[Physics Results from ATLAS]

P. Conde Muíño
on behalf of the ATLAS Collaboration

Probing the Standard Model of Particle Physics at ATLAS

SM Overall Picture

W, Z, top

Cross sections, W mass and Width, …

The Higgs Boson

Couplings, mass, width, invisible decays, Higgs potencial

Searches for new Physics

SUSY and exotic particles

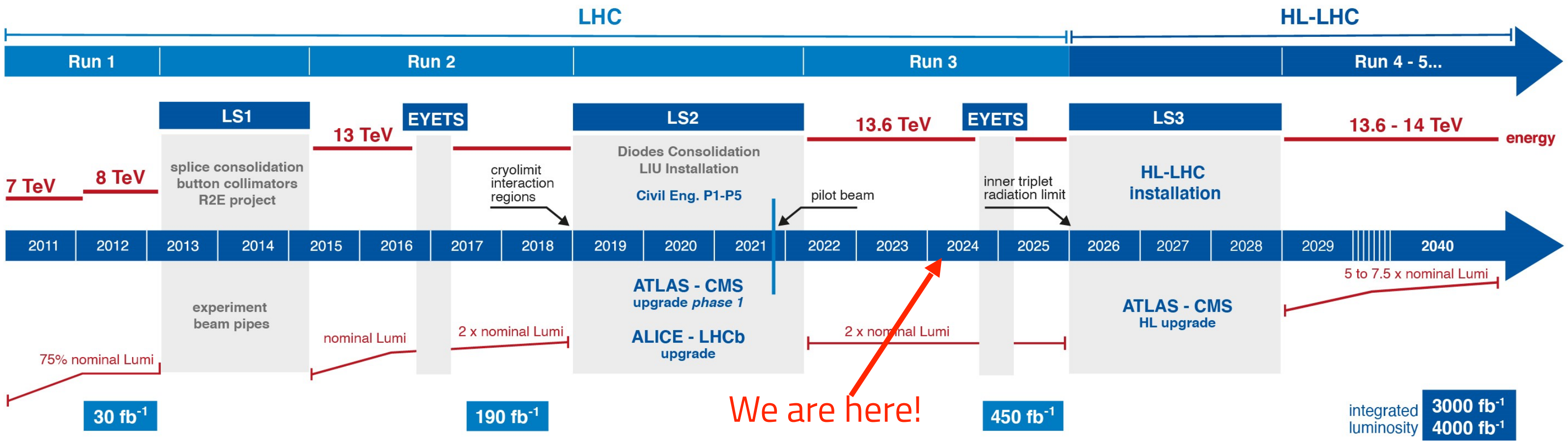
Dark Matter

Unconventional signatures

EFT interpretation of Higgs measurements

Search for CP-Violating Higgs couplings

LHC schedule and ATLAS Data Taking statistics



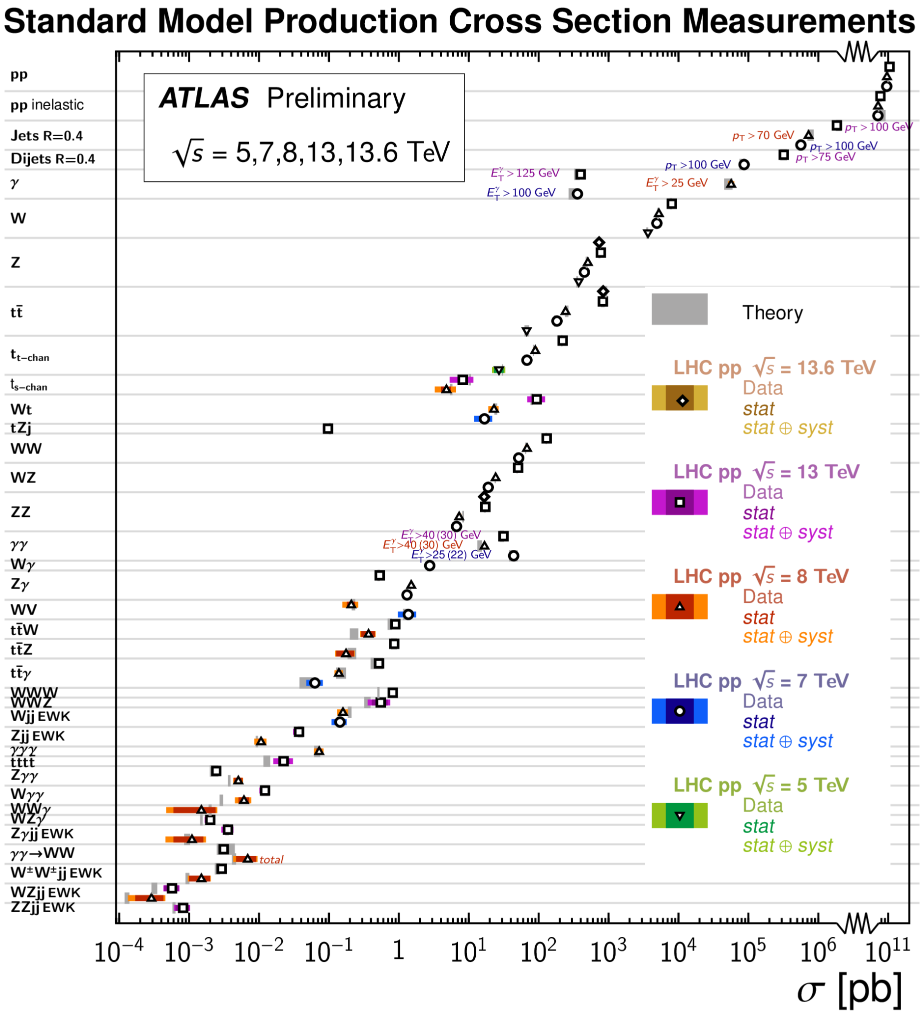
	Center of mass energy	Period	<pp col/BX>	Accumulated luminosity
Run 1	7, 8 TeV	2010-2011	20	35 fb^{-1}
Run 2	13 TeV	2015-2018	34	147 fb^{-1}
Run 3	13.6 TeV	2022-2025	48	84 fb^{-1}
HL-LHC (Run 4 and beyond)	13.6-14 TeV	2029-2040	200	3000 fb^{-1}

ATLAS pp Run-3: 2023

Trigger	Inner Tracker			Calorimeters		Muon Spectrometer			Magnets	
L1+HLT	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC	Solenoid	Toroid
97.5-99.6	99.8	99.7	100	99.5	99.6	99.7	99.9	99.8	100	100

Good for physics: 94.6%-96.5% (27.2-27.8 fb^{-1})

ATLAS Standard Model Measurements in a nutshell



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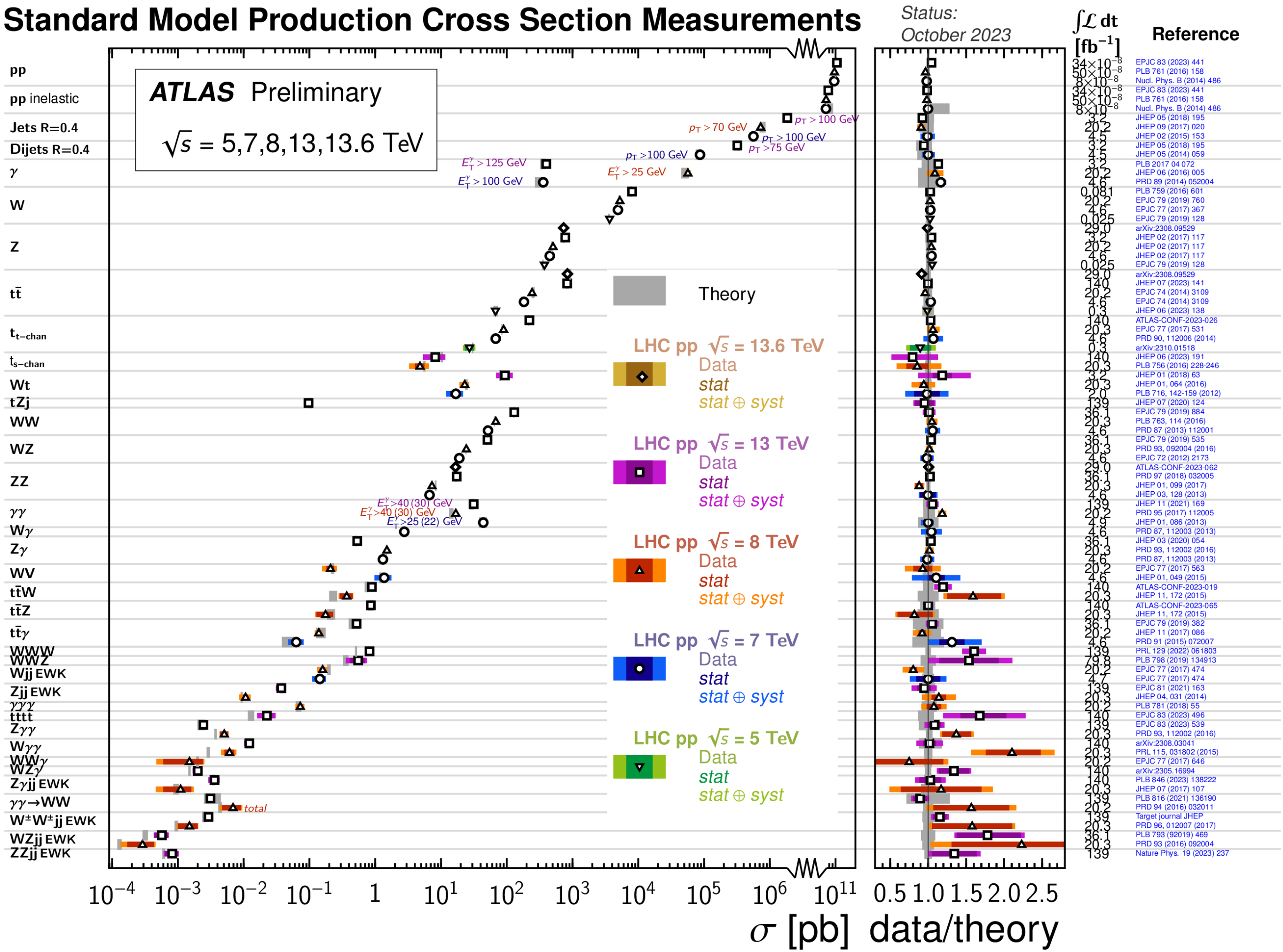
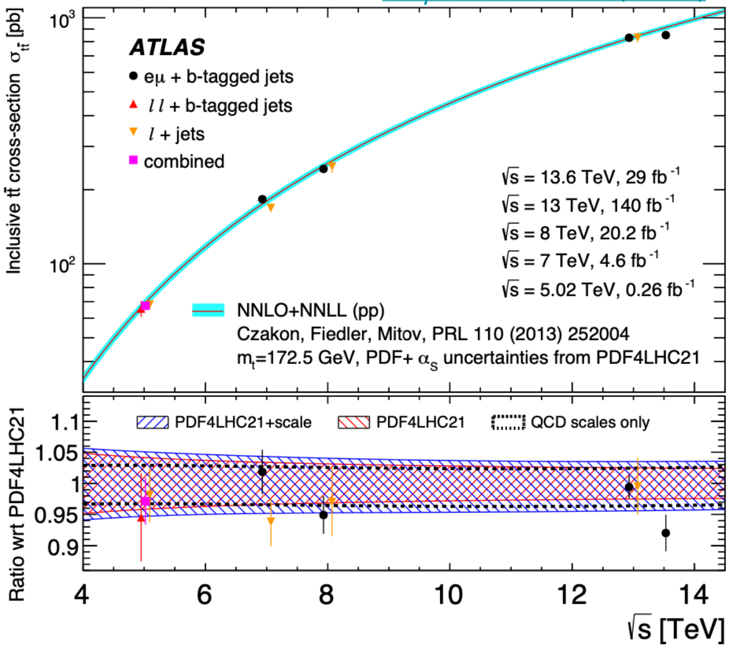


Recent top-quark properties measurements

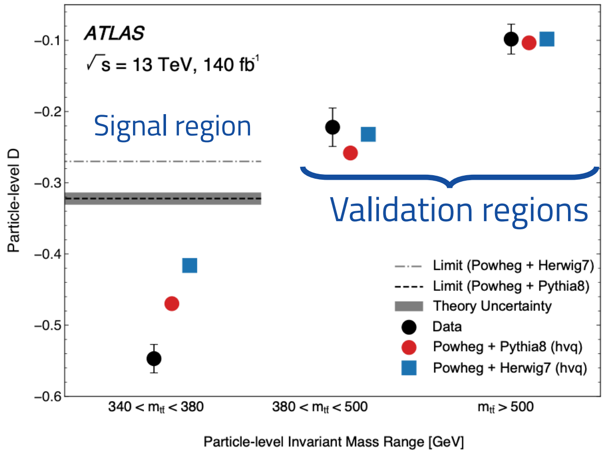
New $t\bar{t}$ production cross-section measurement at 13.6 TeV:

Phys. Lett. B 848 (2024)



First observation of quantum entanglement in $t\bar{t}$ pairs

- Measured using spin correlations
- Entanglement marker $D = -3 < \cos\phi >$
  - ϕ = angle between leptons in special rest frame
- $D = -0.547 \pm 0.002(\text{stat}) \pm 0.021(\text{syst})$



arXiv:2311.07288

Top-quark, W and Higgs mass measurements

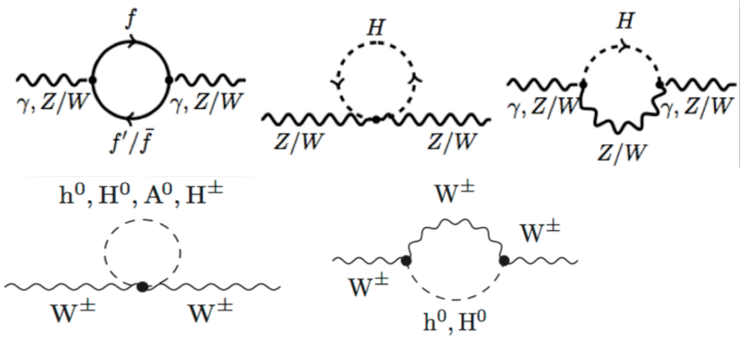
W-boson, top-quark and Higgs Boson mass interrelated in the SM

Tree level   Loop corrections

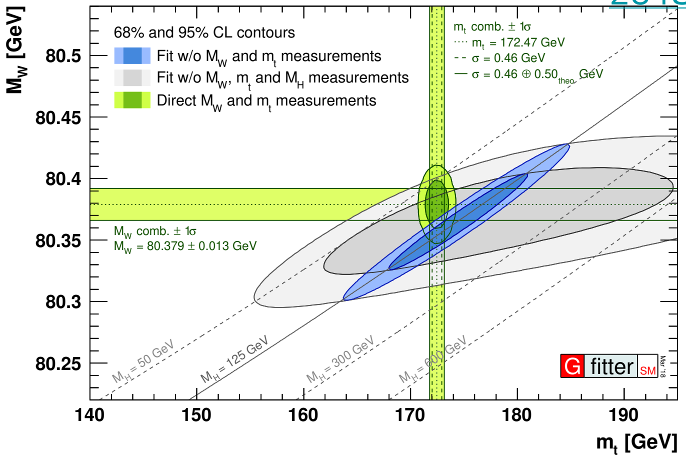
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

Probe the coherence of the SM results

- Precise measurements needed



2018, Gfitter



Top-quark mass measurement

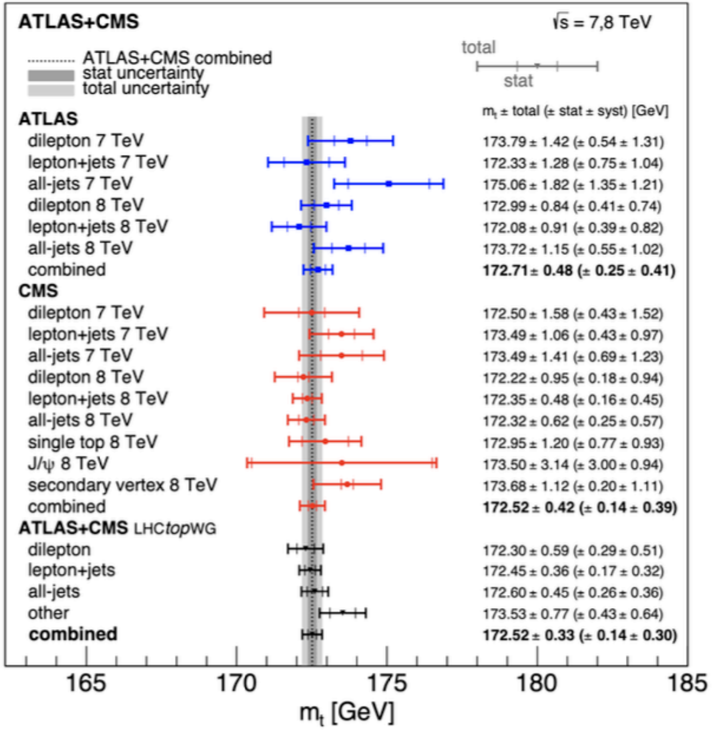
ATLAS and CMS mass combination using 7, 8 TeV analyses in different final states

- Using Best Linear Unbiased Estimator method (BLUE)

$$m_t = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst}) = 172.52 \pm 0.33\ \text{GeV}$$

Best top quark mass measurement up-to-date

- Precision < 0.2%
- improvement of 31% in the total uncertainty relative to the most precise input measurement



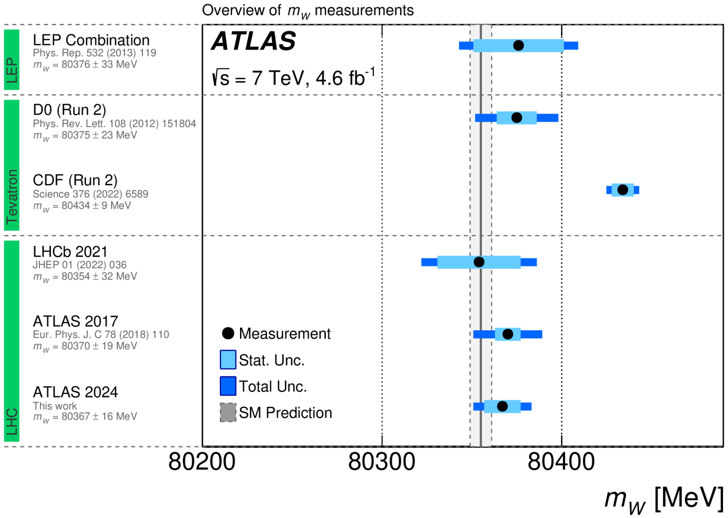
arXiv:2403.15085

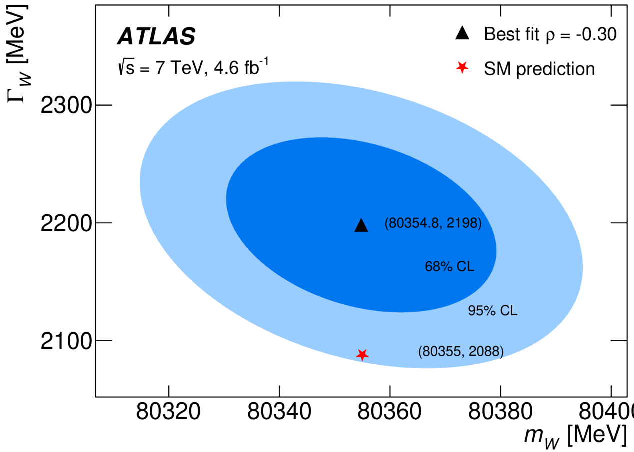
W-boson mass and Width

Combined measurement of the W boson mass and width

Using Run 1, 7 TeV data

- re-analysis with an extensive list of updates to reduce the uncertainties
  - Including PDF updates, improved p_T^W modelling and improved fit
- $m_W = 80360 \pm 5(\text{stat}) \pm 15(\text{syst}) = 80360 \pm 16\ \text{MeV}$
  - Even closer to Standard Model expectations
- $\Gamma_W = 2195.8 \pm 32.2(\text{stat.}) \pm 34.1(\text{syst.}) = 2195.8 \pm 46.8\ \text{MeV}$
  - Most precise Γ_W measurement





Probing the Standard Model of Particle Physics at the LHC

Becoming12 years old

SM Overal Picture

W, Z, top

Cross sections, W mass and Width, ...

The Higgs Boson

Couplings, mass, width, invisible decays, Higgs potencial

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The Standard Model is a very successful theory, but there are many questions that have not yet have an answer....

Is the Higgs boson potential as expected?

Why is there more matter than anti-matter?

Are the Higgs coupling to SM particles as expected?

Is there CP-violation in the Higgs sector?

What is Dark Matter?

Is the Higgs coupling to Dark Matter?

Are there new decay modes of the Higgs boson?

SM Higgs Lagrangian after symmetry breaking

$$\mathscr{L}_{SM} = D_\mu H^\dagger D_\mu H - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Bosons

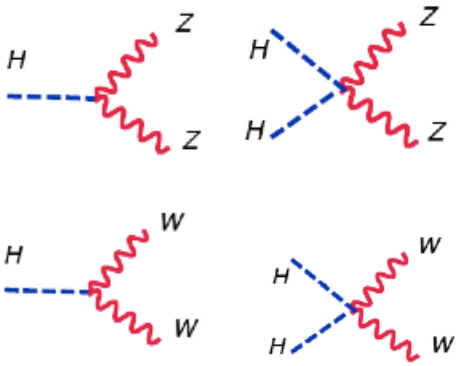
$$(m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0)(1 + \frac{h}{v})^2$$

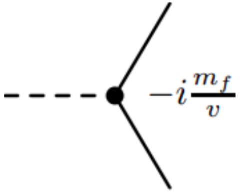
Fermions

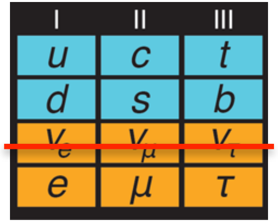
$$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$$

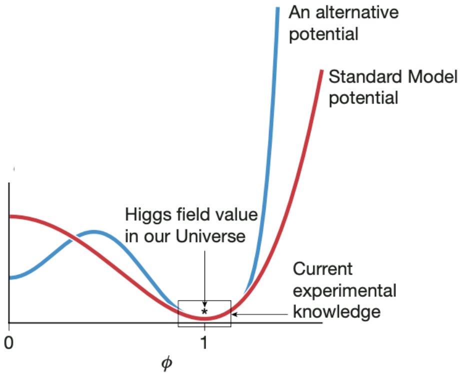
Higgs potential

$$\frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$









G. Salam, L. T. Wang, J. Zanderighi

Phys. Rev. Lett. 131 (2023) 251802

Higgs Boson Mass

Fundamental parameter in the theory

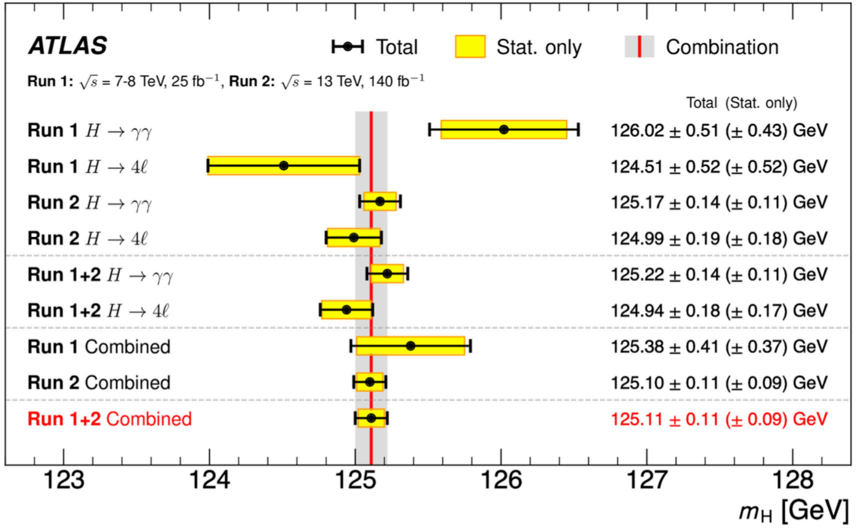
Measured in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels

- Considerable effort to improve the $e/\gamma/\mu$ calibrations in Run 2
- e/γ calibration uncertainty reduced by a factor of 2–3
- μ momentum (resolution) precision down to 0.05% (0.1%)

Currently, most precise measurement:

$$m_H = 125.11 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.}) = 125.11 \pm 0.11 \text{ GeV}$$

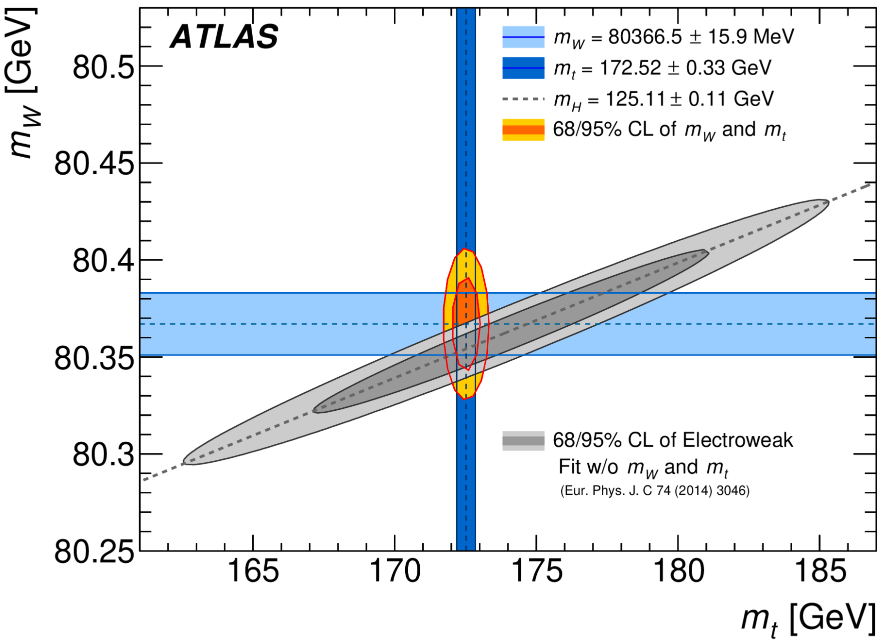
Uncertainty < per-mill level (0.09%)



arXiv:2403.15085

ATLAS Top-quark, W and Higgs Bosons mass compatibility

Electroweak fit without m_W and m_t masses (grey) compared to the ATLAS measurements of m_W, m_t and m_H



Phys. Lett. B 846 (2023) 138223

Higgs Boson Width

SM prediction: $\Gamma_H = 4.1\ \text{MeV}$

Indirect measurement through the on-shell and off-shell

$H \rightarrow ZZ^* \rightarrow 4\ell$ production cross-section:

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

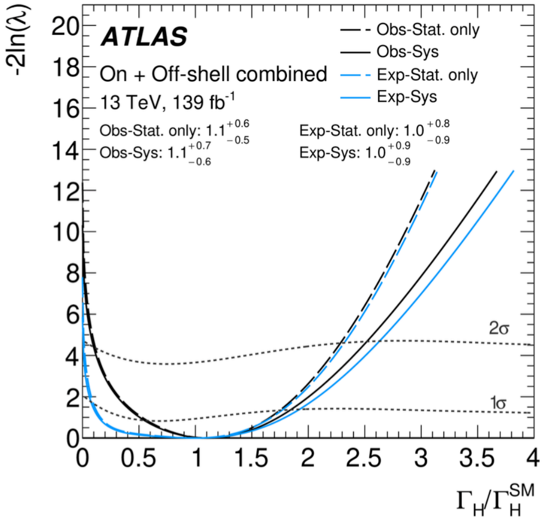
$$\nearrow \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H^2\Gamma_H^2} \quad \text{On-shell}$$

$$\searrow \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2)^2} \quad \text{Off-shell}$$

- Assumes that Higgs production follows SM prediction

New off-shell Higgs production cross-section measurement

- Signal/background interference requires very good MC modelling
- Observed (expected) significance: $3.3\sigma\ \ (2.2\sigma)$



$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ \text{MeV}$$

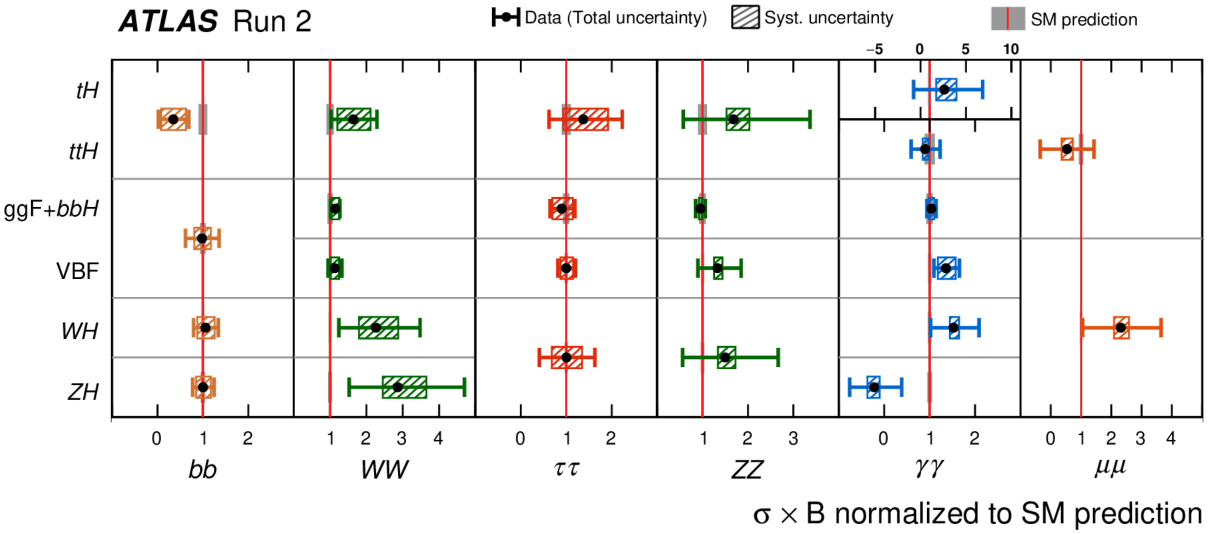
Observed (expected) 95% CL limits:

$$0.5(0.1) < \Gamma_H < 10.5(10.9)\ MeV$$

Higgs boson couplings combination

Direct measurement of $\sigma \times BR$

Nature 607 (2022) 52-59



Good agreement with SM expectations (p-value 72%)

Improved precision:

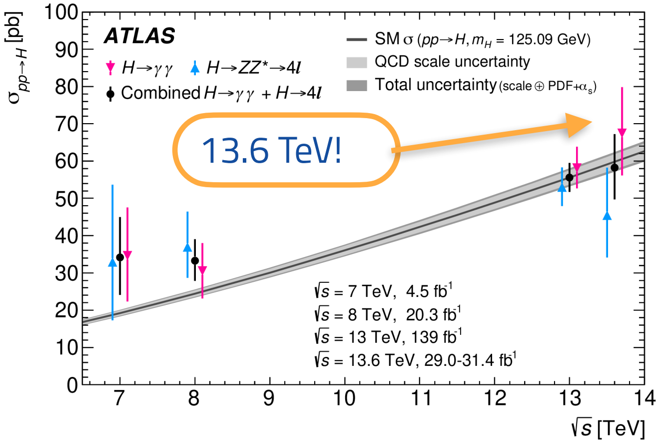
- Cross section: 7-12%
- Branching fractions:10-12%

Recent cross section measurements

Total and differential cross-section measurements performed in different decay channels and for different variables

- Overall agreement with expectations within uncertainties

Eur. Phys. J. C 84 (2024) 78



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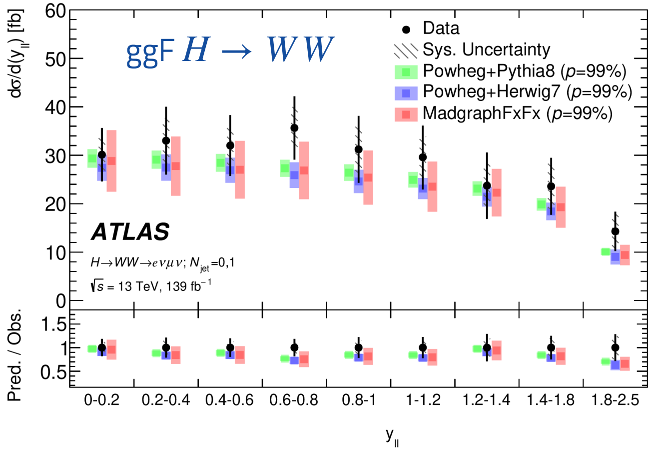
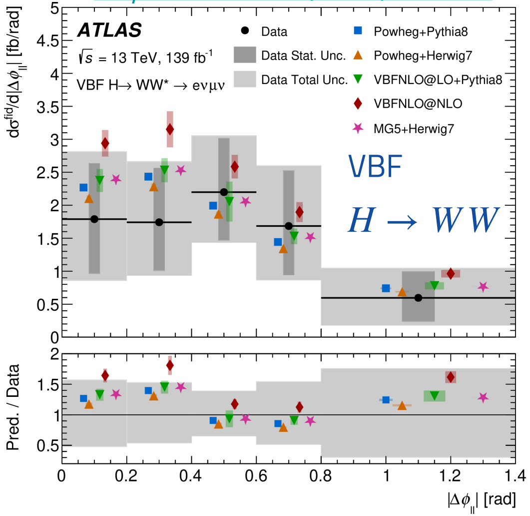
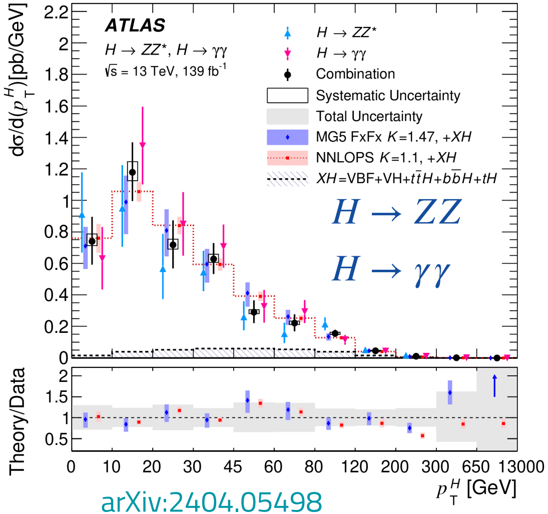


Phys. Rev. D 108 (2023) 072003





arXiv:2404.05498

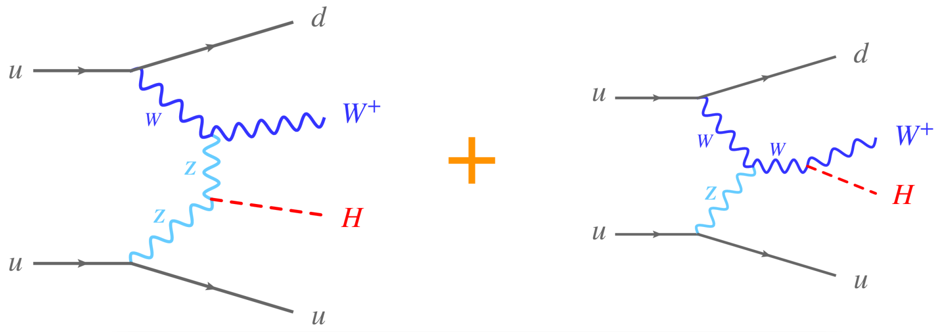
arXiv:2402.00426

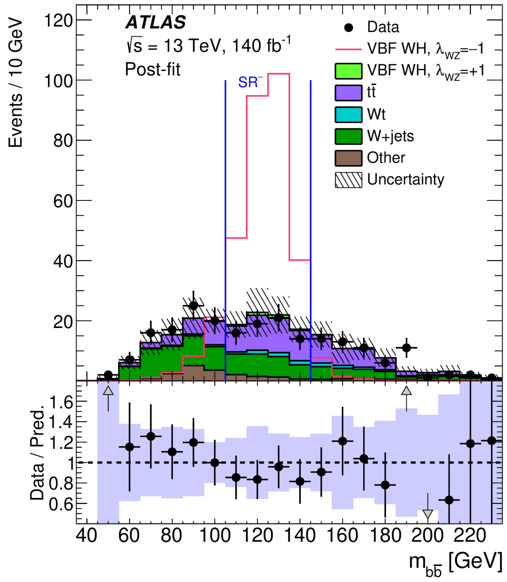
Relative sign of the HWW and HZZ couplings

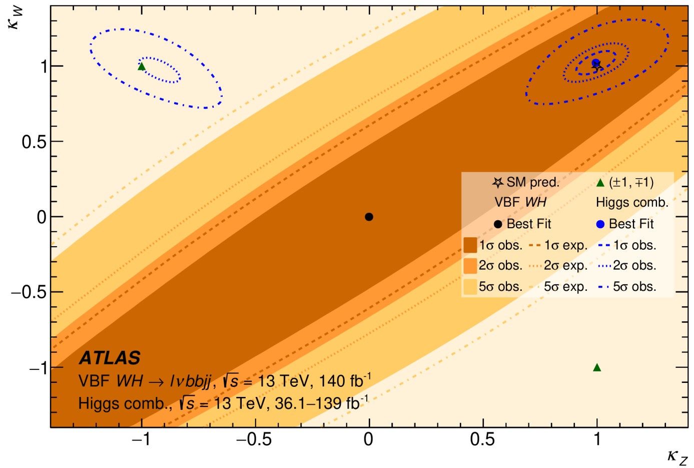
Vector boson fusion production of WH pairs disfavoured by the SM due to cancellation of two different contributions

- Could be enhanced with opposite relative sign

ATLAS Search for VBF WH production with $H \to bb$

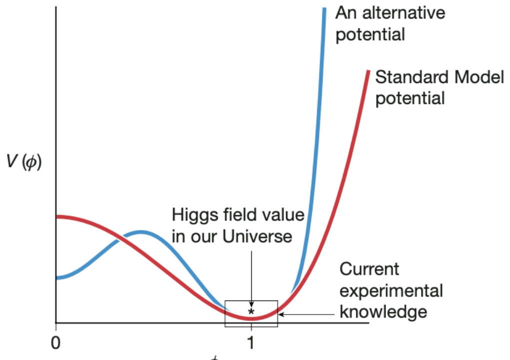






Opposite sign excluded with significance much better than 5σ

Higgs self coupling



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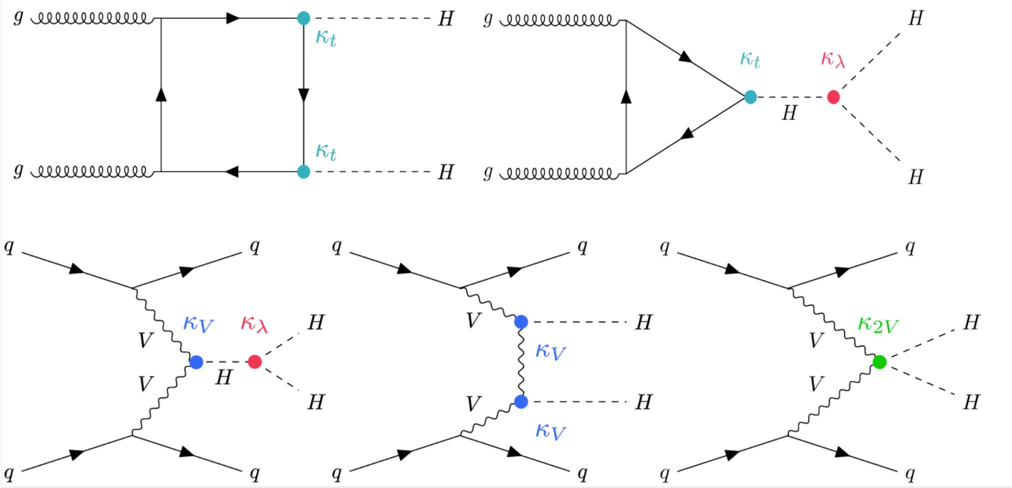
- Determine the shape of the Higgs potential

$$\frac{1}{2}m_h^2h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

- Di-Higgs production



$$\sigma_{ggF}^{SM}(pp \to HH) = 31.05\ ^{+1.9}_{-7.1}\ fb$$

(Destructive interference in the SM)

$$\sigma_{VBF}^{SM}(pp \to HH) = 1.72\ \pm 0.4\ fb$$

ATLAS-CONF-2024-006

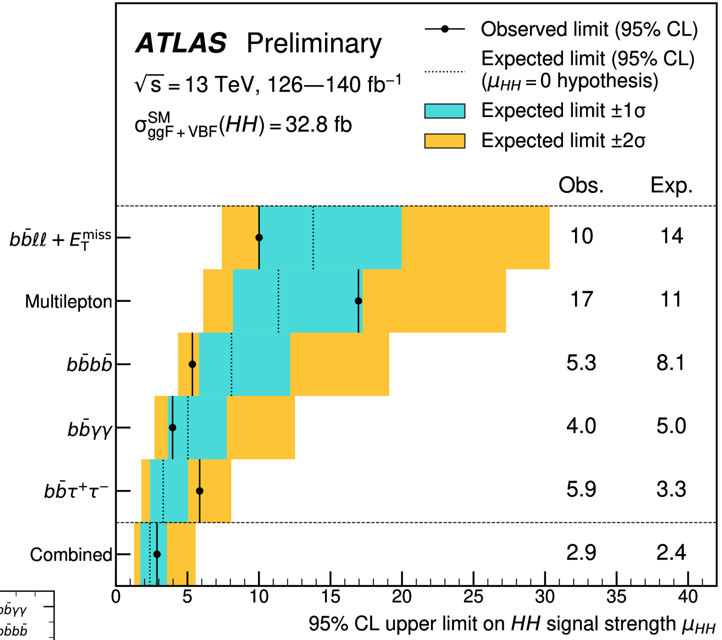
Di-Higgs production

Updated results in some channels:

- $b\bar{b}\gamma\gamma$: obs (exp) 95% CL limit on μ_{HH}: $4\sigma\ (5\sigma)$
- $b\bar{b}\tau^{+}\tau^{-}$: obs (exp) 95% CL limit on μ_{HH}: $5.9\sigma\ (3.2\sigma)$

ATLAS di-Higgs search combination with Run 2 data:

- Using $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, multilepton and $b\bar{b}\ell\ell + E_T^{miss}$

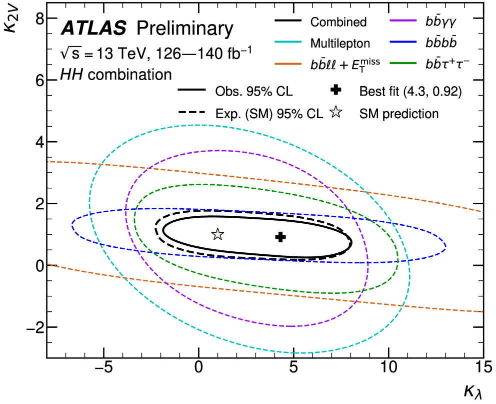


Observed 95% CL constraints

Best expected sensitivity in κ_λ

$$-1.2 < \kappa_\lambda < 7.2$$

$$0.57 < k_{2V} < 1.48$$



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EFT interpretation of Higgs measurements

Search for CP-Violating Higgs couplings

Searches for new Physics

arXiv:2402.05742

EFT interpretations of the Higgs measurements

Effective Field Theory interpretation

- Extend the SM Lagrangian with additional operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

c_i = Wilson coefficients

$\mathcal{O}^{(n)}$= operator of dimension n

Λ = new physics scale

- Calculate cross-sections: $\sigma_{\mathrm{SMEFT}} = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}},$
- To reduce perturbative QCD uncertainties, use ratios:

$$\sigma^{i}_{\mathrm{SMEFT}} = \sigma^{i,((\mathrm{N})\mathrm{N})\mathrm{NLO}}_{\mathrm{SM}} \times \left(1 + \frac{\sigma^{i,(\mathrm{N})\mathrm{LO}}_{\mathrm{int}}}{\sigma^{i,(\mathrm{N})\mathrm{LO}}_{\mathrm{SM}}} + \frac{\sigma^{i,(\mathrm{N})\mathrm{LO}}_{\mathrm{BSM}}}{\sigma^{i,(\mathrm{N})\mathrm{LO}}_{\mathrm{SM}}}\right)$$

ATLAS EFT interpretation:

- Measurements from 17 different papers from all channels used in the combination
- Using ~50 dimension-6 CP-even dominant coefficients

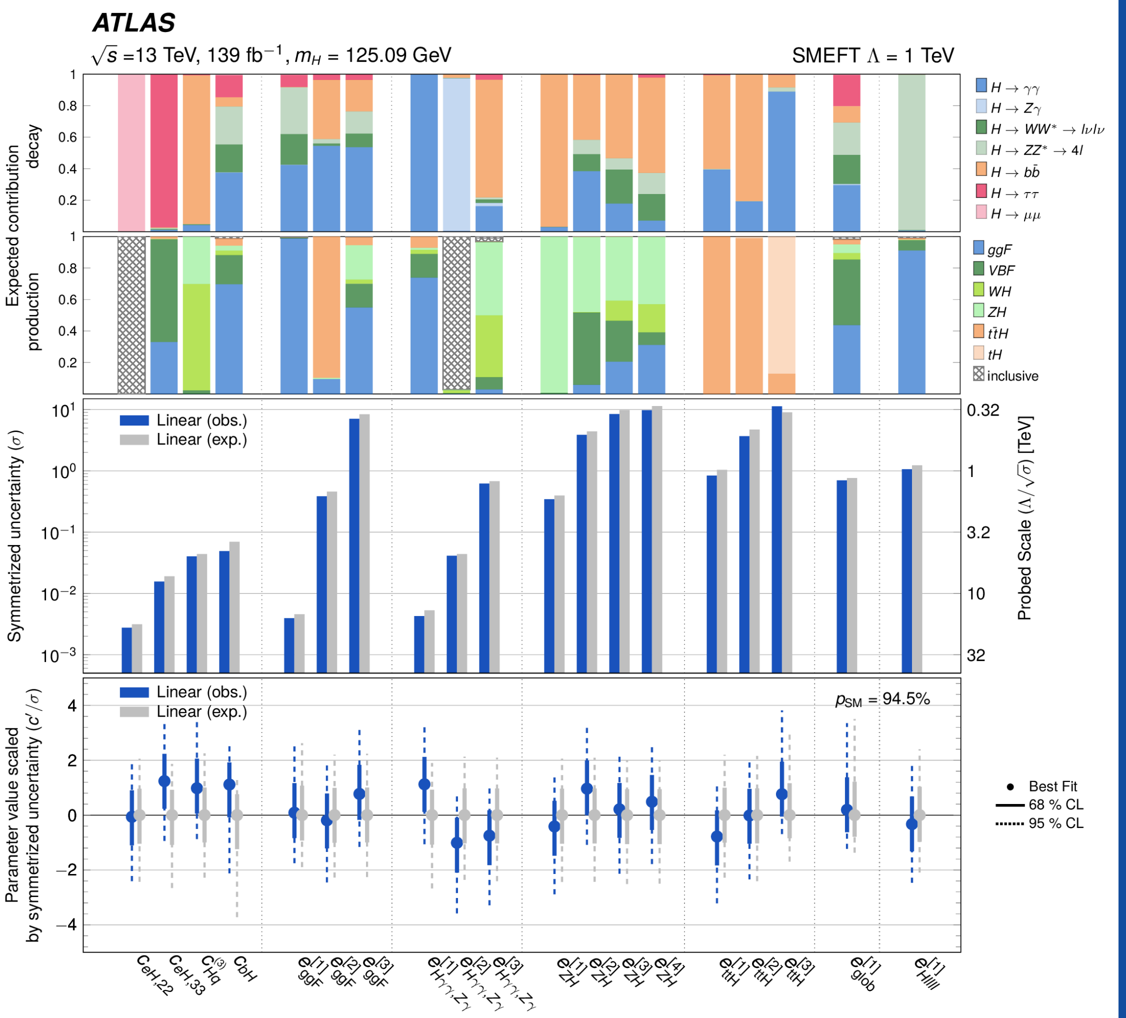
ATLAS EFT Higgs interpretation

Linearised model

Compatibility with the SM = 94.5%

Most parameters still dominated by statistical uncertainties

- But systematics might go up to 50% in some cases



Searching for CP Violation in the Higgs sector

Barion asymmetry of the Universe: still a mystery

Combined results demonstrated H to be mainly CP-even scalar

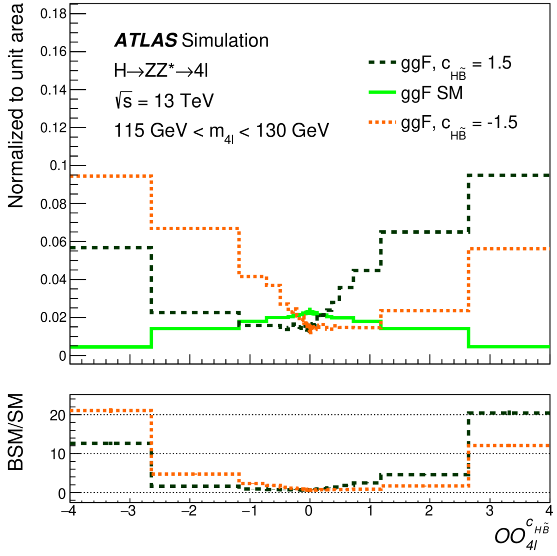
- There is still room for CP violation in the Higgs couplings

Searching for CP-odd components in the Higgs couplings

- Using CP-sensitive observables
  - Angular variables
  - Optimal observable: $OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$

Example OO in $H \to ZZ^* \to 4\ell$

JHEP 05 (2024) 105

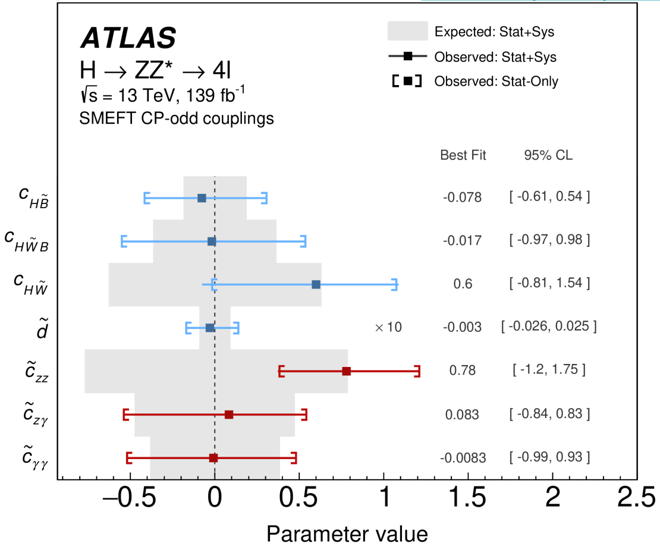


$$\sigma \sim |\mathcal{M}_{SM} + \mathcal{M}_{CP-odd}|^2 = |\mathcal{M}_{SM}|^2 + |\mathcal{M}_{CP-odd}|^2 + 2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})$$

Searching for CP Violation in the Higgs sector

Couplings involving vector bosons

$H \to ZZ^* \to 4\ell$ JHEP 05 (2024) 105

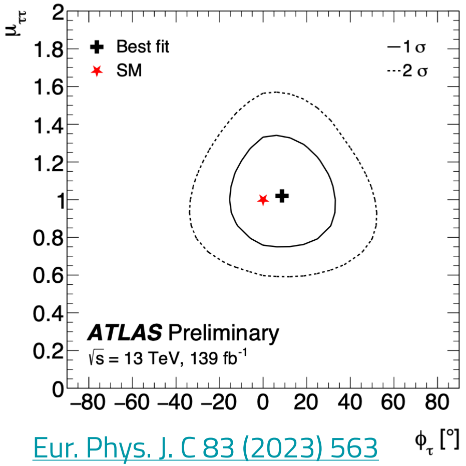


Yukawa couplings

- Typically parameterized with a mixing angle
- $$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

$H \to \tau\tau$

Using angular observables



Eur. Phys. J. C 83 (2023) 563

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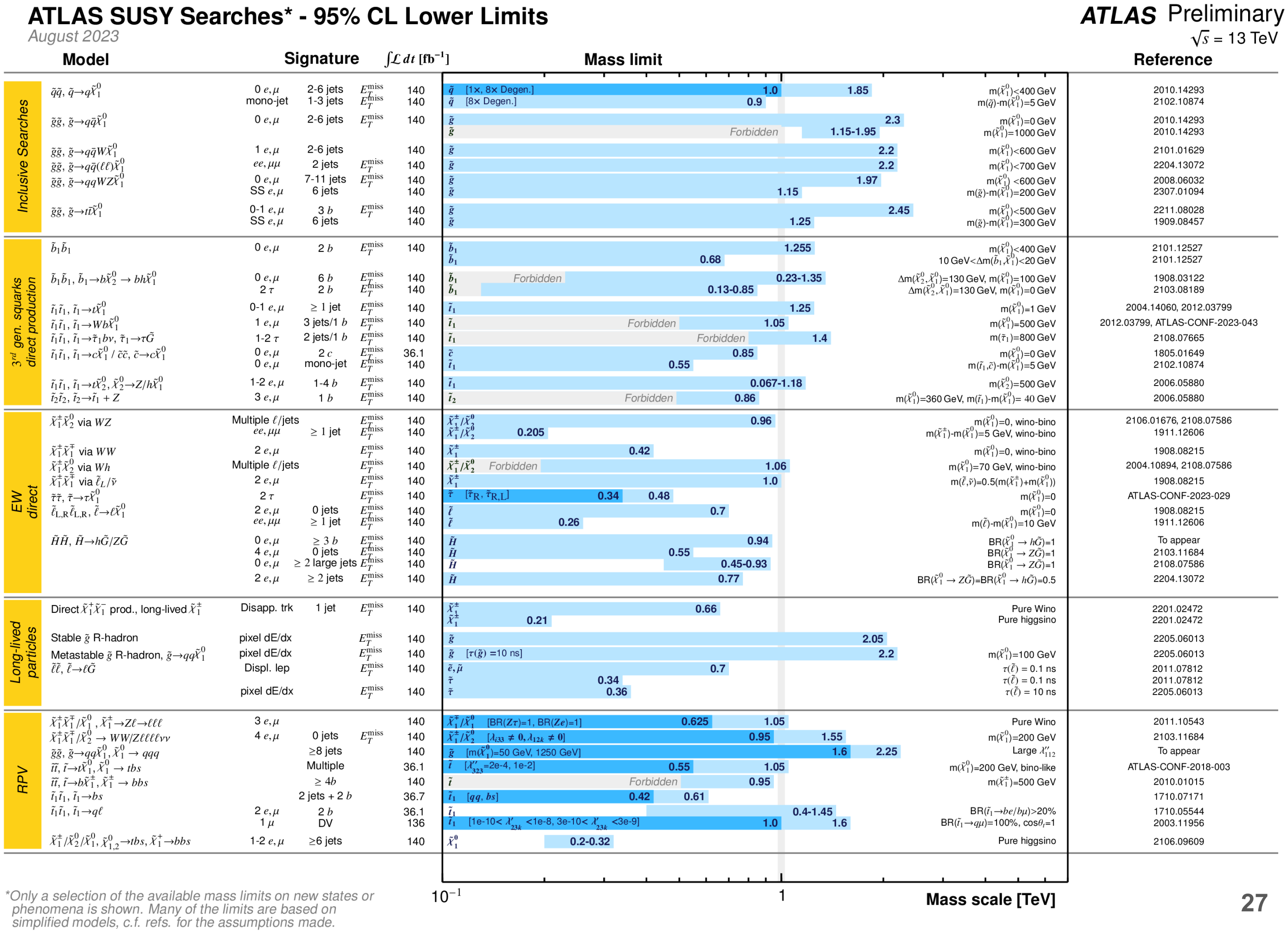
ATL-PHYS-PUB-2023-025

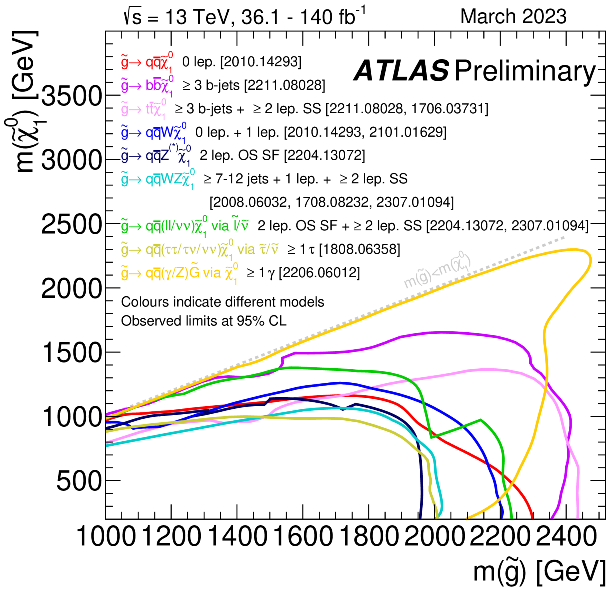
Searches for SUSY Particles

Nothing observed up to now…

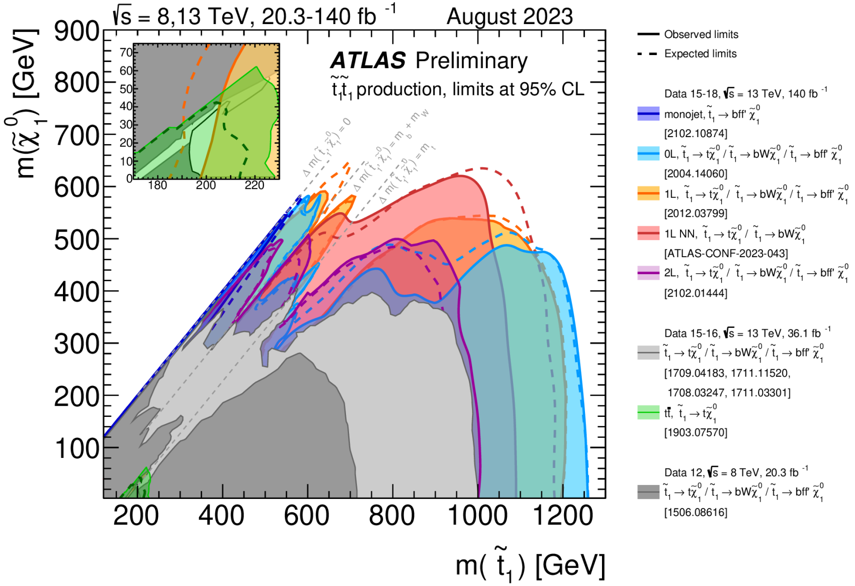


Selected Summary Results from SUSY Searches

Limits from simplified models featuring the decay of the gluino to the lightest supersymmetric particle



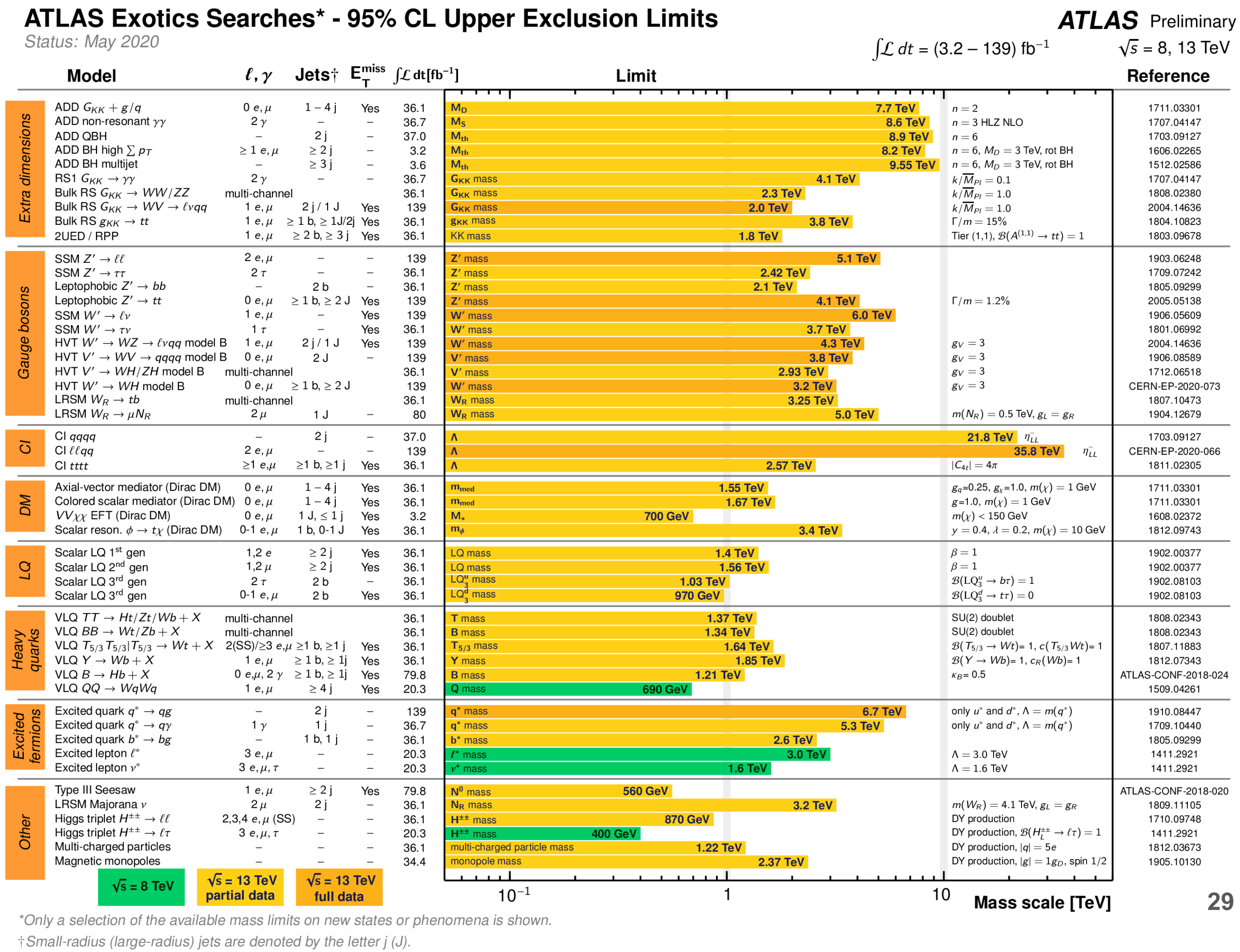
Searches for top squark (stop) pair production



Search for Exotic Particles

Nothing either…

[ATLAS Exotics Summar Plots]



Search for Dark Matter

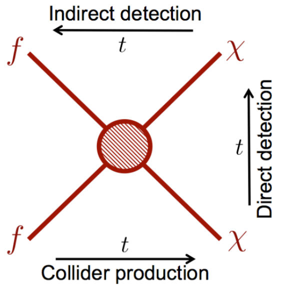
There is compelling cosmological evidence for the existence of Dark Matter

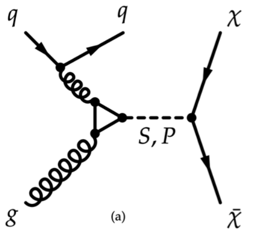
- Yet, we don't know anything about it

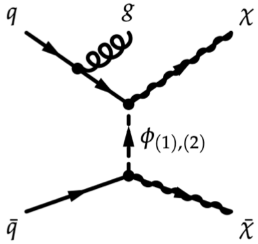
Searches at colliders are complementary to direct/indirect observations

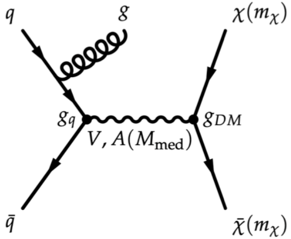
Simplified models

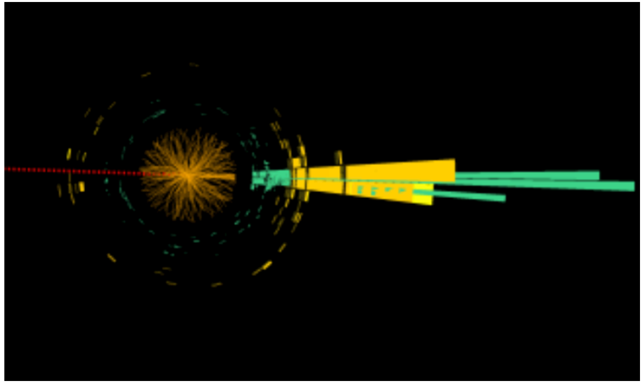
- DM assumed to be a Dirac fermion WIMP χ
- New particle mediator coupling χ to the SM
- Minimal set of parameters $\{M_{med}, m_\chi, g_\chi, g_q, g_\ell\}$







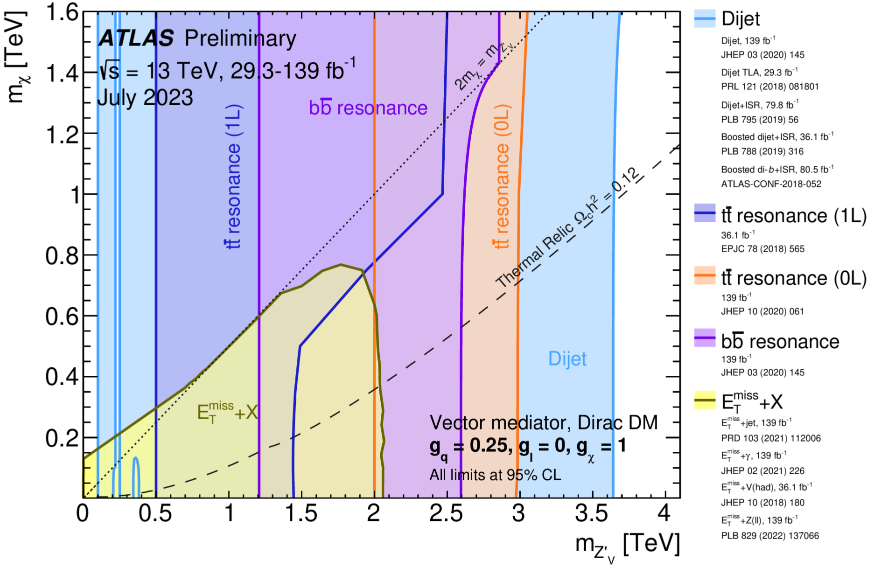




Dark matter searches

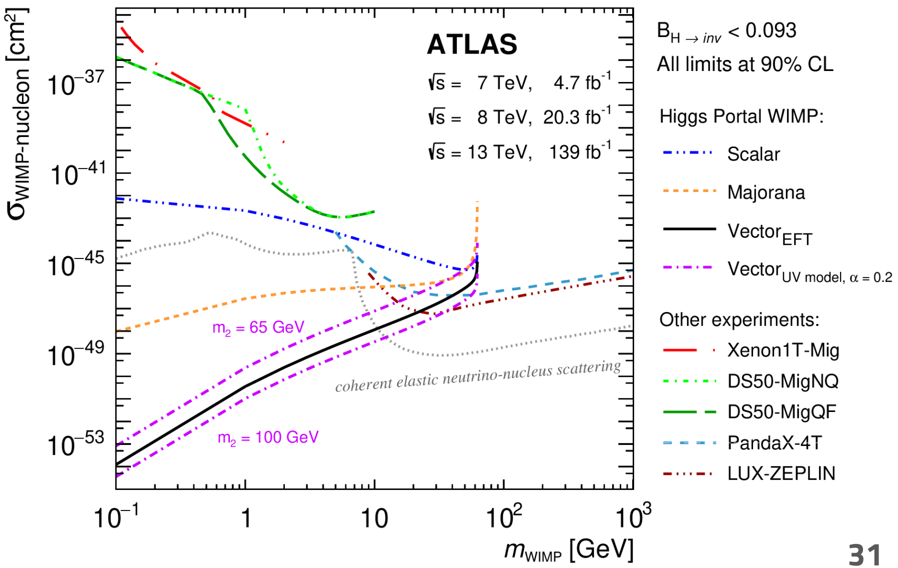
Few selected results

95% CL exclusion limits for DM leptophobic vector mediator simplified models



Higgs Portal WIMP

90% CL limits from $H \rightarrow invisible$ decays



Summary and conclusions

ATLAS is exploiting the Run 1, Run 2 and Run 3 pp collisions data with a comprehensive physics programme

- Standard Model measurements
- Searches for new physics

Measurements of the Higgs Boson are probing the Standard Model prediction and constraining new physics models

Direct searches for new physics have not yet shown any evidence for new particles

However the HL-LHC period will provide a 10 fold increase in statistics

- Increased precision and sensitivity to new physics

Thanks!

Acknowledgments:

REPÚBLICA PORTUGUESA

FCT Fundação para a Ciência e a Tecnologia

ATLAS Search for low mass $\gamma\gamma$ resonances