ATLAS Physics

Andrii Verbytskyi for MPP ATLAS Group

Annual project review of Max-Planck-Institut für Physik
Garching bei München
December 9, 2024

ATLAS MPP Group

- Director: Marumi Kado (2023-)
  - Deputy Institute Representative: Teresa Barillari
  - Director-emeritus: Siegfried Bethke
  - Assistant: Anja Schielke
- 30+ physicists organized in subgroups, taking responsibilities in different areas of the ATLAS experiment:
  - Inner Detector (PL: R. Nisius)
  - Hadronic Endcap Calorimeter (PL: S. Menke, T. Barillari)
  - Muon Spectrometer (PL: O. Kortner, H. Kroha)
  - Muon Trigger (W2 research group, PL: S. Kortner)
  - Computing (PL: S. Kluth)

ATLAS MPP Group

- Seniors: T. Barillari, D. Cieri, A. Kiryunin, S. Kluth, S. Kortner, O. Kortner, H. Kroha (emeritus), S. Menke, R. Nisius, R. Richter (emeritus), P. Schacht (emeritus), S. Stonjek, A. Verbytskyi
- Postdocs: Sh. Bharthuar, D. Britzger, F. Fallavollita, M. Holzbock (left), M. Greco, F. Guescini, Ch. Li, T.H. Park, J. Pena, G. Proto, M. Spalla (left), E. Voevodina
- Phd students: D. Buchin, E. Cuppini, S. Grewe, J. Hessler, E. Schmidt, A. Reed, N. Wenke
- Master, bachelor and work students: D. Costa, P. Düerkop, A. Ali-Dzahn, M. Griese, V. Griniushin, E. Hanser, P. Hebbar, R. Hildebrandt, J. Honal, S. Eder, N. Kube, S. Mavie Metz, N. Meier, J. Murnauer, J. Okfen, A. Pradit, J. Rakich, F. Resende, L. Spitzauer, B. Wesely, F. Zhou
- Engineers: S. Abovyan, V. Danielyan, U. Leis, P. Maly, D. Soyk, J. Zimmermann
- Computing cluster: C. Delle Fratte, M. Tabriz

MPP Coordination roles in ATLAS

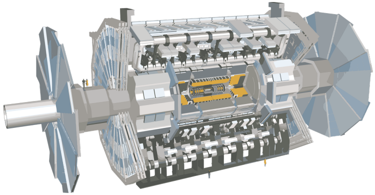
M. Kado	Deputy Spokesperson (2021-2023)
T. Barillari	LAr Phase-II HEC LVPS coordinator (2024-), LAr Phase-II HEC LVPS coordinator (2018-2022), POTS member (2020-2023)
D. Cieri	Muon Efficiency subgroup convener (2020-2023), L0 Muon MDT Trigger Processor coordinator (2024-)
F. Guescini	ITk Pixel System Tests, Test Beams and Irradiations (2021-2023)
F. Fallavollita	Muon Speakers Committee member (2024-)
M. Holzbock[CERN]	SUSY background forum convener (2023-2024), ETmiss Performance subgroup convener (2021-2023)
S. Kluth	PDF Forum convener (2024-)
S. Kortner	Steering Committee and LHC EFT Working group convener (2022-2024), Joint EFT Interpretation and Combination group convener (2022-2024)
O. Kortner	L0 Muon MDT Trigger Processor coordinator (2023-2024)
H. Kroha	sMDT Chambers coordinator (2018-)
Changqiao Li	Xbb/Xcc group convener (2022-2024)
S. Menke	LAr Phase-II Electronics Upgrade Project leader (2018-) LAr Phase-II HEC LVPS coordinator (2022-2024)
T.H. Park	Jet In-Situ Calibration Subgroup convener (2024-)
J. Pena[IFAE]	Trigger L1 Topo Algorithm Commissioning coordinator (2023-), Top Properties and Mass subgroup convener (2021-2023)
G. Proto	Muon Efficiency subgroup convener (2023-)
M. Spalla[left]	Jet Definitions and MC Calibration subgroup convener (2021-2023)
A. Verbytskyi	Generator Infrastructure and Tools subgroup convener (2024-)

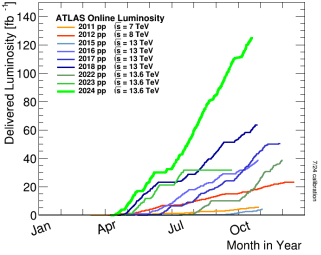
ATLAS experiment

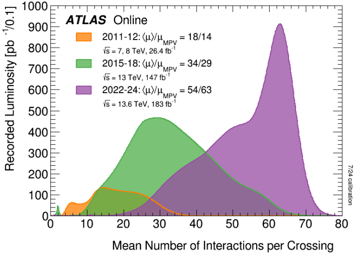
Physics analyses performed with Run 2 (2015–2018) and **Run 3 (2022-2026)** data from *pp* collisions.

- High precision Standard Model (SM) measurements with focus on Higgs and top physics.
- Direct and indirect searches for the signals of Beyond Standard Model (BSM) physics.
- Advanced reconstruction, simulation, analysis techniques.

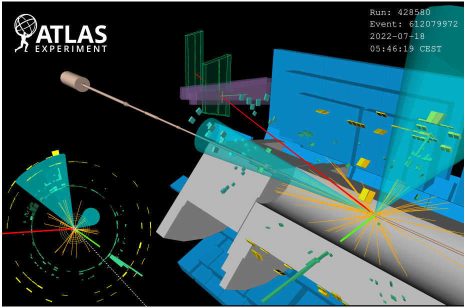
Run 2 Detector







Reconstruction, simulation and more



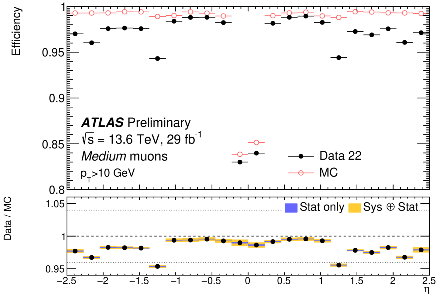
- Muon performance
- LAr Calorimeter topoclusters
- Reconstruction of missing transverse energy
- Geant4 and MPP HEC
- . . . and much more

Muon performance

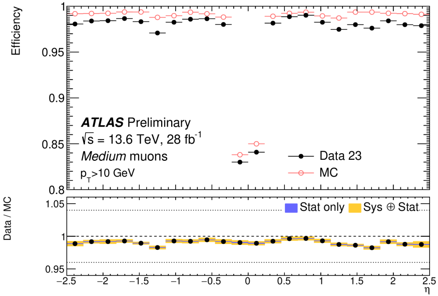
WIP

Long-term institute commitment: Calibration of the muon reconstruction, identification and isolation efficiency with and data.

Run-3, 2022 (without New Small Wheel data)



Run-3, 2023 (with New Small Wheel data)

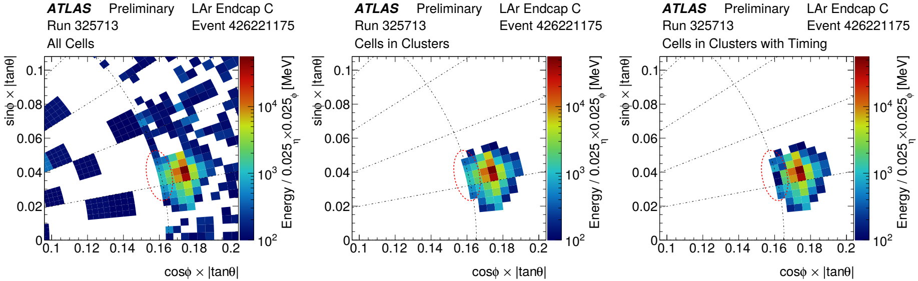


Better performance with new detector, improved efficiency w.r.t. 2022.

Timing information for calorimeter topoclusters

Eur. Phys. J. C **84** (2024) no.5, 455

Jets are constructed from tracks and calorimeter clusters. Clusters are constructed from calorimeter cells so their energy can be reliably calibrated and they can be matched to tracks. The criterion to combine the cells into a cluster – their dimensional proximity and energy prominence over the surrounding cells and noise.
New development – take into account the timing information (LAr intrinsic resolution: 60*ps*, applied discriminator: ± 12.5*ns*).



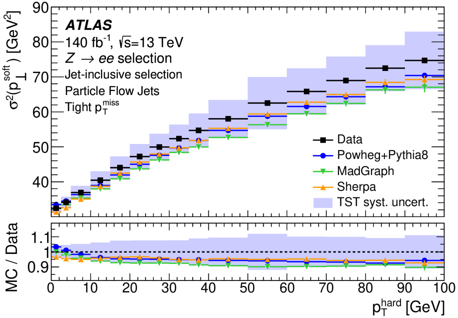
- Suppresses out-of-time pileup by 80%.
- Improves the jet energy resolution by 5%.
- Removes the fakes from γ, τ, *e*.

Excellent timing resolution of LAr now can be used in analysis.

Reconstruction of missing transverse energy

[arXiv:2402.05858 [hep-ex]].

E_T^{miss}: experimental proxy for the transverse momentum carried by undetected particles. Constructed from reconstructed hard objects and recorded tracks in the final state.

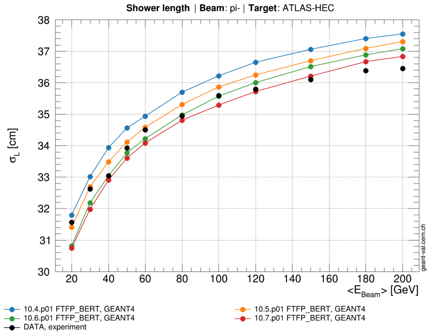


- Tracker instead of the calorimeter for the reconstruction of soft contributions.
- Introduction of particle flow jet algorithm.
- Multiple working points.
- Better control of systematic uncertainties with a larger data set.
- Scale uncertainty reduced by 76%.
- Resolution uncertainty reduced by 51%.

Significant performance improvement in Run 2 compared to Run 1.

Geant4 and MPP HEC

Instruments **6** (2022) no.3, 41



- Geant4 is used as full simulation toolkit for ATLAS physics.
- Showers in the calorimeter are both the most important and the most time consuming aspects.
- Test beam data from ATLAS HEC modules are essential to validate. Geant4 versions
- Test beam data were made available to the Geant4 developers.

Simulated shower length significantly different in different versions. **Top importance for ATLAS.**

Collaboration of the ATLAS HEC Group and the Geant4 team.

Selected public notes

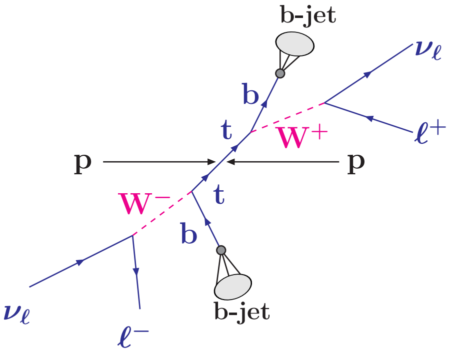
Notes:

- Transformer Neural Networks for Identifying Boosted Higgs Bosons decaying into $b\bar{b}$ and $c\bar{c}$ in ATLAS
  ATL-PHYS-PUB-2023-021
- ATLAS simulation workflow and the particle numbering scheme
  ANA-SIMU-2024-01-PUB
- Interactive web pages for radiation environment exploration of ATLAS (click me!)
  ATL-SOFT-PUB-2020-003

And plots. . .

- *b*-tagging data-to-MC efficiency scale factors for charm jets with the GN2 tagger using Run 2 data (click me!)

Top quark physics

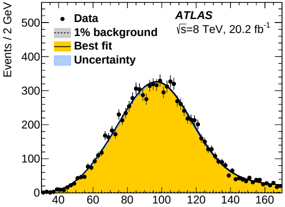


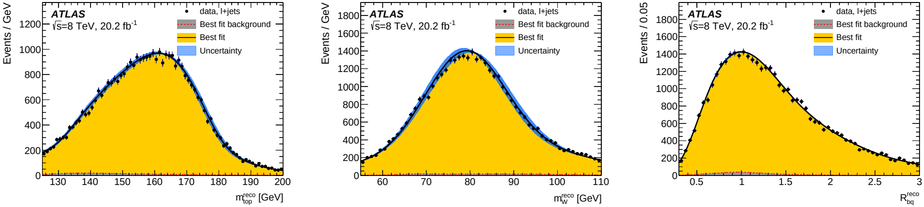
- Top quark mass measurements and their combination
- Measurements of $pp \to W^+W^-b\bar{b}$ process
- Measurements of $pp \to t\bar{t}b\bar{b}$ process

Top quark mass: the latest two published results

Dilepton channel Phys. Lett. B **761** (2016), 350-371

Lepton + jets channel Eur. Phys. J. C **79** (2019) no.4, 290

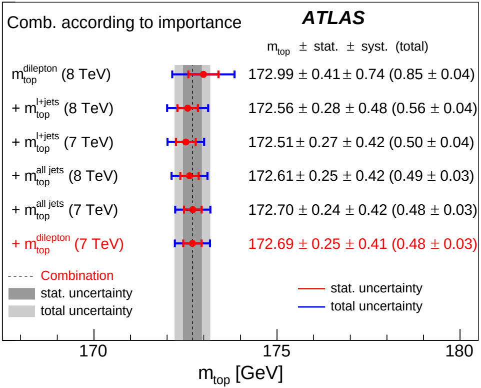




- Template fits in one or three (lepton+jets channel) dimensions on $\sqrt{s} = 8$ TeV ATLAS data.
- Fit m_{top} and two jet energy scale factors (JSF, bJSF) to three distributions $m_{\text{top}}^{\text{reco}}$, $m_{\text{W}}^{\text{reco}}$, $R_{\text{bq}}^{\text{reco}}$.
- Different analysis strategies for the two channels to keep the correlations of the results low.

The $\sqrt{s} = 8$ TeV dilepton channel result is the most precise from ATLAS at Run-1.

The latest ATLAS top quark mass combination

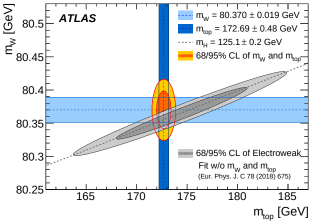


Features of the combination

- Large improvement in precision induced by the low correlations.
- Dominated by jet energy scale and MC modeling uncertainties.

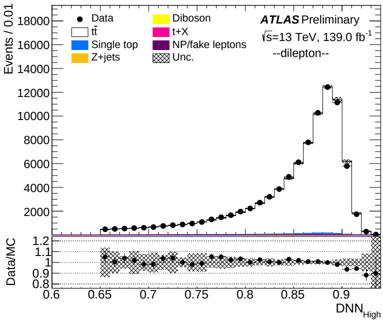
Impact on Standard Model fits

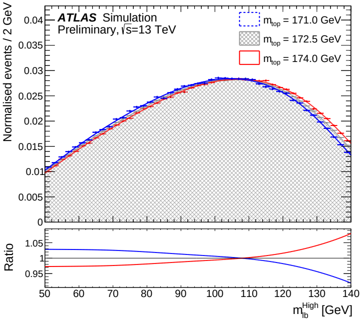
Eur. Phys. J. C **79** (2019) no.4, 290



The combined ATLAS m_{top} measurement has a precision of 4‰.

Improvements since the last dilepton result WIP





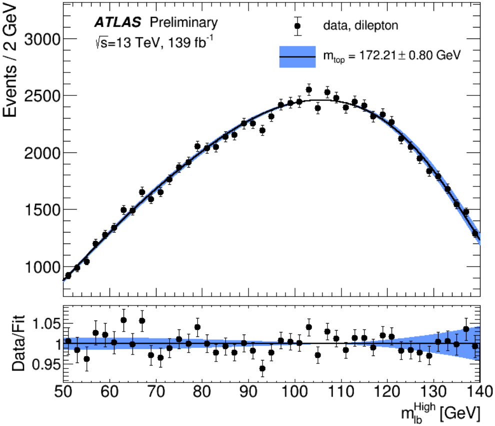
- ☺ Deep Neural Network(DNN) for *b*-jet and lepton pairing. ⇒ Improved chances for correct pairing.
- ☺ DNN-picked $m_{\ell b}$ vs. average in the past. ⇒ Better resolution and systematic uncertainties.
- ☺ Improved reconstruction. ⇒ Smaller systematic variations required for the systematic uncertainties.
- ☹ New modeling systematics: recoil behavior of gluons in FSR.
  ⇒ Increase in theoretical uncertainty.

High precision requires a careful evaluation of all effects.

The latest preliminary ATLAS m_{top} measurement

WIP

The fit to $\sqrt{s} = 13$ TeV data



The list of uncertainties

	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

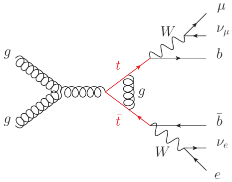
Similar uncertainty as for 8 TeV data, albeit with an additional source of uncertainty.

A publication, together with the lepton+jets results expected soon.

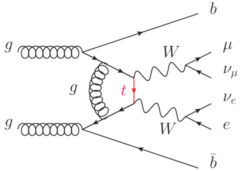
Measurements of $pp \to WWbb$ WIP

WWbb represents the final state of top-quark pair events, but further includes. . .

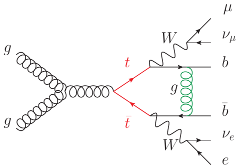
NLO correction to *tt* production



Non-doubly resonant diagram



Non-factorizing diagram



- Details on *WWbb* modeling are very relevant for top-quark mass analyses, SUSY searches, etc... (Interference effects with single-top diagrams, narrow-width approximation, higher order correction in the top-quark decay, definition of the top-quark mass, NLO+PS matching, etc. . .)
- *WWbb* is an important process on its own fixed order predictions, etc. . . sensitivity to m_{top}, top-quark width Γ_{top}, α_S, PDFs, . . .

New measurements are performed:
di-lepton channel: $pp \to bbll$ + MET.

- Understand $t\bar{t} - Wtb$ interference.

l+jets channel: $pp \to WWbb$

- Measure W-boson kinematics.
- Determine SM parameters.
- Major MPP-contributions.

Measurements of $pp \to WWbb$, 1l final state

WIP

Quite special final state at the LHC

- Sizable cross section and small backgrounds (due to $W \to l\nu$ and $W \to jets$).
- W-boson kinematics can be measured with a dedicated W-boson reconstruction algorithm.
- Rich physics (m_{top}, α_S, PDFs, new NLO+PS predictions, quantum interference, Γ_{top}, constraints for searches, etc...)

Cross section measurement

- Rich set of observables in 3 different signal regions, each region targeting more specific physics cases.
- Small systematic uncertainty after unfolding to particle level.
- Good agreement between data and MC prediction.

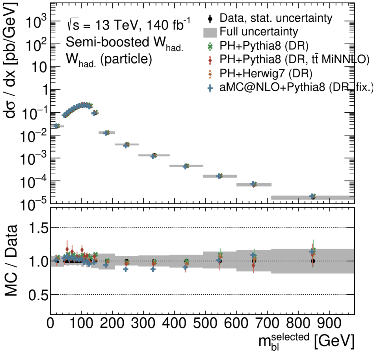


Figure from

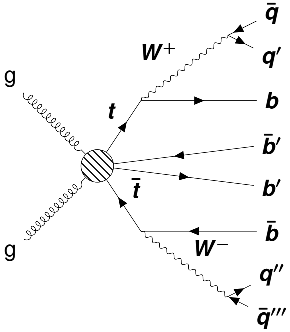
Bohan Chen, PhD. Thesis 2024

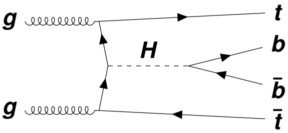
University of Victoria

Preparation for ATLAS top-group approval ongoing.

$pp \to t\bar{t}b\bar{b}$ with all-hadronic top decays

- All hadronic $t\bar{t}b\bar{b}$ is perfect for studying dynamics of heavy quark production and look for physics BSM.
- $t\bar{t}b\bar{b}$ is the main background for the all hadronic ttH process.
- $t\bar{t}b\bar{b}$ final state we could be sensitive to BSM, e.g. $gg \to tbH^+$, $H^+ \to tb$.
- Mastering reconstruction of all hadronic $ttbb$ is useful for HL-LHC: lepton+jets $tttt$ measurements, etc.
- **Full reconstruction.**





Interesting and challenging final state important for HL-LHC.

$pp \to t\bar{t}b\bar{b}$ with all-hadronic top decays

WIP

Control A : ***cuts*** $\bar{\alpha} + \bar{\beta}$ ***Content*** : — ***multijets (ABCD, data)*** — $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$ ***from MC***	***Control B*** : ***cuts*** $\bar{\alpha} + \beta$ ***Content*** : — ***Residual signal*** ($t\bar{t}b\bar{b}$) — ***multijets (ABCD, data)*** — $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$ ***from MC***
Control C : ***cuts*** $\alpha + \bar{\beta}$ ***Content*** : — ***multijets (ABCD, data)*** — $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$ ***from MC***	***Signal D*** : ***cuts*** $\alpha + \beta$ ***Content*** : — ***Signal*** ($t\bar{t}b\bar{b}$) — ***multijets (ABCD, data)*** — $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$ ***from MC***

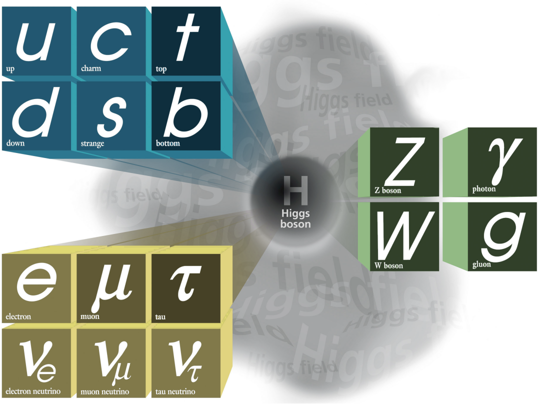
- Complex final state with large background.
- Data-driven method (ABCD) for the estimation of dominant multi-jet background.
- Sophisticated unfolding procedure to take into account sub-leading contributions to background.
- The goal: differential and fiducial cross-sections at particle and parton level for multiple observables.

Selection α limits the ratio $\frac{m(bjj)(top)}{m(jj)(W)}$ and β selects the desirable set of b-jets.

ABCD assumes $multijets_D = multijets_C \times \frac{multijets_B}{multijets_A}$.

Preliminary results available for three observables.

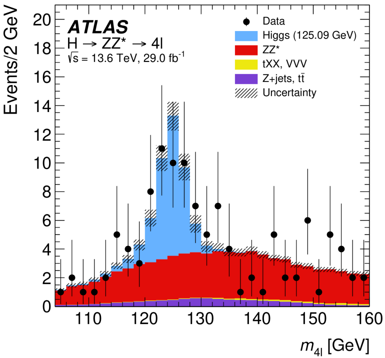
Higgs boson physics

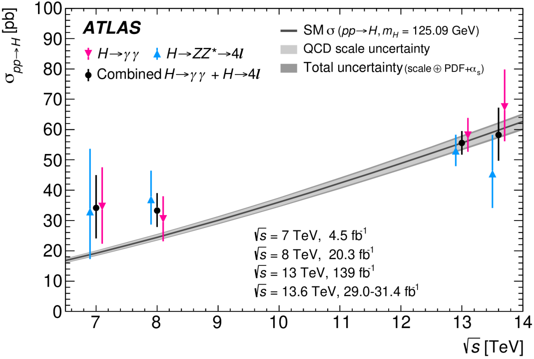


- First cross section measurement with partial Run 3 data ($H \to ZZ^* \to 4l$)
- Effective field theory interpretation of combined Higgs measurements with full Run 2 data
- Search for CP violation in the Higgs sector with full Run 2 data

$H \to ZZ^* \to 4l$ decay channel in Run 3 data

Eur. Phys. J. C **84** (2024) no.1, 78





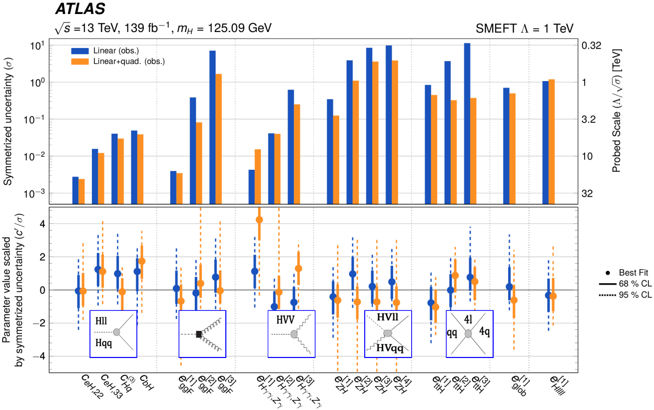
- First LHC measurement of inclusive Higgs production cross section in Run 3 collision data. Combined with the $H \to \gamma\gamma$ channel.
- Work in progress: differential cross sections, couplings, effective field theory interpretation.

Probing Higgs physics at the new center-of-mass energy: 13.6 TeV

EFT interpretation of the combined Higgs Run 2 data

JHEP **11** (2024), 097

Combined measurement of main Higgs production and decay modes in several exclusive phase-space regions.



Probed energy scale:

From 300 GeV for top quark couplings

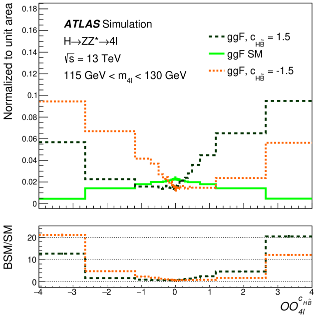
up to 20 TeV for muon and gluon couplings

EFT allows for wide interpretations of data in the context of BSM.

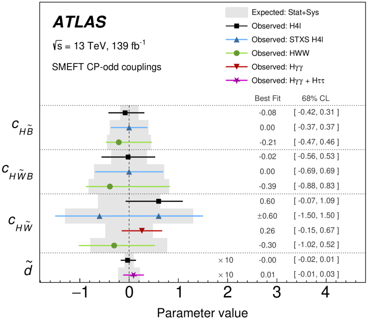
Search for *CP*-violation in the Higgs sector

JHEP **05** (2024), 105 & Phys. Rev. D **108** (2023) no.7, 072003

Dedicated *CP*-odd discriminant observables: interference between SM and *CP*-odd terms.



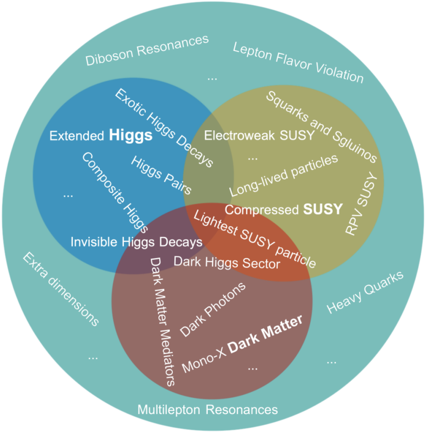
Constraints on *CP*-odd couplings in different channels.



Measurements of Higgs boson spin and charge-parity (*CP*) are consistent with the SM (0^+).

No deviation from SM is observed, constraints on *CP*-odd parameters.

Direct searches for new particles beyond the SM

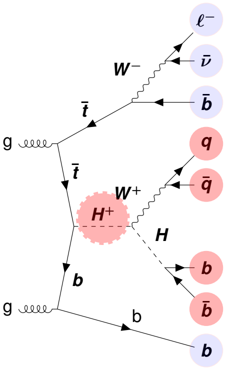


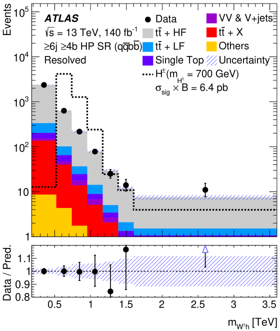
- Charged Higgs bosons.
- DM+Higgs
- Compressed SUSY with nearly mass-degenerate Higgsinos.
- Electroweak SUSY: direct stau ($\tilde{\tau}$) pair-production.
- Leptoquarks.

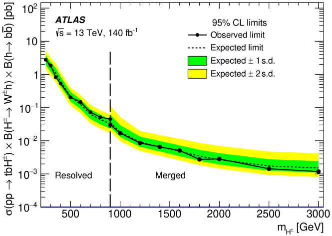
Searches for charged Higgs bosons

[arXiv:2411.03969 [hep-ex]]

- First LHC search for charged Higgs bosons decaying into a boson and SM-like Higgs.
- Initiated and lead by MPP.
- Complex multi-jet final state, difficult to identify jets from Higgs decays.
- Reconstruction of candidates by means of machine learning (BDTs).





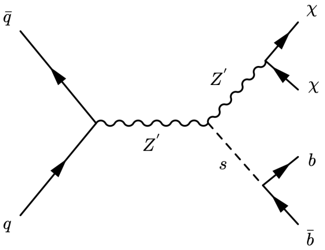


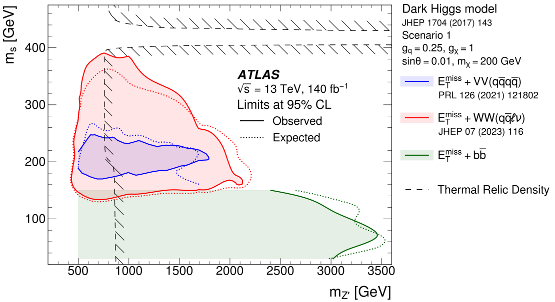
Analysis sensitive to a large range of H^+ masses up to 3 TeV.

Search for dark matter produced in association with a dark Higgs boson in the $b\bar{b}$ final states

[arXiv:2407.10549 [hep-ex]]

- Targets Two-Mediator DM (2MDM) model (6 independent parameters) with Majorana DM, dark Higgs s and new massive vector boson Z'.
- Analysis targets the $s \to b\bar{b}$ decay using the entire Run-2 ATLAS data.
- Signatures: 2 small radius jets or merged single large-R jet, missing transverse energy.



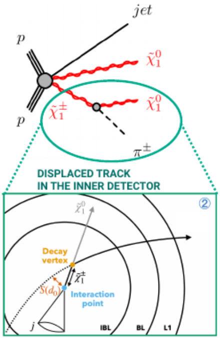


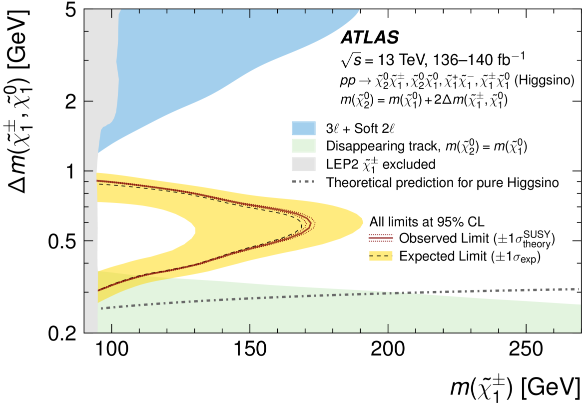
Exclusion limits in previously unexplored region in DM-Higgs sector.

"Compressed" Supersymmetry

Phys. Rev. Lett. **132** (2024) no.22, 221801

Search for the pair production of nearly mass-degenerate Higgsinos, $m(\tilde{\chi}_1^{\pm}) \approx m(\tilde{\chi}_1^0)$, challenging to detect. **Novel signature tried:** low- p_T tracks displaced from primary vertex.



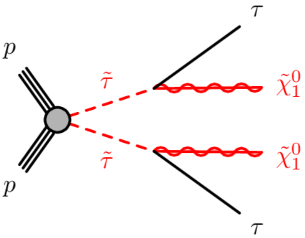


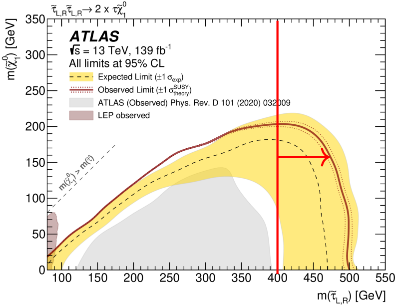
Exclusion limits in a challenging, previously unexplored region.

Electroweak supersymmetry interactions

JHEP **05** (2024), 150

Light sleptons could play a role in the co-annihilation of neutralinos as dark matter candidates in the early universe, providing scenarios that satisfy all cosmological and astroparticle constraints. Search for the direct pair-production of the scalar super-partners of tau leptons (staus, $\tilde{\tau}$):





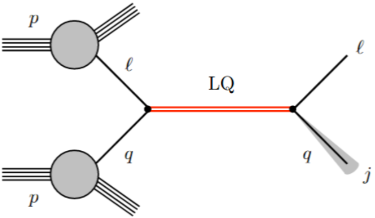
- Hadronically decaying τ-leptons in the final state.
- Machine learning (BDT) to separate the signal from the background, leading to improved results compared to previous analysis with same data.

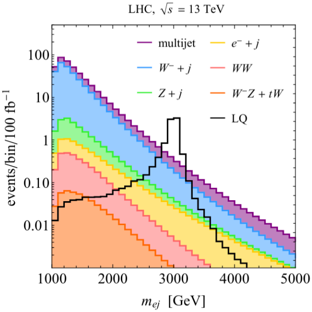
Significantly improved limits using ML analysis methods.

Resonant leptoquark production

WIP

Leptoquarks (LQ) are particles with non-zero baryon and lepton number.





- New LUXlep PDFs with lepton content in proton allow for predictions of resonant leptoquark production. See U. Haisch *et al.*, Phys. Rev. Lett. **125** (2020) no.23, 231804.
- Work in progress, first such search at LHC, bump-hunt in spectrum.

Novel approach to LQ, initiated and lead by MPP.

Conclusions

- MPP is contributing to a wide range of ATLAS physics program.
- Run 3 data sample already matches the full Run 2 data set and is still to be analyzed.
- Looking forward for 10$\times$ more data coming from the the HL-LHC.

Backup slides

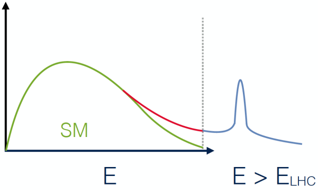
Interpretations within effective field theories (EFT)

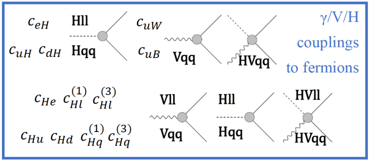
Without any direct evidence for new physics beyond the Standard Model so far, the SM can be viewed as a low-energy approximation to a more fundamental theory.

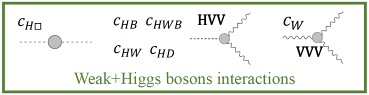
SM Effective Field Theory (SMEFT) Lagrangian:

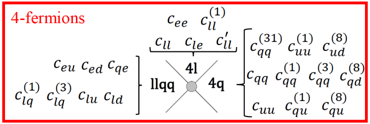
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(d)}}{\Lambda^4}\mathcal{O}_i^{(d)}$$

Wilson coefficients are free parameters that can be constrained from data.









Interpreting the measured cross sections in terms of point-like non-SM interactions scaled by EFT parameters (multi-dimensional fit).

Search for Dark Matter produced in Association with a dark Higgs Boson in the $b\bar{b}$ Final States

Two-Mediator DM (2MDM) model (6 independent parameters), see JHEP **04** (2017), 143.

Parameter	notation
DM mass	m_χ
Z' mass	$m_{Z'}$
Dark Higgs mass s	m_s
Dark sector coupling	g_χ
Quark-Z' coupling	g_q
Higgs mixing angle	θ

Table: 2MDM model parameters