ASTROFÍSICA Y FÍSICA DE ALTAS ENERGÍAS

Physics at the LHC

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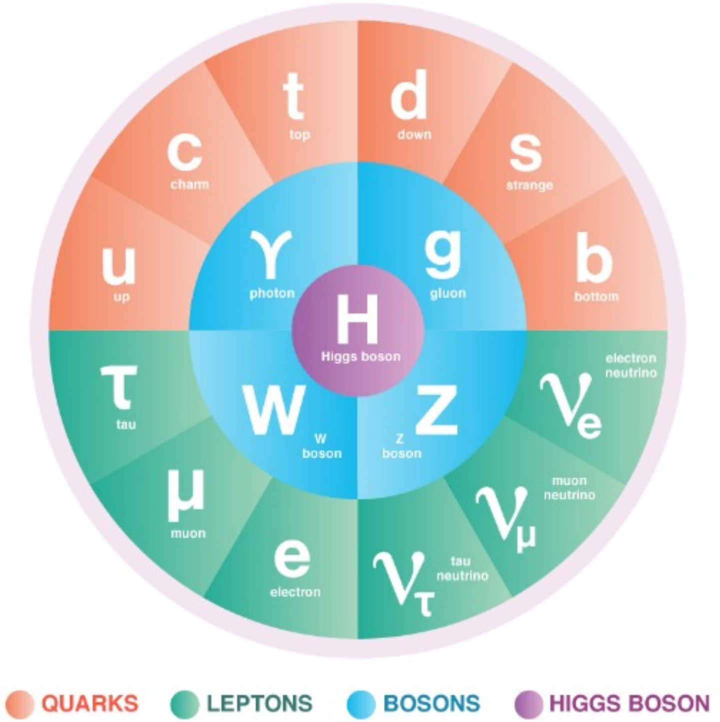
Introduction



- The Standard Model (SM) is the legacy of the 20th century particle physics
- SM encapsulates all our knowledge of the most fundamental components of matter and their interactions:
  - Matter is formed by **spin-1/2 fermions (quarks and leptons)**
  - Forces are mediated by **spin-1 bosons (γ, g, W, Z)**
  - **Higgs boson** explains the mechanism for which elementary particles acquire mass
- Higgs boson discovery in 2012 by ATLAS and CMS completed the SM
- … still many open questions (dark matter, matter/antimatter asymmetry, etc.) could be explained with New Physics beyond the SM (BSM)
- This talk: Highlights of the contributions of ASFAE projects at IFIC to the LHC Physics programme
- Other talks in the workshop:
  - “Computing & AI in … HEP” tomorrow morning
  - “Upgrading the ATLAS and LHCb detectors for the High-Luminosity LHC era” coming up next

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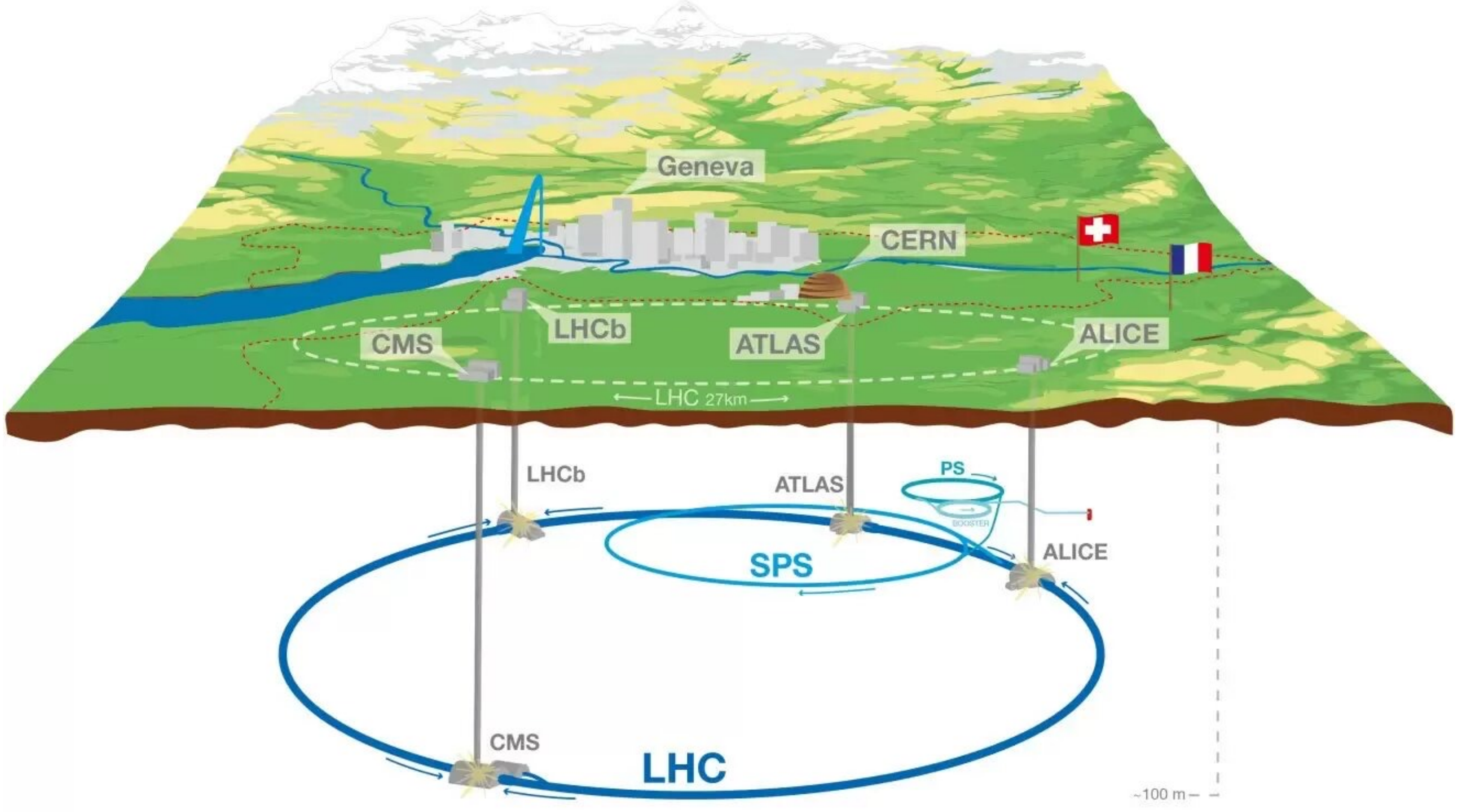
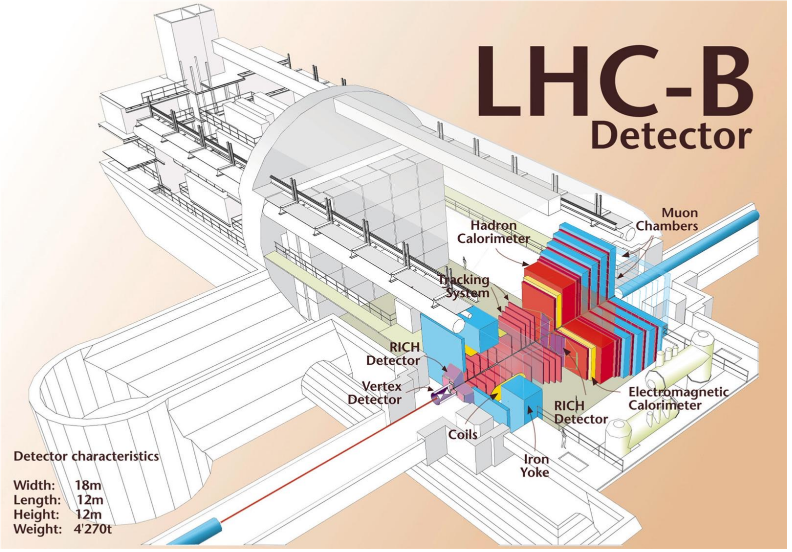
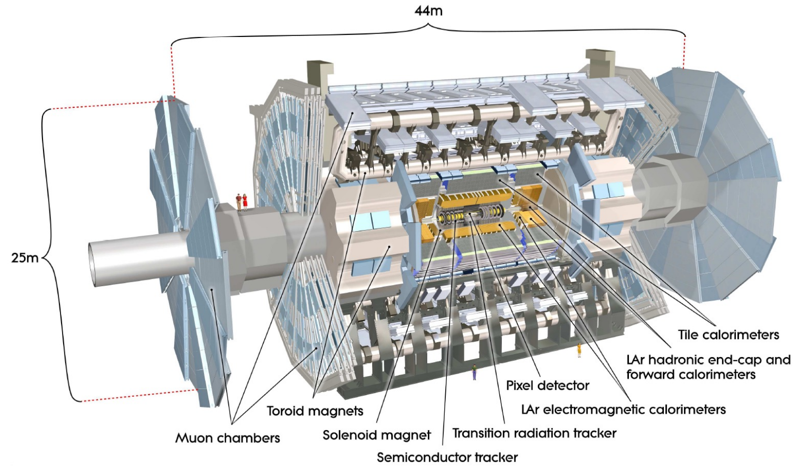
LHC and its experiments

- Large Hadron Collider at CERN: largest particle accelerator ever
- High energy proton collisions recorded and analyzed by 4 main experiments: LHCb, ATLAS, CMS and ALICE







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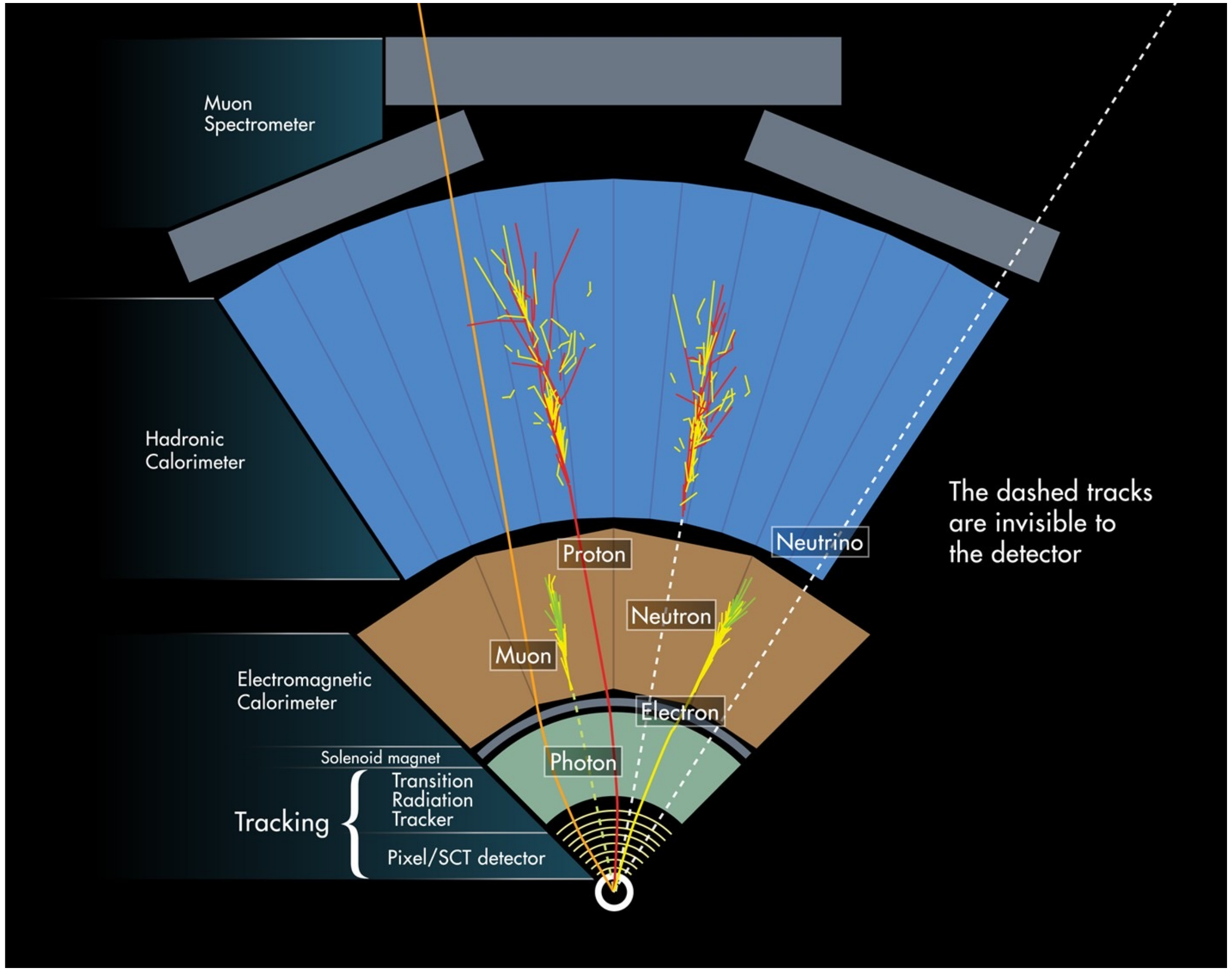
Detecting particles

- Combining information from several detector elements
- Exploiting distinctive signatures:
  - Charged particles → Tracks
  - Electrons/photons → Electromagnetic showers
  - Coloured particles → Hadronic showers
  - Muons → Tracks in the outermost part of the detector
  - Non-interacting particles → Momentum imbalance
  - Hypothesized new BSM particles with long lifetimes → Unconventional signatures
- Signals read out by O(100M) electronic channels each 25 ns in ATLAS
- Powerful trigger system to select in real time the most interesting collision events for offline analysis (discarding 9,999 out of every 10,000 events)
- Reconstruction techniques to identify and precisely measure all the particles produced in the LHC collision



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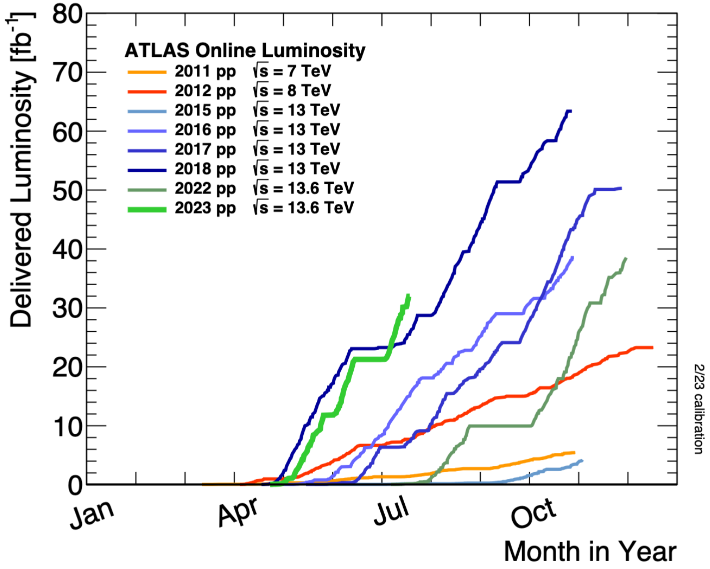
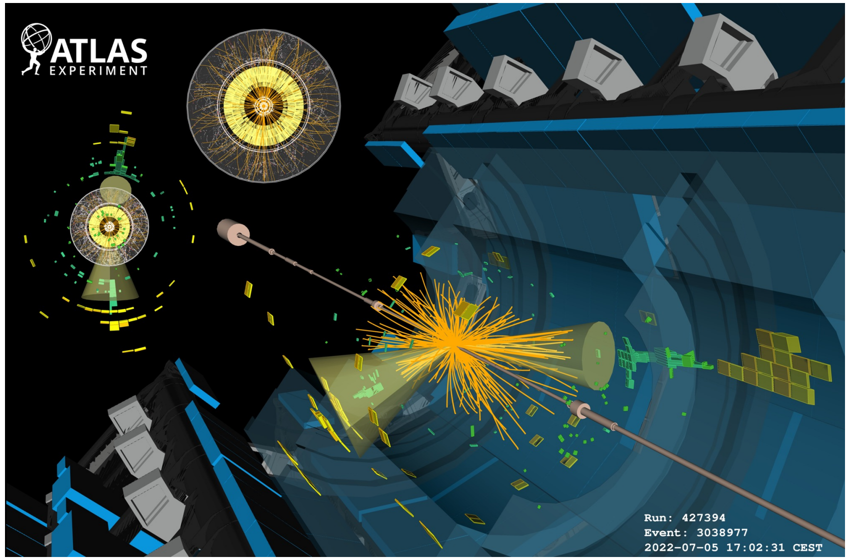
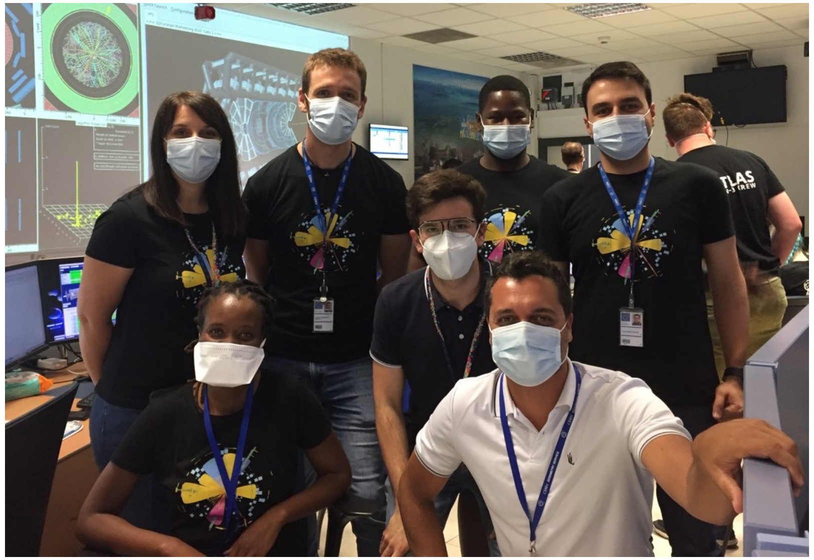
LHC Run 3: detector operation

- Ongoing analysis of the LHC Run 2 (2015-2018) data at √s = 13 TeV
  - Integrated luminosity of ~140 fb^{-1} in ATLAS and 2.5 fb^{-1} in LHCb
- Run 3 stable-beam data-taking started on 5 July 2022 with a new energy world record √s = 13.6 TeV
  - 70 fb^{-1} recorded in ATLAS, 2 more years of data acquisition left
- Hard work from very dedicated teams to ensure a reliable detector operation and high-quality data taking

ATLAS Control room on 5 July 2022







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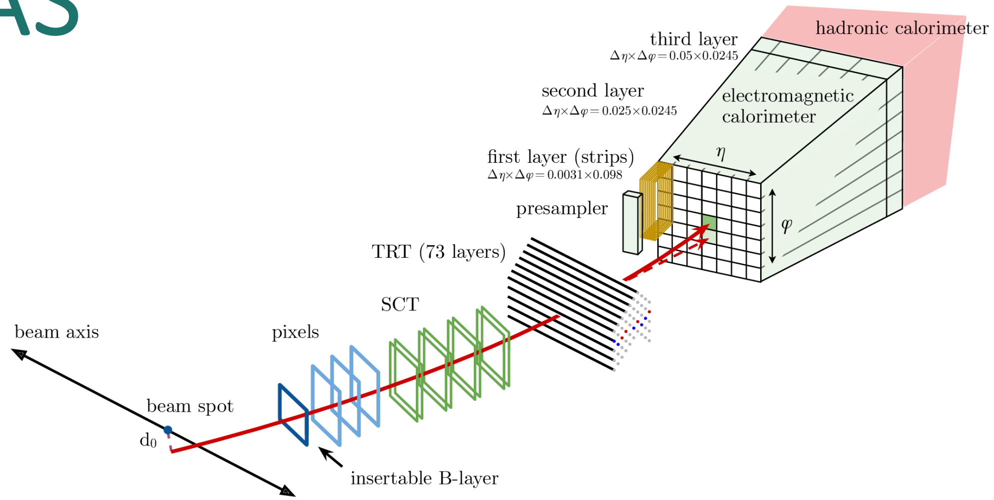
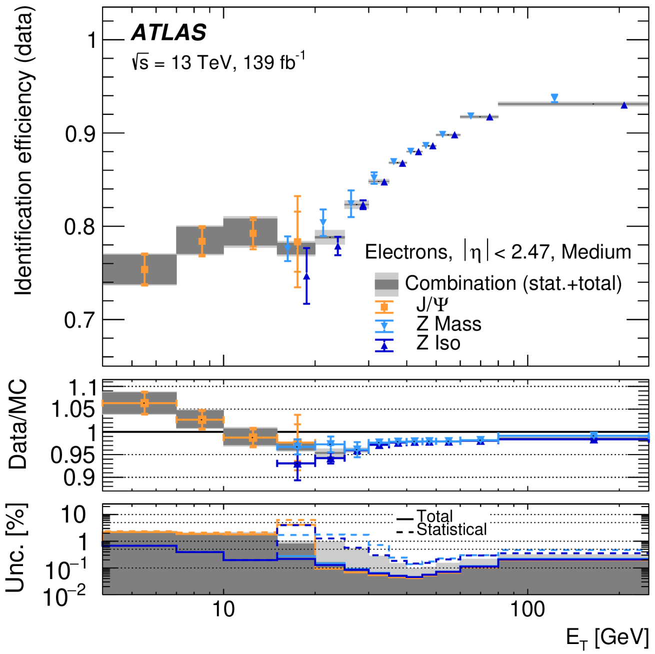
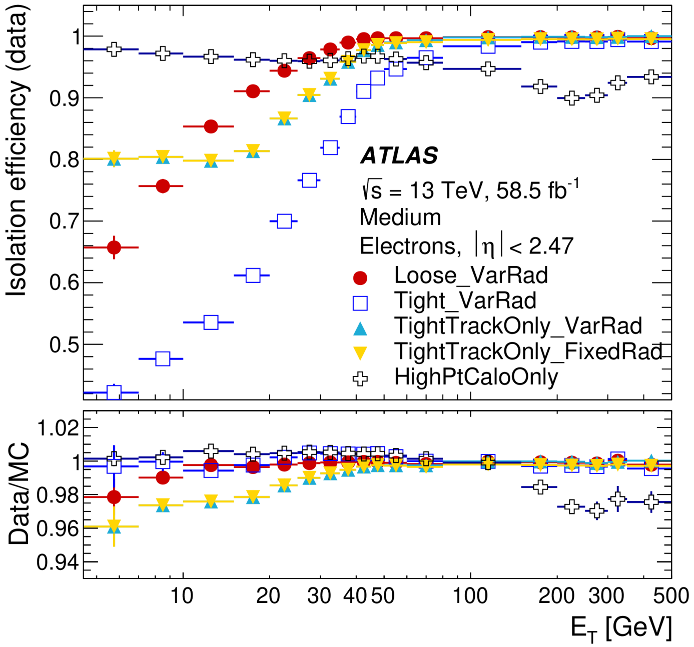
Electron identification in ATLAS

- Results of Run 2 electron performance studies published in arXiv:2308.13362
- Electrons are reconstructed combining the information of tracker and calorimeters
- Identification based on properties of the electromagnetic showers (width, depth, topology, etc) and of the associated tracks (number of hits in the silicon detectors, etc.)







- Efficiencies measured for requirements of identification or isolation (activity around the electron)
- Data-driven techniques relying on well-known resonances like *Z→ee* or *J/ψ→ee*
- Achieving a precision at the per-mille level
- Derived corrections to the Monte Carlo simulations used by physics analyses

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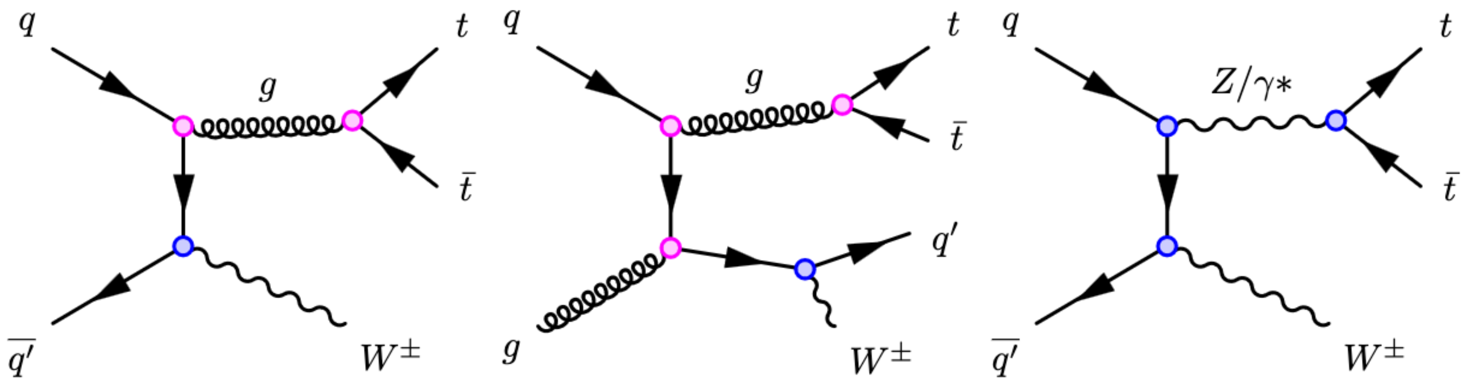
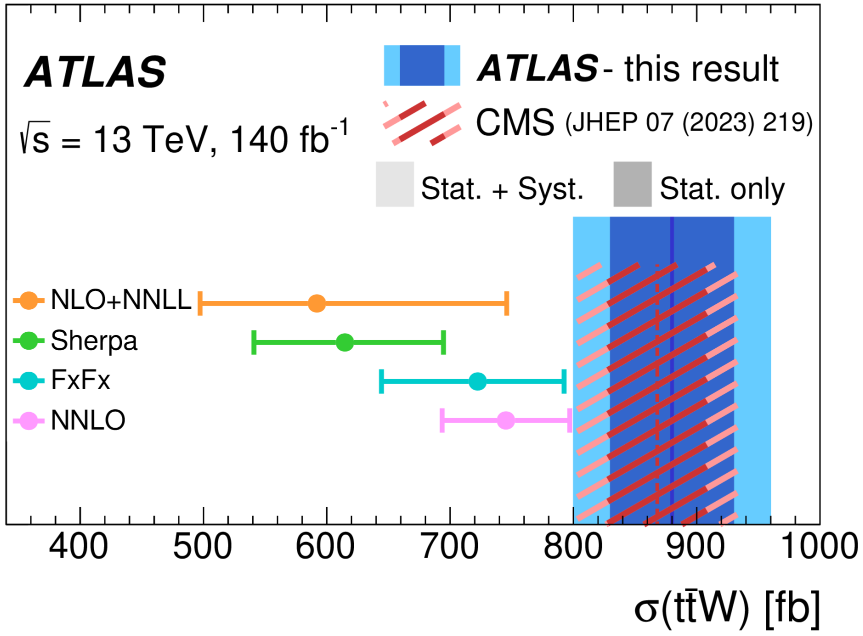
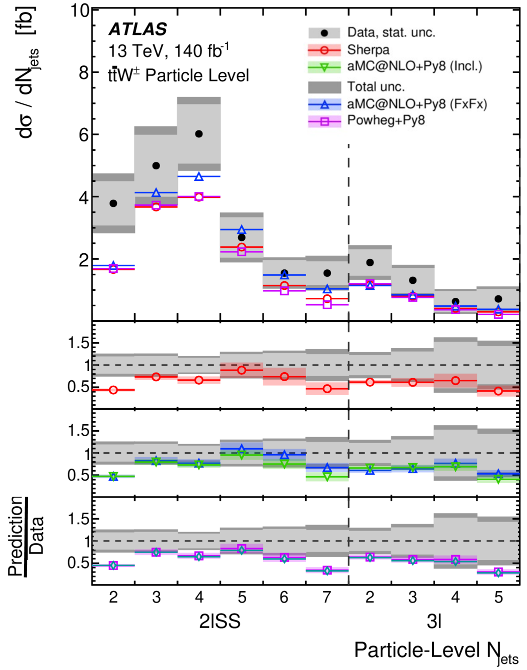
Top quark physics: $t\bar{t}W$ production

- Precise description of the $t\bar{t}W$ process represent a sensitive test of the strong and electroweak sectors of the SM
- Cross-section measurements can also provide indirect hints of BSM physics
- Long-standing discrepancy between experimental results and theory predictions
- Measurement relying on same-sign dilepton of three-lepton final states
- Latest cross-section results by ATLAS (arXiv:2401.05299) more than 1σ larger than state-of-the-art theory predictions
- First differential measurements also performed
- PhD thesis of Marcos Miralles







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Top quark physics: $t\bar{t}W$ charge asymmetry

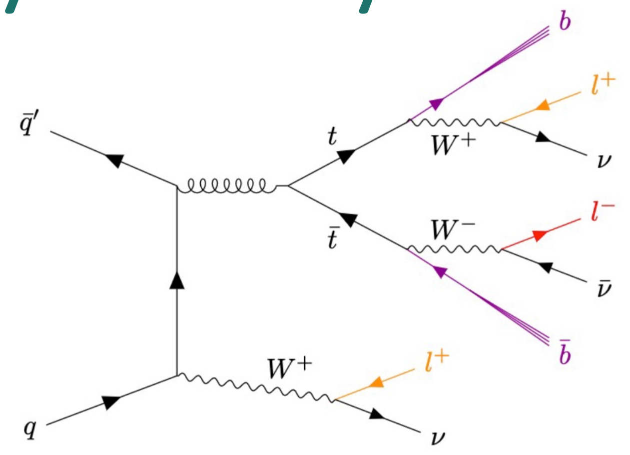
- $t\bar{t}W$ production also characterized in terms of the asymmetry between the decay products of the top quarks and antiquarks (JHEP 07 (2023) 033)
- Top quark preferentially produced in the direction of the incoming quark → Tends to be more forward in the detector than top anti-quarks
- Measurement of the leptonic charge asymmetry

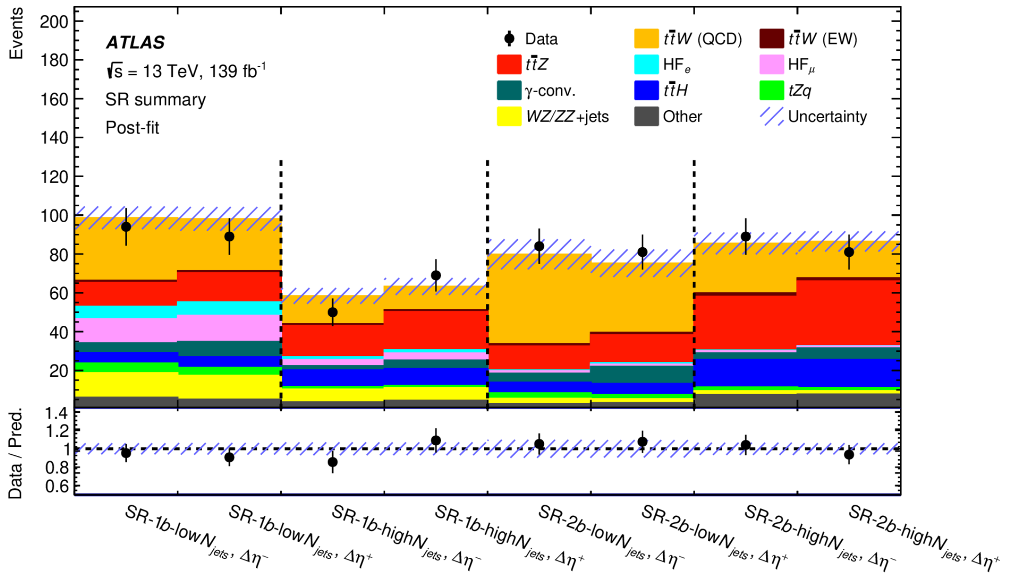
$$A_c^\ell = \frac{N(\Delta\eta^\ell > 0) - N(\Delta\eta^\ell < 0)}{N(\Delta\eta^\ell > 0) + N(\Delta\eta^\ell < 0)}$$

- Profile-likelihood fit to the event yields in several regions with positive / negative $\Delta\eta^\ell$
- Result dominated by statistical uncertainties and compatible with the SM predictions

$$A_c^\ell(t\bar{t}W) = -0.12 \pm 0.14\,(\text{stat.}) \pm 0.05\,(\text{syst.})$$

$$A_c^\ell(t\bar{t}W)_{\text{SM}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$$





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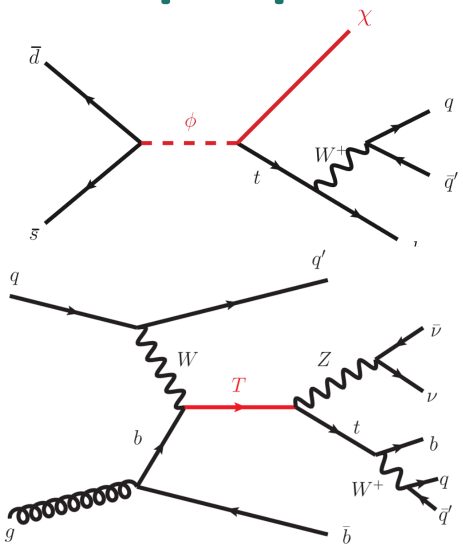
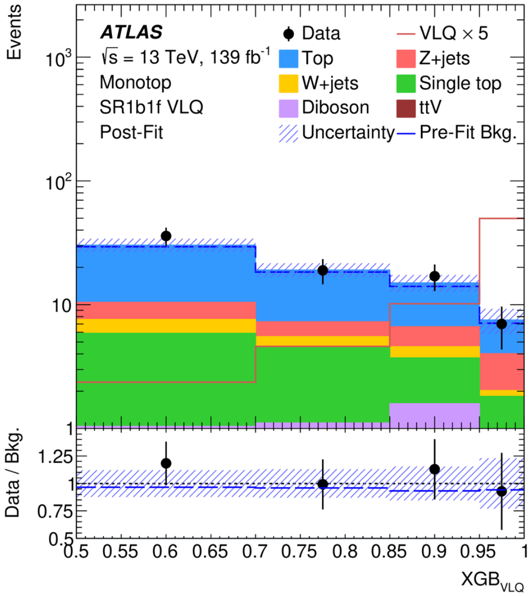
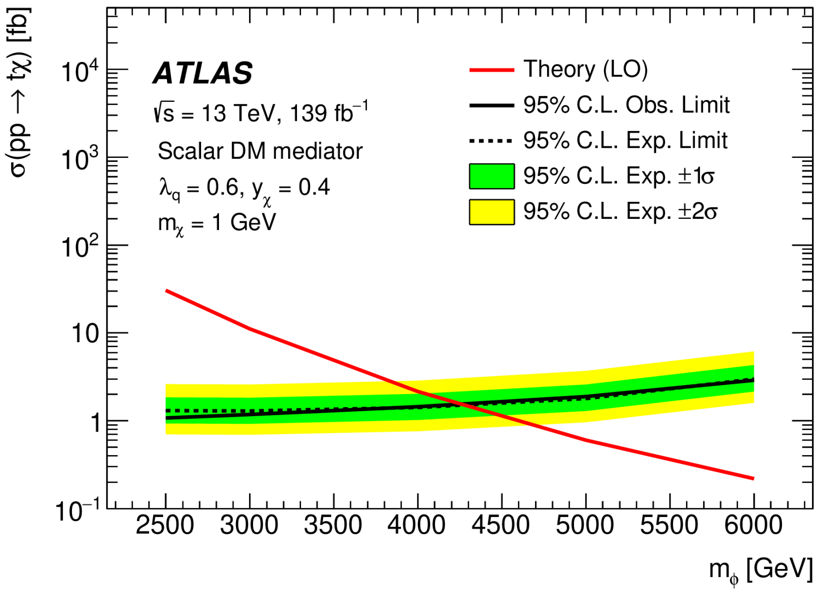
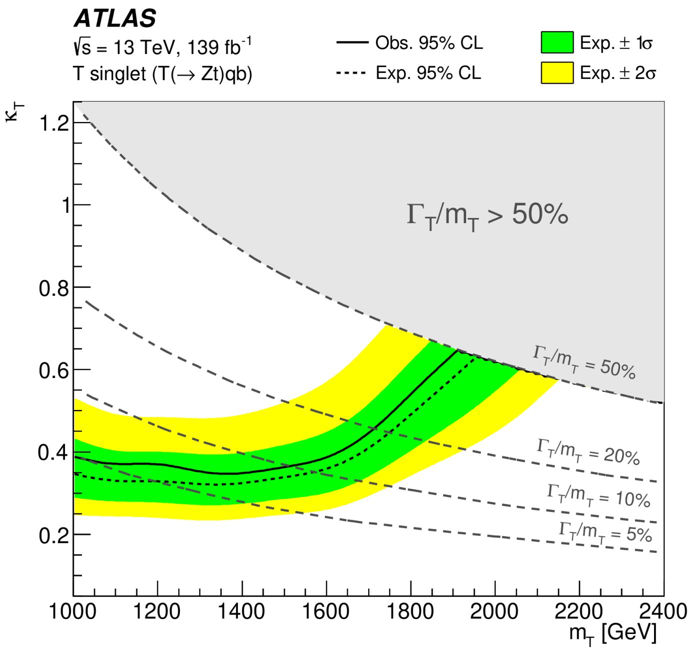
Top quark physics: mono-top



- Search for production of a single top quark with a new invisible dark matter particle (χ) or in vector-like top production (T) (arXiv:2402.16561)
- Signature: boosted hadronically decaying top quark + large missing transverse momentum
- MVAs to discriminate signal from backgrounds
- No excess observed over the SM background
- Exclusion limits reaching 4.2 TeV for scalar dark matter mediator and up to 2 TeV for vector-like top







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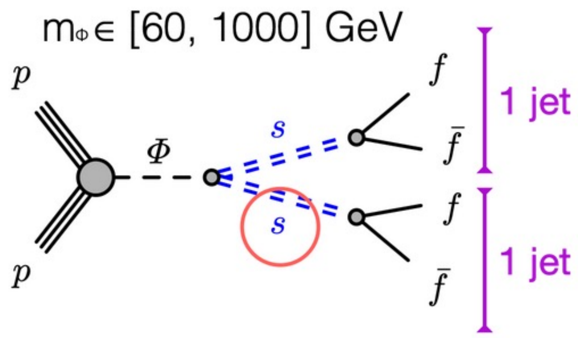
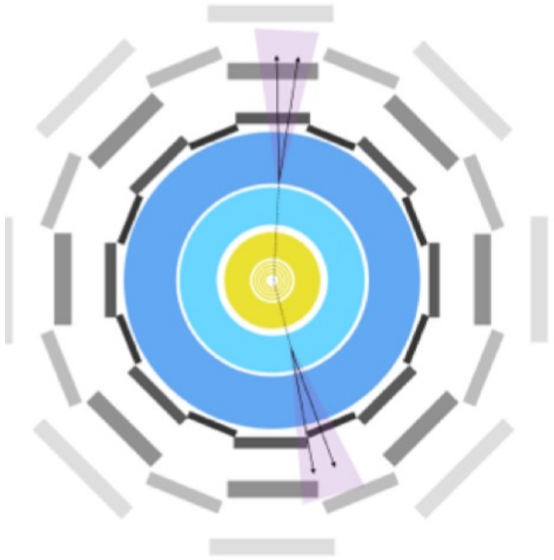
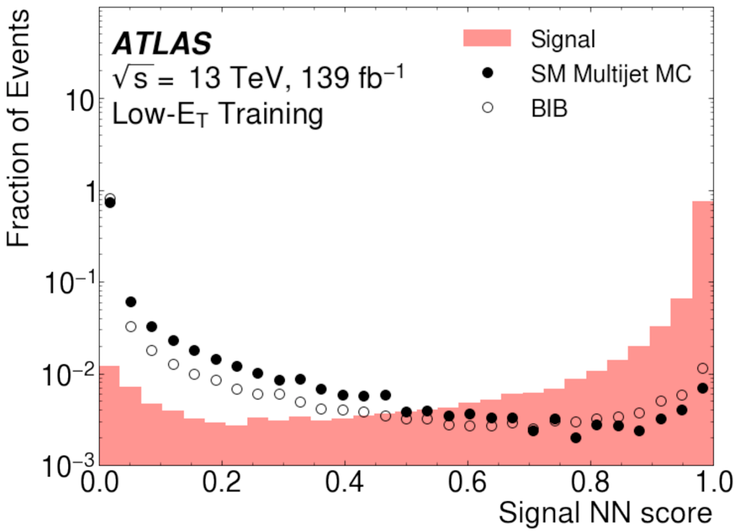
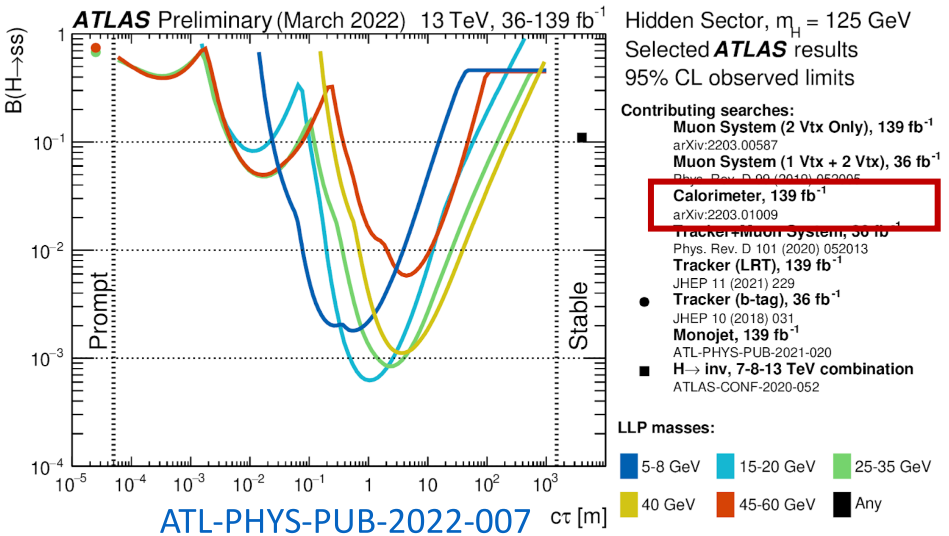
Search for neutral long-lived particles



- “Hidden Sector” model with a heavy boson decaying to long-lived scalars (s)
- Signature: 2 displaced jets in the ATLAS Calorimeter (JHEP 06 (2022) 005)
- Novel Adversarial Neural Network separating signal from SM jet production background
  - Current network trained on displaced jets originated by a *b*-quark (×5 sensitivity improvement)
  - Being adapted to identify displaced jets originated by a top-quark
- Combined with complementary searches for Long-Lived particles in ATLAS, covering a wide range of lifetimes, from mm to tens of meters







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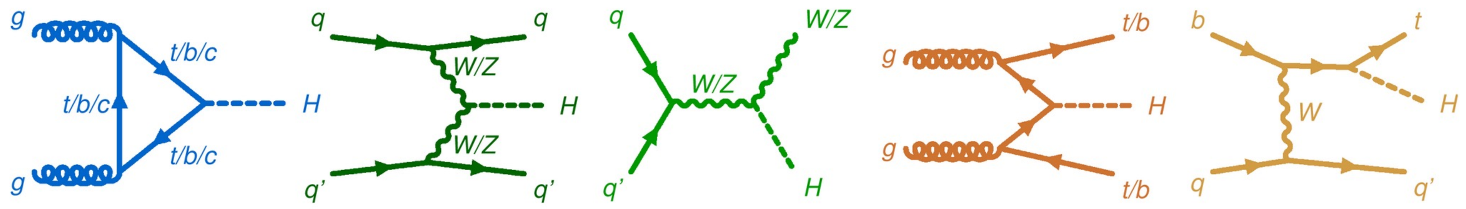
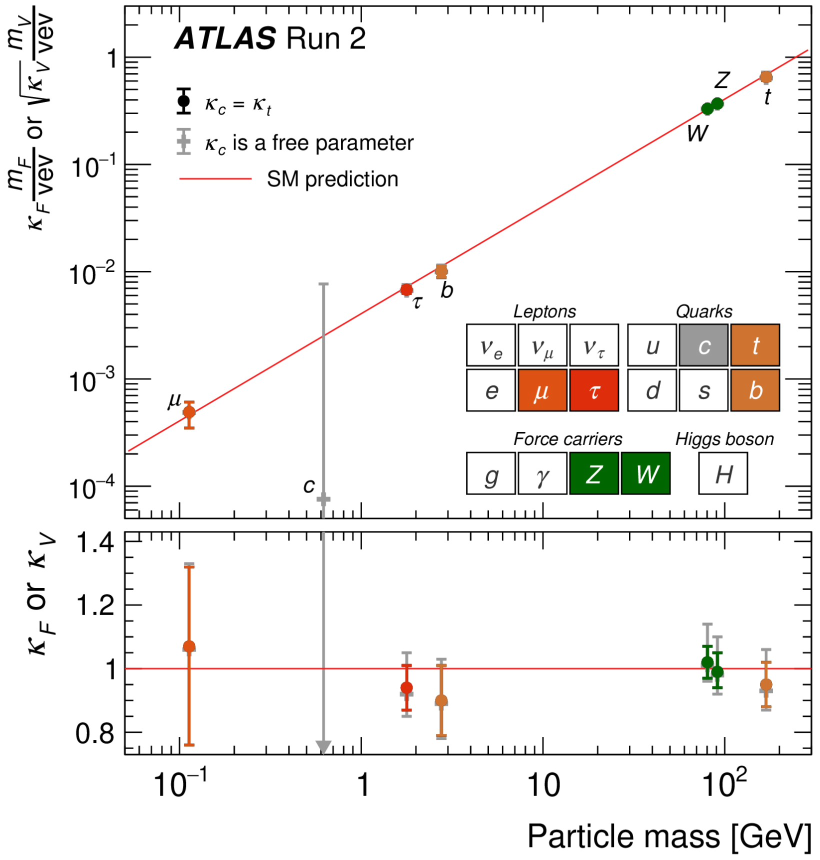
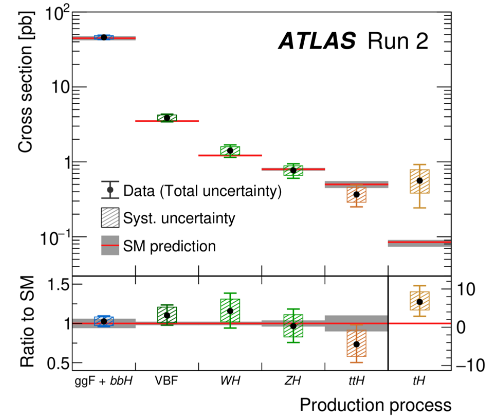
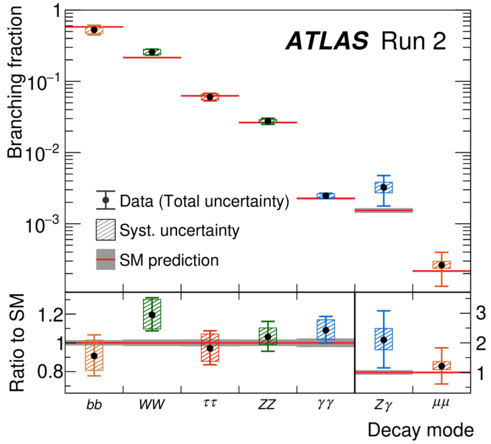
Higgs boson physics

- Extensive characterization of the Higgs sector of the SM with the LHC Run 1 and Run 2 data (Nature 607, 52 (2022))
- Established Higgs boson couplings to fermions and bosons, and its proportionality to the particle mass
- Observed experimentally the main production and decay modes
- Involvement in several ongoing Higgs boson analysis:
  - $t\bar{t}H$ production in multileptonic final states
  - Measurement of tHq production (PhD thesis of Jesús Guerrero)









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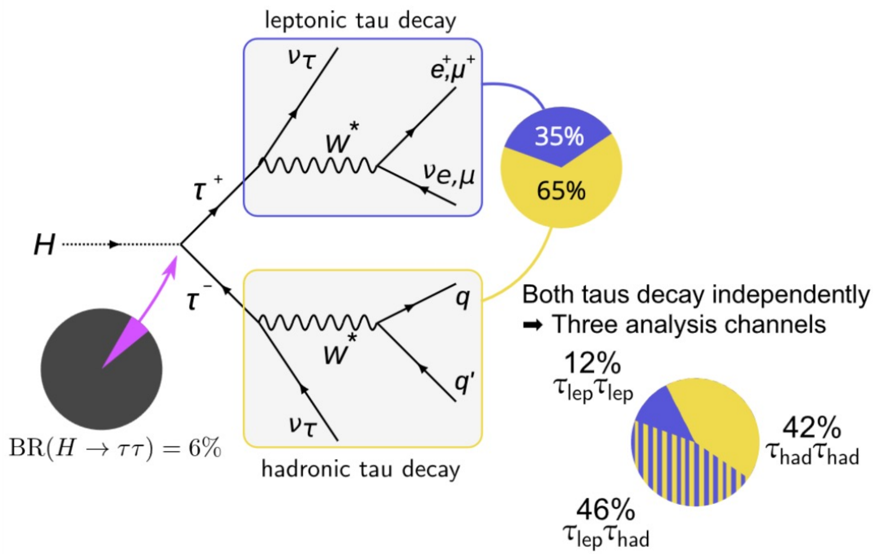
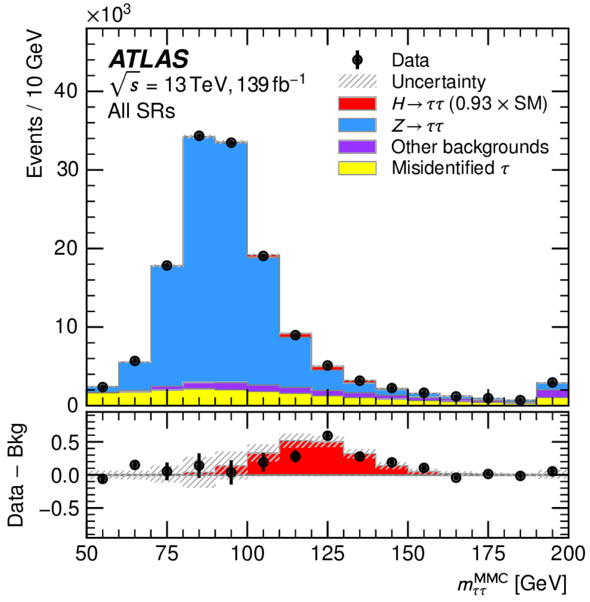
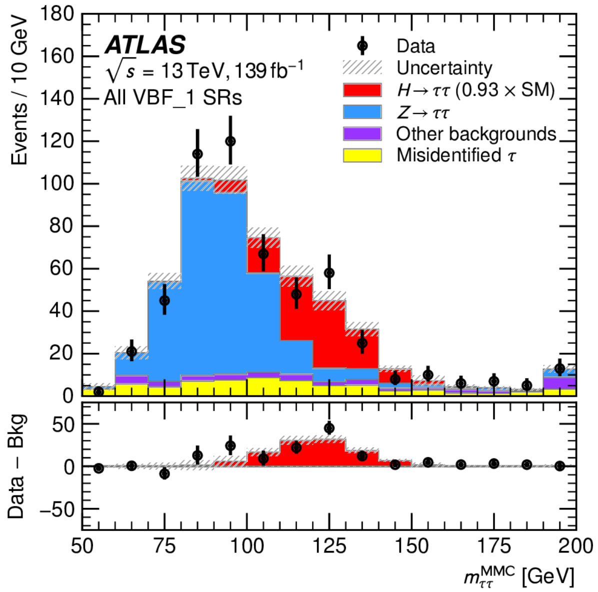
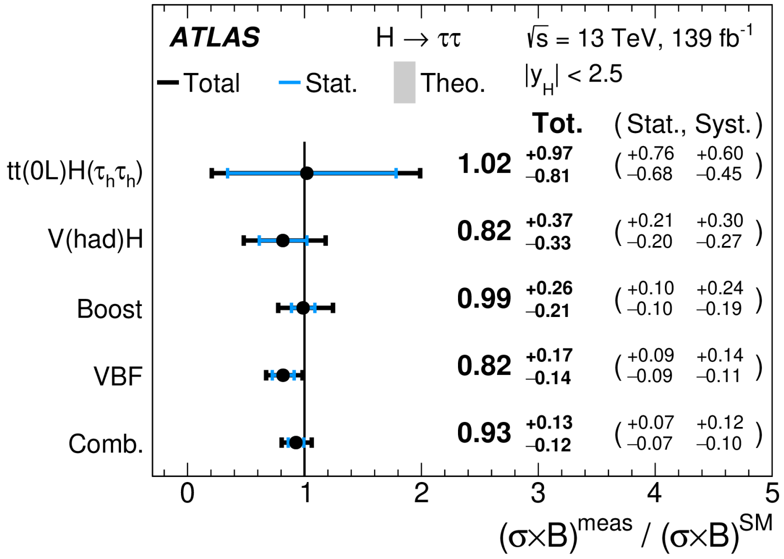
Higgs boson physics: H→ττ

- Detailed measurement of the Higgs boson production in its decays to pair of τ-leptons (JHEP 08 (2022) 175)
- Different analysis channels depending on the τ-lepton decay
- Main background: Z→ττ production
- Use of BDTs to enhance signal / background separation
- Higgs boson coupling to τ-leptons measured inclusively (12% precision) and in each of the main LHC Higgs-boson production modes









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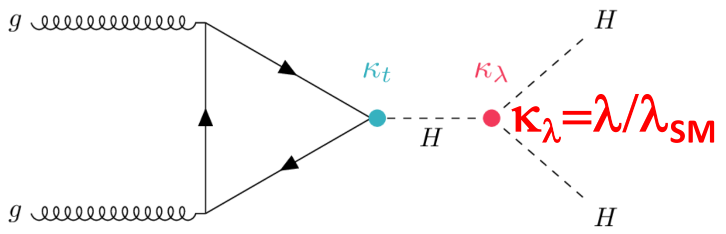
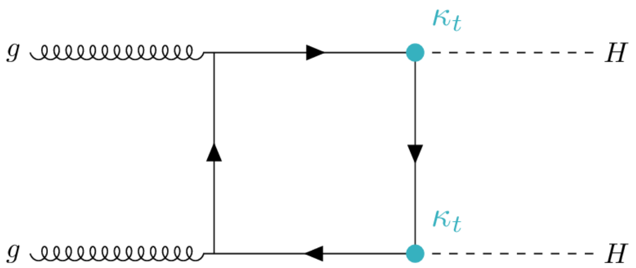
Higgs boson physics

- Higgs boson discovery → Measuring only a portion of the Higgs potential
- Higgs vacuum sitting "close to the edge" of stable and metastable:
  - Metastable vacuum implies a second minimum in the Higgs potential
- Shape of the Higgs potential depends on the **Higgs boson self-interaction (λ)**, which can be studied at the LHC measuring Higgs boson pair production (*HH*)
- *HH* production is very rare: factor 1000 lower than single Higgs production





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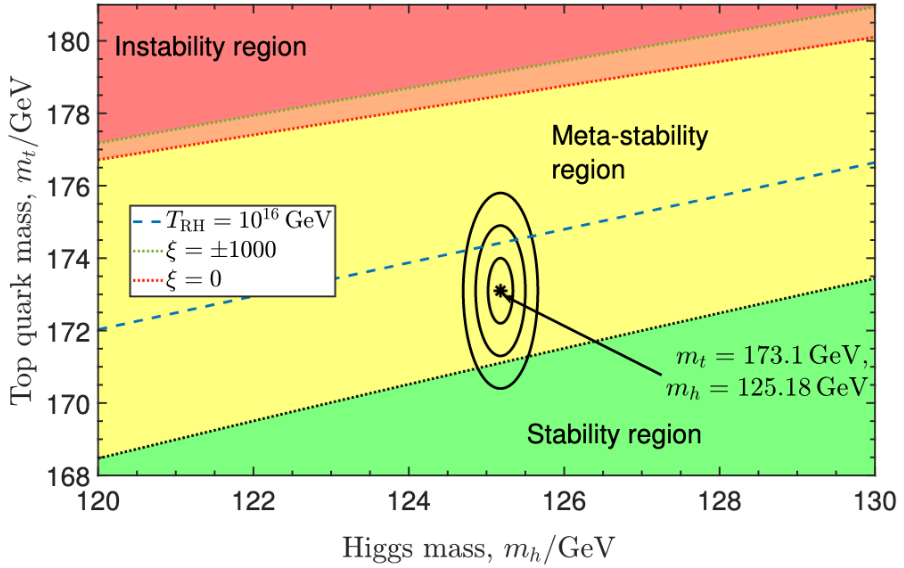
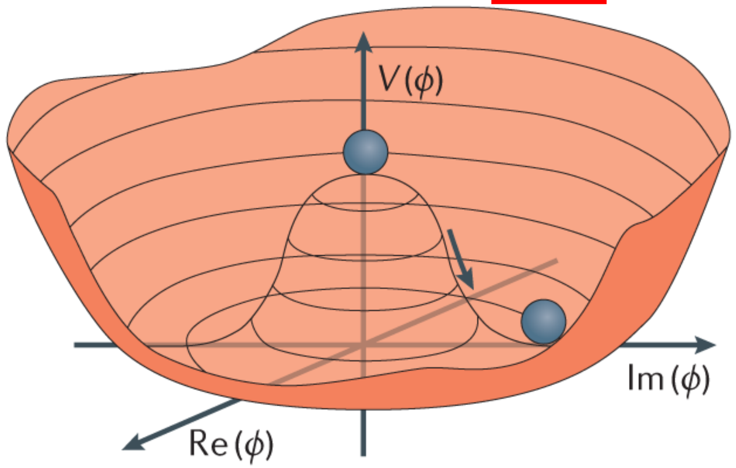
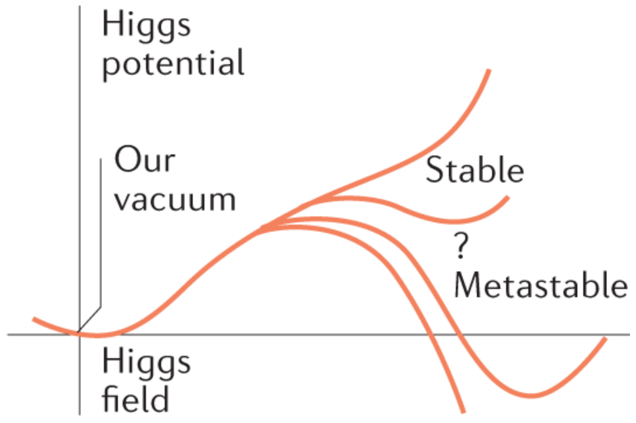


$$V_{higgs} = -\frac{1}{2}m^2|\varphi|^2 + \frac{\lambda}{4}|\varphi|^4$$





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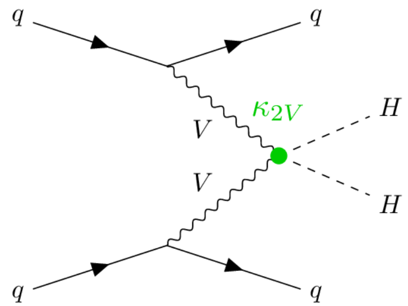
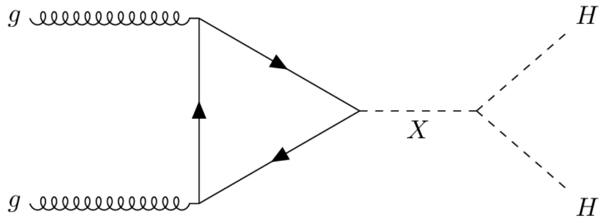
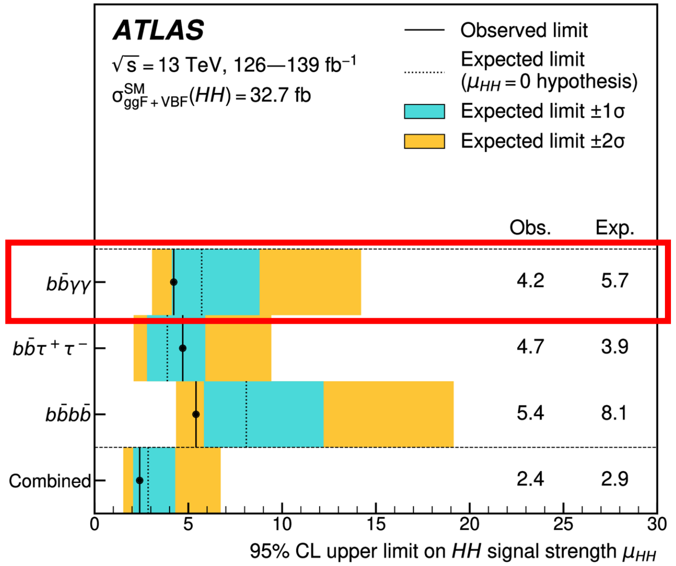
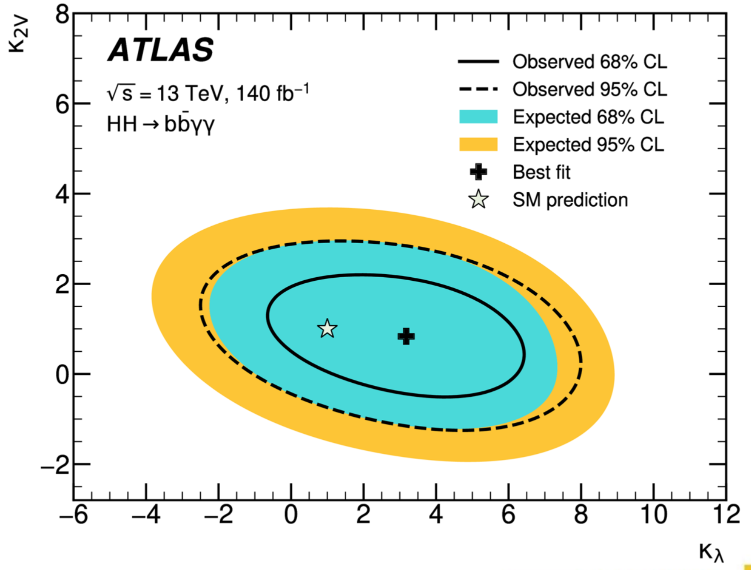
Higgs boson physics: di-Higgs $HH \rightarrow b\bar{b}\gamma\gamma$

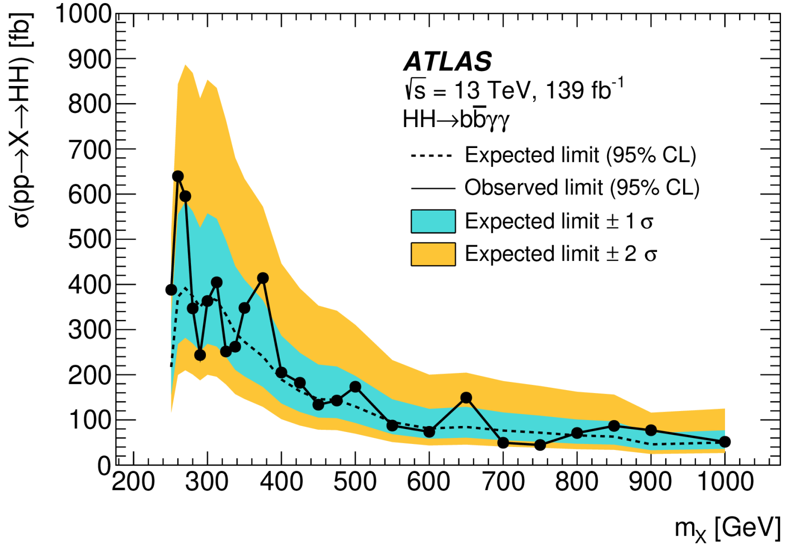
- Exploiting the decays $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$, one of the most sensitive channels together with $HH \rightarrow b\bar{b}\tau\tau$ and $HH \rightarrow b\bar{b}b\bar{b}$
- Using BDTs to separate *HH* signal from single-*H* and SM backgrounds
- Combined limits reaching $\mu=\sigma/\sigma_{SM}>2.4$
- Sensitivity for the **Higgs boson self-coupling κ_λ** but also to the **quartic HHVV coupling (κ_{2V})** (*JHEP 01 (2024) 066*)
- Search for a new scalar particle $X \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$ (*PRD 106 (2022) 052001*)
- PhD thesis of Iván Sayago











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Summary

- The ATLAS and LHCb groups at IFIC are making a strong impact in the physics programme of the LHC in several areas
- ATLAS highlights results on:
  - Detector operation
  - Combined performance
  - Top quark physics
  - Searches for long-lived particles
  - Higgs boson physics
  - Di-Higgs searches
- LHCb results will be featured in the talk by Fernando Martínez tomorrow
- In the middle of Run 3 data taking → Many more exciting results to come!
- LHC beam back next Monday → Re-starting effort in data taking and operation

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BACKUP: ASFAE projects related to LHC Physics

Código	Acrónimo	IPs	Título
ASFAE/2022/008	TILEVAL	FIORINI, LUCA RUIZ MARTÍNEZ, ARANTXA	Electrónica del Tile Calorimeter y Exploración del Programa de Física
ASFAE/2022/010	ATLAS-RUN3-HIGGS-TOP	POVEDA TORRES, JOAQUÍN MORENO LLÁCER, MARÍA	Operación del experimento ATLAS durante el Run 3 del LHC y explotación de sus datos para el estudio del bosón de Higgs y el quark top.
ASFAE/2022/006	ATLASCOMP-IFIC	VILLAPLANA PÉREZ, MIGUEL TORRÓ PASTOR, EMMA	Computación Avanzada para el procesado intensivo de Big Data en ATLAS.
ASFAE/2022/030	LHCb-UPGRADE	MARTÍNEZ VIDAL, FERNANDO OYANGUREN CAMPOS, ARANTZA	Retos tecnológicos para el descubrimiento con el detector LHCb mejorado del CERN

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