Etat et Perspectives de la Physique des Particules

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Outline

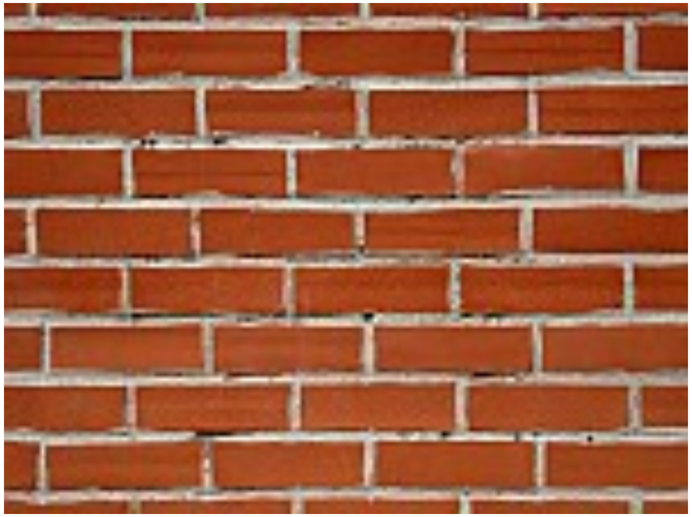
1. Introduction to Particle Physics

2. What did we learn from Large Hadron Collider data?

3. What is next?

Particle Physics (en très bref)

Study the elementary particles (e.g. the building blocks of matter: electrons and quarks) and the forces that control their behaviour at the most fundamental level.

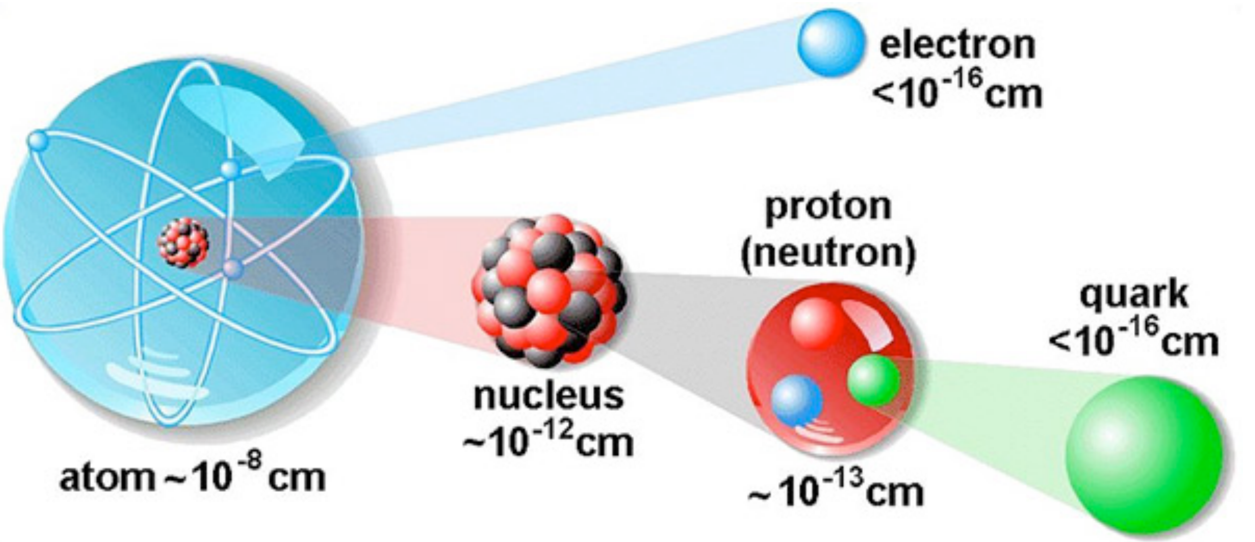


Elementary Particles

Forces

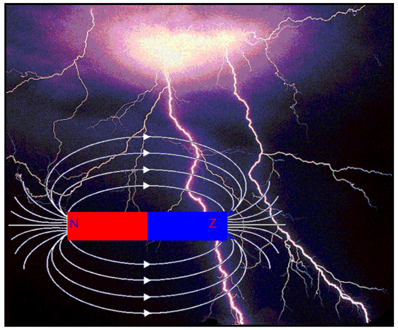
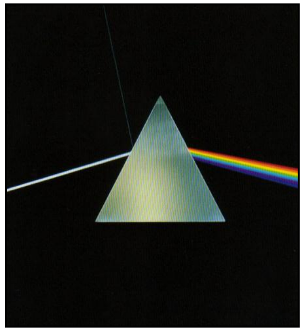
Particles

~1m **molécule ~10^{-6}m**



- The electrons and the quarks are the elementary particles of matter
- Study the fundamental laws of nature on scales down to 10^{-16} cm
  - insight also into the structure and evolution of the Universe
  - from the very small to the very big …

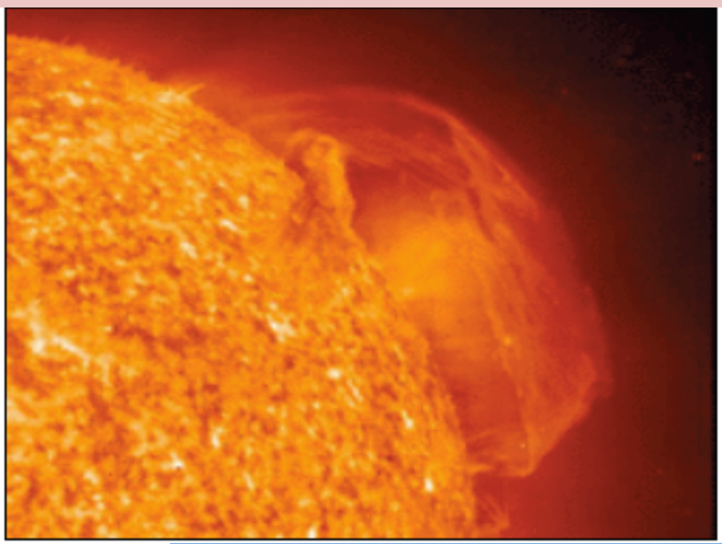
The Fondamental Forces of Nature

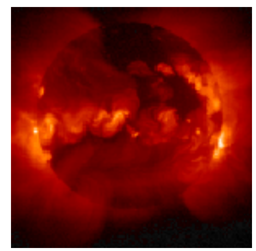
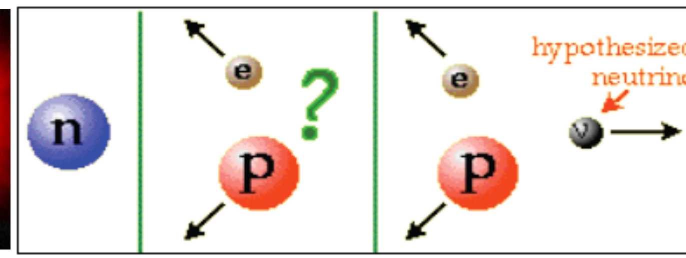



- **Electromagnetism**
  - gives light, radio, holds atoms together

- **Weak Nuclear Force**
  - gives radioactivity

- **Strong Nuclear Force**
  - holds nuclei together

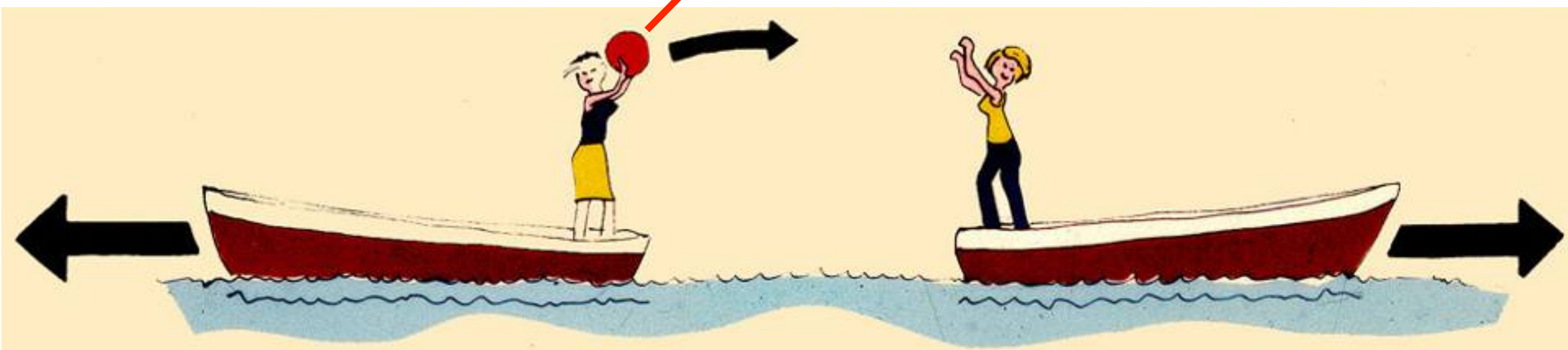


- **Gravity**
  - holds planets and stars together

Forces Carriers

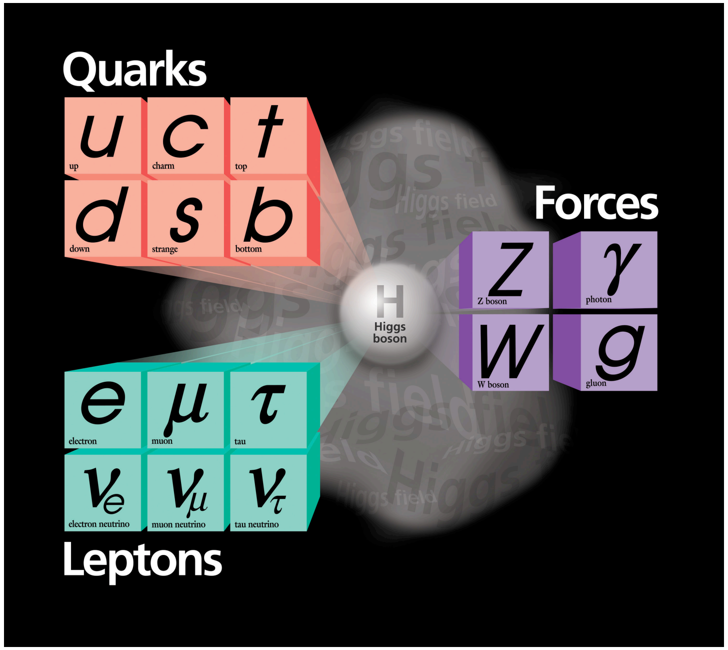
The exchange of Particles is responsible for the Forces

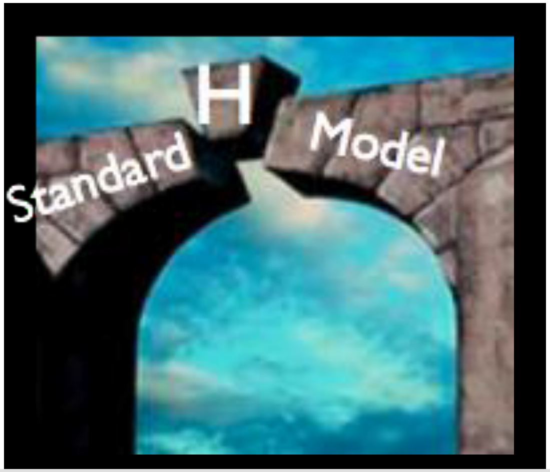


	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon

The Standard Model in Particle Physics

A crowning achievement of 20th Century Science





- Over the last 100 years: combination of **Quantum Mechanics and Special Theory of relativity** along with all new particles discovered has led to Standard Model of Particle Physics
- The new (final?) Periodic Table of fundamental elements
- The SM has been tested thousands of times, to excellent precision.
- All particles foreseen by the SM have been observed.
- A major step forward was made in July 2012 with the discovery of the Higgs boson

The Origin of Particle Masses

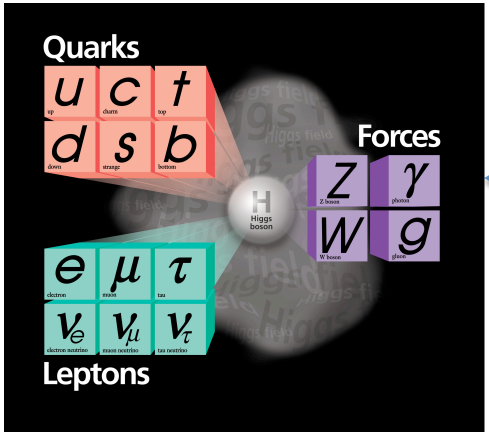
Mass(top) = ~350000 x Mass(electron)

- Why particles (and matter) have masses (and so different masses) ?
- The mass mystery could be solved with the « Brout-Englert-Higgs mecanism » (theory 1964): 10^{-11} s after Big Bang, "Higgs field" became active and ***particles acquired masses*** proportional to strength of interactions with Higgs field

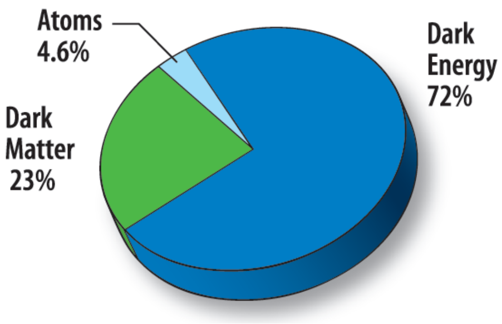
A world without "Higgs" would be a very strange one!

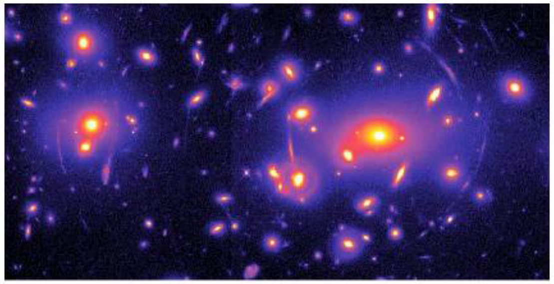
Atoms may not exist, and the Universe would be very different…

But, several open questions remain…



- Astrophysics/cosmological measurements show that **most matter in the universe is NOT in this table** : What is this Dark Matter?





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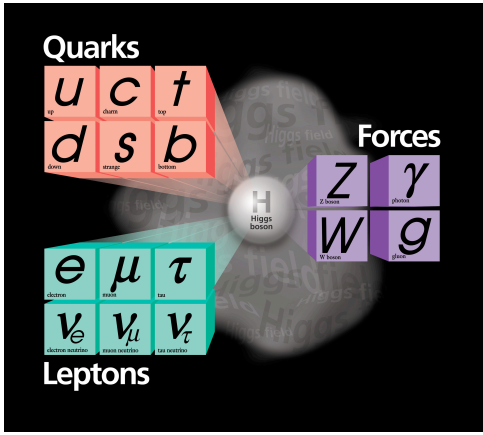

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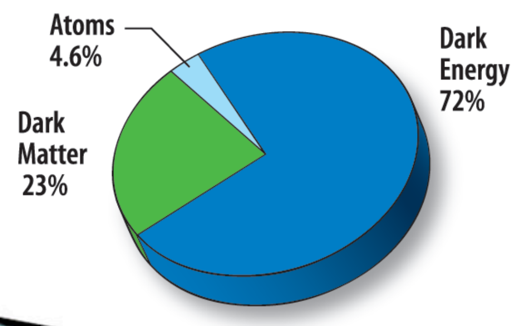

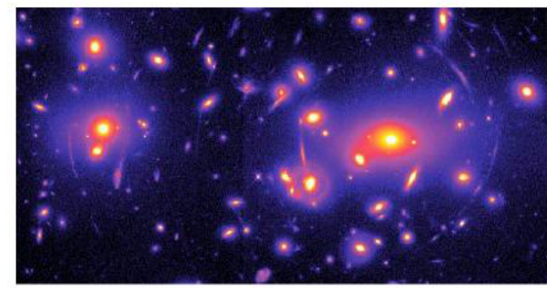

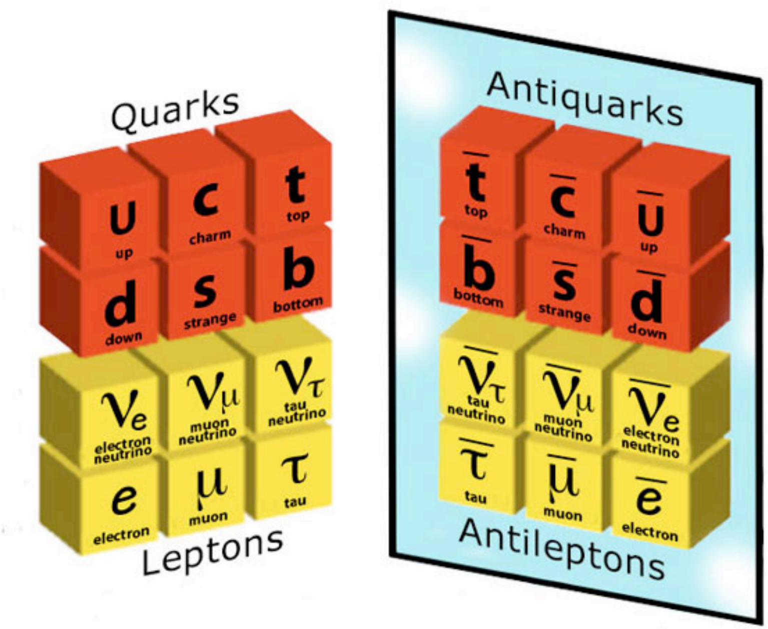

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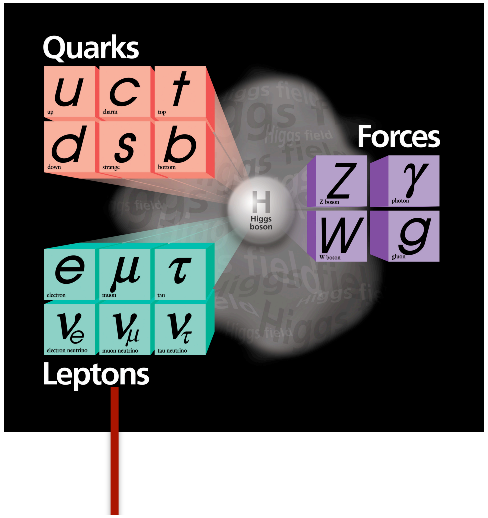

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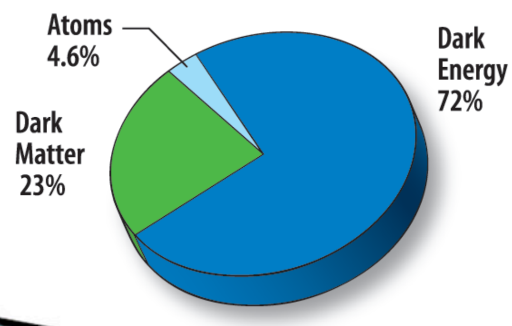
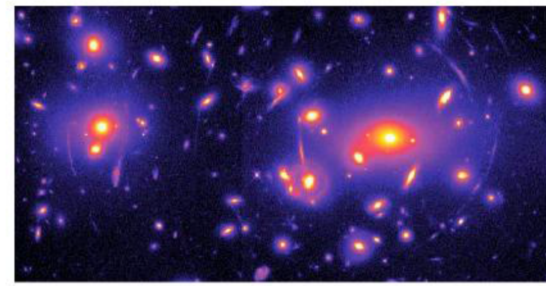
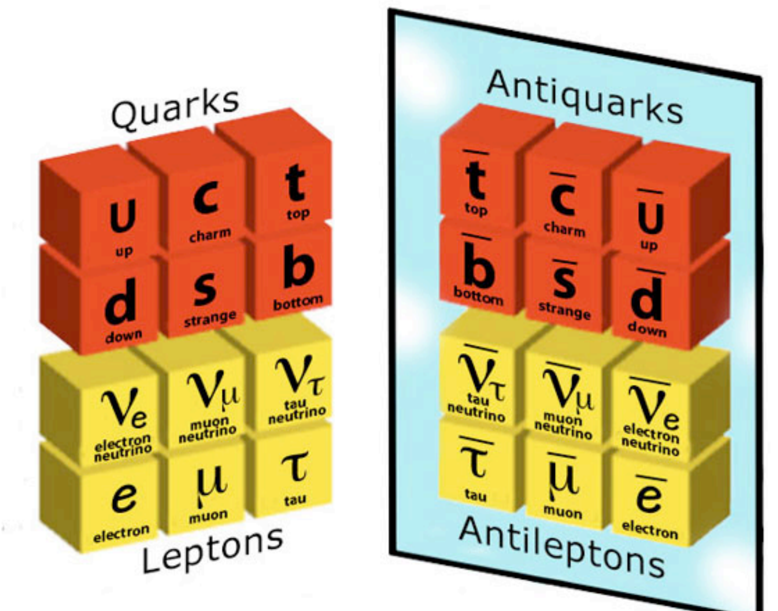
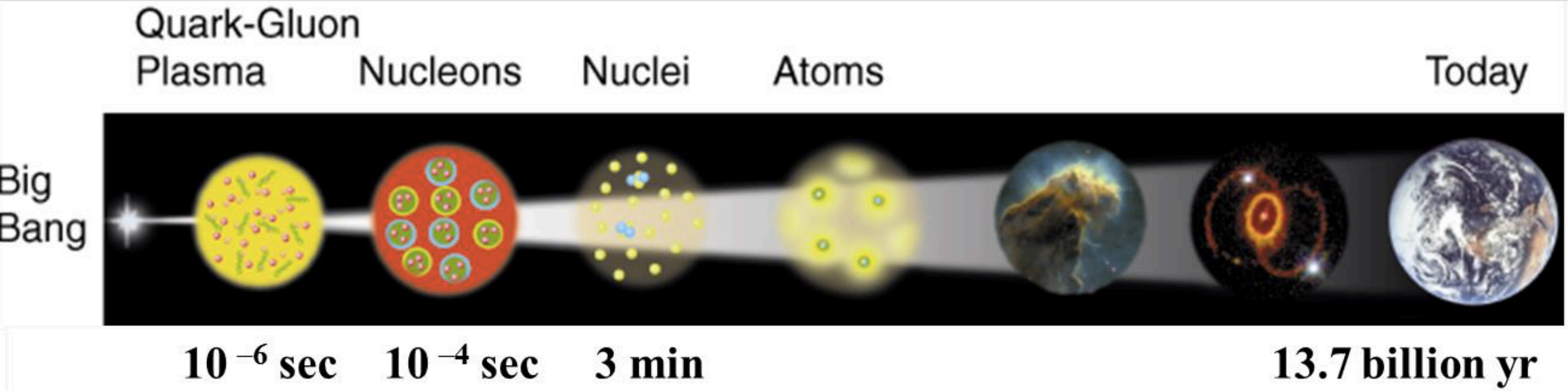




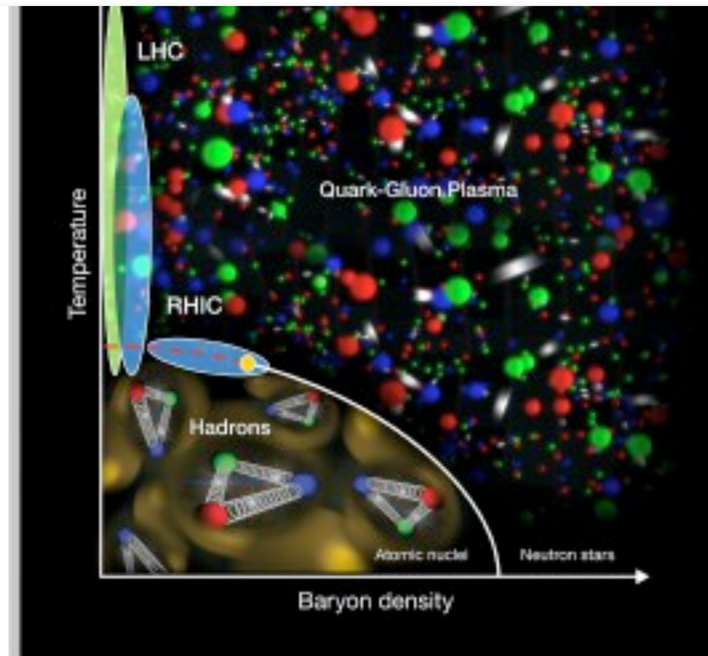


- Why is there so little antimatter in the Universe ?
- Are there other forces in addition to the known four ?
- Are there additional (microscopic) space dimensions ?

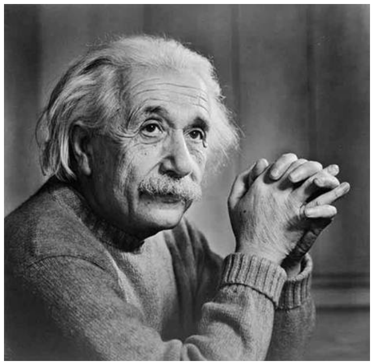
Where do we come from ?



- **Quark-Gluon Plasma (QGP)** : a state of matter where quarks and gluons move freely over distances large in comparison to the typical size of a hadron
- Study the properties of nuclear matter under extreme conditions in **heavy ions collisions**
  - Quantify the properties of the Quark-Gluon Plasma
  - Shed light on the evolution of the early Universe



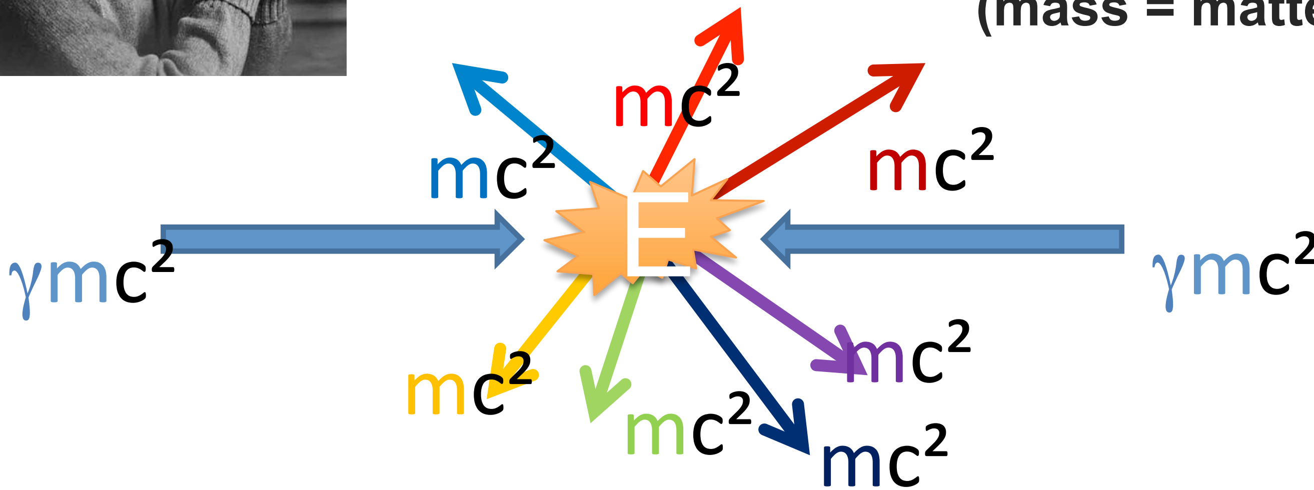
How to produce particles in lab ?



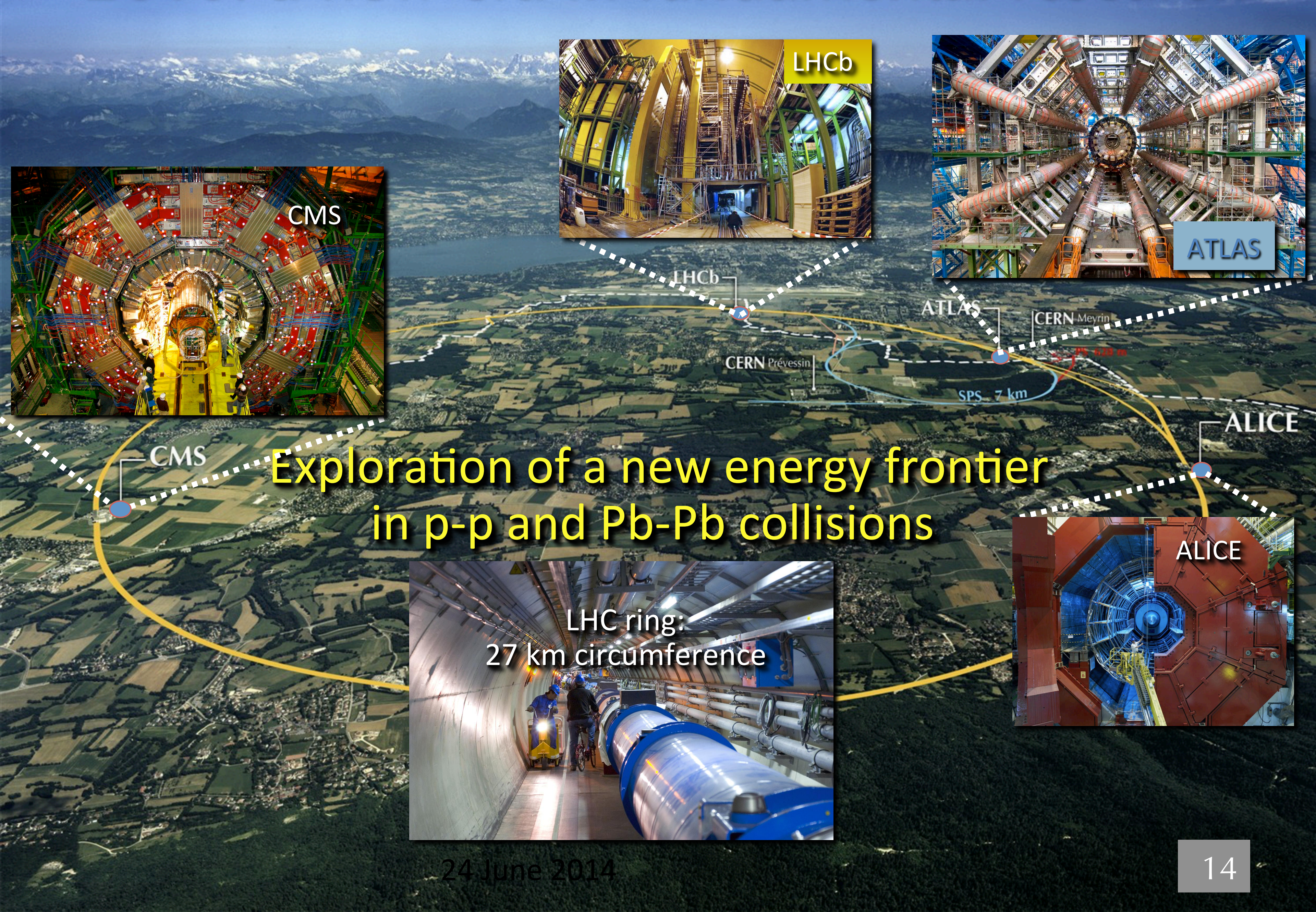
$E = mc^2$

Energy ⇔ Mass

(mass = matter)

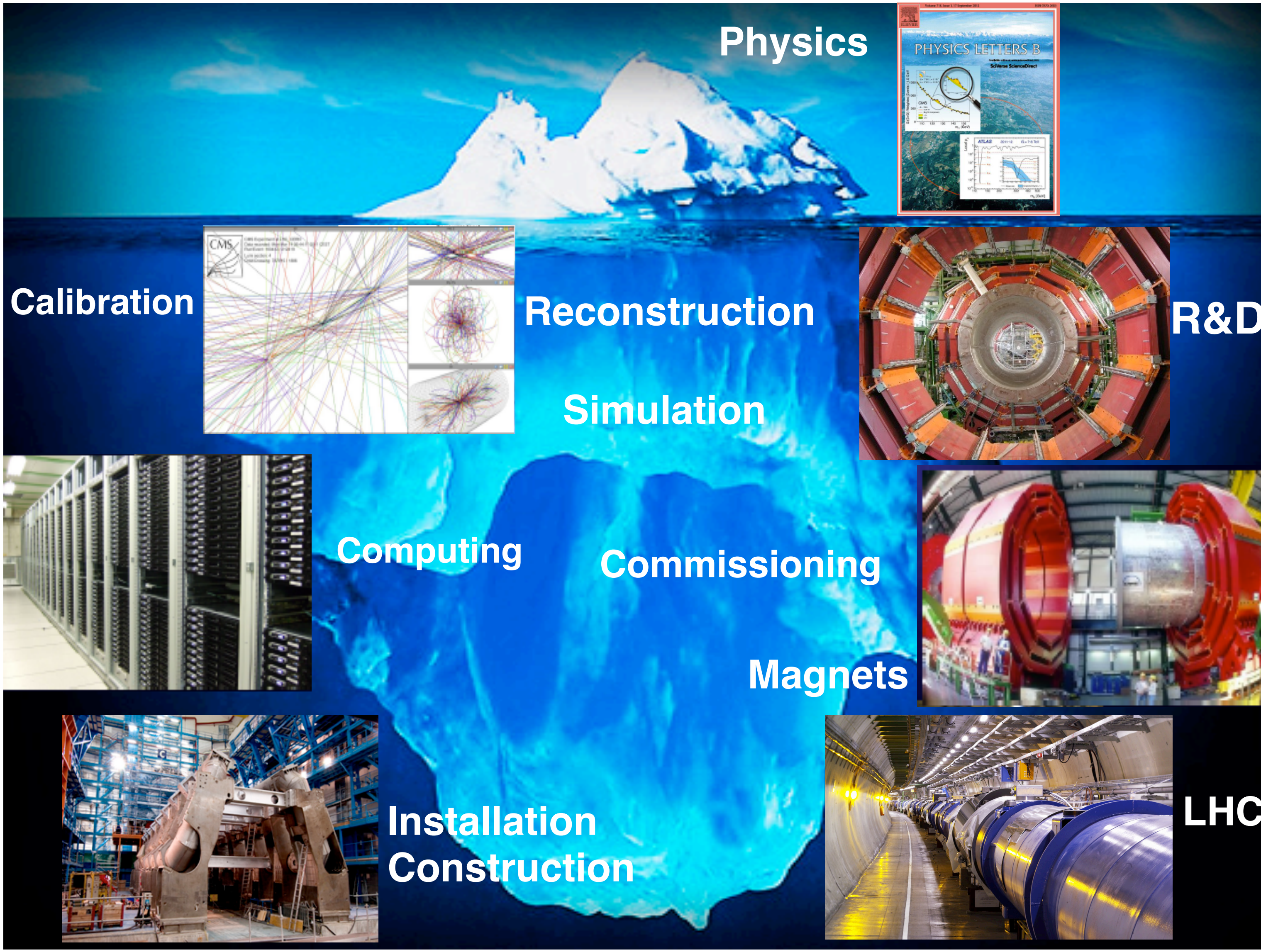


2010: a new era in fundamental research



Exploration of a new energy frontier
in p-p and Pb-Pb collisions

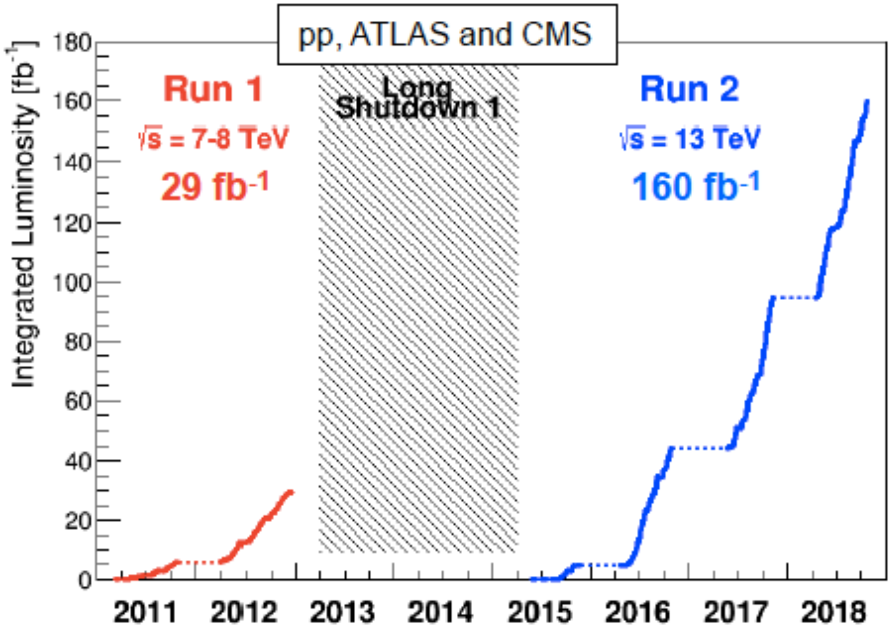
Where did P2I labs contribute?

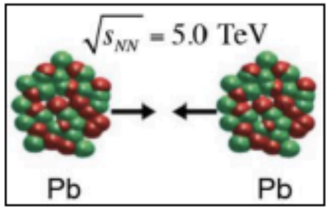


The Context of LHC in P2I

- **Early and strong support to LHC in the P2I labs** (since Lausanne workshop 1984)
- **Contributions to the conception, design and technological choices of LHC experiments**
- **Continuous efforts, strong involvement and extreme dedication by the teams in**:
  - 20 years of detector and physics simulations *(historical contributions to the Higgs studies)*
  - 15 years of detector construction and test beams
  - 8 years of world-wide computing data challenges
  - 3 years of detectors commissioning
  - 9 years of data taking with wealth of physics results
- **Participation to the physics and detector coordination of the experiments**: data preparation, computing , performance convenors, physics convenors, analysis review chairs, publications committee,…
- Many physicists, engineers and technicians from P2I labs are involved in the LHC program. Many PhD thesis/year

LHC data





Total integrated luminosity Run 2 $\sqrt{s_{NN}}$ ~ 5 TeV:

ALICE: ~ 1.3 nb^{-1}

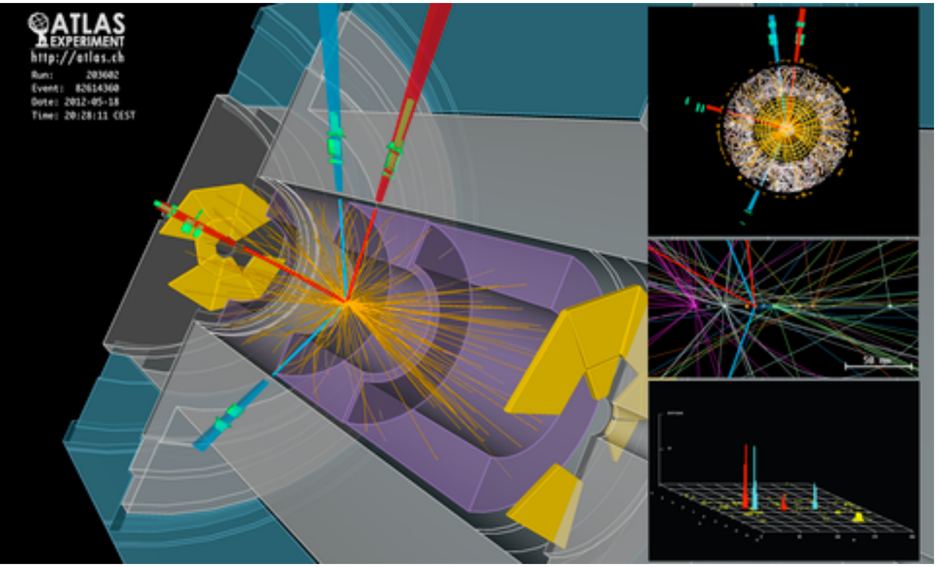
ATLAS, CMS: ~ 2.4 nb^{-1}

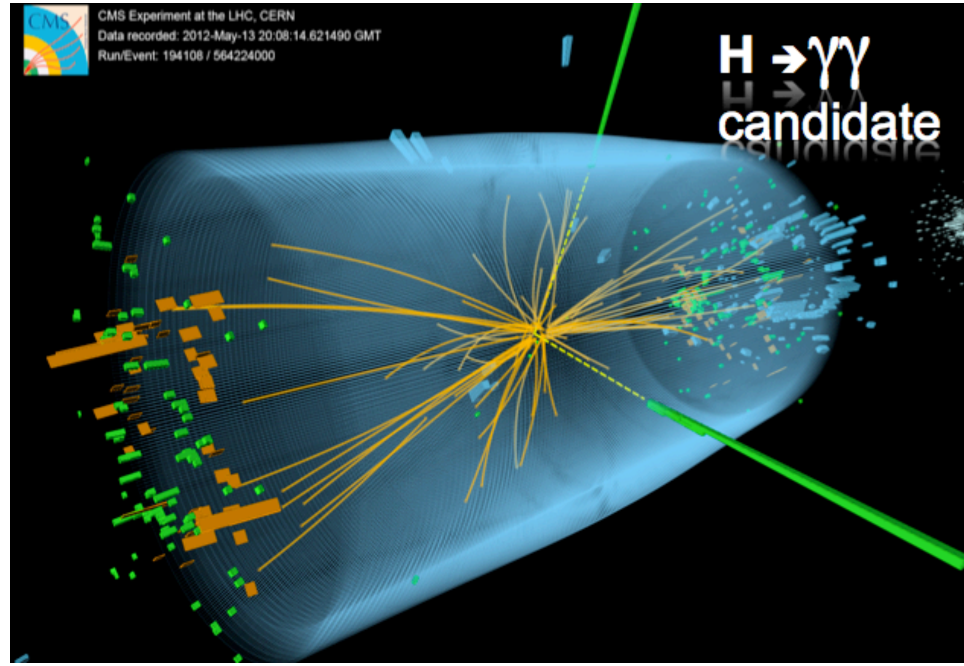
Goal for Run 2 was ~1 nb^{-1}

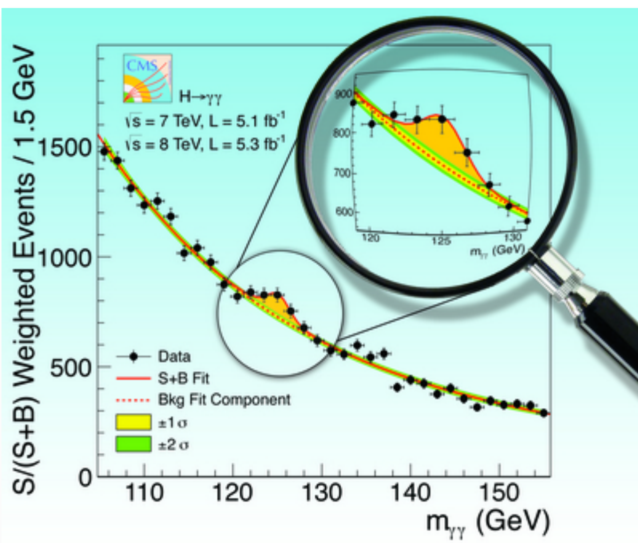
Run 1 + Run 2: ATLAS, CMS: ~**189** fb^{-1} (goal was 150); LHCb: ~**10** fb^{-1}

Luminosity = # events/cross section/time

Observation of New Boson (Higgs) at CERN



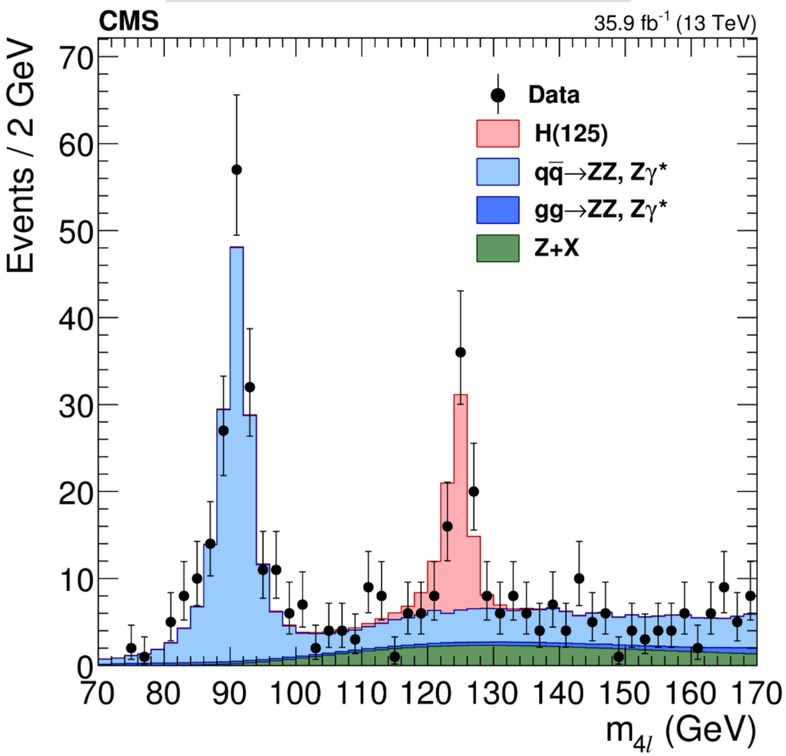




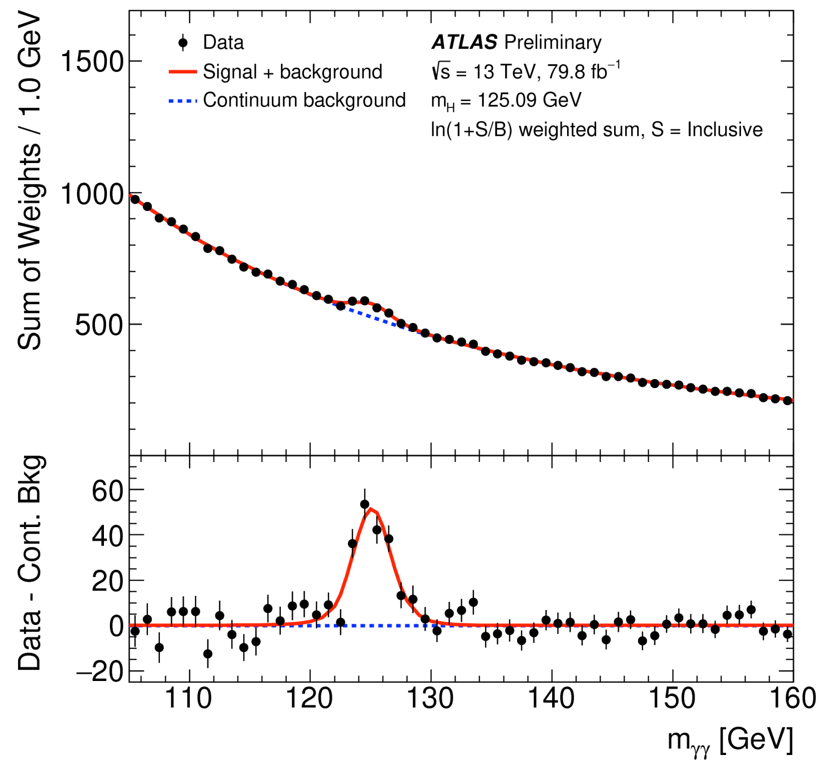
Peak ("resonance") at mass$_{\gamma\gamma}$ around 125 GeV (~130 x proton mass) indicates the production of a **new particle**

Higgs re-discovery@13 TeV

H→ ZZ→4leptons

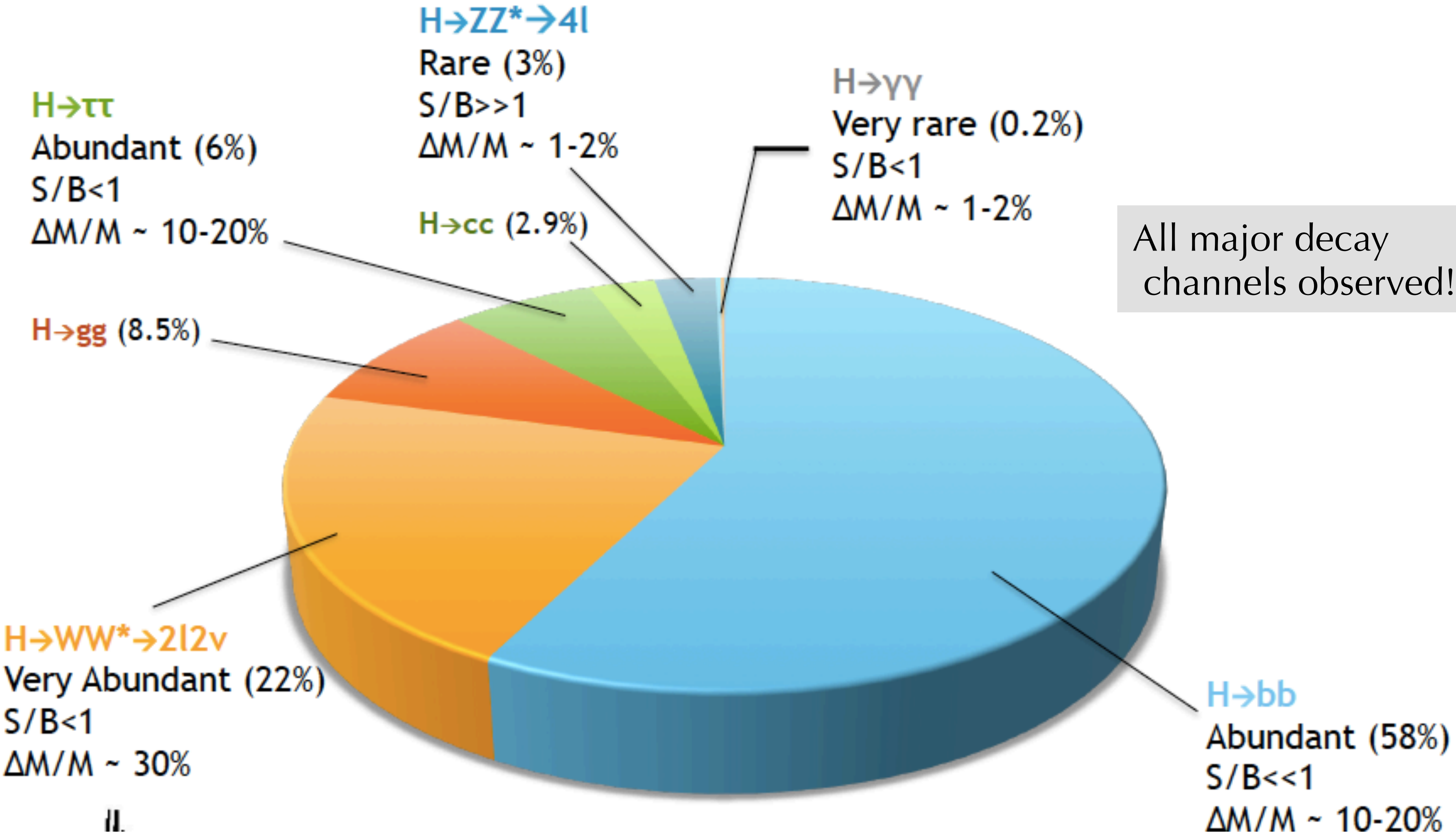


H→ γγ



- Excellent detector resolution.
- Strong contributions of LAL and IRFU teams in detector calibration and data analyses.

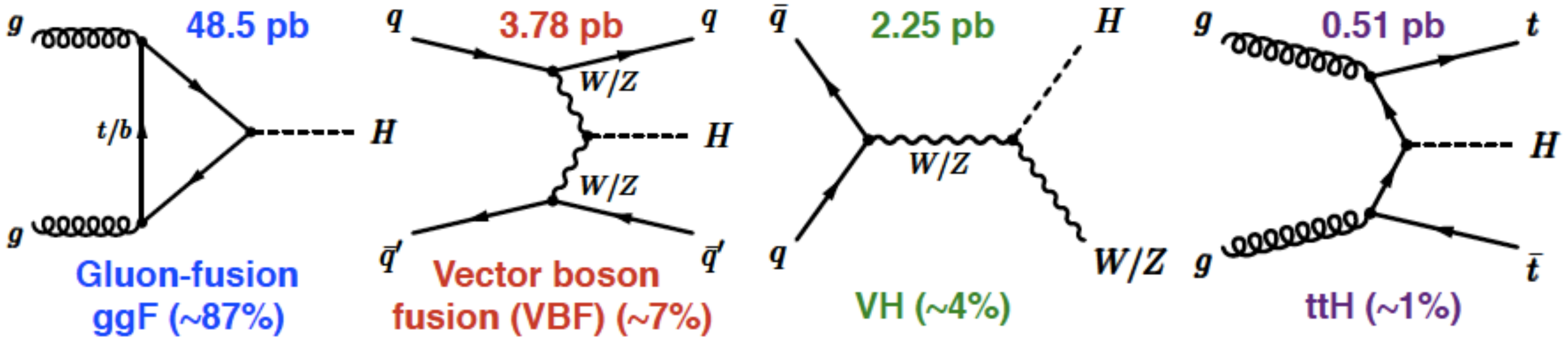
Higgs Decay



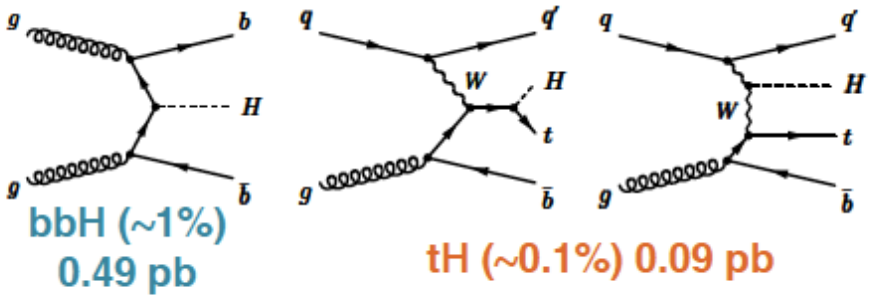
All major decay channels observed!

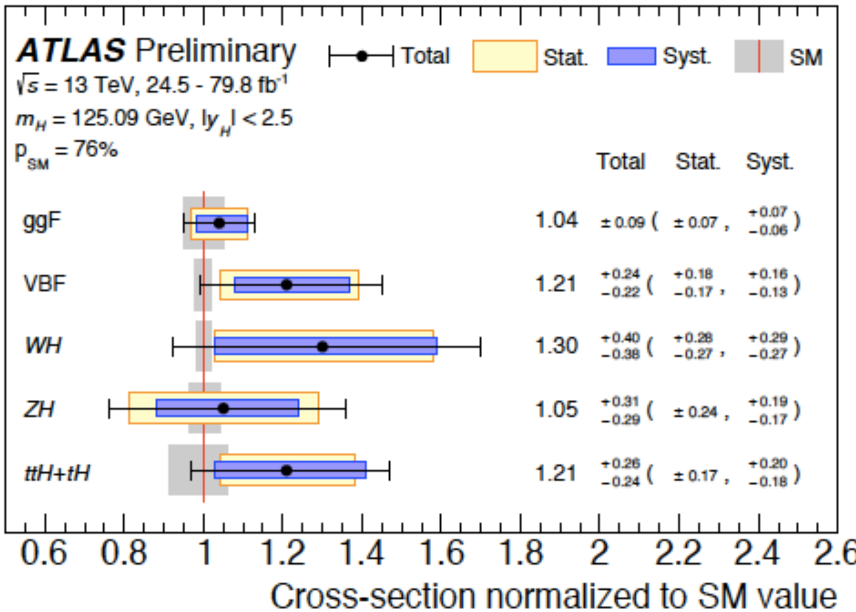
Higgs Production

Main



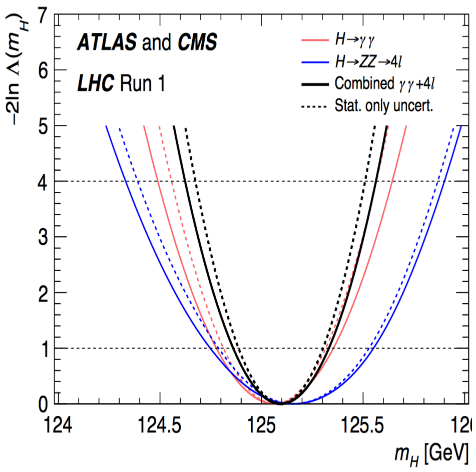
Rare

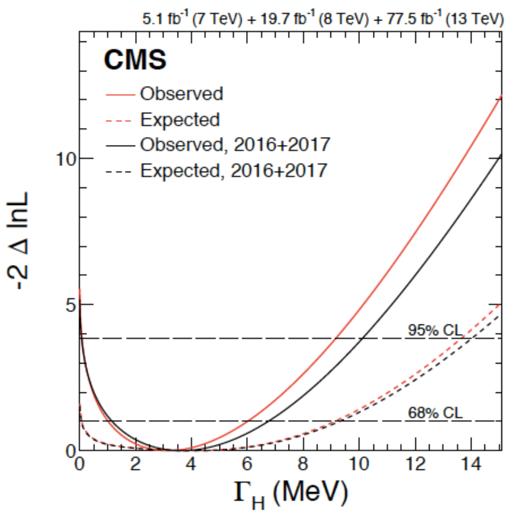


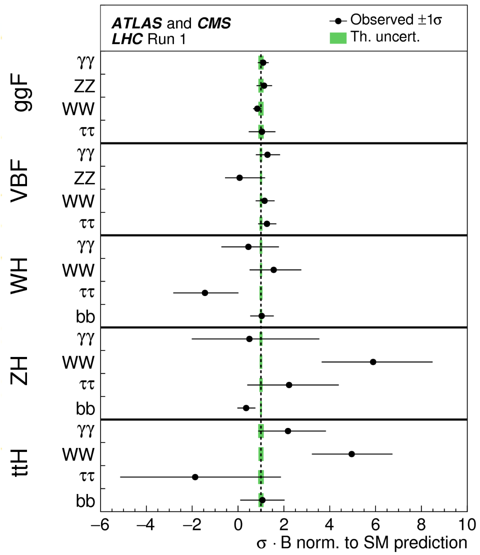


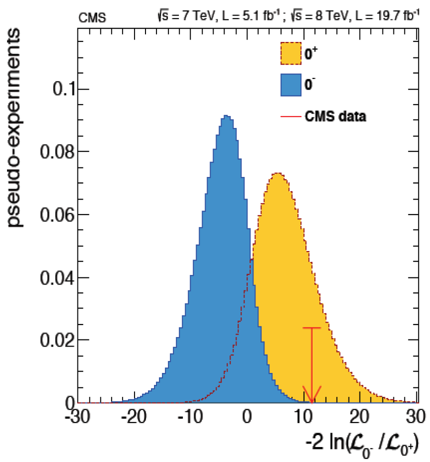
- **All major production modes observed!**
- ggF cross-section now measured with precision of 9%, close to 5% uncertainty on the N^3LO cross section prediction

Higgs : what did we learn ?









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

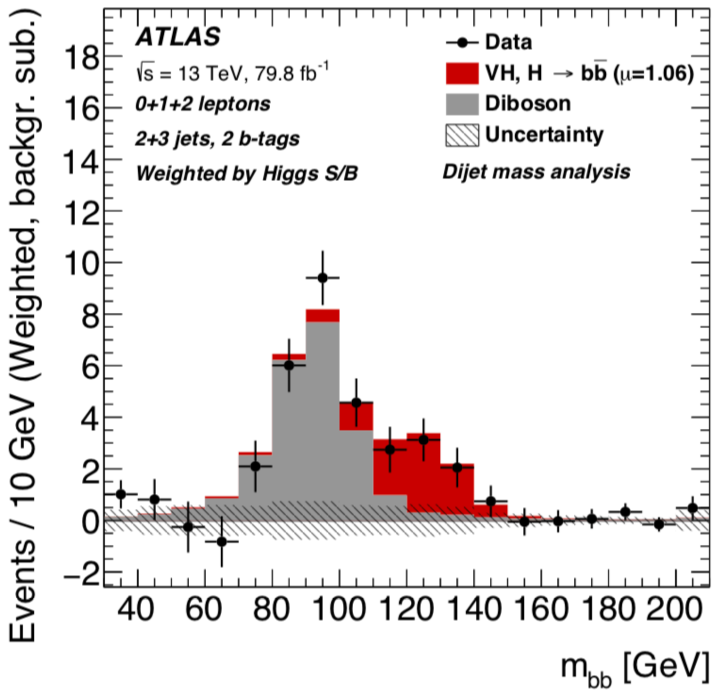
Width
< 9.16 MeV
(95%CL)

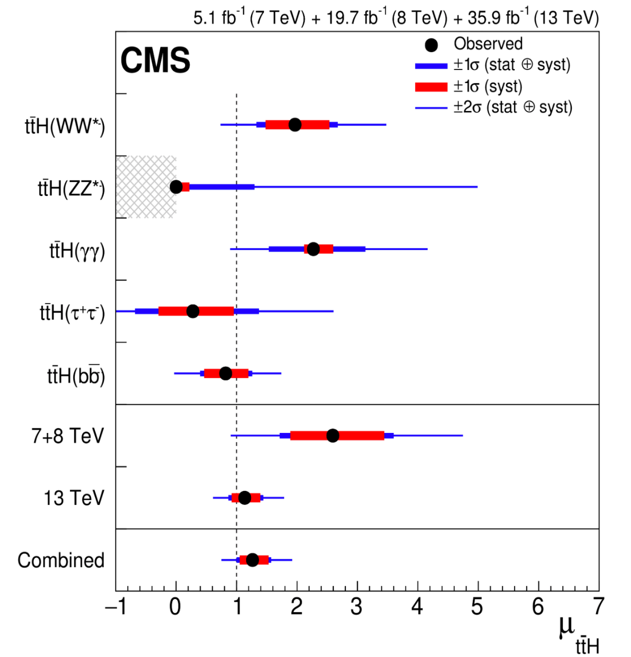
Couplings are within ~20% of the SM values

Spin $J^{CP}=0^{++}$ preferred over 0^-,1,2

- The newly found boson has properties as expected for a Standard Model Higgs
- We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses, charged Higgses…

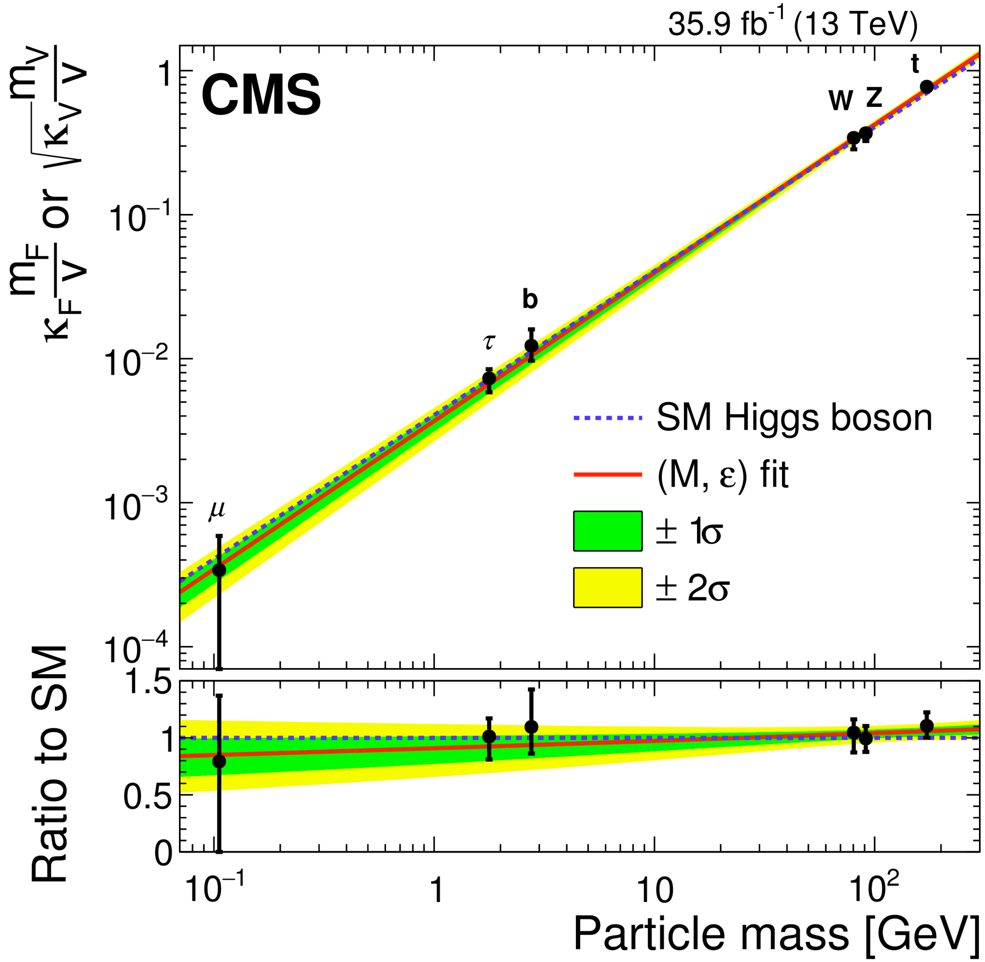
Higgs Results @ 13 TeV





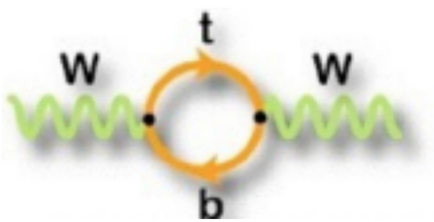
- **H→bb observed** with more than 5σ in both experiments
- **Observation of ttH production**: combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1 → 6.3σ significance

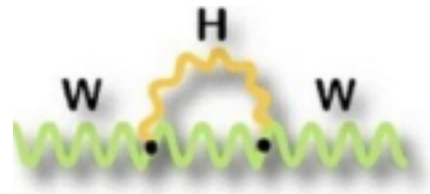
Higgs : Coupling vs Particle mass



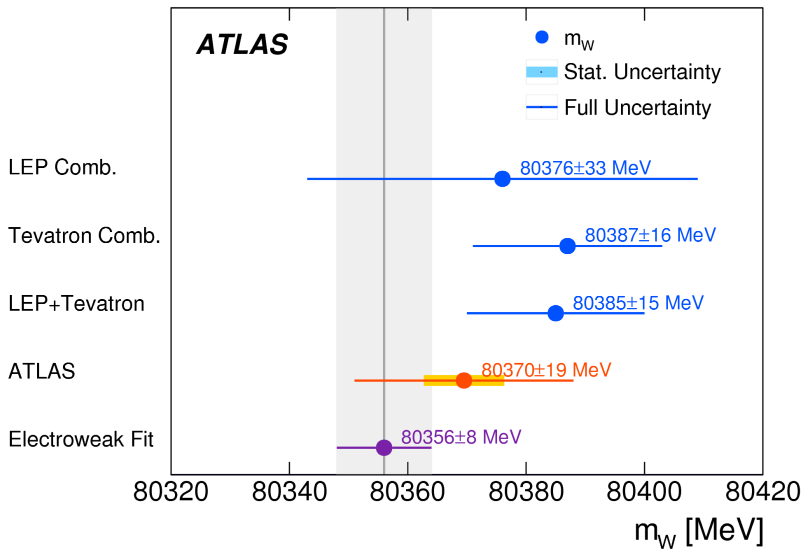
- Observation of good agreement with the Standard Model within uncertainties across 3 orders of magnitude in particle mass.

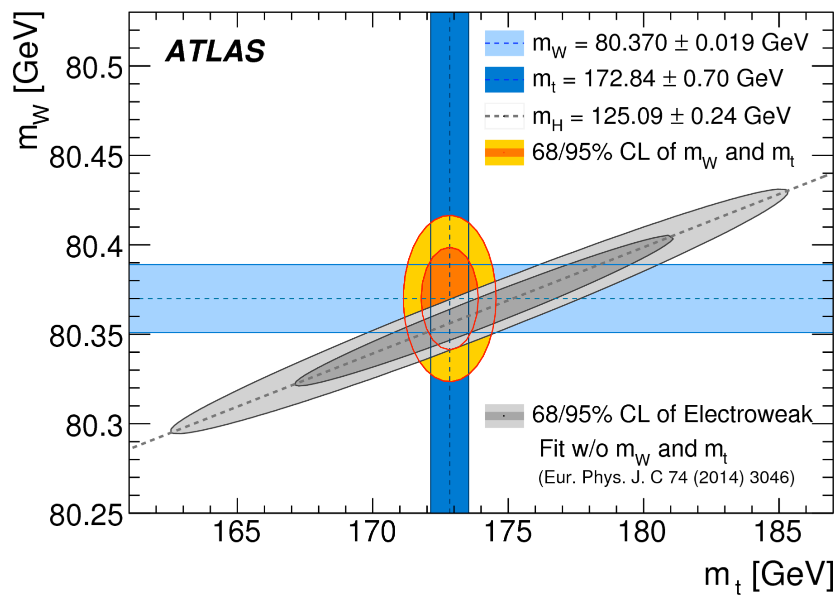
Precision Measurements : W mass





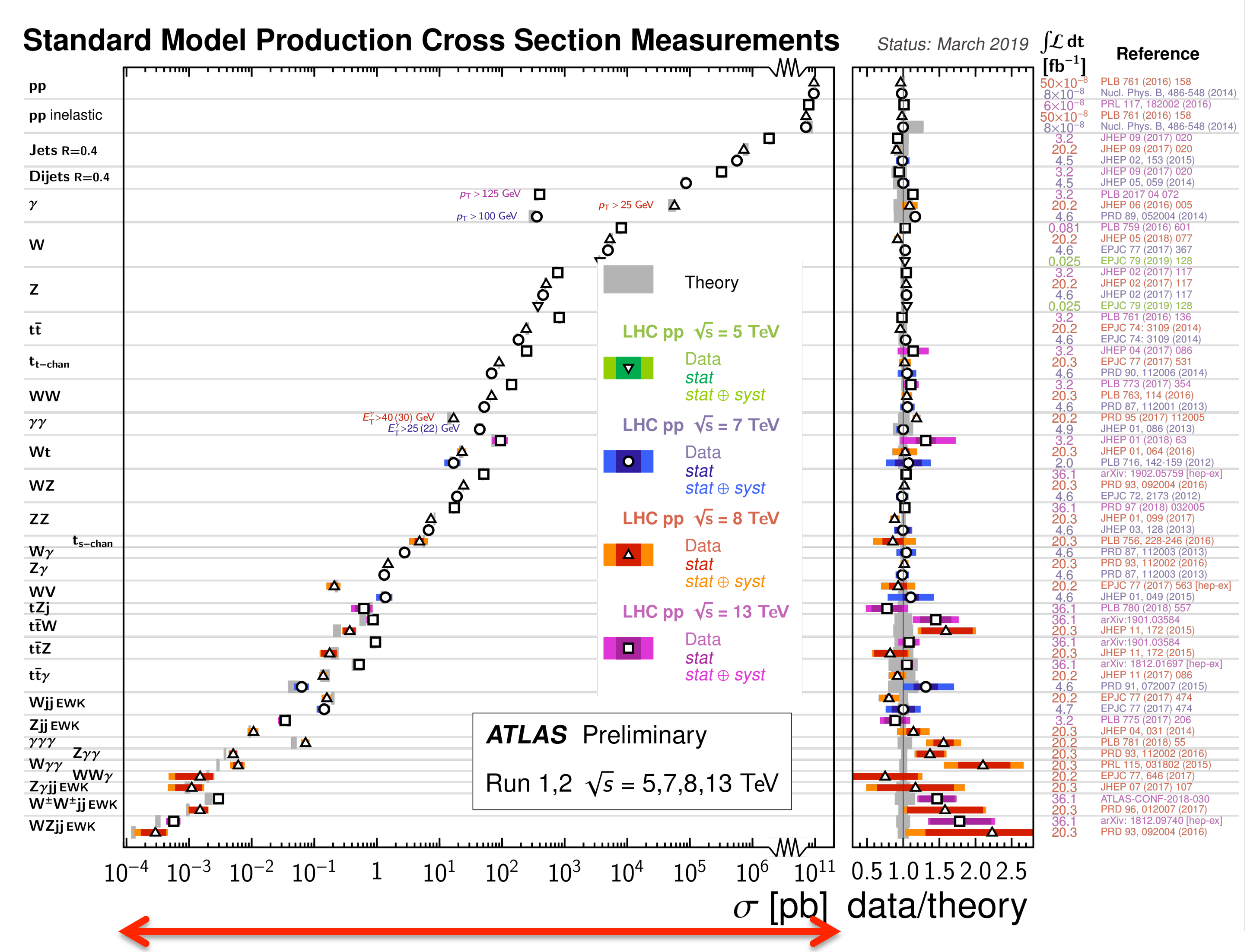
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r),$$





- The relation between W, top, and Higgs masses provides stringent test of the Standard Model consistency and is sensitive to new Physics.
- The result is consistent with the SM expectation.
- The measurement required an accurate calibration of the detector response.

Standard Model Measurements

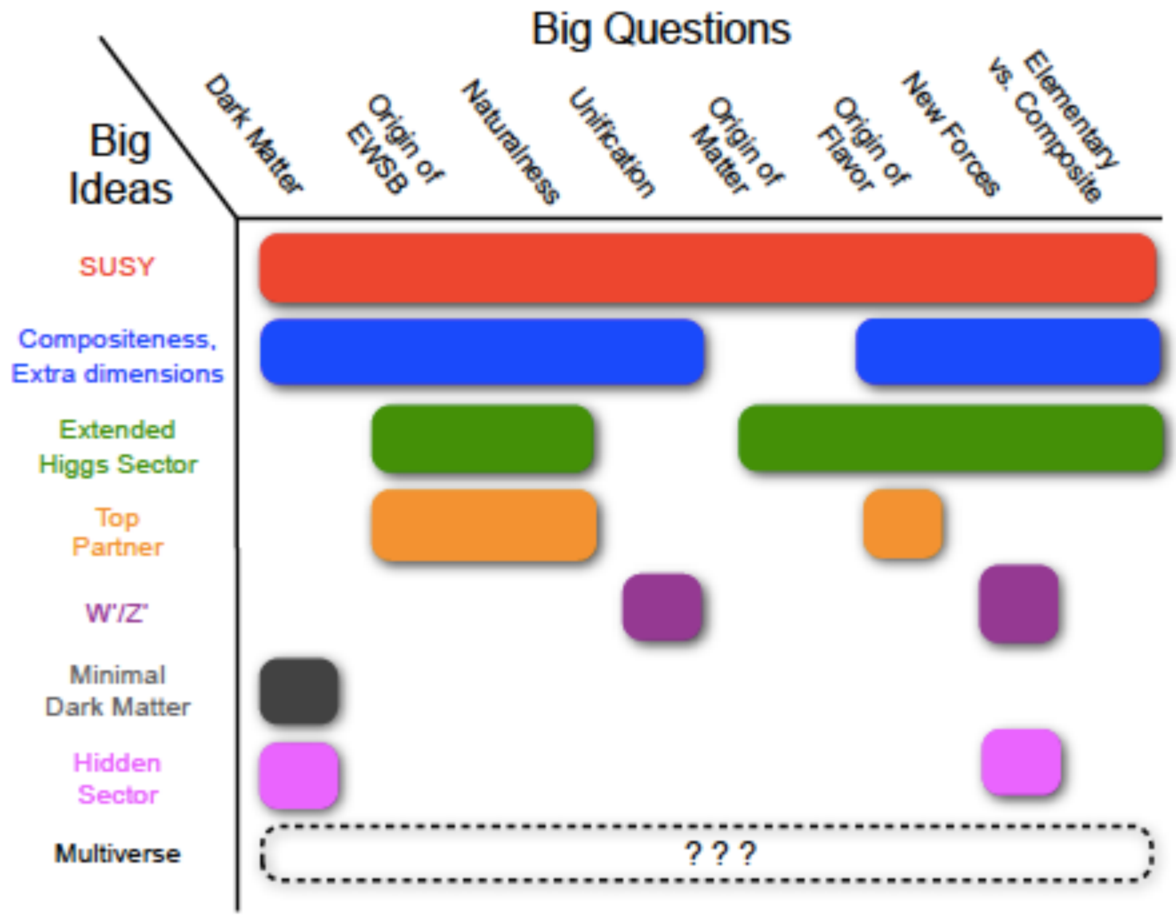


15 orders of magnitude

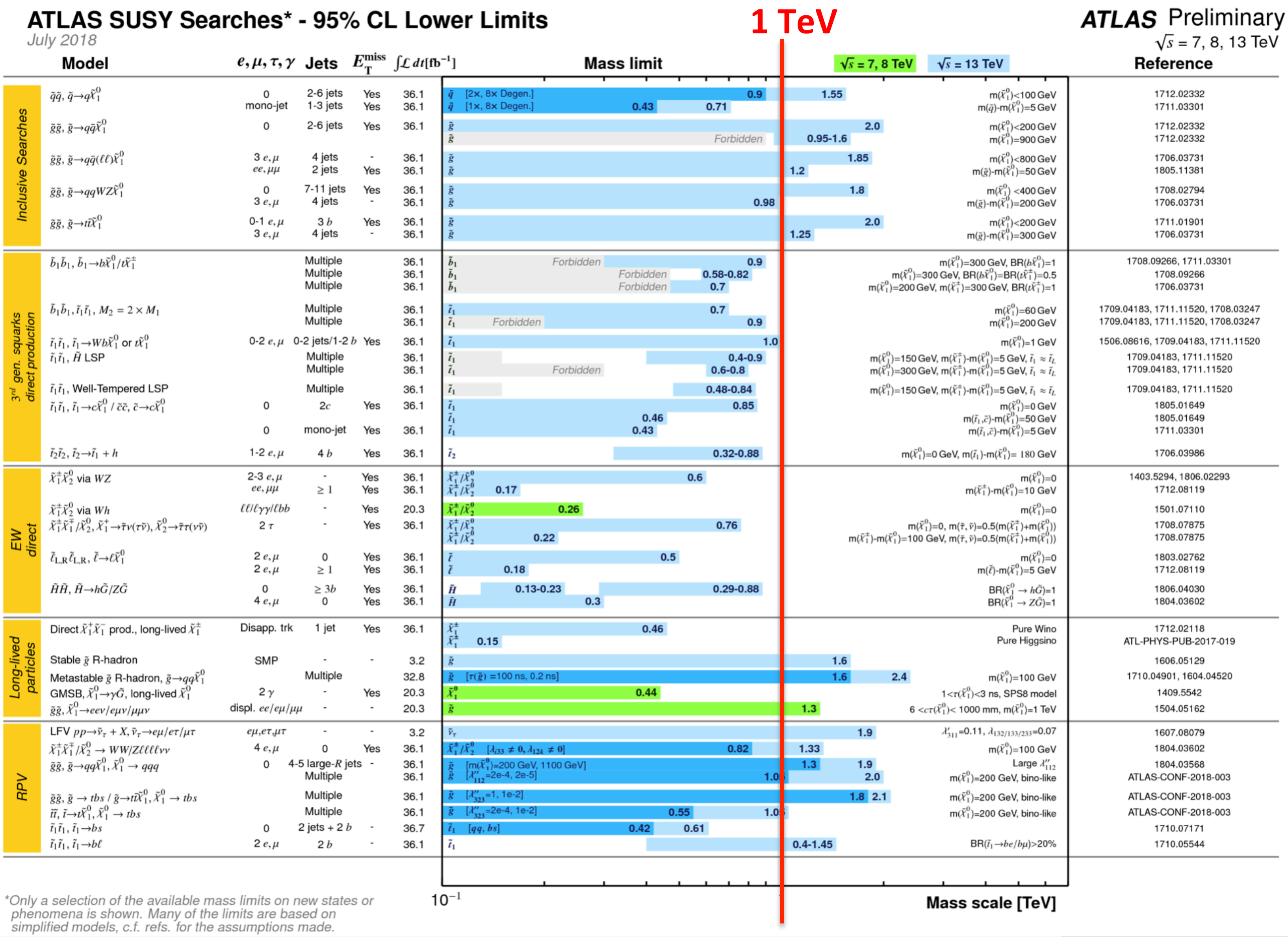
- Agreement with theory across orders of magnitude is impressive.

Exploring the unknown

arXiv:1311.0299v1



SUSY searches: NULL so far…

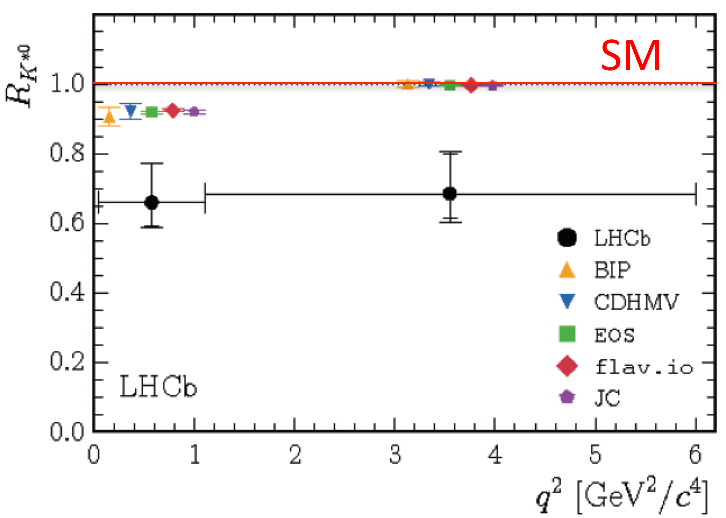


Tests of Lepton Universality

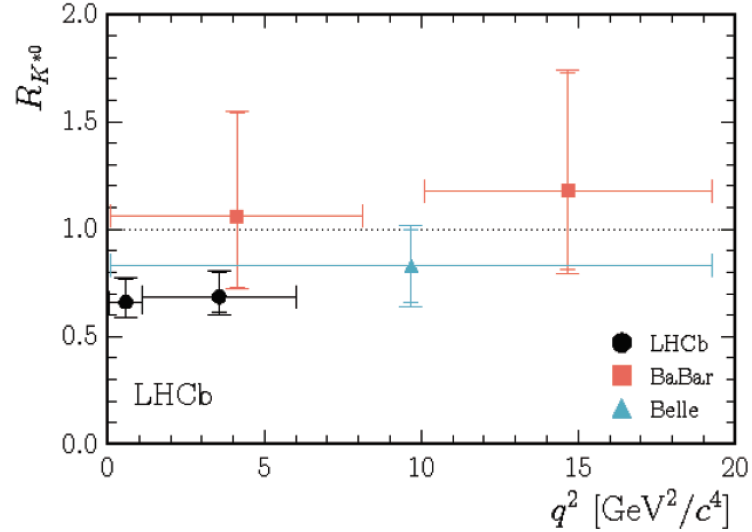
- **Test of the universality of leptonic couplings (e/μ)** by comparing the rates of $B^0 \to K^* \ell^+\ell^-$ (R_{K^*})

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1.0$$

Comparison with SM predictions



Comparison with BaBar & Belle



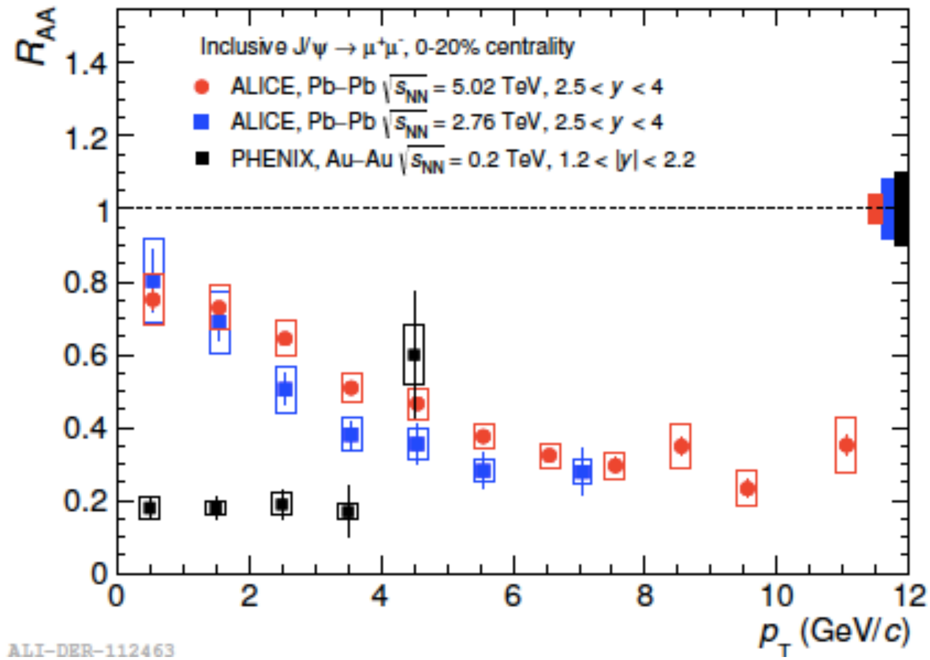
$$R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03 \text{ for } 0.045 < q^2 < 1.1\ \text{GeV}^2,\ \sim 2.2\,\sigma \text{ from SM};$$
$$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05 \text{ for } 1.1 < q^2 < 6.0\ \text{GeV}^2,\ \sim 2.4\,\sigma \text{ from SM};$$

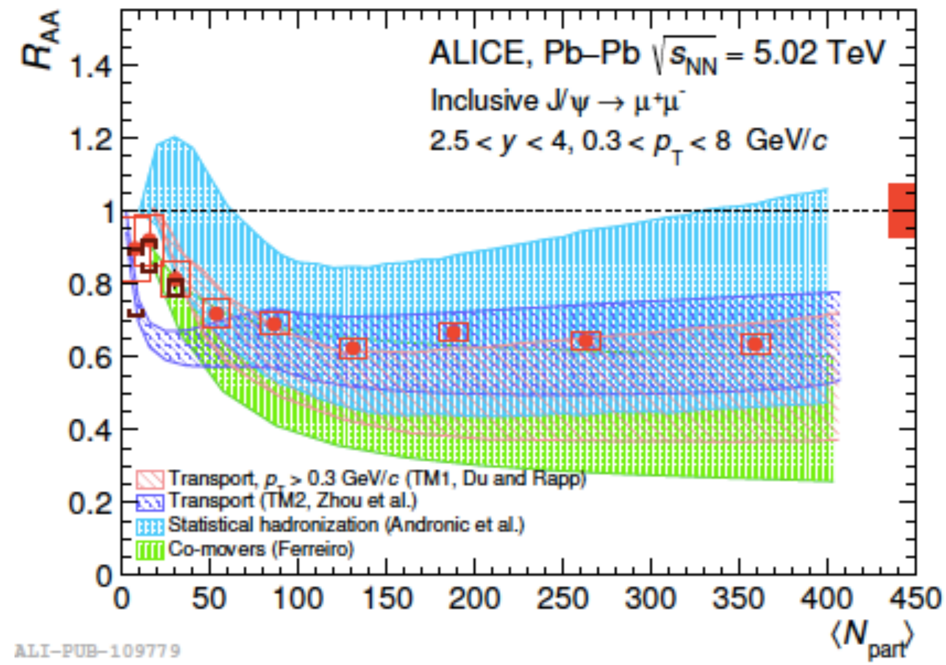
??

- Puzzling results from the LHCb experiment → Update eagerly awaited !!

Quarkonia : Nuclear modification factor R_{AA}

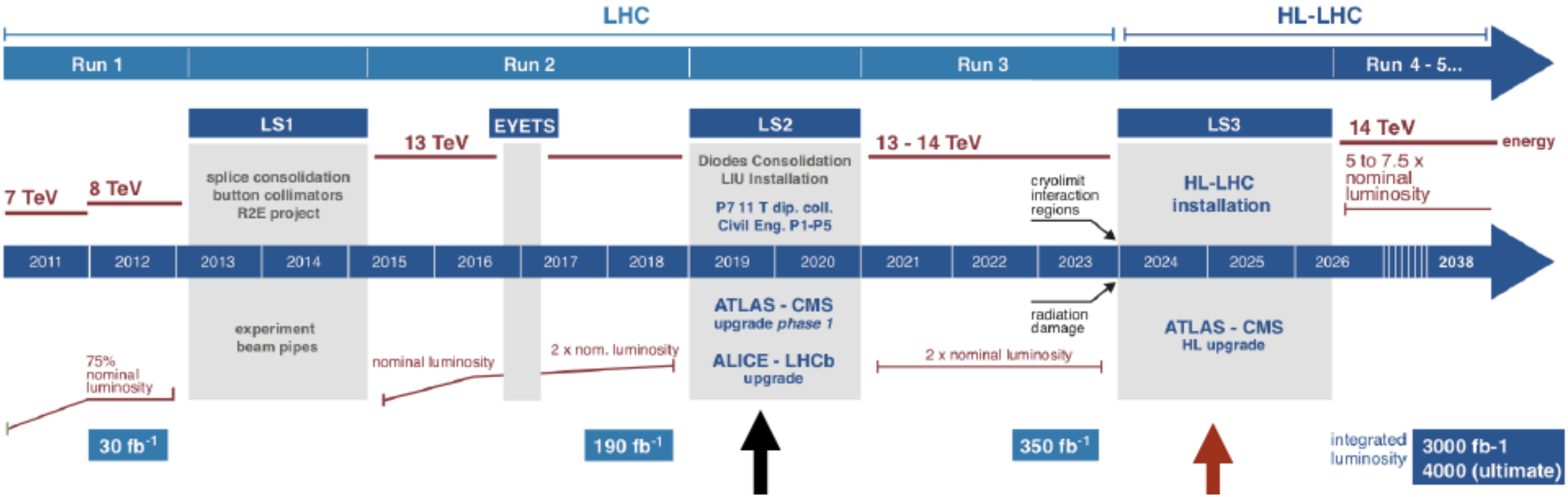
Inclusive J/ψ at low p_T





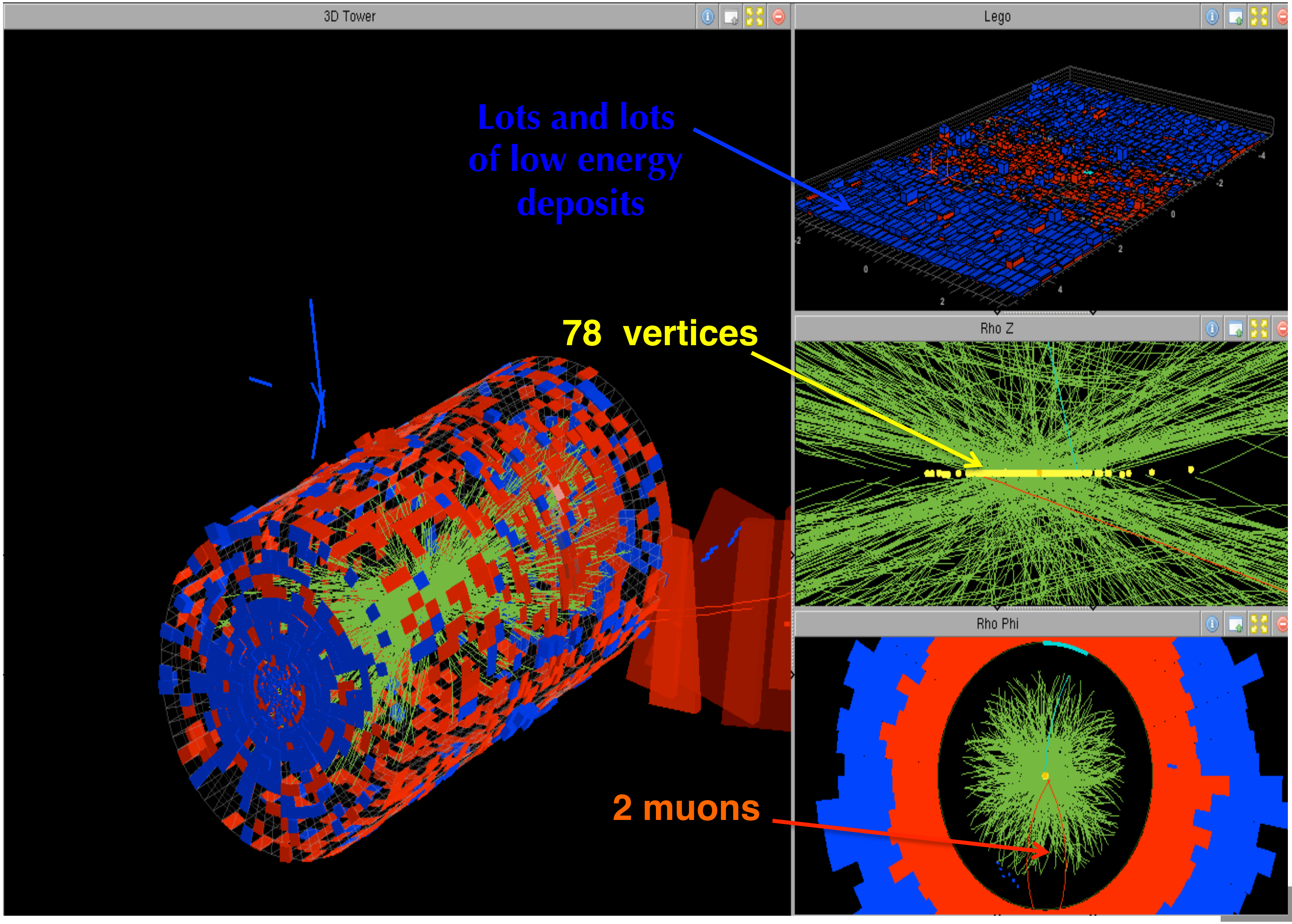
- **Nuclear modification factor R_{AA}** compares Pb-Pb to p-p : 1 means no medium effect
- Less suppression observed at LHC compared to RICH
- Charm regeneration observed at LHC: mainly at low p_T.

LHC Roadmap to achieve Full Potential



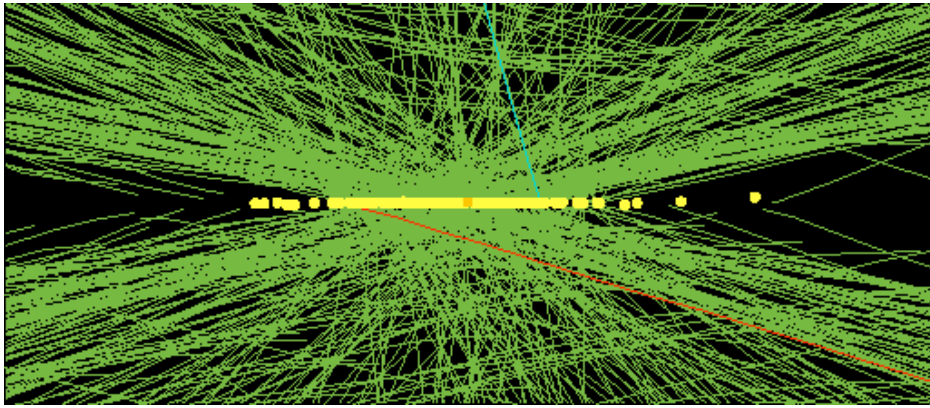
- All LHC experiments plan upgrades for either 2019-2020 or 2024-2026 for the High Luminosity LHC upgrade (ATLAS, CMS and LHCb, ALICE)
- Approved LHC program to collect 3000 fb^{-1} in total with the LHC (HL-LHC)
  - Maximize the reach for searches and for precision measurements (eg Higgs)
- LHC will run till ~2037
  - Only ~5% of the collisions delivered so far…
- Then …?

Detector upgrades



Detector upgrades

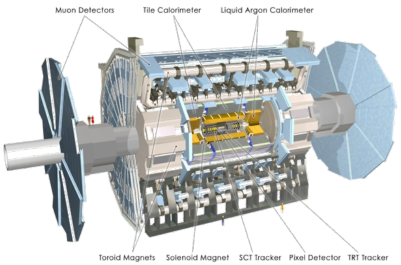
- Detector upgrades are planned so as to maintain or improve on the present performance as the instantaneous luminosity increases
  - **Improve trigger capabilities**
    - better discriminate the desired signal events from background as early as possible in trigger decision
  - **Upgrade and/or replace detectors as they e.g.**
    - Cannot handle higher rate due to bandwidth limitations
    - Suffer from radiation damage making them less efficient



CMS event with 78 interactions per bunch crossing

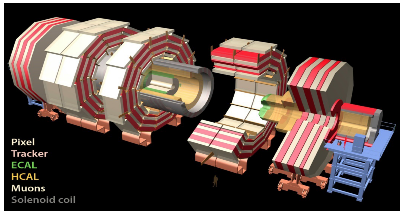
Detector upgrades

ATLAS



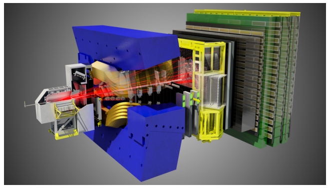
1. Granularity in the trigger scheme of the LArg calorimeter (Run 3)
2. New Small Wheel (Run 3)
3. Granularity in tracking (ITK HL-LHC, Run 4)
4. New Electronics for LArg (HL-LHC, Run 4)
5. Timing (HGTD HL-LHC, Run 4)

CMS



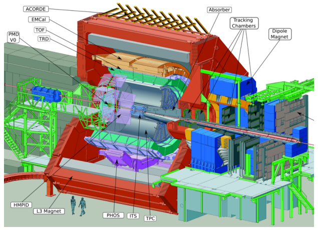
1. ECAL Barrel electronics (Run 4)
2. ECAL Barrel Laser Monitoring (Run 4)
3. Endcap Calorimeter electronics (Run 4)
4. Mip timing detector(Run 4)

LHCb



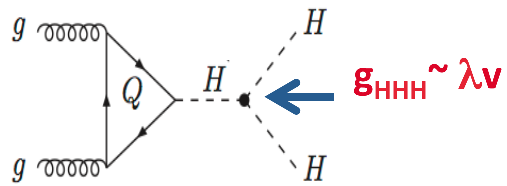
1. 40 MHz readout of the full detector (Run 3)
2. Full reconstruction at the trigger level (Run 3)
3. New ECAL (granularity and timing, Run 4)

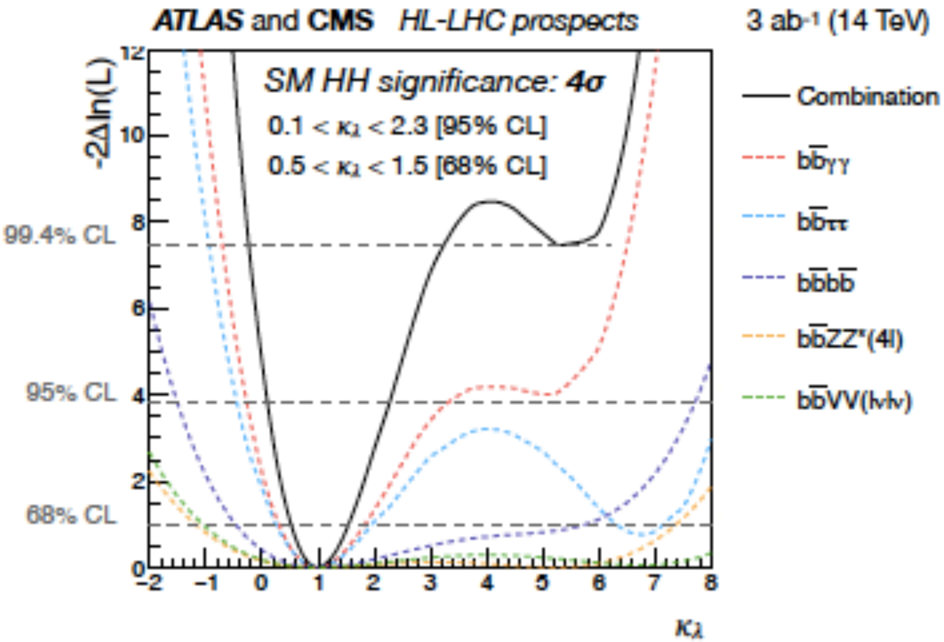
ALICE

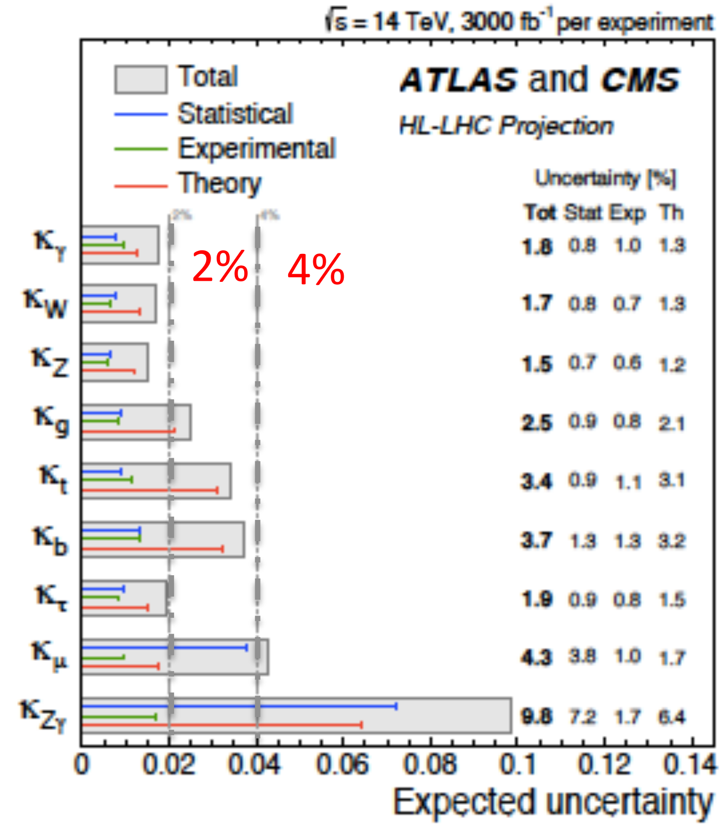


1. New readout electronic for the Muon Tracker (Run 3)
2. Muon Forward Tracker (Run 3/4)

Physics cases at HL-LHC





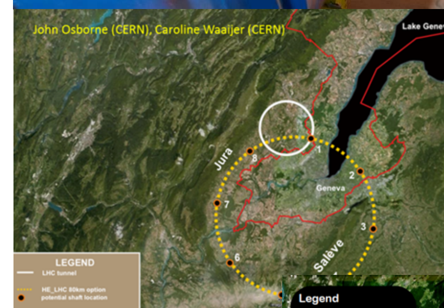


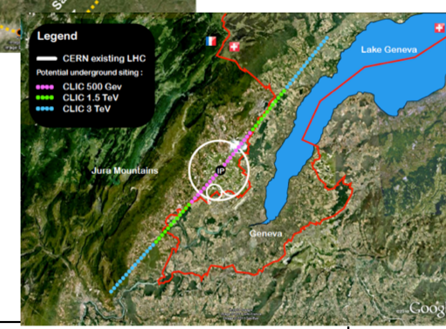
- Evidence for di-Higgs production, 50% precision on self-coupling.
- Few % precision on Higgs boson couplings.
- Establish H→μμ observation.
- Increased discovery potential for many models.

European Strategy for Particle Physics

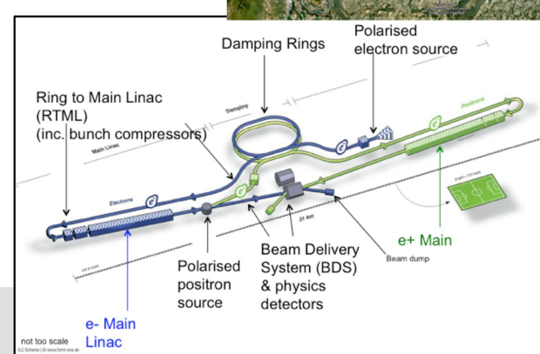
Conclusion in 2012

- Highest priority is exploitation of the LHC including luminosity upgrades
- Europe should be able to propose an ambitious project after the LHC
  - Either high energy proton collider (**FCC-hh**) with lepton collider (**FCC-ee**) as potential intermediate step
  - Or high energy linear lepton collider (**CLIC**)
- Europe welcomes Japan to make a proposal to host **ILC**





New process from 2019-2020



Considered High Energy Frontier Collider

Circular colliders:

- FCC (Future Circular Collider)
  - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
  - FCC-ee: Potential intermediate step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
  - HE-LHC: Stronger magnets in LHC tunnel
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 90 - 240 GeV cms
  - SppC : pp 70 TeV cms

Great technological challenges for accelerators and detectors P2I labs deeply involved

Linear colliders

- ILC (International Linear Collider): e^+e^- 500 GeV cms energy, Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^- 380 GeV - 3 TeV cms energy, CERN hosts collaboration

Mentioned

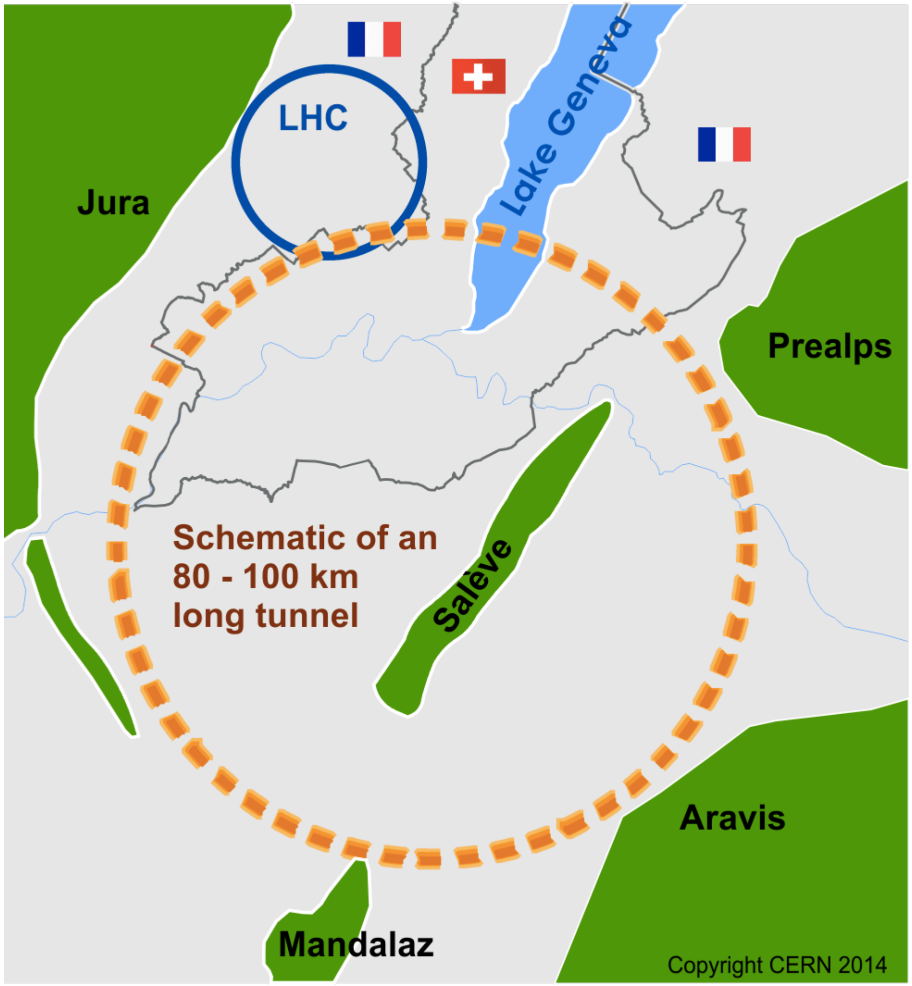
- Muon collider
- Plasma acceleration in linear collider
- Photon-photon collider
- LHeC

Future Circular Colliders (FCC)

International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements

    16 T →100 TeV pp in 100 km
  - ~100 km tunnel infrastructure in Geneva area, site specific
- **e+e- collider (FCC-ee)**, as potential first step
- **HE-LHC** with FCC-hh technology
- **p-e (FCC-he)** option



Precision on Higgs boson couplings

inspired from

FCC-ee TDR (2018)

arxiv:1710.07621v4 arXiv:1812.01644

		HL-LHC	ILC		CLIC	FCC-ee		CEPC
√s	(GeV)	14000	250	+500	380	90-240	+365	90-250
L	(ab⁻¹)	3	2	+4	0.5	5	+1.5	5
Years		13	15	+10	7	3	+6	7
ZZ	(%)	3.5	0.38	0.30	0.4	0.25	0.22	0.25
WW	(%)	3.5	1.8	0.4	0.8	1.3	0.46	1.2
ττ	(%)	6.5	1.9	0.8	2.7	1.4	0.8	1.4
tt	(%)	4.2	–	–	–	–	3.3(*)	–
bb	(%)	8.2	1.8	0.6	1.3	1.4	0.7	1.3
cc	(%)	–	2.4	1.2	4.1	1.8	1.2	1.8
gg	(%)	–	2.2	1.0	2.1	1.7	0.9	1.4
γγ	(%)	3.6	1.1(*)	1.0(*)	-	4.7	1.3(*)	4.7
Γ_H	(%)	50	3.9	1.7	4.7	2.8	1.5	2.6
exo	(%)	–	<1.6	<1.3	<0.7	<1.2	<1.0	<1.2

(*) incorporating HL-LHC results

(B. Lenzi)

Summary: Physics landscape by 2019

- **The Puzzle: The Standard Model is not the ultimate theory of particle physics, because of the many outstanding questions :**
  - **Nature of Dark Matter ? Matter versus antimatter ?...**
- **On the other hand, NO evidence of New Physics**
  - **If New Physics exists at the TeV scale and is discovered at 13 TeV centre-of-mass in the future, its spectrum should be quite heavy and it will require a lot of luminosity and energy to study it in detail.**
- **Future machine : decisions expected in the next years.**

"Prediction is very difficult, especially about the future"

Niels Bohr

Backup

How many Higgs bosons do we have?

Every fb^{-1} of pp collision at 13 TeV	$H\to\gamma\gamma$	$H\to ZZ$	$H\to WW$	$H\to\tau\tau$	$H\to bb$
Produced	130	1,500 (7)	12,000 (280)	3,500	32,000 (310)
Selected	46	1.5	42	17	66

Assuming **m_H = 125.09 GeV** from Run 1 ATLAS-CMS combined measurement

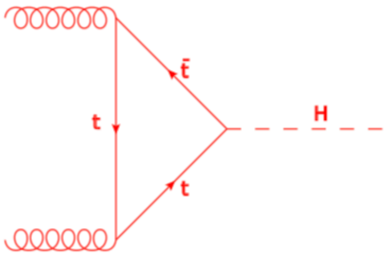
Number in brackets: for $H\to ZZ$ it indicates $H\to 4l$ (l=e, μ). For $H\to WW$ it is $H\to e\nu\mu\nu$. For $H\to bb$, it is VH where vector boson decays to electrons, muons, and/or neutrinos

- With every fb^{-1} of 13 TeV pp collision data, the SM predicts about **56,000** Higgs bosons produced
- Analyses discussed today will select about **170 in every fb^{-1}**
  - Large bkg. at LHC introduces difficulty in trigger and analyses: need to stick to relatively clean signatures (leptonic decay; associated production e.g. VH with $V\to$leptons; high-p_T phase-space regions)

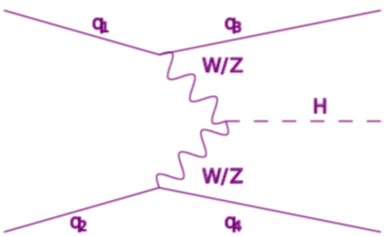
Higgs Production and Decay

Not observed in run-1

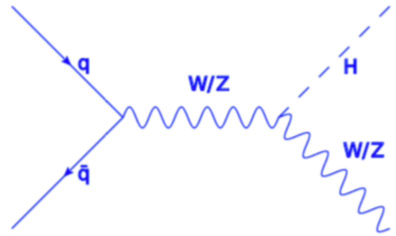
Higgs production mechanisms



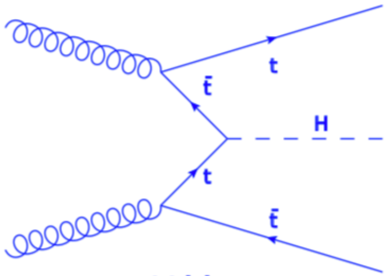
ggF
Run 1



VBF
Run 1 (ATLAS+CMS)
Run 2 (ATLAS alone)

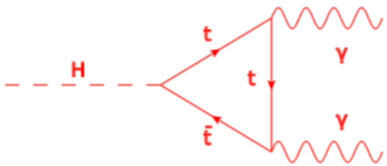


VH
2018

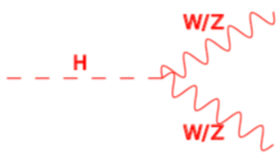


ttH
2018

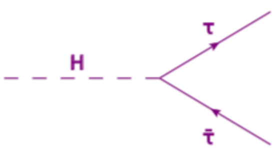
Higgs decay modes



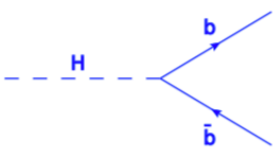
Hγγ
Run 1



HWW/HZZ
Run 1



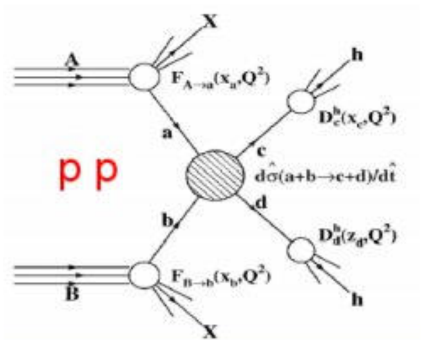
Hττ
Run 1 (ATLAS+CMS)
2018 (ATLAS alone)



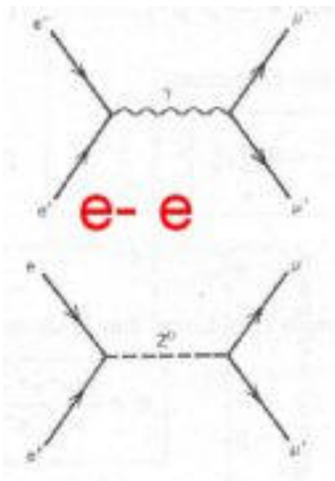
Hbb
2018

Collider Choices

- **Hadron collisions: compound particles**
  - Protons or ions
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
  - **Hadron collisions ⇒ large discovery range**



- **Lepton collisions: elementary particles**
  - Electrons, positrons and muons
  - Collision process known
  - Well defined energy
  - Less background
  - **Lepton collisions ⇒ precision measurements**



- Photons also possible

- Observation

- Observation