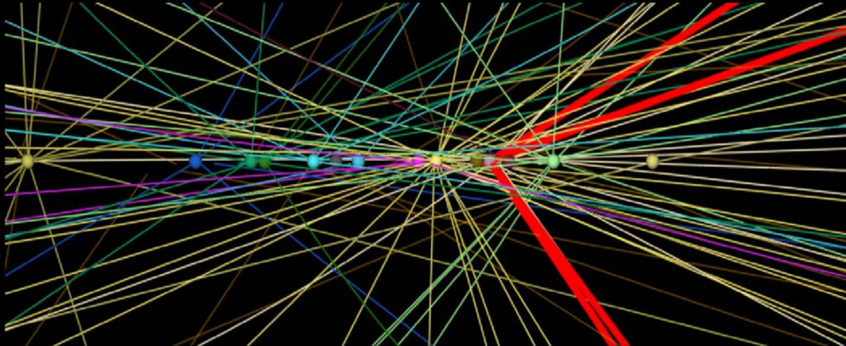
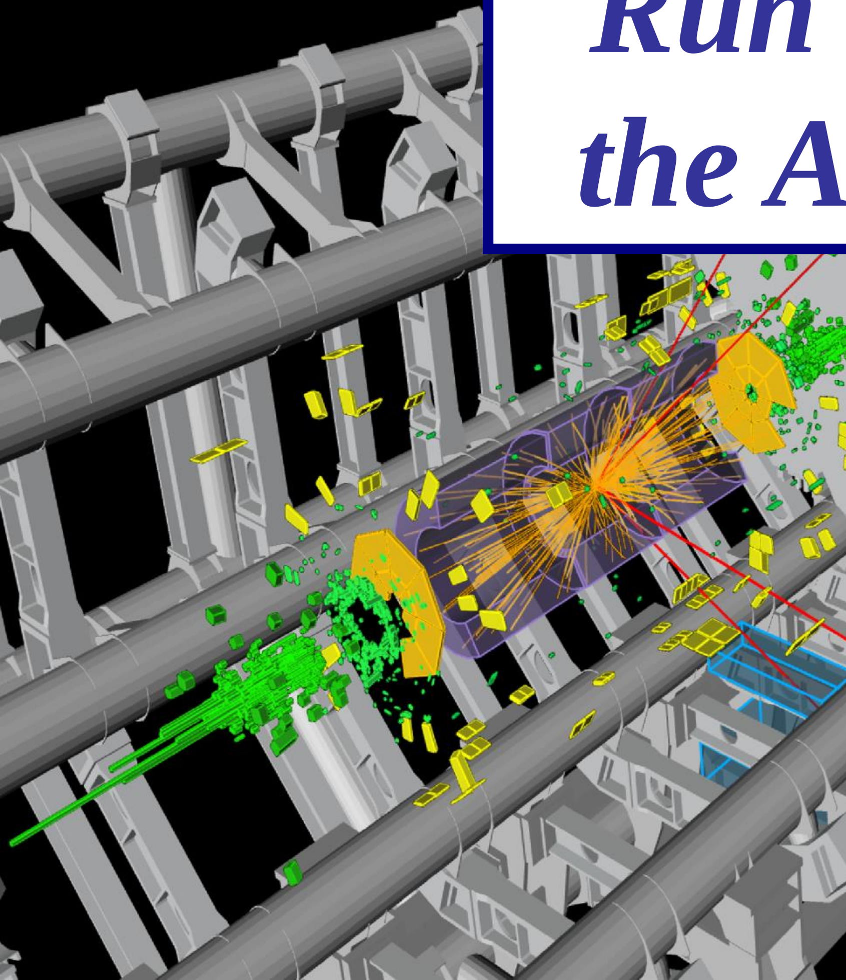


ATLAS EXPERIMENT
http://atlas.ch

Run 2 highlights from the ATLAS experiment



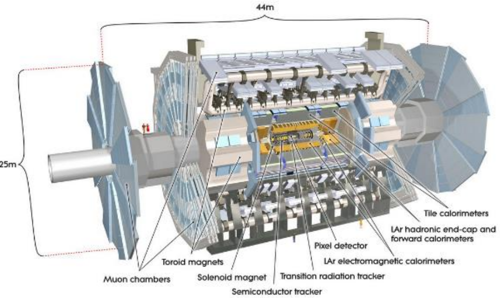
Thibault Guillemin (LAPP),
on behalf of the ATLAS collaboration

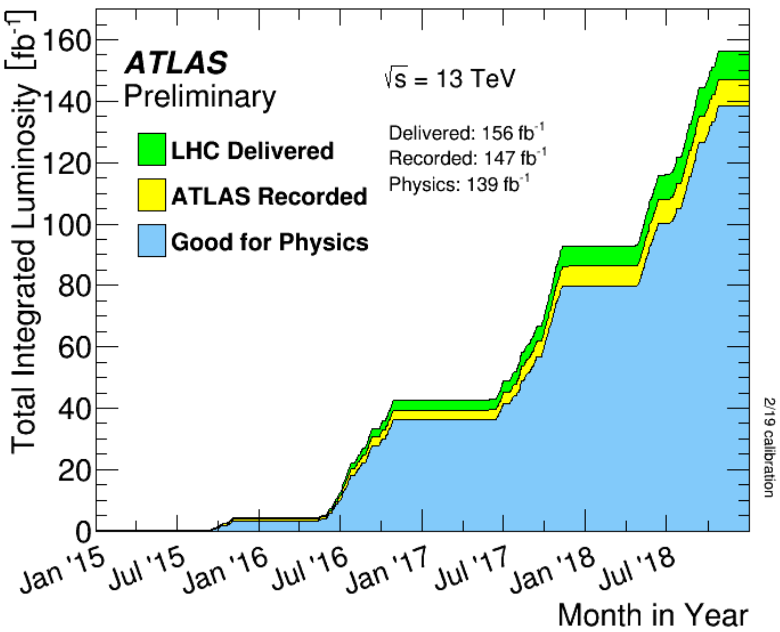
Epiphany 2021,
January 7-10 2021

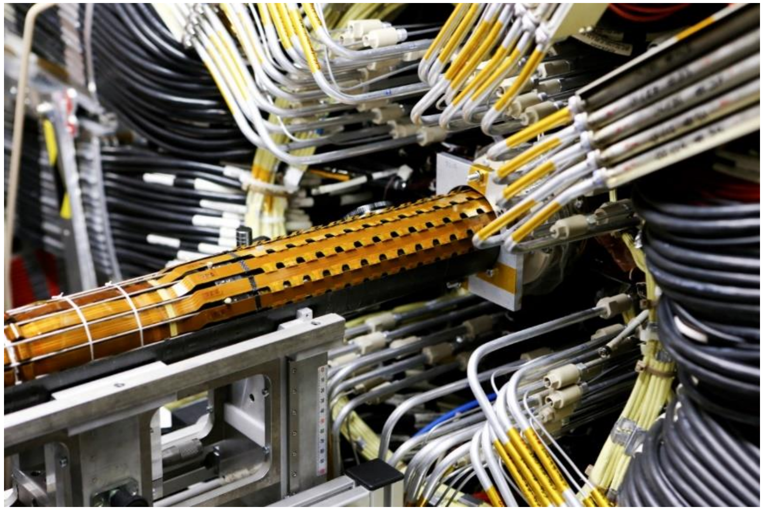
Laboratoire d'Annecy-le-Vieux de Physique des Particules

ATLAS Run 2 proton-proton dataset

Run 1, 2011-2012: 25 fb^{-1}, 7-8 TeV





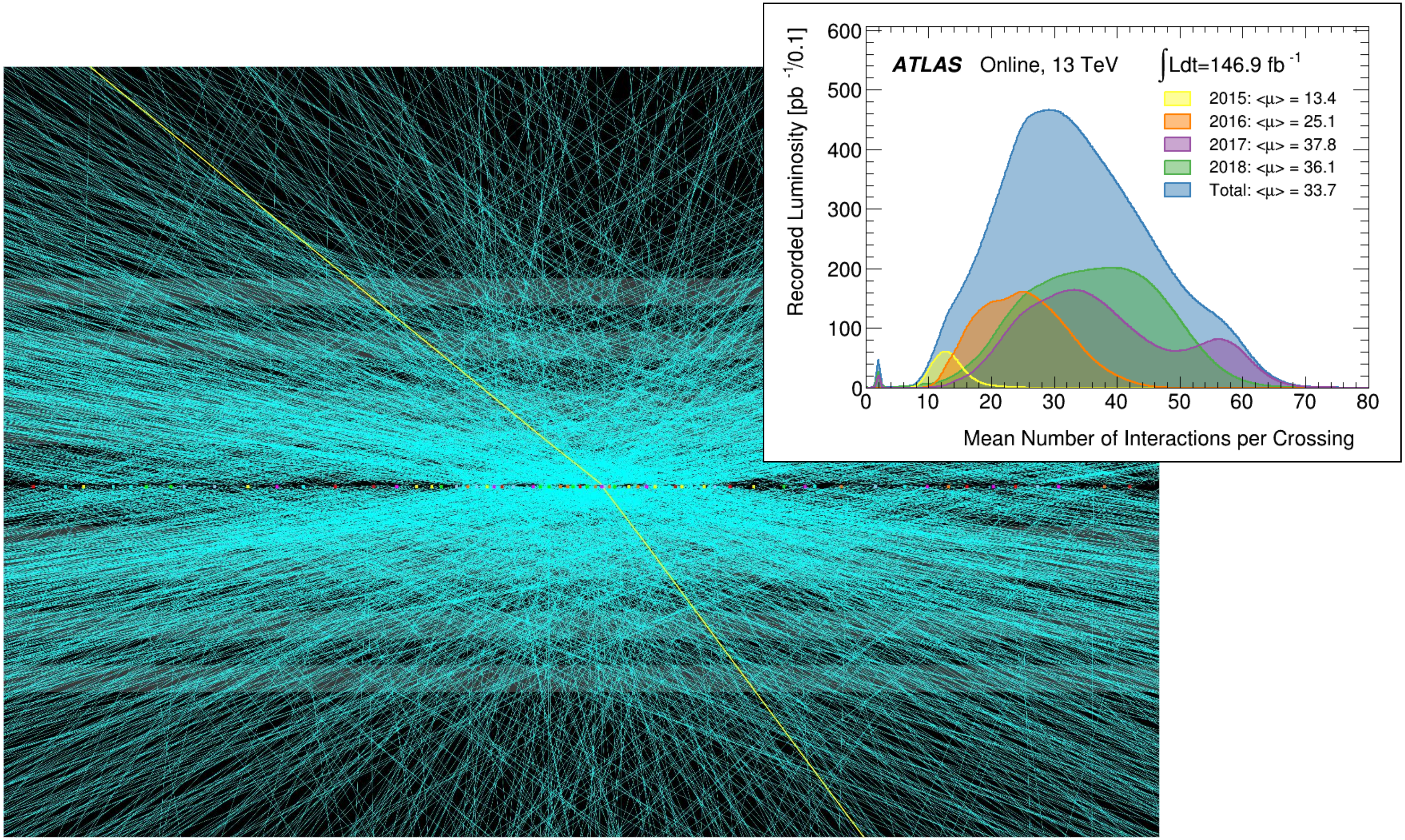


2015-2018: 139 fb^{-1}, 13 TeV
Data taking efficiency: 94.2%
Data quality efficiency: 94.6%

Main detector upgrade for Run 2: addition of an insertable B-layer
➔ 4th pixel layer
(3.3 cm from the beam)

In addition: heavy ion results (not covered)
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

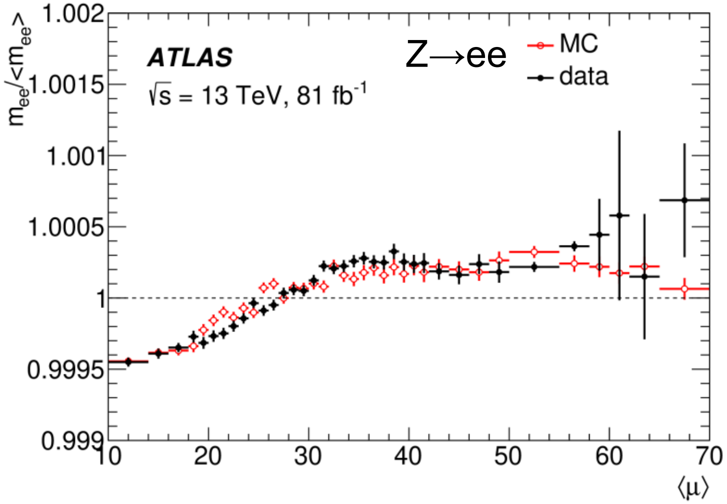
Pileup environment in Run 2



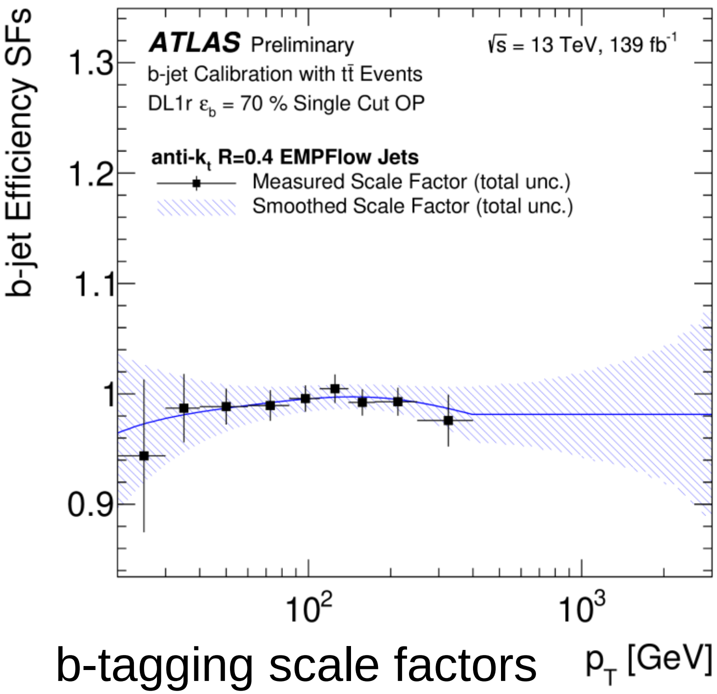
2017: Z→μμ event candidate with 65 reconstructed vertices

Physics object performance

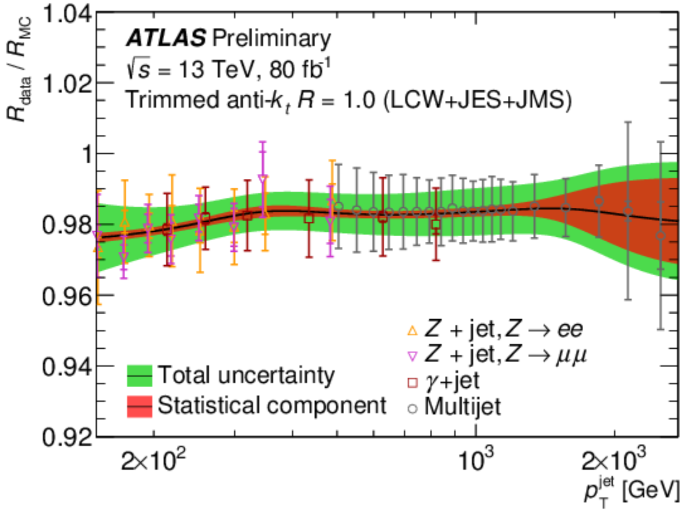
Development and validation of optimized algorithms for reconstruction, identification and calibration: latest multivariate techniques, pileup dependency, boosted topologies, etc.



Electron energy scale stability



b-tagging scale factors
Deep NN tagger



Jet energy scale for large-R jets

Outline

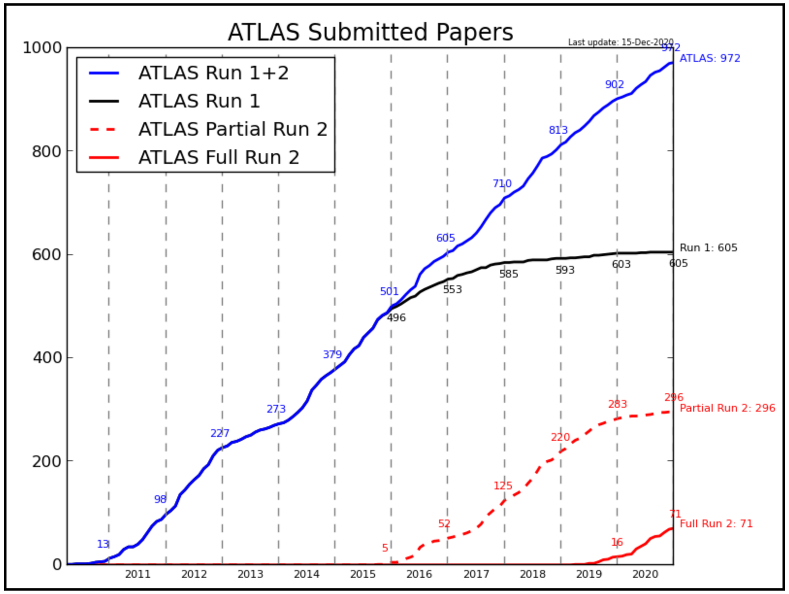
I. BSM

II. SUSY

III. Dark matter

IV. Higgs boson

V. Rare SM processes



367 Run 2 papers over 2015-2020

Priority given to 2020 results

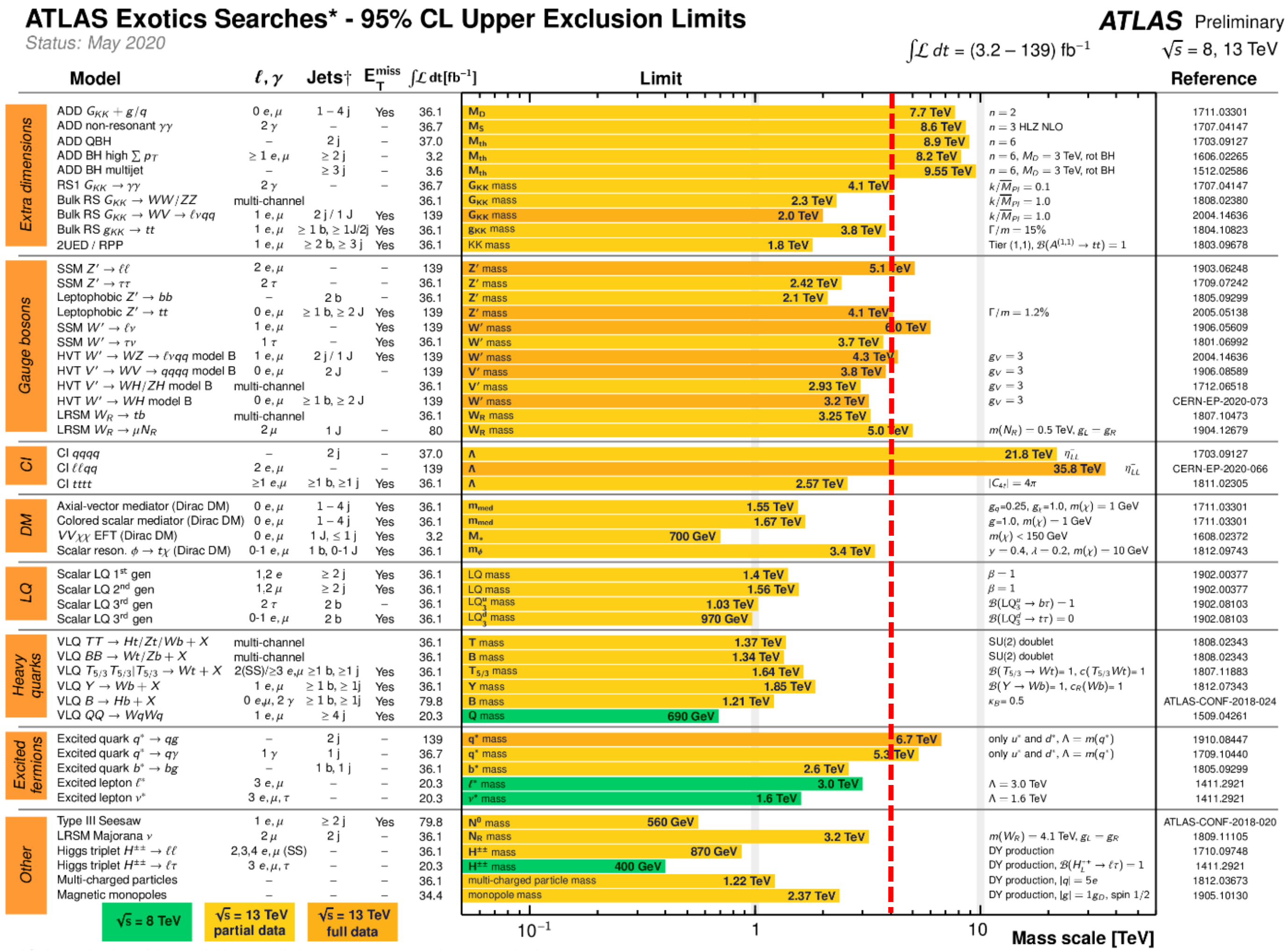
I. BSM

"In the exploration of the unknown, the high-energy frontier remains the best motivated direction to concentrate research efforts in particle physics."

Physics Briefing Book
arxiv:1910.11775

Where is everybody?

No new resonances observed until ~4 TeV



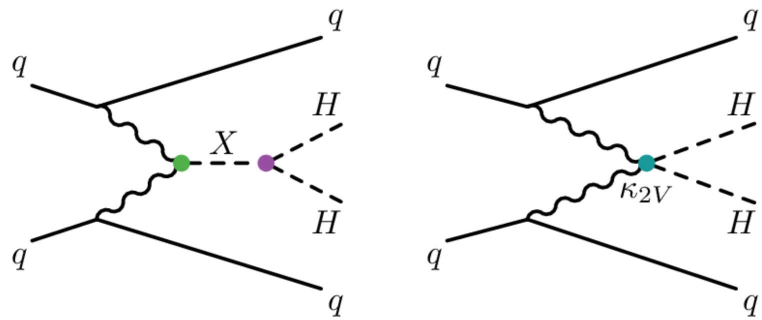
Try to go beyond Run-1 approaches: novel techniques, Higgs in the decay chains, more motivated scenarios, unconventional signatures, etc.

Search for the HH→bbbb process via VBF

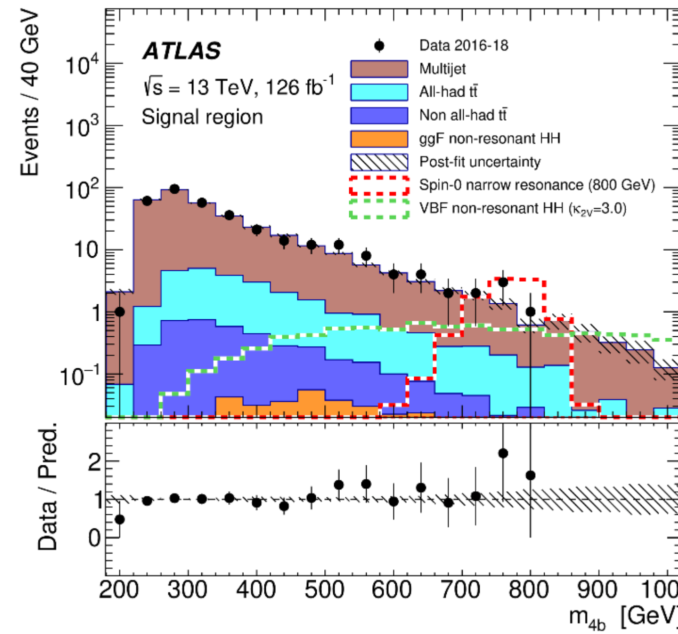
2020

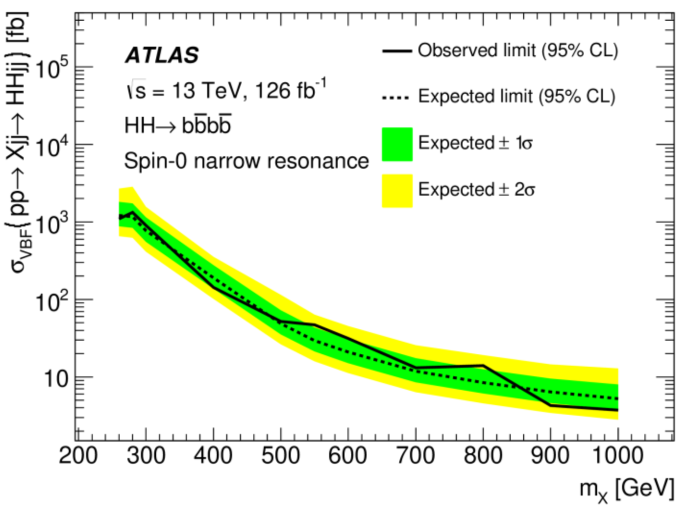
arxiv:2001.05178

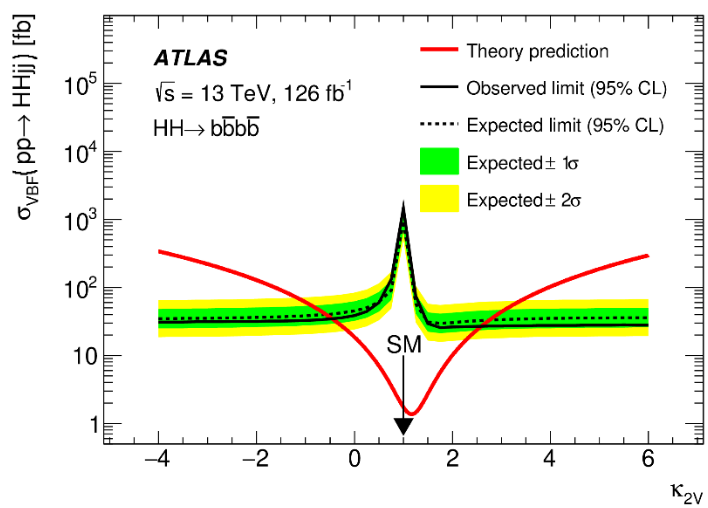
First HH search performed in the VBF mode, for both resonant and non resonant production



VBF topology, exactly 4 b-tagged jets





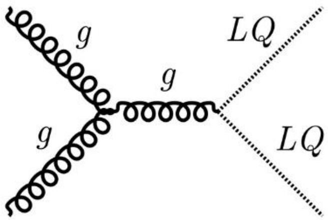


Leptoquarks

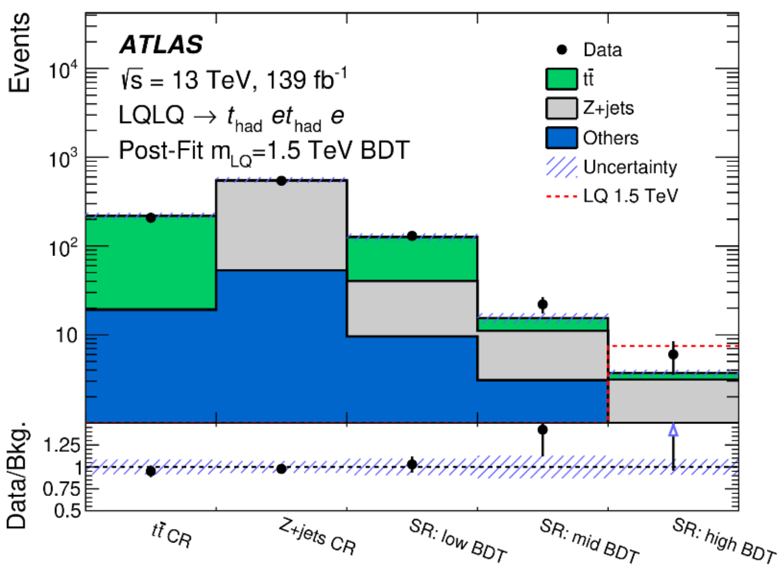
2020

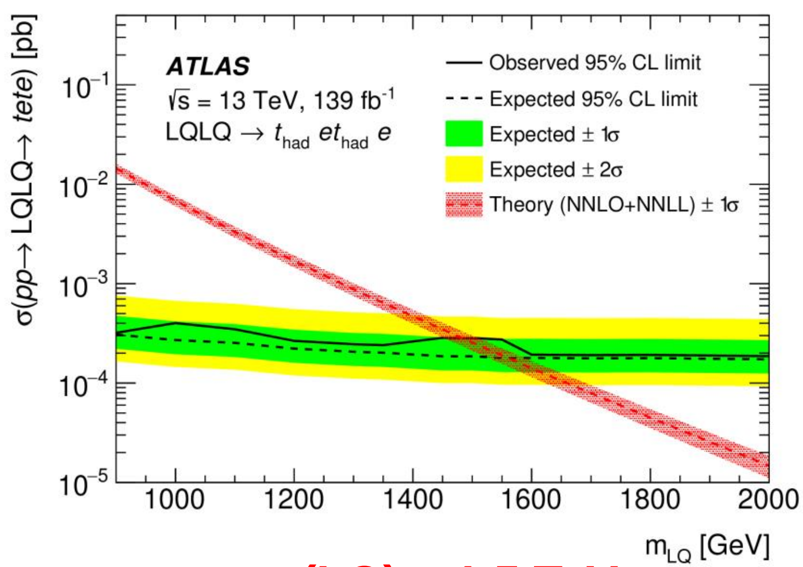
Renewed interest following the hints of B-anomalies: R(D*), R(K*)
Possible lepton flavour universality violation (in b→c/s semi-leptonic decays)

arxiv:2010.02098



- **Search for cross-generational leptoquarks**: LQ to tl tl (e/μ)
- Optimised for m(LQ)>1 TeV: top hadronic decays in the boosted regime (single large-R jet)





m(LQ) > 1.5 TeV
(for BR(LQ→tl)=1)

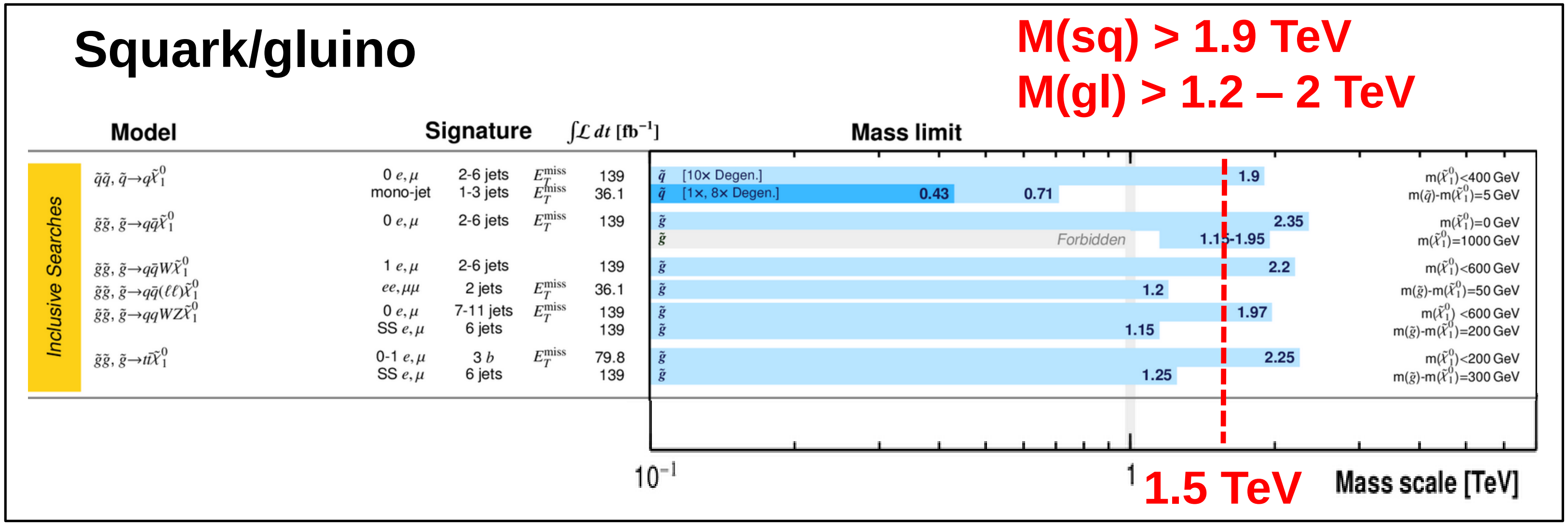
II. SUSY

"Supersymmetry remains the only known dynamical solution to the Higgs naturalness problem that can be extrapolated up to very high energies, in a consistent and calculable way."

Physics Briefing Book
arxiv:1910.11775

Where is hiding SUSY?

Very compelling theory, still attractive in spite of the current stringent limits on 'natural' SUSY



Other main types of searches:
- **EW production**
- **3rd generation squark**

Bulk of SUSY phase space covered by these searches (see backup)

Recent focus on:
compressed mass spectra, R-parity violating SUSY, non-prompt decays, etc.

R-parity violating SUSY

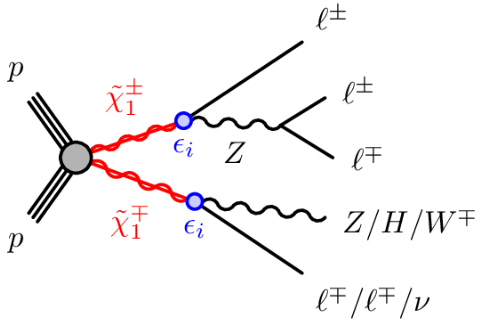
2020

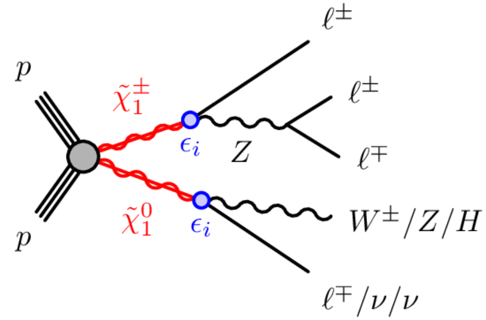
R-parity: $(-1)^{3(B-L)+2s}$

RPV benchmark model: MSSM + extension adding gauged $U(1)_{B-L}$

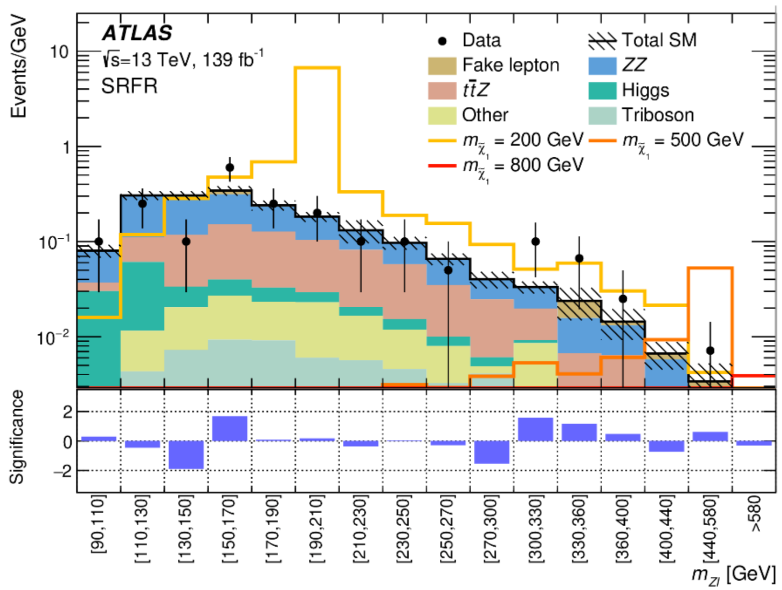
Electroweak pair production of two charginos or chargino/neutralino

arxiv:2011.10543

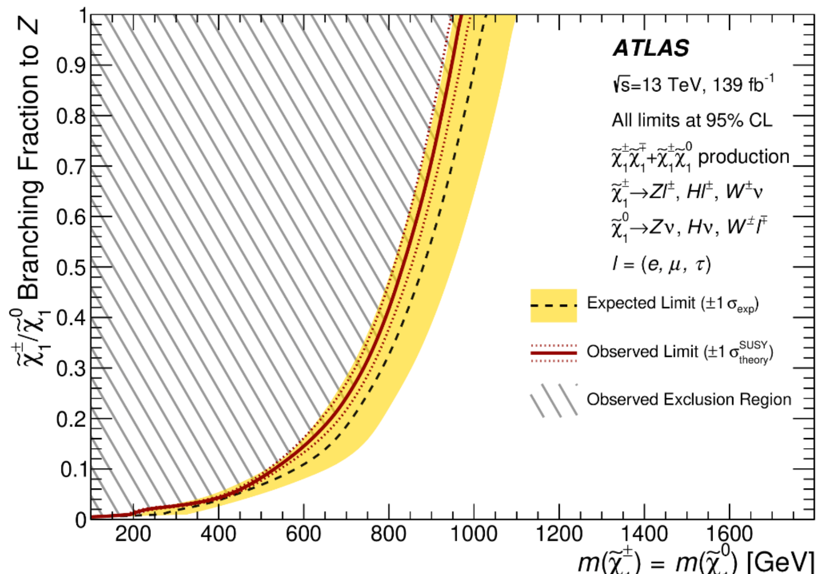




RPV coupling:
- chargino to Zl, Hl or Wv
- neutralino to Wl, Zv or Hv



Trilepton invariant mass

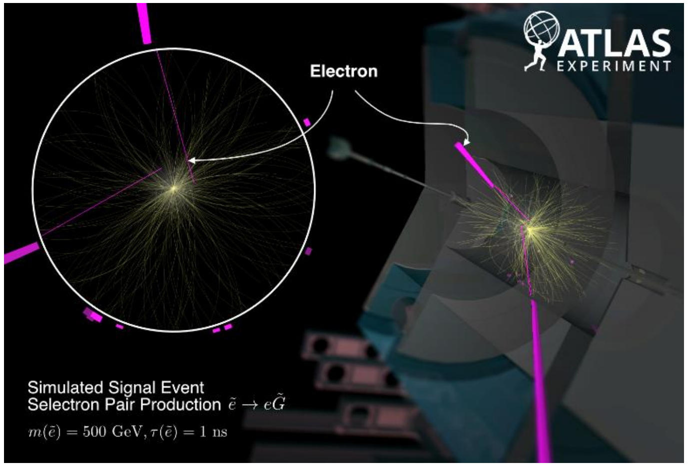


1 TeV limit for (100 % BR)

Long-lived particles

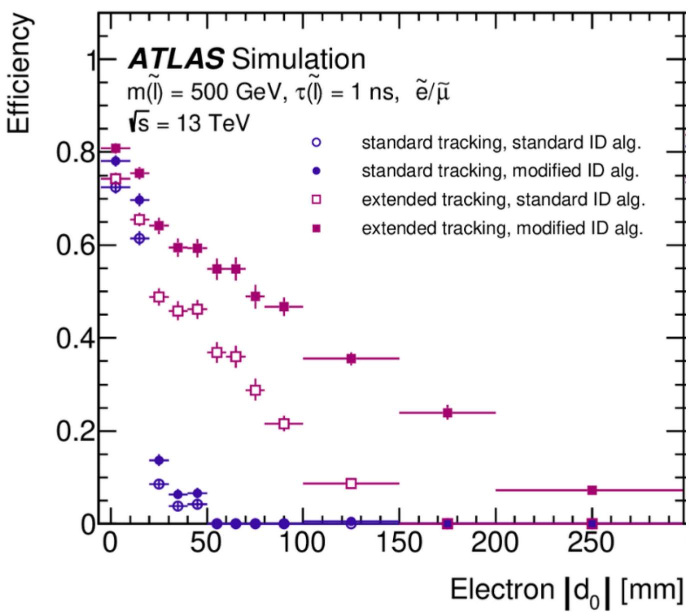
2020

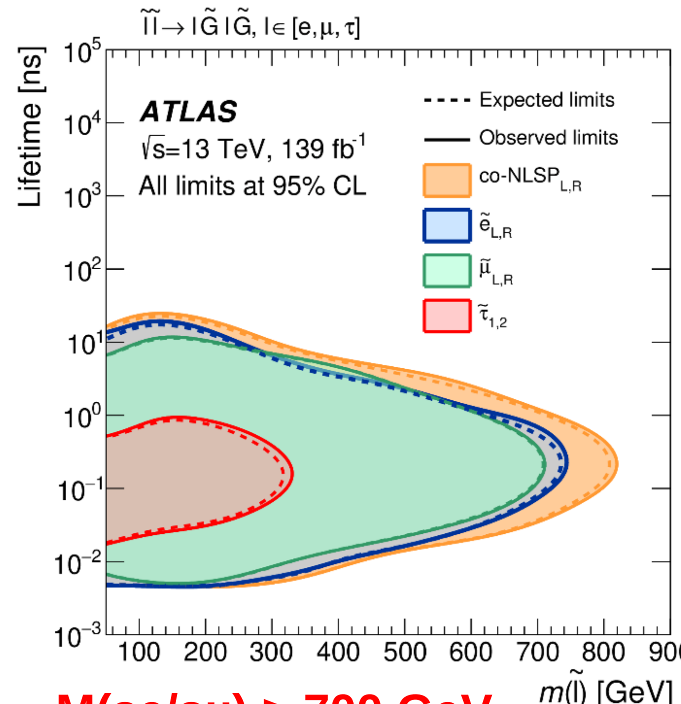
arxiv:2011.07812



- Sleptons search: unique sensitivity to GMSB models
- Lifetimes considered: 10 ps - 10 ns
- Signal leptons (e/μ): large d_0 > 3 mm

➔ **Special reconstruction techniques**





<1 ev. exp.
0 ev. obs.

M(se/sμ) > 700 GeV
M(sτ) > 350 GeV
Previous best limits (LEP) ~90 GeV

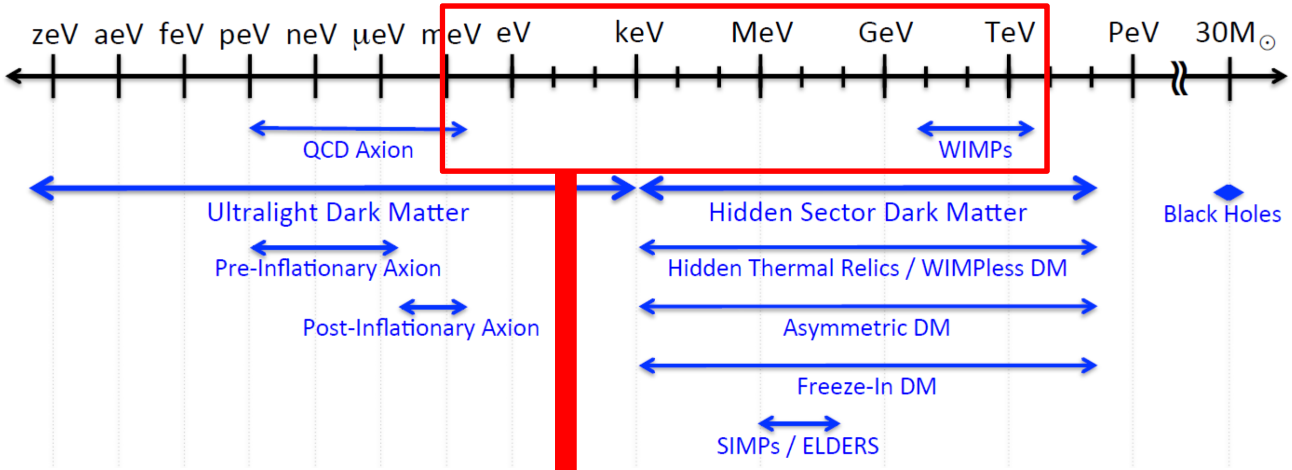
III. Dark matter

"The search for DM is fascinating because it brings together different fields (particle physics, cosmology, astrophysics) and different experimental techniques (accelerators, underground detection, cosmic rays)."

Physics Briefing Book
arxiv:1910.11775

Dark matter opportunity at colliders

Very little clue on the mass scales of the DM particles

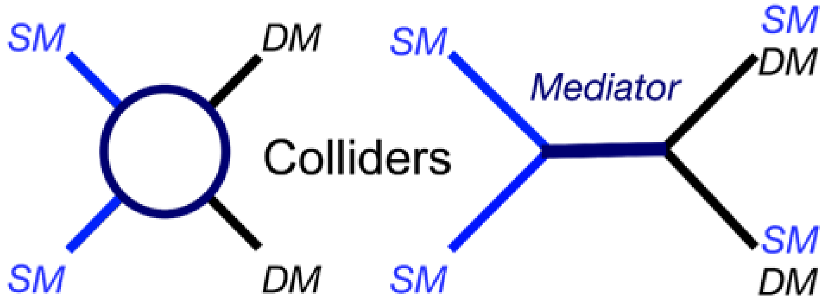


arxiv:1707.04591

Favoured mass window to agree with the relic density

Complementarity with direct/indirect searches

Opportunity for colliders

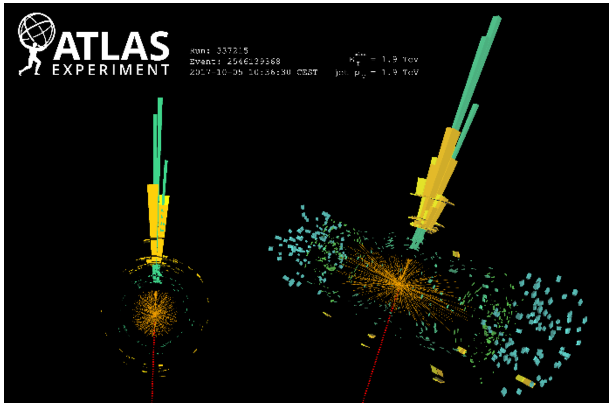


SM/DM mediator→DM (+X)
DM mediator→SM

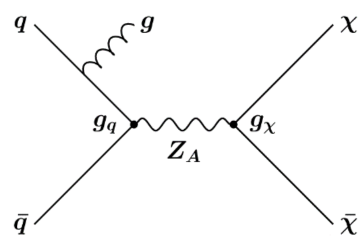
Mediator→DM+X: monojet search

2020

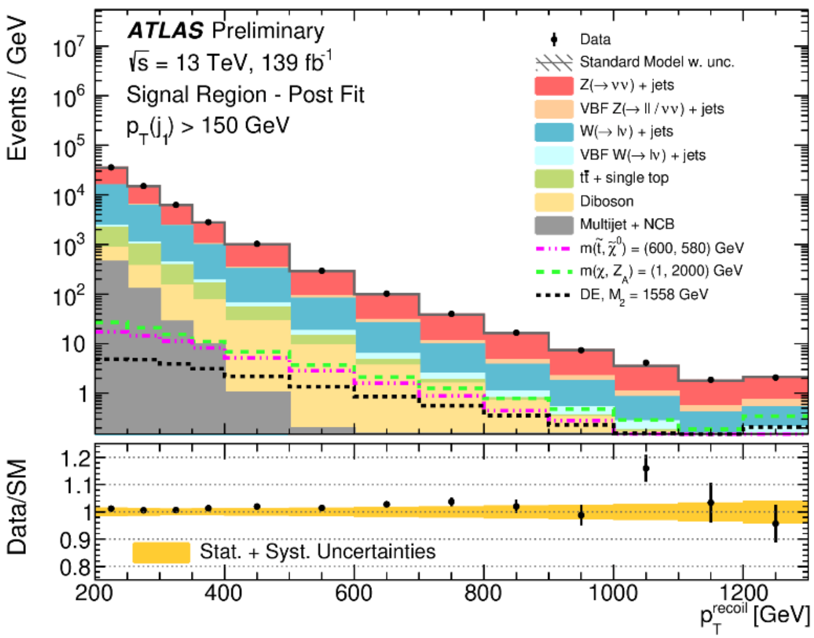
ATLAS-CONF-2020-048

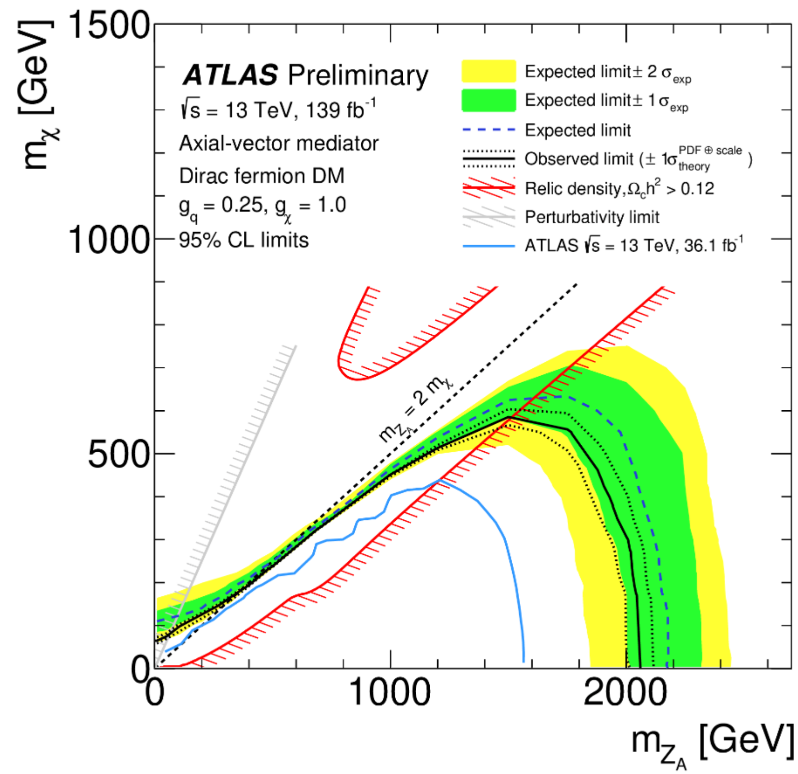


1.9 TeV jet and nothing



Pair-production from quarks via s-channel exchange of:
- spin-1 mediator particle
- or spin-0 mediator particle, with axial-vector or pseudoscalar couplings





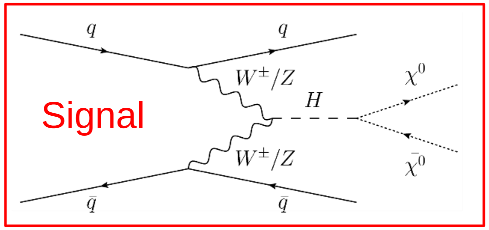
Mediator→DM: Higgs portal model

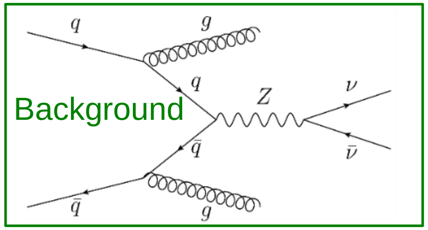
2020

Invisible Higgs decay search

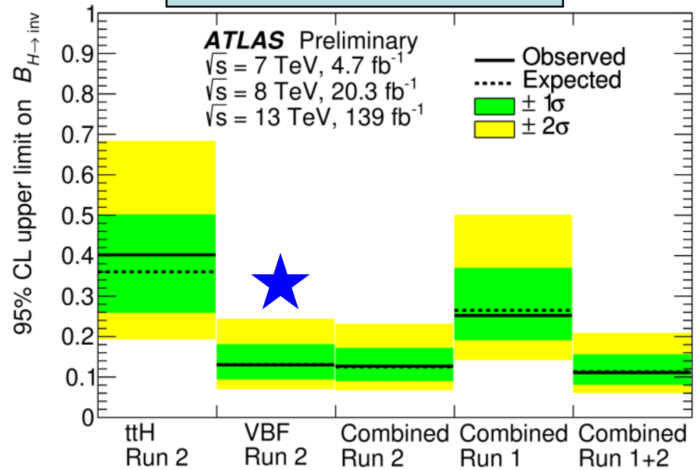
SM: BR_{inv} = 0.1% (via H→ZZ*→4v)

VBF topology most sensitive



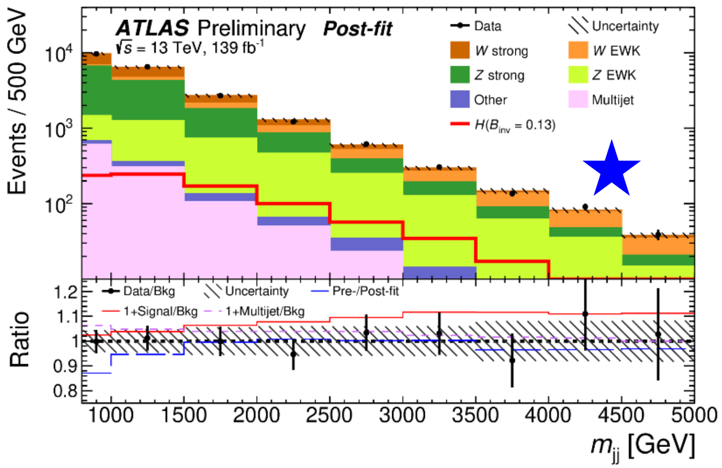


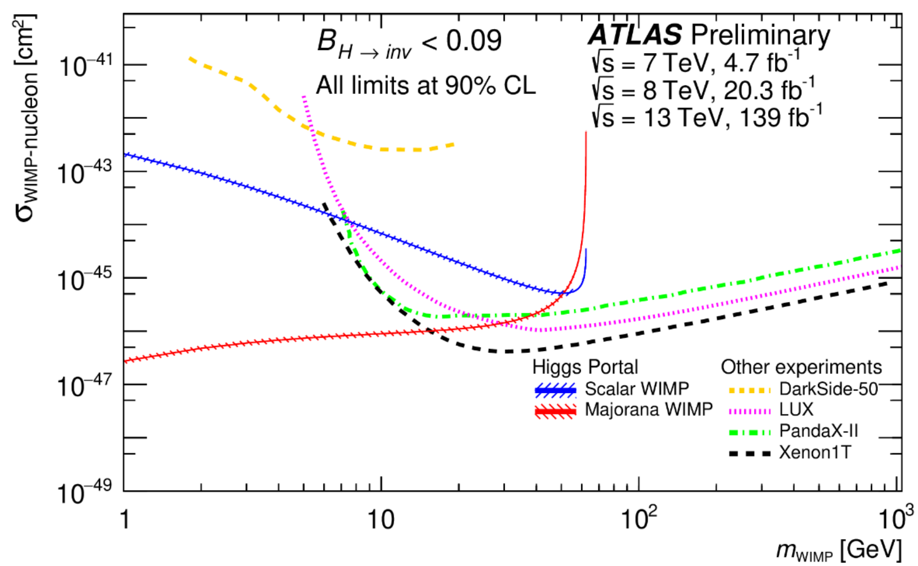
ATLAS-CONF-2020-052



BR < 11% @95% CL

ATLAS-CONF-2020-008





IV. Higgs boson

"The discovery of the Higgs boson has opened a new research programme, which is a clear priority for the future of particle physics."

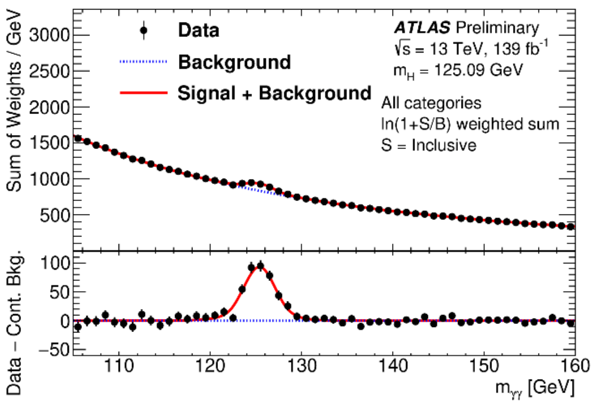
Physics Briefing Book
arxiv:1910.11775

Decays into bosons: refining the Run 1 observations

2020

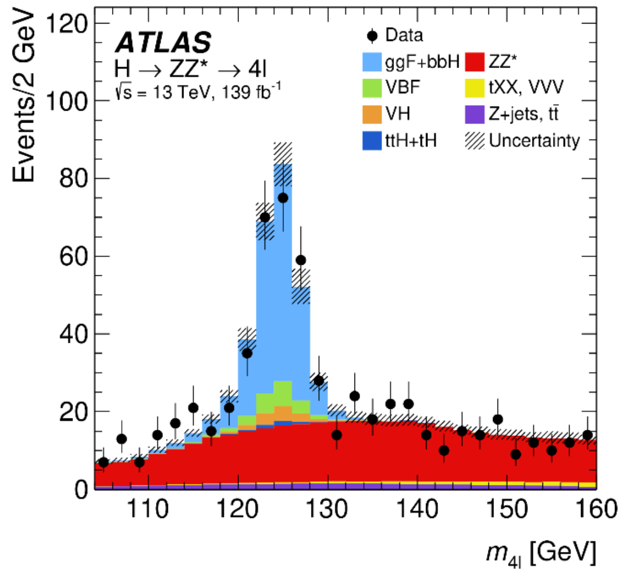
ATLAS-CONF-2020-026

H→γγ



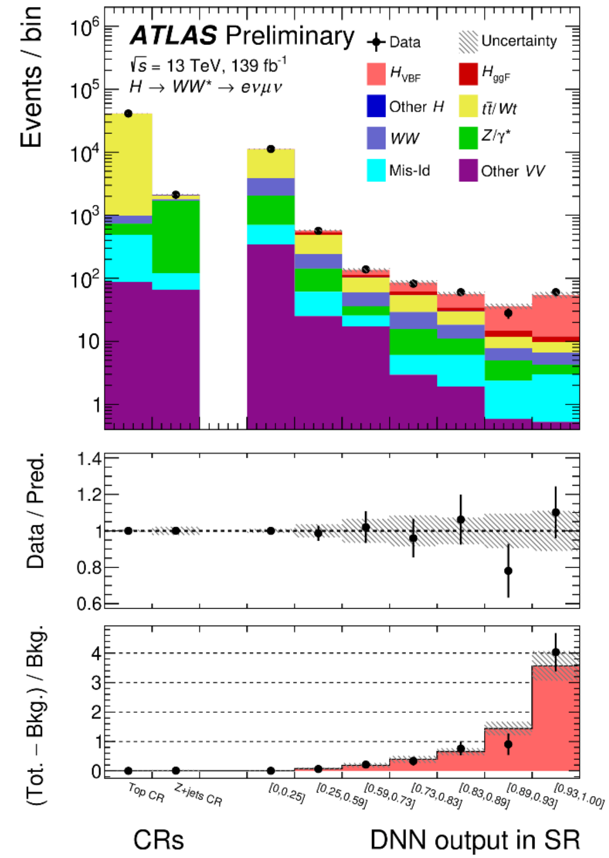
arxiv:2004.03447

H→ZZ*→4l



ATLAS-CONF-2020-045

H→WW*→lνlν



With the larger Run 2 dataset, focus on:
- Production mode observations
- Differential cross section measurements

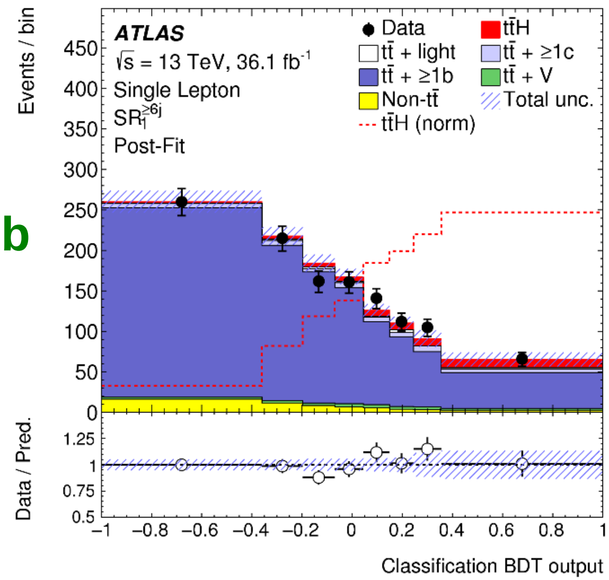
Run 2 = fermionic coupling quest

Observation of the ttH process

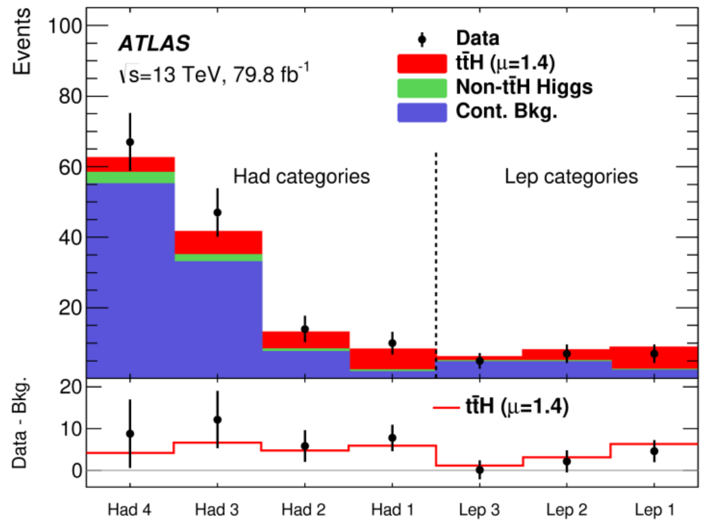
2018

arxiv:1806.00425

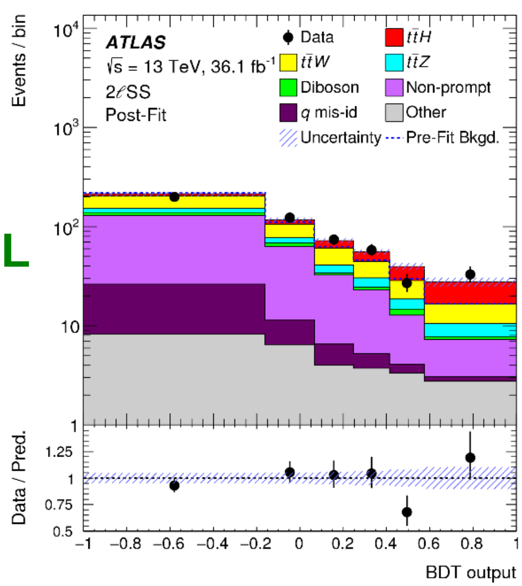
bb

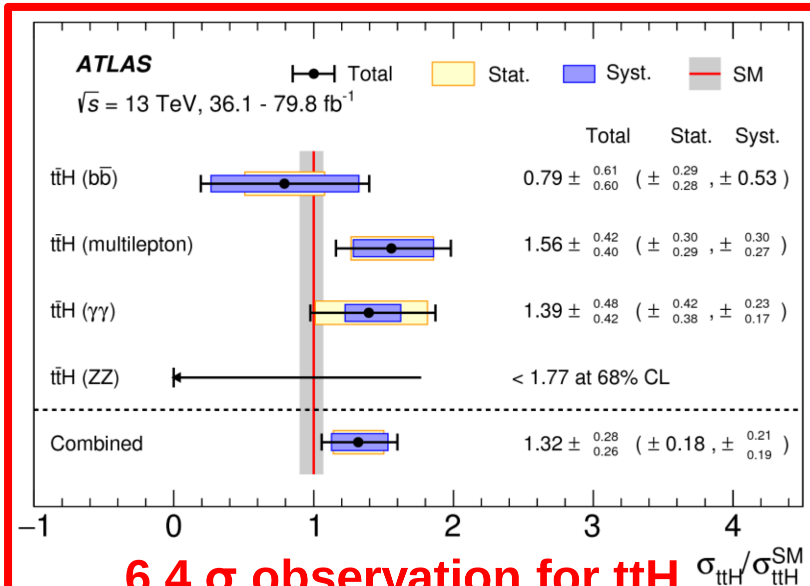


γγ



ML





6.4 σ observation for ttH

H→bb process

2020

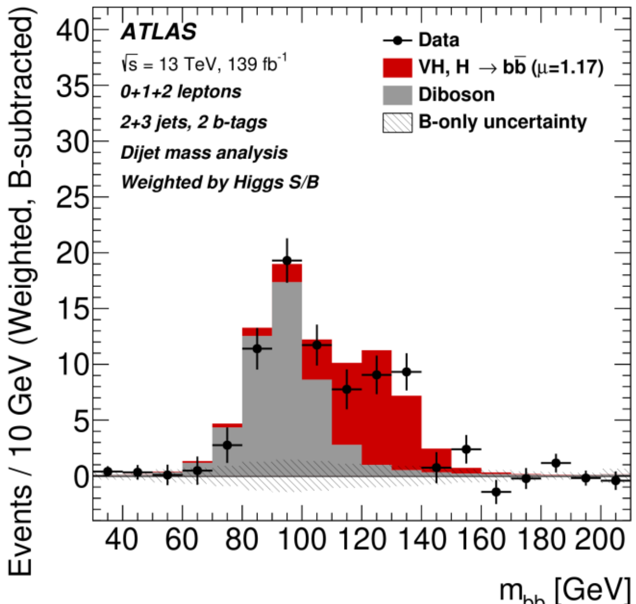
5σ observation reached with VH in 2018 (80 fb^{-1} of Run 2 data)

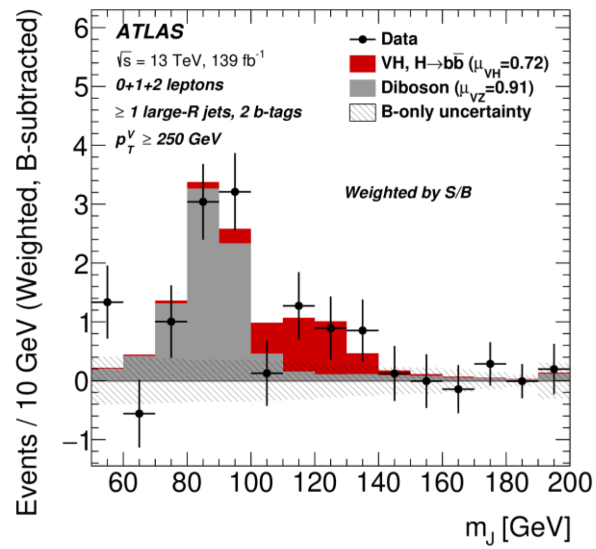
arxiv:2008.02508

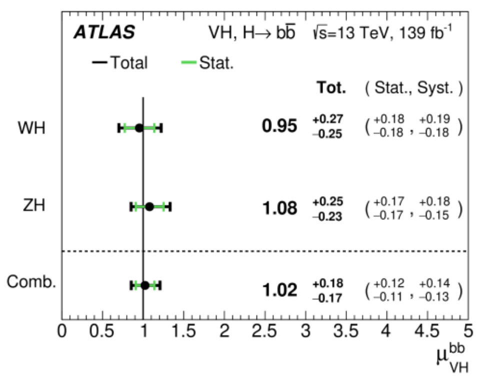
Boosted VH ($p_{T,V}$>250 GeV)
Higgs in one single large-R jet

arxiv:2007.02873

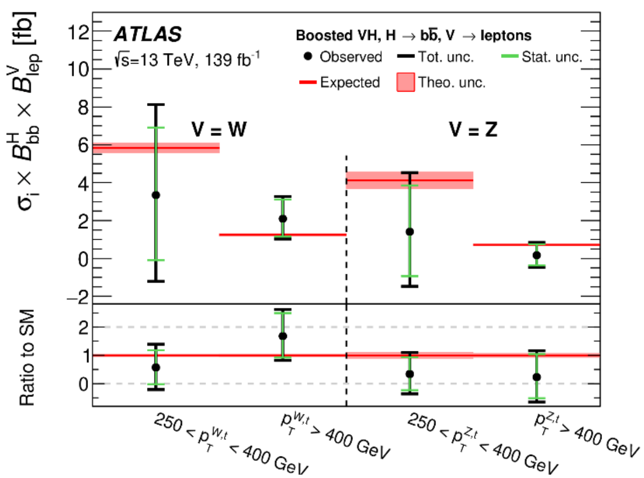
Inclusive VH







WH: 4.3 σ (obs.)
ZH: 4.3 σ (obs.)



EFT richness

Coupling to the 2nd generation of fermions?

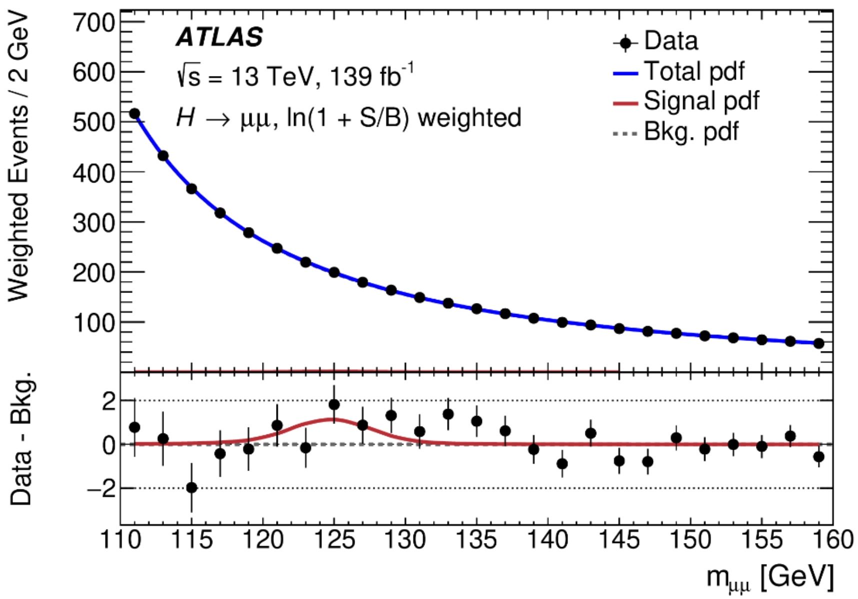
2020

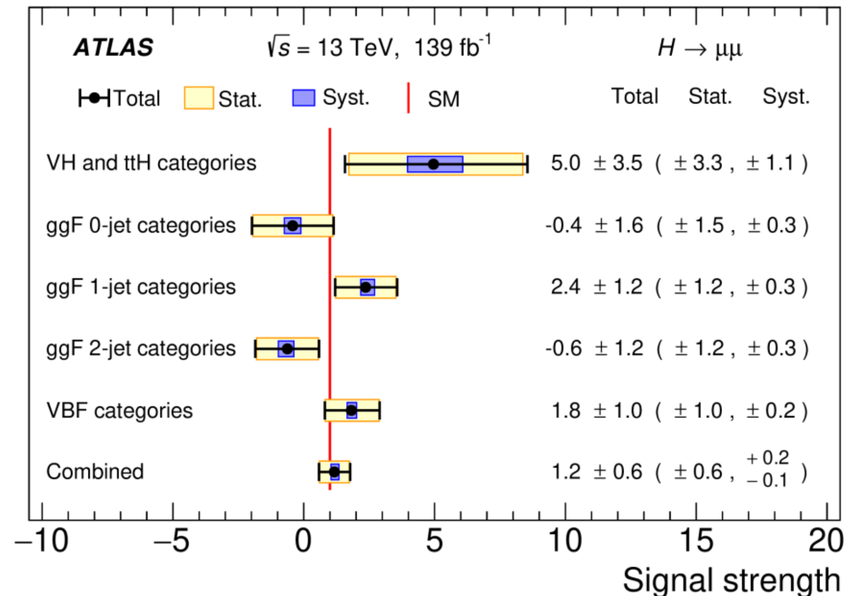
arxiv:2007.07830

- H→μμ most promising

But challenging: BR (H→μμ) ~ 2 10^{-4}

- Huge Drell-Yan background





20 exclusive categories based on production modes and kinematics

2.0 σ (obs.)

Run 3 dataset critical to increase sensitivity

Effective field theory interpretation

2020

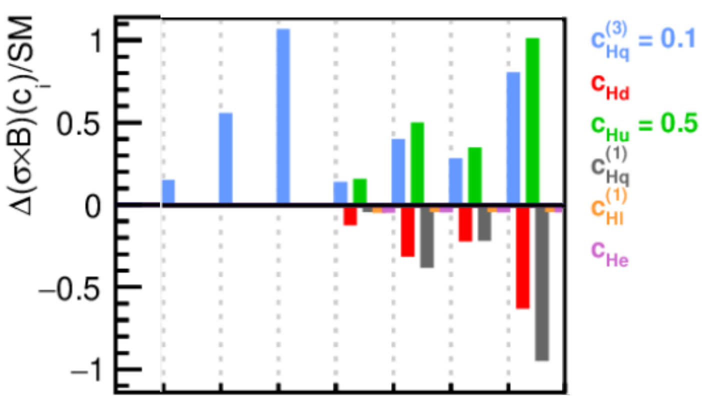
[ATLAS-CONF-2020-053]

Goal: constrain the dimension-6 Wilson coefficients corresponding to operators impacting (in)directly the Higgs boson couplings to SM particles

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)}$$

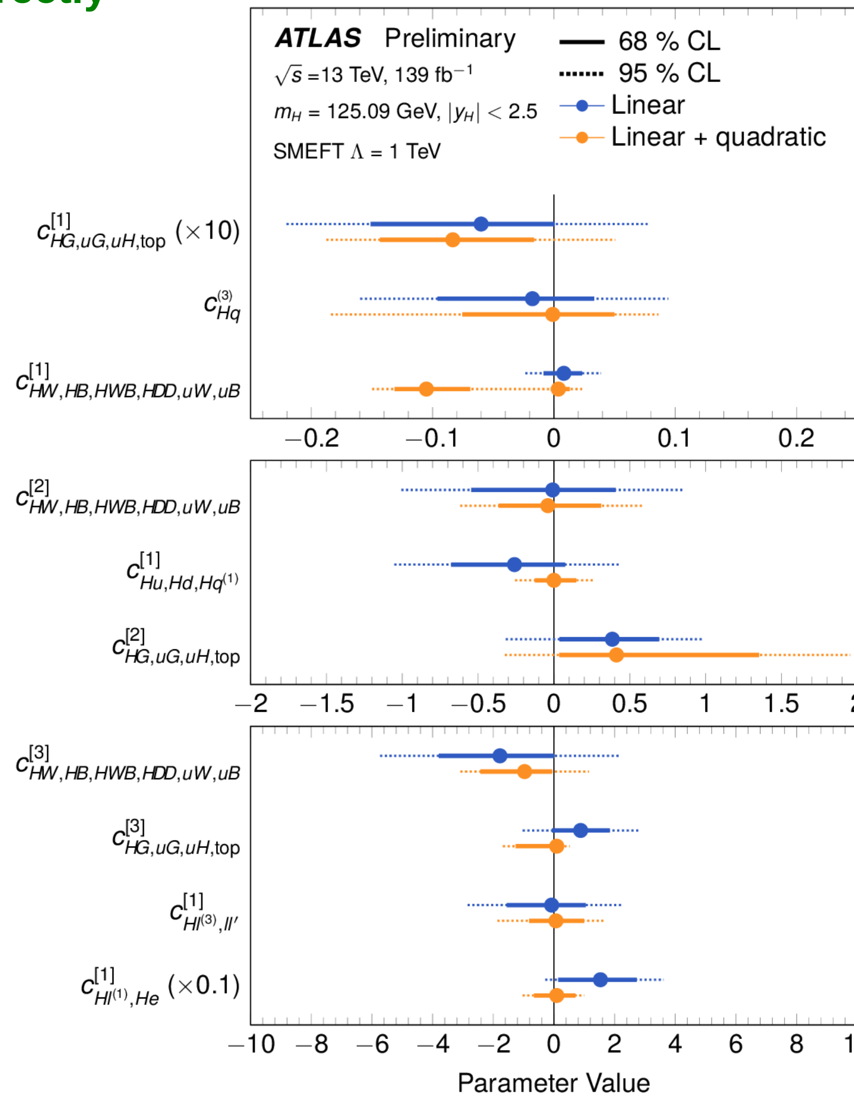
- Warsaw basis
- Reduction to a set of sensitive operators

Impact: operator / STXS* bin



VH STXS bins

10 most-sensitive combinations fitted simultaneously (rotated matrix)



*STXS: simplified template cross section

IV. Rare SM processes

"Making precise measurements of rare or even SM forbidden processes, relying on quantum mechanical effects to probe shorter distances or effectively higher energies."

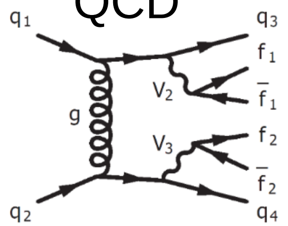
Physics Briefing Book
arxiv:1910.11775

Electroweak production of VVjj

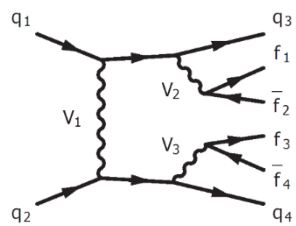
2020

LHC production of VVjj

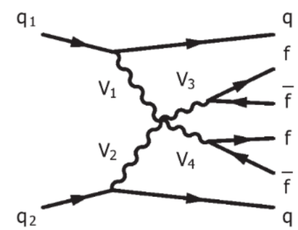
QCD



EW irreducible

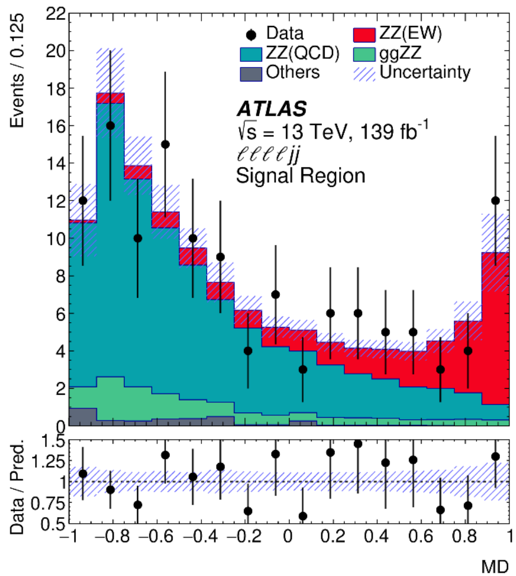


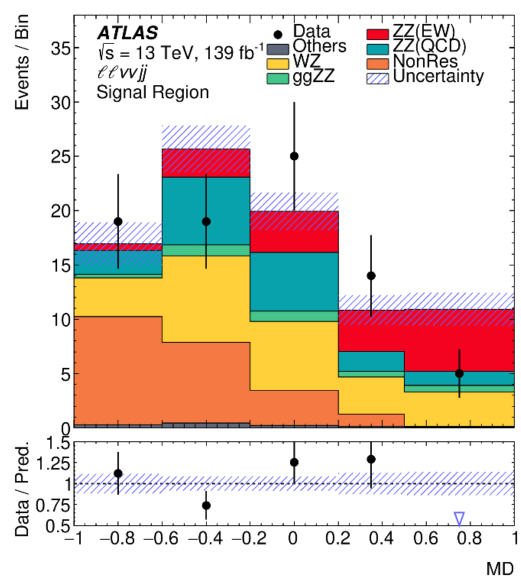
VBS



Very small cross sections (~fb)
ATLAS Run 2: **5σ observations for VVjj EW production in ssWW, WZ→3L and ZZ →4l/2l2ν**
[arxiv:1906.03203, arxiv:1812.09740, arxiv:2004.10612]

4l





2l2ν

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.5 (3.9) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	–	1.2 (1.8) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.5 (4.3) σ

Observation of EW ZZjj

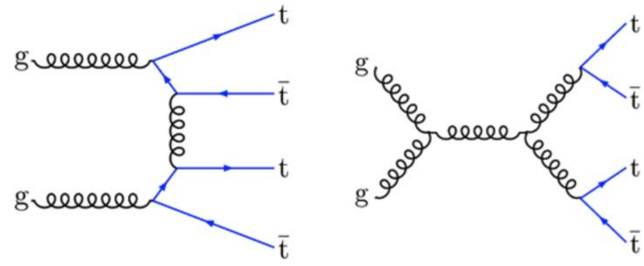
Evidence for tttt production

2020

arxiv:2007.14858

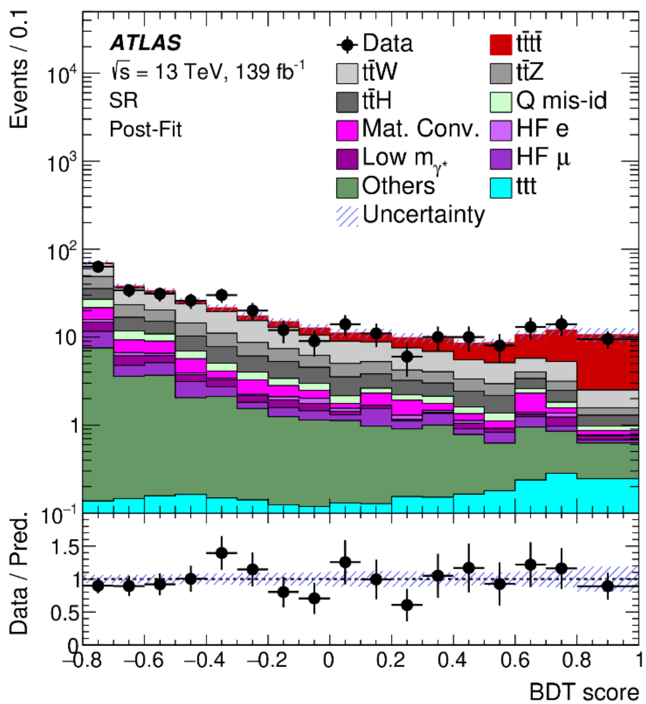
Rare process: $\sigma_{SM} = 12$ fb

Event selection:
- 2 SS leptons or ≥3 leptons
- High event activity ($H_T > 500$ GeV)
- ≥6 jets and ≥2 b-jets

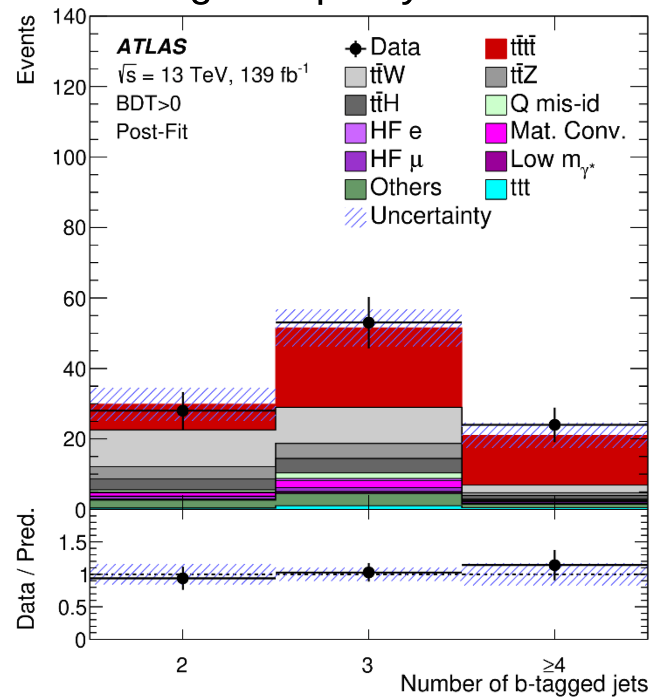


Enhanced in many BSM scenarios

BDT in signal region



b-tag multiplicity for BDT>0



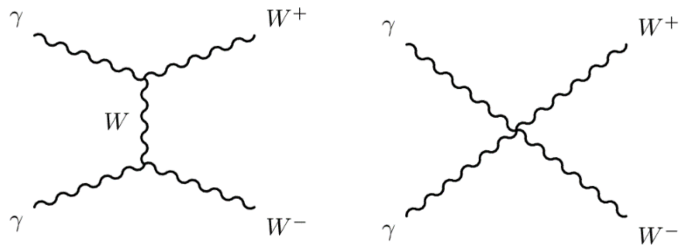
$\sigma_{meas} = 24^{+7}_{-6}$ fb **4.3 σ (obs.)** (2.4 σ exp.)

Observation of the γγ→WW process

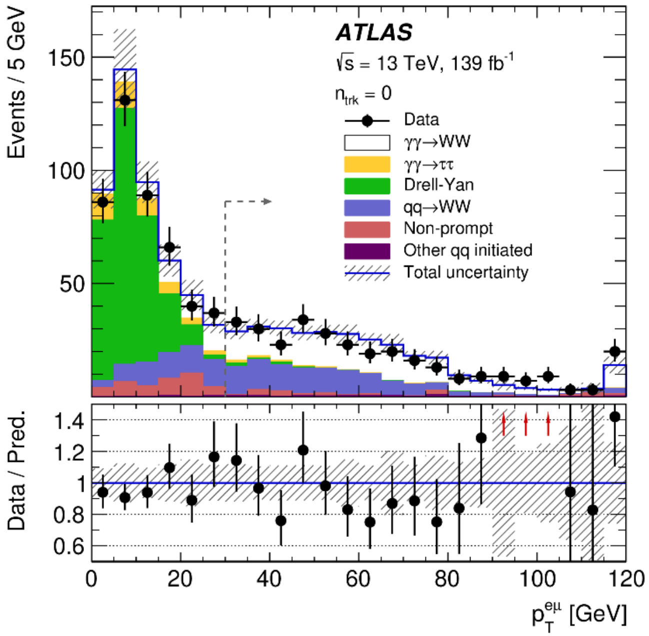
2020

arxiv:2010.04019

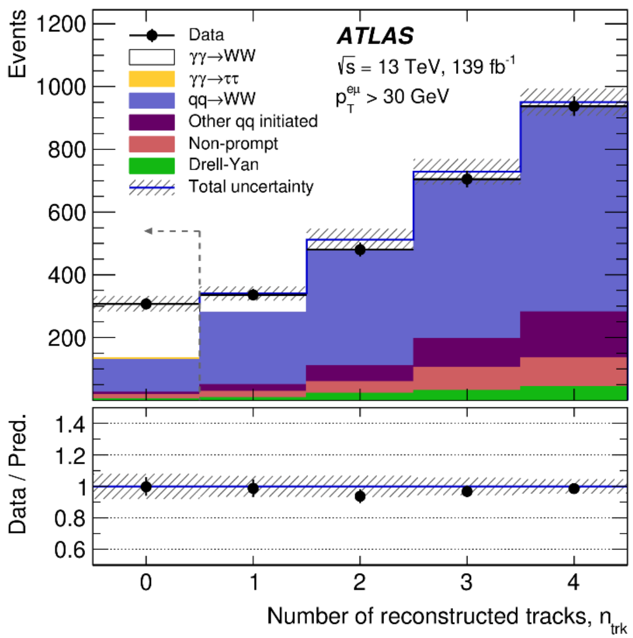
Production through trilinear and quartic gauge-boson interactions



- Test of the gauge structure of the SM
- Sensitivity to anomalous gauge-boson interactions



Event selection:
eμ vertex, **no associated tracks**, $p_T^{e\mu}$>30 GeV



$\sigma_{fid,meas}$ = 3.13 ± 0.31 (stat) ± 0.28 (syst) fb

$\sigma_{fid,exp}$ = 2.8 ± 0.8 fb / 3.5 ± 1.0 fb (rescattering effects)

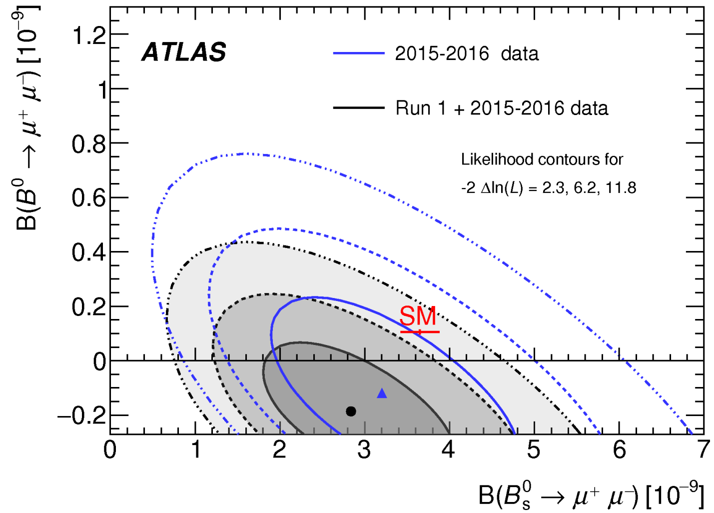
8.4 σ obs. (6.4 σ exp.)

$B_{(S)}{}^0 \rightarrow \mu\mu$

2020

- Search for deviations w.r.t. the SM of the small $B_{(S)}{}^0$ branching ratios
- Reference decay mode for the BR extraction: $B^+ \rightarrow J/\Psi\, K^+$ with $J/\Psi \rightarrow \mu\mu$

$$\mathcal{B}(B^0_{(s)} \rightarrow \mu^+\mu^-) = N_{d(s)} \frac{\mathcal{B}(B^+ \rightarrow J/\psi\, K^+) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\mathcal{D}_{\text{ref}}} \times \frac{f_u}{f_{d(s)}}$$



$B(B_S{}^0 \rightarrow \mu\mu) = 2.8^{+0.8}_{-0.7}\ 10^{-9}$

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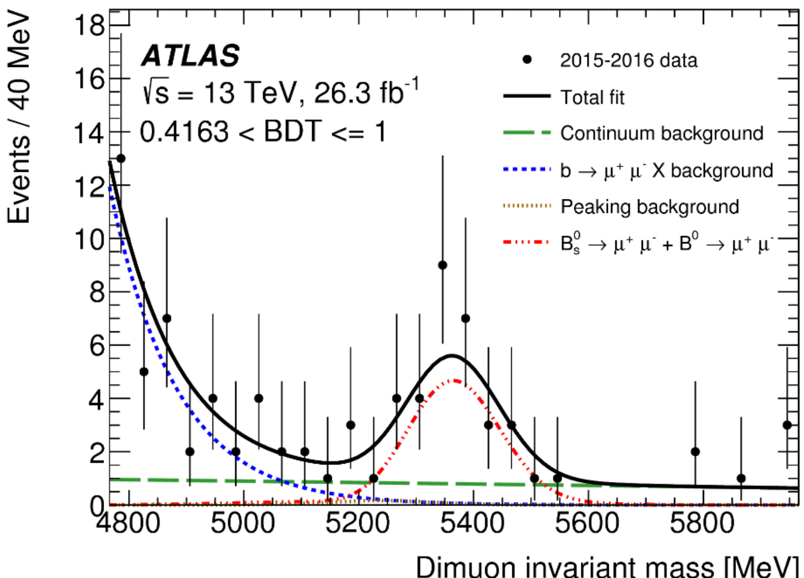
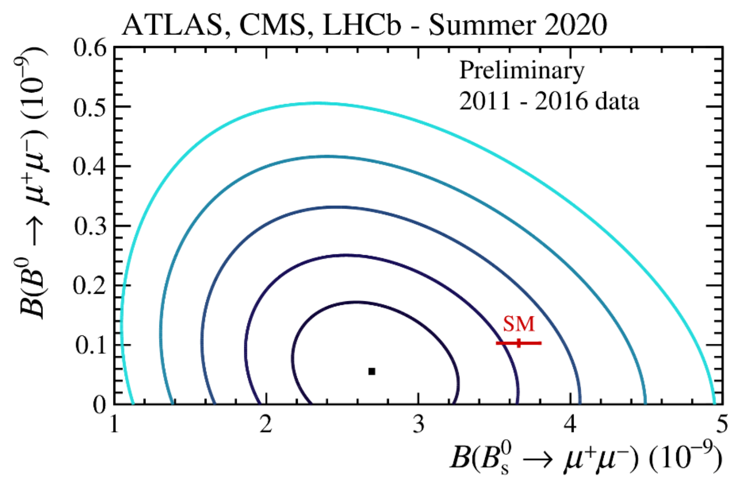


arxiv:1812.03017

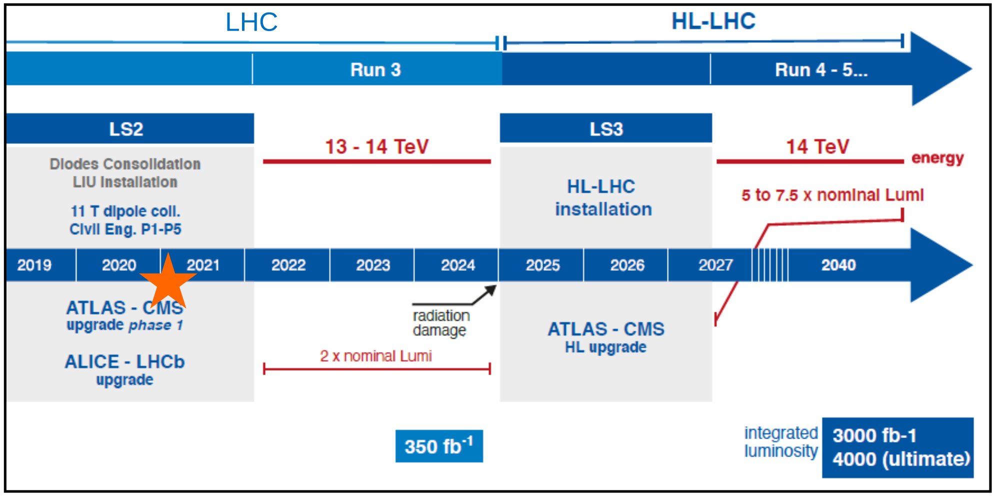


$B(B_S{}^0 \rightarrow \mu\mu) = 2.69^{+0.37}_{-0.35}\ 10^{-9}$

Conclusion and prospects

- ATLAS Run-2 highlights presented around 5 themes:
- **BSM**: nothing found yet in direct seaches
- **SUSY**: focus on more complex scenarios
- **Dark matter**: exploring the collider window
- **Higgs**: everything consistent with the SM predictions so far
- **SM**: pushing towards rare/forbidden processes

- Huge and diverse physics program for Run 3 and beyond
- Run 3: expect to increase the current statistics by a factor ~3
- HL-LHC: 96% of the final dataset still to be collected



Detector upgrades, computing challenges, new reconstruction and analysis techniques, etc.

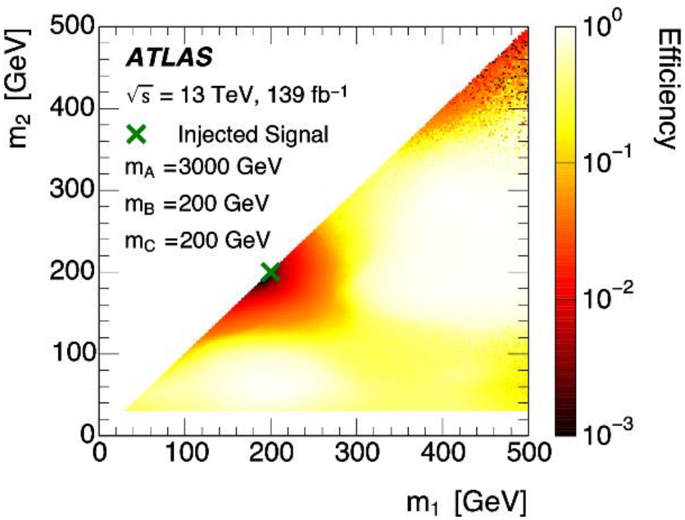
Backup

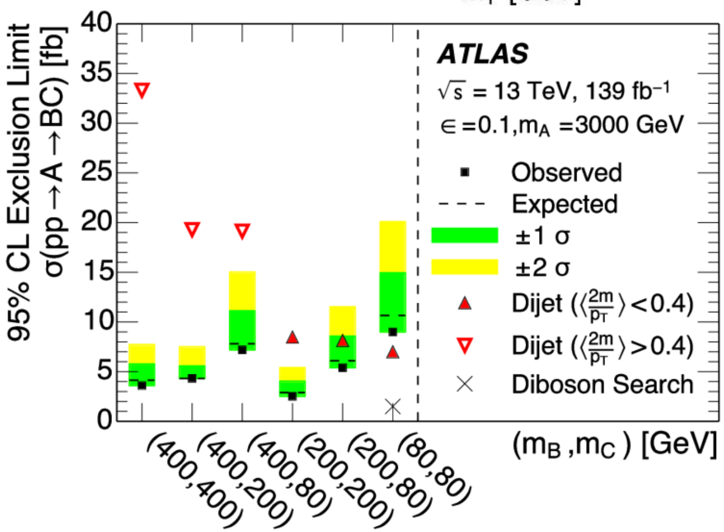
Dijet resonance searches

2020

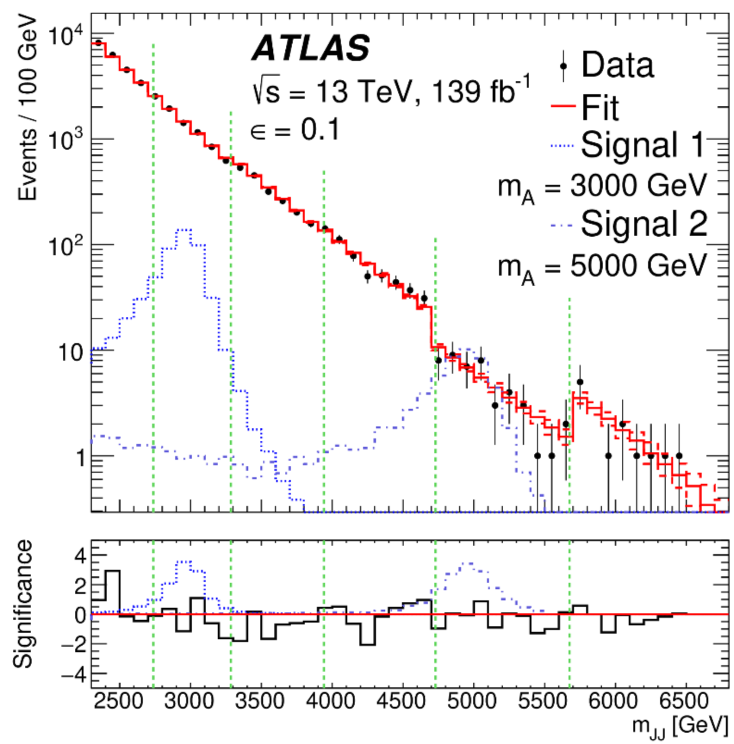
arxiv:2005.02983

Search for resonant new physics using a machine-learning anomaly detection procedure (no signal model hypothesis)



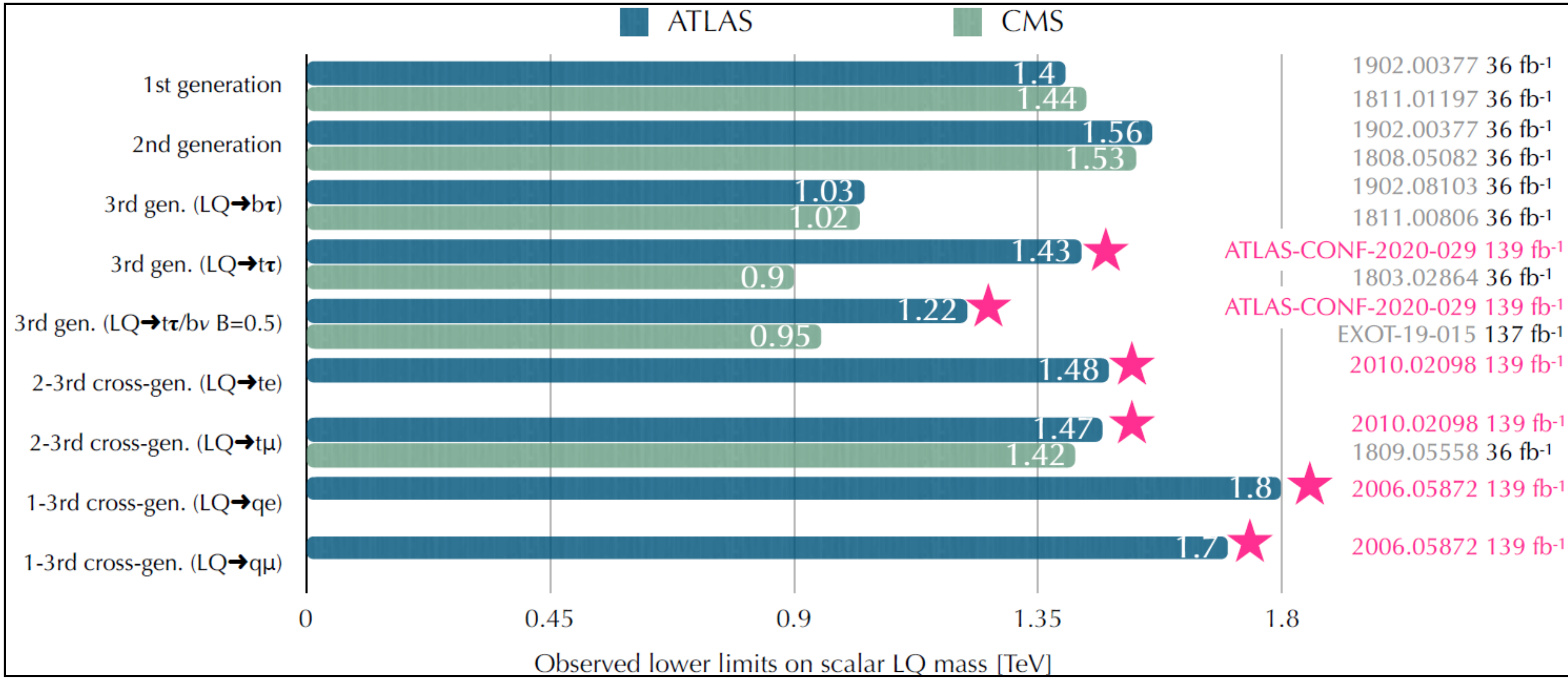


- 3D search: $A \rightarrow BC$ m_A~TeV, $m_{B/C}$~100 GeV
- Boosted single large-radius jets ($30 < m_J < 500$ GeV)
- Weakly supervised classifiers



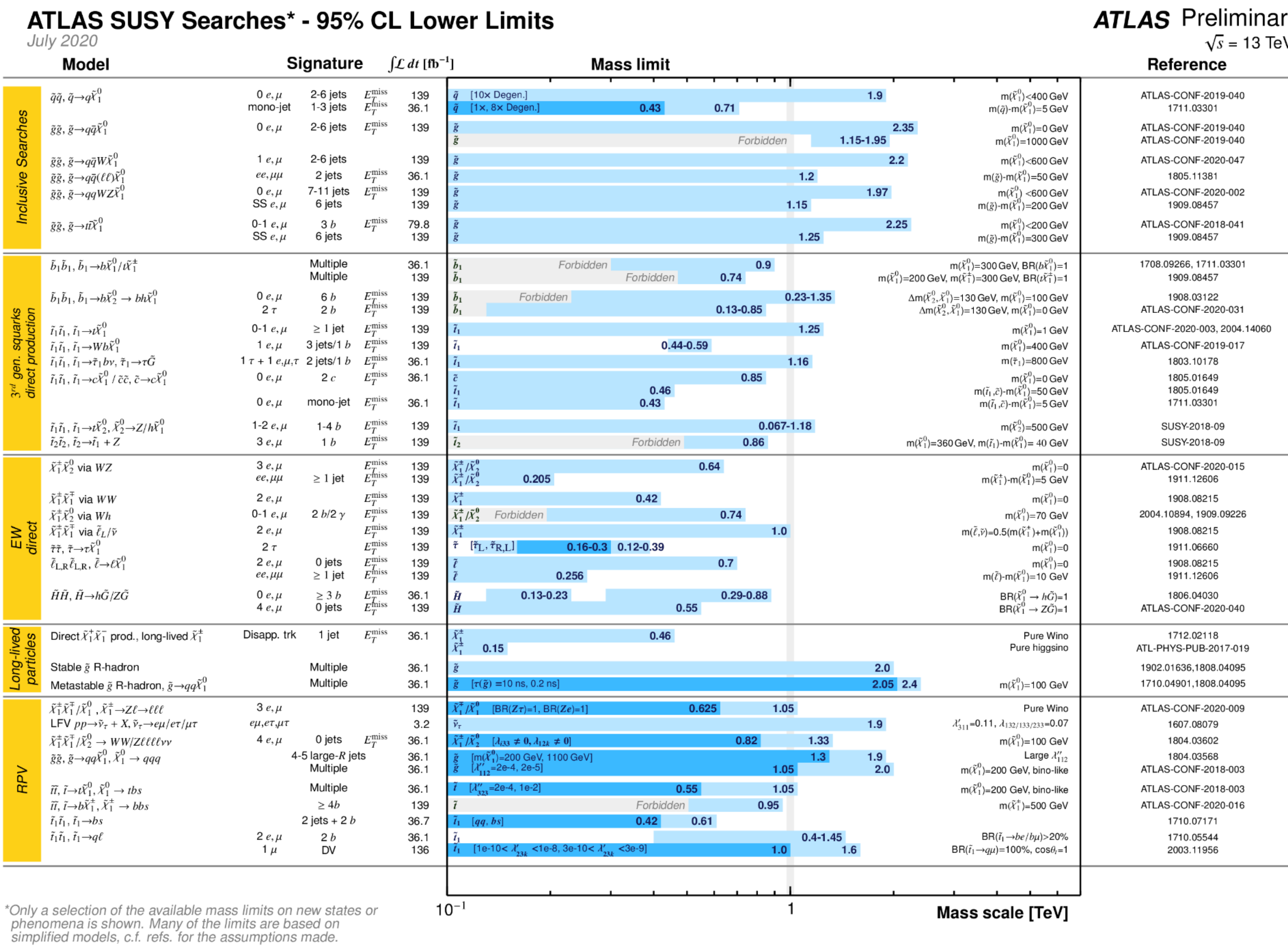
Modern bump-hunt (NN selection applied)

Leptoquark searches



From T. Vázquez Schröder
CERN-LHC seminar
December 8, 2020

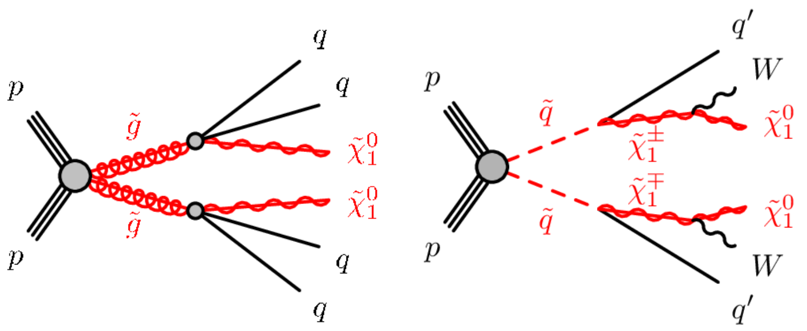
SUSY summary plot



Squarks and gluinos

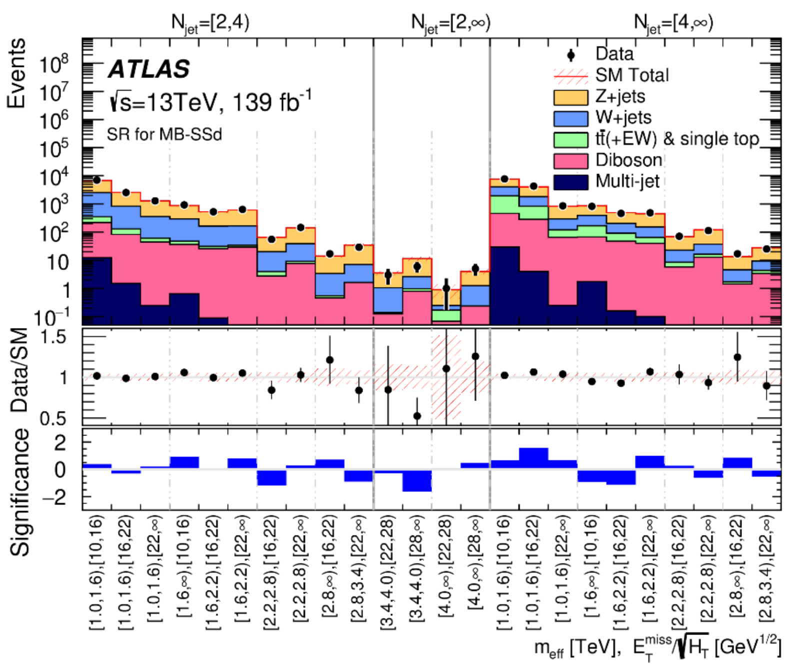
2019

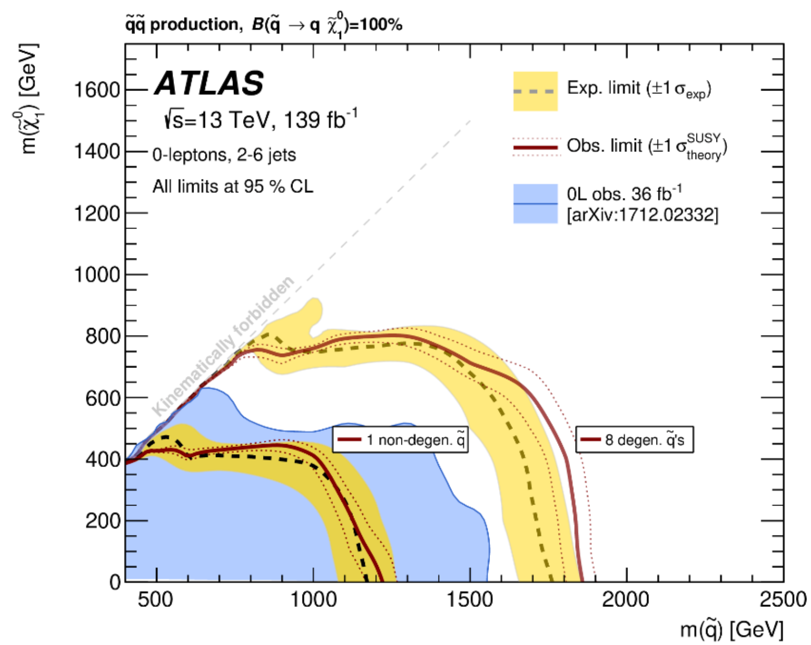
arxiv:2010.14293



Multi-bin search:
MB-SSd (squark-squark-direct)
MB-GGd (gluino-gluino-direct)
MB-C (compressed)

0-lepton, high jet multiplicity, high MET





Simplified models:

m(gl) > 2.3 TeV

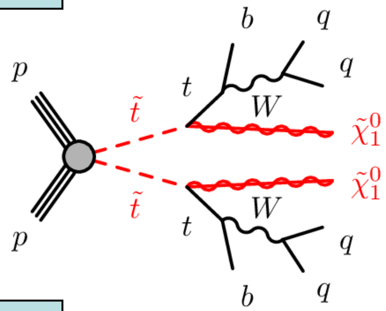
m(sq) > 1.8 TeV

Search for stop pairs in 0/1/2-lepton final states

2020

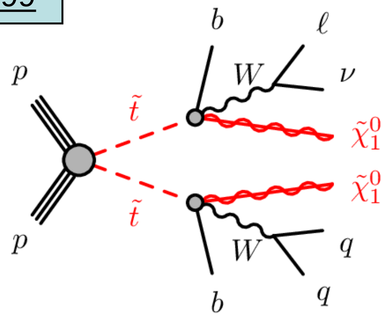
arxiv:2004.14060

0 lepton



arxiv:2012.03799

1 lepton



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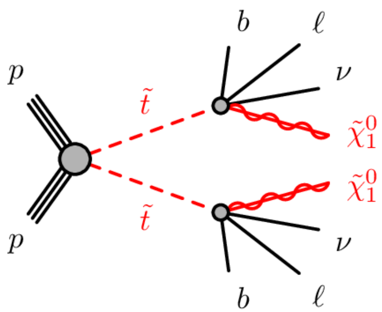
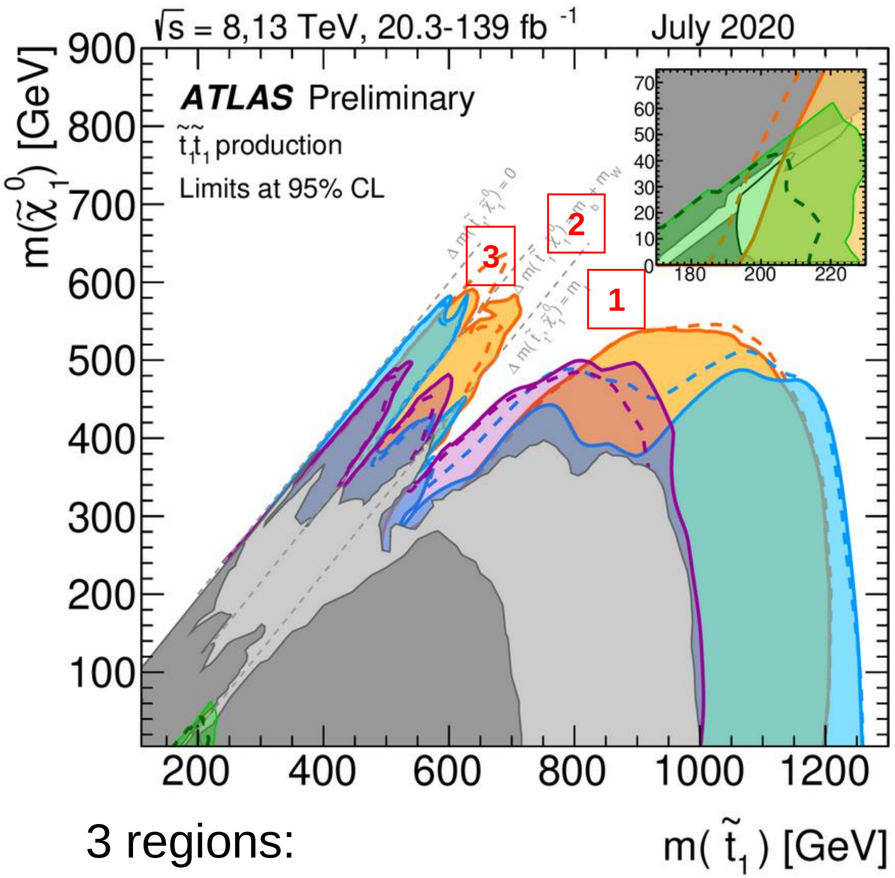
2 leptons



3 decay modes considered in each case:
2-body, 3-body and 4-body decays



3 regions:

1) $m_{stop} > m_t + m_\chi$
2) $m_{stop} \sim m_t + m_\chi$
3) $m_{stop} < m_W + m_b + m_\chi$

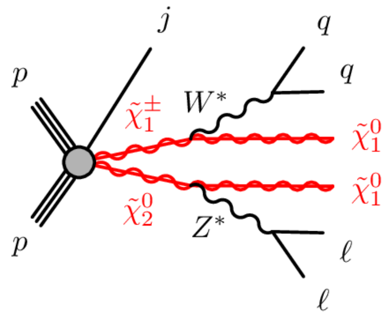
Complementarity

EW production with compressed mass spectra

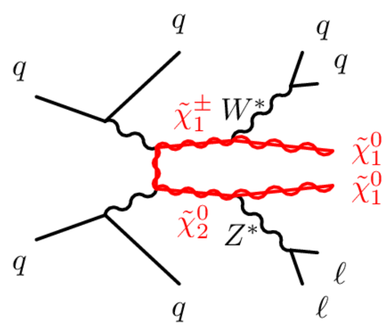
2019

arxiv:1911.12606

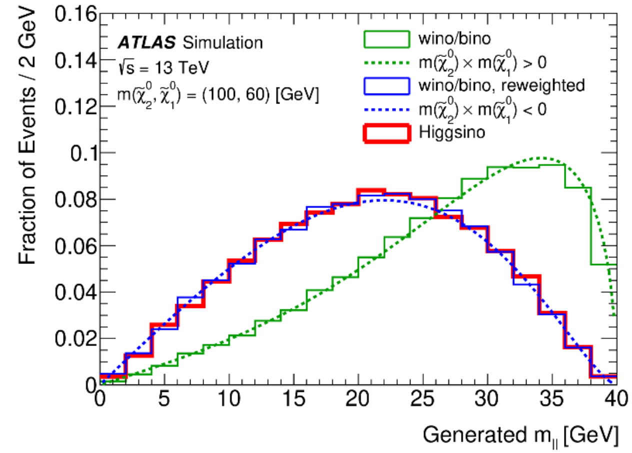
Dilepton search

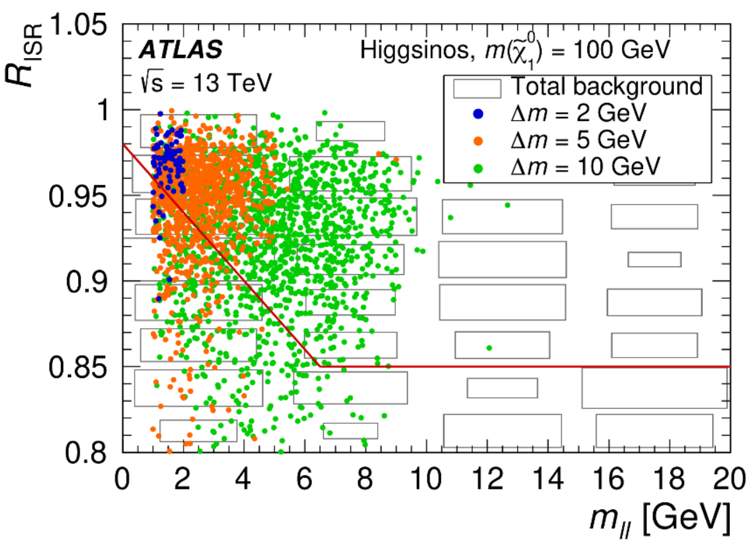


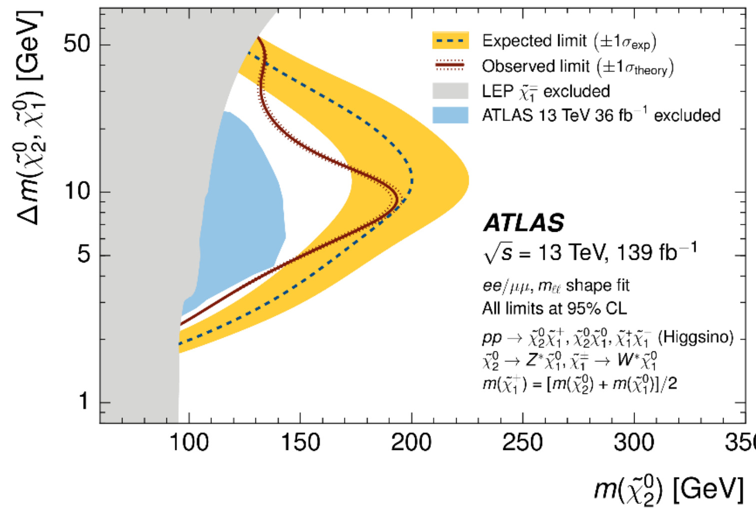
ISR topology



VBF topology







Sensitivity to Higgsino LSP cross section

For $\Delta m \sim 10$ GeV: **$m(\chi_2^0) > 200$ GeV**

Mediator→DM: Higgs portal model

2020

- WIMP taken to interact very weakly with the SM particles, except for the Higgs boson

- BR_{inv} assumed to be fully coming from the decay to WIMPs

- Valid up to $m_{WIMP}<m_H/2$ (decay to 2 WIMPS)

- Limits set on the cross section for scattering between the WIMP and nucleons via Higgs boson exchange

$$\sigma_{\chi N} = \Gamma_{\rm inv}\frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi\left(\frac{m_h}{m_\chi}\right)$$

arxiv:1708.02245, Hoferichter et al.

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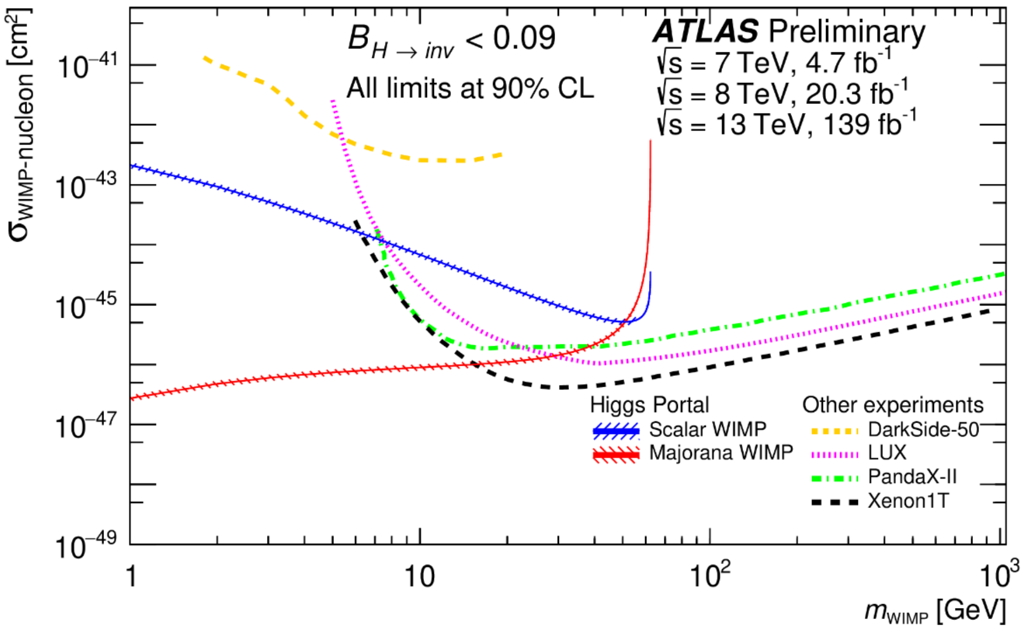


Significantly better limits at low mass (<10 GeV)

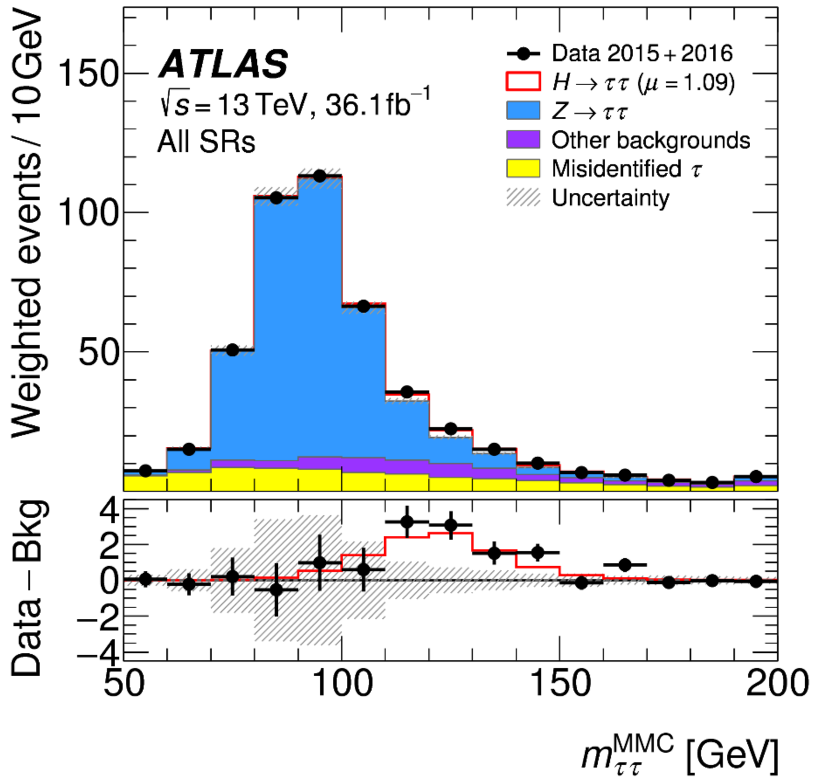
Competitive until the $m_{WIMP} = m_H/2$ threshold

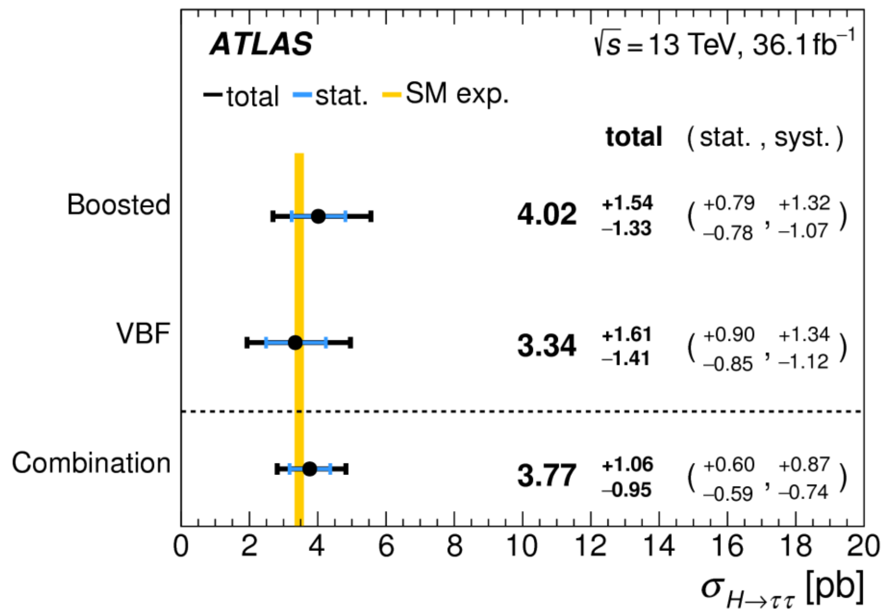
Observation of the coupling to the lepton τ

2017

Evidence at Run 1 from ATLAS+CMS combination

arxiv:1811.08856



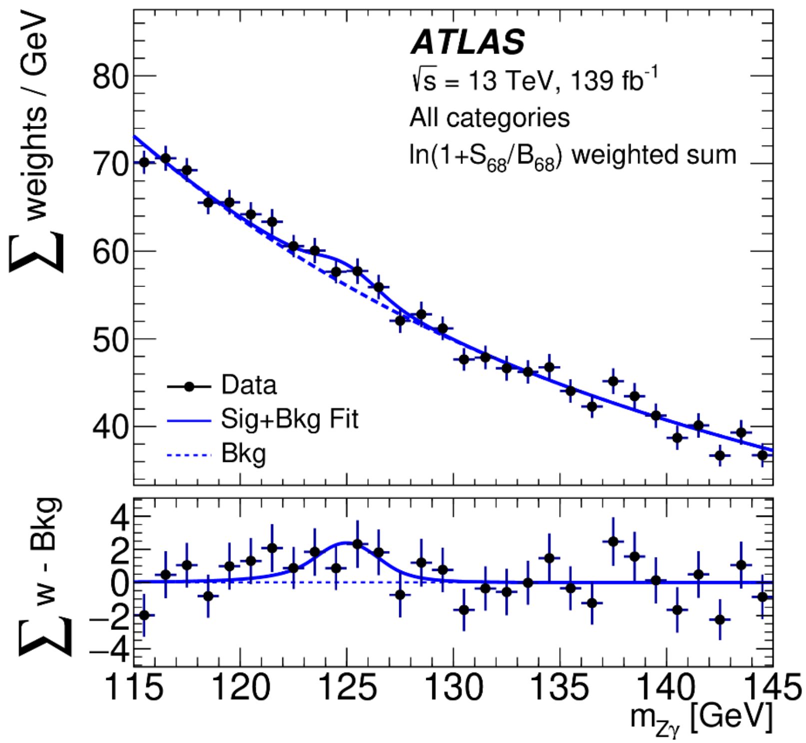


6.4 σ observation
(via combination with Run 1)

2020

arxiv:2005.05382

- Only loop diagrams
- Complementary to ggF and γγ



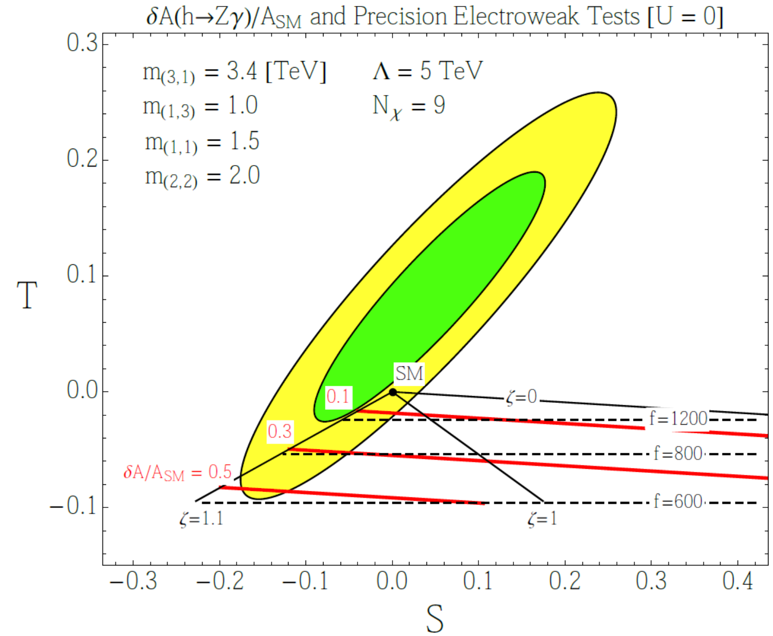
2.2 σ (obs.)

$\mu = 2.0^{+1.0}_{-0.9}$

Crucial to measure all possible couplings accurately

arxiv:1308.2676, A. Azatov et al.

Ex: composite fermions



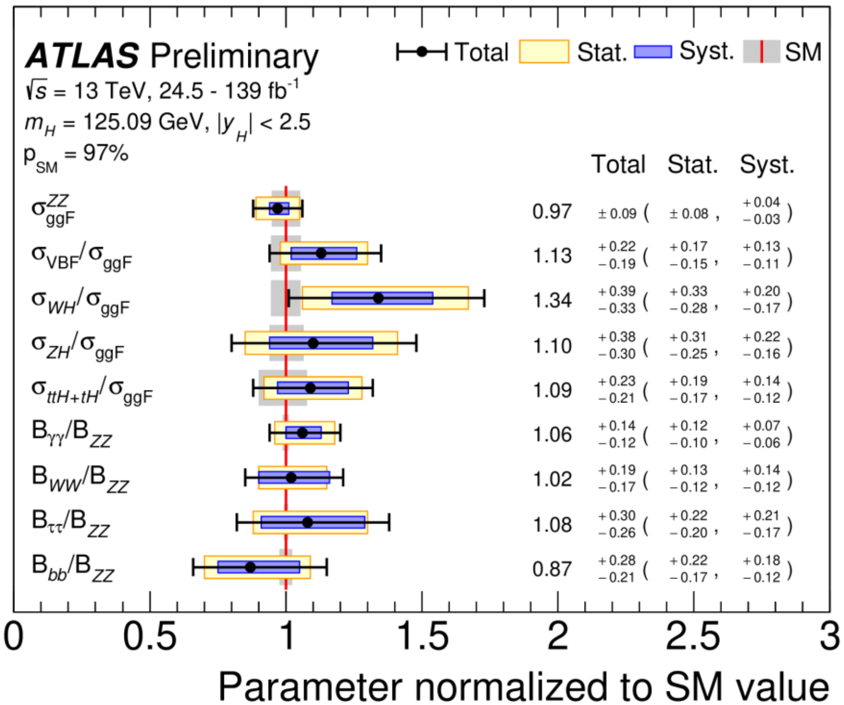
Impact on T/S of modified Higgs couplings due to loops of composite fermions

Combined measurements of production and decay rates

2020

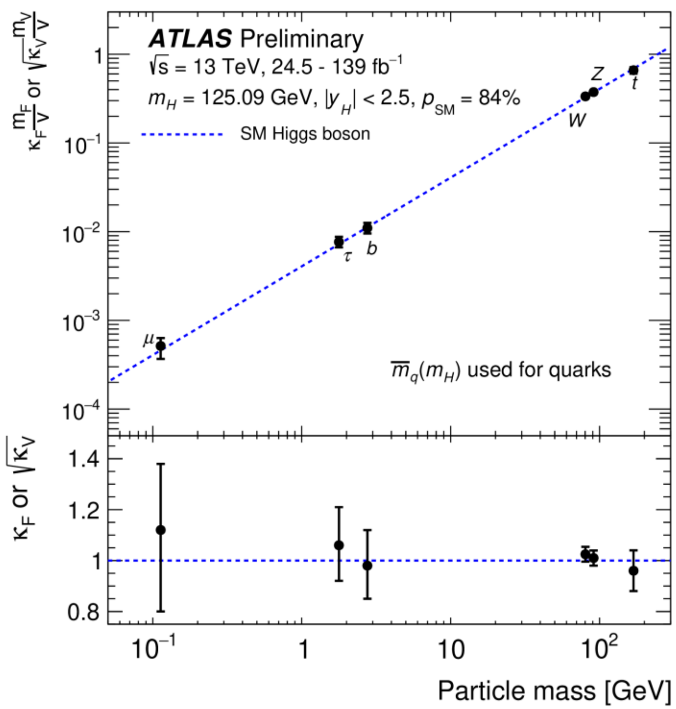
ATLAS-CONF-2020-027

Analysis	Dataset	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	2015–2018	139
$H \to ZZ^* \to 4\ell$		
$VH, H \to b\bar{b}$		
$H \to \mu\mu$		
VBF, $H \to inv$		
$H \to WW^* \to e\nu\mu\nu$	2015–2016	36.1
$H \to \tau\tau$		36.1
VBF, $H \to b\bar{b}$		24.5 – 30.6
$t\bar{t}H, H \to b\bar{b}$ and $t\bar{t}H$ multilepton		36.1



Interpretation in the κ-framework (SM coupling modifiers)

Coupling versus mass



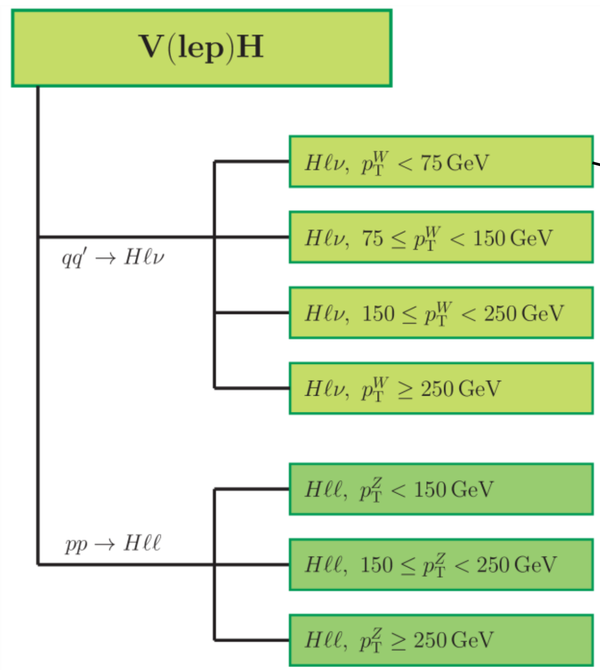
Scaling of the Higgs interaction consistent with the SM prediction over 3 orders of magnitude

Simplified template cross sections

2020

Exclusive regions of phase space for specific production modes

- Combine decay channels
- Decouple theory uncertainties from the measurements
- Retain experimental sensitivity
- Isolate BSM sensitivity regions



STXS stage 1.2

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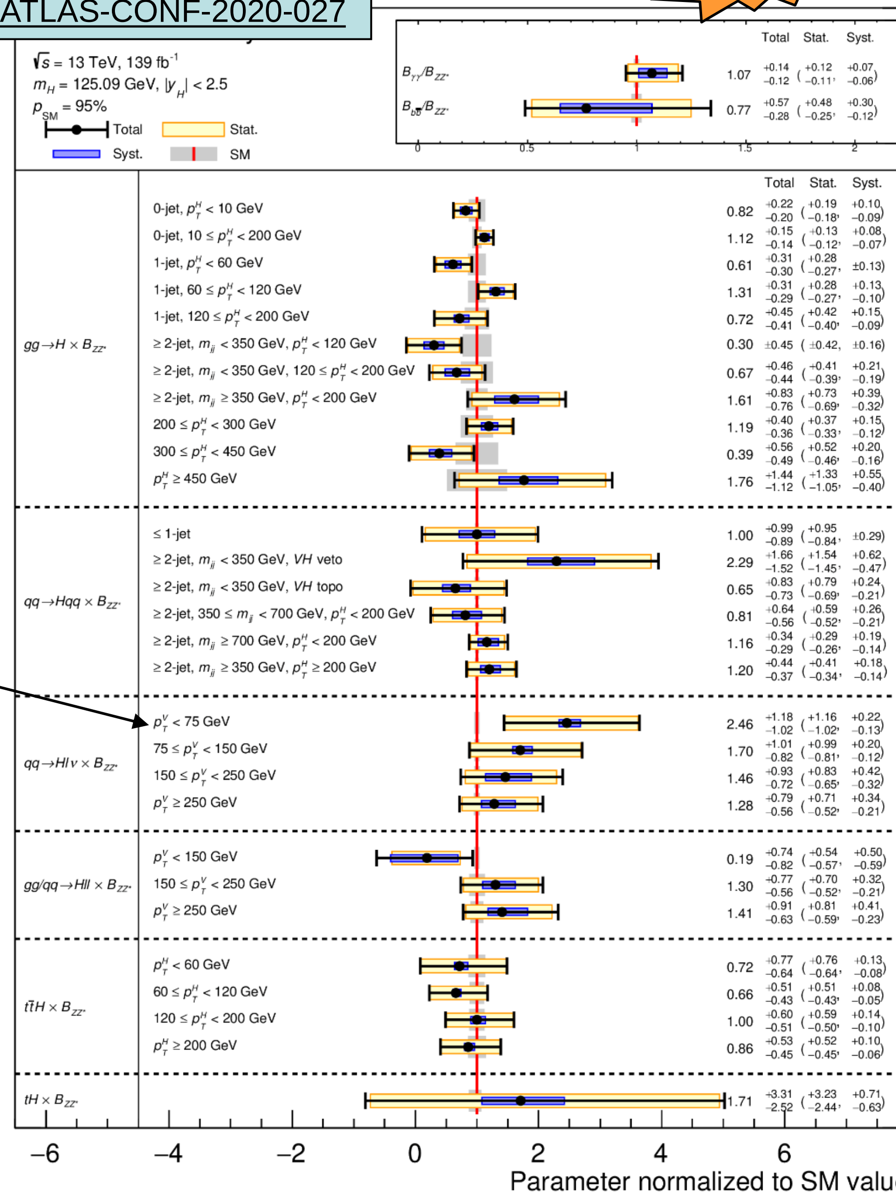
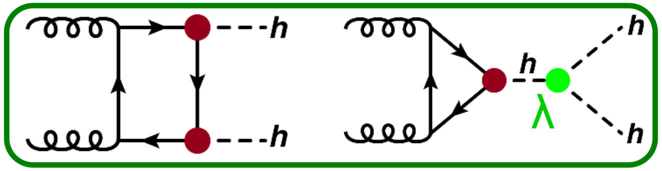


The self-coupling quest

2020

Shape of the Higgs potential: critical to understand the EW symmetry breaking mechanism in the early universe.

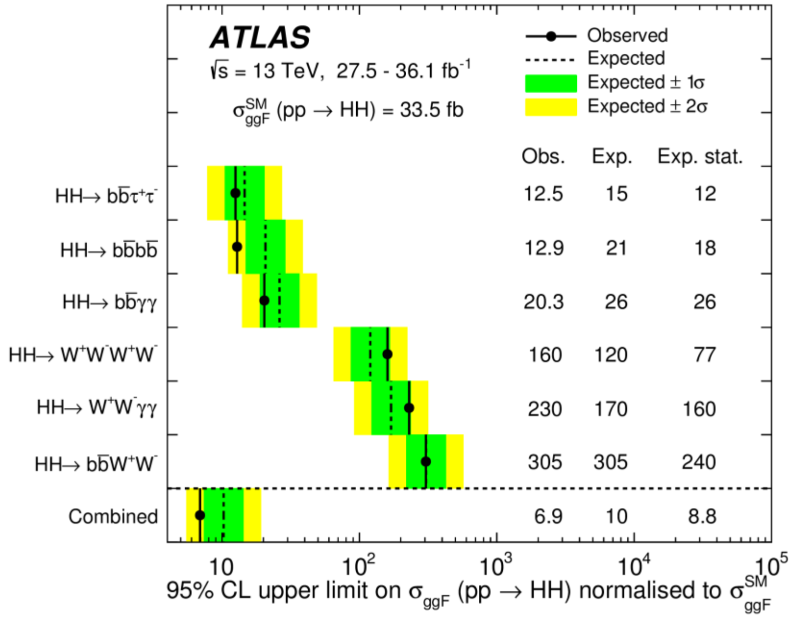
HH



arxiv:1906.02025

arxiv:1908.06765

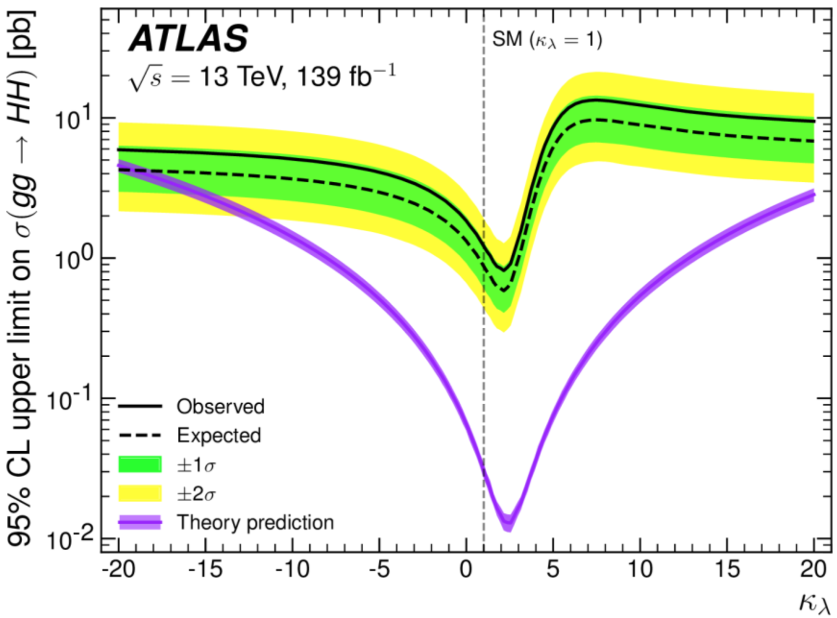
Early Run 2 combination



Sensitivity: ~10 σ_{SM}

($5.0<\kappa_\lambda<12.0$)

HH → bbWW



Sensitivity: ~30 σ_{SM}

3 main channels not yet updated to full Run 2 dataset

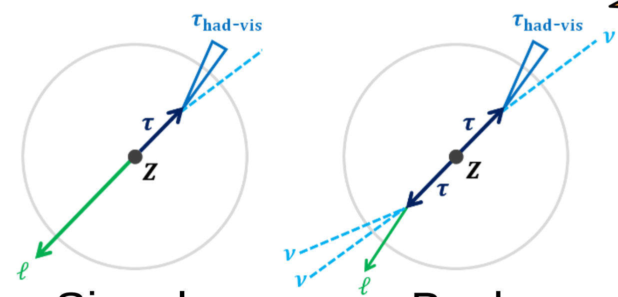
Evidence for HH process may be reachable at Run 3.

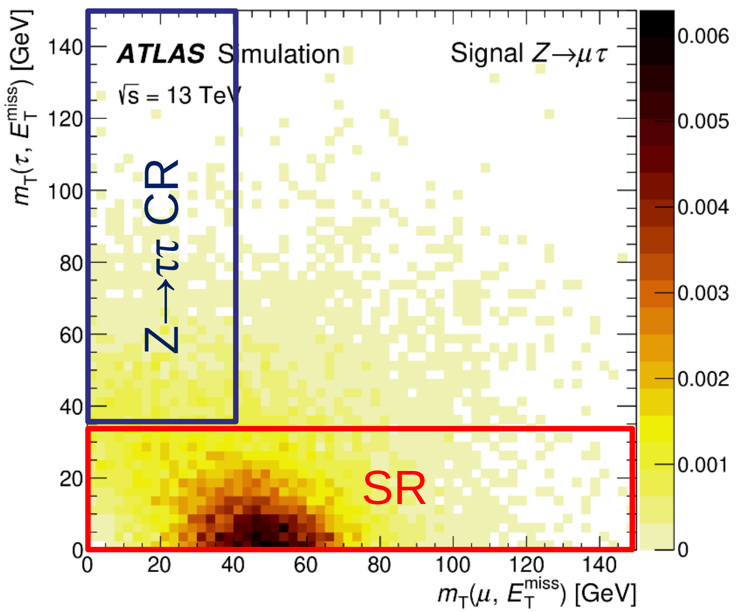
Lepton-flavor violation: Z→eτ/μτ

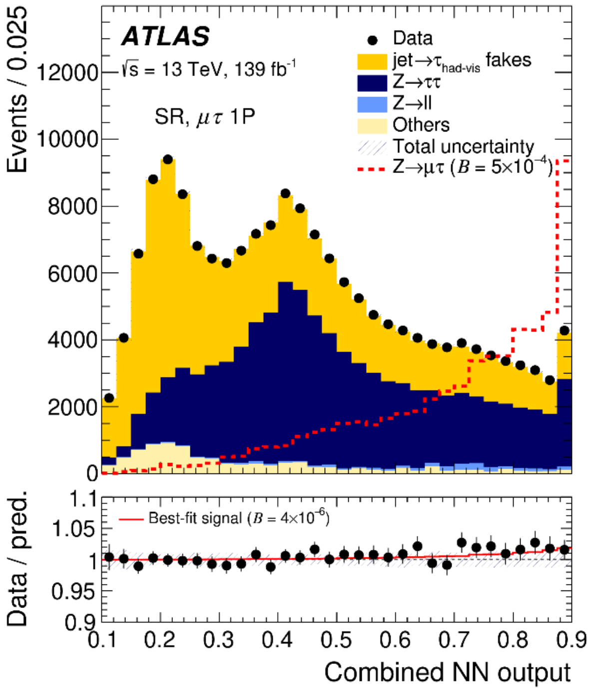
2020

arxiv:2010.02566

- Exploit huge sample of Z decays to search for LFV: Z→eτ/μτ
- Hadronic τ decays (1P and 3P)
- Neural network discriminant







Assuming unpolarized τ

BR(Z→eτ)< 8.1 10^{-6}
BR(Z→μτ)< 9.5 10^{-6}

Stat. dominated
Improve over LEP limits

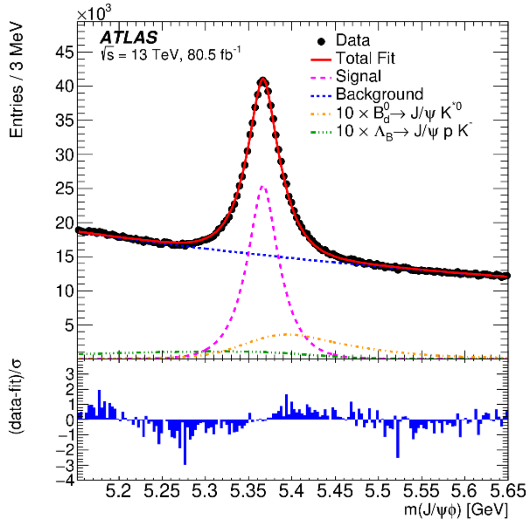
CP-violating phase in Φ_S

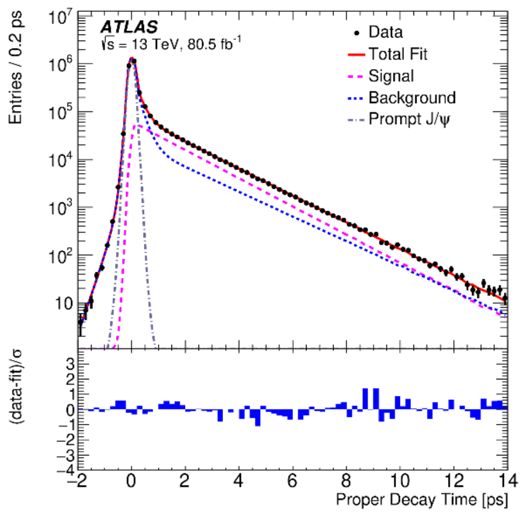
2020

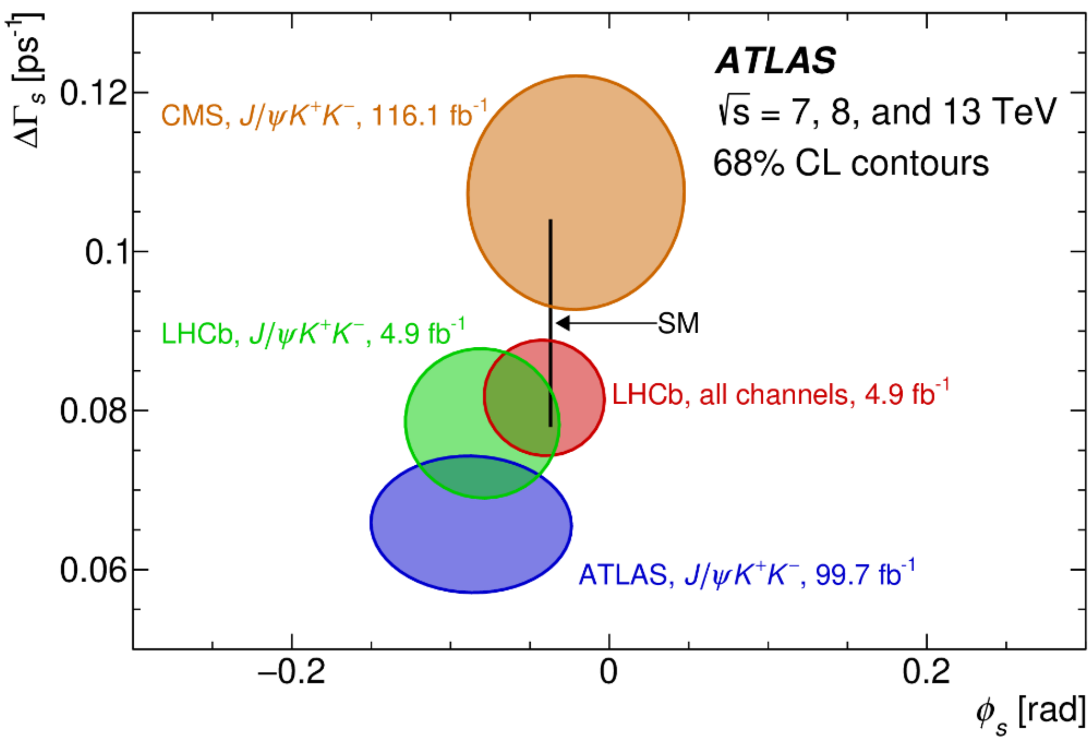
CPV measurement from interference between mixing and direct decay of $B_s \rightarrow J/\psi\Phi$

Time-dependent flavour-tagged angular analysis

arxiv:2001.07115







$$\phi_s = -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.) rad}$$

$$\Delta\Gamma_s = 0.0657 \pm 0.0043 \text{ (stat.)} \pm 0.0037 \text{ (syst.) ps}^{-1}$$

$$\Gamma_s = 0.6703 \pm 0.0014 \text{ (stat.)} \pm 0.0018 \text{ (syst.) ps}^{-1}$$