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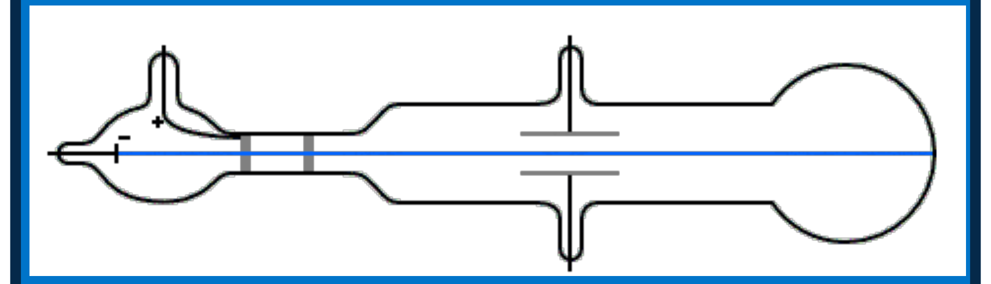
Louis D'Eramo
LPCA, CNRS-IN2P3 Université Clermont Auvergne

A brief (pre)history of ~~time~~ SM

1897

Thomson's electron

Confirming Jean Perrin's hypothesis on the origin cathodic rays.



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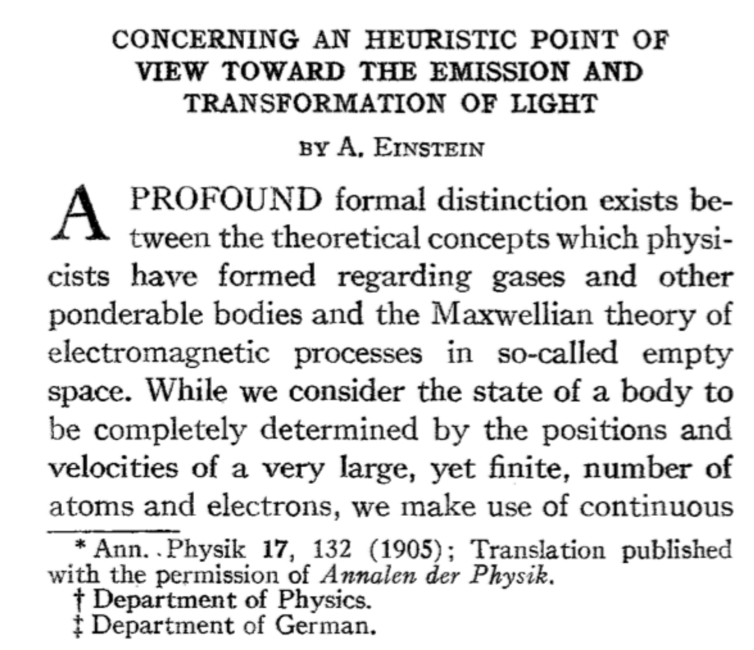
Einstein's photon

Combining results Max Planck's black body experiment and the photoelectric effect, Einstein predicts the existence of photon.



CONCERNING AN HEURISTIC POINT OF VIEW TOWARD THE EMISSION AND TRANSFORMATION OF LIGHT

BY A. EINSTEIN

A PROFOUND formal distinction exists between the theoretical concepts which physicists have formed regarding gases and other ponderable bodies and the Maxwellian theory of electromagnetic processes in so-called empty space. While we consider the state of a body to be completely determined by the positions and velocities of a very large, yet finite, number of atoms and electrons, we make use of continuous

* Ann. Physik 17, 132 (1905); Translation published with the permission of *Annalen der Physik*.
† Department of Physics.
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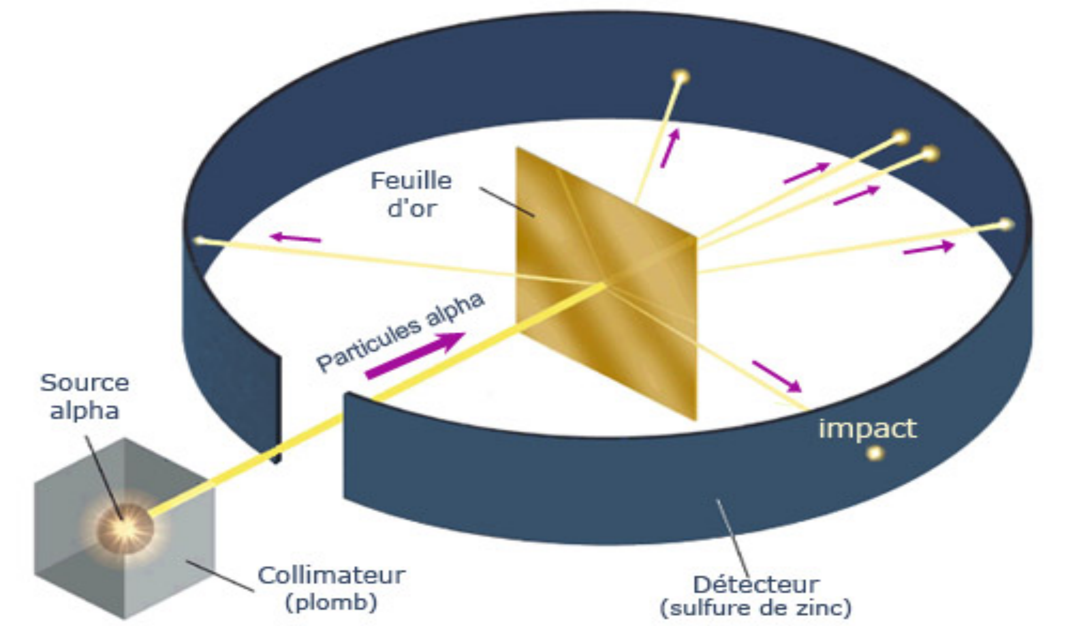
After the discovery of the nucleus in 1911, the most elementary nucleus was called proton (from the ancient Greek "protos", first).



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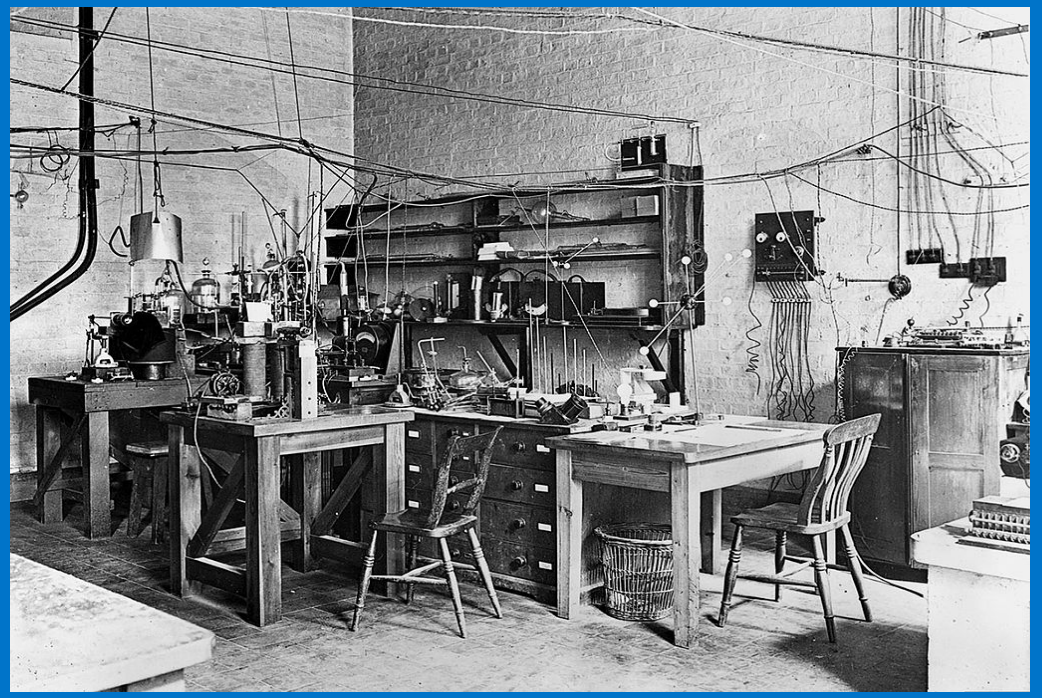
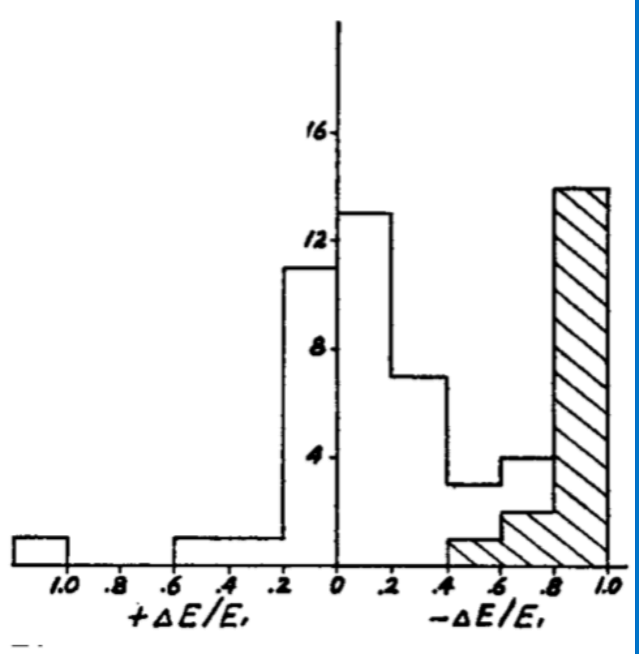


1936

Anderson's muon

When studying the effect of cosmic rays on a platinum plate, some particles deposit less energy than electrons while having the same electric charge.



1930/56

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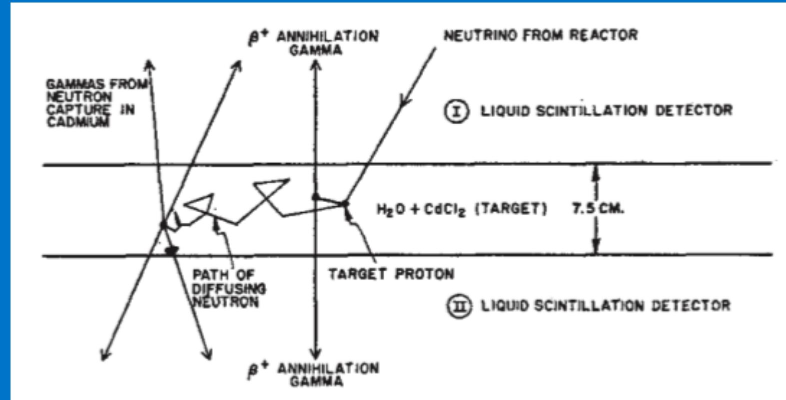
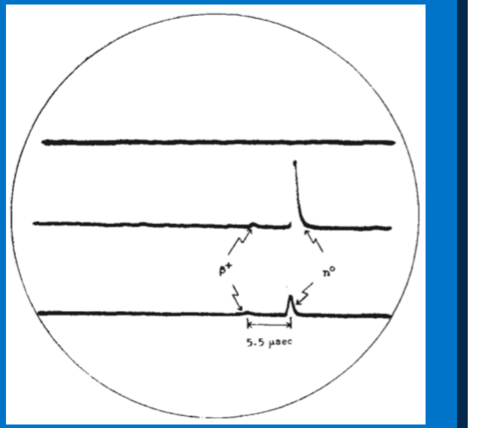


Fig. 1. Schematic diagram of neutrino detector



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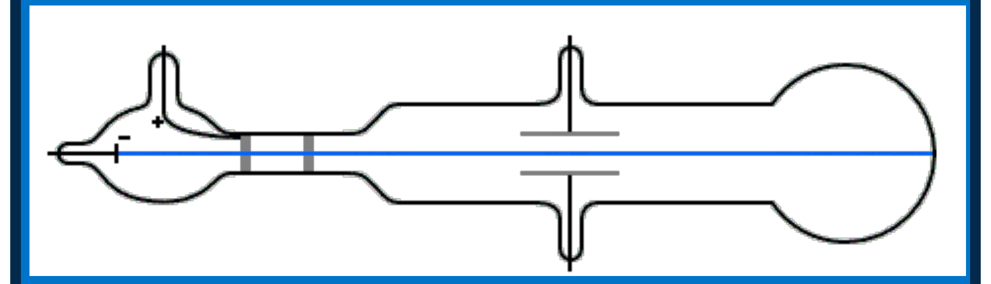

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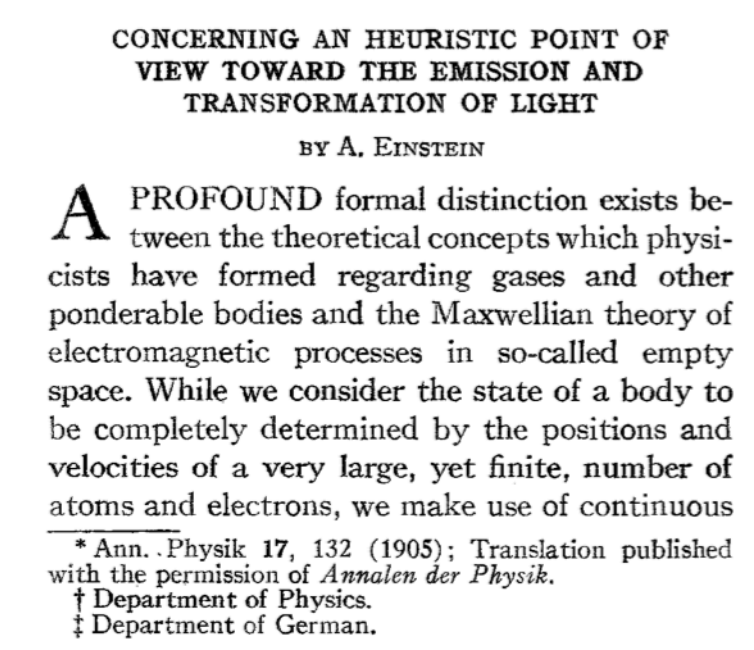

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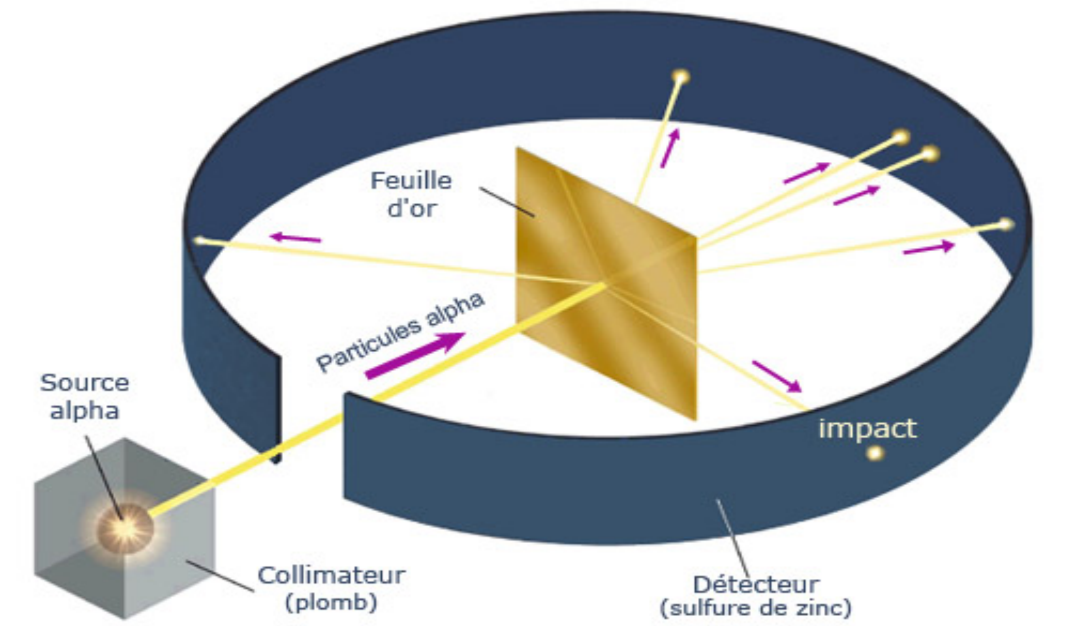

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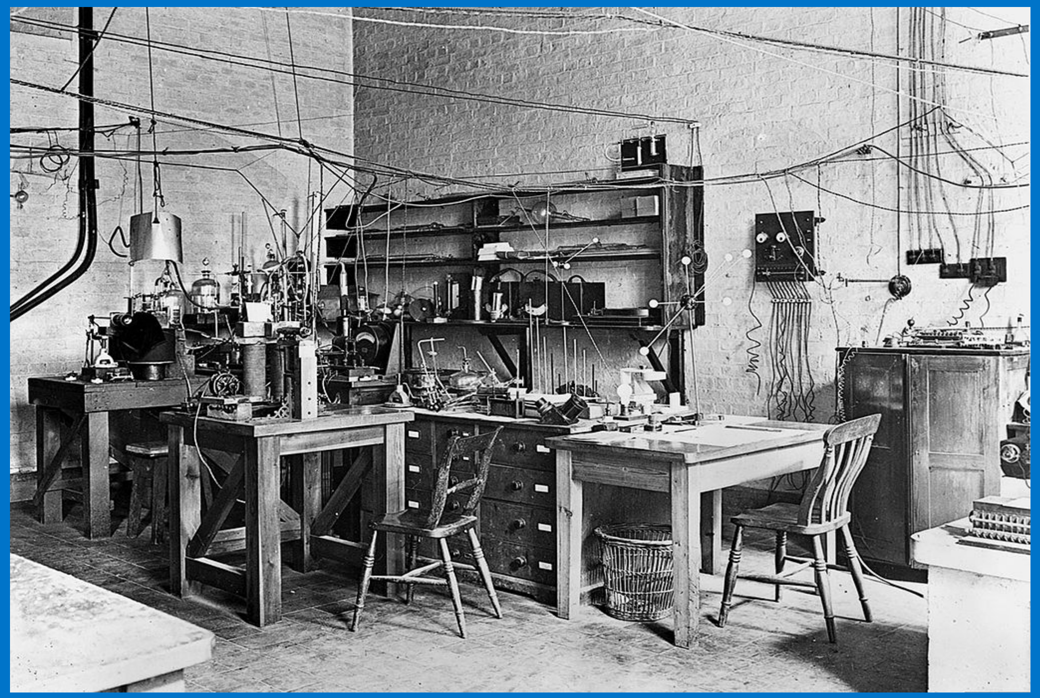

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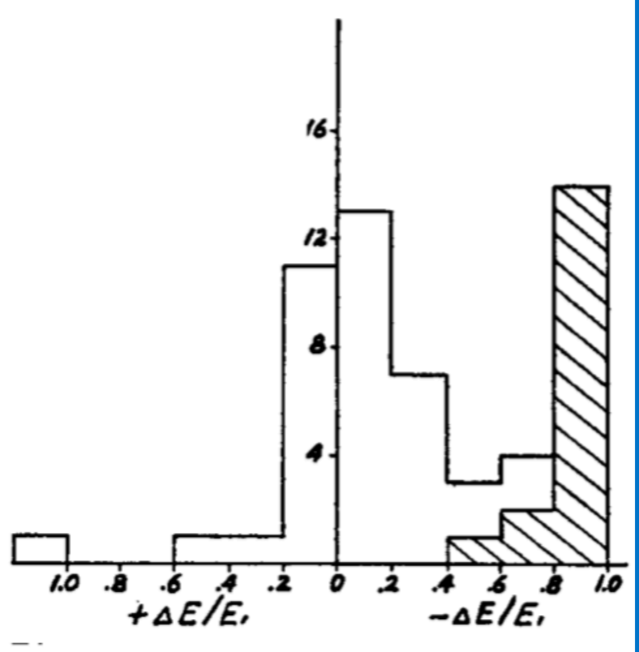

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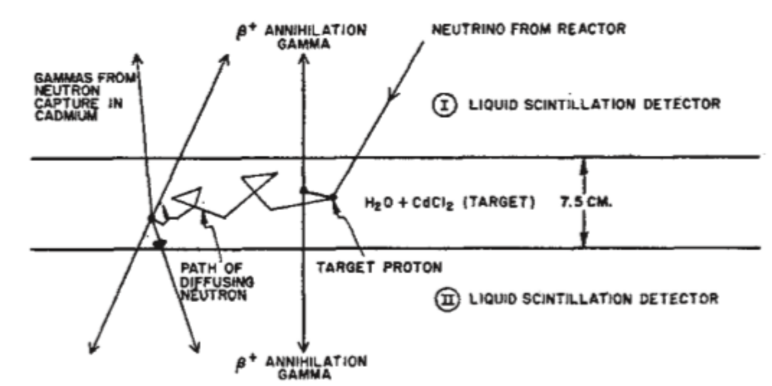

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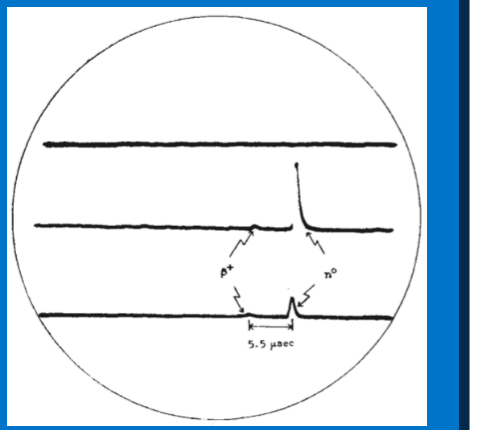
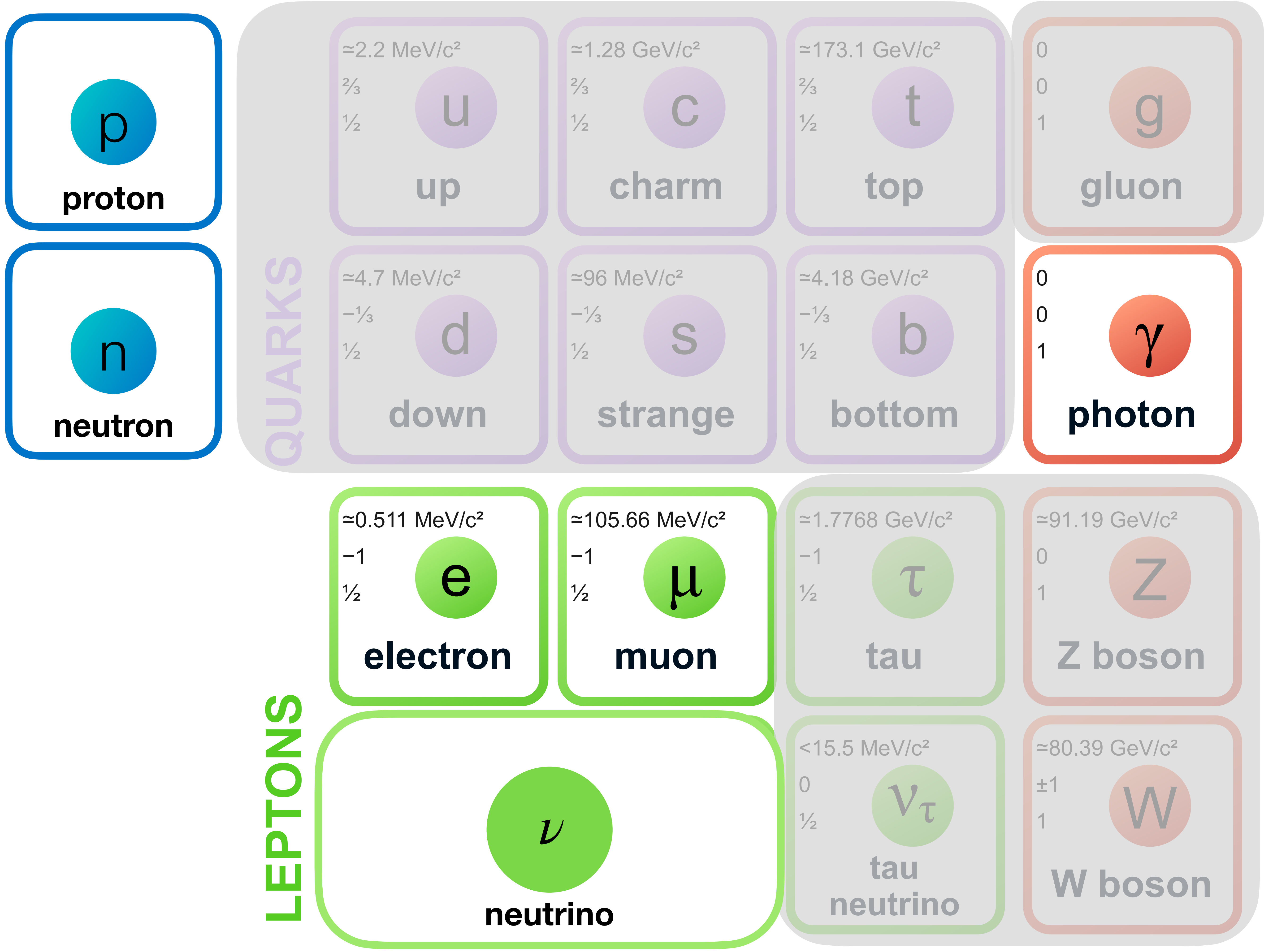


Building the SM

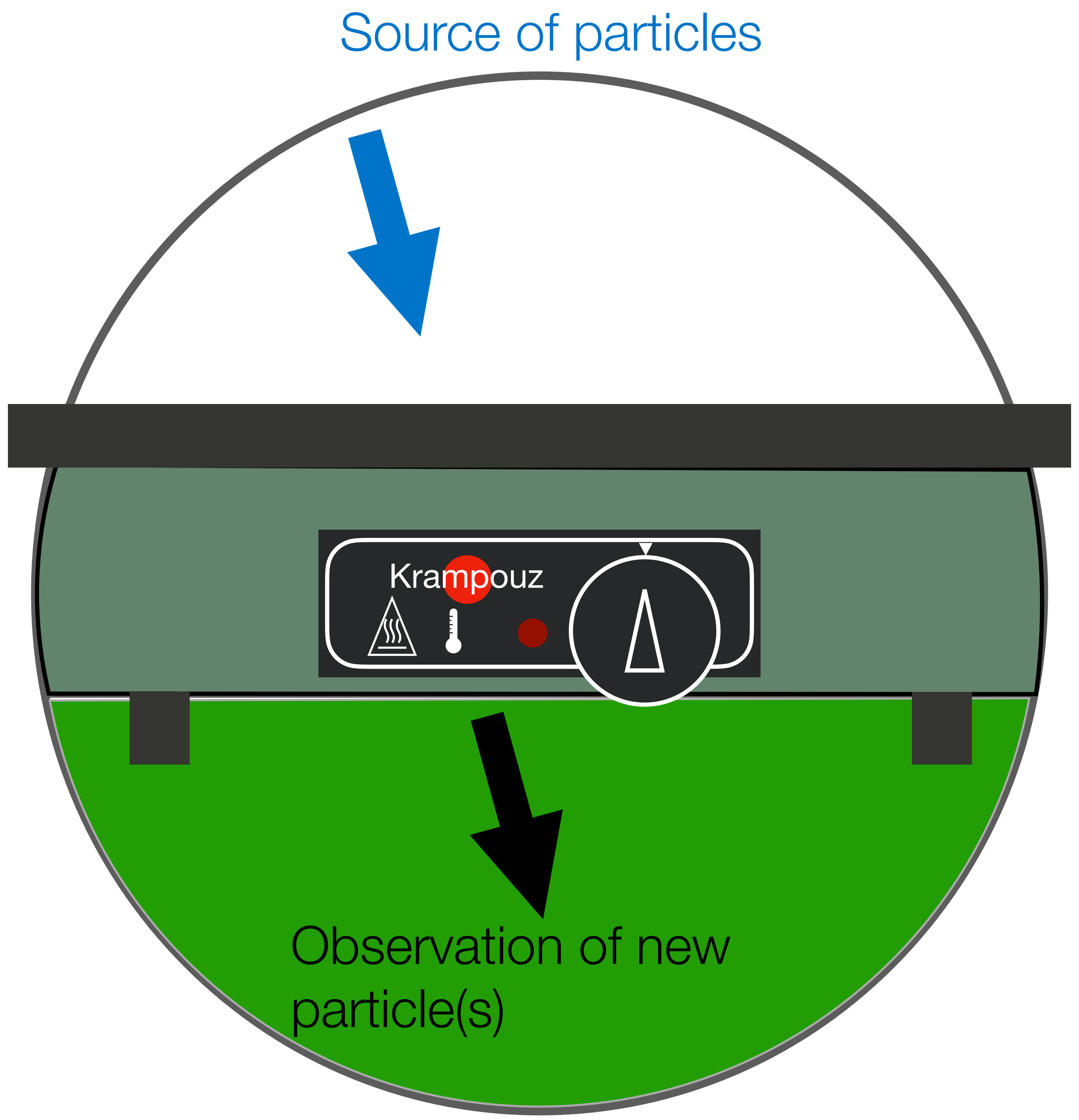
50s



In the **50s**, the SM was looking like more or less similar than St Malo, looking with today's eye: both needed huge efforts

Towards a more complex SM

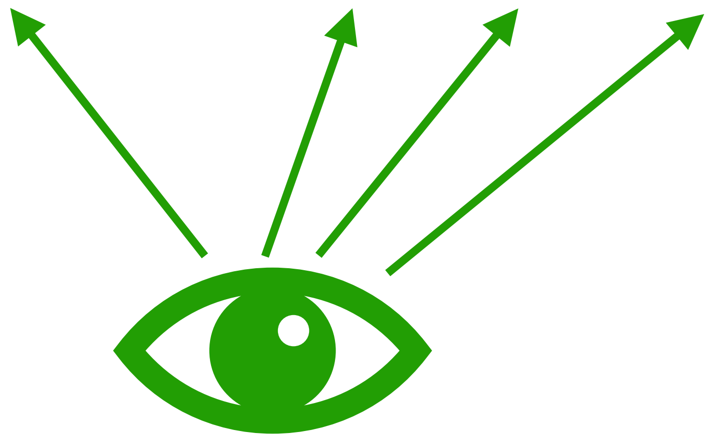
The principle of observing new particles requires 3 ingredients:



Nature 160 (1947) 855-857

- A **source** of energetic particles (coming from the cosmos at first, then from the first particle accelerators);
- A **medium** for these particles to interact;
- a **technique** for observing incident and outgoing particles.

A + **B** → C + D + ...



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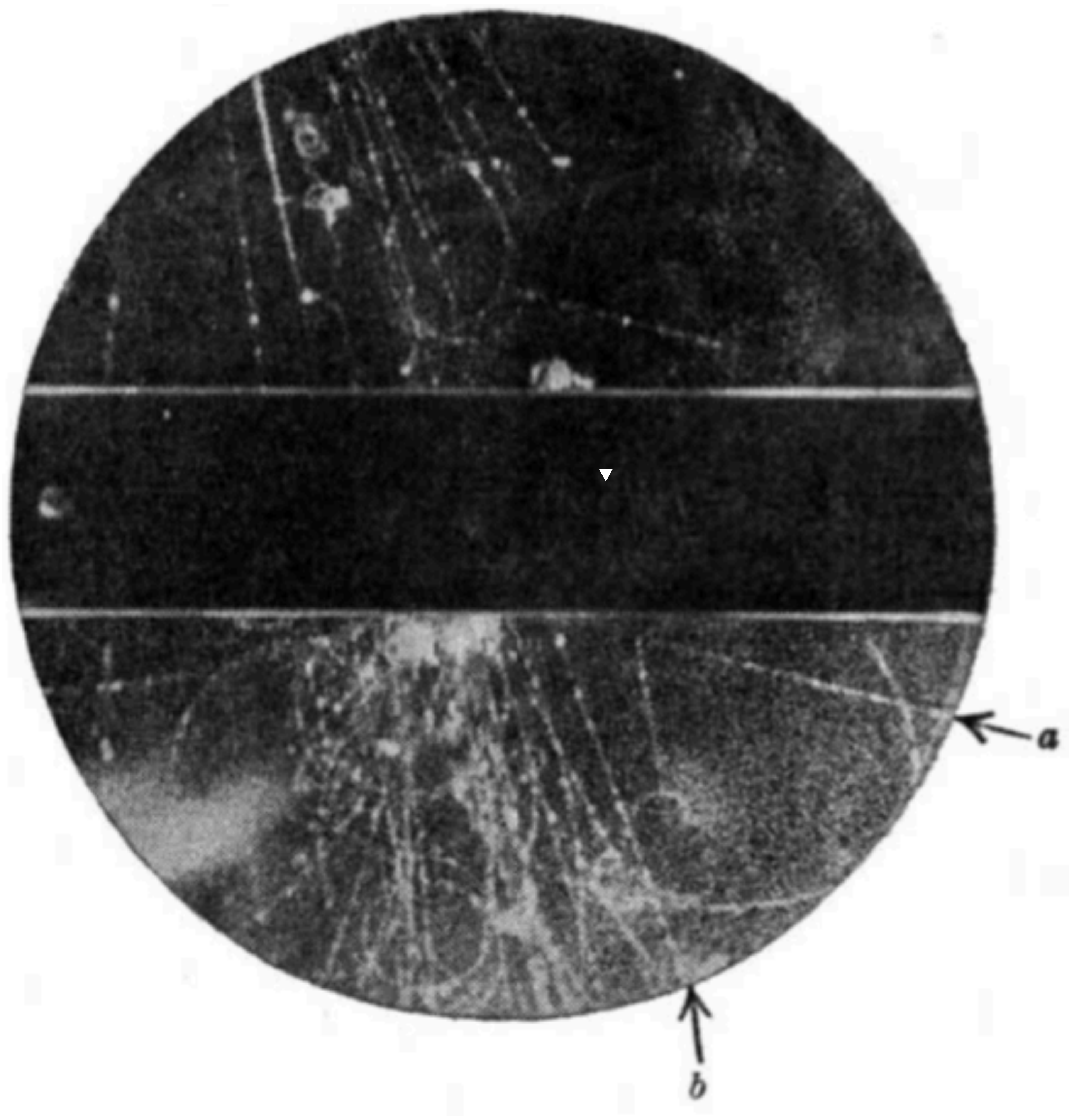

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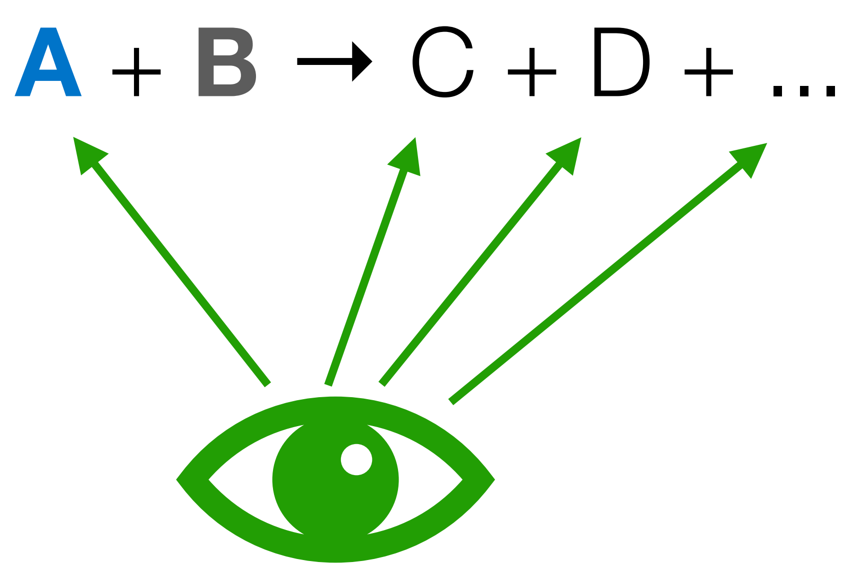

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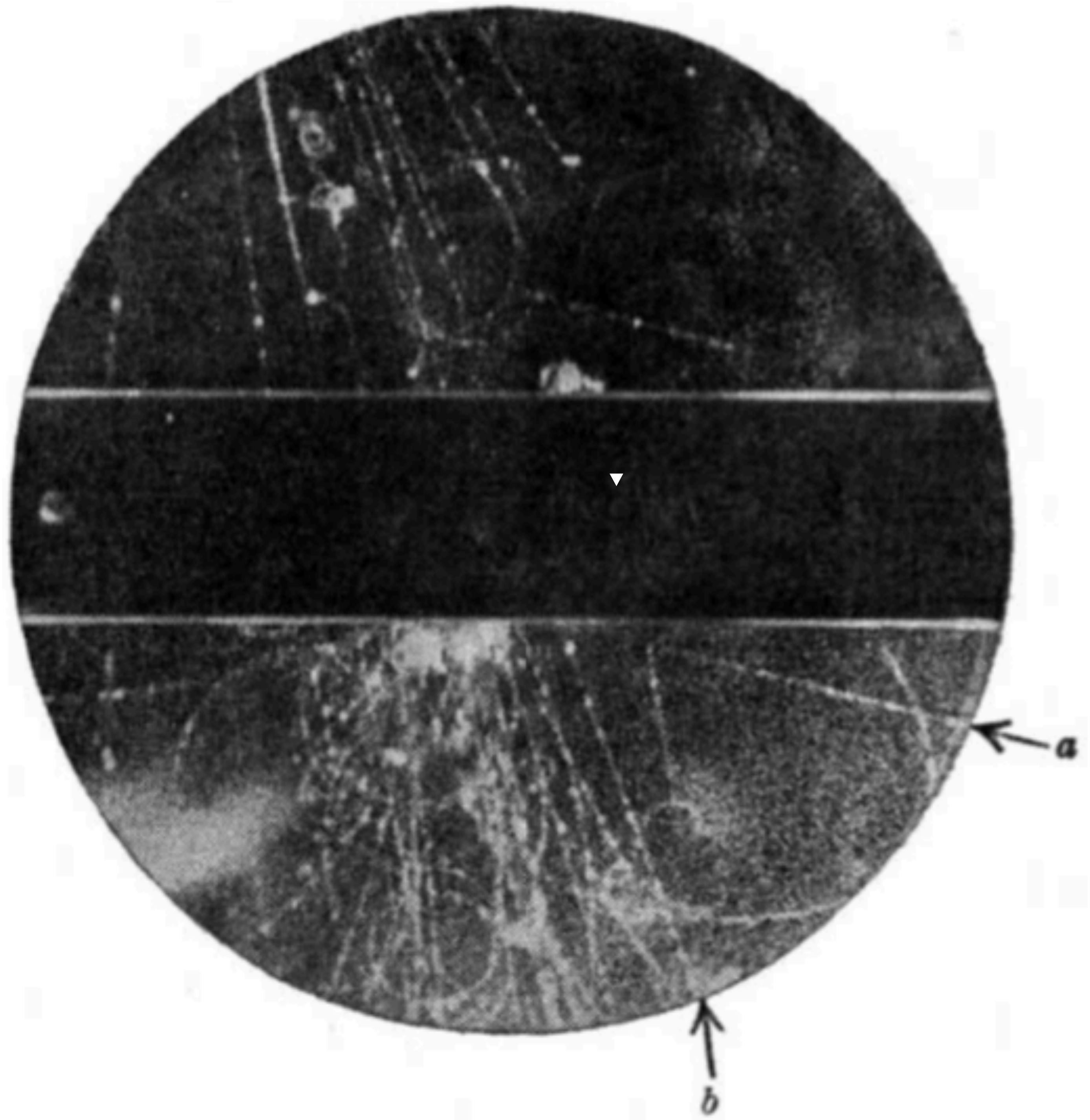

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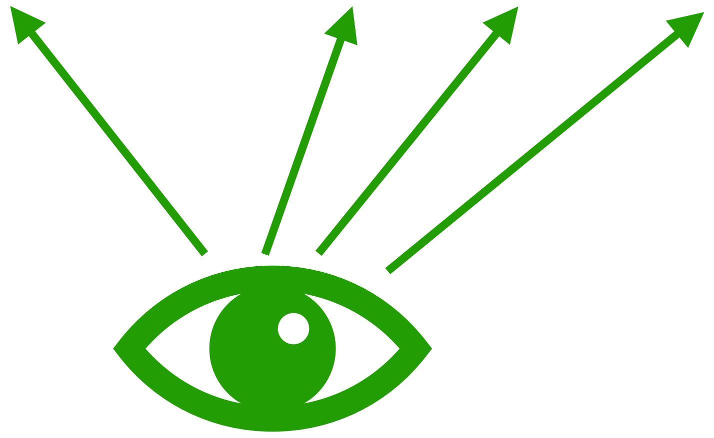
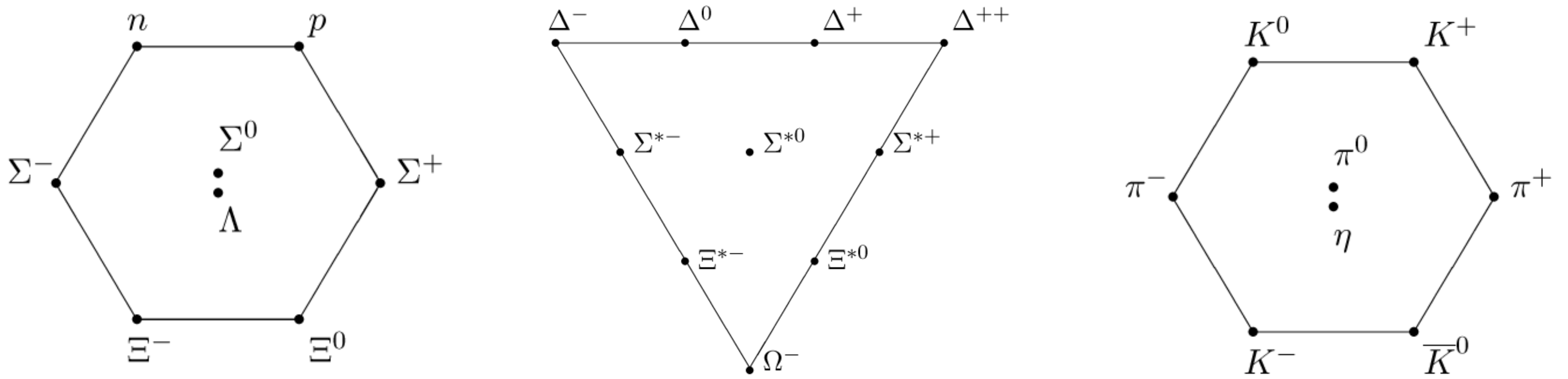
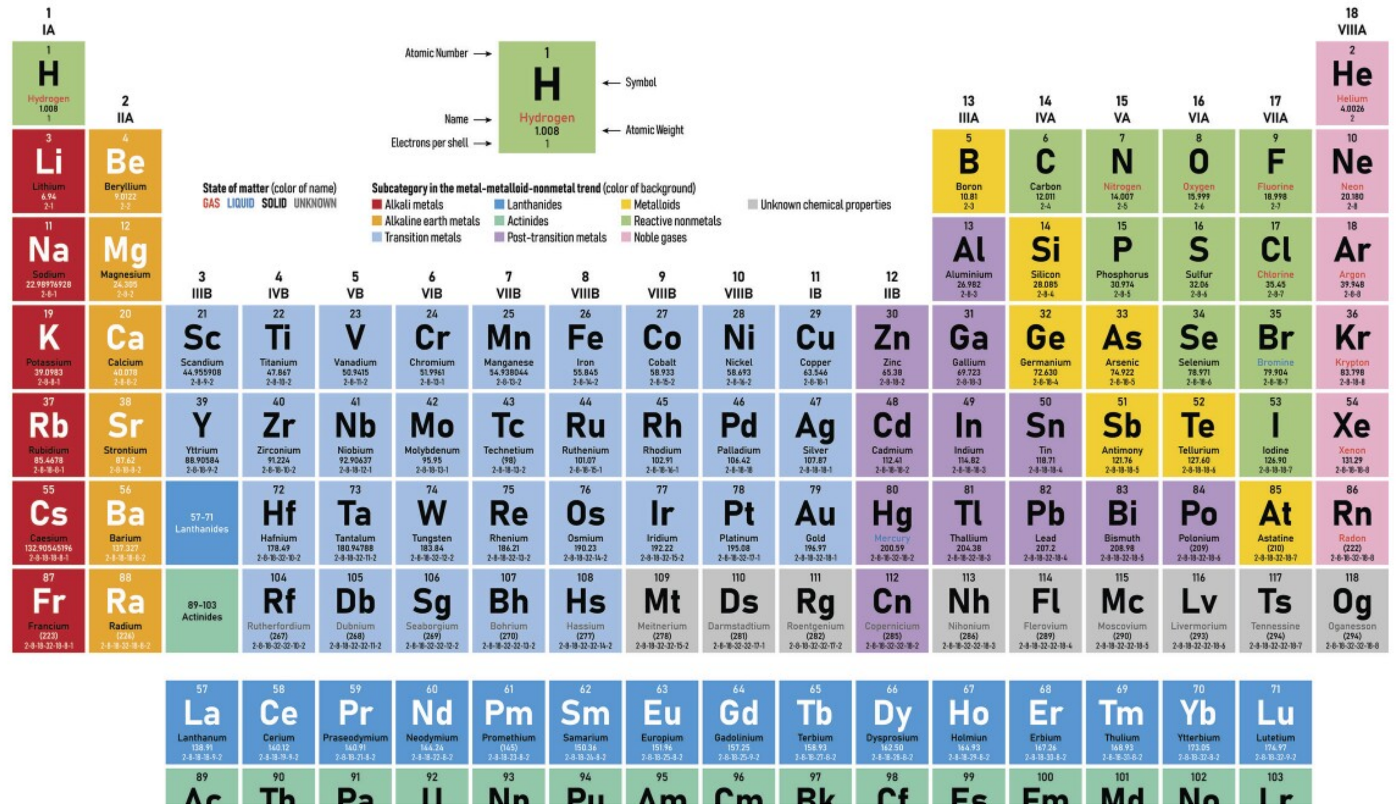




Many new particles are observed !
And there seems to be many of them ...

So we start to classify them by properties.



In **61**, Gell-Mann, Zweig, Glashow and Bjorken worked their way to propose a partonic model, known as **the Eightfold Way**.

A history of accelerators

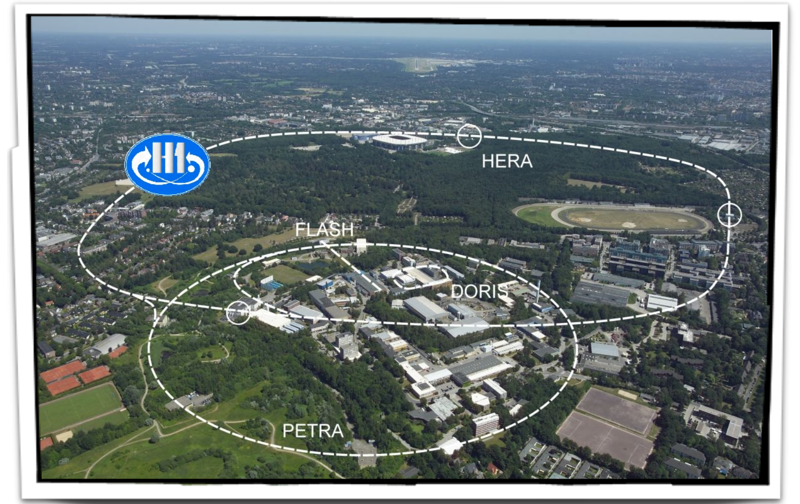
1882 — 1962-68 — 1962 -

Wimshurst machine
~ few keV

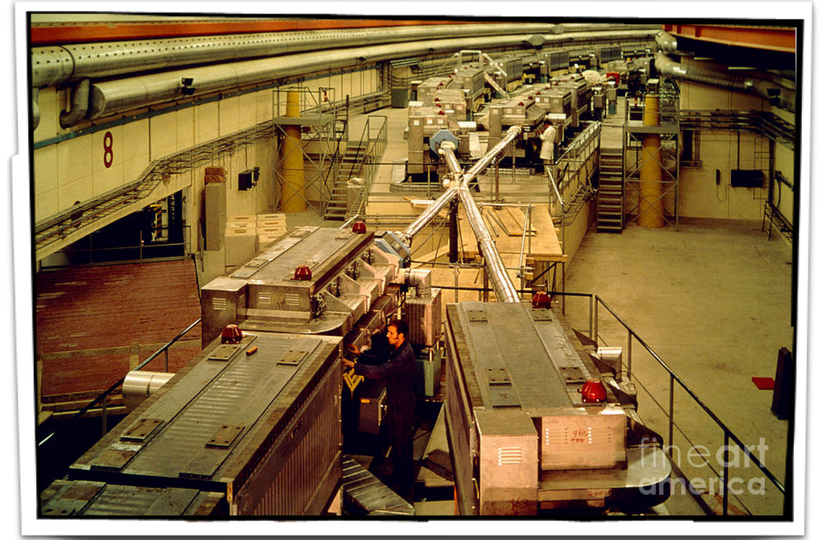
L'accélérateur Linéaire: Orsay
2,3 GeV

Standford Linear Accelerator Center
up to 50 GeV → 3 kms

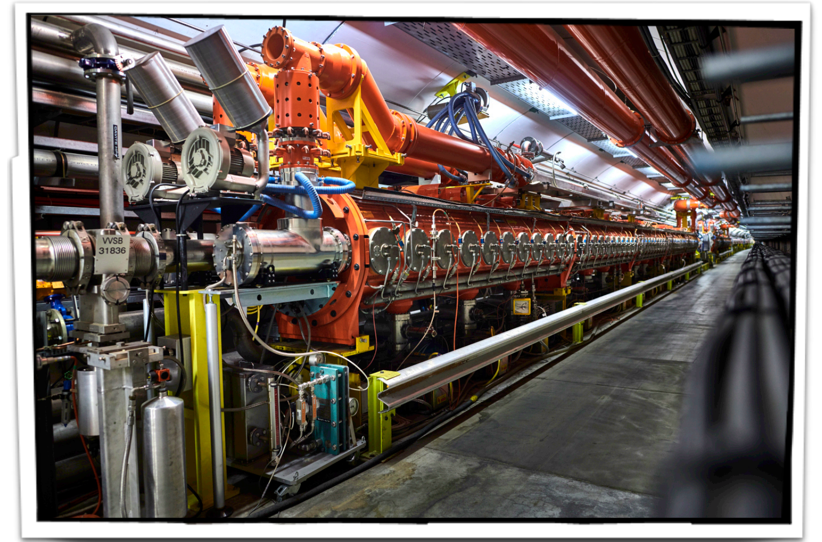
1964 - — 1971 - 84 — 1976 - — 1989 - 2000 — 1992 - 2011



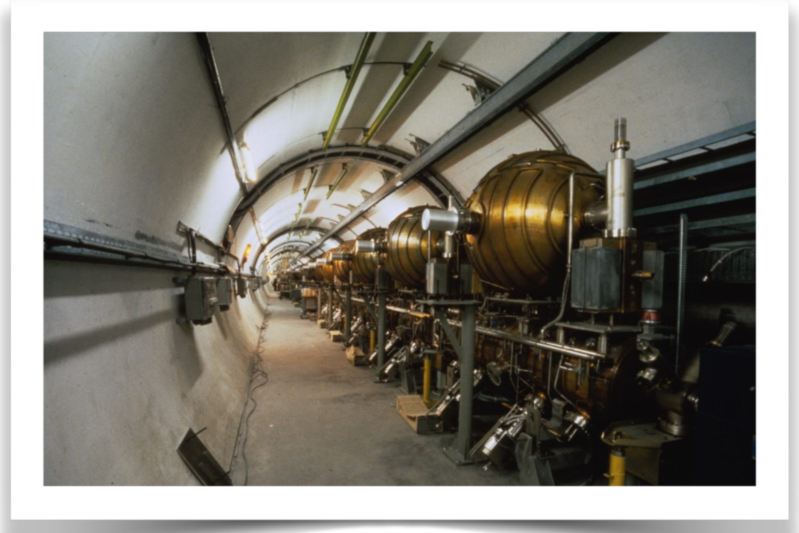
DESY: Hamburg
up to 20 GeV



PS/ISR: CERN
up to 62 GeV



SPS: CERN
up to 450 GeV



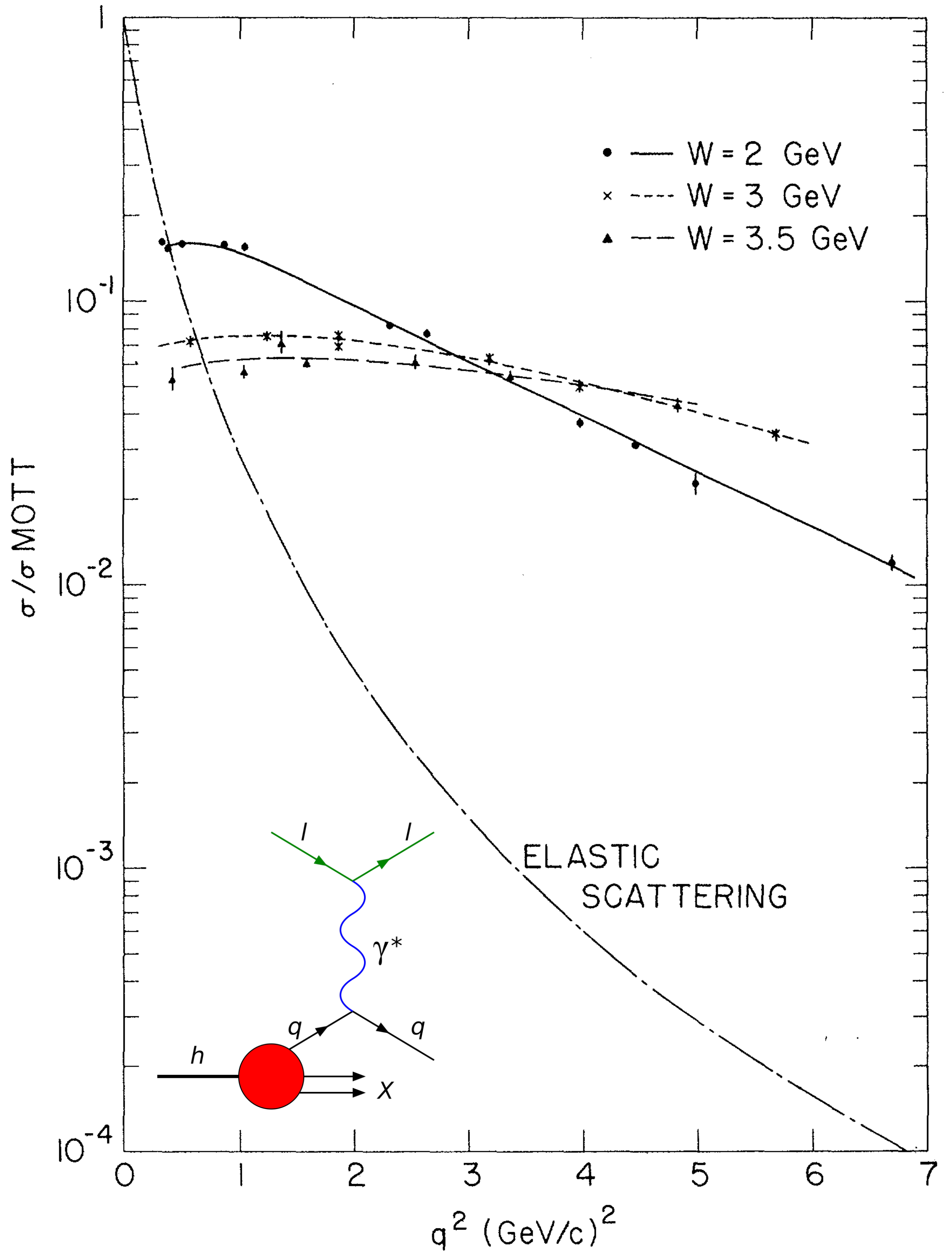
LEP: CERN
up to 209 GeV

Tevatron: Fermilab
up to 980 GeV

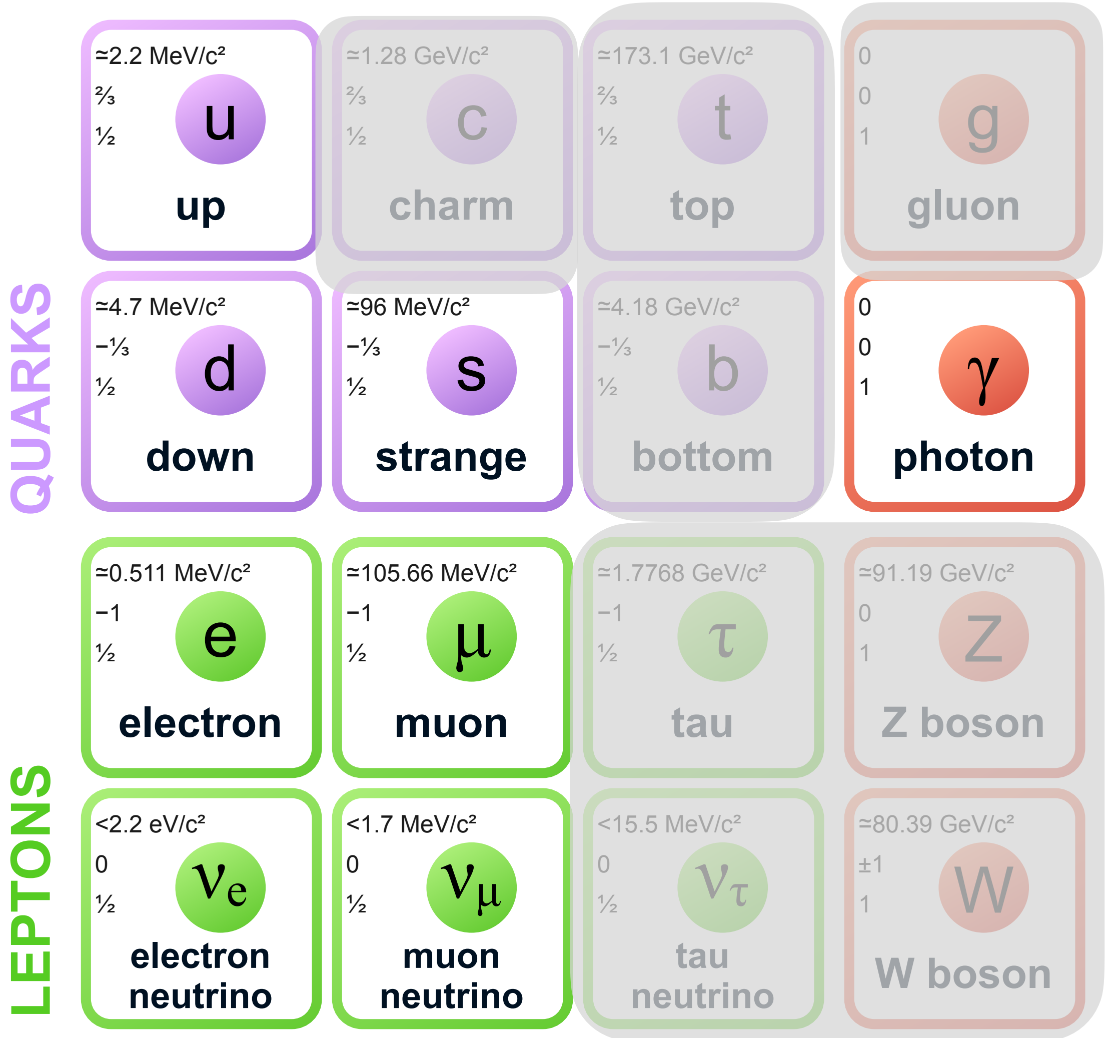
Towards a more complex SM

At SLAC, in **73**, some strange **electron scattering on proton** are observed:

- They are modelled with so-called form-factors modifying the usual photon exchange.
- Only the **parton model** could explain this !
- At that time only 3 K'warks were predicted: u, p, s.



Phys. Rev. Lett. 23, 935



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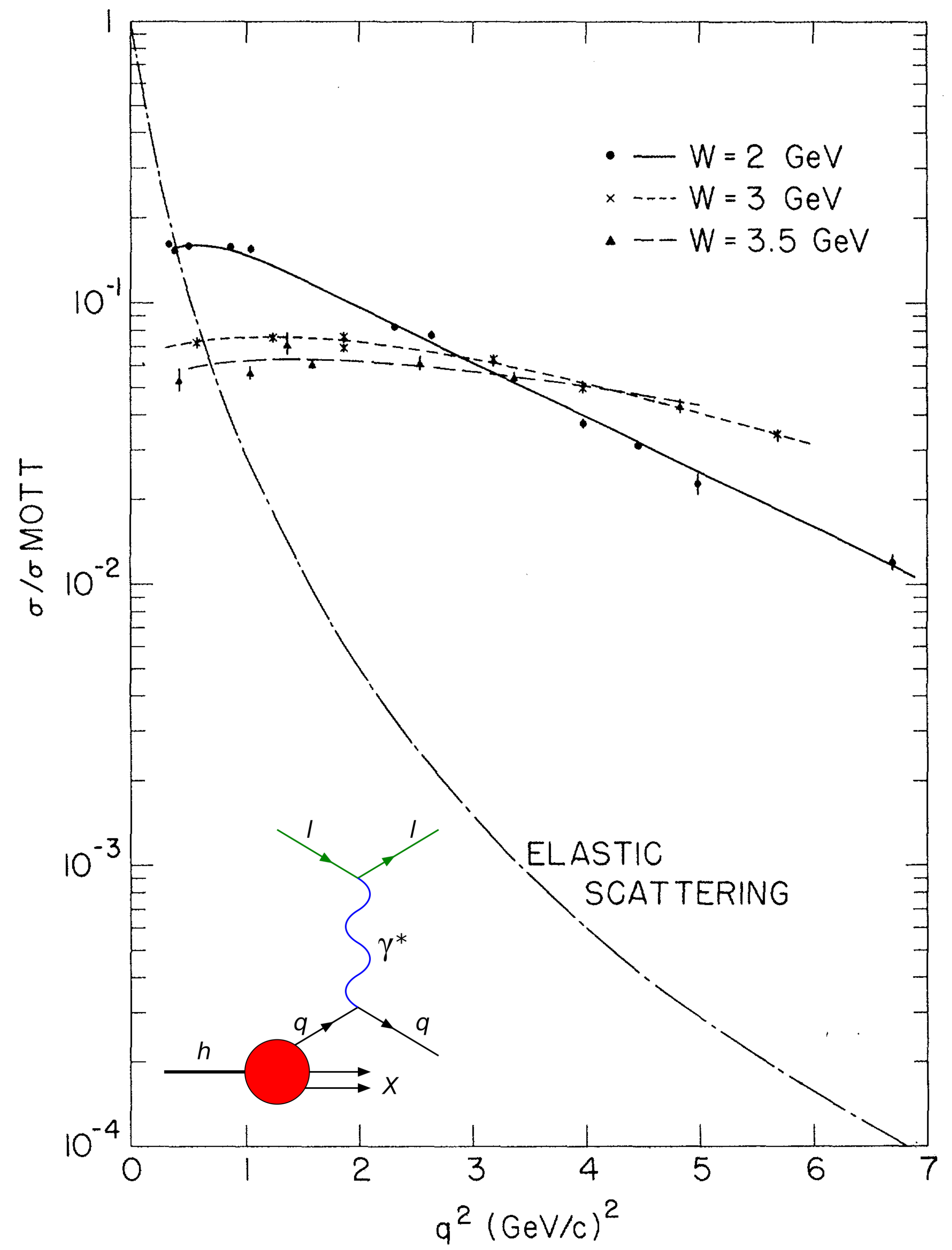

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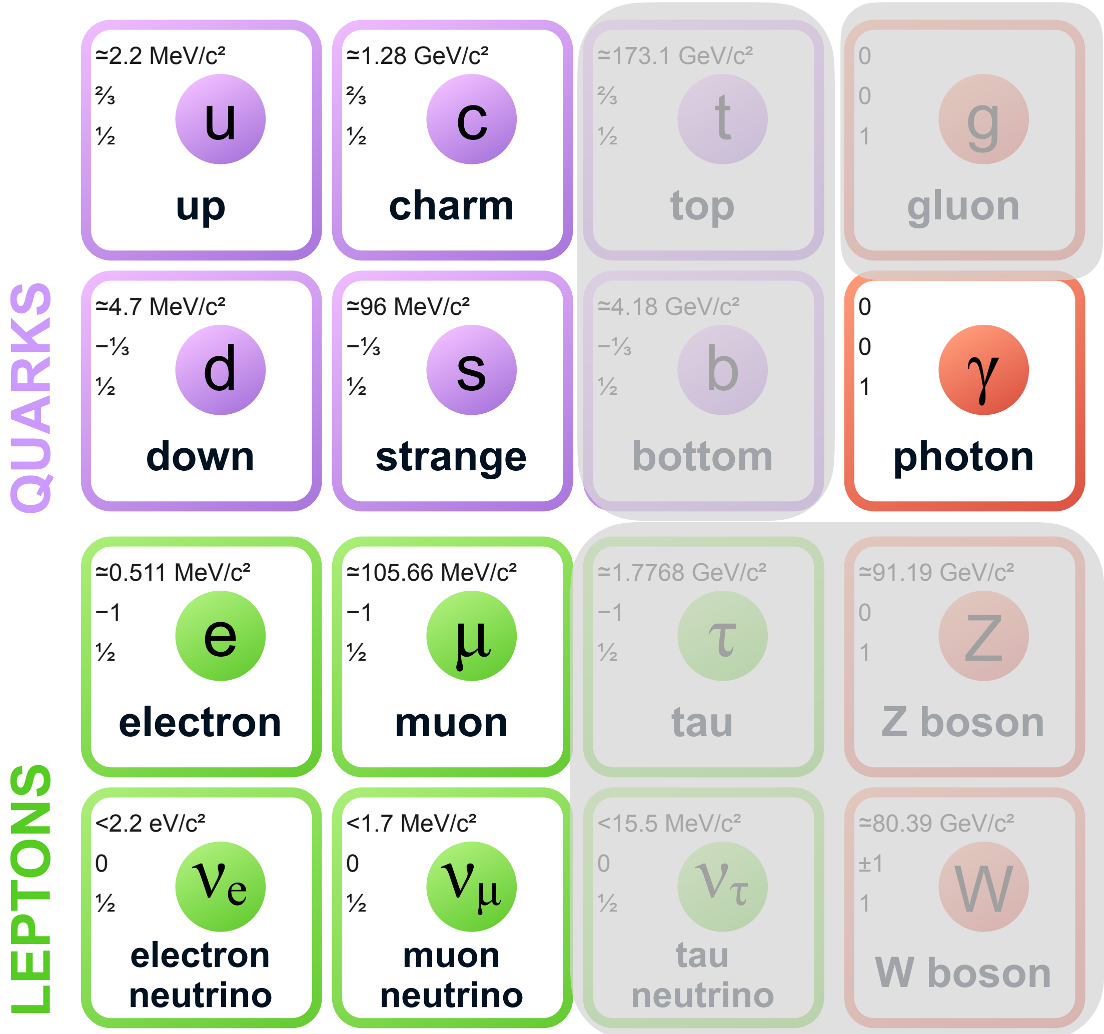
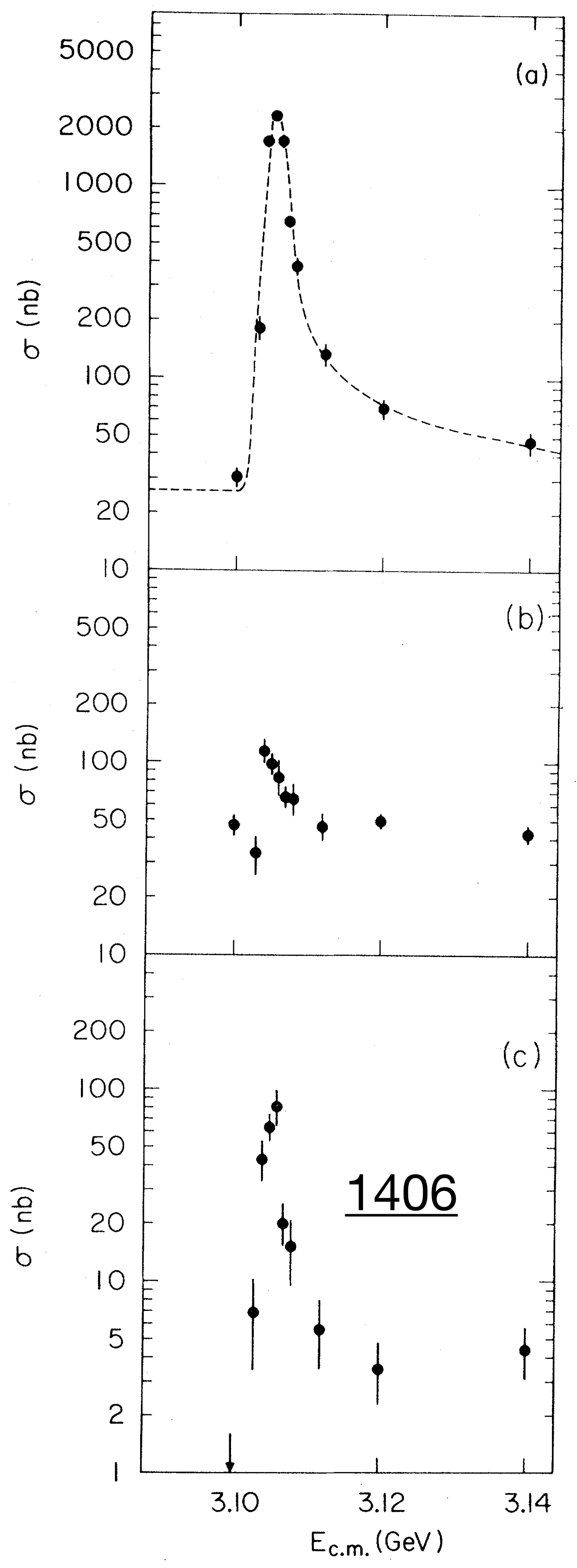
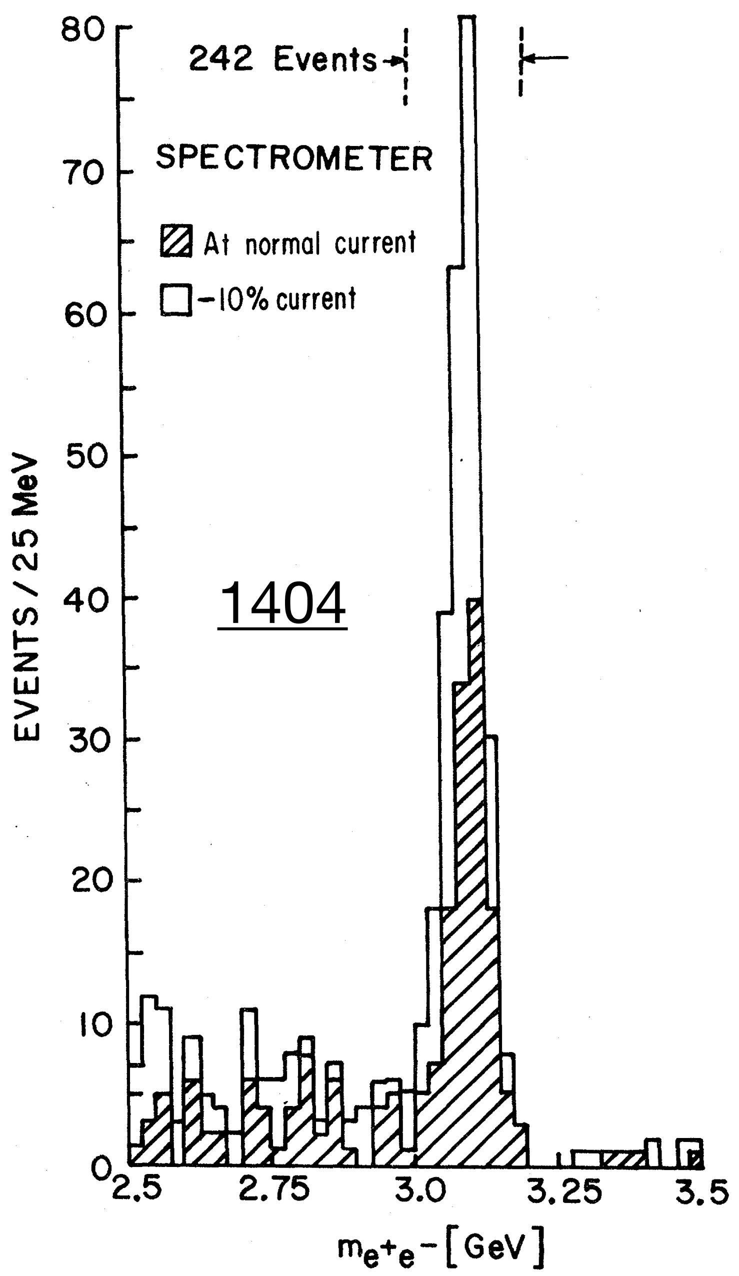


The model was finally accepted after the so called November revolution in **74** :





In the same PRL issue (Phys. Rev. Lett. 33, 1404), the SLAC and BNL teams reported the discovery of a **new meson**, predicted to arise from a **bound** $c\bar{c}$ **state** !

The community got convinced that the K'wark model was real.

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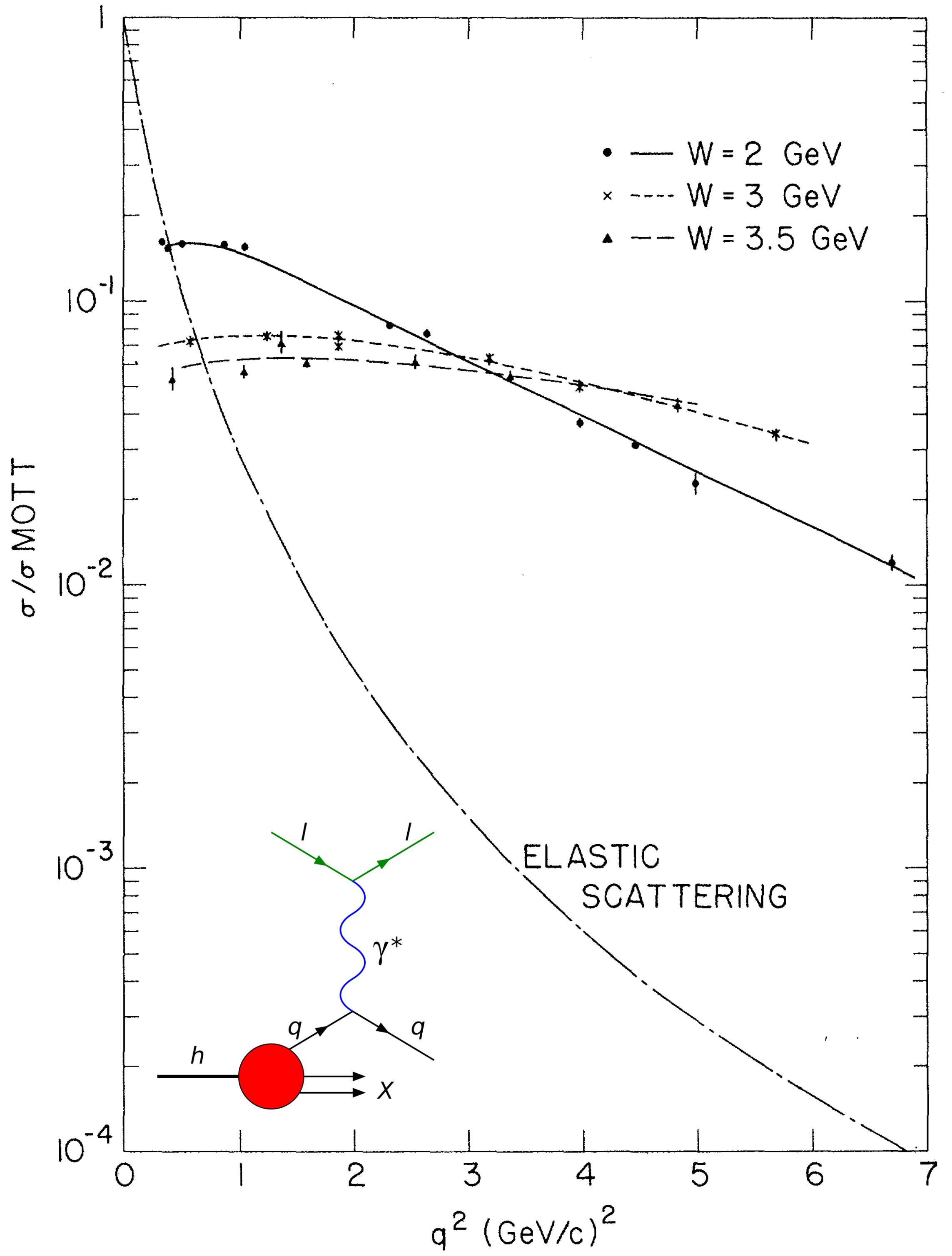

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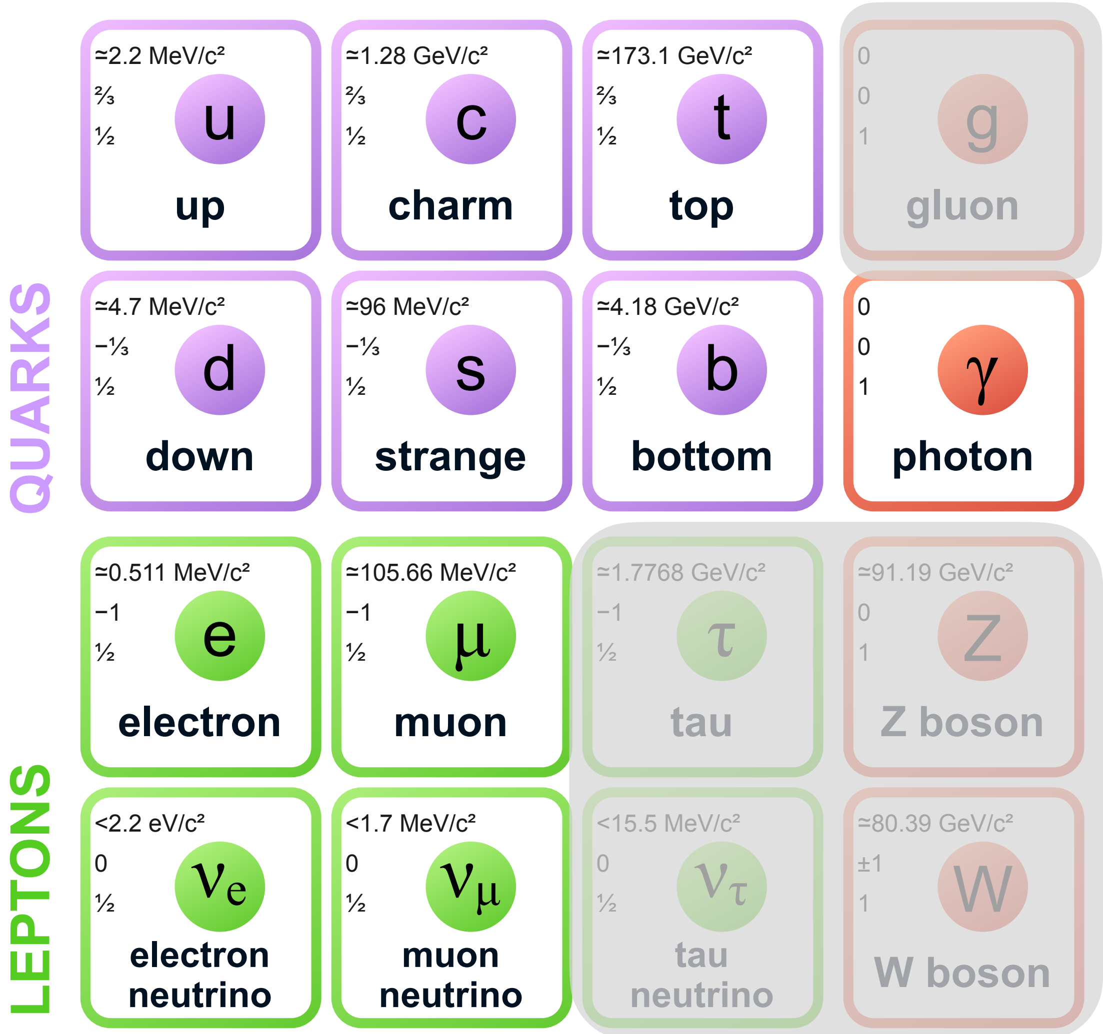

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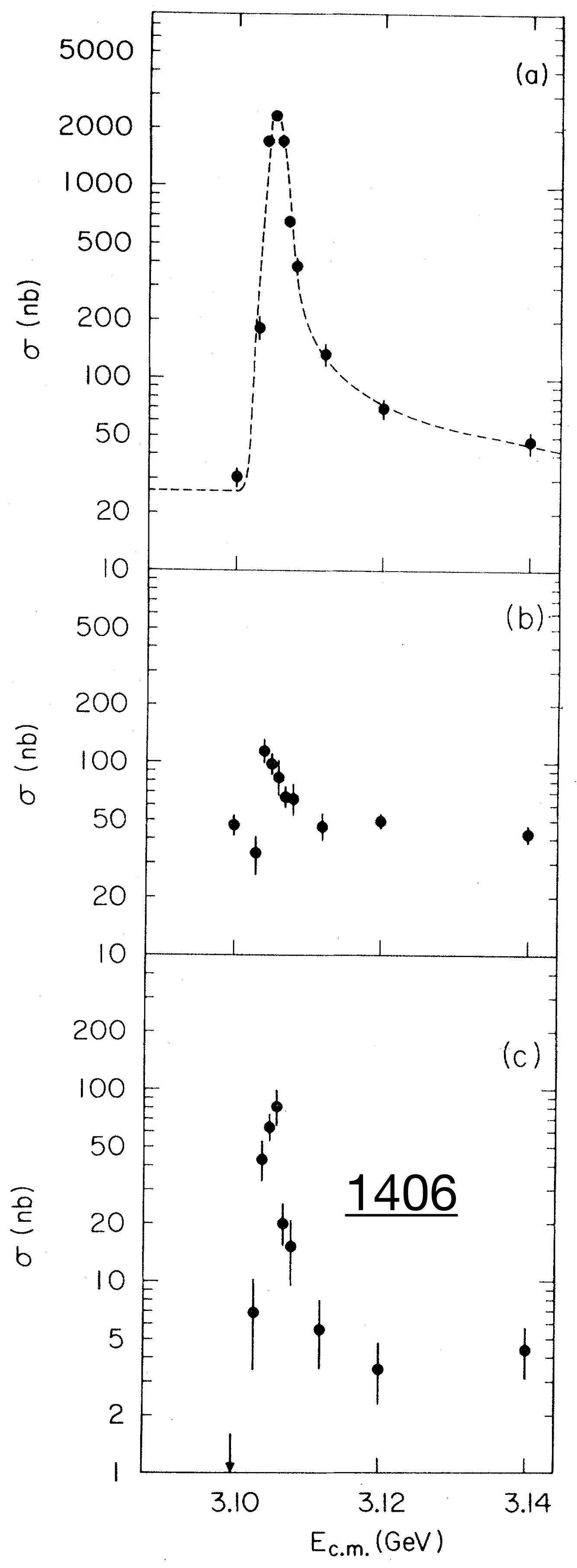

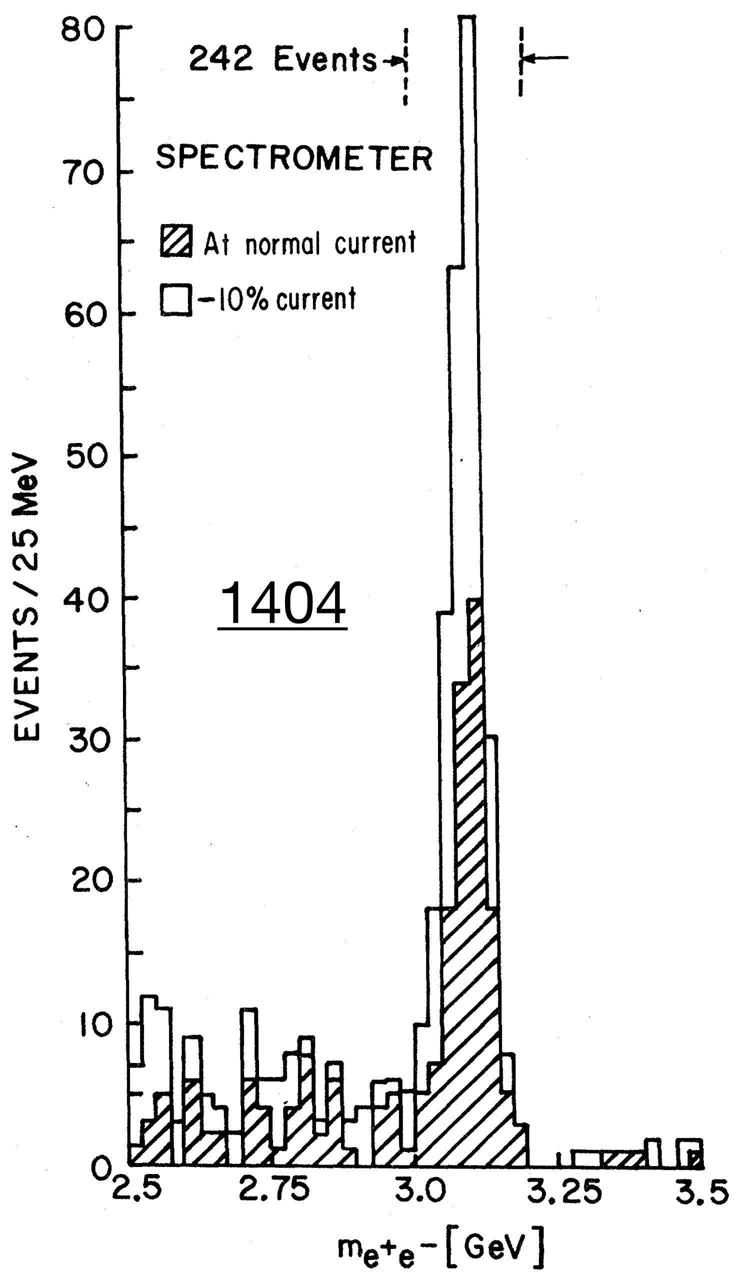

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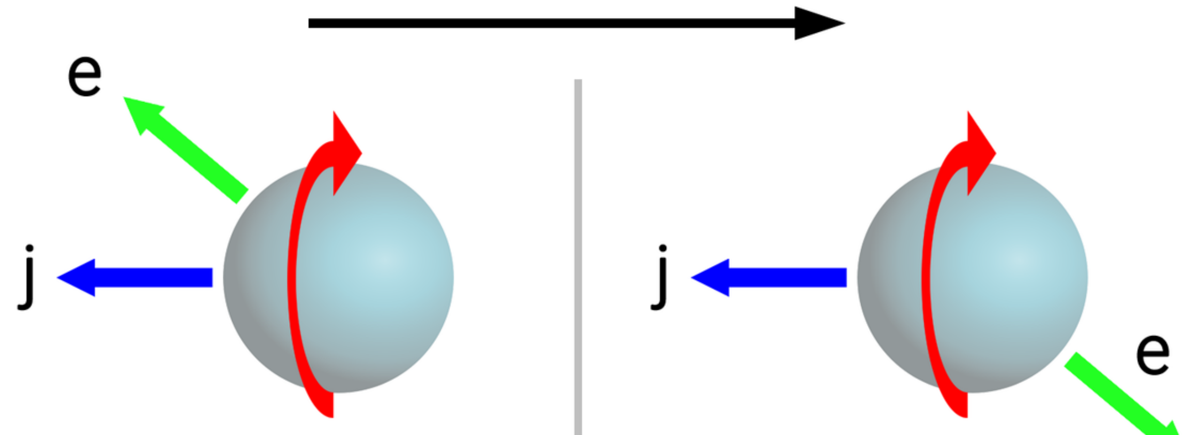
The story went on with the discovery of the **bottom** in **77** and the **top** in **95** both in Fermilab.

The photon, the weak and the Higgs

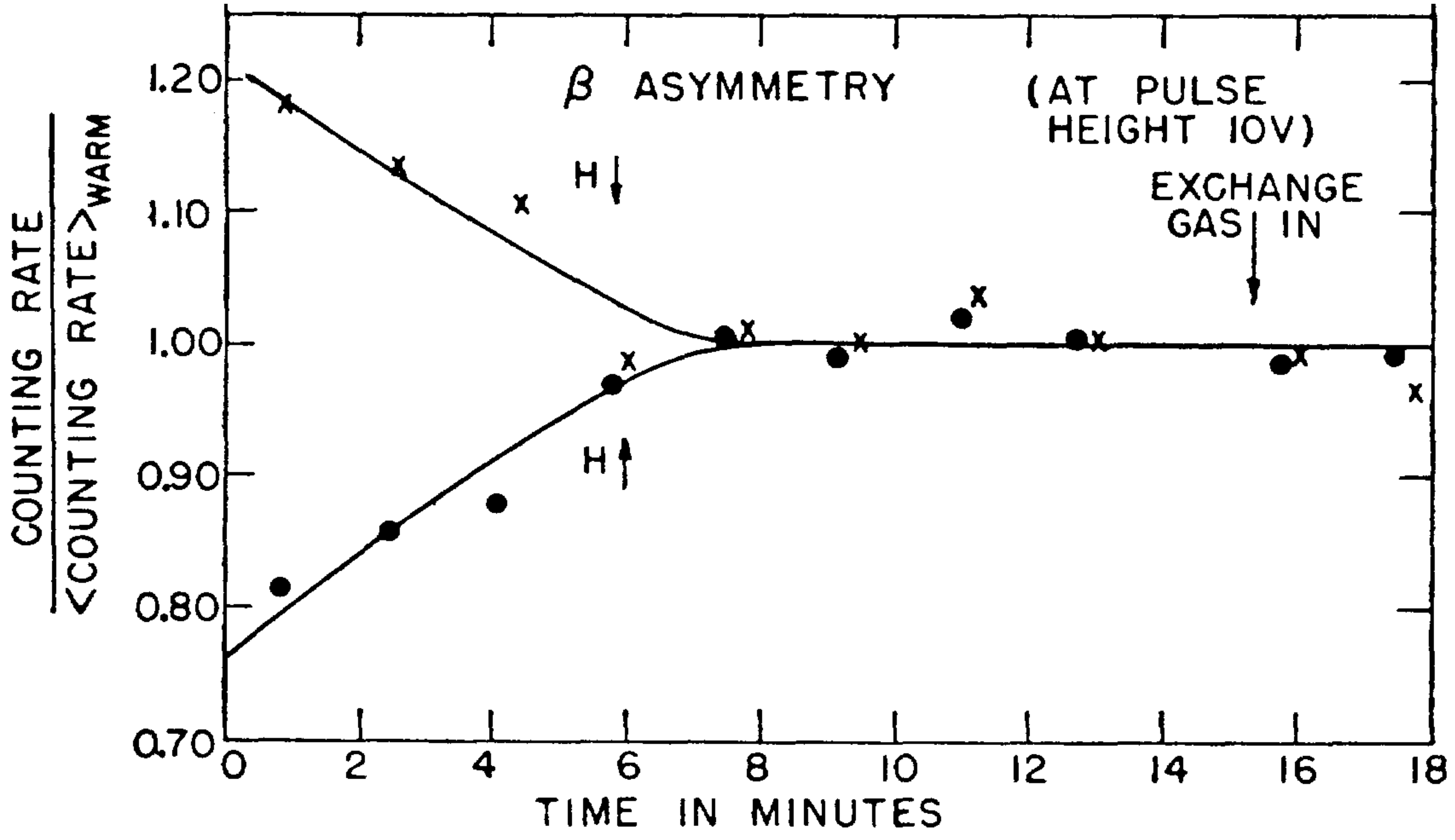
30s 50s 60s

In **1933** Fermi suggested that the β-decay of nucleus was due to a new interaction, designated later on as weak interaction.

But In **1956**, Wu showed that this interaction was violating the so called **parity** property: a breakthrough questioning the interplay between that and other forces like electromagnetism.



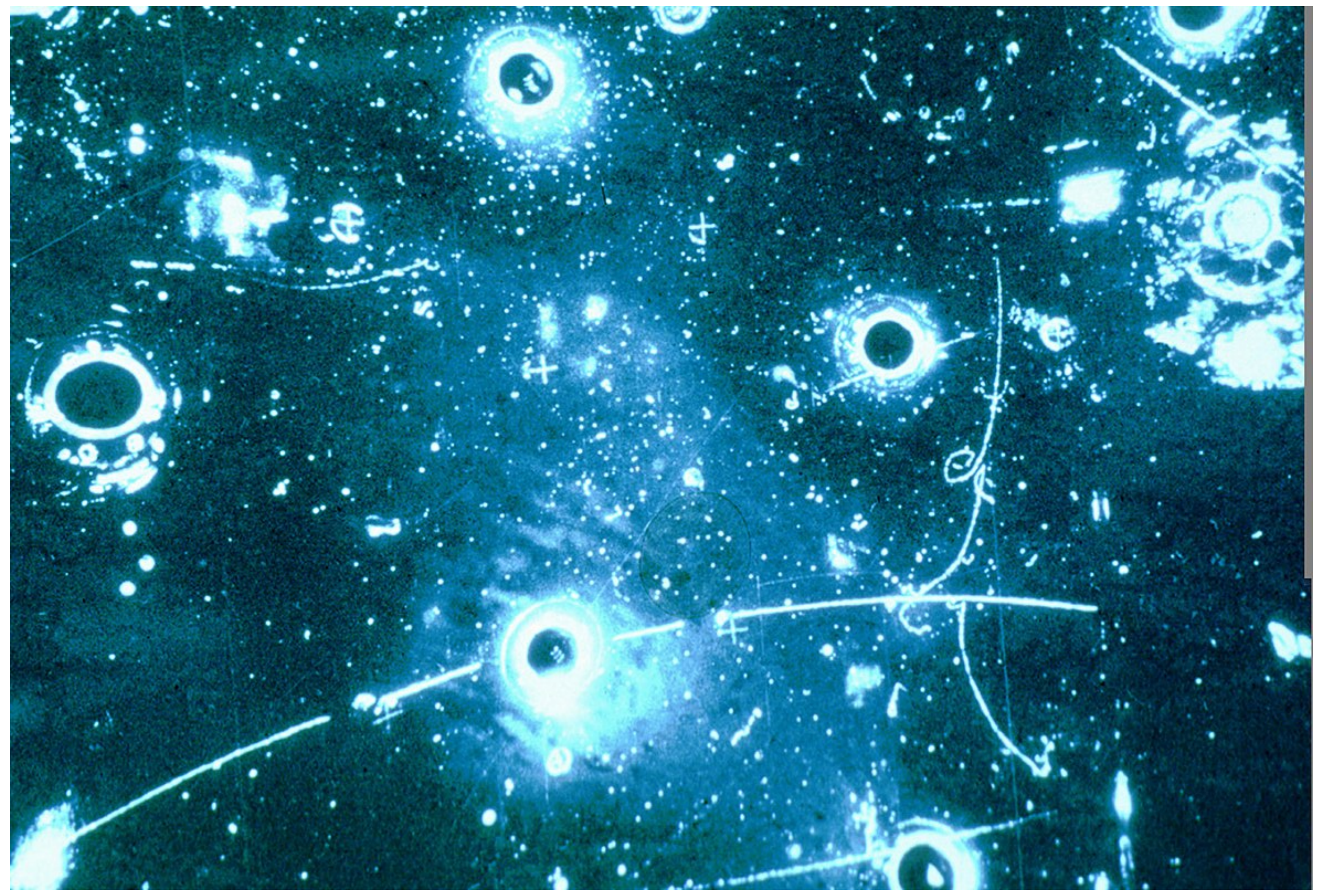
Physical Review. 105 (4): 1413–1415.



Between **61** and **67**, several theorists came out with possible solutions to restore the **"broken" symmetries**.

- Gladshow and Weinberg came with the first idea introducing new massive gauge bosons ;
- They would need another breakthrough to understand the spontaneous symmetry breaking of this...

The photon, the weak and the Higgs



Phys, Lett. B. 46 121 (1973)

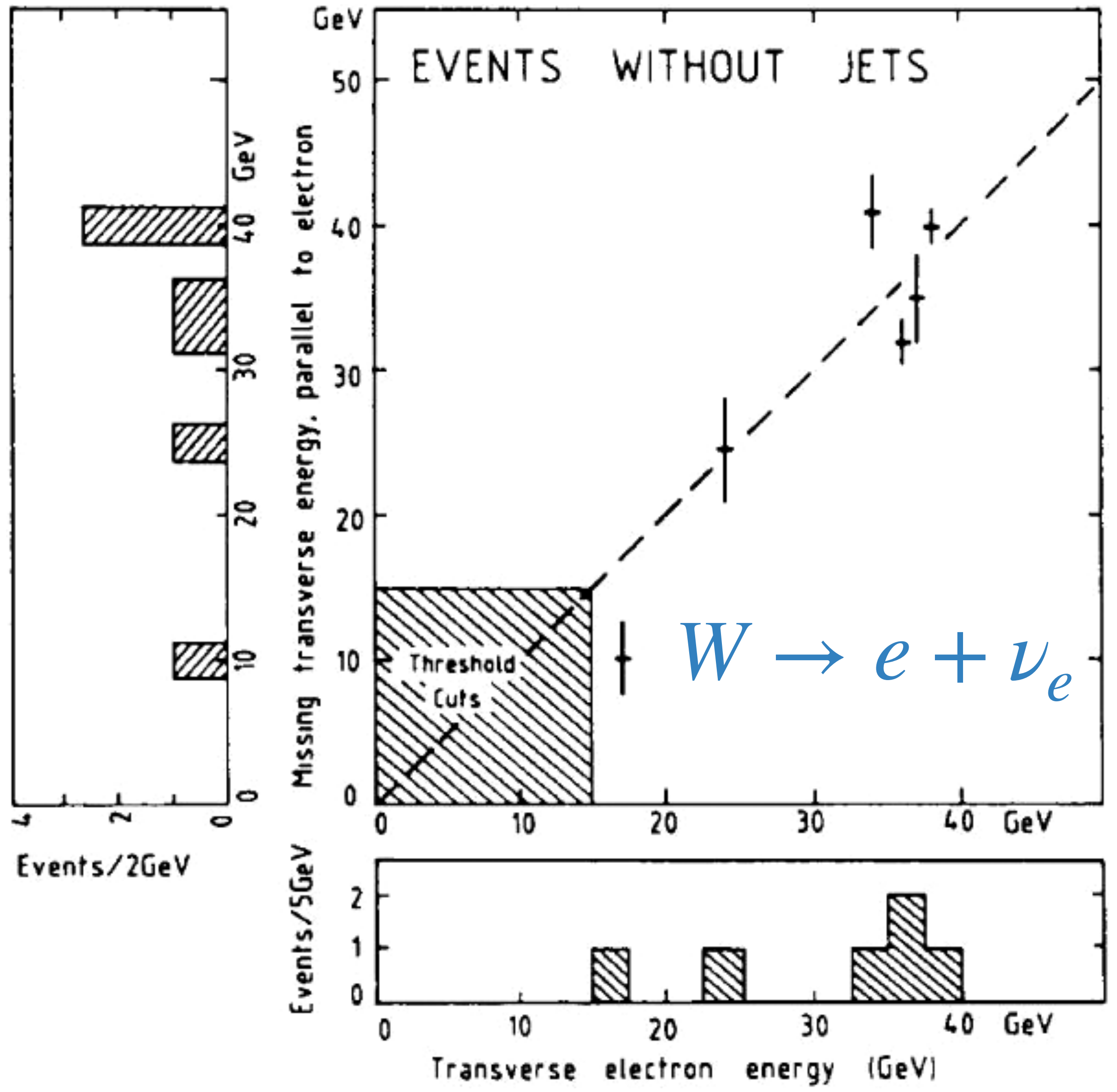
In **73**, Gargamelle at CERN found **evidence of neutral currents** in the leptonic and hadronic channels.

A clear sign that the Weinberg theory was correct.

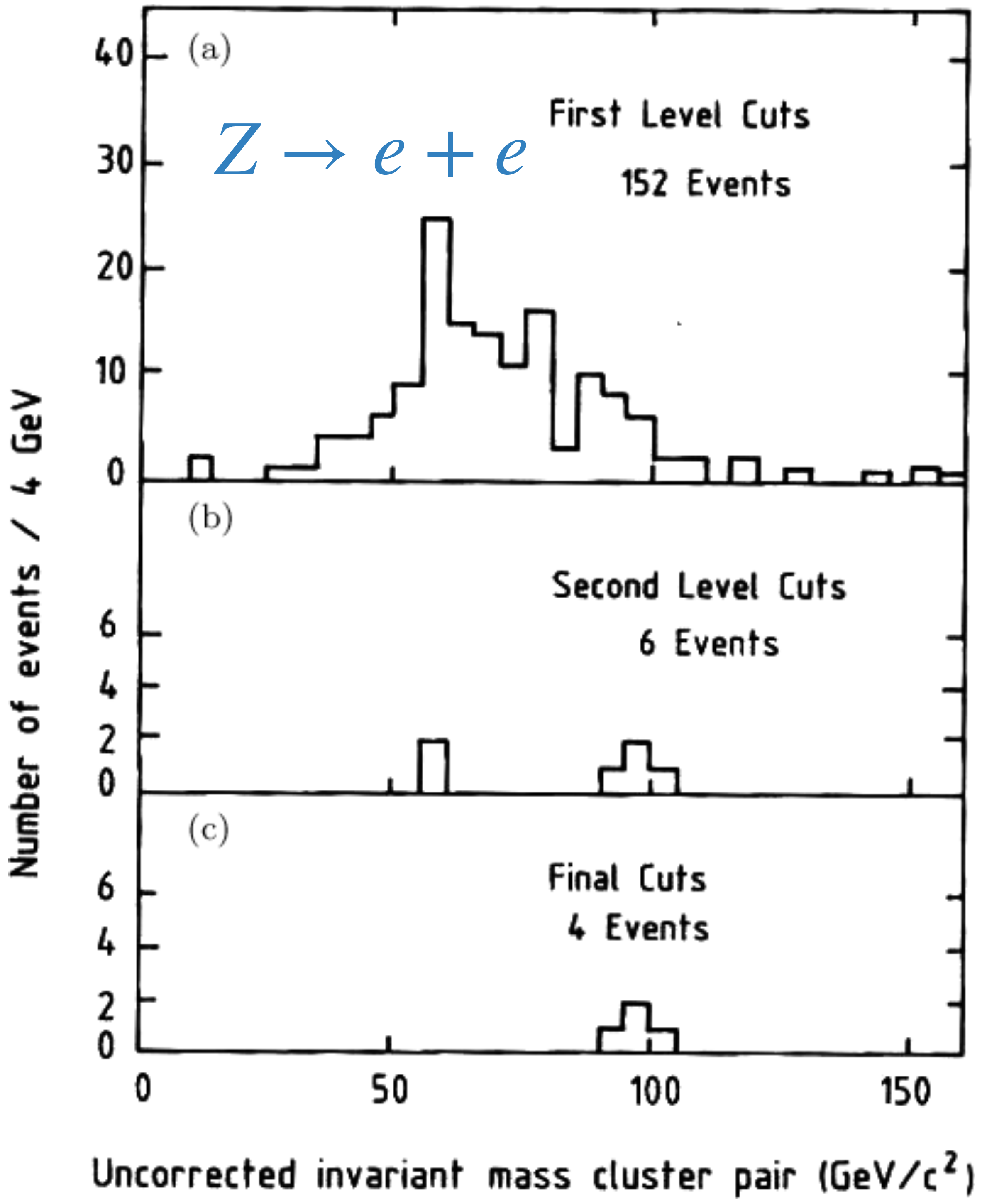
It was not until **1983** and the use of the SPS with a 450 GeV beam, that the UA1 and UA2 experiments could claim the direct **observation of the W and Z bosons** !

Have a look at the small signal and background...

Phys. Lett. B 122, 103 (1983).

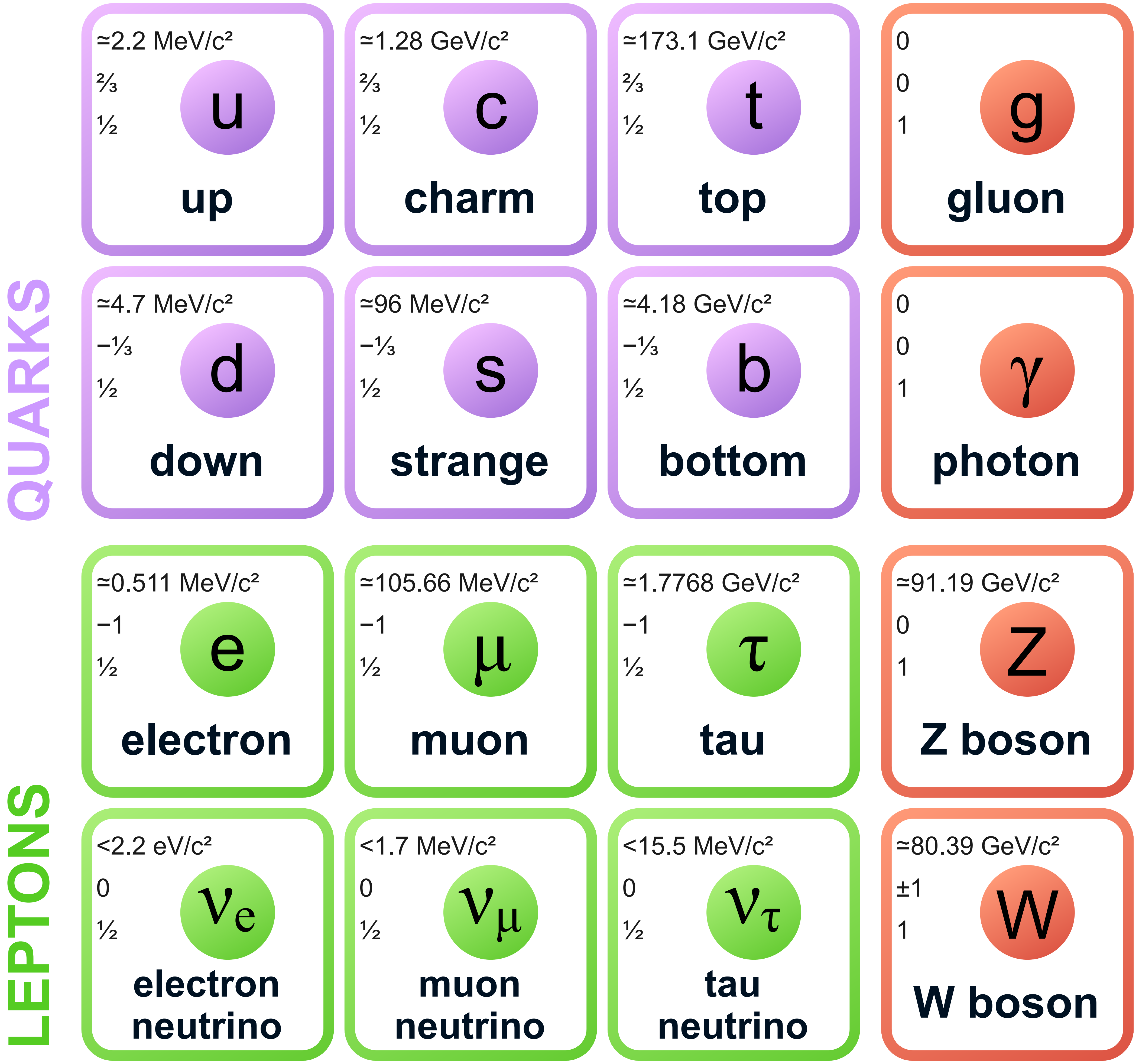


Phys. Lett. B 126, 398 (1983).



The photon, the weak and the Higgs

Now we have the SM as we understand it nowadays.



Or do we ?

The photon, the weak and the Higgs

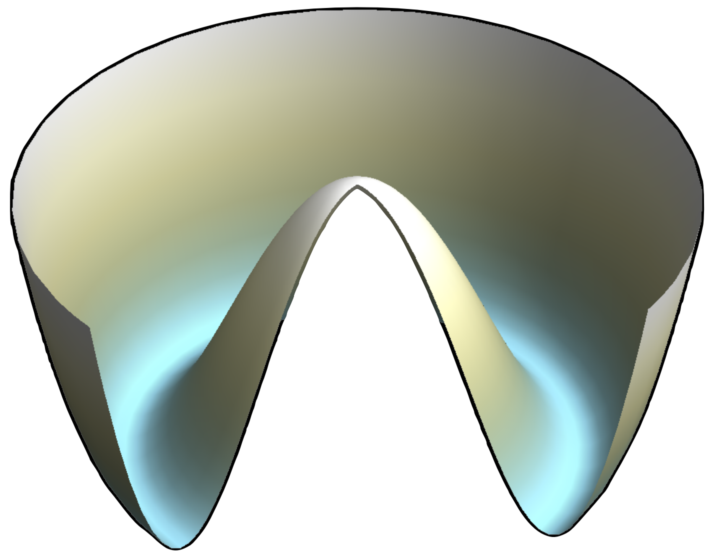
60s 70s

One massive problem in the theory is the need to accommodate for **massive gauge bosons**, while leaving the **photon massless** ...
The general SM theory is also unable to allow other elementary particles to get a mass (not even predicting their values).

Separately in **64** (Brout and Englert), (Higgs) and (Guralnik, Hagen and Kibble) utilised the concept of symmetry breaking through the phase transition of a new scalar field ϕ, causing a non trivial Vacuum Expected Value (v.e.v. noted ν).

The great success of this theory is when linearising the field around this v.e.v. you can get several terms:

- **3 massive gauge bosons** → $W^{\pm}$ (degenerate in mass) and Z with $m_W < m_Z$;
- **1 massless gauge boson** → photon;
- **A new boson** (now called Higgs boson) with unique properties: it can couple to itself !



$$V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

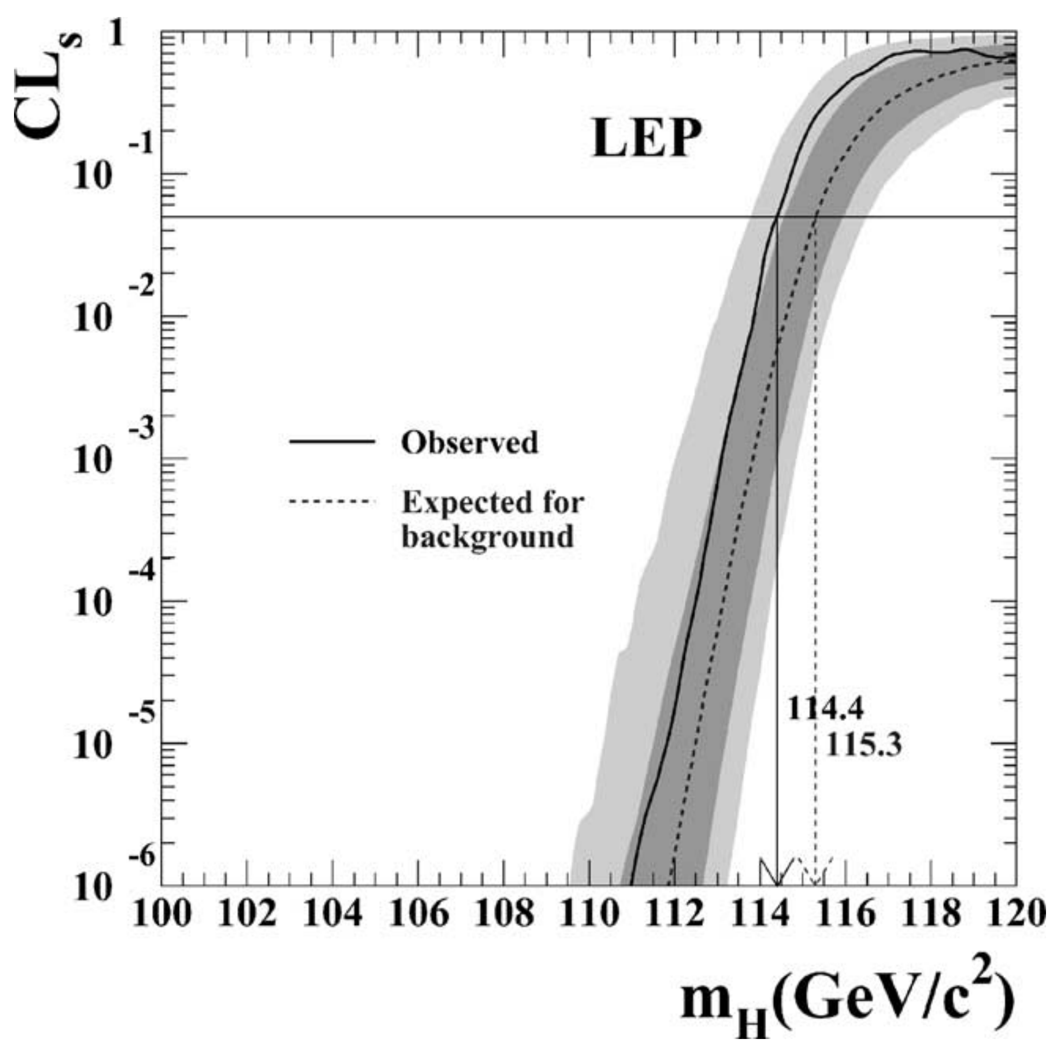
A side effect of this new scalar field, is the possibility to accommodate now for a **mass term for other particles** !

- The so-called Yukawa terms (introduced later on by Weinberg in **67**) are not originating from first principles but allow to describe in a compact way the oscillation and CP violation proposed by Cabibbo–Kobayashi–Maskawa in the famous CKM matrix in **73** !

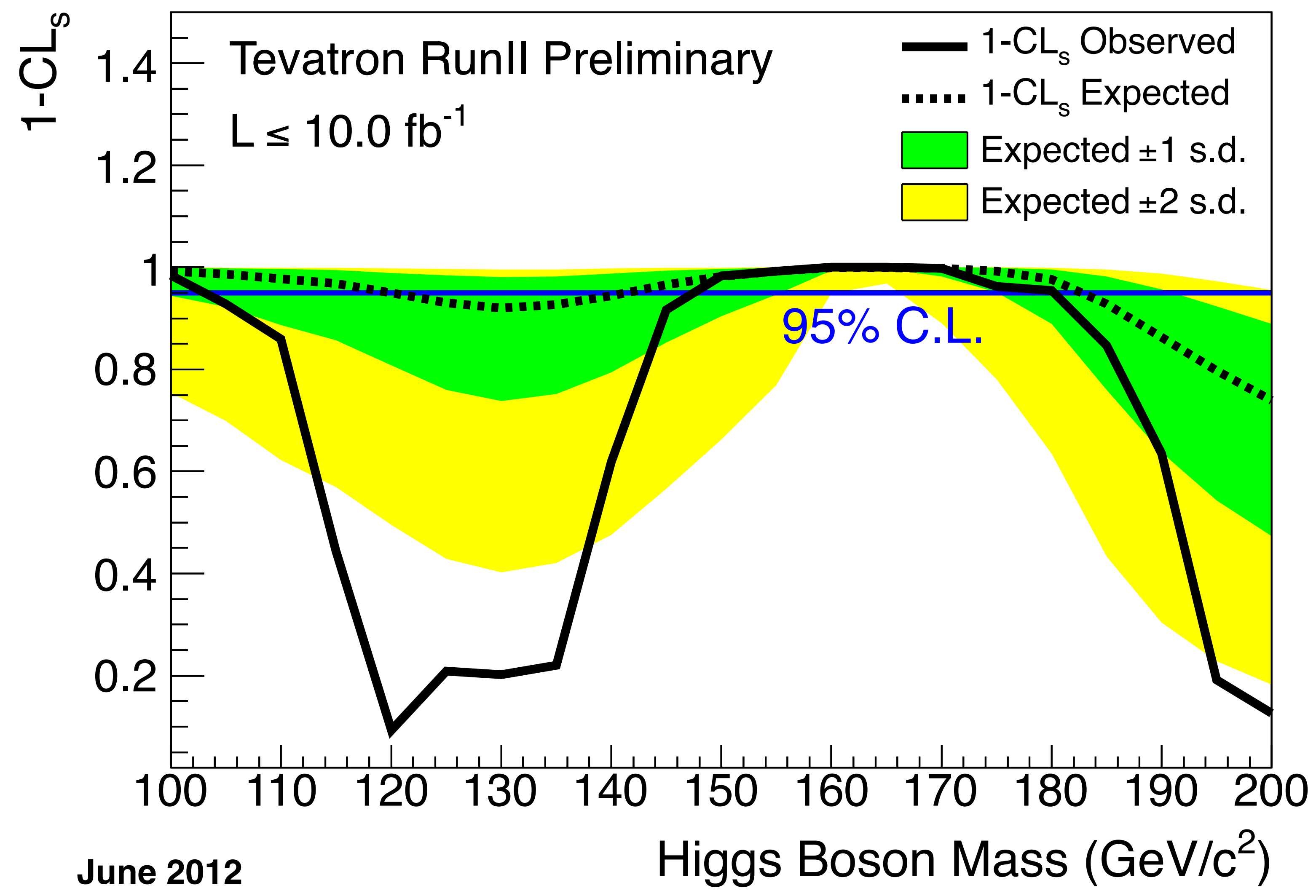
The photon, the weak and the Higgs

90s 10s

It took a long journey even with the most advanced machines to reach the discovery !



Physics Letters B 565 (2003)

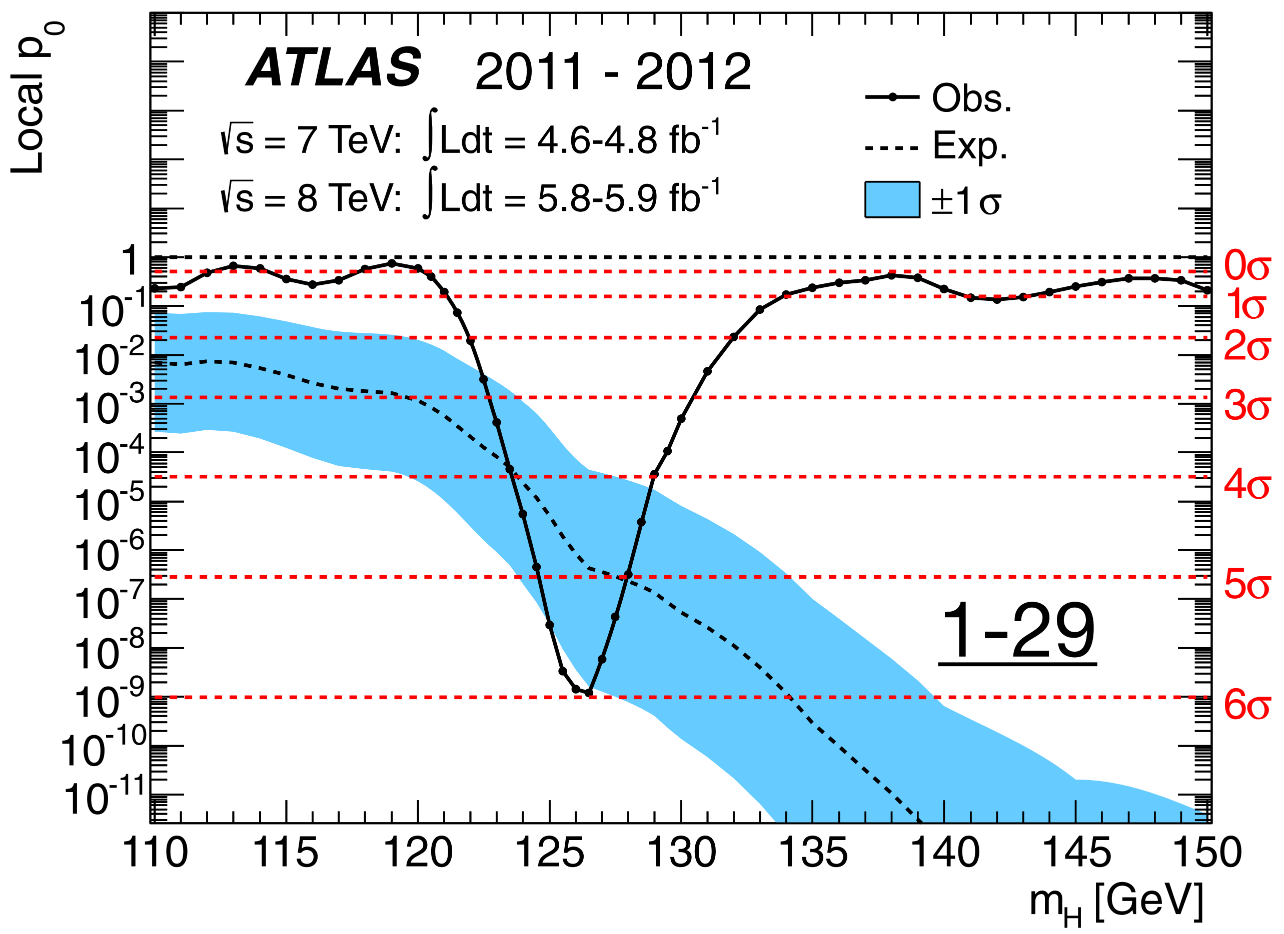


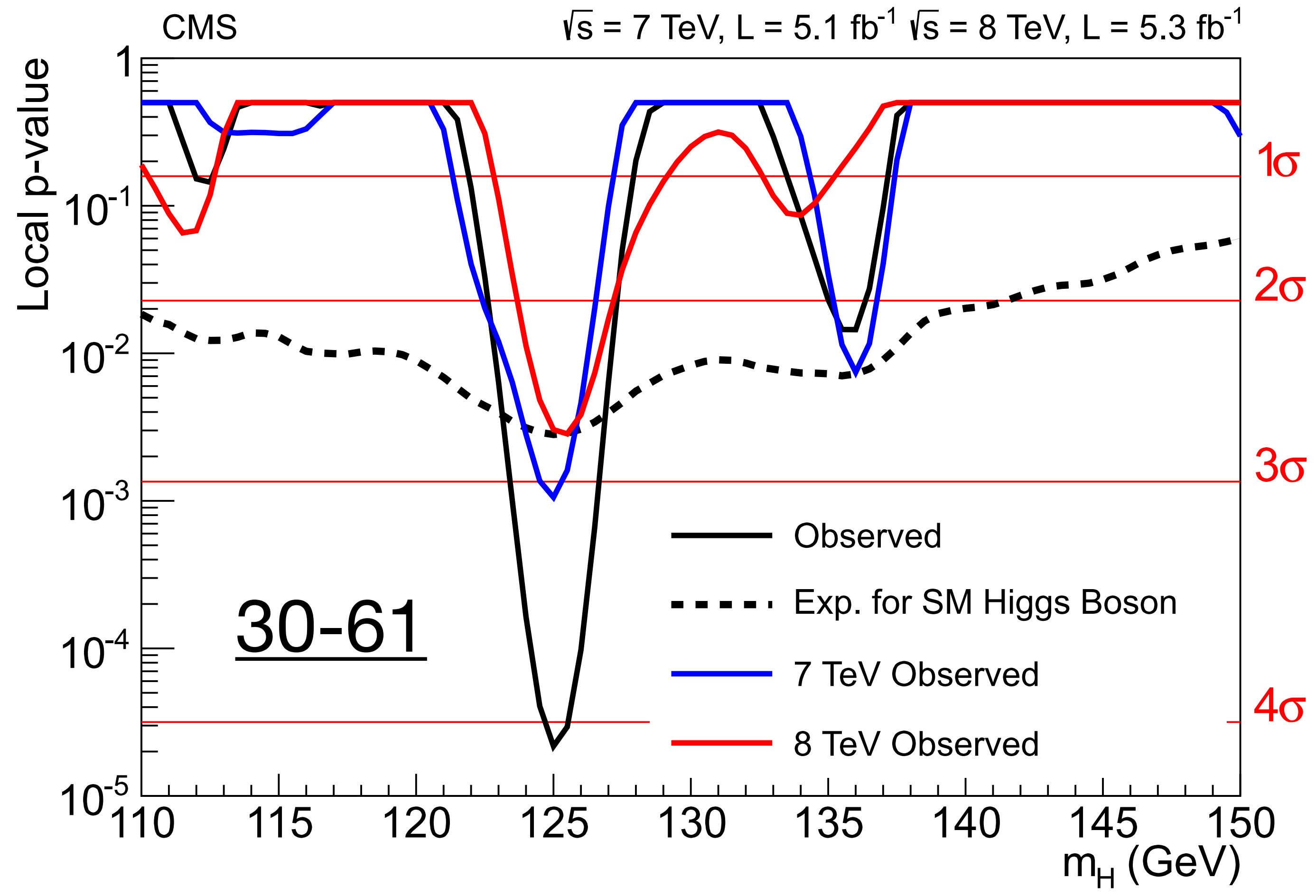
Arxiv:1207.0449

- At **LEP**, a small excess was reported in ALEPH at 114 GeV, but got discarded by the others.
  - CERN decided to stop LEP in **2000** to start the construction of LHC ...
- **Tevatron** ran up until **2011** and published several results in 2012 trying to chase LHC ...

After few ~3σ excesses shown at Moriond QCD 2012 from LHC experiments ATLAS and CMS, a seminar was organised at CERN on the **4th of July 2012**:

"I think we have it"

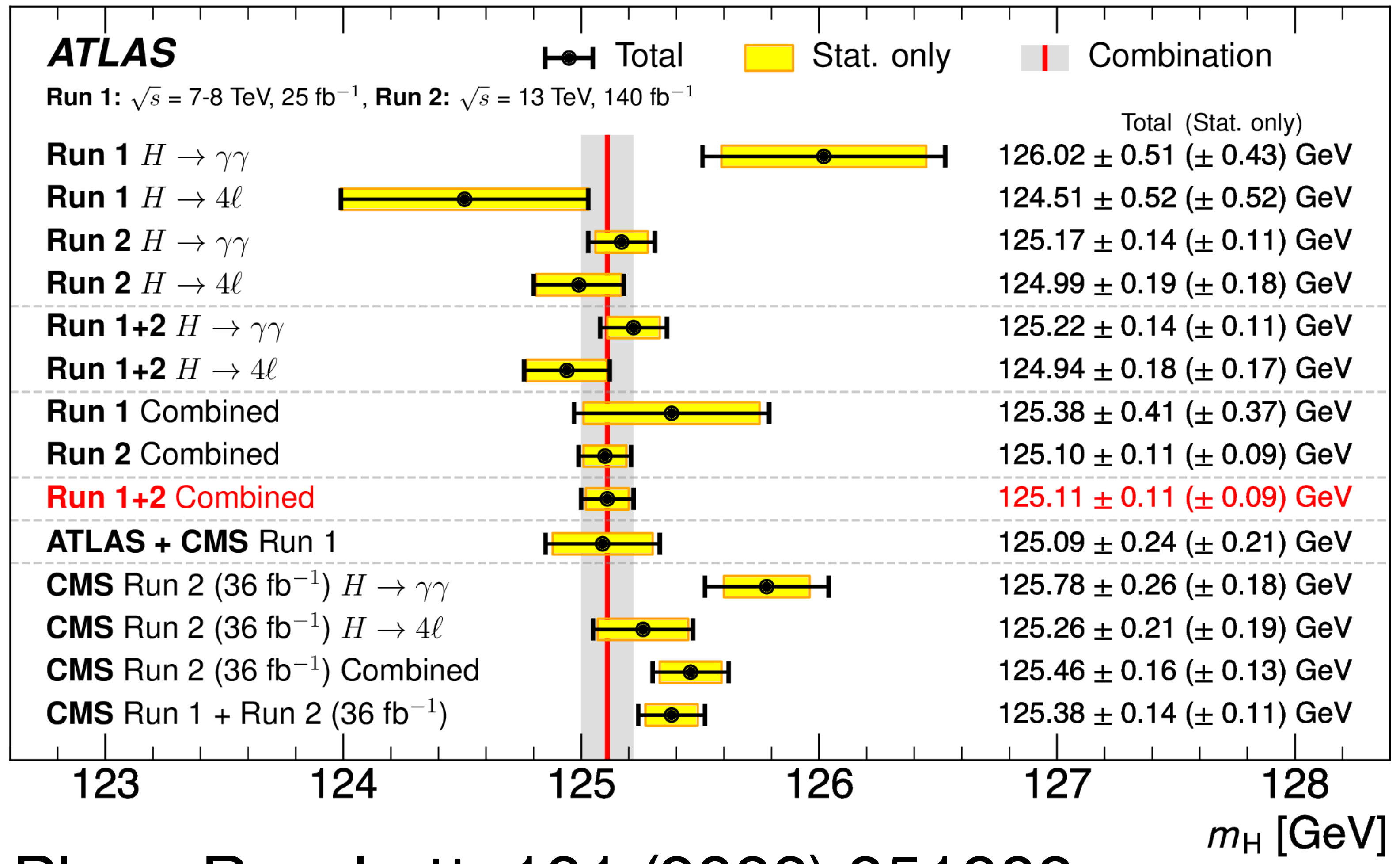




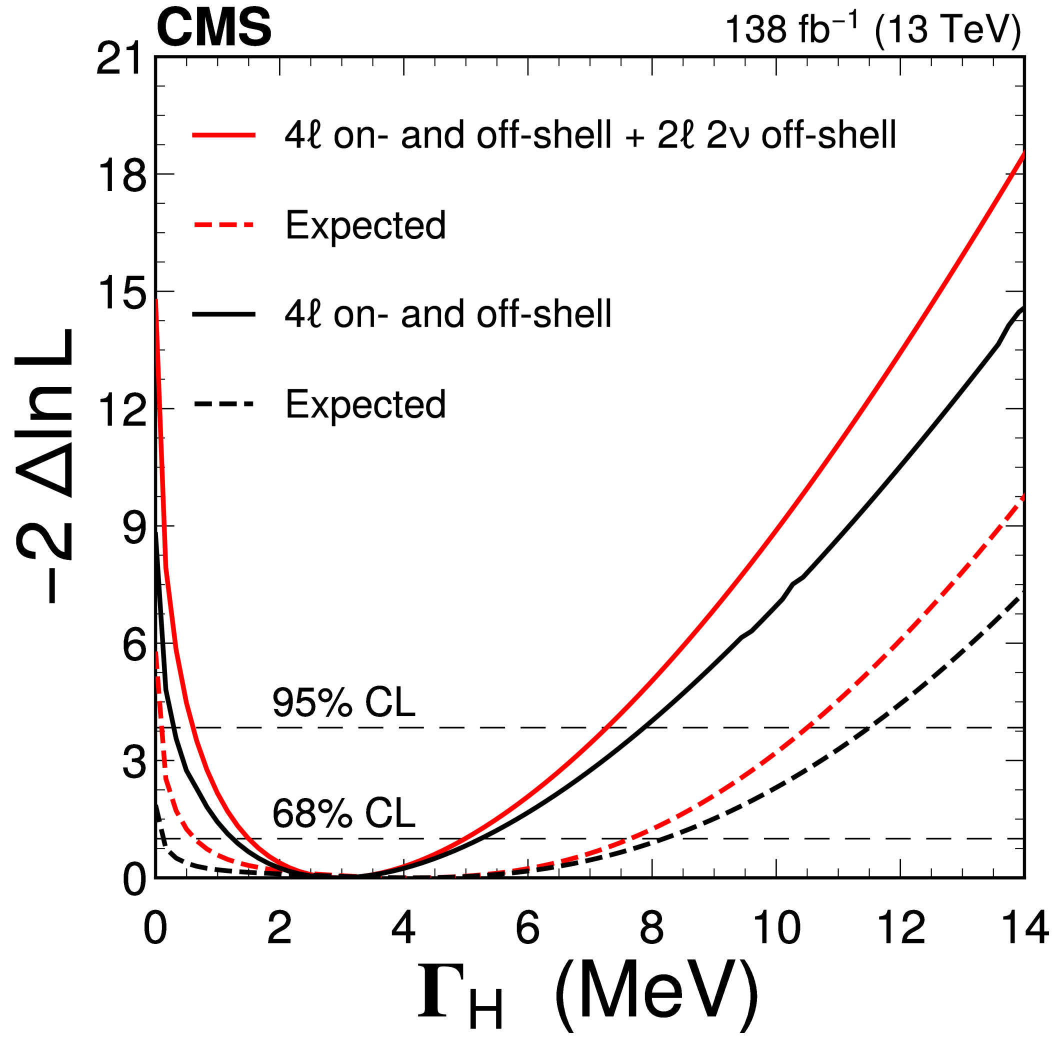
Physics Letters B 716 (2012)

The Higgs portrait to this day

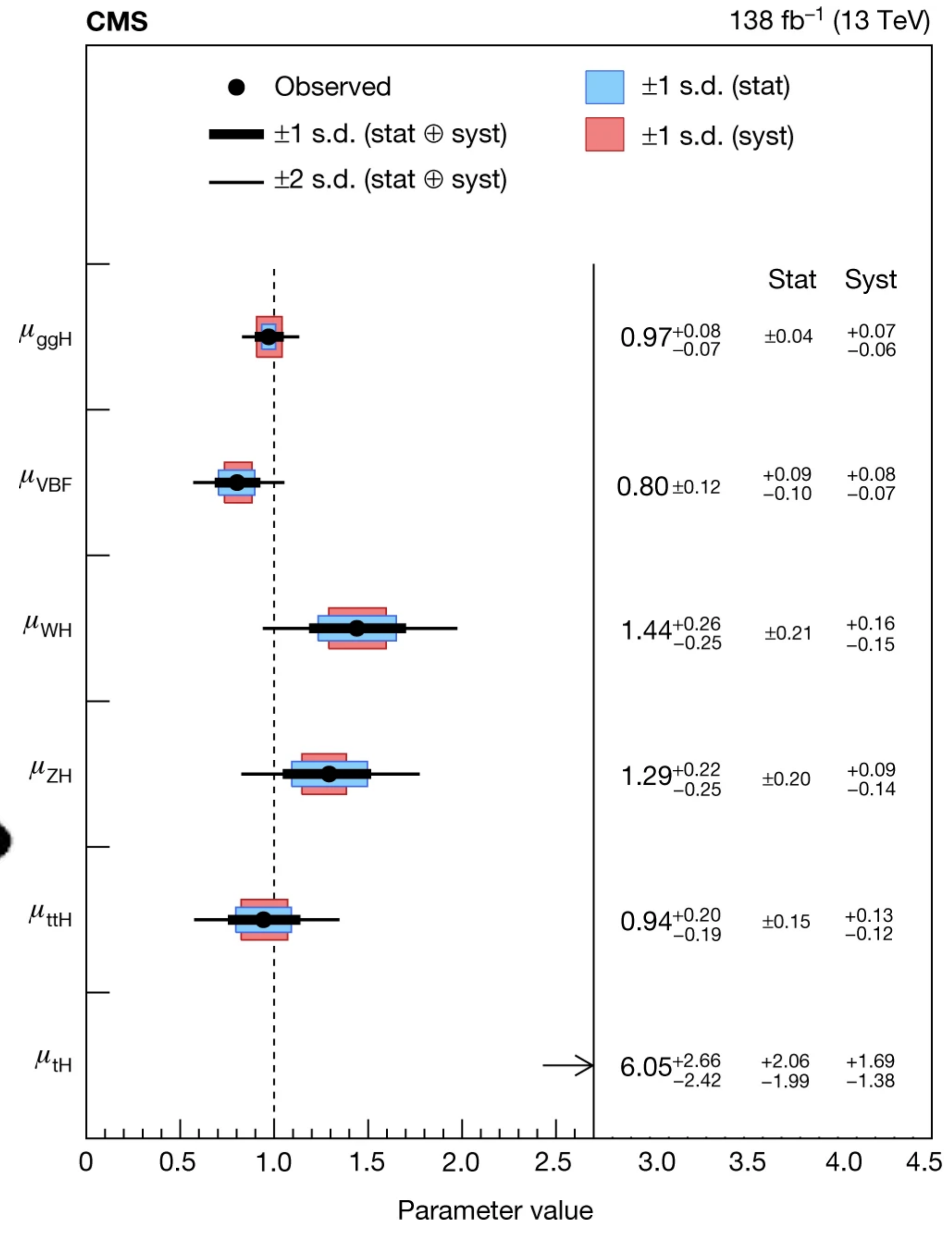
See more in Ragansu's talk

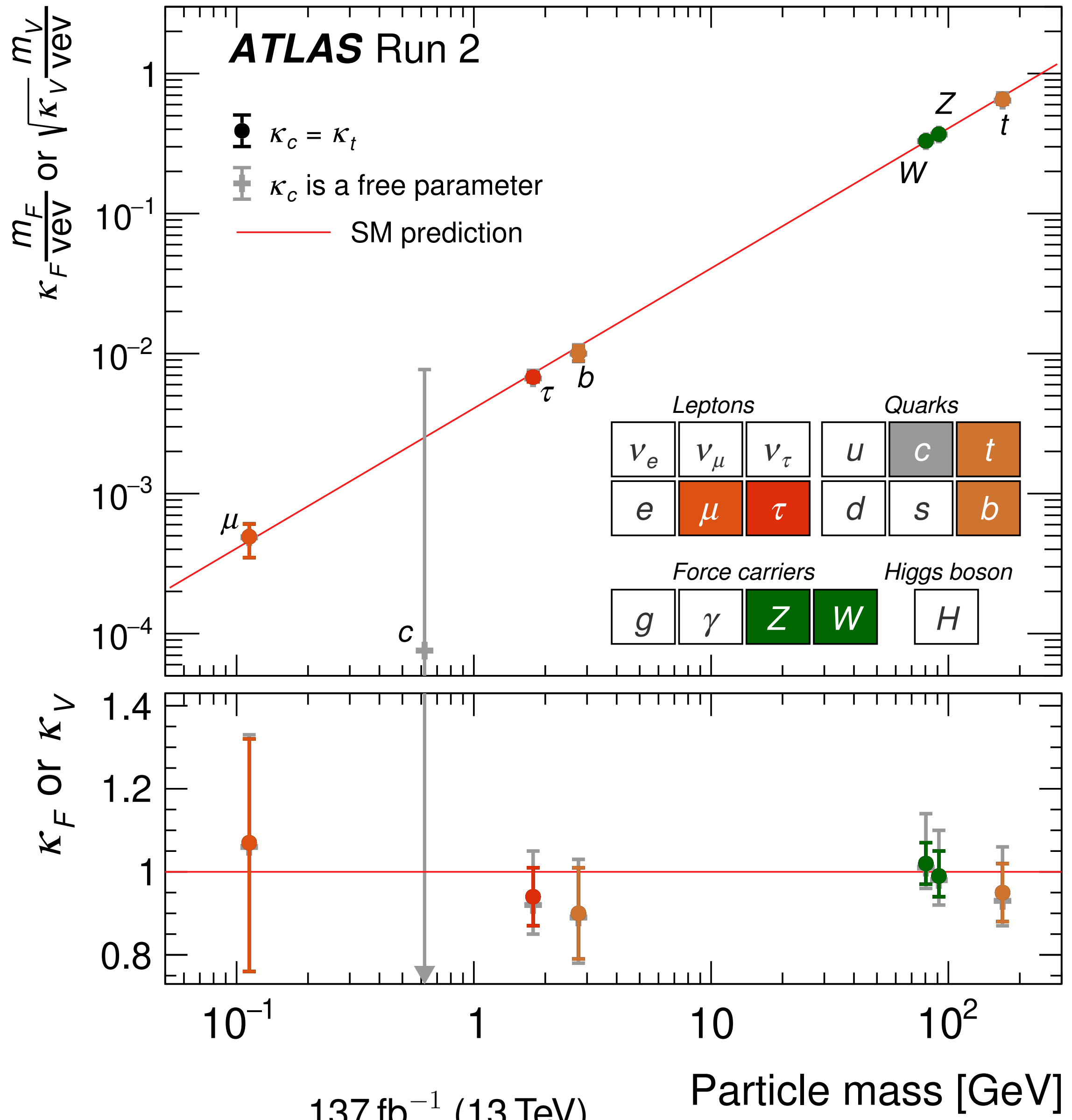


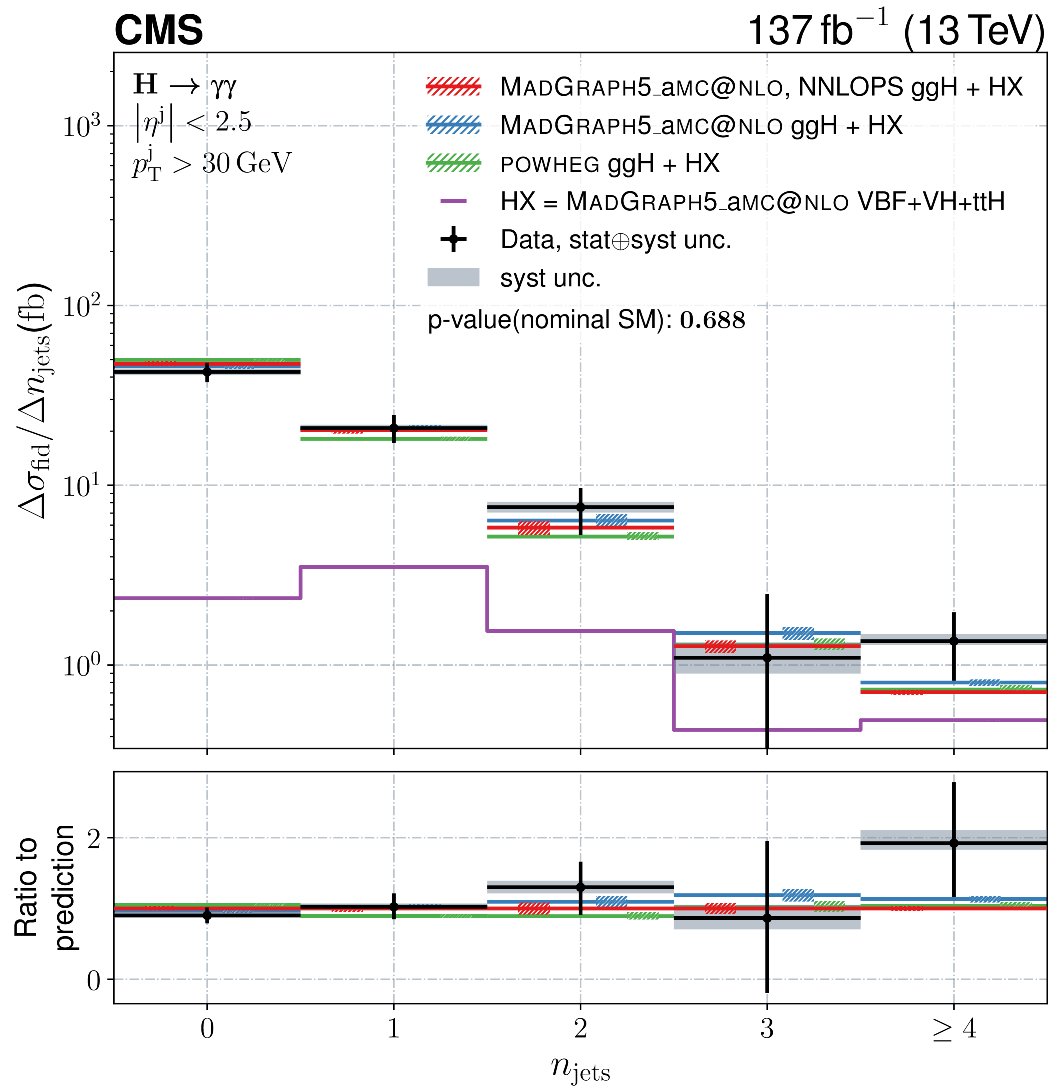
Phys. Rev. Lett. 131 (2023) 251802



Sub. to Phys. Rev. D







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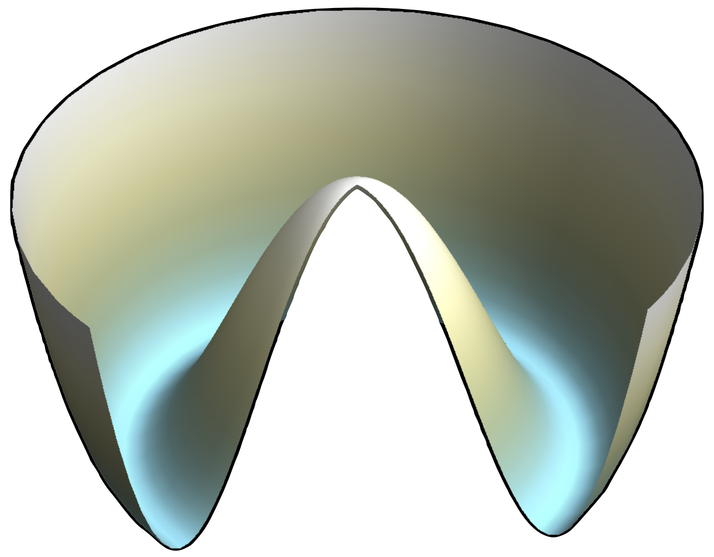
A lots of measurements !

- **Mass** to per mile level;
- The top 4 **production modes** probed;
- All the **decays** to 3rd generation and starting to probe 2nd generation.
- Even the **differential cross-section** is probed.

The future is Higgs

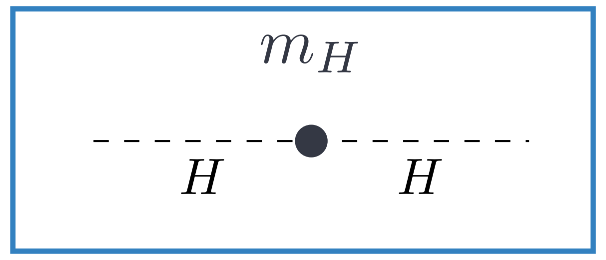
See more in Arthur's talk

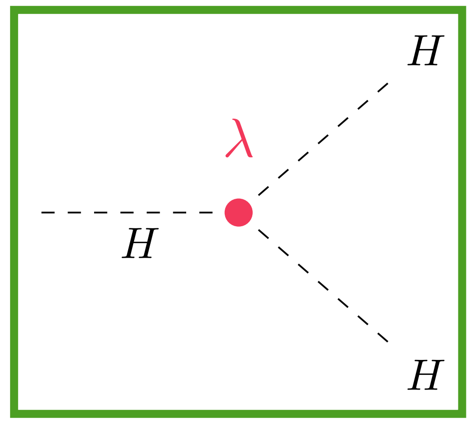
When linearising the Higgs potential around the vev, one gets :



$$V(H) \supset \underbrace{\mu^2}_{\frac{1}{2}m_H^2} H^2 + \lambda \nu H^3$$

Two parameters of the potential linked by: $\lambda = \dfrac{\mu^2}{\nu^2} = \mu^2 \sqrt{2}\, G_F$

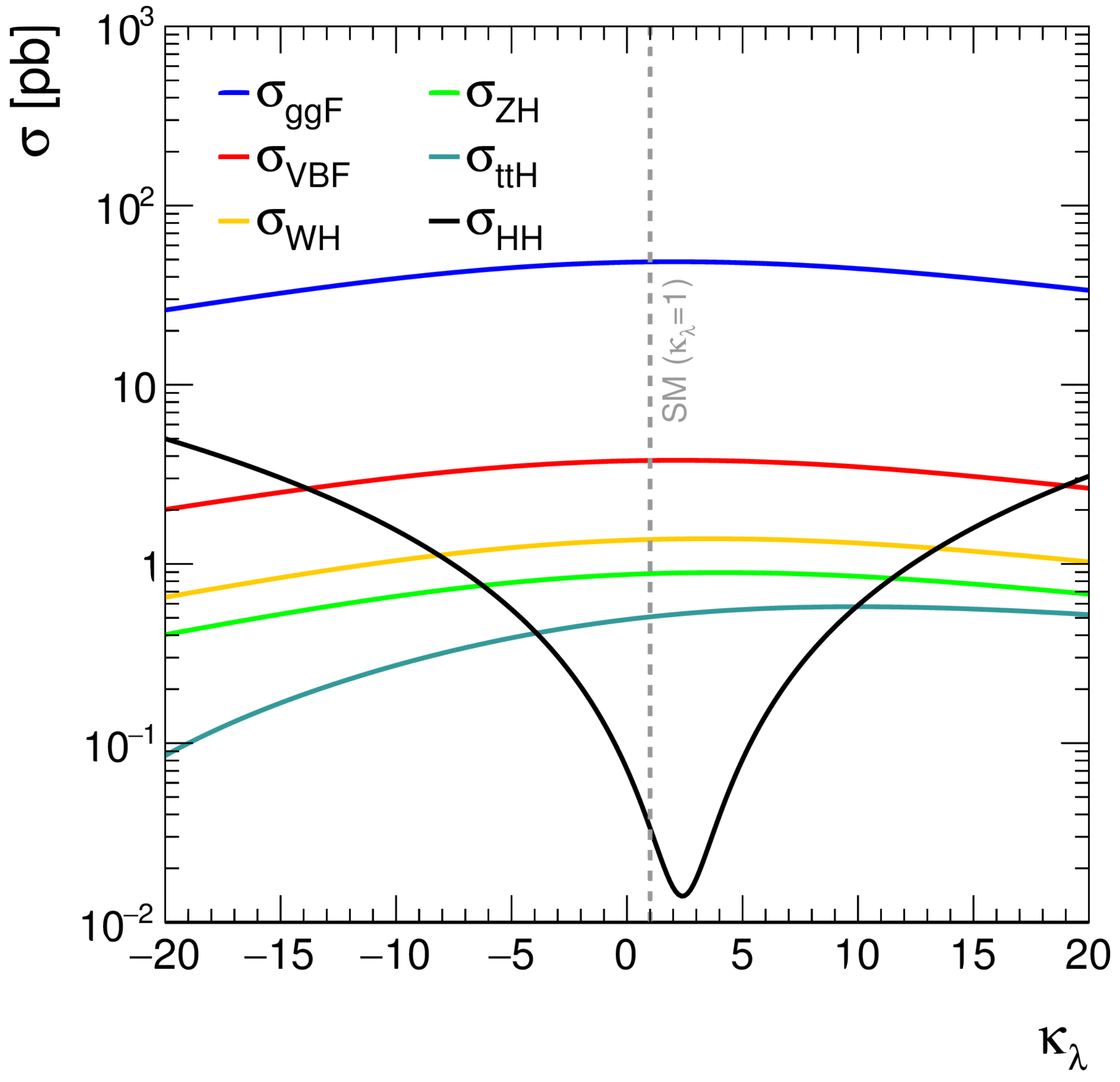


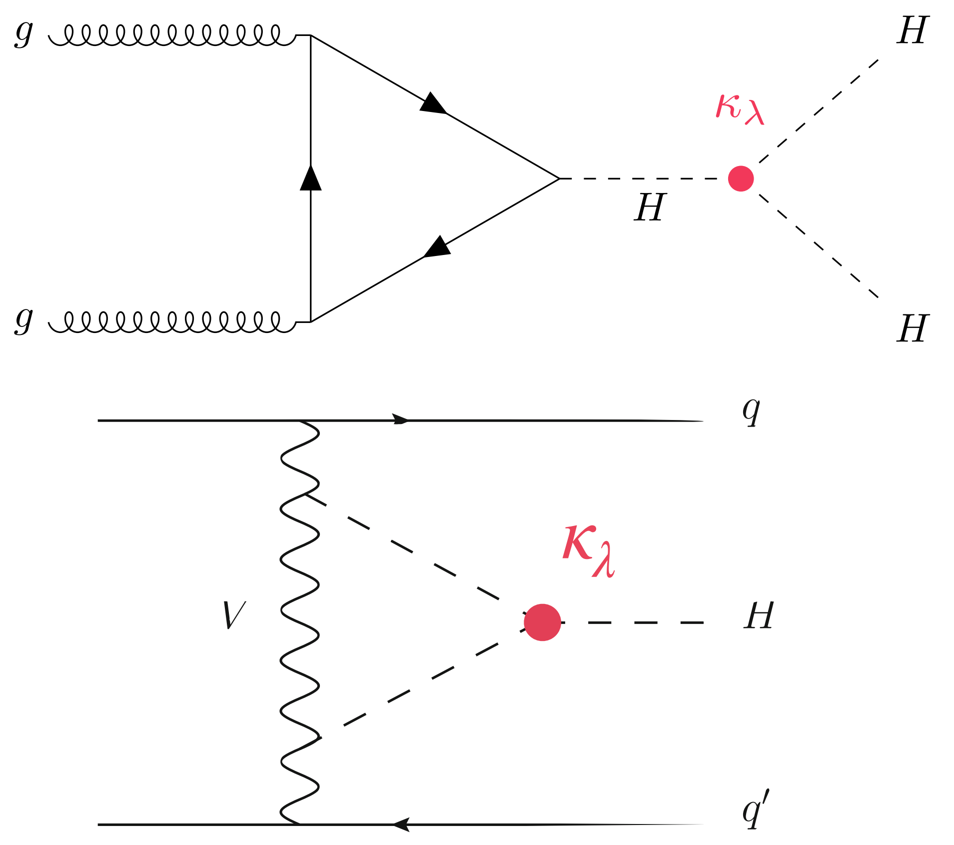


- Direct access to λ through Higgs pair creation:
  - Coupling strength denoted as $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$
  - In direct way this is measured with production of **pair of Higgs bosons** →strong effect on XS.
  - In indirect way this has an effect on the **single Higgs cross-section** and deviations in kinematics.

- The first piece of information came from the Higgs boson discovery:
  - First measurement of Higgs mass, combined with precise determination of G_F:

$$m_H = 125.09 \text{ GeV}$$
$$\leftrightarrow \mu = 88.45 \text{ GeV}$$
$$\leftrightarrow \lambda_{SM} = 0.13$$

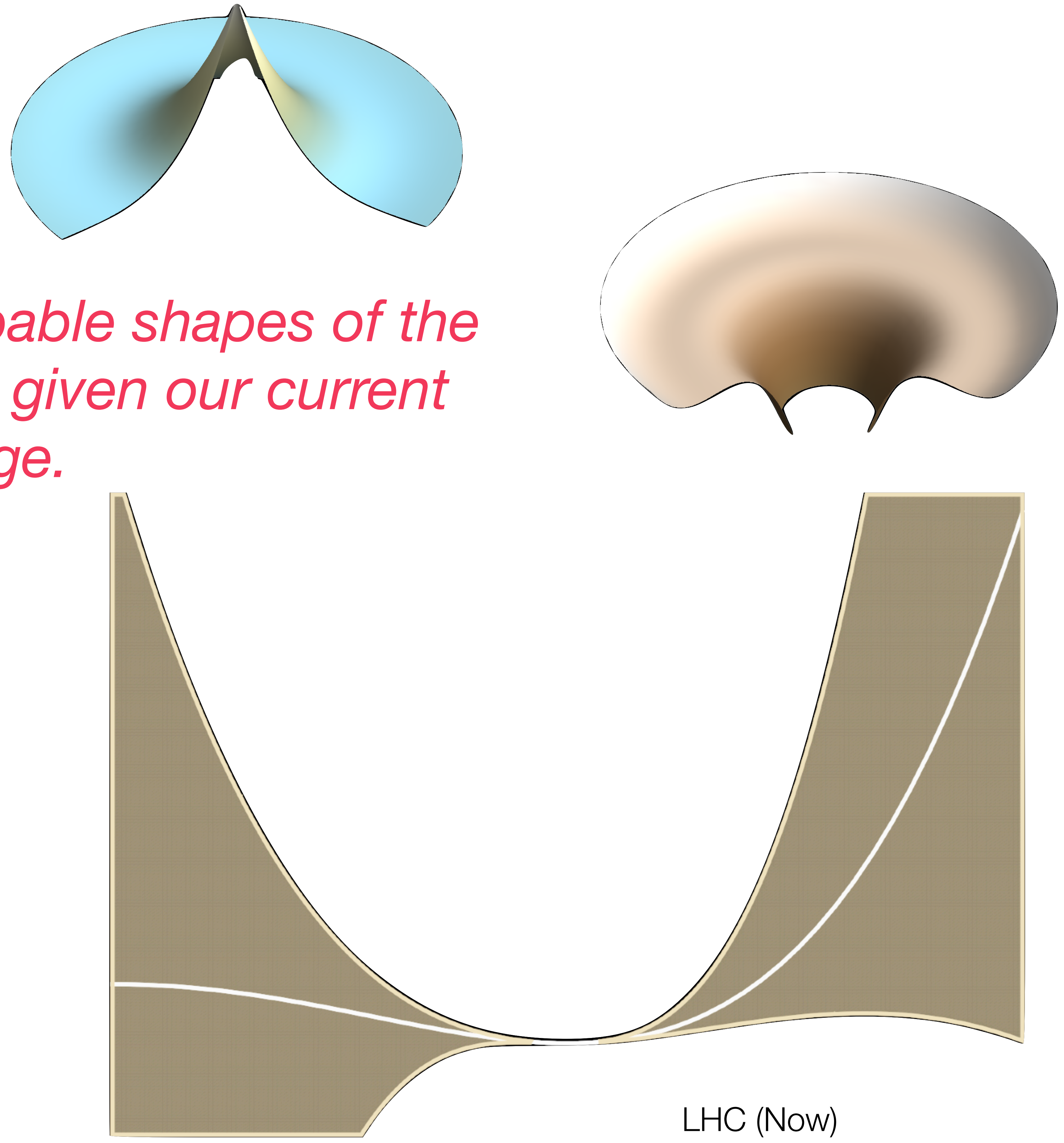


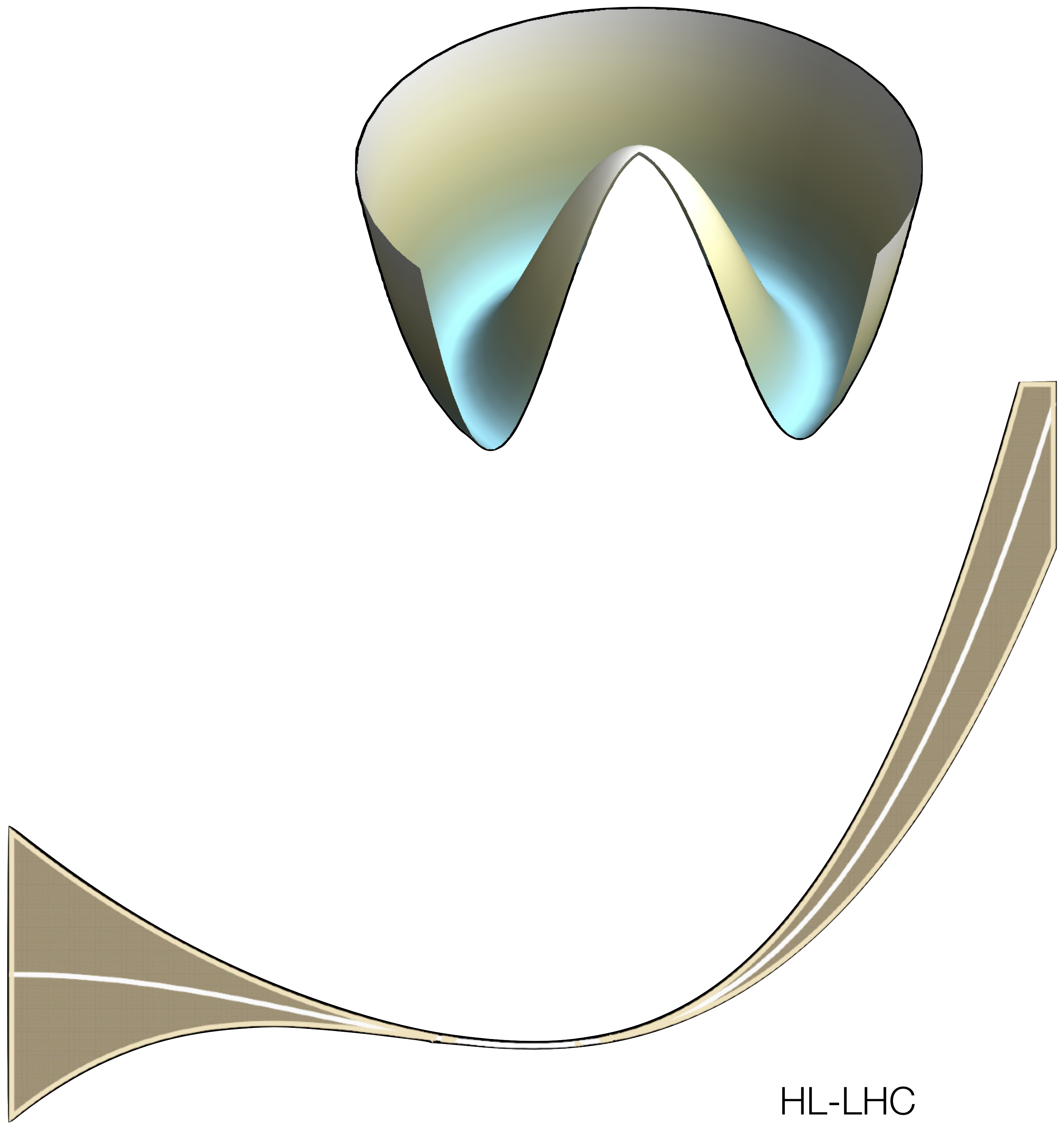


Exploring alternative scenarios

The measurement of the Higgs potential is a key element to answer the **nature of its mechanism**.
The exact value of λ can lead to very different shapes and could help us to understand better the type of transition that occurred from the high temperatures to the current situation.

Equiprobable shapes of the potential given our current knowledge.





Taken from Nathaniel Craig's talk

Exploring alternative scenarios

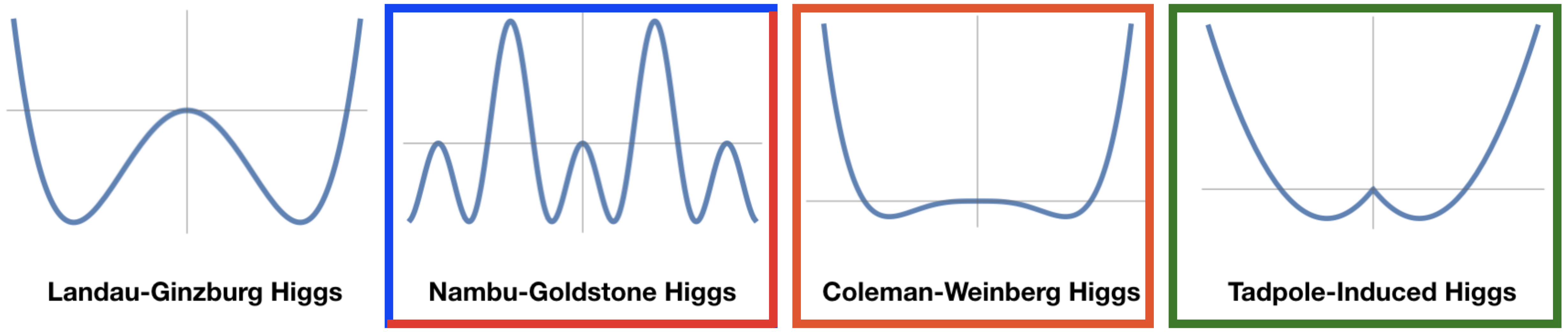
Several other models can show a non zero vacuum expected value with a different second order contribution:

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

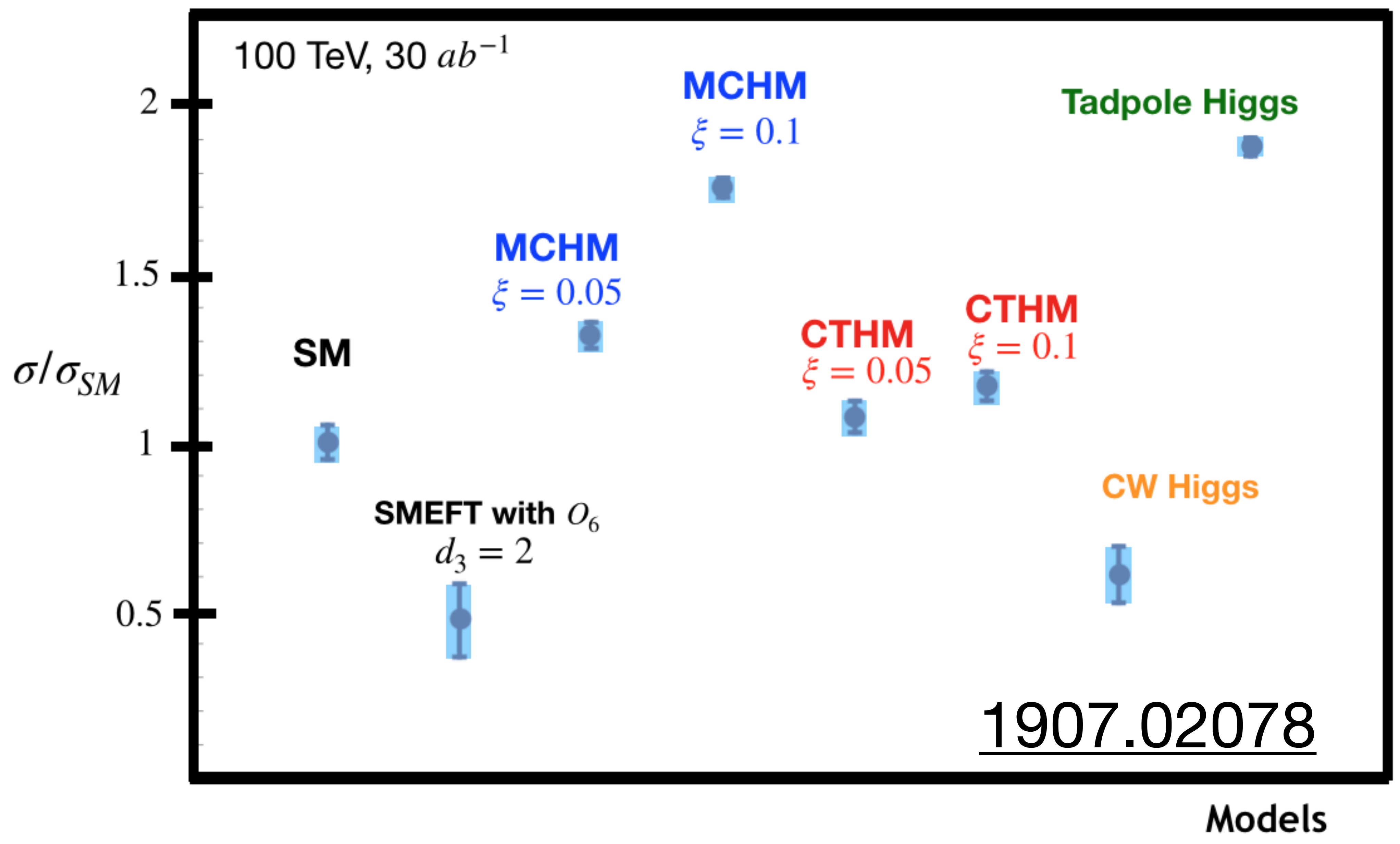
pseudo Nambu-Goldstone boson emerging from strong dynamics at a high scale

EWSB is triggered by renormalization group (RG) effects.

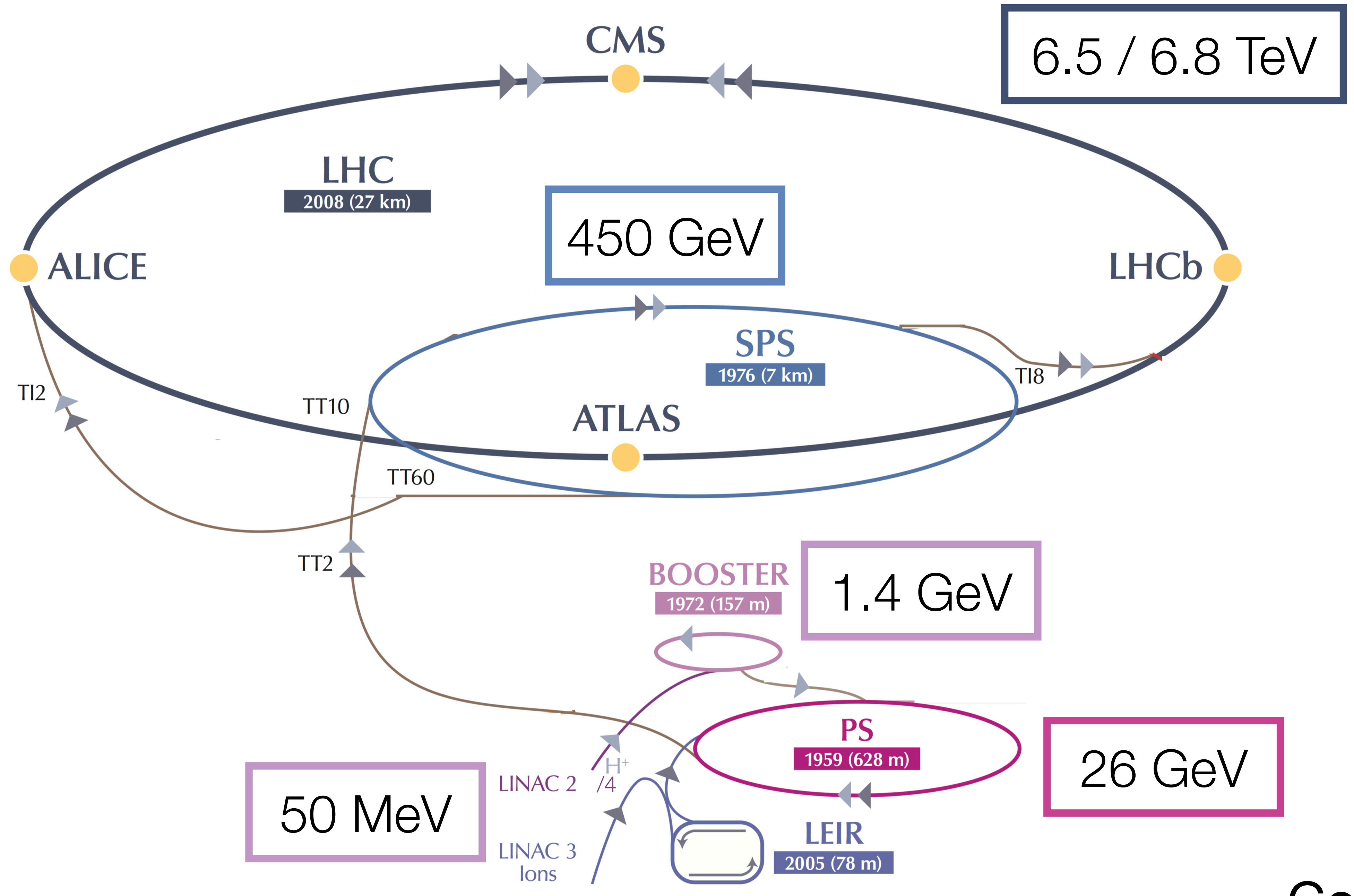
EWSB is triggered by the Higgs tadpole



minimal composite Higgs model/
composite twin Higgs model :
different coupling to top quark



How to produce theses particles ?



Located under the French-Swiss border, the **Large Hadron Collider** is the final piece of a staged acceleration chain allowing high luminosity **proton-proton** collisions.

With a 13 TeV center-of-mass energy, it has allowed the ATLAS and CMS collaboration to record $\mathscr{L} \simeq 140\, fb^{-1}$ of data during the **Run-2** phase of the LHC.

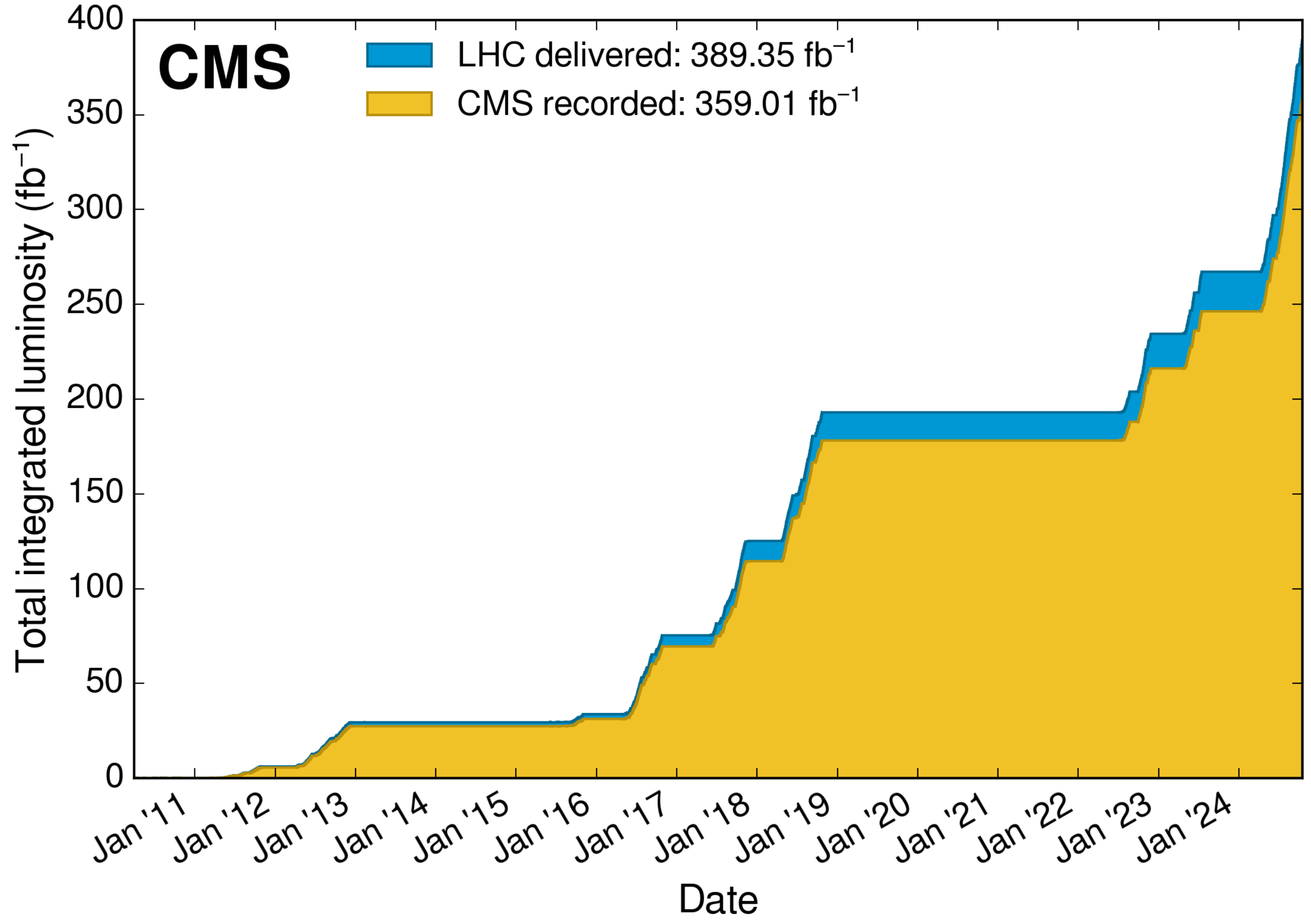
	N_H	N_{HH}
Run-1	512,000	200
Run-2	6,800,000	4,300
Run-3*	7,700,000	5,000
HL-LHC*	165,000,000	110,000

**estimated*

Physics

Collider performance

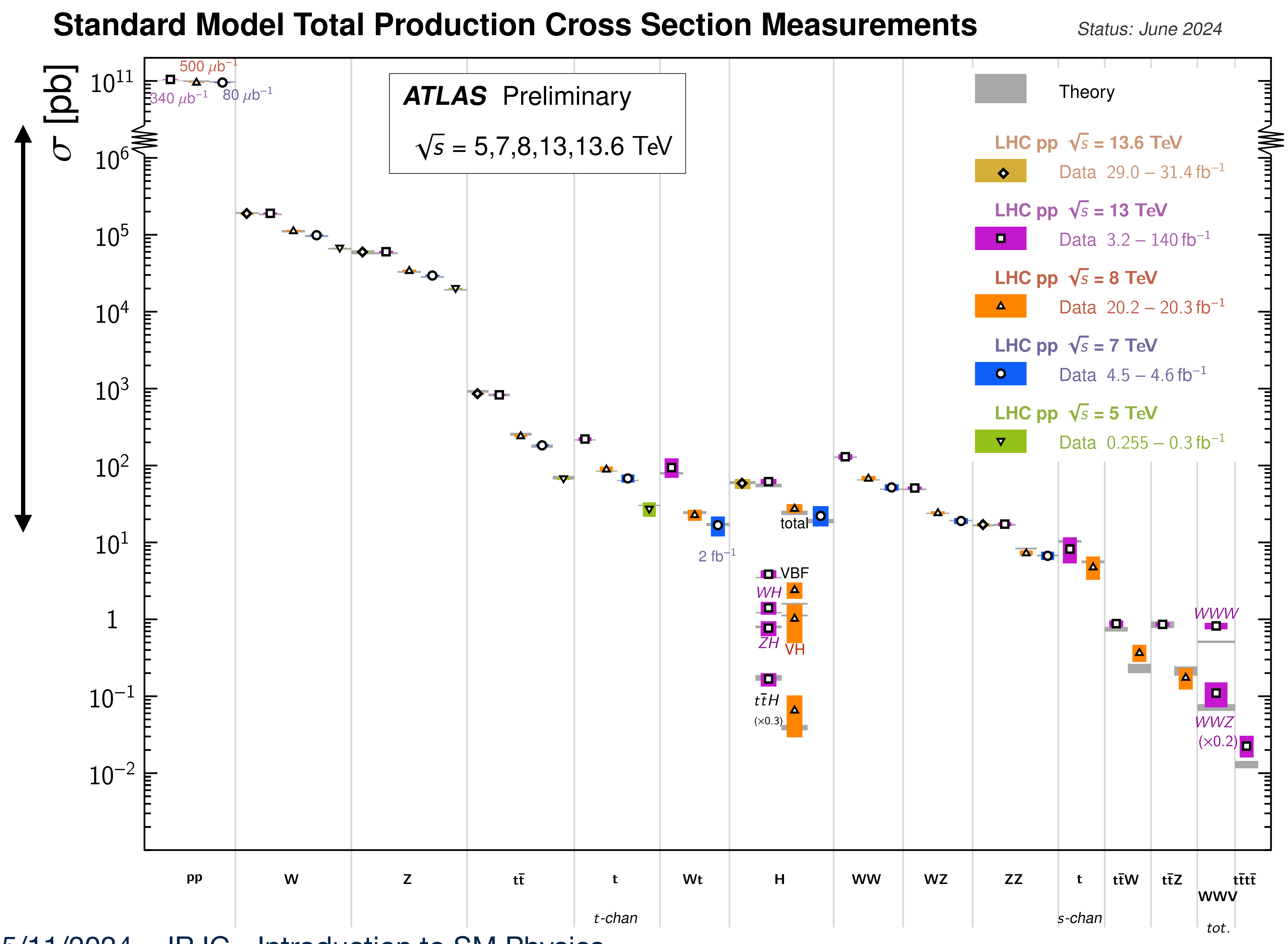
$$N = \sigma \times \mathscr{L}$$



The **Run-3** phase is now ongoing at an unprecedented energy of 13.6 TeV, allowing to record $\mathscr{L} \simeq 183\, fb^{-1}$ of data so far.

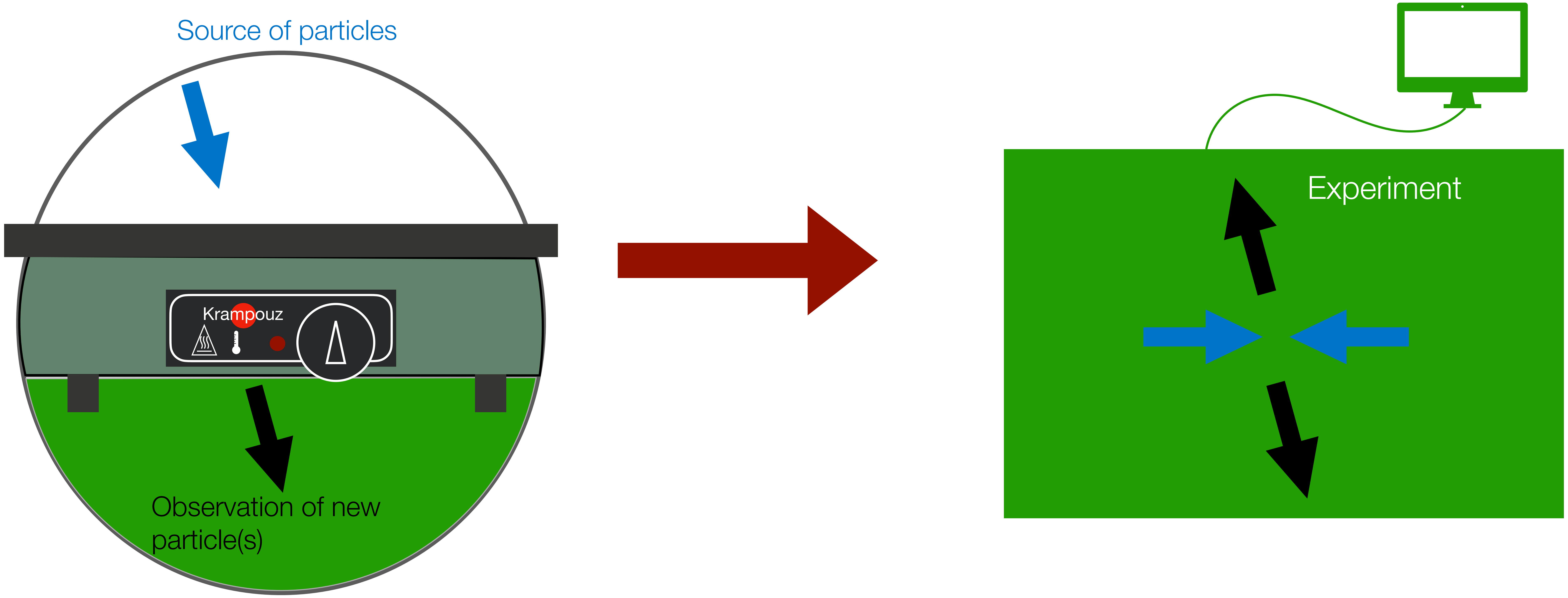
Why is it hard to measure SM ?

Orders of magnitude in particle production at the LHC



How to detect particles ?

We ha upgraded a bit the systems since the first bubble chambers:



A + **B** → C + D + ...

A + **A'** → B + C + ...

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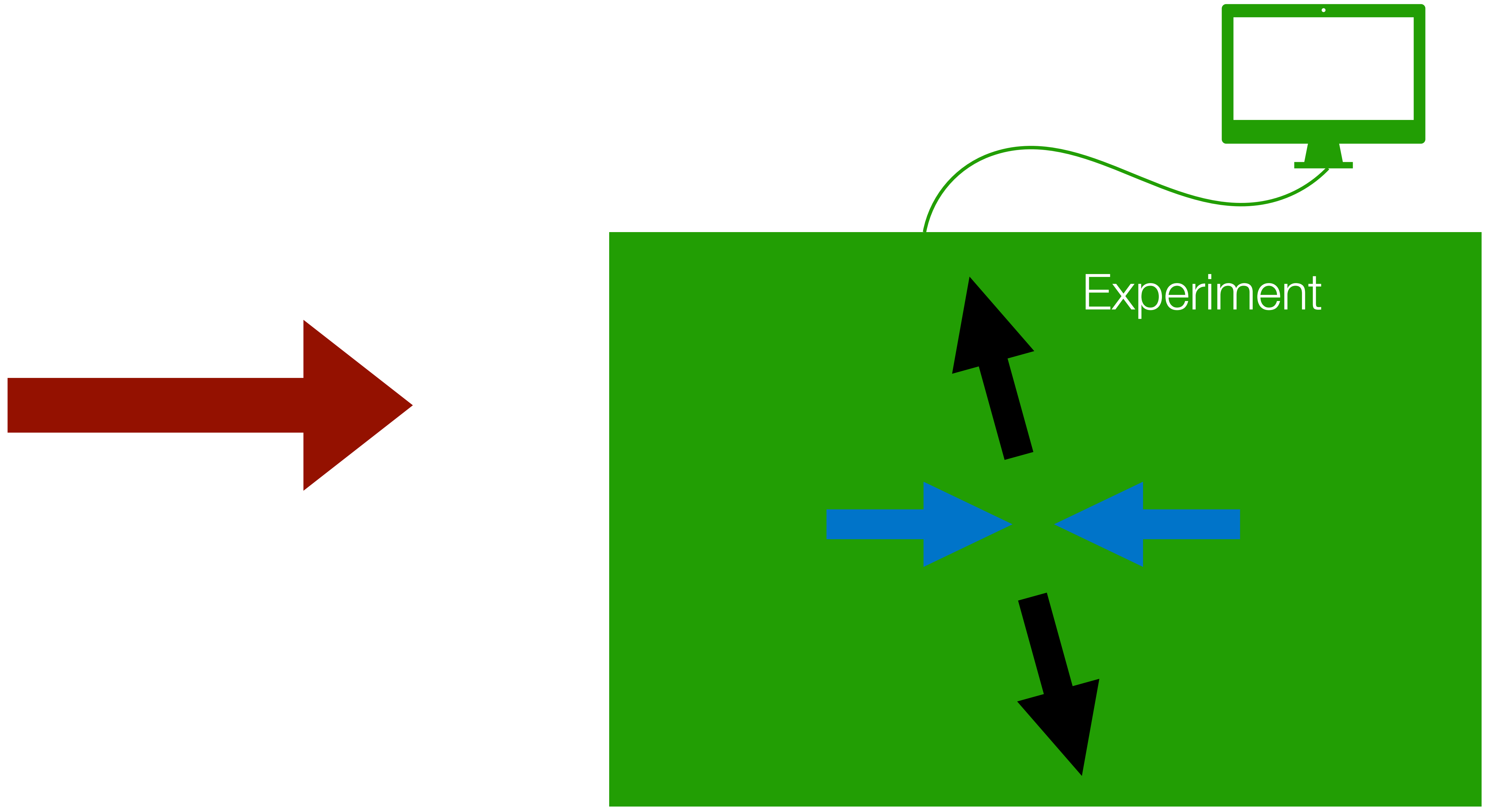

$A + B \rightarrow C + D + \ldots$

$A + A' \rightarrow B + C + \ldots$

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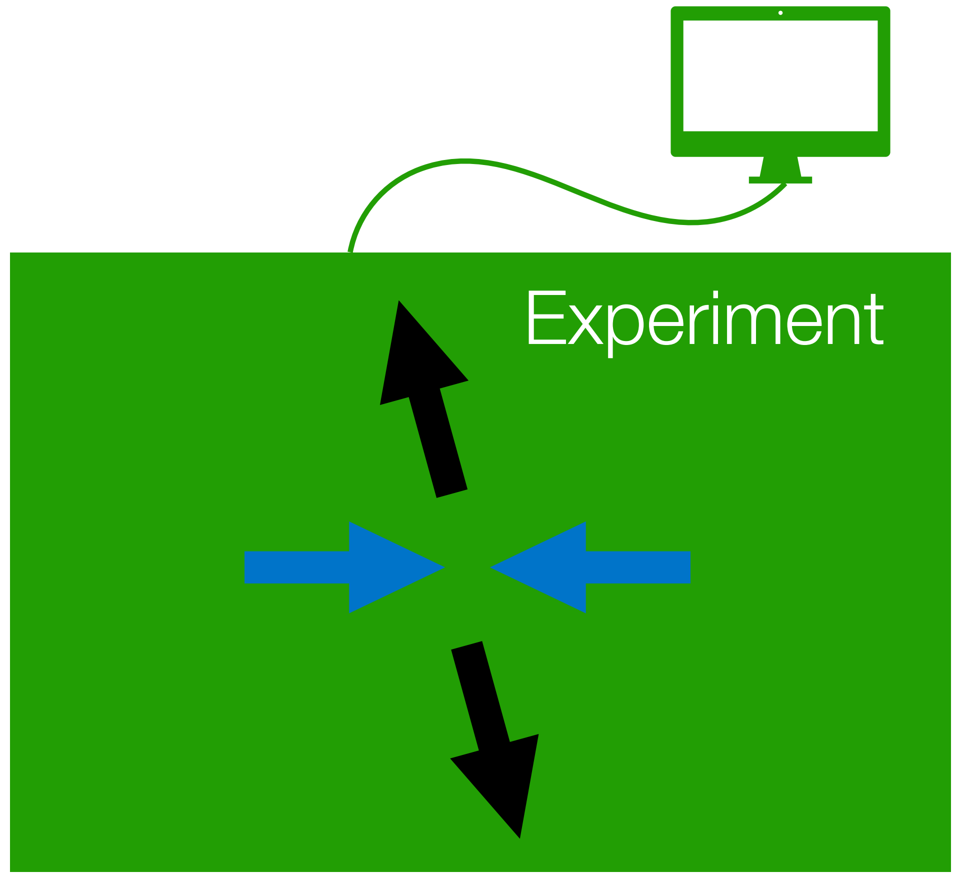
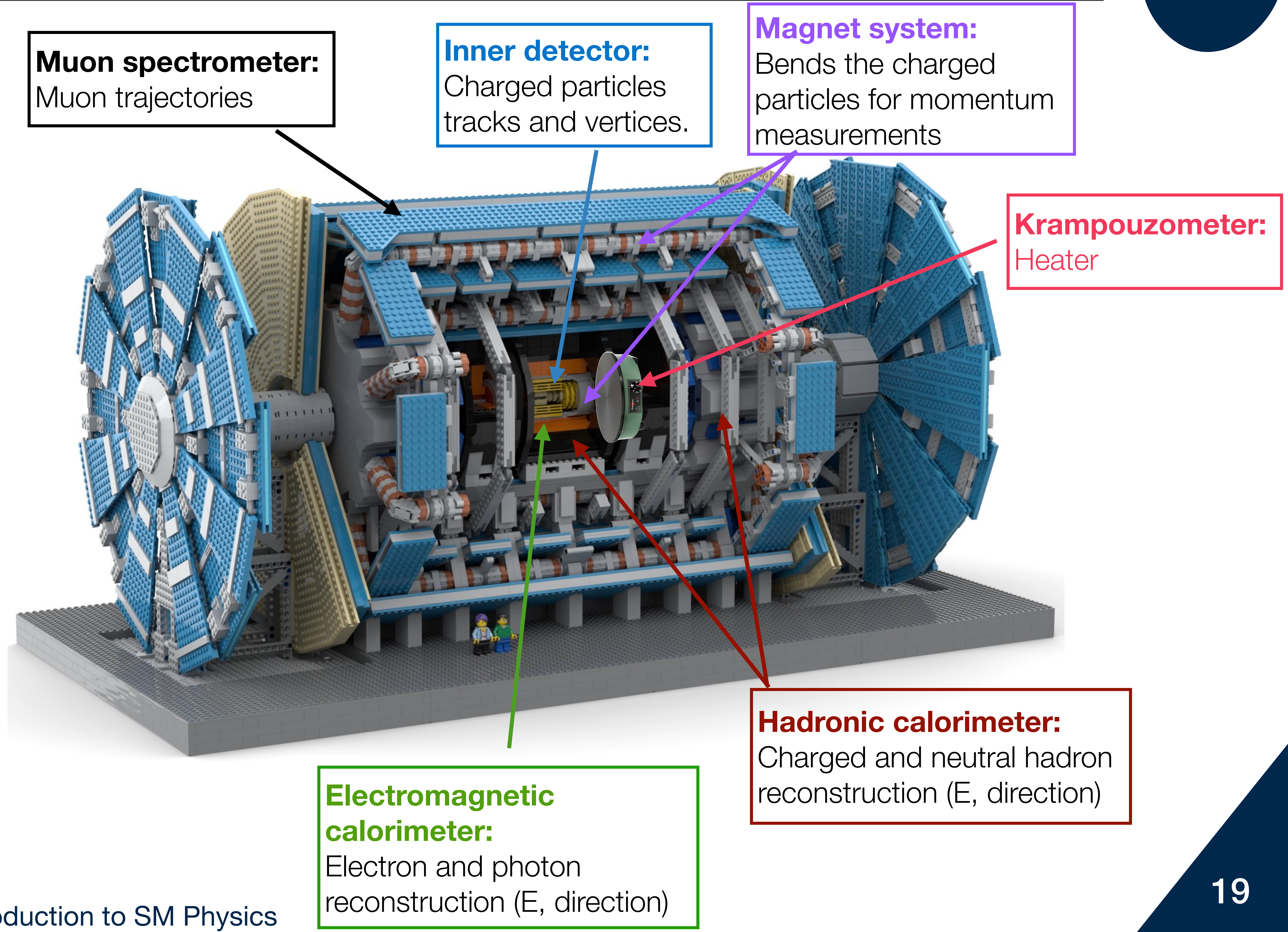


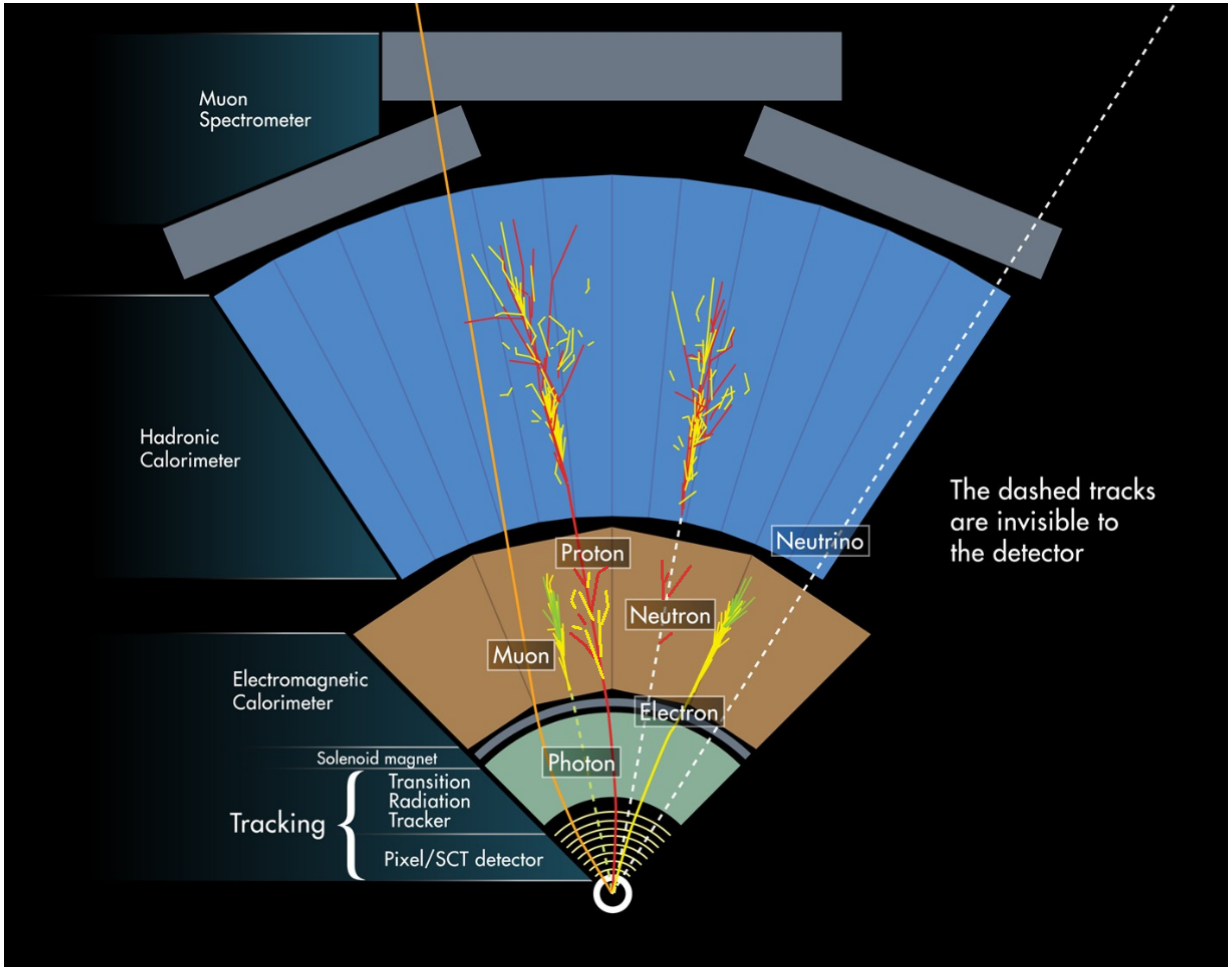
A + **A'** → B + C + ...

Or



How to reconstruct objects ?

See more in Théo's talk



Why aren't we just observing Higgs Boson and counting them ?

- Most of the searches are focussing on **short lived particles** ($1.6\ 10^{-22}$ s for the Higgs) → decaying to (quasi) stable particles.
- Each experiment wants to be **as general as possible** and opened to BSM particles.

Therefore we **classify particles** according to their way to interact with our detector:

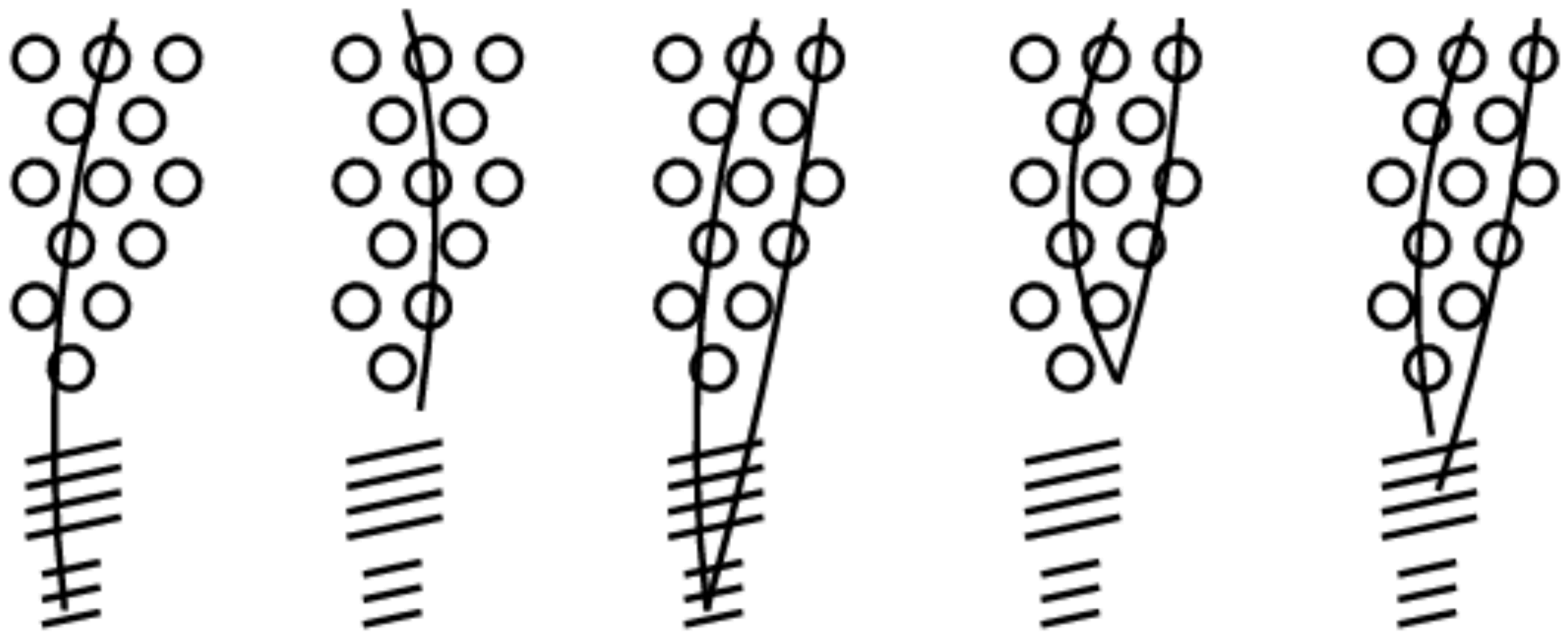
- Photons : will leave a nice deposit in your electromagnetic calorimeter and nothing else;
- Electrons : will leave a nice deposit in your electromagnetic calorimeter and a track !
- Neutrons, protons, and other hadrons: might leave or not a track, a deposit in the electromagnetic and **hadronic** calorimeter;
- Muons: are weakly interacting with the detector and escape it.

Is object reconstruction easy ?

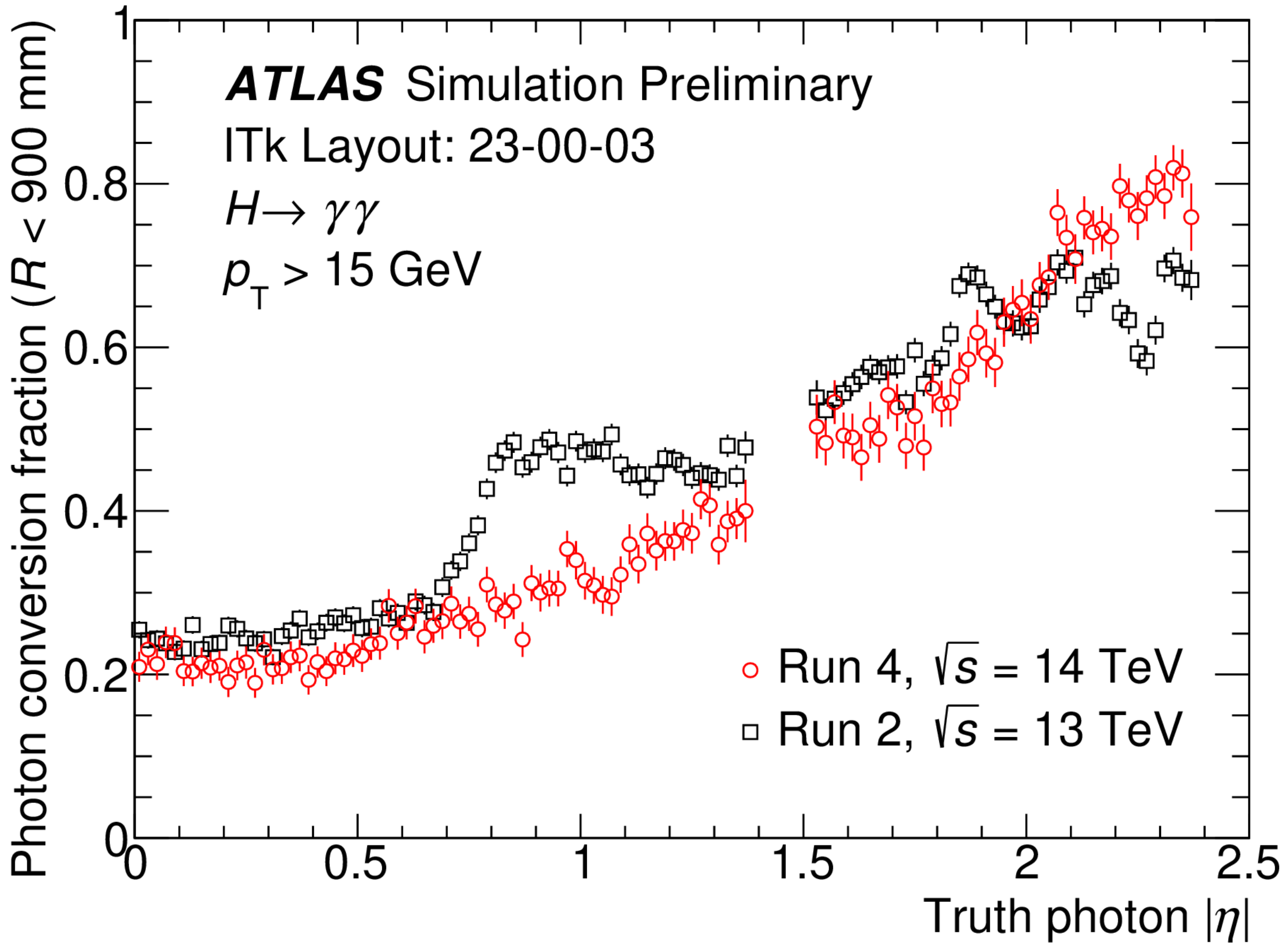
See more in Théo's talk

Guess what ... no ;), one exemple:

Photons can interact with the tracker $\gamma \rightarrow e^{+} + e^{-}$



You need special algorithms not to **mistake photons for electrons** and vice versa: these will take into account the shape of the calorimeter deposit as well as the eventual tracks.



The fraction of converted photons depends on the material of the tracker.

Category	$\sigma_{90}^{\gamma\gamma}$ [GeV]
U, Central-barrel, high $p_{Tt}^{\gamma\gamma}$	1.88
U, Central-barrel, medium $p_{Tt}^{\gamma\gamma}$	2.34
U, Central-barrel, low $p_{Tt}^{\gamma\gamma}$	2.63
U, Outer-barrel, high $p_{Tt}^{\gamma\gamma}$	2.16
U, Outer-barrel, medium $p_{Tt}^{\gamma\gamma}$	2.63
U, Outer-barrel, low $p_{Tt}^{\gamma\gamma}$	3.00
U, Endcap	3.33
C, Central-barrel, high $p_{Tt}^{\gamma\gamma}$	2.10
C, Central-barrel, medium $p_{Tt}^{\gamma\gamma}$	2.62
C, Central-barrel, low $p_{Tt}^{\gamma\gamma}$	3.00
C, Outer-barrel, high $p_{Tt}^{\gamma\gamma}$	2.56
C, Outer-barrel, medium $p_{Tt}^{\gamma\gamma}$	3.20
C, Outer-barrel, low $p_{Tt}^{\gamma\gamma}$	3.71
C, Endcap	4.04
Inclusive	3.32

11%

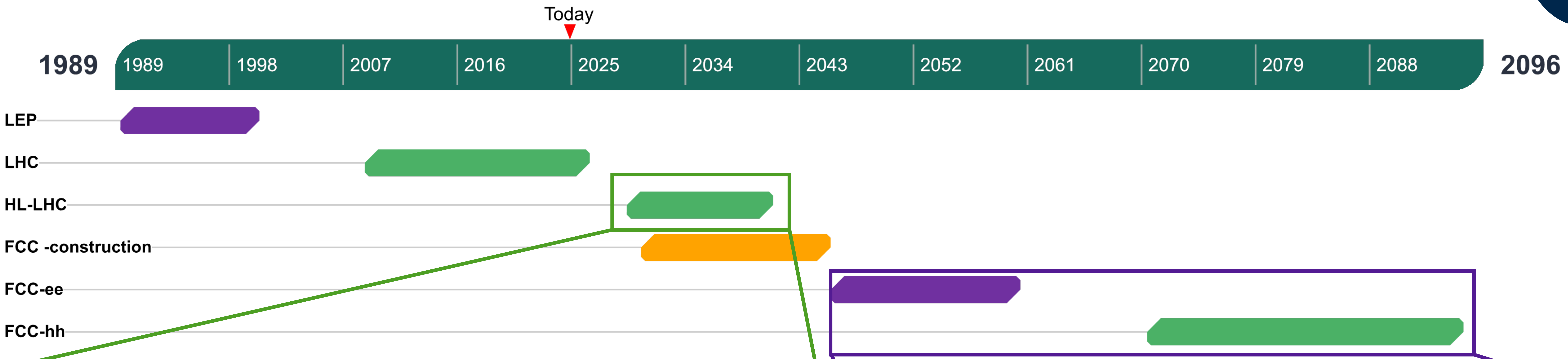
21%

Phys. Lett. B 847 (2023) 138315

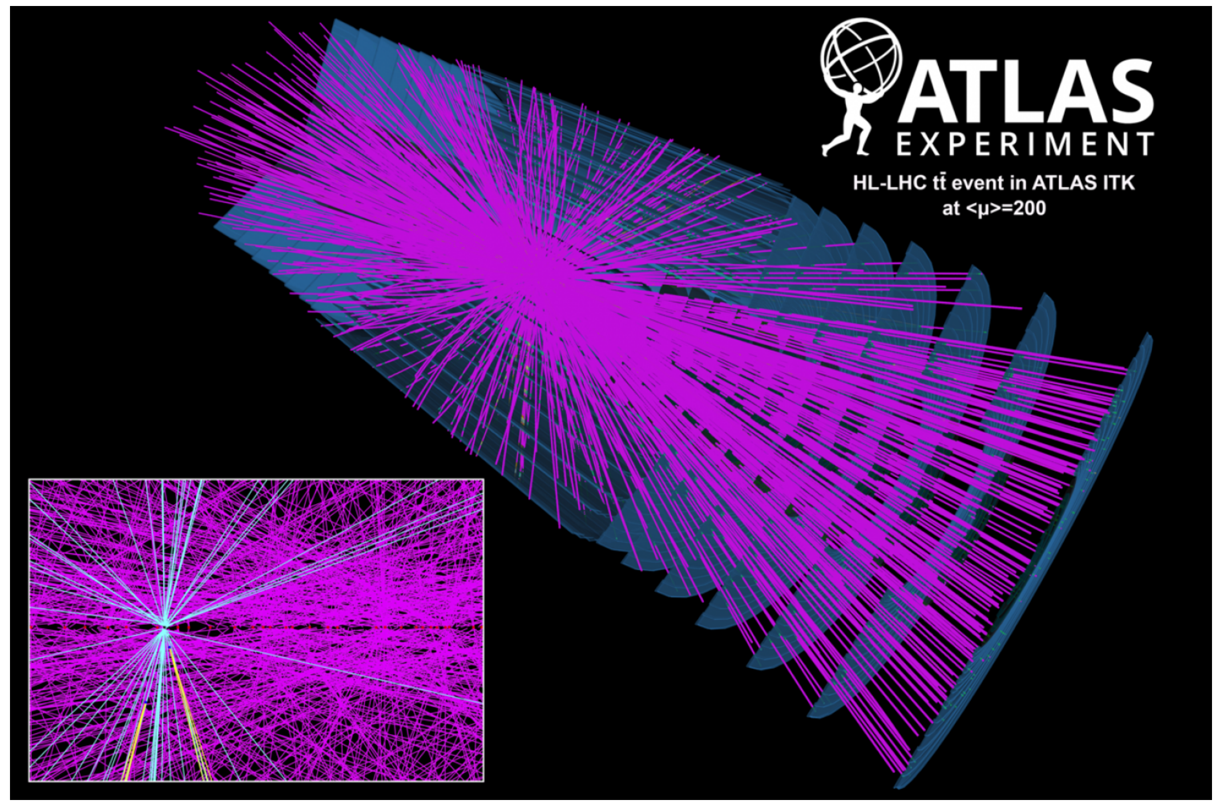
This has an effect on the **resolution of the Higgs mass** measurement, where converted photons have significant worse energy resolution.

What's next ?

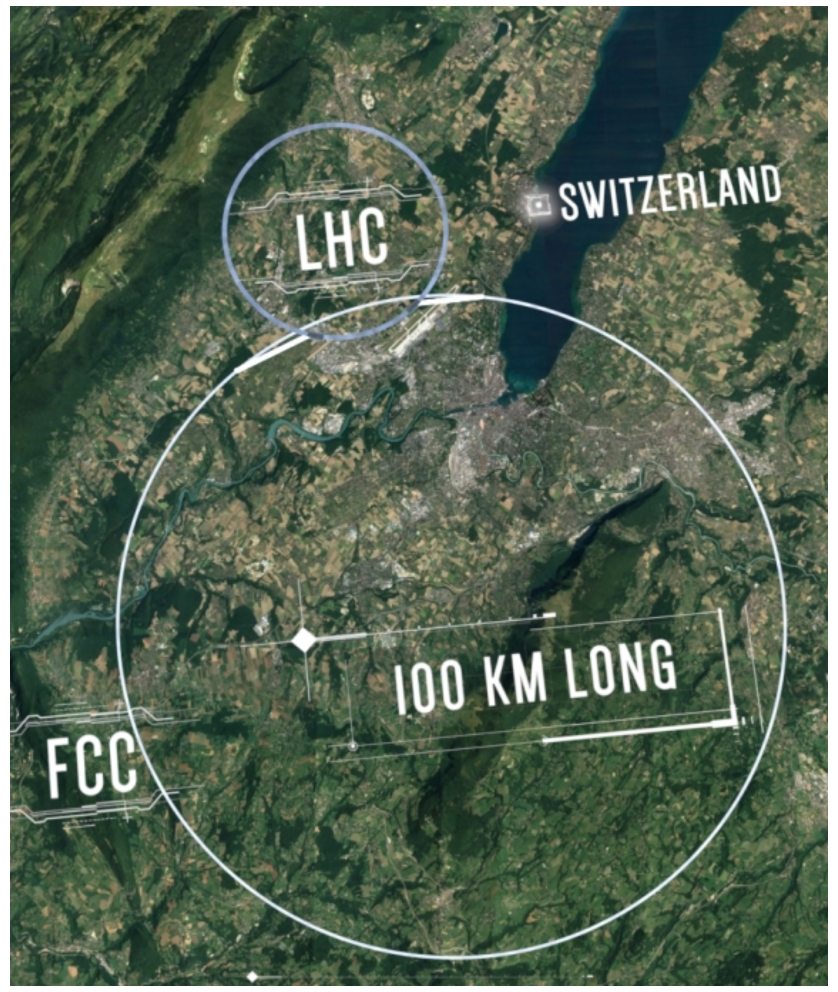
See more in Théo's and Arthur's talks



The LHC will run until 2040, but with an upgraded machine and detectors :



- More collisions per bunch crossing, going from ~40-60 to 200 !
- That means more data but also busier environment !

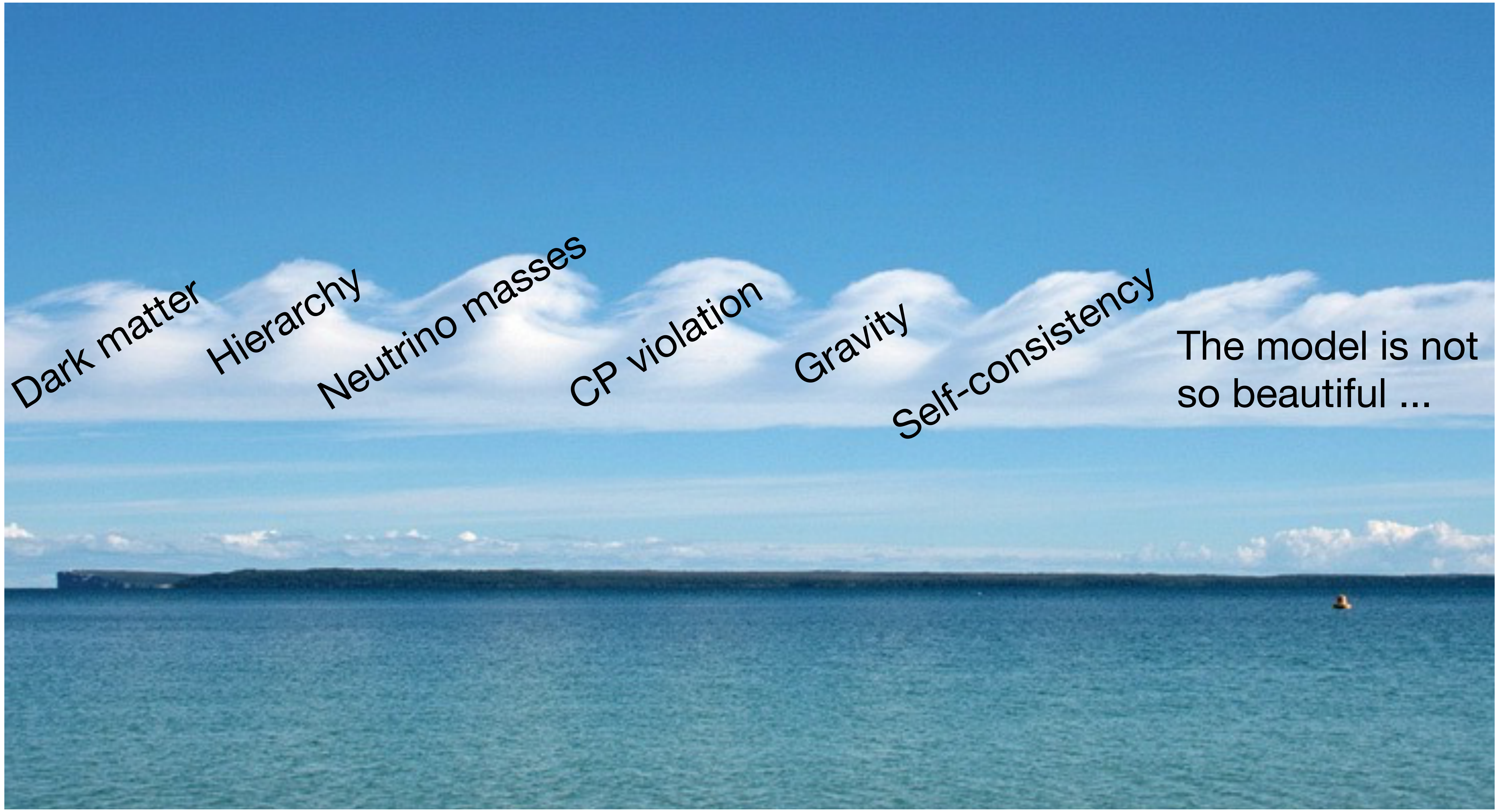


To this day **FCC** is still a project:

- 2 phases like LEP/LHC;
- Other competitors like CEPC, Linear Colliders, muon colliders.
- **Get involved in the ECFA ERC WG !**

Conclusion

The SM has a rich history and still a bright future. Only a couple of small clouds in the blue sky



Just stay until the BSM session on Thursday ;)

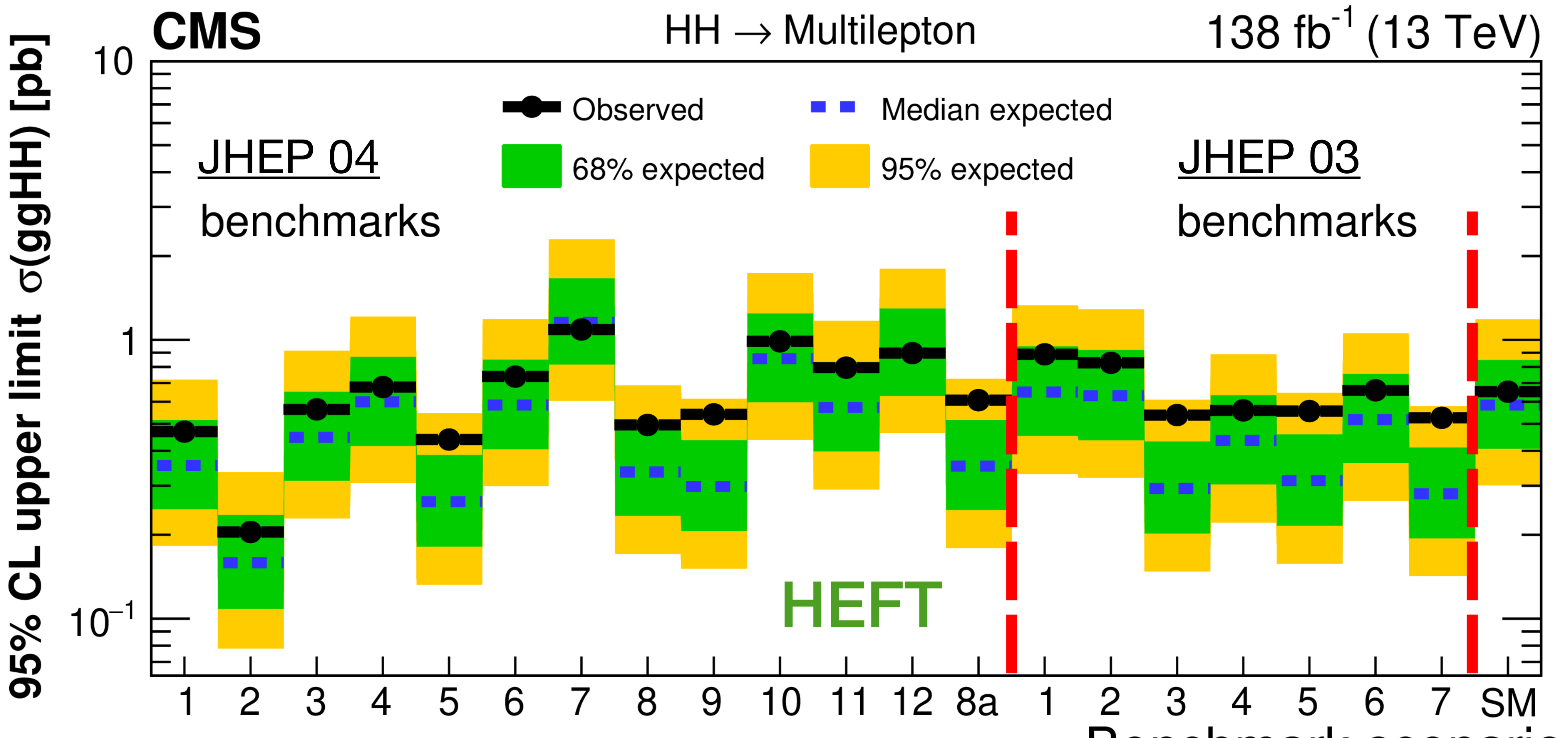
BACK-UP

An overview of EFT

The results can be further interpreted using Effective Field Theories:

- In the Standard Model EFT (SMEFT): the SM Lagrangian is supplemented with a set of extra operators, respecting gauge symmetries of the SM.
- In the Higgs EFT (HEFT): is following the same strategy, but recasting the operators to have a one-to-one correspondance between operators and effective interactions.

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)} O_k^{(6)}$$



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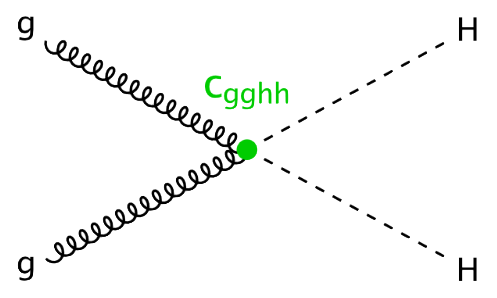
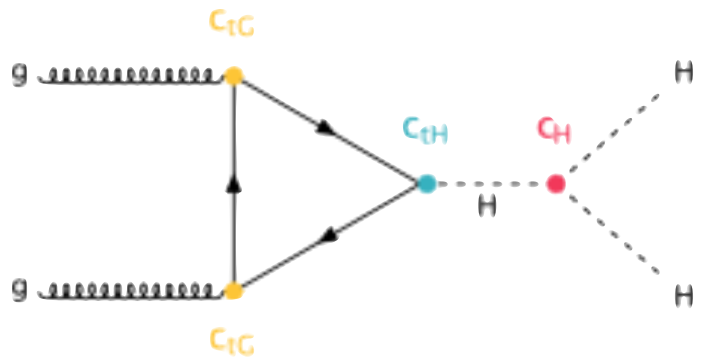
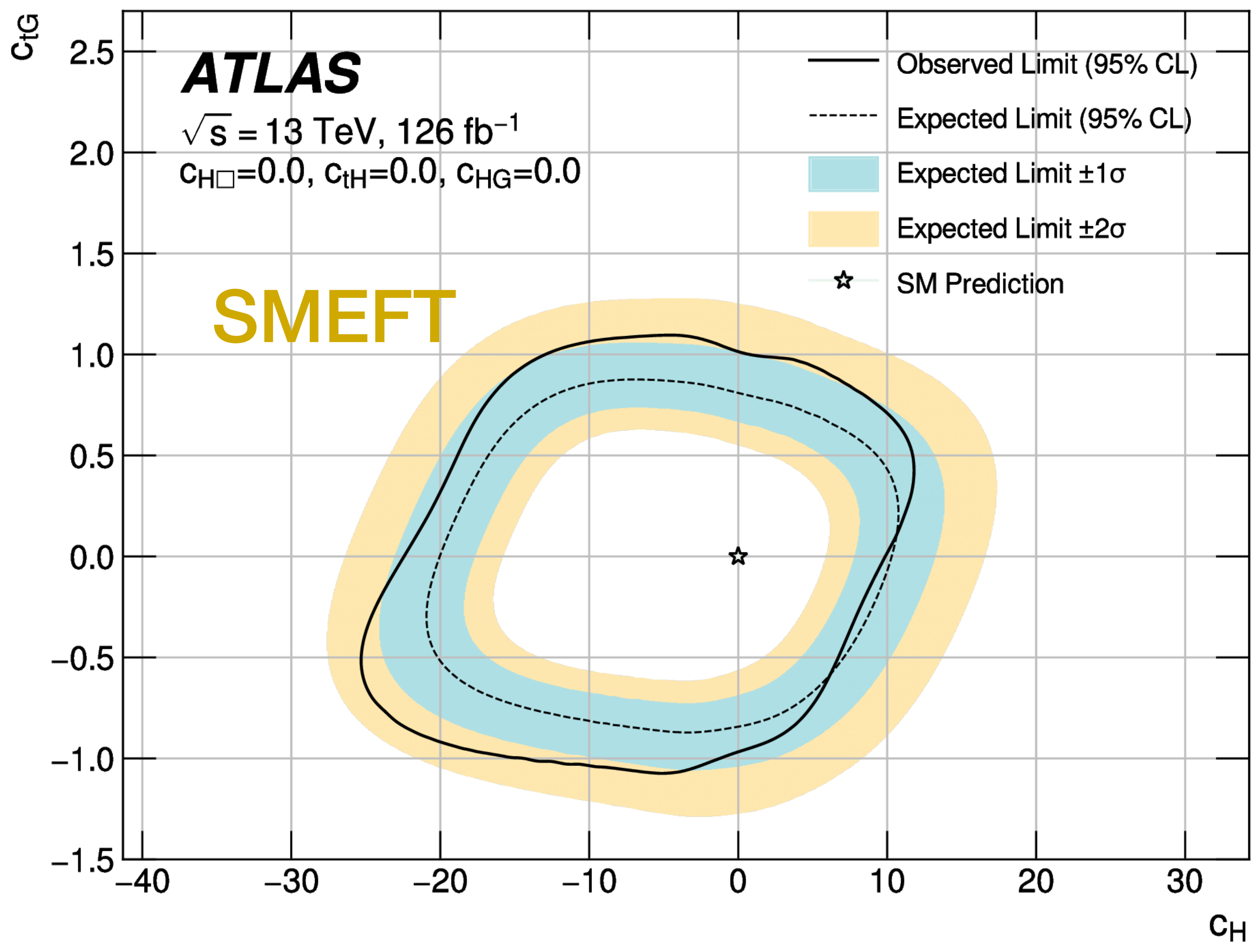


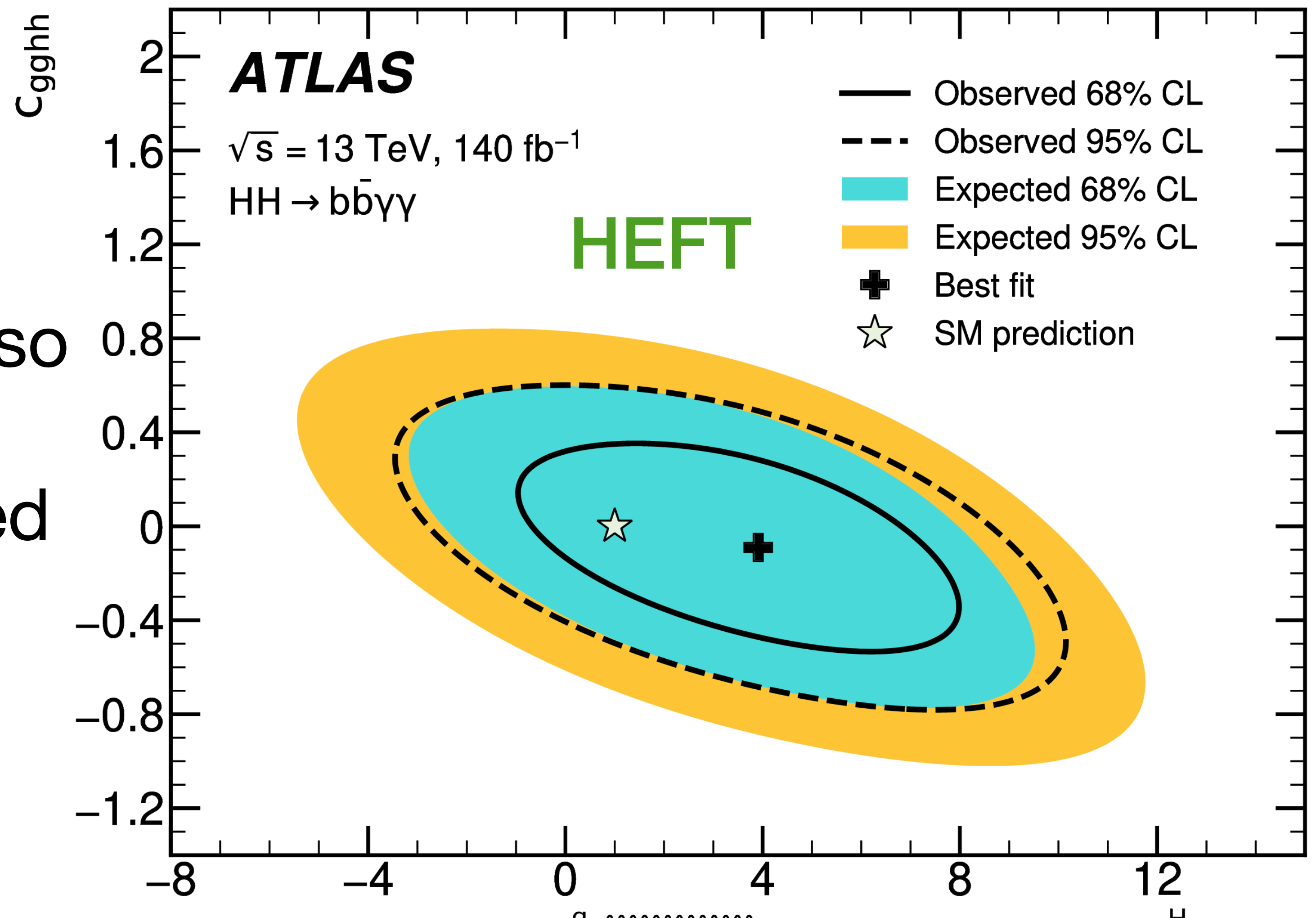
The constraints are often set in terms of coefficients but several sets of benchmark models are also available (be careful though since the definitions might have changed between papers).

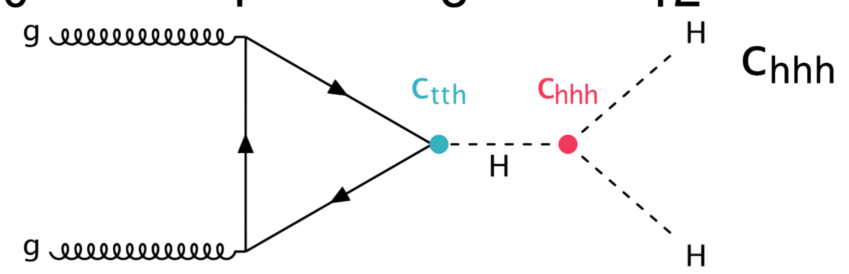


Phys. Rev. D 108 (2023)



JHEP 01 (2024) 066





The pure extra EFT operator effect can be studied in the so-called quadratic case (~ 1/Λ⁴), while the interaction with the SM is taken into account in the linear one (~ 1/Λ²). In all the results released, the linear+quadratic terms are considered.

How to look for Higgs pairs?

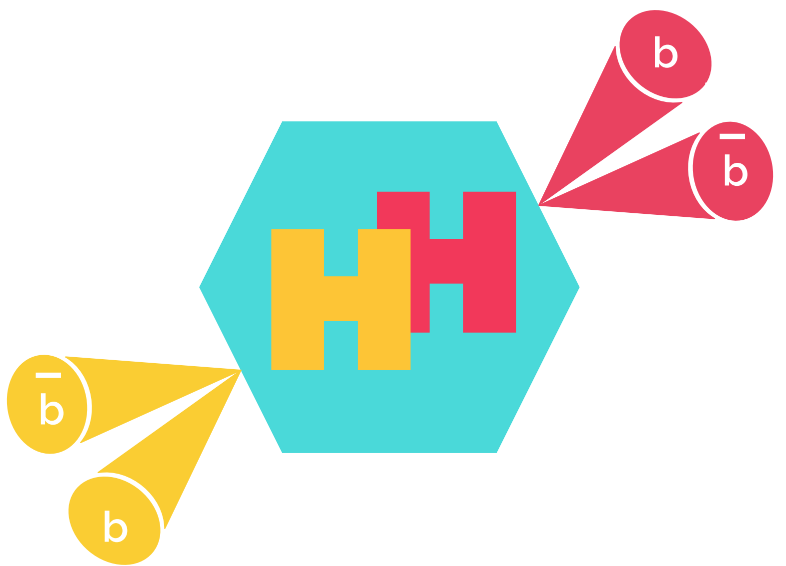
There is no clear **Golden channel for the non-resonant search**, but several promising signatures:

$BR(HH \to XXYY)$ (gluons, c, muon not shown)

	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 % A	0.33 % A	0.069 %	
γγ	0.26 %	0.10 %	0.028 %	0.012 % A	0.0005 %

☐ Full Run-2 analyses: A for ATLAS only

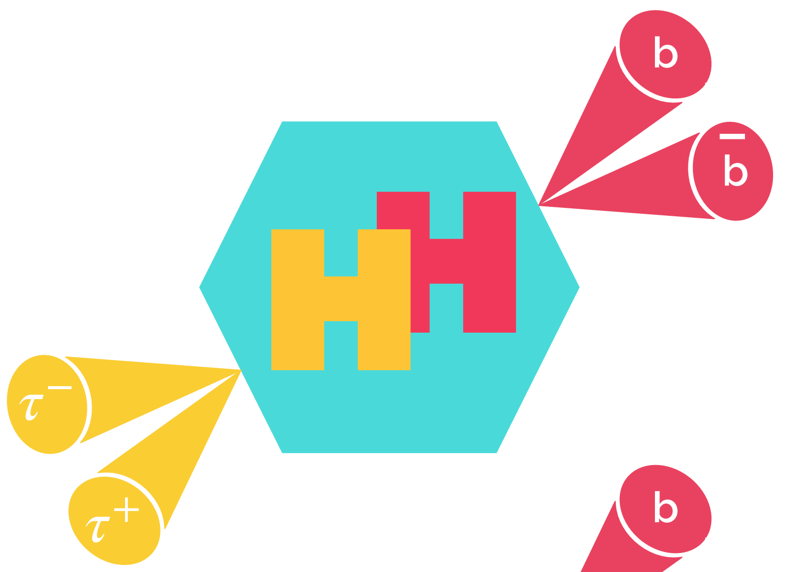
Combining the results is necessary **for observation**.



$HH \to b\bar{b}b\bar{b}$
- $H \to b\bar{b}$: High BR
- Large hadronic background

ATLAS: Phys. Rev. D 108 (2023)
+ ATLAS-CONF-2024-003 (VBF, boosted)
+ Eur. Phys. J. C 83 (2023) 519 (VHH)

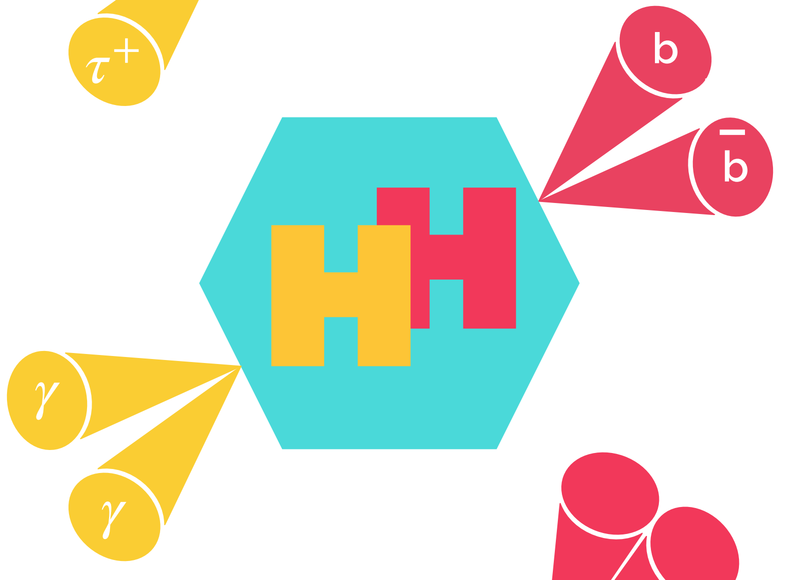
CMS: Nature 607 (2022)
+ CMS-PAS-B2G-21-001 (VBF, boosted)
+ CMS-PAS-HIG-22-006 (VHH)



$HH \to b\bar{b}\tau^+\tau^-$
- $H \to b\bar{b}$: High BR
- $H \to \tau^+\tau^-$: Low background

ATLAS: ATLAS-CONF-2023-071

CMS: Phys. Lett. B 842 (2023)



$HH \to b\bar{b}\gamma\gamma$
- $H \to b\bar{b}$: High BR
- $H \to \gamma\gamma$: Good mass resolution

ATLAS: JHEP 01 (2024) 066

CMS: JHEP 03 (2021) 257

$HH \to b\bar{b}VV$ and friends (with leptons)
- Decent BR from $H \to VV$
- High number of leptonic and hadronic channels

ATLAS: JHEP 02 (2024) 037 ($b\bar{b}(ZZ/WW/\tau\tau)$, 2l+MET)
+ ATL-CONF-2024-005 ($b\bar{b}ZZ/4V/2V2\tau/4\tau/2\gamma 2V/2\gamma 2\tau$)

CMS: JHEP 07 (2023) 095 ($4W/WW\tau\tau/4\tau$, ≥2l)
+ JHEP 06 (2023) 130 ($b\bar{b}ZZ$, 4l)
+ CMS-PAS-HIG-21-005 ($b\bar{b}WW$, ≥1l)
+ CMS-PAS-B2G-21-001 ($\gamma\gamma WW$)
+ HIGG-22-012 ($\gamma\gamma\tau\tau$)

Limits on HH production

One of the key figure of merit is the limit on either the HH **cross-section** to its SM prediction, or the **signal strength μ**. The later incorporates the theoretical uncertainties on the SM prediction.

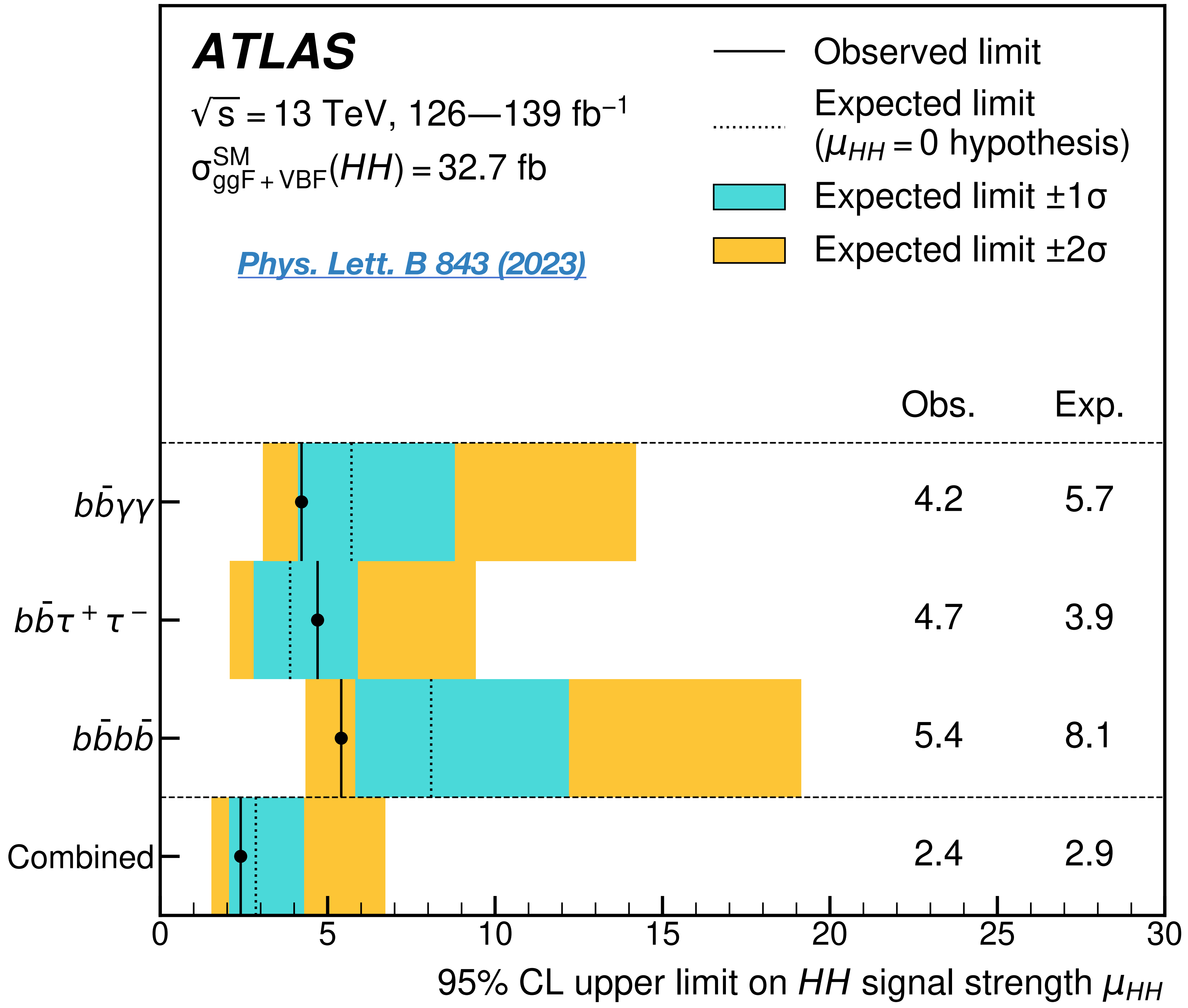
The leading 3 channels ($b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$) are very close by with expected limits around ~ 5 x SM prediction. The global combination leads then to a limit **~ 2.5-3 x SM**.

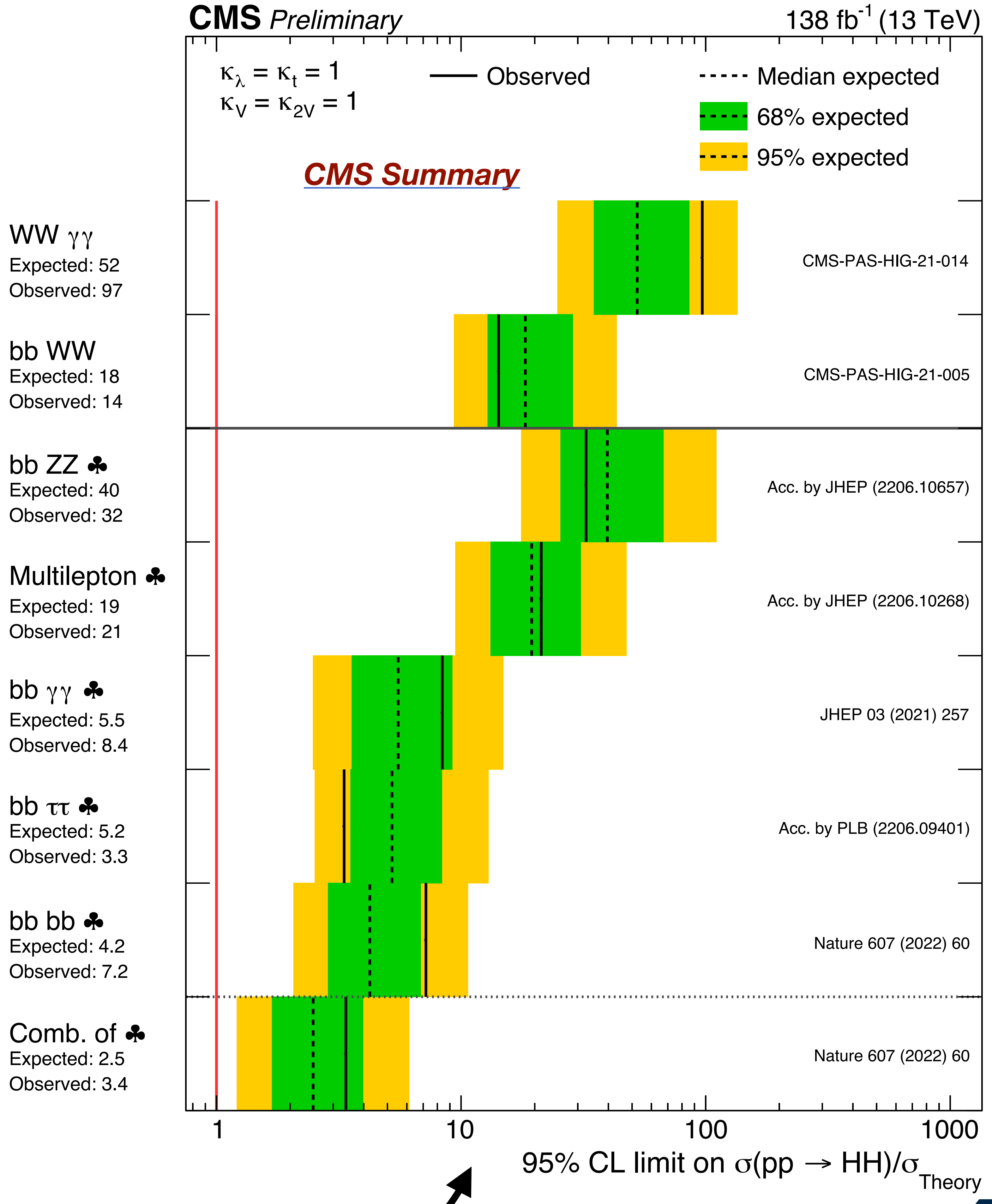
- **ATLAS** hasn't published a combination with their latest $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ results;
- **CMS** is showing a combination between their resolved and boosted analyses for the $b\bar{b}b\bar{b}$ results.

This limit is dominated by the ggF, but some analysis have also shared specific VBF limits:

Obs.	4b	bbγγ	bbττ
ATLAS	130	96	94
CMS	226*	225	124

** Only the resolved analysis is considered*



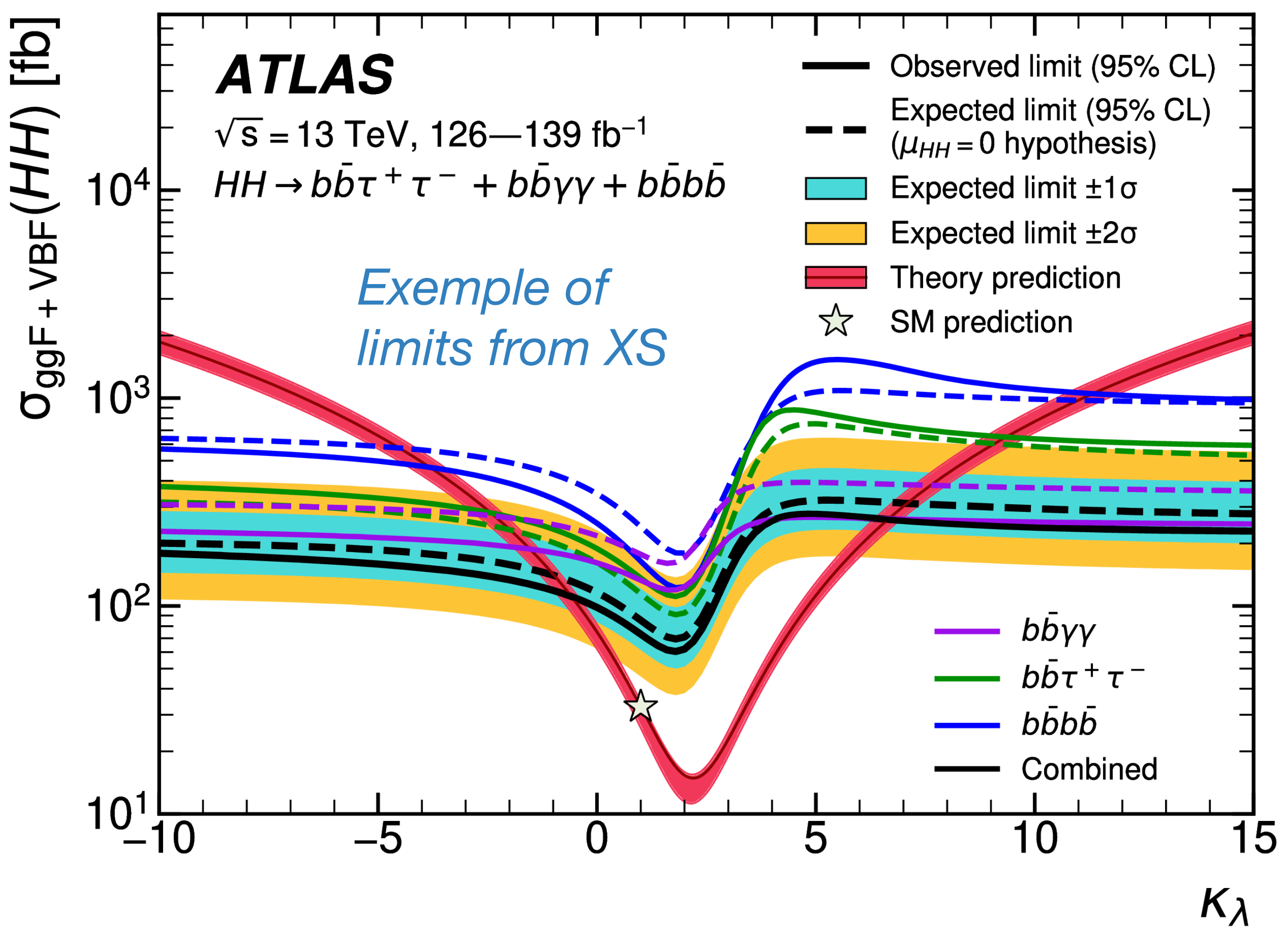


log scale

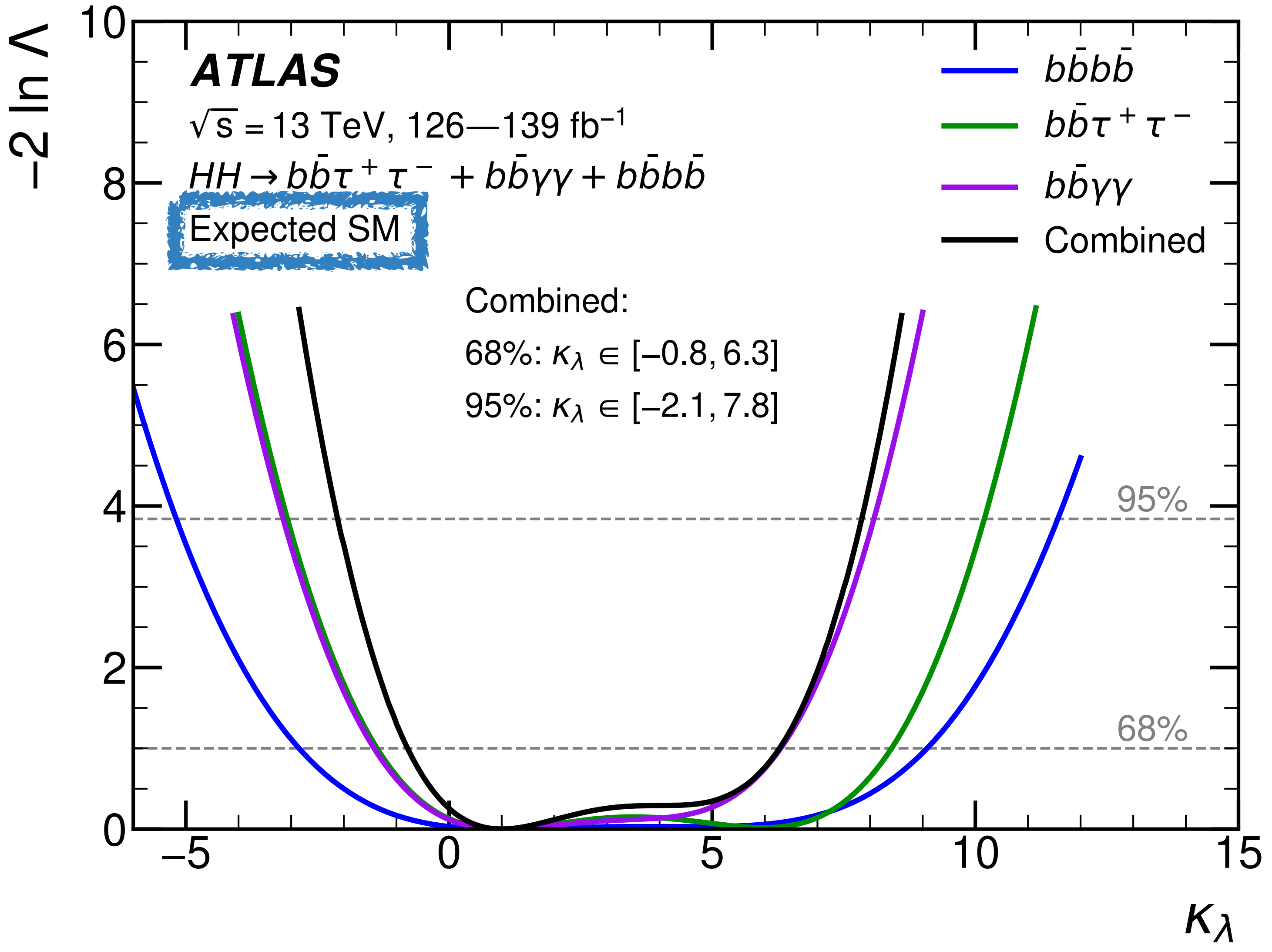
Interpretation in κ framework: κ_λ

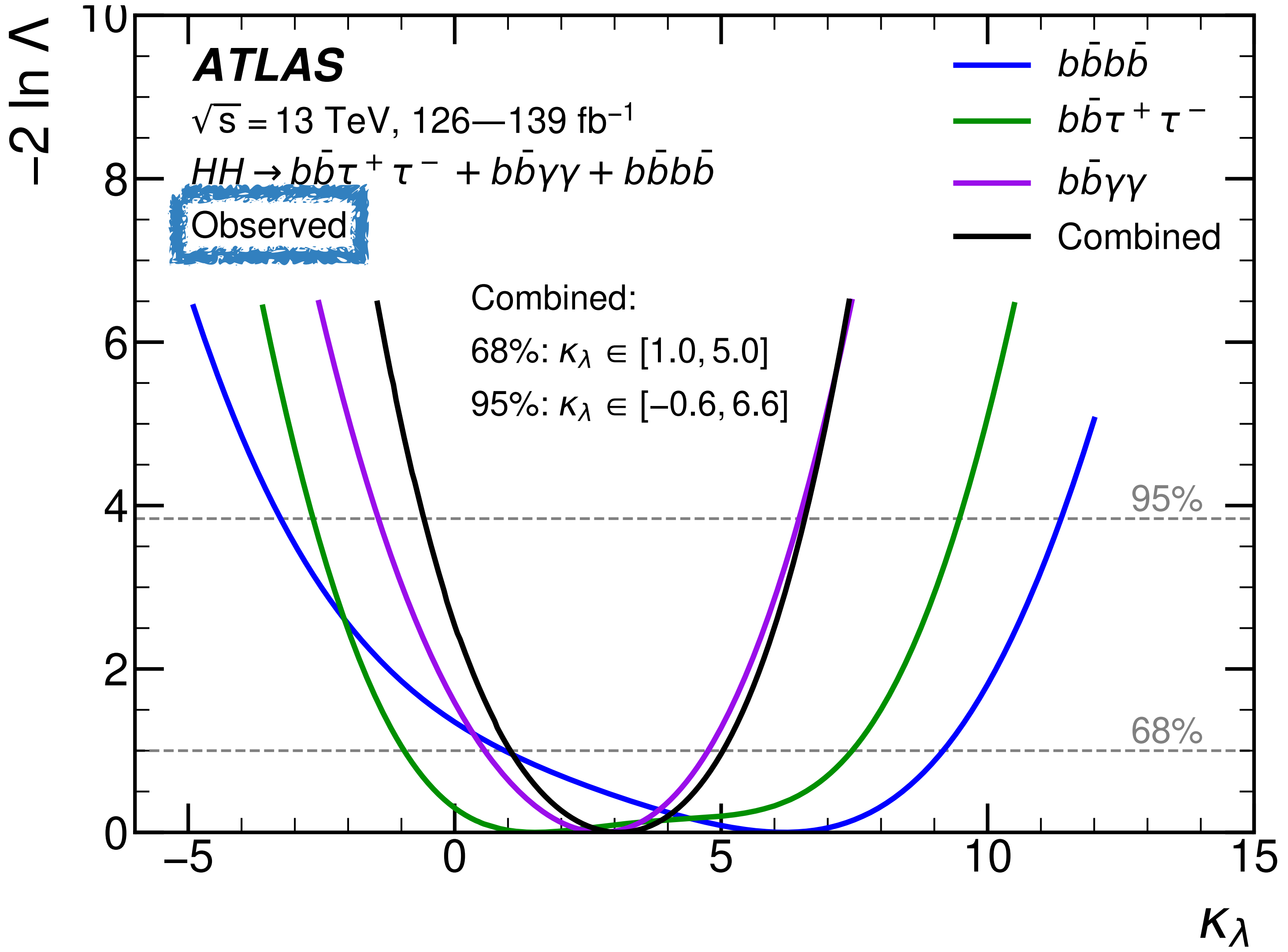
Both collaborations are gradually moving from deriving limits from the cross-section, to providing the likelihood limits.

- ATLAS hasn't published a combination with their latest $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}\tau\tau$ results;
- CMS is showing on the same plot the 95% CL from cross section limit, and the best fit value from likelihood with 1σ error.

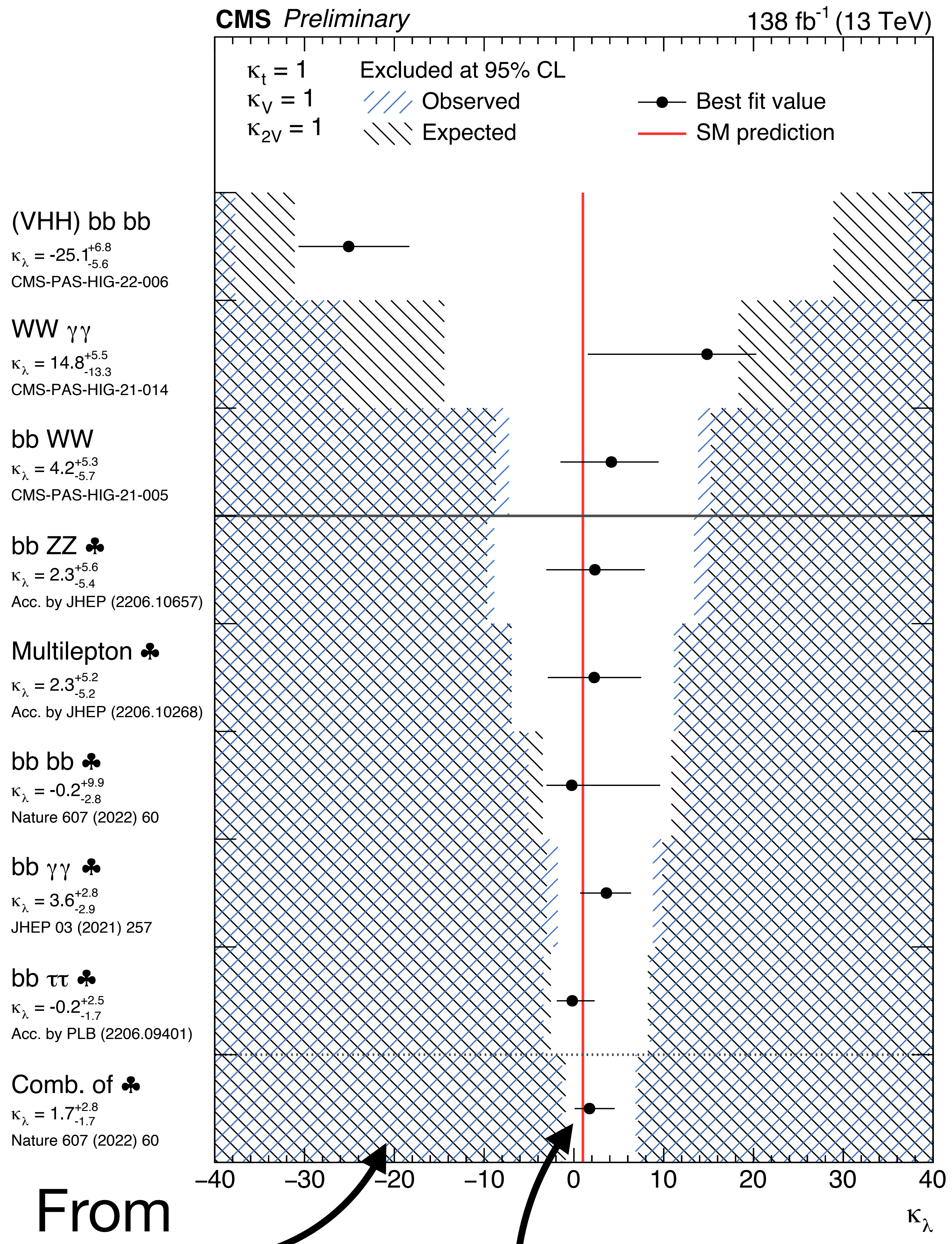


Phys. Lett. B 843 (2023)





CMS Summary



From XS limit

From likelihood result with 1σ error