Search for Higgs boson decay to invisible particles

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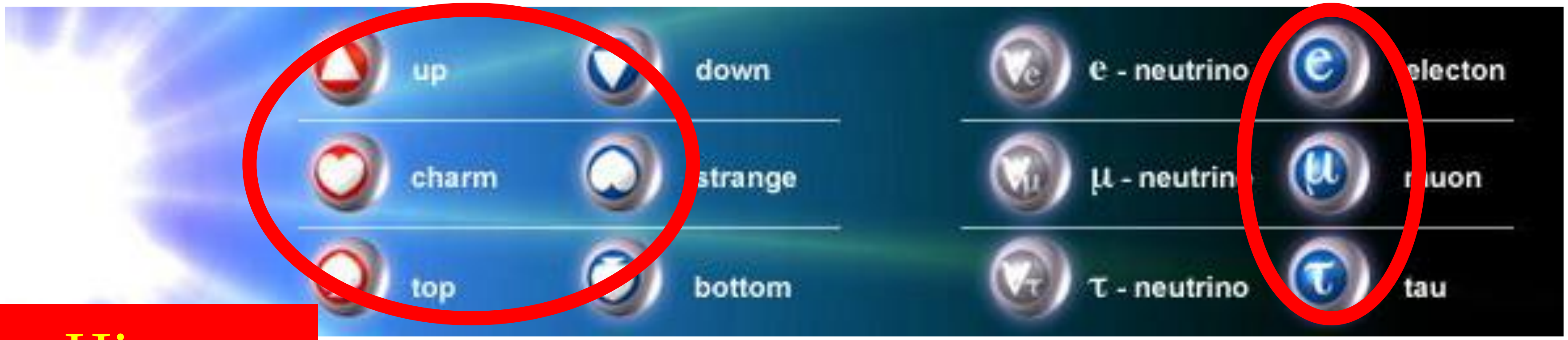
What we aim for …

- **Review Higgs boson discovery channels and properties**
- **The case for physics beyond the Standard Model of particle physics**
- **Search for dark sector states**
- **Higgs decay to invisible particle and interpretation for dark matter**

The ‘Standard Model’

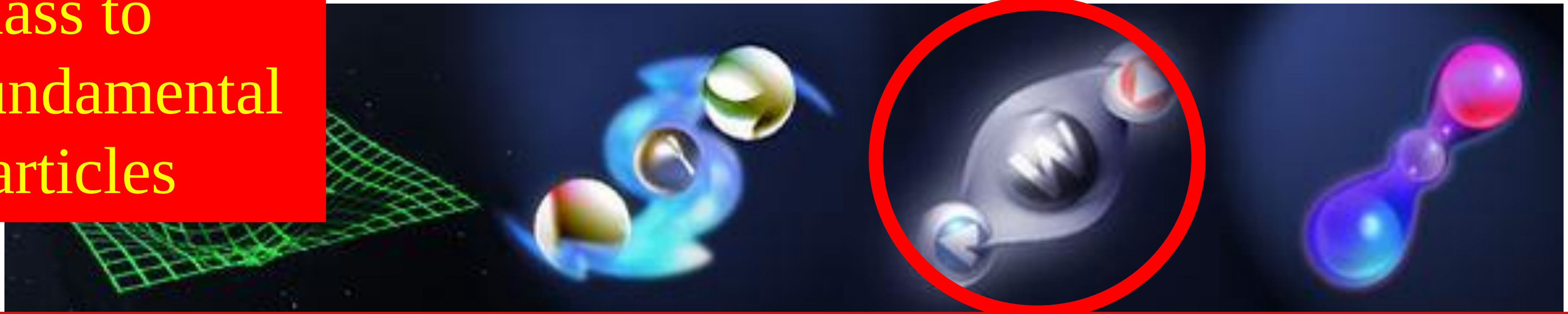
= Cosmic DNA

The matter particles



The Higgs boson gives mass to fundamental particles

The fundamental interactions



Gravitation | electromagnetism | weak nuclear force | strong nuclear force

Without Higgs …

… there would be no atoms

- massless electrons would escape at the speed of light

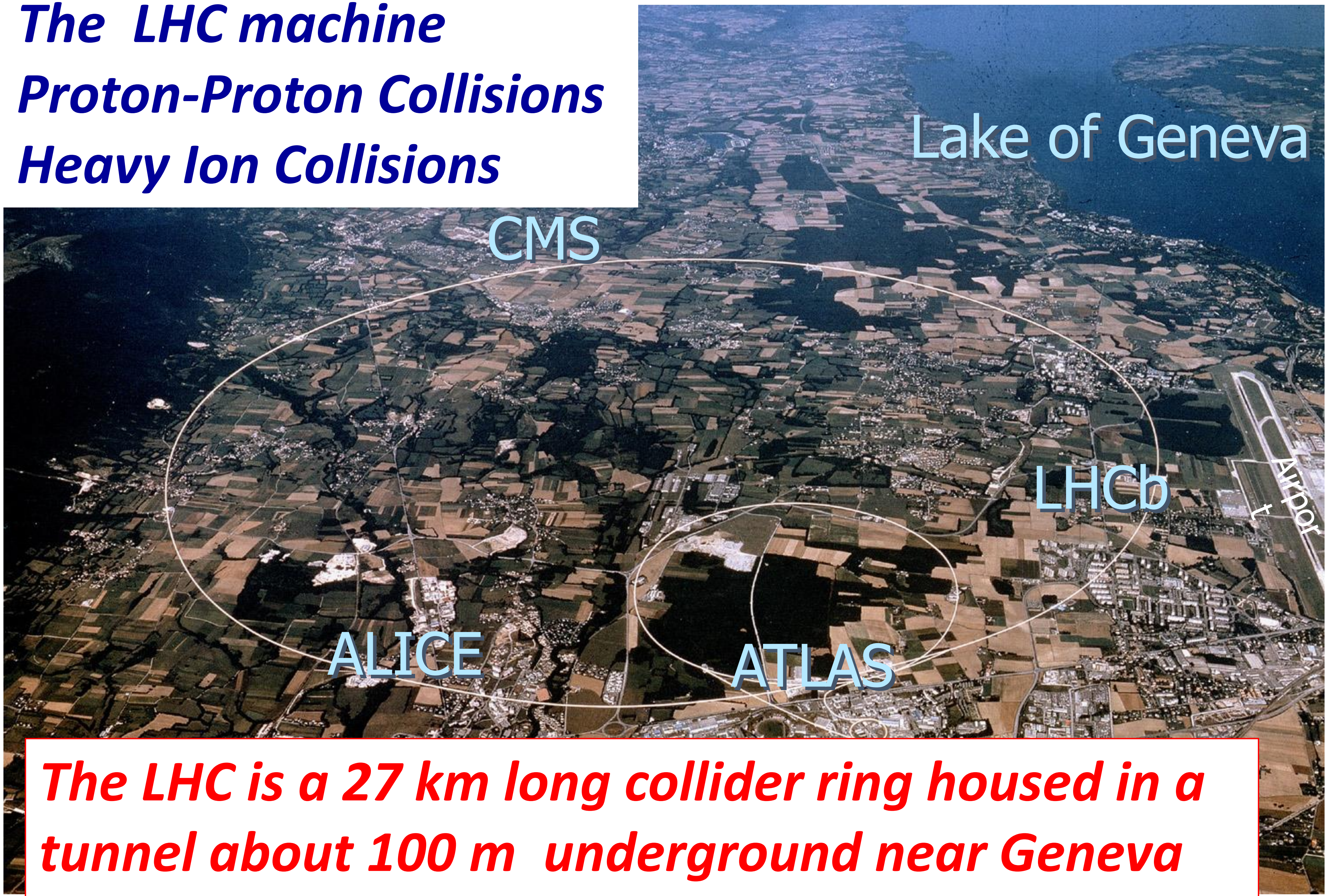
… there would be no heavy nuclei

… weak interactions would not be weak

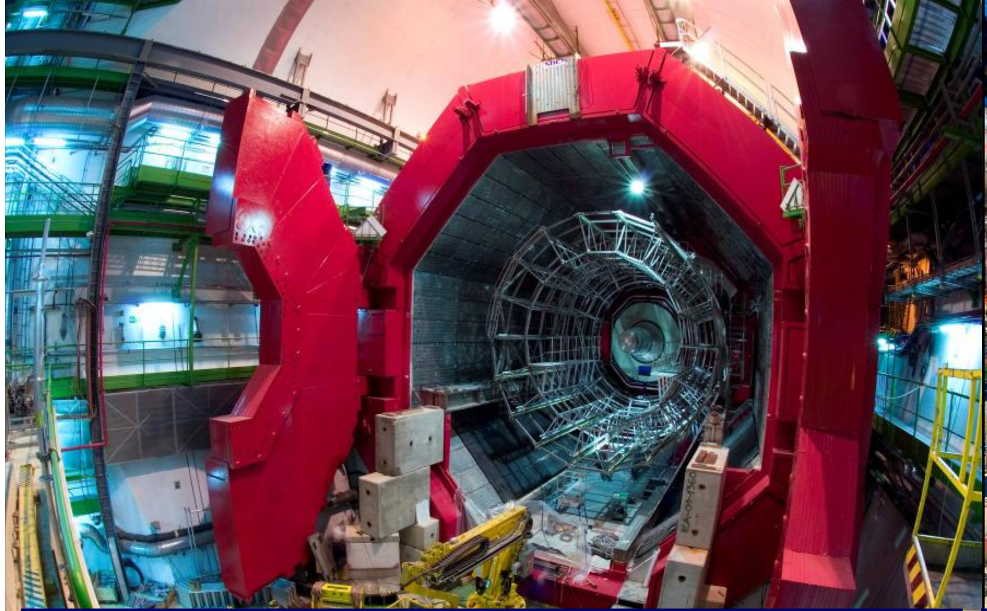
- Life would be impossible: everything would be radioactive

Its existence is a big deal!

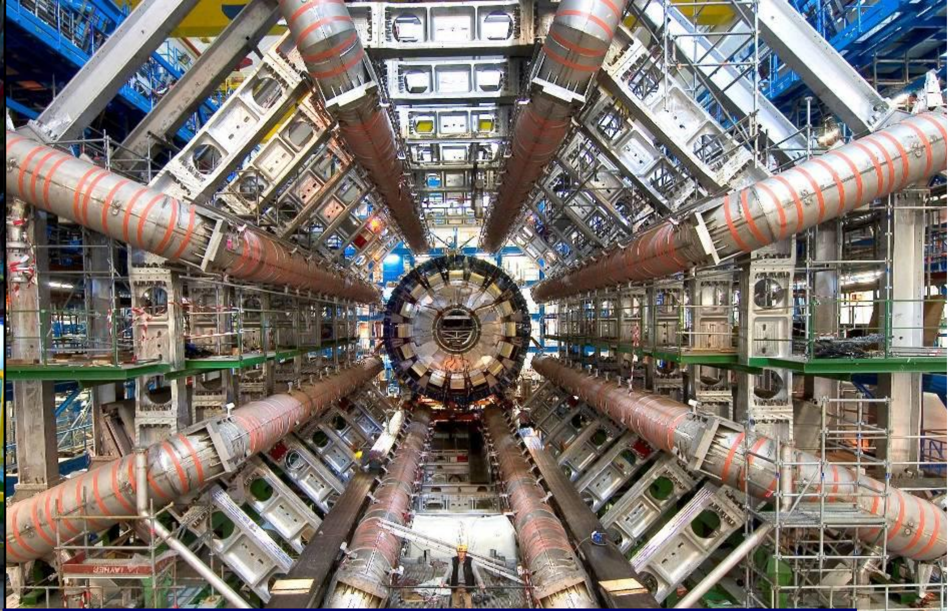
The LHC machine
Proton-Proton Collisions
Heavy Ion Collisions



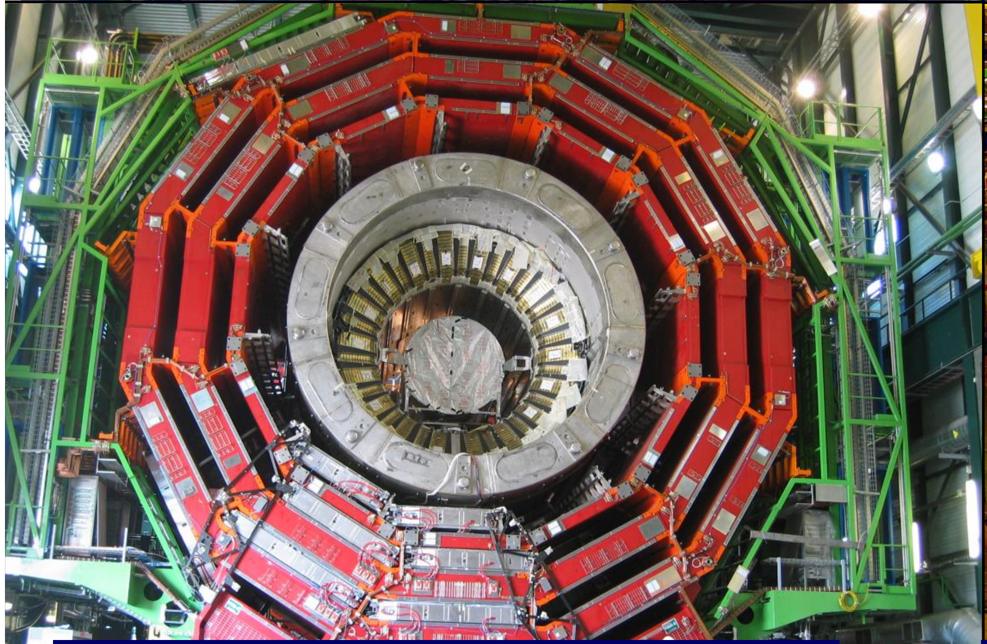
The LHC is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva



ALICE: Primordial cosmic plasma



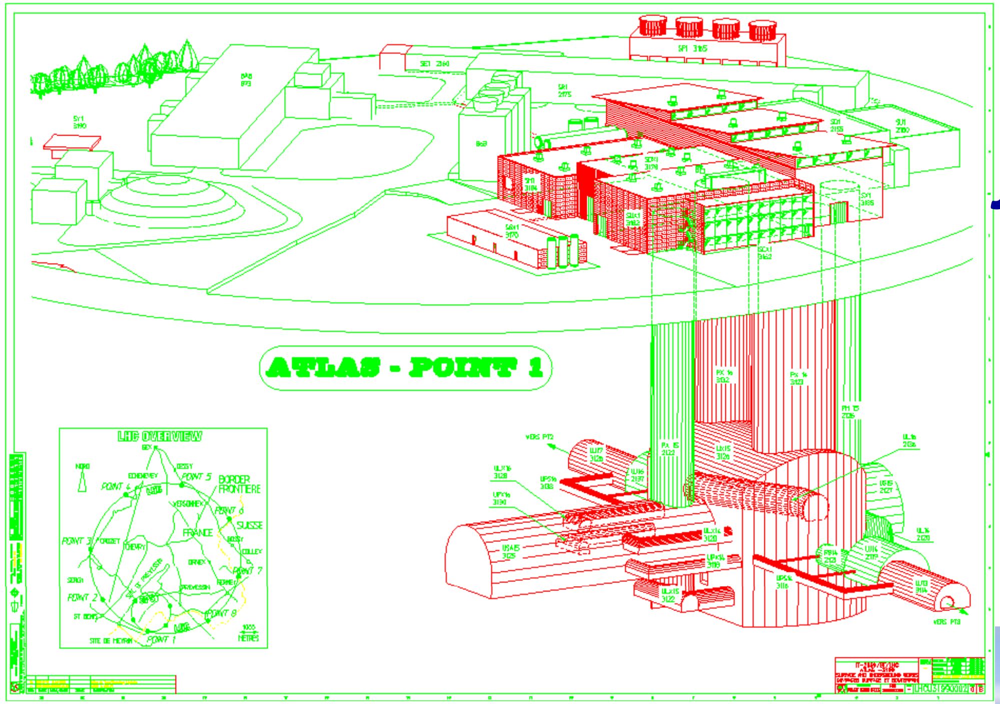
ATLAS: Higgs and dark matter



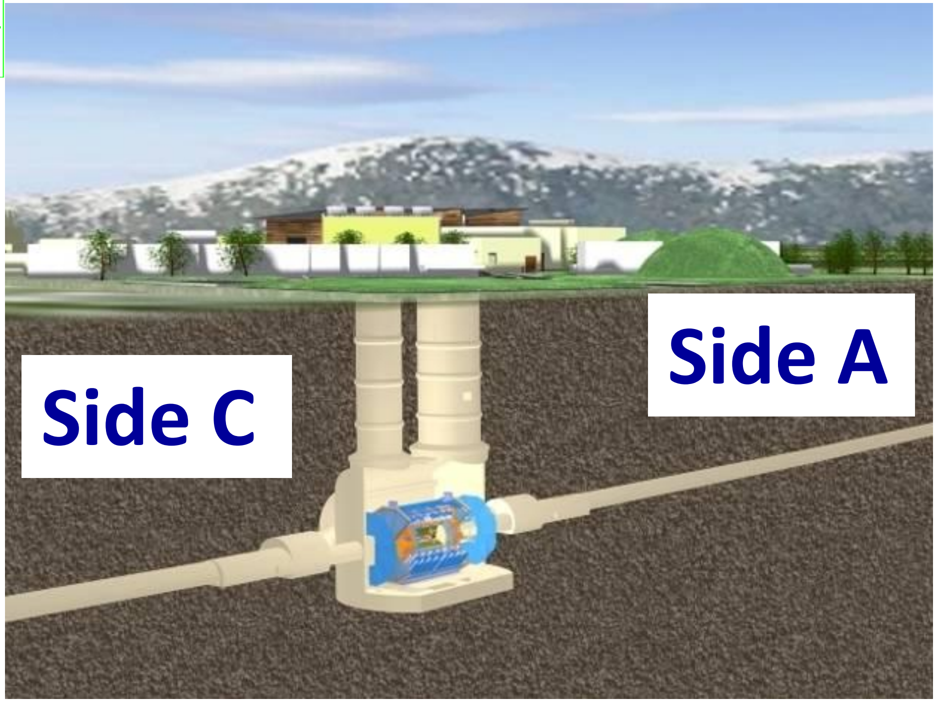
CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

The Underground Cavern for the ATLAS Detector



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

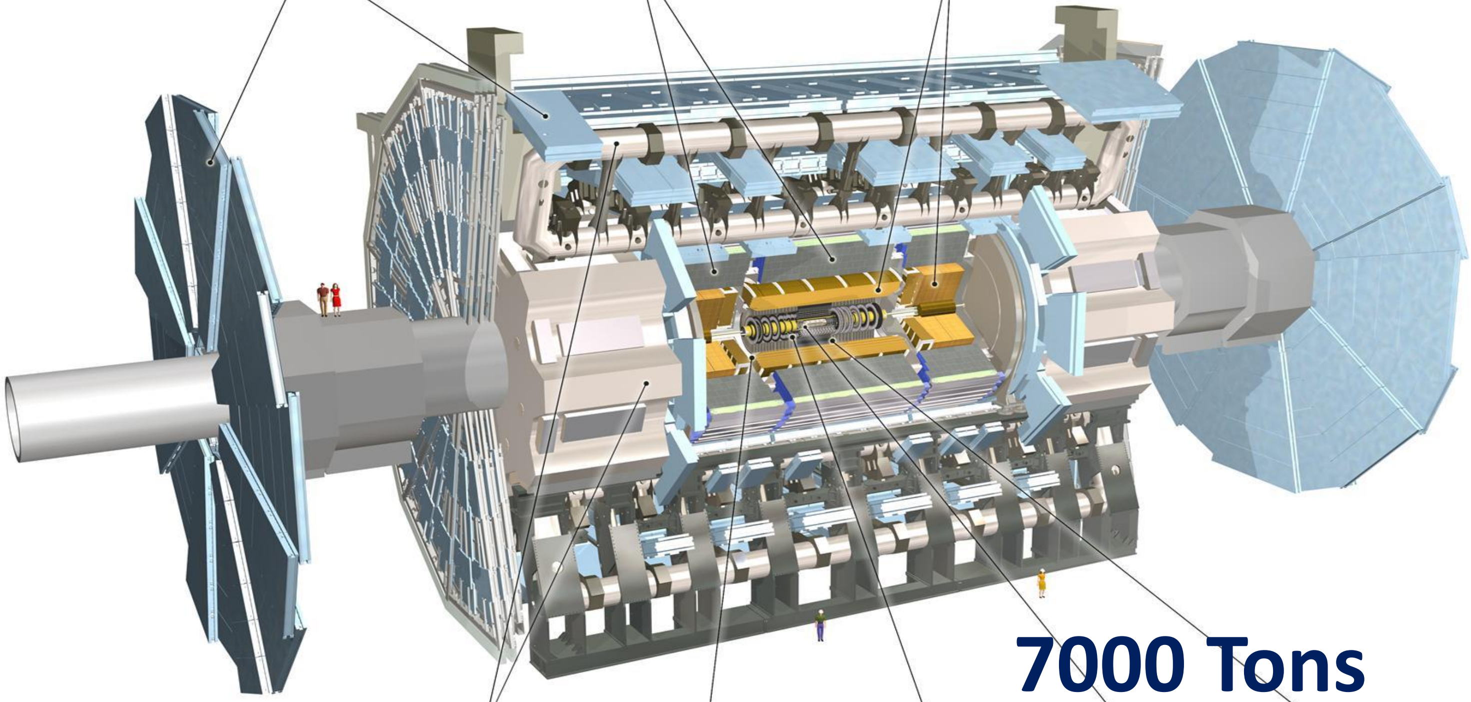


ATLAS Detector at the LHC

3300 Physicists
550M Suisse Franks

45 m

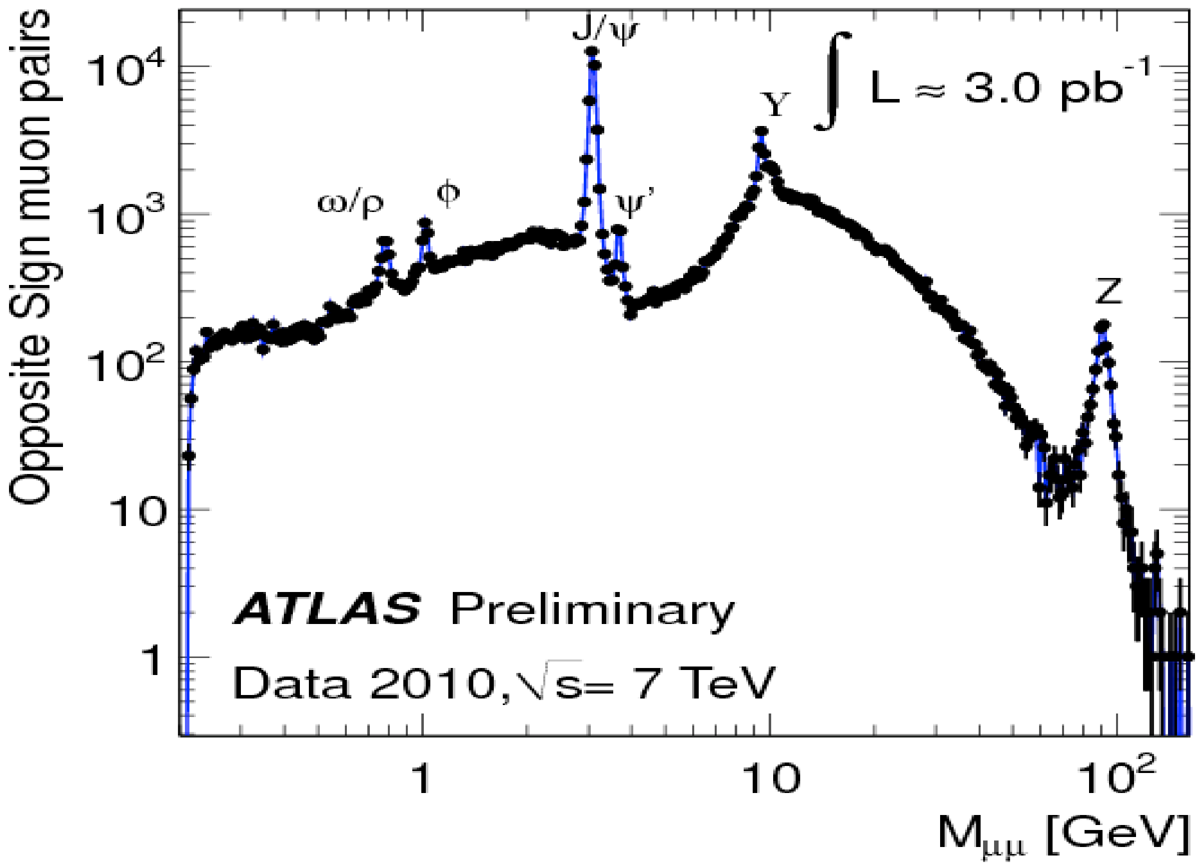
24 m



7000 Tons

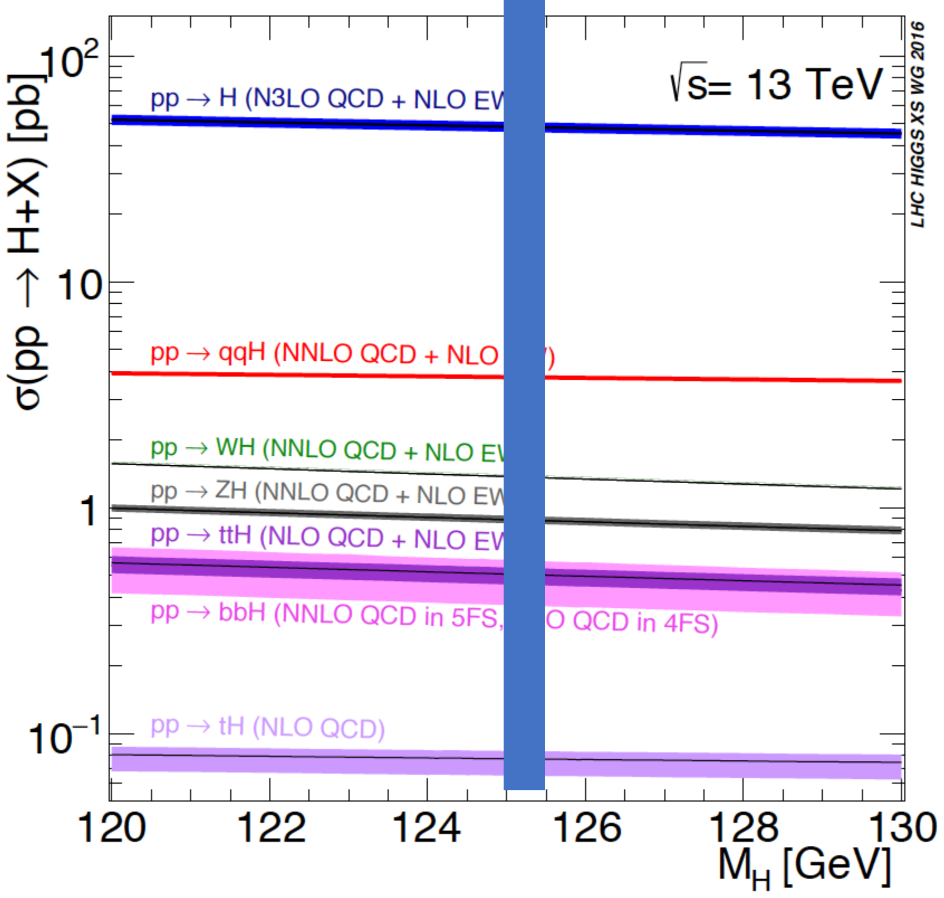
Confirming previous measurements or discoveries

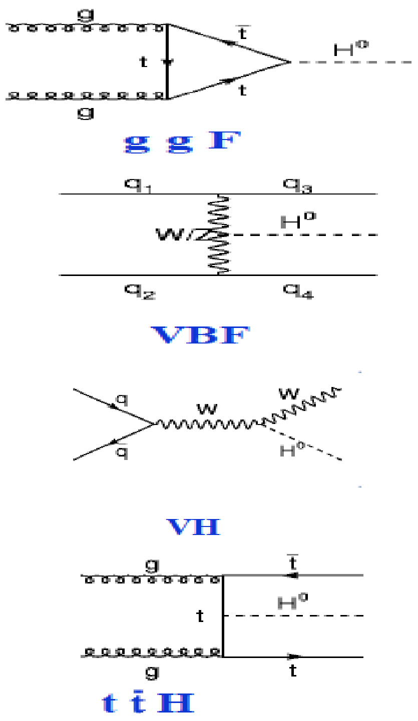
- Before we do new searches, we have to show that we measure accurately what is already known

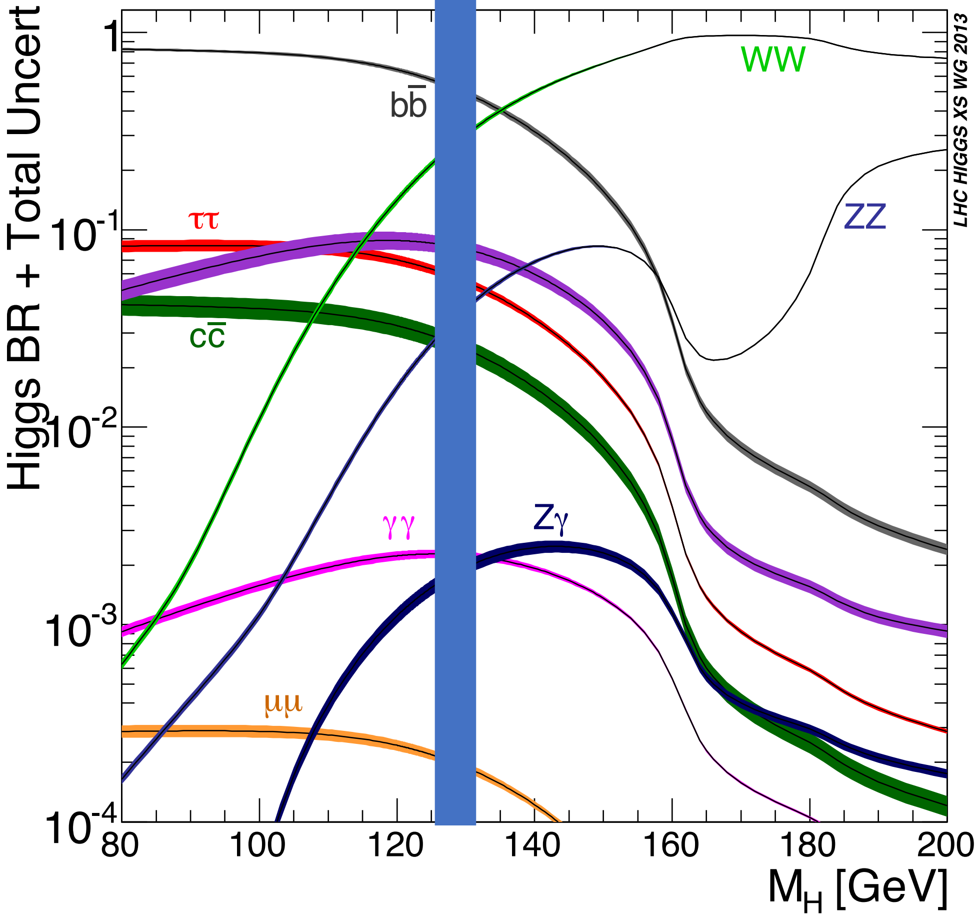


Higgs boson production and decays

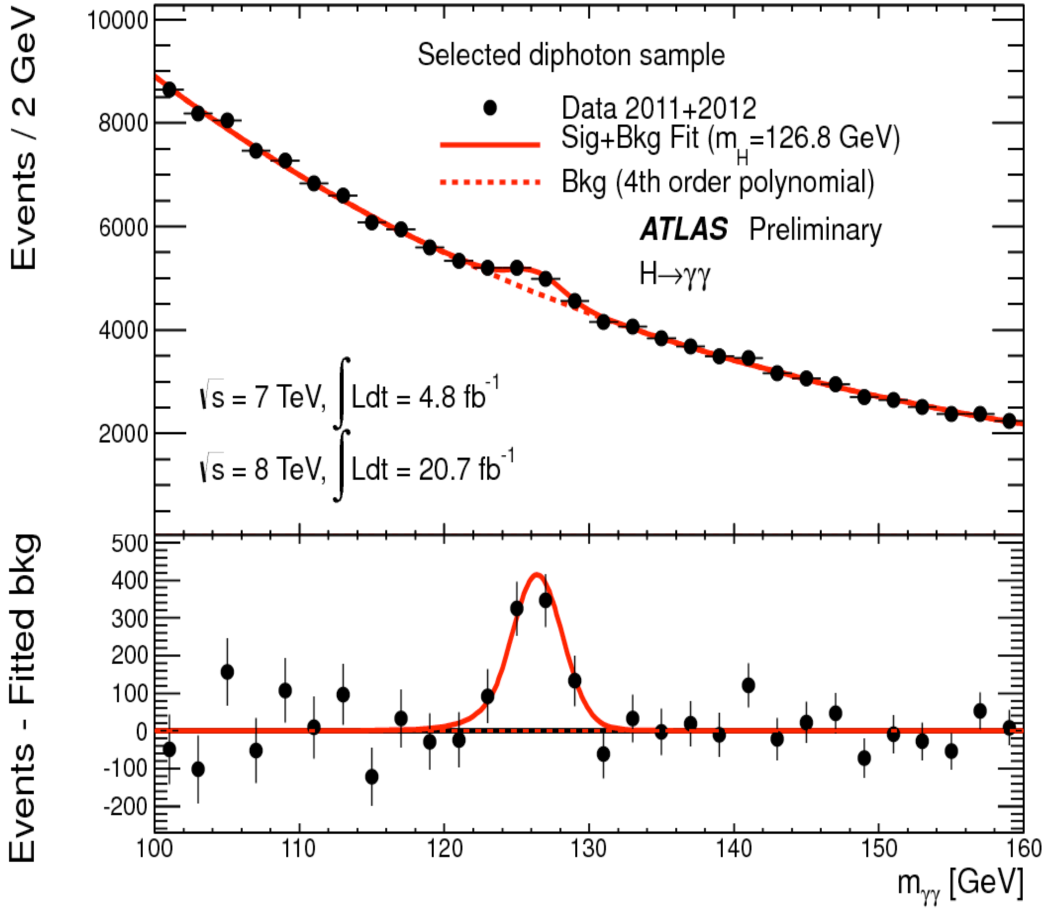
The ATLAS CMS Experiments at the LHC have discovered, independently, a Higgs boson with mass around 125 GeV using these productions and decay modes



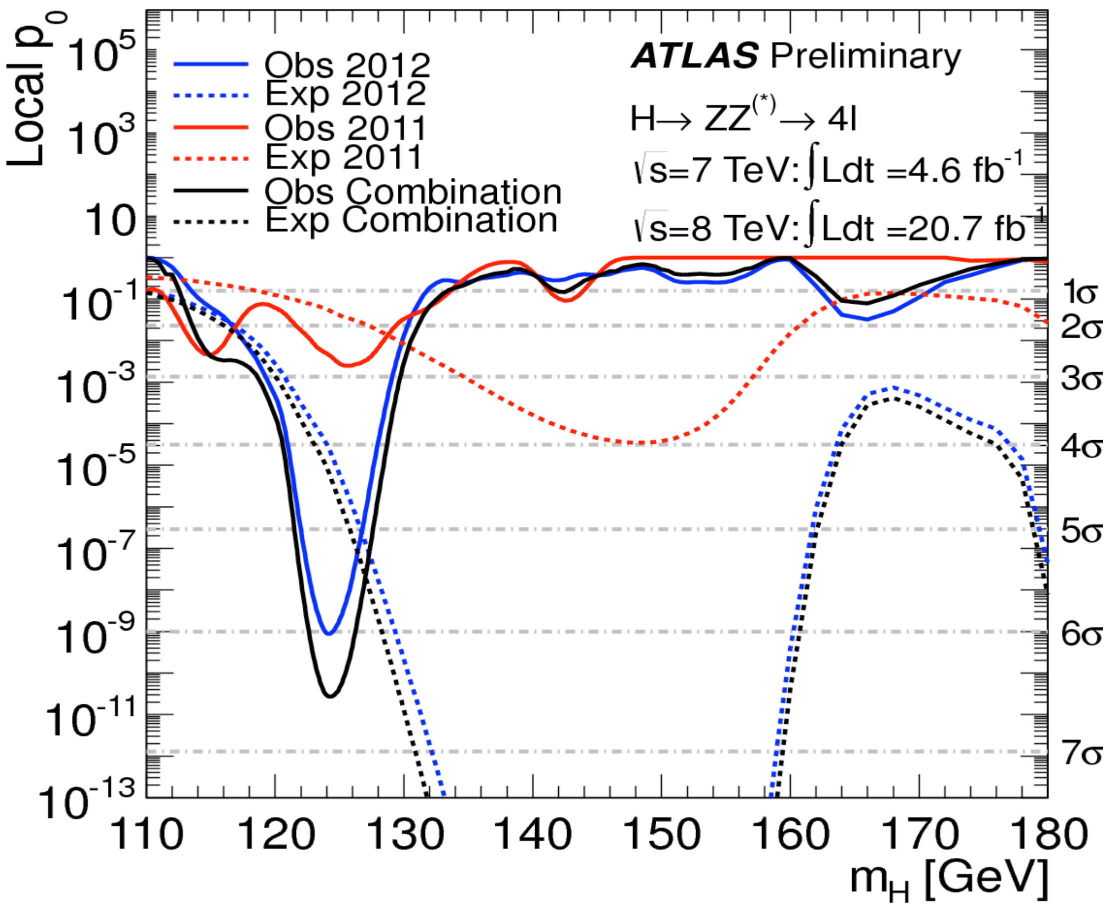




The Higgs Boson Discovery

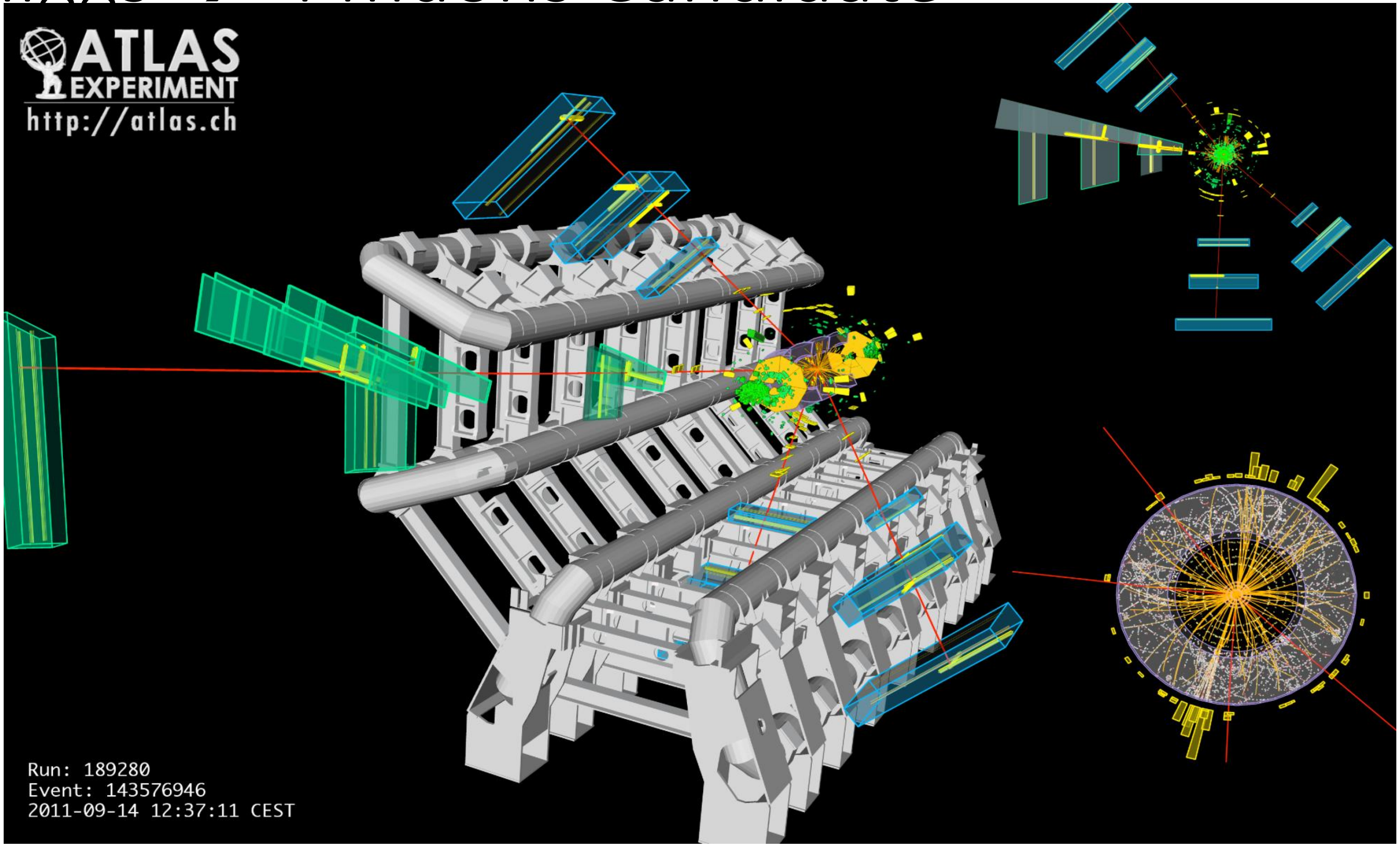


Single channel discovery: 7.4σ

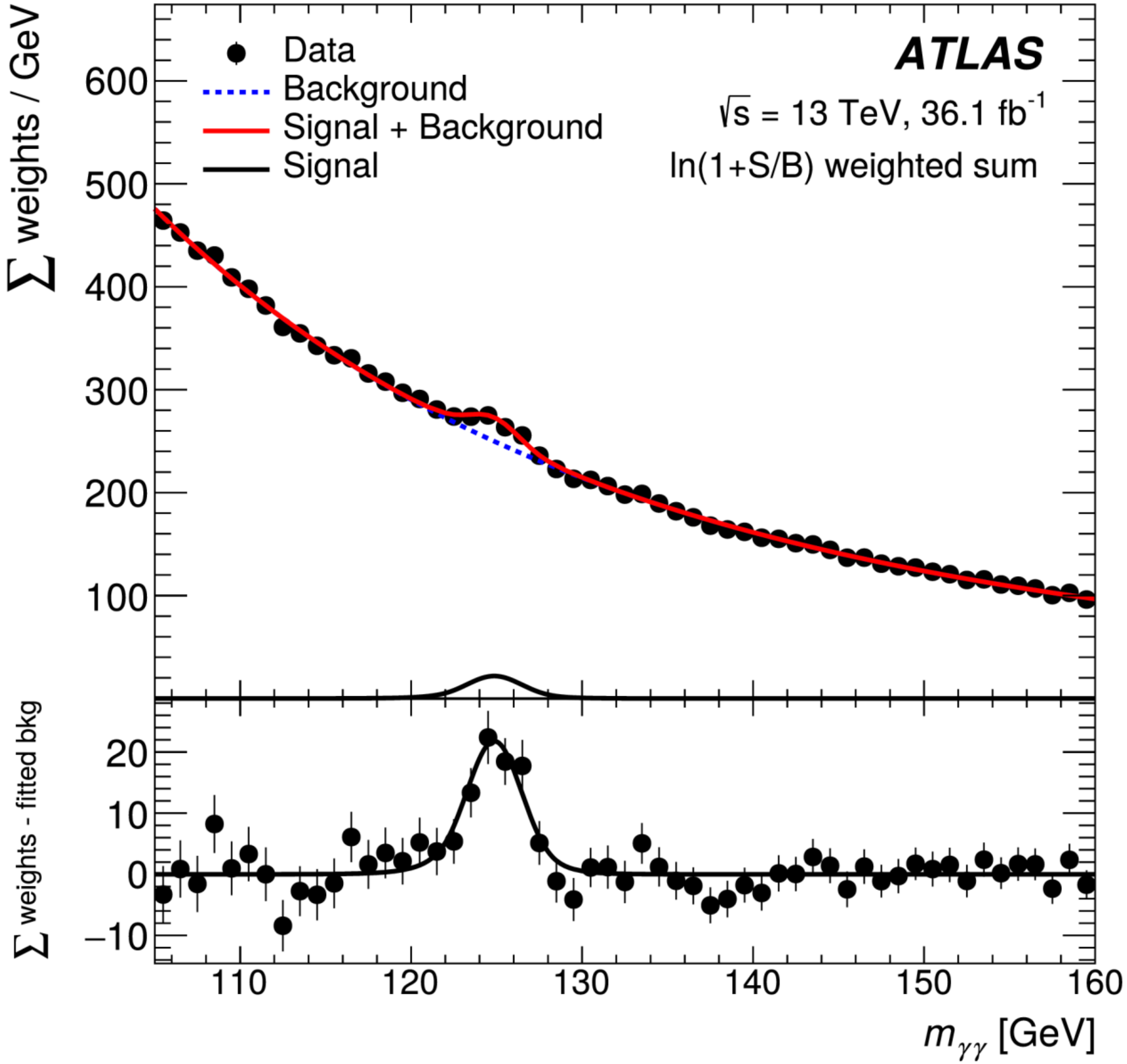


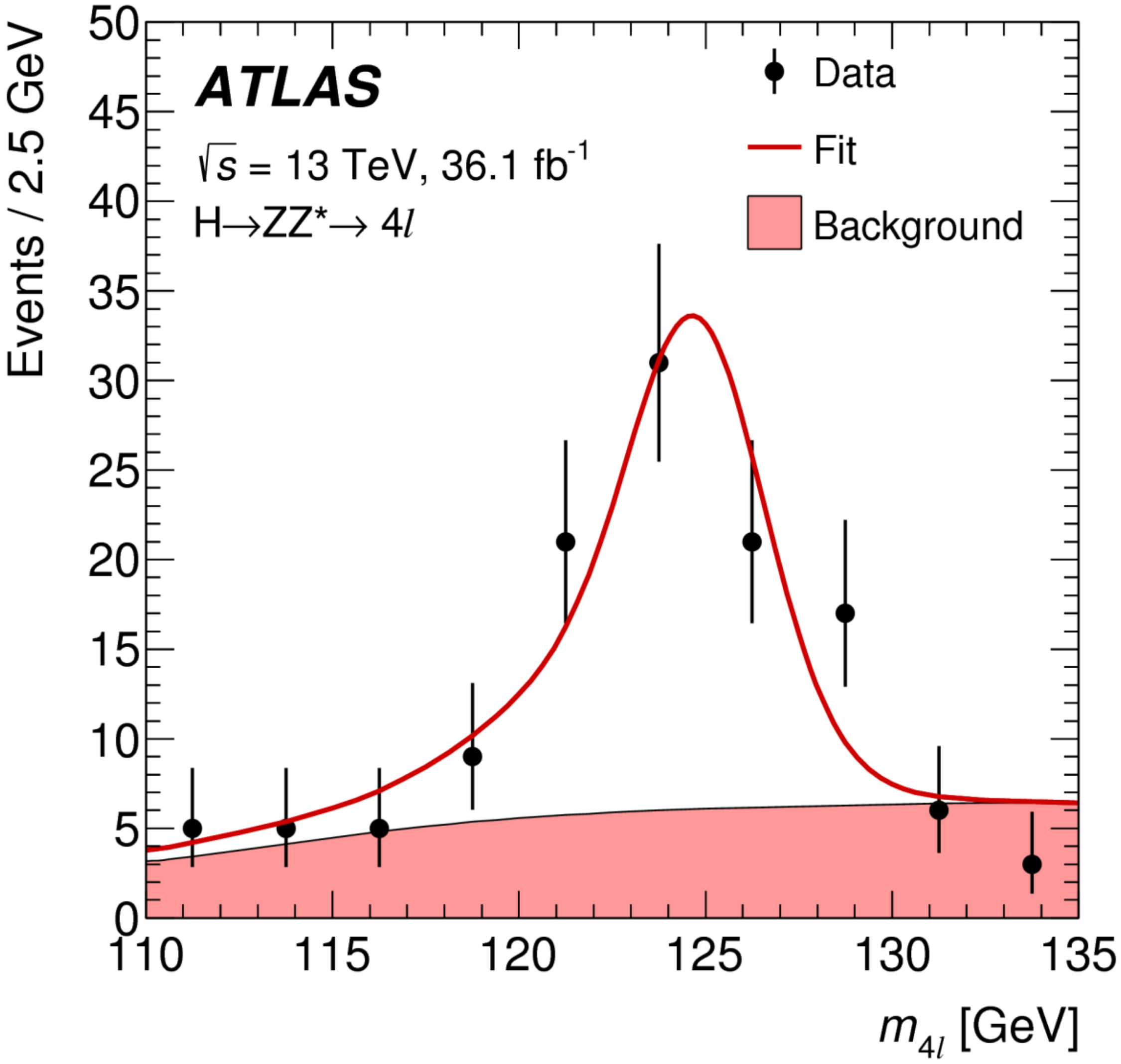
Single channel discovery: 6.6σ

Higgs → 4 muons Candidate



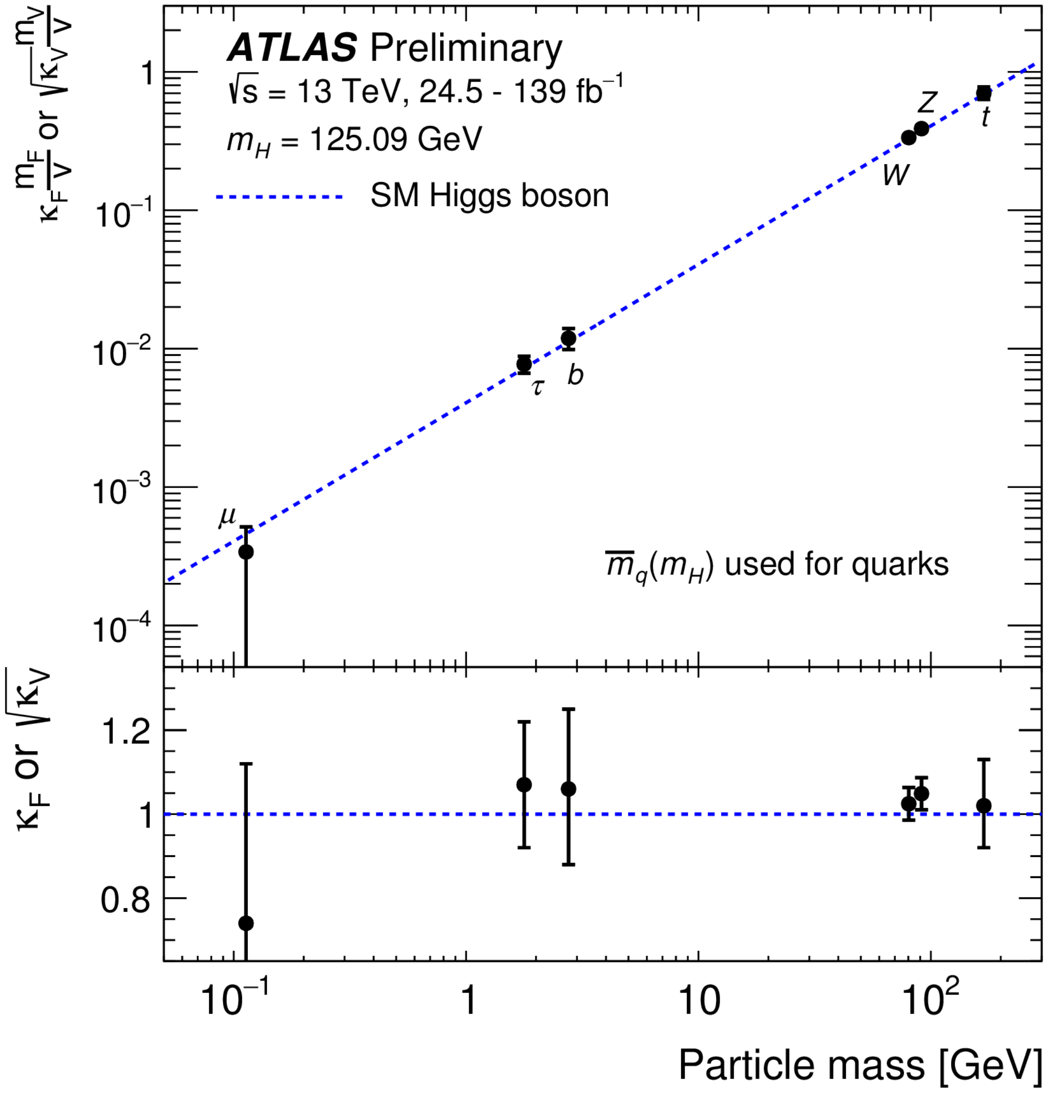
Higgs →γγ, ZZ





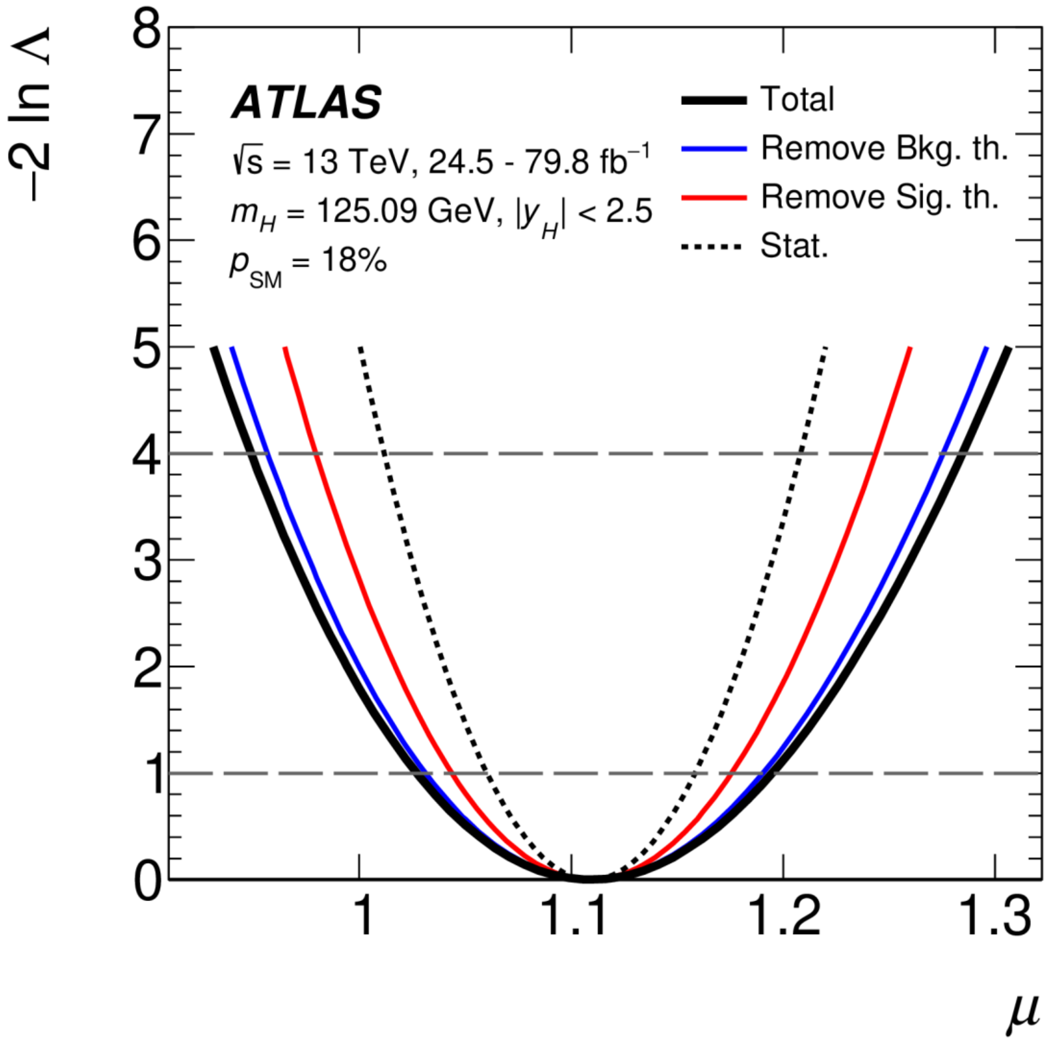
Discovery confirmed in later measurements

Higgs coupling measurements

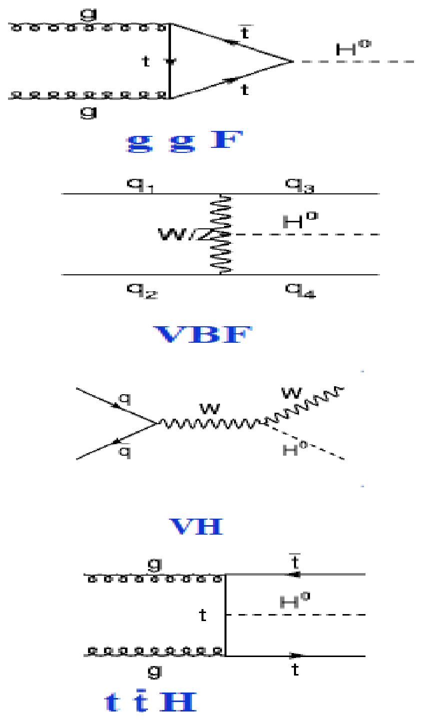


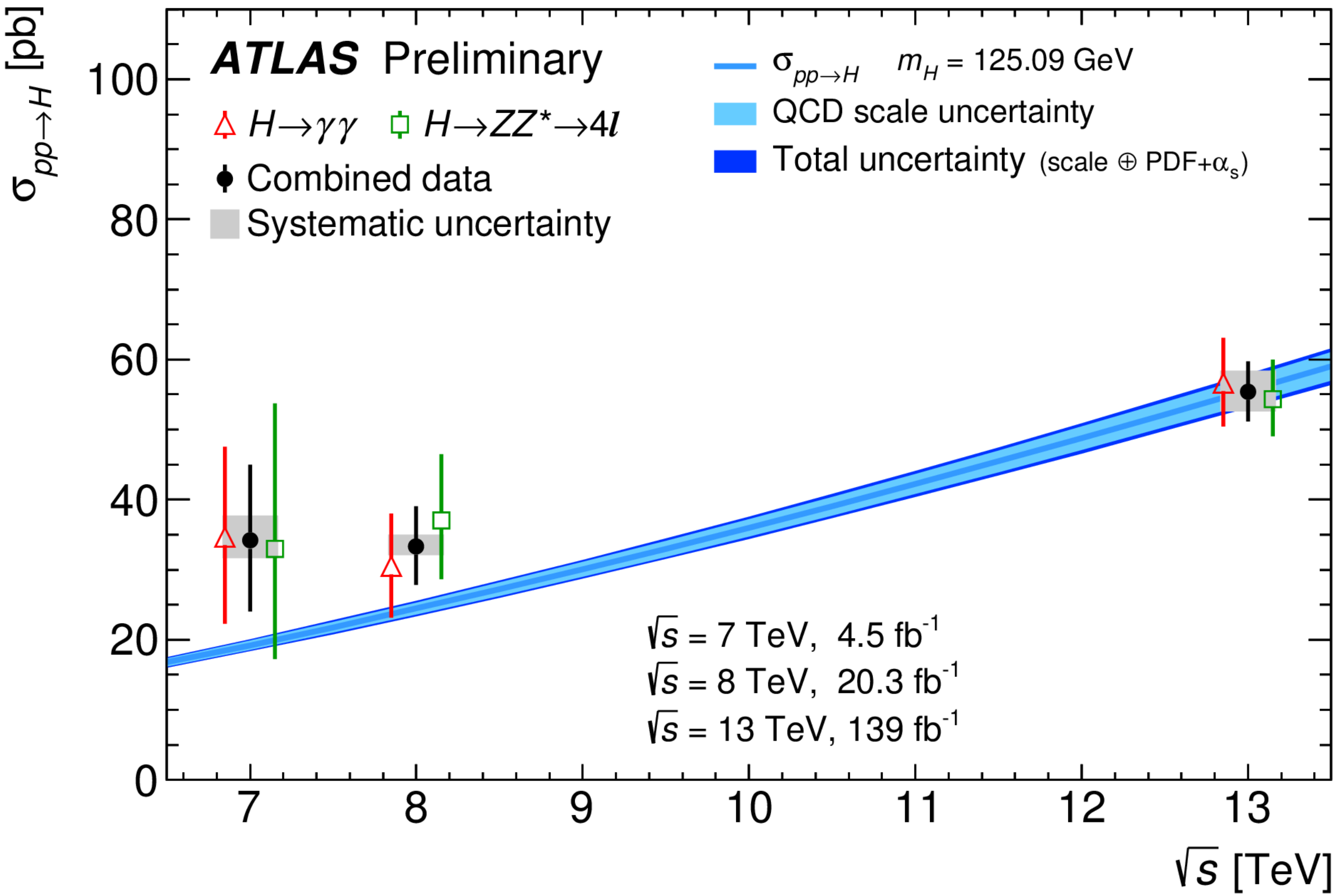
Signal Strength relative to SM

μ=1.11+0.09−0.08



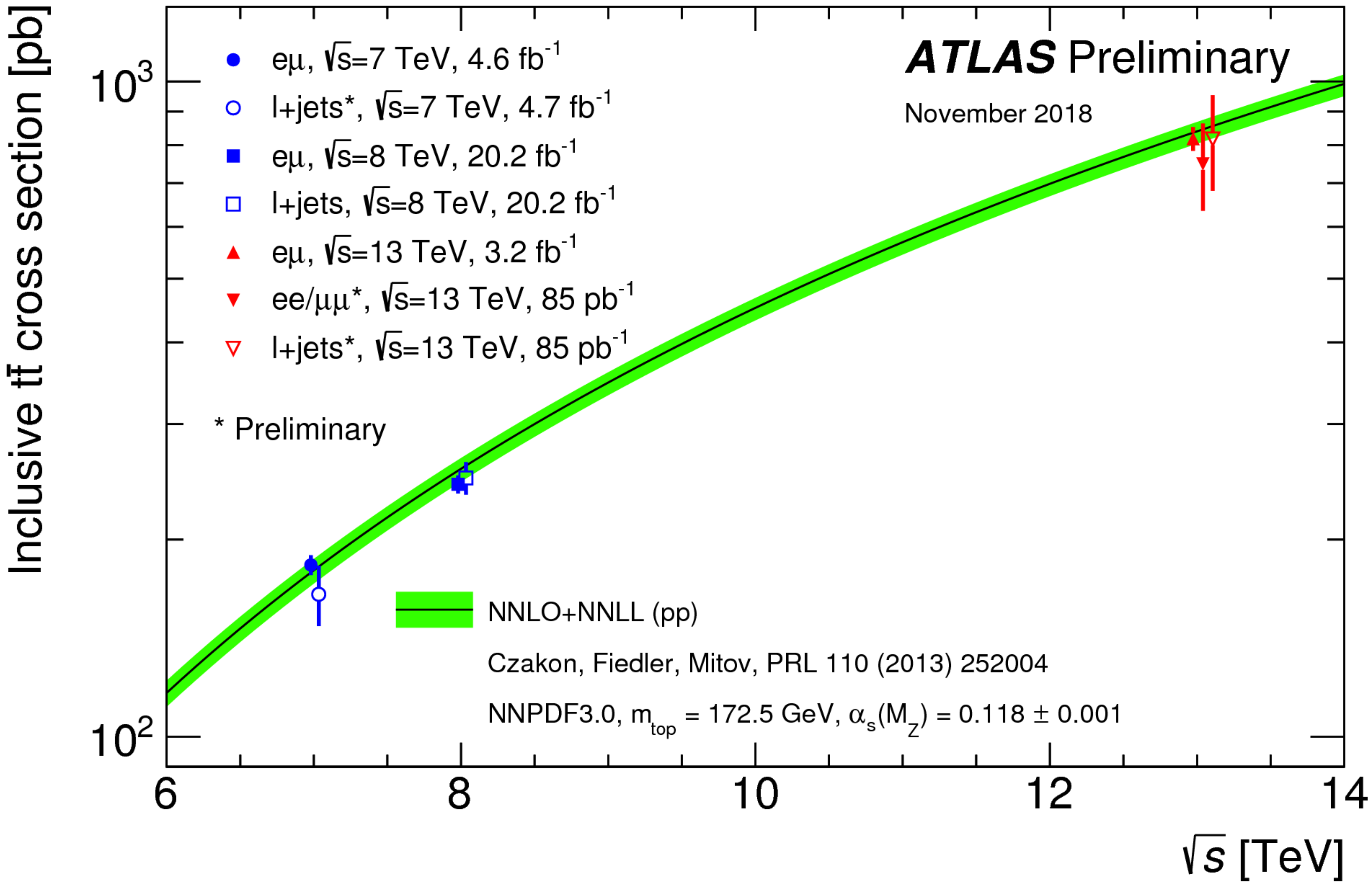
pp → H +X Cross section measurements





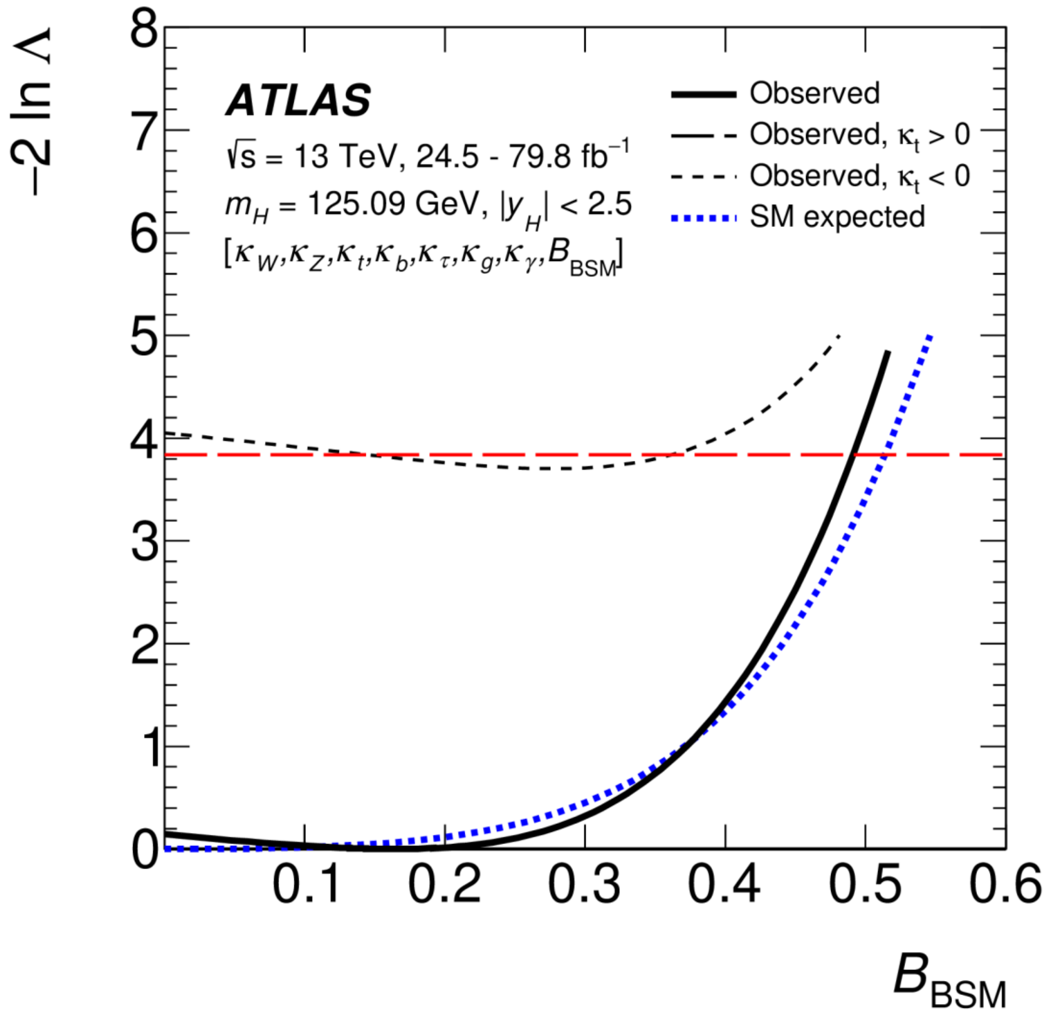
Top-quark sector

Summary of ATLAS measurements of the top-pair production cross-section as a function of the center-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation (top++2.0).



H → BSM contribution to the Higgs width

BR [H→ BSM] < ~45%



Search for new physics

- **Higgs Discovery confirmed in later measurements**
- **Measurement of properties consistent with expectations from the SM**
- **But are there more than one Higgs boson?**
  - **Beyond-the-Standard-Model (BSM) Higgs searches**
- **We can use the Higgs boson as a portal to “new physics” :**
  - **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?**

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

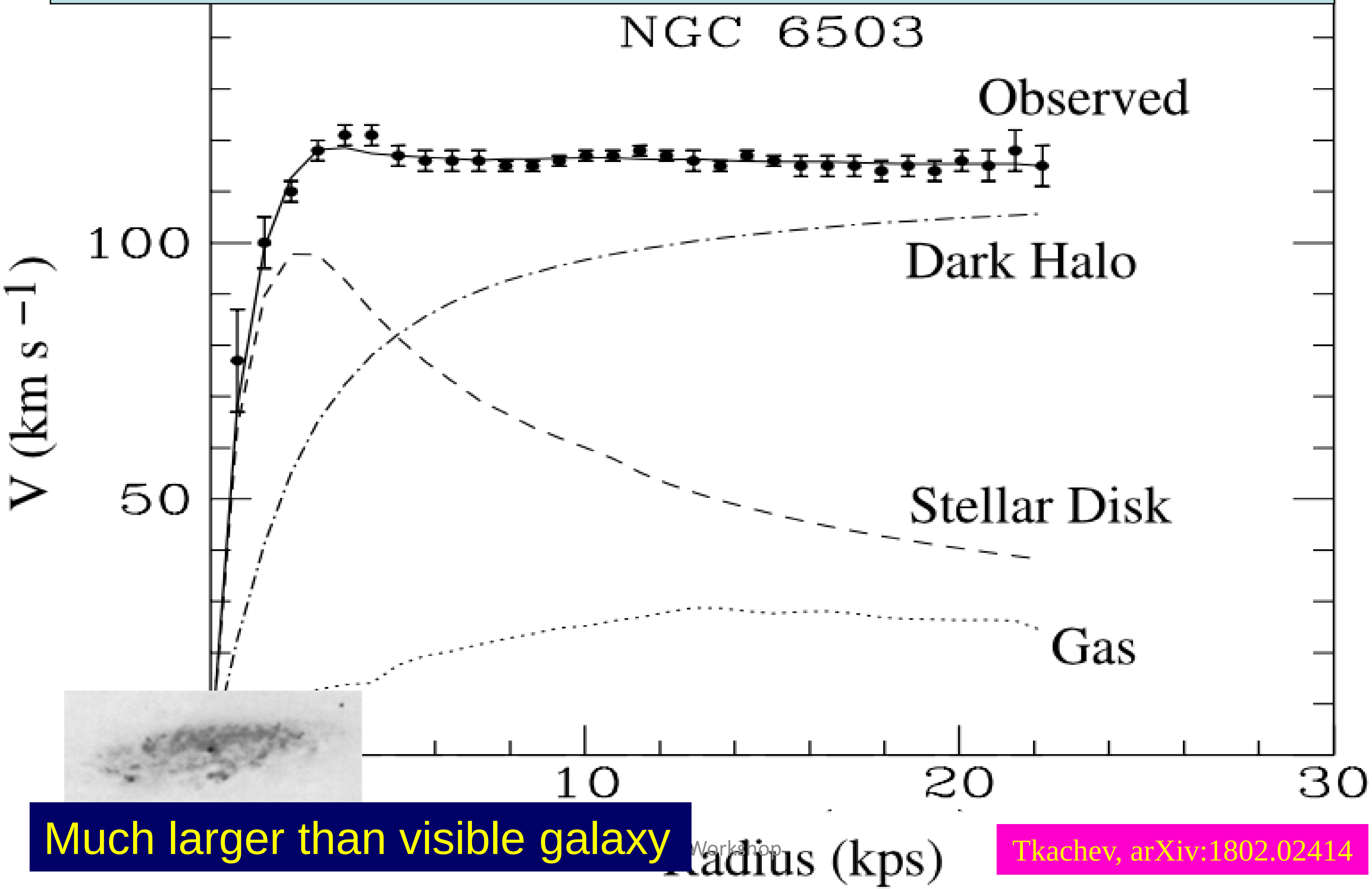
  than provided by the visible matter
- **Dark matter?**

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

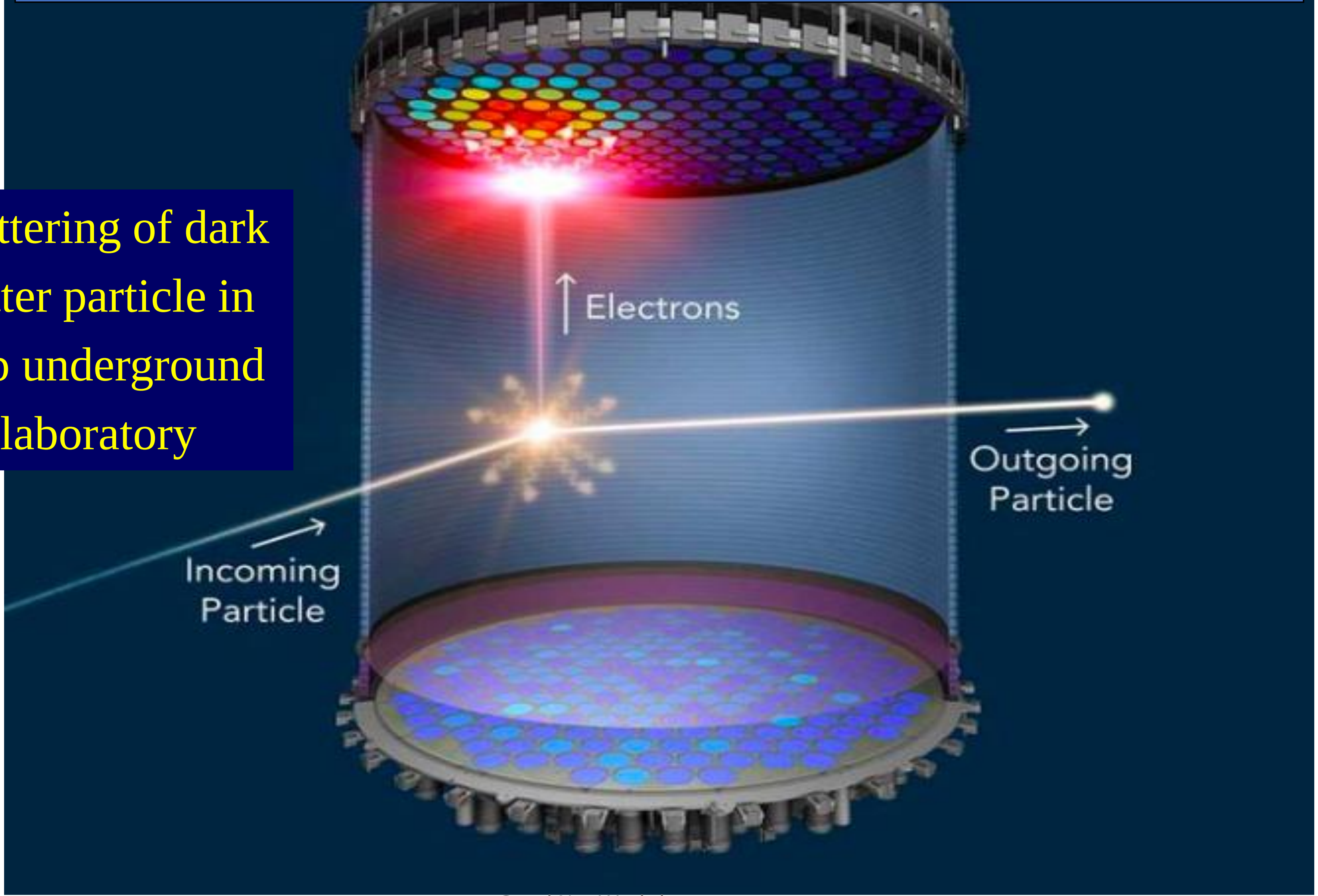


Much larger than visible galaxy

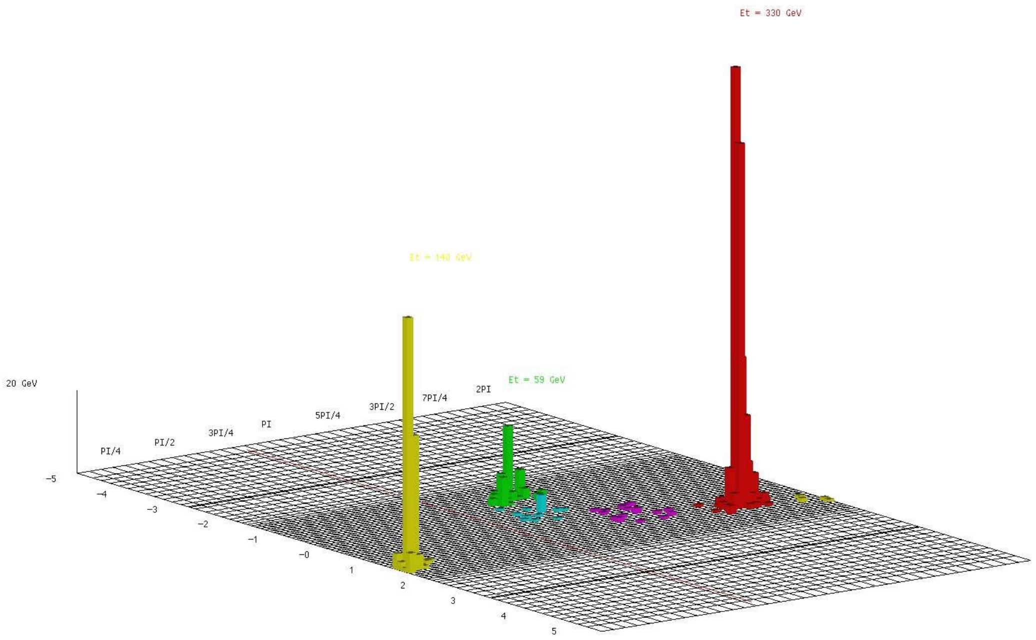
Tkachev, arXiv:1802.02414

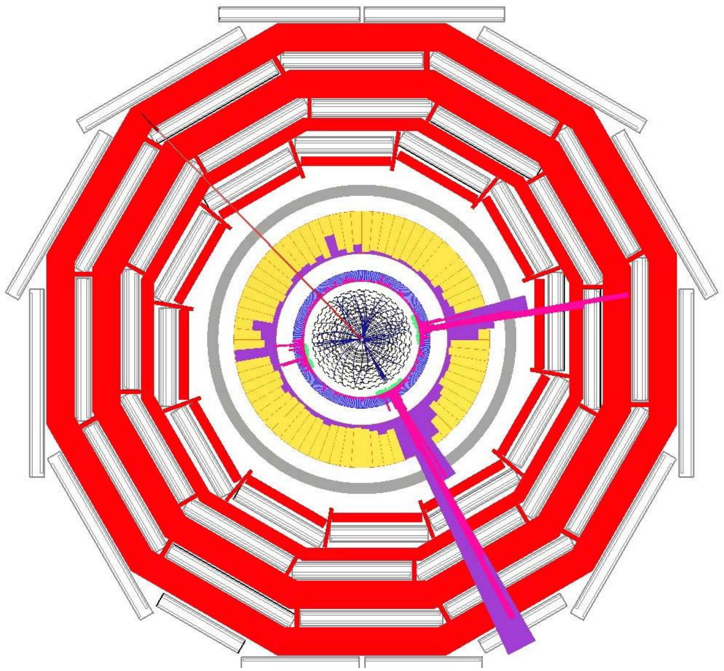
Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory



Classic Dark Matter Signature at LHC

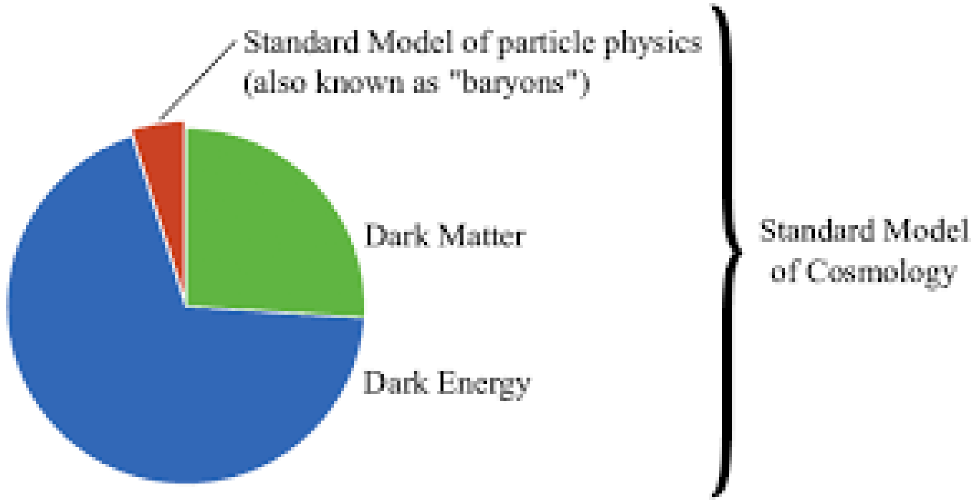


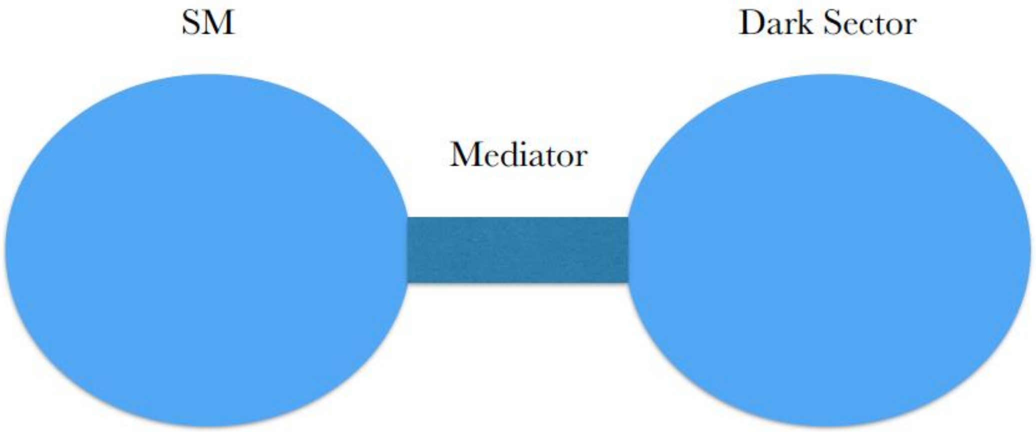


Missing transverse energy
carried away by dark matter particles

Dark Sector

- **Dark Sector states as "New Physics" beyond the SM**



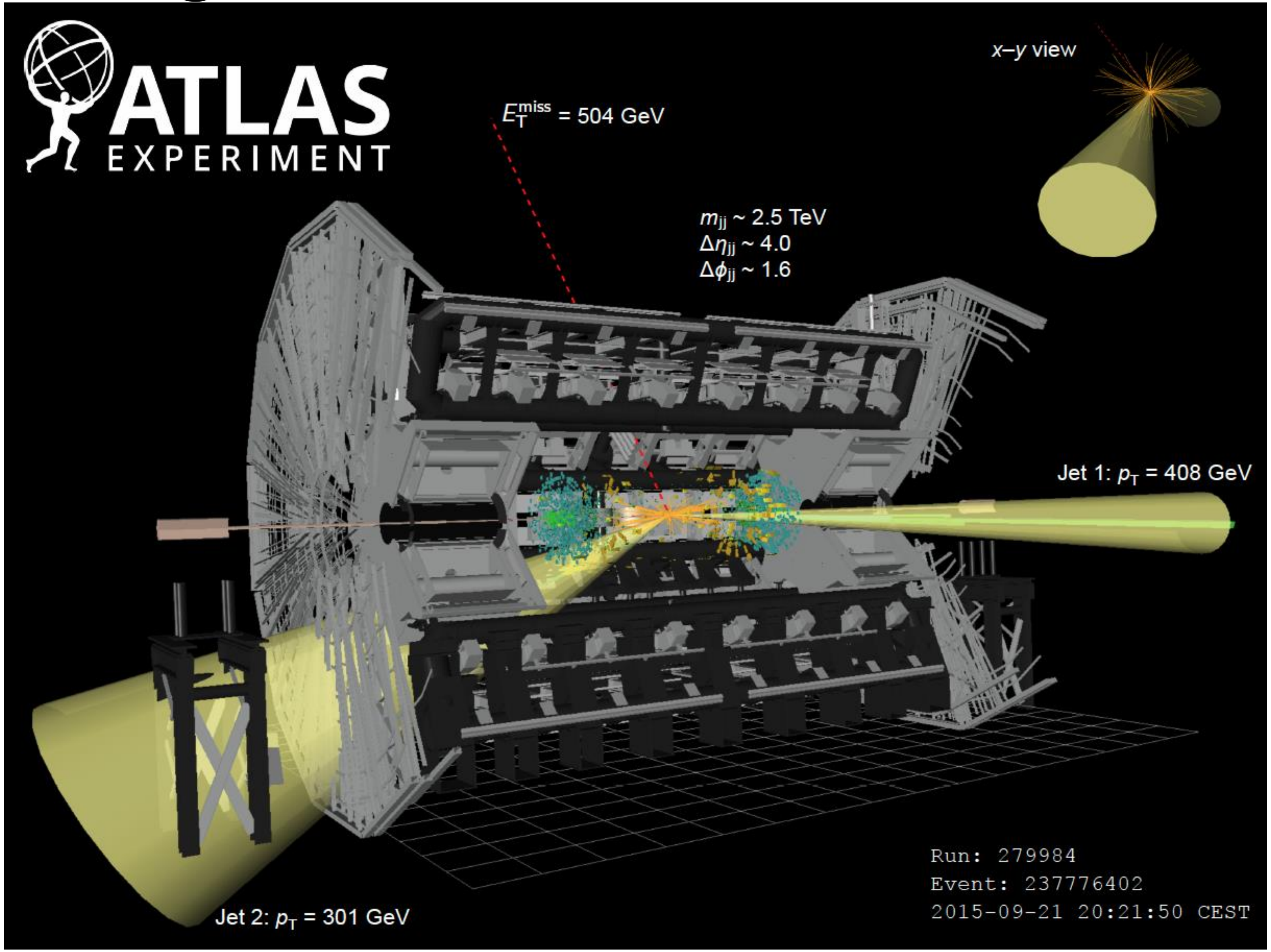


Need new force / interaction
to connect SM to Dark Sector — portals.
Weak couplings through kinetic mixing,
Higgs or mass mixings

Dark Matter could just be one example of Dark Sector States

Some Classic Signatures at LHC

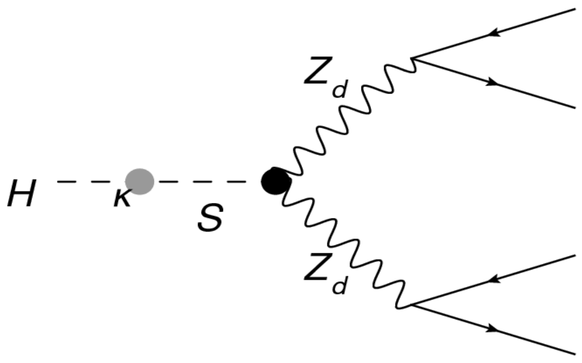
Missing transverse energy carried away by Dark Matter particles

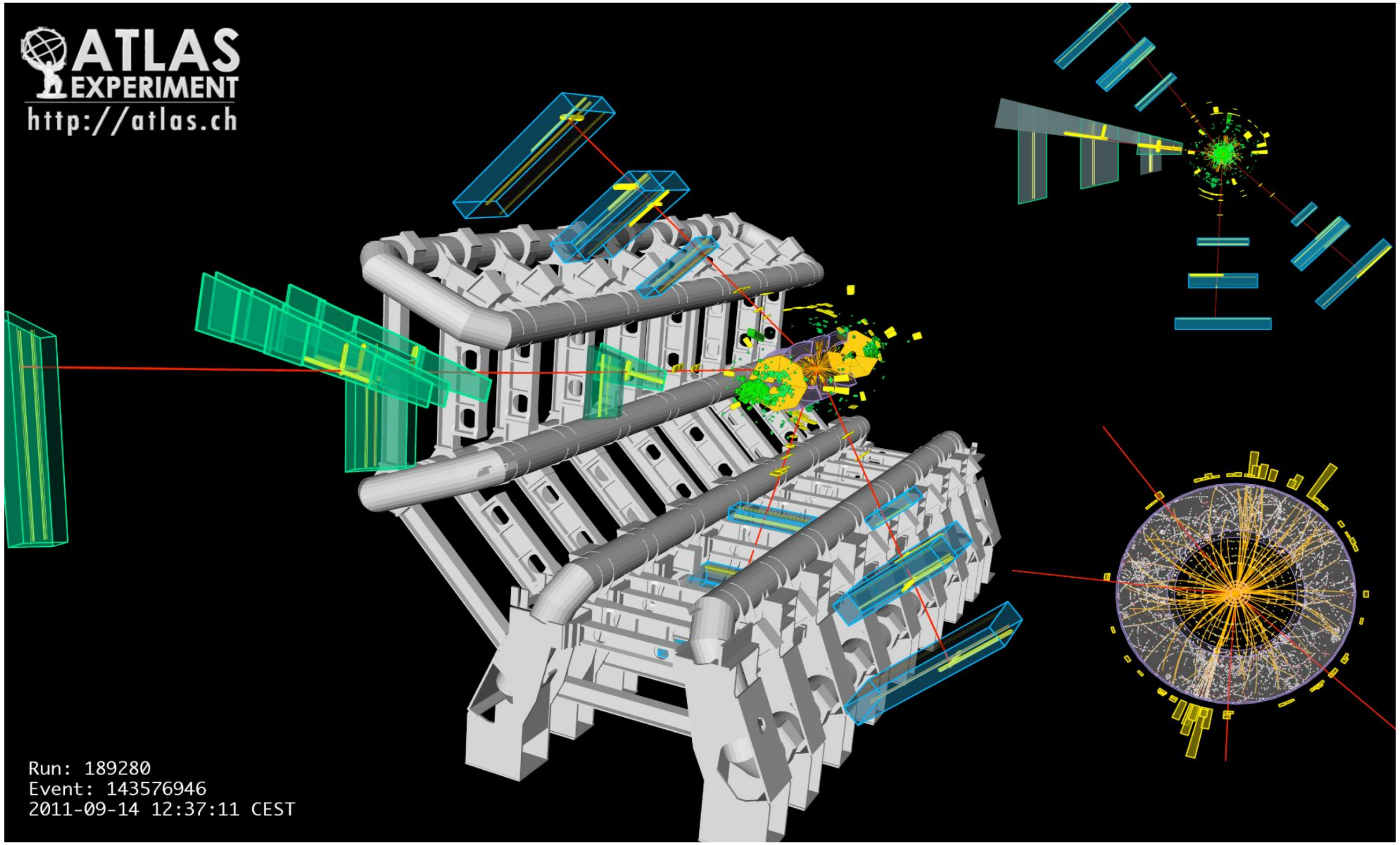


VBF H → invisible

Some Classic Signatures at LHC

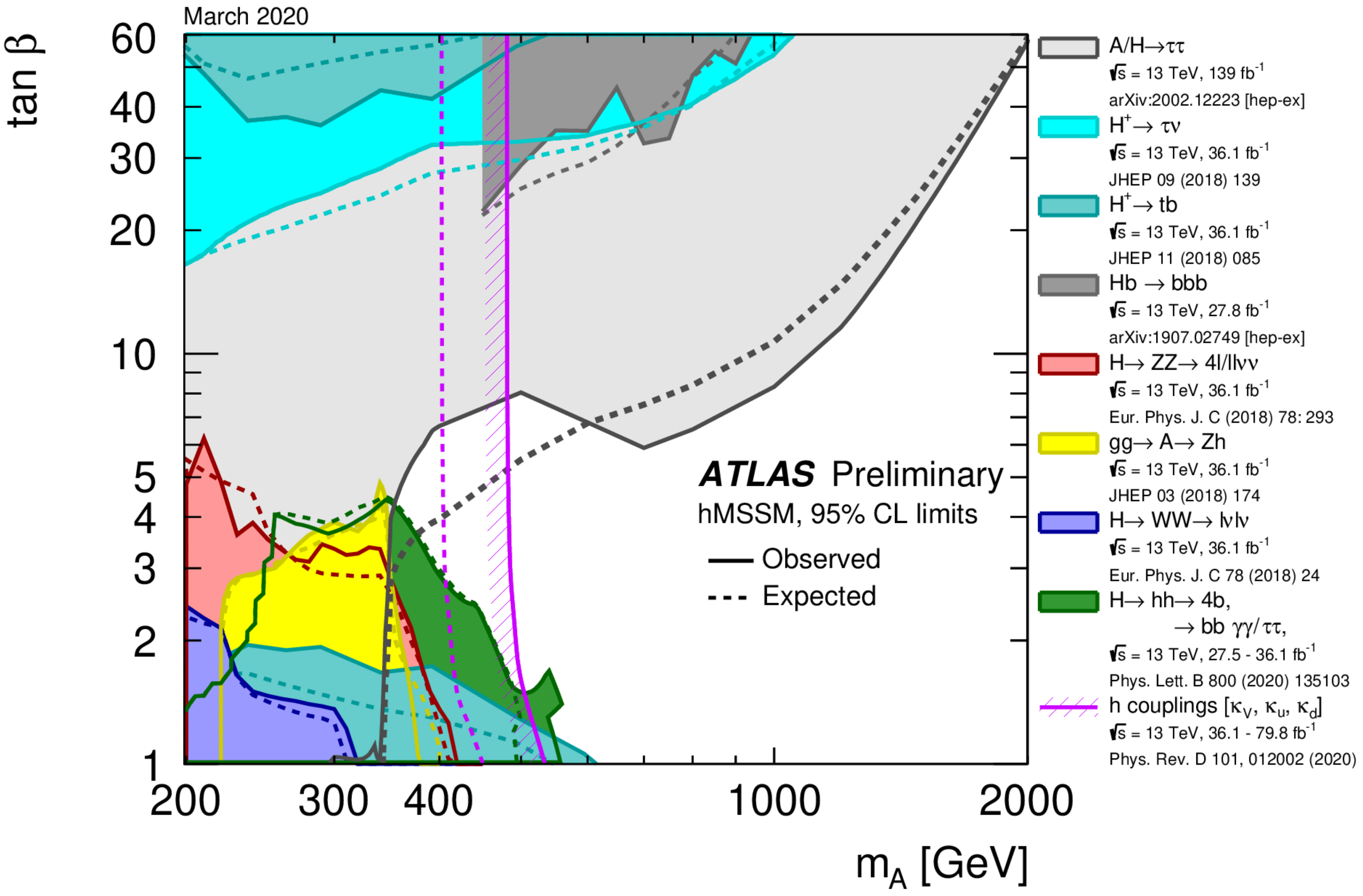
Dark Sector
States decaying
to SM particles





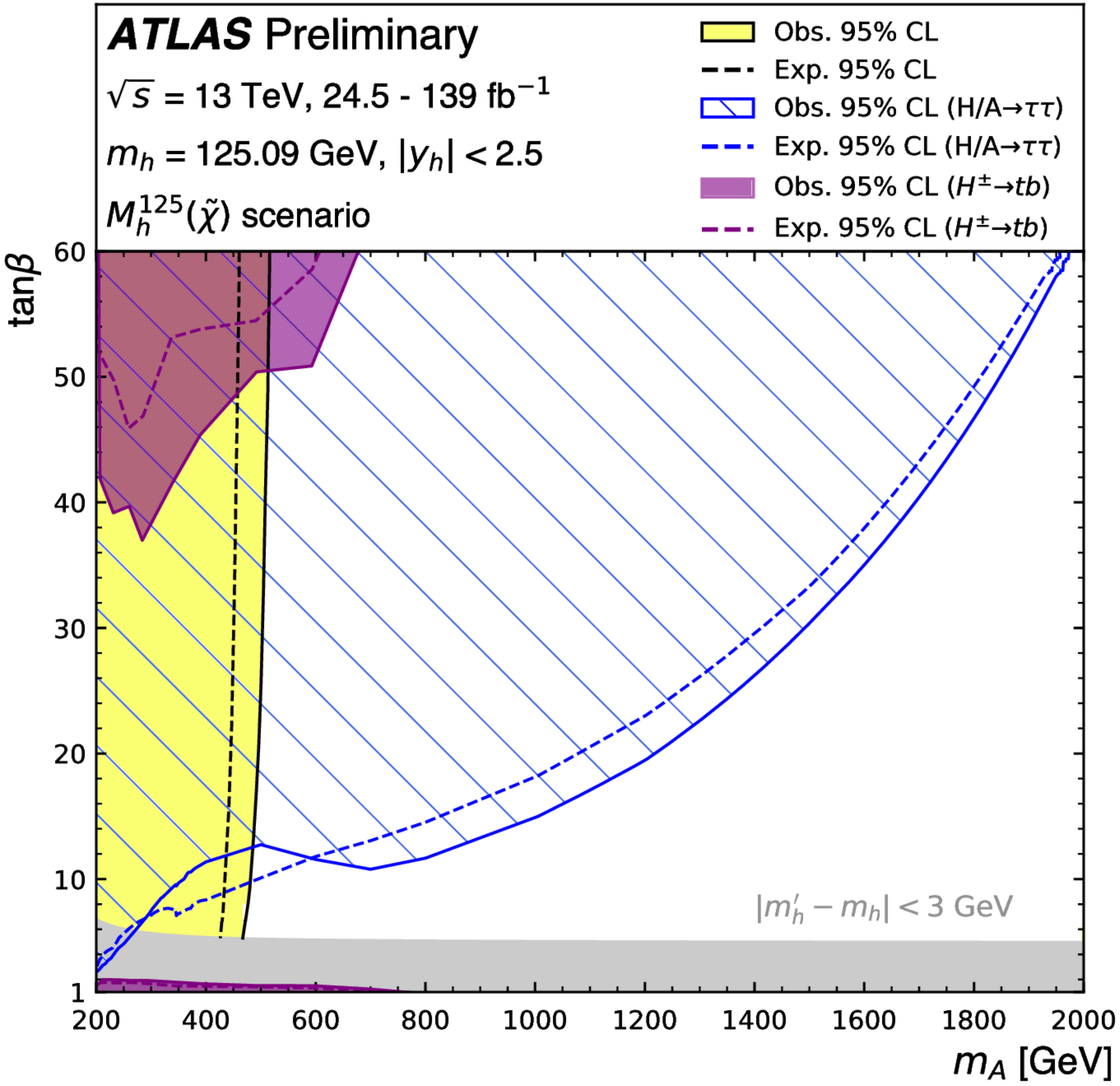
$S / H \rightarrow Z_d\, Z_d \rightarrow 4l$
where S = Dark Scalar
Z_d = Dark Vector Boson

BSM Higgs exclusion in the hMSSM



MSSM constraints from modified Higgs boson production cross sections and decay branching fractions

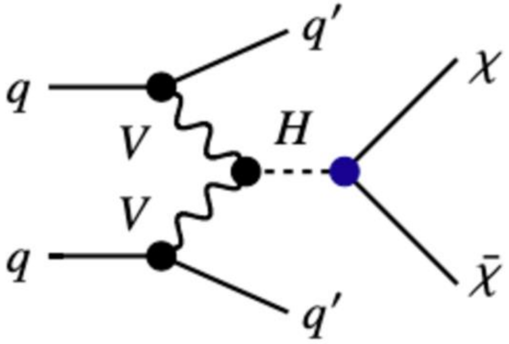
Exclusion contours in the (*mA*, tan*β*) plane for the $M^{125}_h(\tilde{\chi})$ scenario of the MSSM



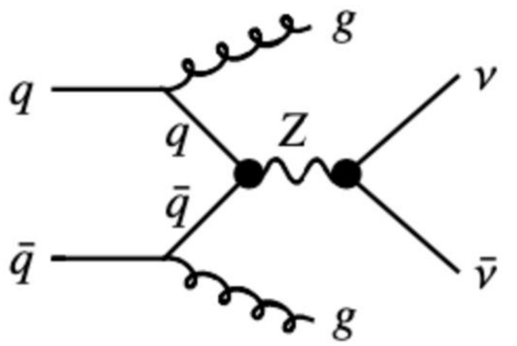
H → invisible

- **Some Dark Sector particle χ, neutral and stable over the range of the detector**
  - It is not a neutrino. A BSM-Particle
  - Its mass $m_\chi < m_H / 2$ such that $H \rightarrow \chi\chi$. 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 χ 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 away, therefore missing
  - So we can measure the missing transverse energy or the missing momentum
  - **χ could be a candidate for Dark Matter particle**

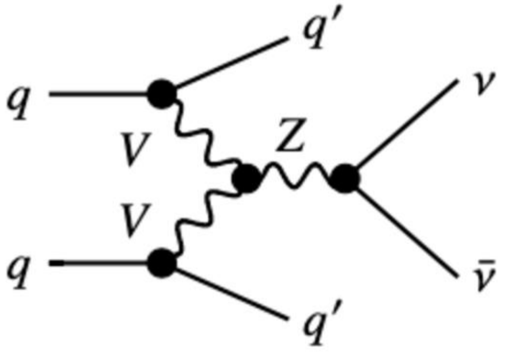
H → invisible



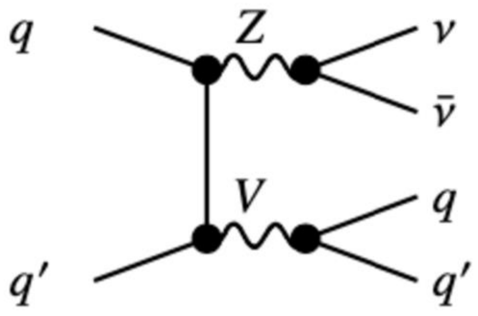
(a) Signal process



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

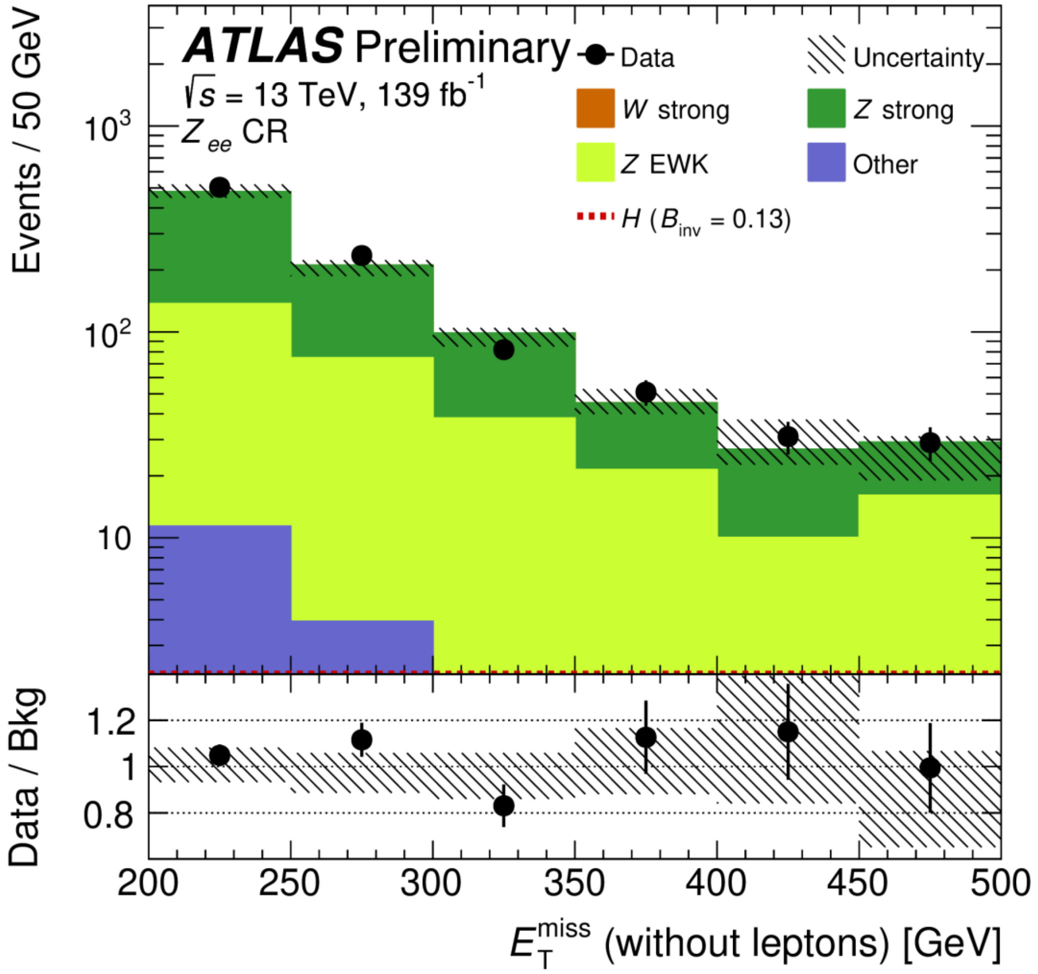


(c) Example diagram for the electroweak VBF Z+jets background process



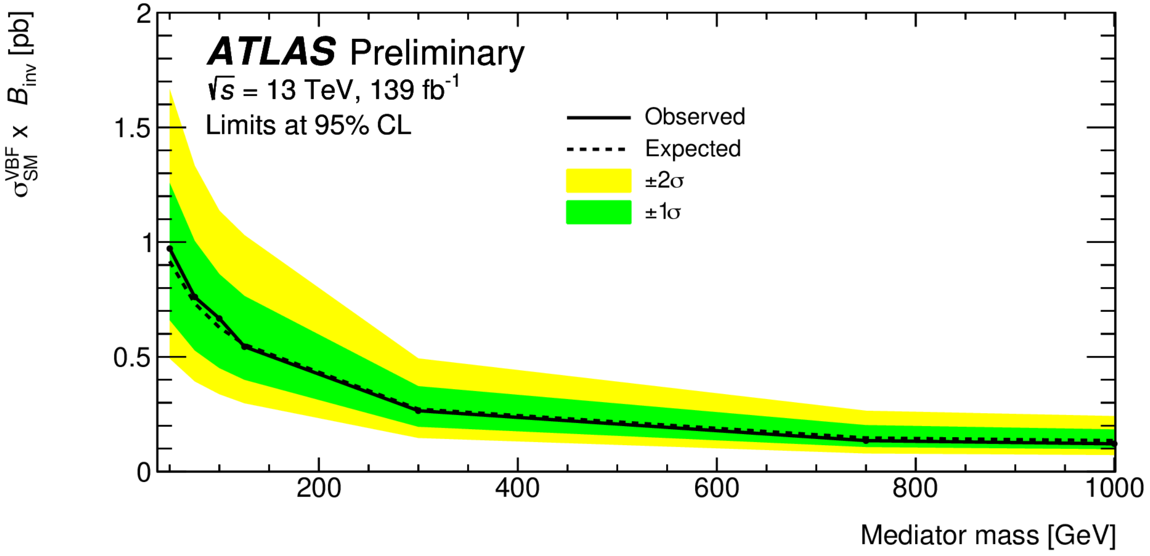
(d) Example diagram for the electroweak diboson process

H → invisible



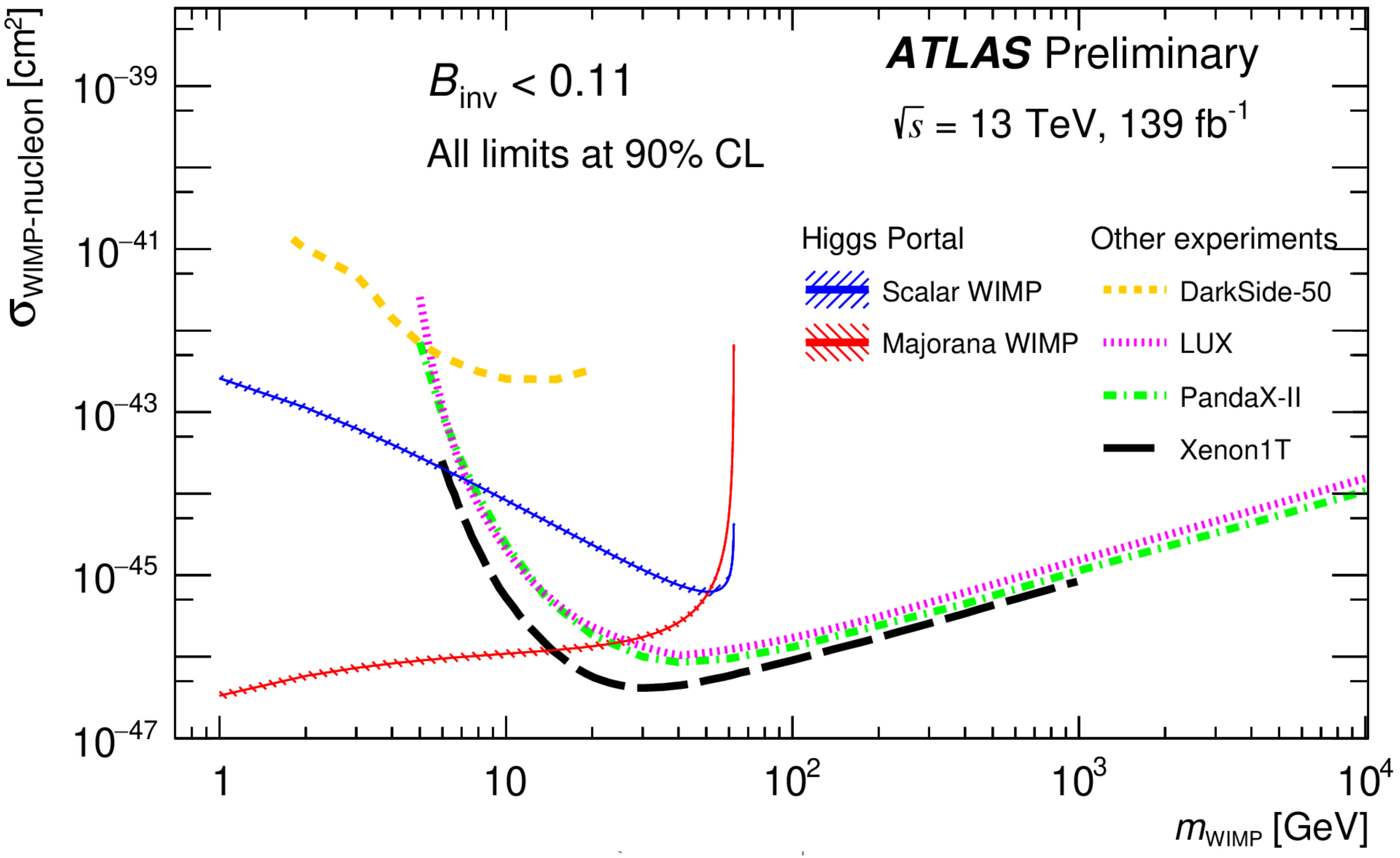
Branching Ratio Limit < 0.13 at 95% Confidence Level

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

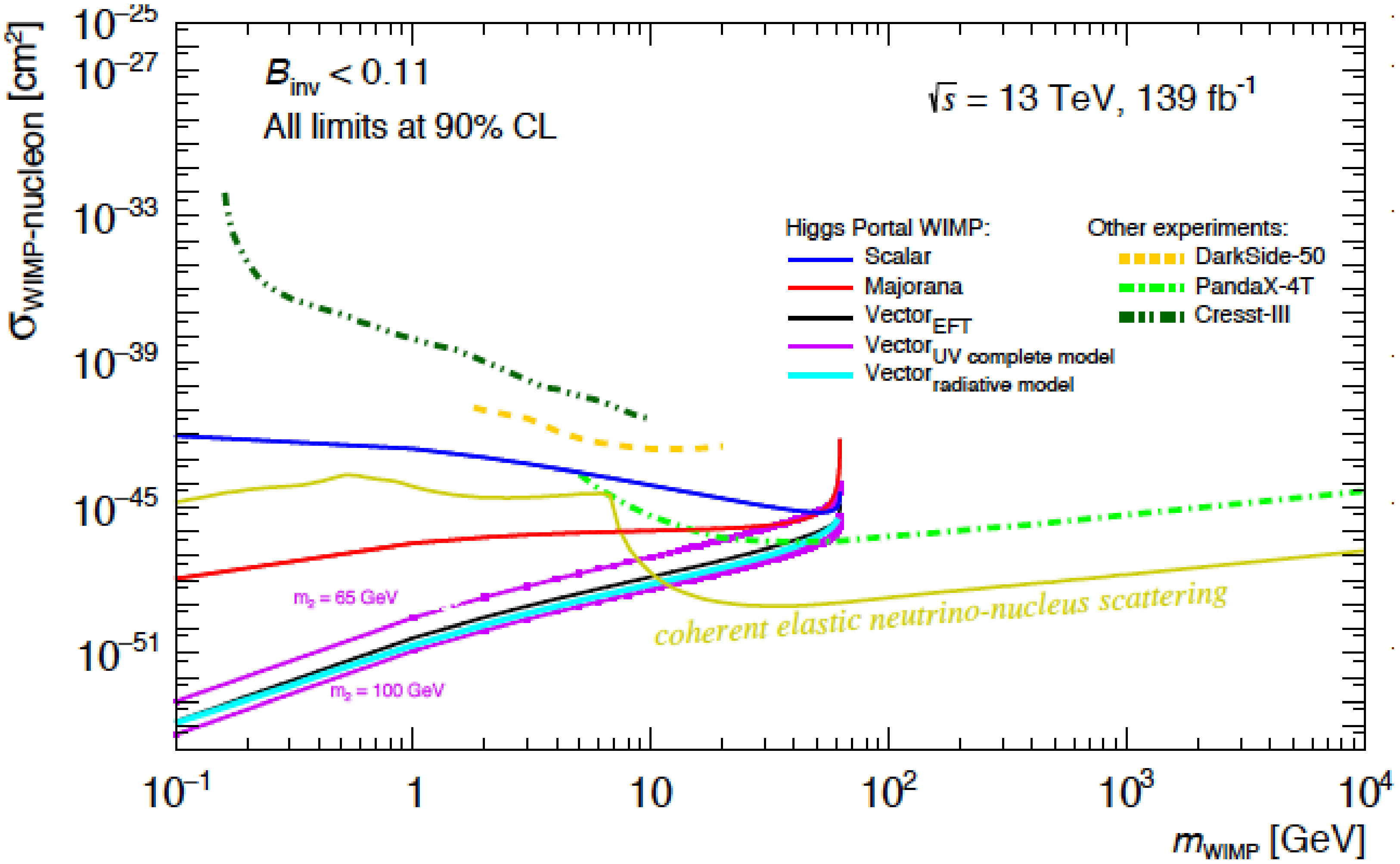


H → invisible — Dark Matter interpretation

Upper bound of the DM-Nucleon Scattering Cross Section



H → invisible — Dark Matter interpretation



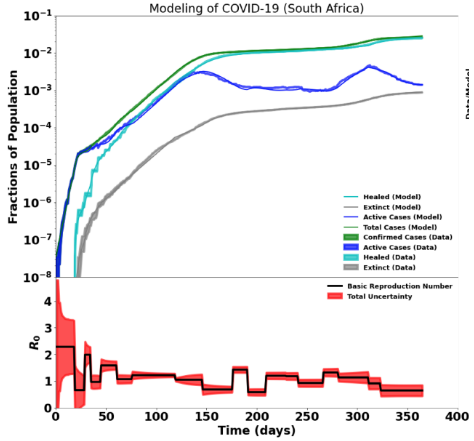
Work I did with a graduate student from Morocco.

Published here https://doi.org/10.31526/lhep.2022.270

Broader Impact

1. **Community Outreach through QuarkNet**
   - ❖ Professional development programs for physics teachers and pupils
2. **Targeted outreach toward US URM and MSI**
   - ❖ Improved and sustained engagements with URM and MSI to increase participation
3. **International Outreach**
   - ❖ Shorter-term visits for research
   - ❖ International physics school
   - ❖ Mentorship / coaching

Summer 2019 BNL



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
- The discovered Higgs boson may be used as probe or portal to “new physics”
  - By searching for BSM particles in the decays of the Higgs boson,
  e.g. H $\rightarrow$ invisible
- So far, no signal of “new physics” detected