Elementary Particle Physics: theory and experiments

10 years of the LHC

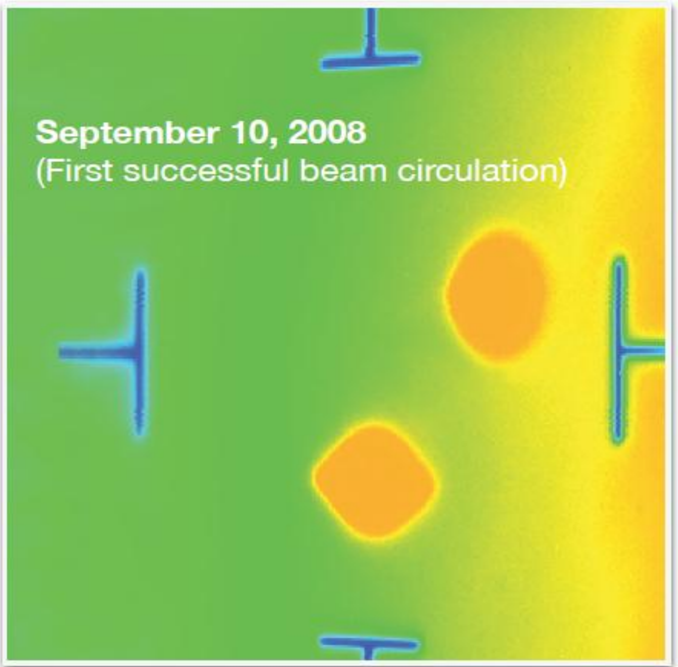
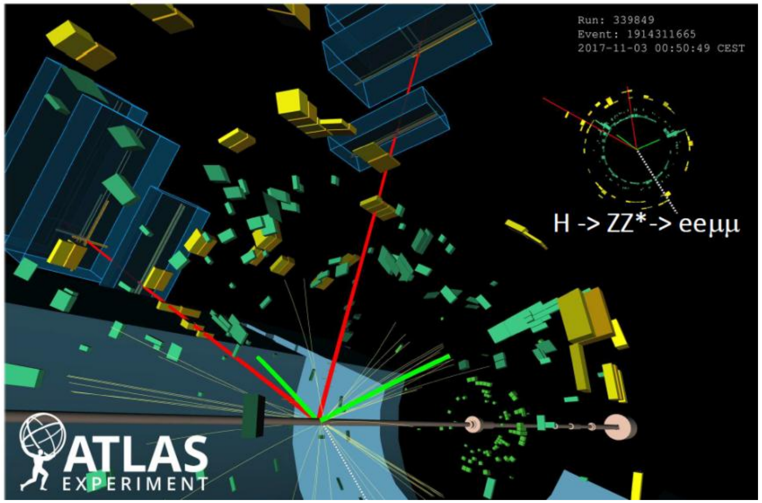


Image of a LHC beam screen recorded on **10 September 2008**: two spots corresponding to the successful circulation of protons once around the machine (CERN)



Prof. dr hab. Elżbieta Richter-Wąs

The LHC

First mention of the LHC in **1977** by **Sir John Adams** (former CERN director) as an option of a superconducting hadron collider to be hosted in the LEP tunnel (requesting that the LEP be made large enough to host a proton collider of at least **3 TeV beam** energy). That was a period very busy with extremely important physics results.

- 1984: CERN and ECFA workshop in Lausanne.
- 1988: LEP tunnel completed (Europe's largest civil engineering project prior to the channel tunnel).
- 1992: ATLAS and CMS letters of intent.
- 1994: Approval of the LHC (1993 cancellation of 40 TeV SSC).
- 1995: LHC CDR published.
- 1997-98: ATLAS, CMS, LHCb and ALICE experiments approved.
- 2003-2005: Caverns completed installation started.
- 2007: LHC dipoles installed in LHC (after having been all individually checked at SM18).
- 2008: Experiments installed.
- 2008 September 10: Start of the LHC.
- 2008 September 19: Incident occurs between dipole and quadrupole.
- **2009** November: Beams are back in the LHC!

Since 2009: 10 years of successful operations and landmark results!

Construction and Commissioning of the LHC

LHC challenges

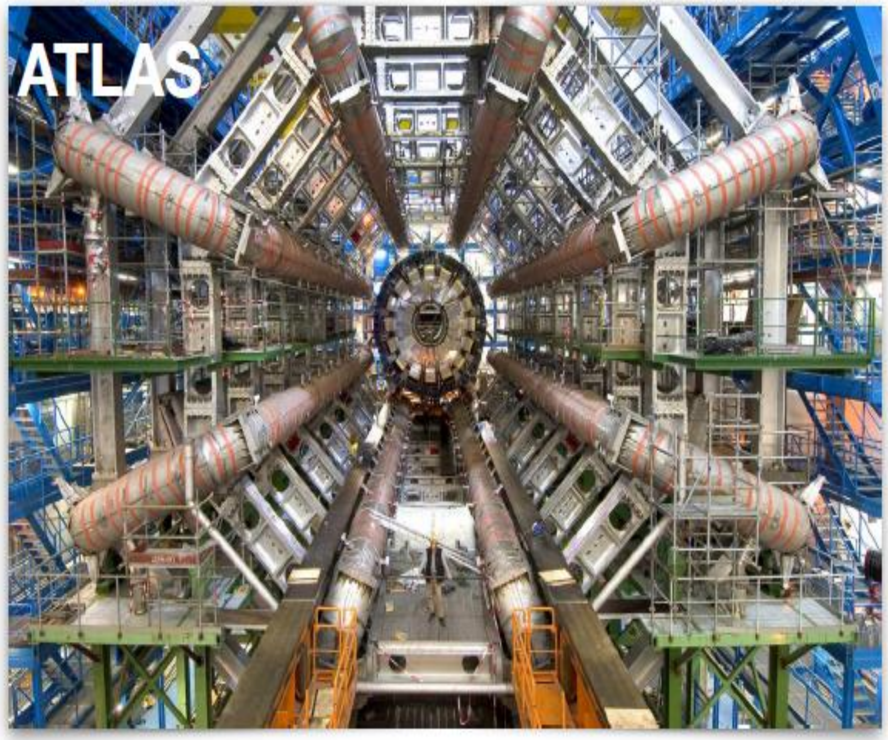
Not only an unprecedented **construction challenge**, also an **operation challenge**: beam energy and luminosities (for a hadron machine)

- Main challenge : Stored beam energy 2 orders of magnitude higher than existing machines… 350 MJ
- Total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

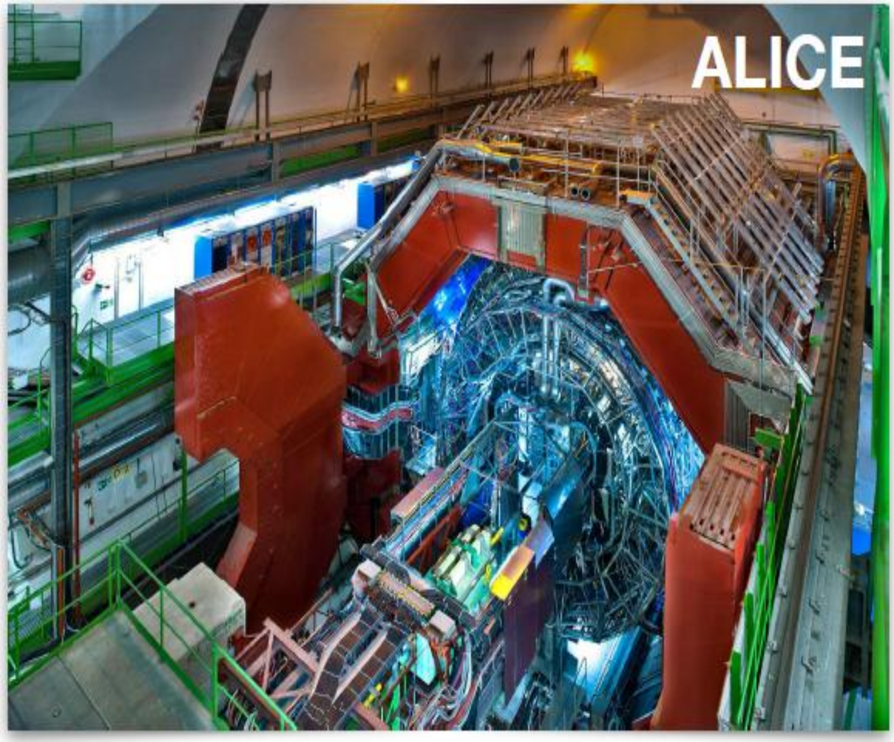
LHC Multi-Purpose detectors

- Challenge in design and construction: the **10 years of running of the LHC** and the Landmark results obtained corroborate the choices made!
  The designs have allowed for much more than was initially foreseen.

- After **10 years of running:** superb operation efficiency typically over the entire running period of **90%** for both ATLAS and CMS (5% data taking and 5% data quality).



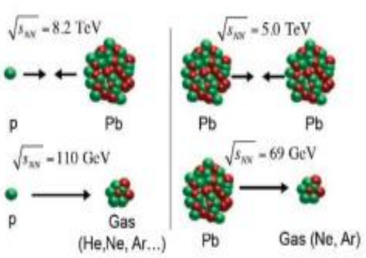
LHC Specialised detectors



Collider mode

Fixed target mode

Using its internal gas target (SMOG)



- **Equally successful designs** achieving landmark results, and much more than was foreseen, with excellent data taking efficiency
- One particular example: SMOG system to perform best luminosity measurement at LHC (Close to 1% precision) and interesting fixed target Heavy Ions collisions.

LHC More Specialised detectors

Detector Challenges

- **Read out and reconstruct** approximately **O(100M)** electronics channels at ~1 kHz.

- **Trigger Challenge** : select ~400-1000 out of 20M events per second while keeping the interesting (including unknown) physics

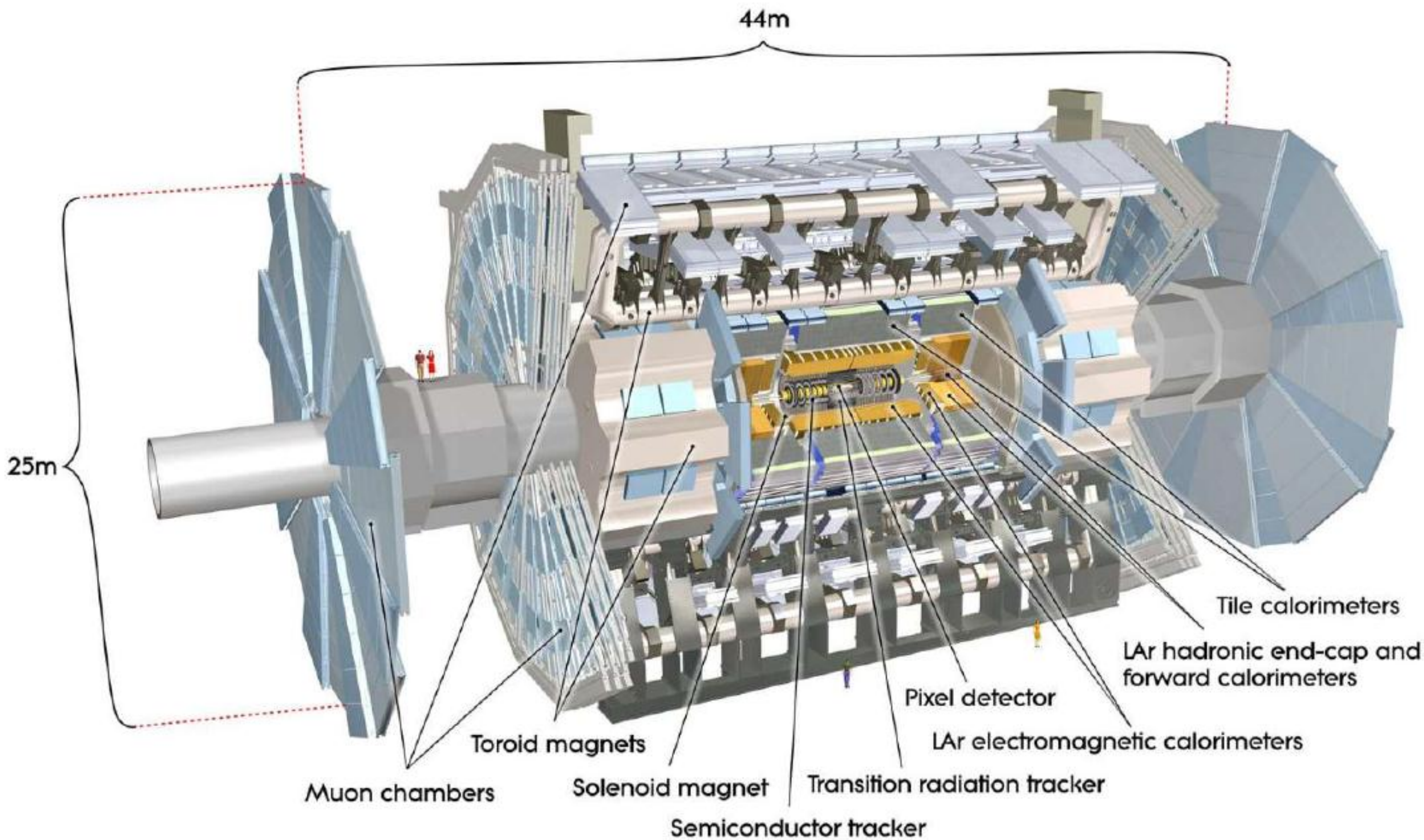
- **Computing Challenge** : reconstruct, store and distribute 1000 complex events per second and the very large amount of simulation (over 100 PB per experiment - Several farms of over 200k Cores).

- **Analysis Challenge** : Maintain high (and as much as possible stable) reconstruction and identification efficiency.

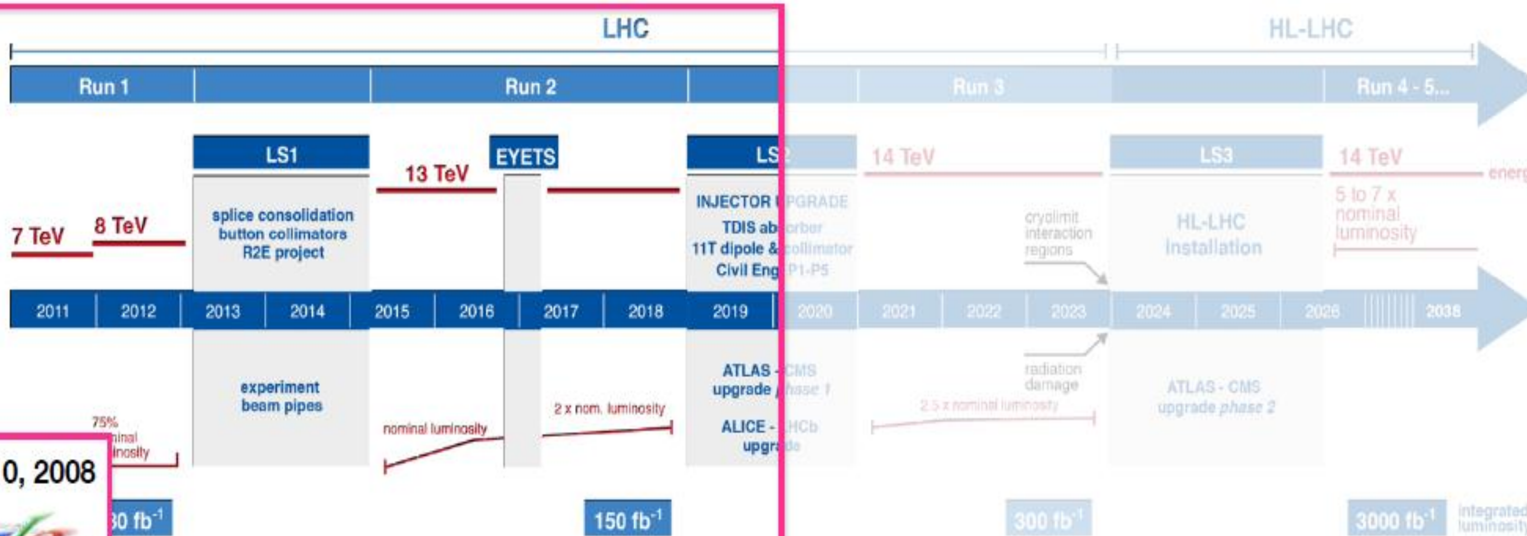
CERN Computing Center

- **Machine Learning** : Ideal environment to develop Machine Learning techniques: in particular in areas such as trigger, reconstruction, object identification, calibration and Pile up Mitigation.

ATLAS: the largest detector at the LHC



10 years of the LHC



September 10, 2008

The day the world switched on to particle physics

- **Run 1 :** COM Energies of 7 and 8 TeV and luminosities of ~20 fb-1 for ATLAS and CMS and Pile-Up of ~30-40.

- **Run 2 :** COM Energy of 13 TeV and luminosities (for ATLAS and CMS) of ~140 fb-1 with Pile Up of ~30-40 (at 25ns - makes quite a difference out-of-time PU!)

Huge number of lessons learned on how to mitigate PU.

The Landmark Higgs Discovery

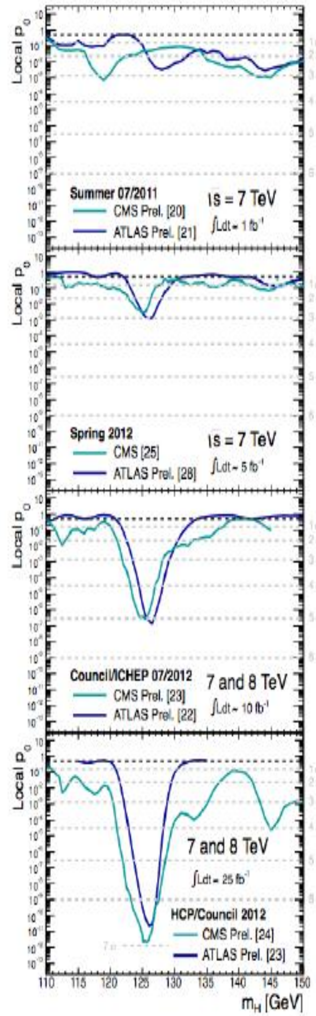
- Summer 2011 EPS and Lepton-Photon: **Still focused on limits.**
- December 2011 CERN Council: **First hints.**
- Summer 2012 CERN Council and ICHEP: **Discovery!**
- December 2012 CERN Council: **Beginning of a new era!**

✓ Strongly Motivated

✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels



It is the first example we've seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing.

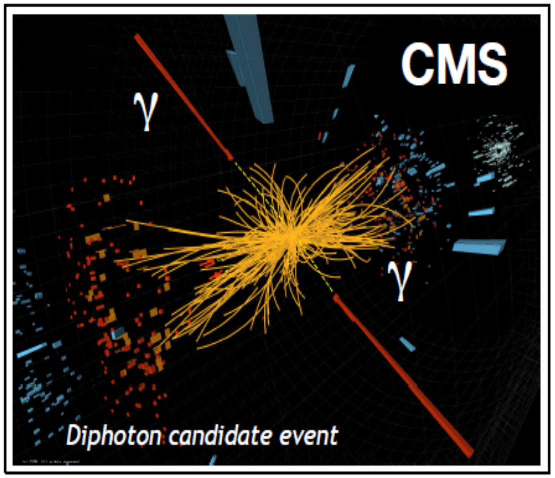
Nima Arkani Hamed

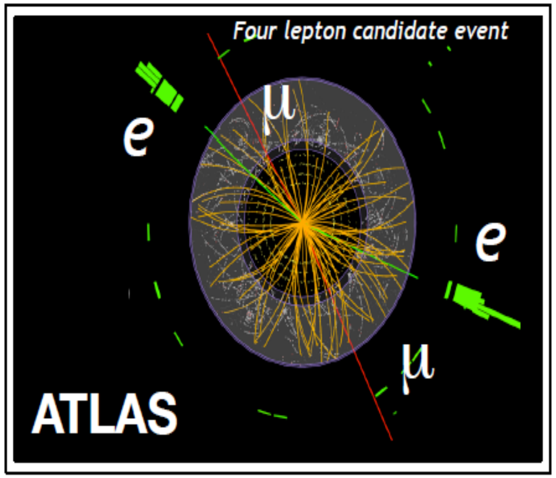
Higgs Discovery announcement July 4, 2012

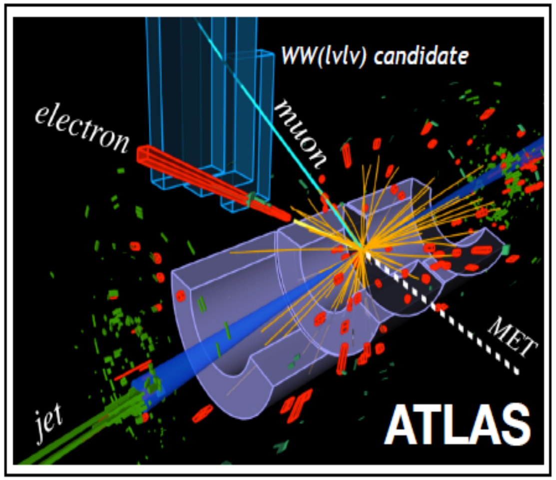
Discovery Channels

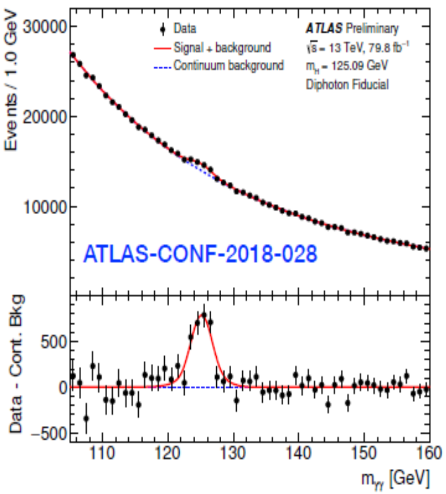
« **Bread and Butter** » O(1%) Mass resolution channels

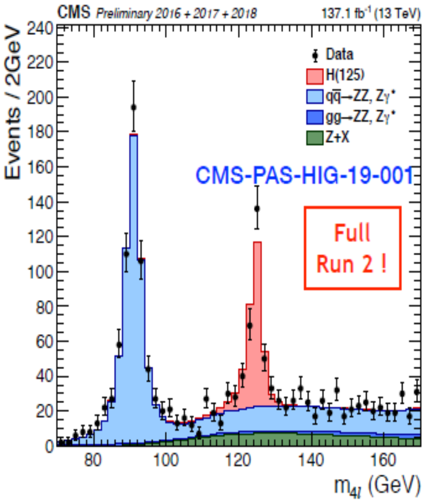
Strong but intricate WW channel

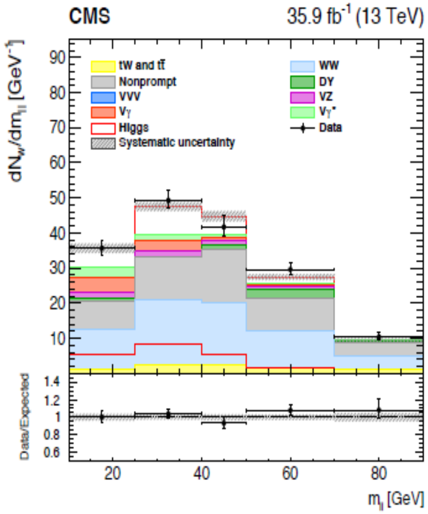




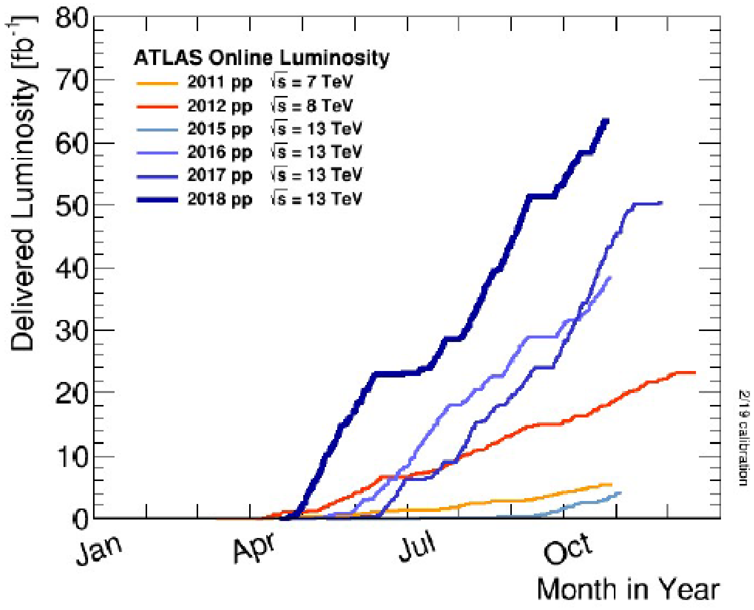


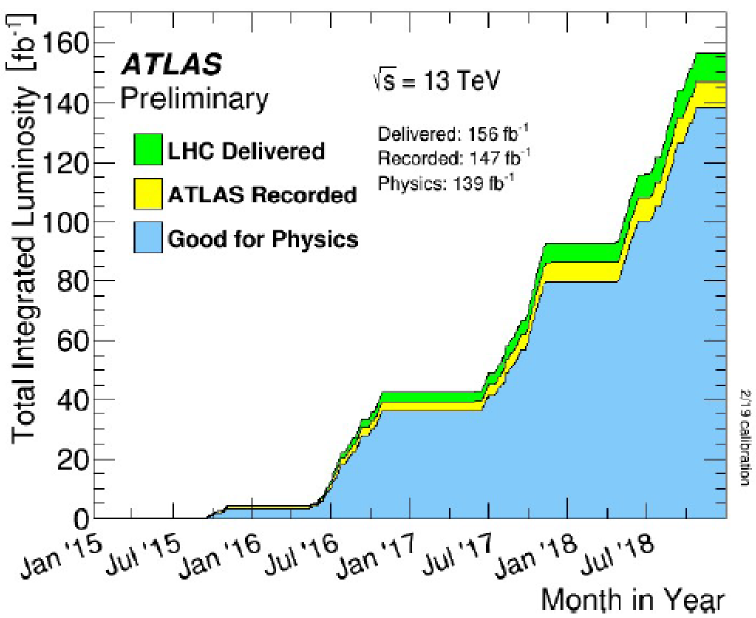






The LHC Run II pp dataset





Increasing performance with time of the collider and of the ATLAS detector !

Year	Integrated delivered luminosity (fb^{-1})	Peak instantaneous luminosity (10^{33} cm^2 s^{-1})	Data taking efficiency (%)
2015	4.2	2-5	92.5
2016	38.5	12	92.5
2017	50.2	15	93.5
2018	63.3	20	96

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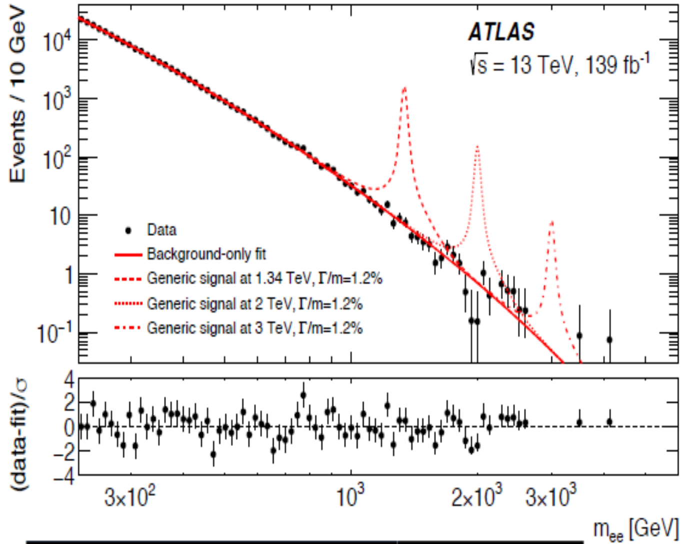
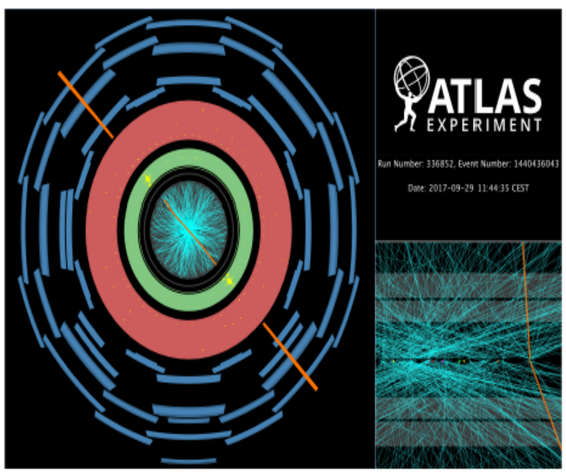
Searches for Higs Mass Resonances

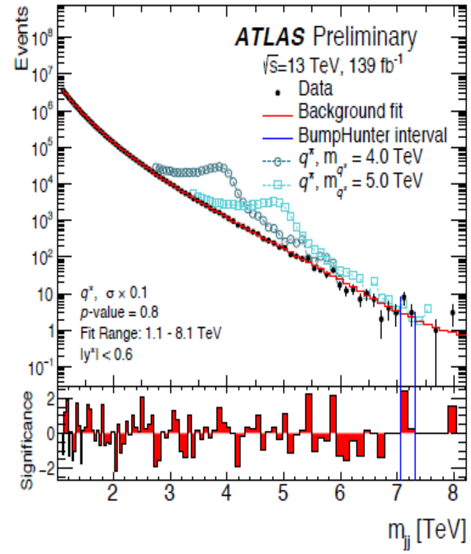
ATLAS Dilepton search ATLAS 1903.06248





Exclusions up to ~5 TeV

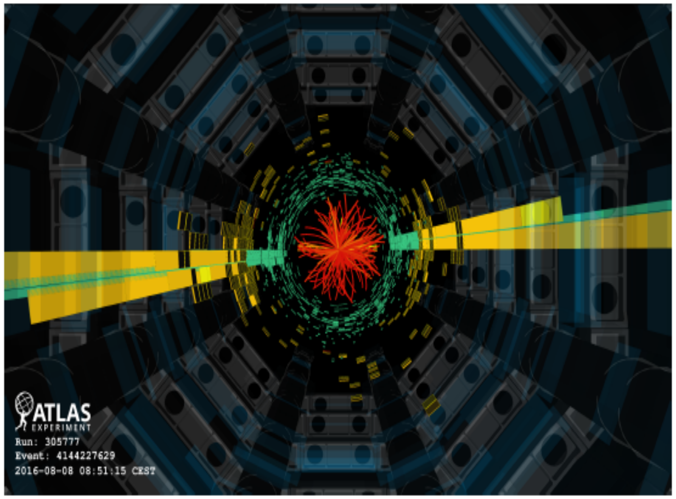
Highest mass di-electron event ~4 TeV



ATLAS Dijet search

ATLAS-CONF-2019-007

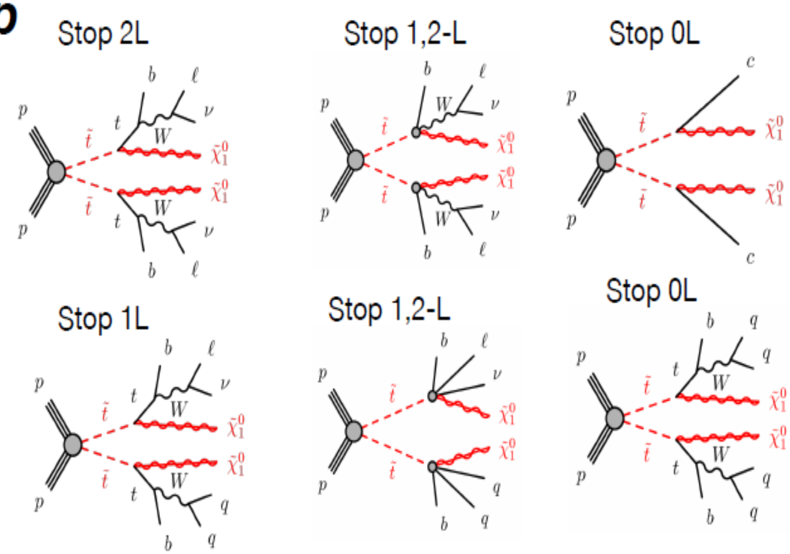
Limits on excited quarks at 6.7 TeV



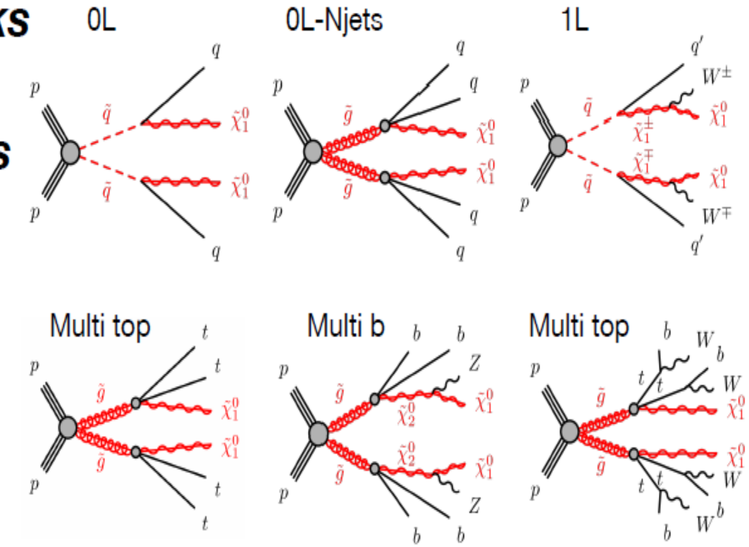
Highest mass (central) dijet event ~8 TeV

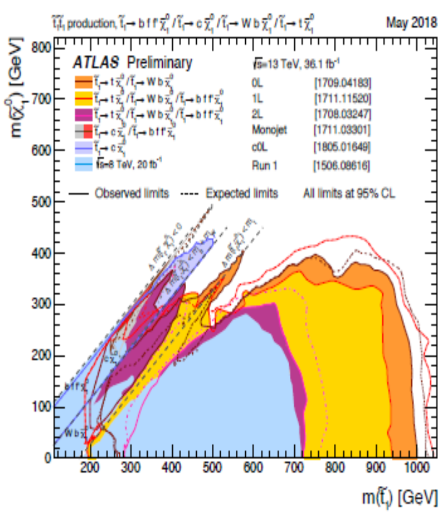
Searches for Natural and Strongly Produced SUSY

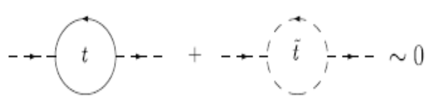
Stop



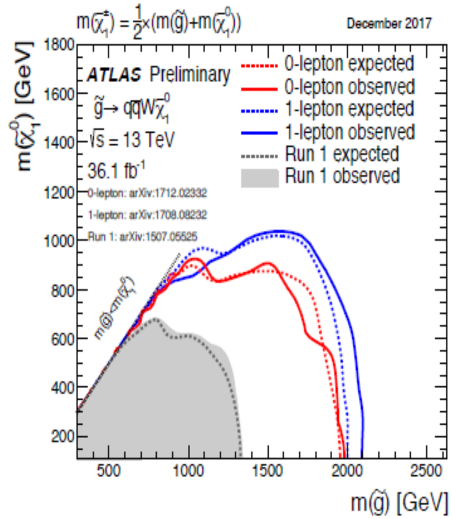
Squarks and gluinos

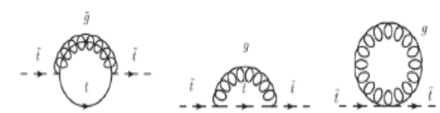






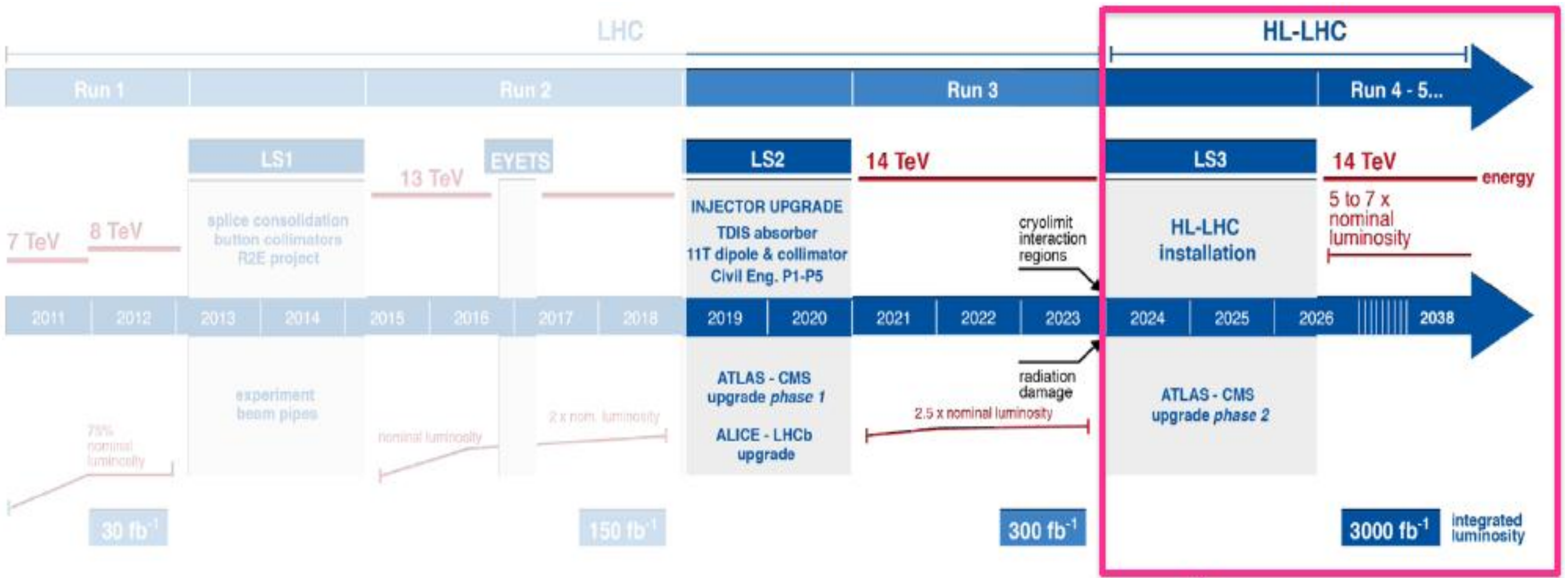
Not so natural SUSY: Stops > 1 TeV ~Tuning of factor **20**, but these exclusions are under specific conditions, and there are unexcluded corridors.

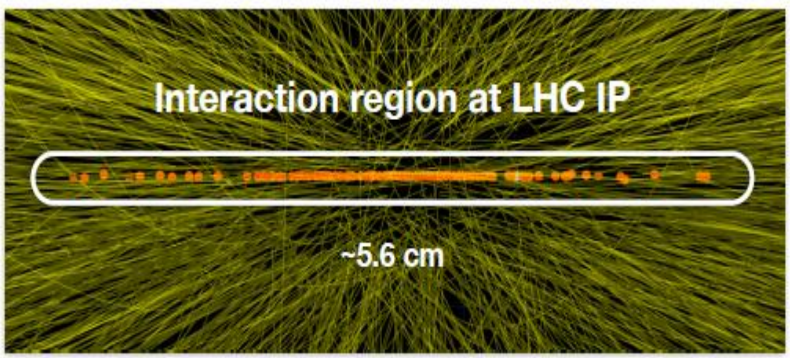


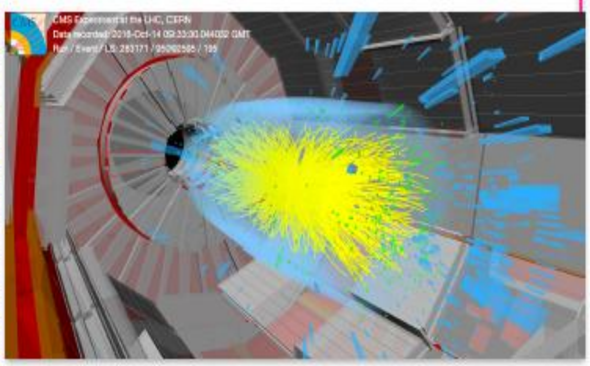


Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of **30**

The next 20 years of LHC: Towards HL LHC



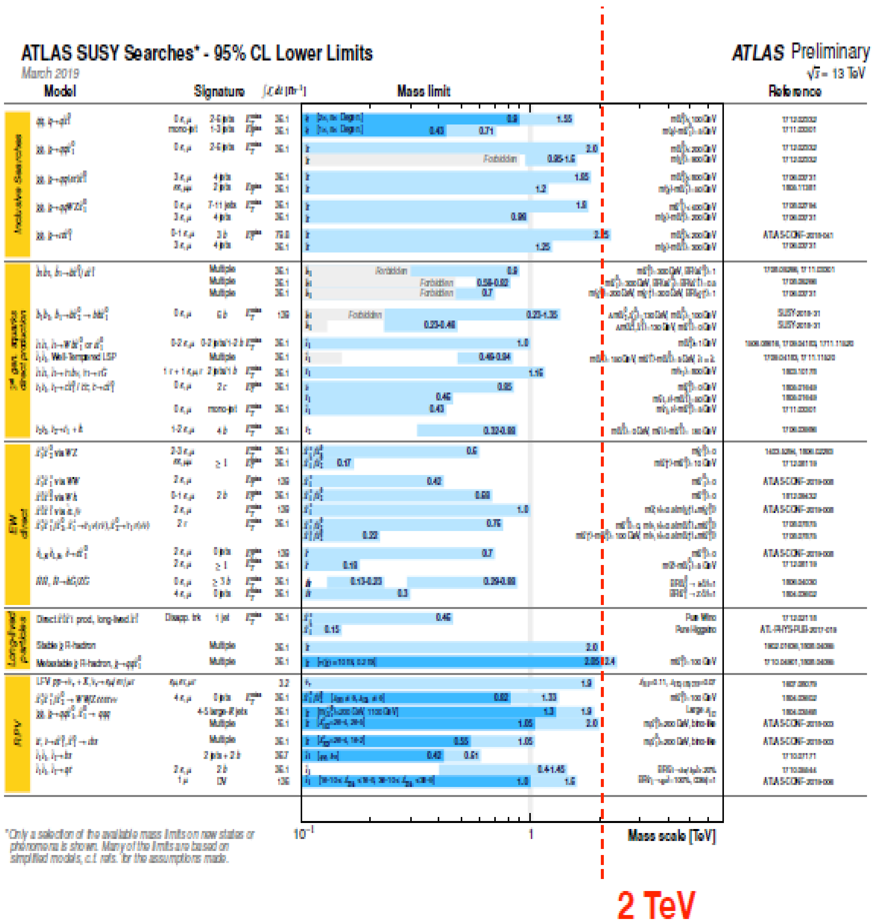




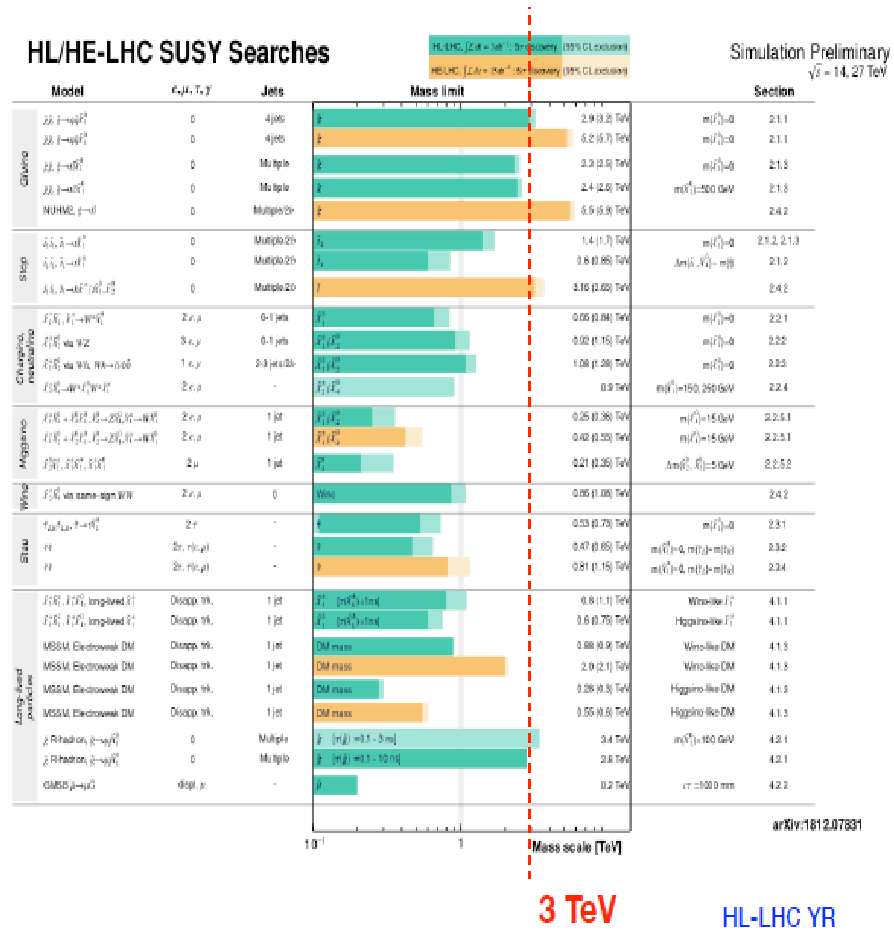
At Run 2 average PU per event was approximately 40.

Expected PU at HL-LHC **140-200**

Very large number of SUSY searches

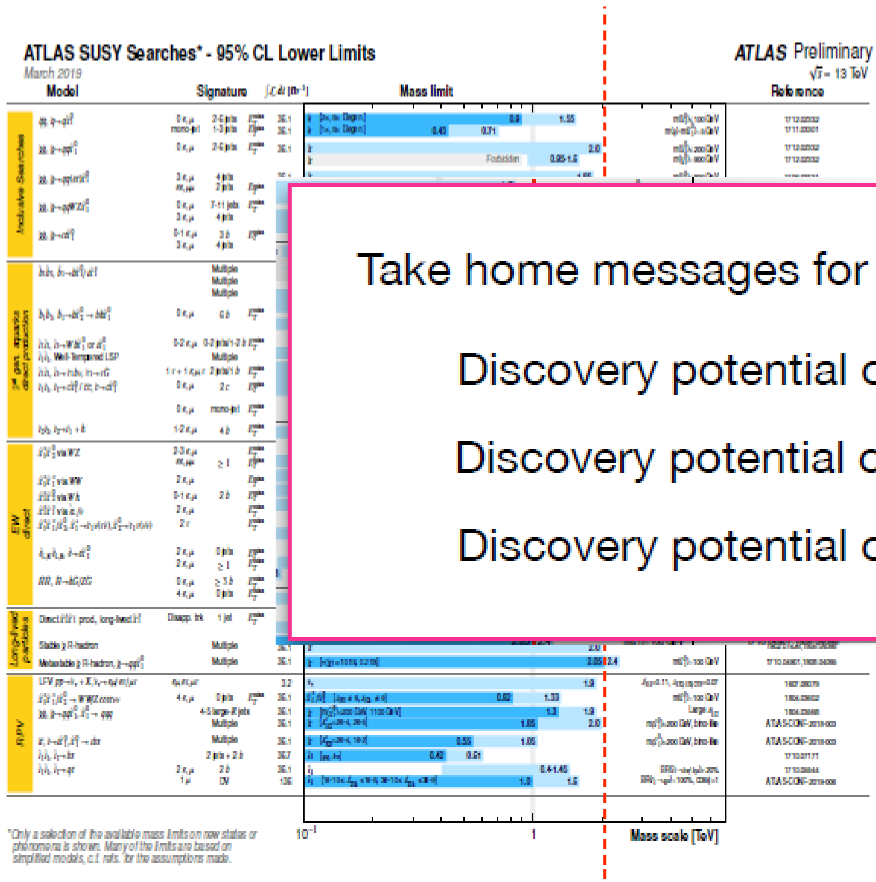


Example from ATLAS (same for CMS)

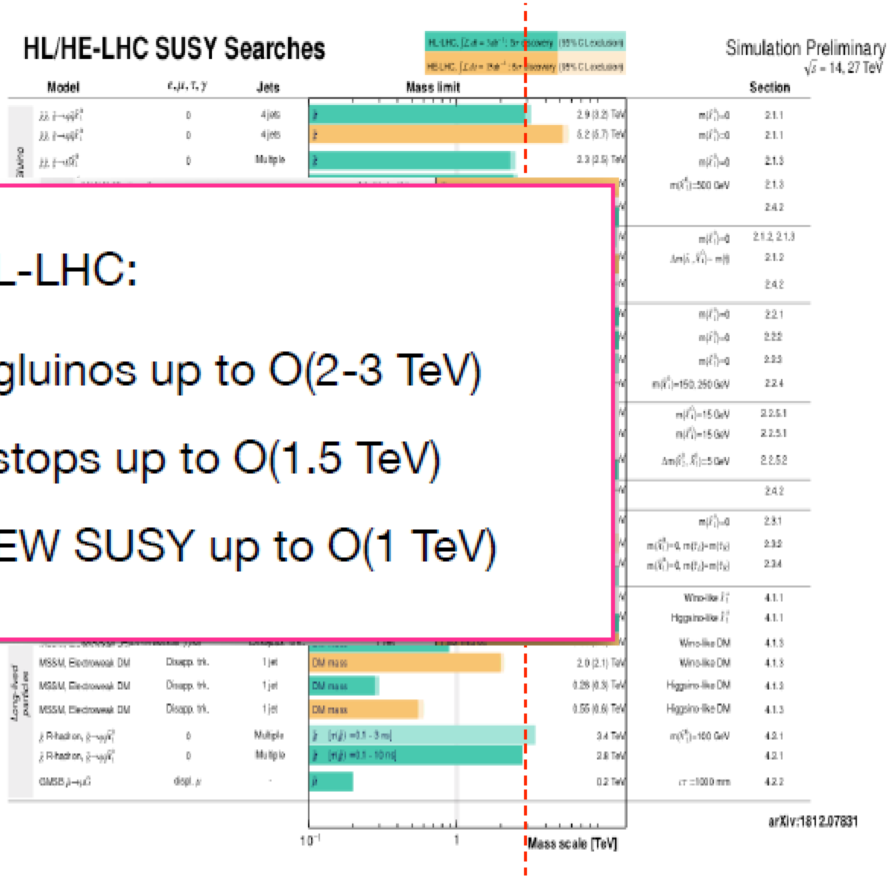


HL-LHC YR
1812.07831

Very large number of SUSY searches



Example from ATLAS (same for CMS)



HL-LHC YR
1812.07831

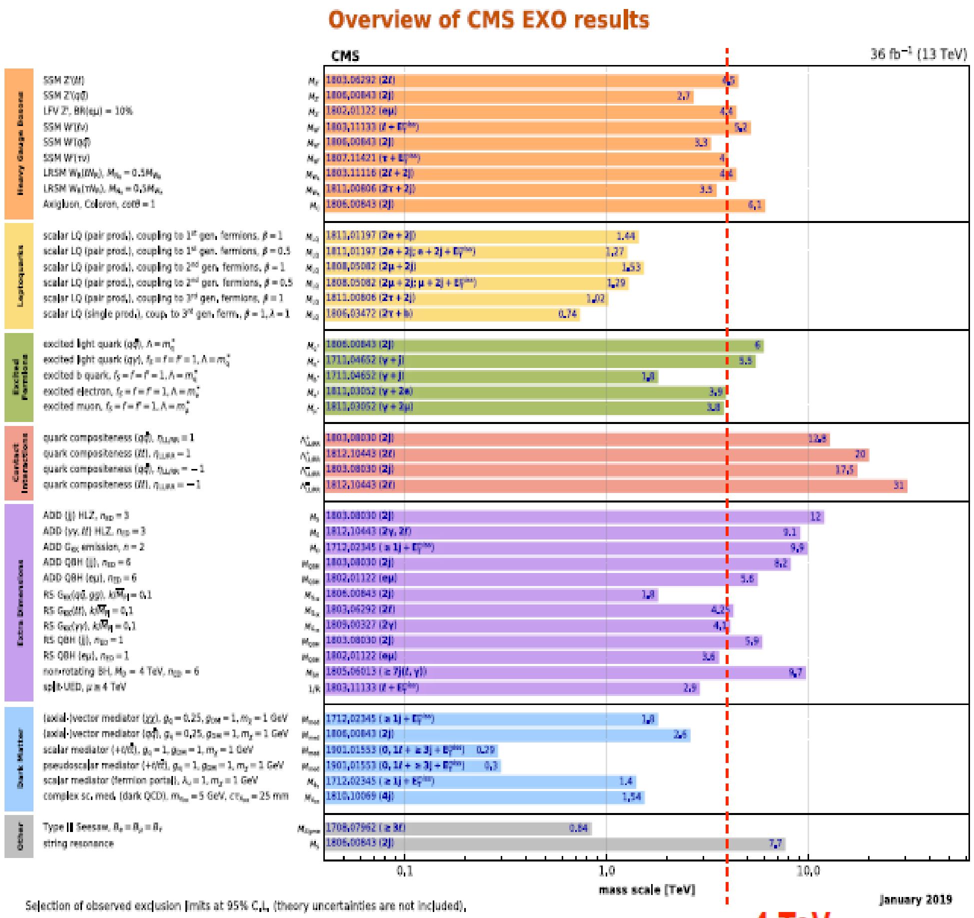
Take home messages for HL-LHC:

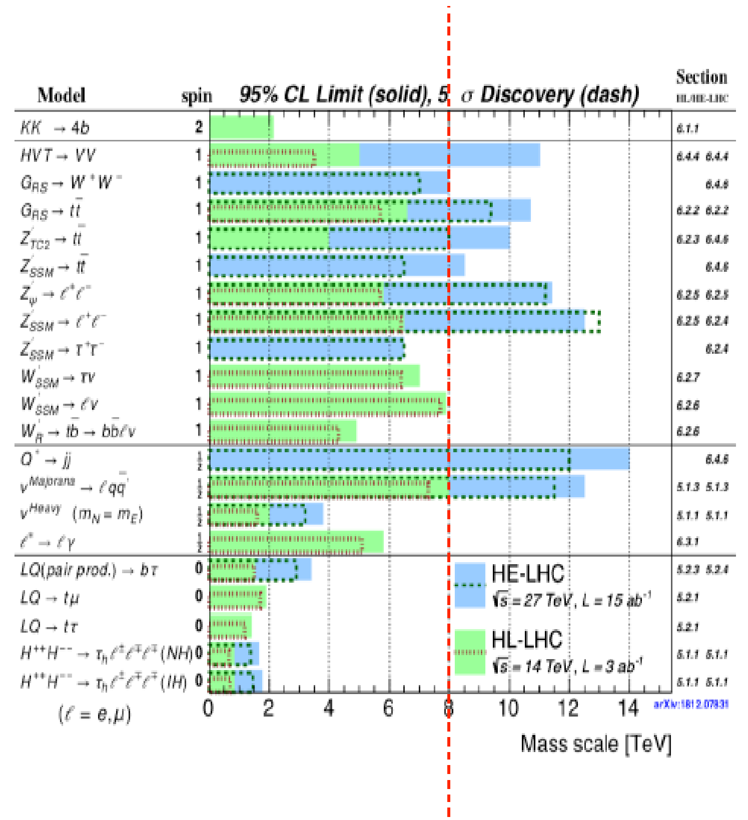
Discovery potential of gluinos up to O(2-3 TeV)

Discovery potential of stops up to O(1.5 TeV)

Discovery potential of EW SUSY up to O(1 TeV)

Very large number of BSM searches

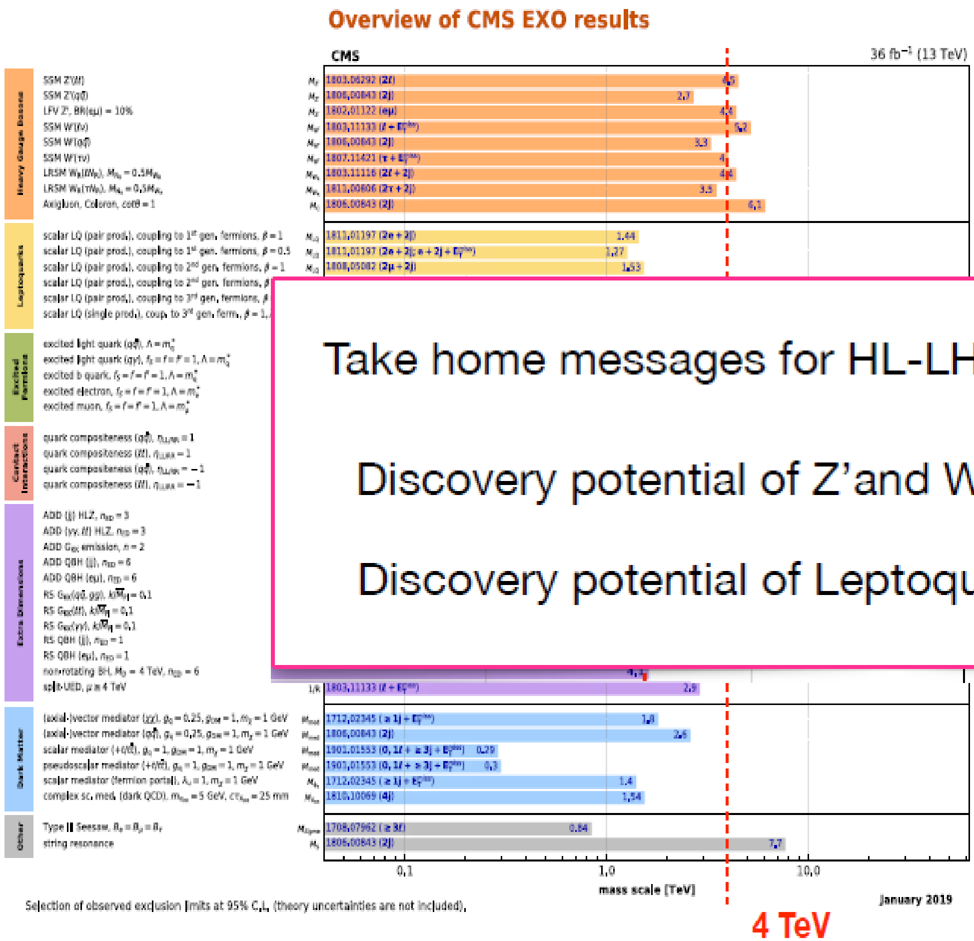


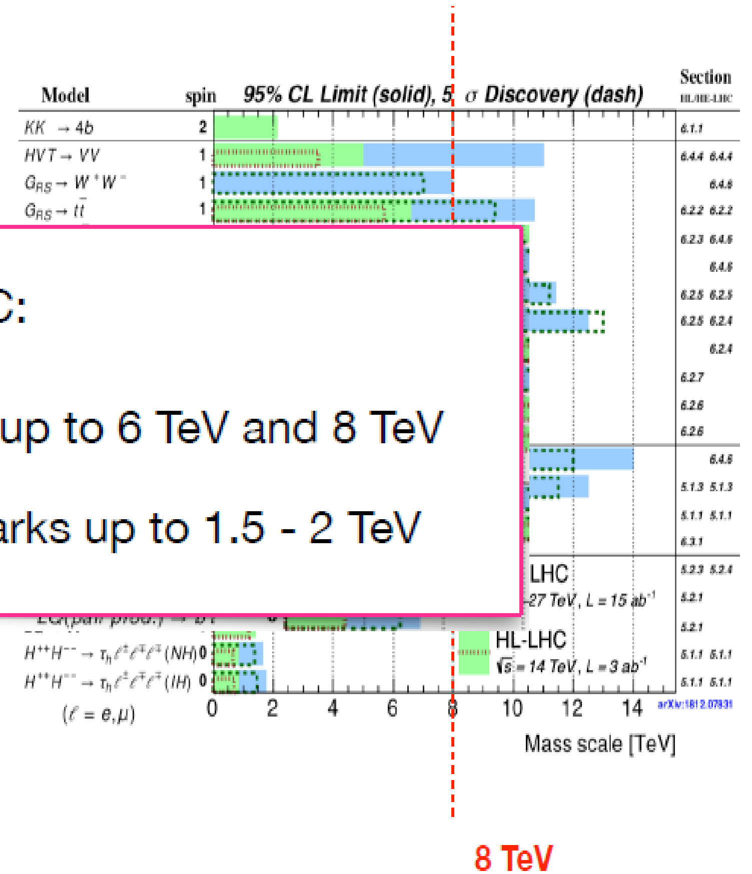


Example from CMS (similar for ATLAS)

HL-LHC YR
1812.07831

Very large number of BSM searches





Take home messages for HL-LHC:

Discovery potential of Z'and W'up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

Example from CMS (similar for ATLAS)

HL-LHC YR
1812.07831

Precision measurements at LHC

Higgs boson mass measurement

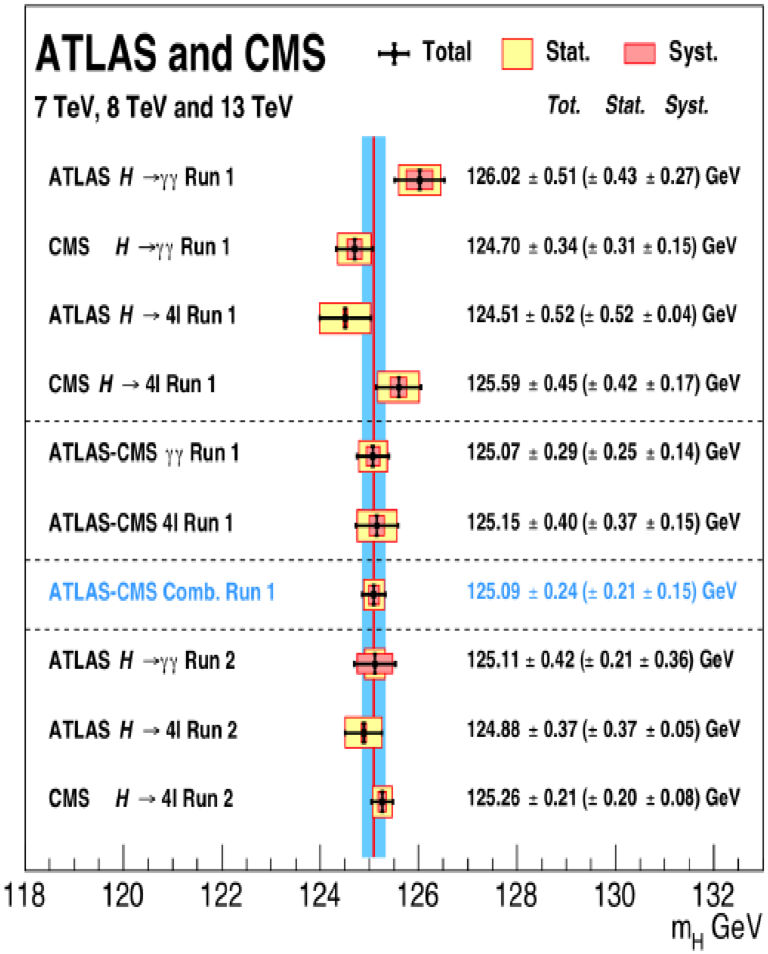
- Measurement in the diphoton and 4-leptons channel exclusively - dominated in sensitivity by the 4mu and 2e2mu channel (Z mass constraint on the 2e).

Current PDG average:

$$m_H = 125.18 \pm 0.16\ \mathrm{GeV}$$

- Measurement not yet dominated by systematic uncertainties.

- With an analysis optimised for mass in high statistics, foresee an ATLAS-CMS combination 10 - 20 MeV precision.



Summary

- After 10 years: the LHC and all LHC experiments have been incredibly successful!
  - **Landmark results:** the **Higgs boson** (Standard Model like) and so far **nothing else!**
  - Performance and precision reached in a number of major measurements (Higgs couplings, W mass, weak mixing angle, CPV in meson systems, top, EW, Heavy Ions, etc...) have **far exceeded our projections.**
  - Many more results with the full Run 2 dataset still to come.
- **Intense times for LHC:** Vast program of Upgrades for Run 3 and for HL-LHC.
- **Towards the precision frontier:** Measurements at LHC are being pursued actively, with a host of new ideas and large number of more precise predictions (where precision is also key in direct searches).
- HL/HE-LHC reports are a milestone, but showed the **remarkable number of opportunities for physics at the LHC**.