SEARCHES FOR DARK SECTOR STATES IN EXOTIC HIGGS BOSON DECAYS AT THE LHC

Dr. Kétévi Adiklè Assamagan

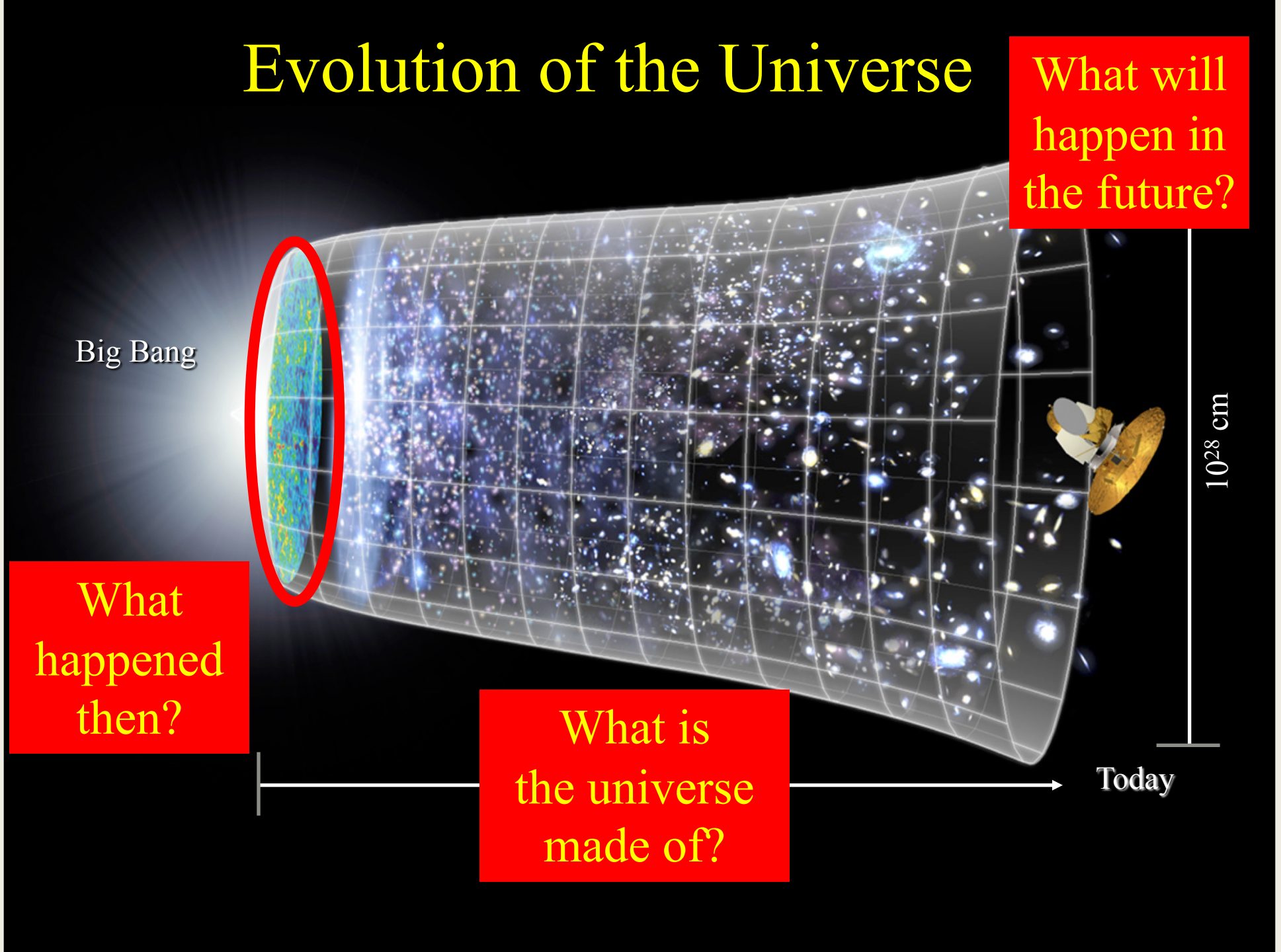
BROOKHAVEN NATIONAL LABORATORY



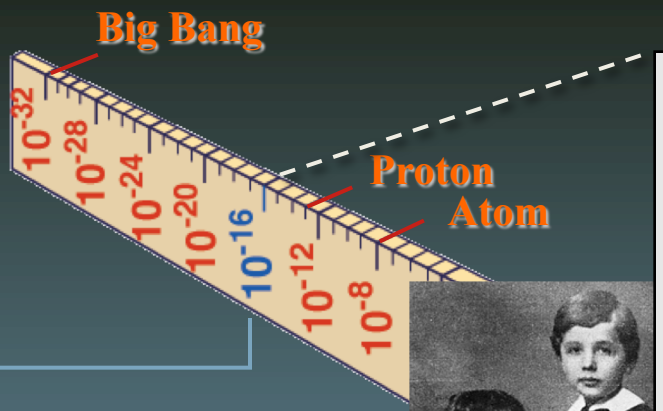
What we aim for …

- Review Higgs boson discovery channels
- Review Higgs boson property measurements
- Make the case for Dark Sector States an extension to the Standard Model
- Discuss selected searches for Dark Sector States

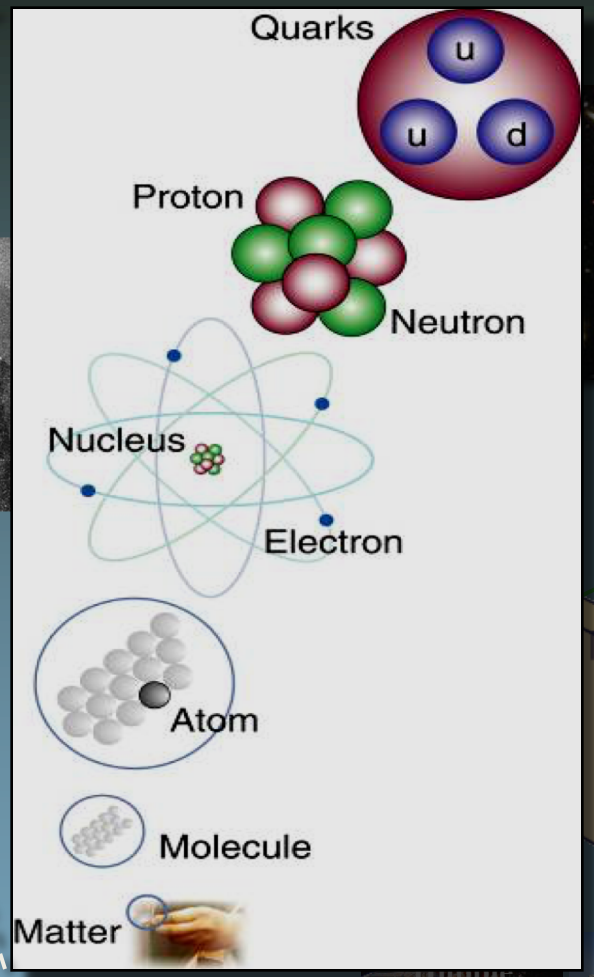
Evolution of the Universe



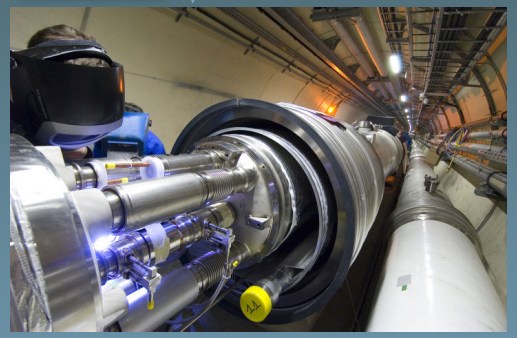
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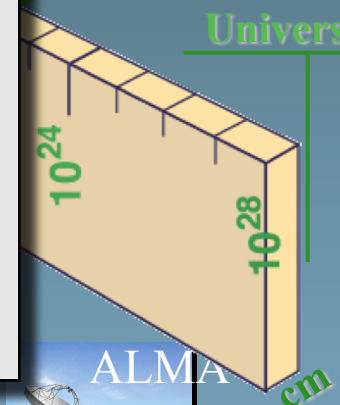


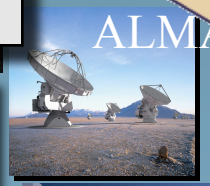


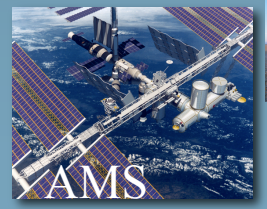


LHC

Super-Microscope









Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

300,000 years

Formation of atoms

3 minutes

Formation of nuclei

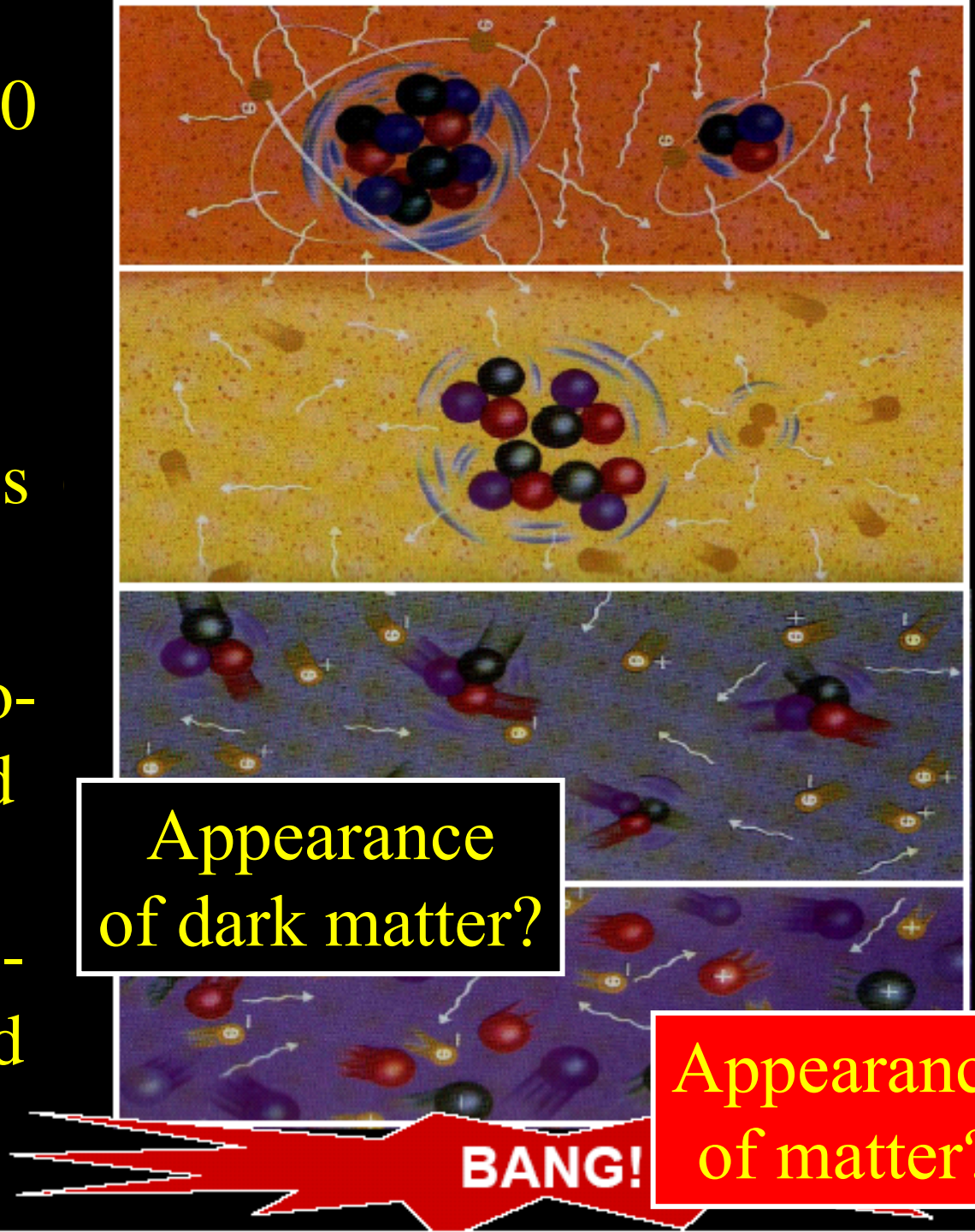
1 micro-second

Formation of protons & neutrons

Appearance of dark matter?

1 pico-second

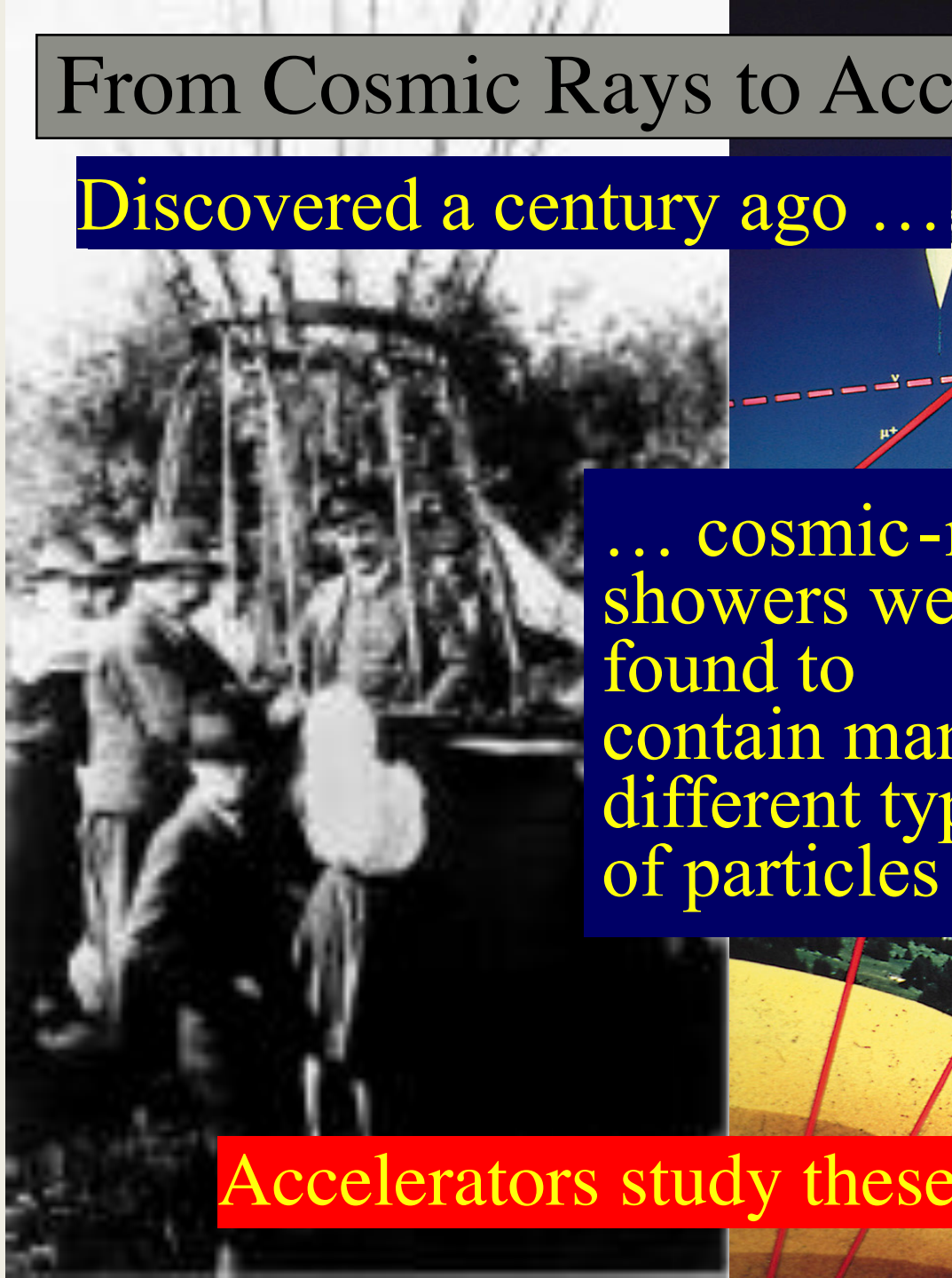
Appearance of mass?

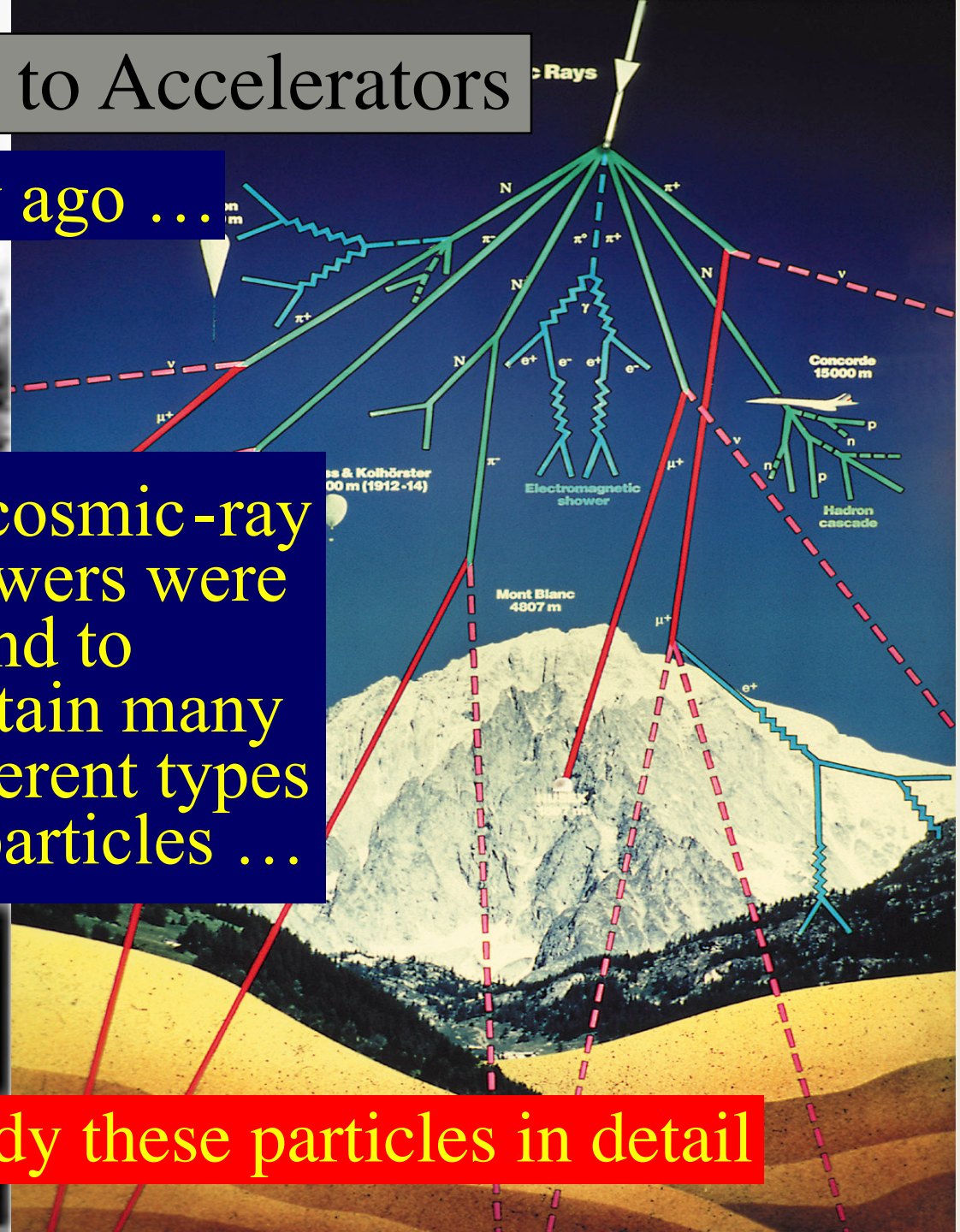


Appearance of matter?

From Cosmic Rays to Accelerators

Discovered a century ago …





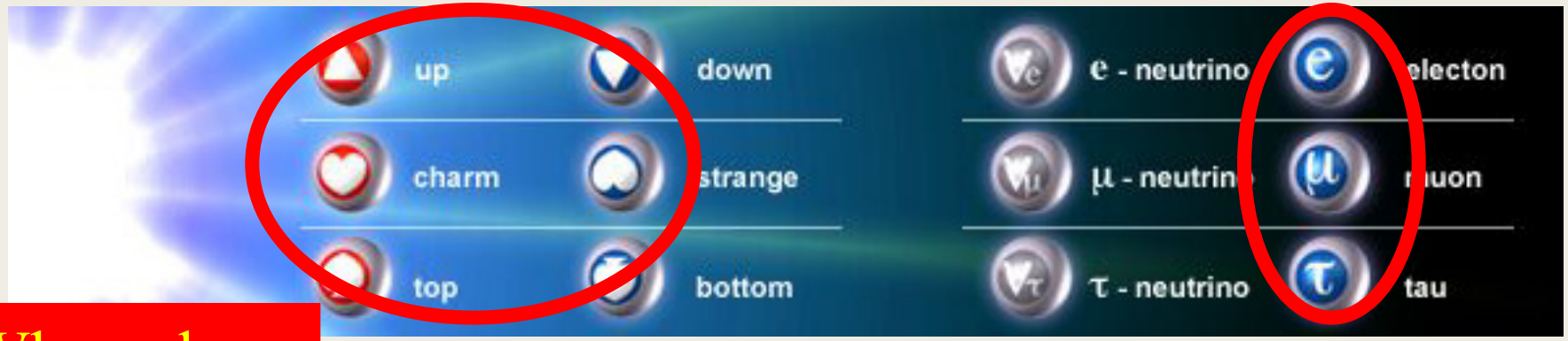
… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

The ‘Standard Model’

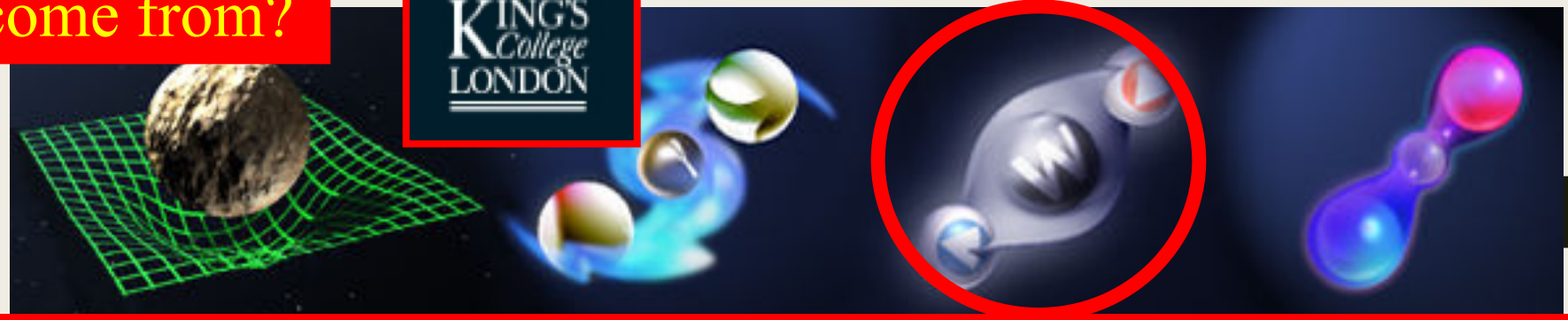
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

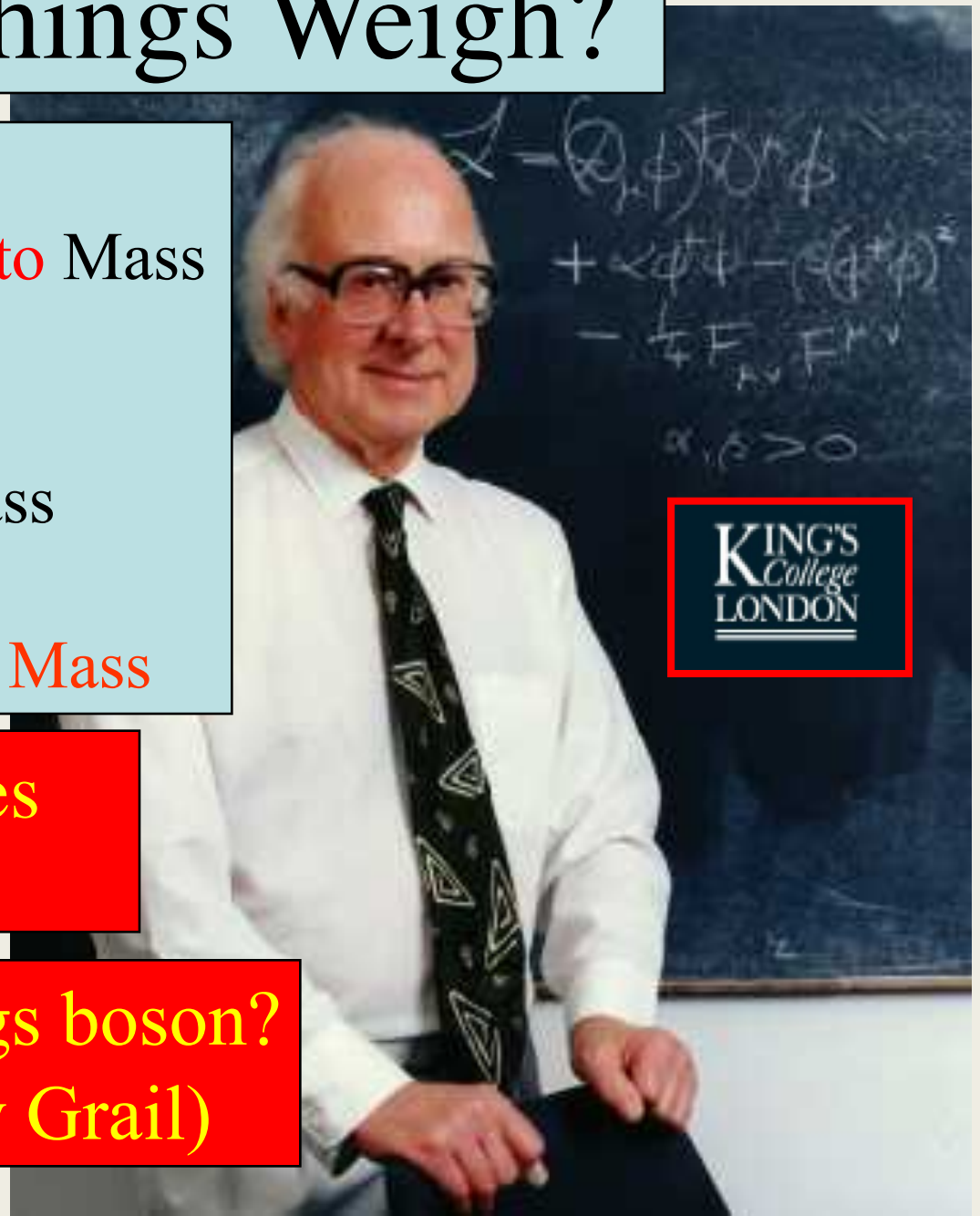
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Where do the masses come from?

Are masses due to Higgs boson? (the physicists' Holy Grail)

Without Higgs …

… there would be no atoms

- *massless electrons would escape at the speed of light*

… there would be no heavy nuclei

… weak interactions would not be weak

- *Life would be impossible: everything would be radioactive*

Its existence is a big deal!

THINK OF A SNOWFIELD



The LHC discovered the snowflake: The Higgs Boson



Skier moves fast:
Like particle without mass
e.g., photon = particle of light

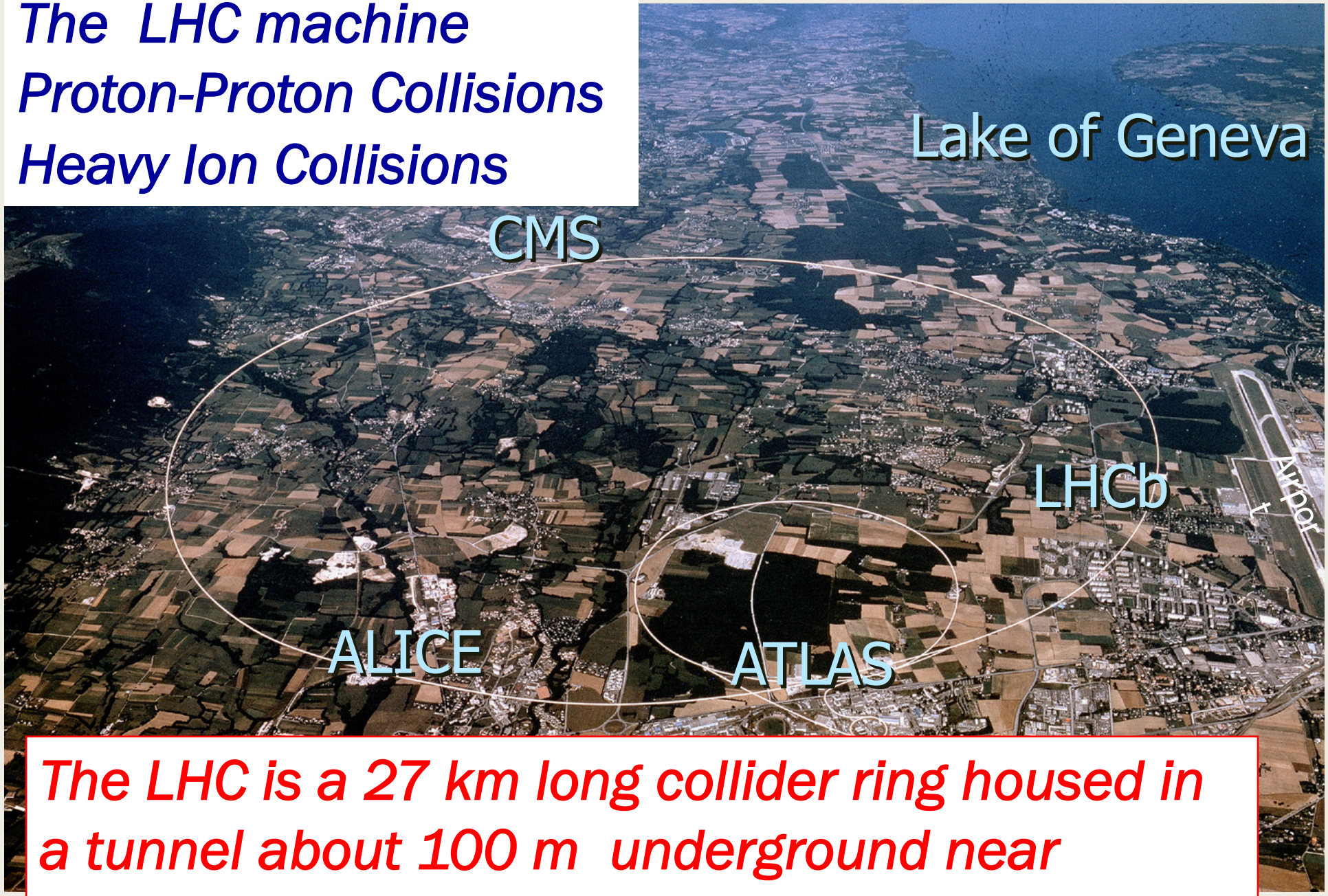


Snowshoer sinks into snow, moves slower:
Like particle with mass
e.g., electron

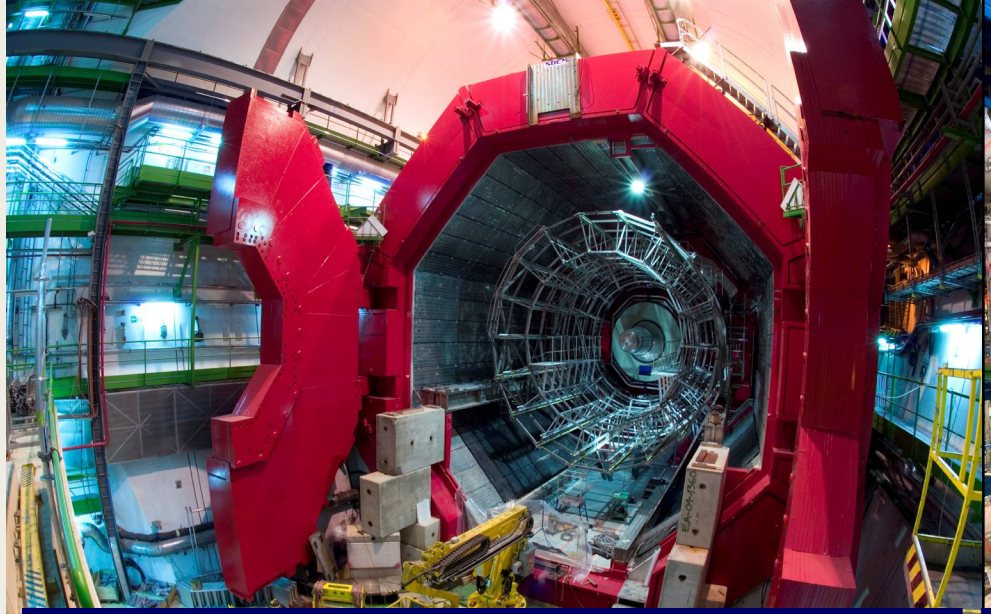


Hiker sinks deep, moves very slowly:
Particle with large mass

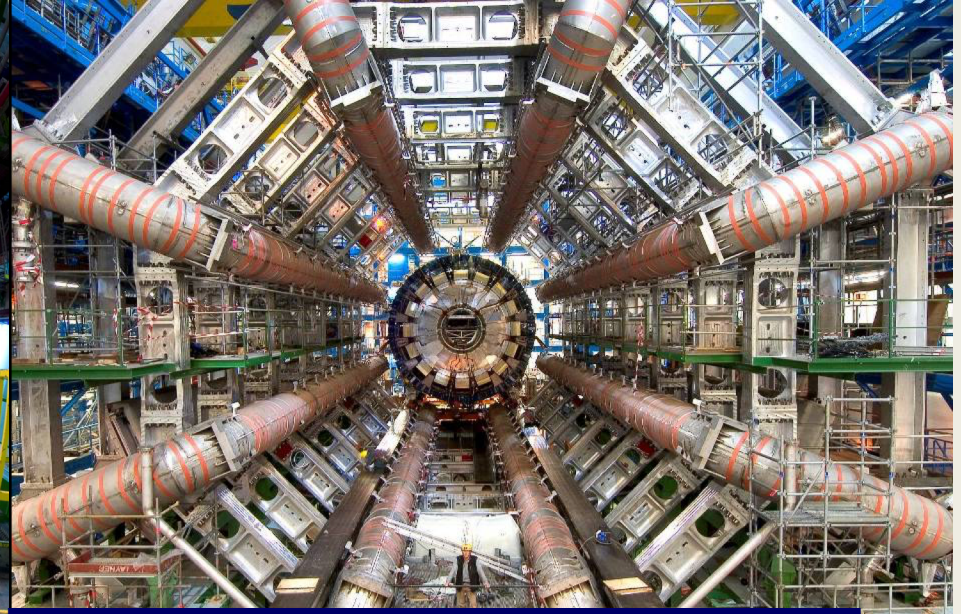
The LHC machine
Proton-Proton Collisions
Heavy Ion Collisions



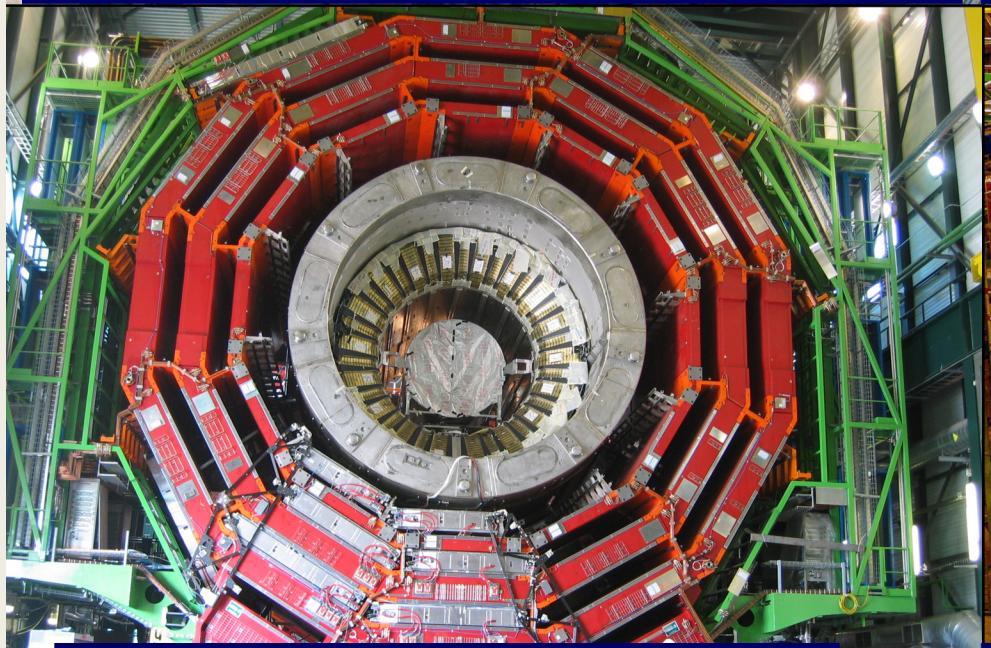
The LHC is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva



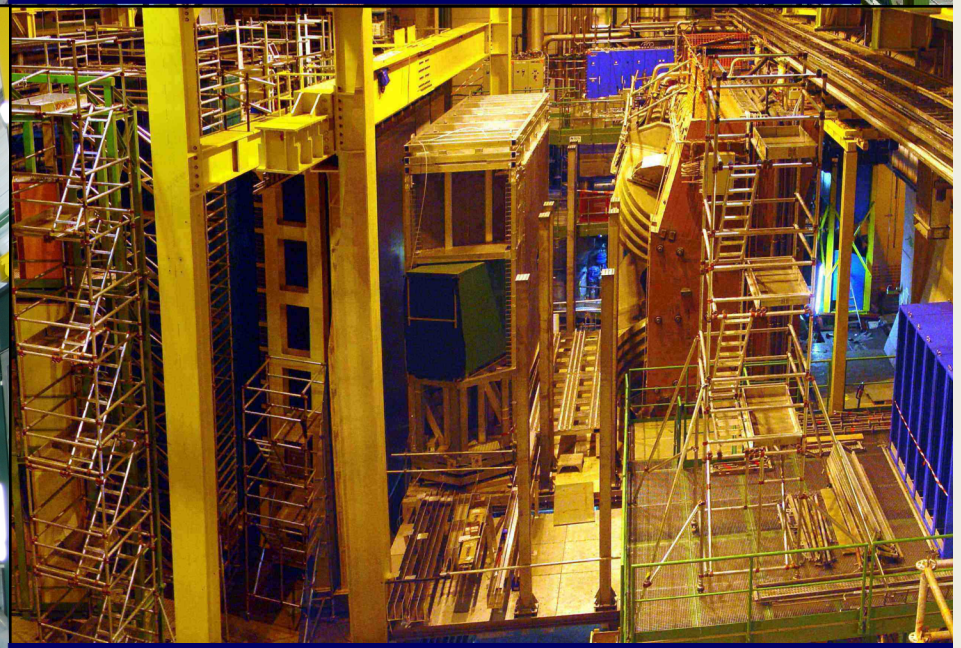
ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

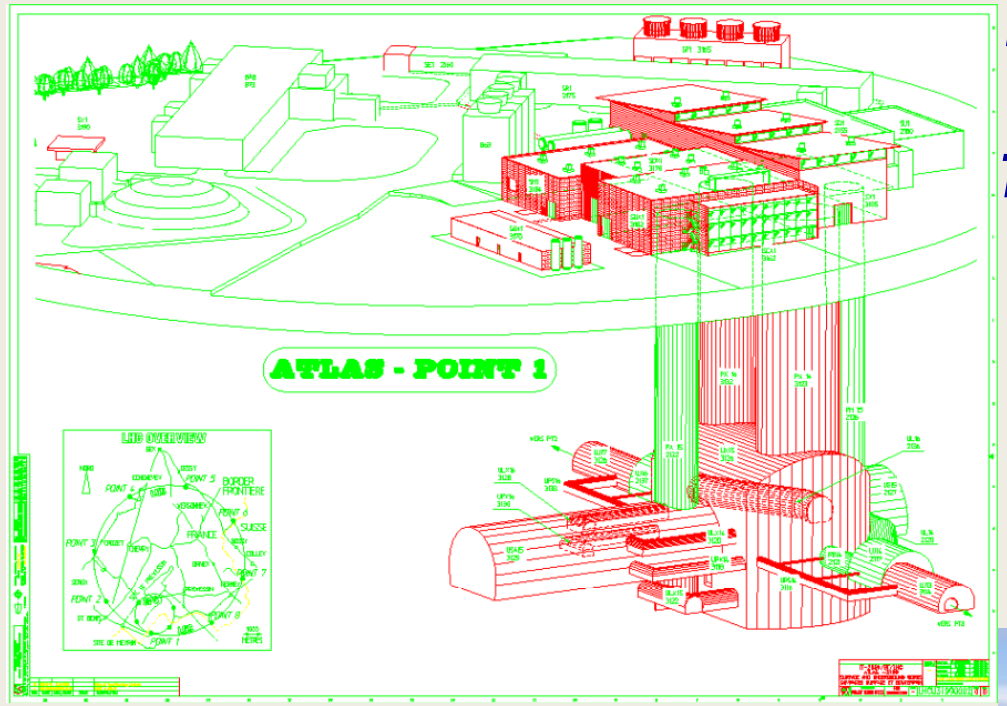


CMS: Higgs and dark matter



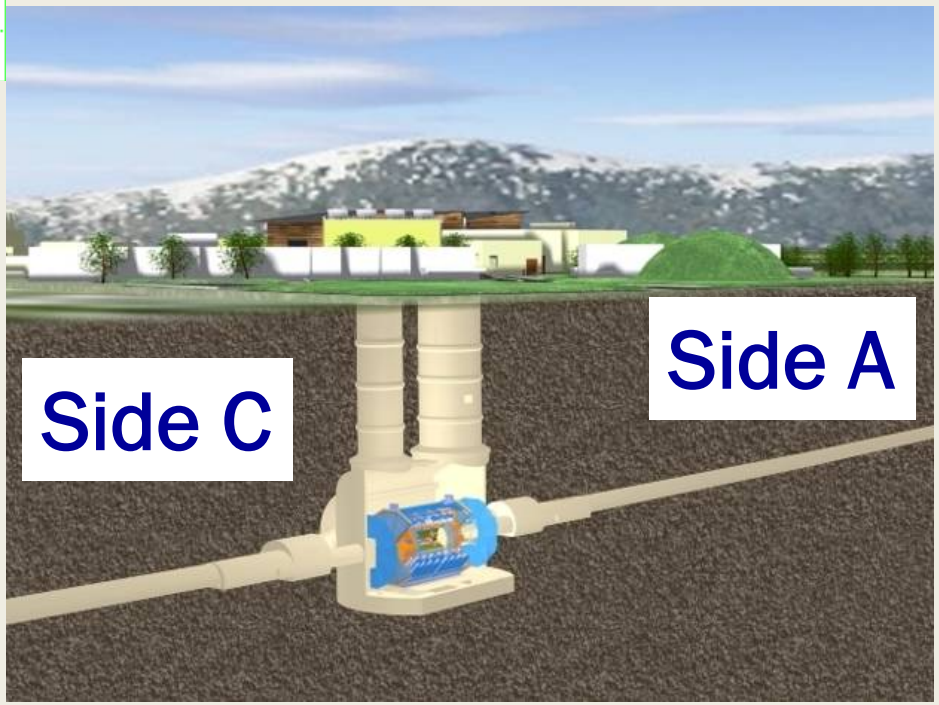
LHCb: Matter-antimatter difference

The Underground Cavern for the ATLAS Detector



Length = 55 m
Width = 32 m
Height = 35 m





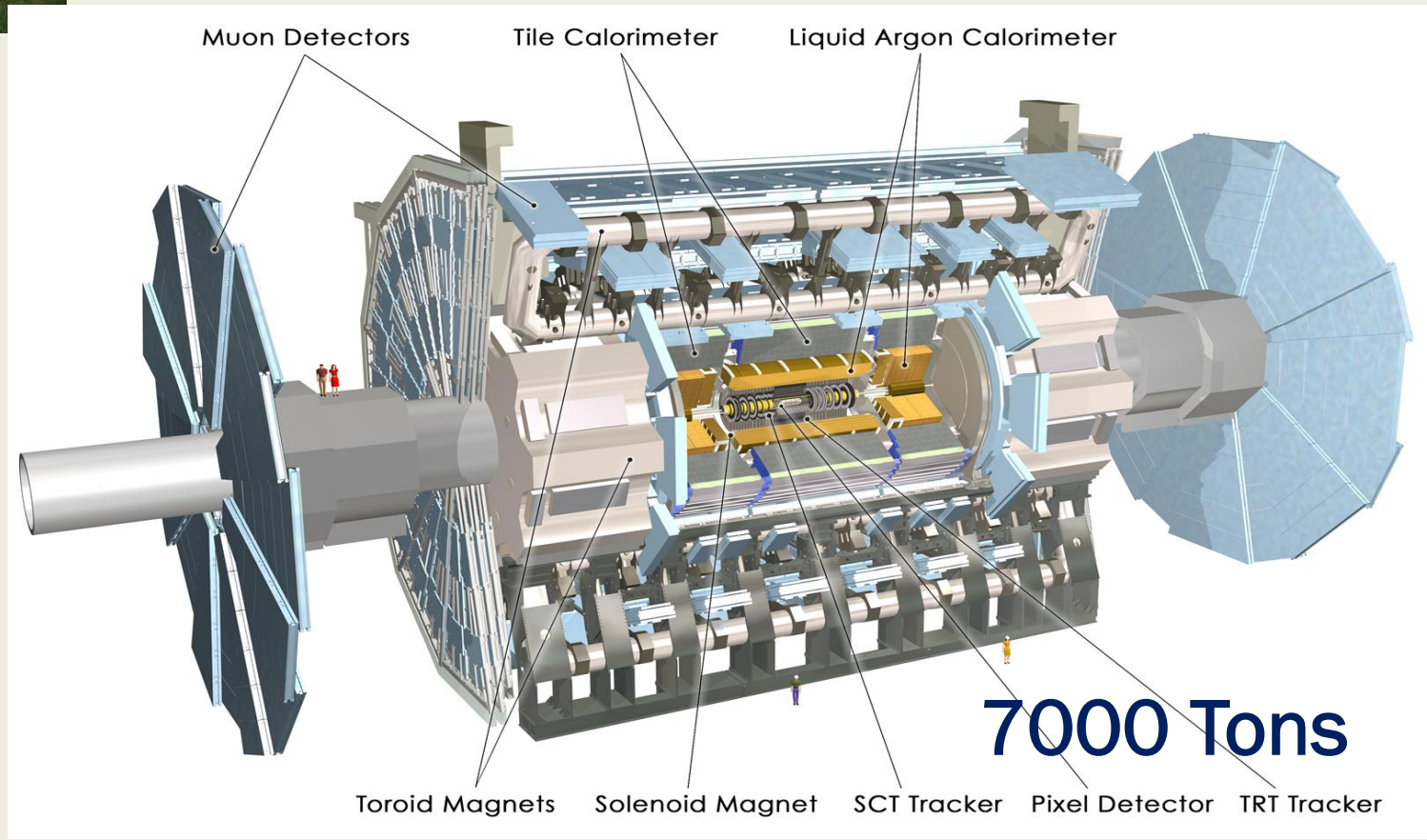


ATLAS Detector at the LHC

3300 Physicists
550M Suisse Franks

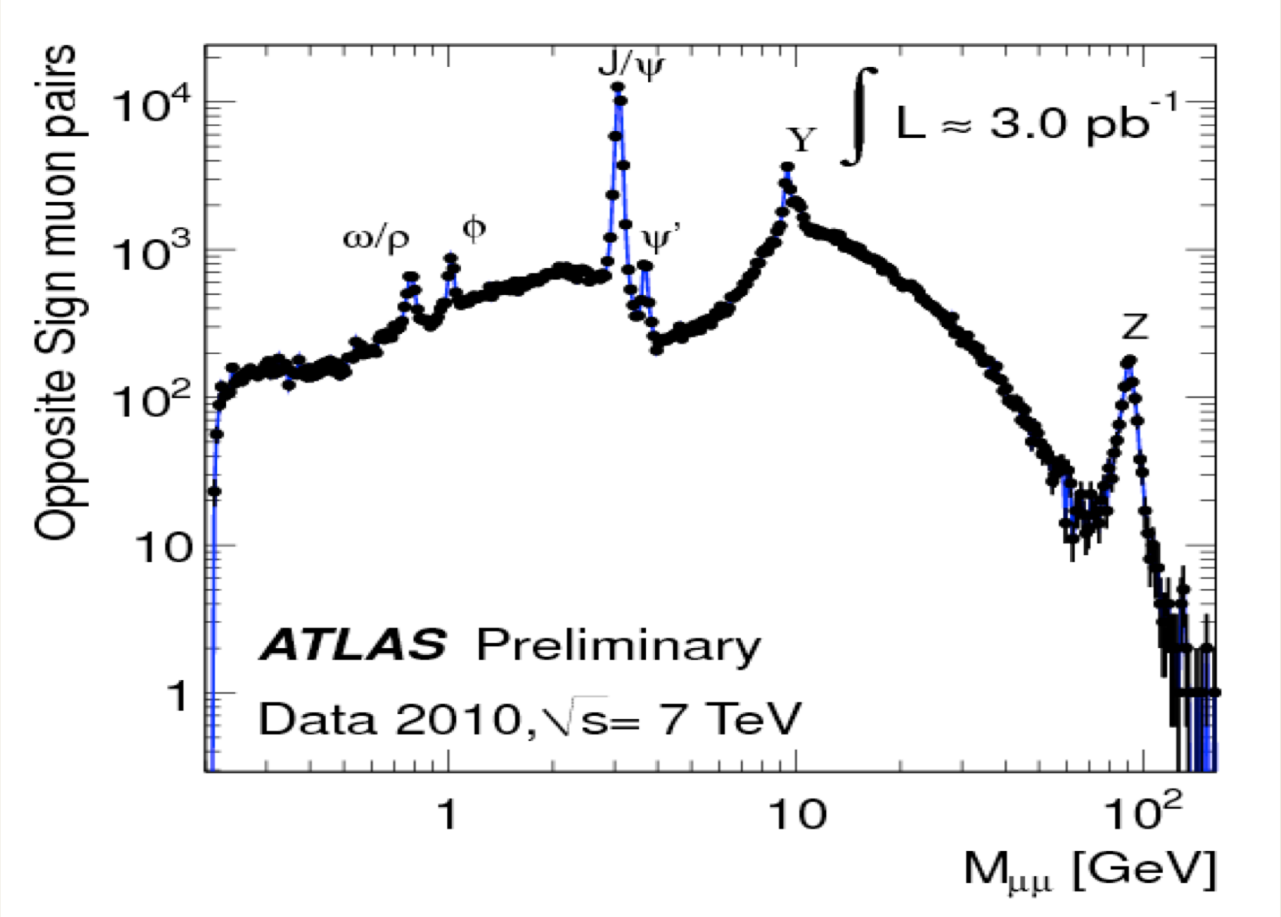
45 m

24 m



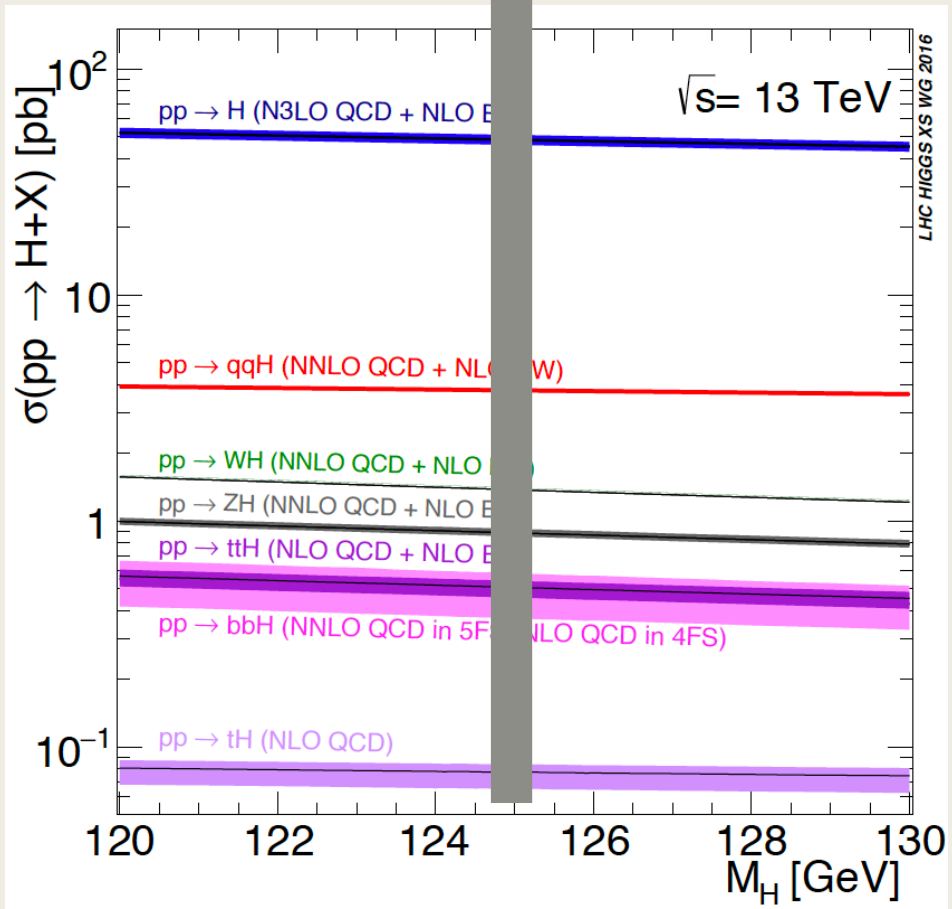
Confirming previous measurements or discoveries

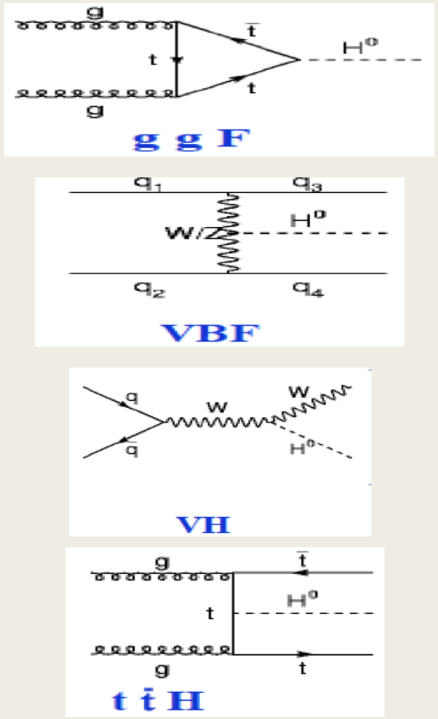
- Before we do new searches, we have to show that we measure accurately what is already known

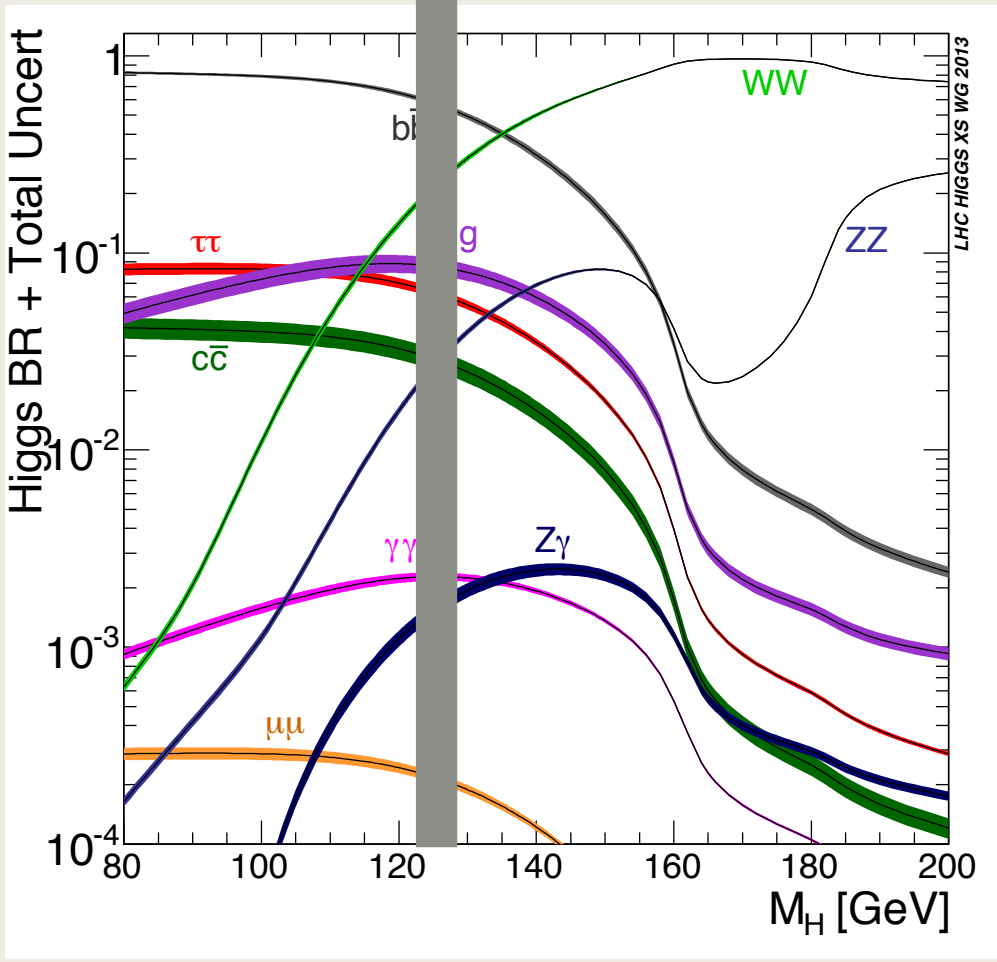


Higgs boson production and decays

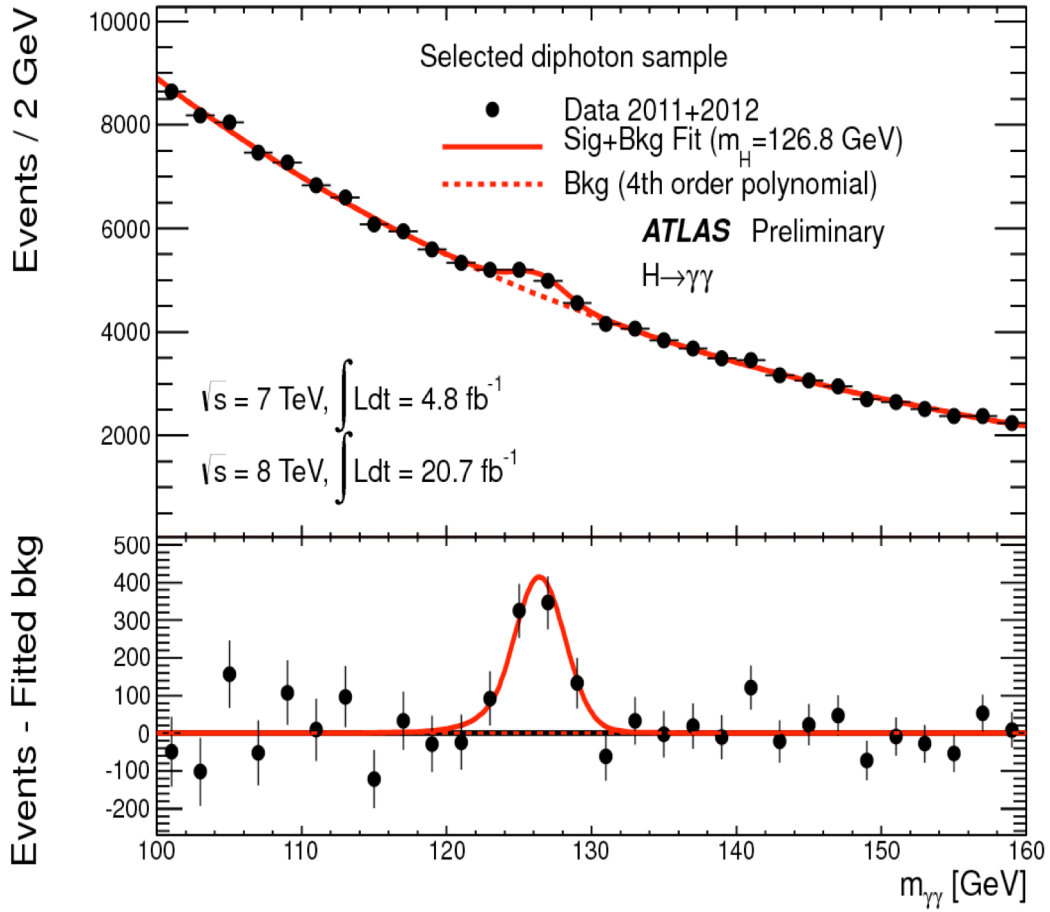
The ATLAS CMS Experiments at the LHC have discovered, independently, a Higgs boson with mass around 125. GeV using these productions and decay modes



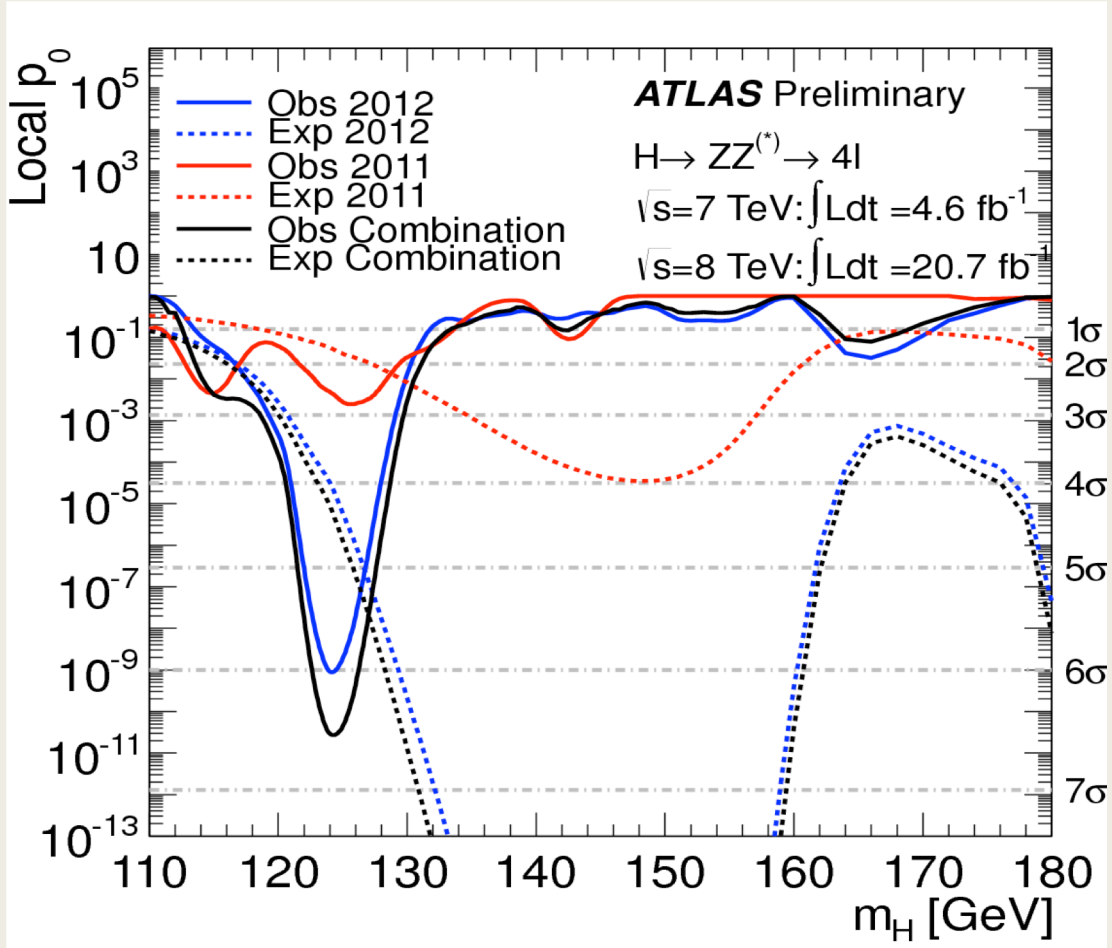




The Higgs Boson Discovery

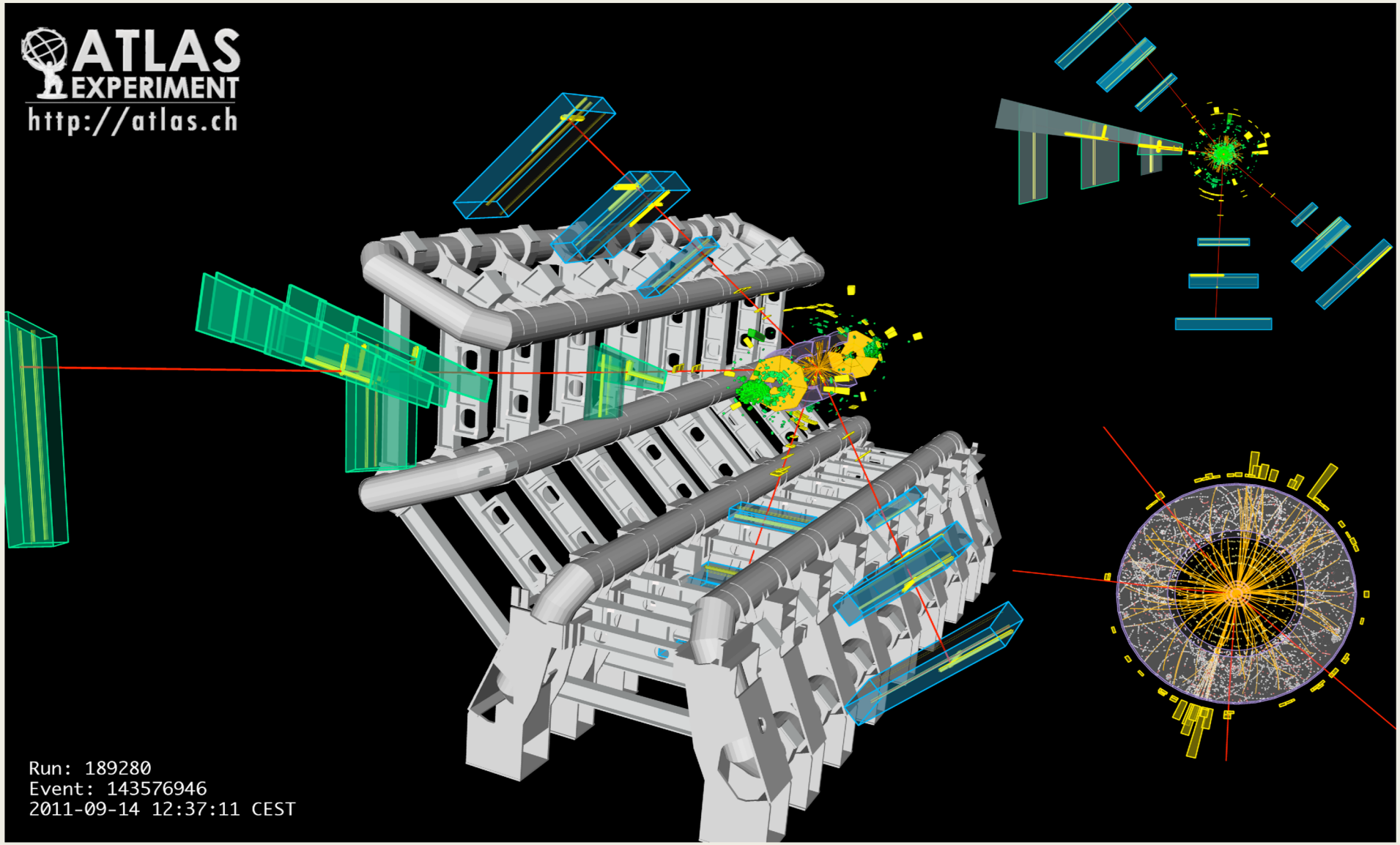


Single channel discovery: 7.4σ

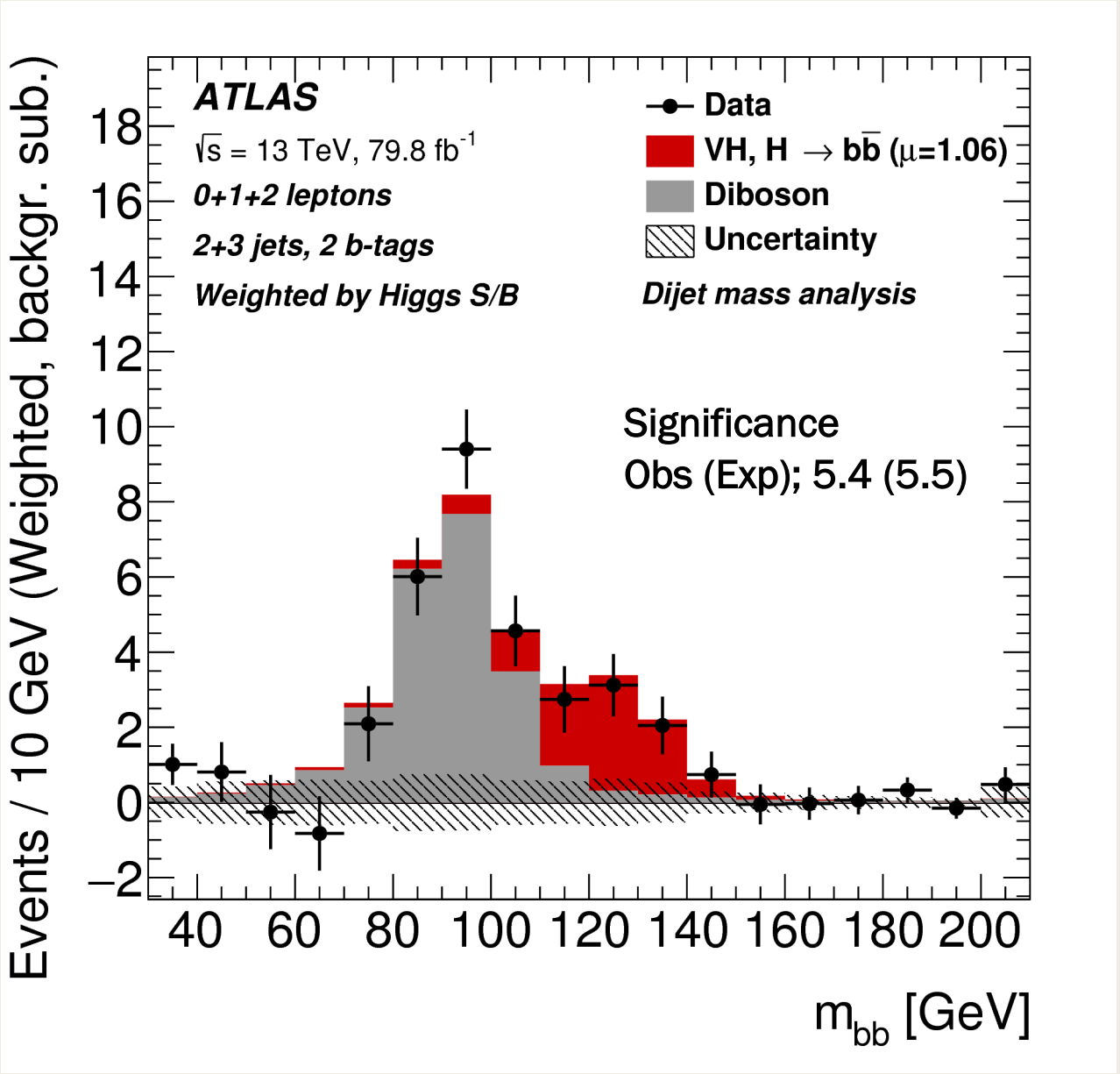


Single channel discovery: 6.6σ

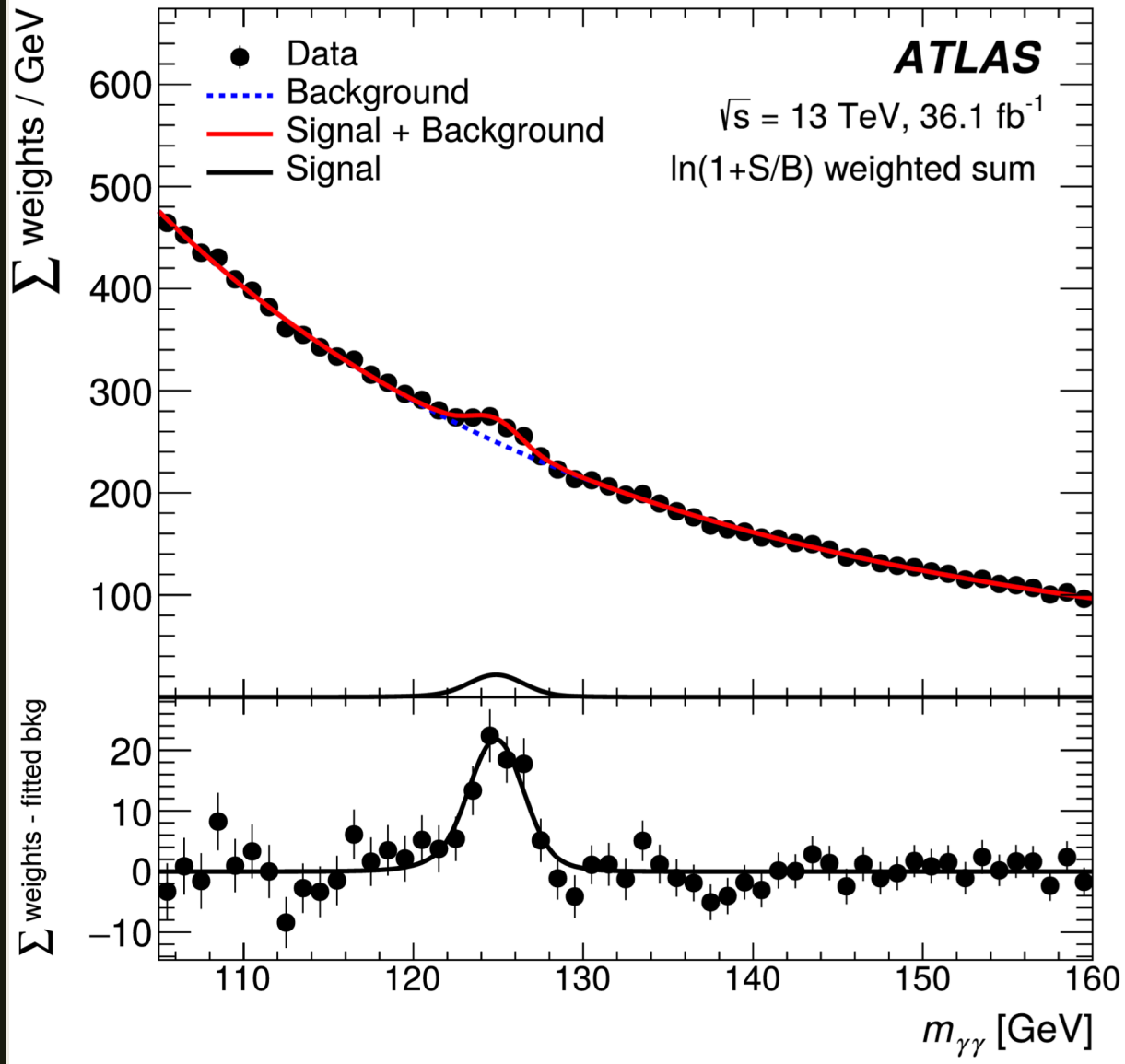
Higgs → 4 muons Candidate

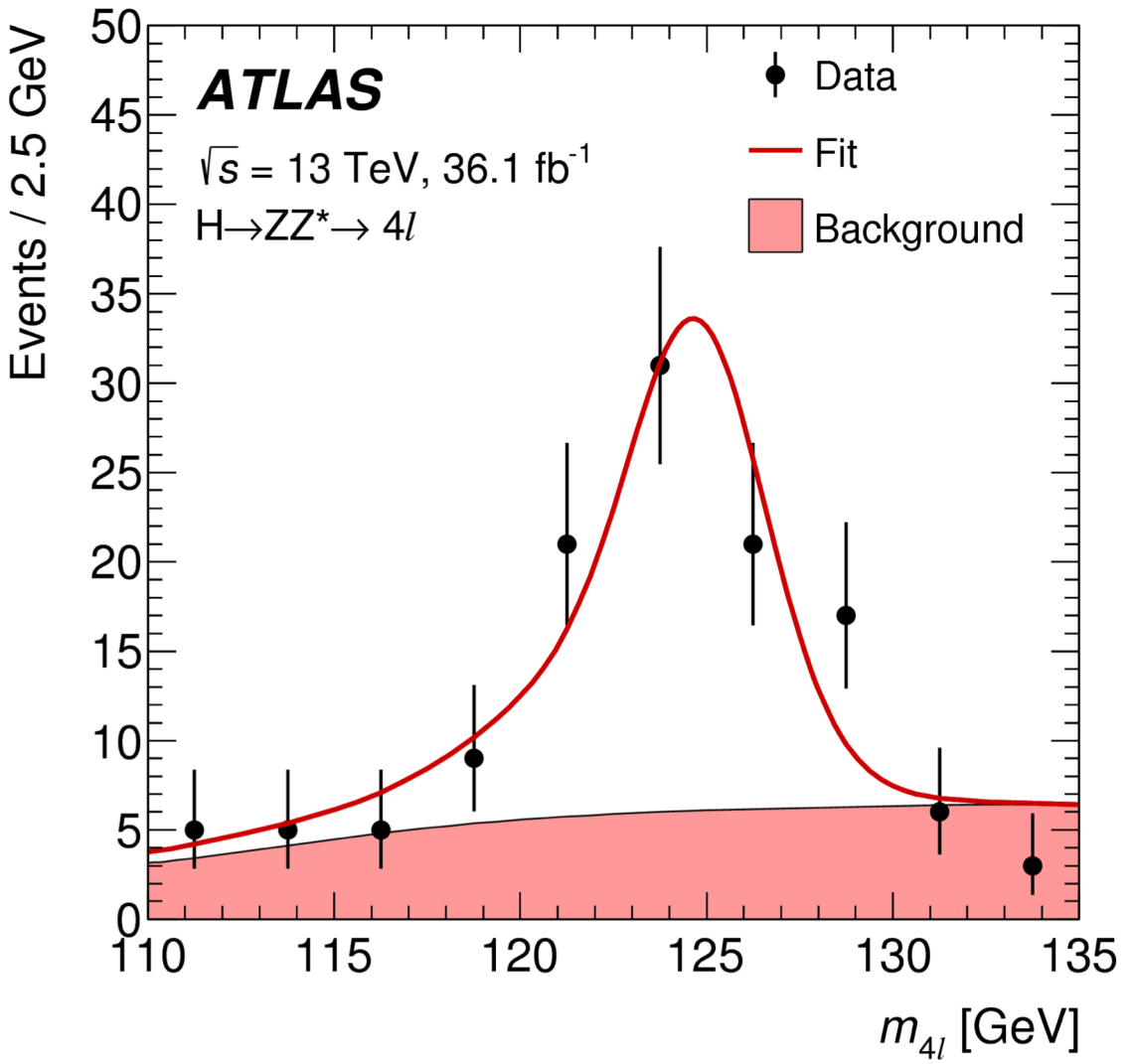


H → bb


ATLAS
√s = 13 TeV, 79.8 fb-1
0+1+2 leptons
2+3 jets, 2 b-tags
Weighted by Higgs S/B
Data
VH, H → bb̄ (μ=1.06)
Diboson
Uncertainty
Dijet mass analysis
Significance
Obs (Exp); 5.4 (5.5)
Events / 10 GeV (Weighted, backgr. sub.)
18
16
14
12
10
8
6
4
2
0
−2
40
60
80
100
120
140
160
180
200
mbb [GeV]

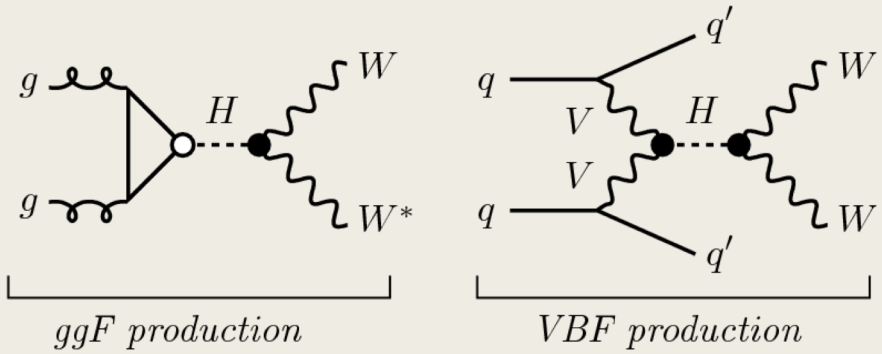
Higgs →gg, ZZ

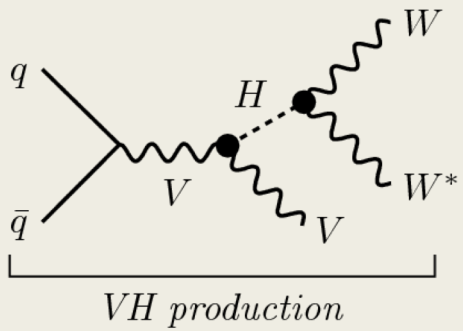


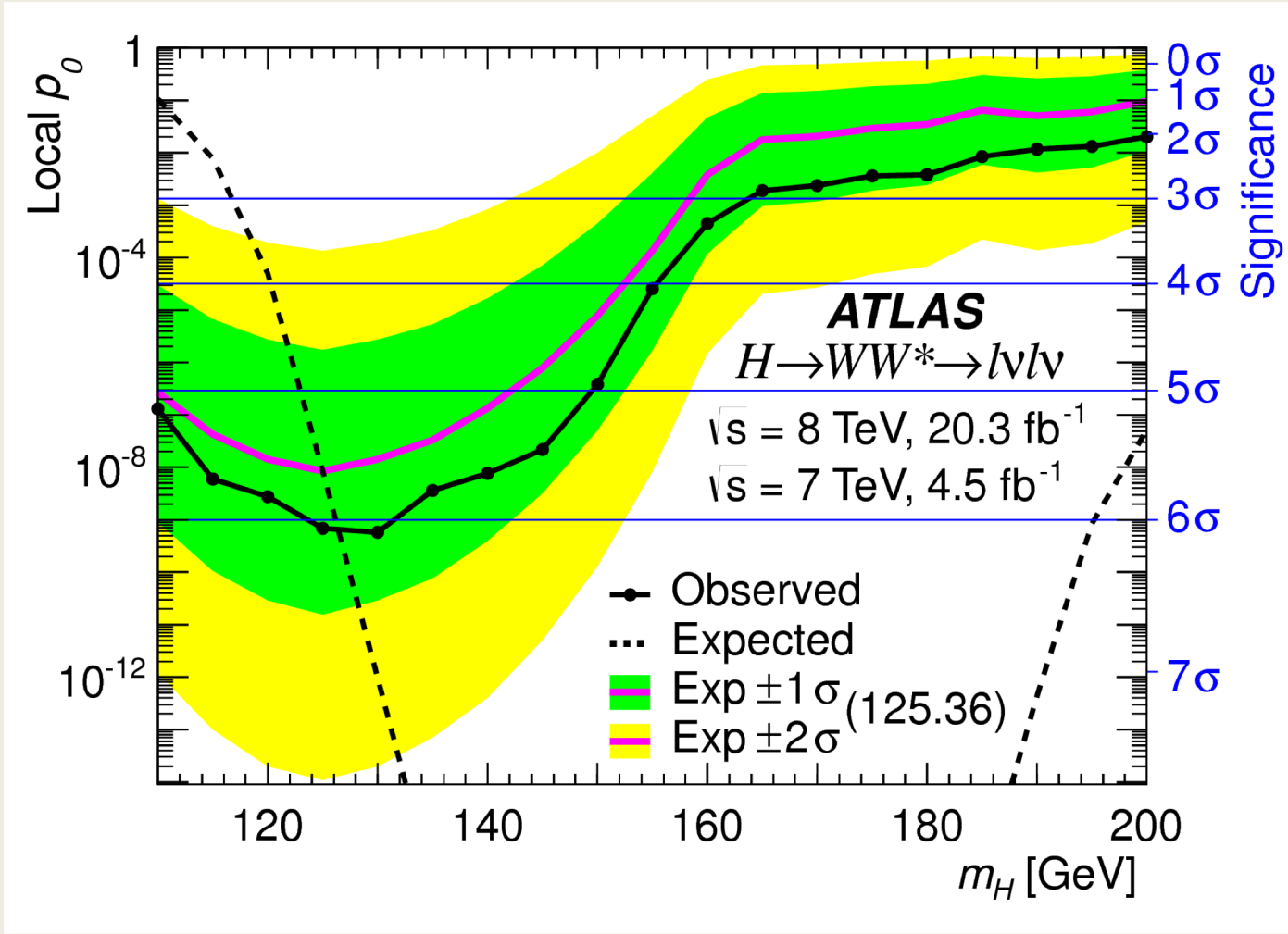


Discovery confirmed in later measurements

H → WW* observation





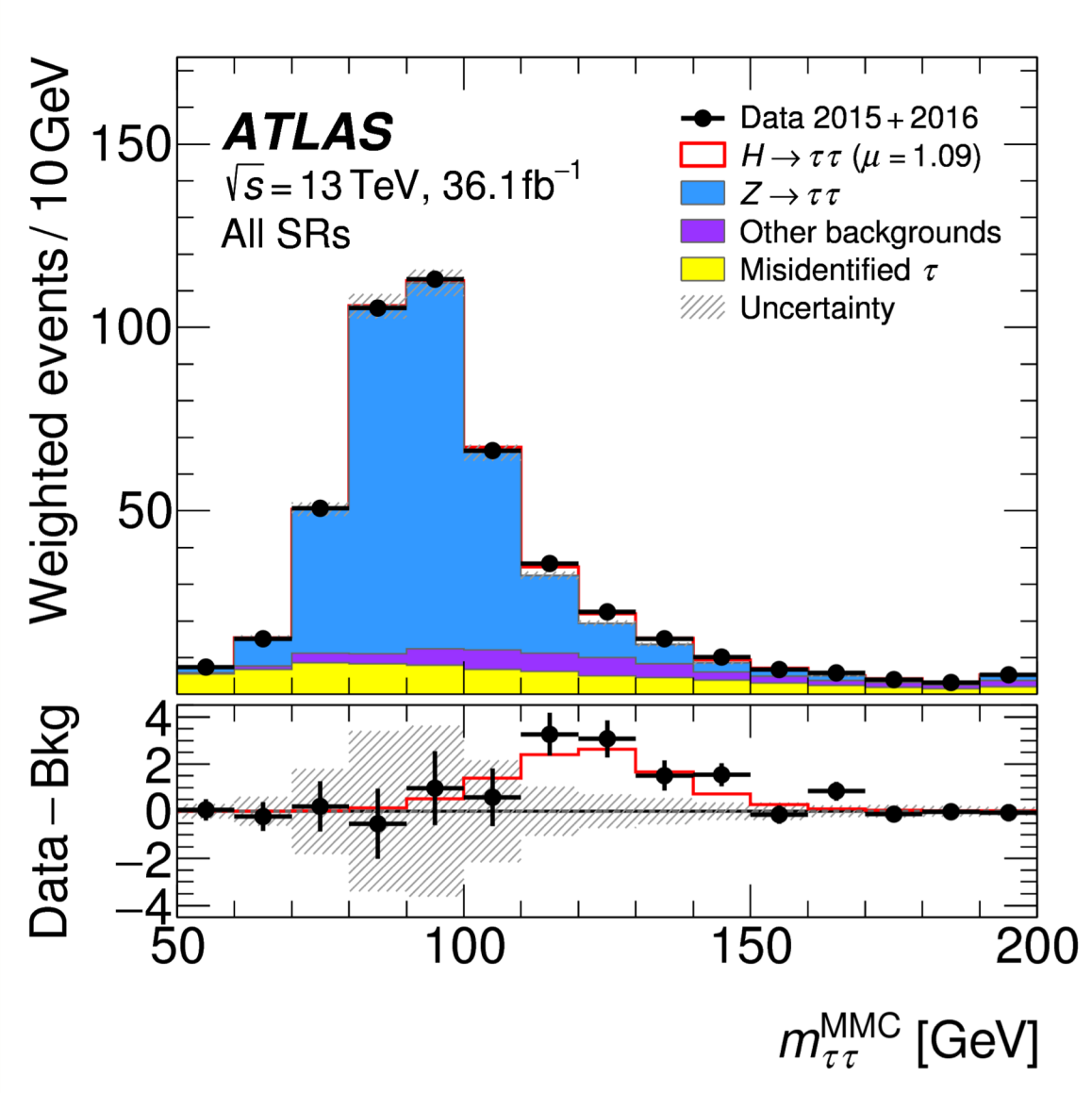


Significance:

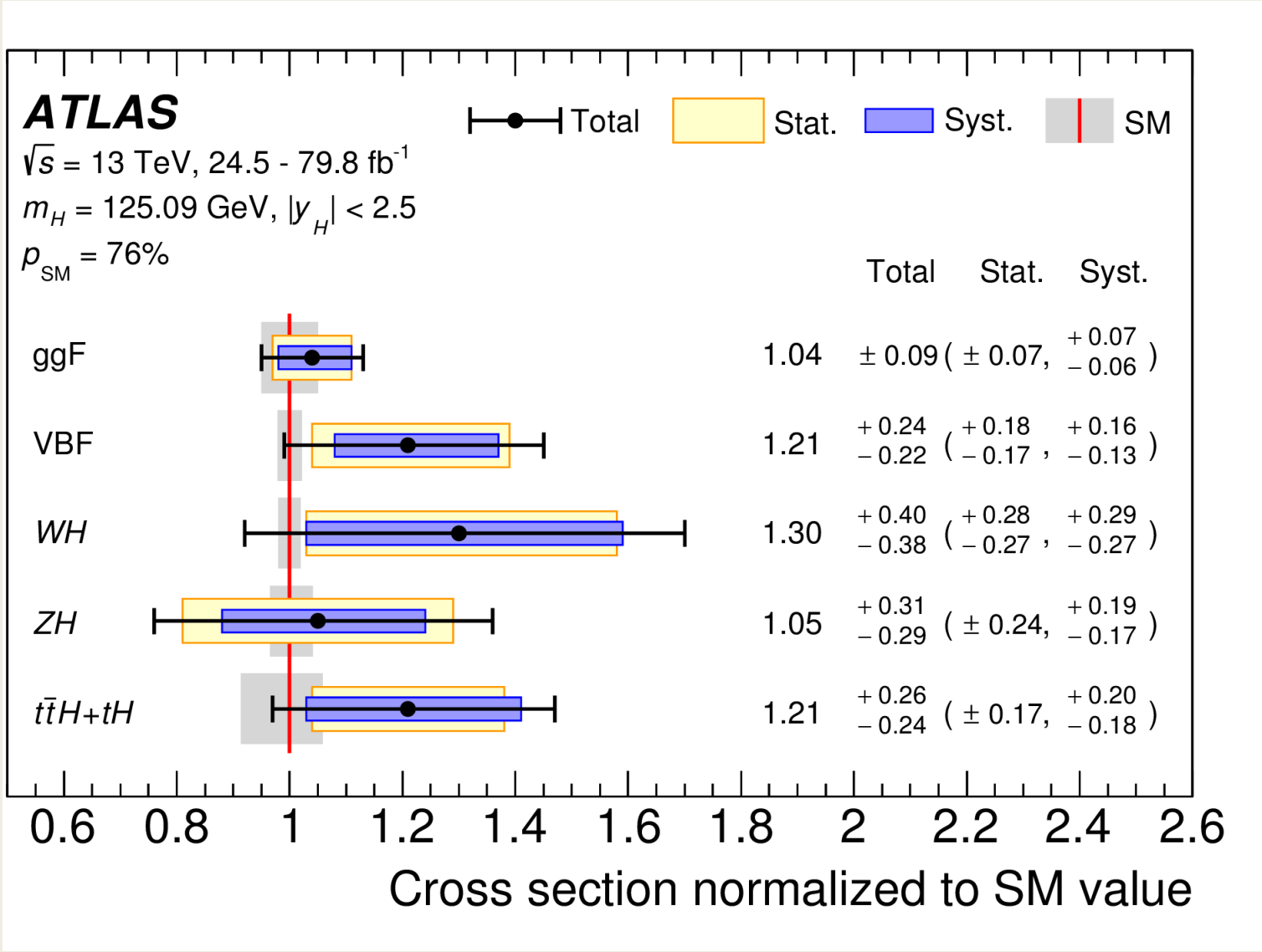
Obs (Exp): 6.1 (5.8)

H → ττ

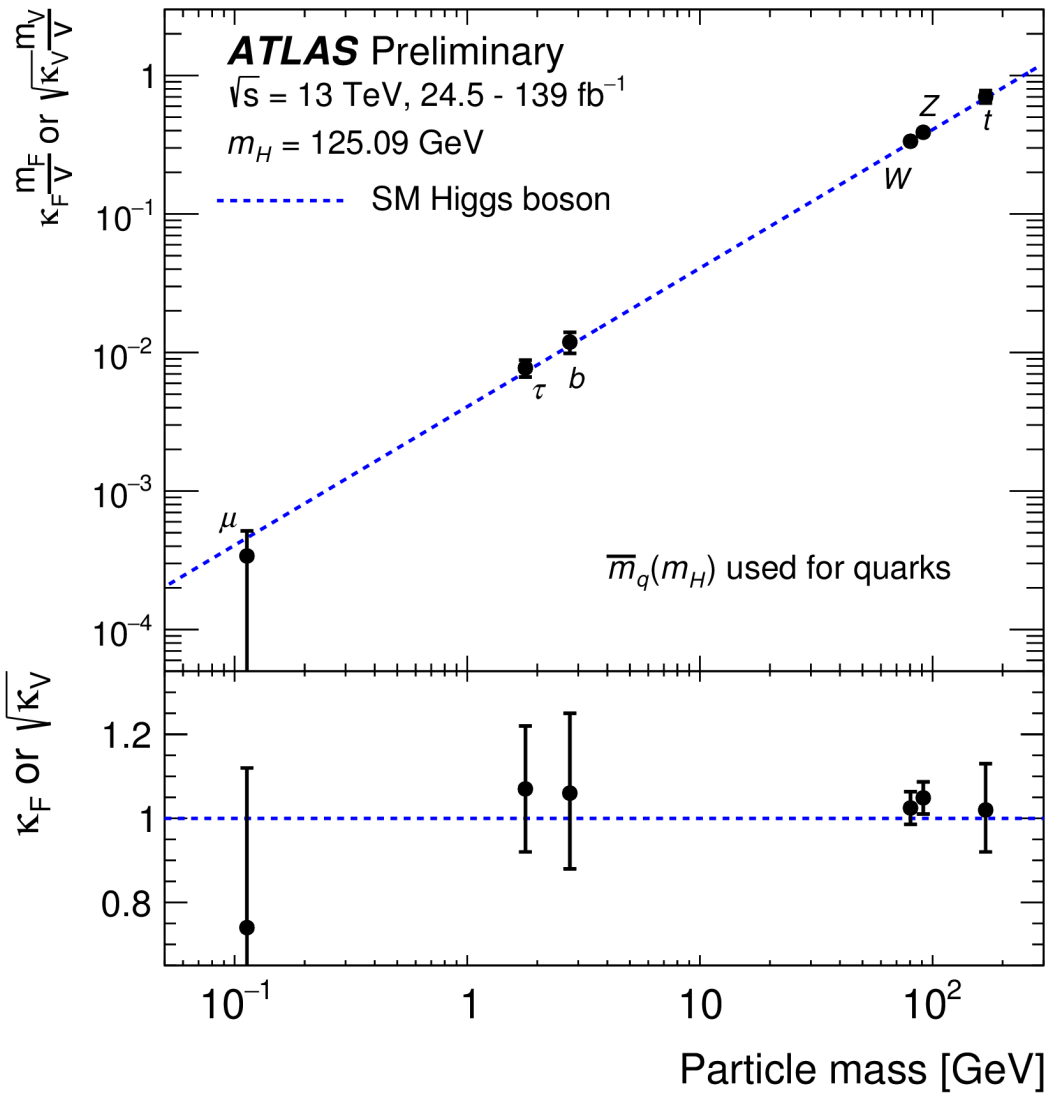
The observed (expected) significance amounts to 6.4 (5.4)



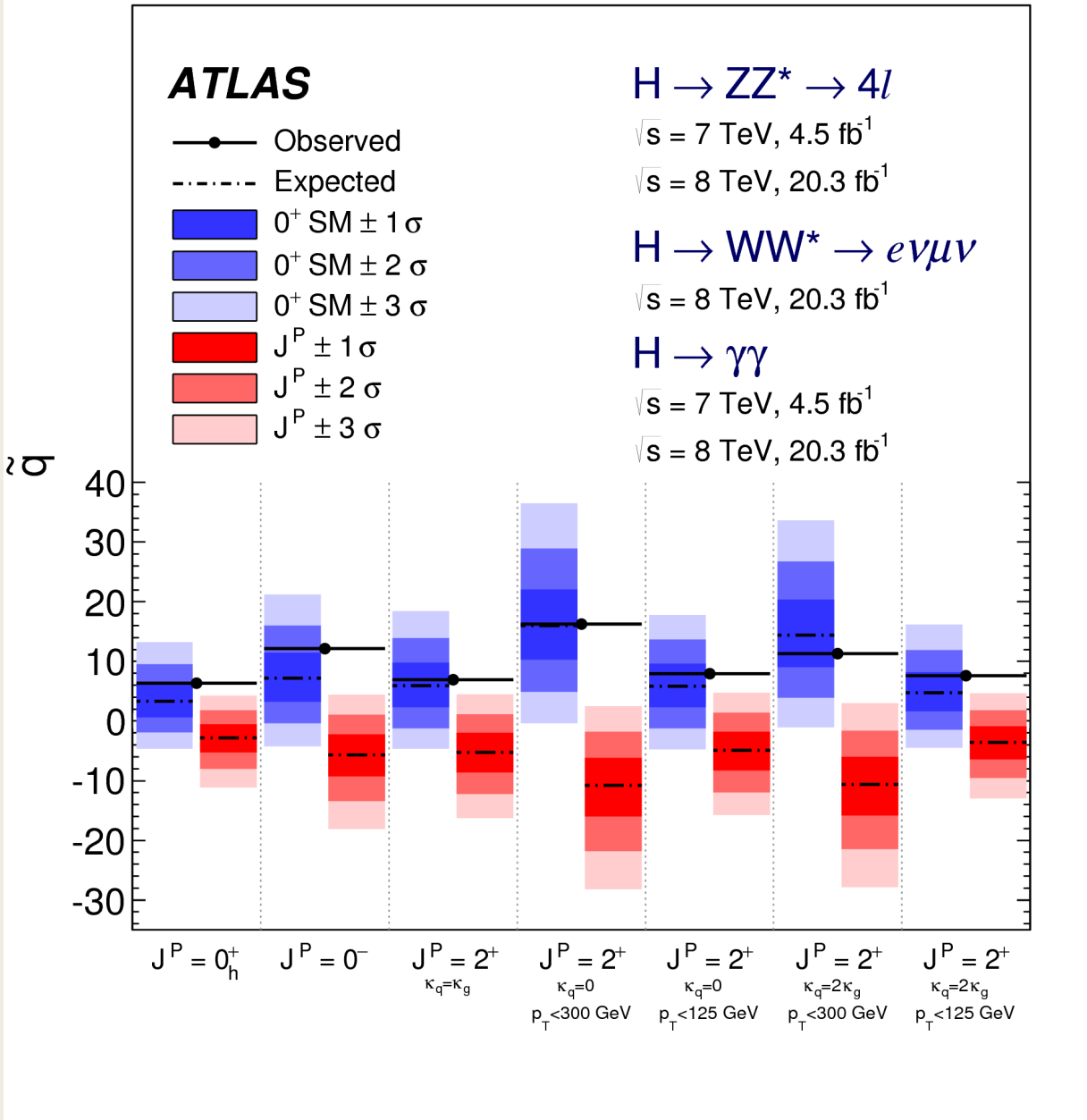
Higgs cross section measurements



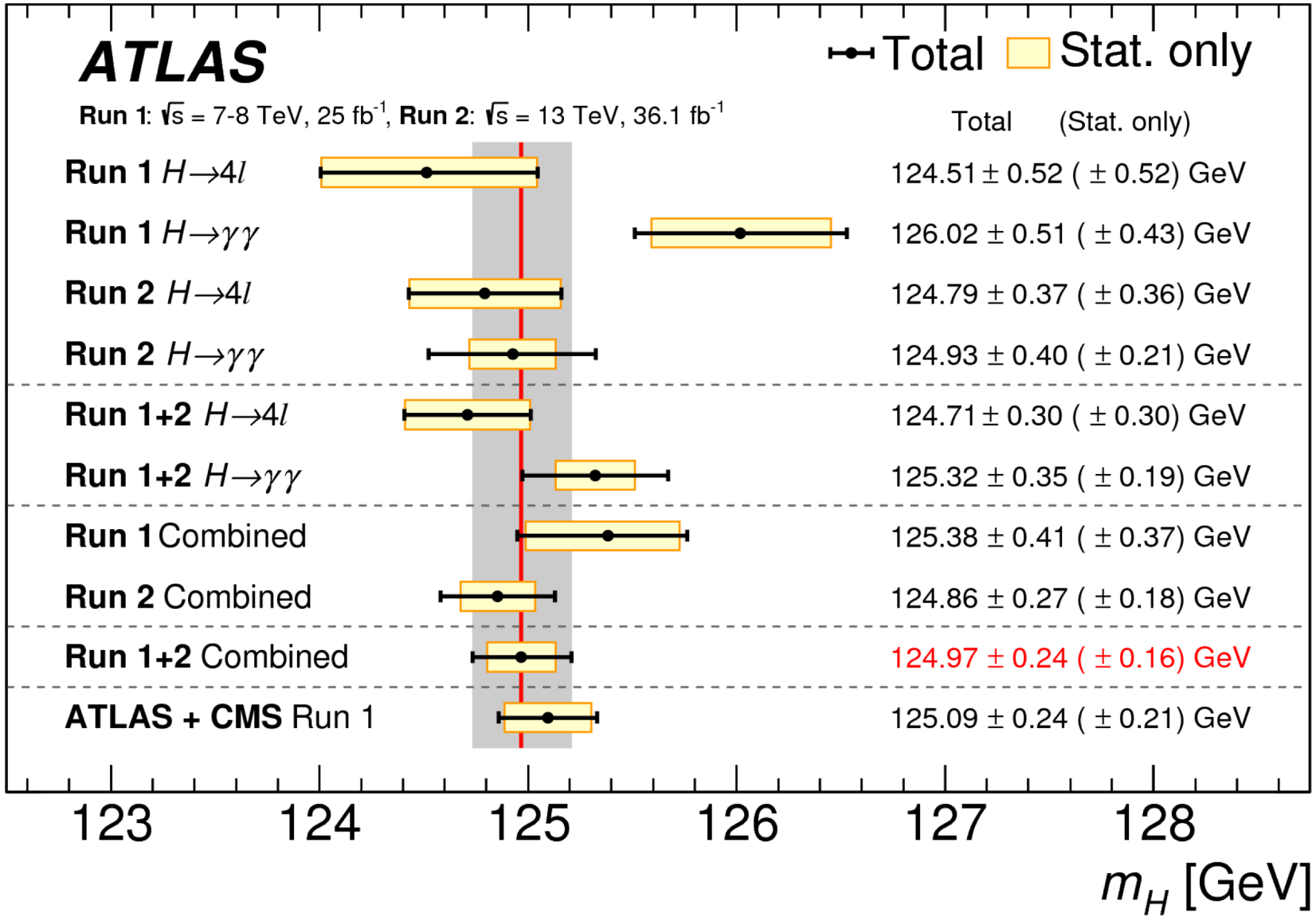
Higgs coupling measurements



Higgs Spin/CP test

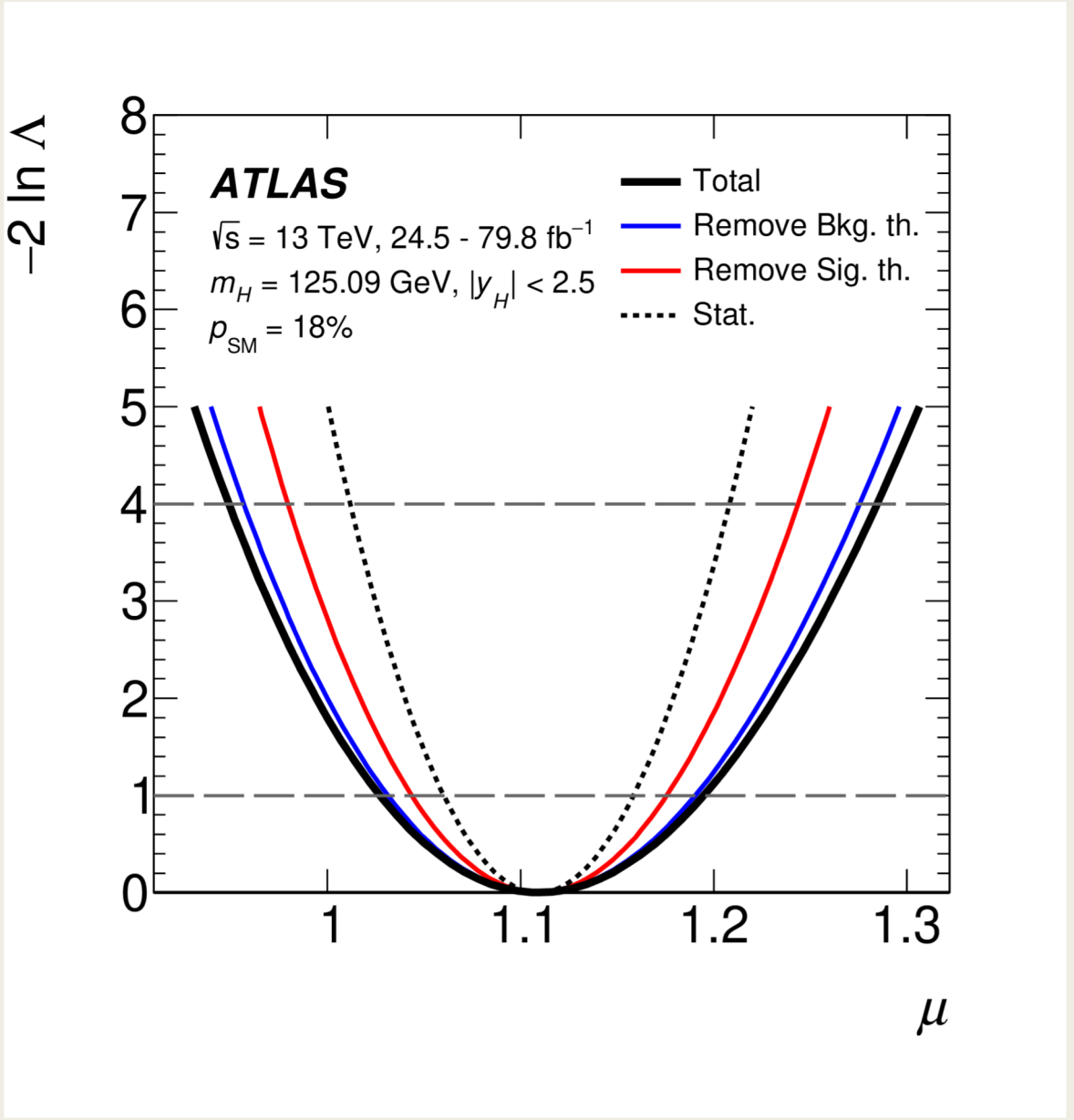


Higgs mass measurement

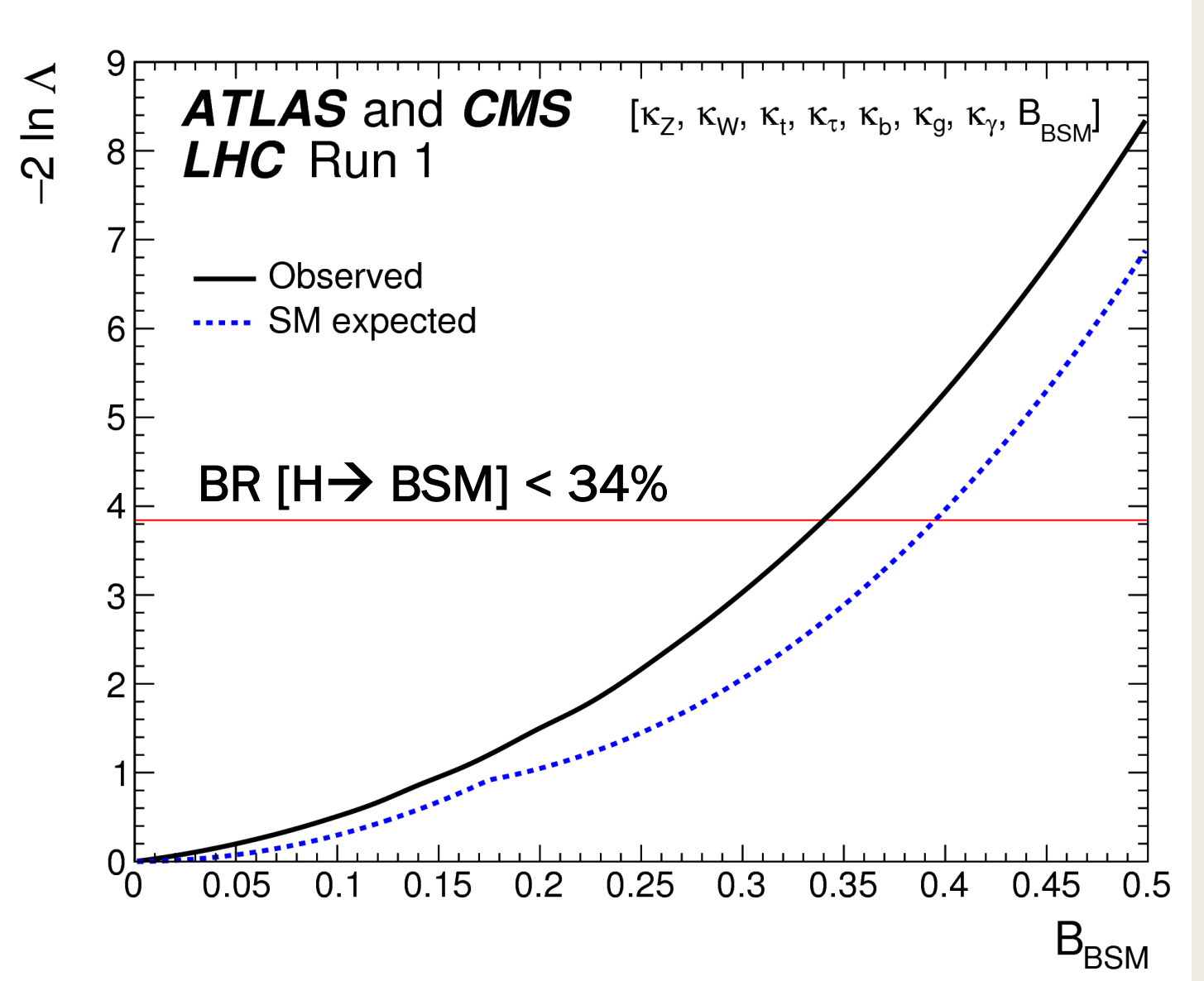


Signal Strength relative to SM

$$\mu = 1.11^{+0.09}_{-0.08}$$



H → BSM contribution to the Higgs width



The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**



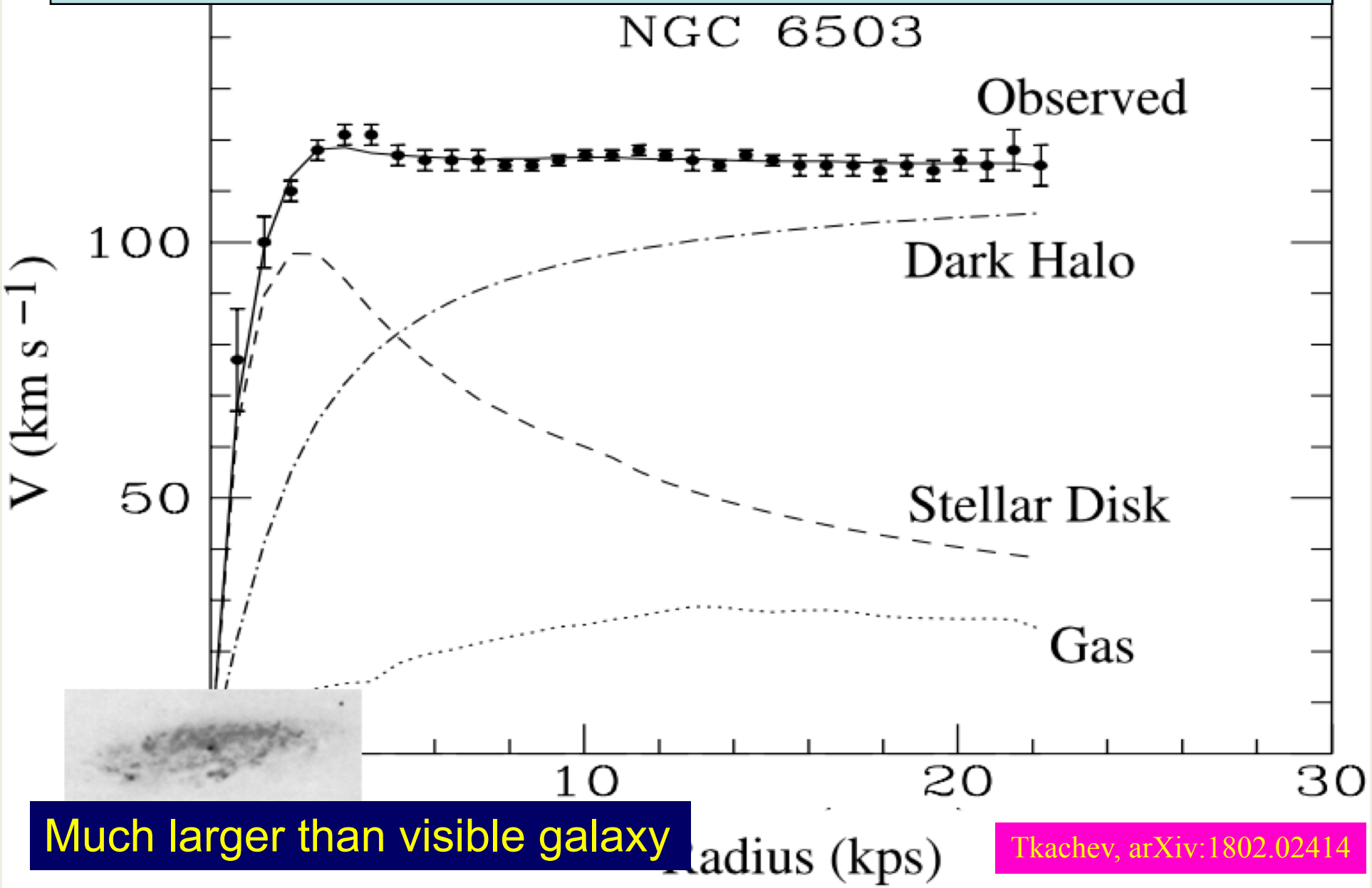
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**



Scanned at the American Institute of Physics

Sample Rotation Curve: NGC 6503



Much larger than visible galaxy

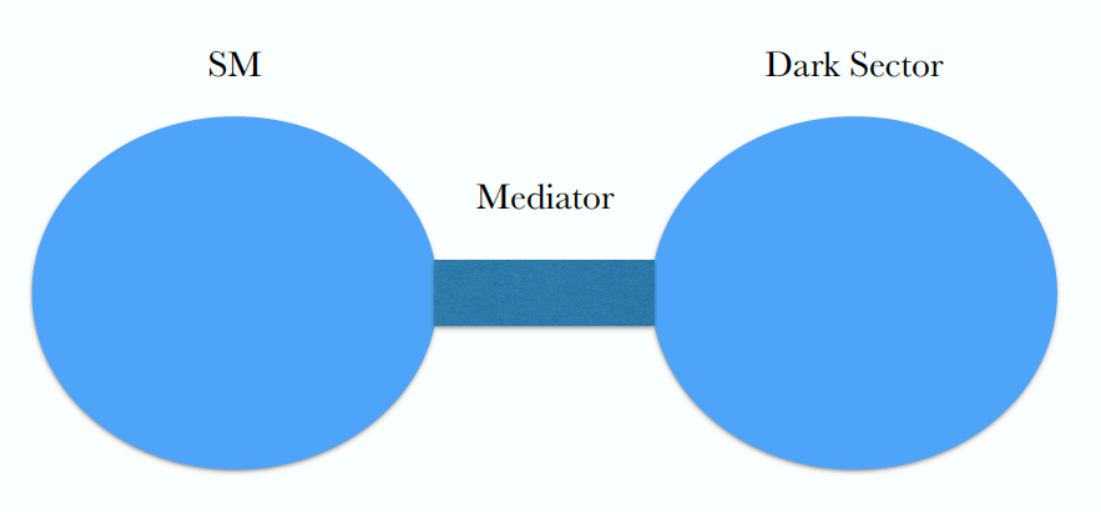
Tkachev, arXiv:1802.02414

Search for new physics in the decays of the Higgs boson

- Higgs Discovery confirmed in later measurements
- Measurement of properties consistent with expectations from the SM
- Now, the questions are :
  - *Can we search for new physics in the decay of the Higgs boson?*
  - *Or in association with it?*
  - *Or in the small deviations in the properties with respect to the SM expectations?*

Dark Sector

- Dark Sector as ”New Physics” beyond the SM



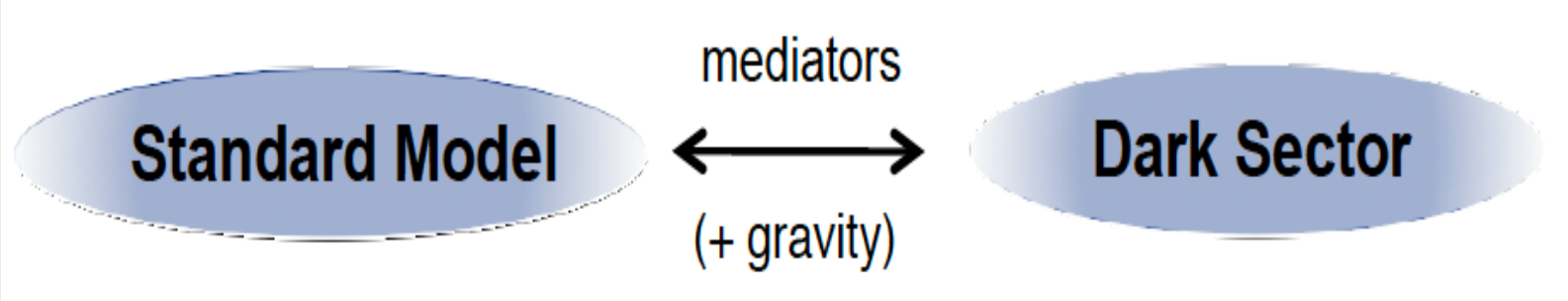
Need new force / interaction
to connect SM to Dark Sector

Dark Matter could just be one example of Dark Sector State

- A hidden or dark sector can be postulated
  - *The dark sector could couple to the SM very weakly*
- Exotic Higgs boson decays have been proposed as a way to search for evidence of new physics
  - *In the decay of the discovered Higgs boson*
  - *To measure the coupling strengths between the SM and the dark sector*
- Such decays predicted in many extensions to the SM to explain
  - *Muon g-2 discrepancy*
  - *Astrophysical observation of positron excess*

Minimal Interactions

- But there physics laws or constraints that SM – Dark Sector interactions must respect



$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j$$

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal

$$+\frac{1}{f_a}\left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F}\right) a + \mathcal{O}(\dim \geq 5)$$

Axion portal [Weinberg, Wilczek, KSVZ, DFSZ]

Vector Portal:

Min. Lagrangian =

SM Lagrangian

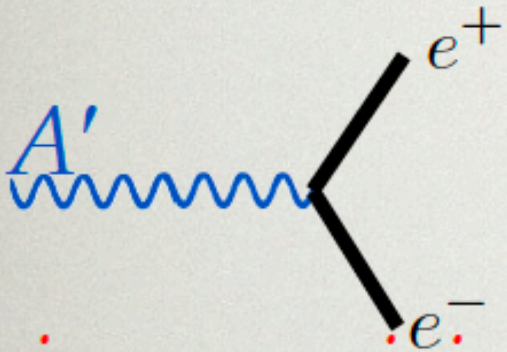
+ Dark QED

+ "Kinetic Mixing (ε)"

Dark Photon Decays

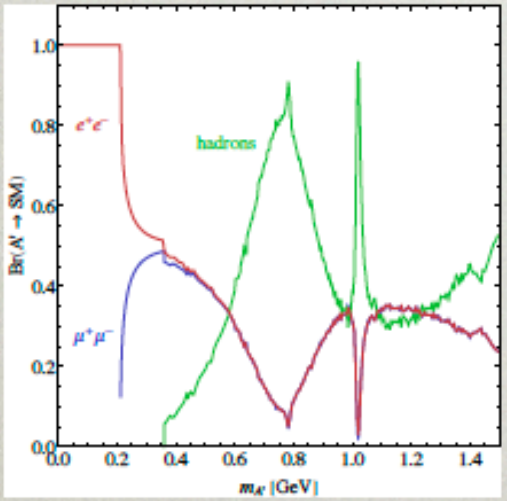
- **Kinetic mixing gives matter of electric charge qe an A' coupling $\propto q\varepsilon e$**

"Minimal" Decay:

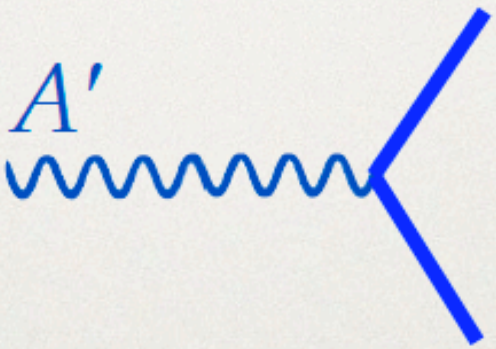


via same mixing operator as production
⇒ tiny width

$$\Gamma \sim \epsilon^2 \alpha m_{A'}$$



"Generic" Decay:



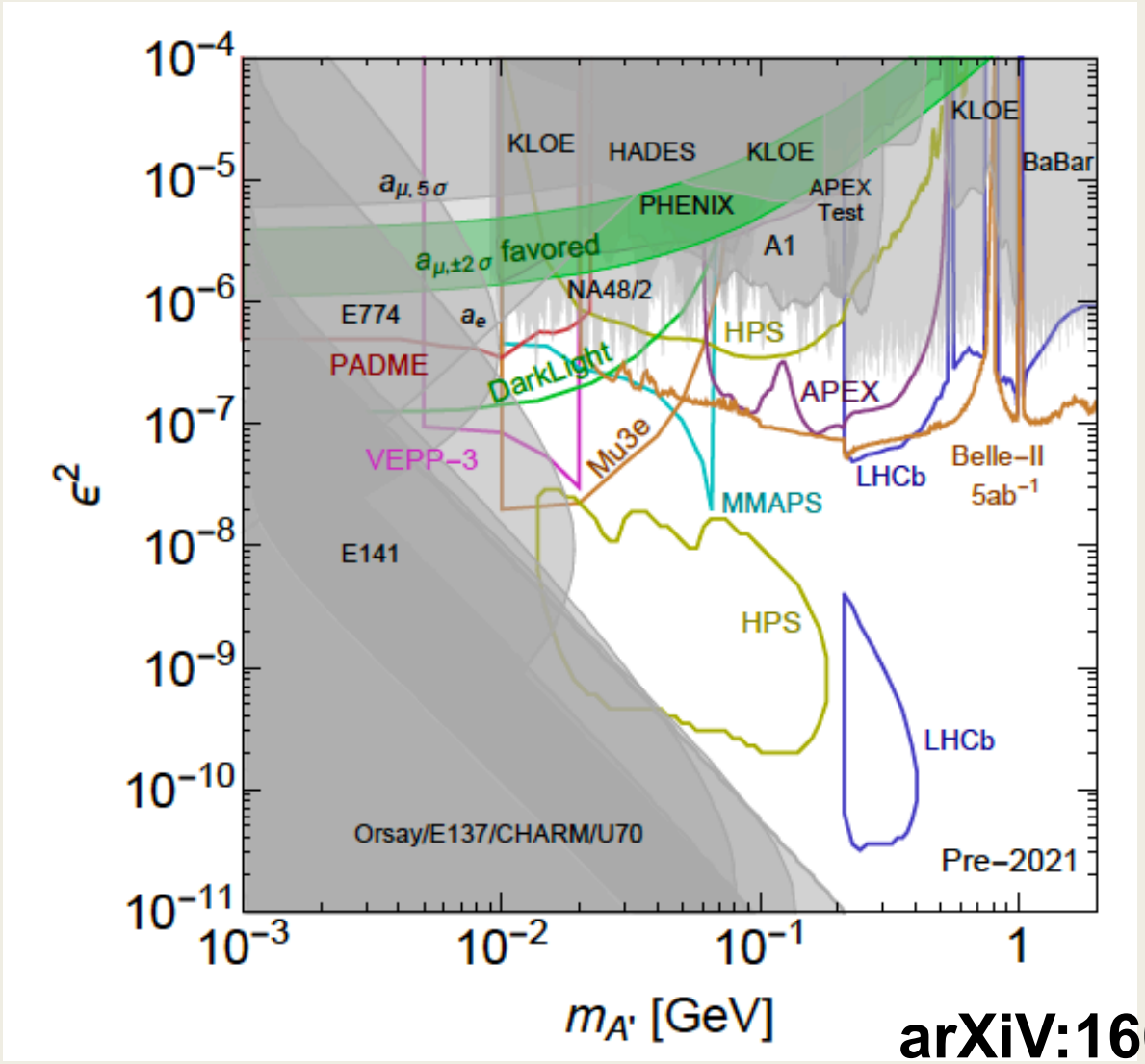
(not ε-supressed!)

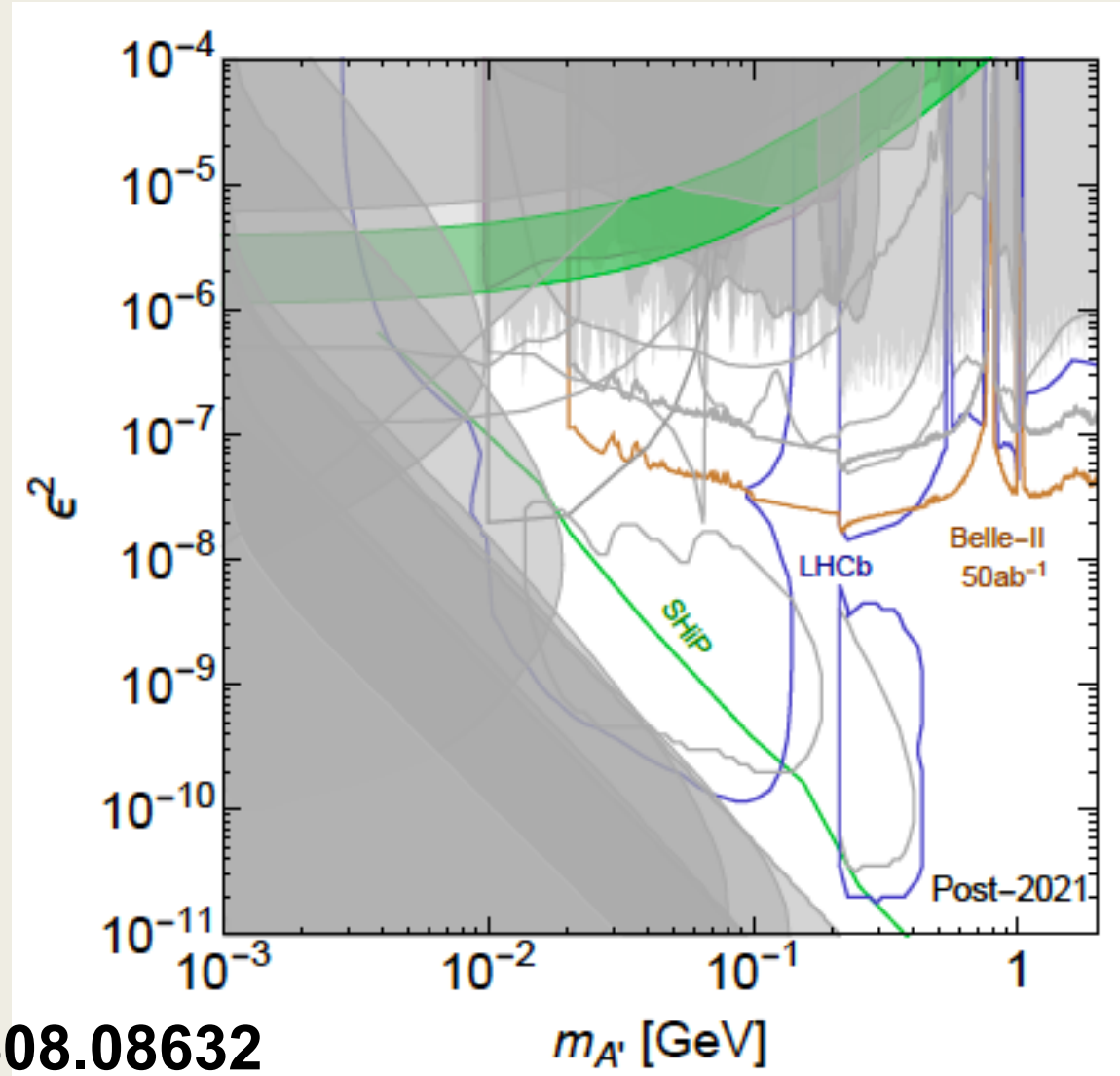
*If **any** dark-sector matter χ has $m_\chi < 2m_{A'}$, this decay dominates*

Two cases:
- χ stable & invisible
- χ decays into SM particles, A′→ >2 charged particles

searches at BaBar and KLOE

Kinetic Mixing – for experiments seeking $A' \rightarrow ll$



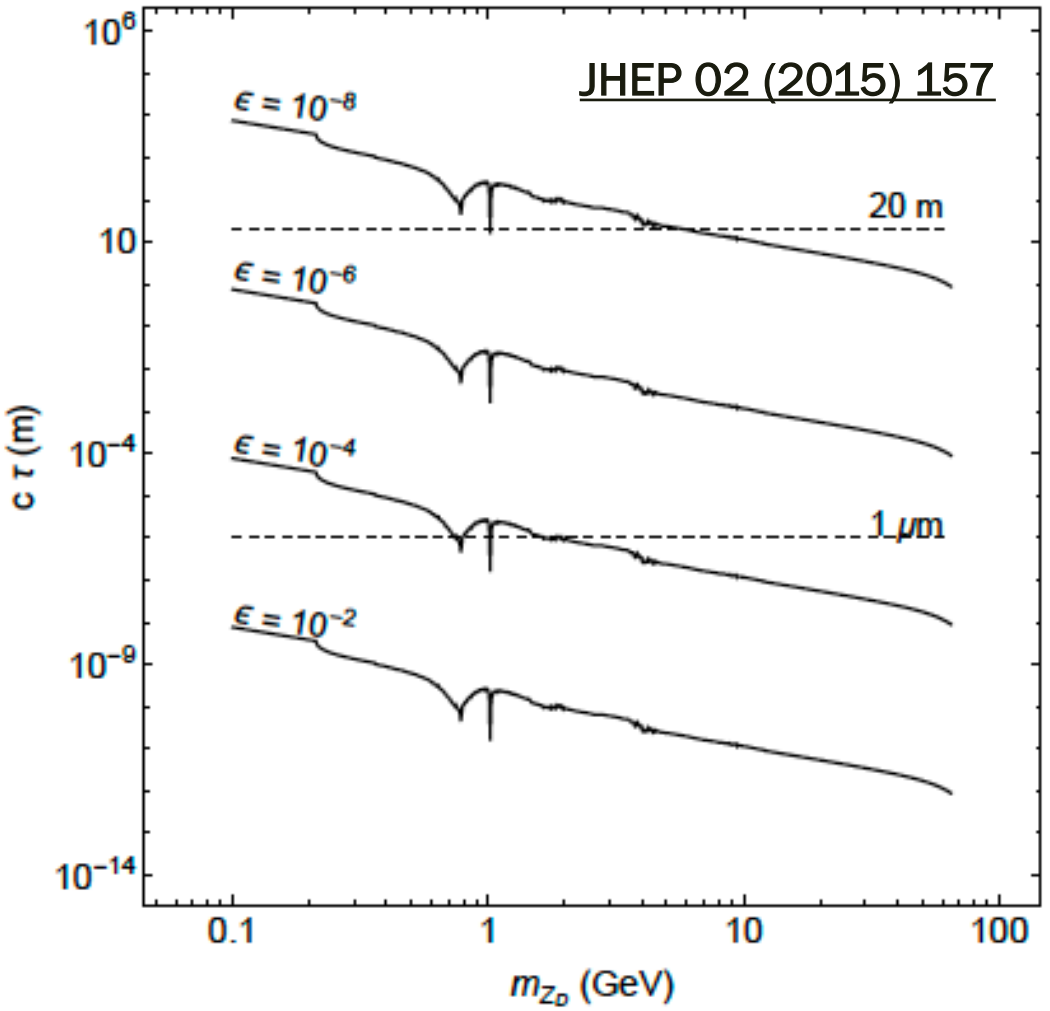


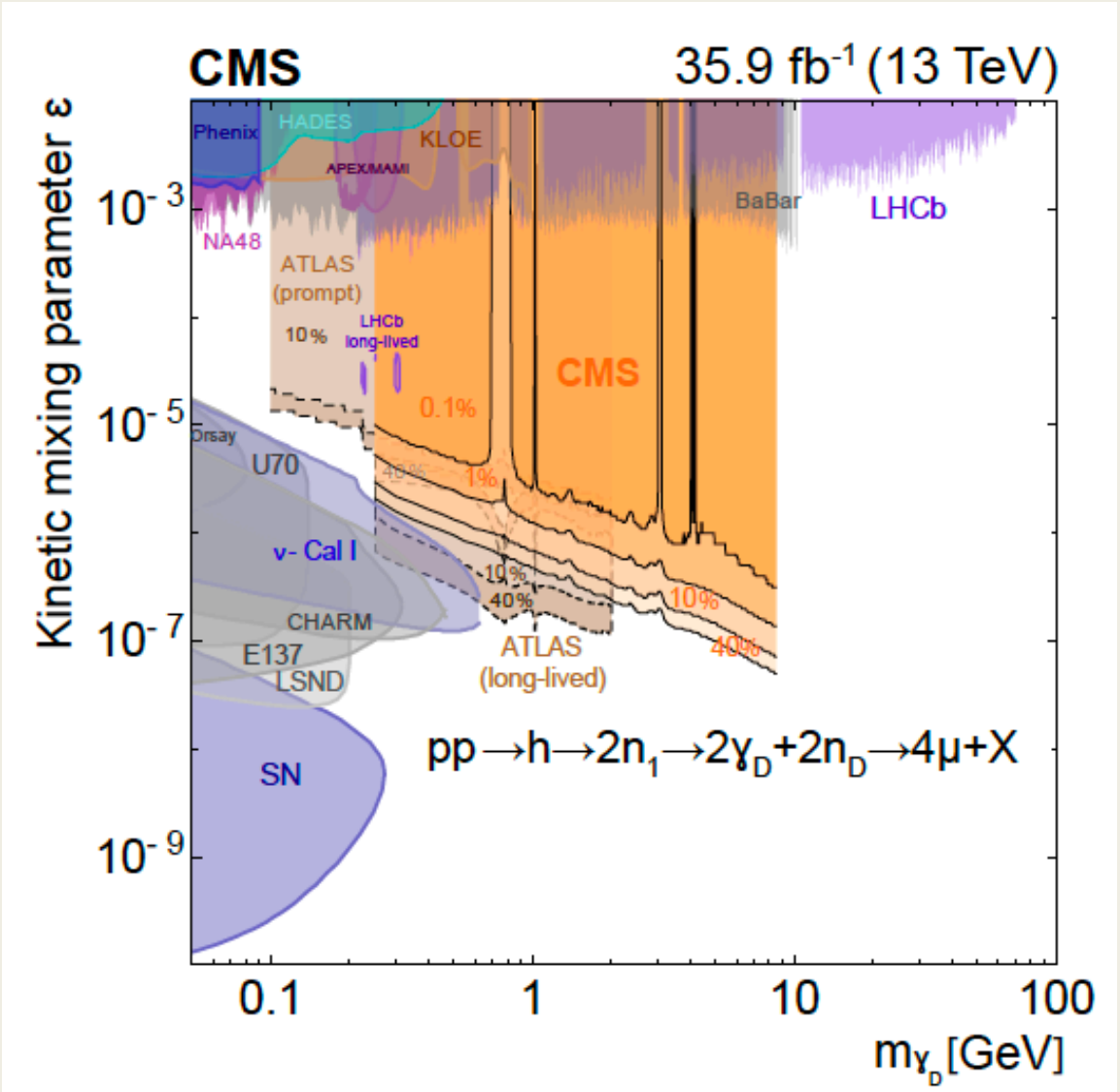
arXiV:1608.08632

Previous constraints

Projections

Kinetic Mixing – ATLAS / CMS Bounds





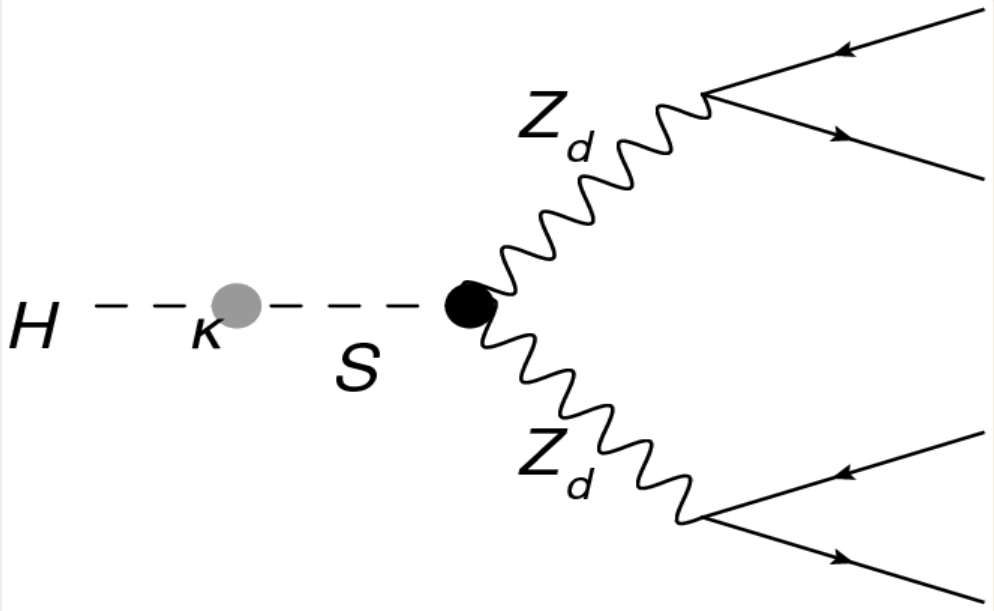
Dark Photon may be prompt or long lived depending of ε and its mass

Phys. Lett. B 796 (2019) 131

The Higgs Portal

Phys. Rev. D 90, 075004 (2014)

$\epsilon_h |h|^2 |\phi|^2$ exotic rare Higgs decays
rare meson decays



- There may be a dark Higgs boson; then there could also be a mixing between the SM Higgs boson (H) and the dark sector Higgs boson (S)

Dark Photon (A'), or Dark Z (Zd)
same thing …

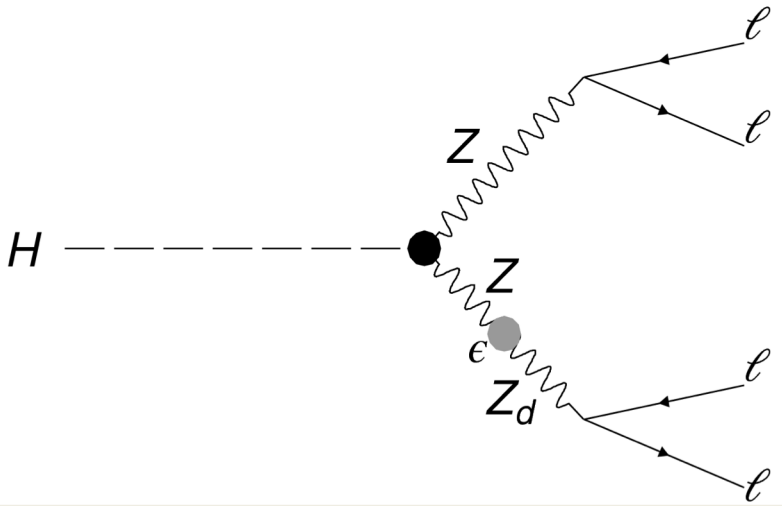
The mixing parameter κ between H and S, can be extracted from H → Zd Zd → 4l, a unique channel to access this parameter

Mass Mixing between SM Z and Zd

- In addition to kinetic mixing, there could be also a mass mixing between SM Z and Zd

Phys.Rev. D 88.1 (2013) 015022

Phys.Rev. D 85 (2012) 115019



$$O_{A,X} = c_{A,X} H X_\mu Z_d^\mu \,, \qquad (2)$$

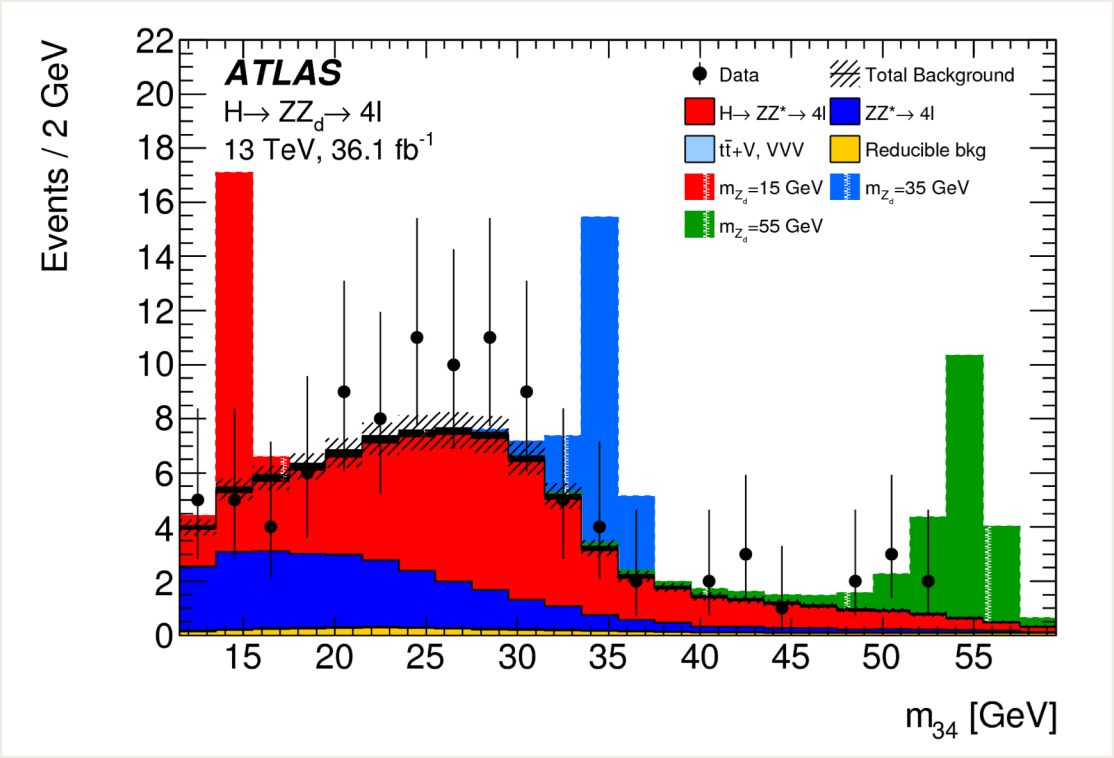
For operators of type $O_{A,X}$ in Eq. (2), we will focus on $X = Z$. Such interactions are typically associated with mixing. For example, the mass term for Z-Z_d mixing can be parametrized as $\varepsilon_Z \, m_Z^2 Z Z_d$, with

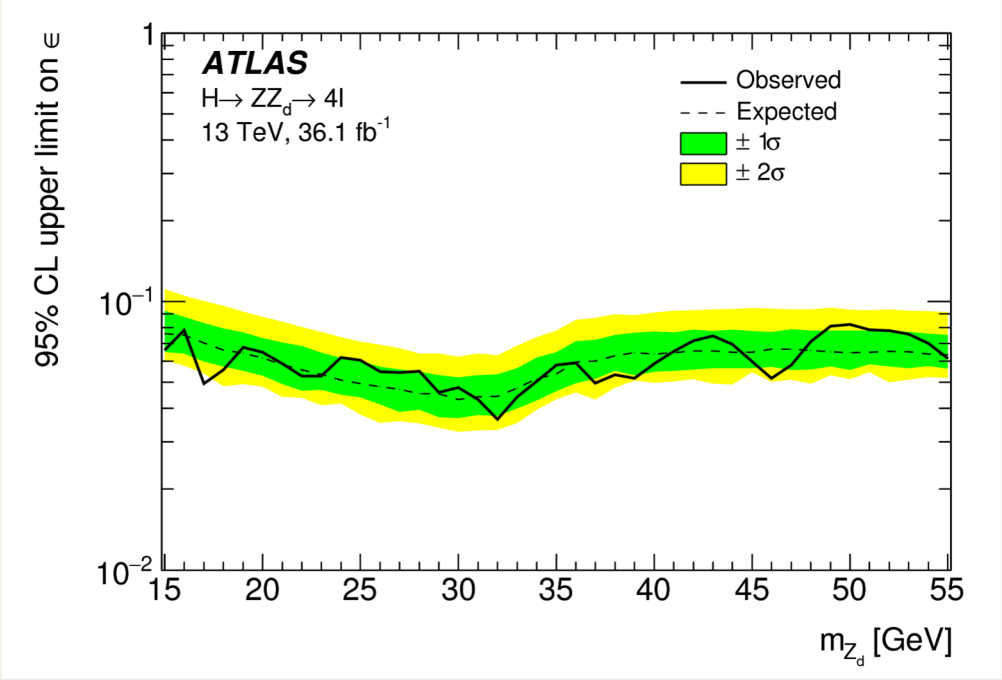
$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta \,, \qquad (4)$$

H → Z Zd → 4l is sensitive to the kinetic mixing parameter ε, and to Z-Zd mixing parameter δ. Unique channel to extract δ

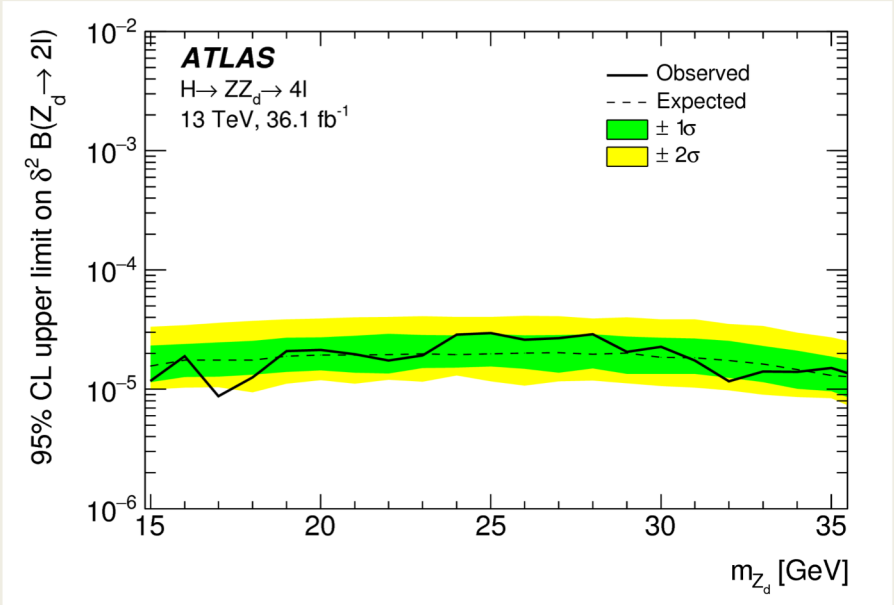
H → Z Zd → 4 leptons

JHEP 06 (2018) 166



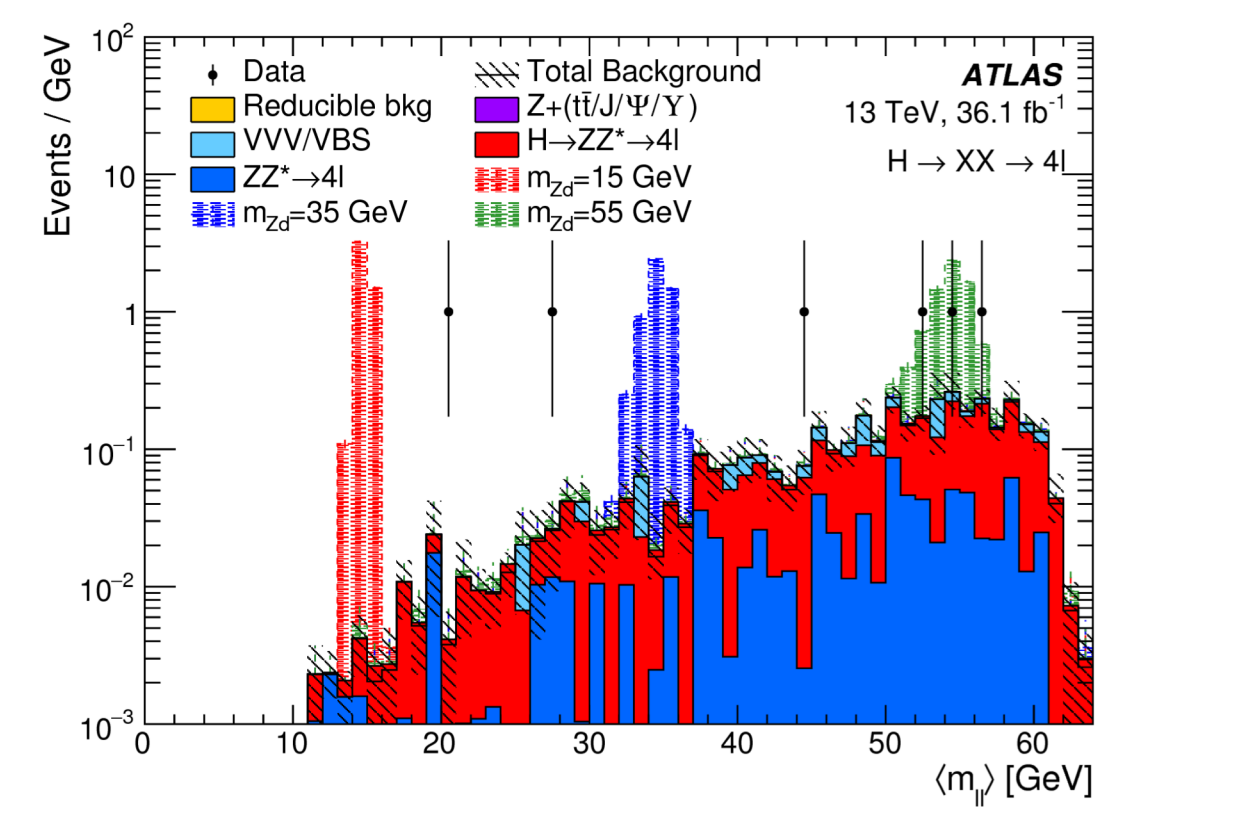


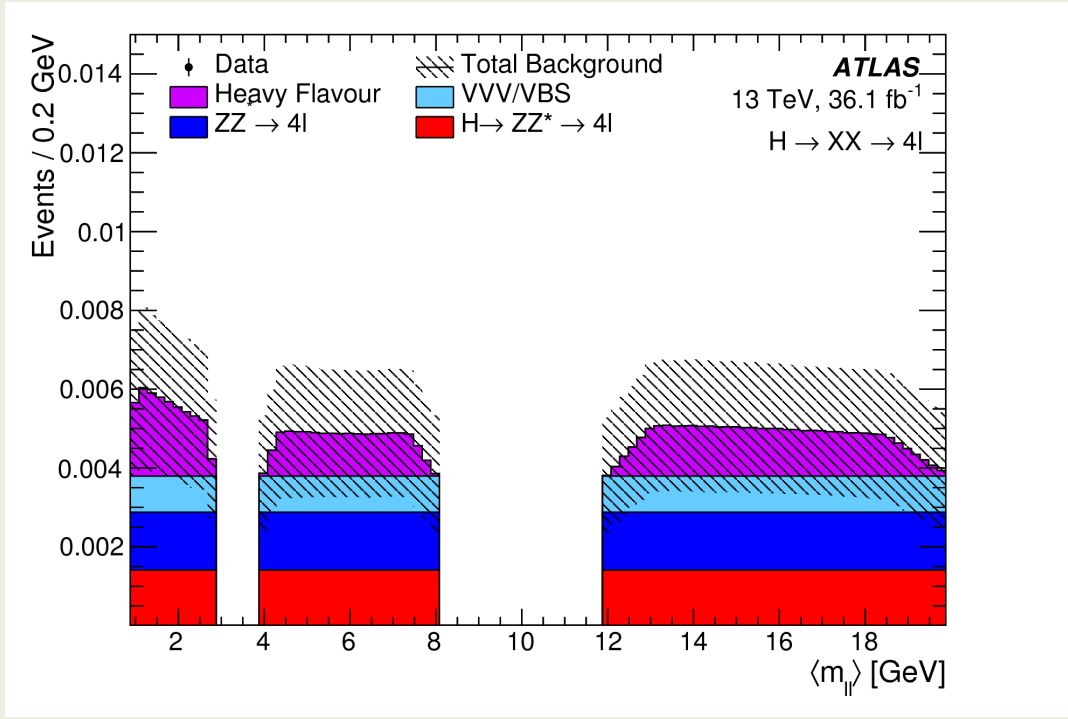
Bound on ε from H → ZZd not competitive. However, this channel is unique to get Z-Zd mixing parameter δ



- No excess of events found
- A constraint on the kinetic mixing parameter between the SM and the dark sector, and on the Z-Zd mass mixing parameter could be derived

H → Zd Zd → 4 leptons





- No excess of events found
- A constraint on the mixing parameter between the SM Higgs boson and the dark sector Higgs boson could be derived

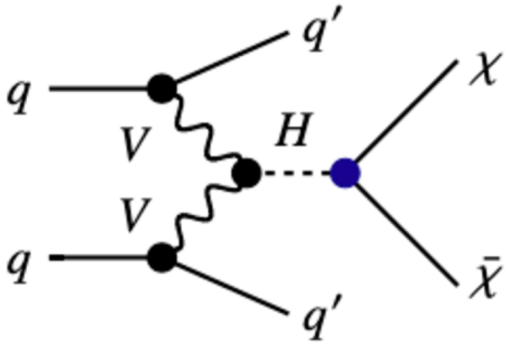
Analysis continues with searches for generic scalar of mass up to 1 TeV decaying into 4l, with dark vector bosons in the intermediate state

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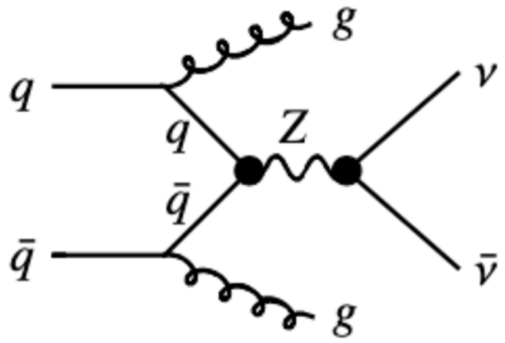
H → invisible

- **Some Dark Sector particle χ, neutral and stable over the range of the detector**
  - *It is not a neutrino. A Beyond-SM-Particle*
  - *Its mass $m_\chi < m_H / 2$ such that H → $\chi\chi$. The detector would be insensitive to such a decay so we call it H --> invisibles*
- **If it is "invisible", how do we detect it?**
  - *Since the particle c does not interact with the detector, it will escape, undetected, with some kinetic energy*
  - *By using conservation of 4-moment, after accounting for all the other detected, particles, we can infer how much energy/momentum is carried, therefore missing*
  - *So we can measure the missing energy or the missing momentum*
  - **χ could be a candidate for Dark Matter particle**

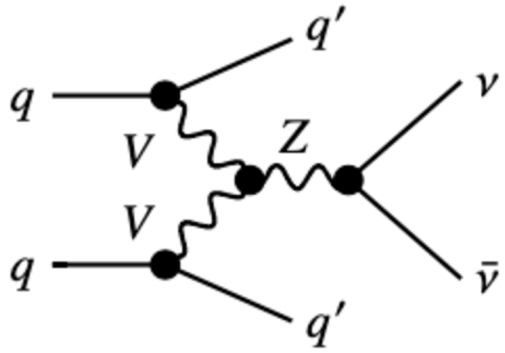
H → invisible



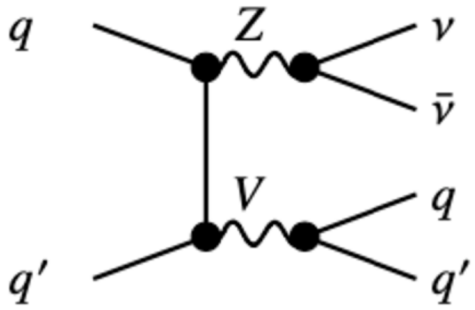
(a) Signal process



(b) Example diagram for the strong Z+jets background process

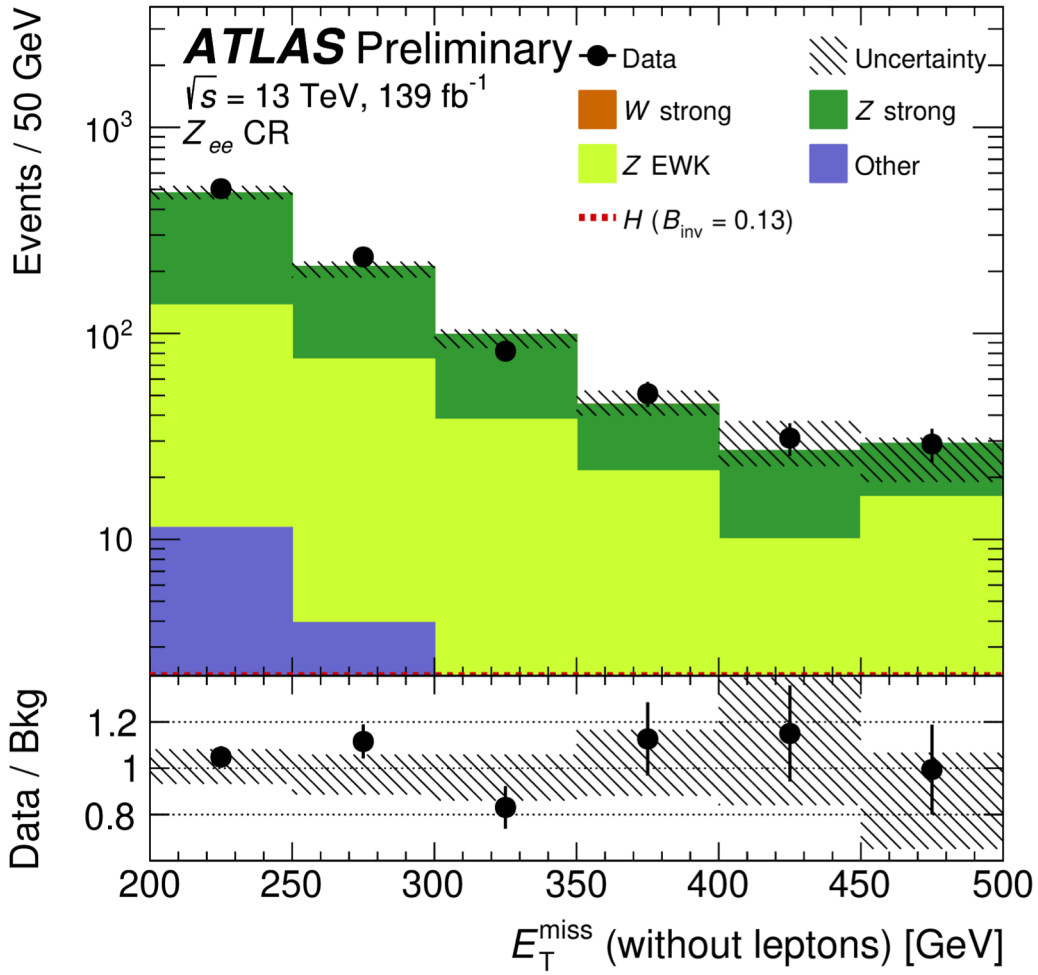


(c) Example diagram for the electroweak VBF Z+jets background process



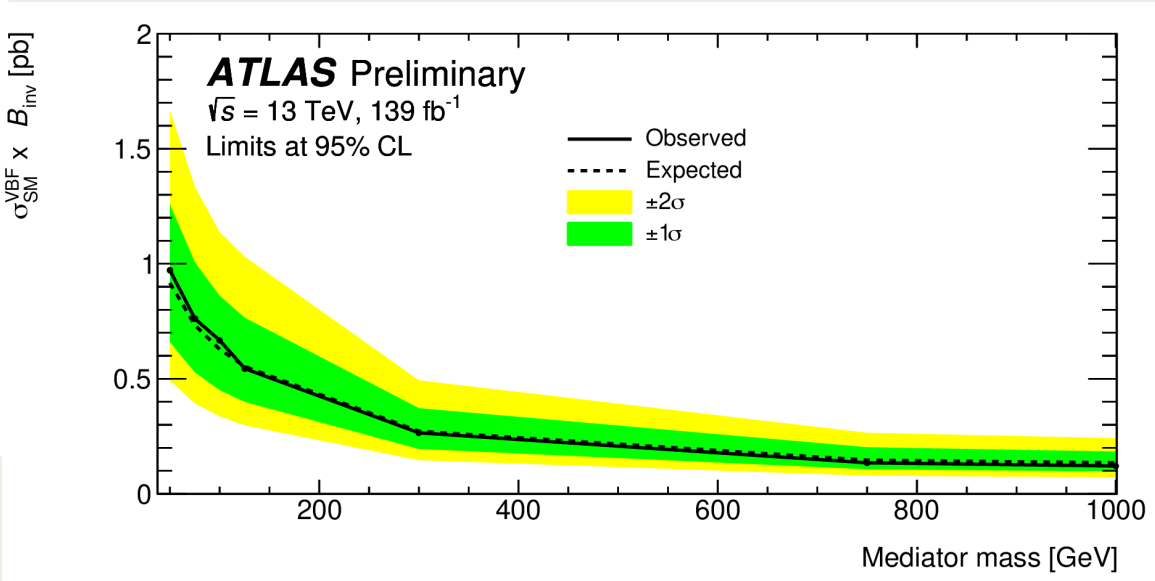
(d) Example diagram for the electroweak diboson process

H → invisible



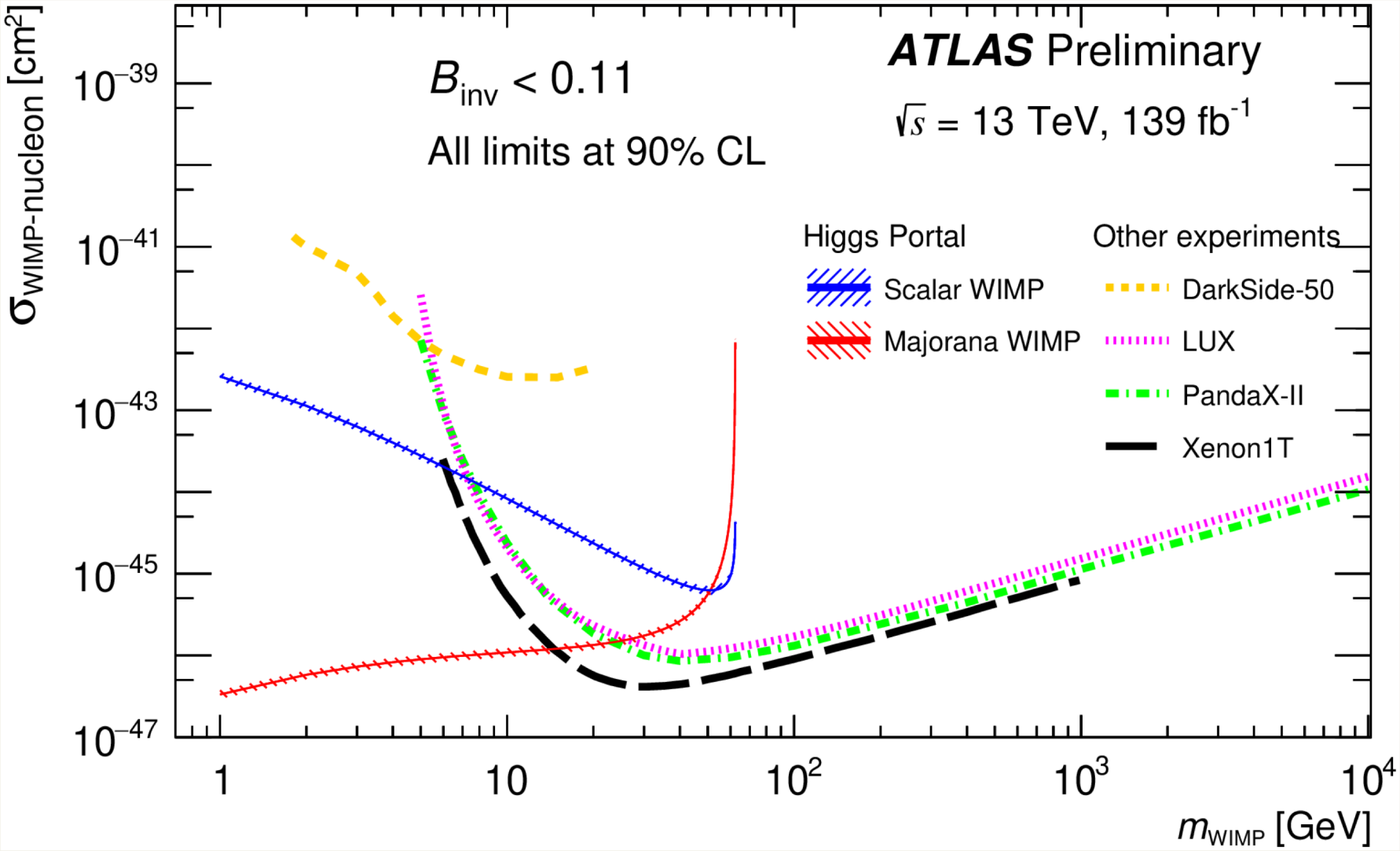
Branching Ratio Limit < 0.13 at 95% Confidence Level

Upper bound on the Cross Section x BR of a generic scalar



H → invisible — Dark Matter interpretation

Upper bound of the DM-Nucleon Scattering Cross Section



Dark Interactions workshop series at BNL

- Started in 2014
- It is biennial
- 70-80 experts in the field gather for 3.5 days
  - *Talks and discussions*
  - *Exchanges of ideas*
  - *Networking and scientific collaboration*
- 4th in the series planned for 2020
  - *But cancelled because of COVID-19*
  - *Will resume in 2022*
- Organized at BNL
  - *In collaboration with BNL theory group and other institutes*



Conclusions

- The Standard Model of particle physics is a very successful theory
  - *Yet, there things we do not understand, e.g. the nature of Dark Matter*
- Dark Matter may be one particle in a rich Dark Sector
  - *it interacts weakly with the Standard Model Sector*
- The discovered Higgs boson may be used as probe or portal to the Dark Sector
  - *By searching for Dark Sector particles in the decays of the Higgs boson*
- So far, no signal of Dark Sector particles detected