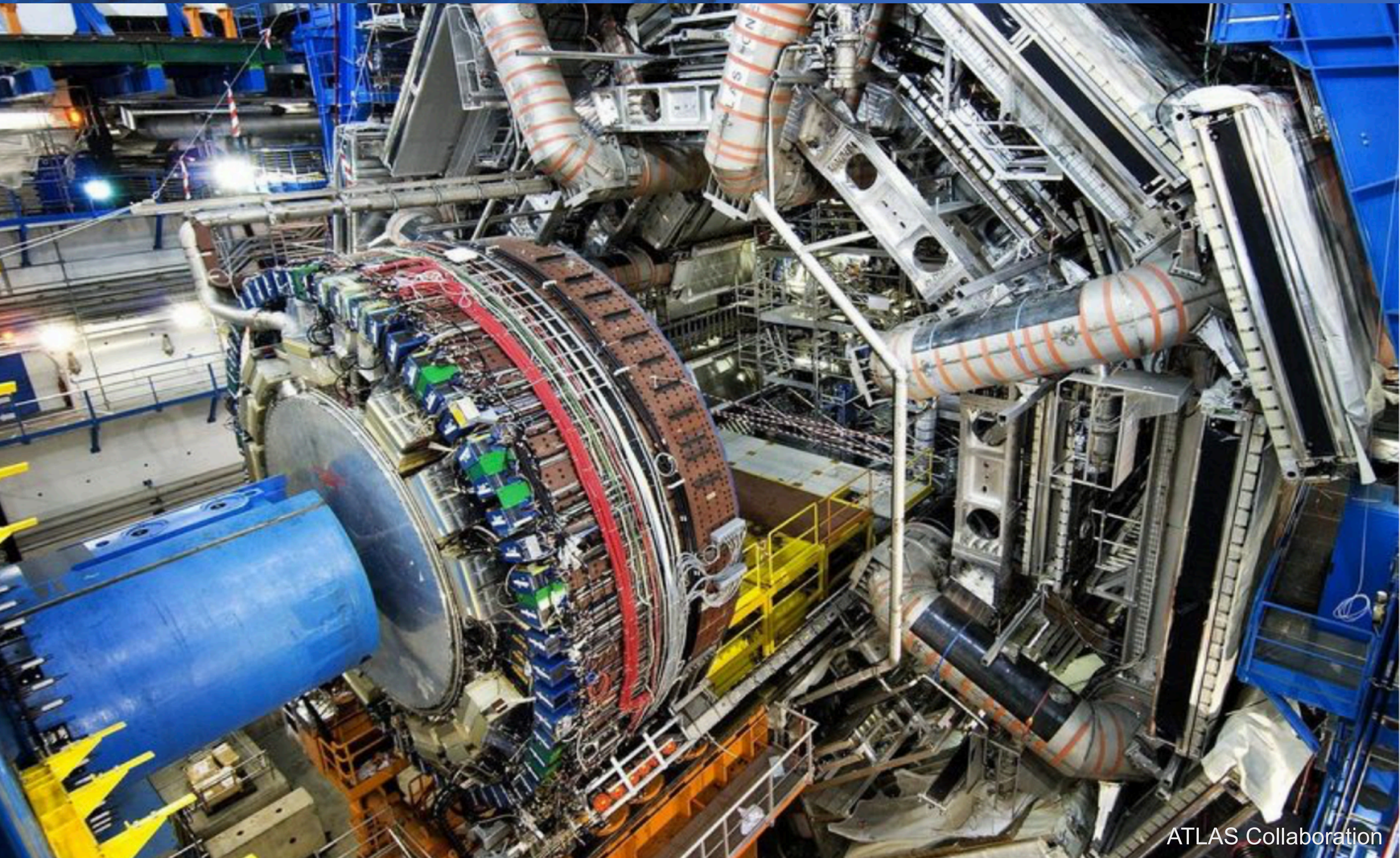
- Test the predictions of the Standard Model
  - Any deviation between measurement and prediction ~~is~~ could be new physics

- Experiments: Record the outcome of particle collisions at extremely high energies
  - $E=mc^2$: New particles should be created in those collisions



ATLAS Collaboration

The Experiments at the LHC

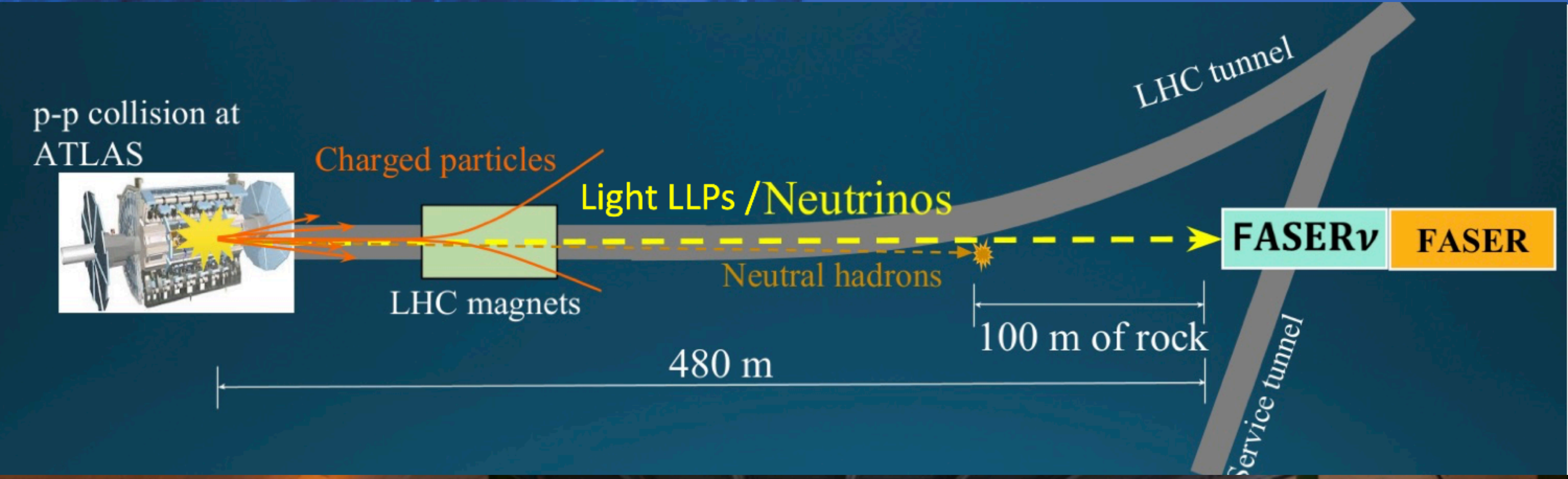


ATLAS Collaboration

Heavy vs. Light New Particles

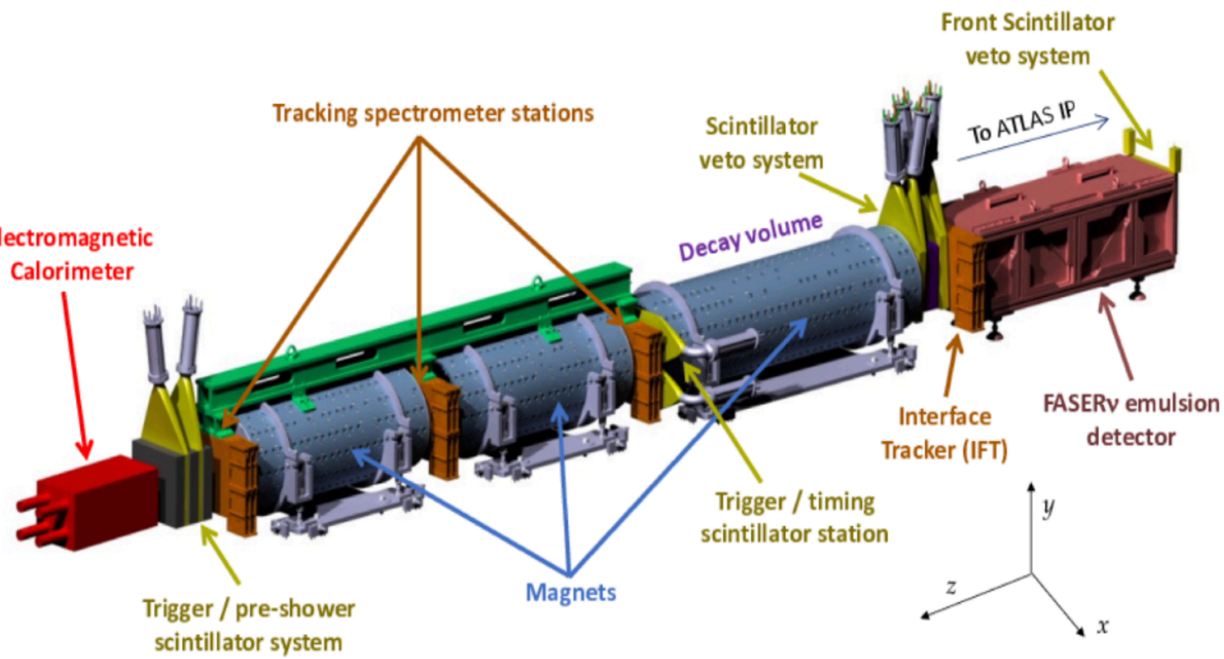
- General Feeling in the early 2000's
  - New physics will involve heavy particles
  - … Top-Quark is heavy
  - … Higgs Boson is heavy
- New Heavy particles will fly in all directions
  - Try to build detector as much as possible around the beam pipe
- Light particles will fly dominantly in the forward direction
  - There are no detectors, since there is the beam pipe for the protons

… and then came FASER



What's the idea of FASER?

- Detector for charged particles in the beginning, to veto „ordinary" stuff
- Decay Volume: Essentially nothing
- Magnet System to separate charge particles
- Tracking Station to measure momenta
- Calorimeter to measure energies of photons and electrons



Who pays for it?

- 1st funding rule in science
  - New ideas are always great if they don't cost anything
- Idea: Reuse as much as possible left-over / spare sub detectors of other experiments
  - Tracking from ATLAS
  - Calorimeter from LHCb
- Still need money: Wallstreet!
  - Heising and Simons
- 2nd funding rule in science
  - Once there is money on the table, others might put some money on top

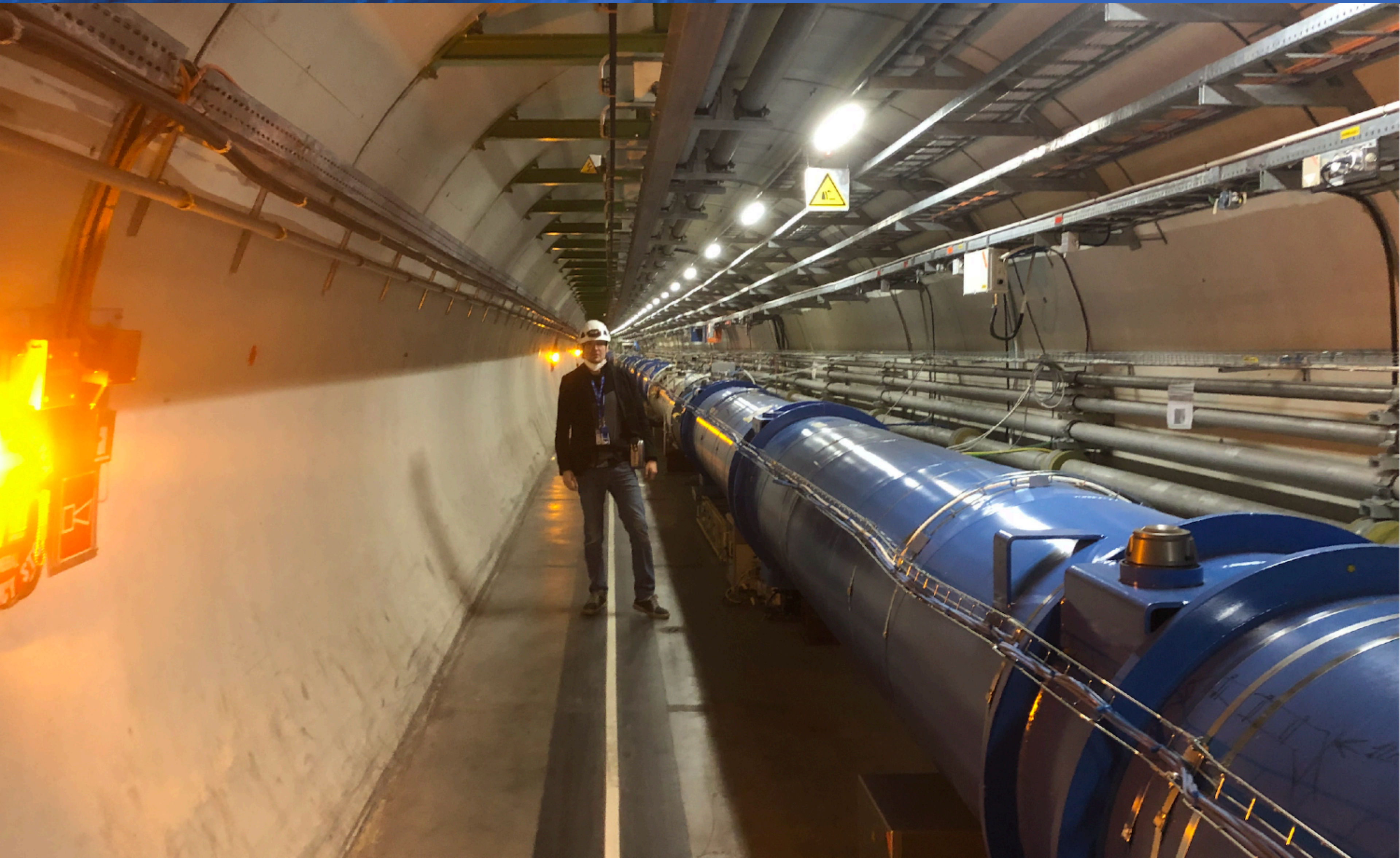
Credit: CERN

Installation of FASER

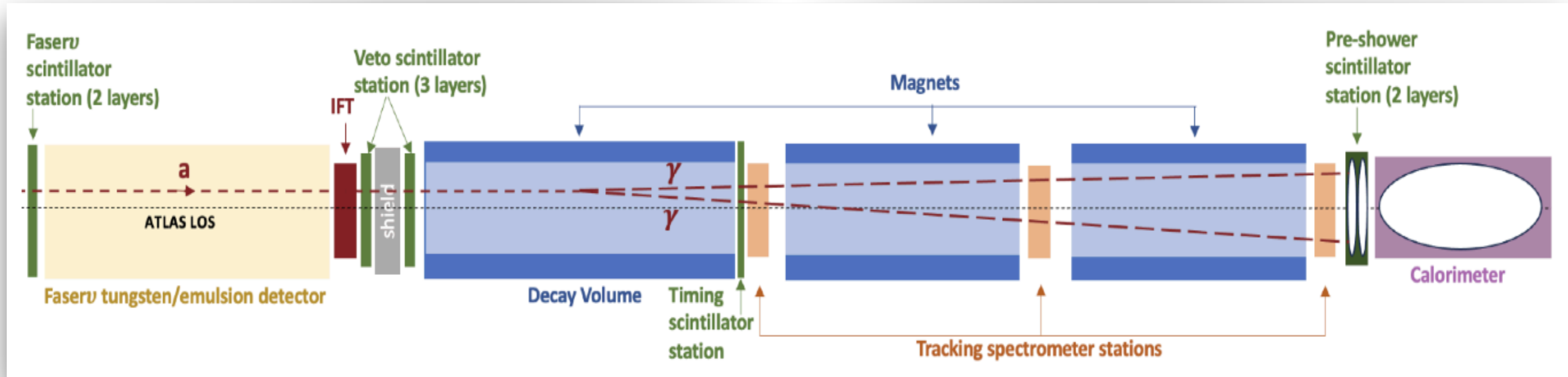
Installation of FASER

FASER Collaboration

The LHC Tunnel



Physics Program at FASER



- Search for light and long lived particles
- Dark Photons
  - just a signature in the calorimeter and in the tracking system
- Axion-Like Particles
  - just a signature in the calorimeter
- Dominant Background, that might fake our signal
  - Neutrinos!

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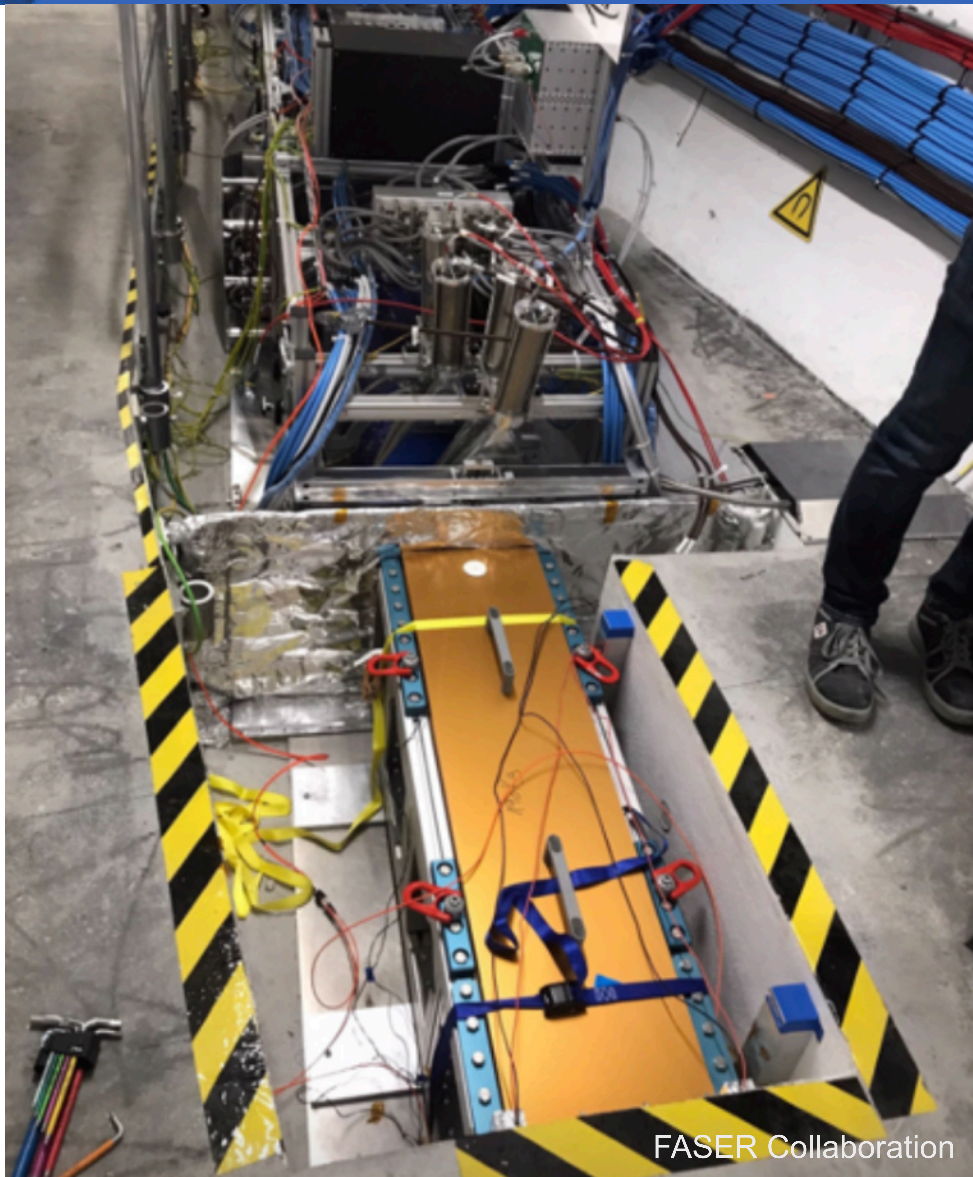
Discovery of Neutrinos at Colliders

Neutrinos at FASER!

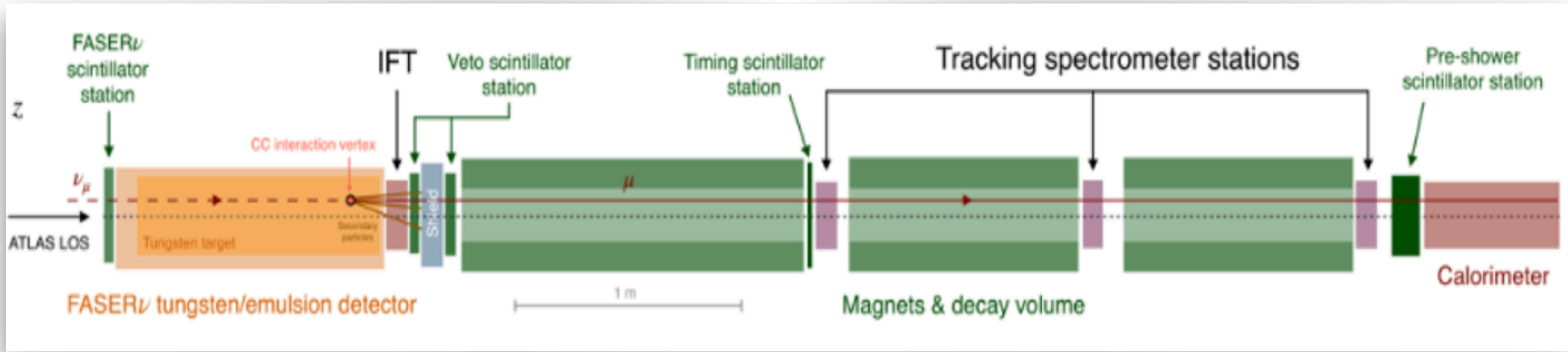
- 600 million proton-proton collisions at the LHC per second
  - Electron, Muon and Tau Neutrinos are produced in all collisions
  - Huge flux of neutrinos

- Just need some „heavy stuff“ in front of FASER, where neutrinos might interact
  - Tungsten!



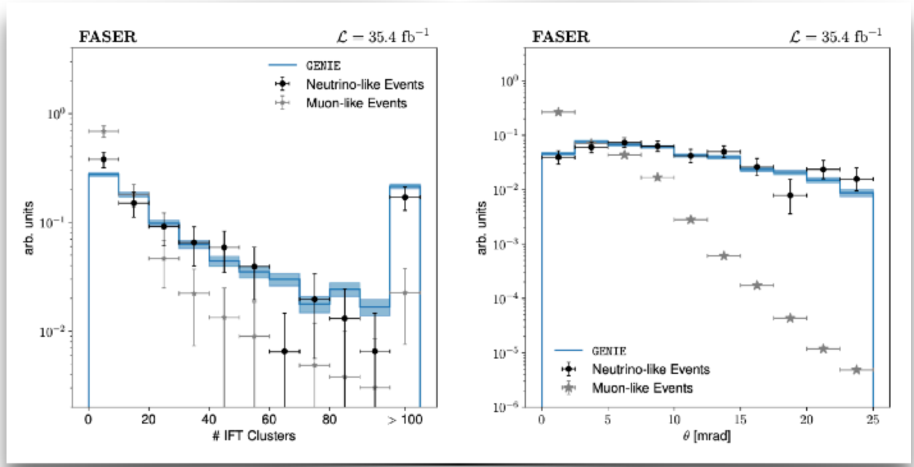
FASER Collaboration

First observation of collider neutrinos

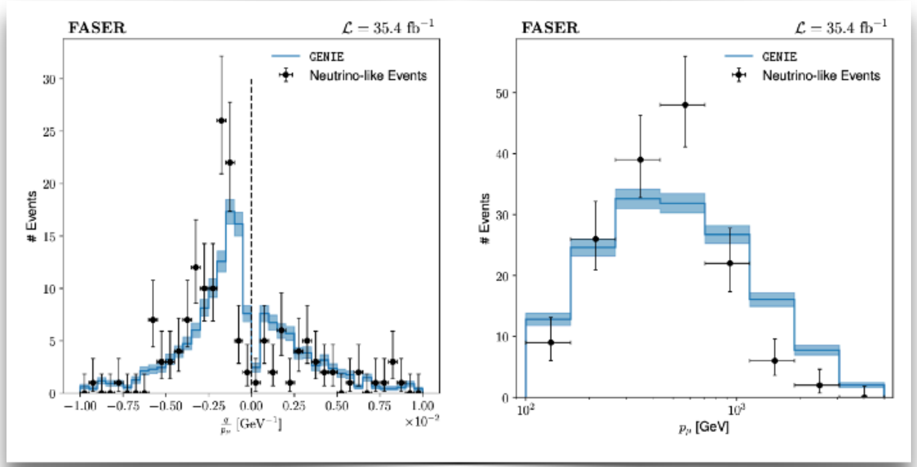


- Search for muon-neutrino interactions
  - muon-neutrino hits a nucleon within tungsten and transforms into one muon and one electron neutrino
- Super simple cut-and-count analysis
  - No signal in the front of FASER, but then tracks appearing „out of nothing"

Why is that cool?

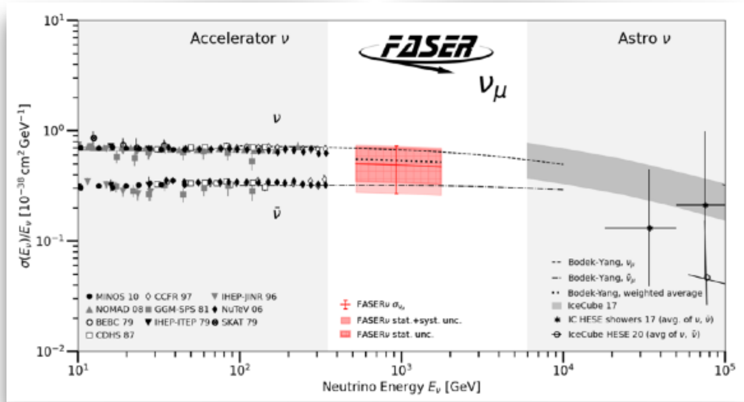


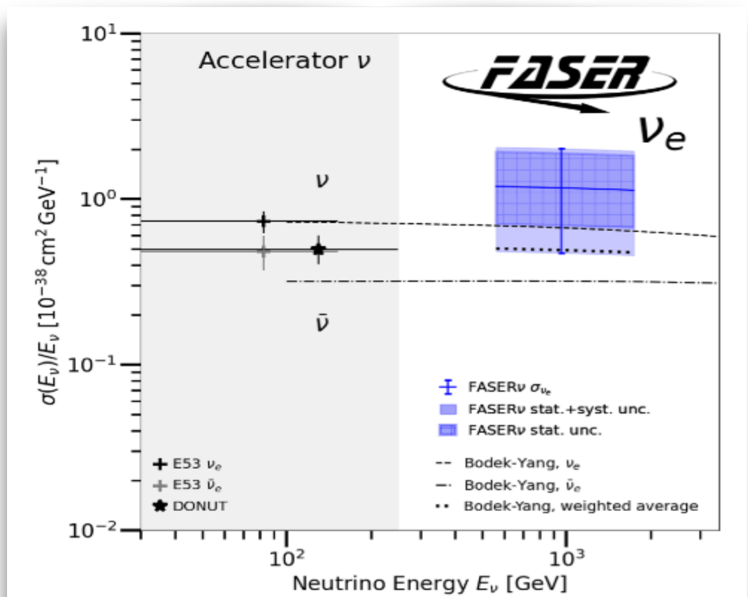
- We have observed neutrinos from
  - Reactors
  - Beam-dump experiments
  - The cosmos
  - The Sun



- What is so special to observe neutrinos that have been produced at particle colliders?
  - Lot's of nice publicity …

But can't we learn anything from this?

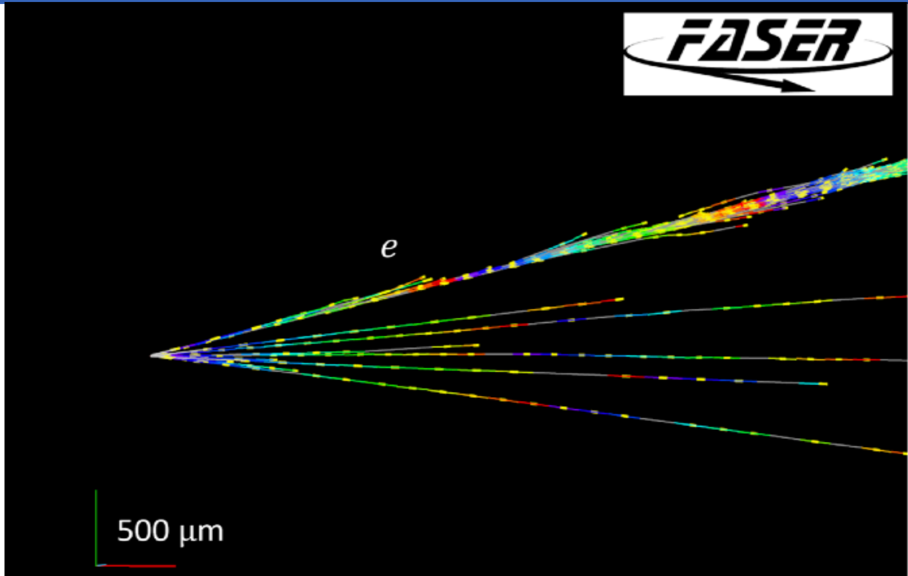


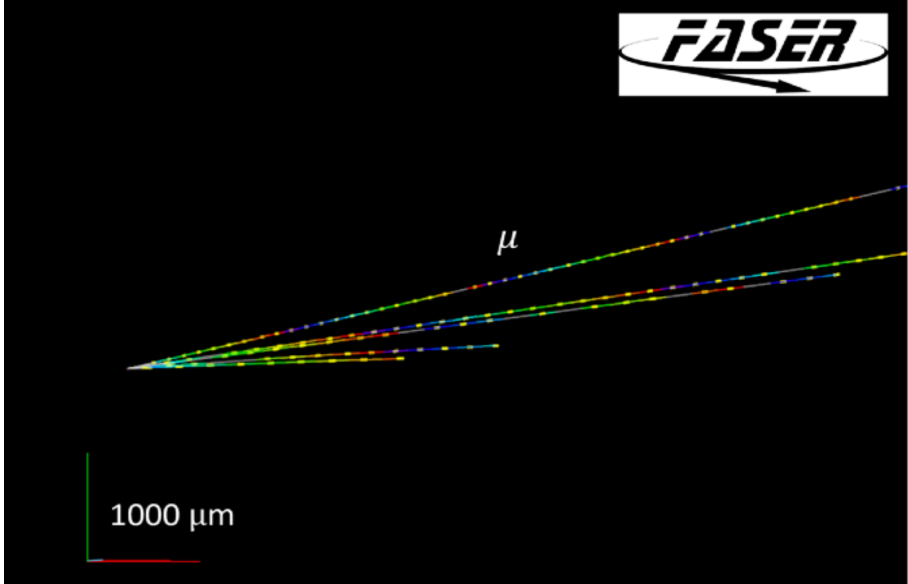


- Collider Neutrinos have extremely high energies
- Interaction probabilities of neutrinos depend on their energy
  - Super important for neutrino astrophysics
- Interaction probabilities depend on the quark structure of nucleons (inside the tungsten)
  - Collider Neutrinos open up a new tool for studying the strong force

Neutrino Signatures

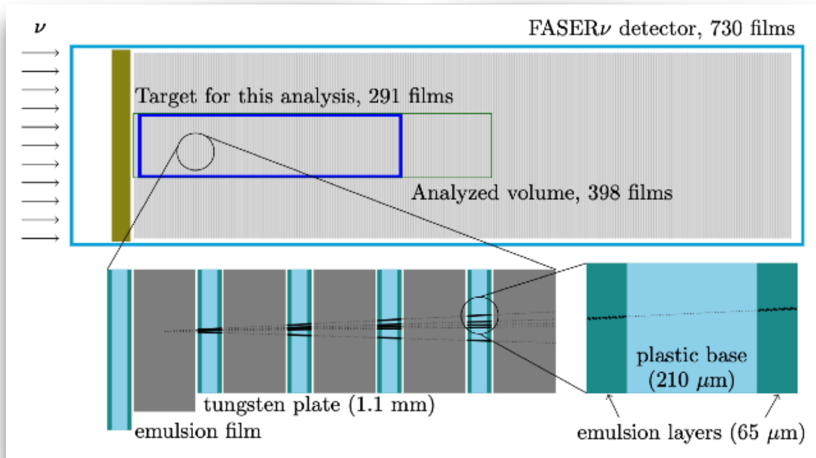
- Learn even more, when distinguishing electron-, muon- and tau neutrinos…
  - Idea: Use their characteristic interaction signatures
- Electron Neutrinos
  - Electromagnetic Shower
- Muon Neutrinos
  - Muon out of nothing
- Tau Neutrinos
  - … later





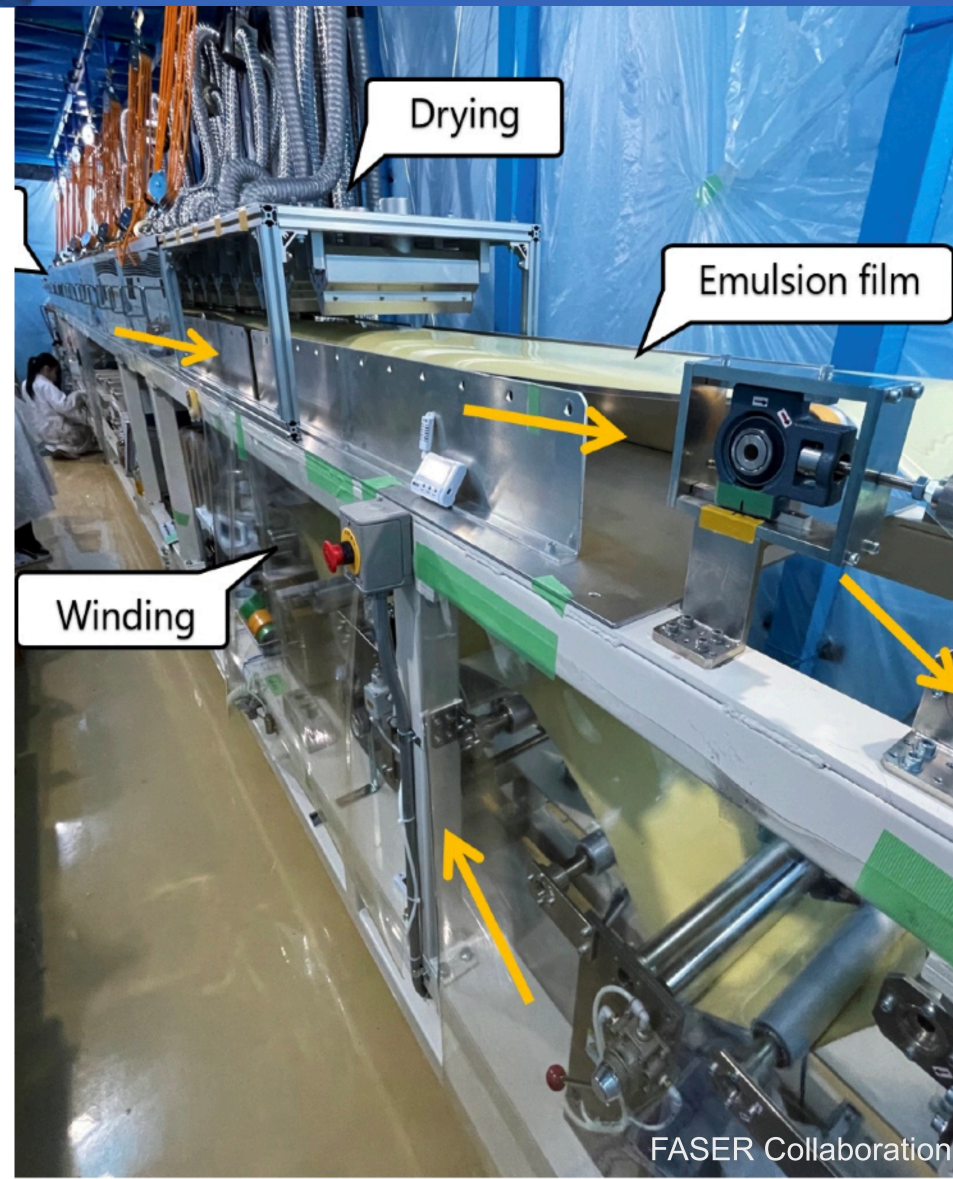
Emulsion Detectors

- Experimental approach: Emulsion



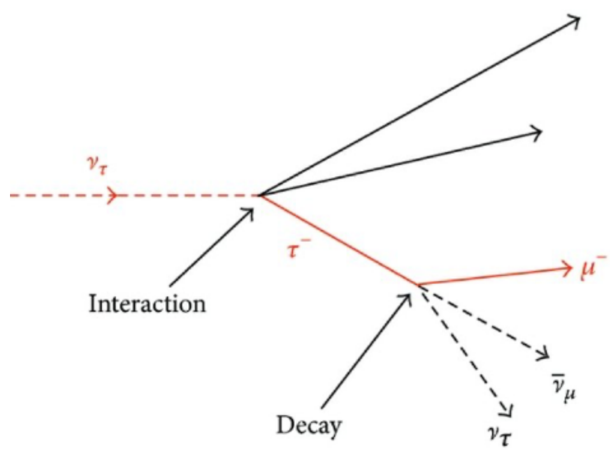
- Advantage: Super precise

- Disadvantages
  - Who has still photographic films?
  - Scanning those films takes ages
  - Replacement of film every few months

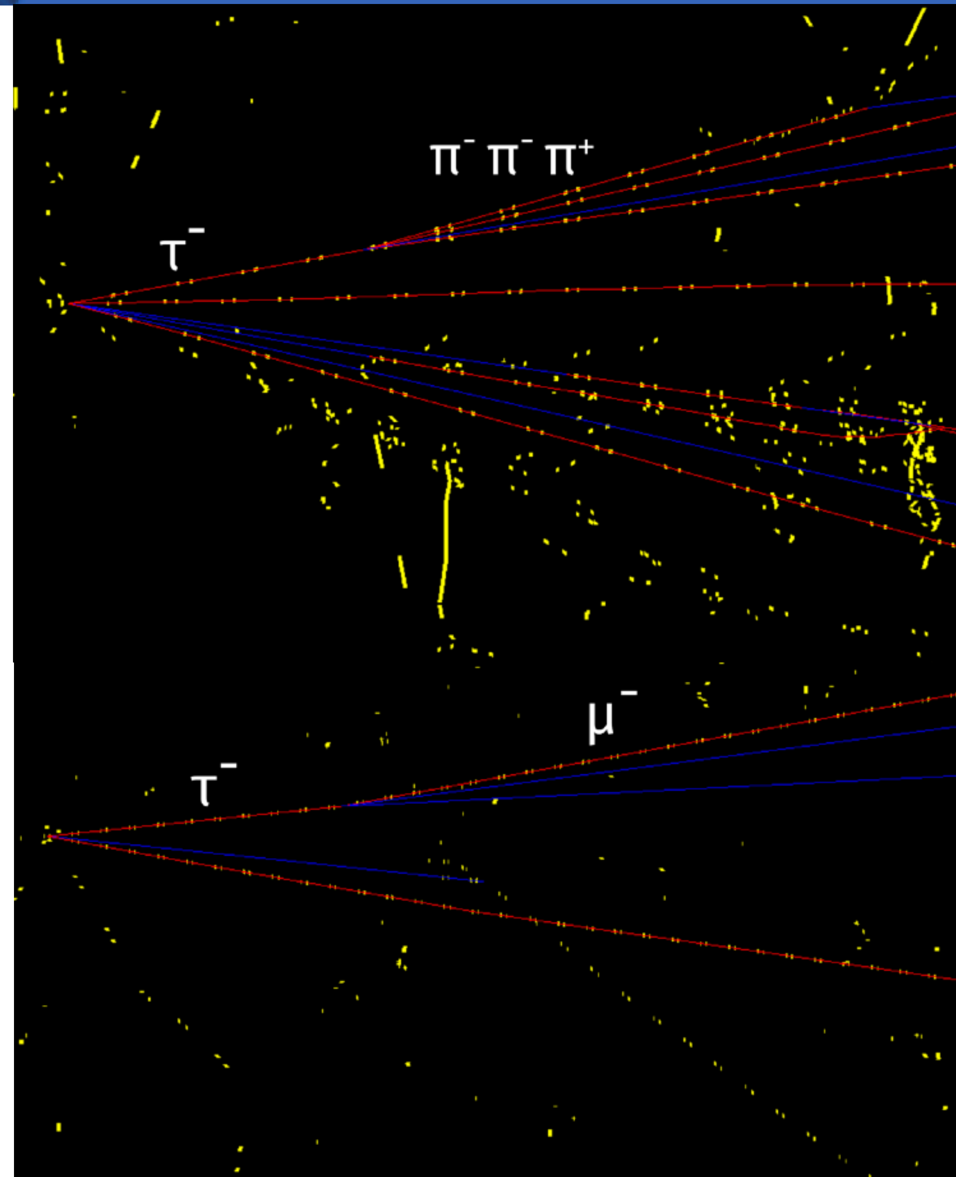


How to discover Anti-Tau Neutrinos

- Tau- And Anti-Tau neutrino? Need to identify tau charge
  - Problem: Lifetime of tau is short
- Idea: Study tau-decays into muons



- My bet: Discovery of Anti-Tau Neutrino by 2030
  - Is this a major breakthrough?

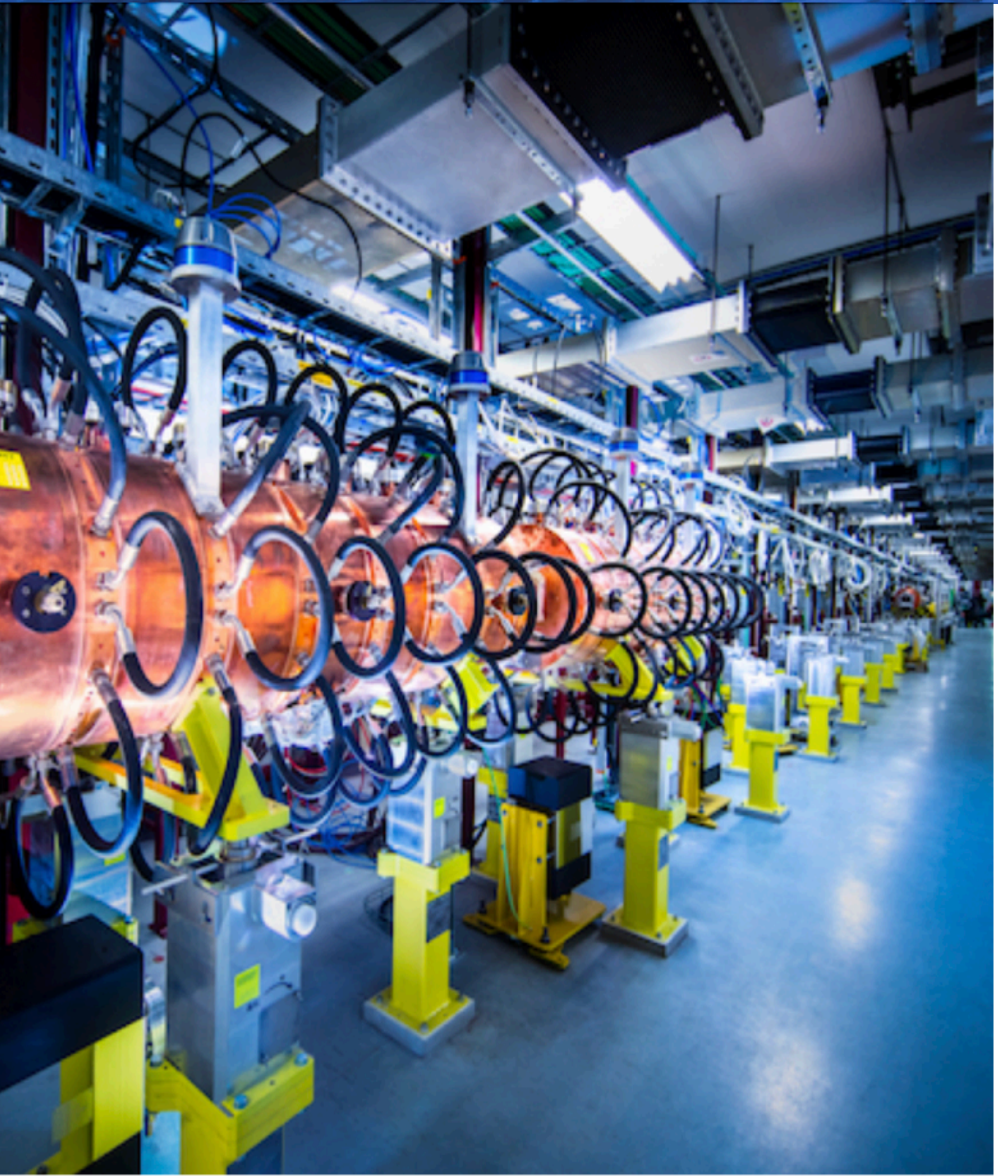


Future of FASER and the LHC

Lots of data is ahead of us

- FASER will take data until 2030s
  - Four times more data
- Significant detector upgrades planed in the coming years
- We definitely will understand Quantum-Chromo Dynamics better using neutrinos
- … we might find the anti-tau neutrino
- … and maybe even a new elementary particle

The Future of Collider Physics



- The situation is quite unsatisfactory
  - We know there must be physics beyond the Standard Model
- Some new/old ideas are largely ruled out …
  - … but not completely (and maybe never will)
- Maybe we have to reconsider some stuff fundamentally
- Our theory friends need experimental data as guidance
  - Precision physics might guide us the way beyond

Funding

- My research is paid by tax-payers
  - It is therefore not my but our research
  - I am extremely grateful to all of you who pay taxes

- You are rich and don’t know what to do with your money?

- Your company wants to fund fundamental science and recruit excellent people?

  - Buy your own professor (endowment chairs)
  - Finance your own particle physics experiment
  - Let’s have a chat

Take-Aways

- Neutrinos at the LHC are a new tool to study the strong interaction
- The Anti-Tau Neutrino was never discovered
- Particle Physics is so much fun
- We are living in interesting times