Overview of ATLAS and CMS results at the LHC

IAS 2024 conference

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On behalf of the the ATLAS and CMS collaborations

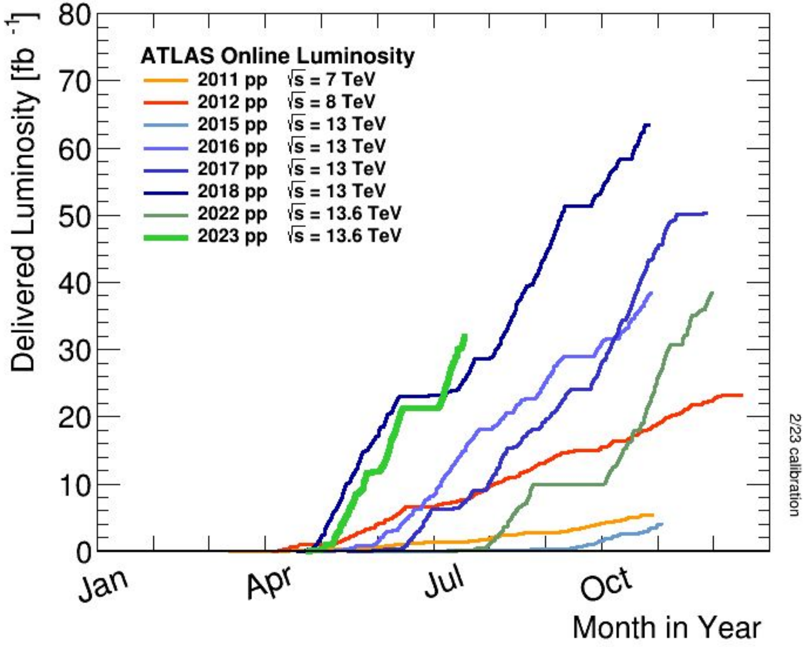
22nd January 2024

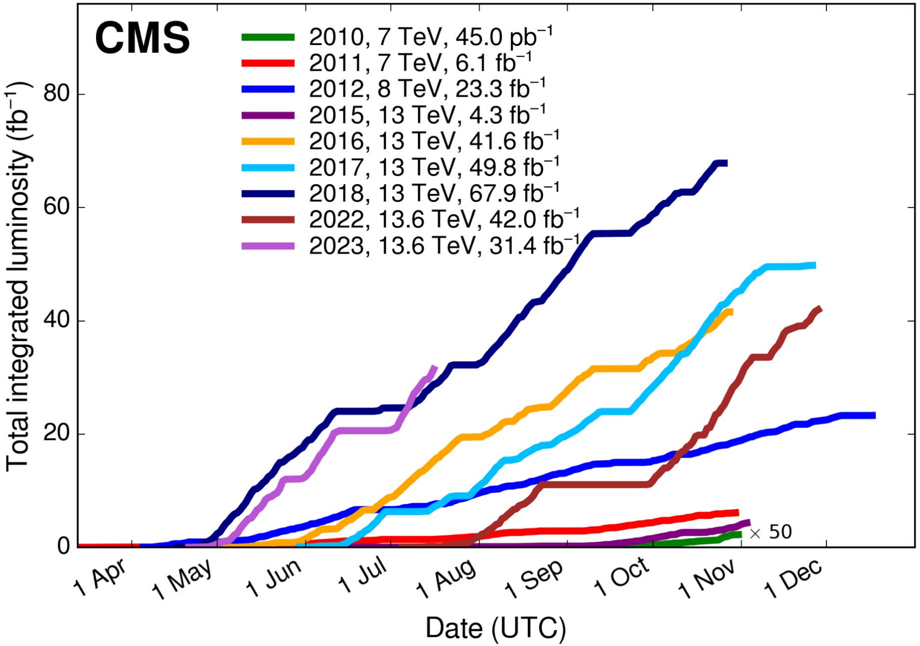
Introduction

- ATLAS and CMS have a broad and ambitious physics programme
    - Determine fundamental parameters of the SM with high precision
    - Measure rare SM processes for the first time
    - Direct and indirect searches for new physics
        - Probe for new particles and interactions at the **multiple-TeV scale**
- Had many interesting physics results in recent years at the LHC
    - Presenting a selection of ATLAS & CMS results (including many personal favorites)

Lots of pp collisions at the LHC

- **Run 1 ($\sqrt{s}$ = 7-8 TeV)**
    - 5 + 20 fb^{-1} per experiment
- **Run 2 ($\sqrt{s}$ = 13 TeV)**
    - ~150 fb^{-1} per experiment





- **Run 3 ($\sqrt{s}$ = 13.6 TeV)**
    - ~70 fb^{-1} per experiment

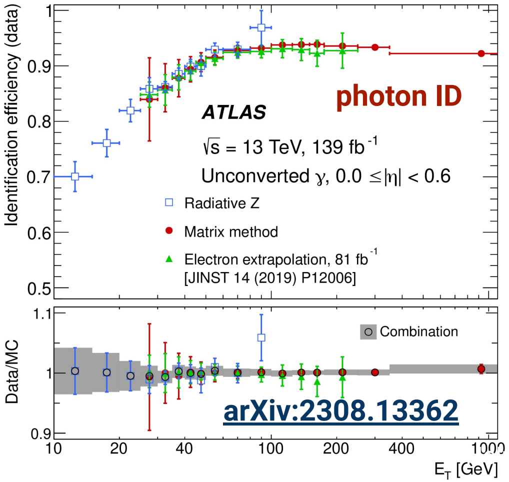
ATLAS/CMS physics programme

- Precision measurements of SM processes:
    - Higgs boson
    - Top quark
    - Vector bosons
    - QCD physics
    - B Physics and Quarkonia
- Search for rare SM processes (VVV, 4tops)
- Searches for new physics:
    - Dark matter
        - SUSY
        - Long-lived particles
    - Rare or exotic decays of SM particles
    - Extended gauge sector
    - Extended Higgs sector
- Heavy ion physics (not covered in this presentation)

Presenting a selection of recent results from the ATLAS and CMS collaboration. Additional results can be found via the **ATLAS** and **CMS** publication pages

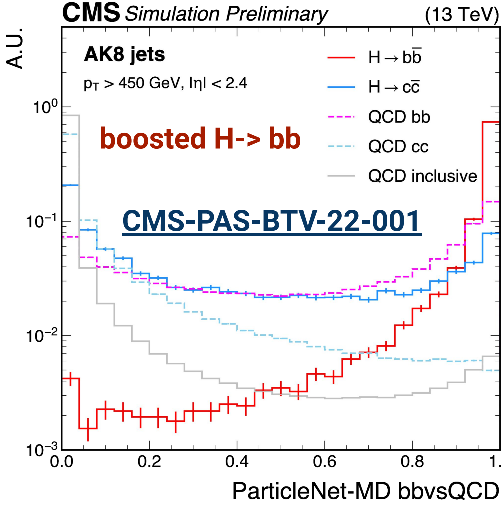
Detector performance

- Require **excellent understanding of the detector performance and high-performant object ID** to carry out high-precision measurements and BSM searches
  - A lot of effort is put into improving understanding of detector and development of reconstruction/identification algorithms



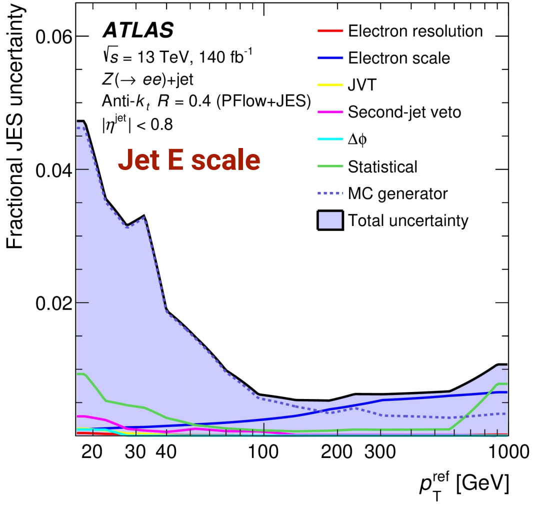
photon ID

arXiv:2308.13362



boosted H-> bb

CMS-PAS-BTV-22-001



Jet E scale

Eur. Phys. J. C 83 (2023) 761

- **New ATLAS luminosity measurements**
  - Determined with a precision of 0.83% for total Run 2 dataset [*Eur. Phys. J. C* 83 (2023) 10, 982]

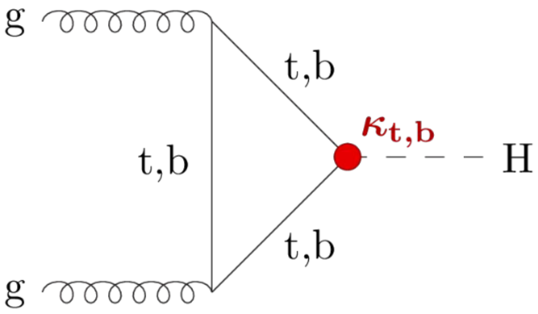
Higgs boson property measurements

- Couplings
- Mass
- Width
- Spin/CP

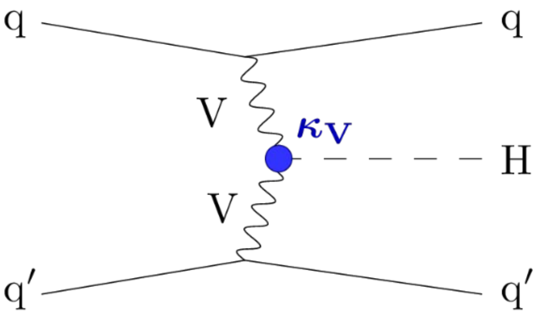
Dedicated presentation by **Chen Zhou**

Higgs boson production modes

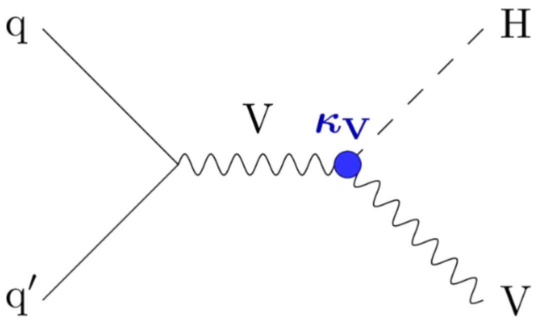
gluon fusion (86%)



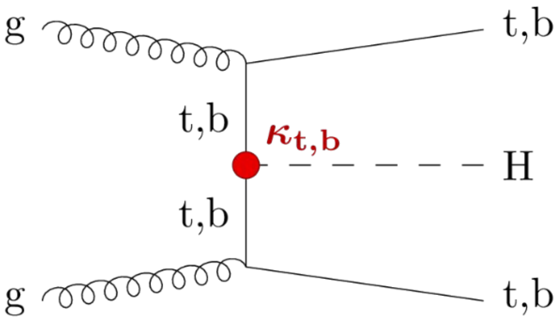
vector boson fusion (7%)



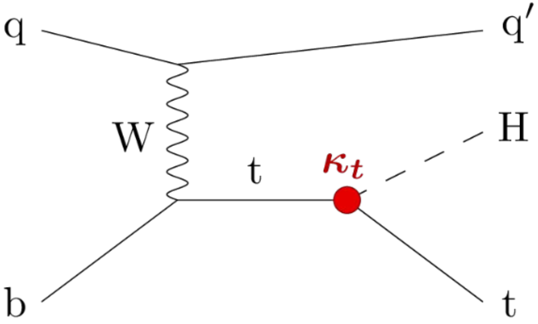
Higgs-Strahlung (5%)



ttH/bbH (~1%)



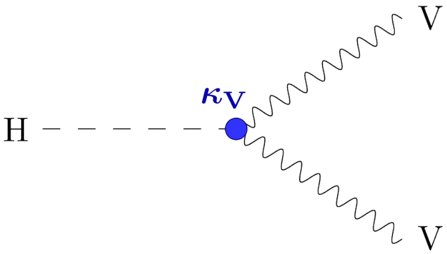
tqH (< 1%)

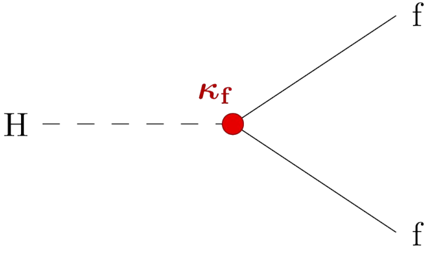


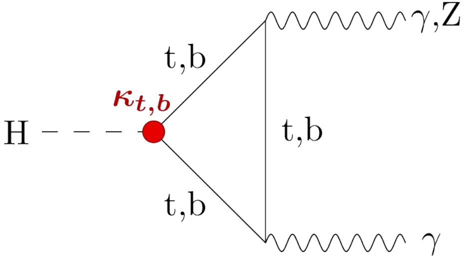
- **All main production modes are probed at the LHC**

Higgs boson decay modes

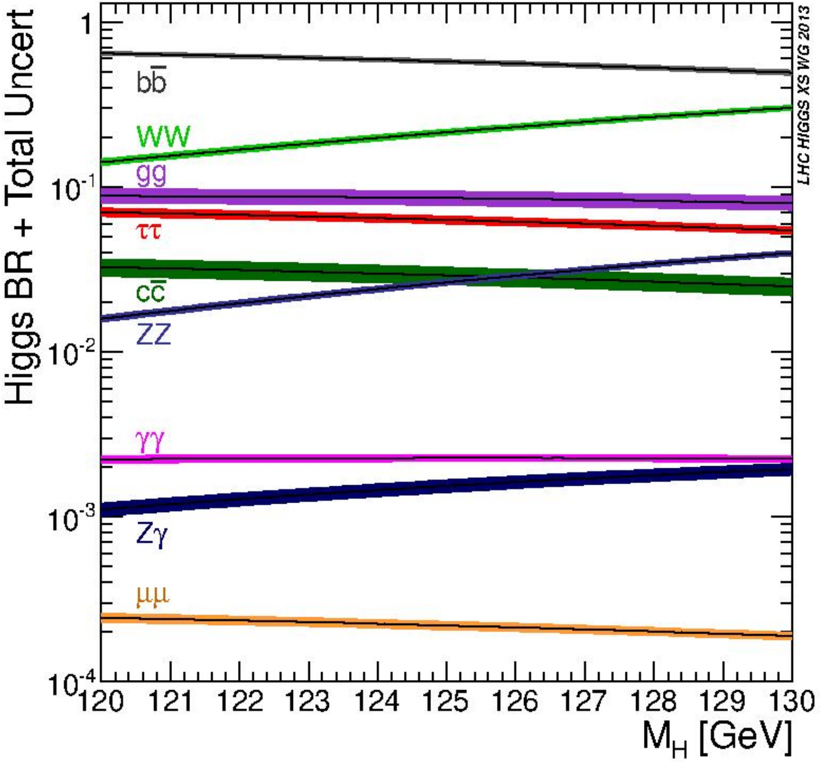
- Almost all major decay modes of the Higgs boson are studied by ATLAS/CMS







CERN Yellow Report 4

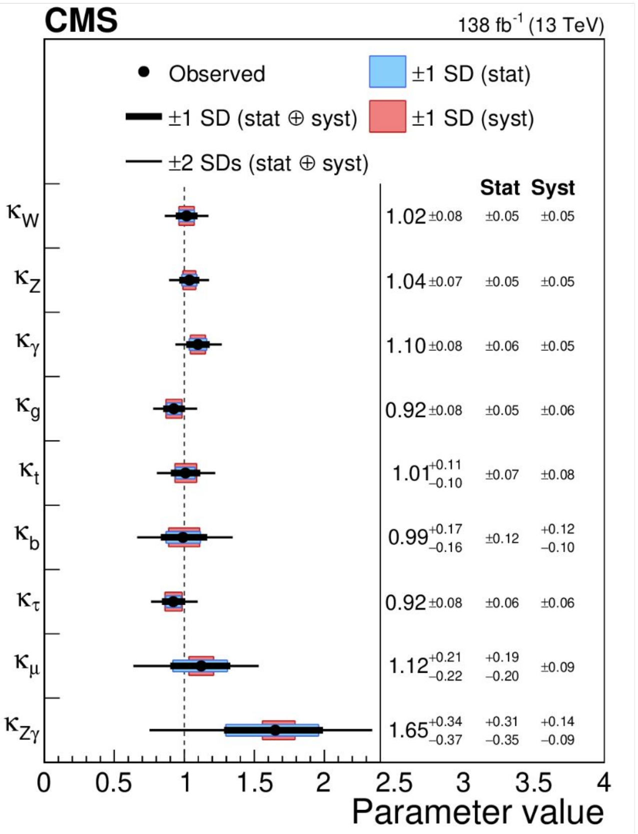


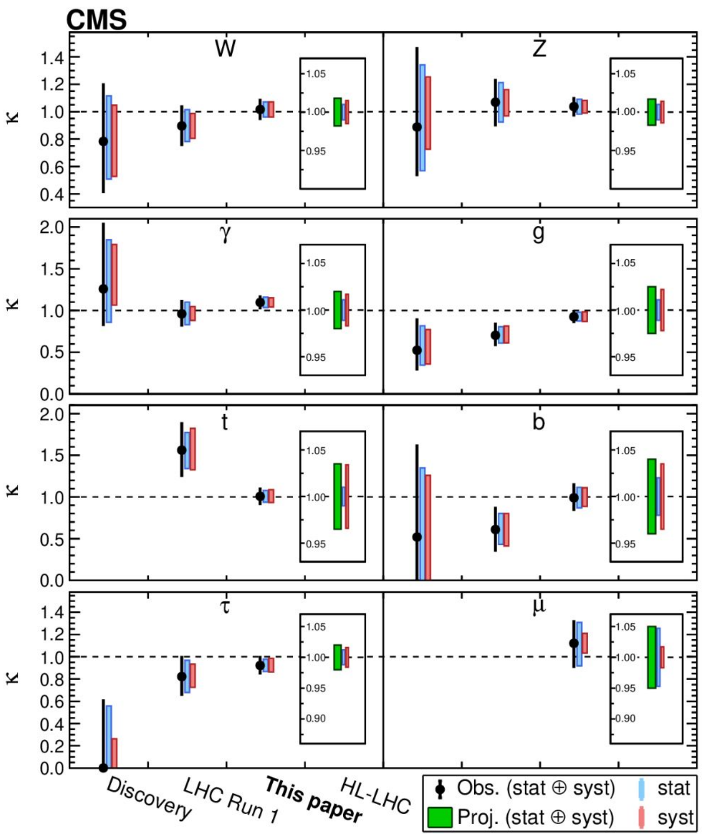
Higgs boson couplings

- **Coupling modifiers:**

$$\kappa_i = \sigma_i/\sigma_i^{SM} = \Gamma_i / \Gamma_i^{SM}$$

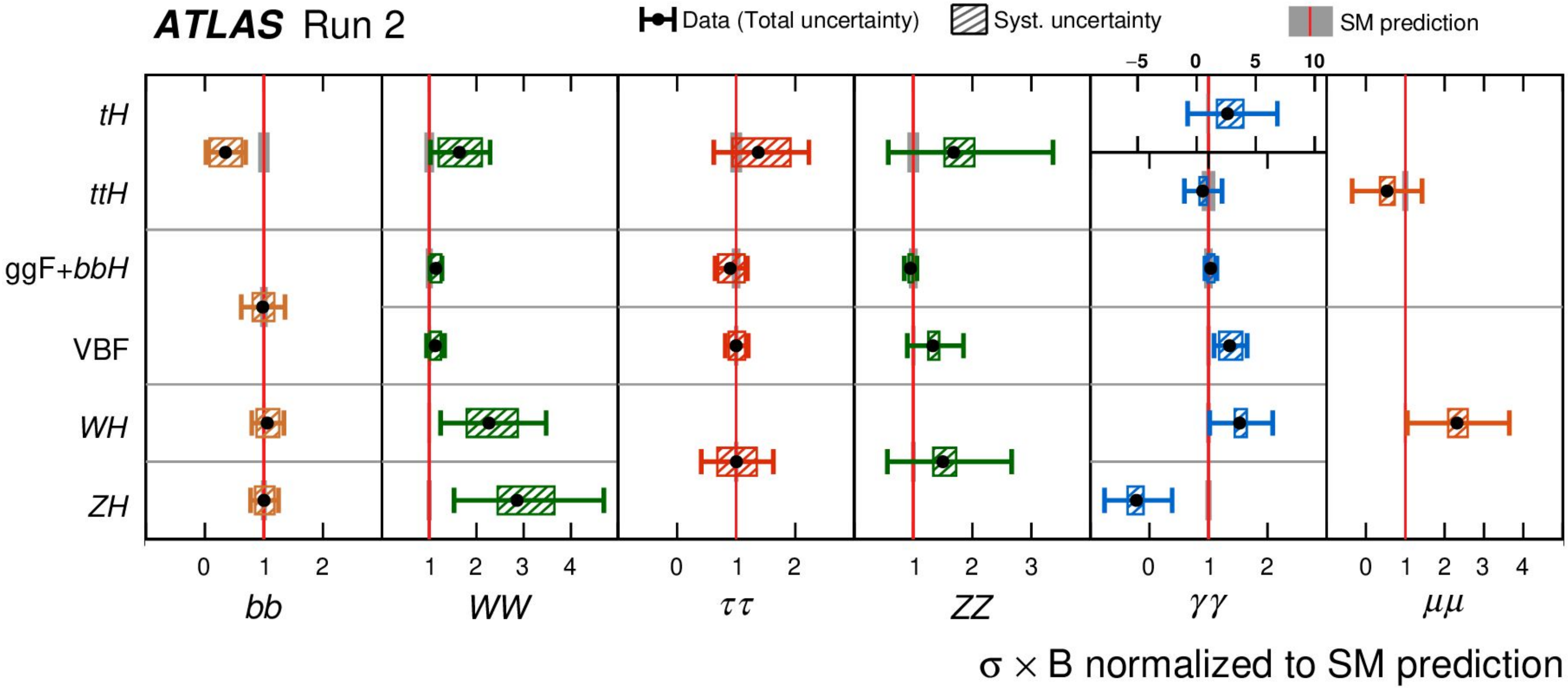
Parametrise deviations with respect to SM predictions





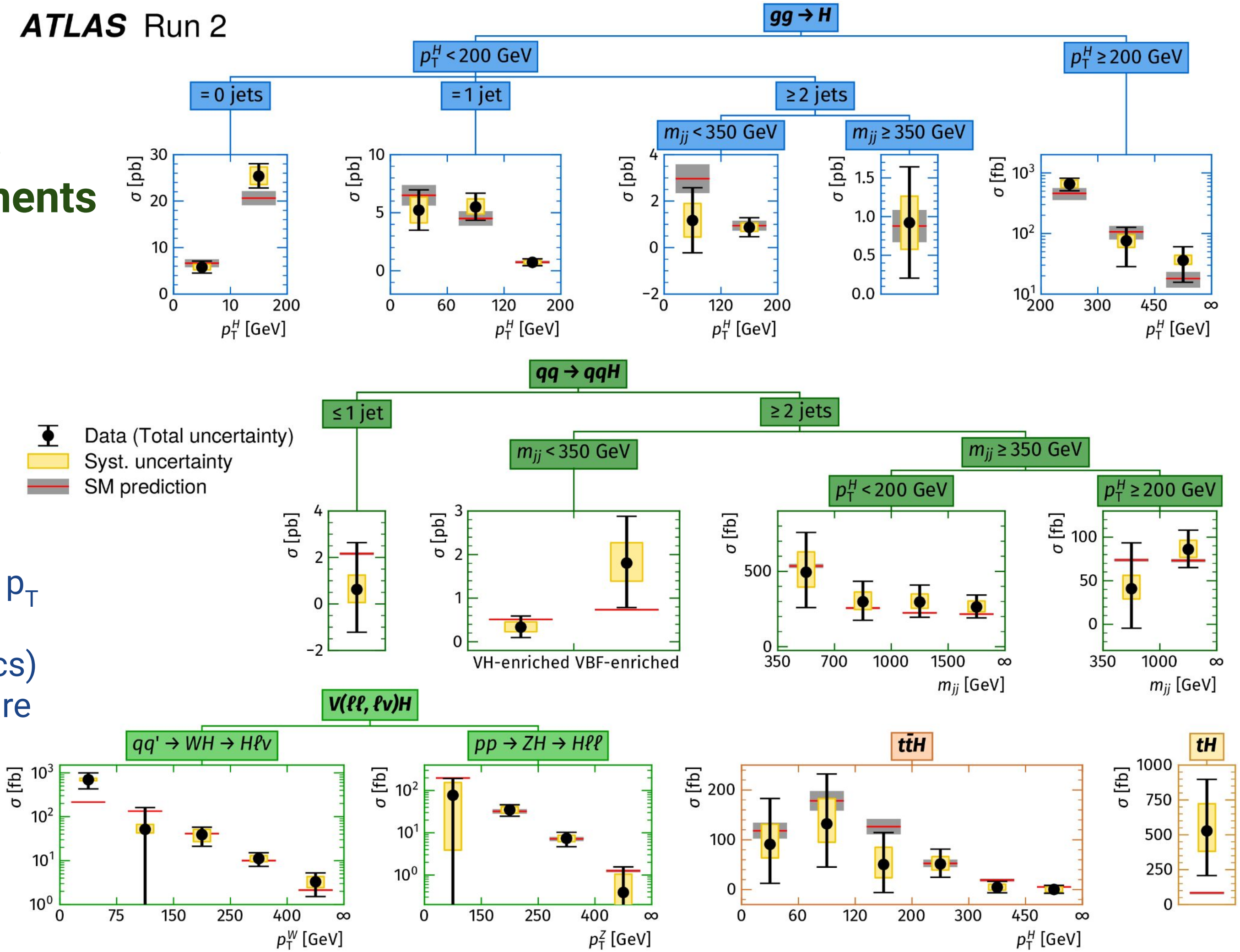
[Nature 607 (2022) 60-68](#)

Higgs boson couplings



Nature 607, 52 (2022)

- **Most recent cross section measurements in kinematic bins**

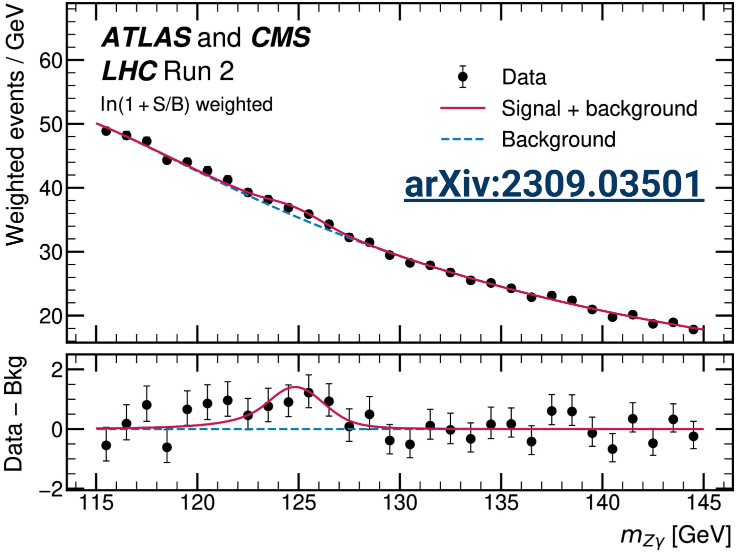


- Shifting focus towards measurements at high p_T (which are particularly sensitive to new physics) and observables that are CP-sensitive

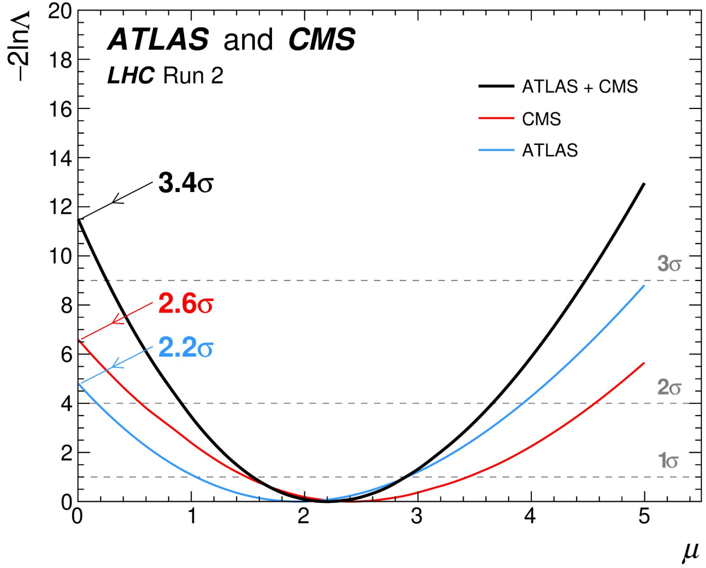
Nature 607, 52 (2022)

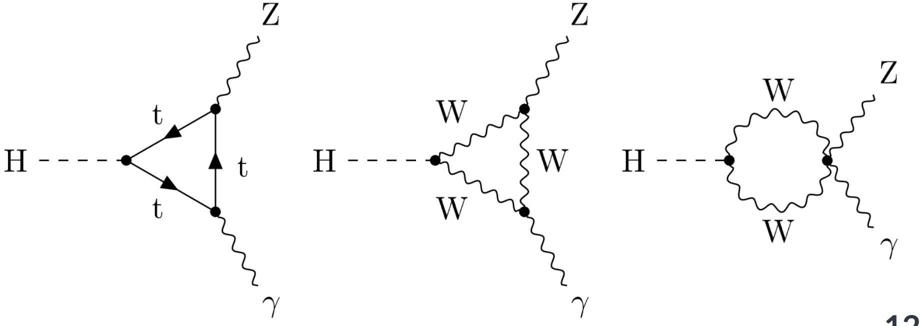
First evidence for the Higgs boson decay to a Z boson and a photon

- Combined search by ATLAS and CMS
  - Obtain statistical significance of 3.4σ, while a significance of 1.6σ was expected
  - Signal yield is 2.2 ± 0.7 times the SM prediction
    - Agrees with the expectation within 1.9σ



arXiv:2309.03501

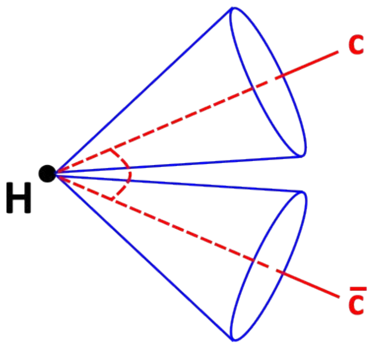




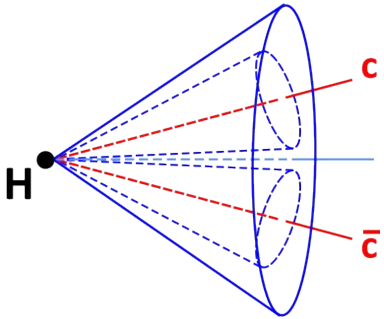
Search for boosted Higgs boson decays to charm quark pairs

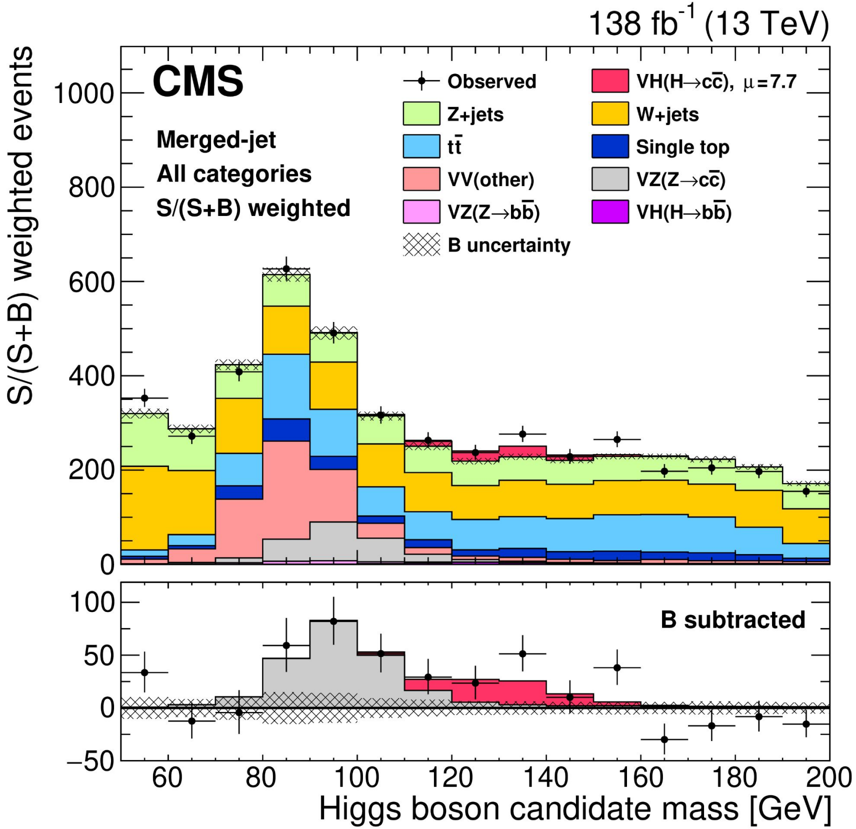
- Higgs decay to charm quarks was long considered to be inaccessible at the LHC.
- Recent developments by CMS give us hope to find this decay mode after all.
  - **Merged H→ cc decay** channel is the most sensitive
  - **ParticleNet algorithm** exploits information of charged particle tracks

Resolved



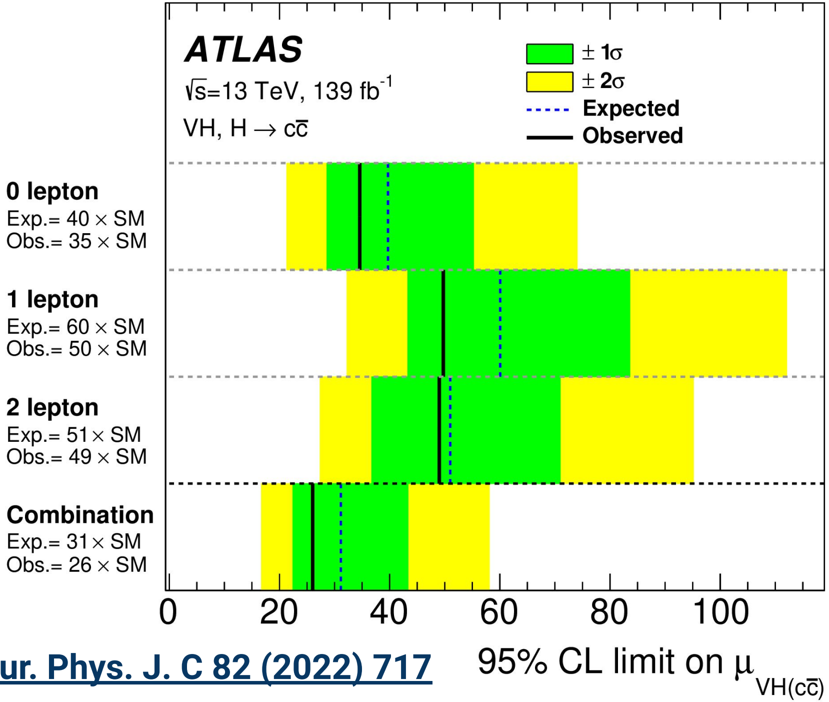
Merged



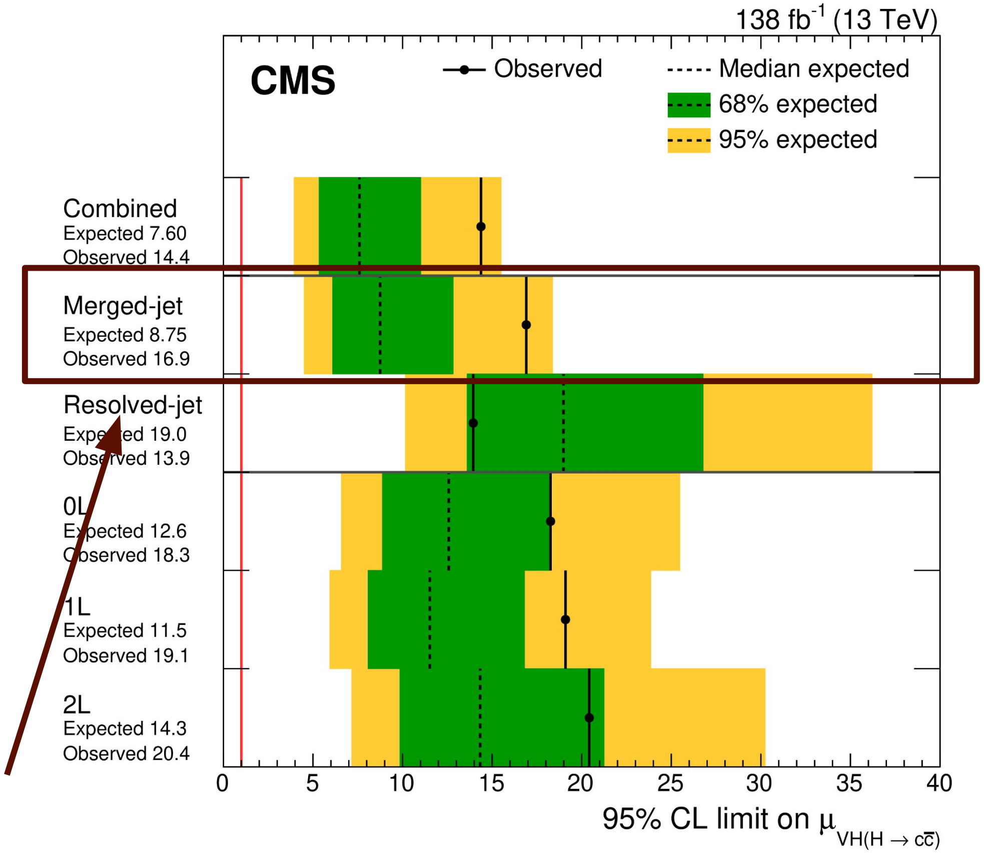


Phys. Rev. Lett. 131 (2023) 061801

Searches for Higgs boson decays to charm quark pairs



[Eur. Phys. J. C 82 (2022) 717]



[Phys. Rev. Lett. 131 (2023) 061801]

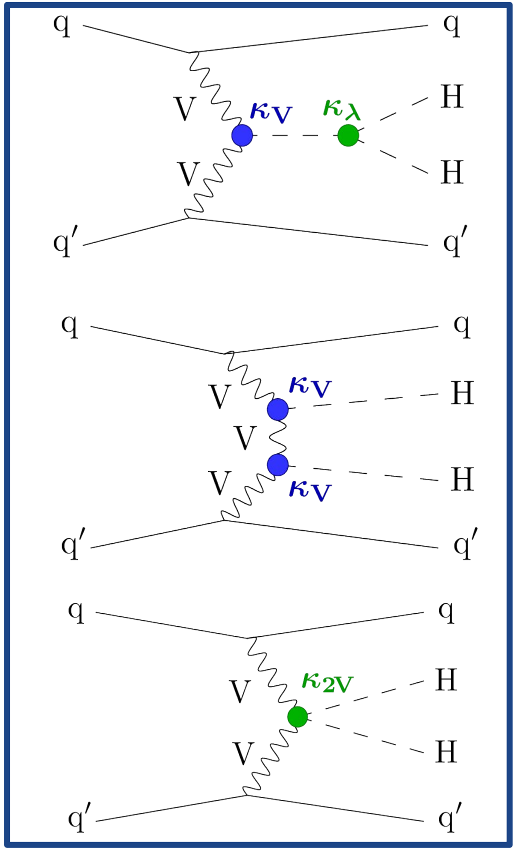
- **Impressive demonstration that its always worth to invest time in the development of novel reconstruction techniques**

Searches for Higgs boson pair production

- Higgs boson pair production is sensitive to **self-interaction strength λ**
- Define self-interaction strength modifier:

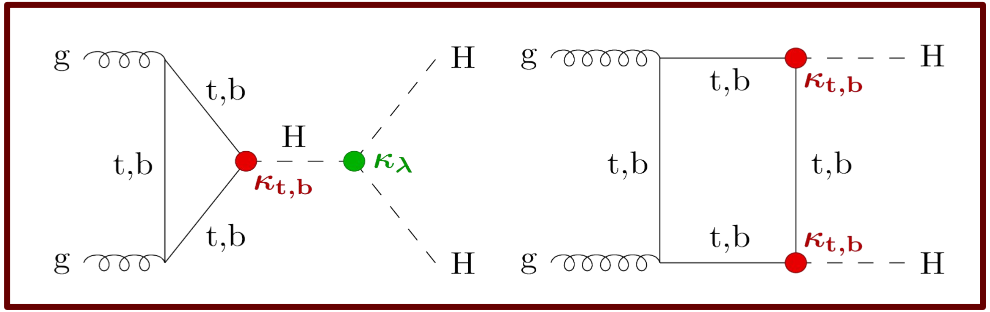
$$\boxed{\kappa_\lambda = \frac{\lambda_{\text{measured}}}{\lambda_{SM}}}$$

vector boson fusion production



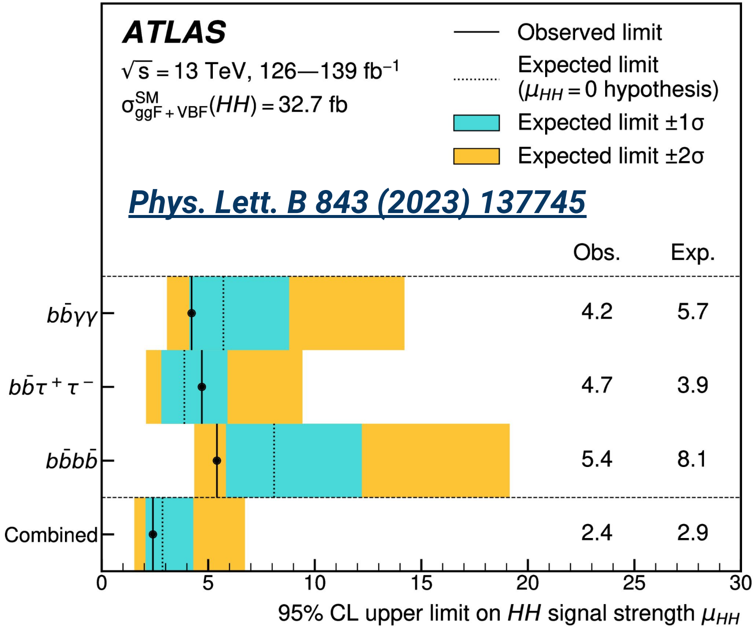
Pair production cross section is three orders of magnitude smaller than the single Higgs boson cross section.

gluon fusion production

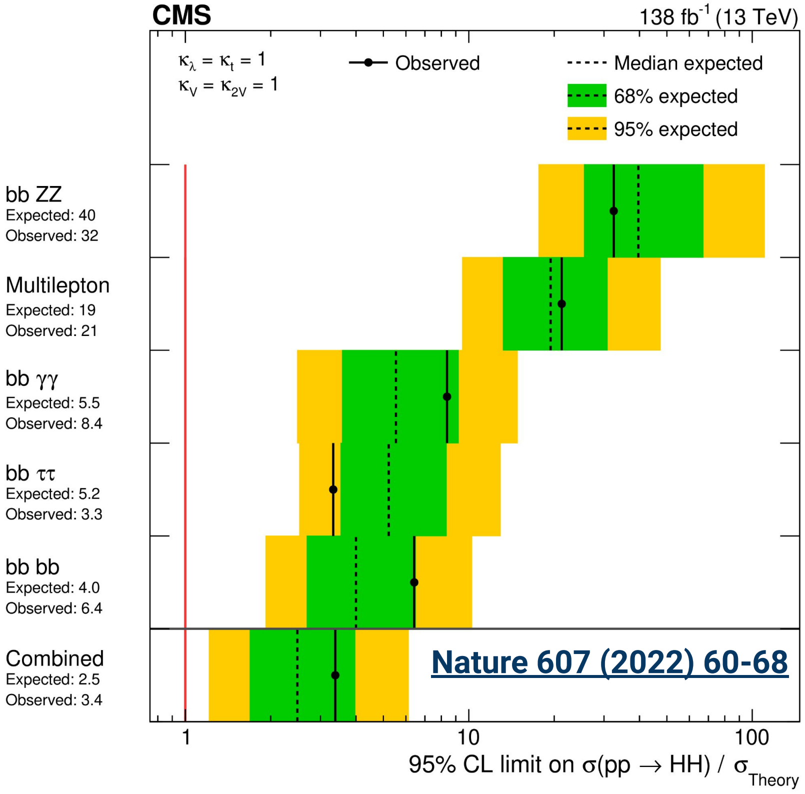


Searches for Higgs boson pair production

Most recent limits on pair production cross section



Phys. Lett. B 843 (2023) 137745



Nature 607 (2022) 60-68

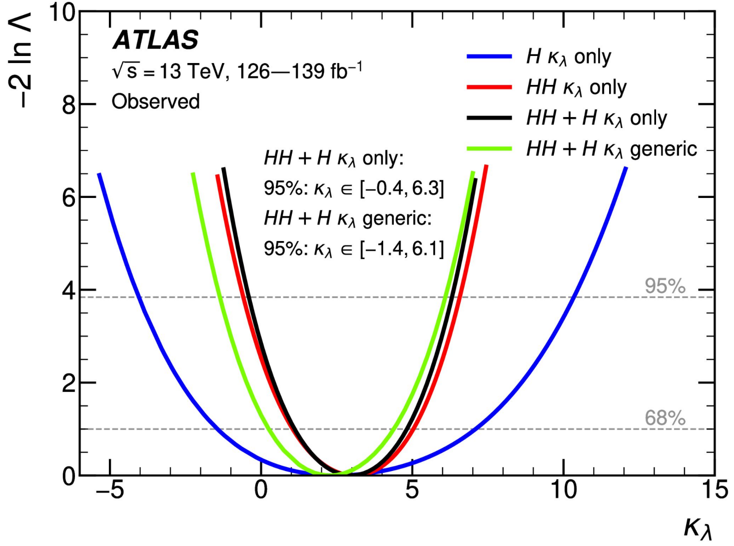
- New/updated HH results by ATLAS:
  - **Multi-lepton** (WW, ZZ): 9.7obs (16.2exp) [arXiv:2310.11286]
  - **bbγγ:** 4.0obs (5.0exp) [arXiv:2310.12301]
  - **bbττ:** 5.9obs (3.1exp) [ATLAS-CONF-2023-071]

Run 2 constraints are significantly better than what was predicted 10 years ago

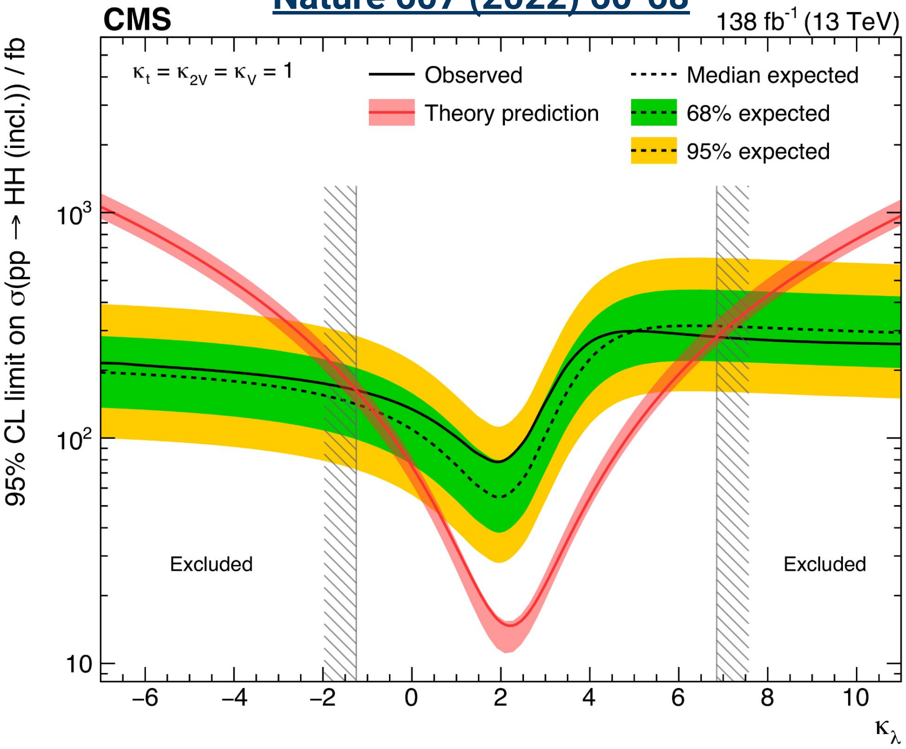
Constraints on Higgs boson self-interaction strength

ATLAS observed (expected) at 95% CL:
−0.4 (−1.9) < κ_λ < 6.3 (7.6)

Phys. Lett. B 843 (2023) 137745



Nature 607 (2022) 60-68



New/updated HH results by ATLAS:

- **bbγγ:** −1.4 (−2.8) < κ_λ < 6.9 (7.8) [arXiv:2310.12301]
- **bbττ:** −3.2 (−2.5) < κ_λ < 9.1 (9.2) [ATLAS-CONF-2023-071]
- **Multi-lepton** (WW, ZZ): −6.2 (−8.1) < κ_λ < 13.3 (15.5) [arXiv:2310.11286]

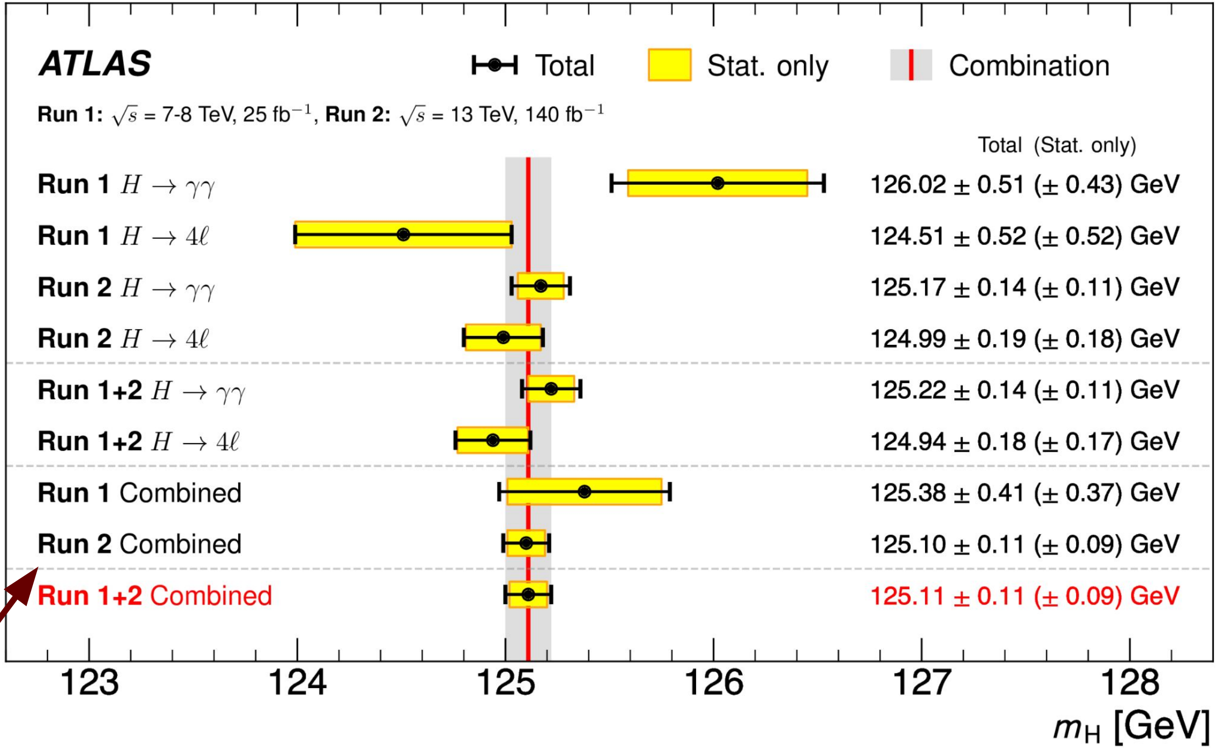
CMS observed: **−1.24 < κ_λ < 6.49**

Higgs boson mass measurement

- Latest combination of CMS results from **H→γγ** and **H→ZZ*→4ℓ** measurements (2016 + Run 1):

$$125.38 \pm 0.14\ (\pm 0.11)\ \text{GeV}$$

[Phys. Lett. B 805 (2020) 135425]



[Phys. Rev. Lett. 131 (2023) 251802]
[Eur. Phys. J. C 83 (2023) 686]
[arXiv:2309.05471]

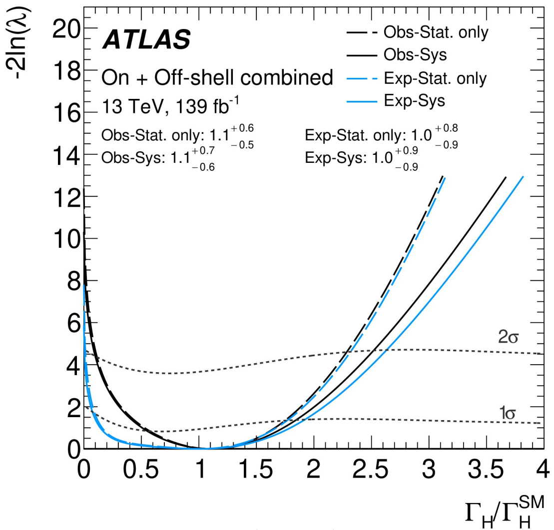
- **Most precise Higgs boson mass measurement to date**
  - Thanks to outstanding work on μ/e/γ energy calibrations

Higgs boson width

Nat. Phys. 18 (2022) 1329

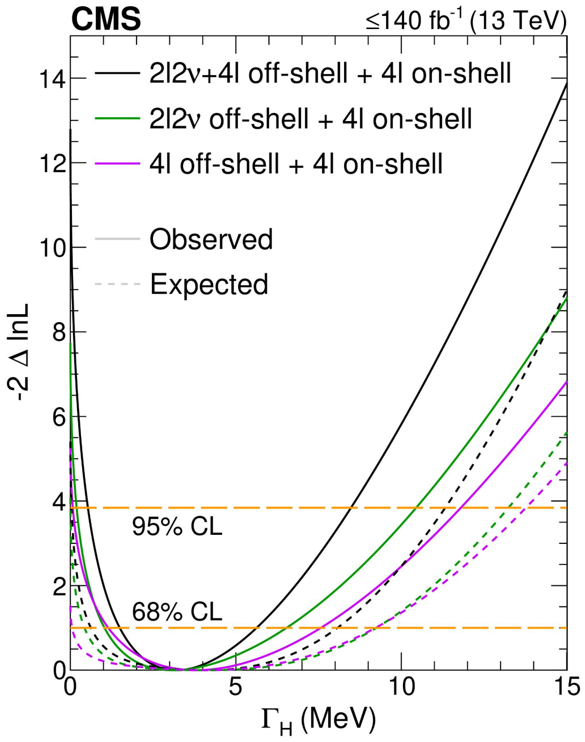
- ATLAS and CMS have both found evidence for off-shell production
- Assuming identical coupling between on-shell and off-shell productions:

$$\boxed{\Gamma(H) = (\mu_{\text{off-shell}}/\mu_{\text{on-shell}})\ \Gamma_{SM}(H)}$$



ATLAS: $\Gamma_H = 4.6^{+2.6}_{-2.5}\,\text{MeV}$

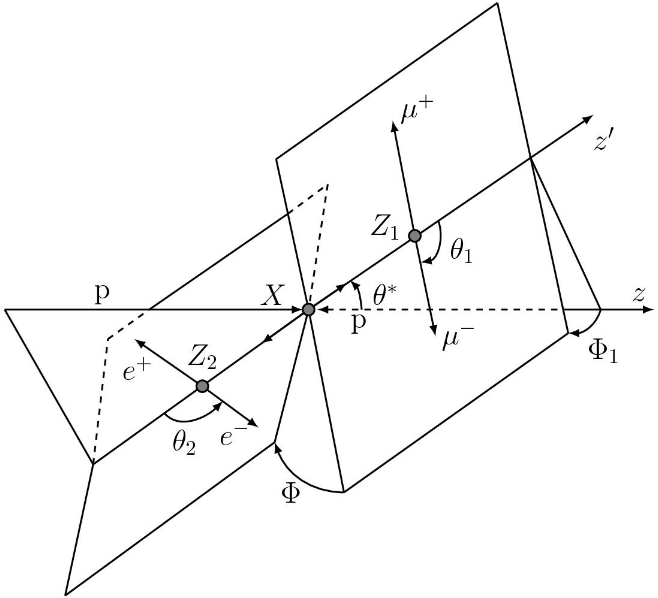
CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}\,\text{MeV}$

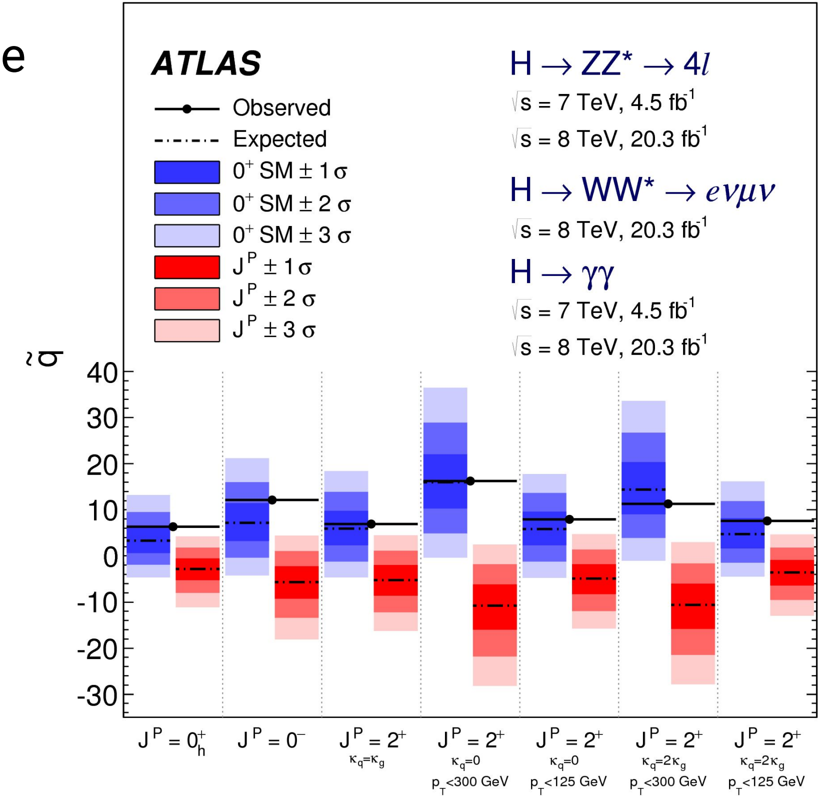


Phys. Lett. B 846 (2023) 138223

Spin/CP

- Studies of Higgs boson decay products have strongly hinted that spin/CP of the Higgs boson is $J^P = 0^+$
    - Alternative hypotheses have been excluded at more than 99.9% C.L.



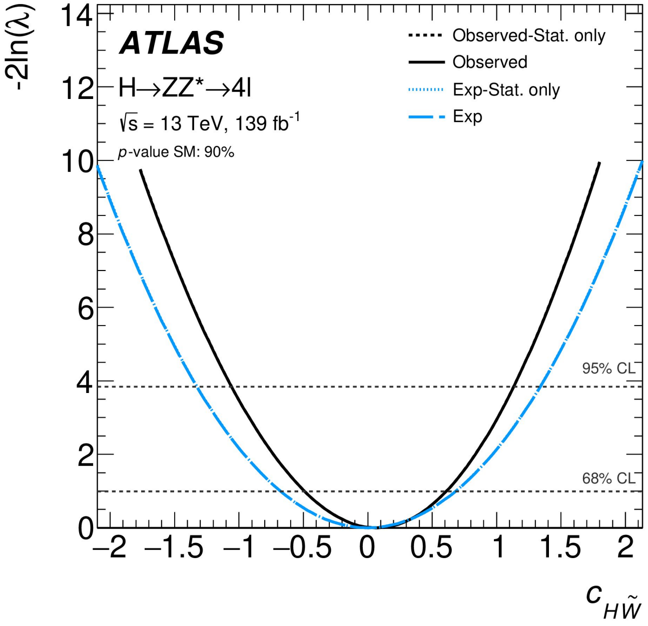


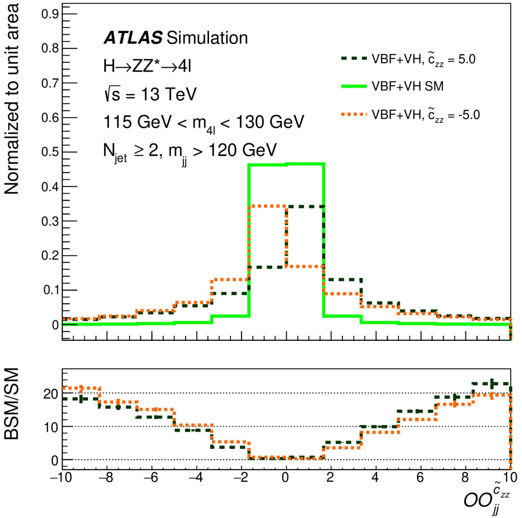
Eur. Phys. J. C 75 (2015) 476

Spin/CP

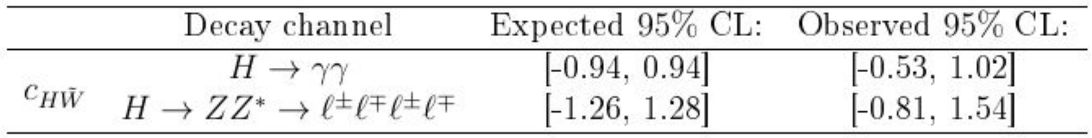
- Run 2 analyses focus on production vertices
  - Study particles produced in association to the Higgs boson (**VBF/VH** modes)
  - Probe **Optimal Observable:**

$$\boxed{OO = 2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP-odd}})/|\mathcal{M}_{\mathrm{SM}}|^2}$$





- Set constraints on dim-6 operators modulating the HVV coupling

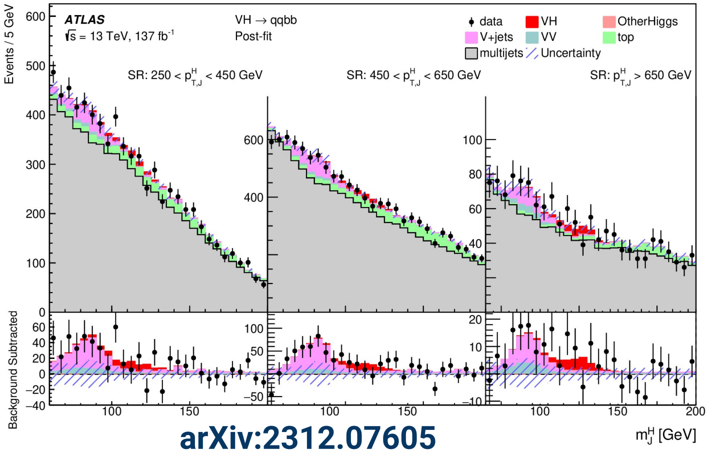


	Decay channel	Expected 95% CL:	Observed 95% CL:
$c_{H\tilde{W}}$	$H \to \gamma\gamma$	[-0.94, 0.94]	[-0.53, 1.02]
	$H \to ZZ^* \to \ell^\pm\ell^\mp\ell^\pm\ell^\mp$	[-1.26, 1.28]	[-0.81, 1.54]

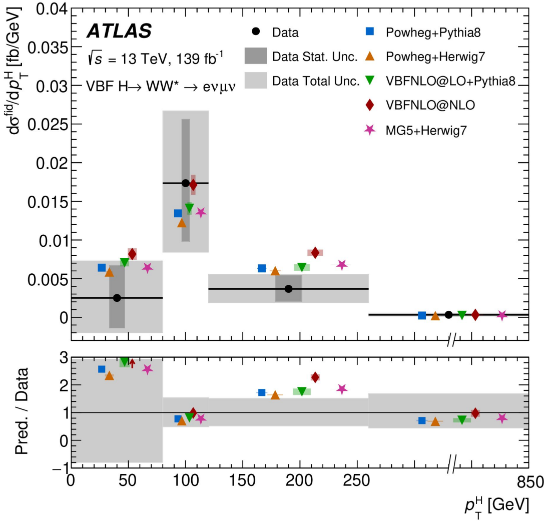
Phys. Rev. Lett. 131 (2023) 6, 061802 arXiv:2304.09612

Some more highlights

- Differential cross section measurements in VBF H→ WW*
- High-momentum Higgs production via **VH → qqbb**
  - Observed (expected) significance is 1.7σ (1.2σ)



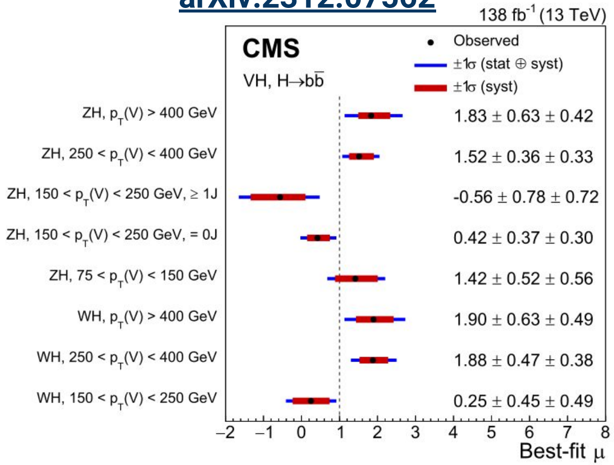
arXiv:2312.07605

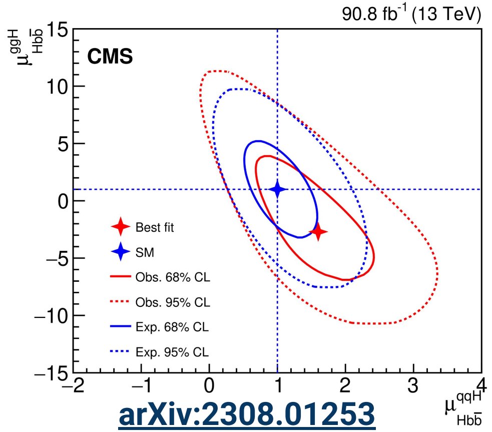


Phys. Rev. D 108 (2023) 072003

- Measurement of VBF production in H→ bb
- Measurements of Higgs properties in kinematic bins in VH(→ bb)

arXiv:2312.07562

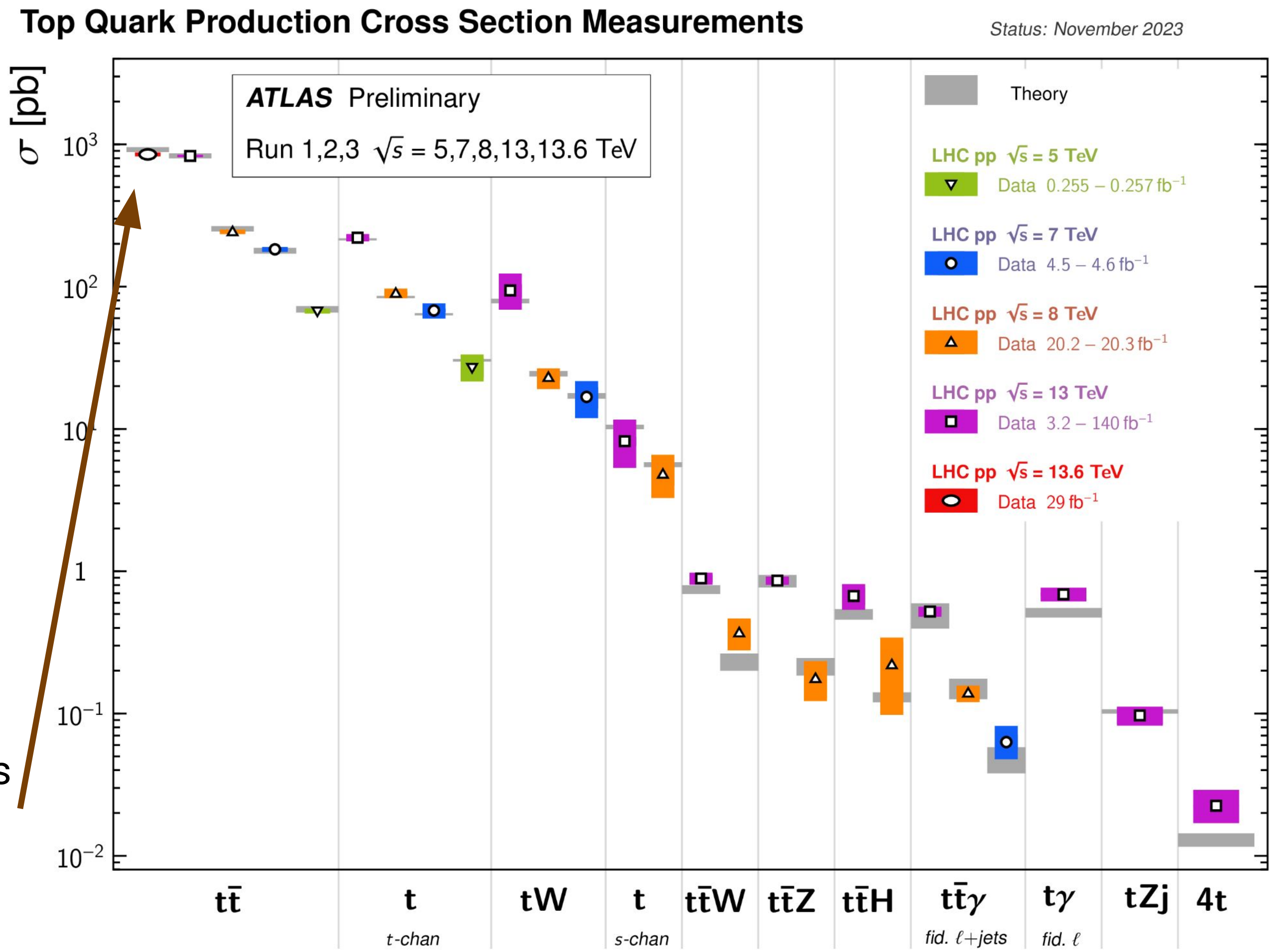




arXiv:2308.01253

Top quark property measurements

- Production cross section measurements
- Rare processes
- Mass measurements
- Quantum entanglement



- Top quark pair production cross section measurements
    - **Reach precision of around 1.8% at 13 TeV**
    - **Reach precision of around 3.2% at 13.6 TeV (already systematics limited)**

ATL-PHYS-PUB-2023-038

Four top quark production

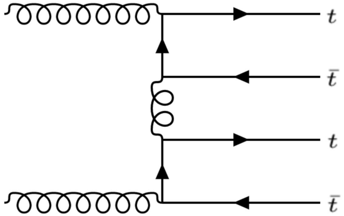
- ATLAS/CMS both recently observed the simultaneous production of 4 top quarks
- Particularly interesting since the process is very sensitive to BSM contributions:
  - Gluino pair production (SUSY)
  - Associated production of a heavy Higgs boson (2HDM)

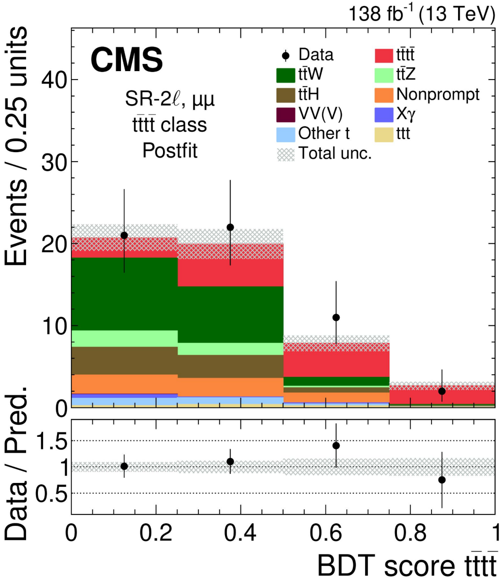
- Measured Cross sections:

ATLAS: $22.5^{+6.6}_{-5.5}$ fb

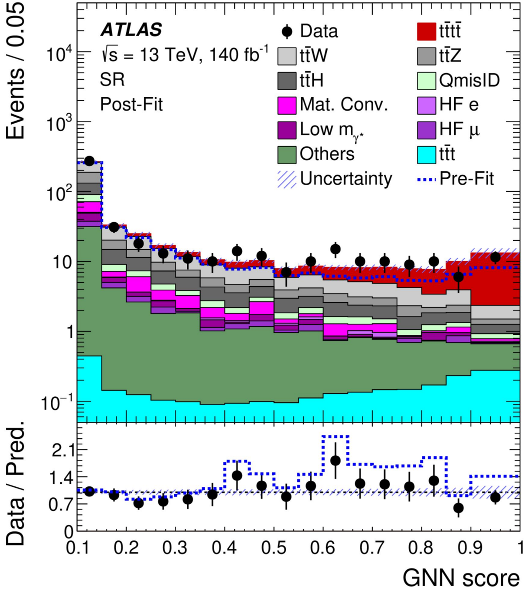
CMS: $17.7^{+4.4}_{-4.0}$ fb

- Constraining EFT parameters





[Phys. Lett. B 847 (2023) 138290](#)



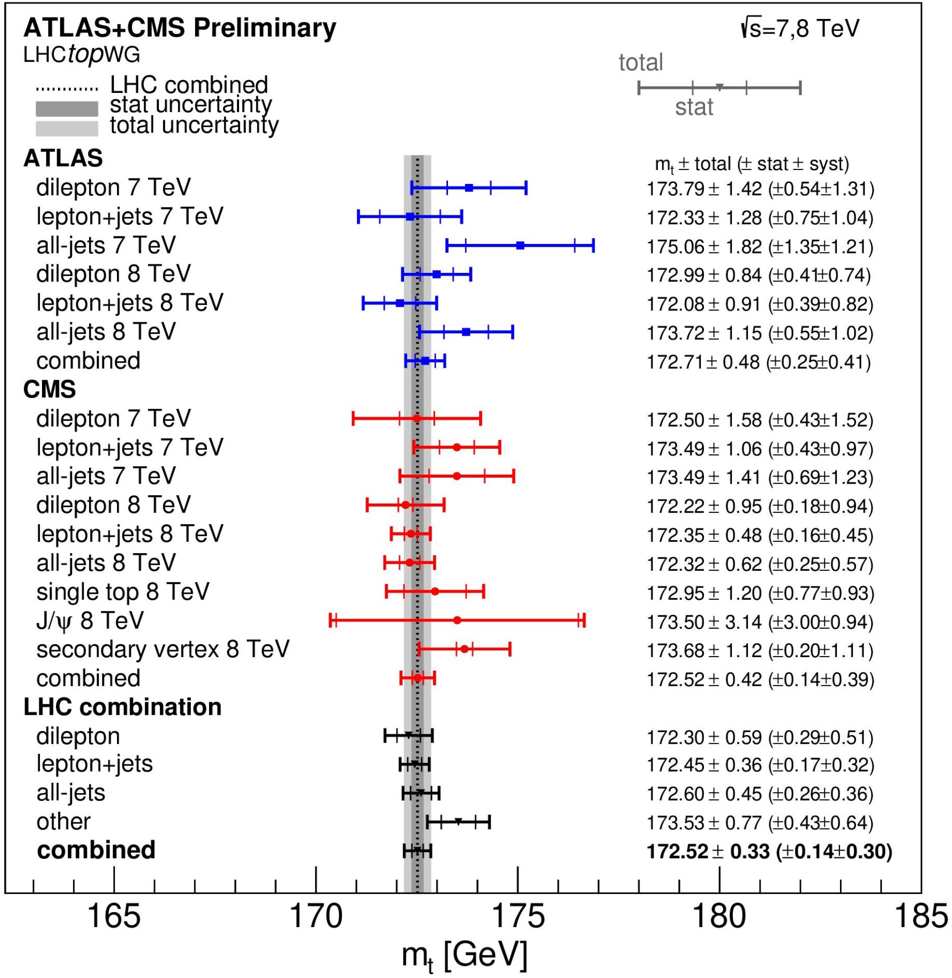
[Eur. Phys. J.C 83 (2023) 6, 496](#)

Combination of top quark mass measurements

Statistical combination of fifteen top quark mass measurements with LHC Run-1 datasets collected in 2011 and 2012

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

Top quark mass is determined via this combination with a relative uncertainty below 2 permille, which is an outstanding achievement



CMS-PAS-TOP-22-001 ATLAS-CONF-2023-066

Observation of quantum entanglement in top-quark pairs

- Top quark lifetime is shorter than hadronisation time
  - **Spin information are transferred to decay products of the top quark**
  - **Angular correlation of the final state particles**
- Spin entanglement is detected from the measurement of

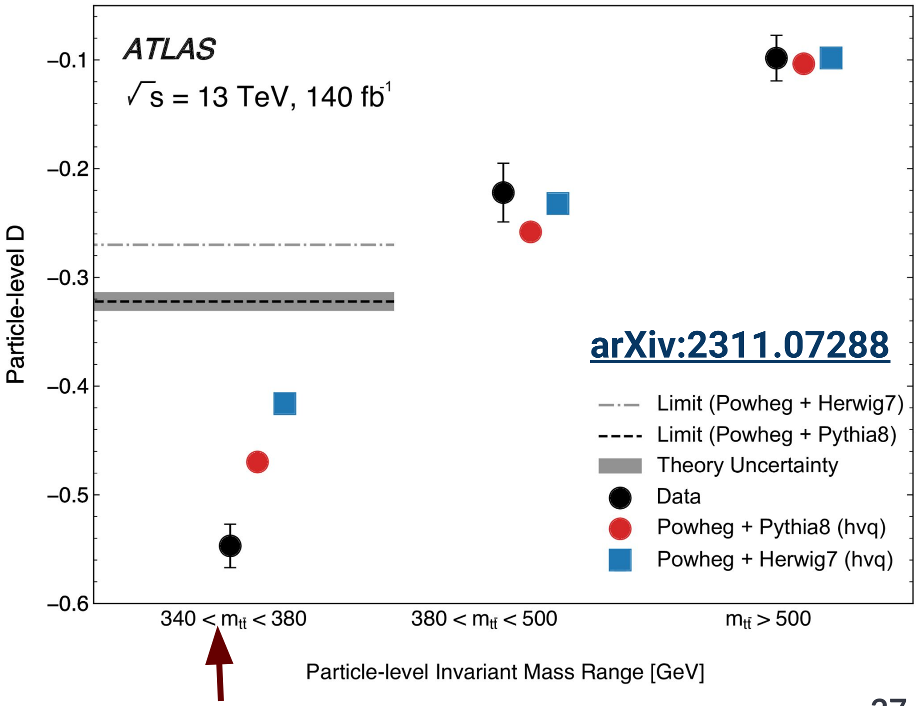
$$\boxed{D = -3 \cdot \langle \cos \varphi \rangle}$$

where φ is the angle between the charged leptons in their parent top- and antitop rest frame

- Observe:

$$\boxed{\mathbf{D = -0.547 \pm 0.002\ (stat.) \pm 0.021\ (syst.)}}$$

The existence of an entangled state is demonstrated for $D < -1/3$

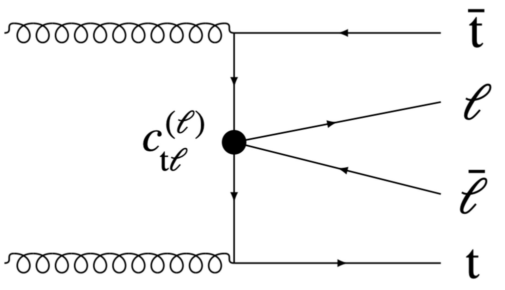


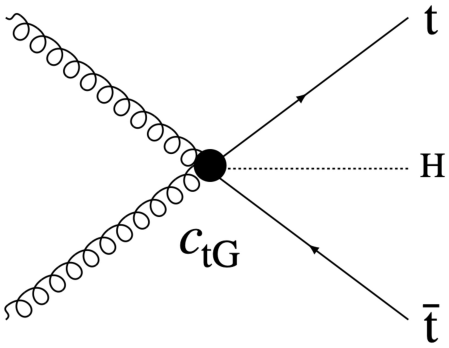
arXiv:2311.07288

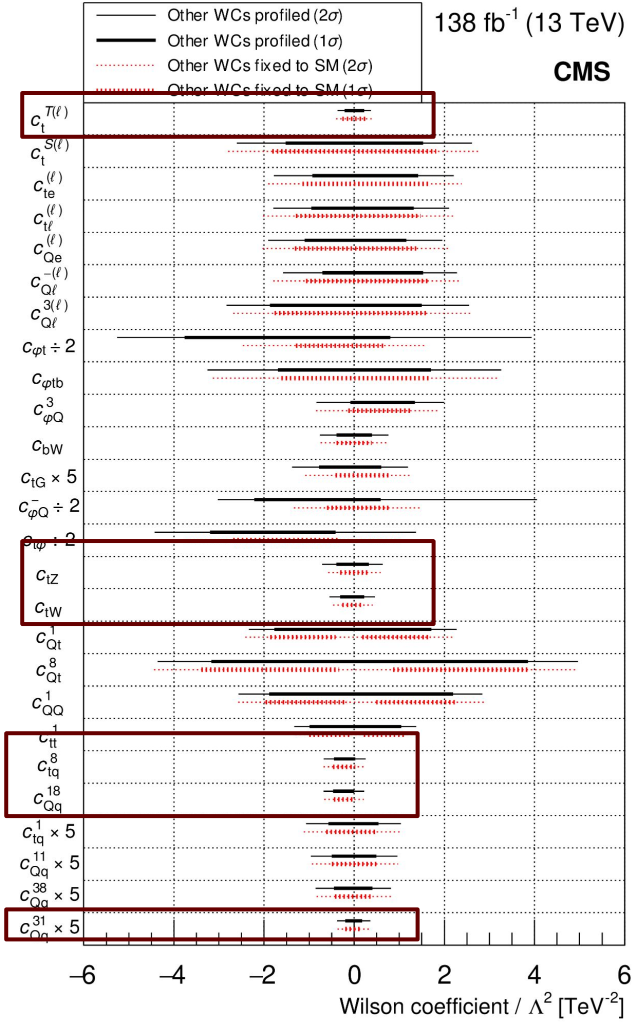
Particularly sensitive to the entangled state

Search for BSM physics in top quark production with additional leptons

- Probe BSM effects in various classes of events
    - Lepton & jet & b-jet multiplicities
- **Set strong constraints on relevant dimension-six EFT operators**
    - Study p_T spectra of leptons, jets and Z bosons







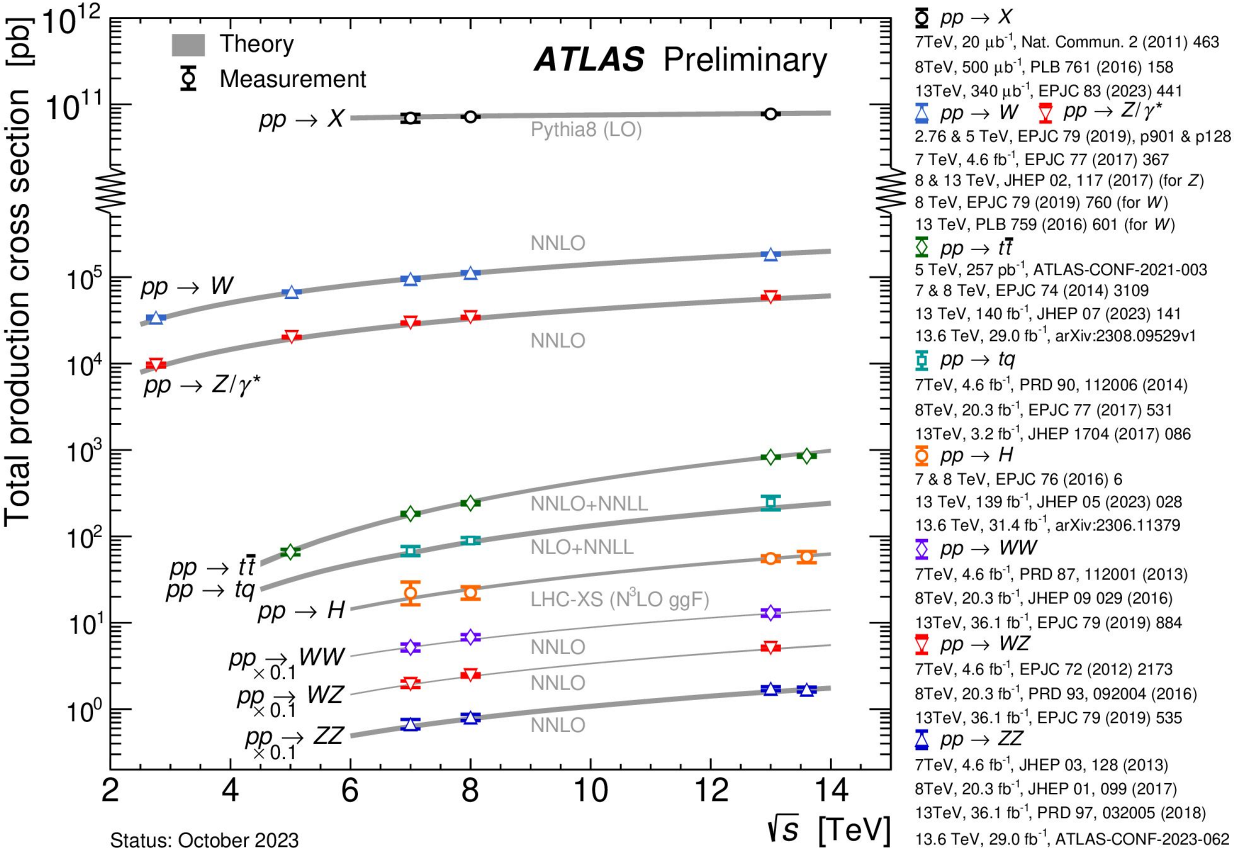
JHEP 12 (2023) 068

Vector boson property measurements

- W and Z boson cross section measurements
- W boson mass measurements
- Differential Cross section measurements
- Z boson polarisation studies
- Di-boson cross section measurements
- Observation of tri-boson production

Production cross section measurements

- **Measurements at:**
  - 2.76 TeV
  - 5 TeV
  - 7 TeV
  - 8 TeV
  - 13 TeV
  - 13.6 TeV



Impressive agreement with state-of-the-art cross section calculations

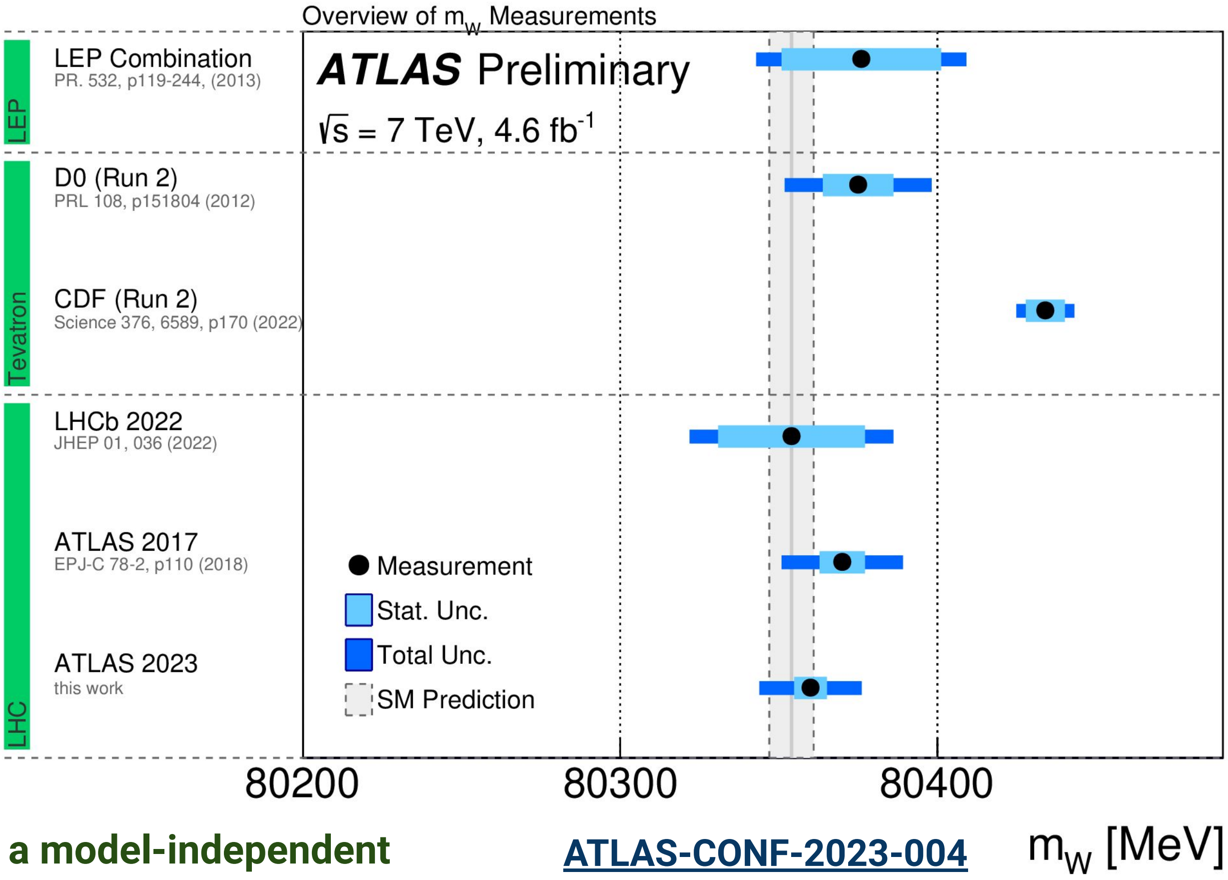
Updated measurements of the W/Z cross sections by CMS can be found **here** and **here**

Improved W boson mass measurement

Newest measurement yields:

m_W = 80360 ± 5(stat.) ± 15(syst.) MeV

(consistent with the SM)

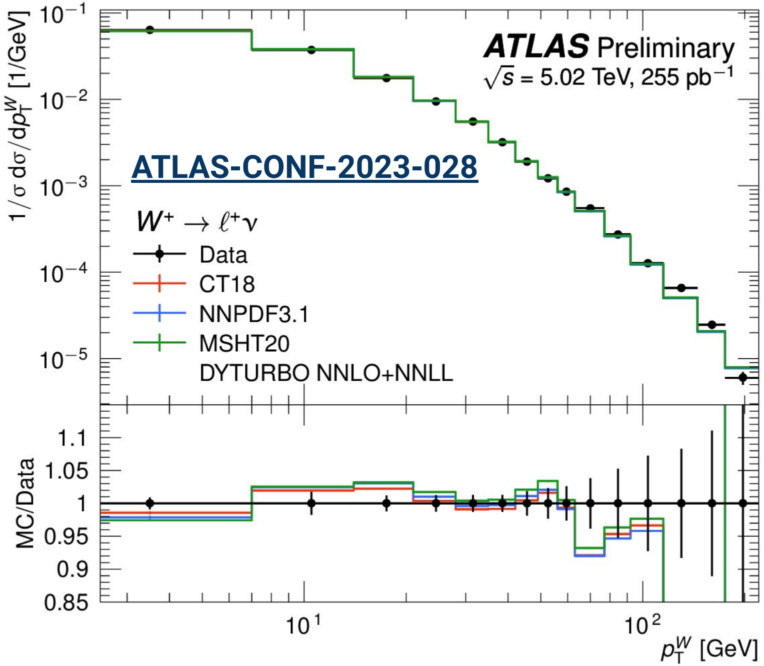


Studies of the W boson mass are a model-independent probe for effects of new physics

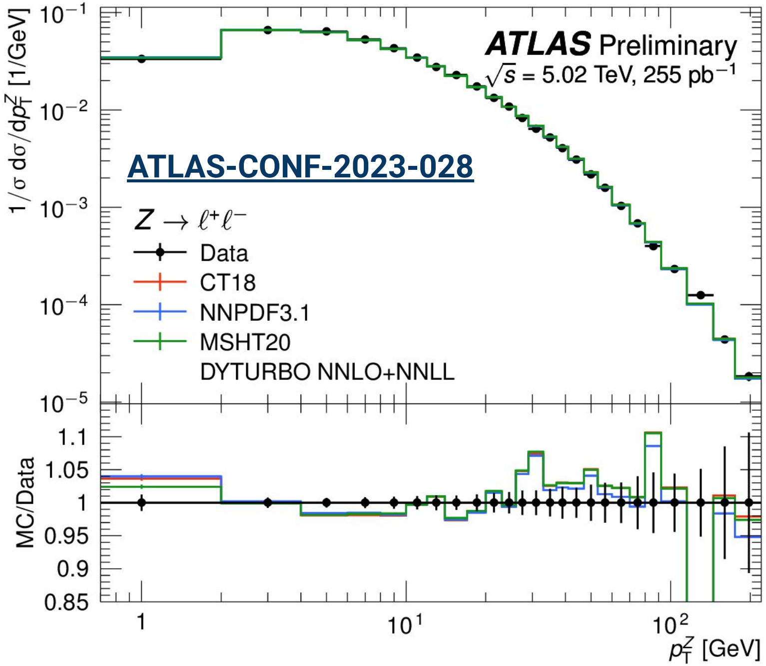
ATLAS-CONF-2023-004

W and Z boson p_T measurements

- Measurements of the W/Z boson production are a sensitive test of QCD
  - **p_T arises from higher order corrections to the LO Drell–Yan processes**



ATLAS-CONF-2023-028



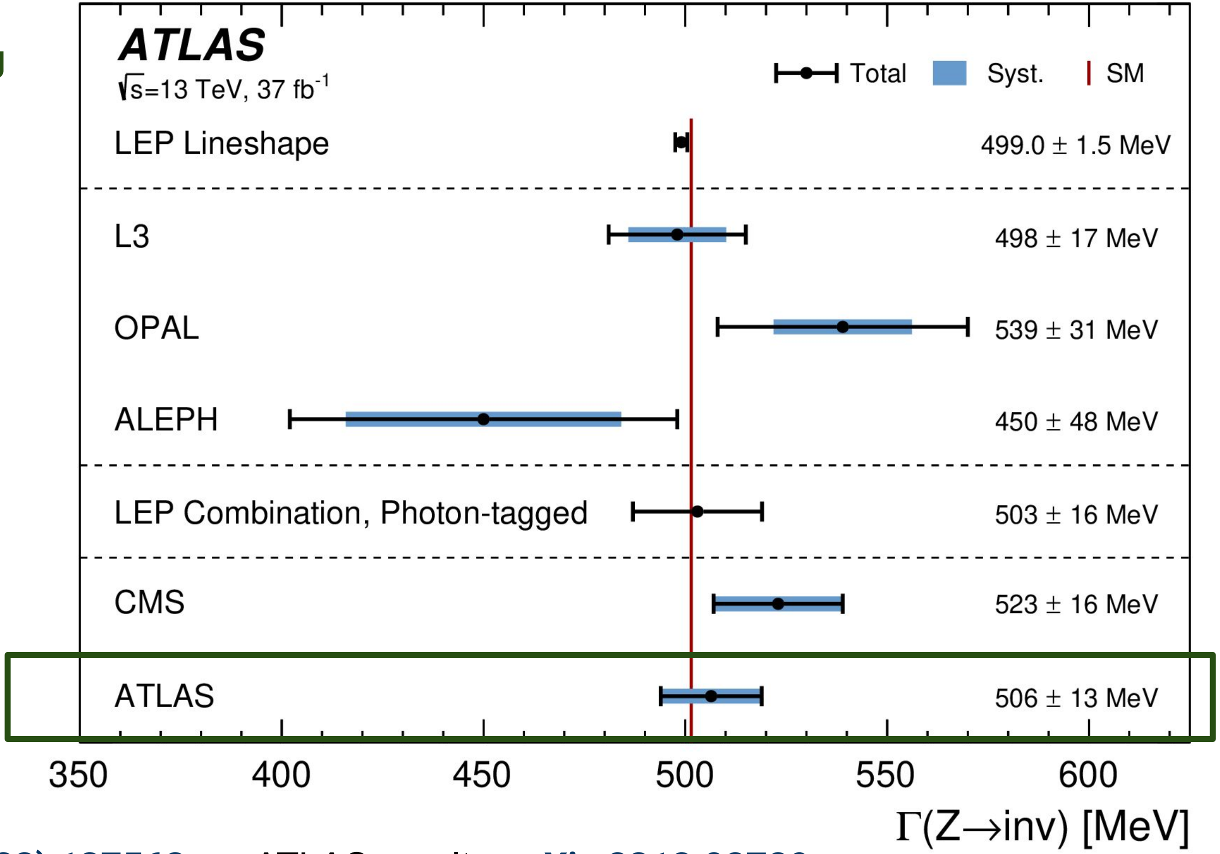
ATLAS-CONF-2023-028

- **Precise measurements of unfolded p_T spectra allow to constrain various modelling effects (PDF, radiation effects, ..)**
- **Studies are crucial for refined measurements of the W boson mass**

Measurement of the Z boson invisible width

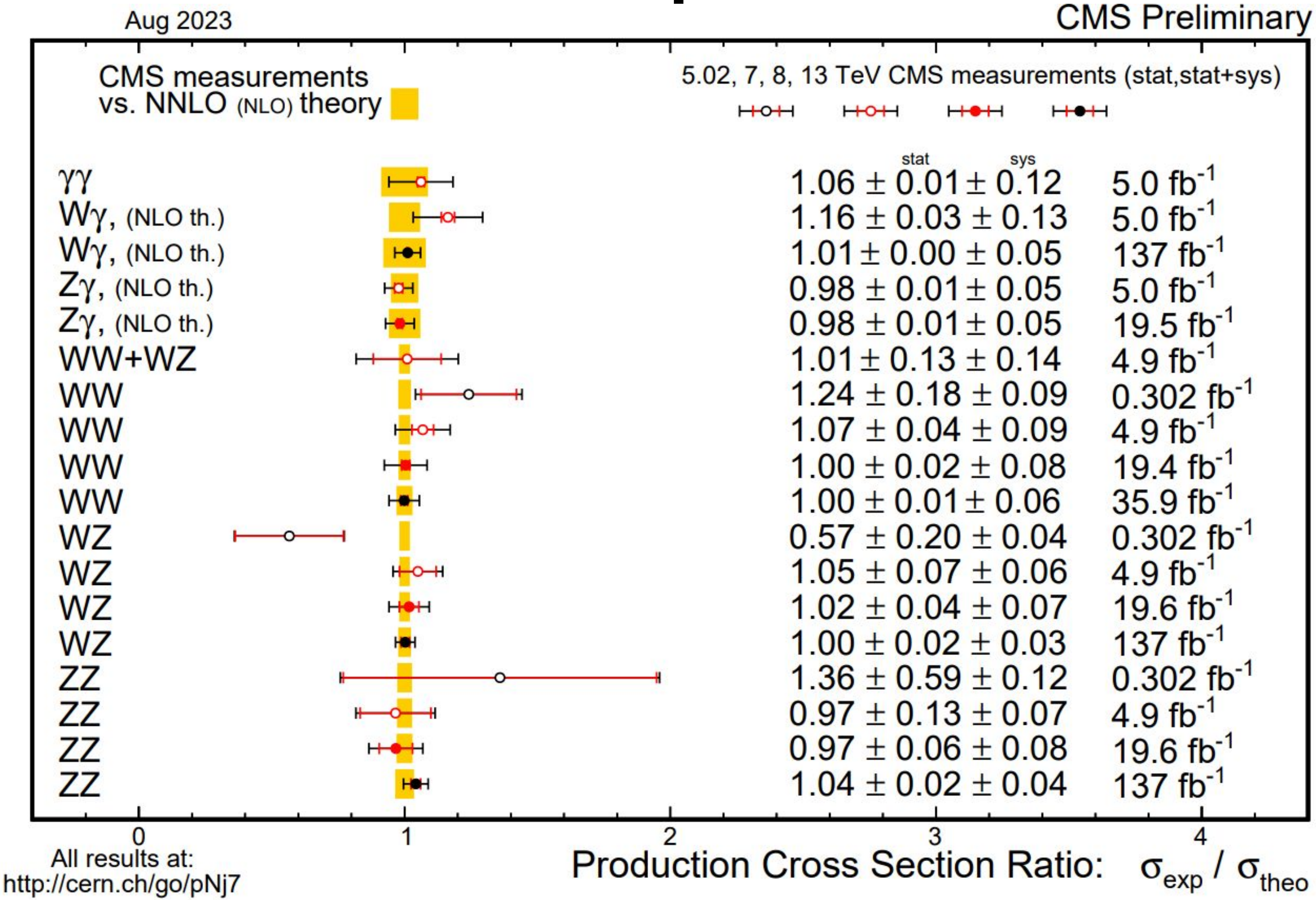
Probe events with jets and missing transverse momentum

In agreement with the LEP results and the SM prediction (based on three neutrino generations)



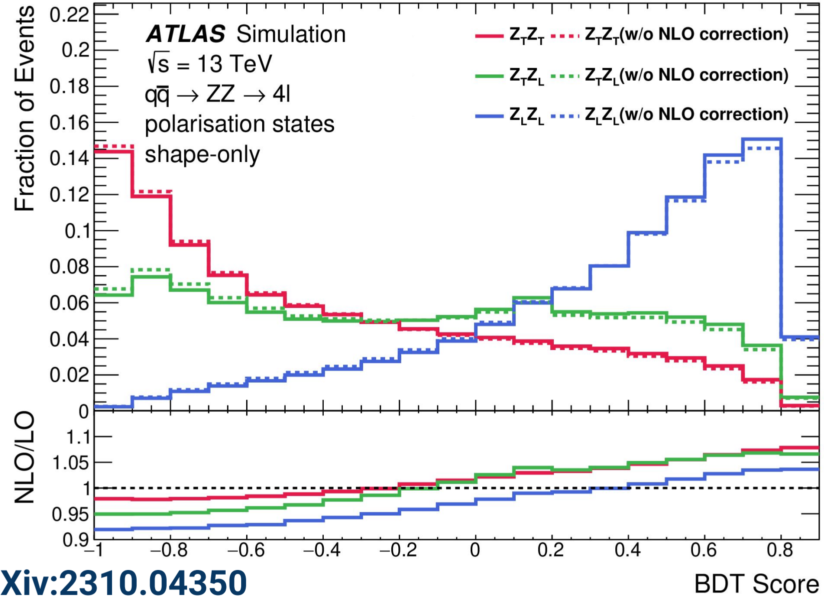
CMS results: **Phys. Lett. B 842 (2023) 137563** ATLAS results: **arXiv:2312.02789**

Di-boson production

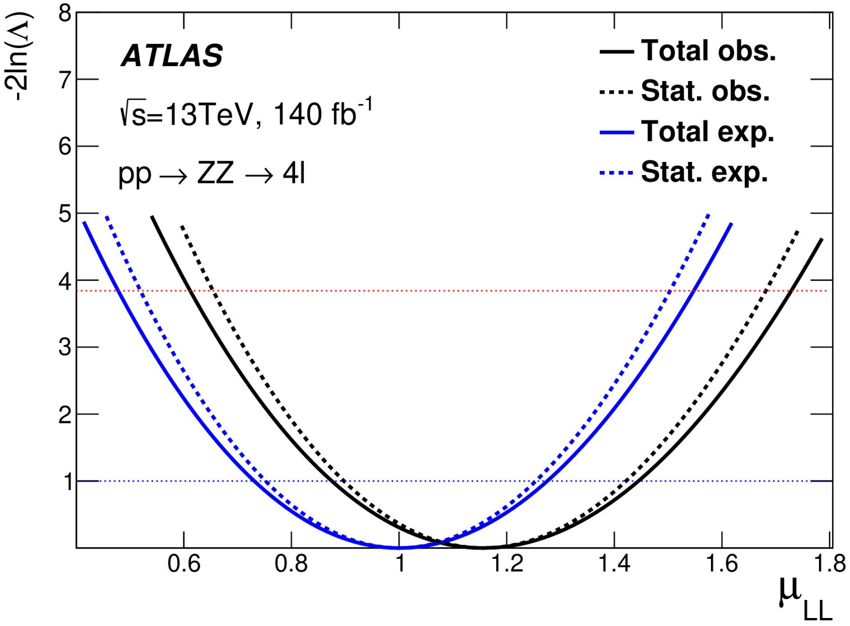


Evidence of pair production of longitudinally polarised Z bosons

- Diboson polarisation measurements, provide unique sensitivity to BSM physics
- Use BDT (based on lepton angles) to separate Z_LZ_L, Z_TZ_L, and Z_TZ_T



[arXiv:2310.04350]

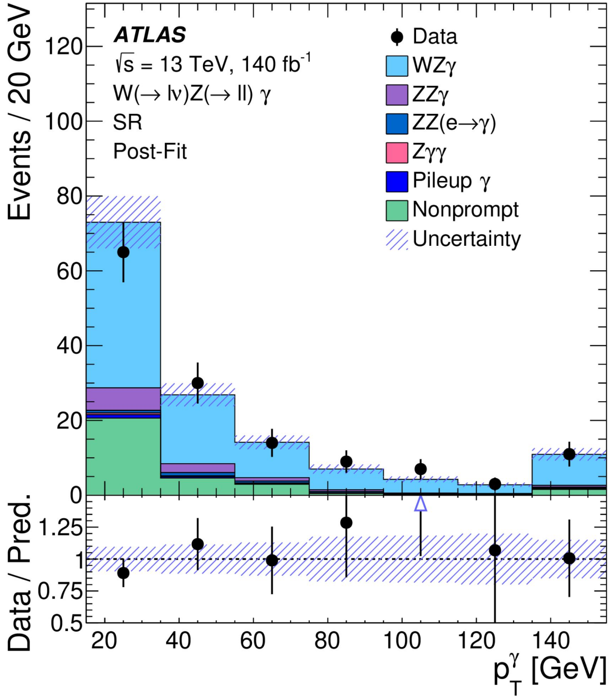


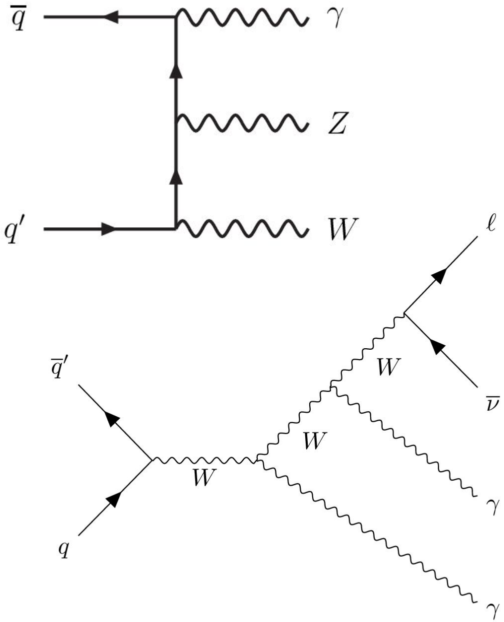
$\boxed{\mu_{LL} = 1.15 \pm 0.27(\text{stat.}) \pm 0.11(\text{syst.})}$

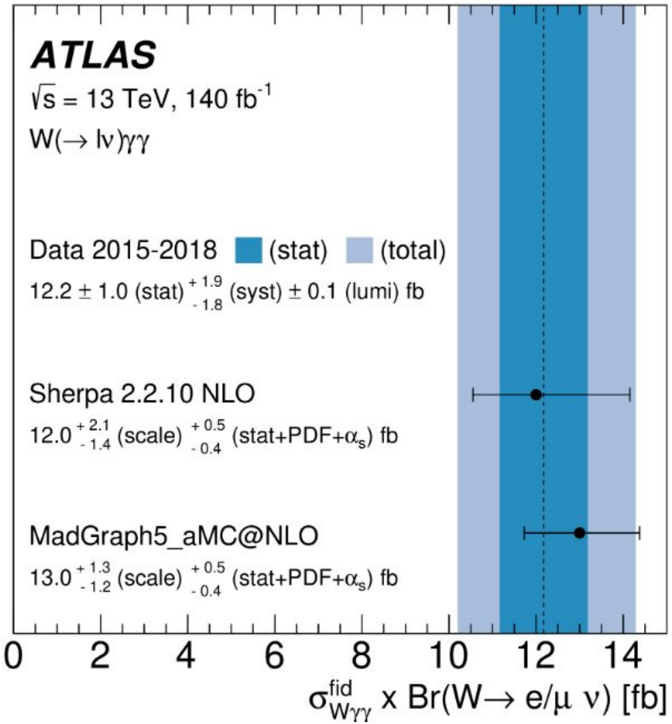
Measured with a significance of 4.3 standard deviations

Observations of tri-boson production

WZγ observation at 6.3σ (5.0σ exp)







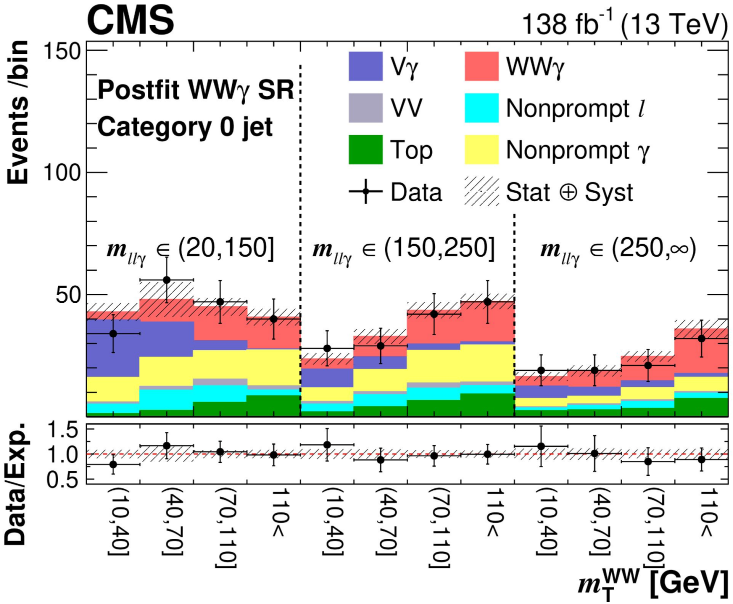
Wγγ observation at 5.6σ (5.6σ exp)

[arXiv:2305.16994]

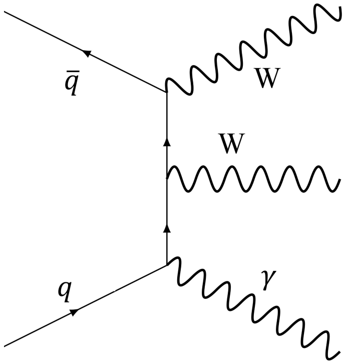
[Phys. Lett. B 848 (2024) 138400]

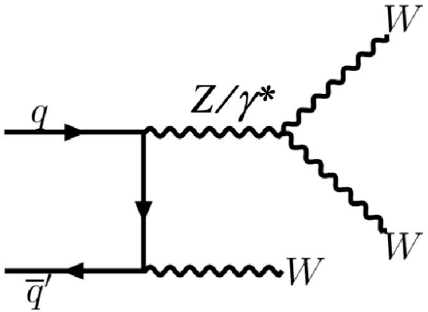
Observations of tri-boson production

WWγ observation at 5.6σ (4.7σ exp)

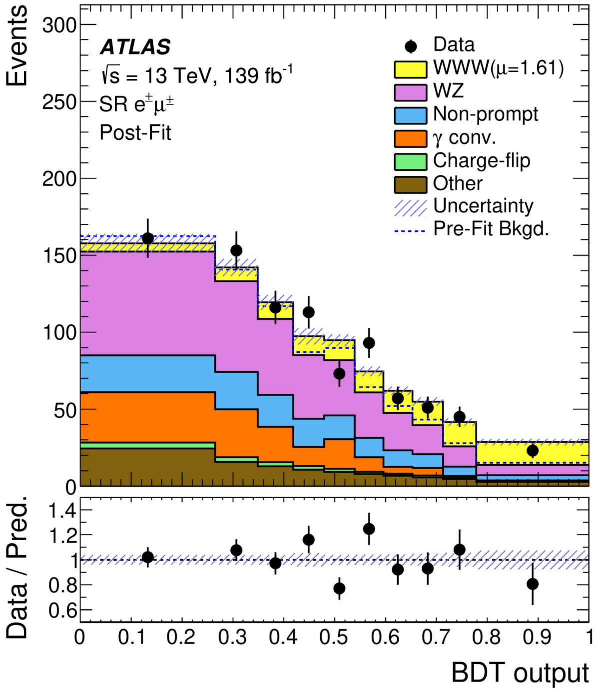


arXiv:2310.05164





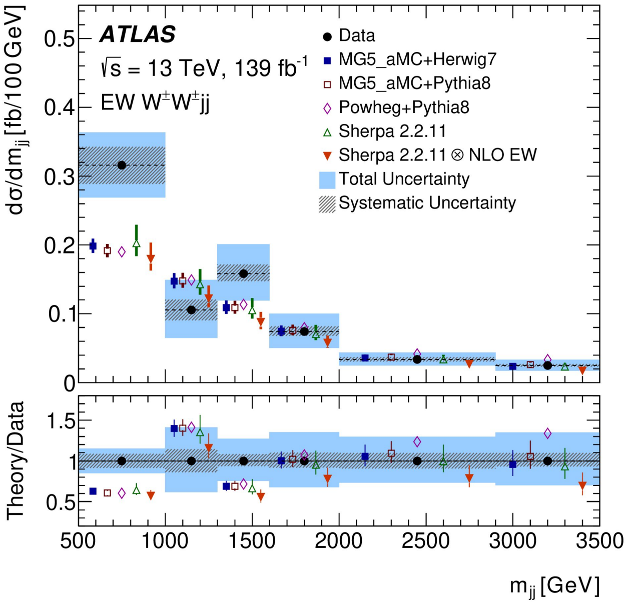
Phys. Rev. Lett. 129 (2022) 061803

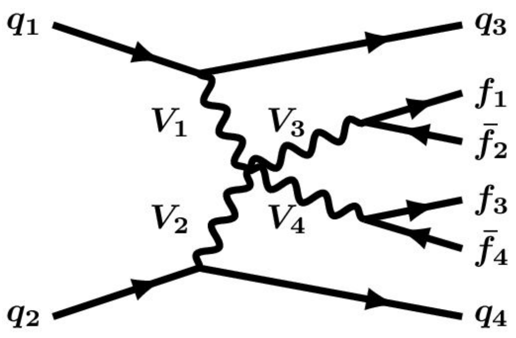


WWW observation at 8.0σ (5.4σ exp)

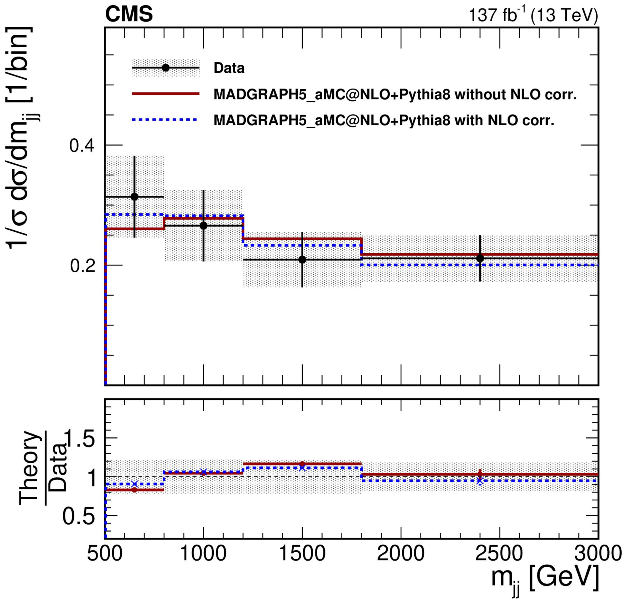
Measurement of EW $W^{\pm}W^{\pm}jj$ production

arXiv:2312.00420





Phys. Lett. B 809 (2020) 135710



Sensitive to constrain anomalous quartic gauge couplings

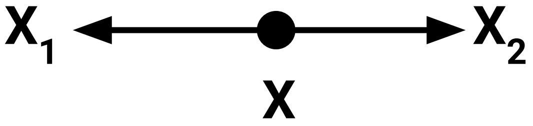
- **Fiducial cross section:**
  - **ATLAS:** 2.92 ± 0.22 (stat.) ± 0.19 (syst.) fb
  - **CMS:** 3.98 ± 0.37 (stat.) ± 0.25 (syst.) fb

Searches for New Physics

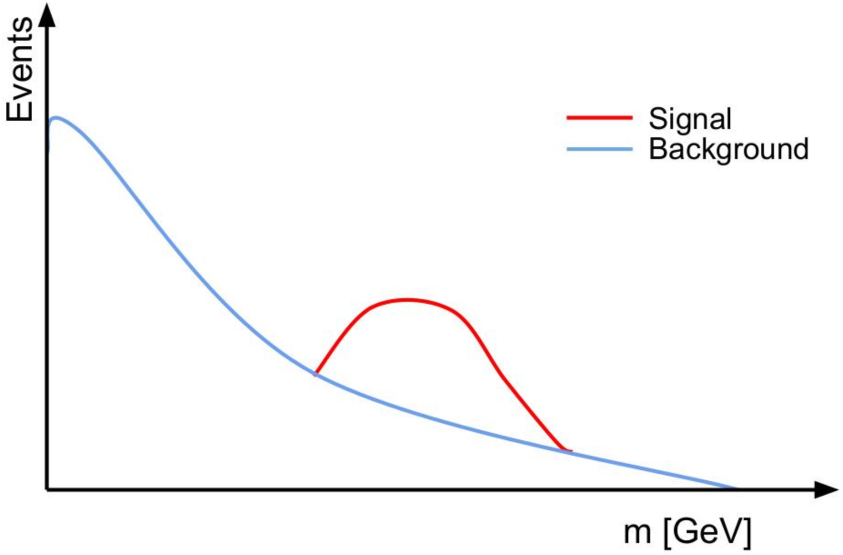
- Resonance searches
- Exotic decays of SM particles
- Searches for SUSY and other exotic particles

Searches for new resonances:

- **Focus: Searches for a (heavy) resonance X decaying into X_1 and X_2 (with X_1/X_2 = γ, Z, W, H, q, ℓ, BSM particles)**
  - Searches are performed for different production modes
  - Targeting diverse sets of final states:
    - Multi-lepton
    - Di-photon
    - Di-tau
    - Lepton + jets
    - Multi-jets

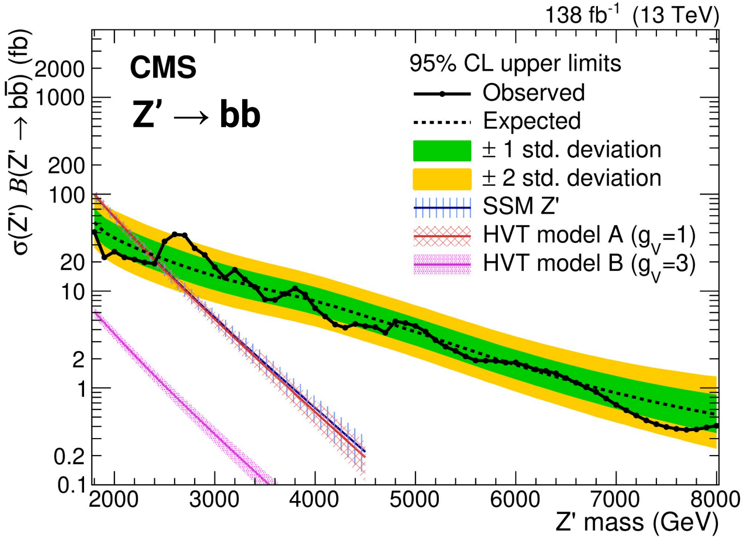


- Perform (quasi) **model-independent searches for a bump in a smoothly falling mass spectrum**
  - **Interpretations in generic frameworks:**
    - **Extended Higgs sector:**
      - Two Higgs Doublet Model (2HDM)
    - **Other generic frameworks:**
      - Heavy Vector Triplet (HVT) models
      - Extra-dimensional models

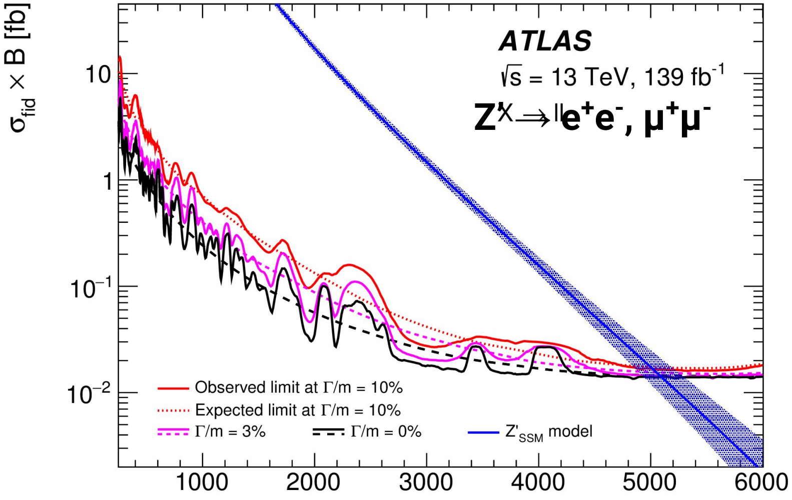


Di-lepton and di-jet resonance searches

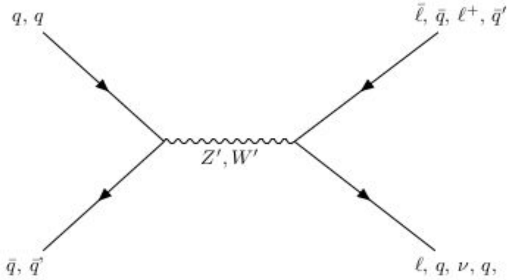
- ATLAS/CMS also have a wide range of searches for qq, ℓℓ and ℓv resonances:
  - e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $e^\pm v$, $\mu^\pm v$, and $\tau^\pm v$
  - q_lq_l, bb, tb, tt



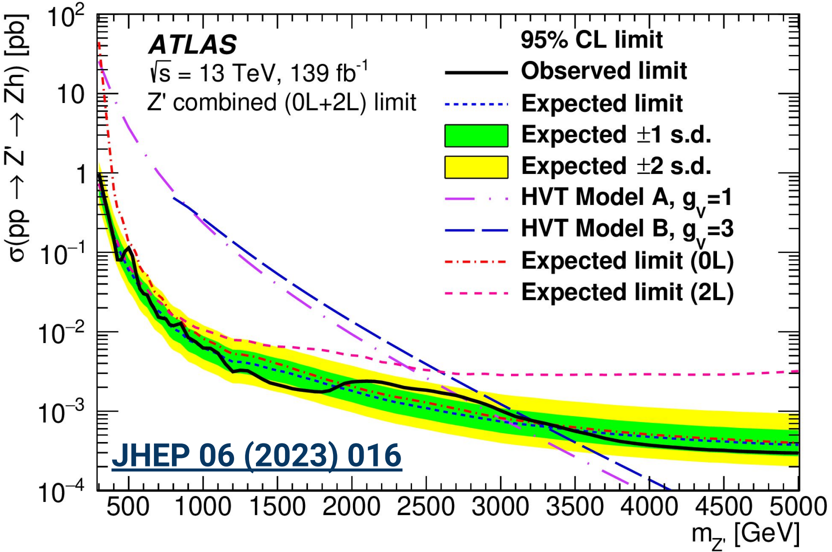
[Phys. Rev. D 108 (2023) 012009](#)



[Phys. Lett. B 796 (2019) 68](#)

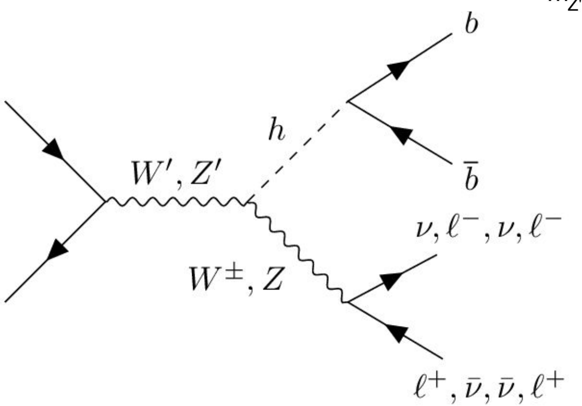


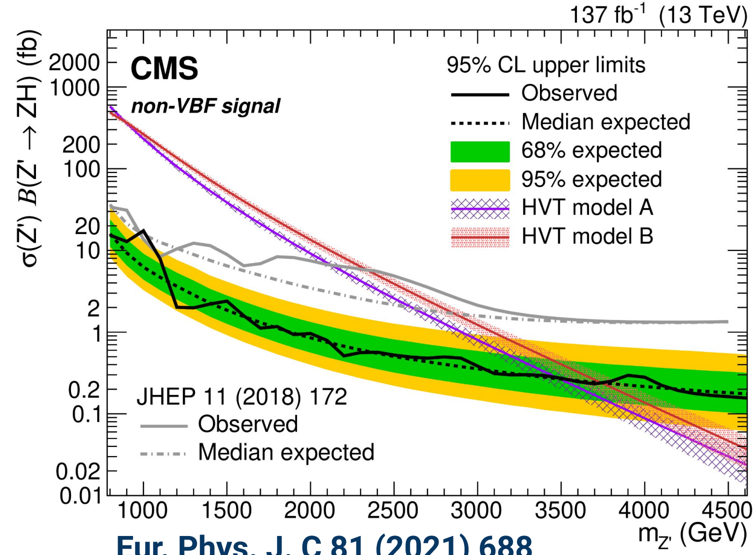
Di-boson resonance searches: ZH



JHEP 06 (2023) 016

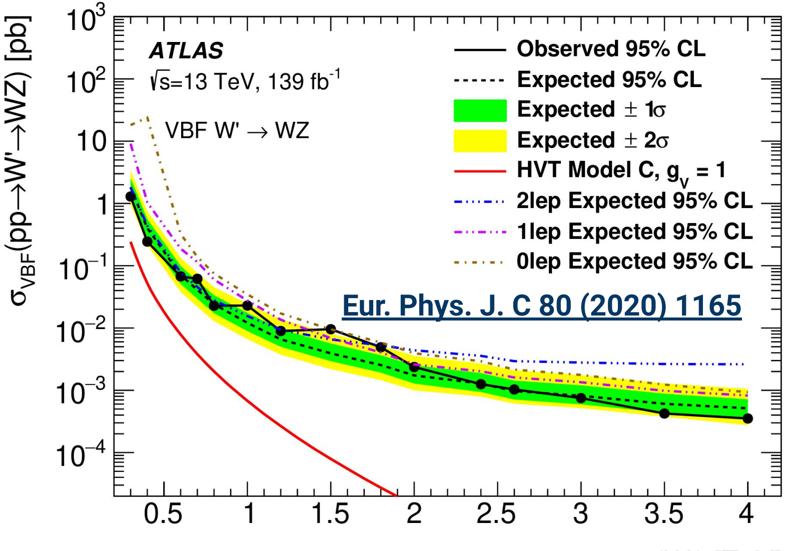
- Search for Zh resonance
    - Signature:
        - **MET, 2lep**
        - **2 small-R jets or 1 large-R jet**
    - Predicted by:
        - **HVT**
        - **Extended Higgs Sector models**



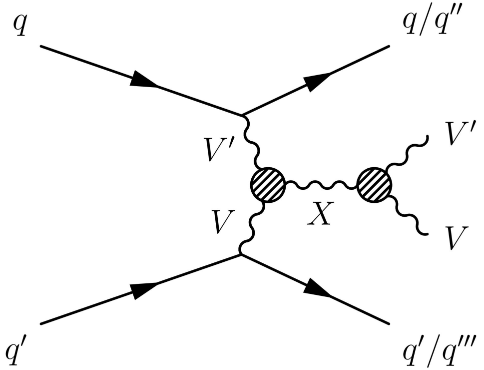


Eur. Phys. J. C 81 (2021) 688

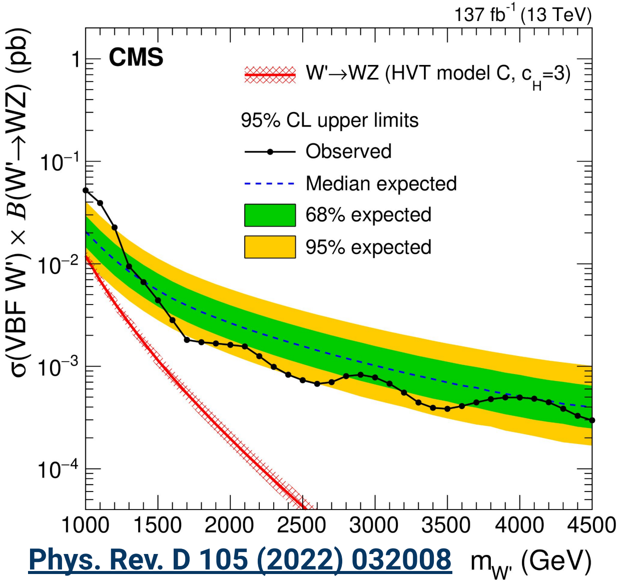
Di-boson resonance searches: WZ



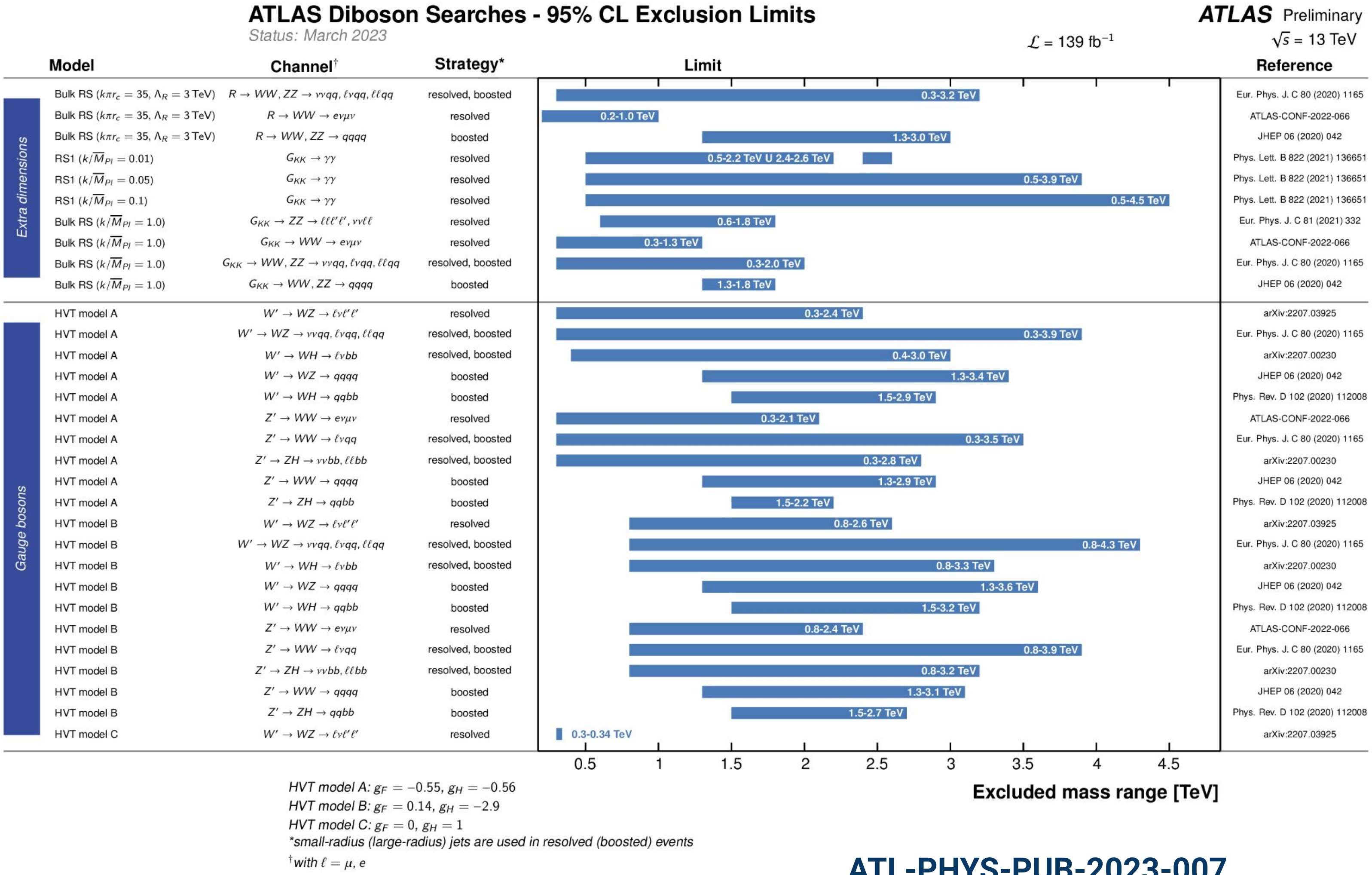
Eur. Phys. J. C 80 (2020) 1165



- Search for WZ resonance
  - Signature:
    - **MET, 1lep + MET, 2lep**
    - **2 small-R jets or 1 large-R jet**
  - Predicted by:
    - **HVT**
    - **Extradimensional models**



Phys. Rev. D 105 (2022) 032008



ATLAS Diboson Searches - 95% CL Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\mathcal{L} = 139\ \mathrm{fb}^{-1}$

$\sqrt{s} = 13$ TeV

	Model	Channel†	Strategy*	Limit	Reference
Extra dimensions	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.2 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW \to e\nu\mu\nu$	resolved	0.2-1.0 TeV	ATLAS-CONF-2022-066
	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW, ZZ \to qqqq$	boosted	1.3-3.0 TeV	JHEP 06 (2020) 042
	RS1 ($k/\overline{M}_{Pl} = 0.01$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-2.2 TeV U 2.4-2.6 TeV	Phys. Lett. B 822 (2021) 136651
	RS1 ($k/\overline{M}_{Pl} = 0.05$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-3.9 TeV	Phys. Lett. B 822 (2021) 136651
	RS1 ($k/\overline{M}_{Pl} = 0.1$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-4.5 TeV	Phys. Lett. B 822 (2021) 136651
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to ZZ \to \ell\ell\ell'\ell', \nu\nu\ell\ell$	resolved	0.6-1.8 TeV	Eur. Phys. J. C 81 (2021) 332
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.3-1.3 TeV	ATLAS-CONF-2022-066
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-2.0 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to qqqq$	boosted	1.3-1.8 TeV	JHEP 06 (2020) 042
Gauge bosons	HVT model A	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.3-2.4 TeV	arXiv:2207.03925
	HVT model A	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model A	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.4-3.0 TeV	arXiv:2207.00230
	HVT model A	$W' \to WZ \to qqqq$	boosted	1.3-3.4 TeV	JHEP 06 (2020) 042
	HVT model A	$W' \to WH \to qqbb$	boosted	1.5-2.9 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model A	$Z' \to WW \to e\nu\mu\nu$	resolved	0.3-2.1 TeV	ATLAS-CONF-2022-066
	HVT model A	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.3-3.5 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model A	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.3-2.8 TeV	arXiv:2207.00230
	HVT model A	$Z' \to WW \to qqqq$	boosted	1.3-2.9 TeV	JHEP 06 (2020) 042
	HVT model A	$Z' \to ZH \to qqbb$	boosted	1.5-2.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model B	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.8-2.6 TeV	arXiv:2207.03925
	HVT model B	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.8-4.3 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model B	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.8-3.3 TeV	arXiv:2207.00230
	HVT model B	$W' \to WZ \to qqqq$	boosted	1.3-3.6 TeV	JHEP 06 (2020) 042
	HVT model B	$W' \to WH \to qqbb$	boosted	1.5-3.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model B	$Z' \to WW \to e\nu\mu\nu$	resolved	0.8-2.4 TeV	ATLAS-CONF-2022-066
	HVT model B	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.8-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model B	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.8-3.2 TeV	arXiv:2207.00230
	HVT model B	$Z' \to WW \to qqqq$	boosted	1.3-3.1 TeV	JHEP 06 (2020) 042
	HVT model B	$Z' \to ZH \to qqbb$	boosted	1.5-2.7 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model C	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.3-0.34 TeV	arXiv:2207.03925

HVT model A: $g_F = -0.55$, $g_H = -0.56$
HVT model B: $g_F = 0.14$, $g_H = -2.9$
HVT model C: $g_F = 0$, $g_H = 1$
**small-radius (large-radius) jets are used in resolved (boosted) events*
†with $\ell = \mu, e$

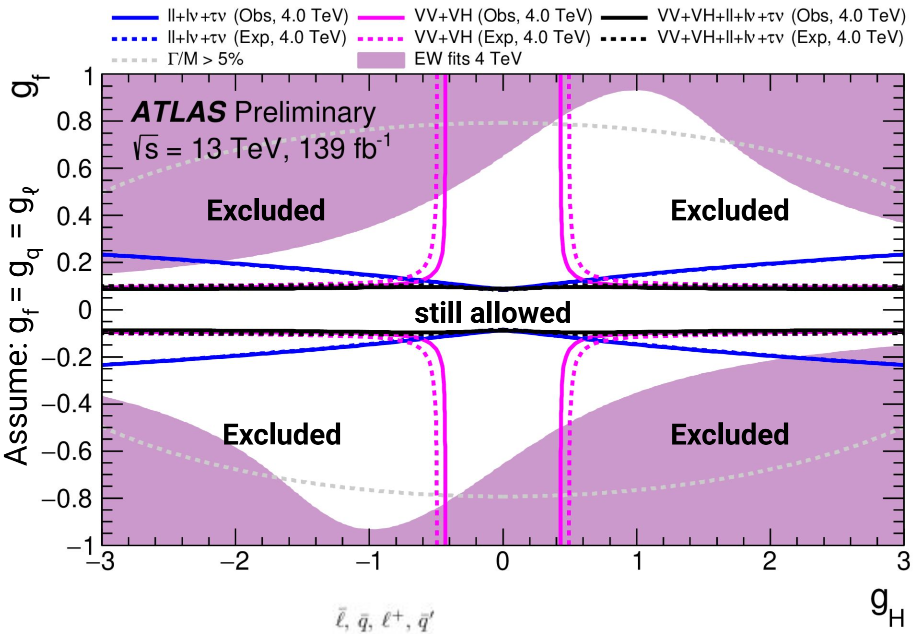
ATL-PHYS-PUB-2023-007

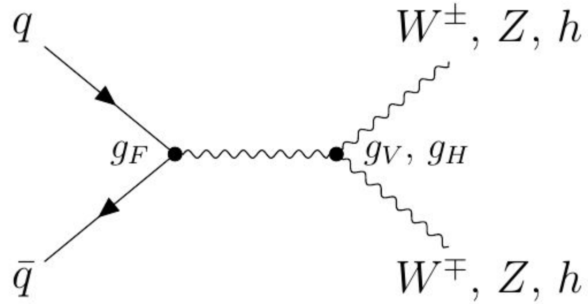
Summary of CMS di-boson searches can be found **here**

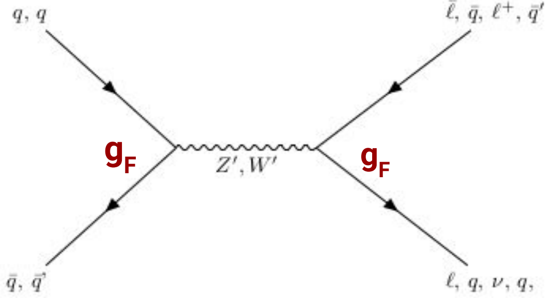
Combination of Resonance Searches

ATLAS-CONF-2022-028

- Combine searches for diboson, di-quark, and di-lepton resonances:
  - **Include large number of individual channels:**
    - **Fully leptonic**
    - **semi-leptonic**
    - **fully hadronic**
  - Exploit complementarity of different channels to improve constraints
  - By now, better than EWK precision constraints for masses ≤ 5 TeV

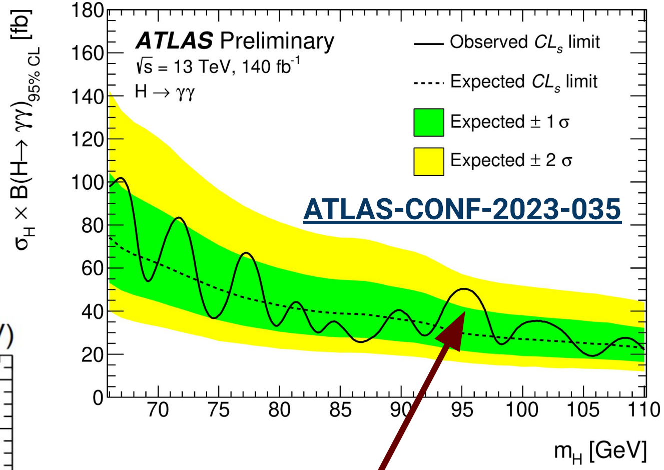






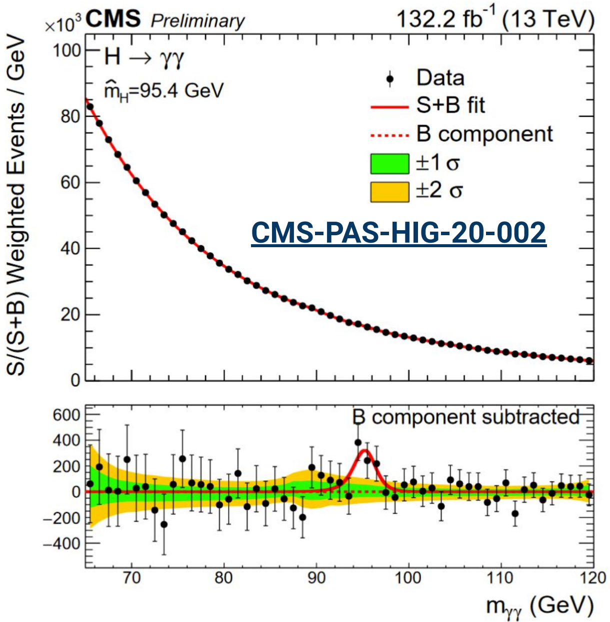
Low-mass di-photon resonance searches

- Search for a SM-like Higgs boson in the mass range between 70 and 110 GeV
    - Allowed by 2HDMs, N2HDMs, and other extended Higgs sector models

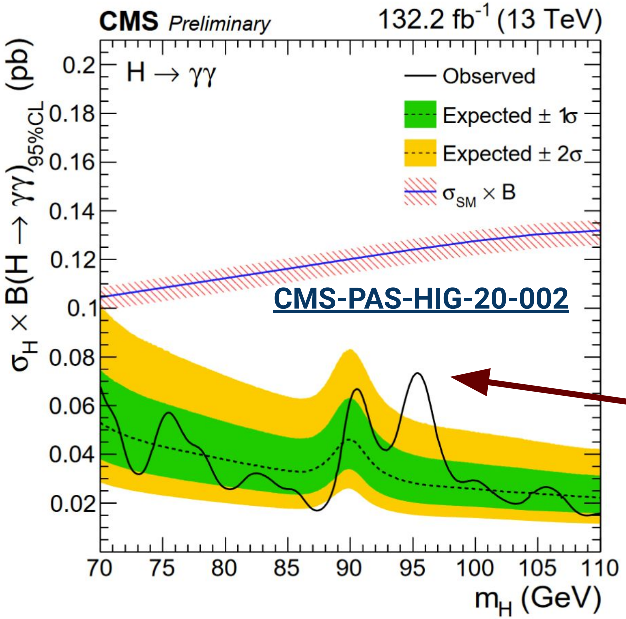


ATLAS-CONF-2023-035

Found small excess for mass around 95 GeV with a local significance of 1.7σ



CMS-PAS-HIG-20-002

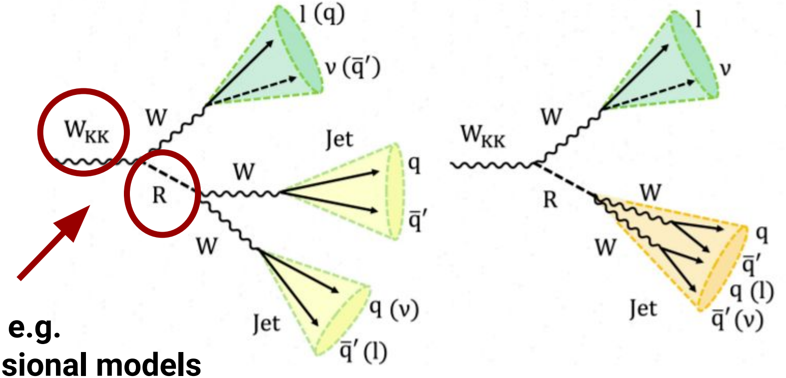


CMS-PAS-HIG-20-002

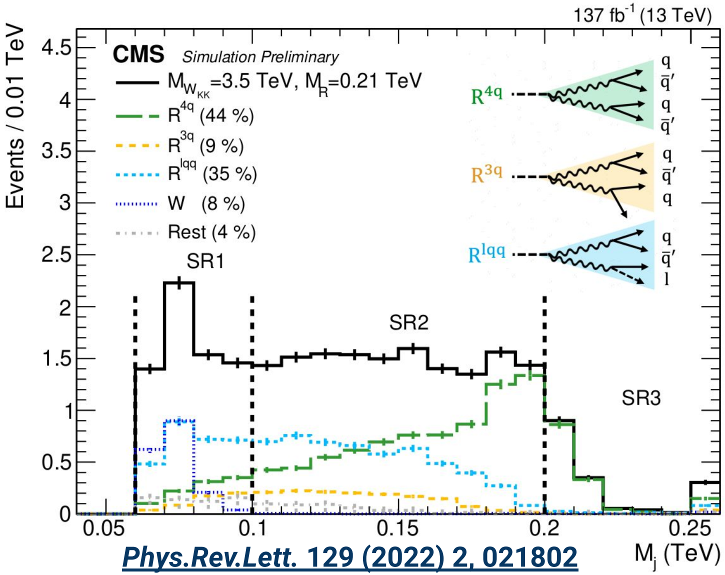
Found small excess for mass around 95 GeV with a local (global) significance of 2.9σ (1.3σ)

Cascade decays

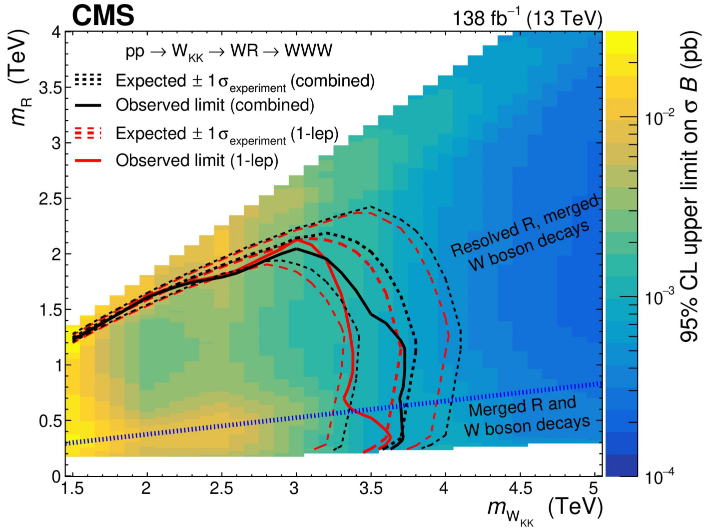
- **Search for resonances decaying to triple W-boson final states:**
    - Search for cascade decays leading to merged ℓνqqqq (ℓ = μ, e) final states
        - **Study events with 1 or 2 large-R jets**



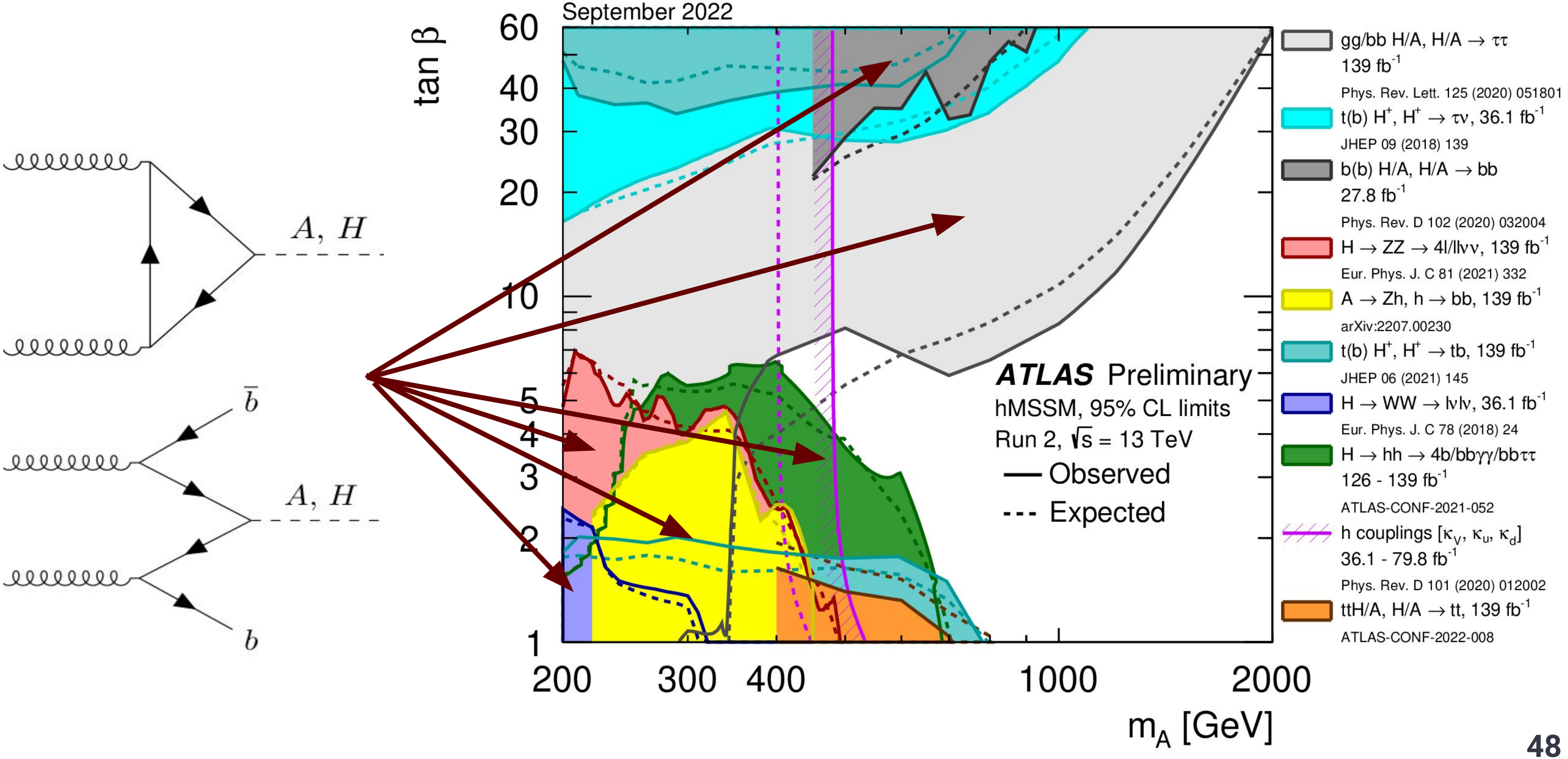
Predicted in e.g. extra-dimensional models



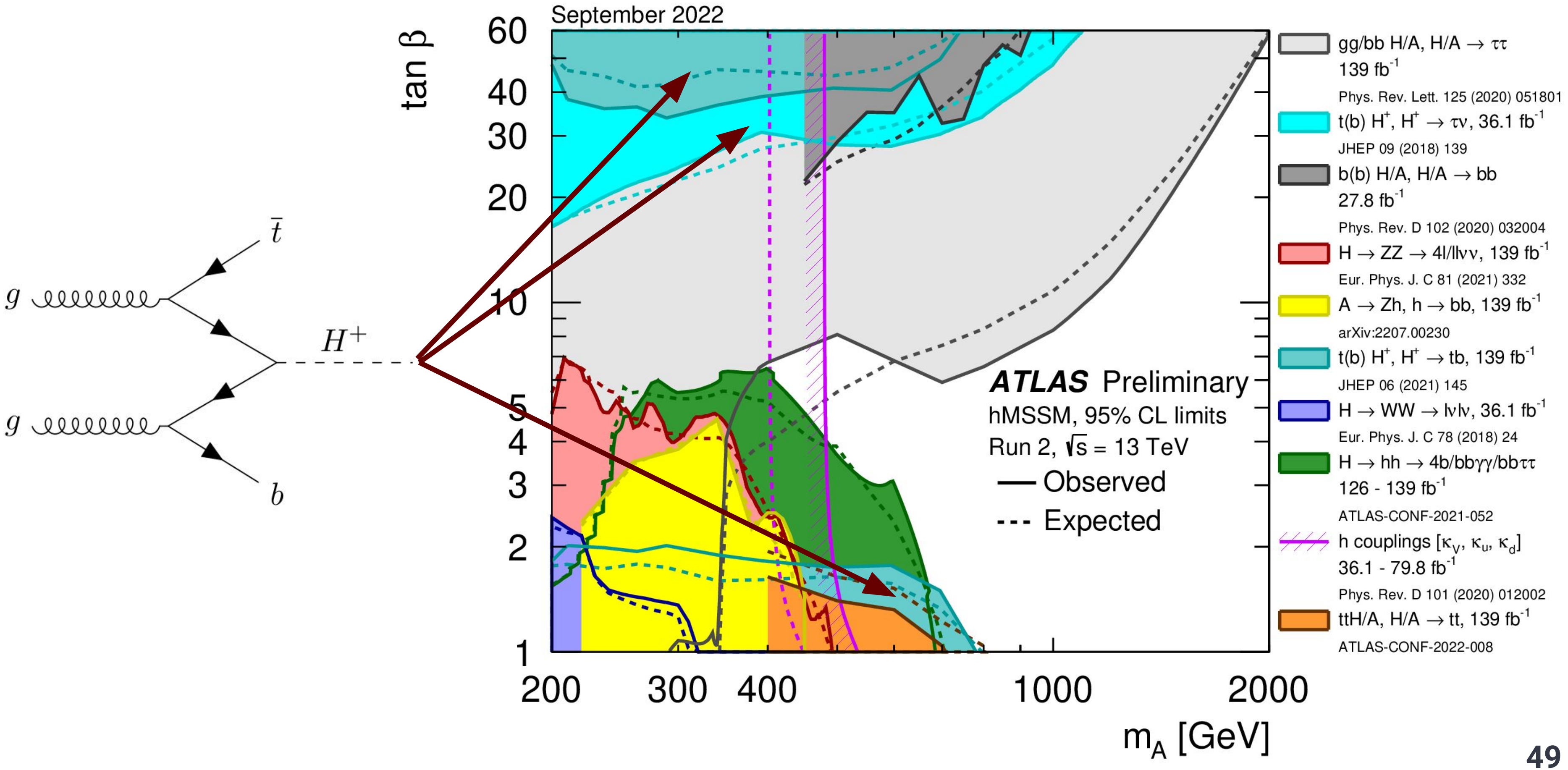
[*Phys.Rev.Lett.* 129 (2022) 2, 021802]()



Searches for additional Higgs bosons

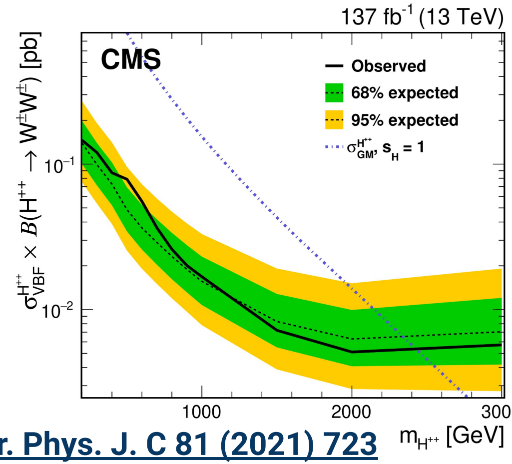


Searches for additional Higgs bosons

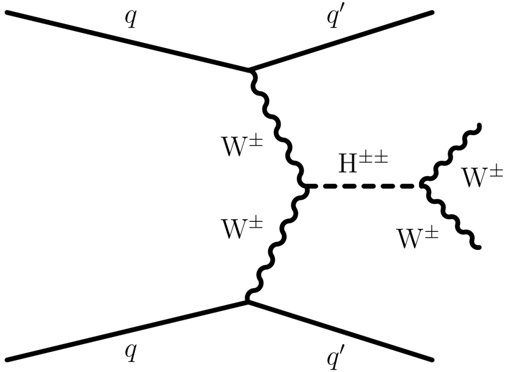


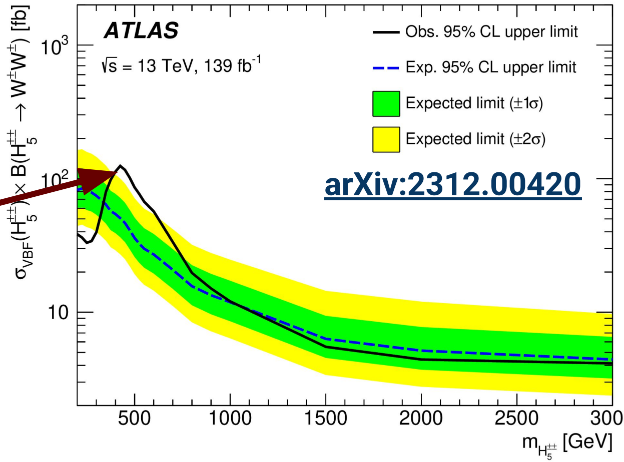
Searches for double charged Higgs bosons

- Search for W±W± resonances produced via VBF
  - Signature:
    - **MET, 2lep (same-sign)**
    - **2 small-R jets in the forward direction**
  - Predicted by:
    - **Georgi-Machacek model**
      - And other Higgs triplet models



Eur. Phys. J. C 81 (2021) 723



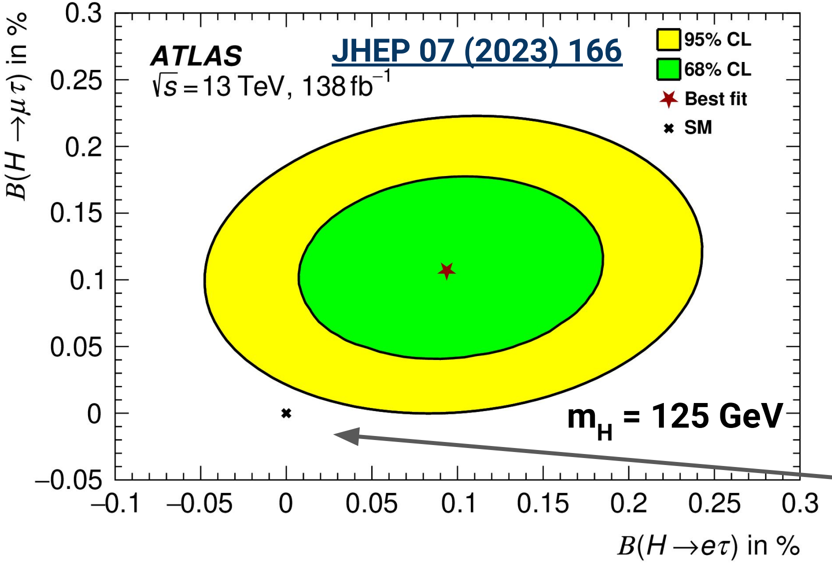


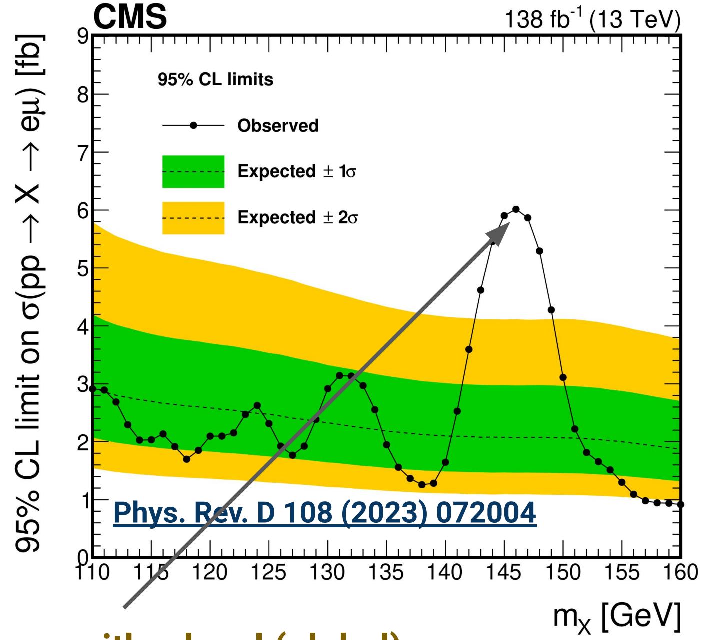
arXiv:2312.00420

Found small excess for mass around 450 GeV with a local (global) significance of 3.3σ (2.5σ)

Lepton-flavor violating decay of the Higgs boson and additional Higgs bosons in the eμ, eτ, and μτ final states

- **Predicted by:**
  - Flavour-violating 2HDMs
- Particularly interesting due to flavour anomalies observed by e.g. g − 2





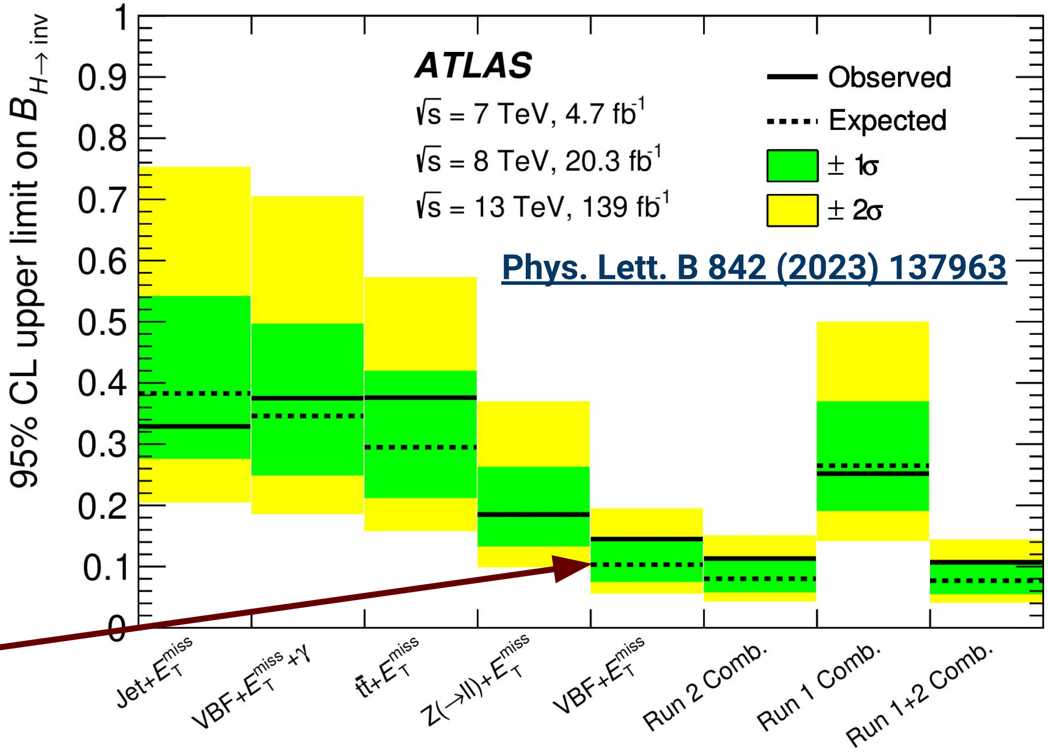
See small excess with a local (global) significance of 3.8 (2.8) standard deviations

Results are consistent to SM predictions within 2.1σ

Searches for invisible decays of the Higgs boson

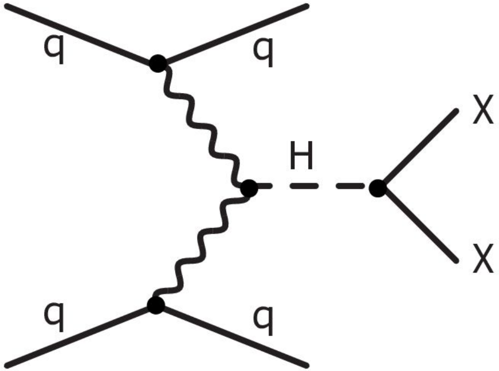
- **ATLAS:** Observed (expected) combined branching ratio limit:

BR(H→inv.) < 0.113 (0.080 ± 0.27)



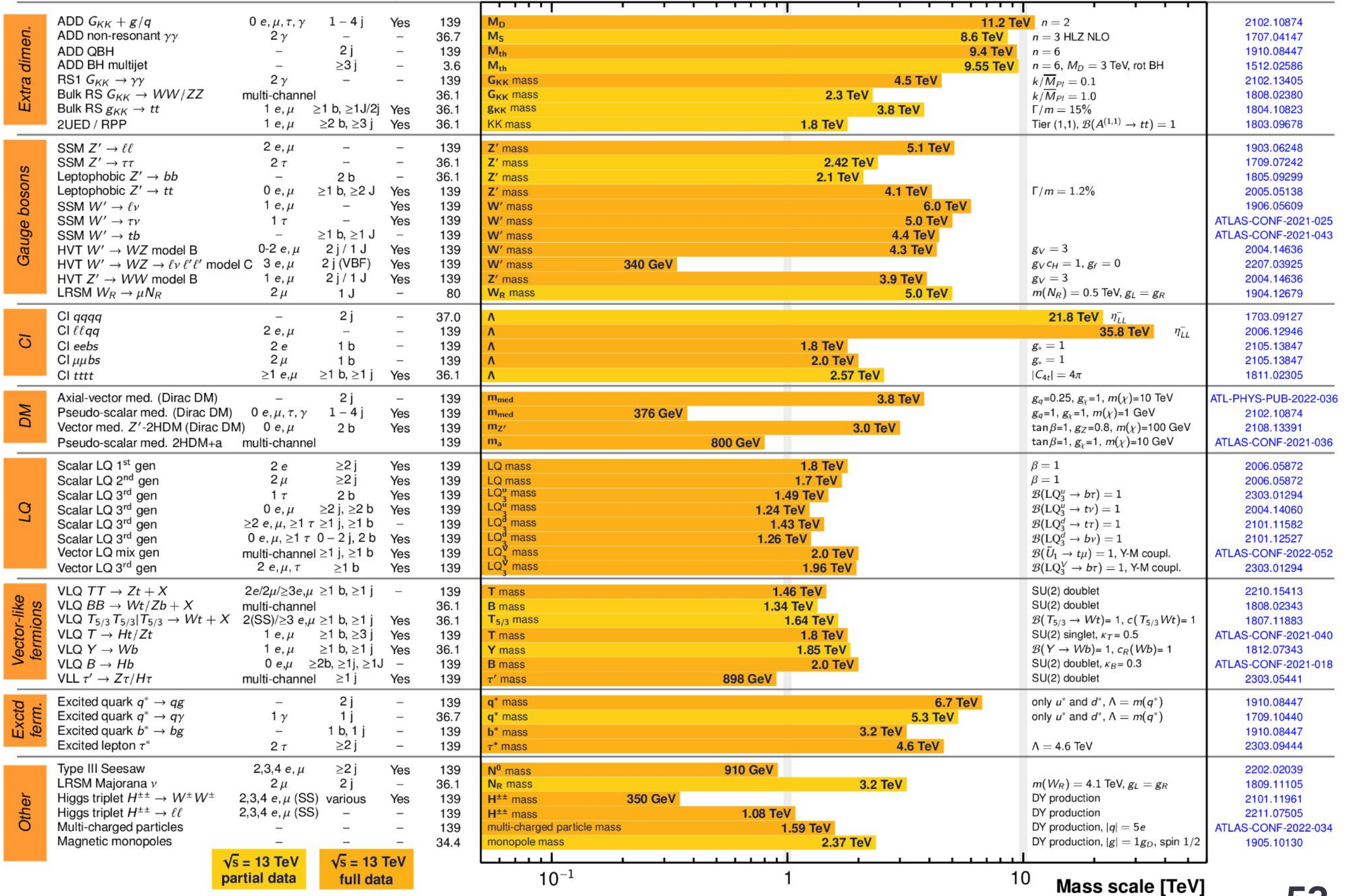
Phys. Lett. B 842 (2023) 137963

Most sensitive channel:



CMS sets an observed (expected) upper limit of 0.18 (0.10) on BR(H→inv.) in VBF events [*Phys. Rev. D* 105 (2022) 9, 092007]

Mass reach of BSM searches by ATLAS



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 13$ TeV

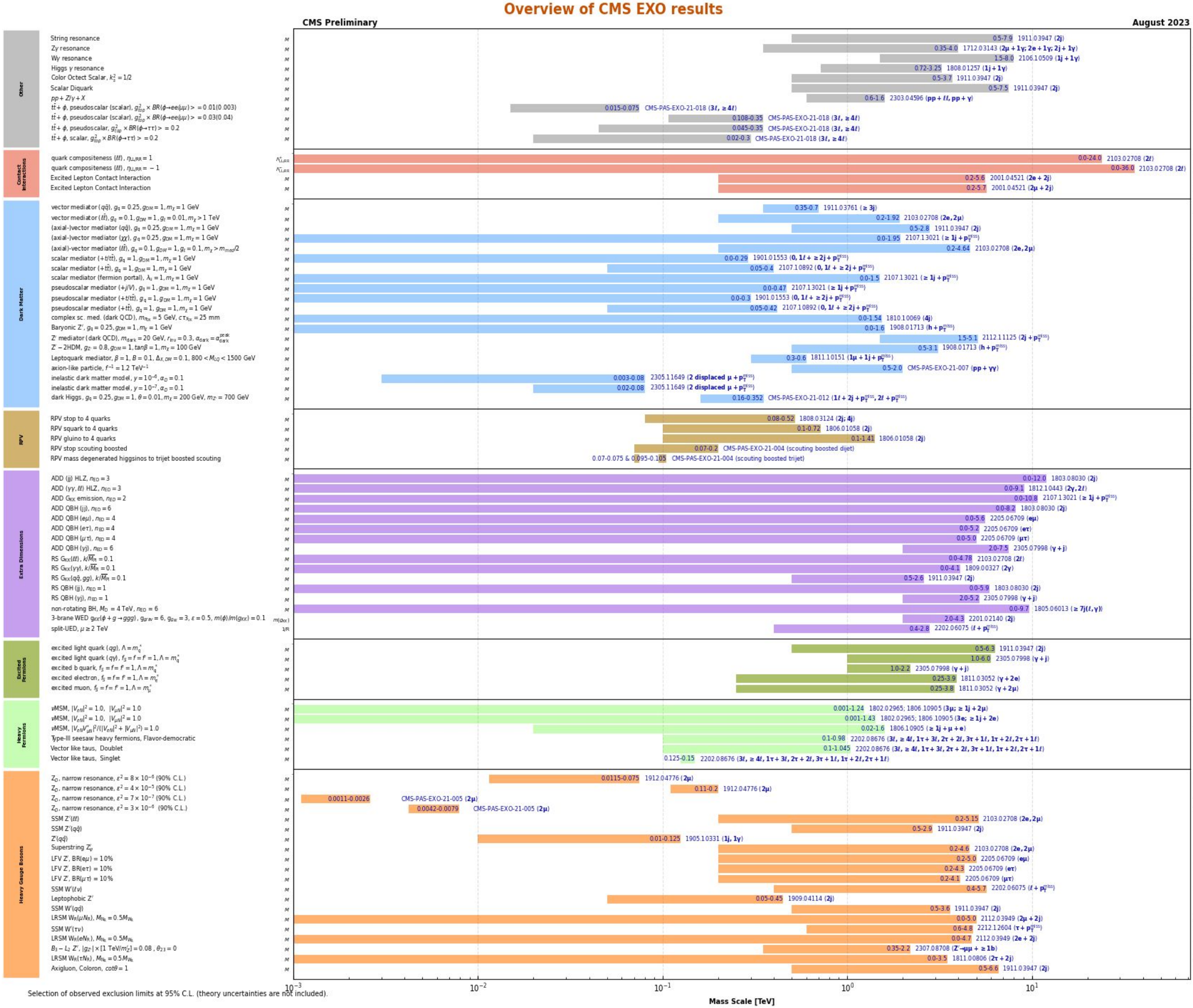
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	M_D	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ$ model B	$0\text{-}2\ e, \mu$	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \to WW$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	Z' mass	3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ	35.8 TeV	η_{LL}^{-}	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ	1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ	2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	$\geq 1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med}	3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	$m_{Z'}$	3.0 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a	800 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass	1.49 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	$\geq 2\ e, \mu, \geq 1\ \tau$	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu, \geq 1\ \tau$	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass	2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	$2\ e, \mu, \tau$	≥1 b	Yes	139	LQ_3^V mass	1.96 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e,\mu$	≥1 b, ≥1 j	–	139	T mass	1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.08447
	Excited lepton τ^*	$2\ \tau$	≥2 j	–	139	τ^* mass	4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	$2,3,4\ e, \mu$	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	$2,3,4\ e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2,3,4\ e, \mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $\lvert q \rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATL-PHYS-PUB-2023-008

Mass reach of BSM searches by CMS

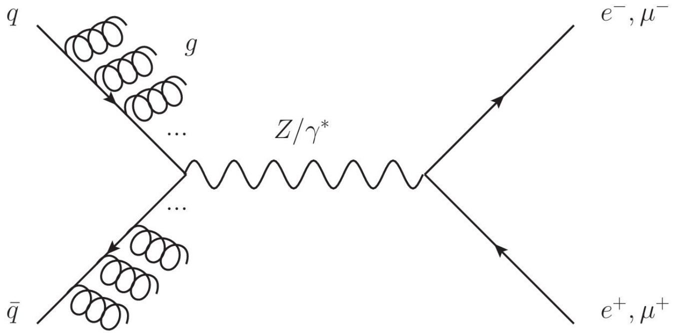


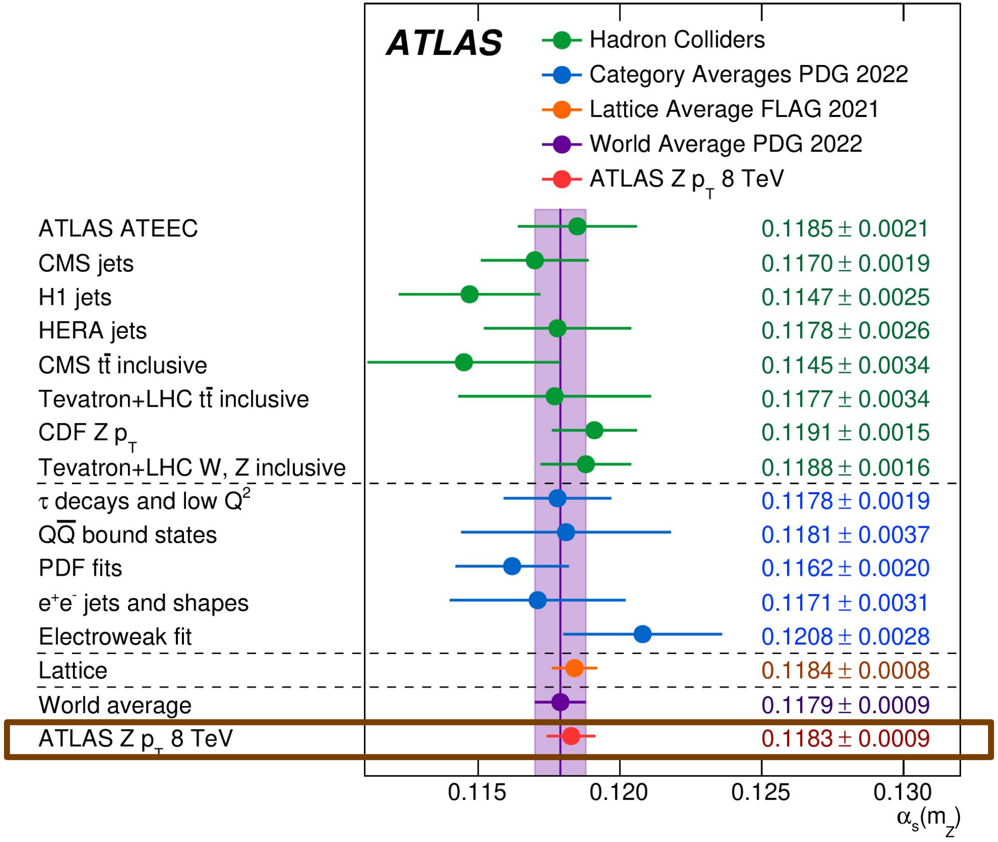
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Other Highlights

Measurement of the strong coupling constant

- Exploit recoil of Z bosons
  - i.e. study the transverse-momentum distribution of Z bosons
  - **Shape of Z boson pT distribution depends on α_s value**
- Most precise experimental determination of $\alpha_s(m_Z)$ so far

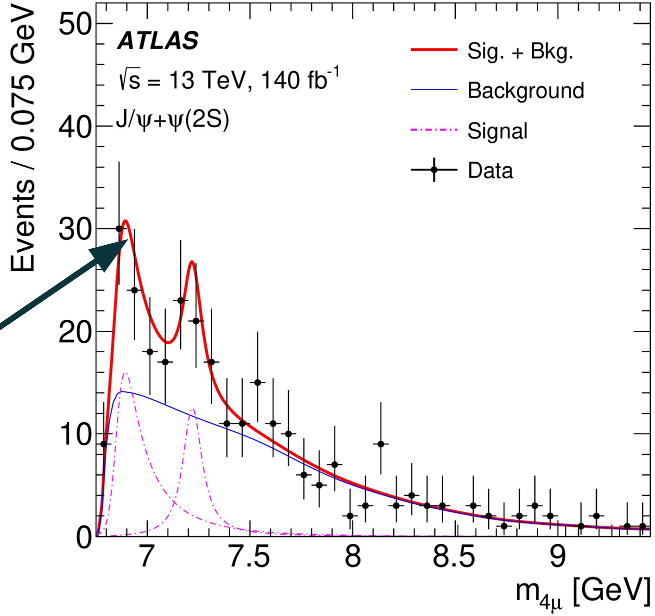




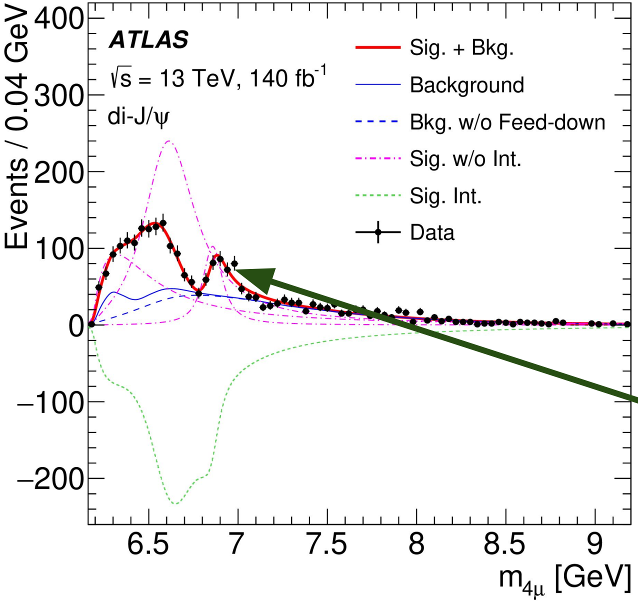
arXiv:2309.12986

Observation of an excess of di-charmonium events

- Search for Tetra-quarks by probing for:
  - ○ **(TQ) → J/ψ + J/ψ → 4μ**
  - ○ **(TQ) → J/ψ + ψ(2S) → 4μ**
- Found peaks around 6.9 GeV, consistent with the **LHCb observed X(6900)**



Phys. Rev. Lett. 131 (2023) 15, 151902



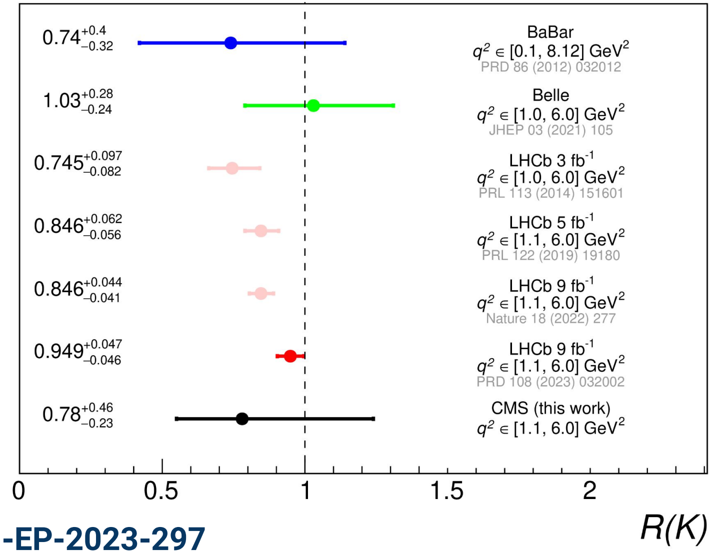
Peak has a significance around 4.7σ

Peak has a significance far above 5σ

Flavour-Physics (rare decays)

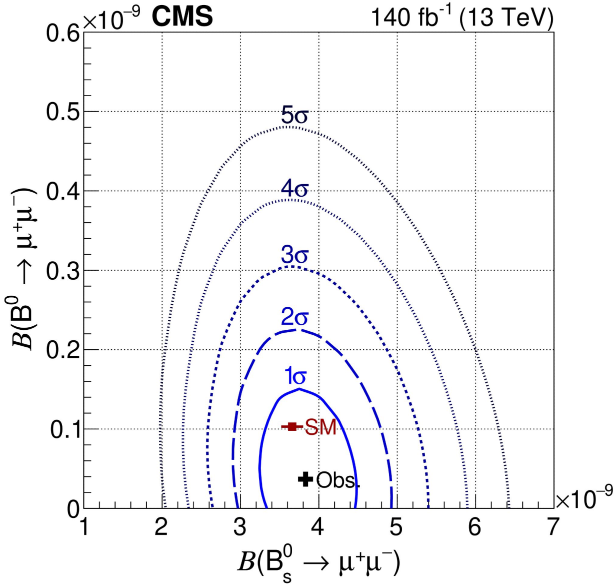
- Test of lepton flavor universality in $\mathbf{B^\pm \to K^\pm \mu^+\mu^-}$ and $\mathbf{B^\pm \to K^\pm e^+e^-}$ decays
- Ratio of branching fractions is probed for deviations from the SM predictions

$$R(\mathrm{K})_{\text{theory}}(q^2) = \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)(q^2)}{\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-)(q^2)}$$



CERN-EP-2023-297

***Phys. Lett. B* 842 (2023) 137955**



- **Rare B meson decays provide an excellent and complementary environment to search for BSM effects**
- **Measurement of $\mathbf{B(B_s \to \mu^+\mu^-)}$** is the most precise single measurement to date
- No evidence for $\mathbf{B(B^0 \to \mu^+\mu^-)}$ yet

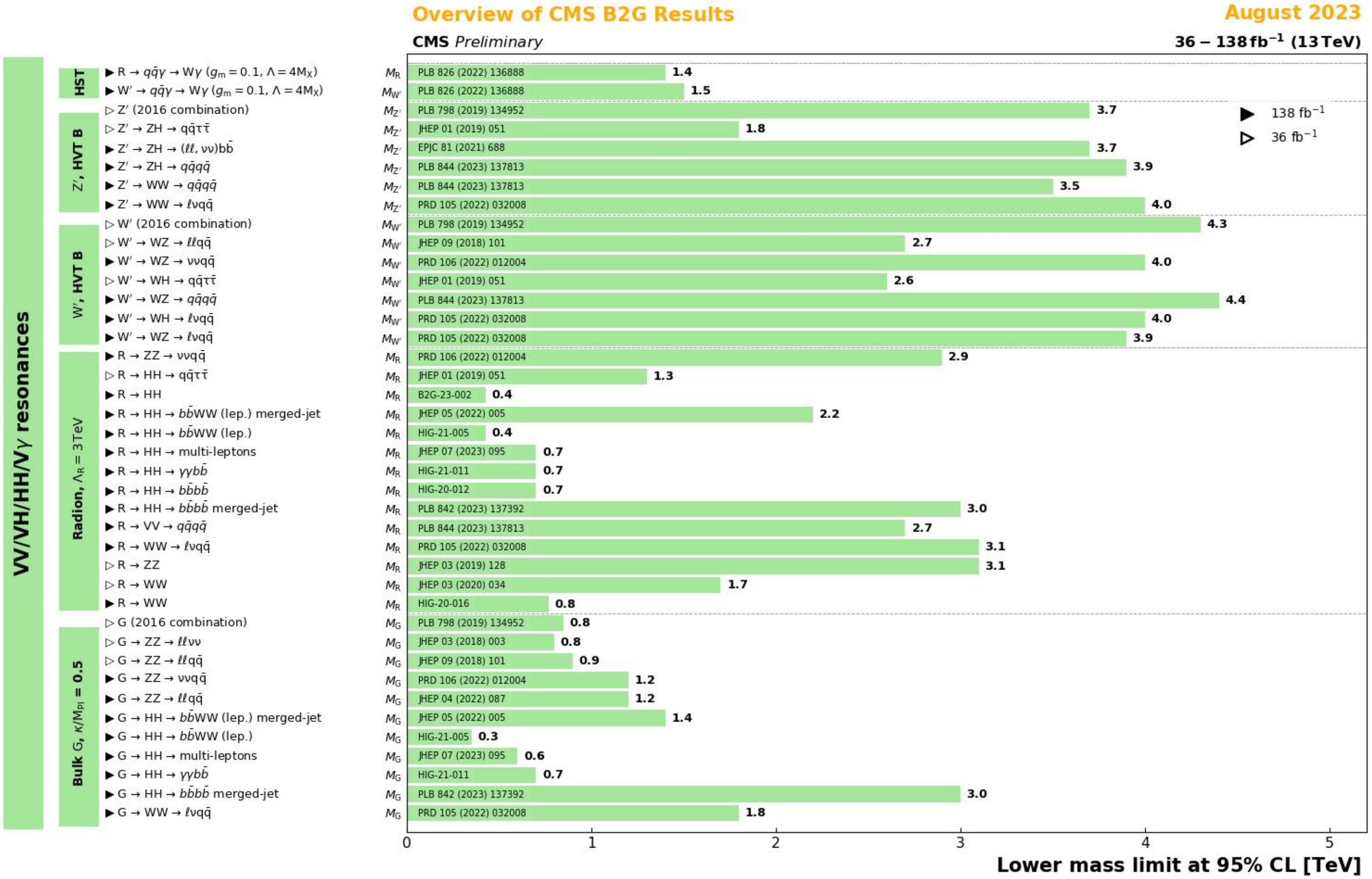
Concluding remarks

Concluding remarks

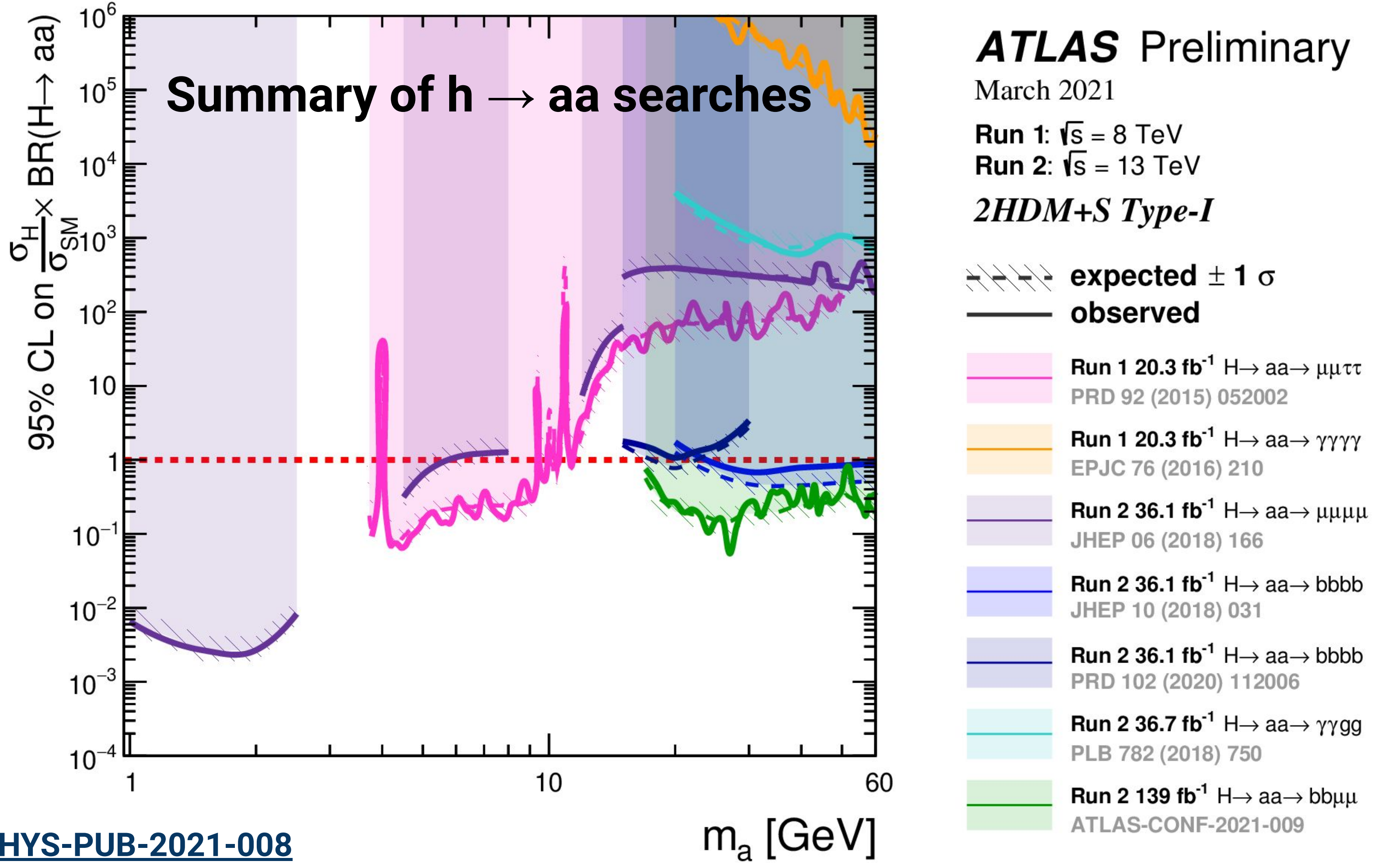
- ATLAS and CMS have exciting physics programmes
    - **Precision measurements** in many areas
        - Higgs boson, top quark and vector boson properties
        - Flavour-Physics
        - Rare processes: quartic gauge boson couplings, 4tops
    - **New physics searches** ranging up to the multi-TeV range
        - Extended Higgs/gauge sector
        - Dark matter/ long-lived particles
        - Indirect constraints from EFT fits
- Ongoing work on **improved reconstruction/identification techniques** promises significant gain in sensitivity (for both precision measurements and searches)
- Run 3 will double the size of the ATLAS/CMS datasets
    - Have already first results based on 13.6 TeV data
- HL-LHC is approaching (expecting an increase in statistics by a factor of ~20)

Back-up

Summary of CMS di-boson resonance searches

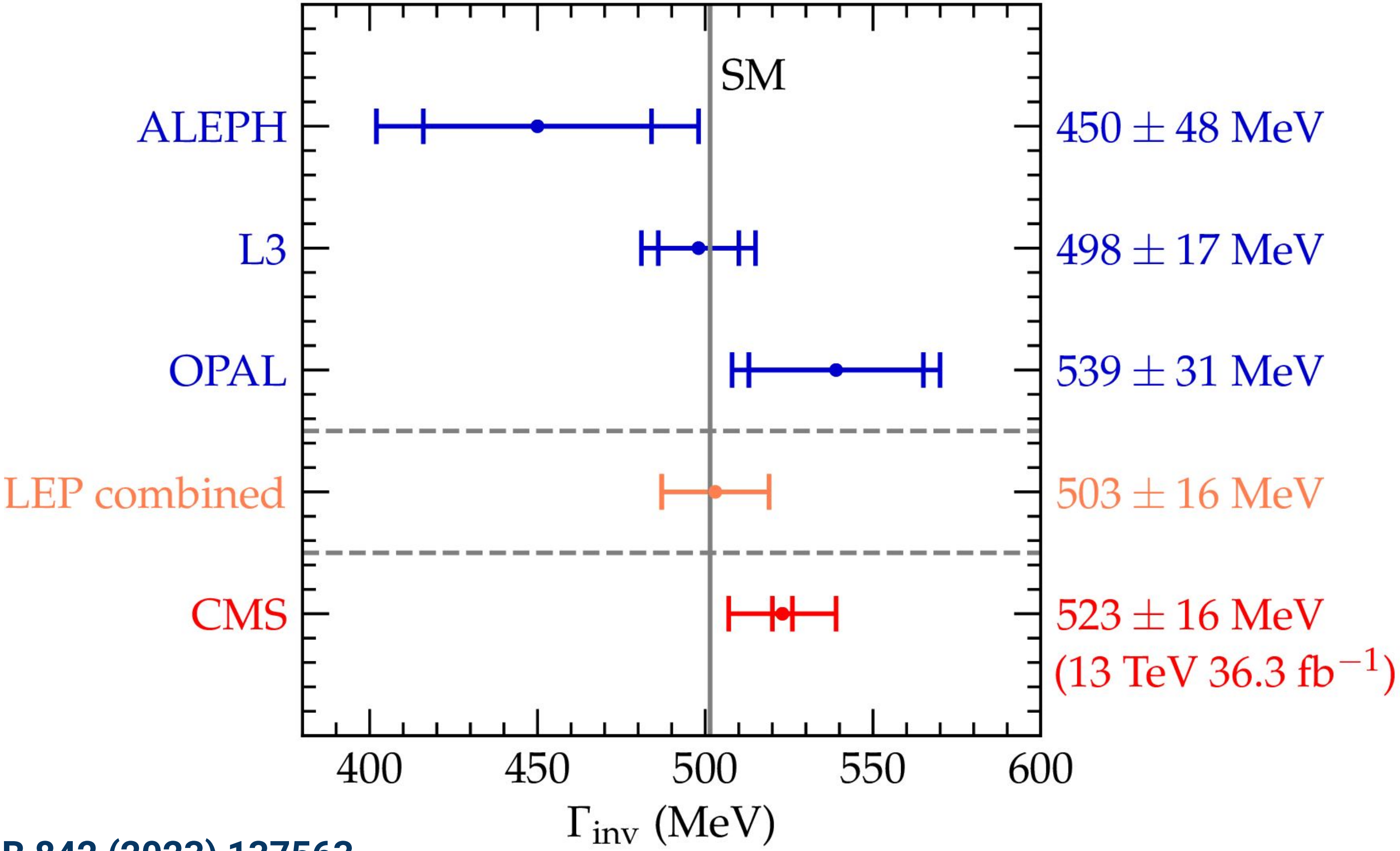


Summary of h → aa searches



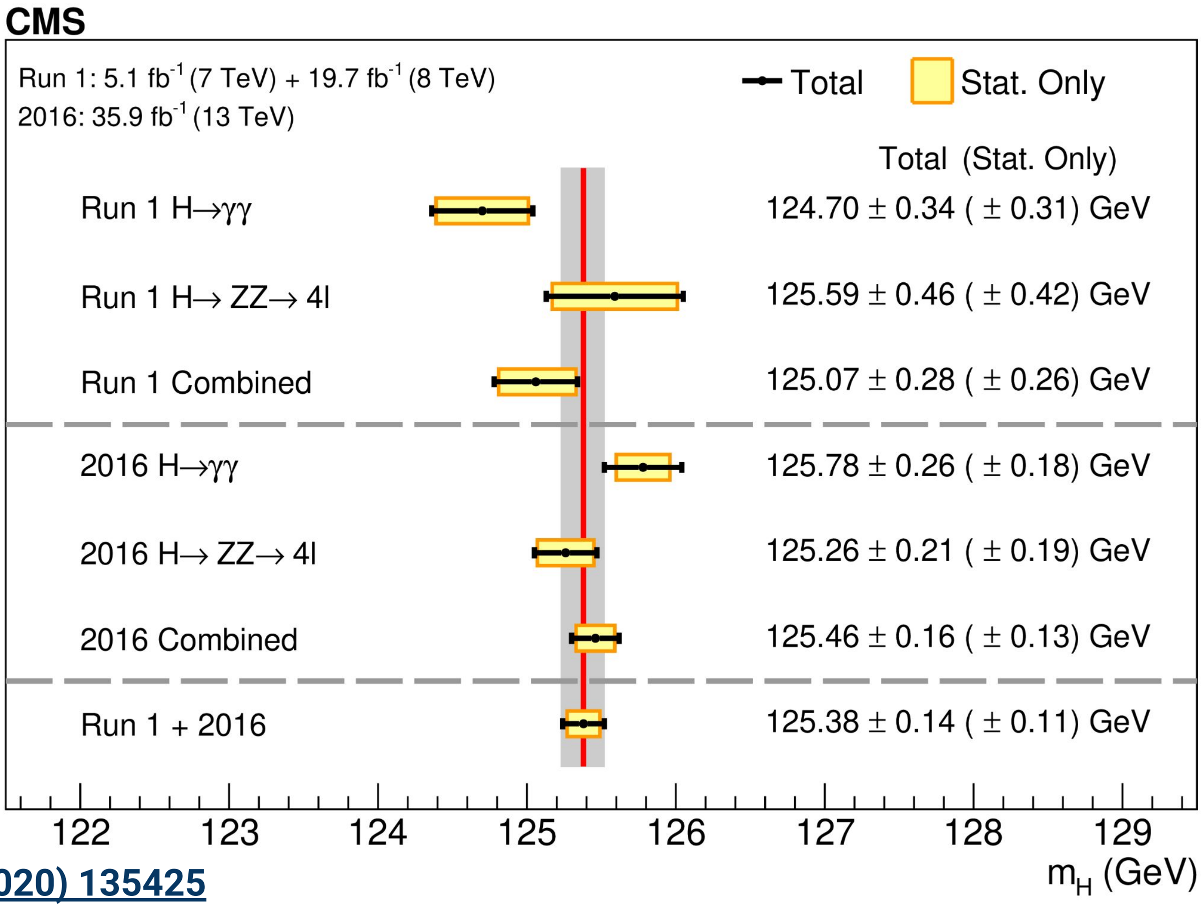
ATL-PHYS-PUB-2021-008

Measurement of the Z boson invisible width



Phys. Lett. B 842 (2023) 137563

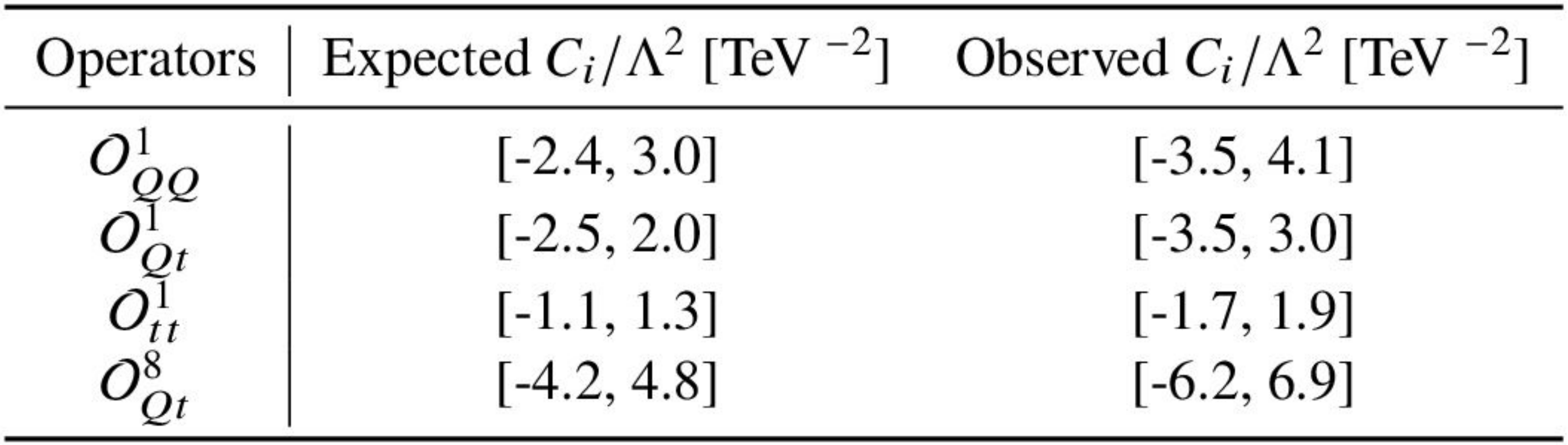
Higgs boson mass measurement



Phys. Lett. B 805 (2020) 135425

Observation of four top production

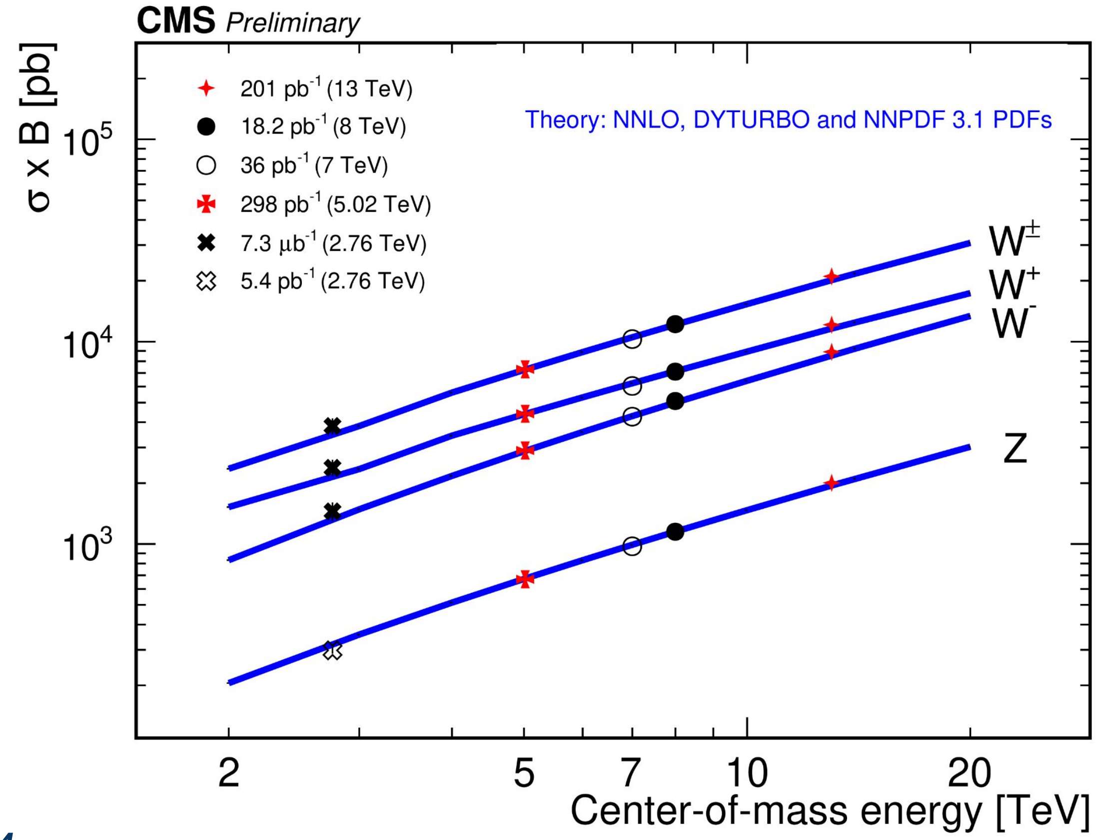
Expected and observed 95% CL intervals on EFT coupling parameters assuming one EFT parameter variation in the fit.



Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
$\mathcal{O}^1_{QQ}$	[-2.4, 3.0]	[-3.5, 4.1]
$\mathcal{O}^1_{Qt}$	[-2.5, 2.0]	[-3.5, 3.0]
$\mathcal{O}^1_{tt}$	[-1.1, 1.3]	[-1.7, 1.9]
$\mathcal{O}^8_{Qt}$	[-4.2, 4.8]	[-6.2, 6.9]

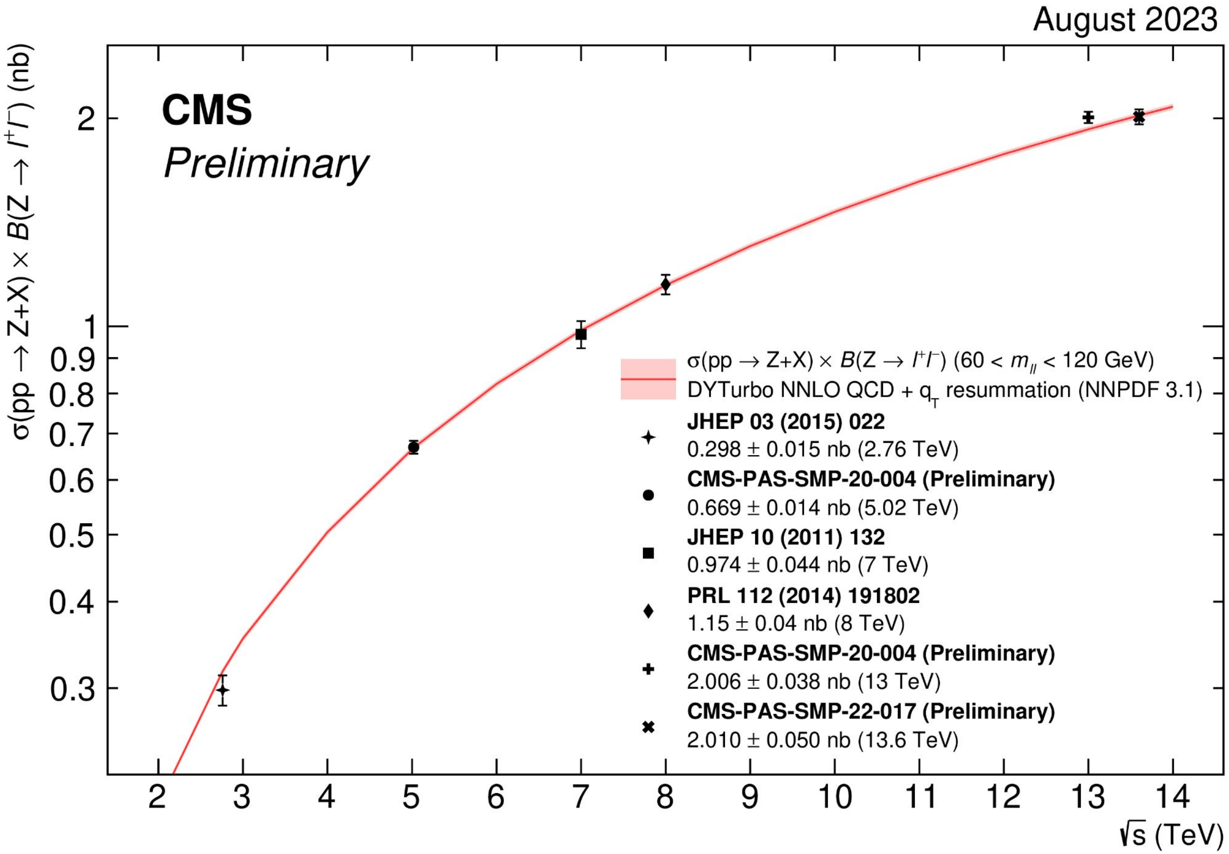
Eur. Phys. J.C 83 (2023) 6, 496

W/Z boson cross section measurements



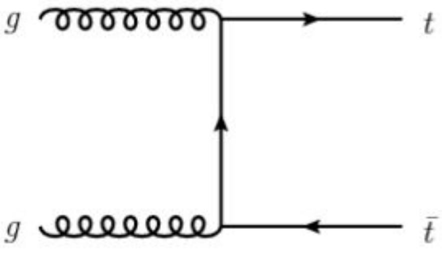
CMS-PAS-SMP-20-004

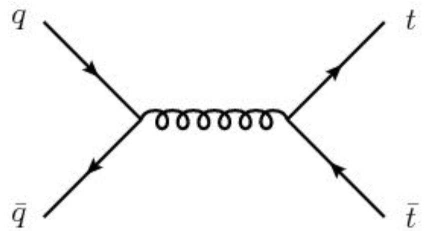
Z boson cross section measurements

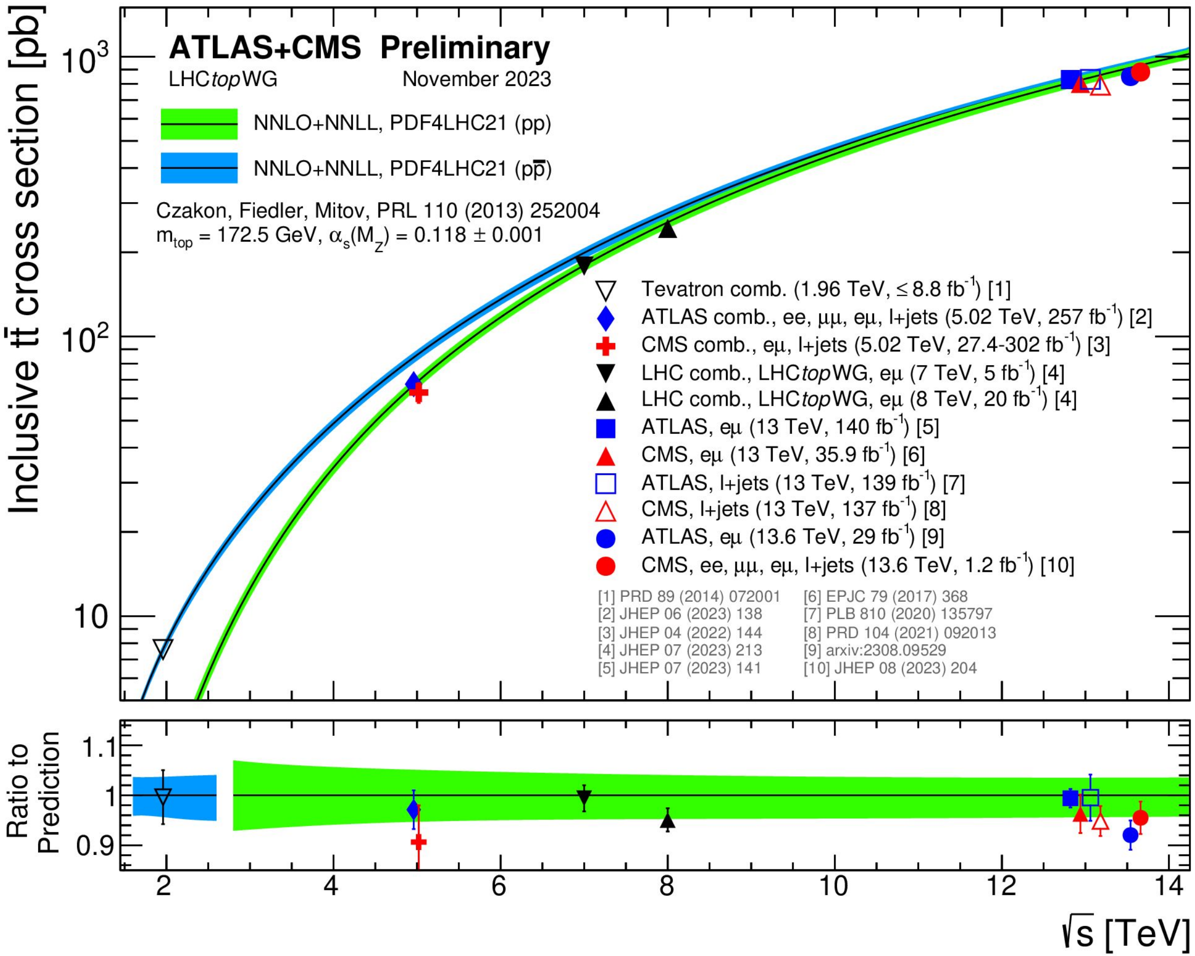


CMS-PAS-SMP-22-017

Top-quark pair production



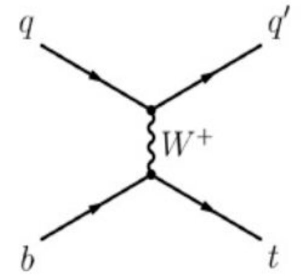




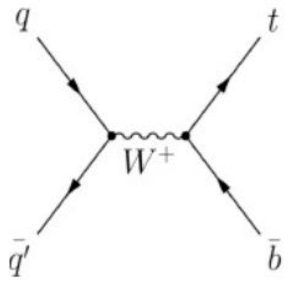
ATL-PHYS-PUB-2023-038

Single top quark production

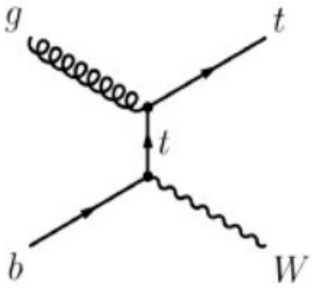
t-channel

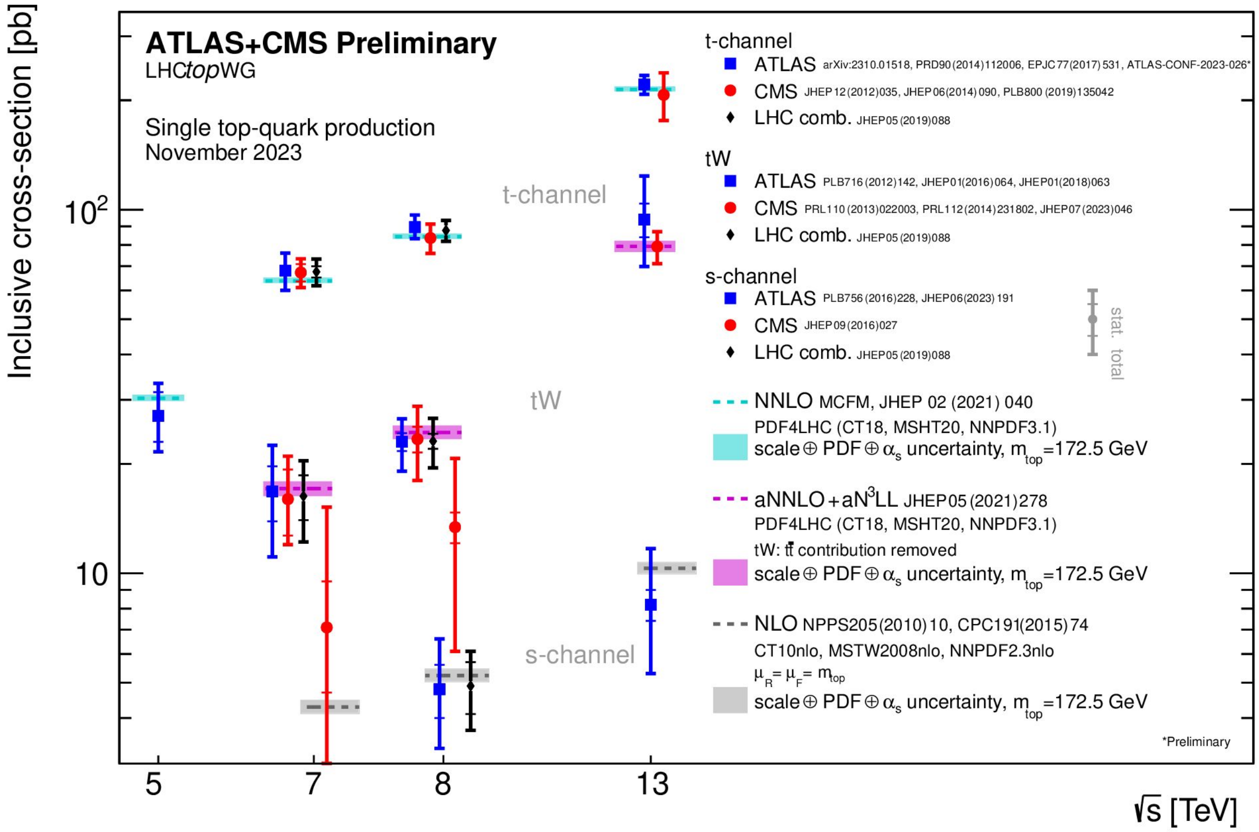


s-channel



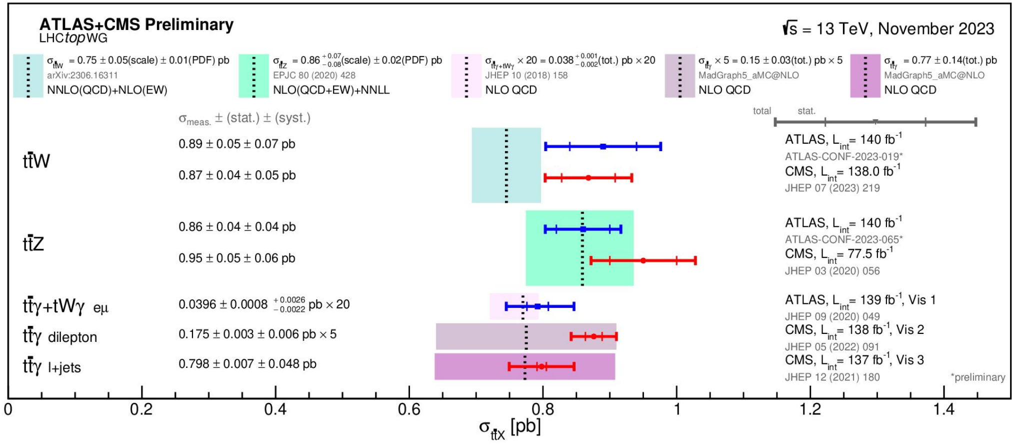
Wt

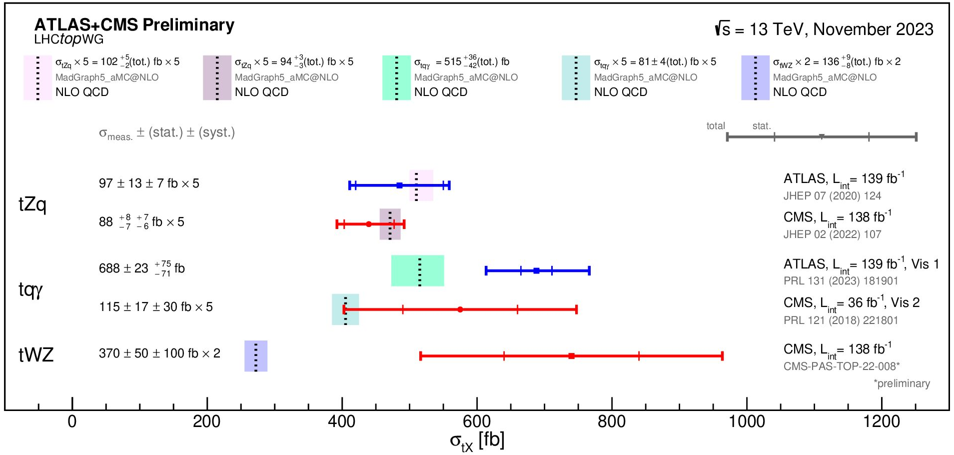


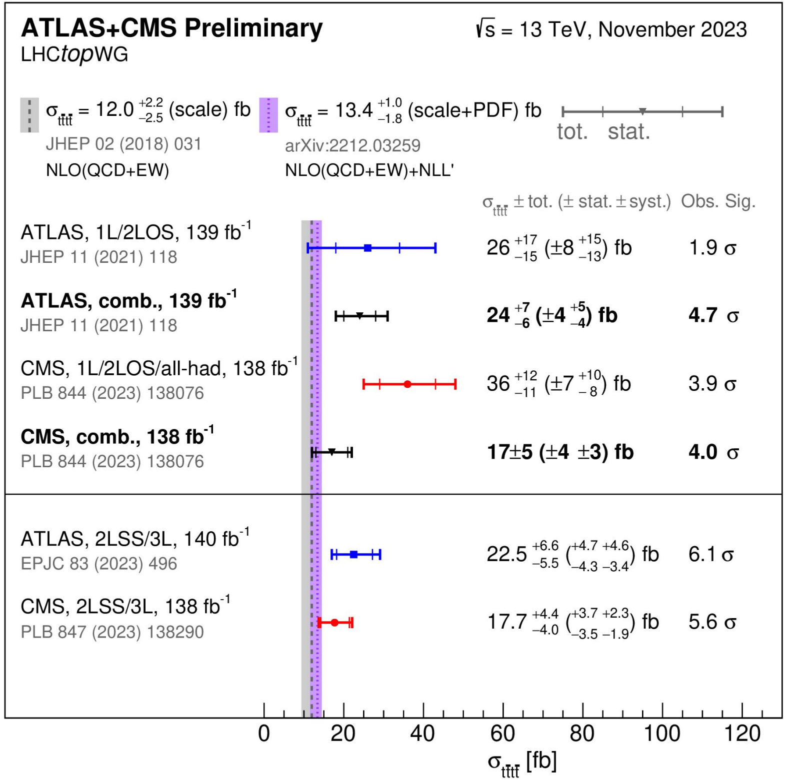


ATL-PHYS-PUB-2023-038

Top-quark + X production



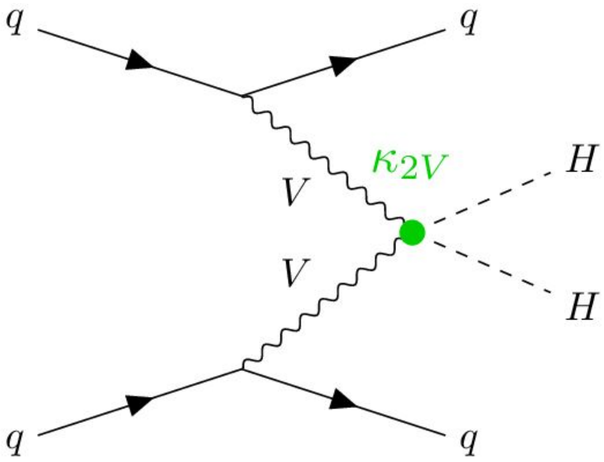


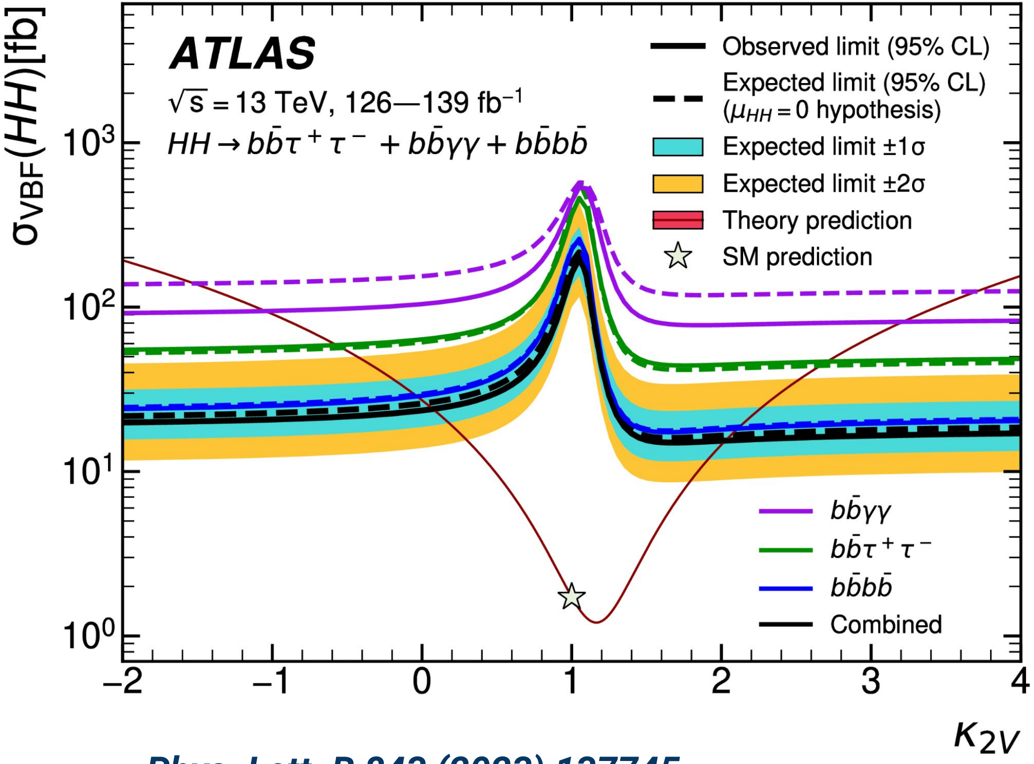


ATL-PHYS-PUB-2023-035

Searches for Higgs boson pair production

- **Interaction between two vectors bosons and two Higgs bosons.**

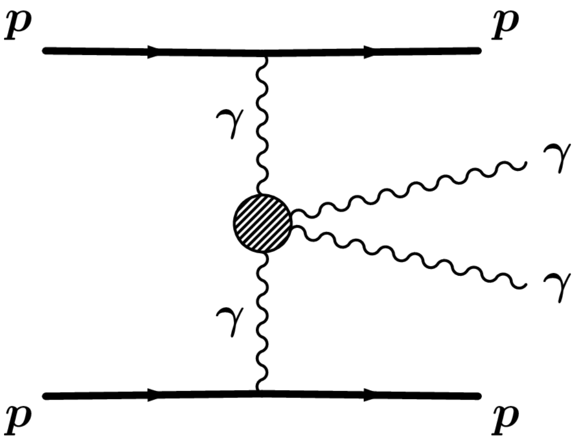


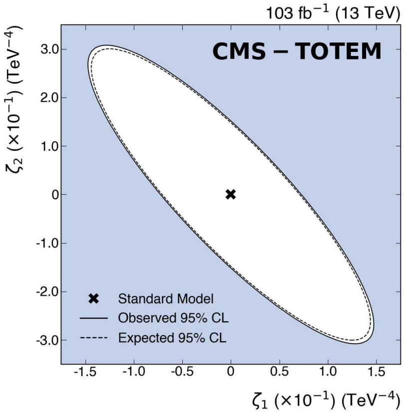


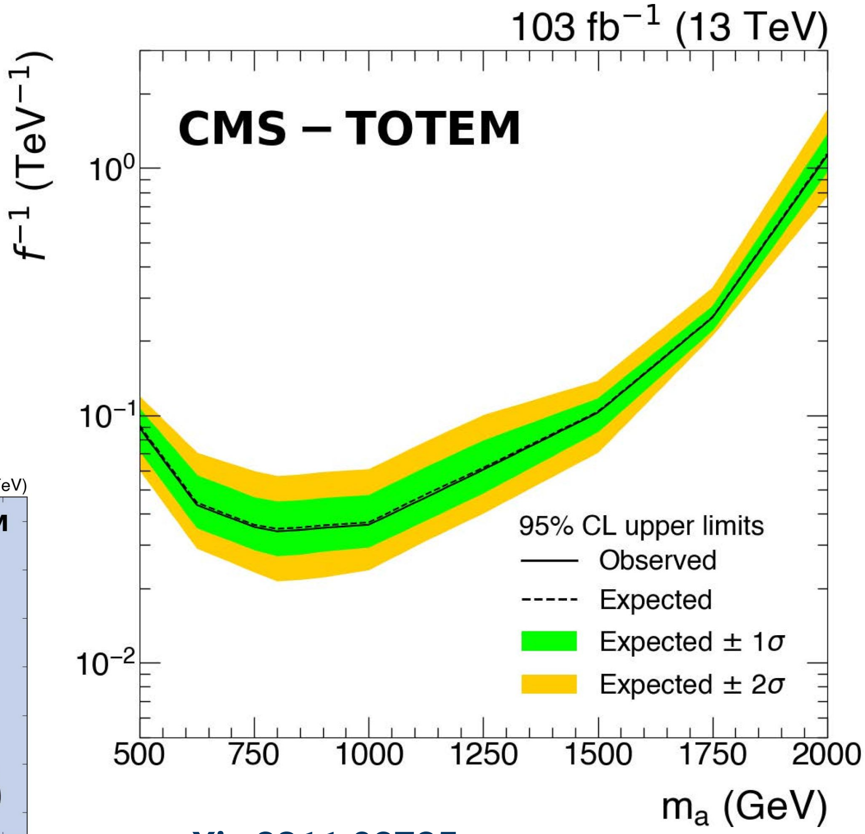
[*Phys. Lett. B 843 (2023) 137745*]

Search for high-mass exclusive diphoton production with tagged protons

Limits at 95% confidence level are derived for the four-photon anomalous coupling parameters and the production of axion-like particles with coupling strength to photons

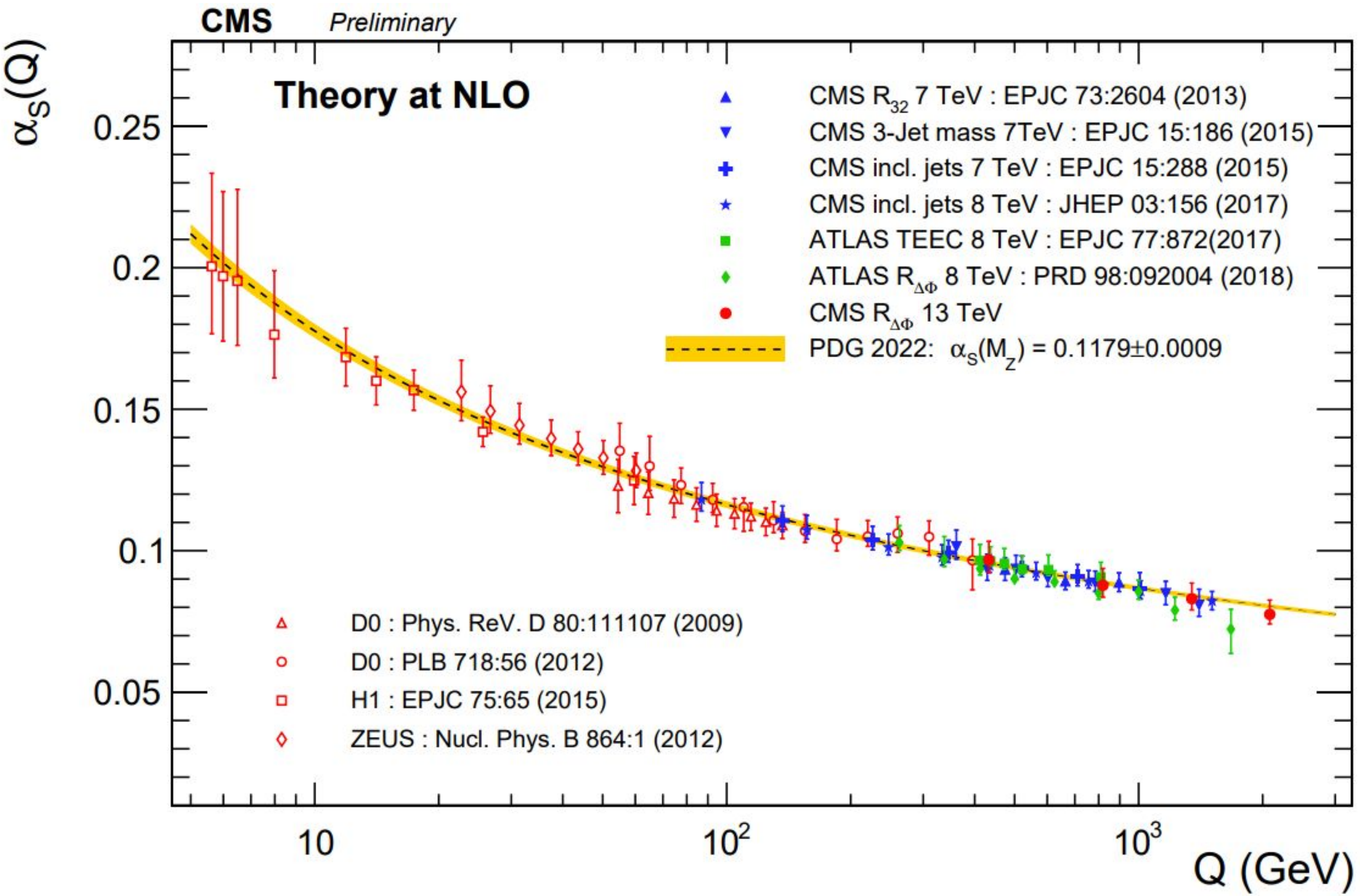






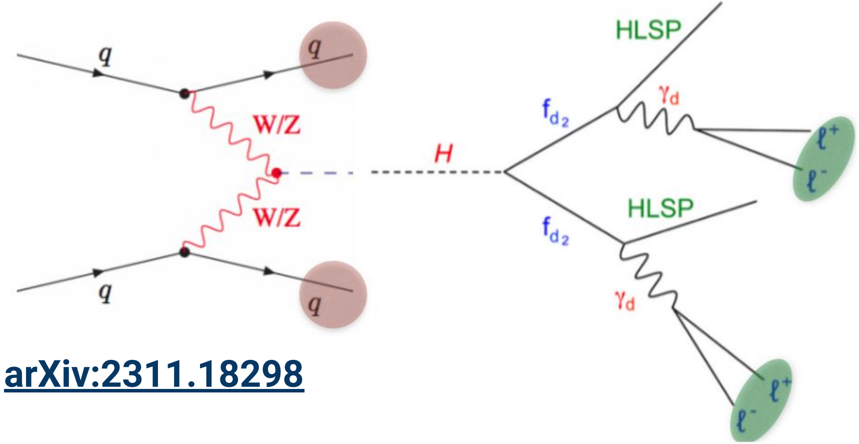
arXiv:2311.02725

Measurement of the strong coupling constant



Search for light long-lived neutral particles from Higgs boson decays

- Target: VBF production mode of the Higgs boson (for the first time)



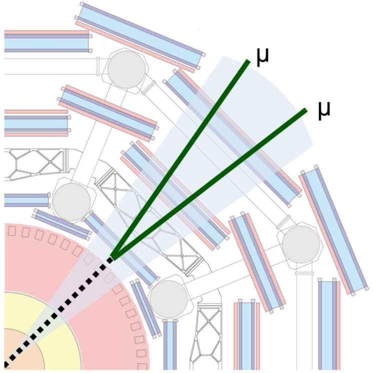
arXiv:2311.18298

- Predicted in dark sector models with additional $U(1)_d$ symmetry weakly coupled to SM.
  - Leads to H ⟶ $2\gamma_d$ + X decays via Higgs & vector portals
  - Final states ($\gamma_d \longrightarrow \ell^+\ell^-$/qq) + MET signature
- Focus on:
  - Small couplings ε ⟶ long-lived γ_d
  - $m_{\gamma d} << m_H$ ⟶ collimated γ_d decays

For $\gamma_d \longrightarrow \mu^+\mu^-$

Decays outside Inner Tracking acceptance

Pair of close-by Tracks in the Muon Spectrometer

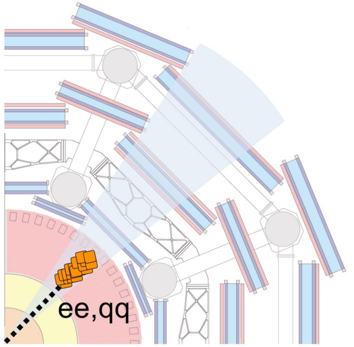


muonic DPJ

For $\gamma_d \longrightarrow e^+e^-$/qq

Targeting decays in Hadronic Calorimeter

Low EM fraction jets

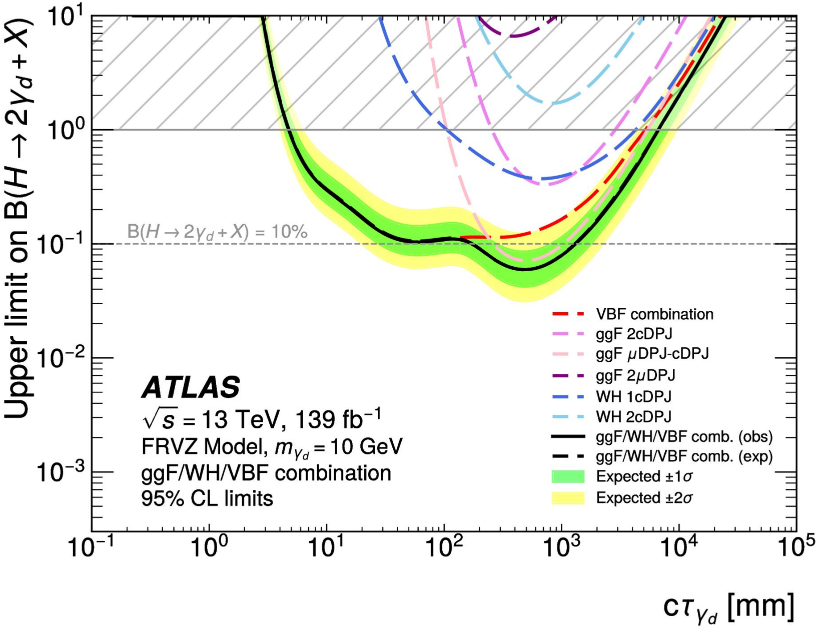


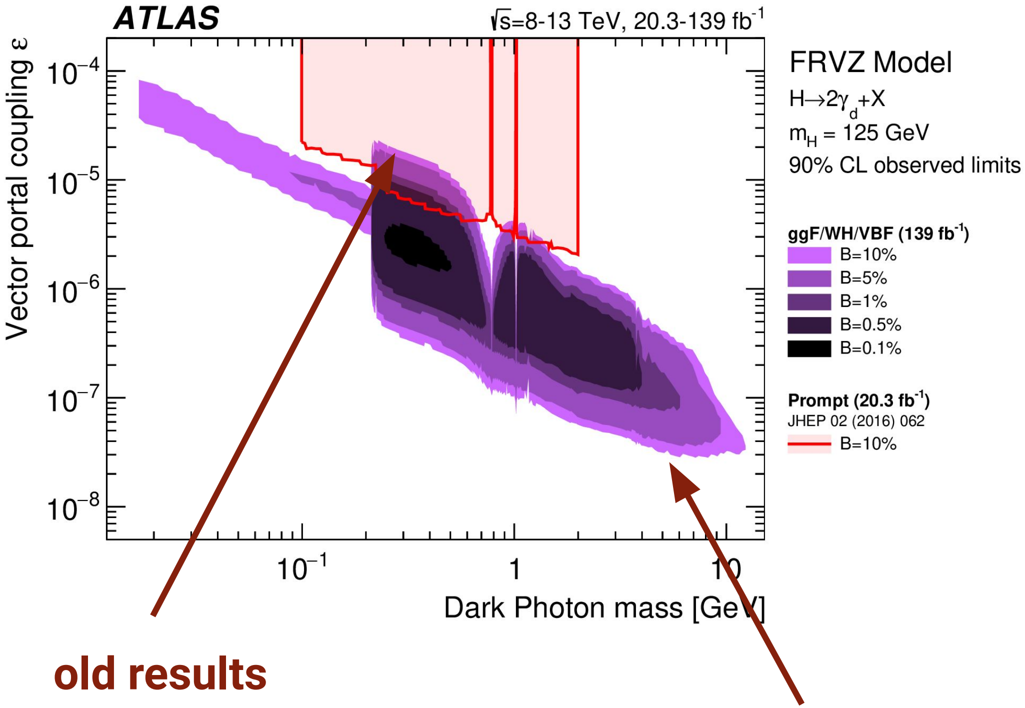
calorimeter DPJ

Search for light long-lived neutral particles from Higgs boson decays

- Perform statistical combination with results from studies in other Higgs boson production modes

[arXiv:2311.18298](https://arxiv.org/abs/2311.18298)





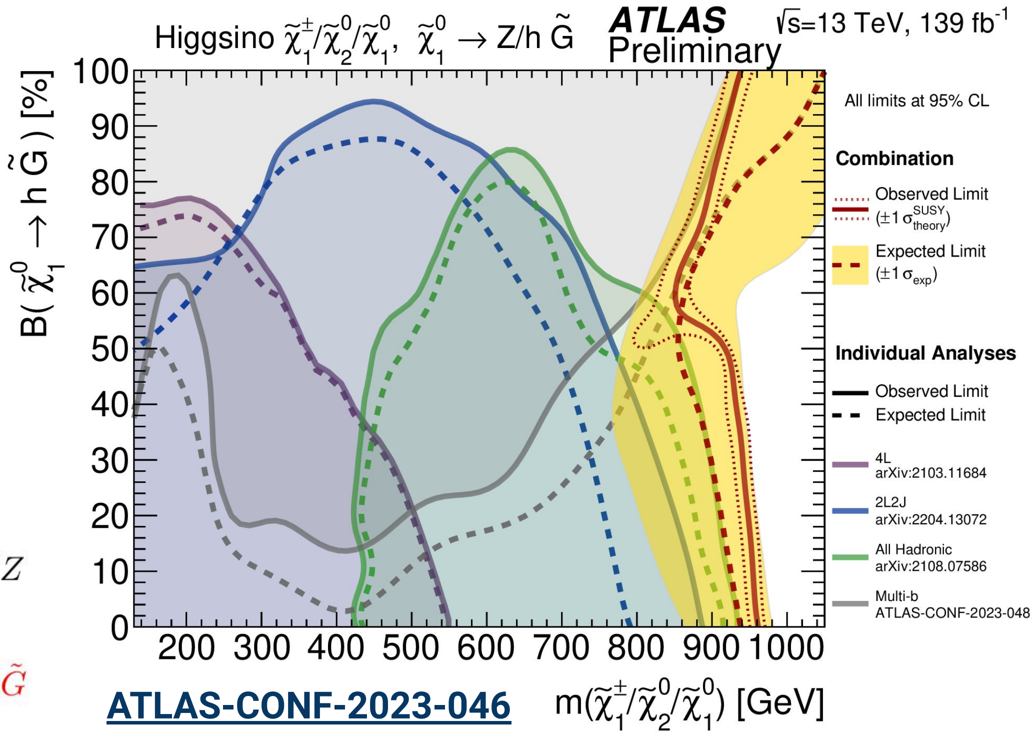
old results

newest results

[arXiv:2311.18298](https://arxiv.org/abs/2311.18298)

Statistical combination of Run 2 searches for electroweakinos

- Effort to combine 12 EWK analyses
    - **Focus on events with WW/WZ/Wh/ZZ/Zh/hh + MET**
- Consider a wide range of different signal scenarios
    - Wino pair-production with bino LSP
    - Gauge mediated models with gravitino LSP



ATLAS-CONF-2023-046