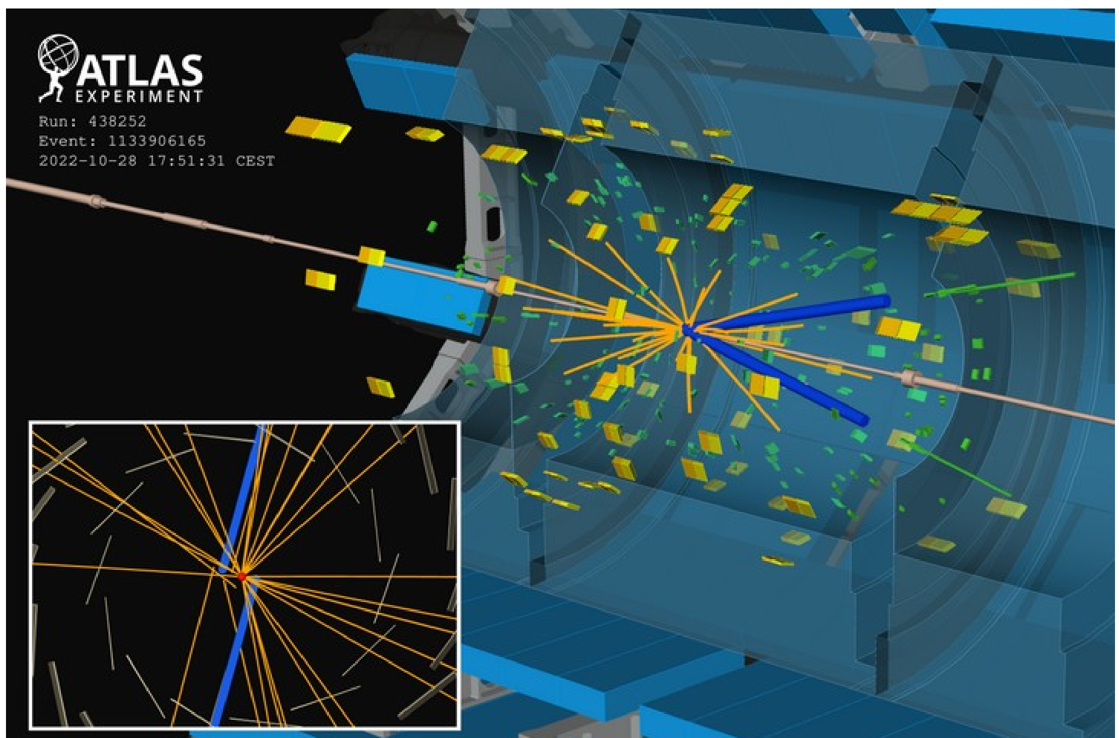
Recent results from the ATLAS experiment

S. V. Chekanov (ANL)

On behalf of the ATLAS collaboration

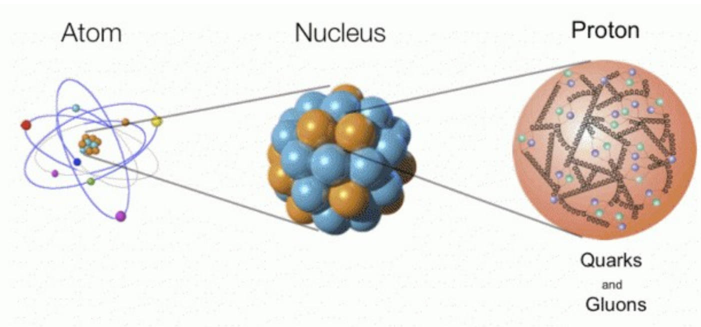
Miami 2024, USA, December 12- 19, 2024



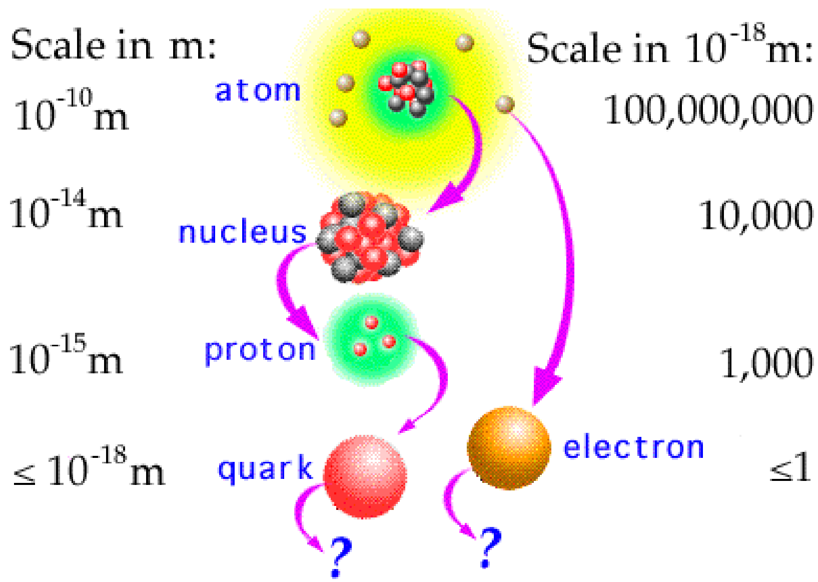
Collision event recorded by the ATLAS detector at an energy of 13.6 TeV, featuring two candidate displaced electrons

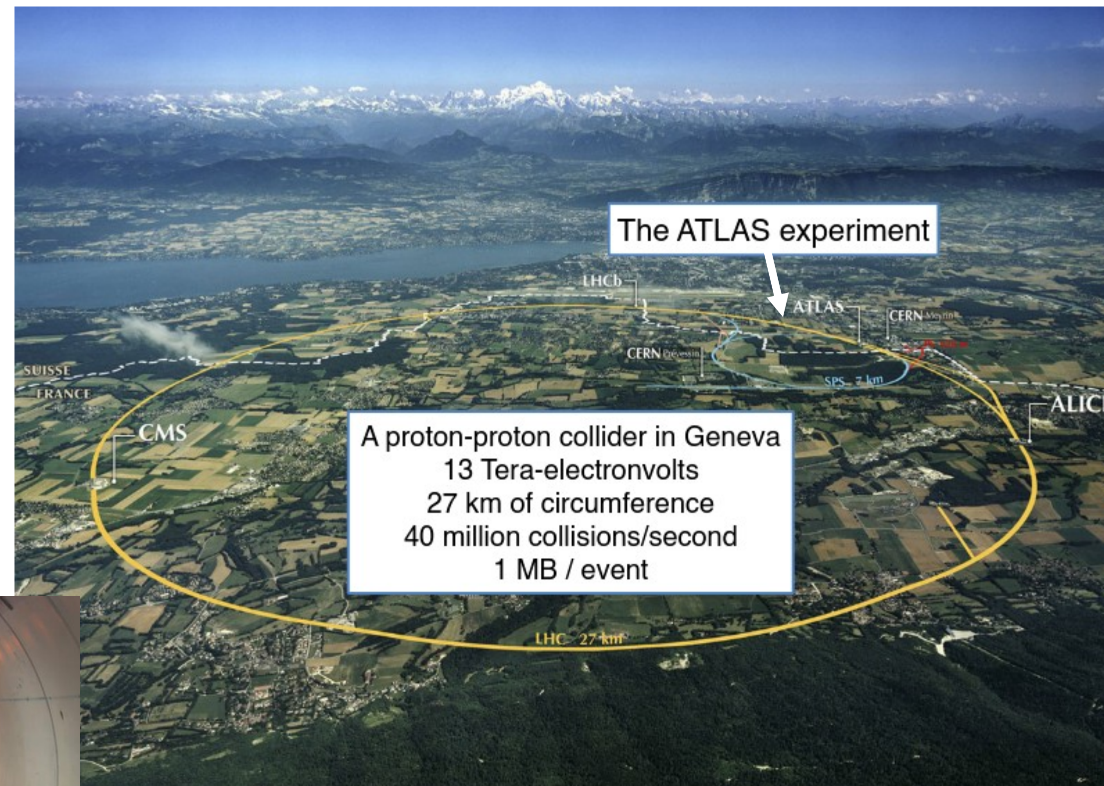
LHC Large Hadron Collider

the world's highest-energy particle accelerator



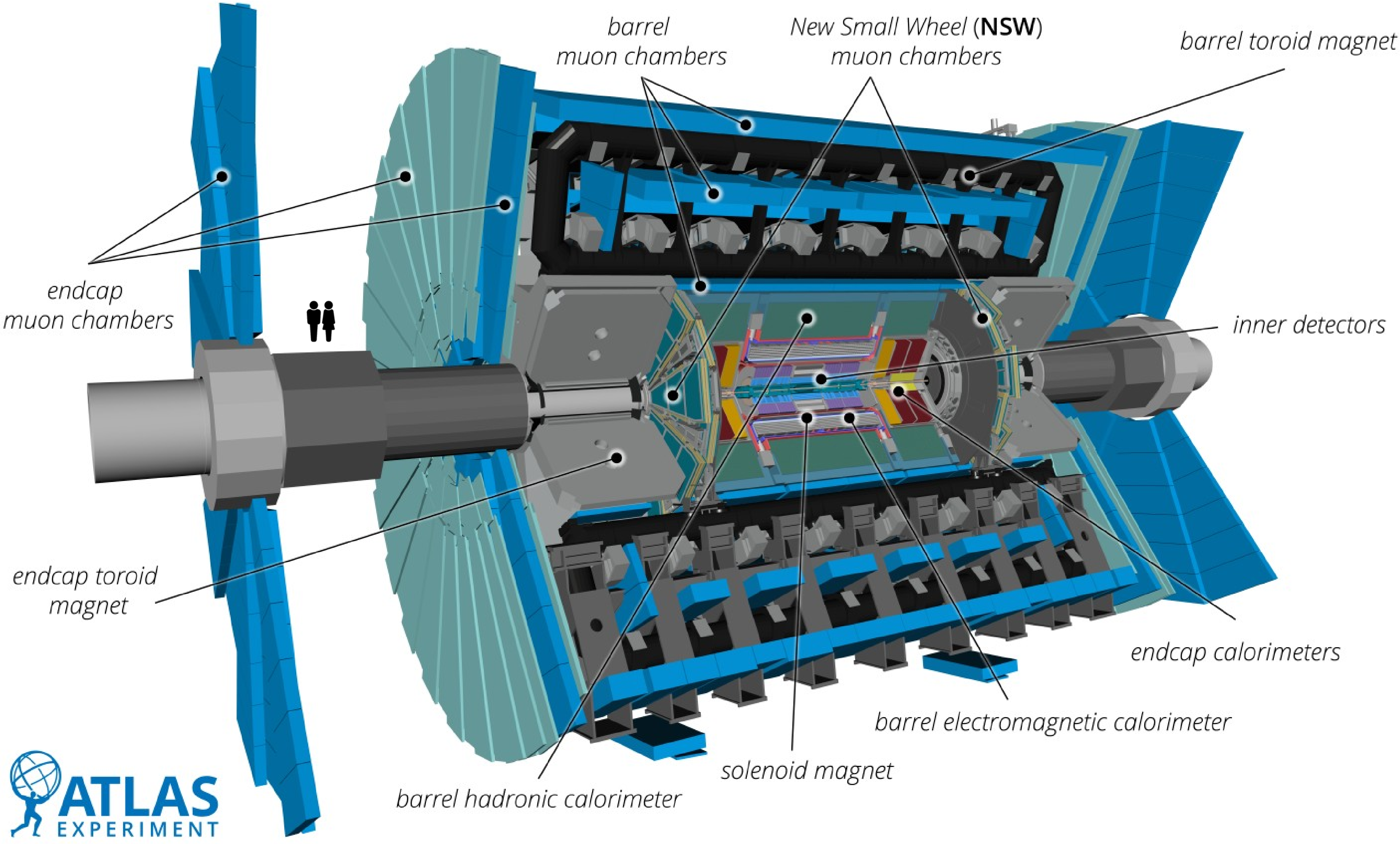
- protons are accelerated to ~13 – 13.6 TeV
- kinetic energy is transformed into matter at the collision
- new particles are being produced





ATLAS detector for Run3

ATLAS-PHOTO-2022-055-1



Studies of elementary particles at highest energy

- Focus Energy into tiny spot → produce new matter / energy $E = mc^2$

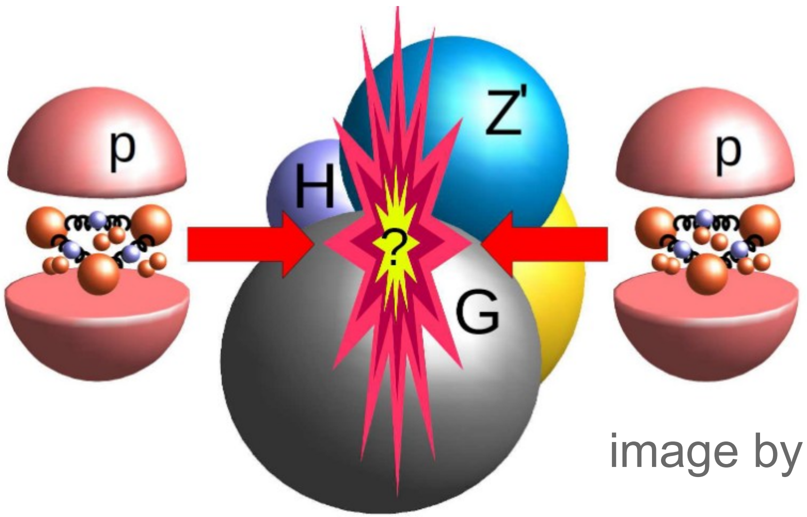
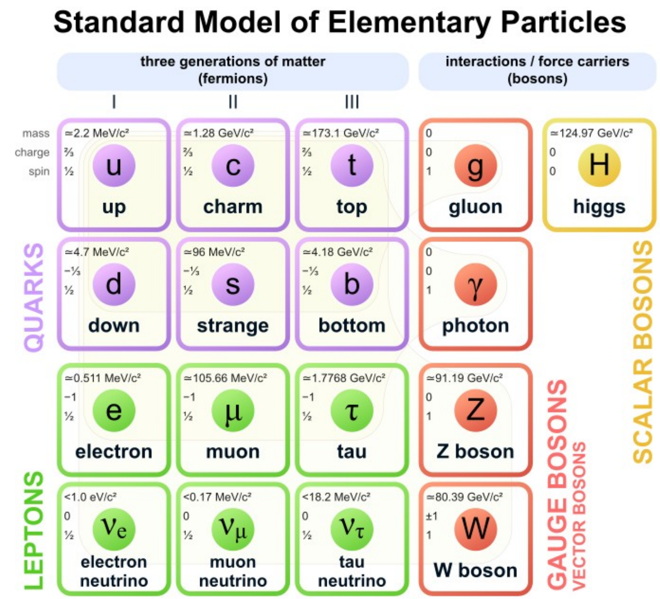


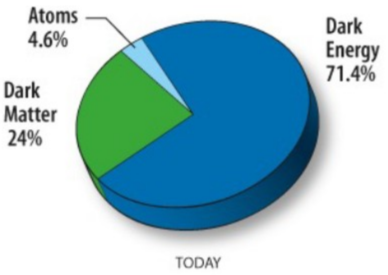
image by A.Gritsan



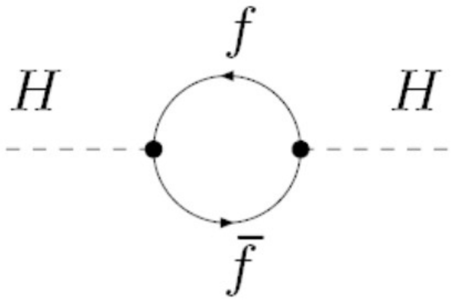
- The Standard Model – the current best framework to describe the most basic building blocks of the universe.
- Successfully explained almost all experimental results and precisely predicted a wide variety of phenomena, including the Higgs boson
- 2012: Discovery of Higgs bosons at the LHC at the mass 125 GeV

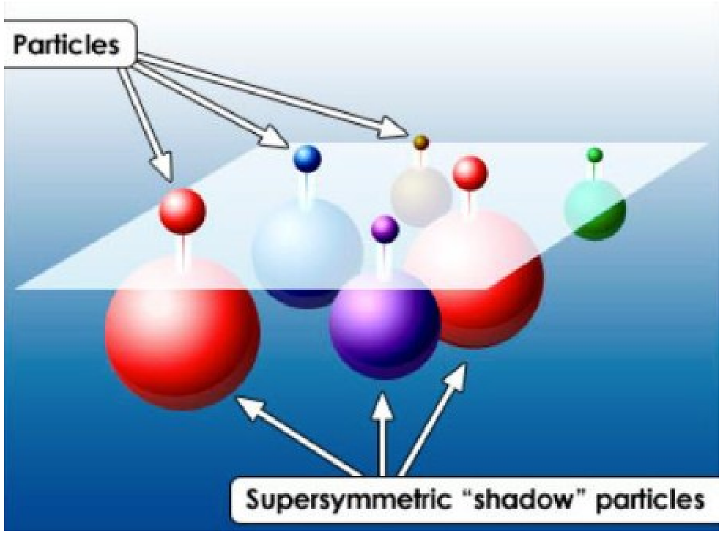
Many open questions

- What is the origin of the Higgs?
- What is the origin of dark matter and dark energy?
- Matter and almost no antimatter
- What is the origin of ~20 free parameters of Standard Model?
- What is origin of fine tuning in the Standard Model?



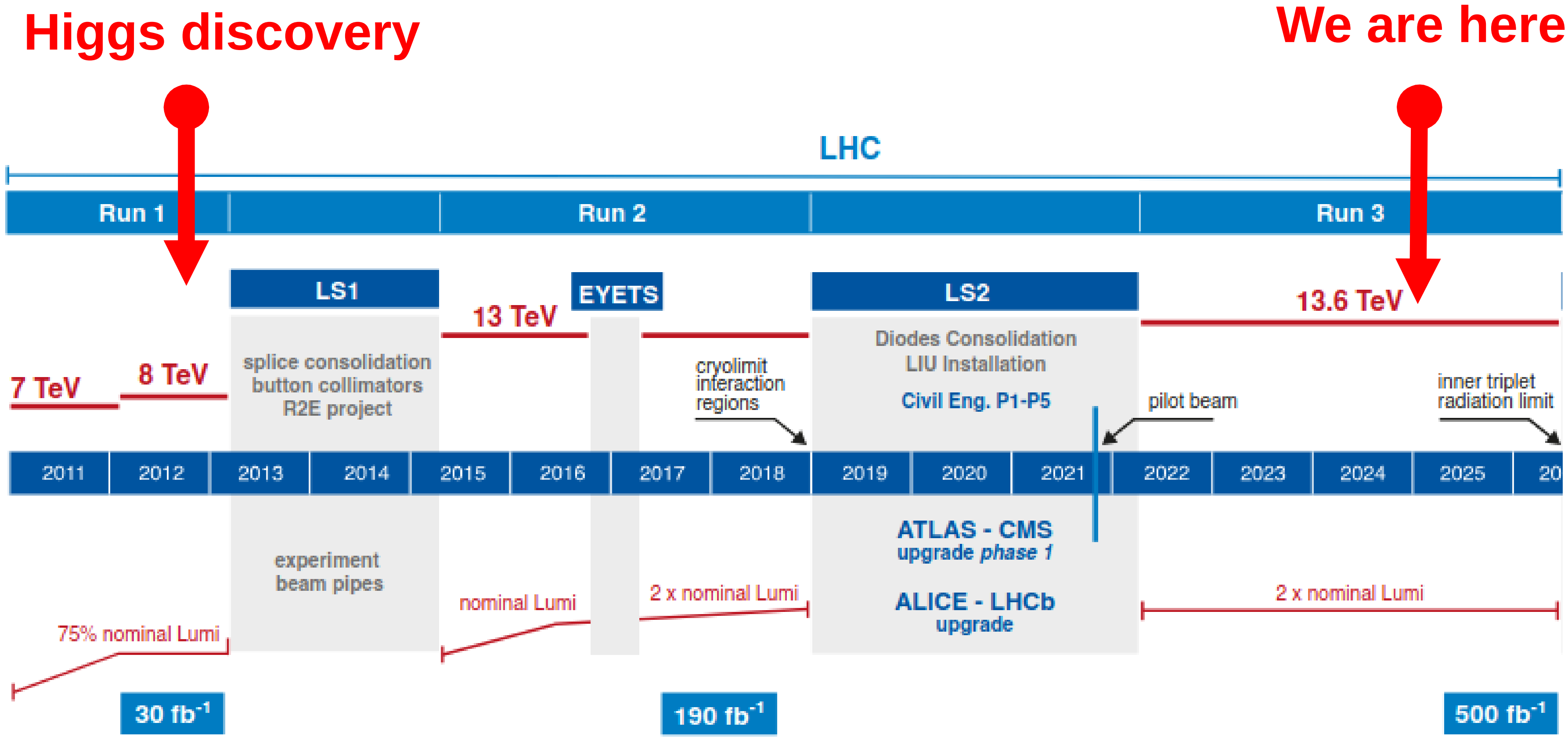
Example:
Higgs mass is a measured parameter, but it mass should be very large if we calculate it from a theory large contributions from quadratic diverges due to radiative corrections.





In order for the Higgs boson mass to be finite, a fine tuning (cancellation) of various loops is required ("hierarchy problem"). **New particles** can cancel such divergencies and will lead to the finite 125 GeV mass

Current LHC status: From Run2 to Run3



LHC pp collision timeline:

- Run1: 2011 – 2012 - 7 & 8 TeV collisions
- Run2: 2015 – 2018 - 13 TeV collision
- Run3: 2022 - 2026 - 13.6 TeV collisions (ongoing)

Abbreviations:

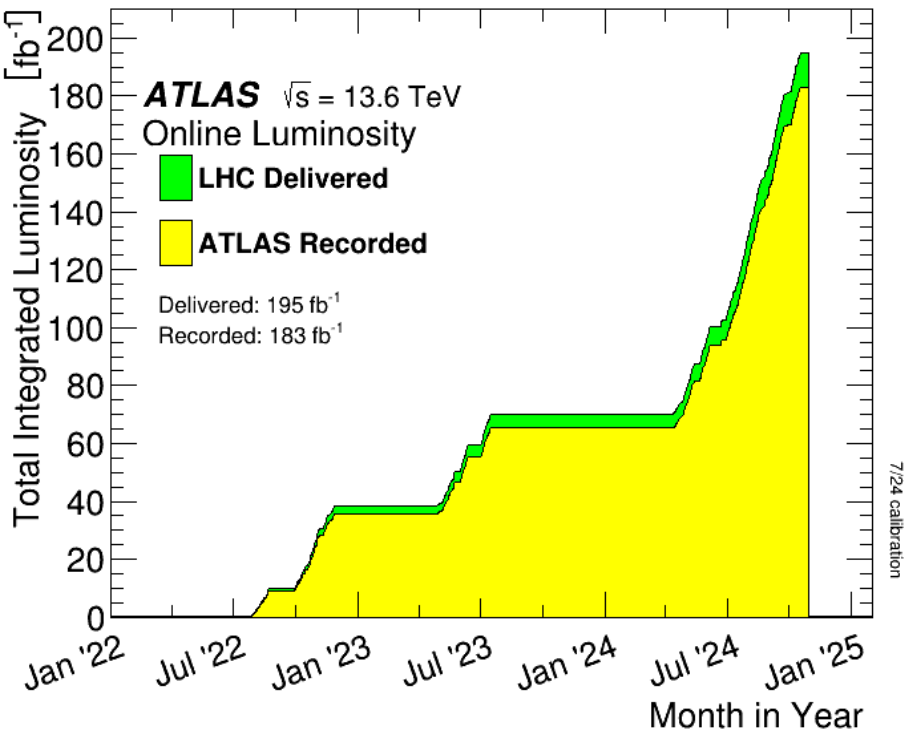
- **LS1,2**: - Long Shutdowns 1 & 2
- **EYETS** - Extended Year-End-Technical-Stop

Run3 data taking

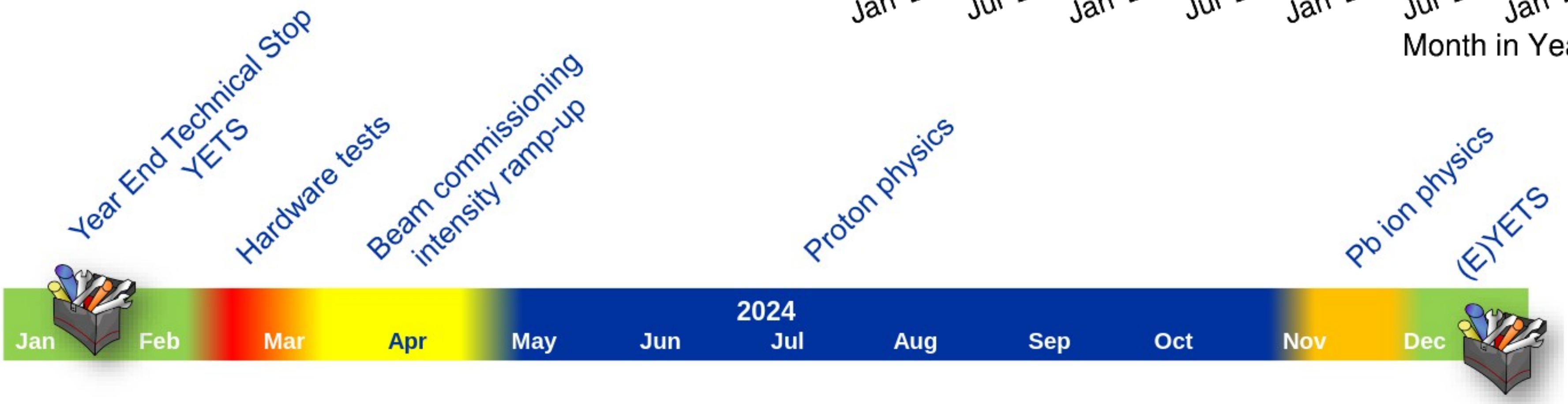
Link to ATLAS public plots

- **2022-2024: LHC is delivering as scheduled, at 13.6 TeV**
- **Expected total: ~500 fb^{-1}**

Reached LHC RUN2 luminosity collected during 4 years of running 2015- 2018 (13 TeV)



2024 LHC Machine Timeline

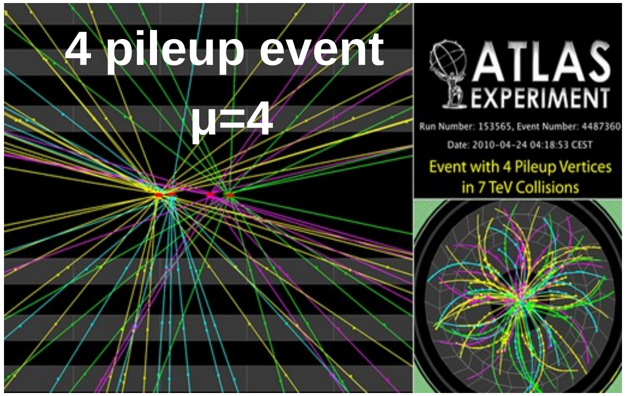


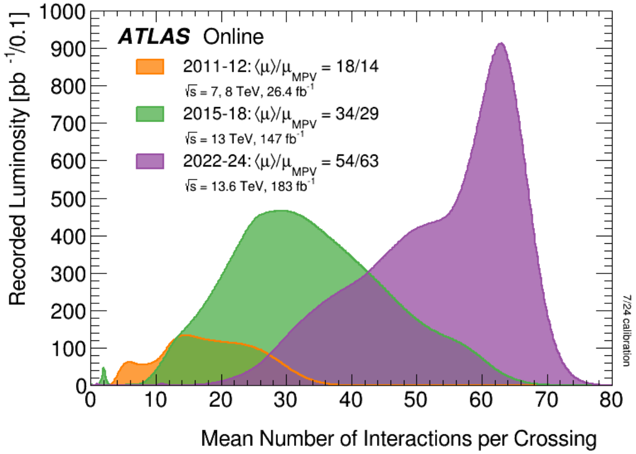
From R. Steerenber

Collision environment & detector improvements for Run3

JINST 19 (2024) P05063

- LHC had **μ=63** for Run3 (x2 larger than for Run2)
- ATLAS was running at 94% recording efficiency





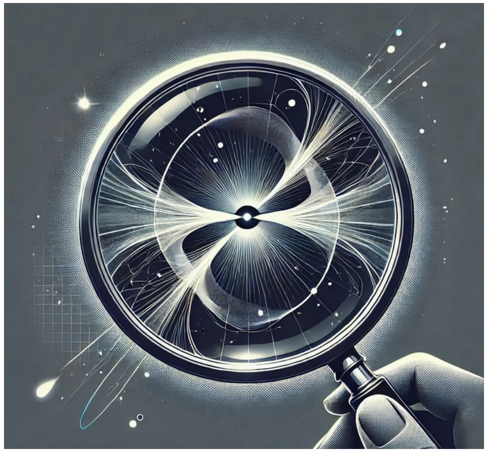
Changes in performance for Run3

- Muon New Small Wheel system included in data resulted in increased efficiency for muons in 2023
- Improved Large Radius Tracking (LRT) for Run 3
- Calorimeter timing information to reject contributions from pileup to topoclusters (used for jets)
- Machine-Learning (ML) entering all stages of the reconstruction/calibration chains
- Improved flavor tagging using ML (“GN2”)
- Improved trigger menus to address larger pileup
- .. etc.

Physics program at the LHC

- **Precision Standard Model measurements**

  Improving our knowledge of what we have already discovered, understanding Standard Model fundamental parameters



- **Search for new physics**

  Searching for deviations from our expectations – discovering unusual effects and new particles

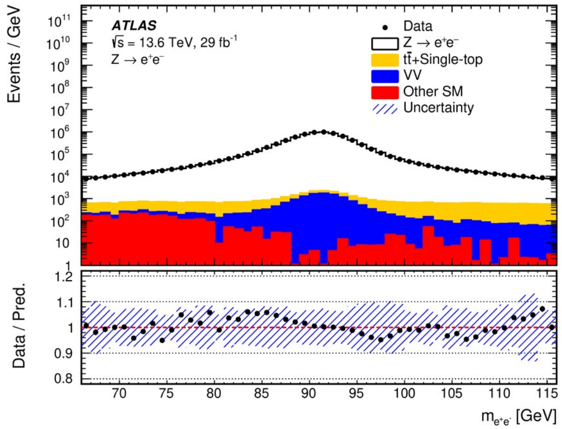
Precision Standard Model (SM) measurements

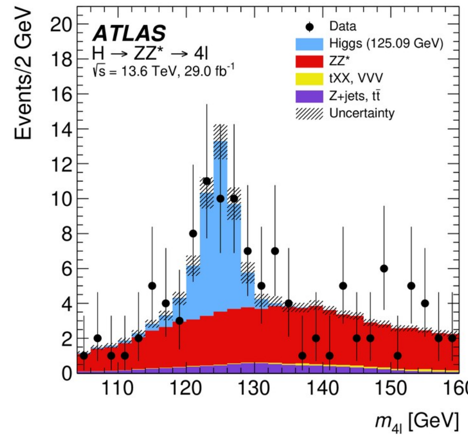
- Improving our knowledge of what we have already discovered and understanding Standard Model (SM) fundamental parameters

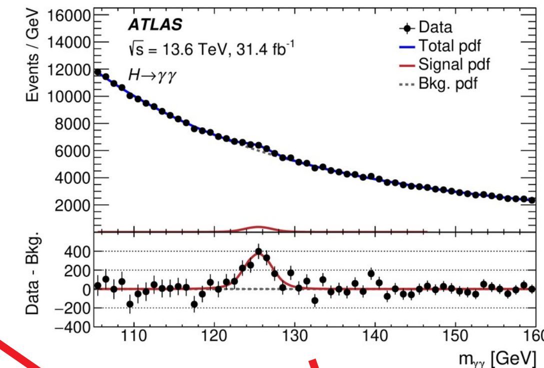
Tests of Standard Model at Run3

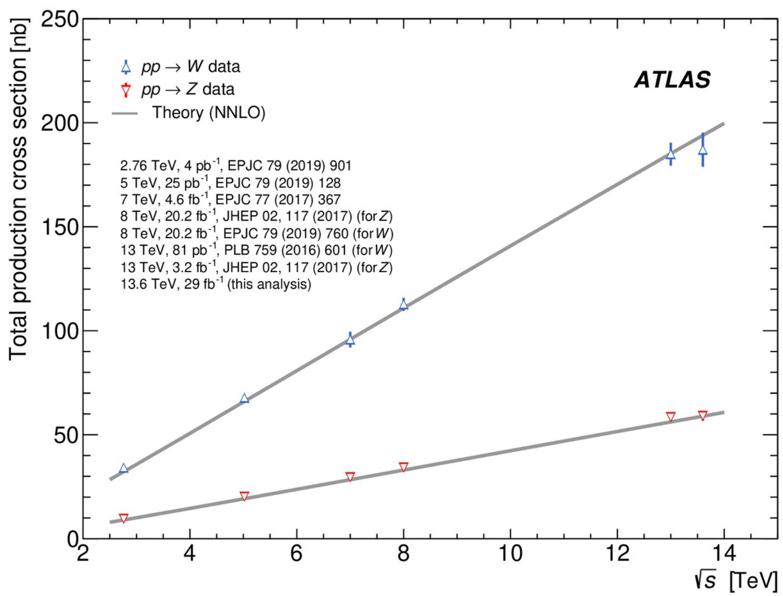
CERN-EP-2024-069
CERN-EP-2023-114

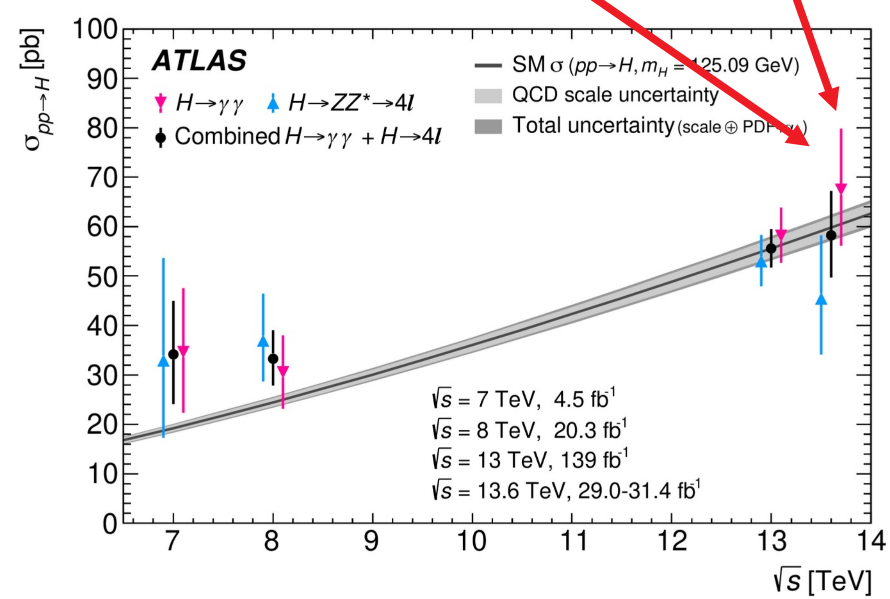
- Basic tests of energy dependence of cross sections at Run3 before anything else
- Agreement with the expectations for Z, W and Higgs bosons at 13.6 TeV







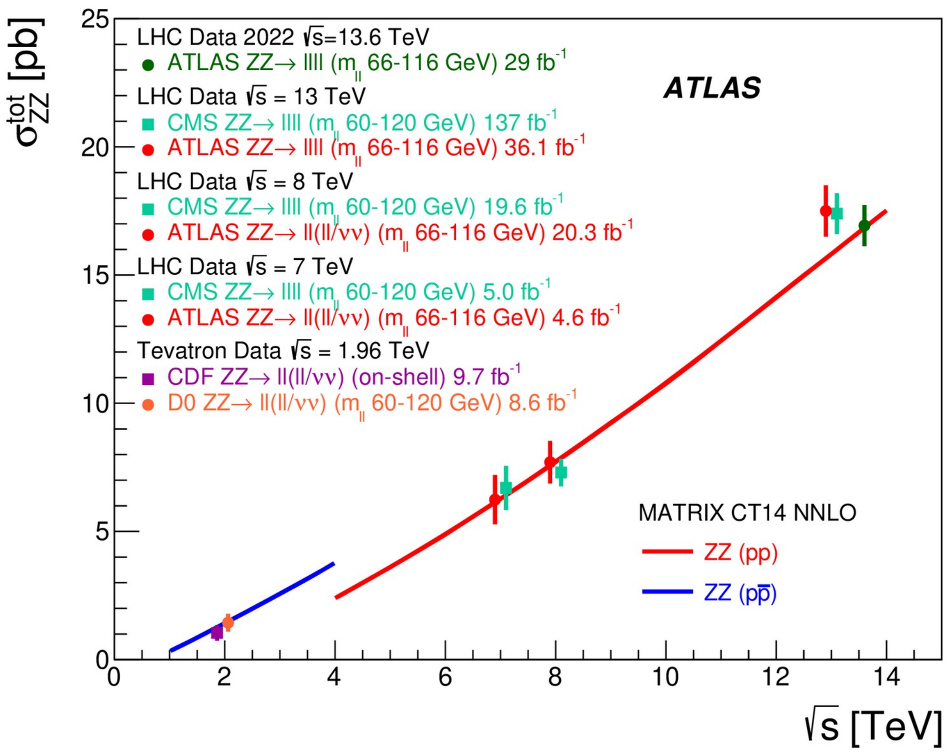


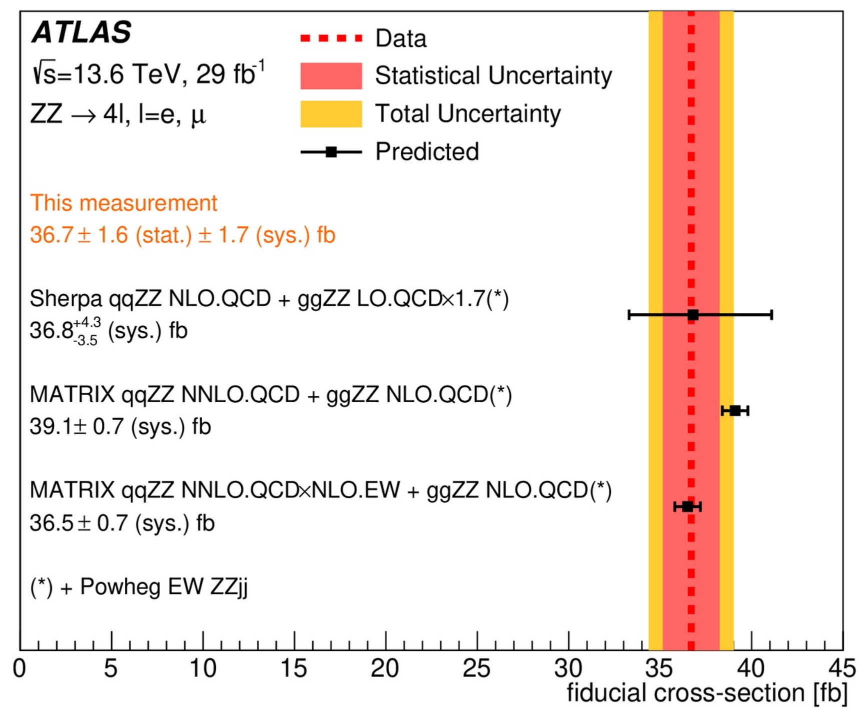


Tests of Standard Model at Run3

CERN-EP-2024-069

- Basic tests of the energy dependence before anything else
- Double boson production (ZZ) is excellent probe for new scalar bosons, off-shell production of the Higgs boson etc.
- Measurements of figucial ZZ cross section in lepton decays:



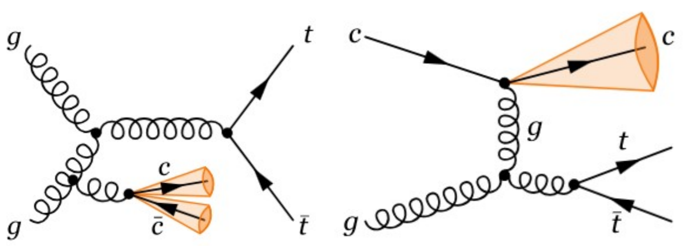


Agreement with the SM expectations

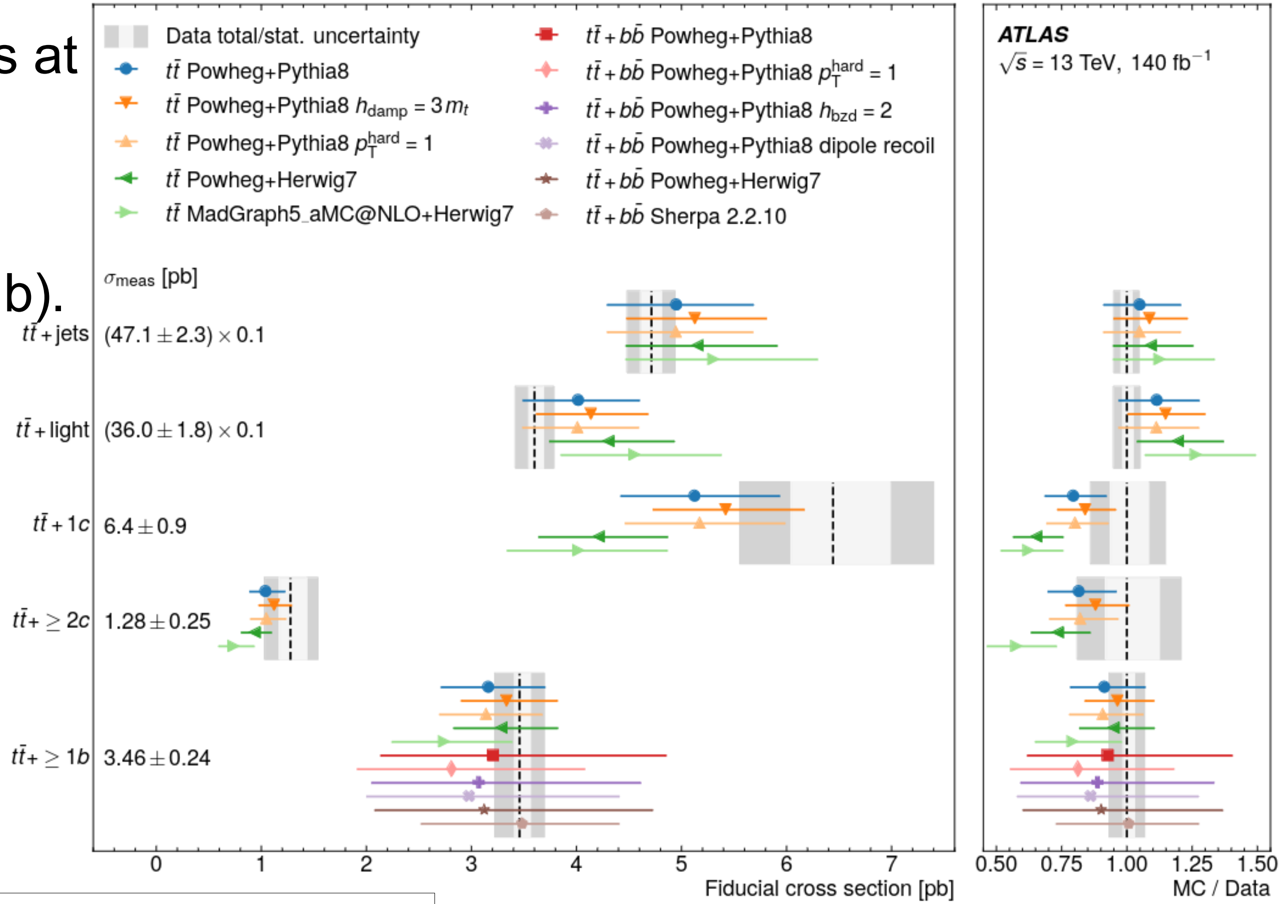
Top-quark production associated with other quarks

CERN-EP-2024-242
CERN-EP-2024-191

After the discovery of top quarks at TEVATRON, and precision measurements at the LHC, main focus - on final states with top and multiple quarks (c, b).



+ similar diagrams replacing c-quarks by b-quarks



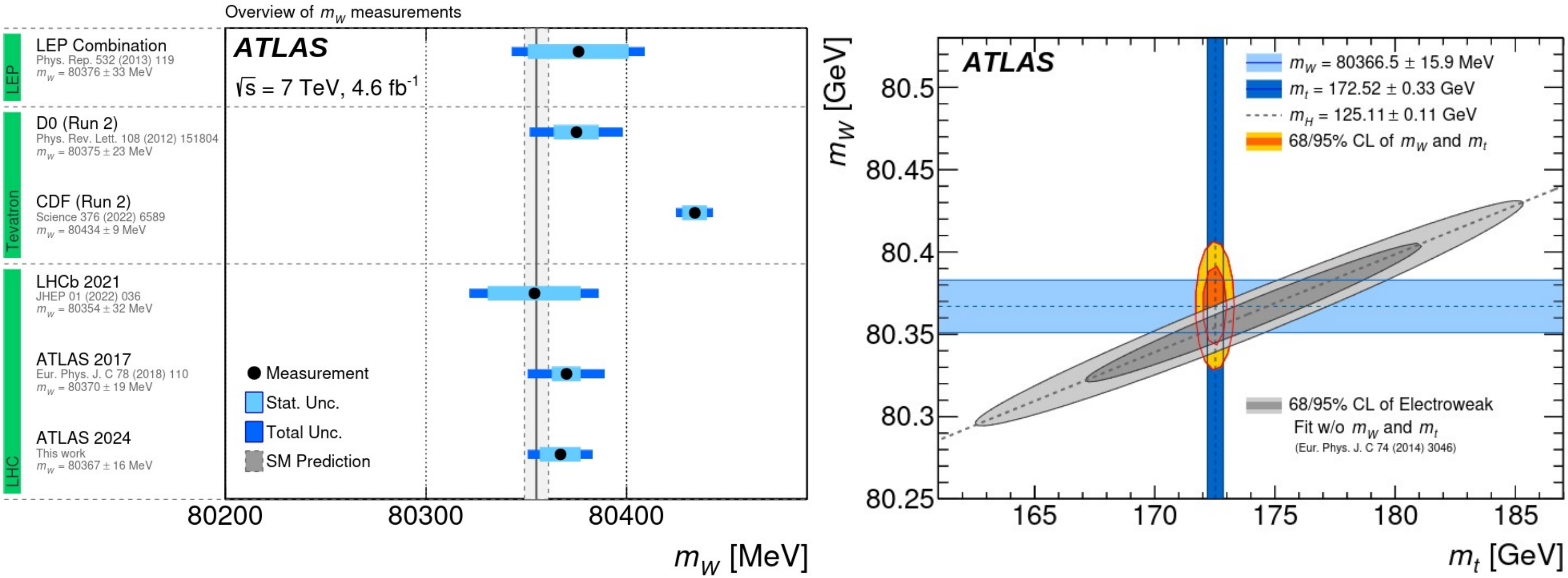
A custom flavor tagging tailored to simultaneously tag c-jets and b-jets. NLO+PS predictions for tt + ≥2 and tt + 1 are largely consistent with the measurement, though all underpredict the observed values.

Essential for precision measurements of rare SM processes

W mass measurements

CERN-EP-2024-074

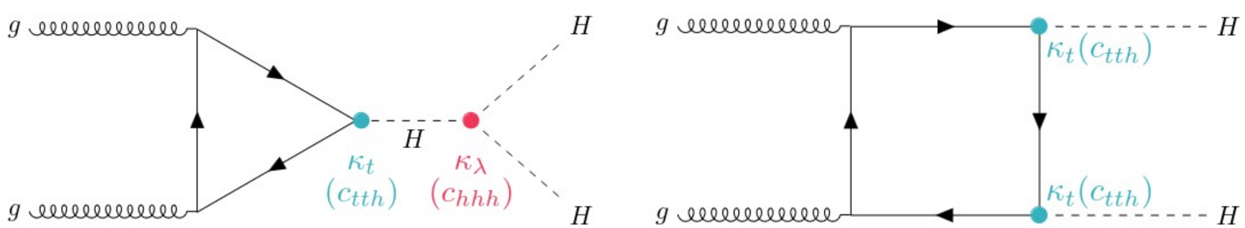
- W mass is one of the most important parameter of the Standard Model
- Closely related to the masses of heaviest particles - top quark and the Higgs boson



- ATLAS finds M(W) to be 80366.5 MeV, with an uncertainty of just 15.9 MeV.
- The measured value is 10 MeV lower than the previous ATLAS result but in agreement with the Standard Model.
- Agrees with a similar CMS measurement of 80360.2 ± 9.9 MeV
- Also improvements in the measured width : 2202 ± 47 MeV

Higgs boson pair (HH) production

- Non-resonant pairs of Higgs bosons (HH) → the prime experimental signature of the Higgs boson self-interaction. Simplest self-replicated process in nature!
- Non-resonant HH arises from several diagrams, dominated by gluon-gluon fusion (ggF) and vector-boson fusion (VBF)



+ VBF (small)

- **Some diagrams interfere destructively**
  - → very small rate
- **Typical total SM cross section: σ ~ 35 fb**

  or ~10,000 events for 300 fb^{-1}
- **No "golden" channel for HH decays, but there are 3 most promising:**

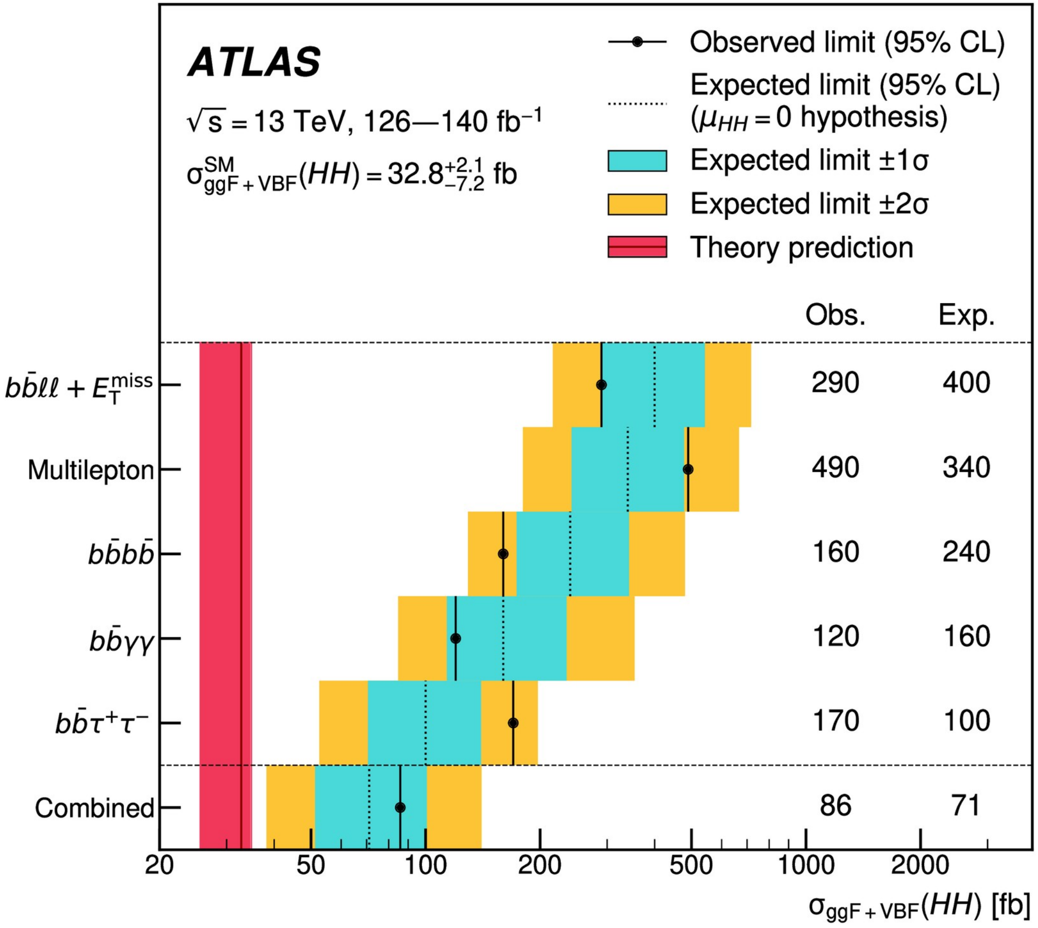
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Best channels

Higgs boson pair production

Phys. Rev. Lett. 133 (2024) 101801

- Currently, only limits are possible for various channels, but their combination is already close the the expected SM cross section.



Obs (exp) for signal strength/SM :
2.9 (2.4) × SM

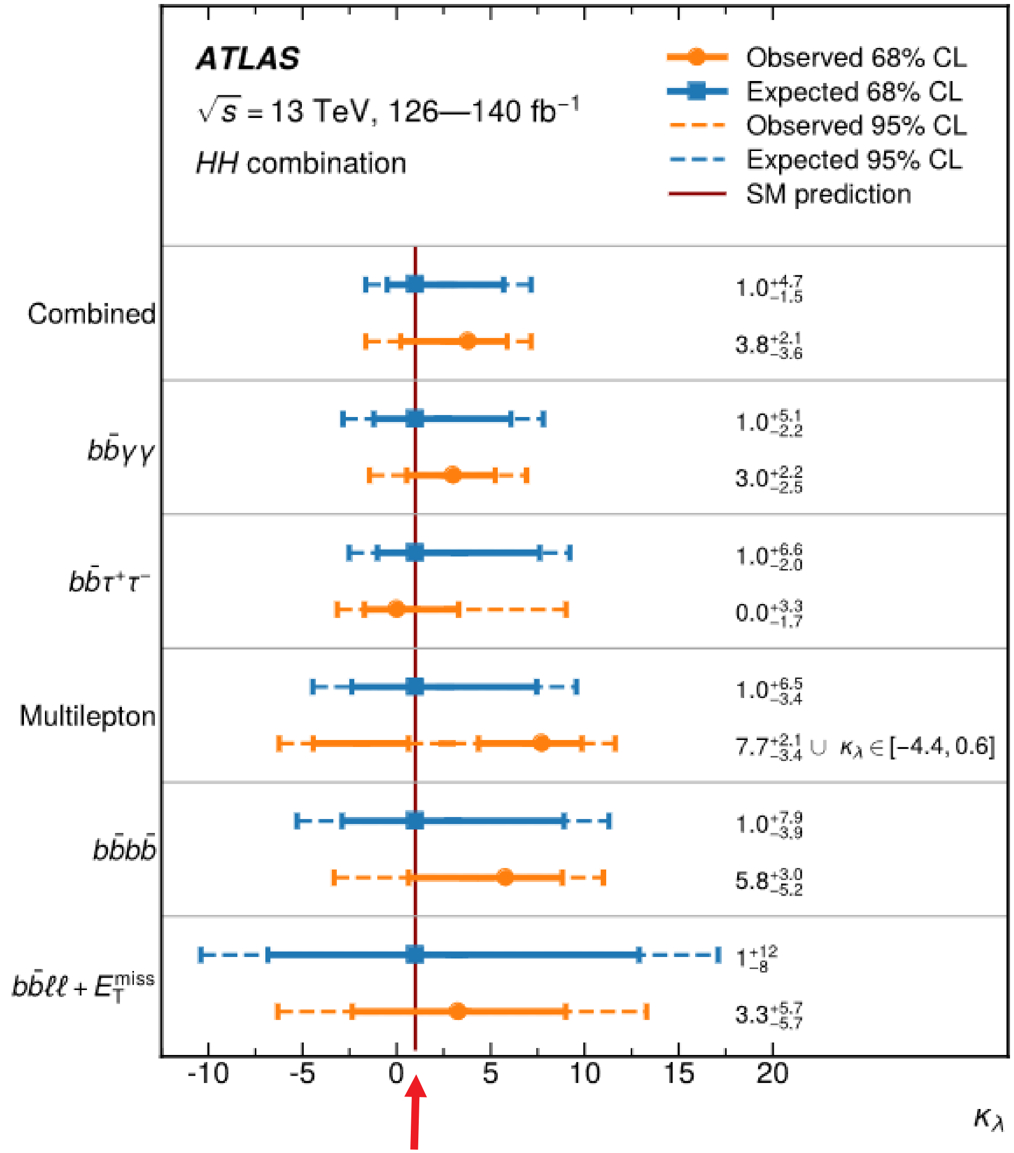
- Best sensitivity from $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$
- Combined results are limited by statistical uncertainties, but some channels ($b\bar{b}b\bar{b}$) starting to get limited by systematics
- Ongoing effort for an ATLAS+CMS combination

Phys. Rev. Lett. 133 (2024) 101801

- Measure the ratio of the Higgs boson couplings to their SM value:

$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{\mathrm{SM}}$$

- Summary of the SM expected (blue) and observed (orange) one-dimensional intervals at 68% CL on κ_λ
- When profiling k_λ, other Higgs boson couplings are set to their SM values.
- Results are fully consistent with the SM predictions

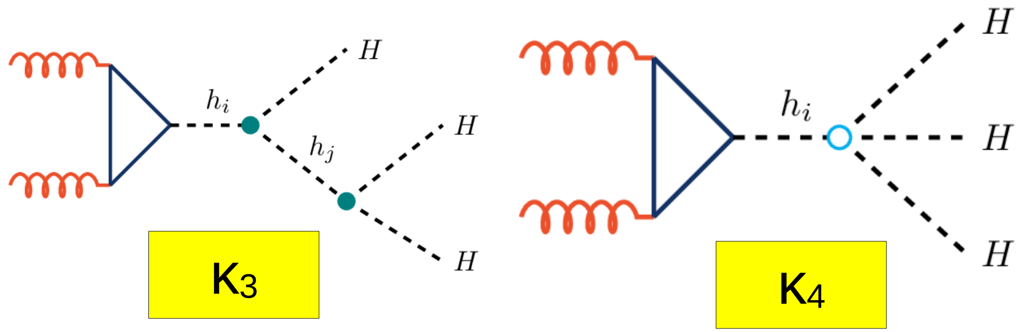


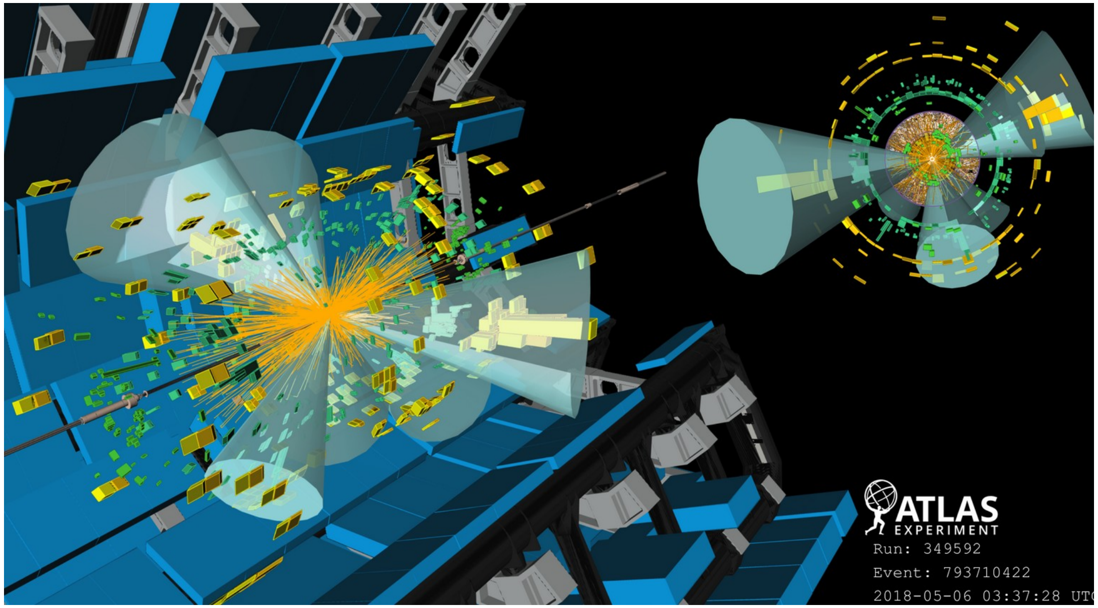
SM prediction (=1)

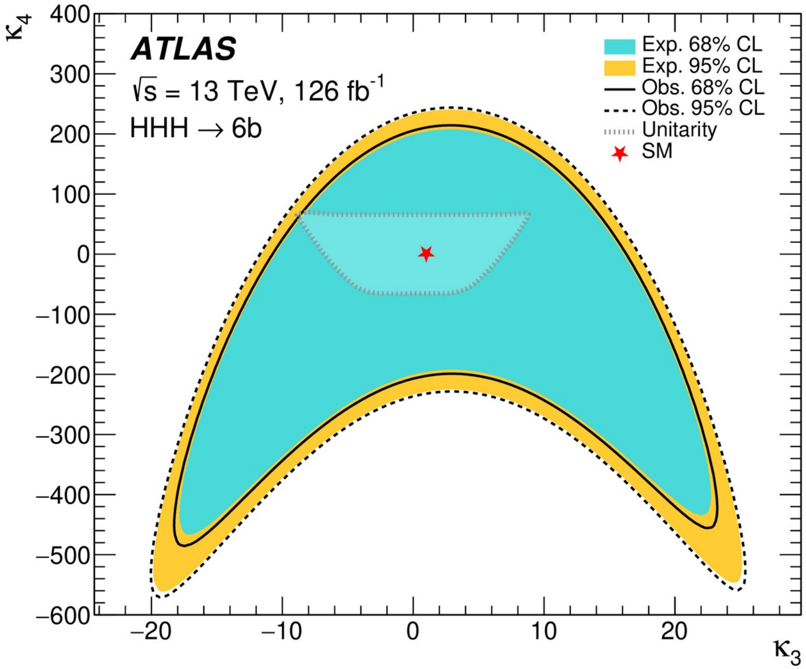
3-boson Higgs production (HHH)

CERN-EP-2024-285

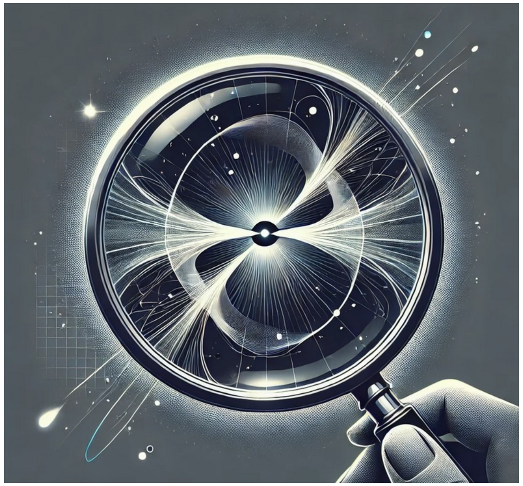
- Even more challenging analysis
  – 3 boson production to 6-bjets !
- What is the interplay between κ_3 and κ_4 couplings?
- No evidence for HHH production.
  An upper limit of 59 fb is set at 95% confidence level on the cross-section for Standard-Model HHH production.







Searches for physics Beyond Standard Model (BSM)



- BSM: Searching for deviations from our expectations – discovering unusual effects and new particles.

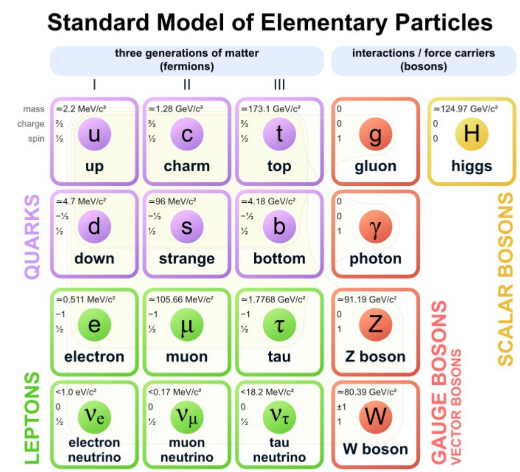
- BSM signal models:
  - *SUSY - is an extension of the SM aiming to fill some of the gaps and predicting partner particles for SM particles.*
  - *Sequential SM predicting heavy W' / Z' bosons*
  - *Grand unified theories*
  - *Two Higgs Doublet Models (2HDM)*
  - *Heavy Vector Triplet (HVT) models*
  - *Extra dimensions*
  - *Models with CP-violation*
  - *Leptoquark (LQ) models*
  - *Dark matter (DM) models*
  - *.. etc. etc.*

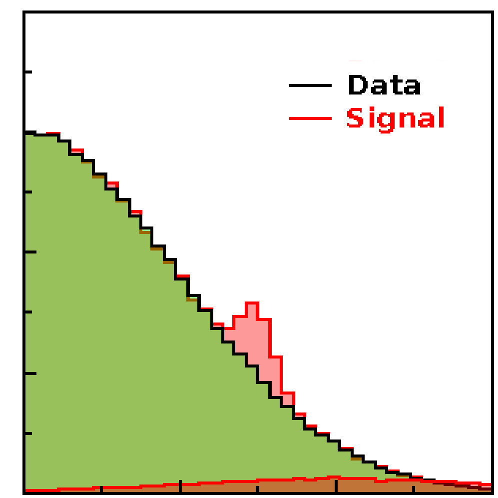
New particles at collider experiments

- Standard Model (SM) is successful for particle collisions
- Discrepancies may indicate new physics ≡ new particles/fields

- **<u>Direct observations</u> of new particles**
  - Combine known particles/jets to create “invariant masses” & search for “resonance” enhancements above background
  - or observe through unusual signatures in detector (anomalously high dE/dx tracks etc)

- **<u>Indirect observations</u> of new particles**
  - Compare SM predictions with data
  - Search for any discrepancy with SM background
  - Explain using theoretical frameworks beyond SM (BSM)





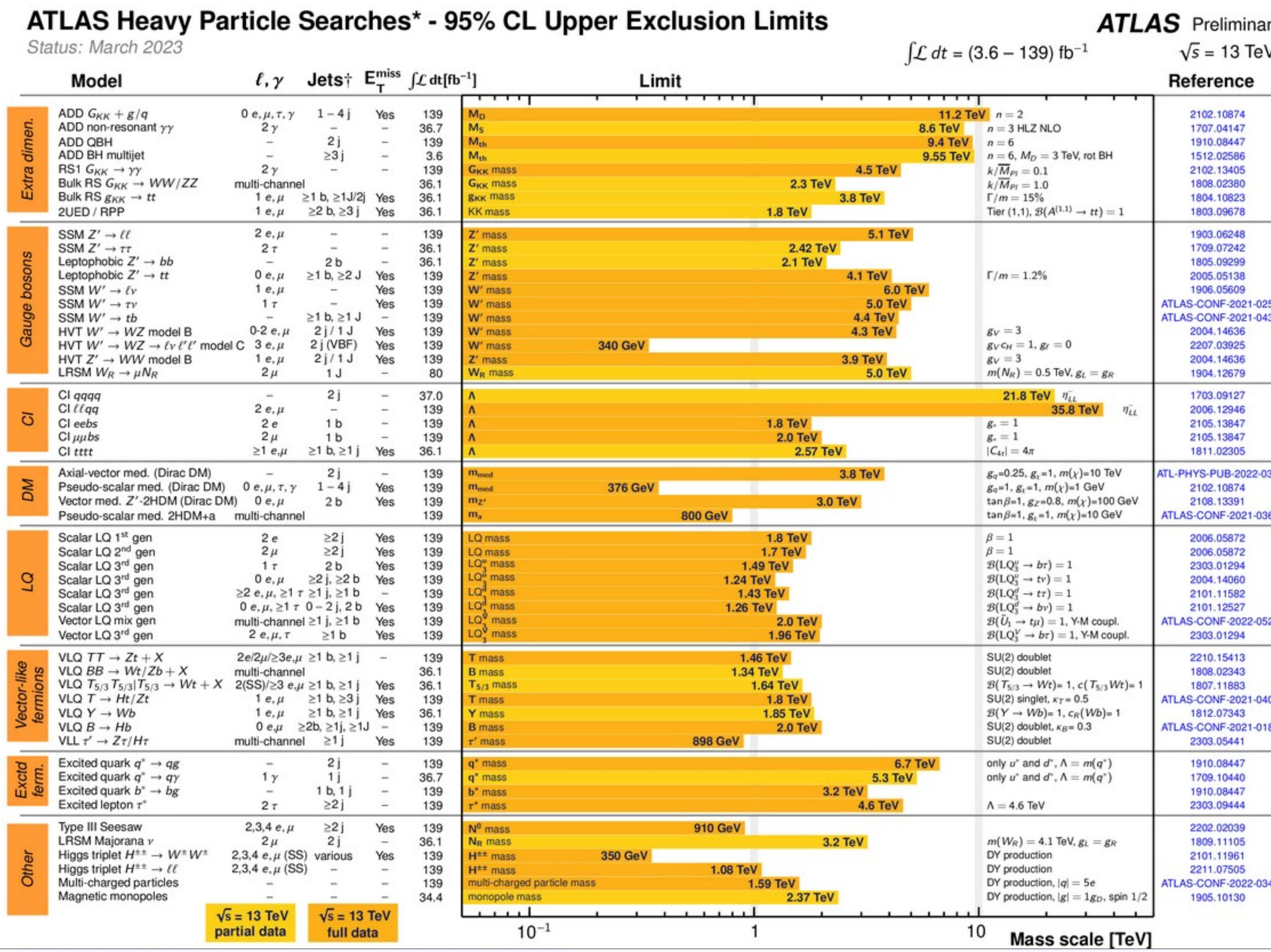
$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$

Invariant mass from known particle/jet with energy E and **p**

No evidence yet but no shortage of models predicting exotic heavy particles

ATLAS searches for new particles

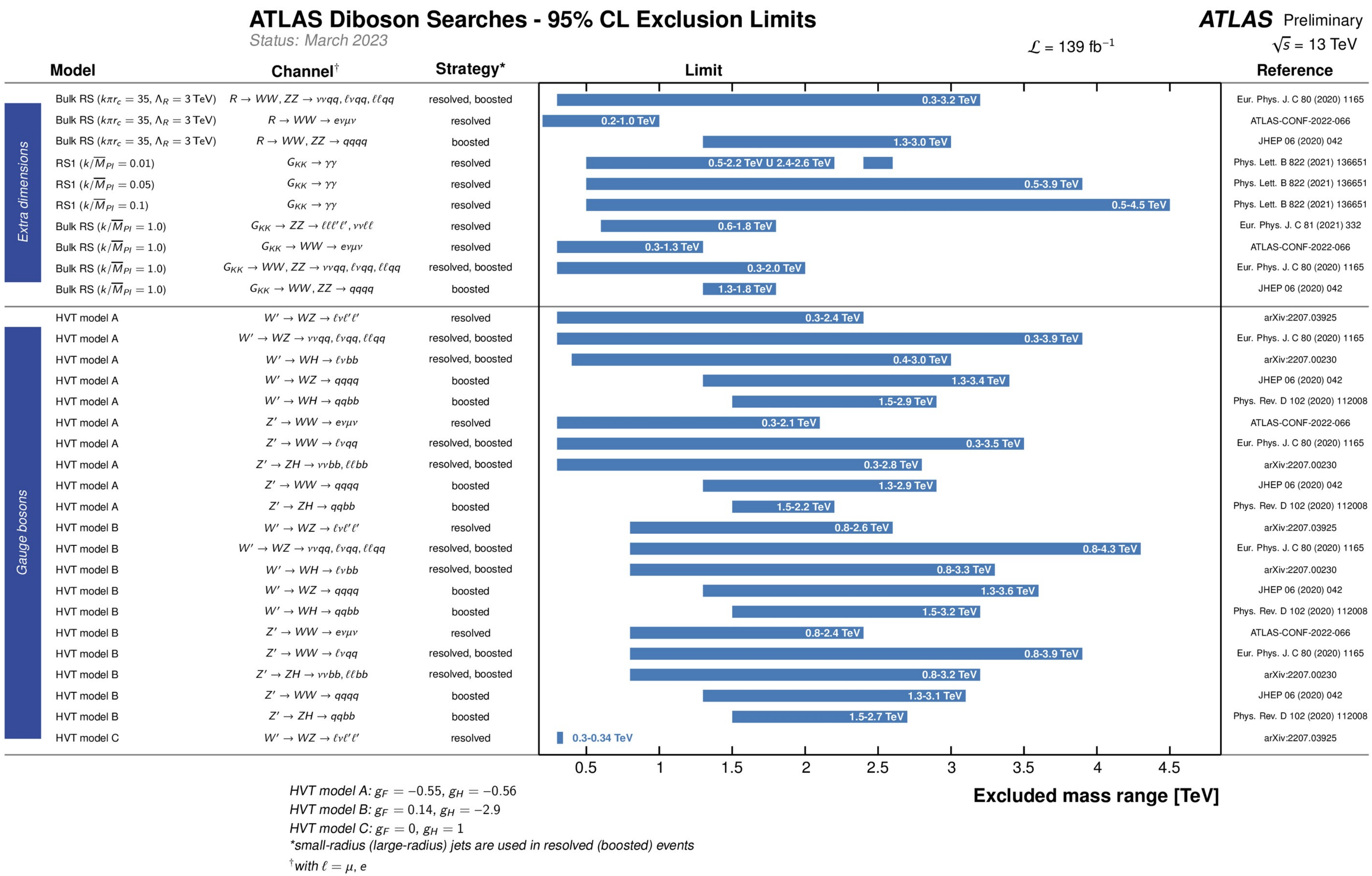
(URL to the Summary plots)



Heavy particles excluded up to 12 TeV mass for ~50 BSM signatures

ATLAS searches for new particles: Diboson decays

(URL to the Summary plots)

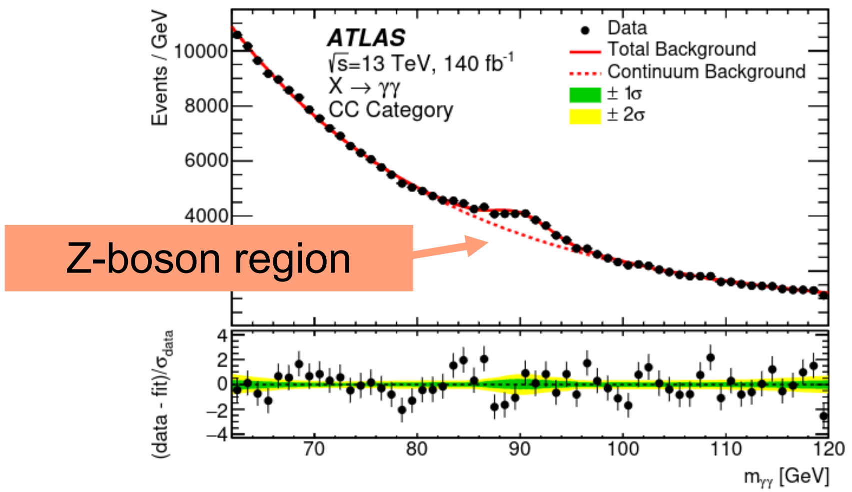


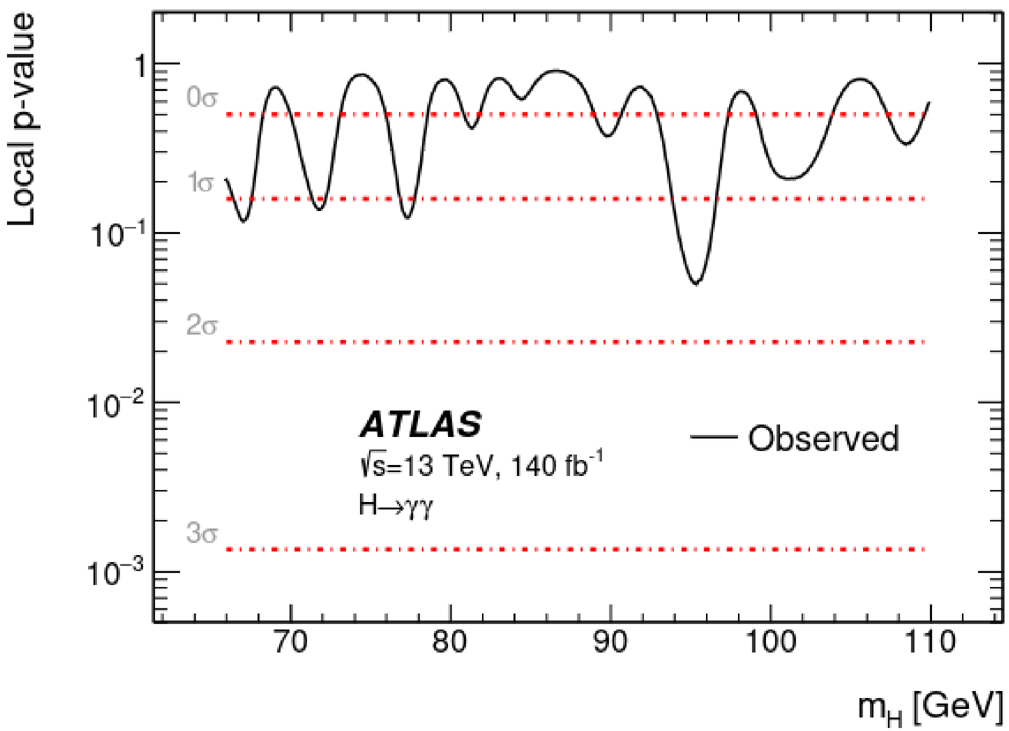
Heavy particles with VV decays excluded up to 4.5 TeV for several BSM scenarios

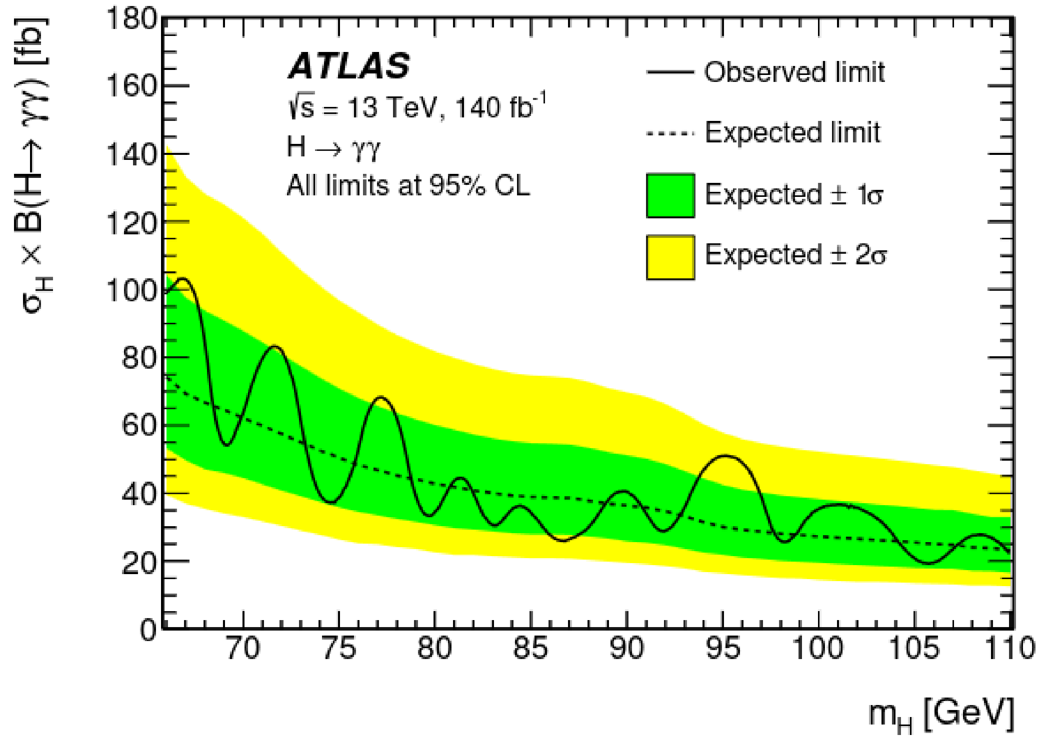
Search for diphoton resonances

CERN-EP-2024-166

- Some models predict new resonances below the Higgs mass in extended Higgs sector: two Higgs Doublet Models (2HDM) or Axion-like particle in SUSY models, etc.
- Slight excess around 96 GeV (~1.7 σ)



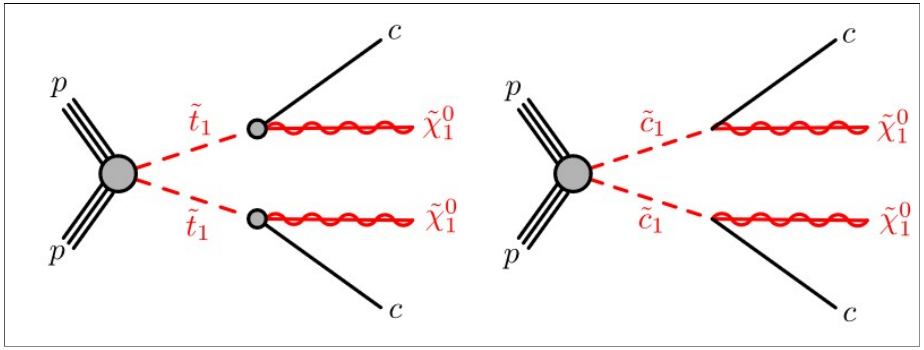


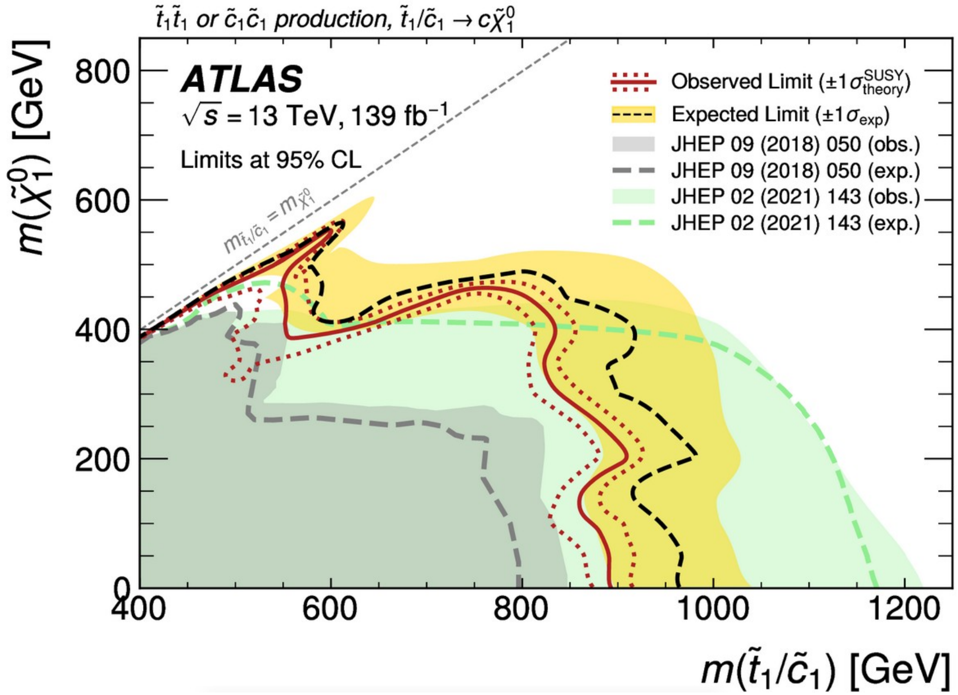


Search for SUSY in events with missing transverse momentum and charm-tagged jets

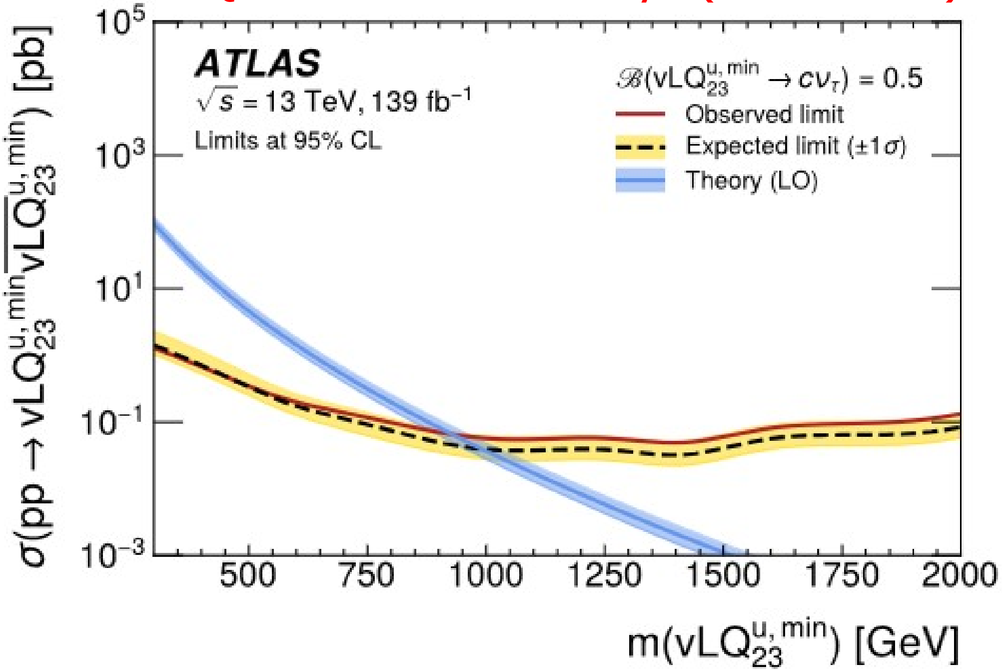
CERN-EP-2024-218

- Reanalyzing Run2 data with improved c-quark tagging and new rec. technique
- Top/charm squark masses excluded up to ~900 GeV at 95% CL, assuming each squark decays into a charm quark and a lightest supersymmetric particle $\tilde{\chi}_1^0$





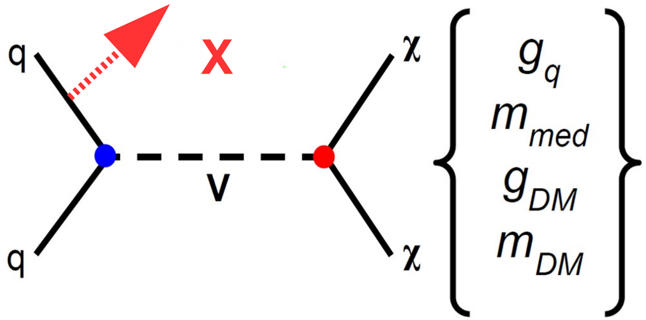
+ LQ limits with cv decays (as a bonus)



New exclusion regions at 95% confidence level

Searches for Dark Matter (DM) at the LHC

- LHC collides pp under well-controlled conditions
- SM particles can radiate other SM particles **"X"** (via initial-state radiation)
- Undetected DM → imbalance in transverse momentum

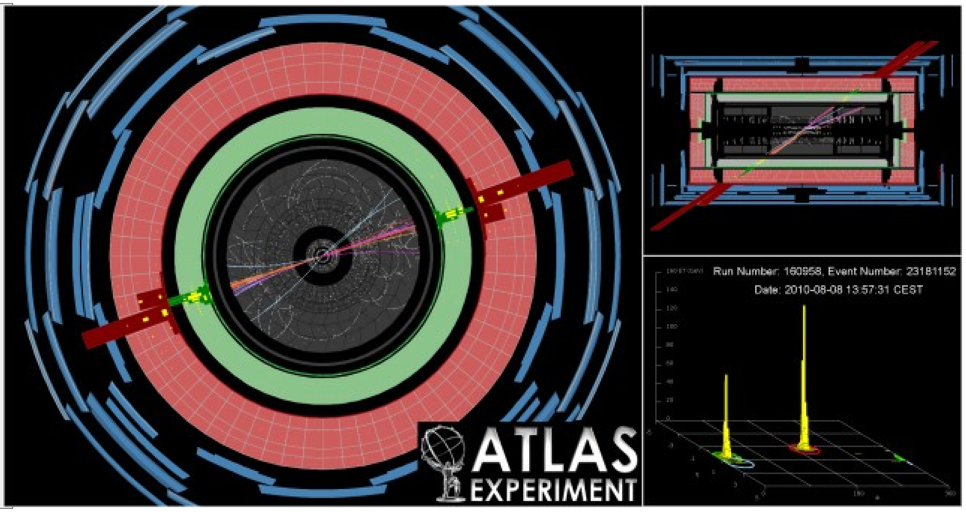


Adopt simplified model with a "mediator" **V**

- g_q (g_{DM}) – mediator coupling to quarks (DM)
- m_{med} (m_{DM}) – mass of mediator (DM)

ATLAS & CMS: **g_q=0.25 (S=1), g_q=1 (S=0), g_{DM} =1**

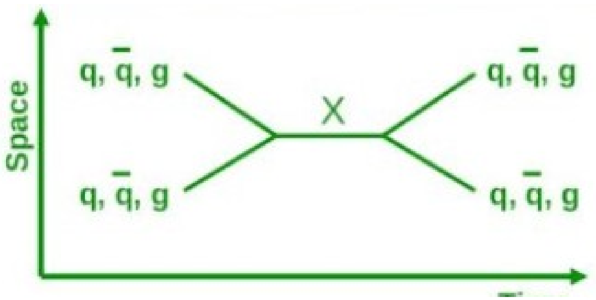
Γ=minimum width formula



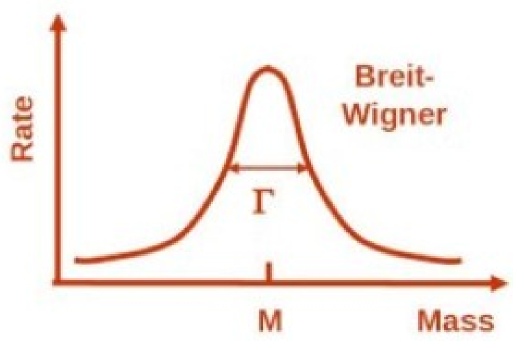
- Due to large number of unknown parameters, the exclusion limits are model dependent (i.e. assumptions of spin, couplings, masses etc)

Search for high mass dijet resonances

JHEP 03 (2020) 145

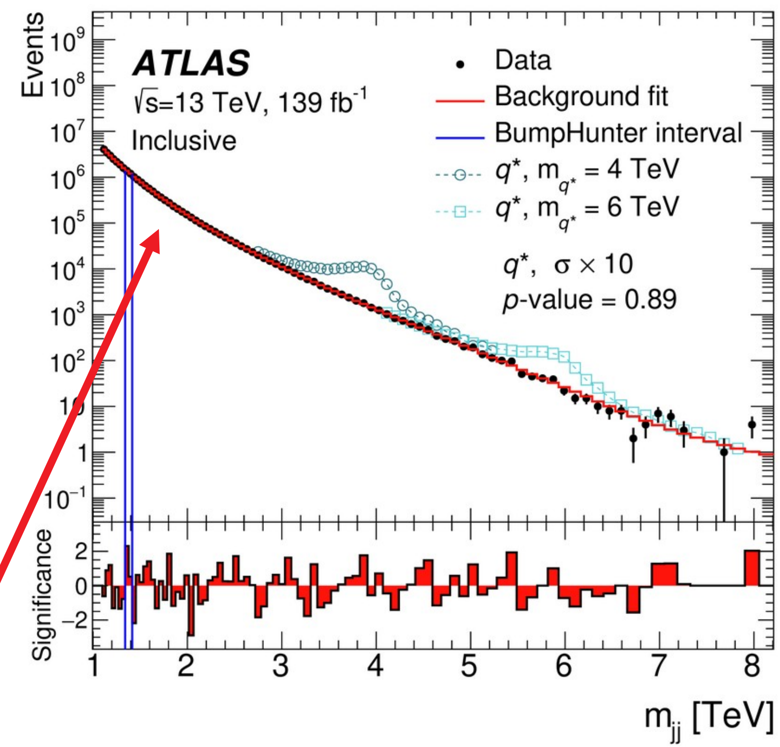


Resonance shapes depend on qq, qg and gg interactions



Physics of Z'/W' bosons:
(review by P.Langacker Rev.Mod.Phys.81:1199 (2009))

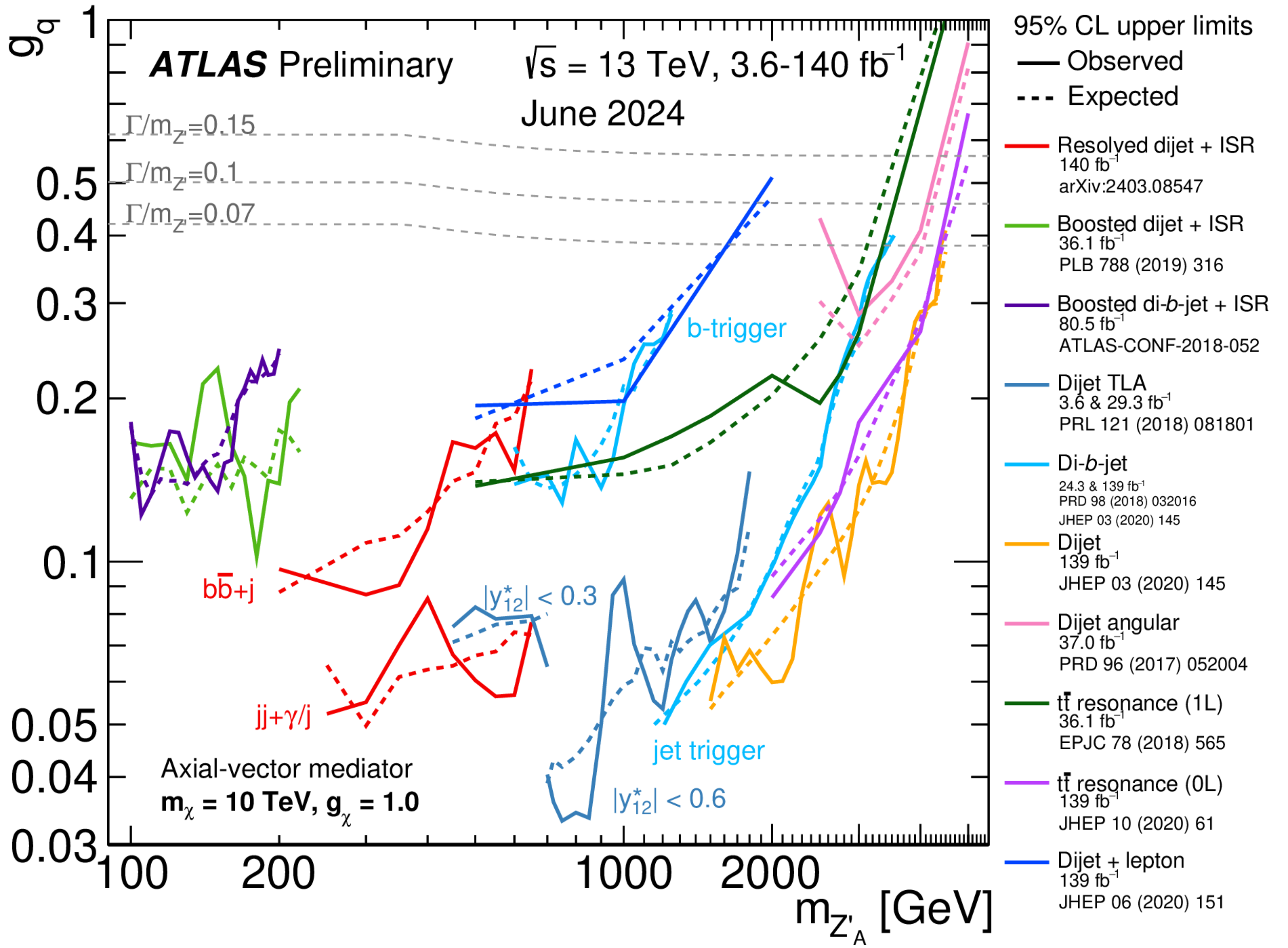
- *Similar to the SM W/Z bosons (but heavier)*
- *Extending SM to group SU(3) × SU(2) × **U(1)***
- *Sequential Standard Model*
- *Grand unified theories, fine tuning problem*
- *Extra dimensions*
- *Dark matter mediator etc. etc.*



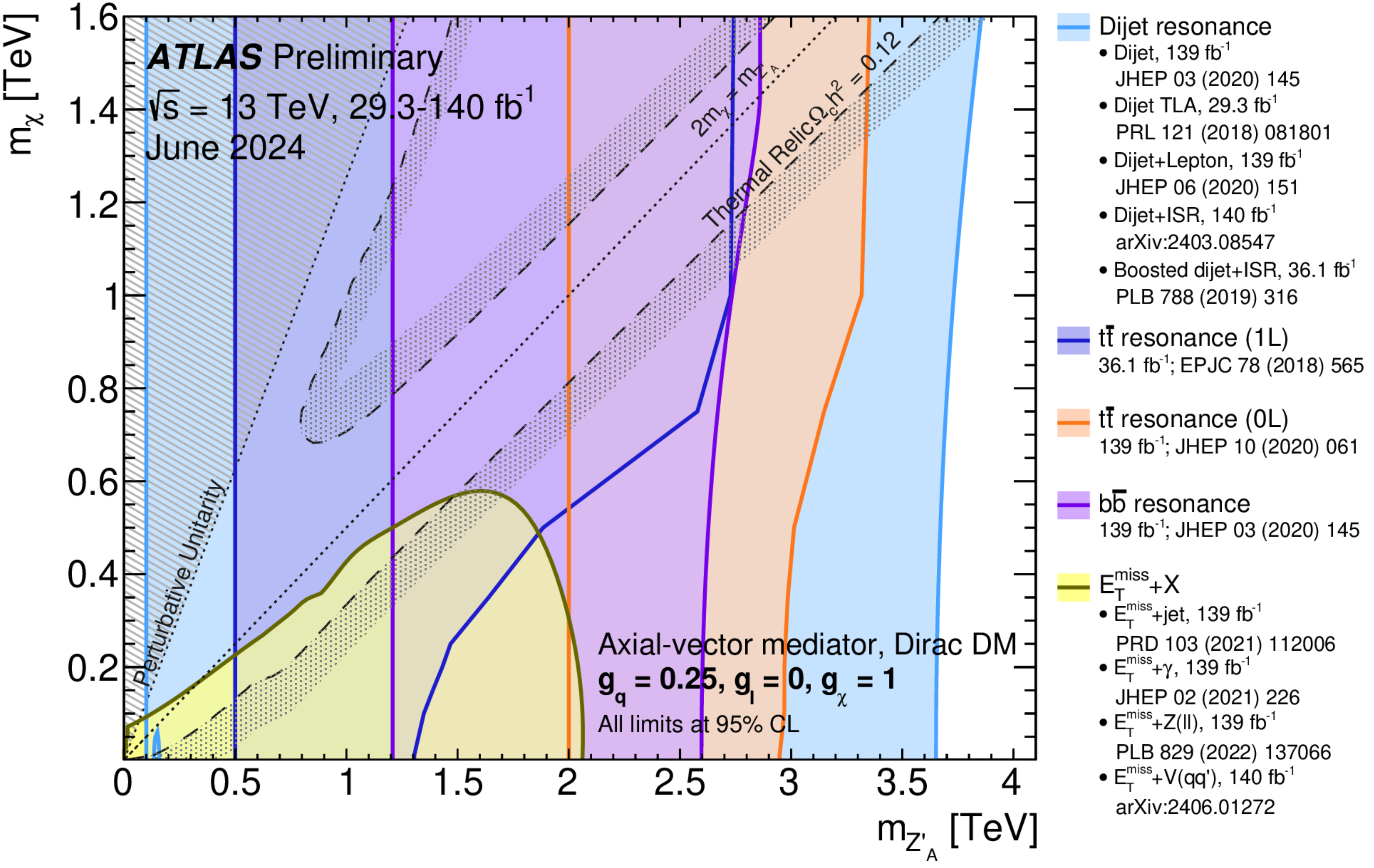
- Calculate invariant mass from 2 hadronic jets
- Fit with smooth analytic functions (red lines)
- Competitive limits up to ~8 TeV

$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}$$

Summary of searches for Dark Matter



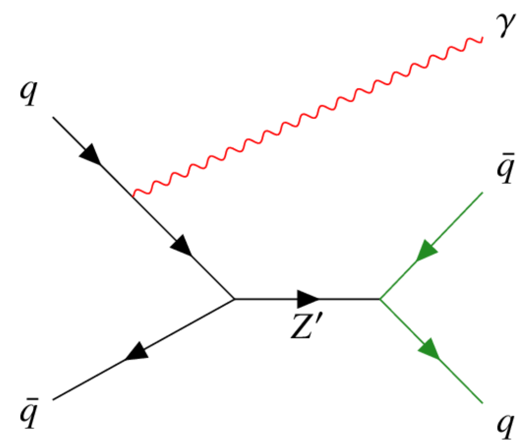
Summary of searches for Dark Matter (cont.)

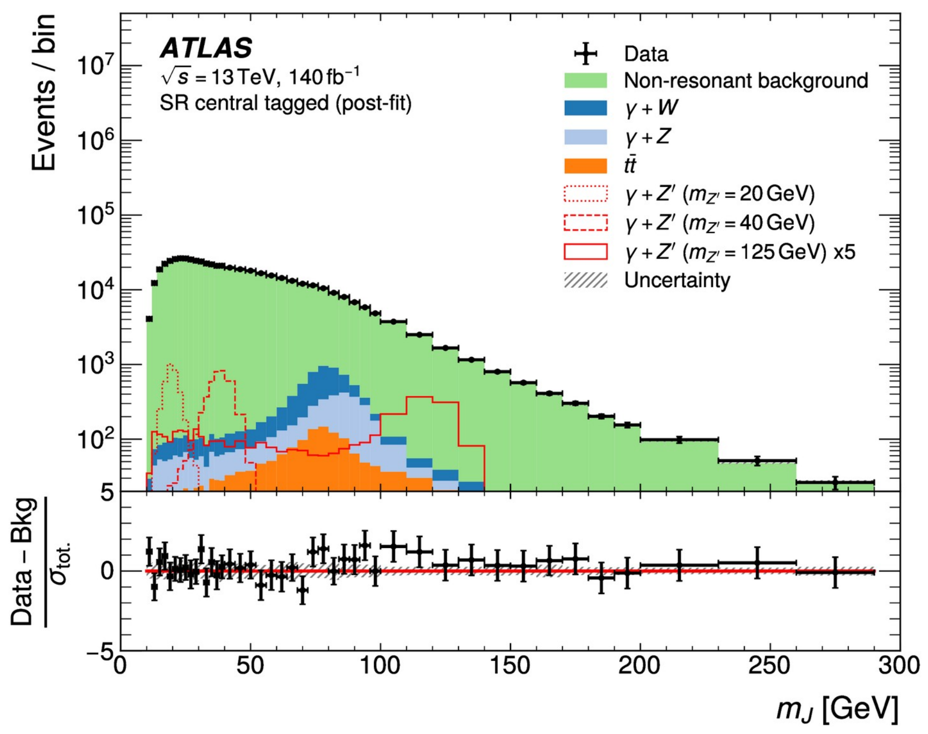


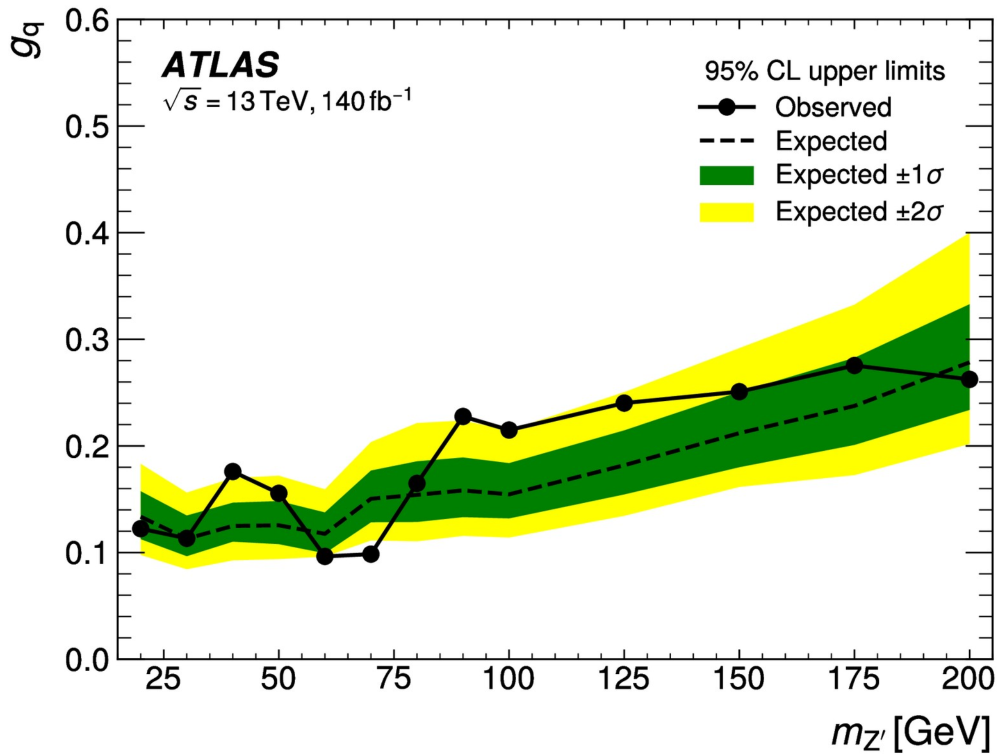
And for low mass resonances too..

CERN-EP-2024-188

- Searches with S=1 mediator (Z')
- Focus on not well explored region of 50-100 GeV
- For pT>140 GeV, decay products of Z' are collimated
- Use invariant mass of the large-radius jet
- No significant deviations from SM



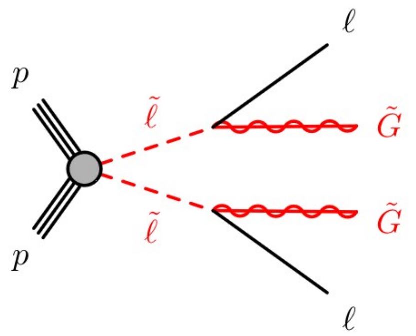


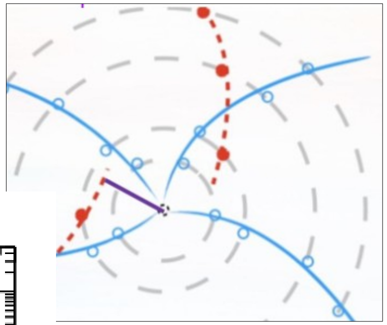


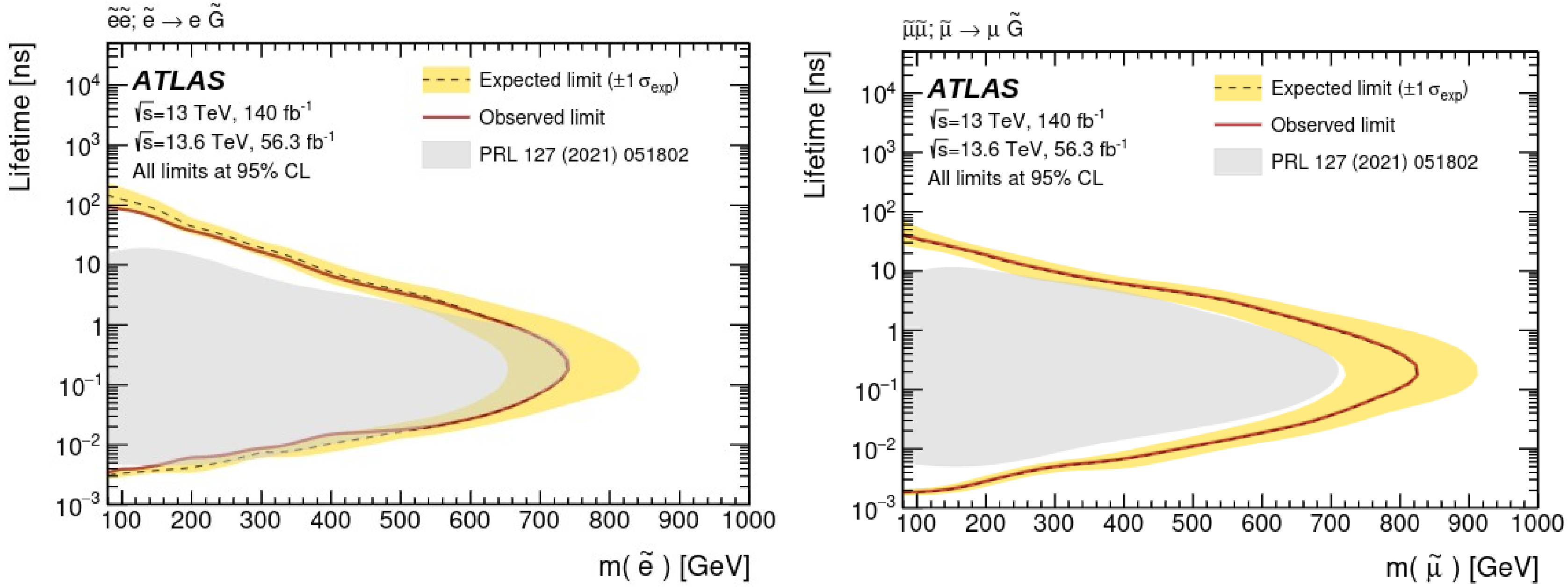
Displaced leptons. First 13.6 TeV result

CERN-EP-2024-257

- Long-lived particles (LLPs) occur in the Standard Model. Predicted for many BSM scenarios (SUSY etc)
- LLPs with lifetimes longer than a few picoseconds travel at least hundreds of microns before decaying.
- New large radius tracking and new boosted decision tree trigger used to enhance sensitivity







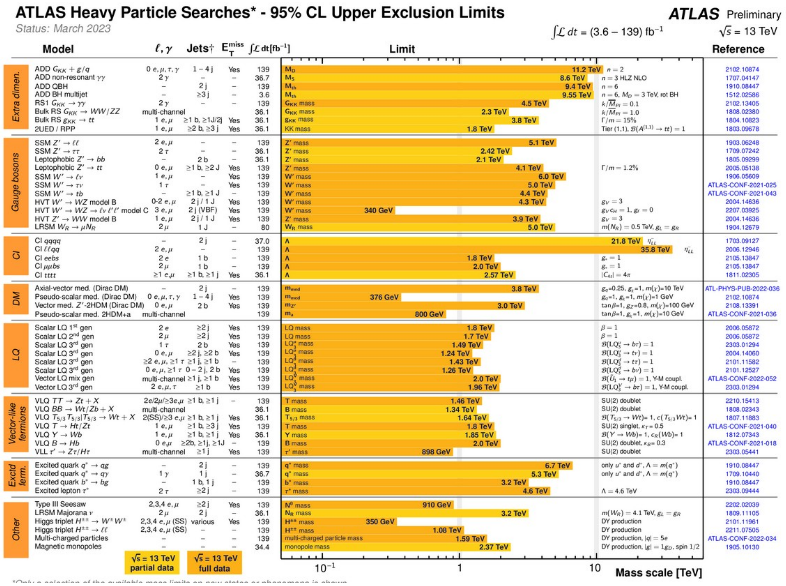
Improved limits compare Run2 only analysis

Strategy for “wide” model-independent searches

- Despite very impressive searches using *proposed models*, no new physics has been observed at the LHC.
- For model-agnostic searches, one can ask about how many *exclusive* event classes with leptons, jets, photons, etc., may potentially contribute to *pp* collisions. The answer ~ 20,000 (S.C. Universe, 2024, 10(11), 414)

$$\textbf{PP collisions} \sim \sum^{20,000} W_i \;\; x\,(\mathrm{MET}, N_{jets}, N_{bjets.}, N_e, N_{\mu}, N_{\gamma}\, ..)$$

BSM-specific searches (~50 signatures)



- **So far the LHC studied a small fraction of such exclusive event categories.**
- **Focus on rejecting known Standard Model events while analyzing 'anomalous' events which may not be covered by specific BSM models ?**

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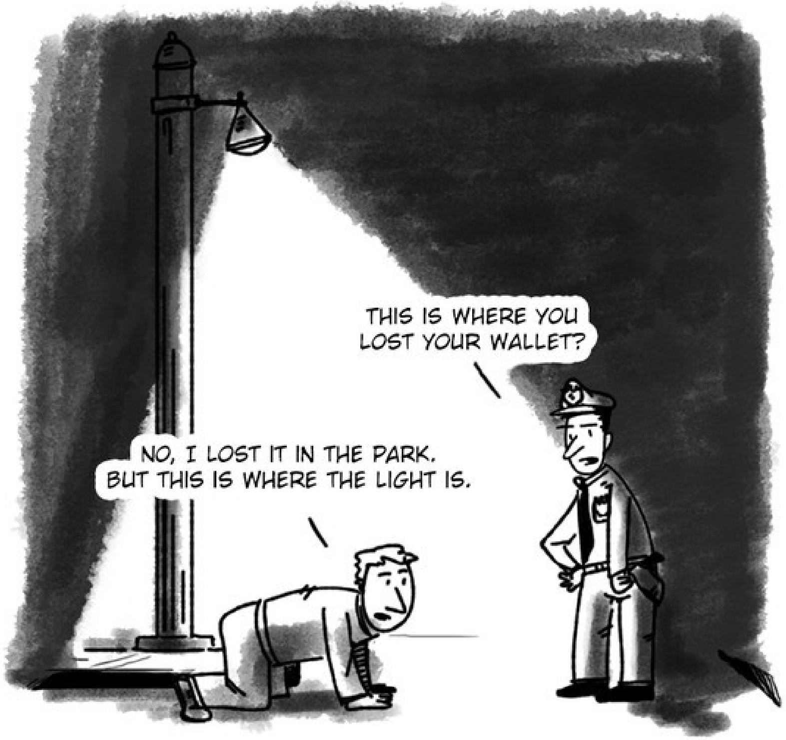

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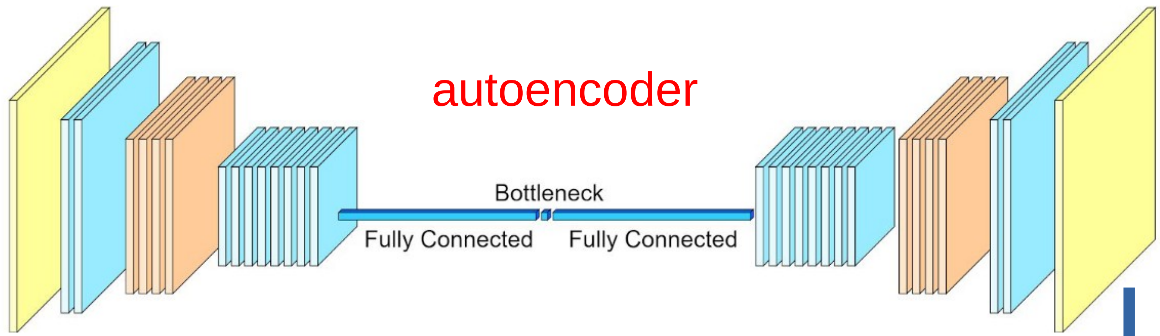
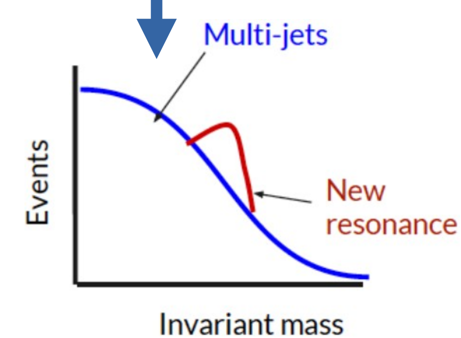
Searching in anomaly regions

Input LHC data

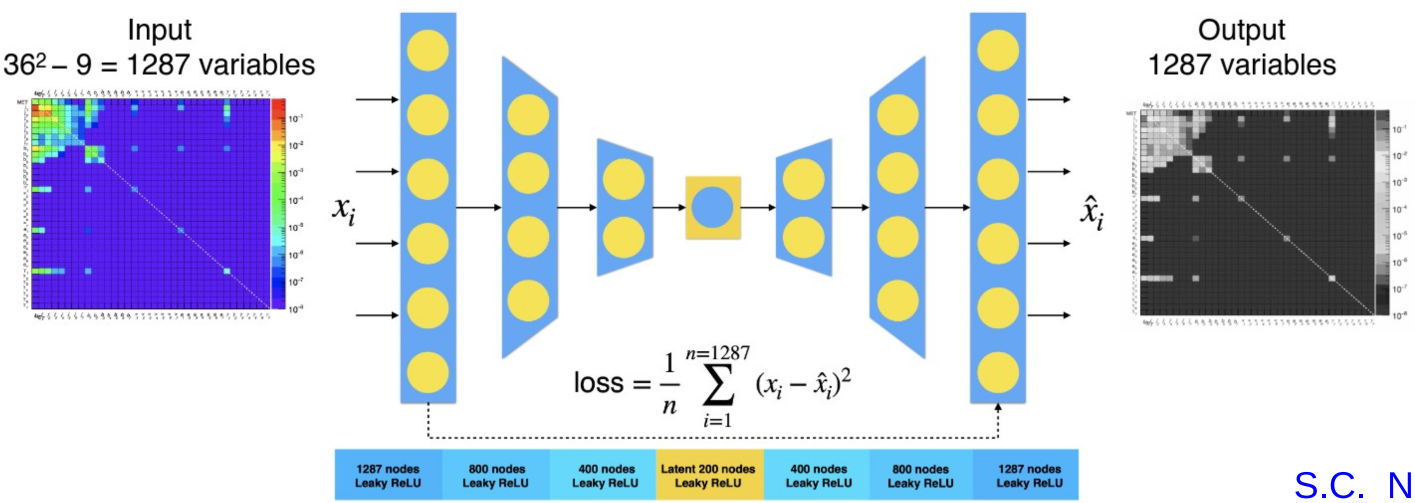


Replica of LHC data

"Bad replica"



Autoencoder
(~ 2 million neurons)

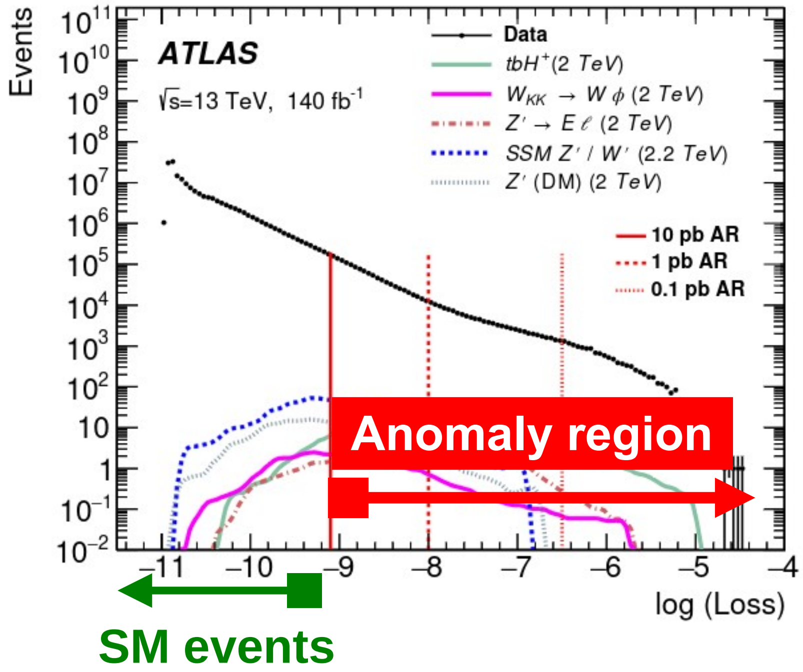


Input:
LHC events as matrices similar to "QR" codes

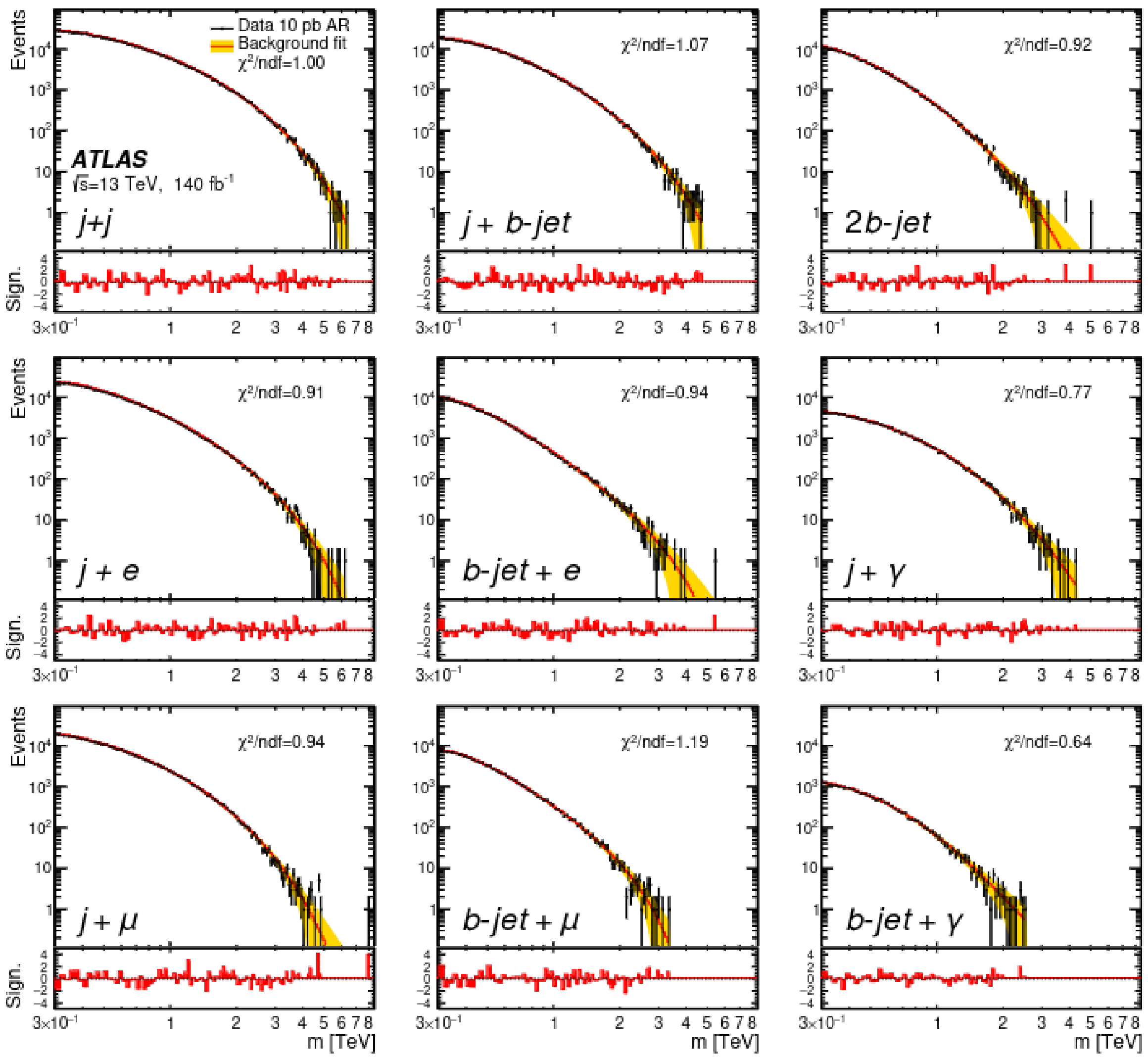
S.C. NIMA 931 (2019) 92-99
S.C, W. Hopkins, Universe 2022, 8(10), 494

Invariant masses in the anomaly region

Phys. Rev. Lett. 132 (2024), 081801

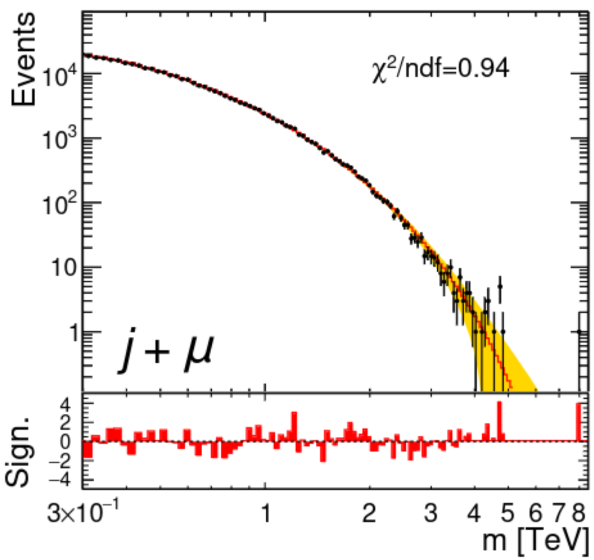


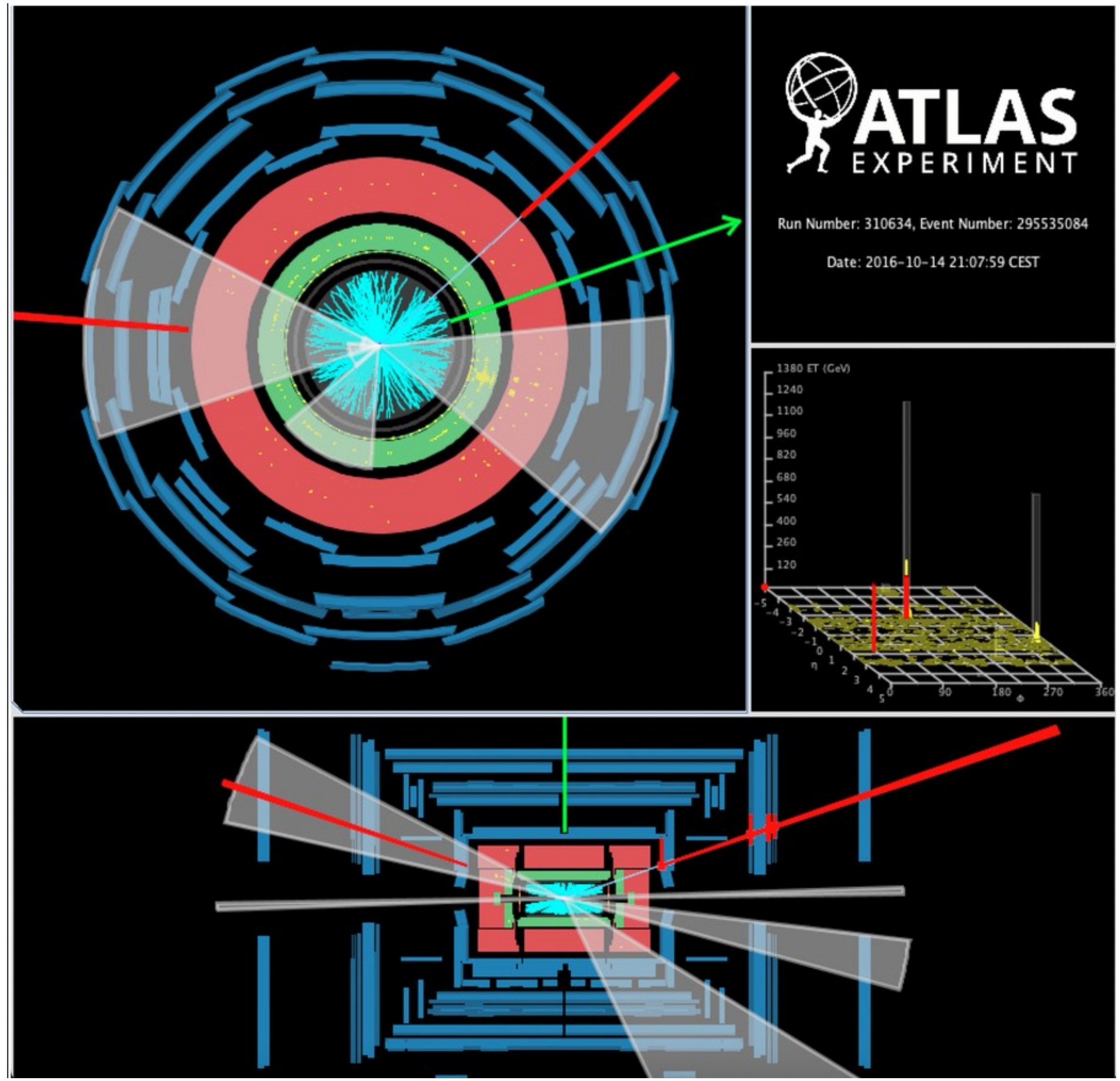
jet+X masses in the anomaly region



- Sensitivity of data to most BSM events in the anomaly region increased by 100-300%
- Invariant masses show no significant deviations
- 9 limits in the anomaly region are available for theorists

Typical event in anomaly region near 4.8 TeV (largest deviation)

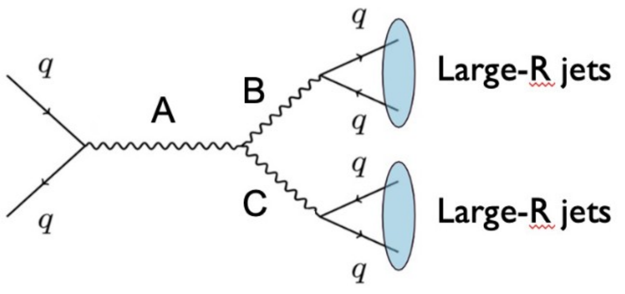




ATLAS Physics Briefings. *https://atlas.cern/Updates/Briefing/Anomaly-Detection*

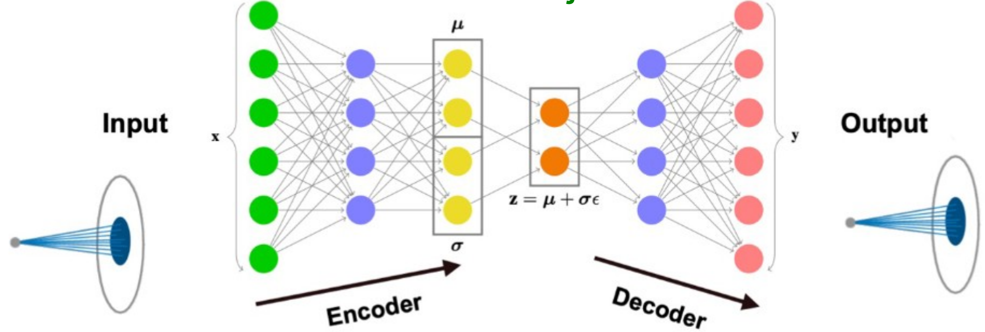
Jet-based anomaly detection

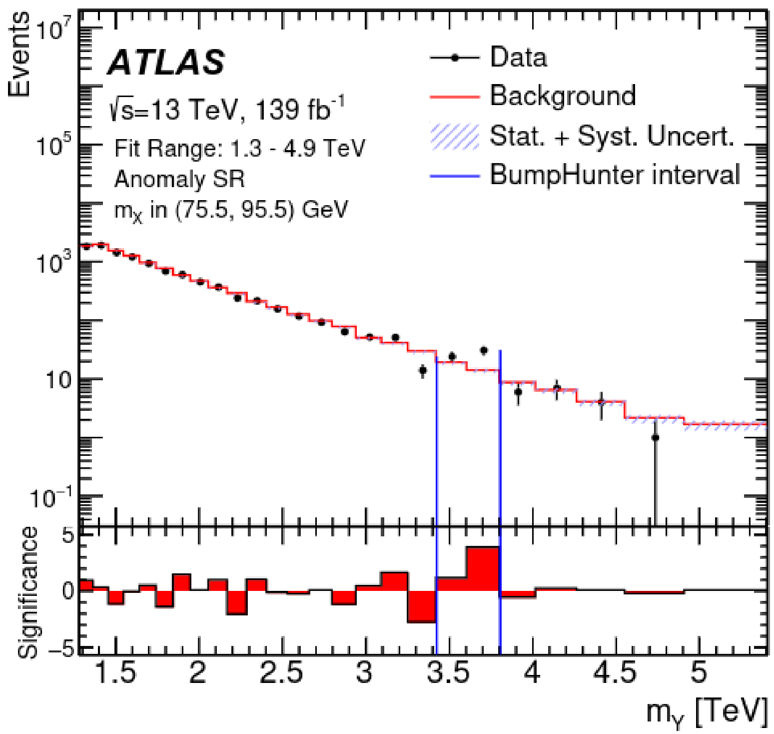
Credits to Antonio D'Avanzo



- Searches for massive particles in dijets in specific BSM events like A→ BC
- Train autoencoders on jet constituents. Look at the scores sensitive to various decay hypotheses, like 2-prong (e.g. heavy flavor, three-prong and dark jet) or decays that do not fall in any category ("**anomaly**")
- A similar method adopted for $Y \rightarrow X\,H \rightarrow q\bar{q}b\bar{b}$

Generic representation of autoencoder for jet constituents

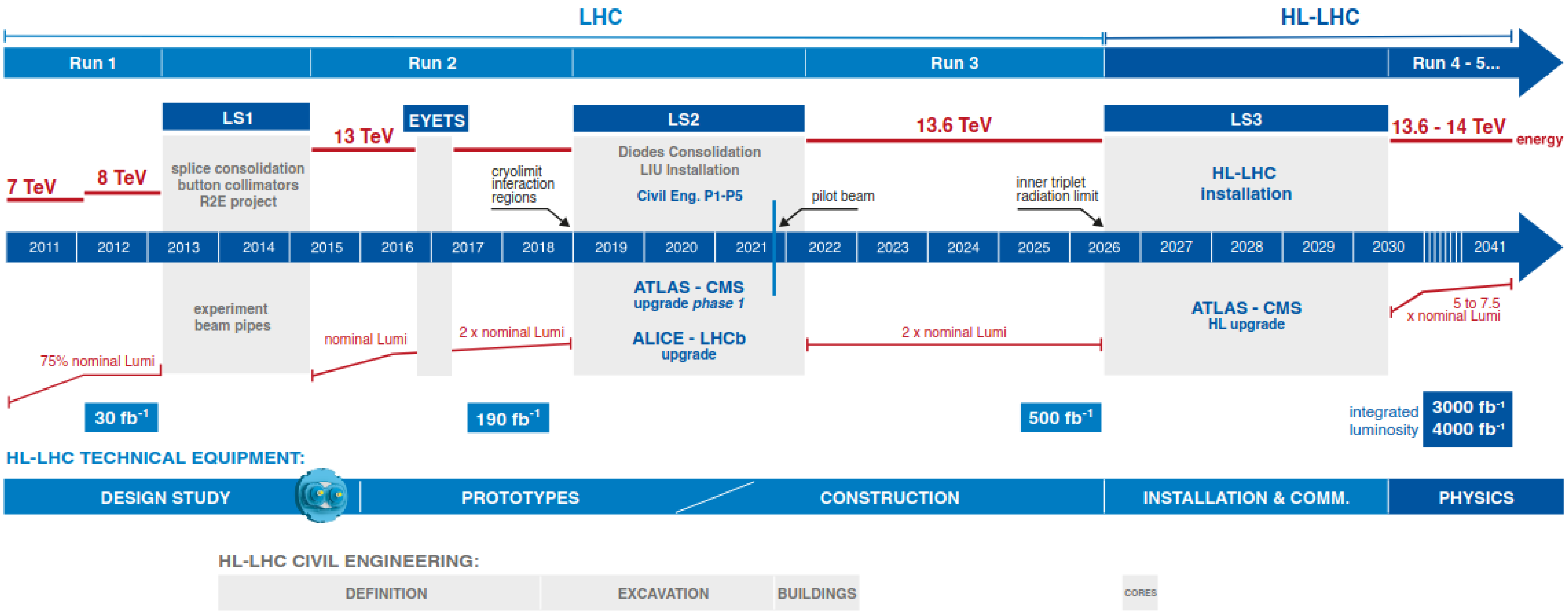




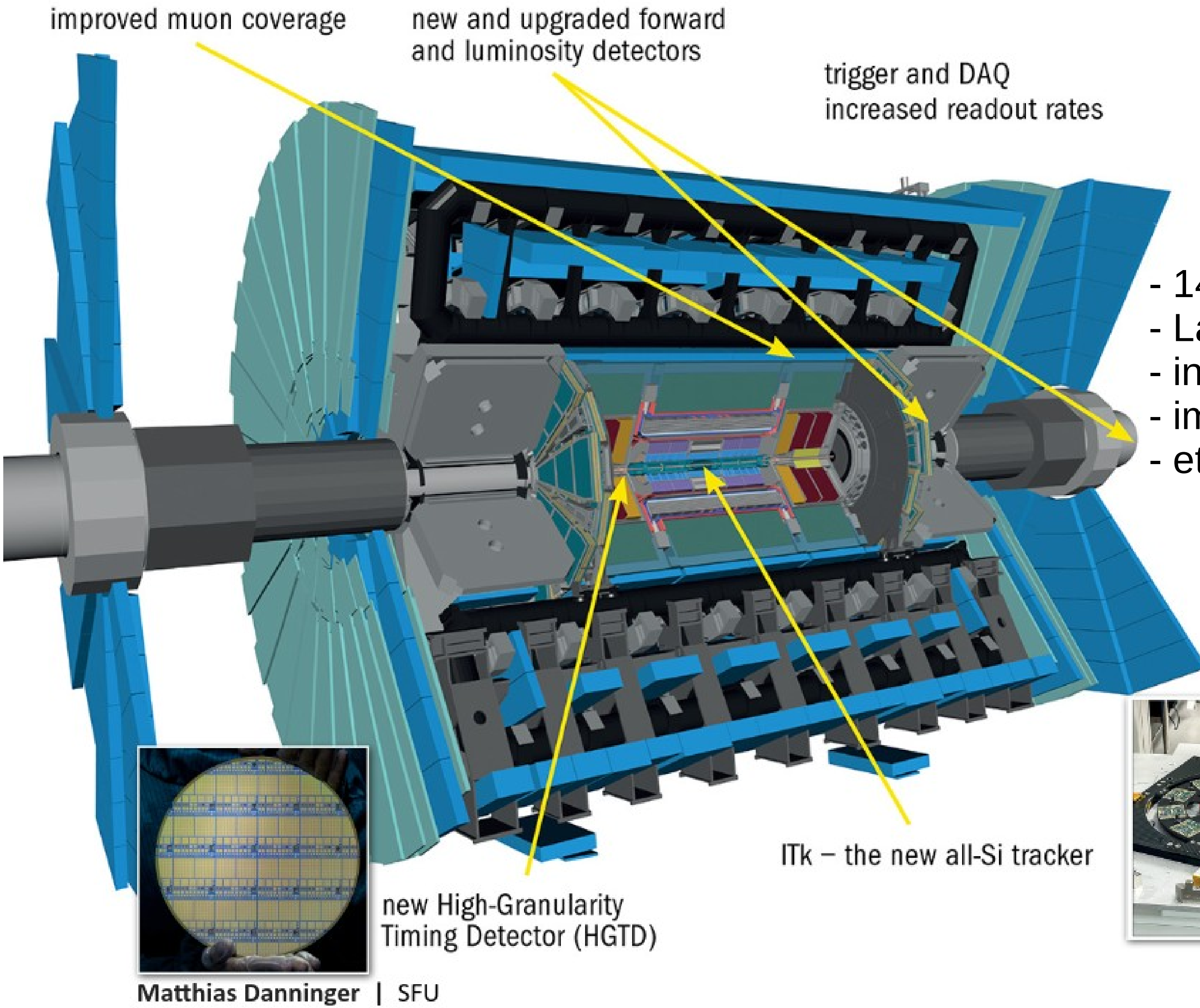
- Largest deviation near 3.7 TeV at 1.4σ (global)
- 95% confidence-level upper limits are set on the cross section of $Y \rightarrow X\,H \rightarrow q\bar{q}b\bar{b}$ in various event topologies including "anomalous" decays

LHC / HL-LHC and future plans

- LS3 for the LHC is now scheduled to begin at the start of July 2026, seven and a half months later than planned.
- HL-LHC (Run 4) moved approximately by one year (June 2030)
- HL-LHC 5 -7.5 x $L_{nominal}$ → 3 - 4 ab^{-1} (**<μ>=63)**



ATLAS detector for the HL-LHC



- 14 TeV energy
- Large statistics
- increased solid angle
- improved vertexing
- etc.

Conclusions

- **Many more new and interesting results from Run 2,3 which I had no time to discuss : focus on full data sets and newest results**
- **Extensive program for SM measurements and searches for BSM**
- **Refined studies with complex final state (jet, top, γ, $t\bar{t}$, W, Higgs, etc)**
- **Stay tuned: Ongoing Run3 analyses, some with very wide search using AI**
  - 13 TeV → 13.6 TeV CM energy, Increase in luminosity (x 2 → larger statistics!)

This conference:

- Highlights of SM measurements including Top with the ATLAS experiment at the LHC (John Patrick Mc Gowan)
- Recent searches for new phenomena with the ATLAS detector (Zackary Lee Alegria)
- Higgs boson property measurements at the ATLAS experiment (Michela Biglietti)

More information about ATLAS publications on ATLAS twiki - ATLAS public results