Physics at the Large Hadron Collider:
The Higgs Turns 10 !

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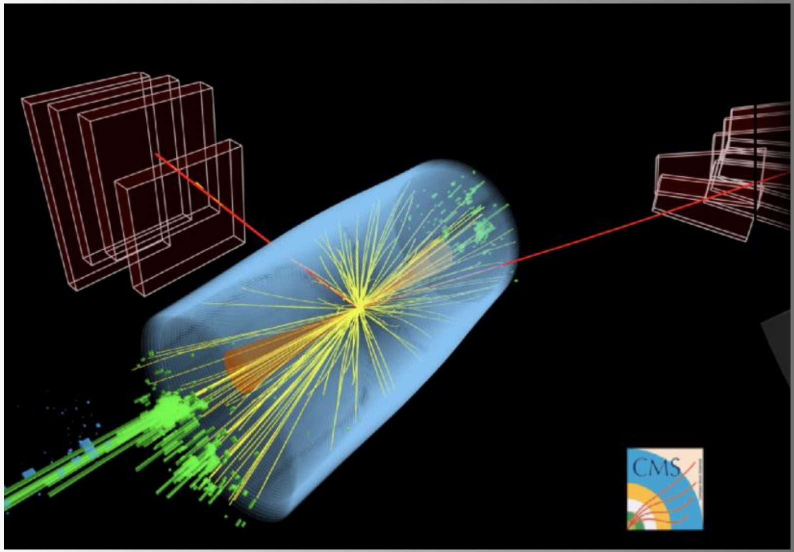
July 15th On-Line Workshop

HEPSummerDays 高能物理研讨会 2022 07.15JUL.

CERN 10 years HIGGS boson discovery

Contents



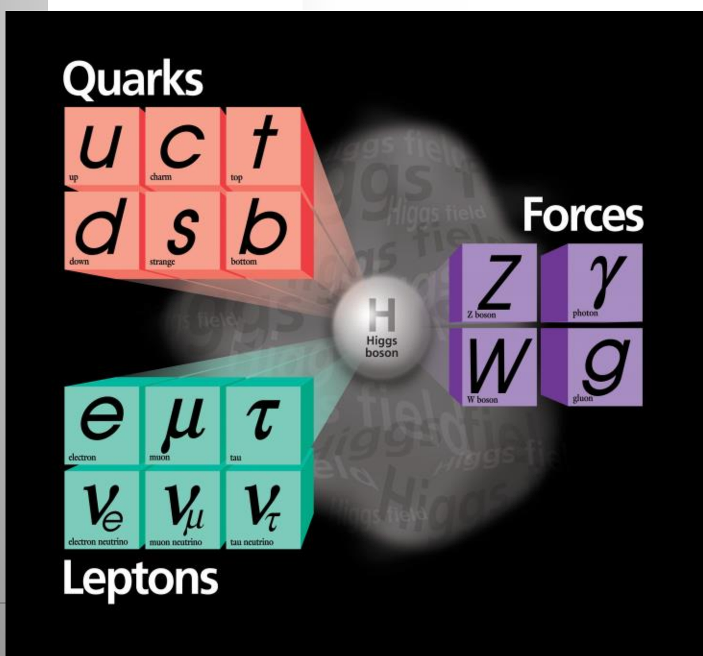
- Introduction: 4th of July 2012
  A day to remember
- A Higgs particle in Run-1:
  First contact with an entirely new particle
- A Higgs particle in Run-2:
  Completing the Higgs pattern
- The Future:
  Quo Vadis LHC?

The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Fermions Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

The Hunt for the Higgs

Where do the masses of elementary particles come from?

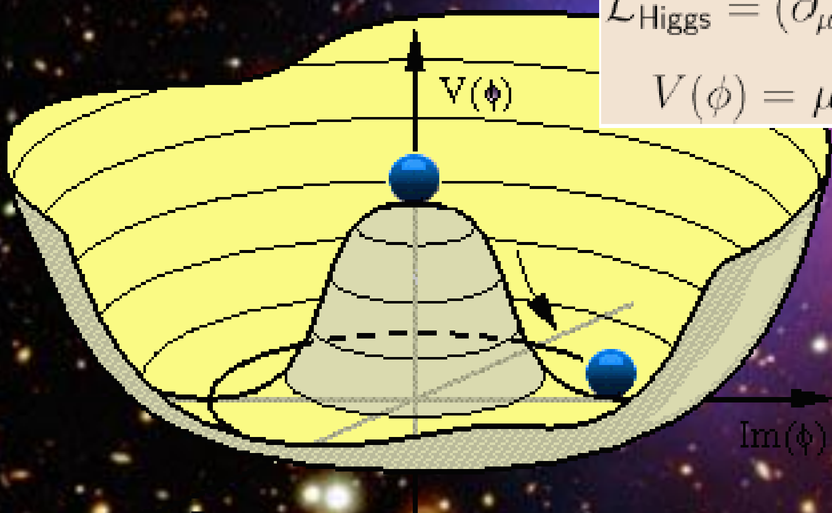
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

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

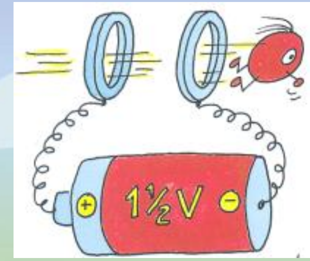


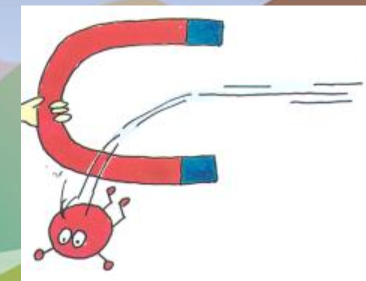
Scalar field with at least one scalar particle

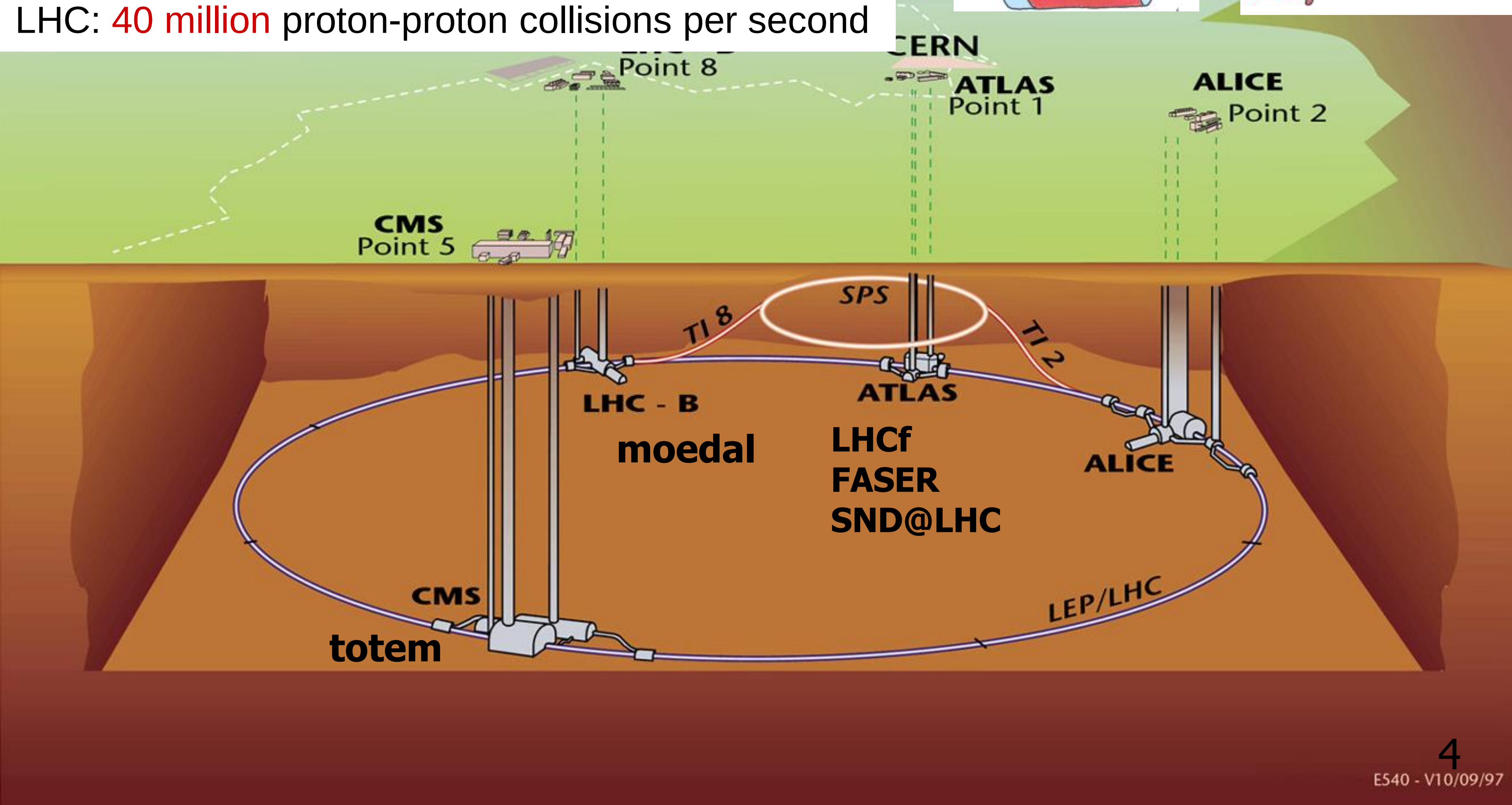
It could be anywhere from 114 to ~700 GeV

The LHC Machine and Experiments

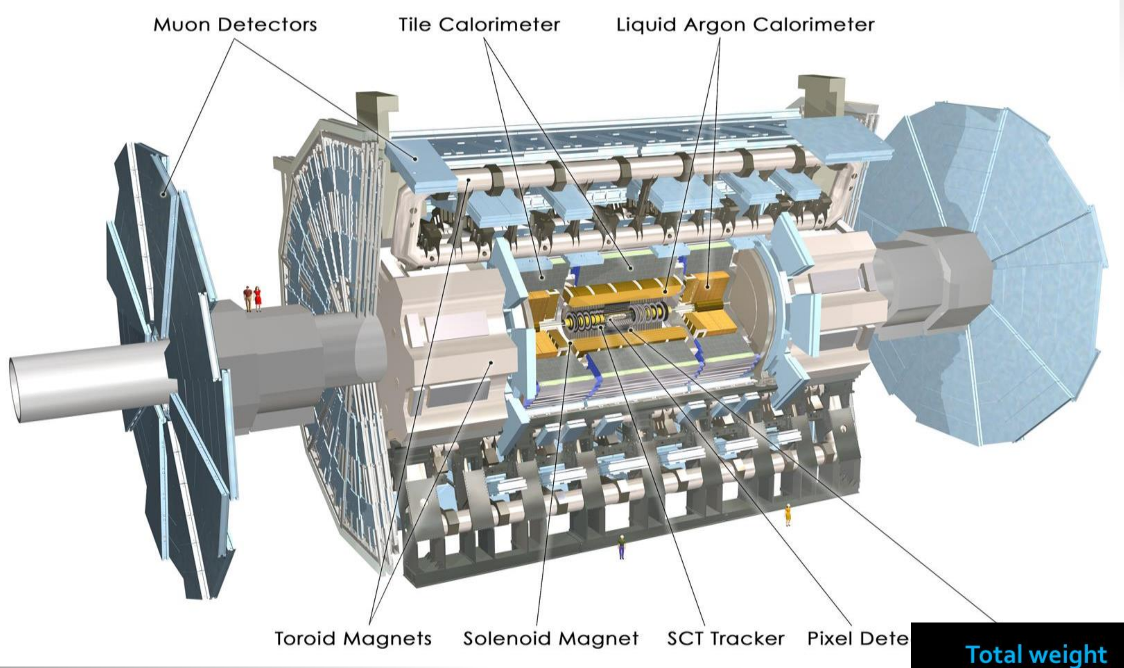
LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second



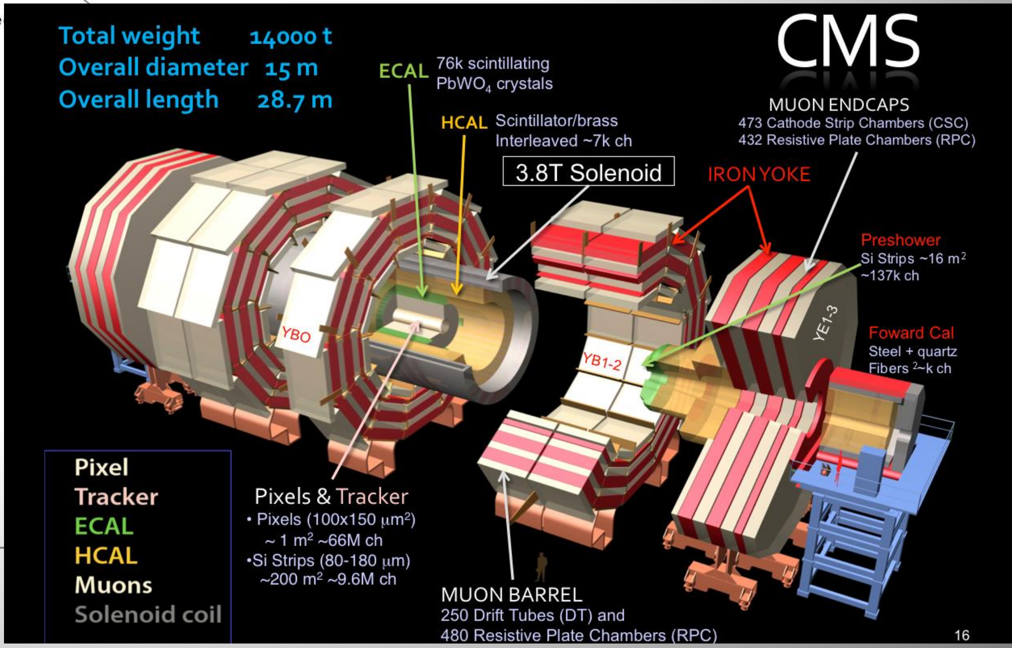




Higgs Hunters @ the LHC



The ATLAS experiment

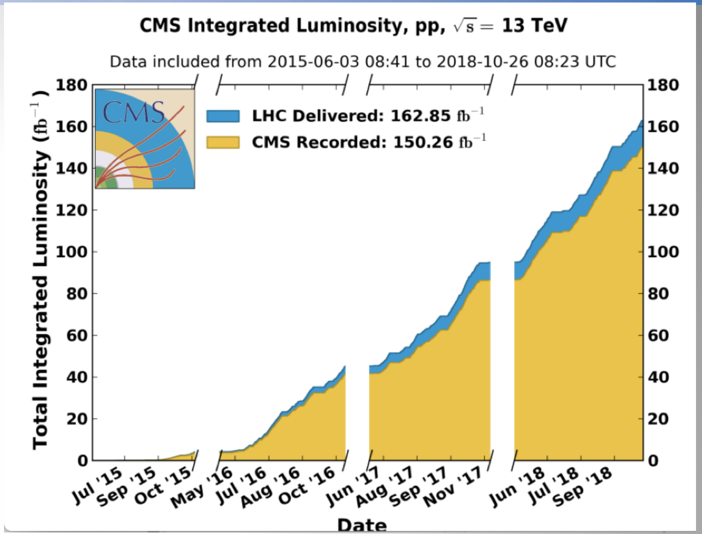


The CMS experiment

LHC Operations

pp Run-2 was finished on 24/10/18 6:00am

- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 25 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM energy
  - Collected ~ 140 fb^{-1}



You are here

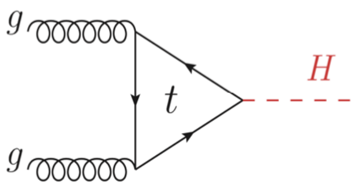
LHC is restarting after more than 3 years

Expect >250 fb^{-1} by 2025 in Run-3 at 13.6 TeV CM energy.
Run-3 started on 5/7!!

Followed by HL-LHC: 3000 fb^{-1} per exp.

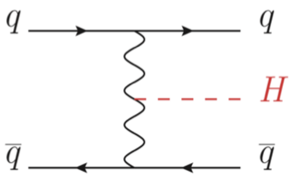
Higgs Production and Decay Processes

Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



Gluon fusion process

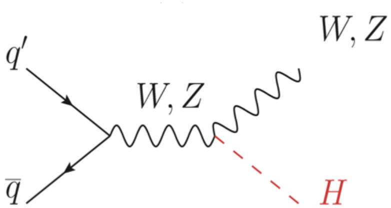
~8 M events produced



Vector Boson Fusion

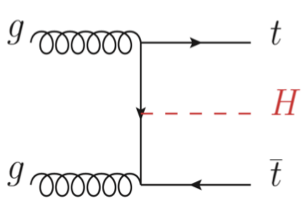
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

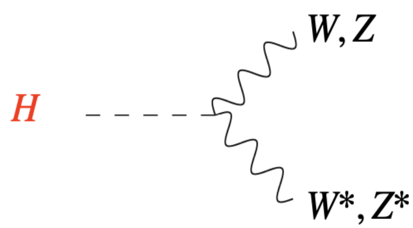
~400 k events produced



Top Assoc. Prod.

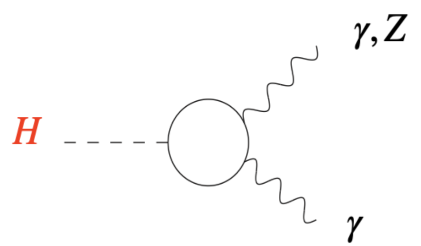
~80 k evts produced

Decay branching fractions



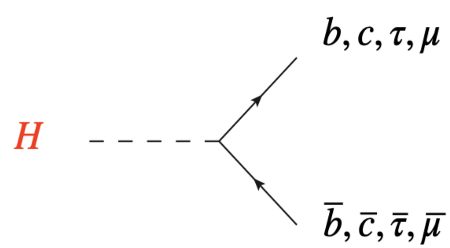
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

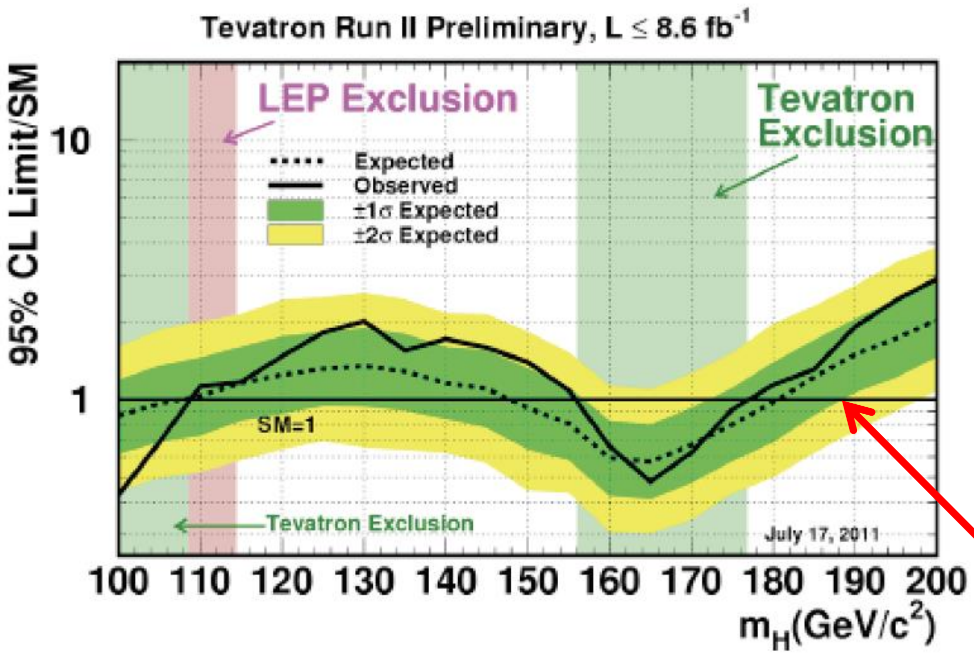
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

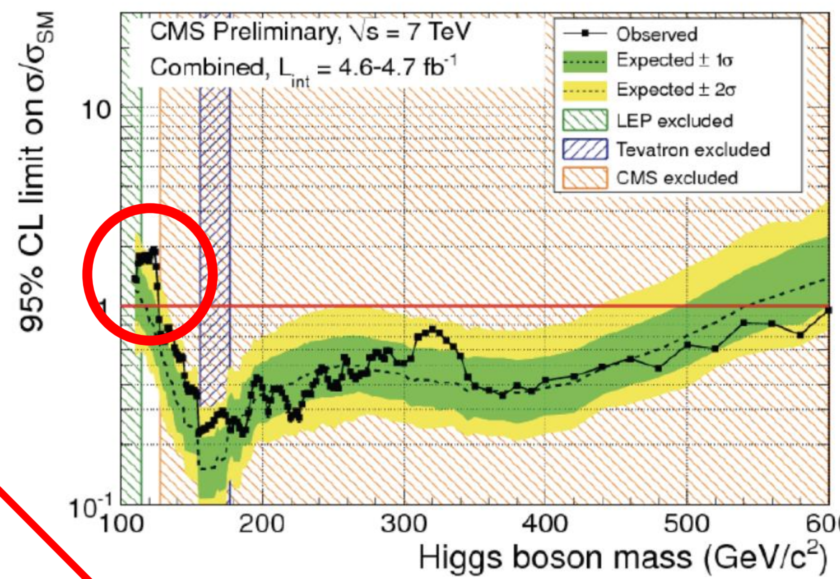
The Search for Higgs in 2011

Before the LHC



The LHC in 2011

Oct 2012



- Direct searches
  - LEP: $M_H > 114.4$ GeV
  - Tevatron: 156 GeV < M_H <176 GeV
- Indirect limits from electroweak searches
  - $M_H = 96^{+31}_{-24}$ GeV, M_H<169 GeV at 95% CL (standard fit)
  - $M_H = 120^{+12}_{-5}$ GeV ,M_H<143 GeV at 95% CL (including direct searches)
- SUSY prefers light Higgs boson (<~140 GeV)

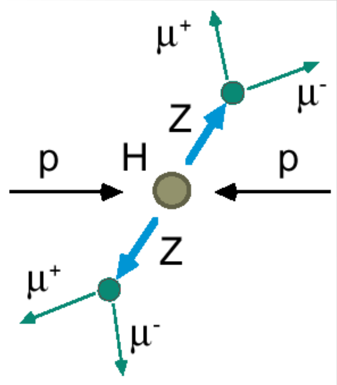
Closed all mass space for a SM Higgs except for the region 114.5-127 GeV This region "refuses to be excluded" with 2011 data and shows a slight excess. What will 2012 data say?

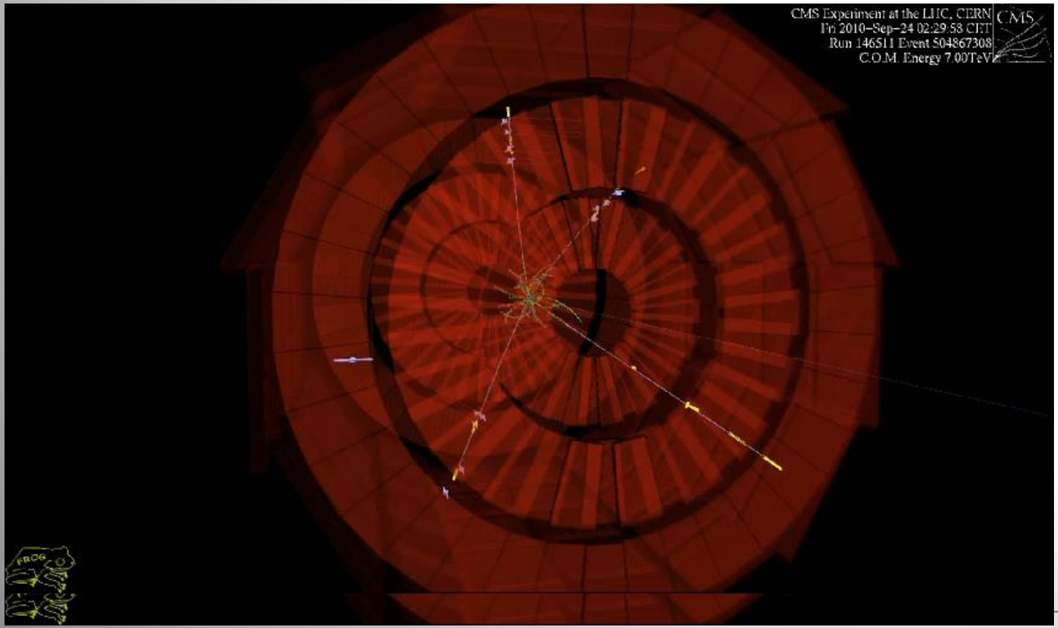
July 4th 2012

Example: H→ ZZ→ Four Leptons

A Higgs particle will decay immediately, eg in two heavy Z bosons
-> Select Z decays into electron or muon pairs

Eg we look for 4 muons
in the detector



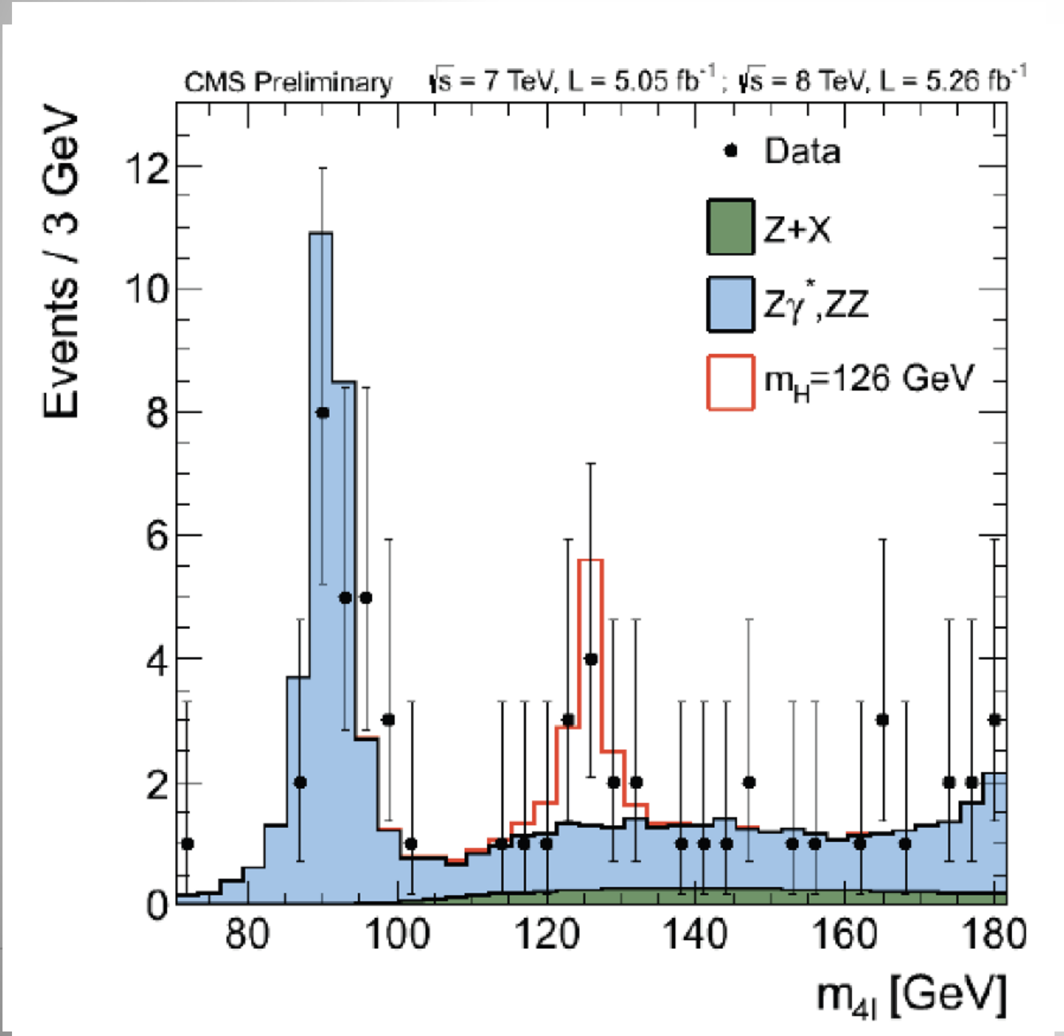


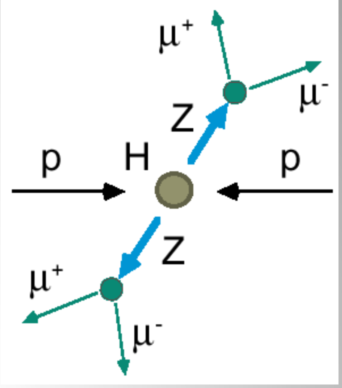
Real event from the original sample

But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for sure on event by event (but we can reconstruct the total mass with the leptons)

Example: H→ ZZ→ Four Leptons

Data collected and analysed till 4th July 2012.
-> Invariant mass distribution of 4 charged leptons





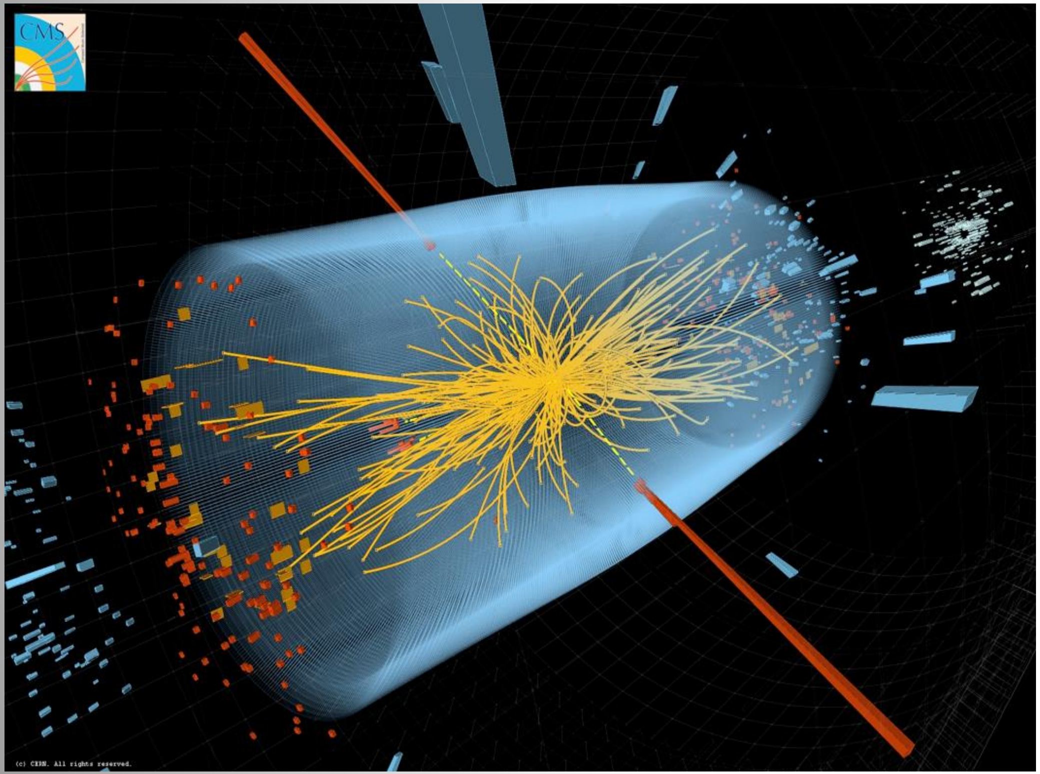
Any sign of a new particle here? We need a yardstick i.e. what do we expect from the SM on ZZ production?

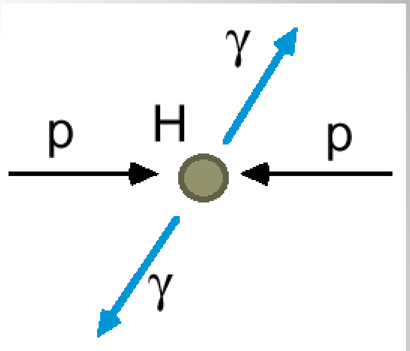
Add Monte Carlo prediction: some excess above SM at 125 GeV.
Consistent with a Higgs?

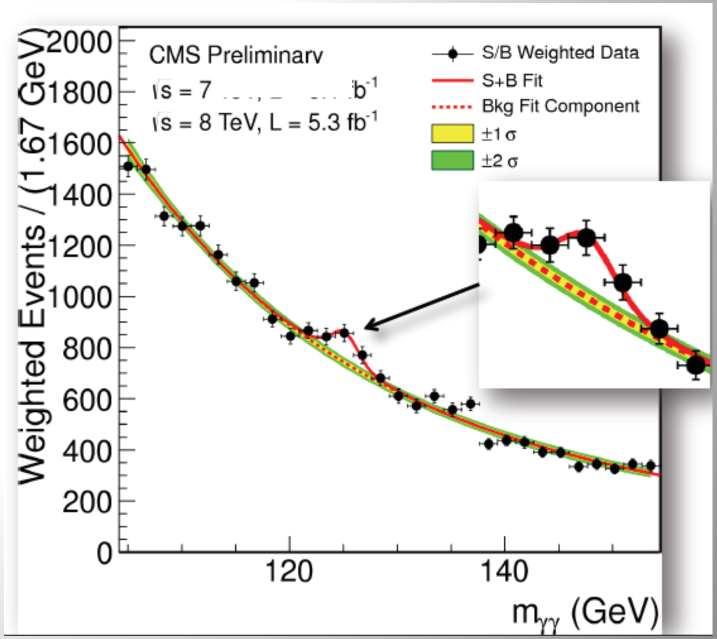
Add 126 GeV SM Higgs prediction: A nice match…

Example: H→ Two Photons

Different Higgs decay channel: decay to two photons



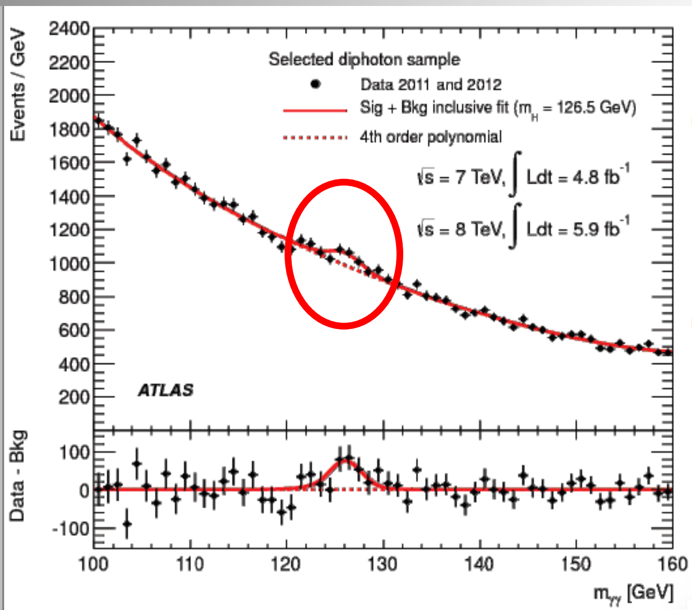


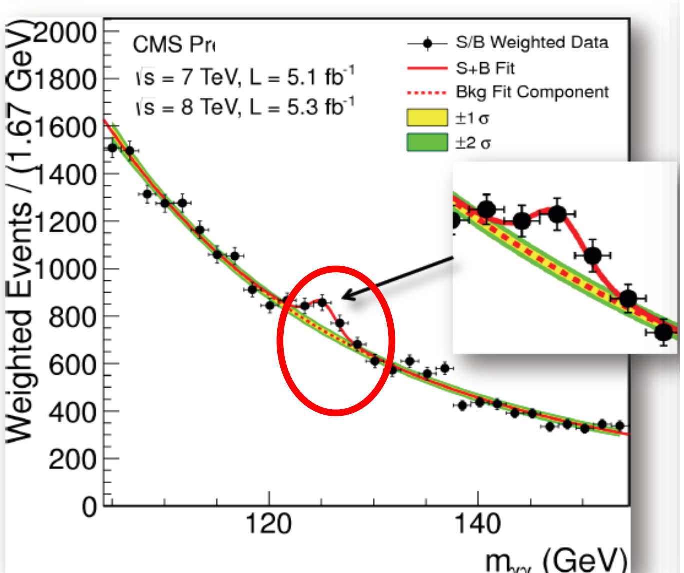


Observe an excess also at around 125 GeV

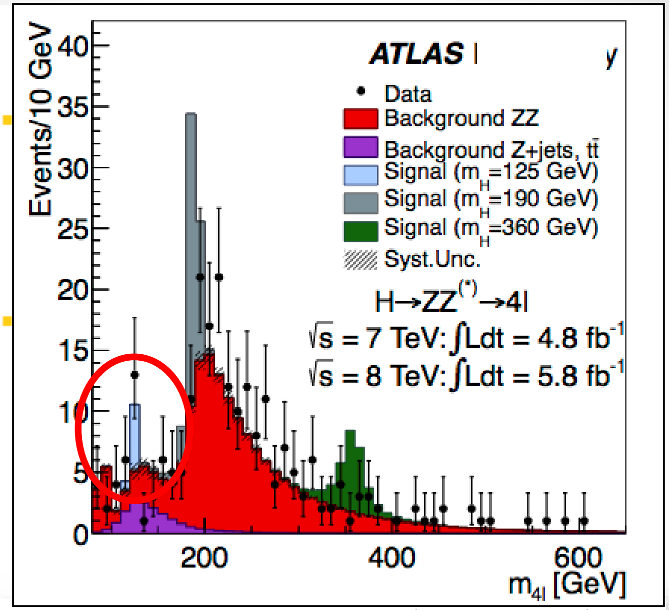
Results from all Channels

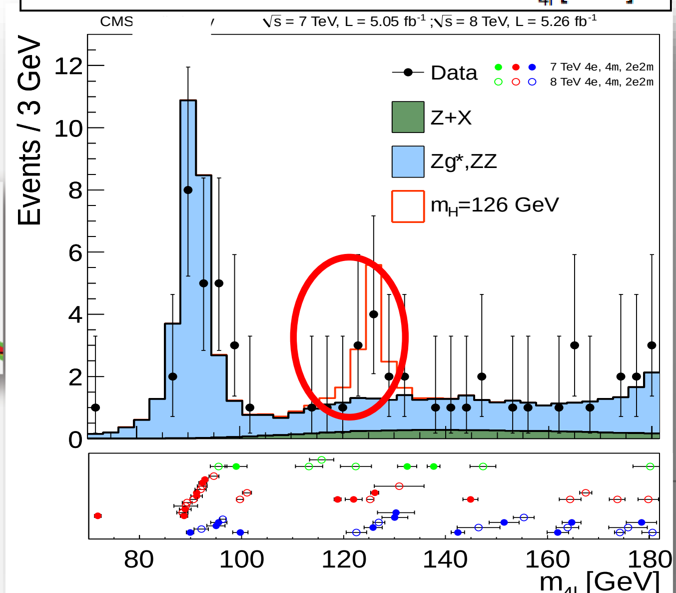
Higgs → 2 photons!!





Higgs → 2 Z →4 leptons!!





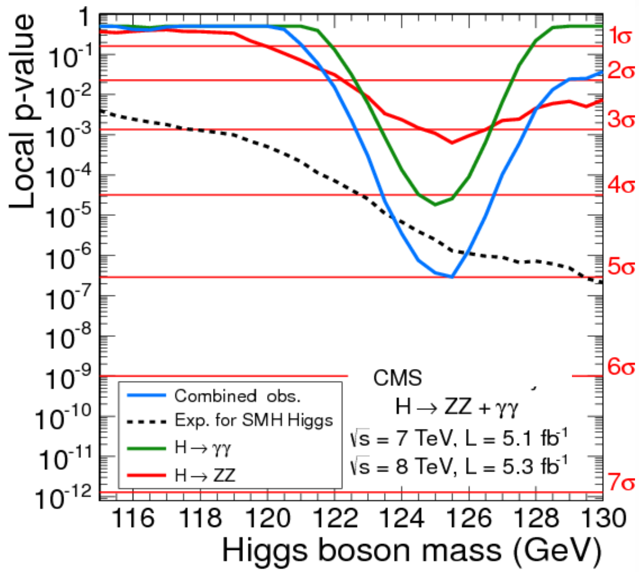
A clear "excess" of events seen in both experiments around 125-126 GeV

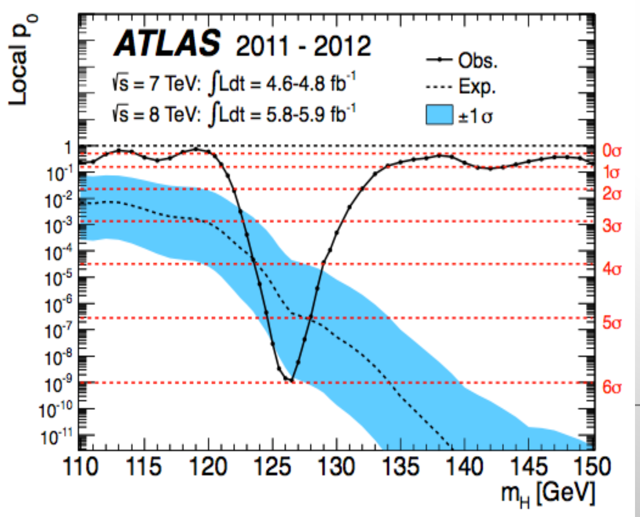
It became very significant in 2012

Sophisticated Statistical Methods have used to fully analyse this.

Results from the Experiments

July 4th 2012
Combined statistical strenght

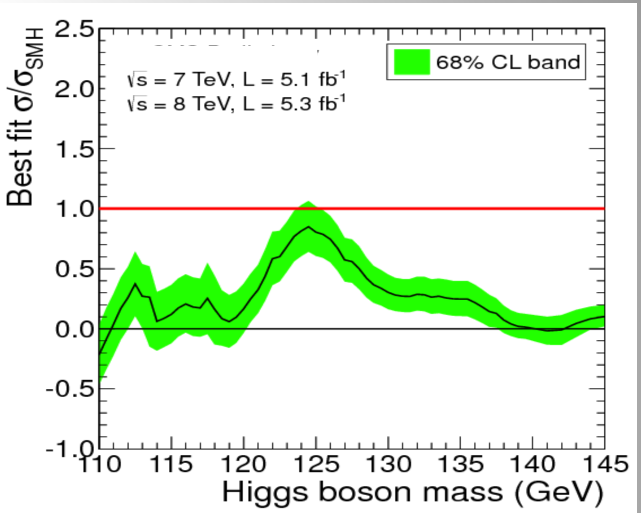


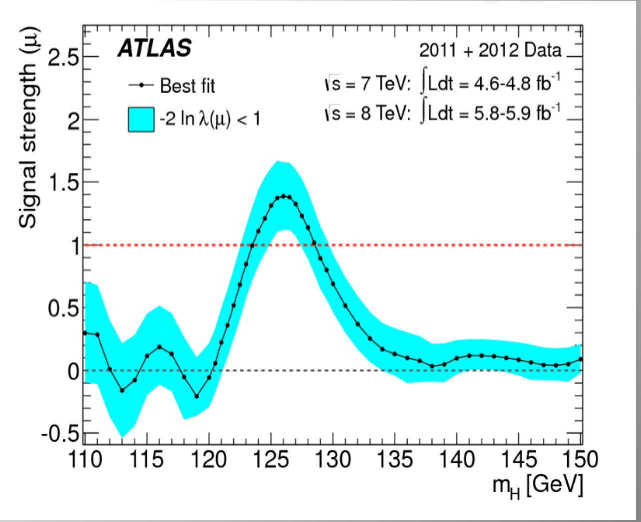


CMS and ATLAS observe a new boson with a significance of 5 sigma or more

The particle is consistent with a Higgs-like boson

July 4th 2012
Consistency with a SM Higgs





July 4th 2012

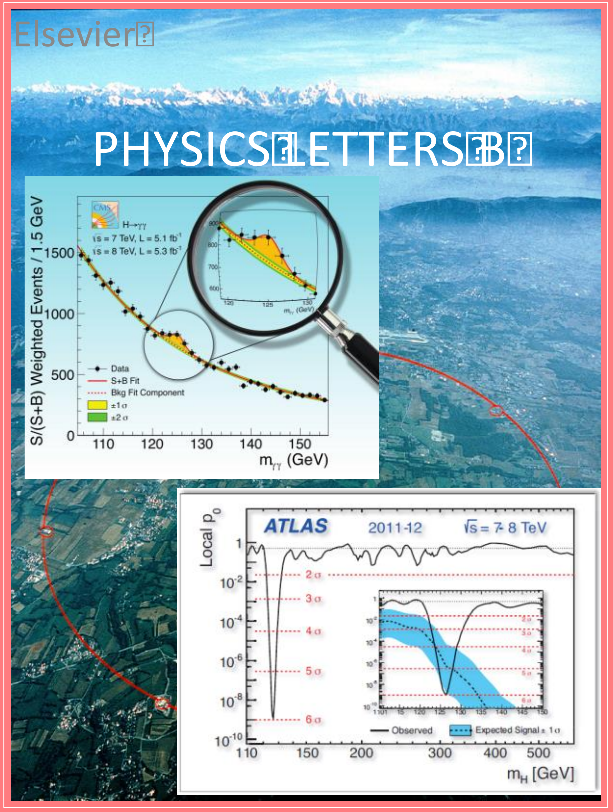
- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN

Melbourne

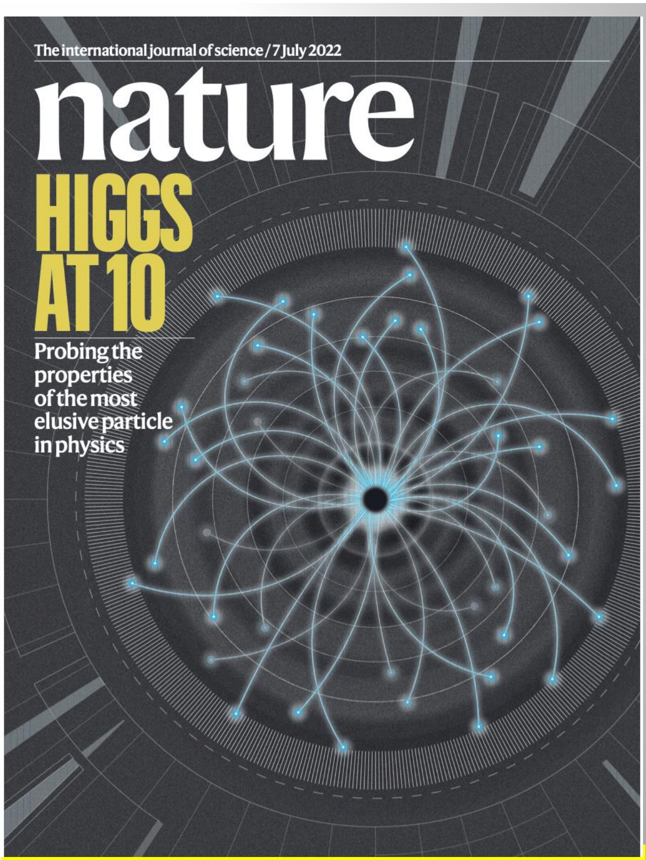
Now: 10 Years of Higgs Studies

2012: Special Physics Letters B edition with the ATLAS and CMS papers on the Higgs Discovery



More than 13,000 times cited so far…

2022: Special Nature magazine edition with the ATLAS and CMS papers on 10 years of Higgs



Released by Nature and to arXiv last week:2207.00043

Two Papers for Nature

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

2207.00043

CERN-EP-2022-039
2022/07/07

CMS-HIG-22-001

Two summary papers with state of the art results from ATLAS and CMS

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

The CMS Collaboration

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Nature

CERN-EP-2022-057
4th July 2022

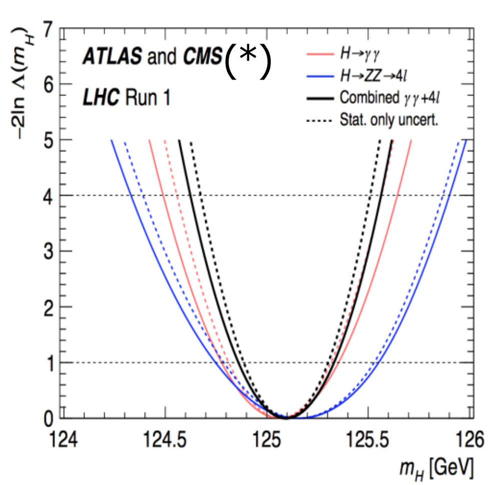
2207.00092

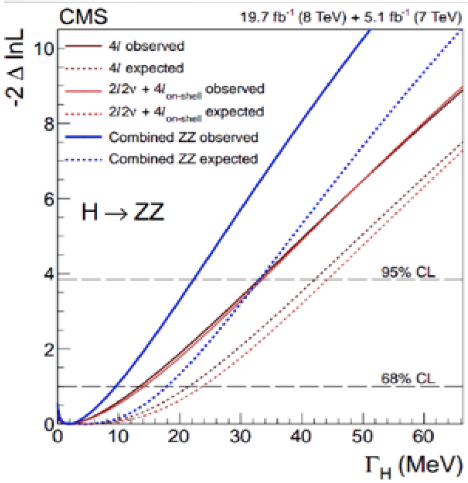
A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

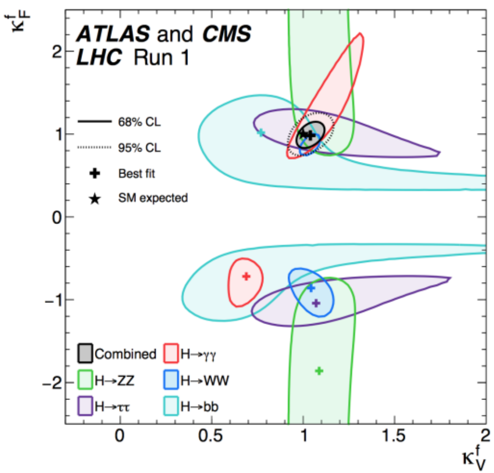
The ATLAS Collaboration

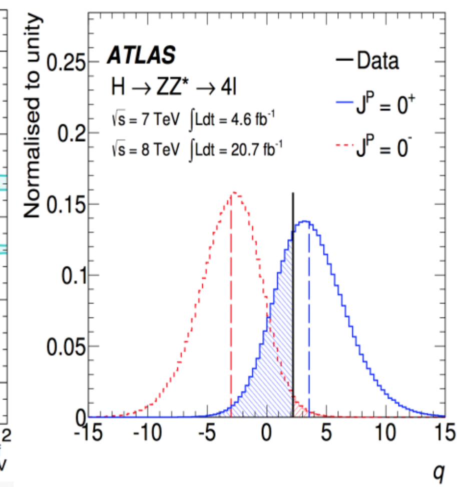
Brief Higgs Summary from Run-1

We knew already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 24 MeV
(95%CL)

Couplings are
within ~15-20%
of the SM values

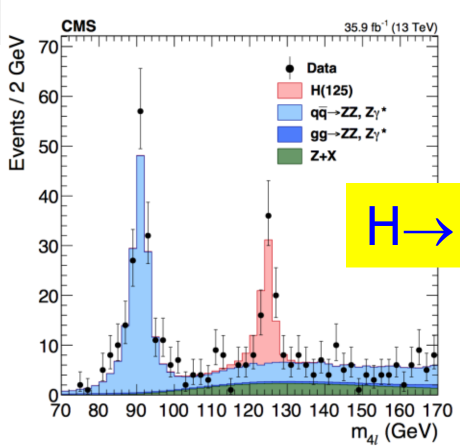
Spin =
$0^{+(+)}$ preferred
over 0^-,1,2

SM-like behaviour for most properties, but continue to look for anomalies, new/unexpected decay modes or couplings, multi-Higgs production…

(*) First ATLAS+CMS paper : > 5000 authors, a new record as noted by Nature!!

The Higgs Today

Higgs @ 13 TeV in Run-2



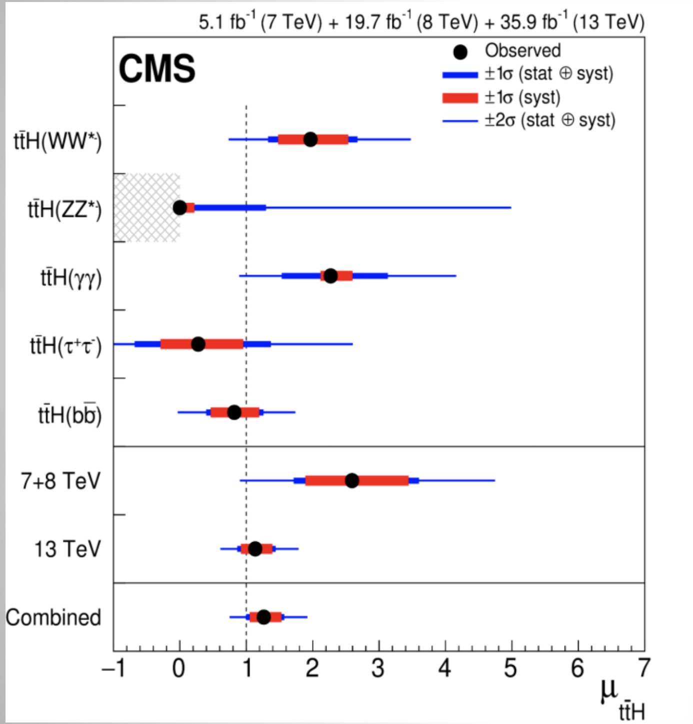
H→ ZZ

- Higgs particle is still there !! ☺
- More precision on Higgs properties
- New Combined Fits with all data
- Observation of H→ττ
- Direct observation of ttH production
- Observation of H→bb
- Evidence for H→$\mu\,\mu$ (second generation fermions)
- Detailed CP analysis eg in H→VV & H→ττ
- Differential distributions/STXS event classification…

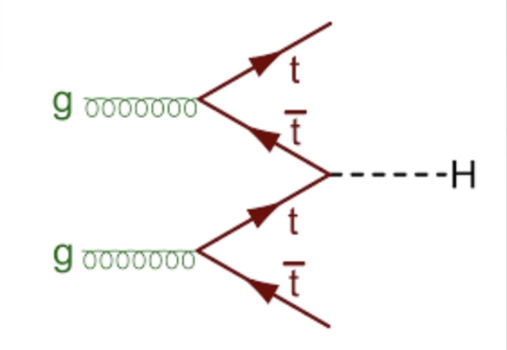
- The mild deviations seen in Run-1 seem to be gone ☹
- NEW: 10 year Anniversary Paper with Run-2 legacy

Higgs ttH Production

Observation of ttH production: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1



arXiv:1804.02610



7+8+13 TeV data

$$\mu_{t\bar{t}H} = 1.26\,^{+0.31}_{-0.26}$$

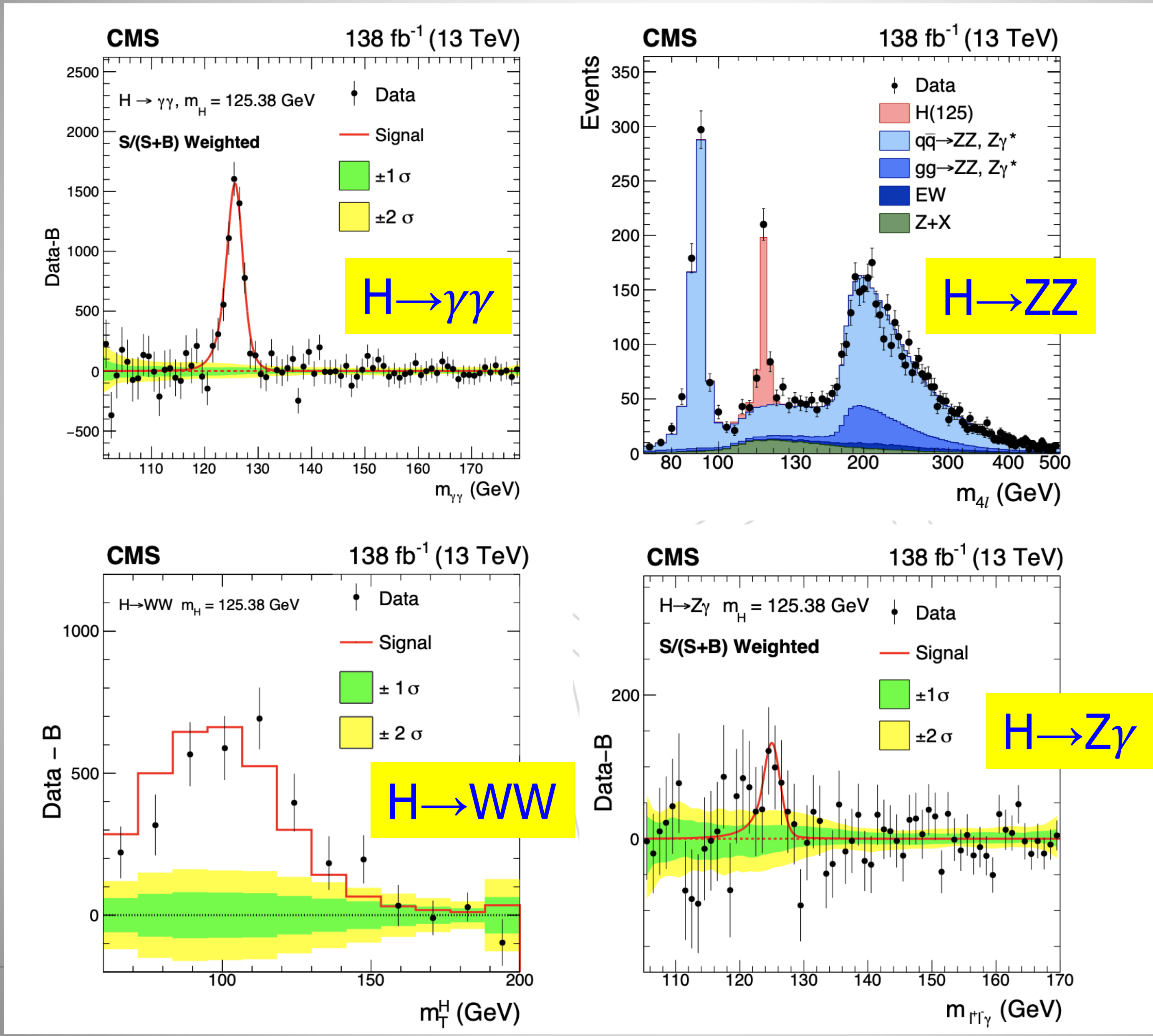
Significance = 5.9σ (exp 4.2σ)

arXiv:2011.03652

NEW: ttH and tH in final states with muons, electrons and hadronic taus using the full Run-2 data, giving the following μ values:

ttH: $0.92 \pm 0.19\,(\text{stat})\,^{+0.17}_{-0.13}\,(\text{syst})$ and tH: $5.7 \pm 2.7\,(\text{stat}) \pm 3.0\,(\text{syst})$

Higgs Decaying to Vector Bosons



2207.00043

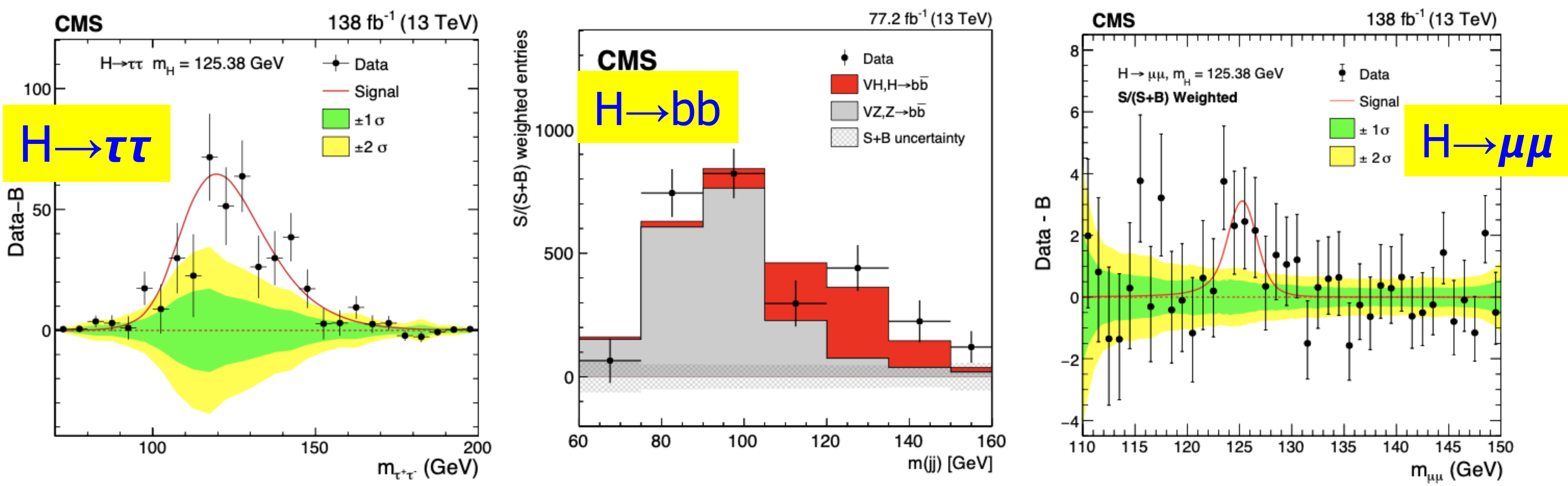
These are the CMS Run-2 legacy results!

Full run-2 data sample

Higgs Decaying to Fermions

2207.00043

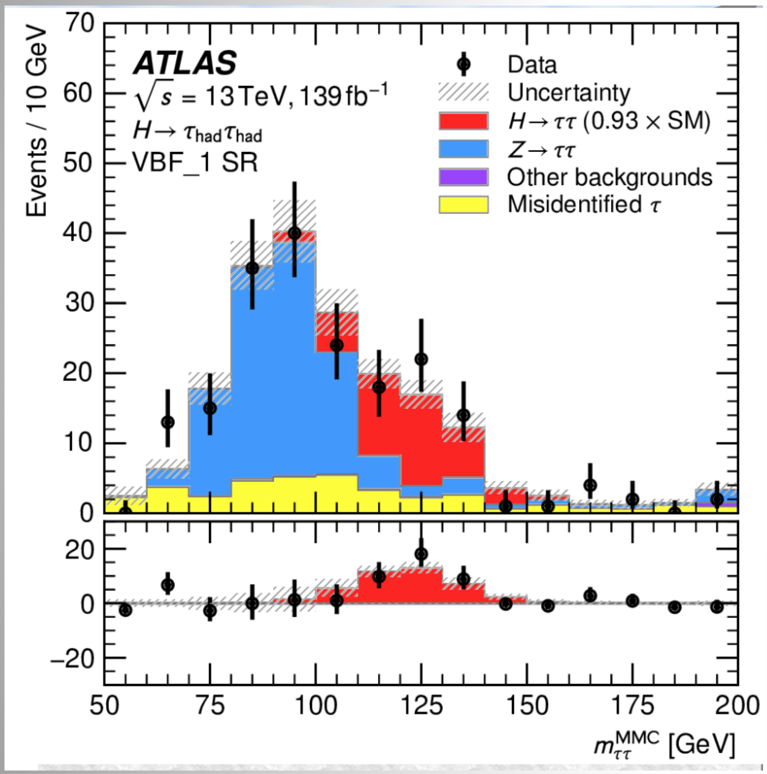
Background-subtracted results for H→*ττ*, H→bb and H→*μμ* channels



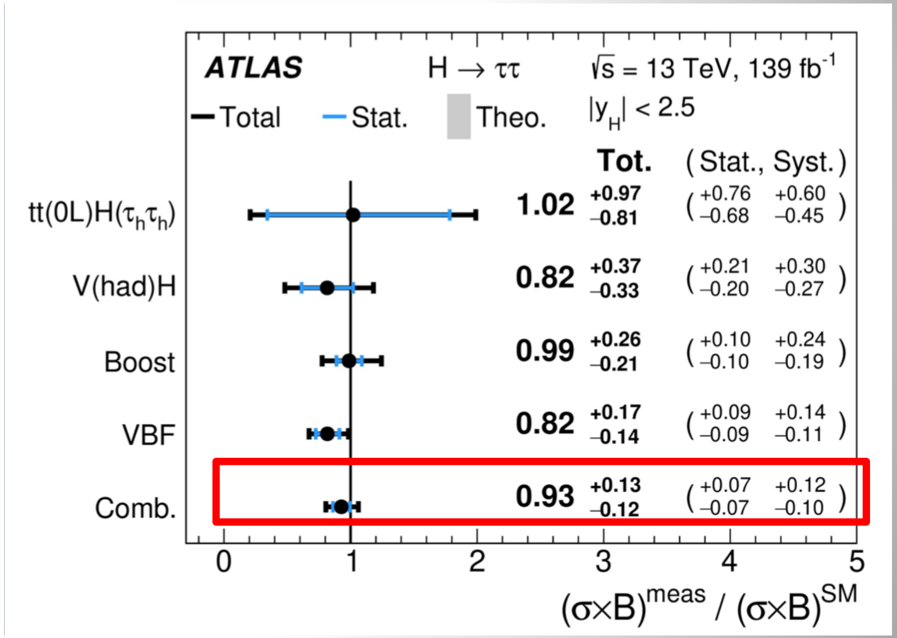
CMS Run-2 legacy results!

Higgs to $\tau\tau$ Decay

H-> $\tau\tau$ decay: Combination of the tau decay channels h-h, l-h and e-μ and total Run-2 statistics



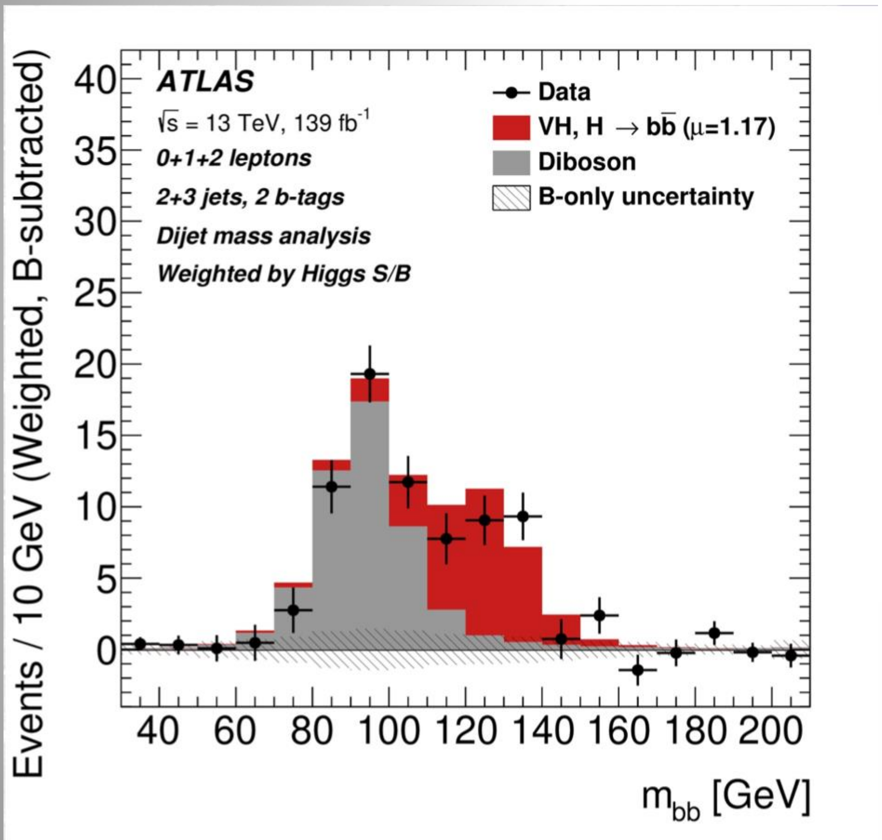
arXiv:2112.11876



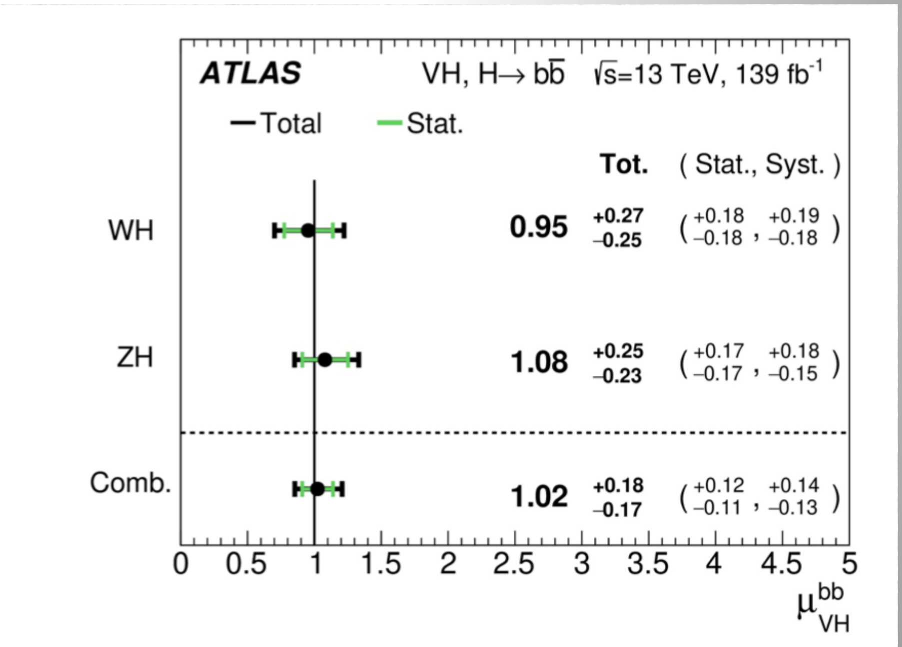
H->$\tau\tau$ sample large -> allows for cross section measurements and CP studies

Higgs to bb Decay

H->bb decay: VH production channels with tagged leptons including all Run-2 data



arXiv:2007.02873



H->bb observed with 6.7σ significance

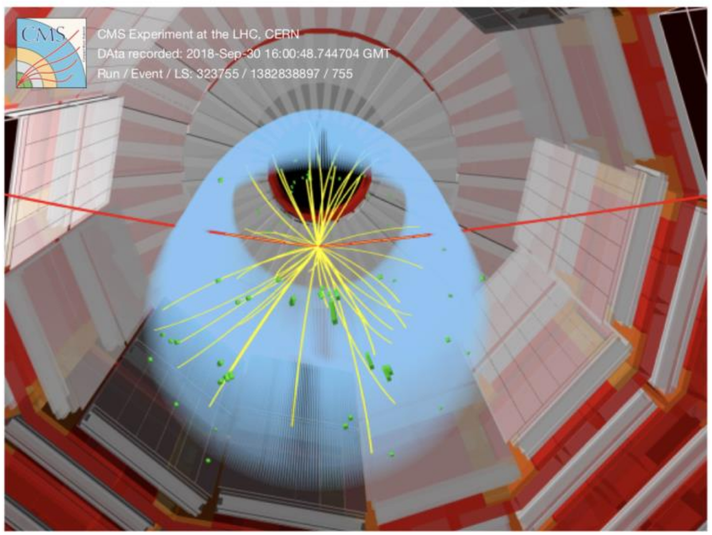
Combined best fit $\mu^{bb}_{VH} = 1.02^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.})$

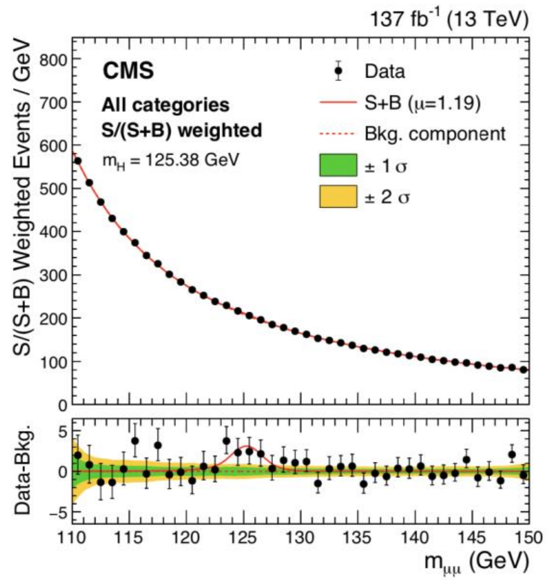
Higgs Decaying to Di-Muons

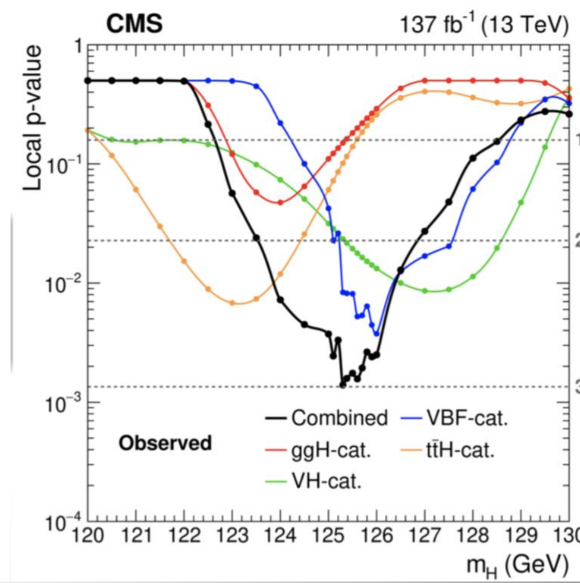
Evidence for H->$\mu\mu$ with full run-2 data sample (3 sigma)
-> Clean signature but small Branching Ratio: 0.02% only

SM coupling strenght $\boldsymbol{\mu}$ $1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$.

2009.04363







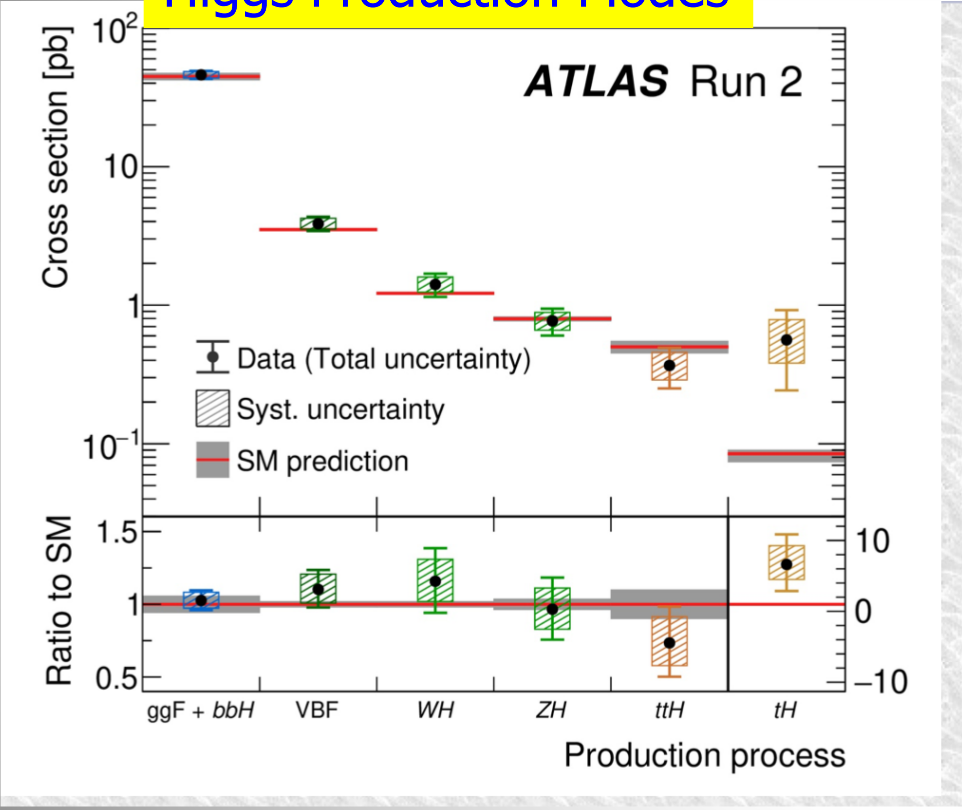
First evidence of Higgs coupling to second generation!

Combined Results using all Data

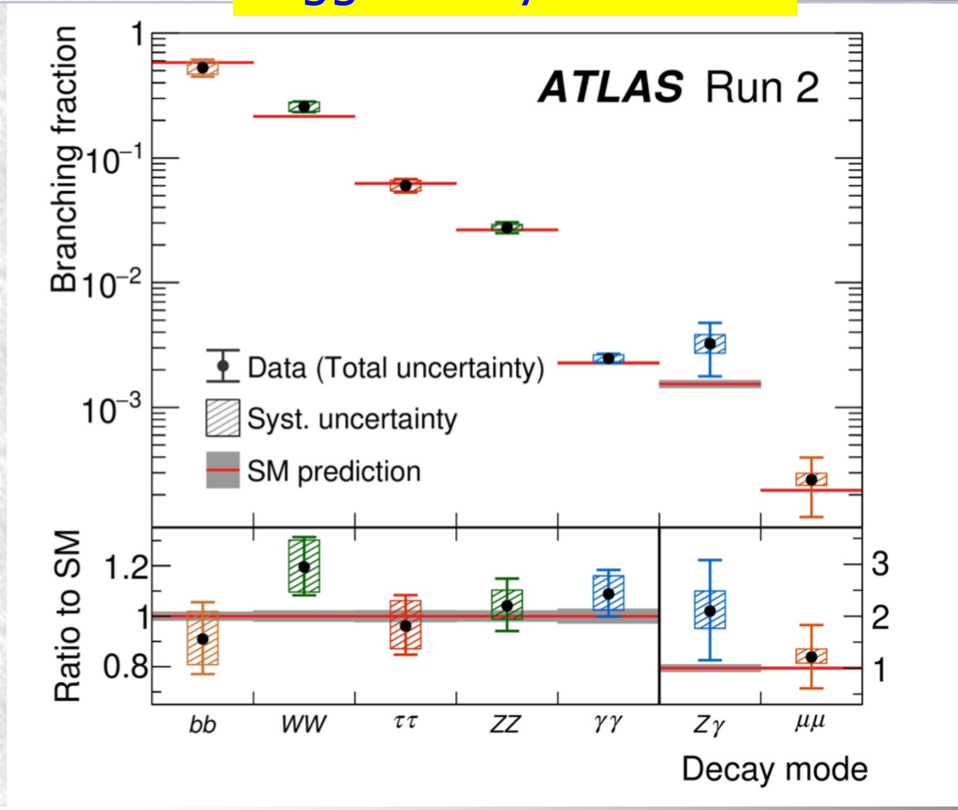
Production cross sections branching ratio

2207.00092

Higgs Production Modes



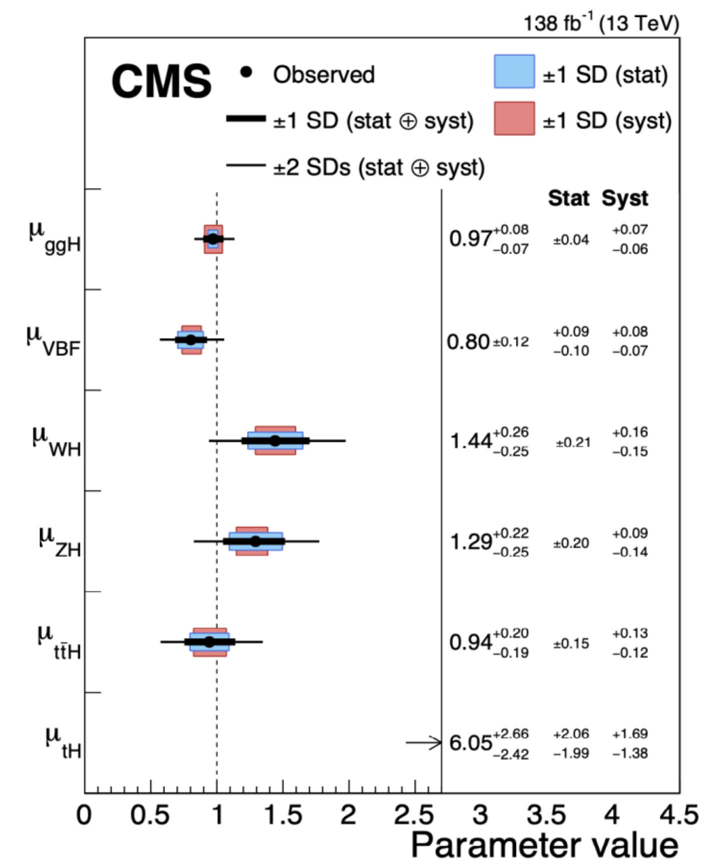
Higgs Decay Channels



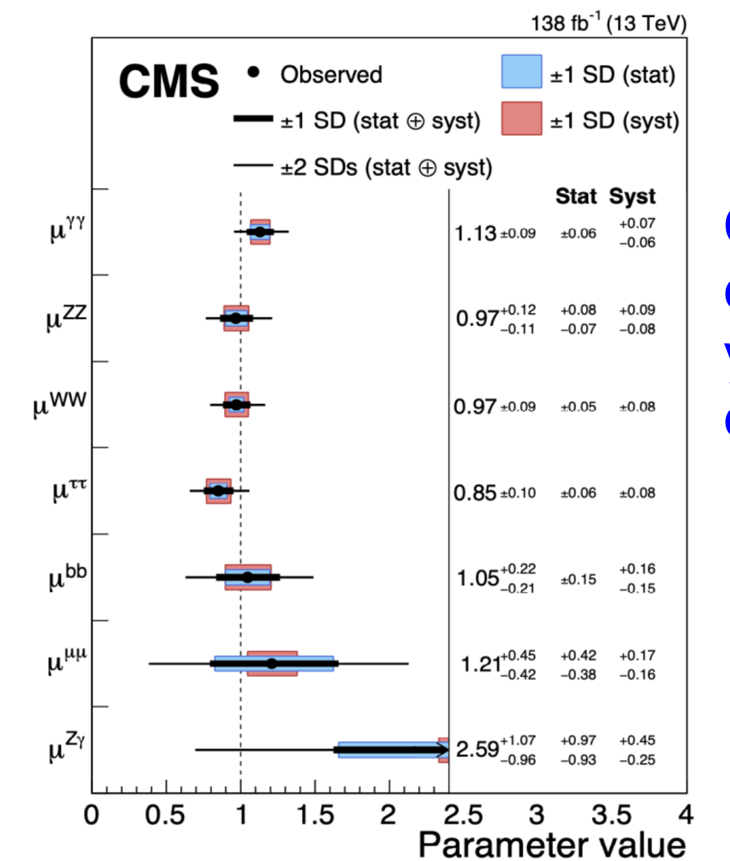
- Production and decay in agreement with SM predictions
- Order 10% precision on 'big five' decay modes

Signal Strenght Parameters

Higgs Production Modes



Higgs Decay Channels



2207.00043

Compare observed yield with SM expectation

$$\mu_i = \sigma_i / (\sigma_i)_{SM}$$

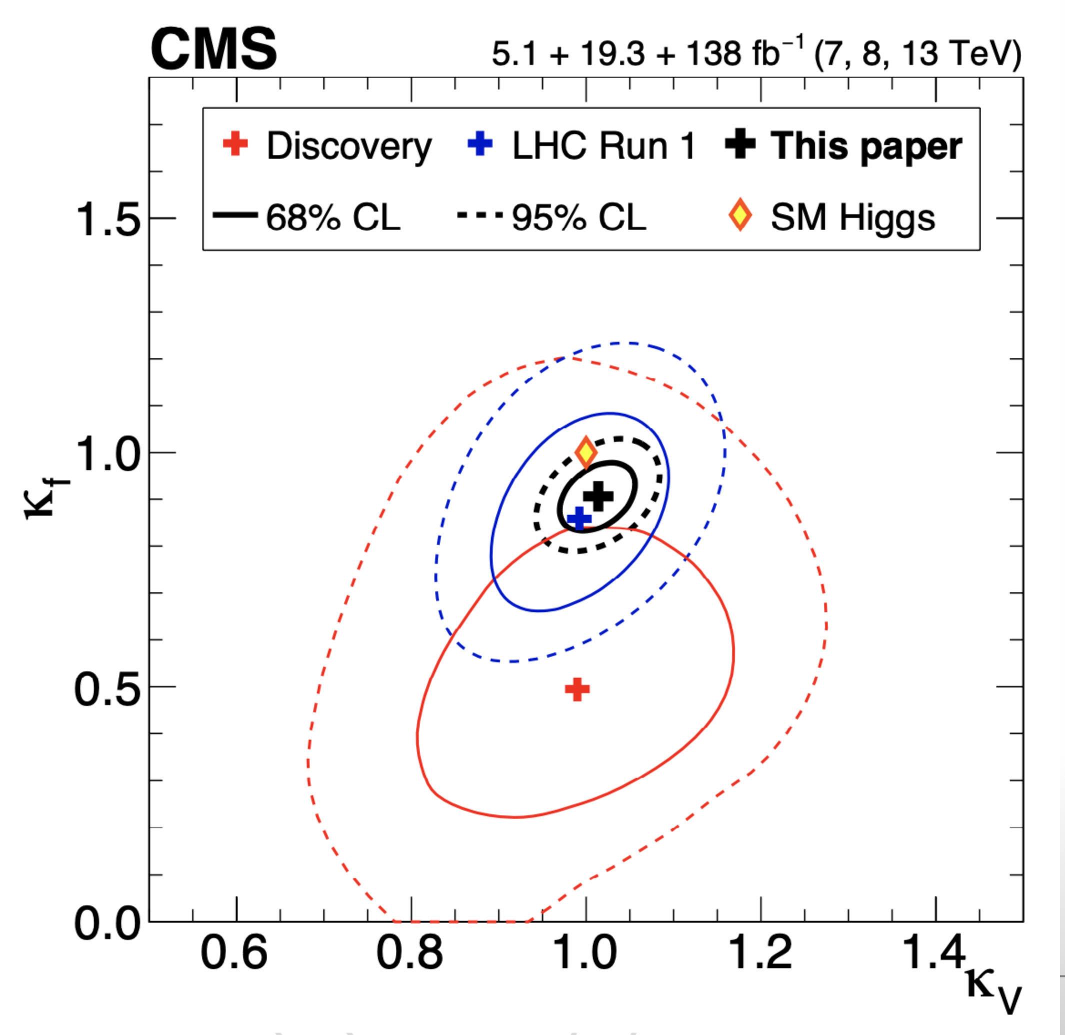
$$\mu^f = \mathcal{B}^f / (\mathcal{B}^f)_{SM}$$

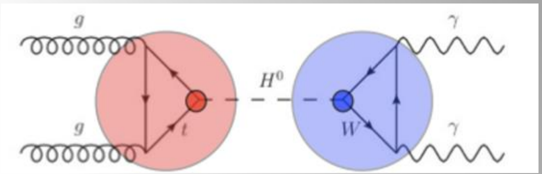
Global Higgs Signal Strenght: $\mu = 1.002 \pm 0.057$

The value $\mu = 1$ is the expected value for the Standard Model

Coupling Modifiers

Constraints on the Higgs coupling modifiers to fermions and heavy gauge bosons, and the evolution with time from discovery till today





Coupling Modifiers:
In the κ-framework for cross sections and branching ratios

In the SM: κ=1

For a single contribution

$$\kappa_j^2 = \Gamma^j/\Gamma^j_{SM}, \quad \kappa_j^2 = \sigma_j/\sigma_j^{SM}$$

Coupling Modifiers

Constraints on the Higgs coupling modifiers to fermions and heavy gauge bosons, and sensitivity to "invisible" contributions

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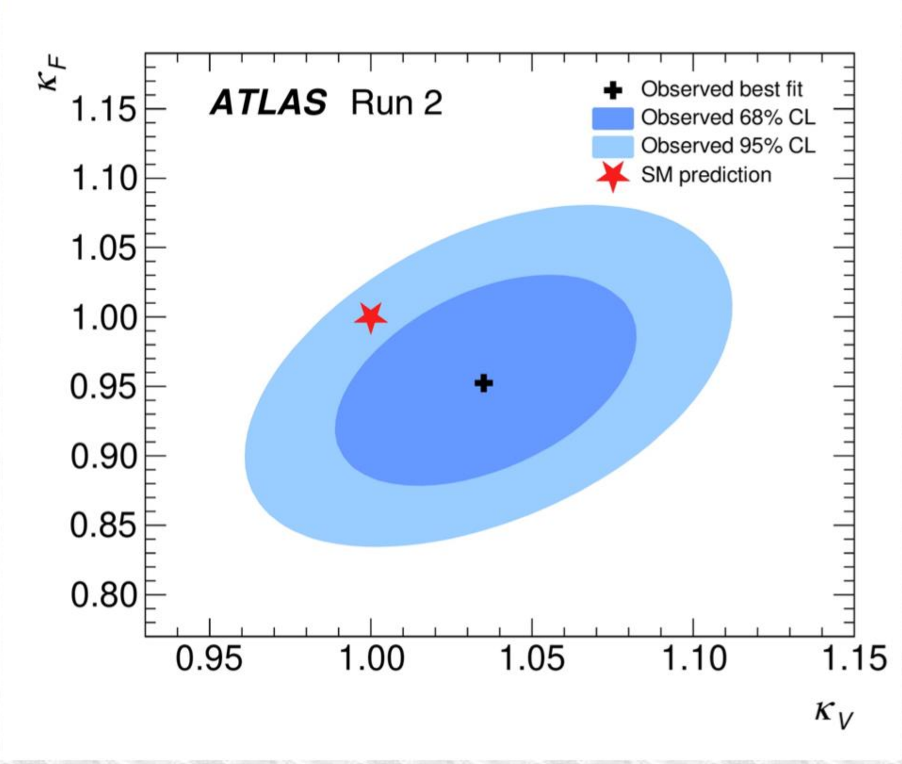

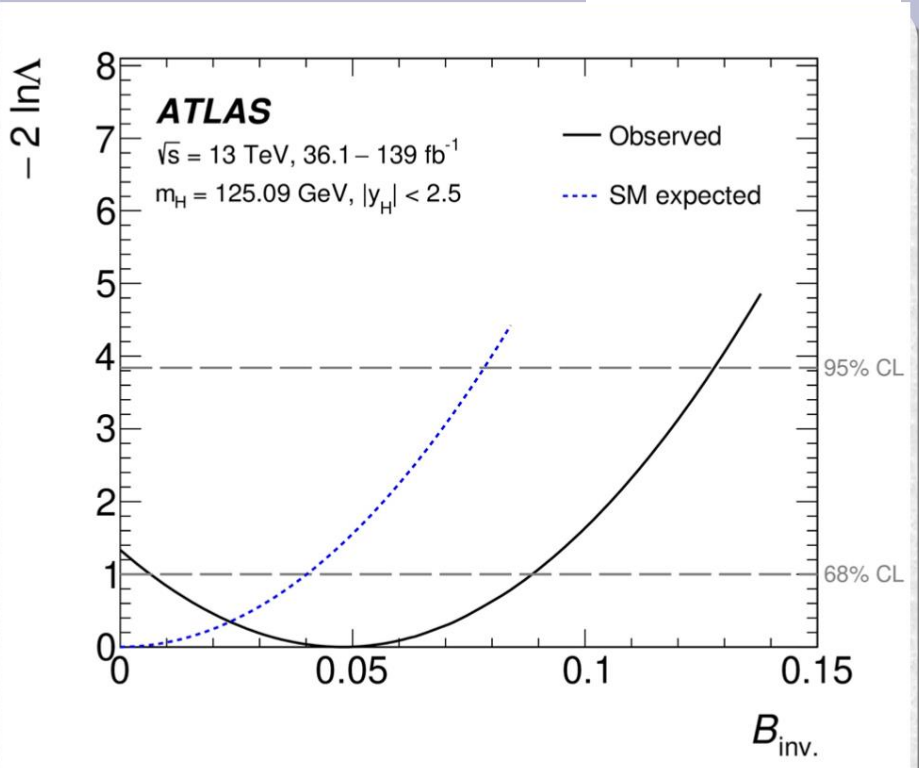

- Assuming a scaling for each of vector and fermion couplings, errors 5% for fermion, 3% for boson.
- B_{inv} < 13% (8% expected) with κ_V constrained ≤ 1

Higgs Coupling to Fermions and Bosons

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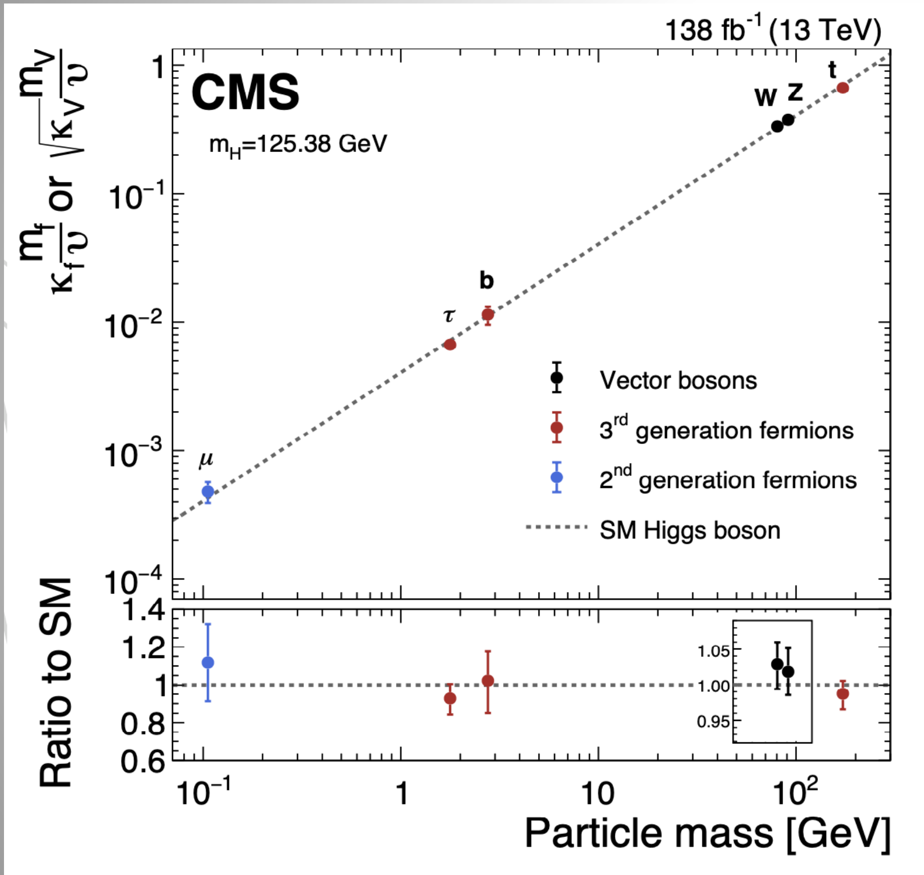

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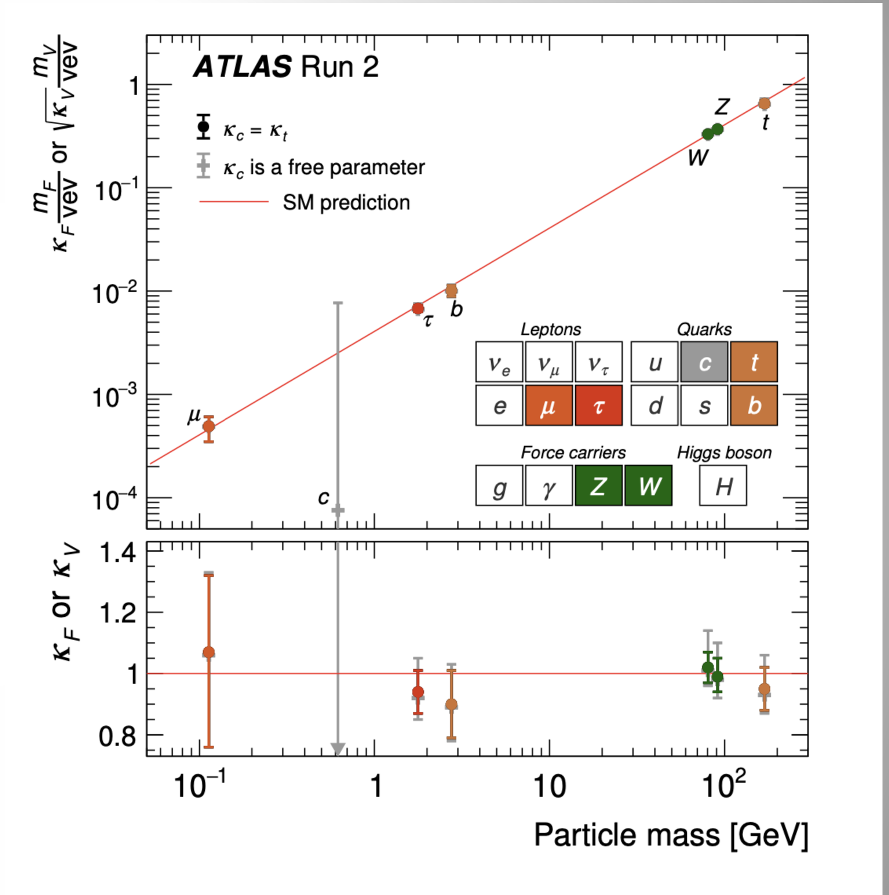
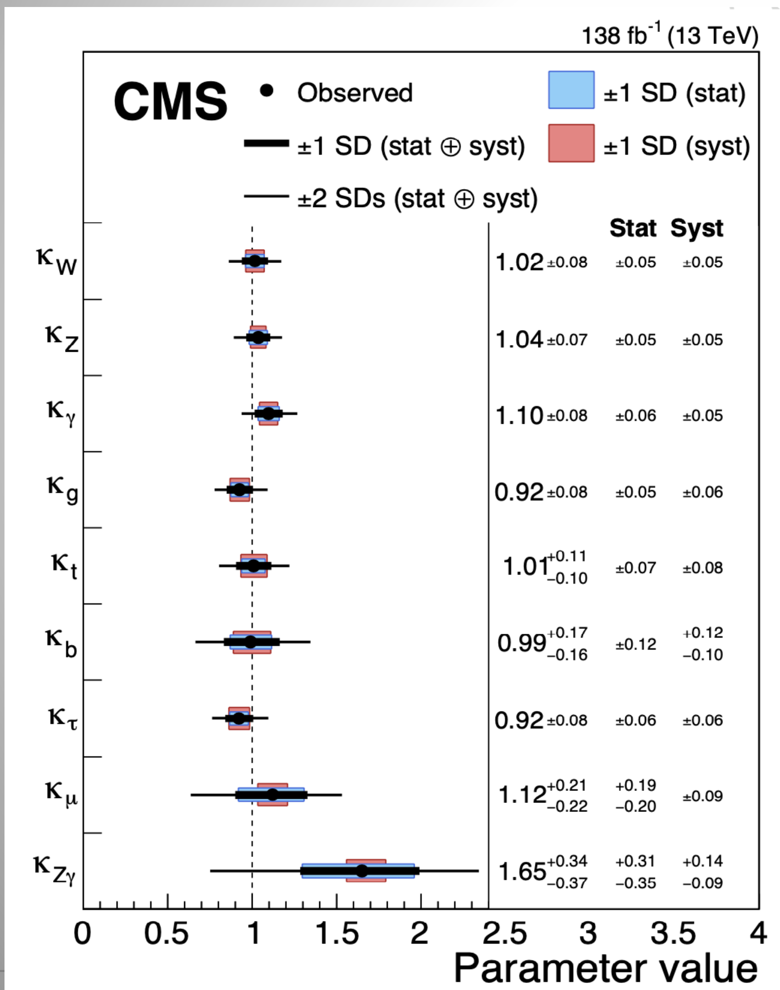
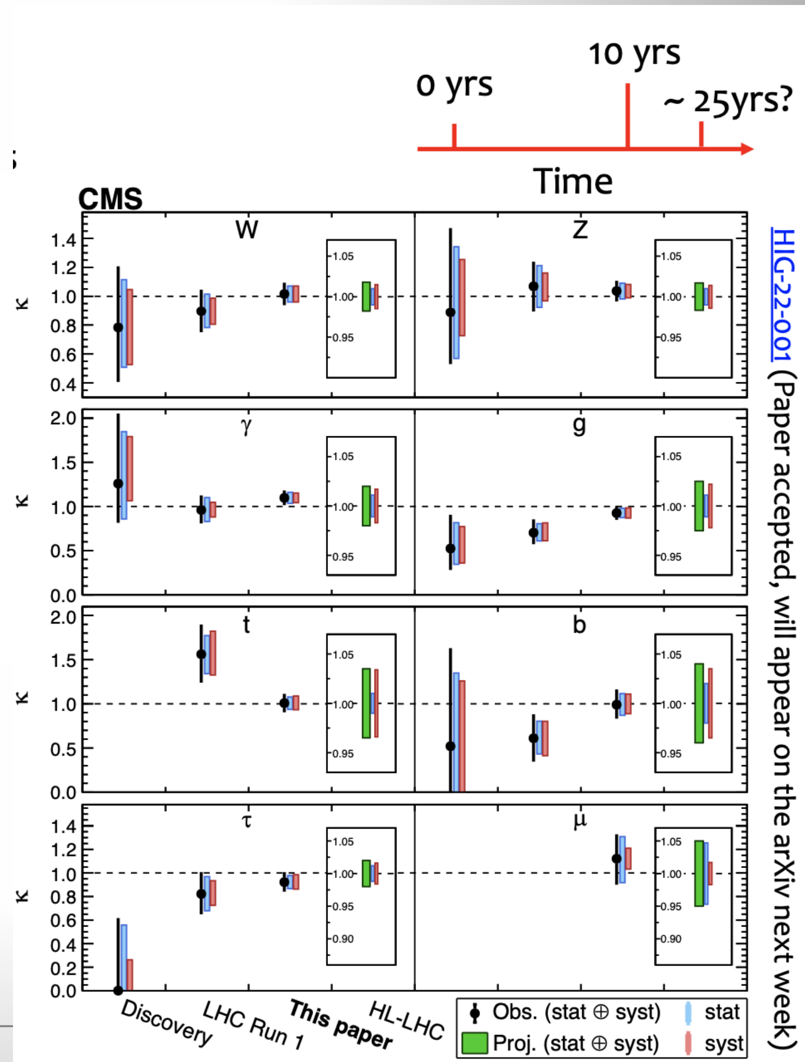


- Scaled coupling modifiers for bosons and fermions
- υ is the vacuum expectation (246 GeV)

Results from the fit of all channels

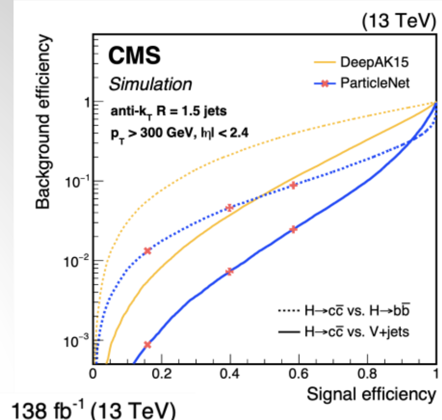
Different coupling modifiers and evolution with time from discovery till today





Higgs to Charm?

Search for H→ cc in HV assoc. production mode.
Find c-jets using the PARTICLENET graph neural network, with jet tagging via particle clouds.
-> Observation of Z→ cc with 5.7σ significance



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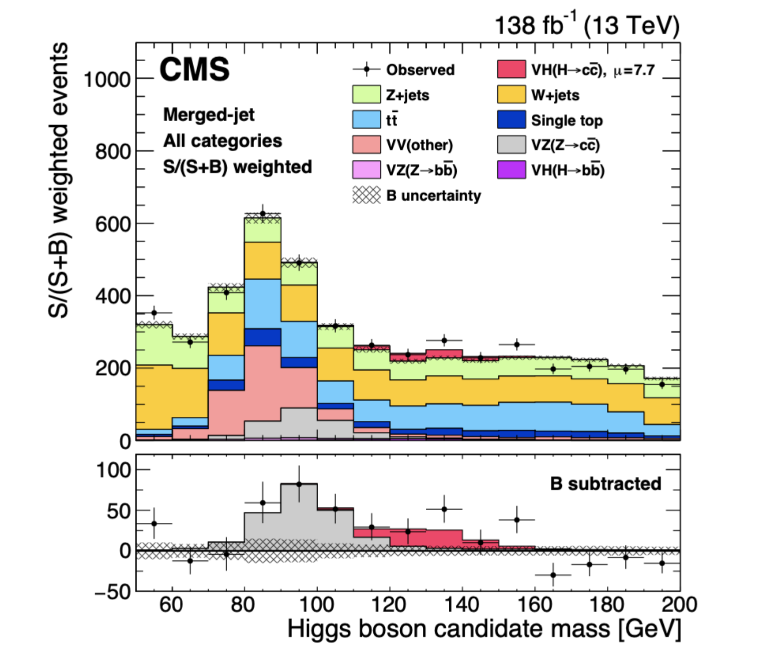
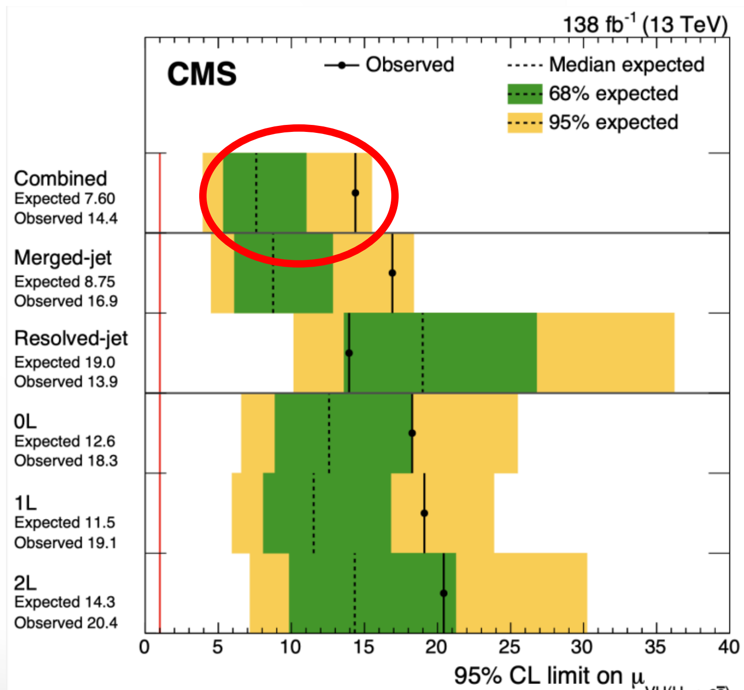
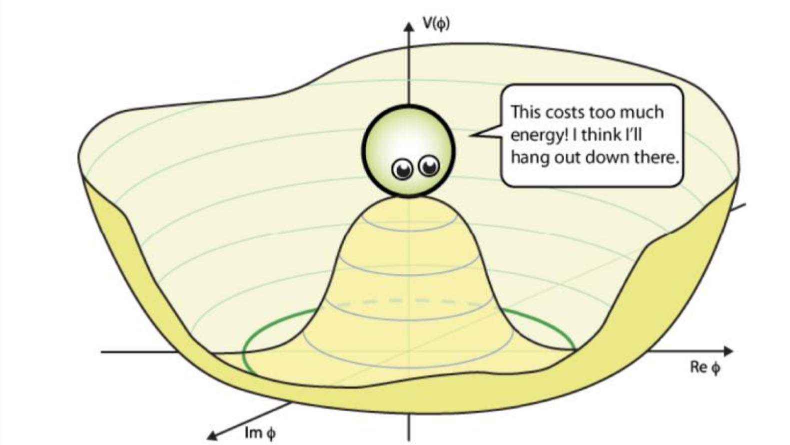




Observed (95%): **μ** upper limit <14 SM prediction, Yukawa coupling $1.1 < |\kappa_c| < 5.5$

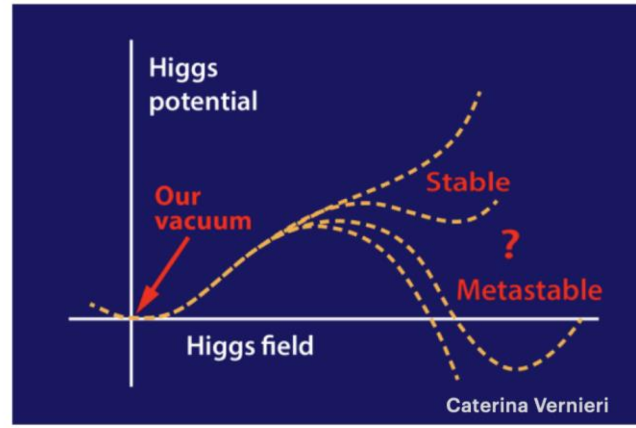
Higgs Self Coupling



$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

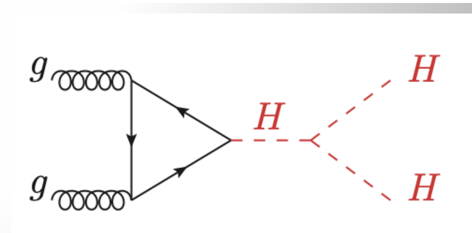
- Does the Higgs couple to itself?
- Access the shape of the Higgs potential…

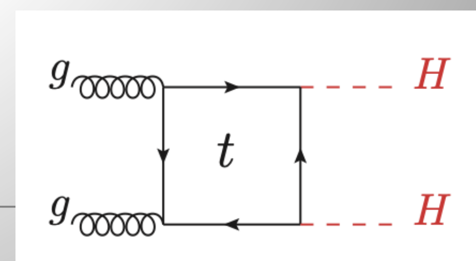


Main tool at the LHC to measure the Higgs self-coupling is via Higgs Pair production

- Small cross sections
- Negative interference with background
- Many decay channels to study

->A challenging measurement @ LHC!





Higgs Pair Production

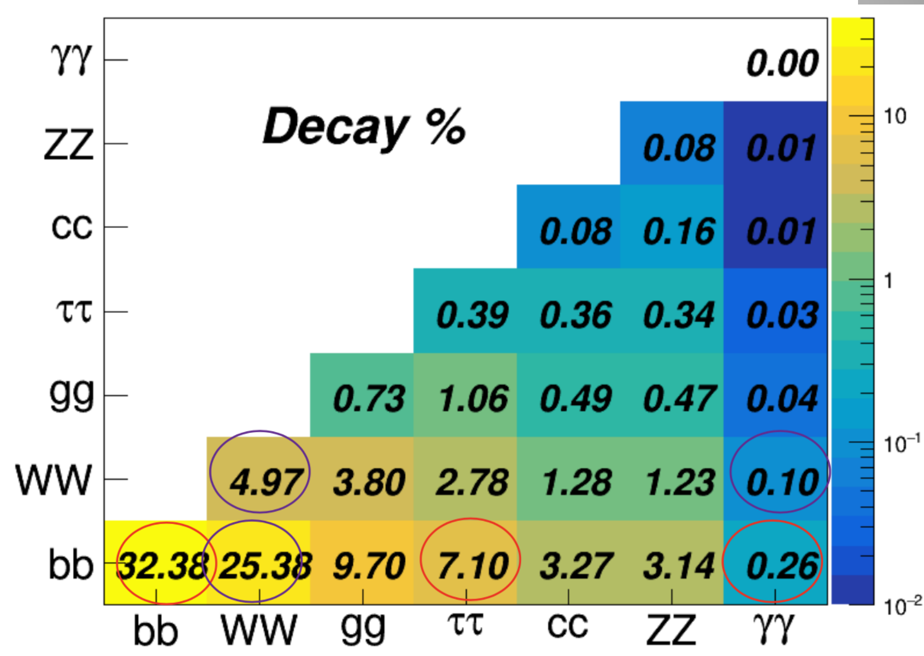
There are many decay Higgs channel combinations to consider

Example: ATLAS analyses

Branching ratios of various decay modes

Purple have results at 13 TeV

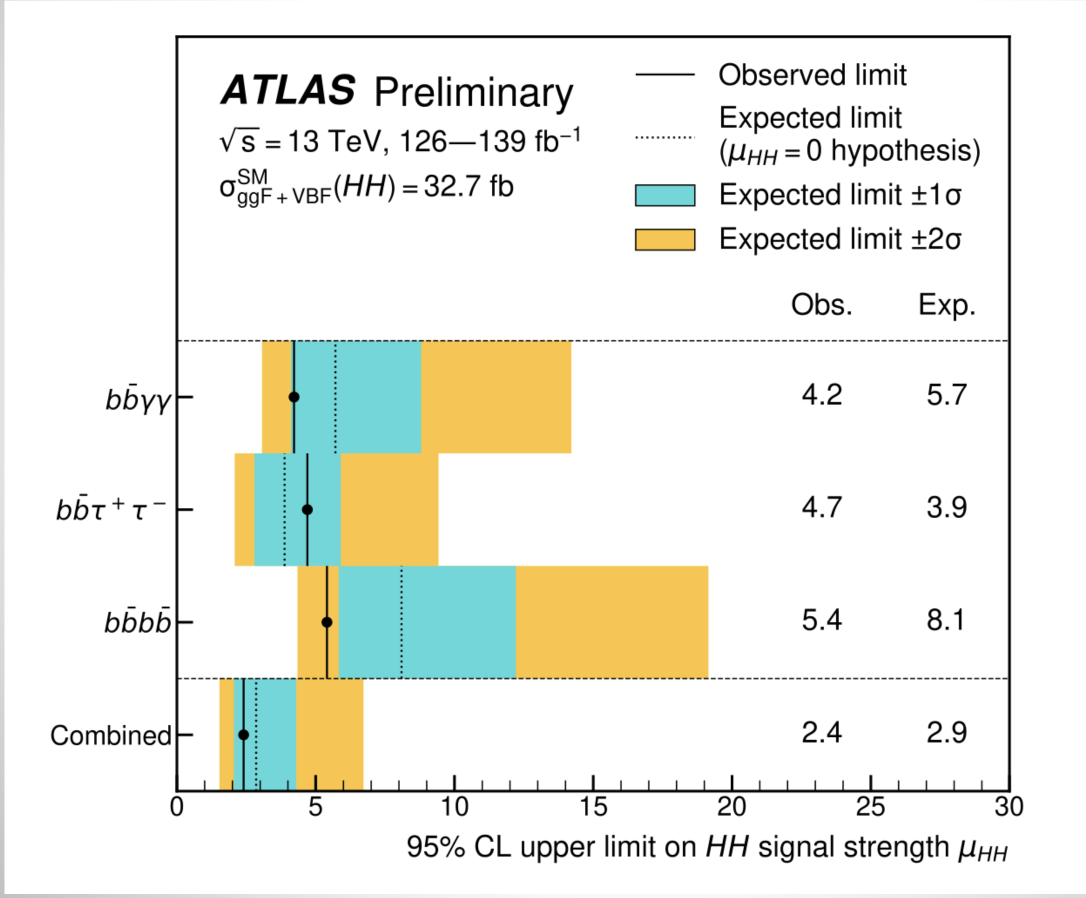
Red circled channels have full run 2 data



Many weak channels are not exploited – some gain possible

Combined Sensitivity to HH

Double Higgs production rate normalized to SM expectation



ATLAS-CONF-2022-050

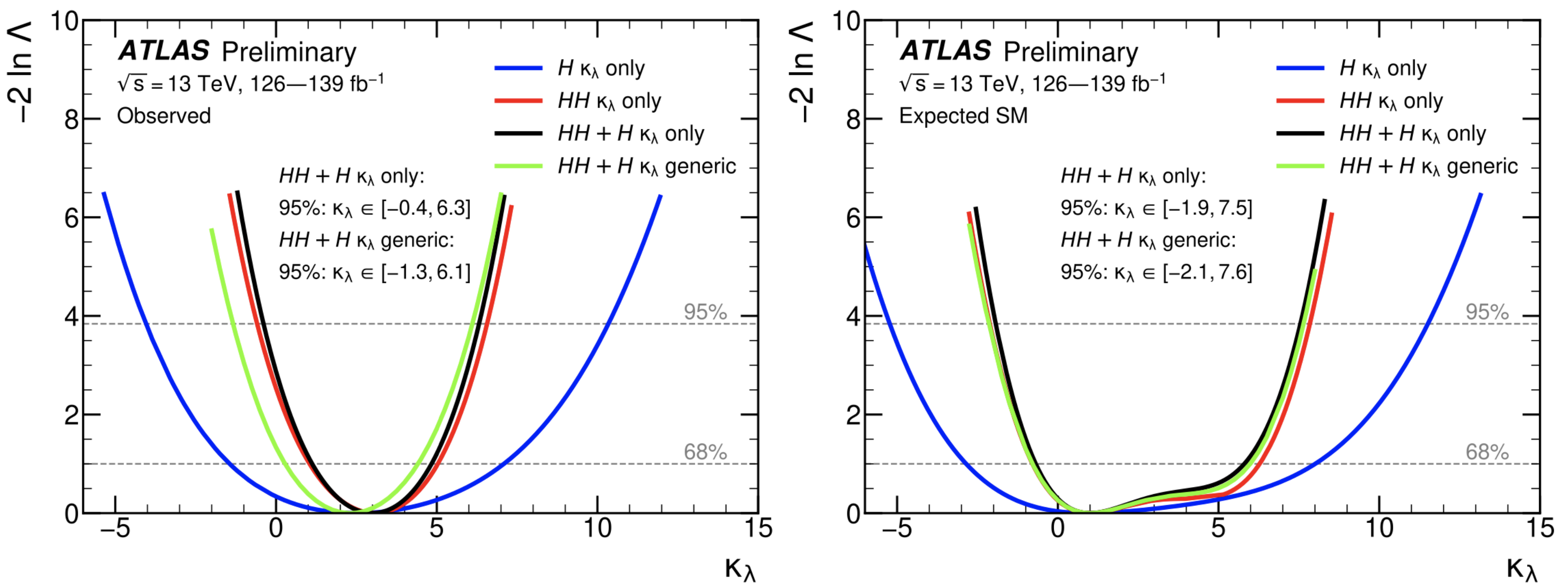
Limit on HH production is now at 2.4 x SM strength

While 2.9 expected (no HH) or 4.0 (SM)

Constraints on the Self-Coupling

Include also single Higgs production constraints

ATLAS-CONF-2022-050



κ_λ restricted to values of -1.3 – 6.1 (-2.1 – 7.6 expected)

-Tightest constraint on κ_λ so far

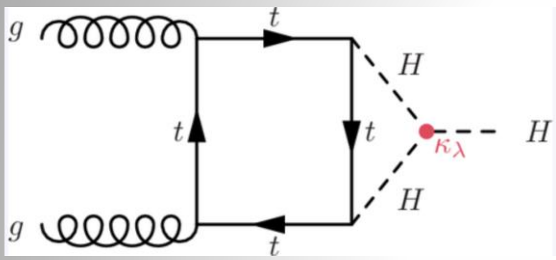
- …When only κ_λ is free

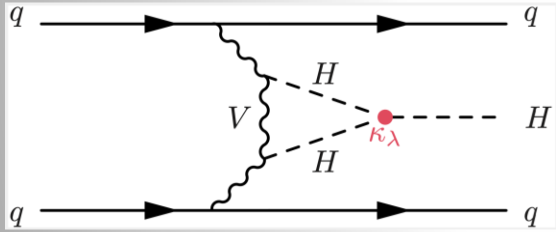
Range expands slightly, if κ_V, κ_t, κ_b, κ_τ are all released

Double and Single Higgs Production

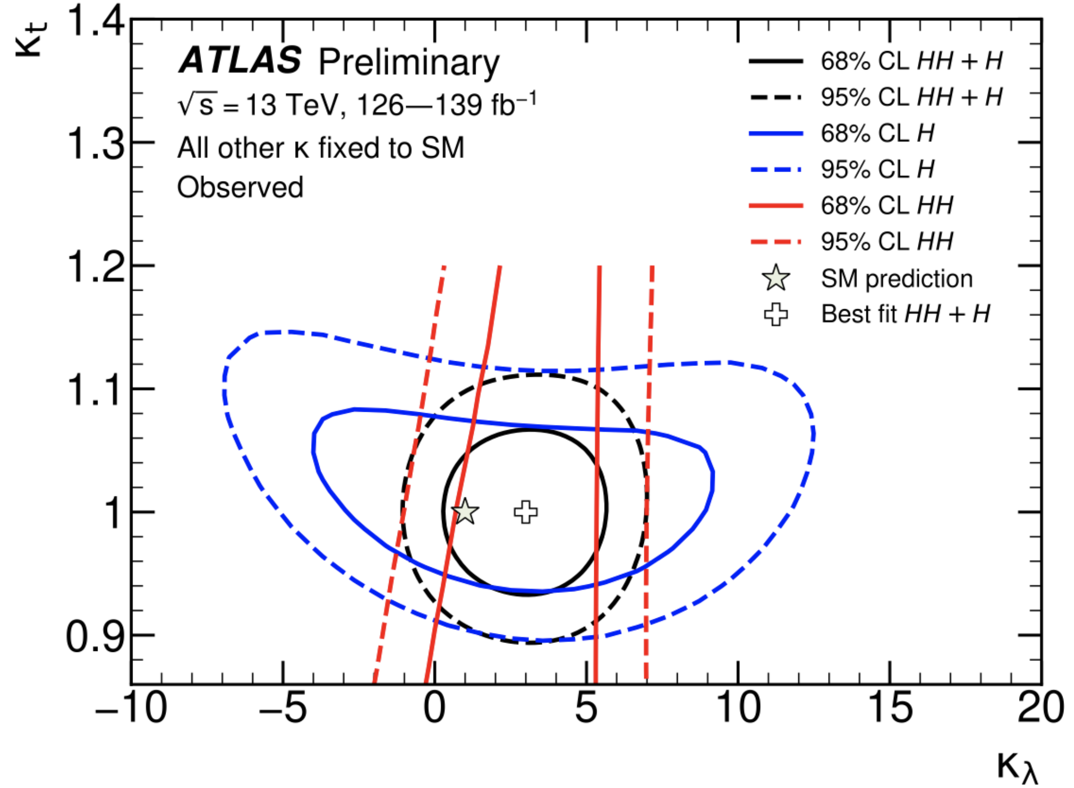
Also single Higgs production is sensitive to the Higgs self-coupling

ATLAS-CONF-2022-050





NLO EW corrections



Fit with κ_λ and κ_t free

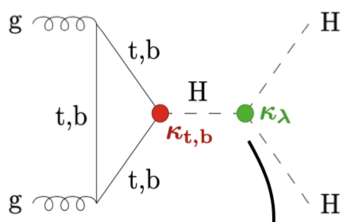
- With diHiggs alone, κ_λ bound expands for low κ_t
  Combination with bounds from single Higgs
- DiHiggs and single Higgs complementary.

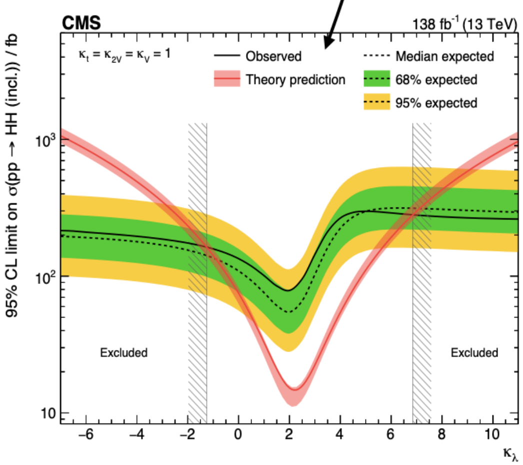
Higgs Pair Production

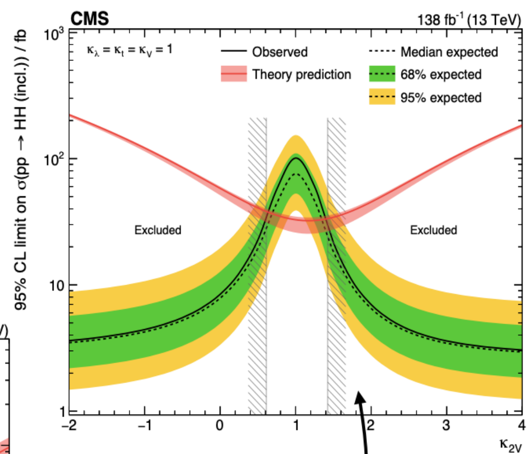
State of the art studies, including bbZZ, bb$\gamma\gamma$, bb$\tau\tau$, bbbb and multi-leptons

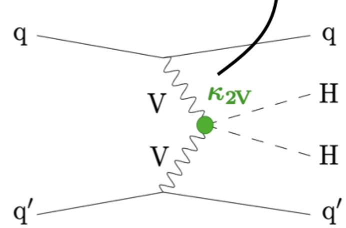
2207.00043

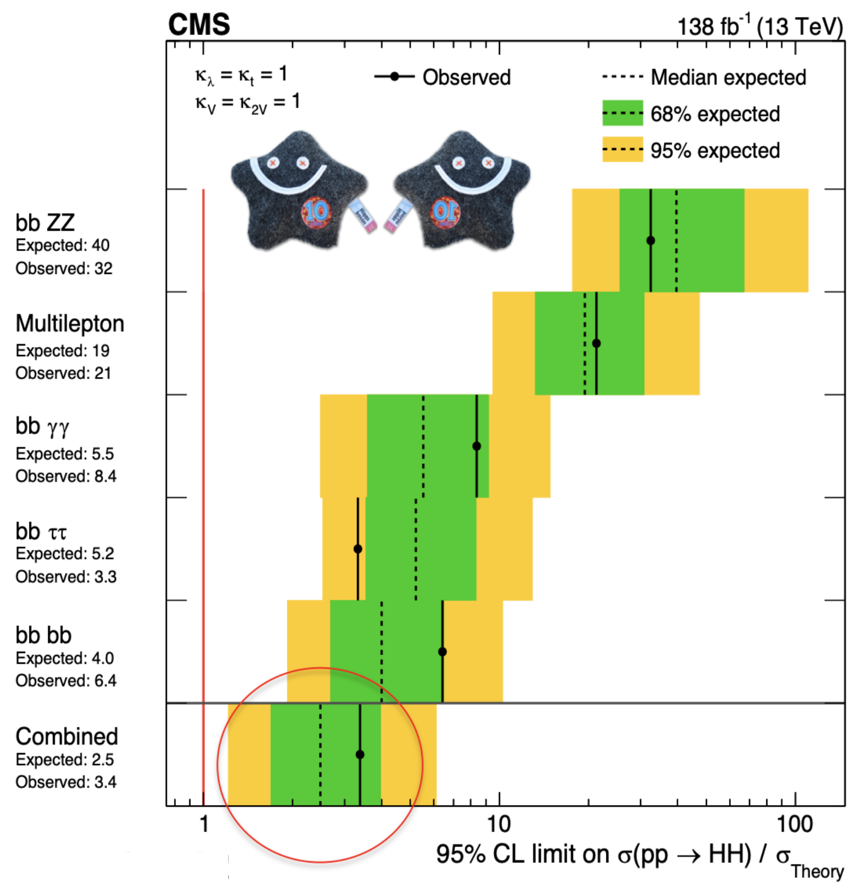
95% upper limits for κ_Λ and κ_{2V}











N. Wardle

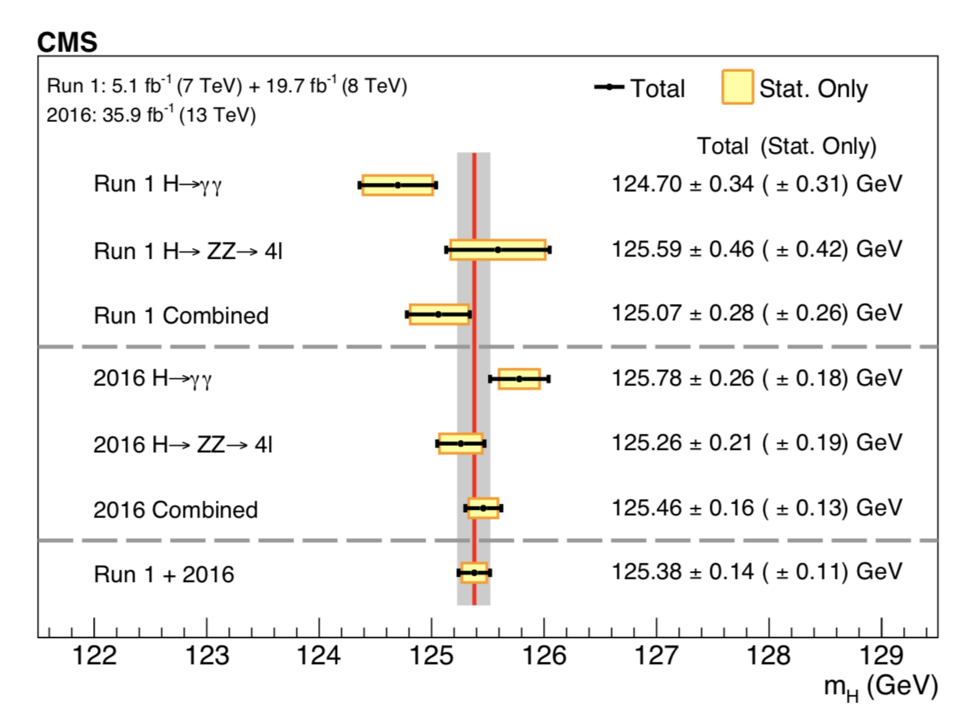
Result is a few times SM value already! Very promising for Run-3/HL-LHC

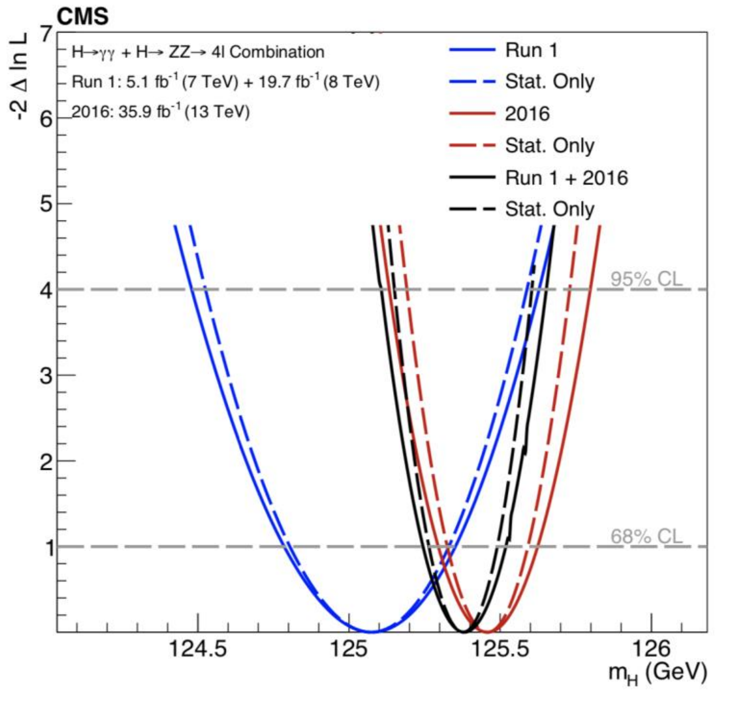
Higgs Properties: Higgs Mass

Higgs Mass from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow$4leptons with run-1 and 2016 data

- Excellent detector performance and lepton/photon energy scale calibration
- Results still dominated by statistical uncertainties

2002.06398





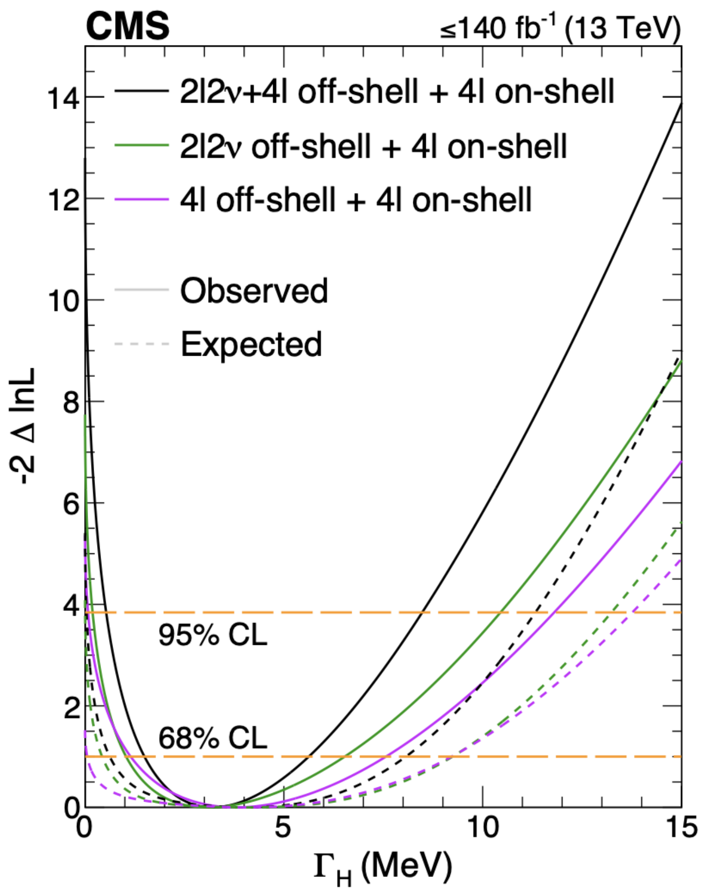
$$m_{\mathrm{H}} = 125.38 \pm 0.14\,\mathrm{GeV}$$

M_H is known to a precision of almost 1 per mille

Higgs Properties: Higgs Width

arXiv:1901.00174
arXiv:2202.06923

Direct resonance width measurement not possible.
Technique used: on-shell to off-shell cross section in H→ZZ



SM Higgs(125)
width = 4.1 MeV

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2\kappa_V^2)_{on\ shell} = (\kappa_t^2\kappa_V^2)_{off\ shell}$$

		68% | 95% CL	68% | 95% CL
Γ_H	$2\ell 2\nu + 4\ell$	$3.2^{+2.4}_{-1.7}$ | $^{+5.3}_{-2.7}$	$^{+4.0}_{-3.48}$ | $^{+7.2}_{-4.065}$
Γ_H	$2\ell 2\nu$	$3.1^{+3.4}_{-2.1}$ | $^{+7.3}_{-2.91}$	$^{+5.1}_{-3.67}$ | $^{+9.1}_{-4.099}$
Γ_H	4ℓ	$3.8^{+3.8}_{-2.7}$ | $^{+8.0}_{-3.727}$	$^{+5.1}_{-4.047}$ | < 13.8

➡ Result: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

in addition

Evidence for Off-Shell production at 3.6σ

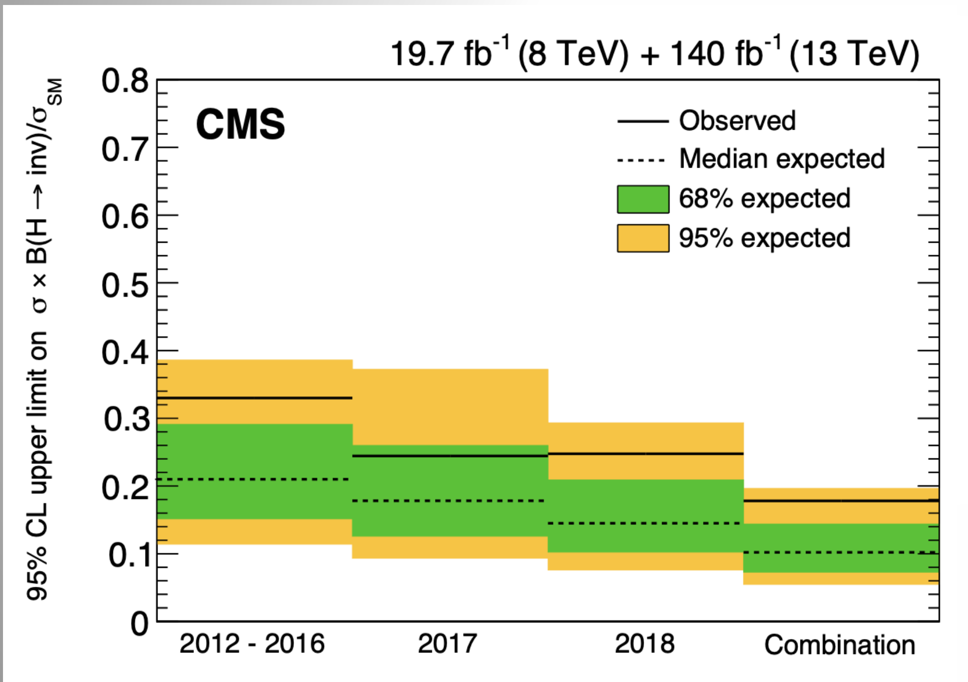
Invisible Decays of the Higgs Boson

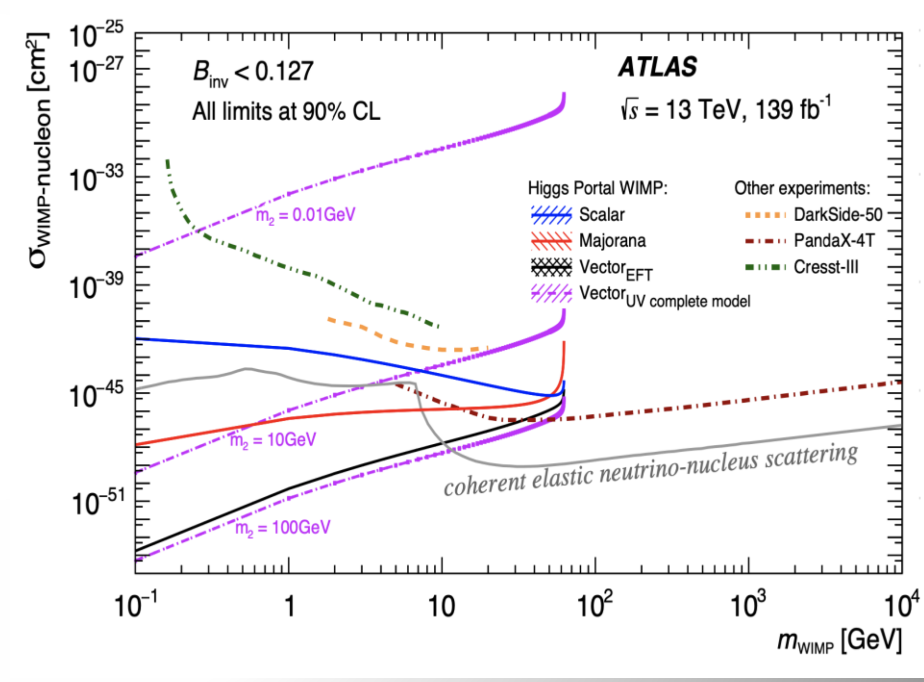
Direct search for H decaying into invisibles, using VBF channels

- Major challenge is control of backgrounds
- CMS limit BR(inv.) < 0.18 @ 95% CL (0.10 exp.)
- ATLAS limit BR(inv.) < 0.15 @ 95% CL (0.10 exp.)

2201.11585

2202.07953





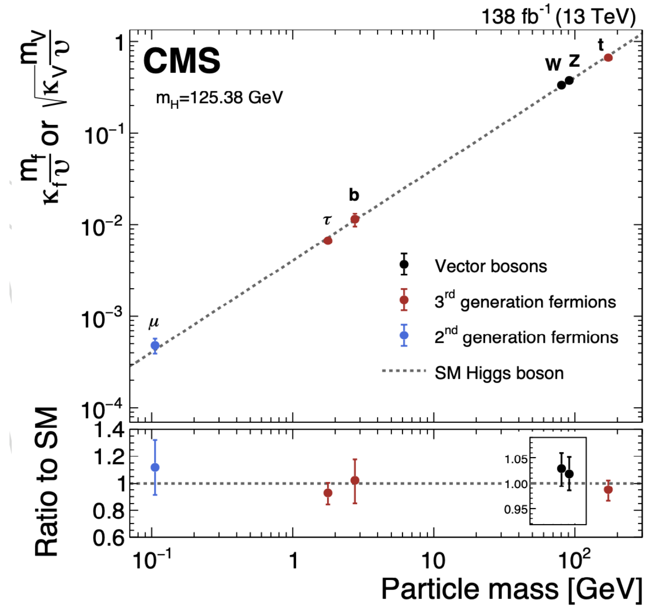
HL-LHC projection $\left(\mu_{\mathrm{VBF},VH} \cdot \mathrm{BR}_{\mathrm{inv}}\right)^{\mathrm{HL\text{-}LHC}} \leq 2.5\%$

Dark Matter interpretation in terms of WIMP-Nucleon cross section limits

Brief Summary

- Channels covered with Run-2 data

	Channel categories	Br	ggF ~8 M vets produced	VBF ~600 k vets produced	VH ~400 k vets produced	ttH ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓



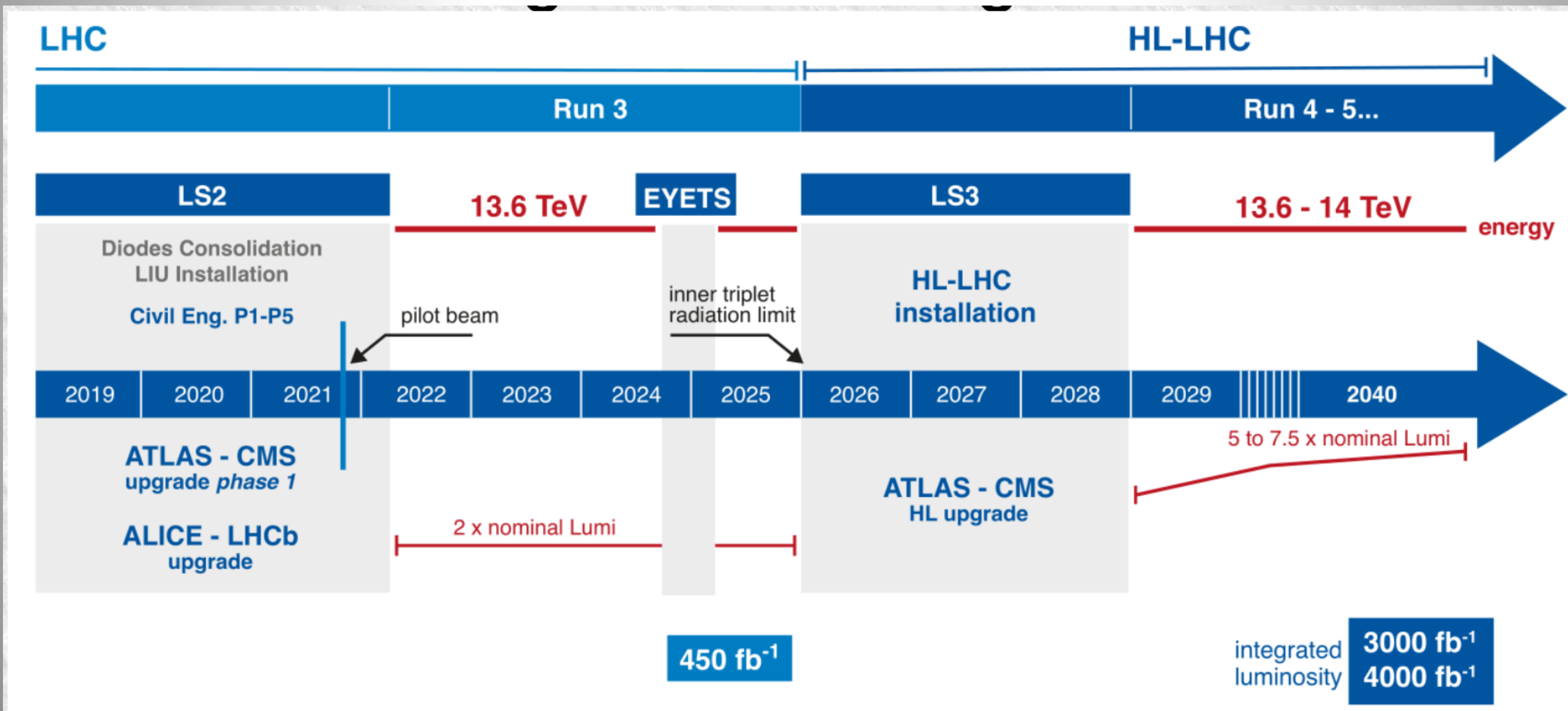
More rare processes remain to be observed…

- Coupling uncertainties in range 5-12%
- Mass of the Higgs $m_{\mathrm{H}} = 125.38 \pm 0.14\,\mathrm{GeV}.$
- Width of the Higgs $\Gamma_H = 3.2^{+2.4}_{-1.7}\,\mathrm{MeV}$
- Run-2 data is only 5% of the total data sample with HL-LHC!

The Future @ the LHC

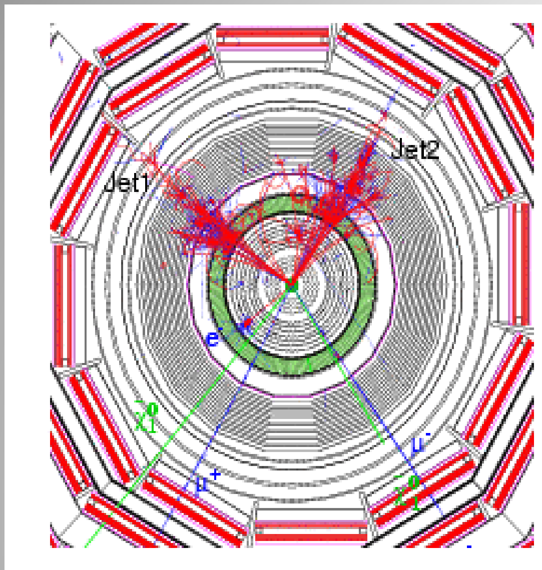
The Future @ the LHC

- CMS/ATLAS using ~140 fb^{-1} @ 13 TeV for most results
- Run-3 may bring up to 300 fb^{-1} @ 13.6 TeV
- HL-LHC will bring an even larger increases, e.g 3000 fb^{-1} @ 14 TeV

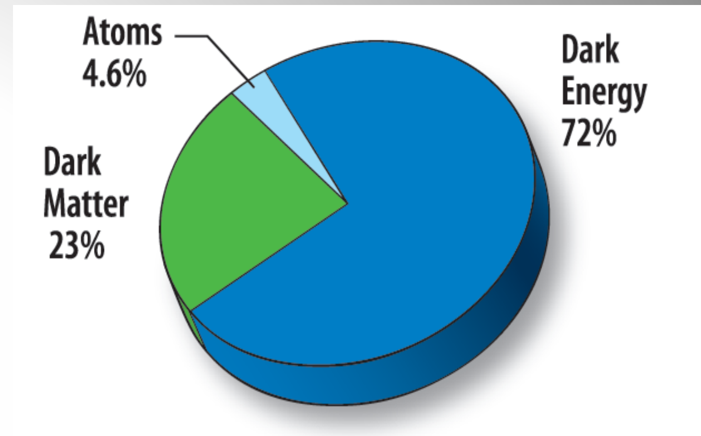


…as well as increasing experimental challenges

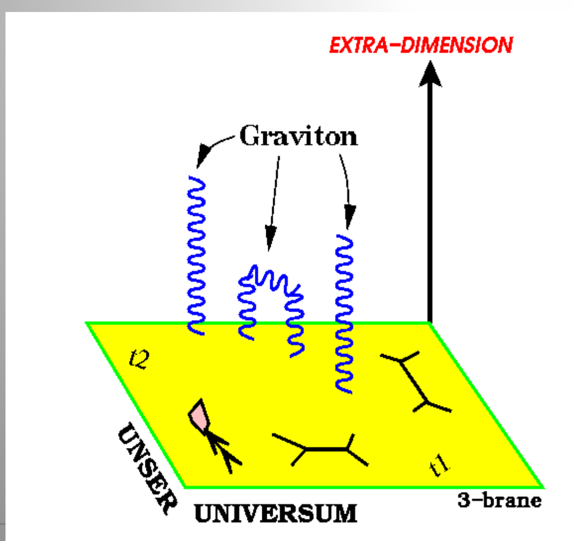
Next LHC Physics Targets



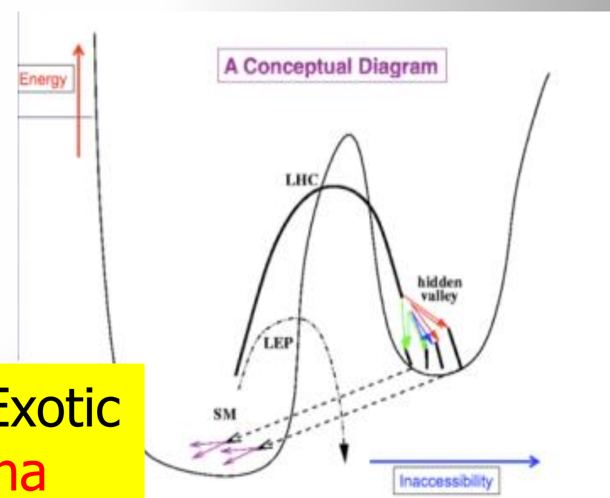
Searching for Supersymmetric or other New Particles



Searching for Dark Matter



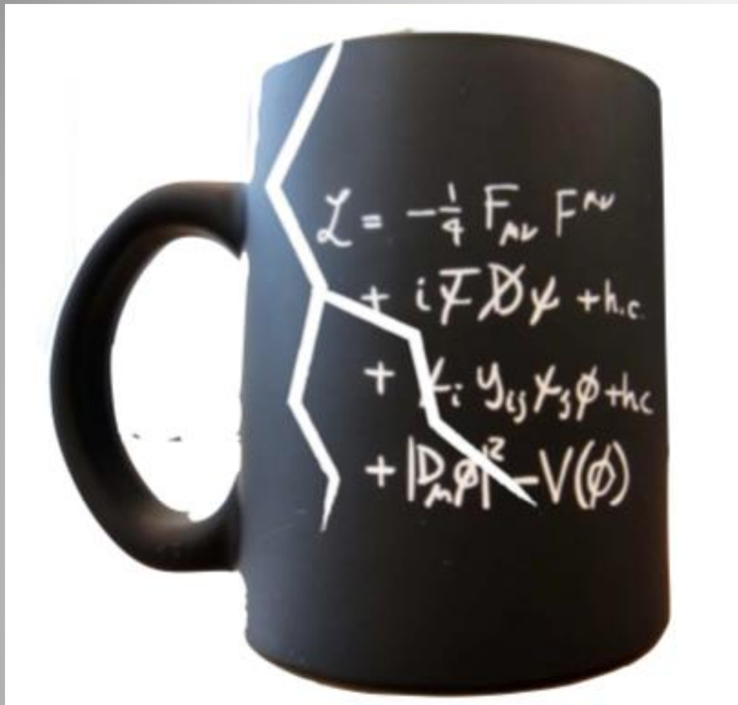
Searching for Extra Dimensions or other New Effects



Searching for Exotic BSM Phenomena

And many more topics…

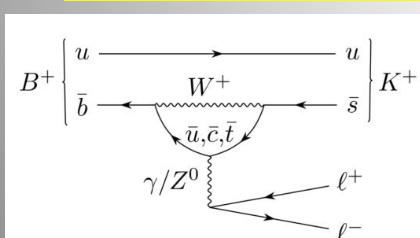
In Short…



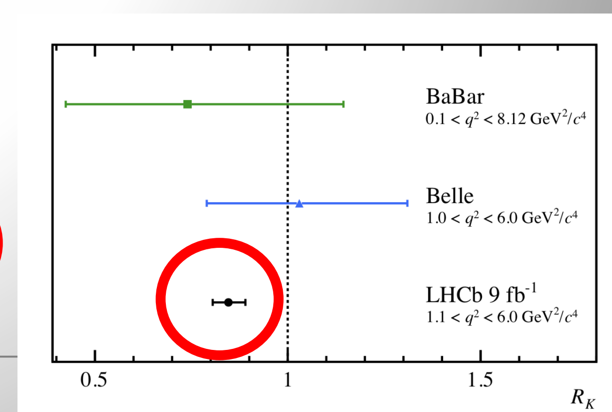
Search for cracks in the Standard Model that will teach us what is beyond..

- Precision Measurements of SM processes
- Direct searches for new particles or phenomena

NB: LHCb rare B decays



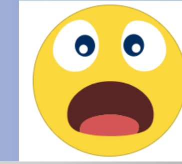
$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2} \cong 1$$



Possible explanations: Zprimes, Leptoquarks


Micro-Black Holes
Hunters
at the LHC…
No micro-black holes found…

The Dark World??



Does it mean that there are also….

Dark Forces?

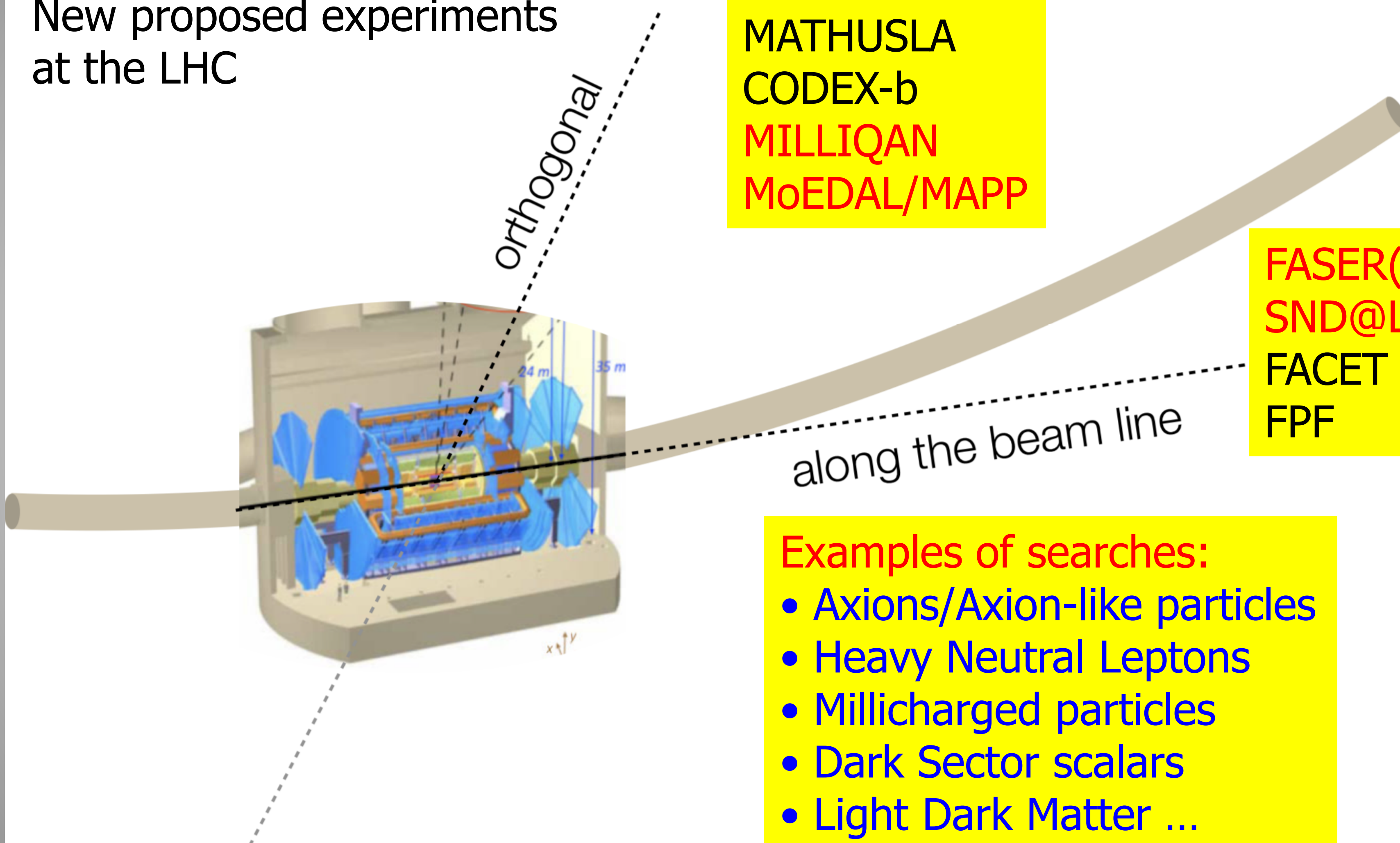
Or even Dark People?

No! We assume some simple interactions between dark matter particles in their environment, and a way to detect them

So far Dark Matter particles have not been found yet, not at the LHC or any other direct search experiment!! -> We need to explore new ideas!

New Directions – New Searches

New proposed experiments at the LHC



ANUBIS
MATHUSLA
CODEX-b
MILLIQAN
MoEDAL/MAPP

FASER(Nu)
SND@LHC
FACET
FPF

Examples of searches:
- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Light Dark Matter …

"RED" approved and installed experiments for Run-3

Summary: Studying the Higgs

The Higgs gets 10 today

We know already a lot on Higgs but:

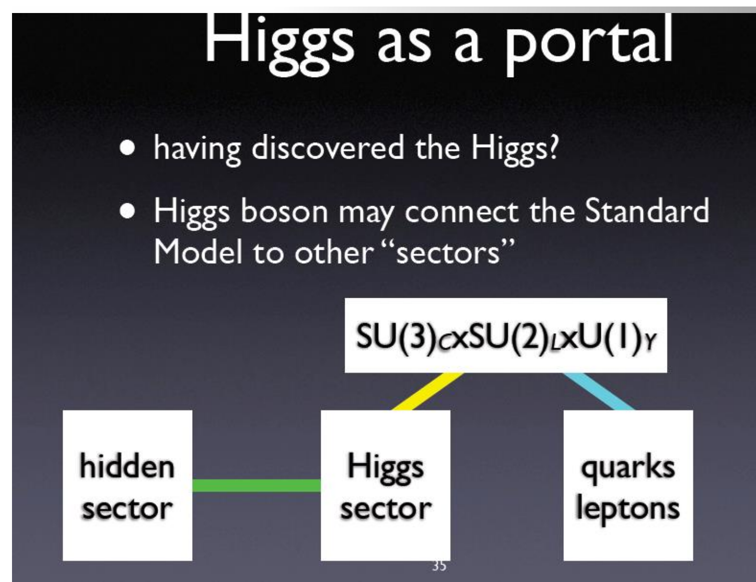
Many questions are still unanswered:

- What explains a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- What is the connection with Dark Matter?
- Is the boson fundamental or composite?
- Will BSM physics show up in the Higgs ?
- Are there more Higgs bosons?
- etc…

- A program for detailed studies is in place
- More LHC Data 2022-2025 with Run-3
- HL-LHC Data 2029-2040+ with 3000fb^{-1}
- Other/new machines in the future??
- ⑤

Will the Higgs shows us some surprises?

The Future will tell



Post Scriptum

In an interview in 2017 I said the following

- "I was the Higgs convener when the Higgs was discovered, meaning I was one of the first people that saw we had a discovery. How to describe it… it's sensational. I imagine it's like what people feel when they go to climb Mount Everest and reach the top. I've never done that…"
- Update November 2021:

  Nepal, Mount Everest Base Camp

  Approx. at 6000 meters elevation

  ….almost there!!

Backup

LHCb: Tests of Lepton Universality

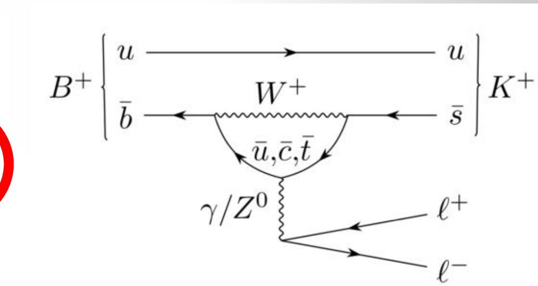
A few puzzling results from the LHCb experiment…

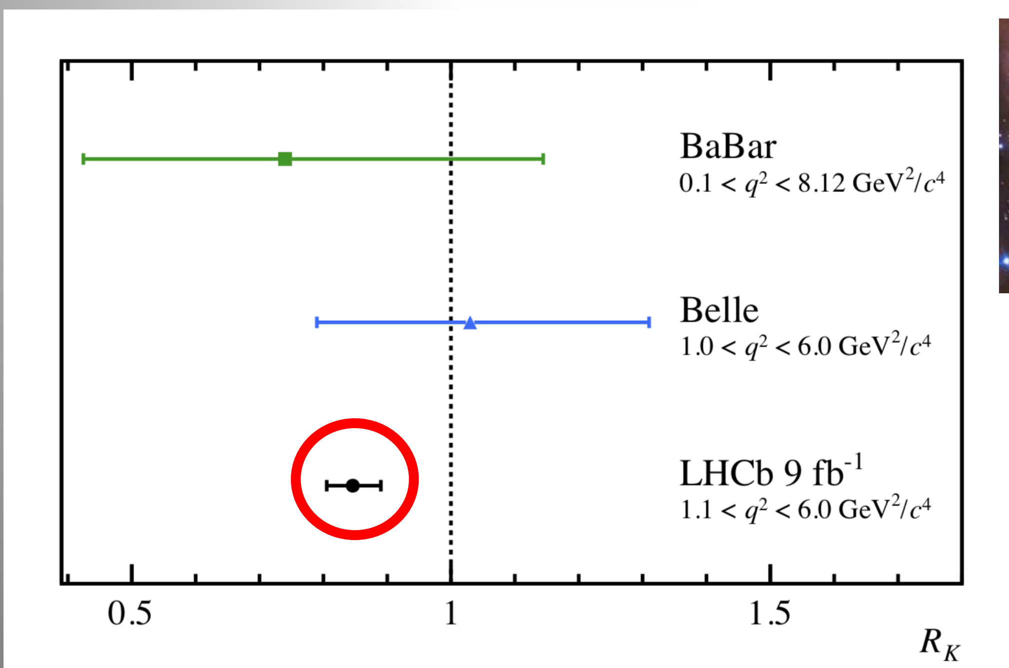
Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$

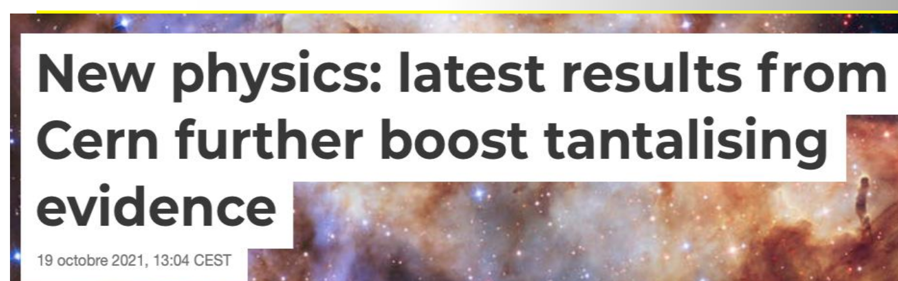
$H = K, K^*, \phi, \ldots$

Standard Model

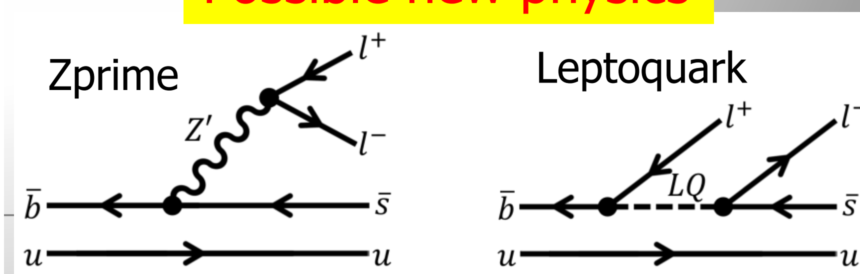
$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \cong 1$$







Possible new physics

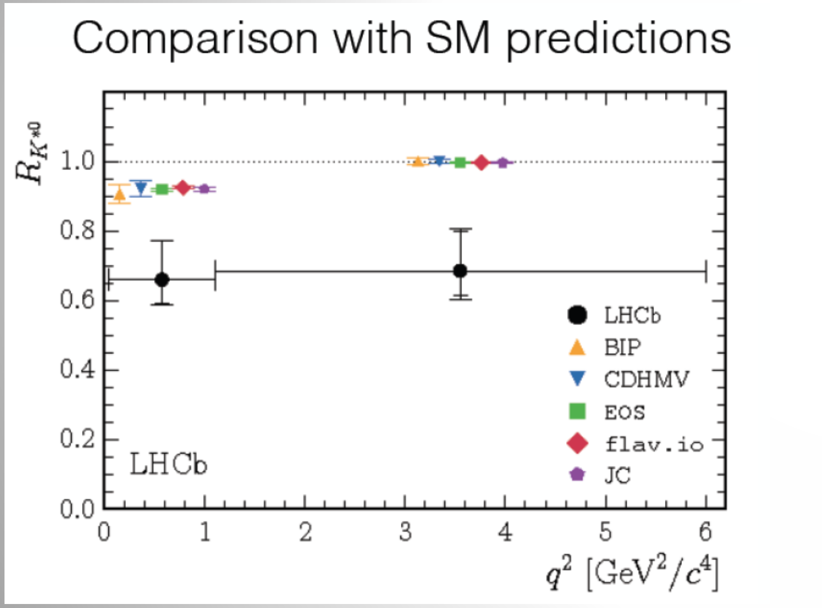


LHCb: Tests of Lepton Universality

It started a few years ago in 2016 with a few puzzling run-1 results from the LHCb experiment…

Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$

$H = K, K^*, \phi, ...$



If confirmed, independent checks will become very important.
Belle II? ->in a few years form now

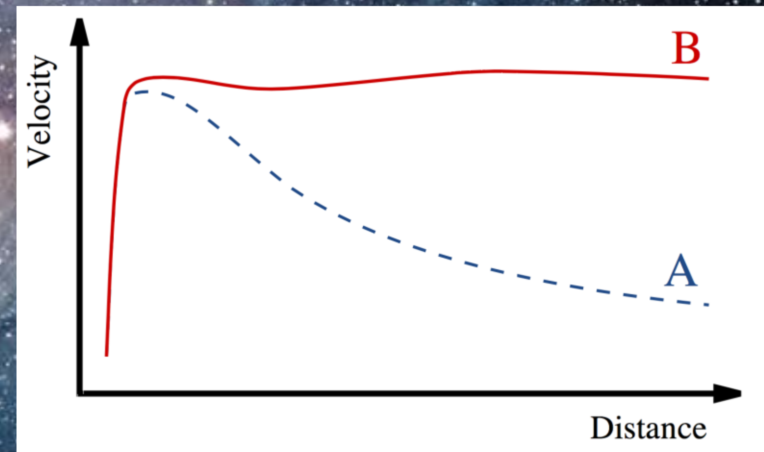
CMS has installed a special trigger to collect an unbiased b-sample which was active during 2018
-> more than 10^{10} b-pairs collected during 2018 via parked data stream!
Analysis under way!!

First LHCb run-2 results did not yet clarify the situation (Moriond 2019) ☹
But recent results show the same tendency -> NEW PHYSICS?

The jury is still out…

Dark Matter in the Universe

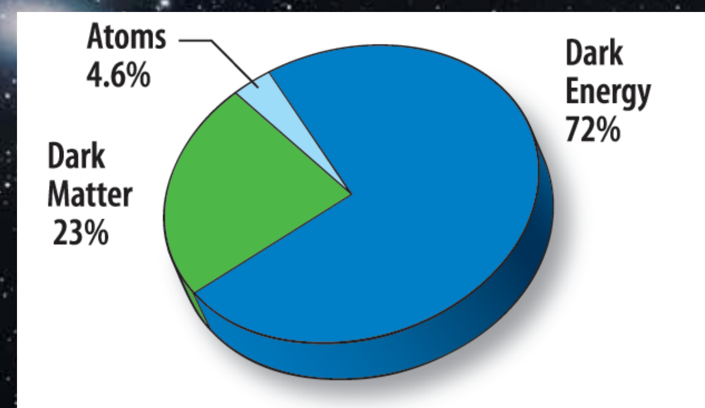
Astronomers found that most of the matter in the Universe must be invisible Dark Matter

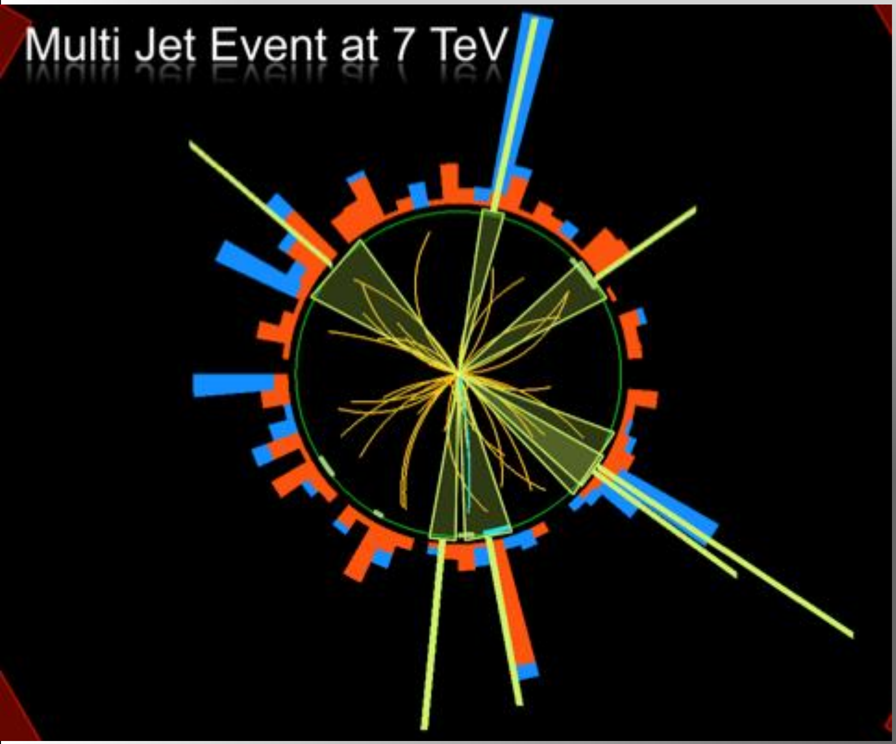


'Supersymmetric' particles ?

F. Zwicky 1898-1974

Vera Rubin ~ 1970





Outline

- Introduction: What is CERN?
- The Large Hadron Collider and its Experiments
- The Higgs discovery
- New Physics Searches at the Large Hadron Collider
- Do millicharged particles exist?: The MilliQan Experiment Project
- Summary

What is the world made of?
What holds the world together?
Where did we come from?

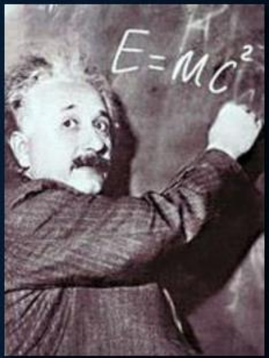
CERN is the largest research laboratory that provides the tools for conducting these studies: Particle Accelerators

Innovation
Education
CERN
uniting people
Research

The Mission of CERN

- **Push back** the frontiers of knowledge

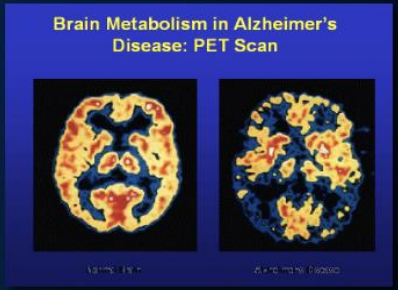
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?



- **Develop** new technologies for accelerators and detectors

  Information technology - the Web and the GRID

  Medicine - diagnosis and therapy



- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures

CERN: founded in 1954: 12 European States
"Science for Peace"
Today: 23 Member States

Employees: ~2700 staff, 800 fellows
Associates: ~12600 users, 1800 others
Budget (2021) ~ 1200 MCHF

Member States: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Spain, Sweden, Switzerland and United Kingdom

Associate Members in the Pre-Stage to Membership: Cyprus, Slovenia

Associate Member States: India, Lithuania, Pakistan, Turkey, Ukraine

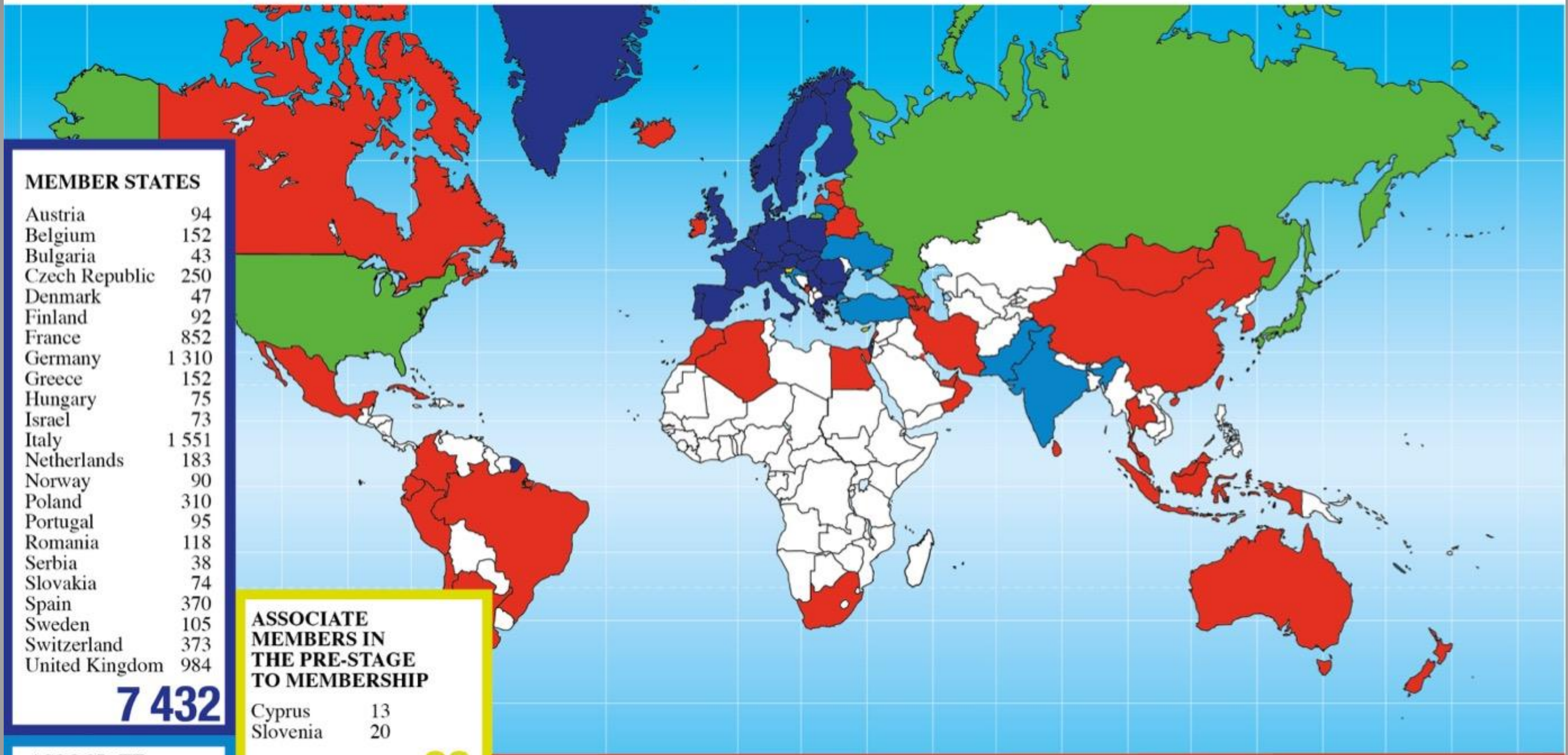
Applications for Membership or Associate Membership:
Brazil, Croatia, Estonia

Observers to Council: Japan, Russia, United States of America;
European Union, JINR and UNESCO

CERN

CERN World-Wide

Distribution of All CERN Users by Location of Institute on 9 December 2019



MEMBER STATES

Austria	94
Belgium	152
Bulgaria	43
Czech Republic	250
Denmark	47
Finland	92
France	852
Germany	1 310
Greece	152
Hungary	75
Israel	73
Italy	1 551
Netherlands	183
Norway	90
Poland	310
Portugal	95
Romania	118
Serbia	38
Slovakia	74
Spain	370
Sweden	105
Switzerland	373
United Kingdom	984
	7 432

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

Cyprus	13
Slovenia	20
	33

ASSOCIATE MEMBERS

Croatia	42
India	198
Lithuania	20
Pakistan	40
Turkey	132
Ukraine	36
	468

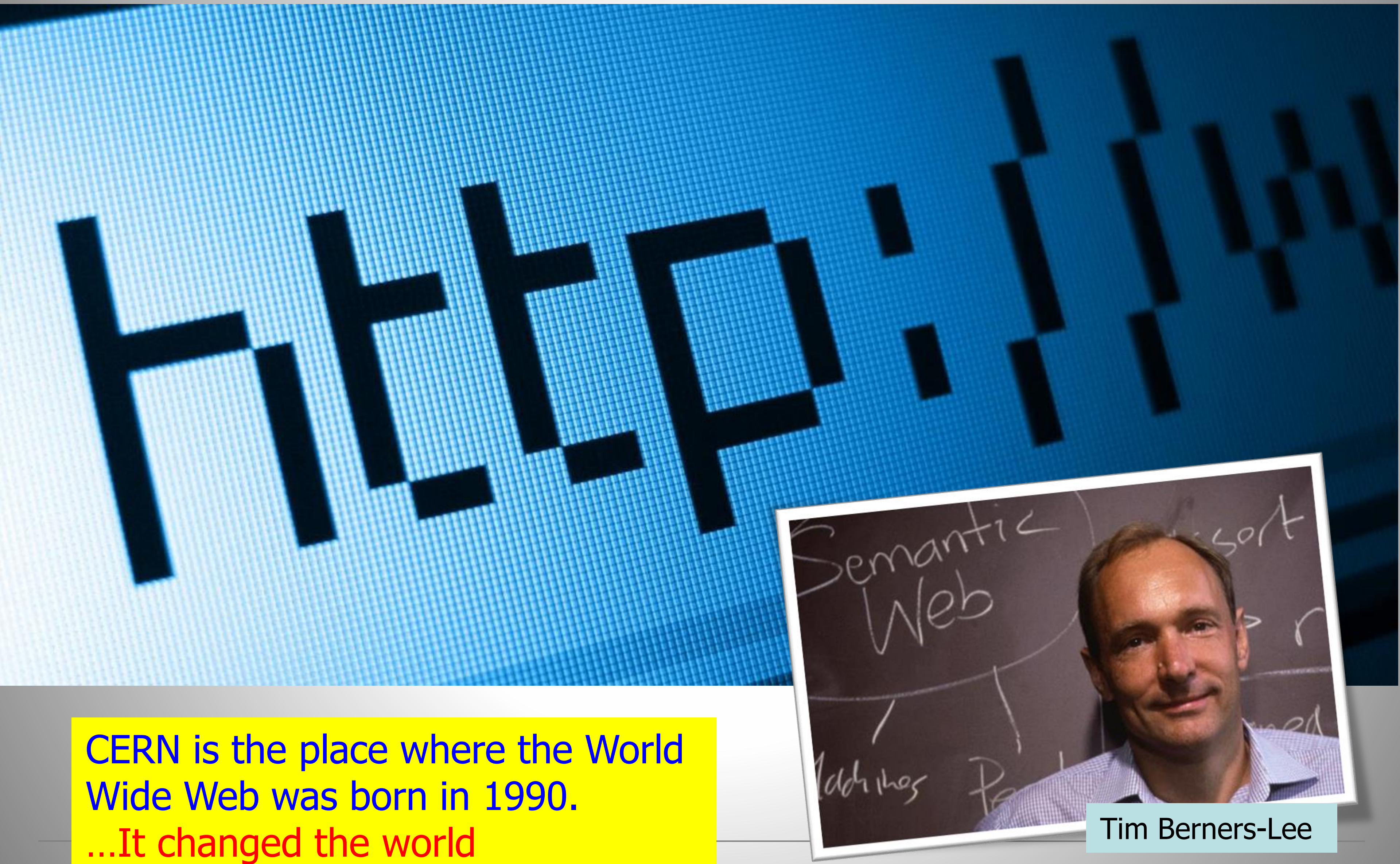
OBSERVERS

Japan	244
Russia	1 099
USA	2 002
	3 345

OTHERS

Algeria	3
Argentina	16
Armenia	13
Australia	25
Azerbaijan	3
Bahrain	3
Belarus	27
Brazil	114
Canada	213
Chile	22
China	376
Colombia	24
Cuba	3
Ecuador	4
Egypt	16
Estonia	24
Georgia	36
Hong Kong	21
Iceland	3
Indonesia	8
Iran	12
Ireland	7
Korea	150
Kuwait	2
Latvia	2
Lebanon	17
Malaysia	9
Malta	4
Mexico	58
Mongolia	2
Montenegro	5
Morocco	16
New Zealand	12
Oman	4
Peru	3
Puerto Rico	1
Singapore	3
South Africa	89
Sri Lanka	8
Taiwan	57
Thailand	20
U.A.E.	2
	1 437

CERN and the World Wide Web



CERN is the place where the World Wide Web was born in 1990.
…It changed the world

Tim Berners-Lee

Bahrain and CERN

Prof. Albert de Roeck, senior physicist at CERN, talks about the discovery of the Higgs Boson - work which won a Nobel Prize for Physics

8 years ago… March 2014
Main contact: Mar de Fez

- An Open Lecture by Professor Albert de Roeck, senior physicist at CERN Geneva, on 'The Discovery of the Higgs Boson' was jointly-hosted by Ahlia and the Bahrain Engineering Society. The event attracted great attention in the Kingdom, coming just six months after the theorists were awarded the Nobel Prize for Physics

2018: CERN Exhibition

BIN MATAR HOUSE
ART SPACE

Since 2017: Regular visits of Bahrain delegations to CERN
2019: University of Bahrain becomes an associate member in CMS

2020: Kick-starting the scientific collaboration with CERN & CMS!!
Various projects ->Computing and Mechanical Engineer @ CERN

Accelerators are Powerful Microscopes

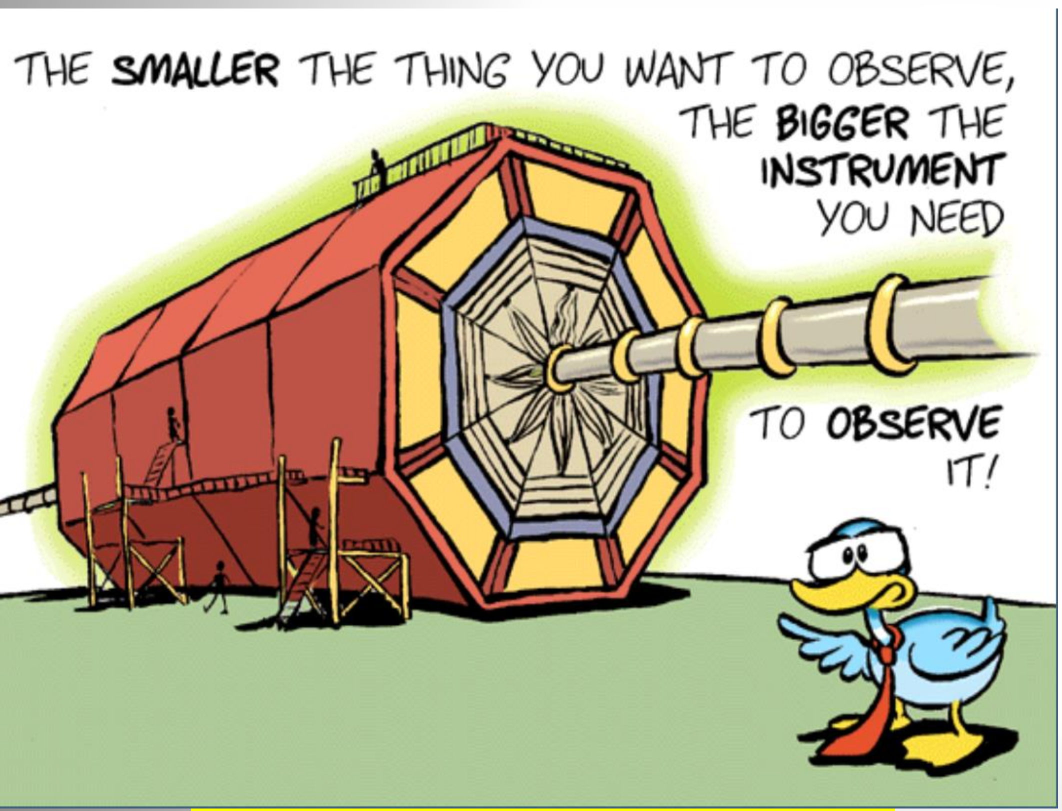
They make high energy particle beams that allow us to see small things.

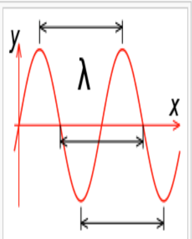
$$\lambda = \frac{h}{p}$$

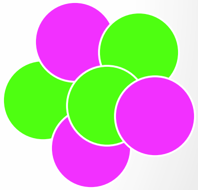
Planck constant

wavelength

momentum
~ energy

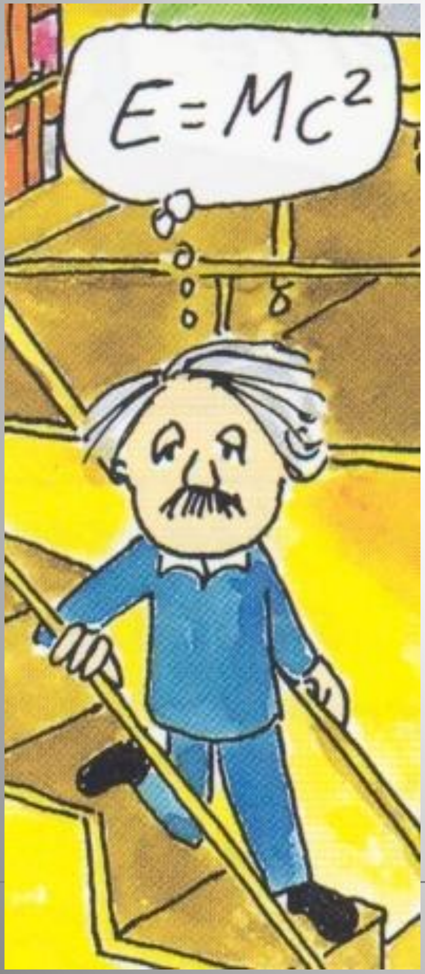






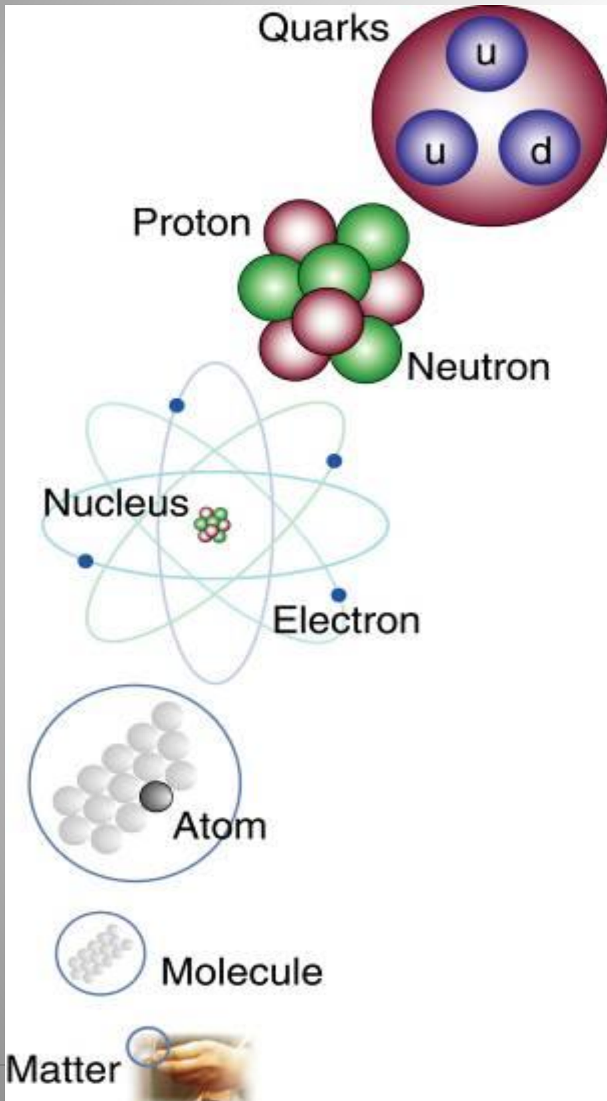
seen by high energy beam of particles (better resolution)

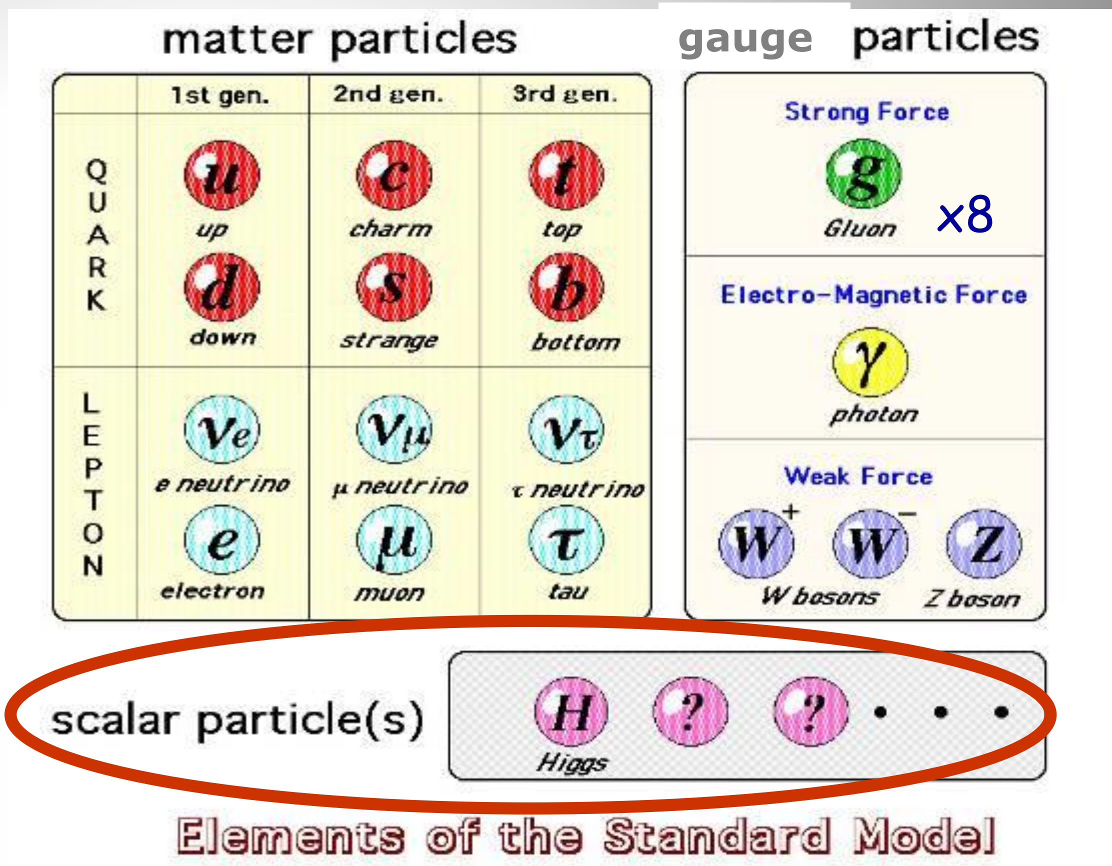
We can create particles from energy



- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang

The Standard Model





Until 2011 no single fundamental scalar had been observed yet! Do they exist in Nature?

The Hunt for the Higgs

Where do the masses of elementary particles come from?

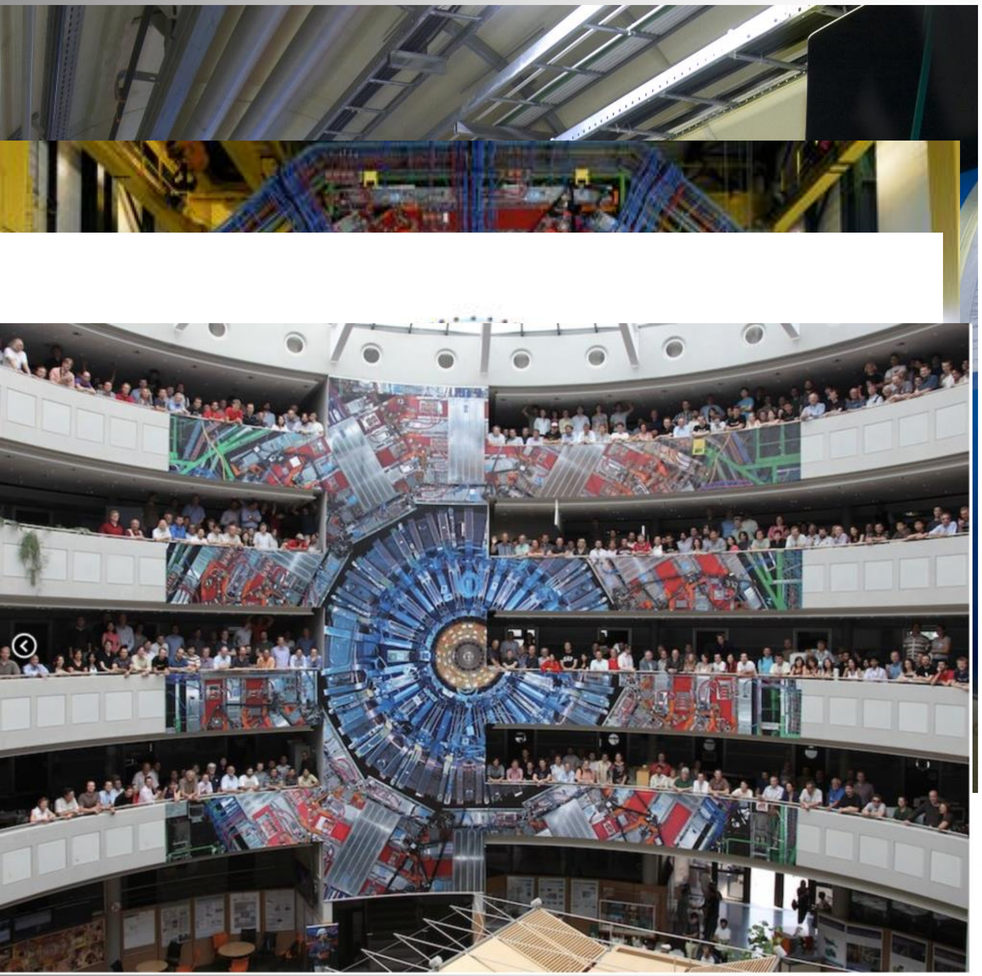
The key question (pre-2012): Does the Higgs particle exist?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson!

Proton mass: 1 GeV $\sim 10^{-27}$ kg

This Search Requires…….



1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

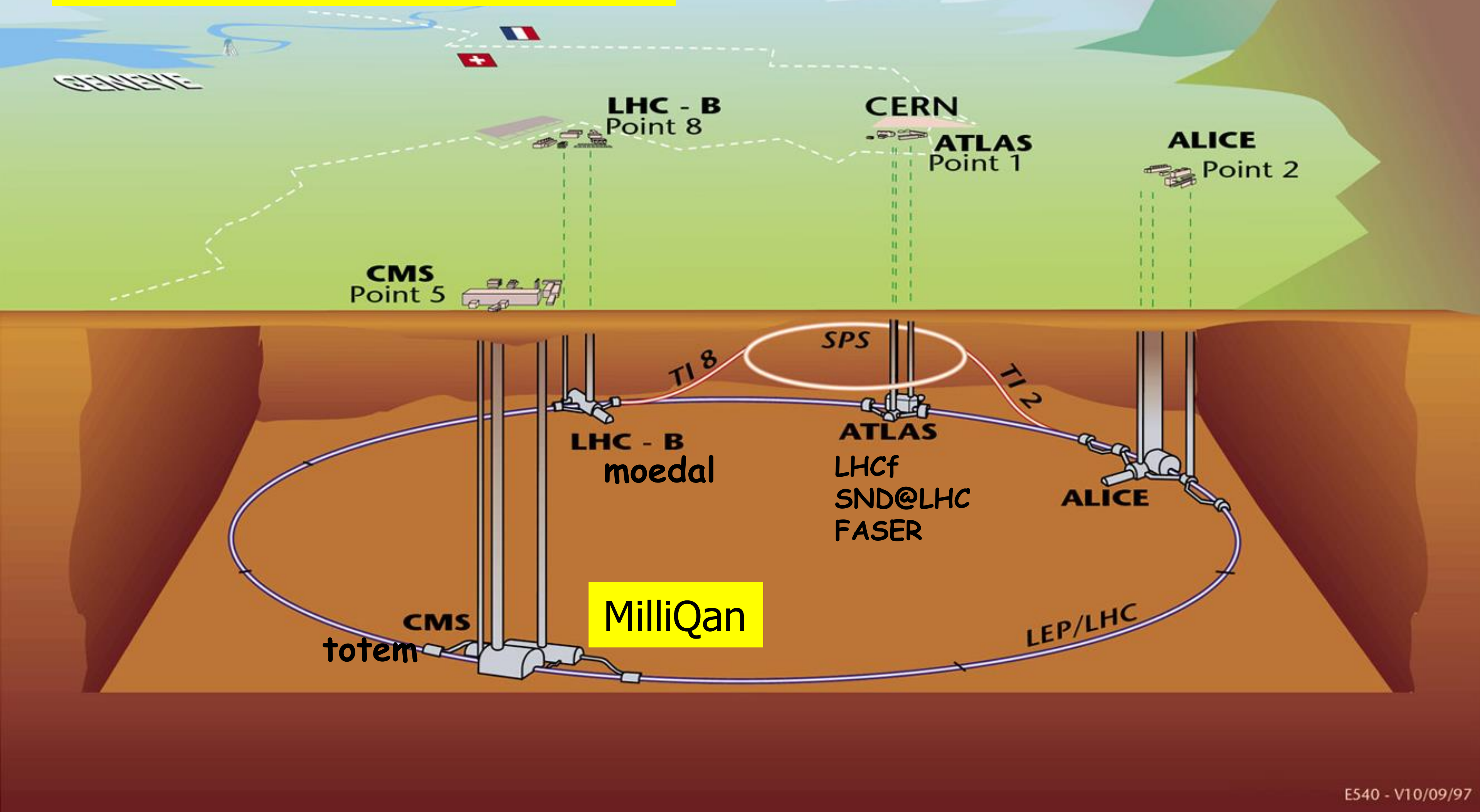
2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

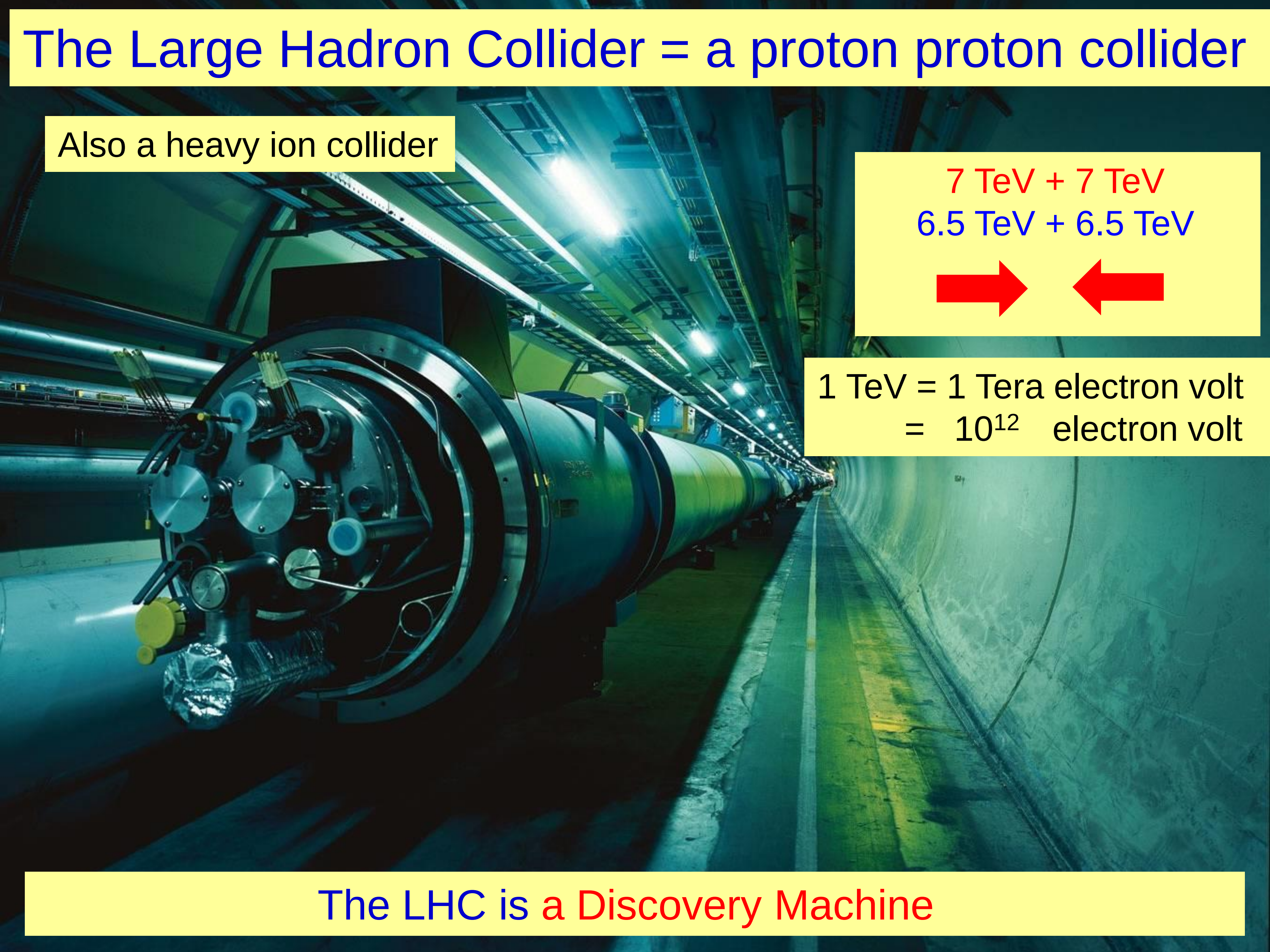
4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

The LHC Machine and Experiments

27 km long, 100 m underground



The Large Hadron Collider = a proton proton collider



Also a heavy ion collider

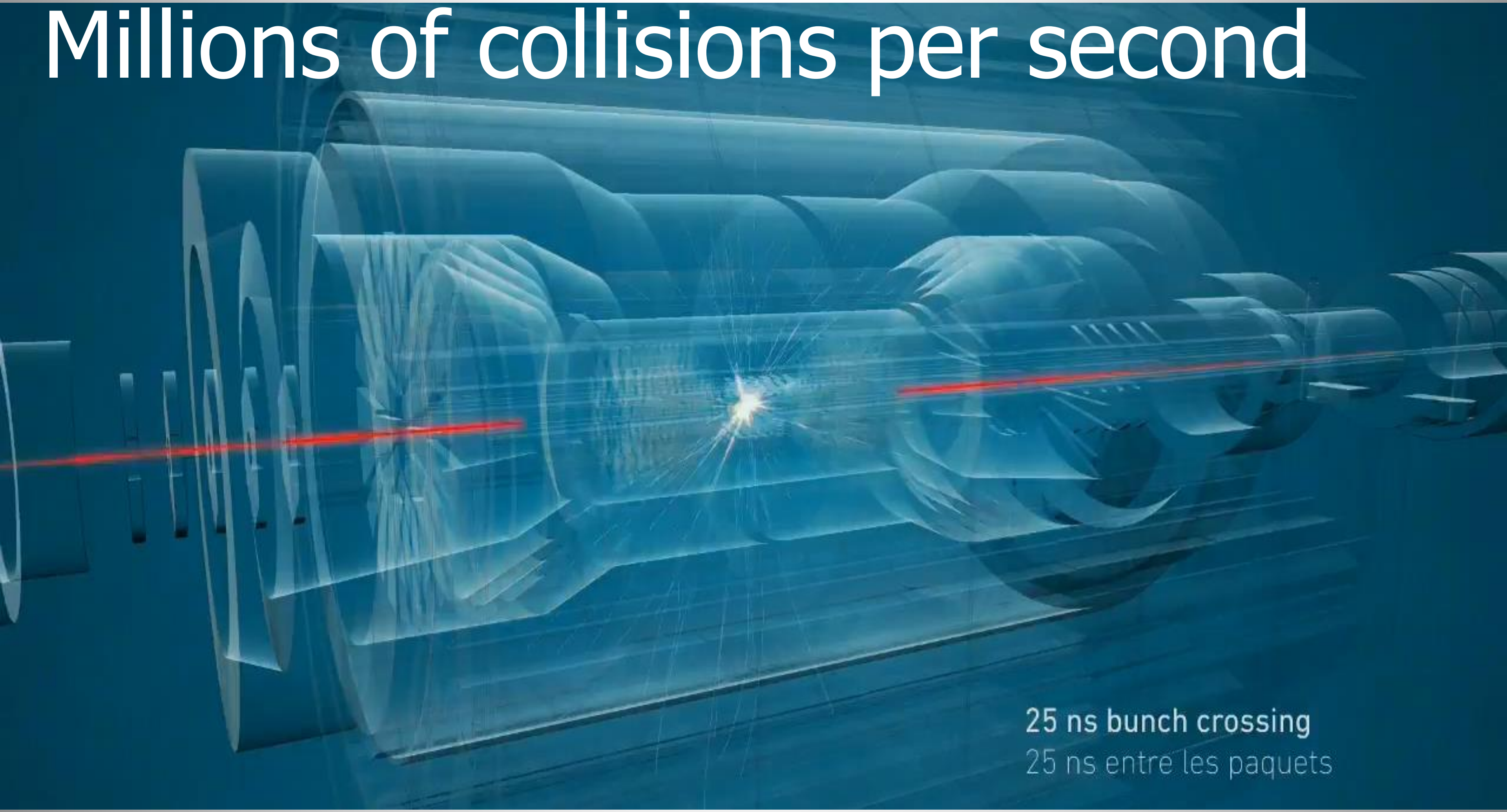
7 TeV + 7 TeV
6.5 TeV + 6.5 TeV

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

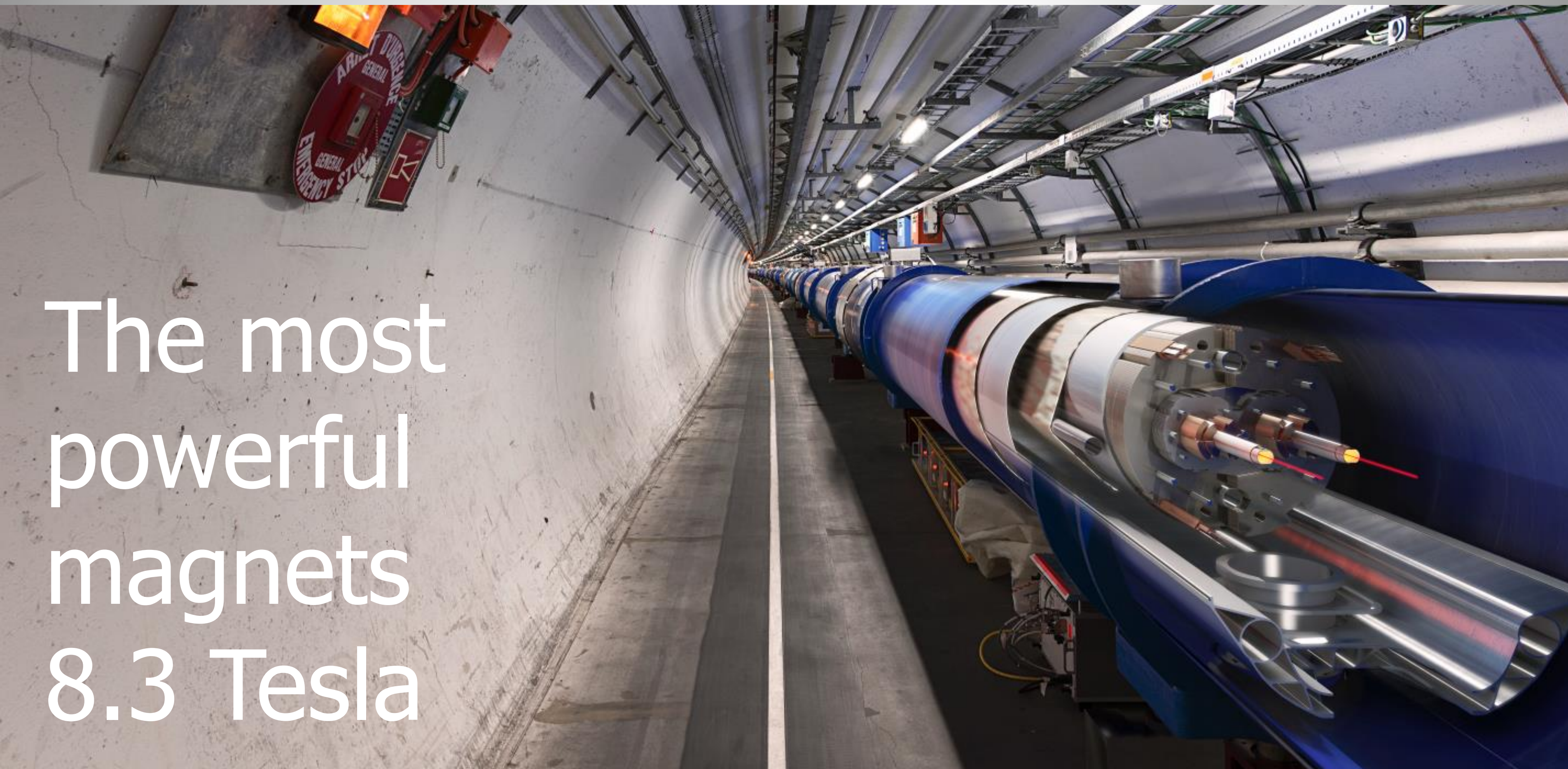
The LHC is a Discovery Machine

The CERN Science Program

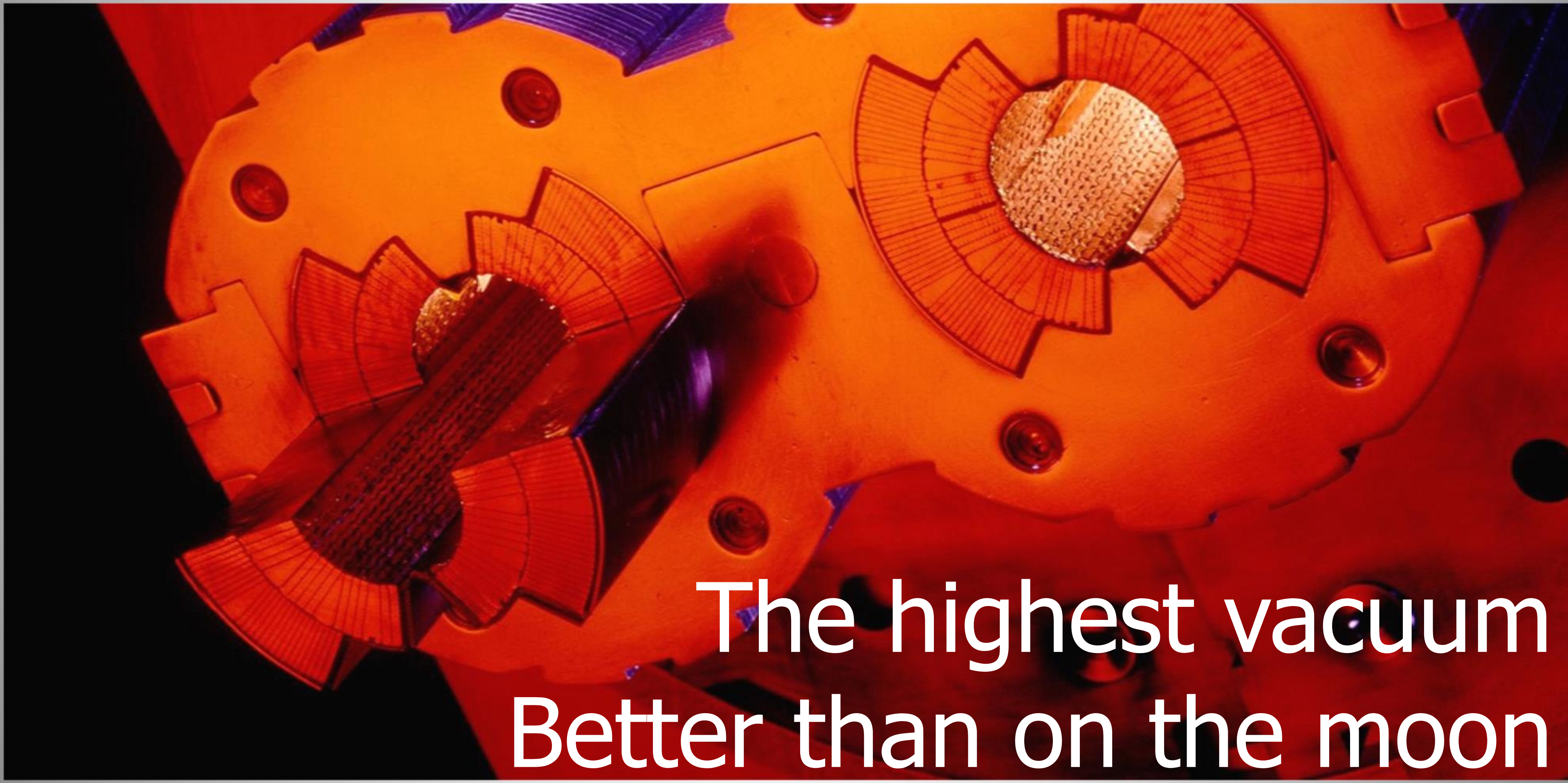
The LHC


Millions of collisions per second
25 ns bunch crossing
25 ns entre les paquets

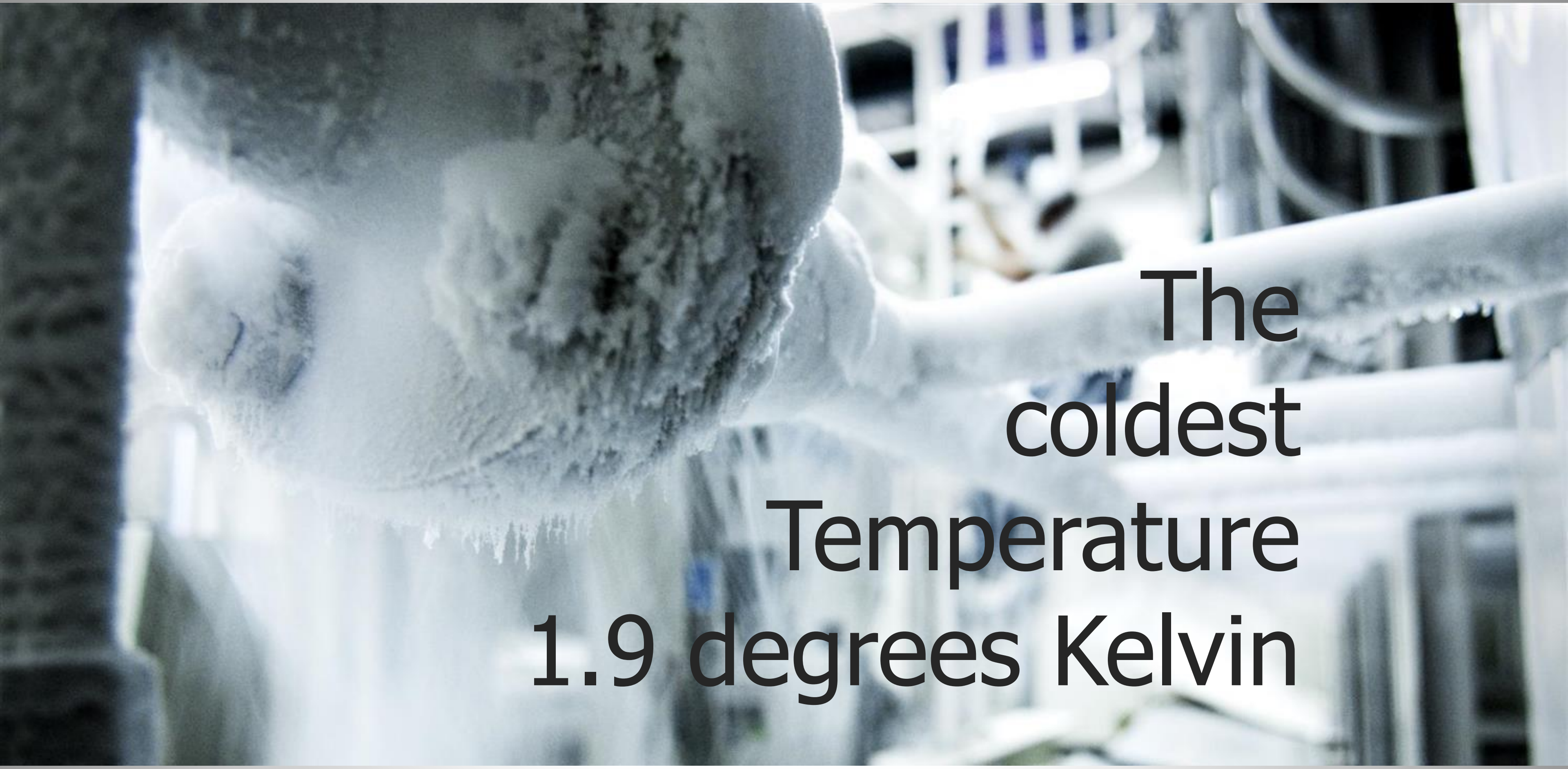
The LHC



The LHC



The LHC



Cables made of Niobium Titanium (NbTi) are «superconducting» at 1.9K

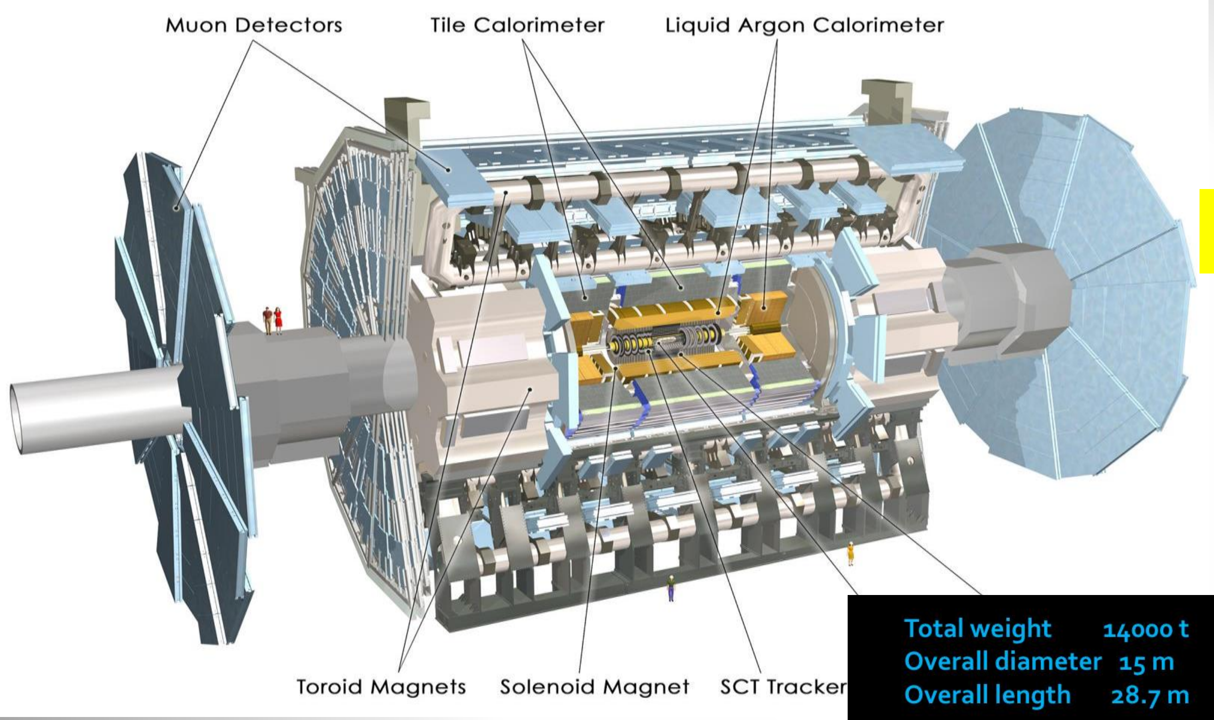
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts

proton-proton Run-2 finished 24/10 6:00am

- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 27 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected ~ 150 fb^{-1}
- 2022-2025: Run-3 at 13.6 TeV starts in June!

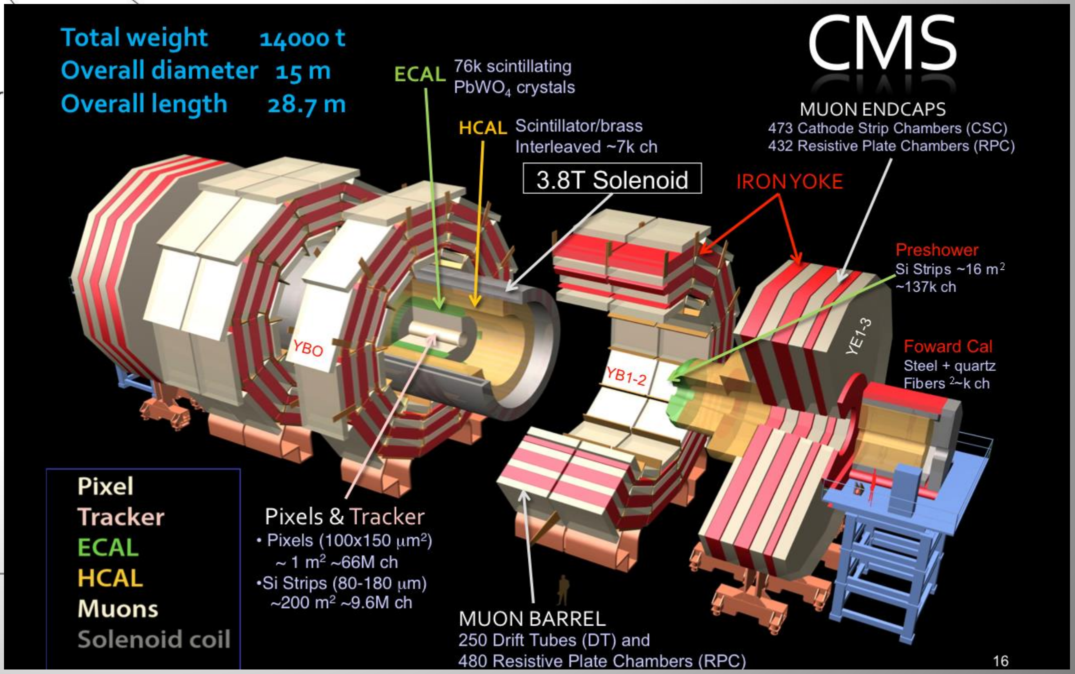
The Largest Experiments at the LHC

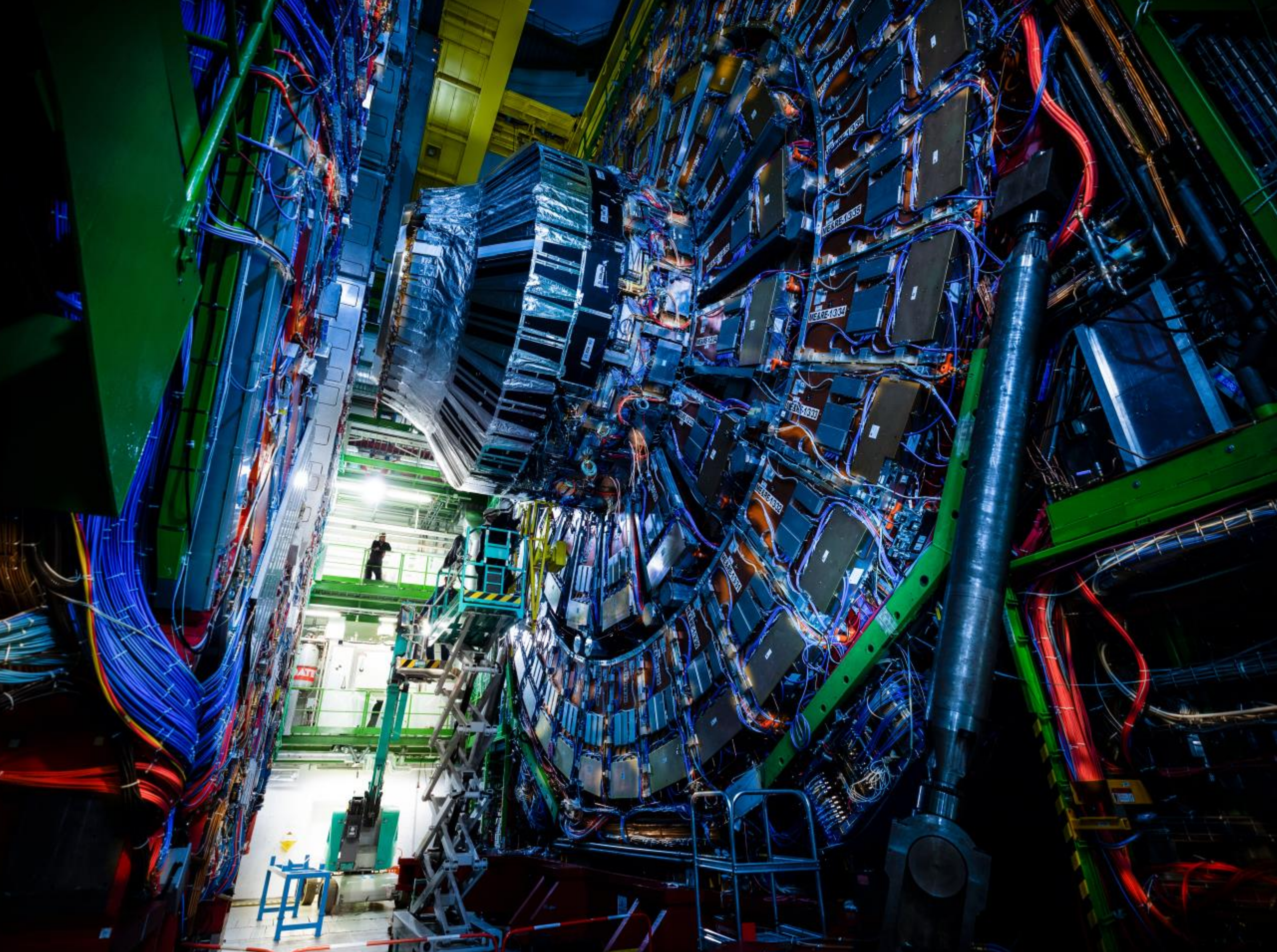


The ATLAS experiment

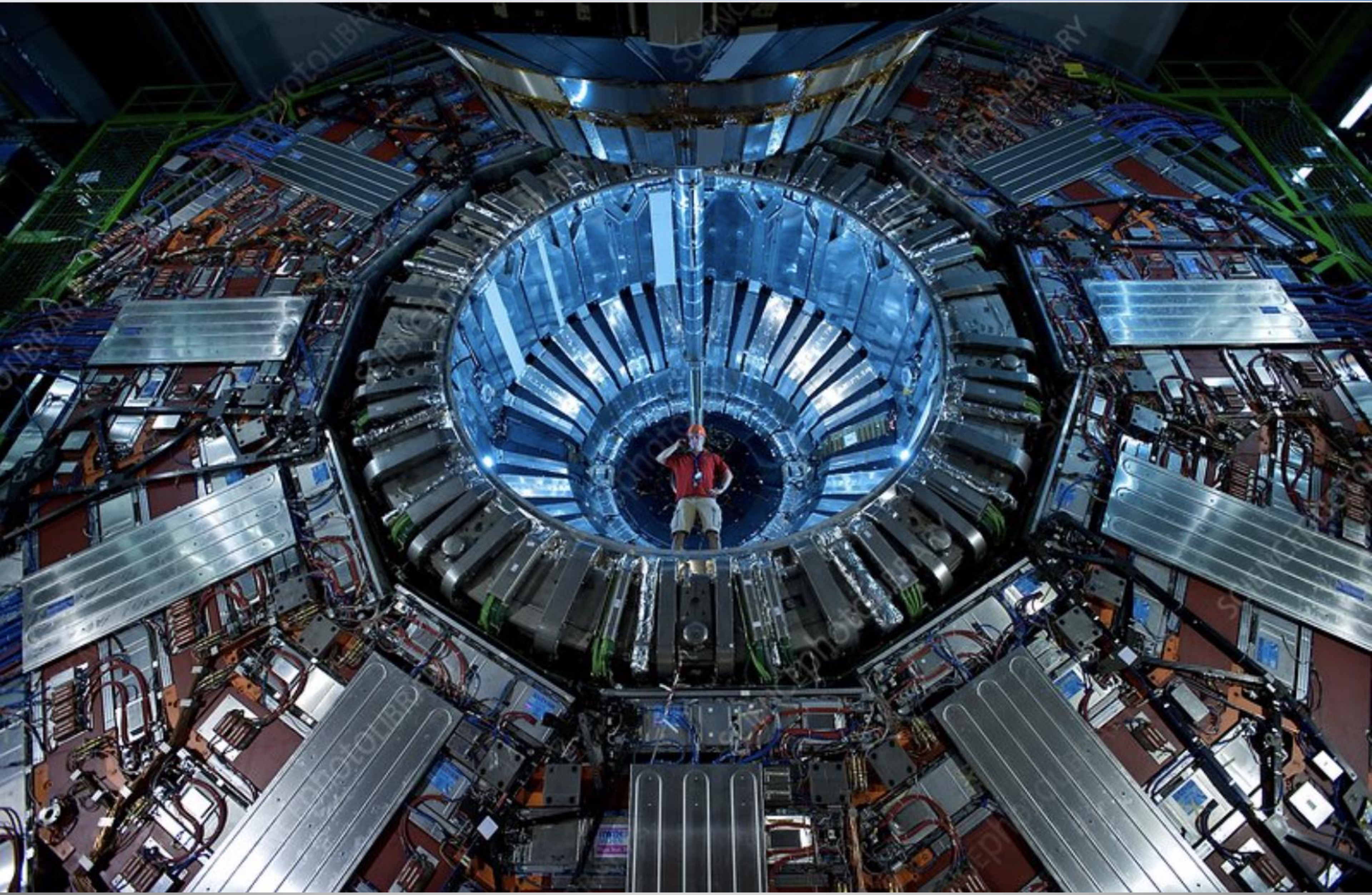
The CMS experiment

These experiments use different technologies for their detector components





Artistic CMS



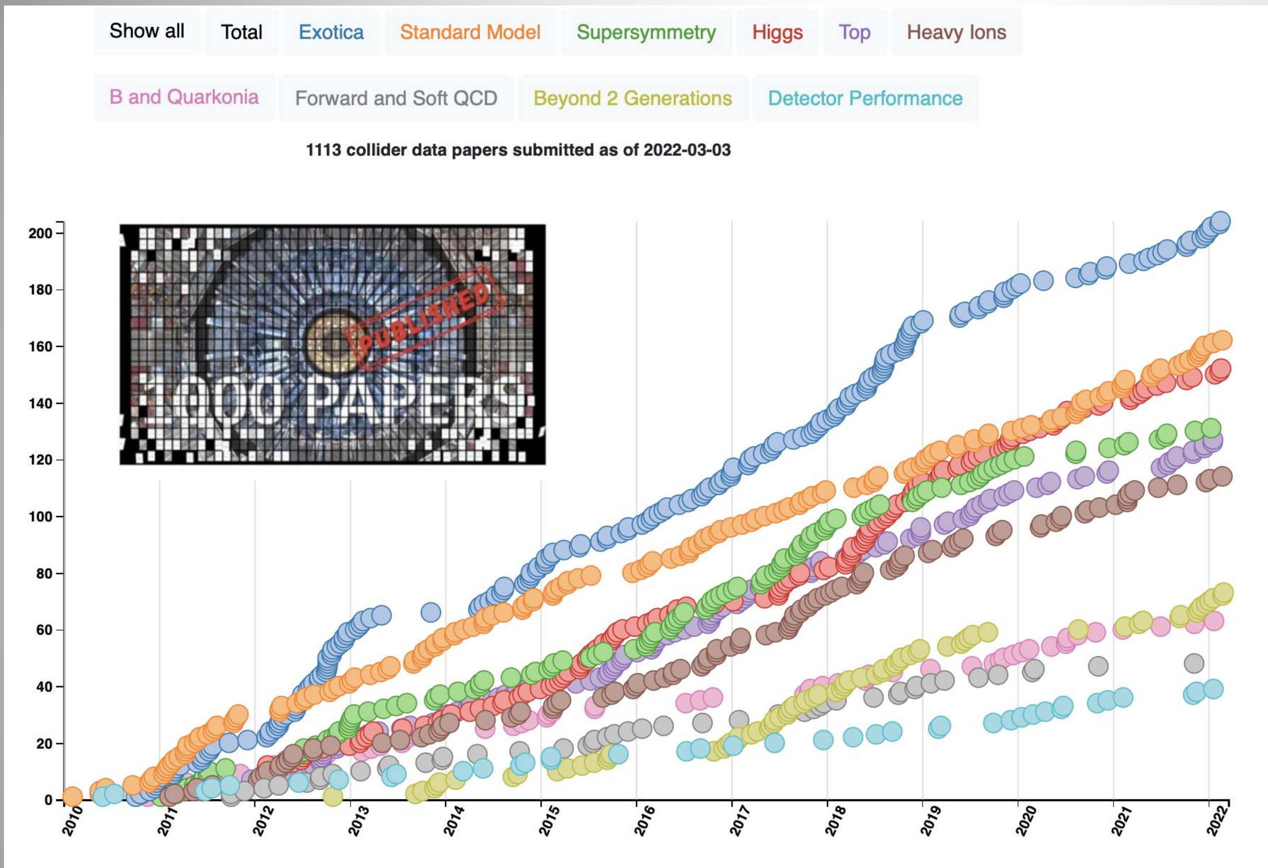
CMS before closure

CMS Experiment: A World Collaboration

The CMS Collaboration: >3200 scientists and engineers, >800 students from 236 Institutions in 54 countries .

Members/contacts in CMS from the region:
-> Bahrain, Qatar, Oman, KSA, Kuwait

The Scientific Output from CMS

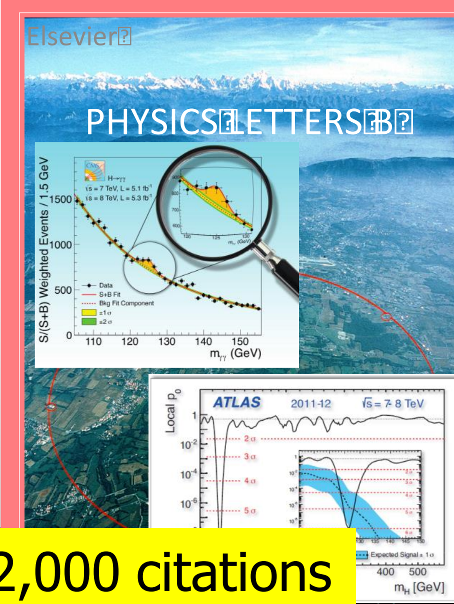


>1000 publications on pp (and pPb/PbPb) physics since 1/2010

About 100 papers on Higgs studies!!

Paper 16 was the discovery paper!

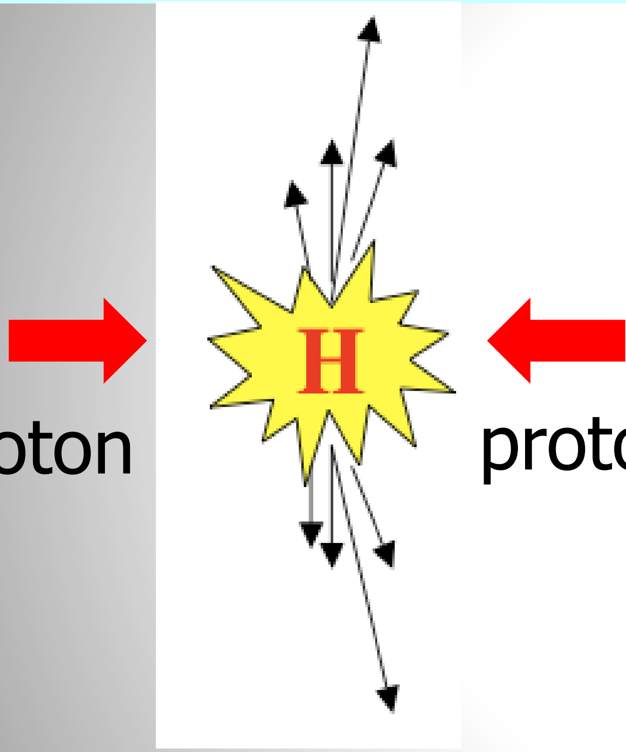
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/



>12,000 citations

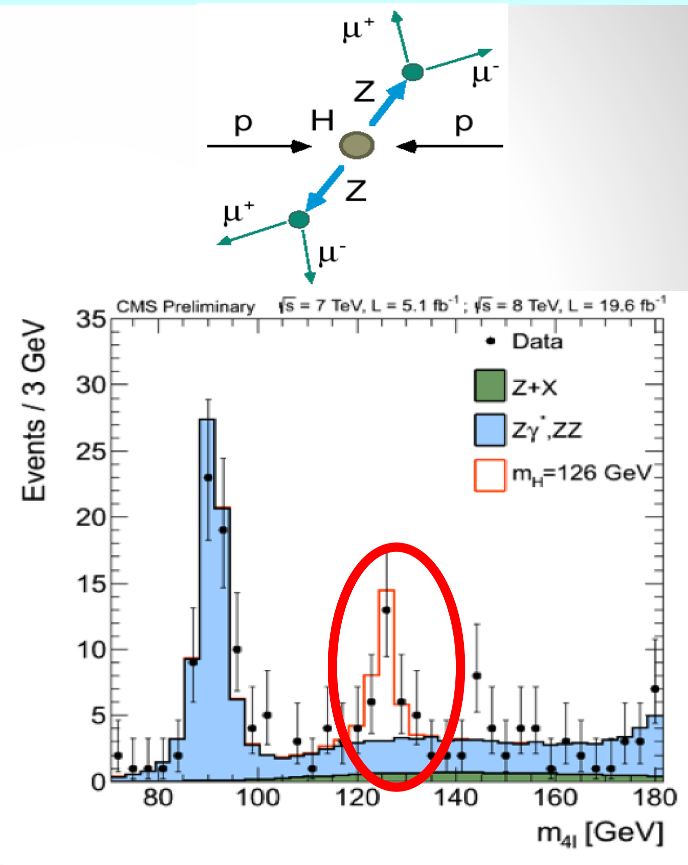
2012: A Milestone in Particle Physics

Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

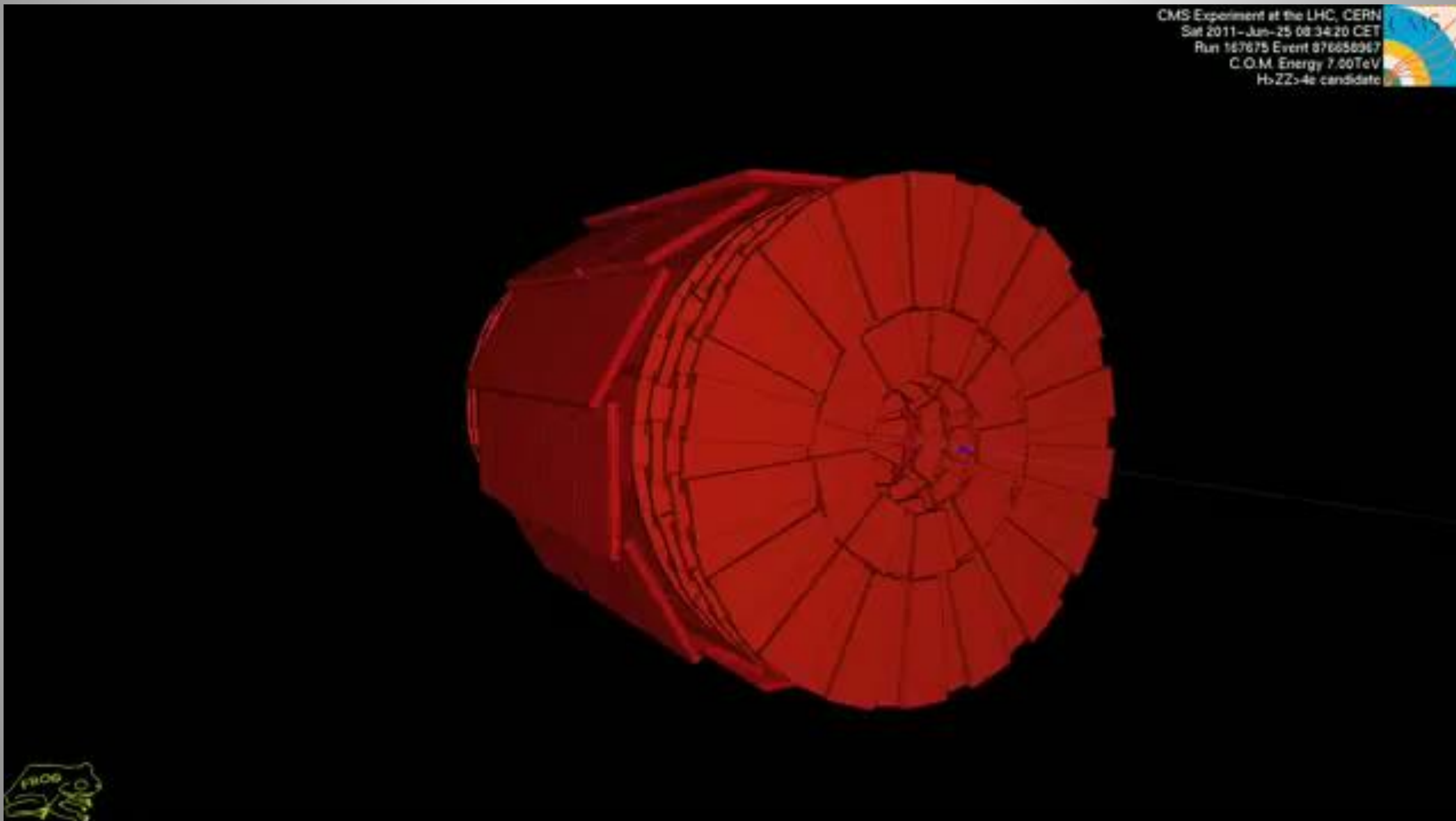
proton



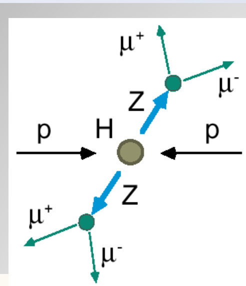
2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

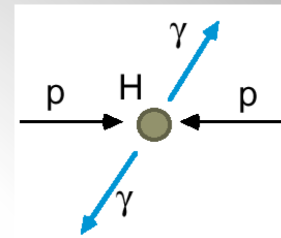
A Higgs Particle Candidate…

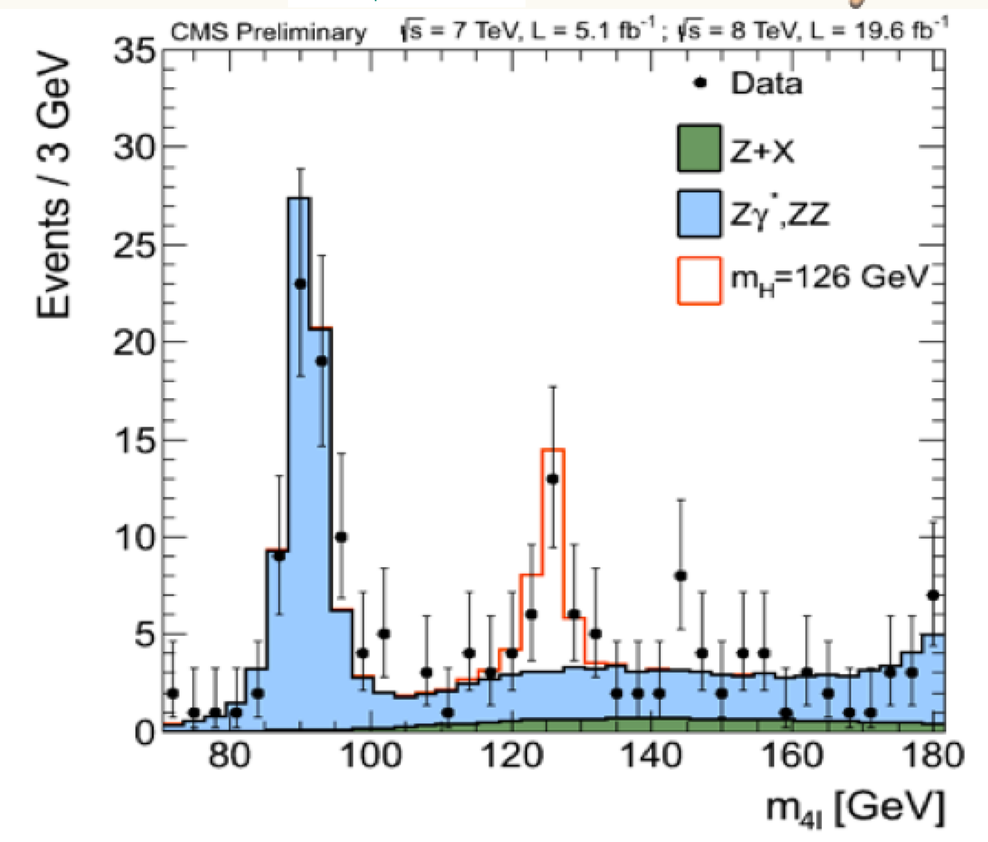


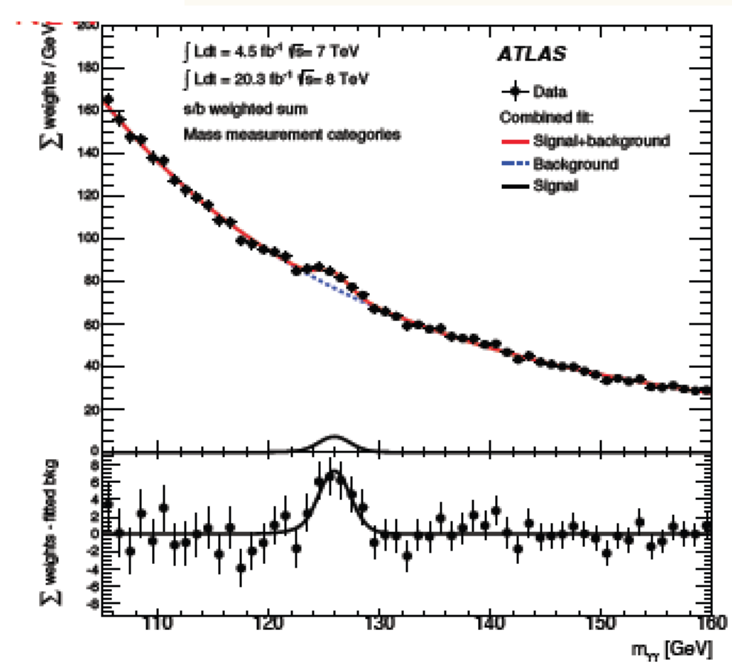
Higgs → ZZ and γγ



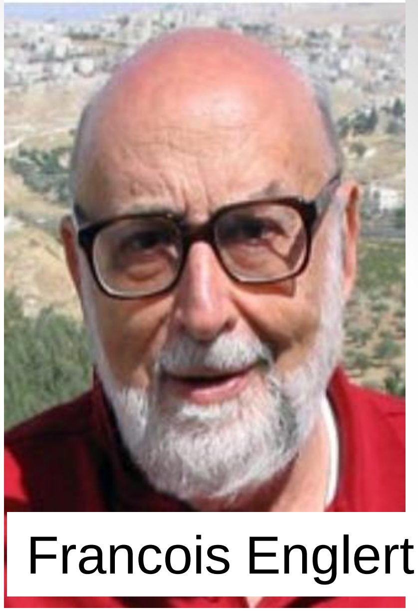
Discovery Channels!



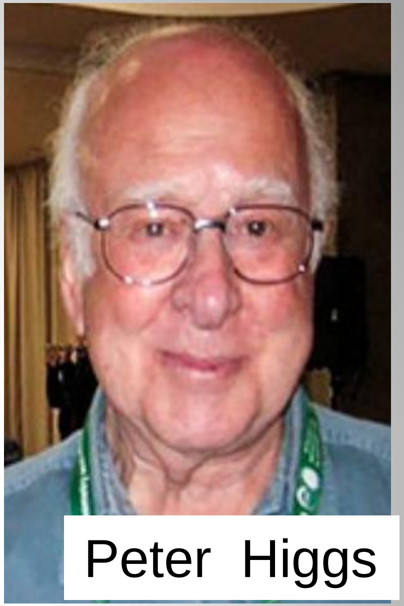




Tuesday 8 October 2013



Francois Englert

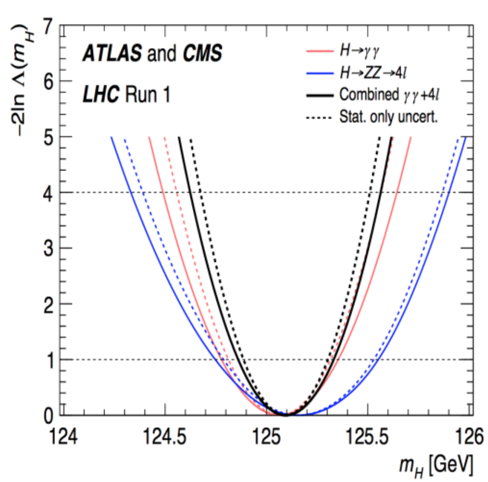


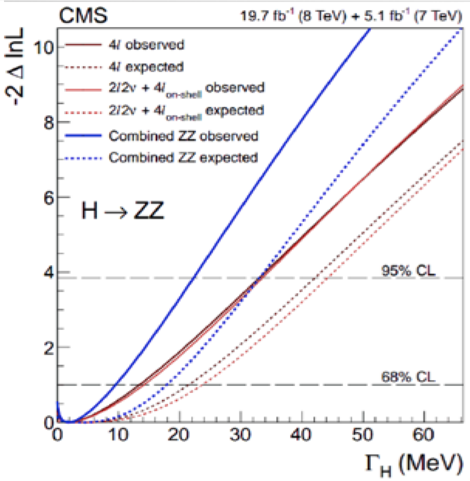
Peter Higgs

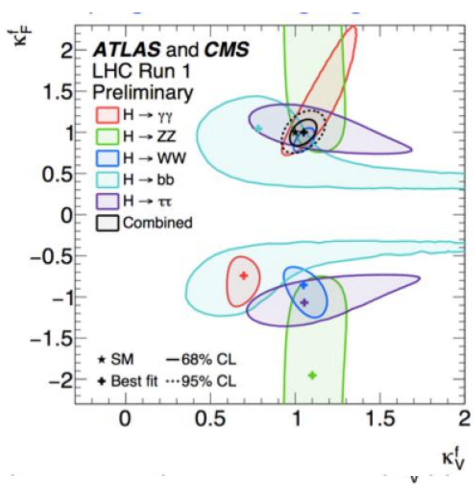
Congratulations!!!!

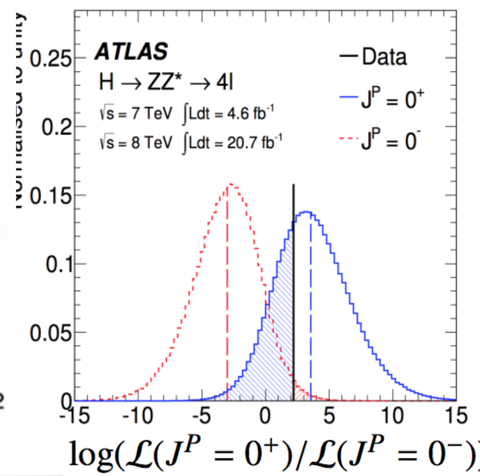
Brief Higgs Summary

We know already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

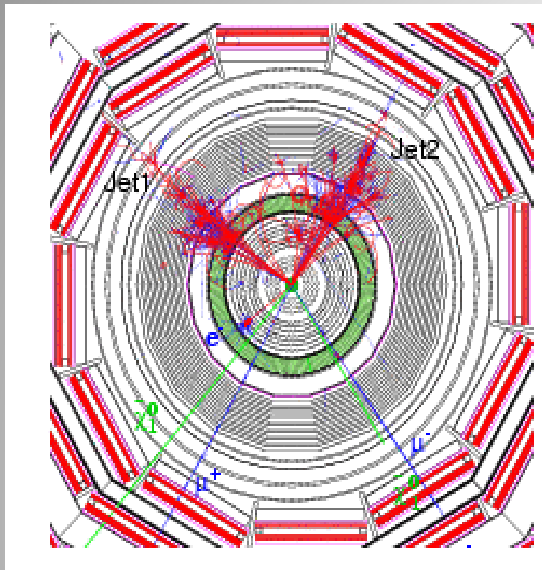
Width
< 9 MeV
(95%CL)

Couplings are
within ~10-15%
of the SM values

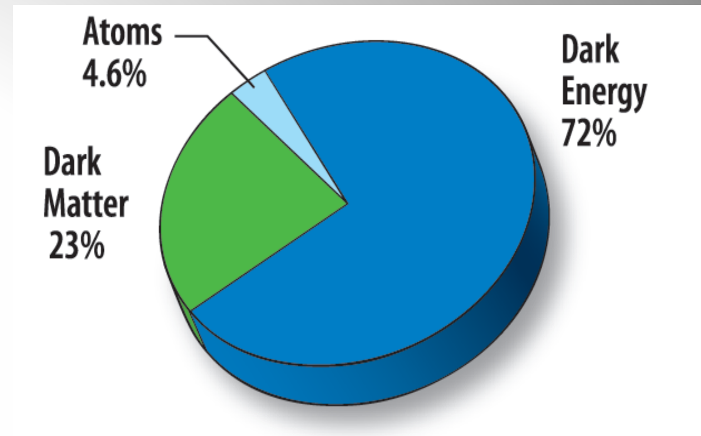
Spin =
$0^{+(+)}$ preferred
over 0^{-},1,2

SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production…

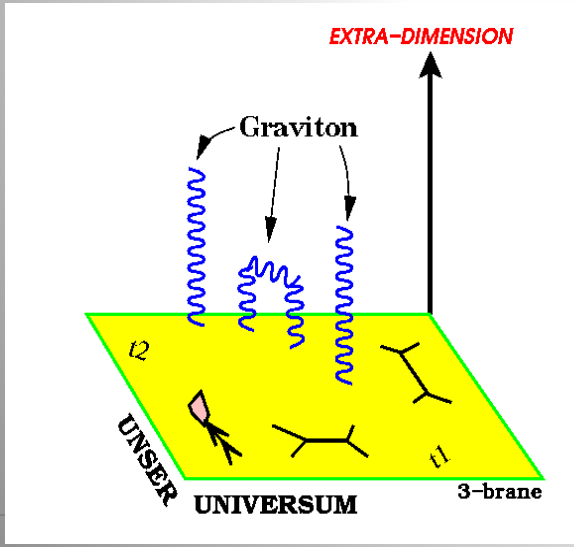
Next LHC PhysicsTargets



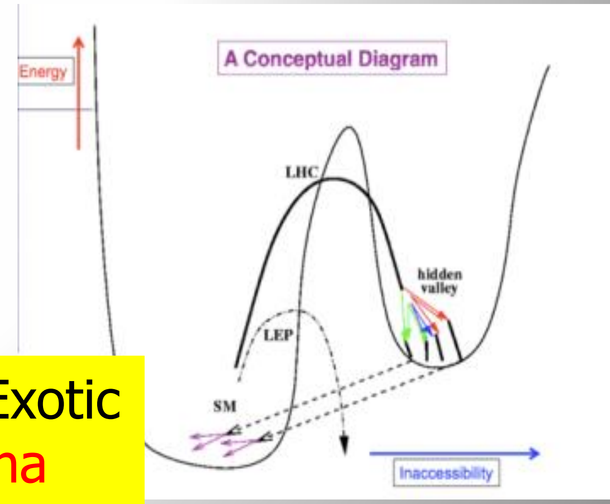
Searching for
Supersymmetric
Particles



Searching for
Dark Matter



Searching for
Extra Dimensions



Searching for Exotic
BSM Phenomena

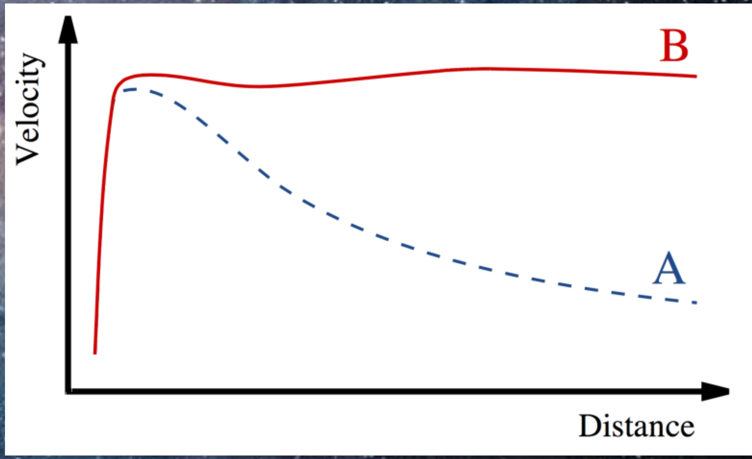
And many more topics…

Micro-Black Holes Hunters at the LHC…

No micro-black holes found…

Dark Matter in the Universe

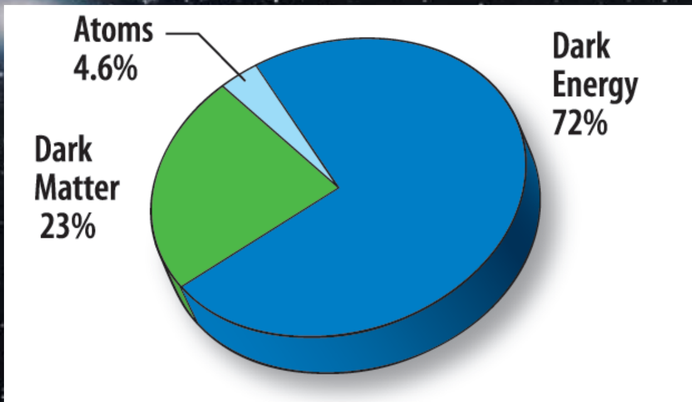
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



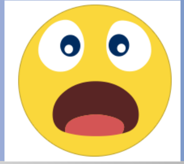
'Supersymmetric' particles ?


F. Zwicky 1898-1974


Vera Rubin ~ 1970



The Dark World??



Does it mean that there are also….

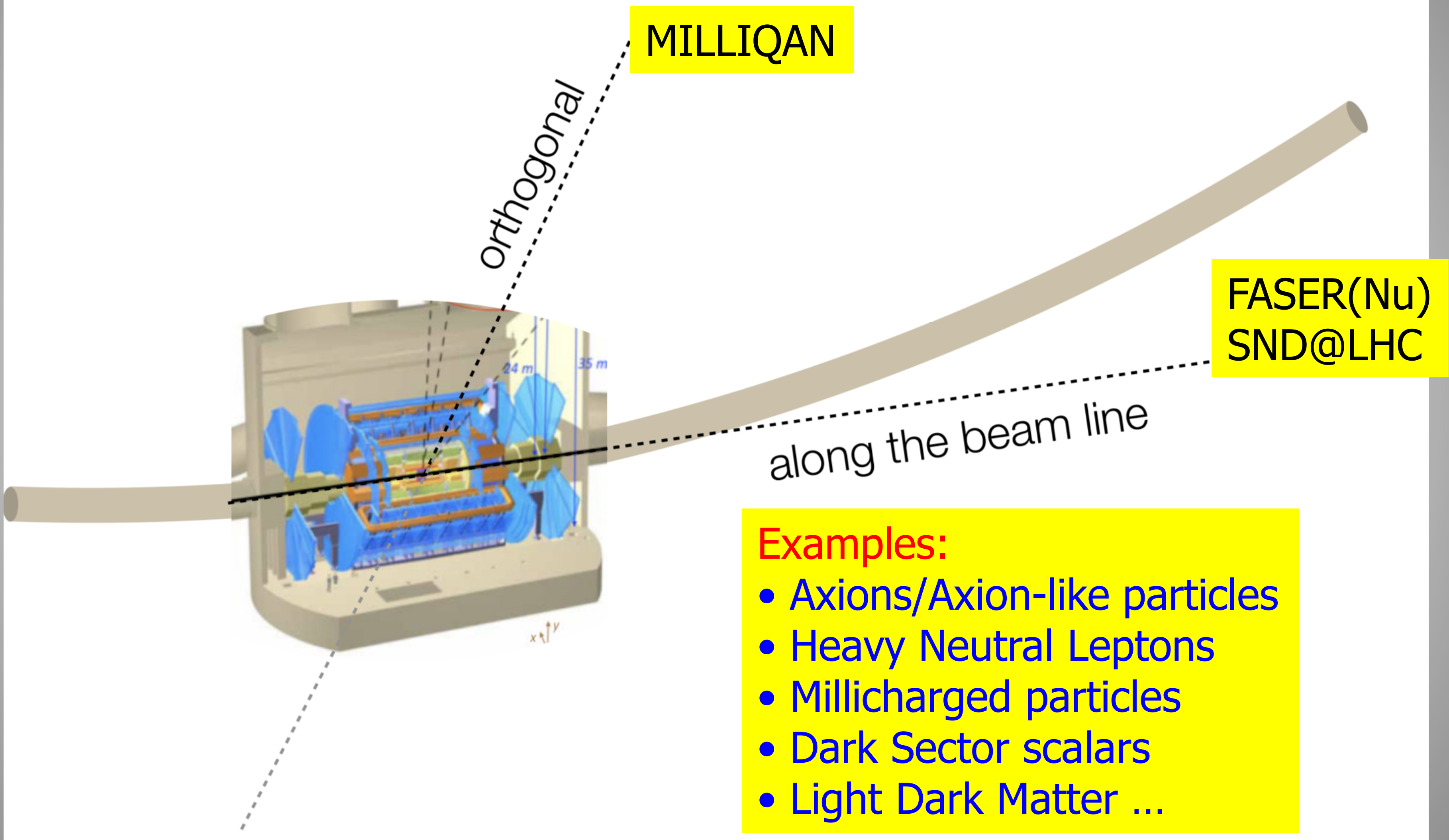
Dark Forces?

Or even Dark People?

No! We assume some simple interactions between dark matter particles in their environment, and a way to detect them

So far Dark Matter particles have not been found yet, not at the LHC or any other direct search experiment!! -> We need to explore new ideas!

New Directions – New Searches



Examples:

- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Light Dark Matter …

Leave no stone unturned!! => Extend the LHC experiments!

Example: Searching for Particles with a Millicharge

Minicharged particles (or **milli-charged particles**) are a proposed type of subatomic particle. They are charged, but with a tiny fraction of the charge of the electron. They weakly interact with matter.

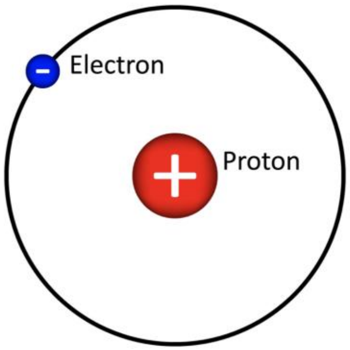
Minicharged particles are not part of the Standard Model.

The Electron

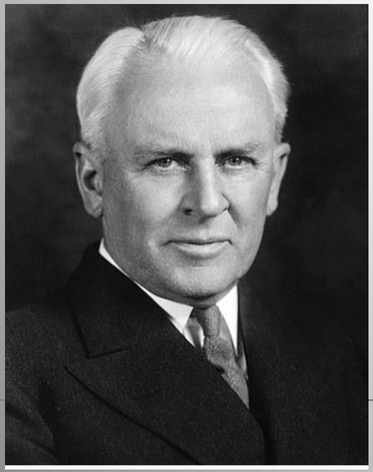
- The charge of the electron is still a mistery

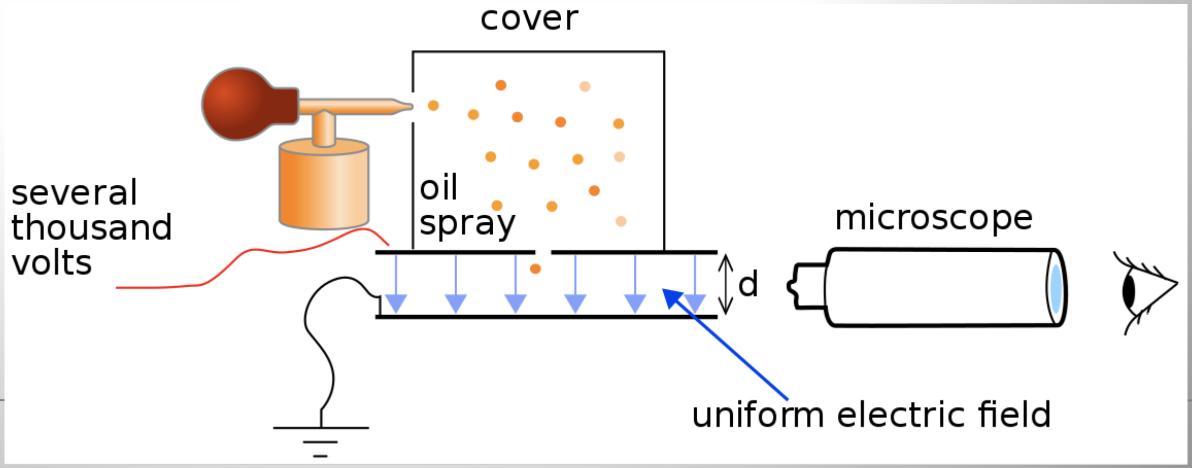
  The value is $1.602176634 \times 10^{-19}$ C
- Is it the fundamental charge? All charges seem to be multiples of the electron charge !

  (except for quarks that can have 2/3 or 1/3 fractional charge)
- Is it everywhere the same in the universe?
- Robert Millikan measured the electron charge (1910). Noble Prize in physics in 1923



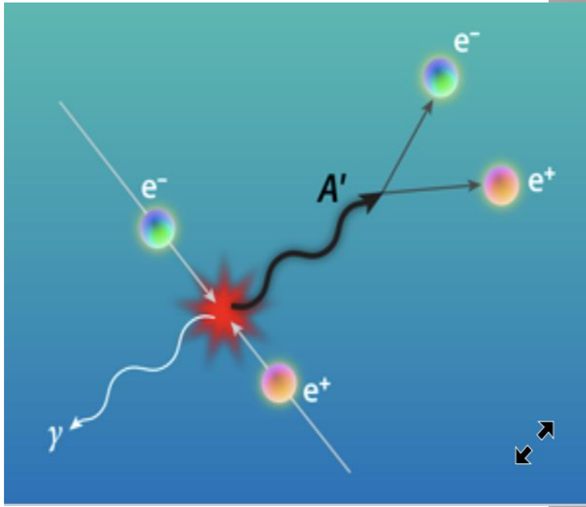
hydrogen atom





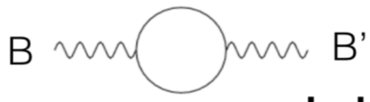
Dark Matter

- Fundamental question: Are there smaller charges in the Universe?
- In a world with Dark Matter smaller charges can naturally occur in simple scenarios to explain this dark matter.
- Assume dark matter is not just one unknown new particle, but there are also forces between the dark particles as in our world!
- Assume that there is a Dark Electromagnetic Interaction similar to QED



$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} \longleftarrow$$

kinetic mixing



massless U'(1) boson in the dark sector

'dark EM'

$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim \alpha/\pi$)

This can lead to particles with a millicharge

$$\frac{\text{Charge of the electron}}{\text{Charge of the dark particle}} = \frac{e}{\kappa} \ll e$$

Charge of the electron

= e

Charge of the dark particle

κ << e

The MilliQan Experiment

A. Ball,[1] G. Beauregard,[2] J. Brooke,[3] C. Campagnari,[4] M. Carrigan,[5] M. Citron,[4] J. De La Haye,[1] A. De Roeck,[1] Y. Elskens,[6] R. Escobar Franco,[4] M. Ezeldine,[7] B. Francis,[5] M. Gastal,[1] M. Ghimire,[2] J. Goldstein,[3] F. Golf,[8] J. Guiang,[4,*] A. Haas,[2] R. Heller,[4,†] C.S. Hill,[5] L. Lavezzo,[5] R. Loos,[1] S. Lowette,[6] G. Magill,[9,10] B. Manley,[5] B. Marsh,[4] D.W. Miller,[11] B. Odegard,[4] F.R. Saab,[7] J. Sahili,[7] R. Schmitz,[4] F. Setti,[4] H. Shakeshaft,[1] D. Stuart,[4] M. Swiatlowski,[11,‡] J. Yoo,[4,§] H. Zaraket,[7] and H. Zheng[11]

At this time ~40 collaborators, 11 Institutes

A direct search experiment for particles with a fractional charge

A Milli-Charge Hunter at the LHC

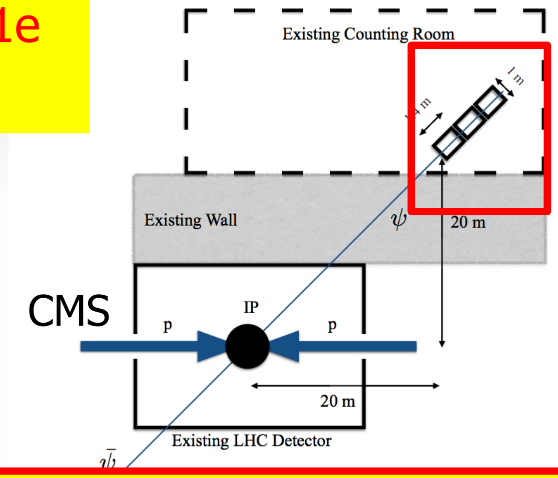
"New" idea -> Hunting for particles with charges ~ 0.3-0.001e

A Proposal for a new experiment

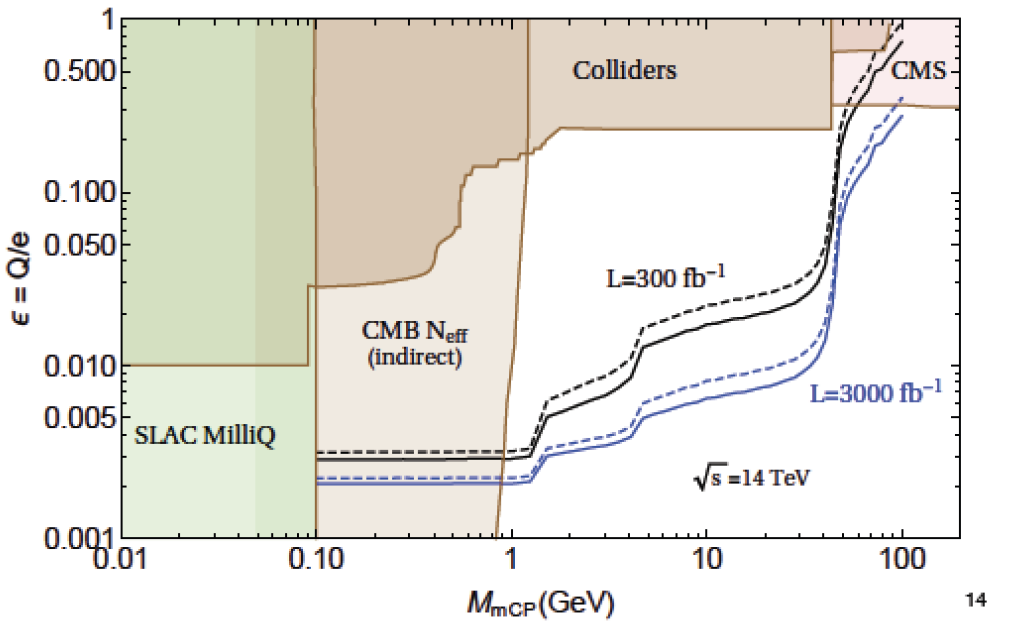
A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

arXiv:1607.04669

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]



MilliQan Experiment



Motivation:

- Particles with small charges?
- "Dark QED" ie QED in the dark sector that kinematically mixes withthe SM QED.
- The EDGES astronomical anomaly...?

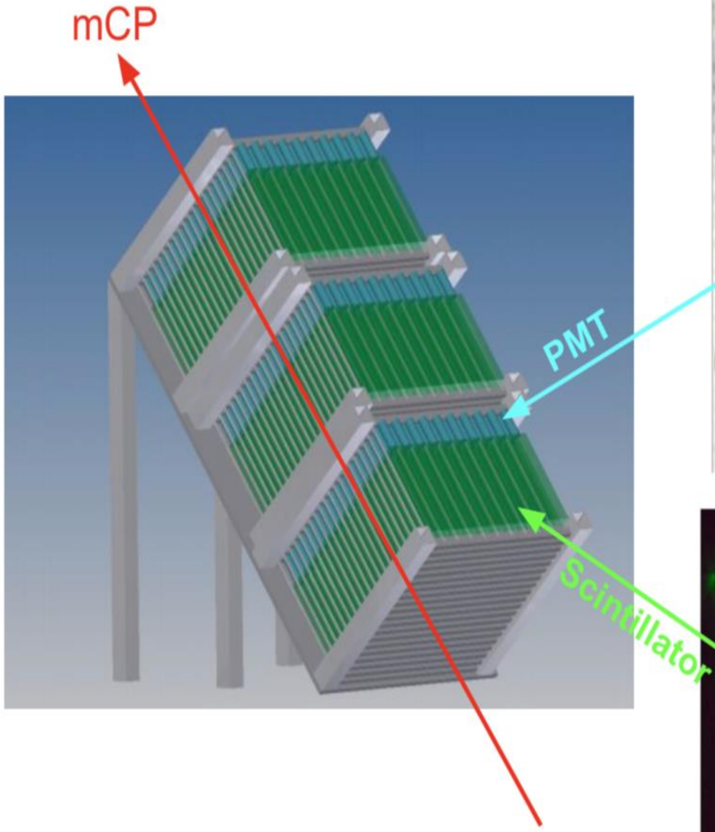
Detection technique:

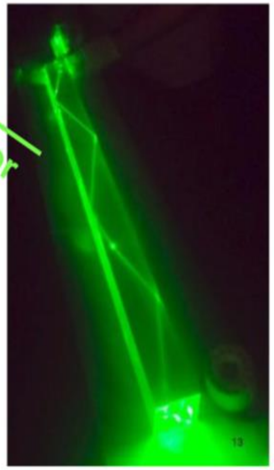
scintillators-> low photon signals

MilliQan Experiment

- Array of **scintillator bars** coupled to **PMTs** that can detect individual photoelectrons produced by through-going milli-charged particles
- Key concept is the **three-layer design**, requiring simultaneous hits in all three layers – drastically cuts down on backgrounds
- Signal would appear as a handful of in-time photoelectrons in three bars in a straight-line path

We have a baseline design but have room for further developements



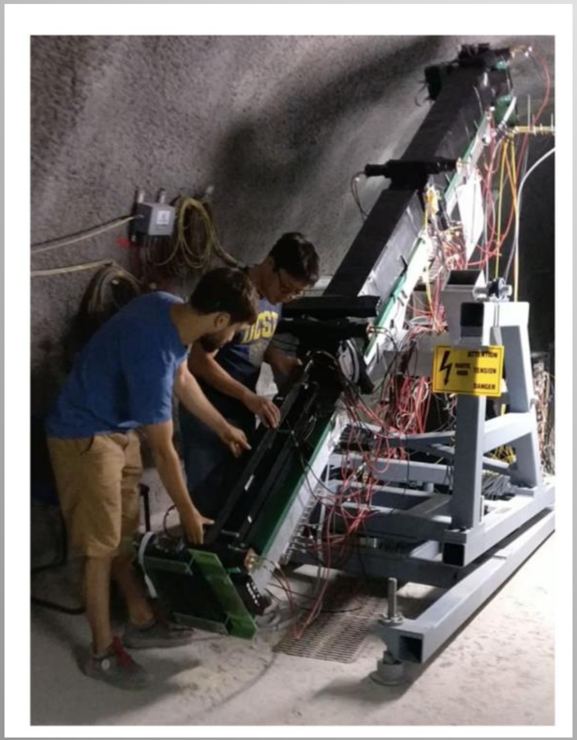


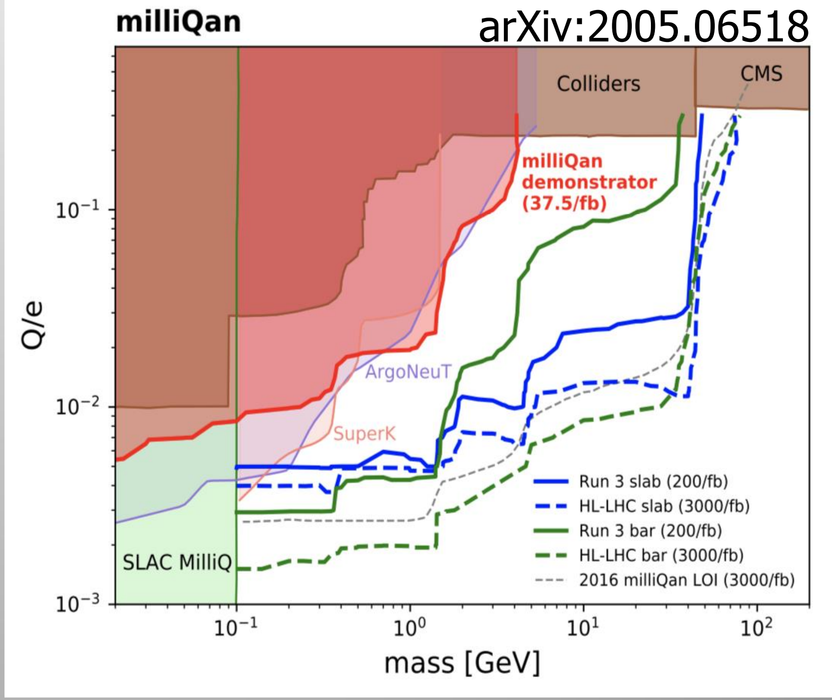
LOI (2015): arXiv:1607.04669

MilliQan is an experiment @ the LHC, in connection with the CMS experiment: same cavern and services.

MilliQan Experiment

2017-2018: A 1% demonstrator put in place. It worked fabulously well!
2020: We published a first physics result!
2022: Phase I detector is being installed at the LHC for Run-3





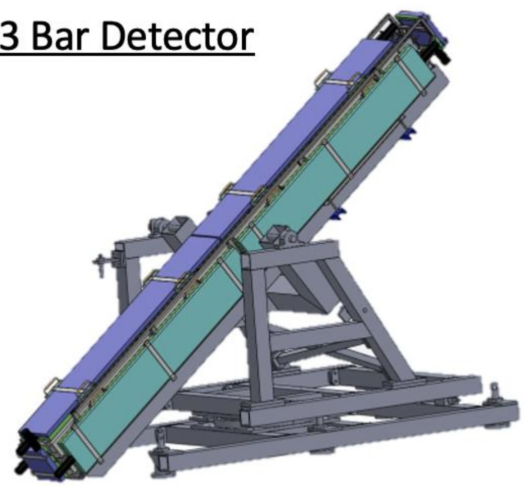
MilliQan is a project where students and enigineers can learn all aspects of high energy experimental particle physics from detector design, construction, operation and data analysis in a few years!!!

MilliQan Experiment

Search for Millicharges: Particles with very small charges, compared to the electron, expected e.g. in Dark Sector theories.

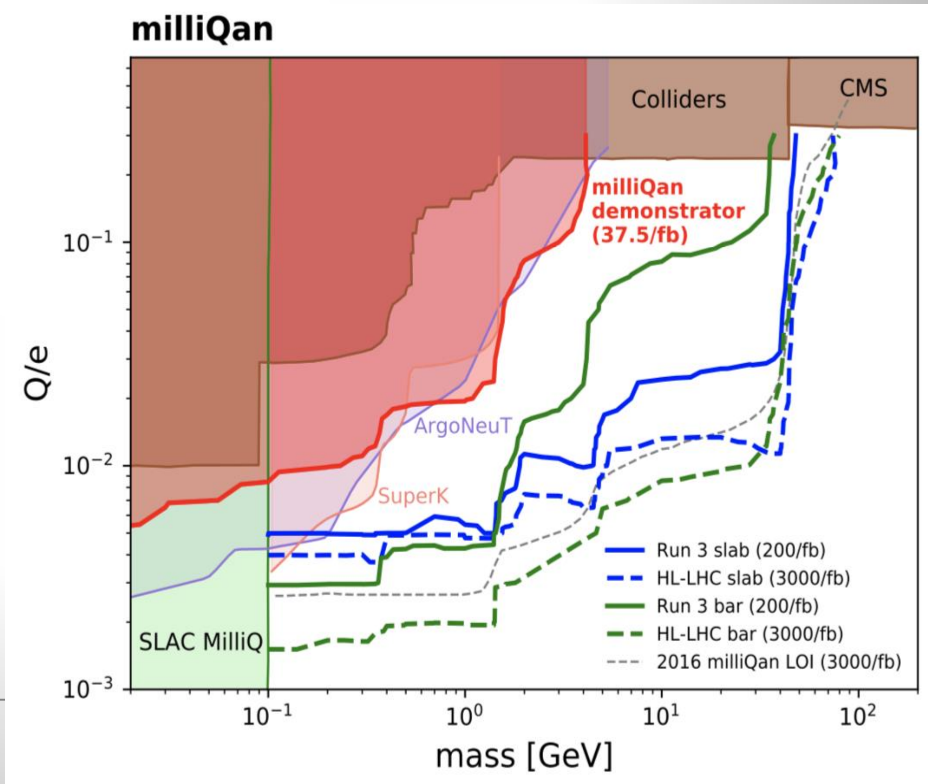
- MilliQan was approved as a LHC project on 2021, and is being installed now
- Scintillator bar and slab based detectors

Run 3 Bar Detector



Run 3 Slab Detector

Due to budget limitations the first phase will include both scintillation bars and slabs



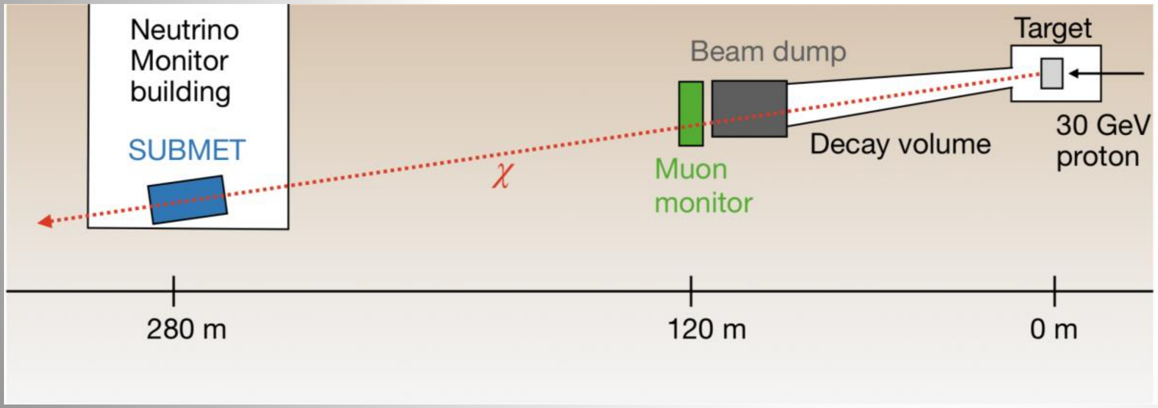
What MilliQan Can Offer:

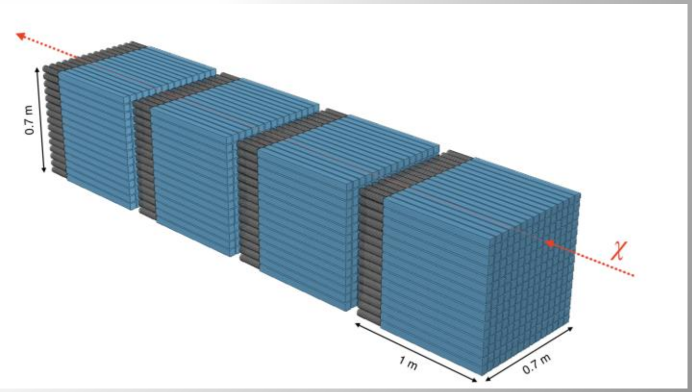
- MilliQan is a relatively small & cost effective experiment with an exciting and unique and important discovery potential!
- MilliQan is a project where students, scientists and enigineers can learn all aspects of high energy experimental particle physics from detector design, construction, operation and data analysis in a few years!!! And at the Large Hadron Collider!
- MilliQan is an excellent experiment for a new group in High Energy Physics & CERN to make significant international impact
- MilliQan is also an experiment for very interesting collaborations with theorists on dark matter and dark quantum electro-dynamics…
- Status of MilliQan
  - Demonstrator shows that the concept works, first physics paper out
  - Design being finalized: Starting phase-I detector construction!
  - Not all funding in place yet, an additional 0.5 MCHF will be required to make it a full success in phase-II

MilliQan: a new type of new physics hunter

- The idea of detector and the success of the demonstrator in 2018-2020 has led to new proposals for MilliQan-like experiments..
  - SUBMET: T2K 'neutrino' beam (mass< @ GeV). Proposal submitted last month. Most funding available. arXiv:2007.06329 (Japan)
  - FerMINI: FNAL fixed target experiment arXiv:1812.03998 (USA)
  - MoEDAL/MAPP: @LHCb IP arXiv:1909.05216 (CERN)
  - FORMOSA: @FPF Cavern of the HL-LHC arXiv:2203.05090 (CERN)

E.G the SUBMET proposal (largely funded)





MilliQan collaboration is involved in SUBMET, FerMINI & FORMOSA Detectors
=>This is a science program for up to 2040 and beyond!!

Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought fundamental scalar boson, postulated in 1964.

This is a brand new fundamental particle, as we never seen before.

This Higgs boson is ‘very light’ which suggest new physics Beyond the Standard Model will be needed. We look for it at the LHC!!

One of the Big Mysteries today in Physics is: what is the nature of Dark Matter? Can we produce Dark Matter at the LHC? MilliQan offers a new experimental way to probe for the Dark Sector

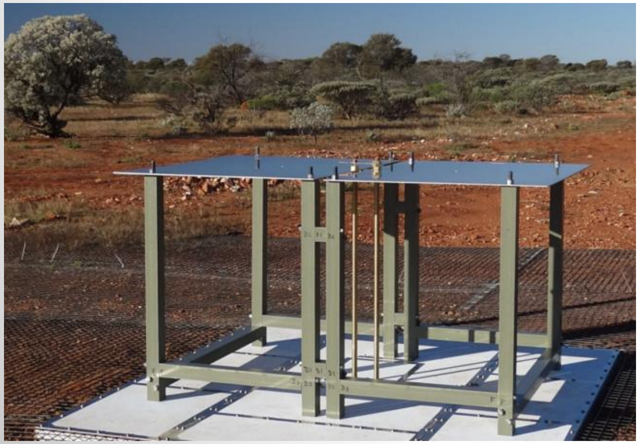
We are on the verge of a revolution in our understanding of the Universe and our place within it!! Will secrets be revealed by discovering millicharges? Bahrain can play a very important role!

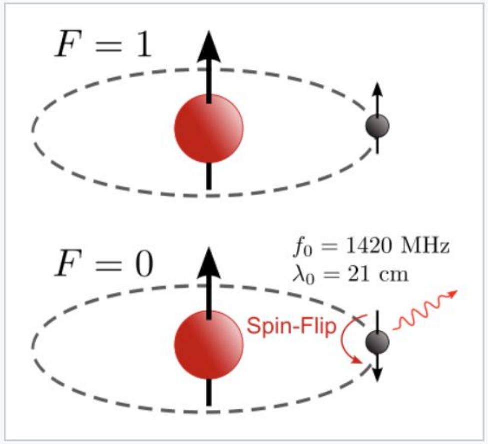
This is only the beginning!!!

Backup

The EDGES Experiment Anomaly

- EDGES is an radio detection experiment of hydrogen signatures from the formation Universe at the time of first stars and galaxies
- The typical 21-cm signal is produced by a electron spin-flip on the hydrogen atom.
- Edges found that the exact position of the signal (z-shift) is not as expected by the standard cosmological model, and seems to indicate the hydrogen gas at that epoque is colder than predicted by the model.





Hydrogen 21-centimeter line

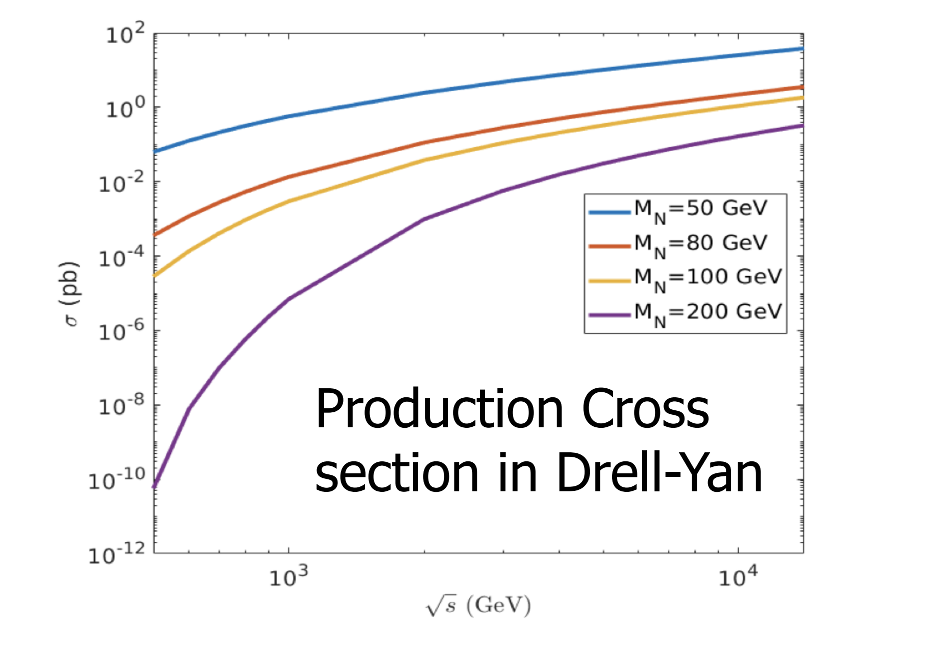
Colder hydrogen can be explained by the presence of millicharges in the Universe (eg in Two component dark matter models)

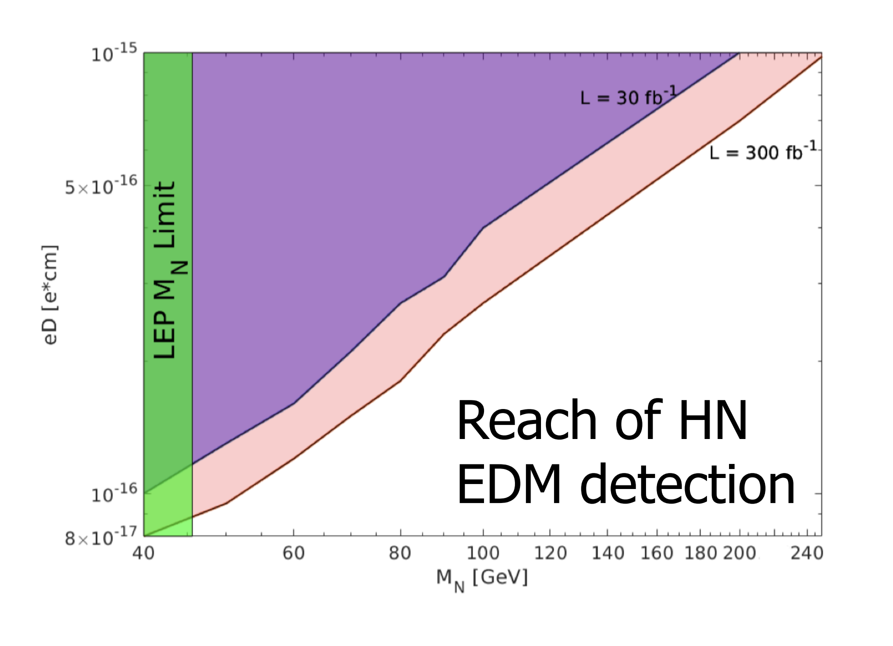
MilliQan Experiment

arXiv:1909.05216

Other topics: e.g. Searching for Heavy Neutrinos (HN)

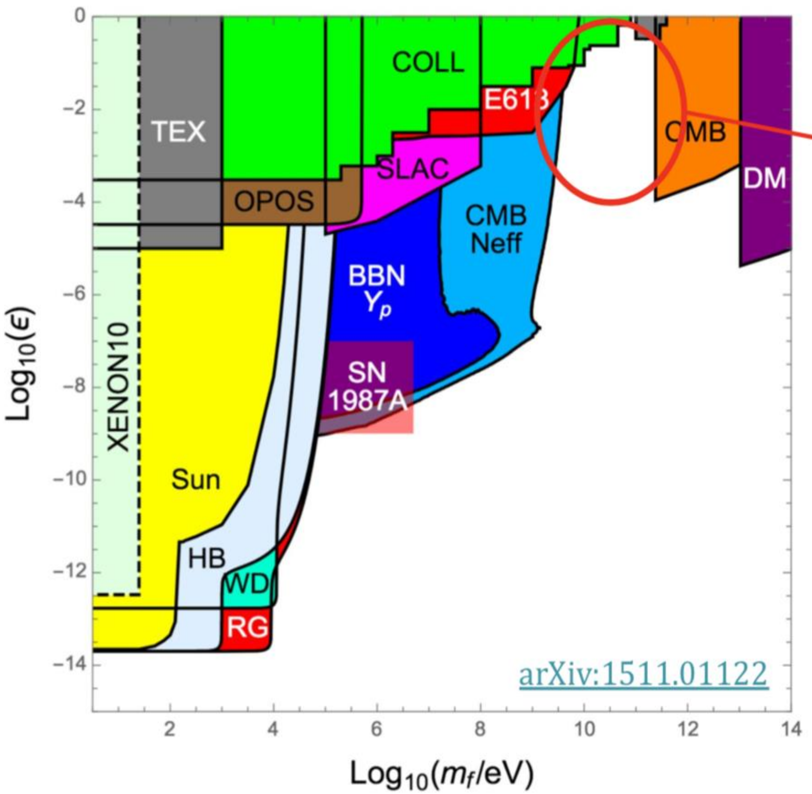
Assume a 4th generation doublet, with an electric dipole moment (EDM)
The EDM could be as large as 10^{-15} ecm

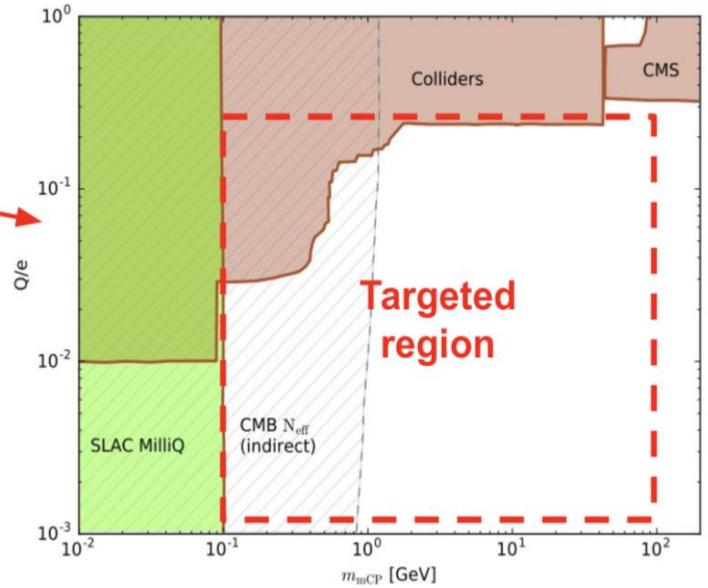




Milli-Charges

Status of searches

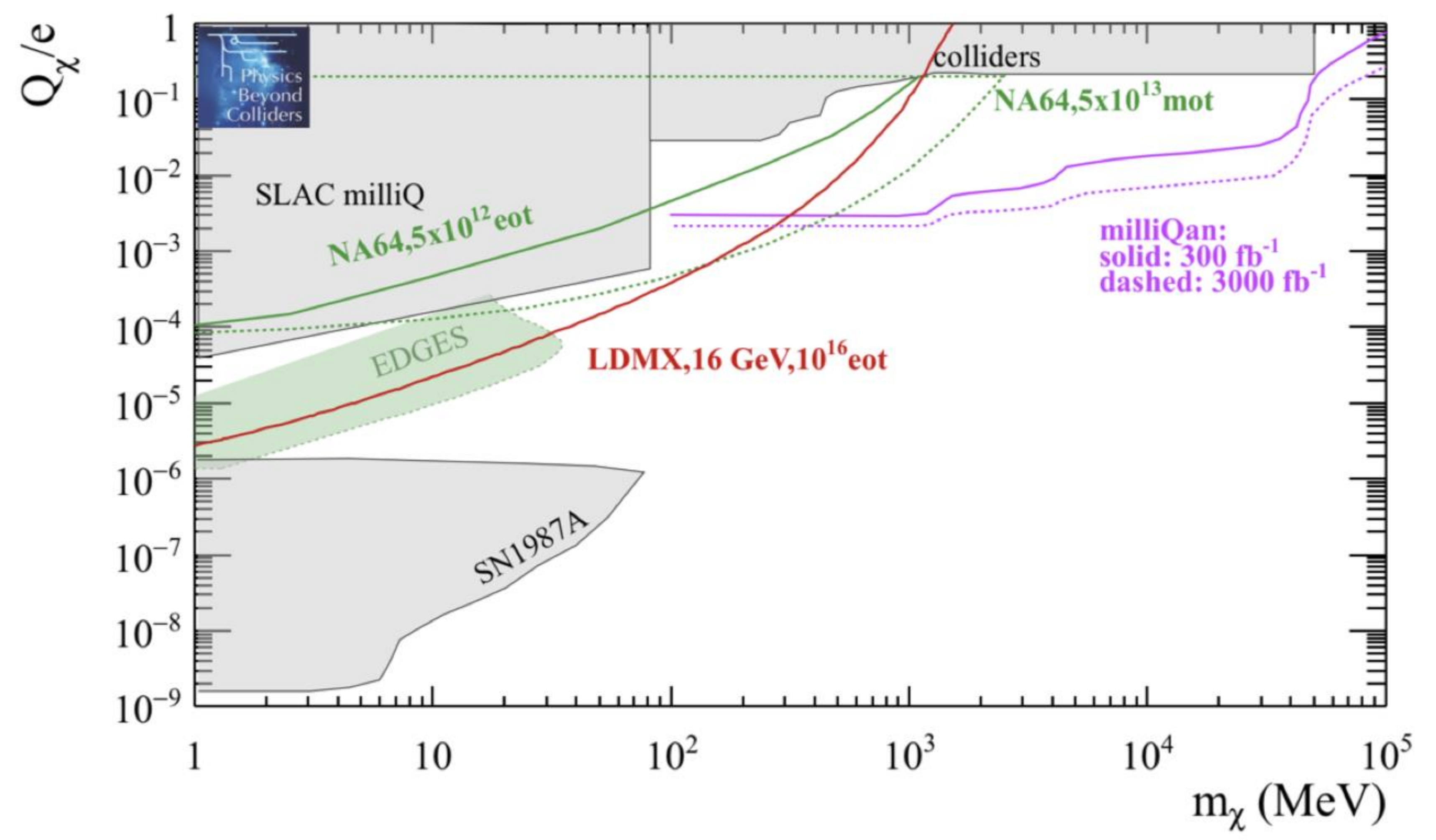




Gap at high mass and charge between 10^{-3} and 10^{-1} e

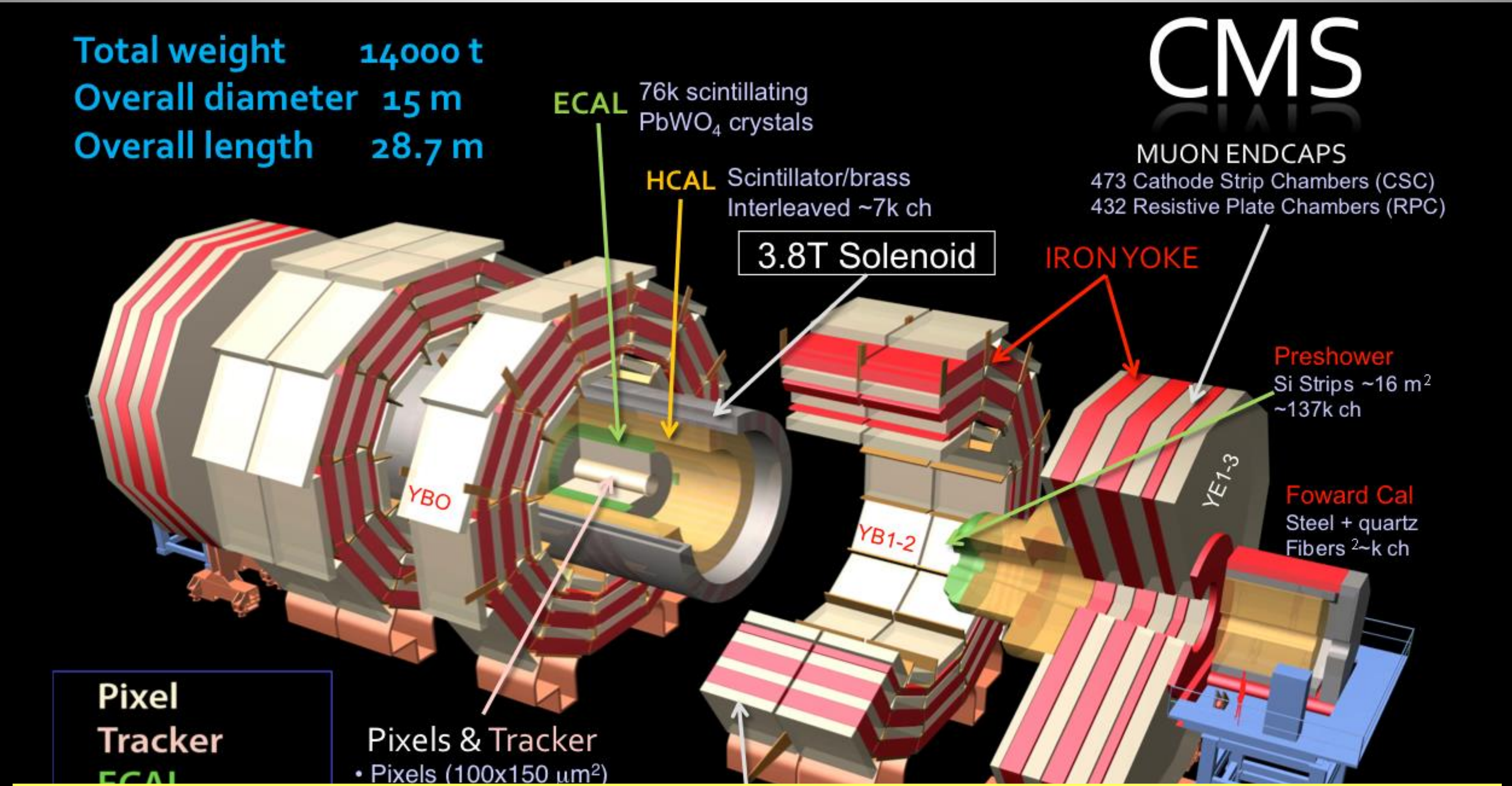
Can target with a dedicated experiment at the LHC!

MilliQan Experiment and the World



No other experiment can reach the sensitivity of MilliQan

The Compact Muon Solenoid Experiment



In total about ~100 000 000 electronic channels

Each channel checked 40 000 000 times per second (bunch X rate is 40 MHz)

An on-line trigger selects events and reduces the rate from 40MHz to ~ 1kHz

Amount of data for just one bunch crossing ~2 000 000 Bytes

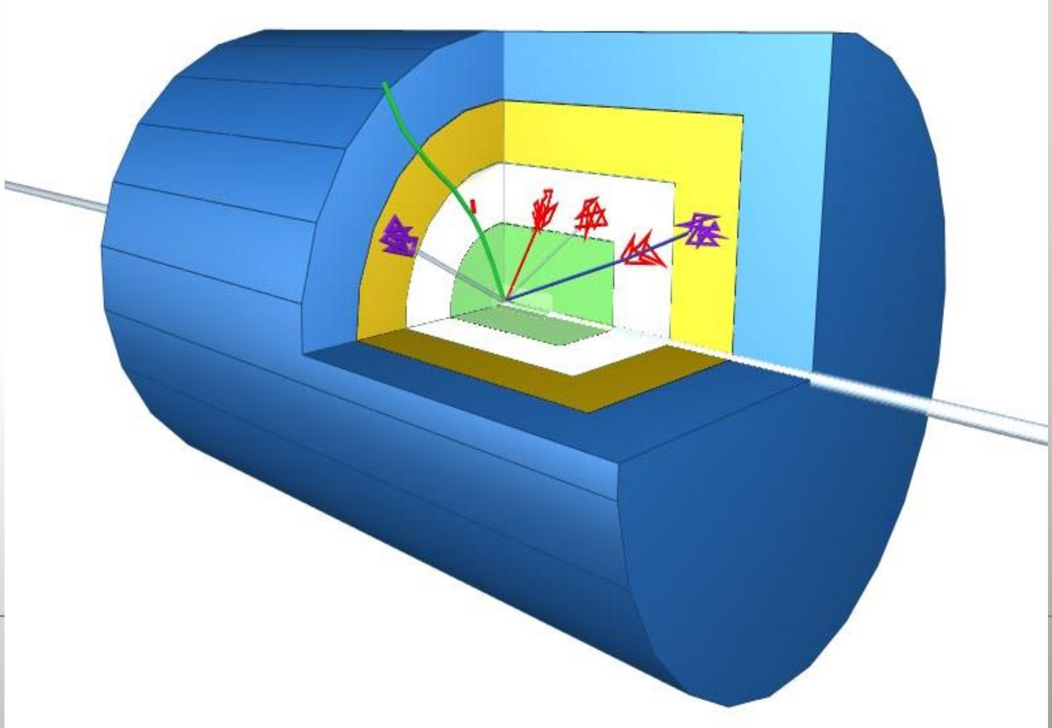
Schematic of a LHC Detector

Physics requirements drive the design!

Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Such an experiment has ~ 100 Million read-out channels!!



We Expect Answers from the LHC, but…

Will LHC answer all questions?: Likely not

Some/all New Particles out of mass range?
Need for higher energies at colliders?

Higher precision measurements needed
Need for higher luminosity or e+e-?

Measuring details of the Higgs?
Need for a Higgs factory?

Many ideas are emerging for new accelerators since June 2012
So far only projects being studied, none is scheduled yet

Future Circular Collider Study

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** **≥100 TeV *pp*-collider (*FCC-hh*)**

≥16 T magnets

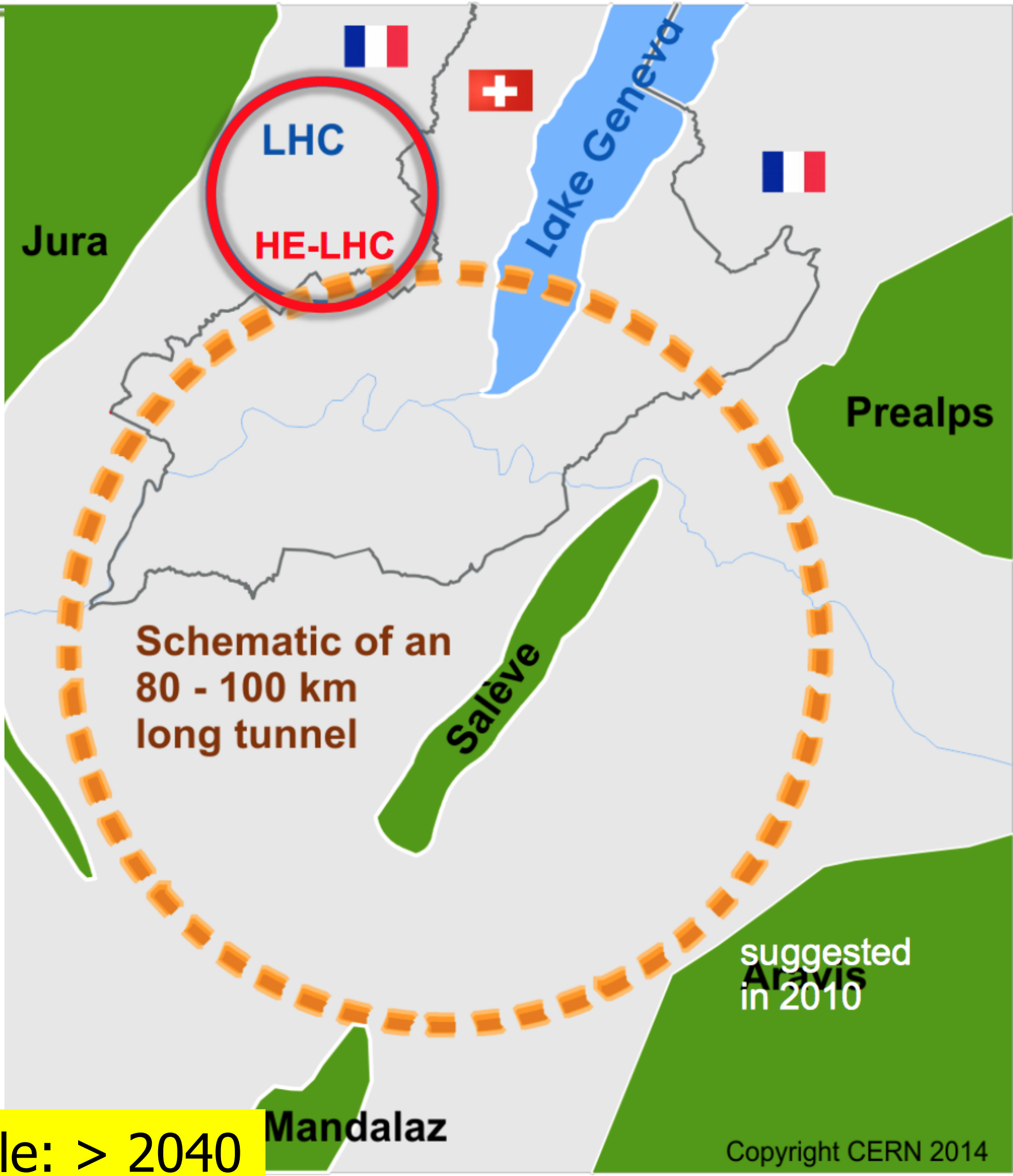
→ defining infrastructure requirements

Two possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC* 16T ⇒ 27 TeV**
  in LEP/LHC tunnel

Possible addition:

- ***p-e* (*FCC-he*) option**



Timescale: > 2040