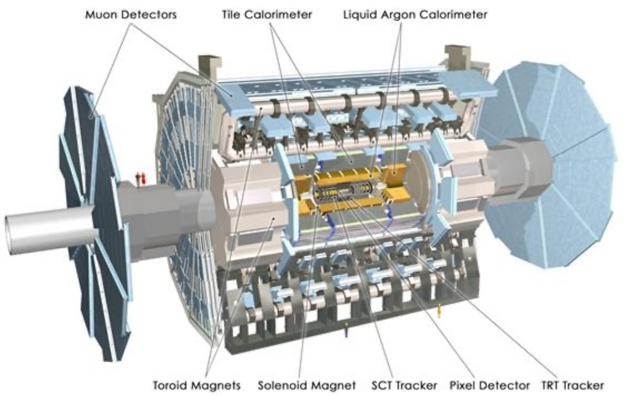
The ATLAS Experiment:
physics results by the MPP group

Margherita Spalla,

on behalf of the ATLAS MPP group

Physics analyses with the ATLAS detector

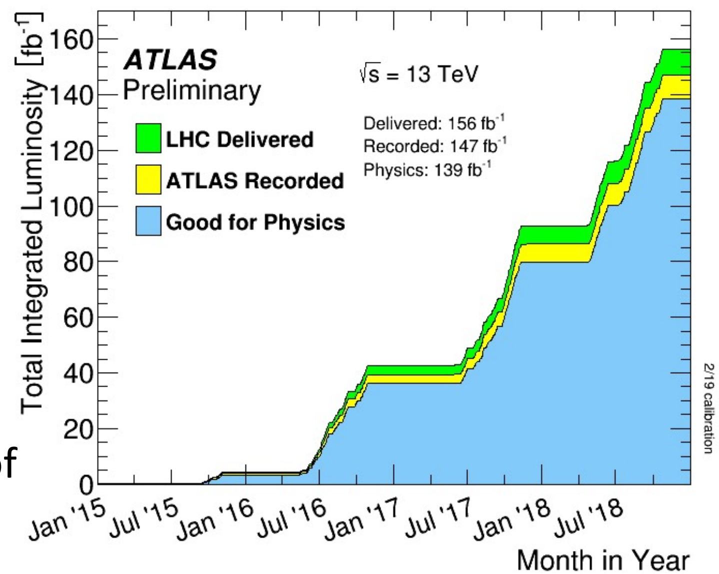
- Physics results and ongoing analyses by the MPP ATLAS group
  - Detector performance and upgrade discussed in the previous talk



- Vast analysis program, most results based on full Run 2 data
  - Integrated luminosity: 139 fb^{-1}

✓ High precision measurements of Standard Model (SM) processes
  - Detailed comparison with latest SM predictions and limits on Beyond the Standard Model (BSM) schemes

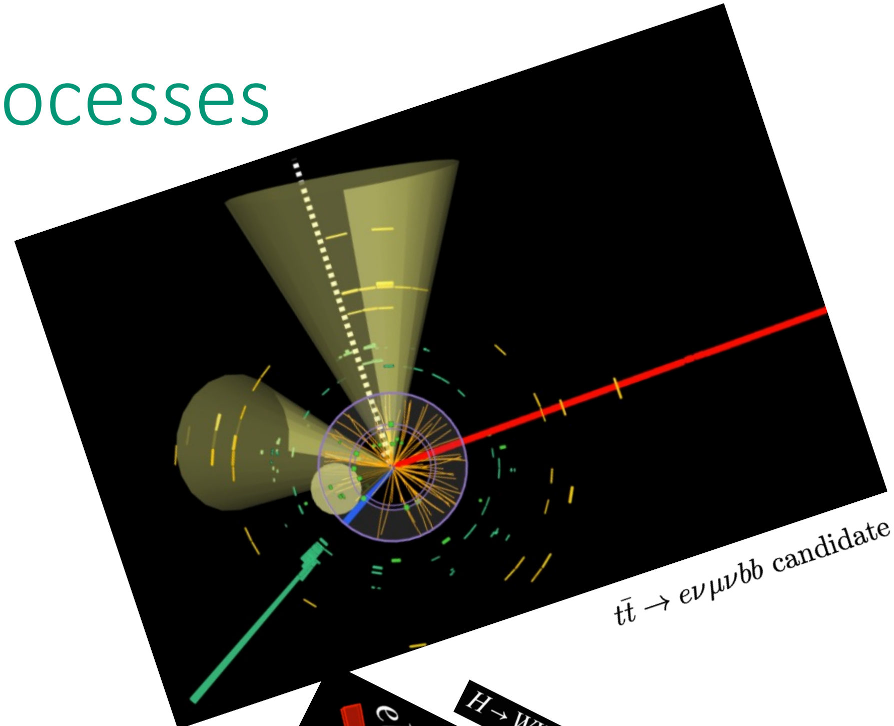
✓ Direct search of BSM signals
  - Explicitly look for BSM signals in a wide variety of processes



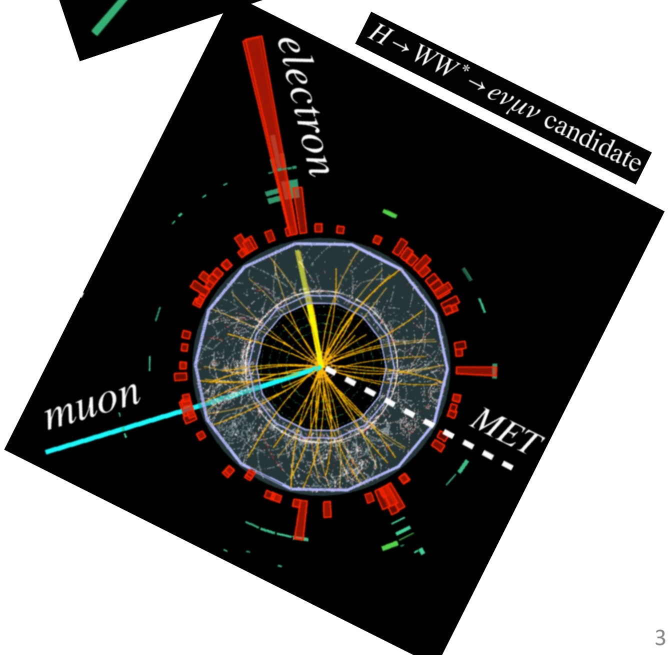
Measurements of SM processes

Long standing effort in:

- top-quark physics



- Higgs boson physics



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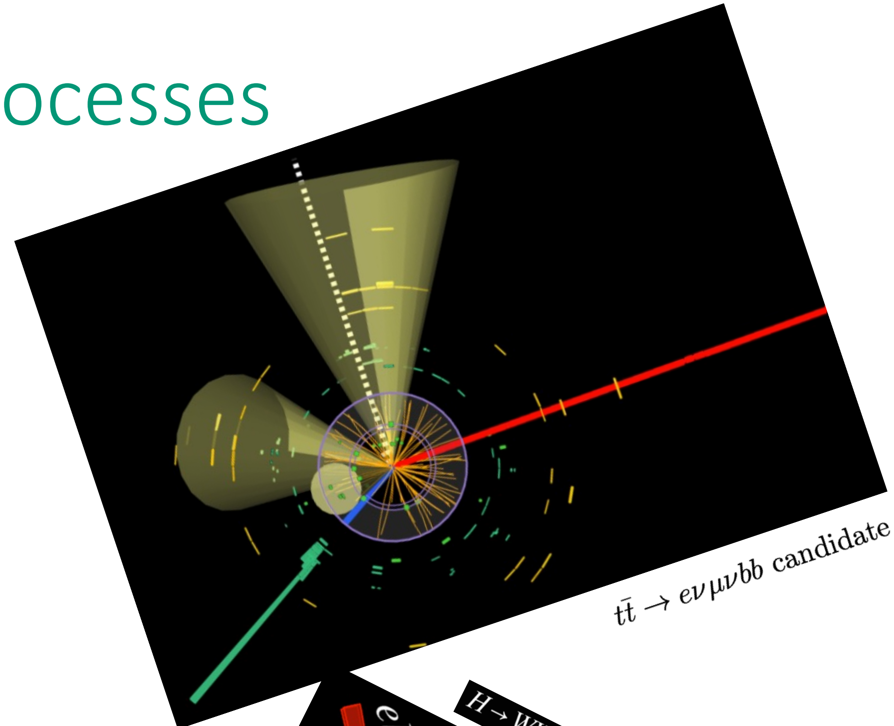
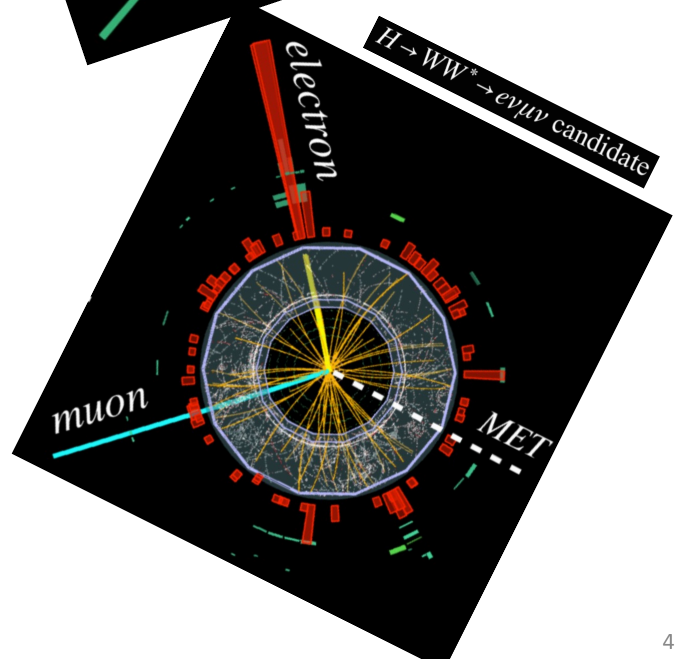
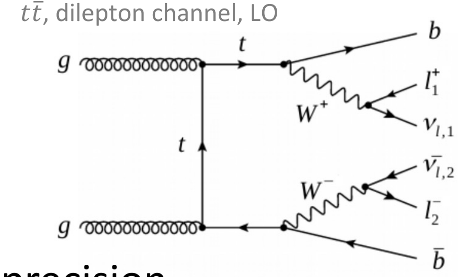


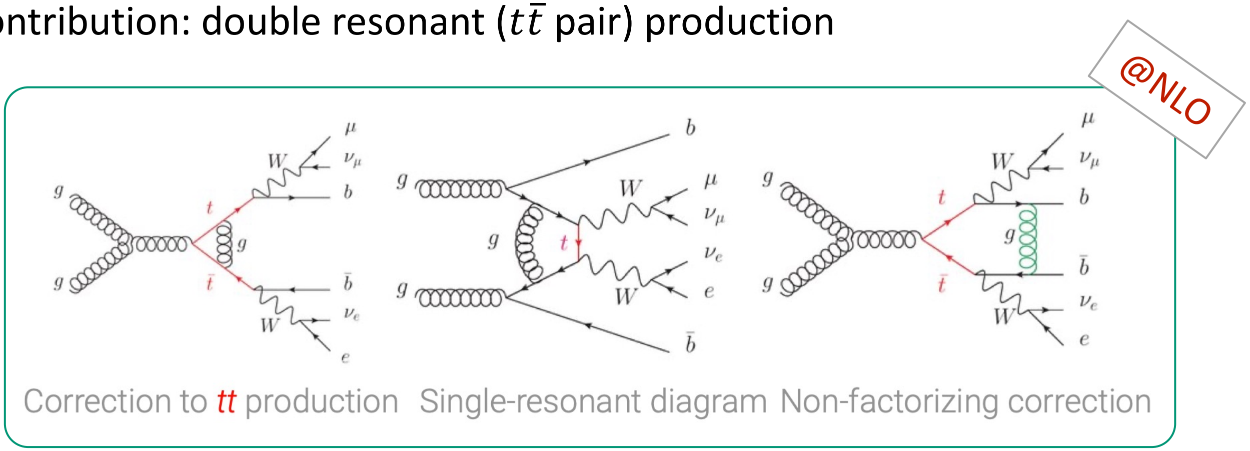


Top-quark precision measurements:

beyond on-shell $t\bar{t}$



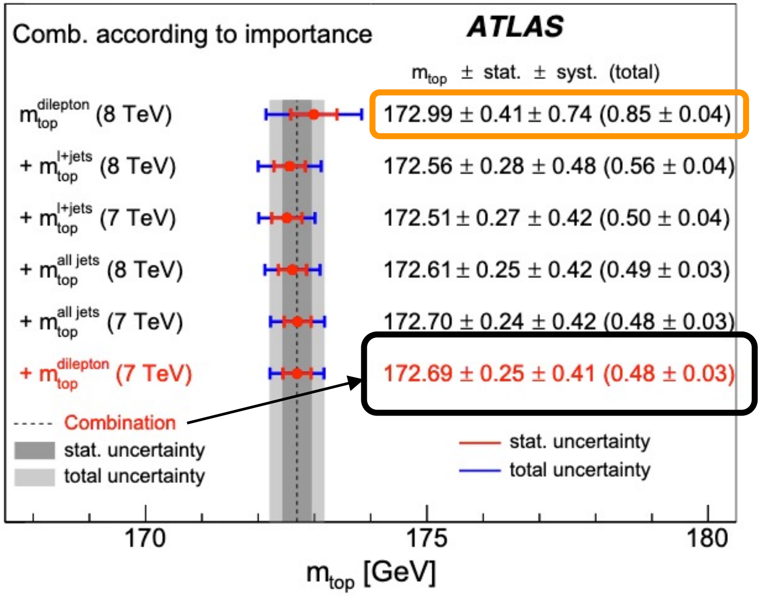
- Large cross-sections for top-quark production at the LHC, allows high precision
  - Important test of SM prediction
- *WWbb* is the preferred final state for top-quark precision measurements at LHC
  - Largest contribution: double resonant ($t\bar{t}$ pair) production



- Interference with single resonant (single t) production and non-resonant production
  - New Powheg-bb4l generator: double resonant, single resonant and non-resonant diagrams all included in Matrix Element calculation
    - Next-to-Leading Order (NLO) in production and decay.
    - However, restricted to the bb lnuv l'nu' final state
- <u>Two of our analyses are directly addressing this effect</u>

Top-quark mass precision measurements

- Top-quark mass plays important role in the SM and for the understanding of evolution of the universe
- ATLAS combination of top-quark mass direct measurements
  - Most precise single measurement: dilepton channel
- Ongoing work to reduce the systematic uncertainties:
  - Lepton+jets and dilepton channel analyses with 13 TeV data
    - optimised selections (Deep Neural Network) and improved phase space restrictions.
  - Reduction of signal modelling uncertainties:
    - NLO signal prediction in production and decay, parton showering and hadronisation.



Eur. Phys. J. C79 (2019) 290

Phys. Lett. B 761 (2016) 350

Top-quark mass precision measurements

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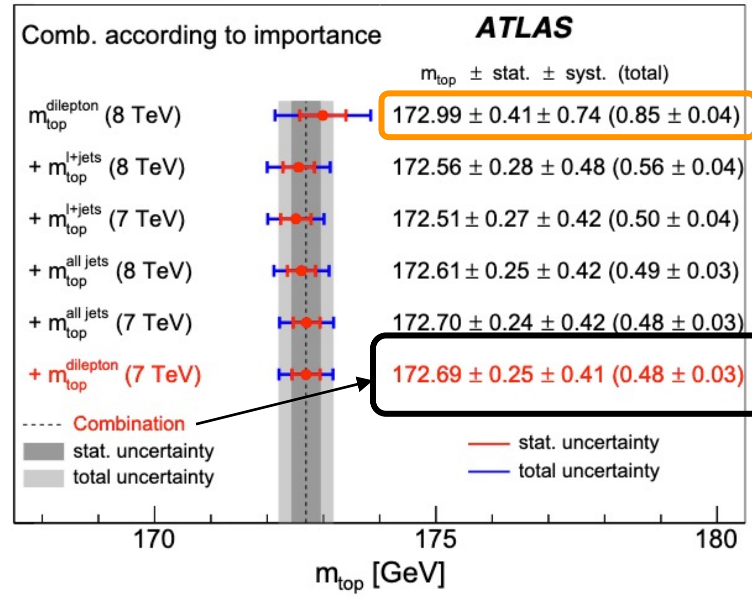
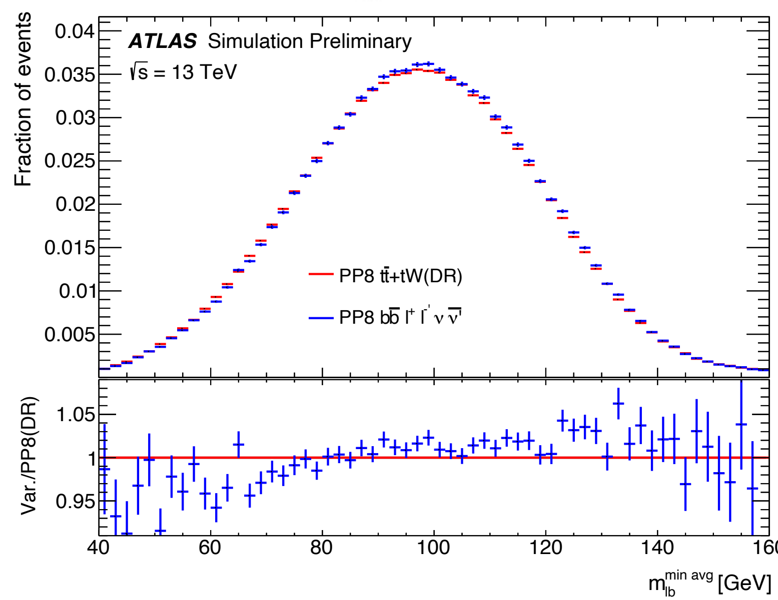


ATL-PHYS-PUB-2021-042

- Exploration of new Powheg-bb4l generator in the dilepton channel.

- New: PUB note comparing Powheg-bb4l to previous default Powheg (ttbar+tW)
  - Test effect on top-quark mass measurement
    - Template fit to the new bb4l sample (m_{top}=172.5 GeV), using default Powheg as templates:

$$m_{top}^{bb4l} = 172.86 \pm 0.08 \text{ GeV}.$$



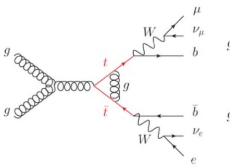
    - Fitted mass differs from initial simulated value by 0.36 ± 0.08 GeV

  similiar size to total signal modelling uncertainty in the published ATLAS result.

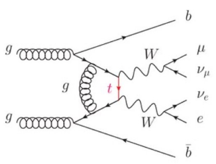
Work in progress

Cross section measurements of: $pp \longrightarrow WWbb$

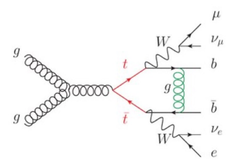
- The final state of two W-boson and two b-jets can be directly measured
  - *WWbb* analysis, aims at both resonant and non-resonant production
    - Sensitivity top-quark mass and width, α_s, PDFs, ...
    - WWbb modelling relevant for multiple SM and BSM analyses (m_t, Supersymmetry…)



Correction to *tt* production



Single-resonant diagram



Non-factorizing correction

- Two new cross section measurements are performed

<u>Di-lepton channel</u>

$pp \rightarrow WWbb \rightarrow bbll$ + missing-E_T

- Study *tt*−*Wtb* quantum interference
- support top-quark mass measurements
- Sensitivity to top-quark mass

<u>lepton+jets channel</u>

$pp \rightarrow WWbb \rightarrow lvbbjj$

- Measure W-boson and top-quark properties
- Determine SM parameters, like m_t
- Challenge latest theoretical predictions

- High precision needed to be sensitive to sub-dominant contribution
  - Cannot rely on kinematic constraints from the top-quark for event reconstruction

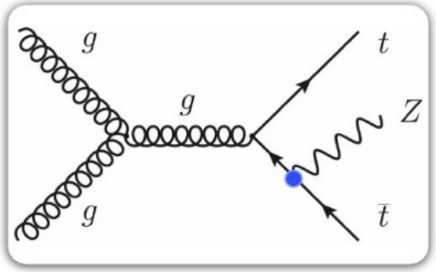
Rarer top-quark production processes:

$t\bar{t}Z$ differential cross section

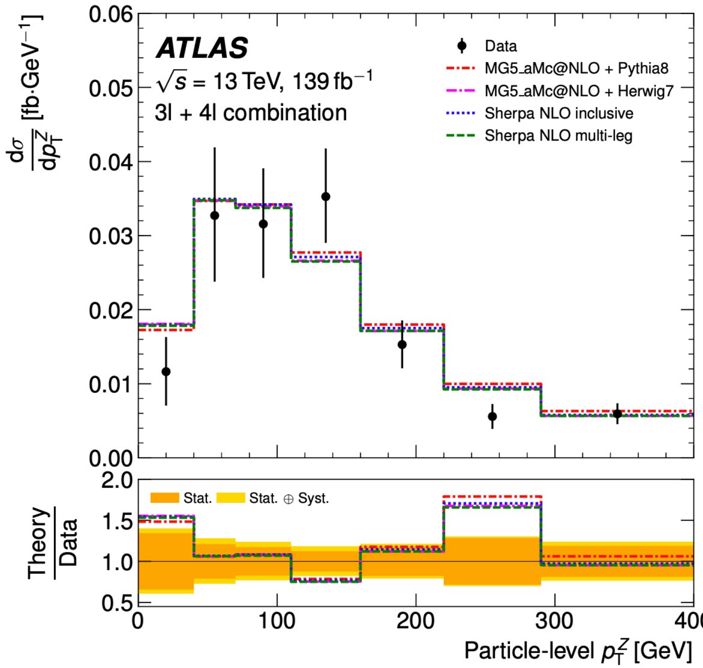
Eur. Phys. J. C 81 (2021) 737

- Rarer processes also starting to be measured at the LHC

- $t\bar{t}Z$ production
  - interesting test of the SM, involving QCD & Electroweak coupling
  - relevant background for multiple BSM searches
  - Final state:
    - $Z \to \ell\ell$
    - $t\bar{t} \to b\bar{b}\ell\nu\ell\nu$ or $t\bar{t} \to b\bar{b}\ell\nu jj$
  - Differential cross section as a function of multiple kinematic variables
    - Extensive comparison with multiple SM predictions



$$\sigma_{t\bar{t}Z} = 0.99 \pm 0.05\ (\text{stat.}) \pm 0.08\ (\text{syst.})\ \text{pb}$$



Rarer top-quark production processes:

all hadronic $t\bar{t}b\bar{b}$ differential cross section

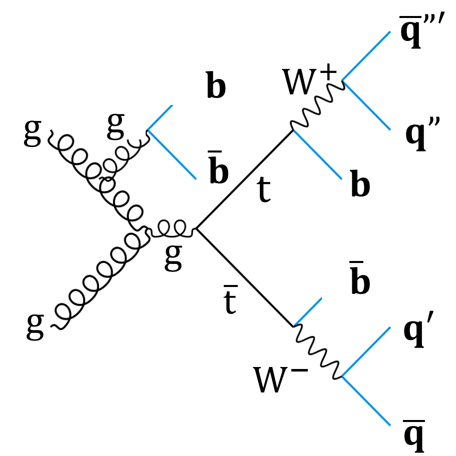
Work in progress

PhD Thesis (in progress): N. Wenke

- Heavy quarks production dynamics
  - Sensitive to BSM physics
- Large and not so well modelled background for e.g. $t\bar{t}H$
- Full final state reconstruction
  - Useful knowledge for future analyses

From PowHeg all-hadronic simulation:

$\rightarrow \sigma^{\text{all had}}_{t\bar{t}b\bar{b}} \simeq 12.1 \times 10^{3}\ \text{fb}$



- Rare process, never measured by ATLAS in the all-had. channel
- An inclusive CMS measurement exists
  - Considered predictions (PowHeg, MadGraph) about 1σ from measured cross section (Phys. Lett. B 803 (2020) 135285)
    - ➤ Deviations observed also between multiple simulations (e.g. arXiv:1610.07922)
- Challenging final states: 8 jets, 4 b
  - large effort spent on optimising final state reconstruction
    - ➤ kinematic fitting, min. χ^2...
  - large multi-jet background, data-driven approach

CMS results

	Fiducial, parton-based (pb)	Total (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($t\bar{t}$)	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($t\bar{t}$) + HERWIG++	0.8 ± 0.2	3.0 ± 0.5
MADGRAPH5_aMC@NLO (4FS $t\bar{t}b\bar{b}$)	0.8 ± 0.2	2.3 ± 0.7
MADGRAPH5_aMC@NLO (5FS $t\bar{t}$+jets, FxFx)	1.0 ± 0.1	3.6 ± 0.3

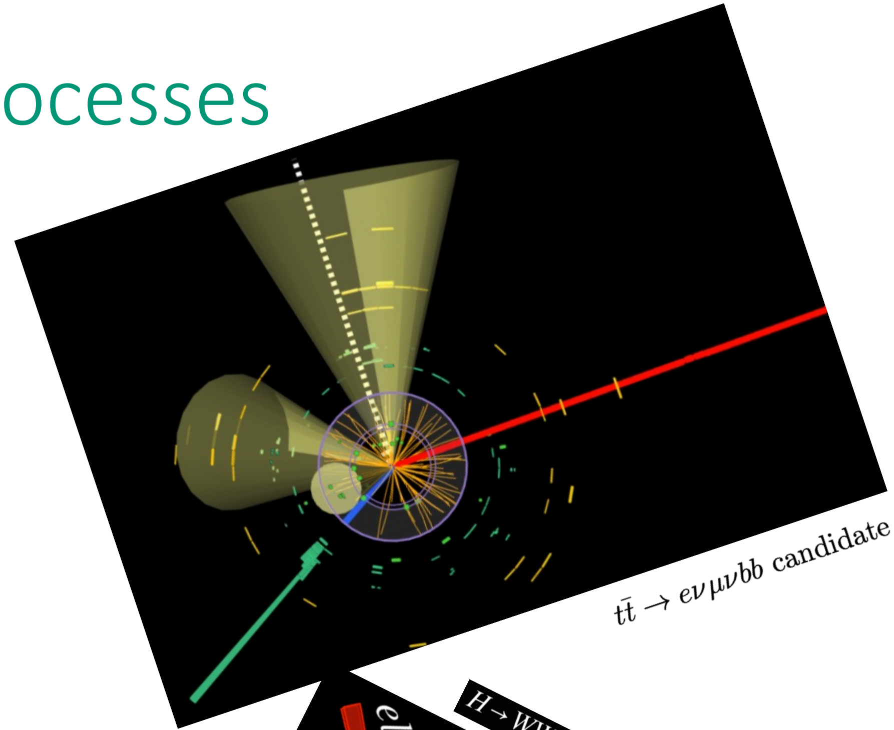
Phys. Lett. B 803 (2020) 135285

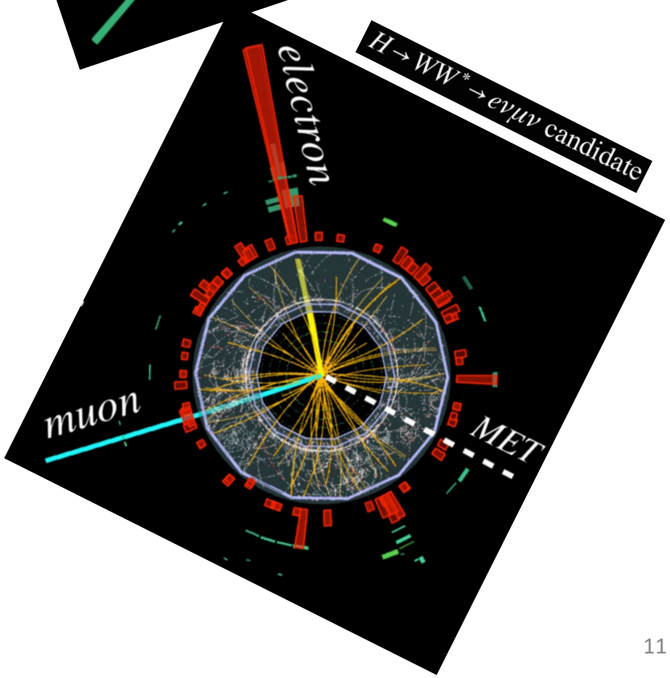
Measurements of SM processes

Long standing effort in:

- top-quark physics

- Higgs boson physics

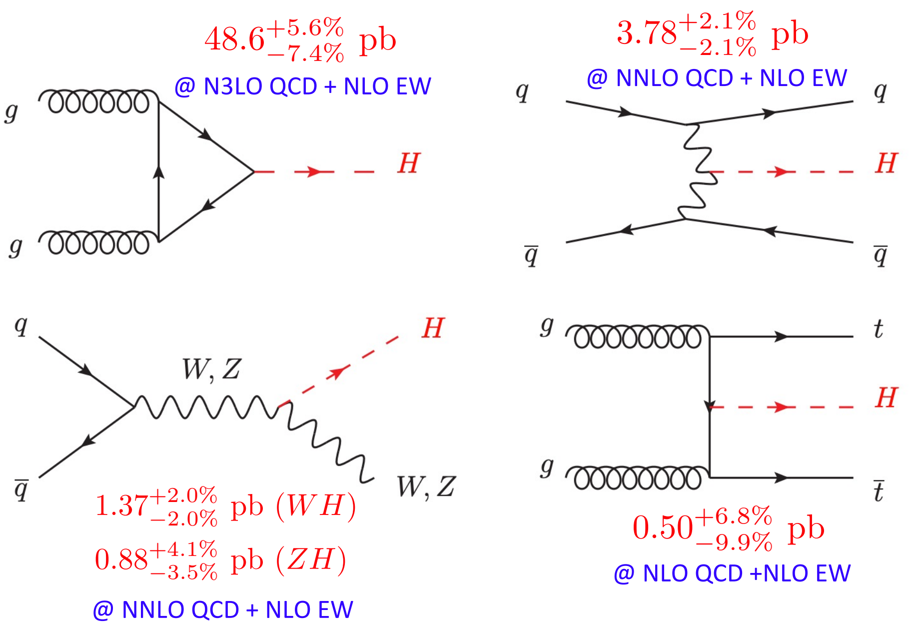




Higgs boson physics

- Extensive measurements of all key Higgs production and decay modes
  - Comparison to the corresponding state-of-the-art SM theory predictions
  - Interpretation within theories beyond the Standard Model (BSM).

Main H production channels at the LHC, from .



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Decay channel	Branching ratio	Rel. uncertainty
$H \to b\bar{b}$	$5.82 \cdot 10^{-1}$	$^{+1.2\%}_{-1.3\%}$
$H \to W^+W^-$	$2.14 \cdot 10^{-1}$	$\pm 1.5\%$
$H \to \tau + \tau -$	$6.27 \cdot 10^{-2}$	$\pm 1.6\%$
$H \to ZZ$	$2.62 \cdot 10^{-2}$	$\pm 1.5\%$
$H \to \gamma\gamma$	$2.27 \cdot 10^{-3}$	$\pm 2.1\%$
$H \to Z\gamma$	$1.53 \cdot 10^{-3}$	$\pm 5.8\%$
$H \to \mu^+\mu^-$	$2.18 \cdot 10^{-4}$	$\pm 1.7\%$

H branching ratios in size order.

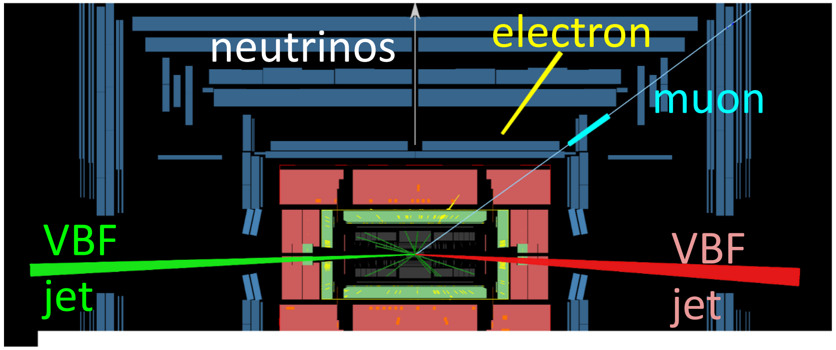
➢ Higgs boson production and decay calculated to high precision

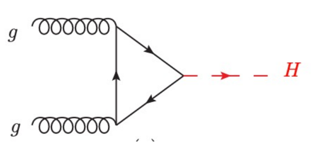
Numbers on the slide from: P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2021)

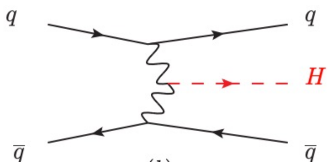
Higgs Properties: $H \to WW \to e\nu\mu\nu$

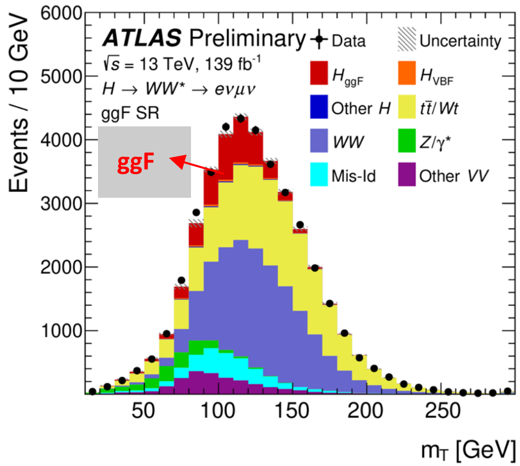
ATLAS-CONF-2021-014

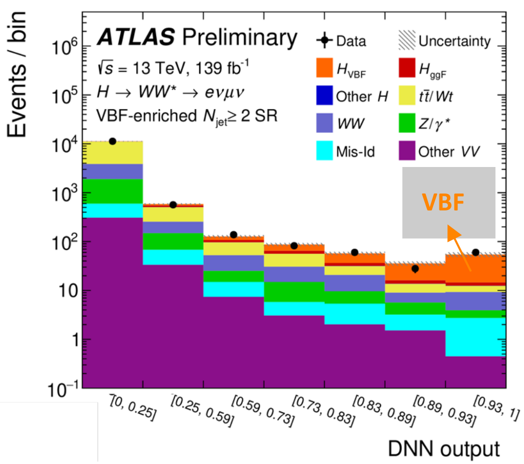
- Measurement updated with full Run 2 data.
  - Gluon-gluon fusion (ggF) and vector boson fusion (VBF)
    - measured using neural networks.
  - This channel provides the most precise VBF measurement.

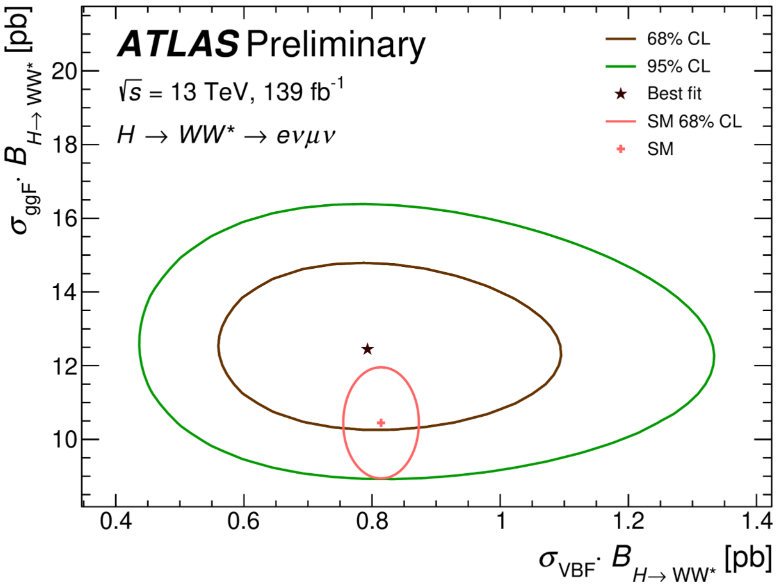








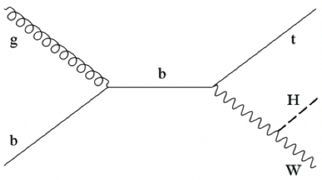




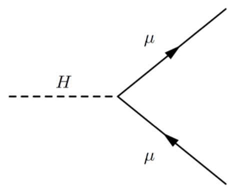
Higgs Properties: Combined Measurement

ATLAS-CONF-2021-053

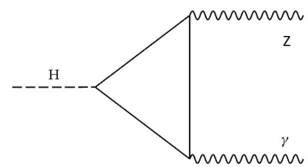
- All key analyses channels now using full ATLAS Run 2 data.
- Access to rare processes (tH production, $Z\gamma$ and $\mu\mu$ decays).



tH signal significance: **1.0σ**



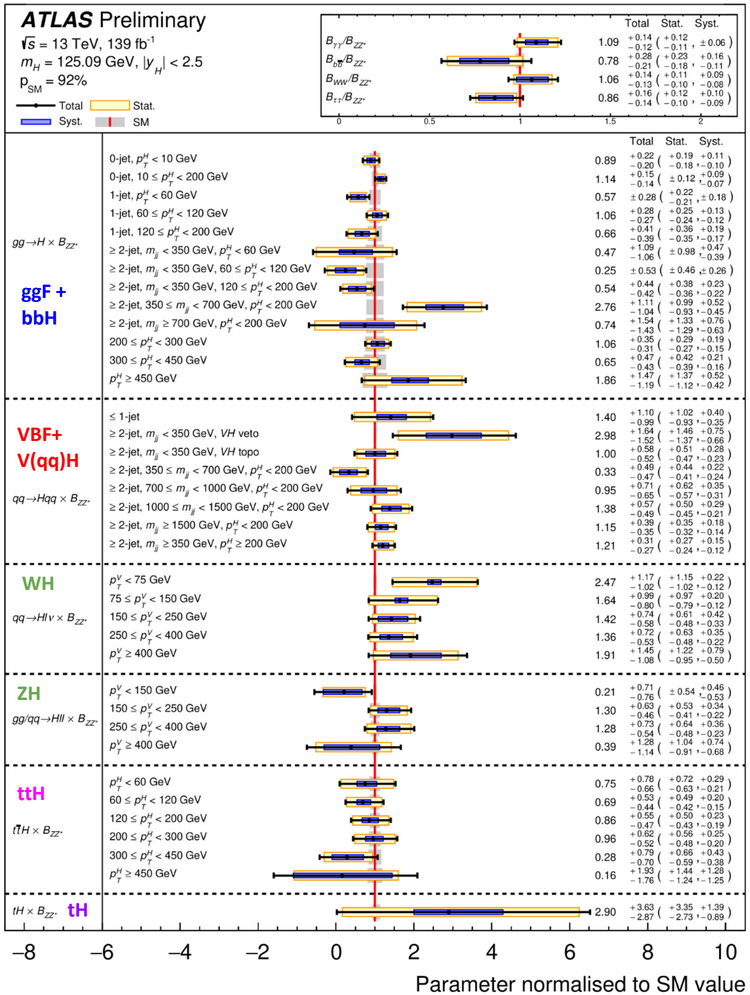
$\mu\mu$ signal significance: **1.1σ**



$Z\gamma$ signal significance: **2.2σ**

- Highly increased granularity of the probed production space
  - different jet multiplicities, Higgs transverse momenta...
- Allows for an increased sensitivity to BSM physics. Interpretations within:
  - kappa-framework (assumes SM tensor structure of Higgs couplings)
  - Theory frameworks introducing BSM tensor structure (e.g. EFT)
  - UV-complete theory models (e.g. Two Higgs Doublet Model)

Cross section in exclusive regions of prod. phase space:

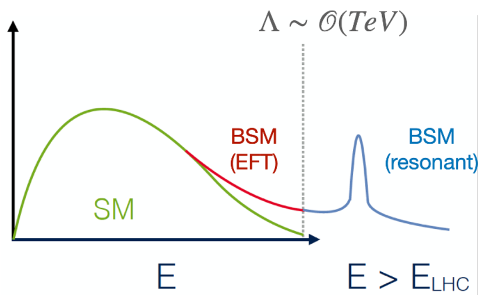


Higgs Properties: EFT-Interpretation

ATLAS-CONF-2021-053

PhD Thesis (in progress): A. Reed

In the absence of direct evidence for BSM physics so far, the SM could be viewed as a low-energy approximation to a more fundamental theory.



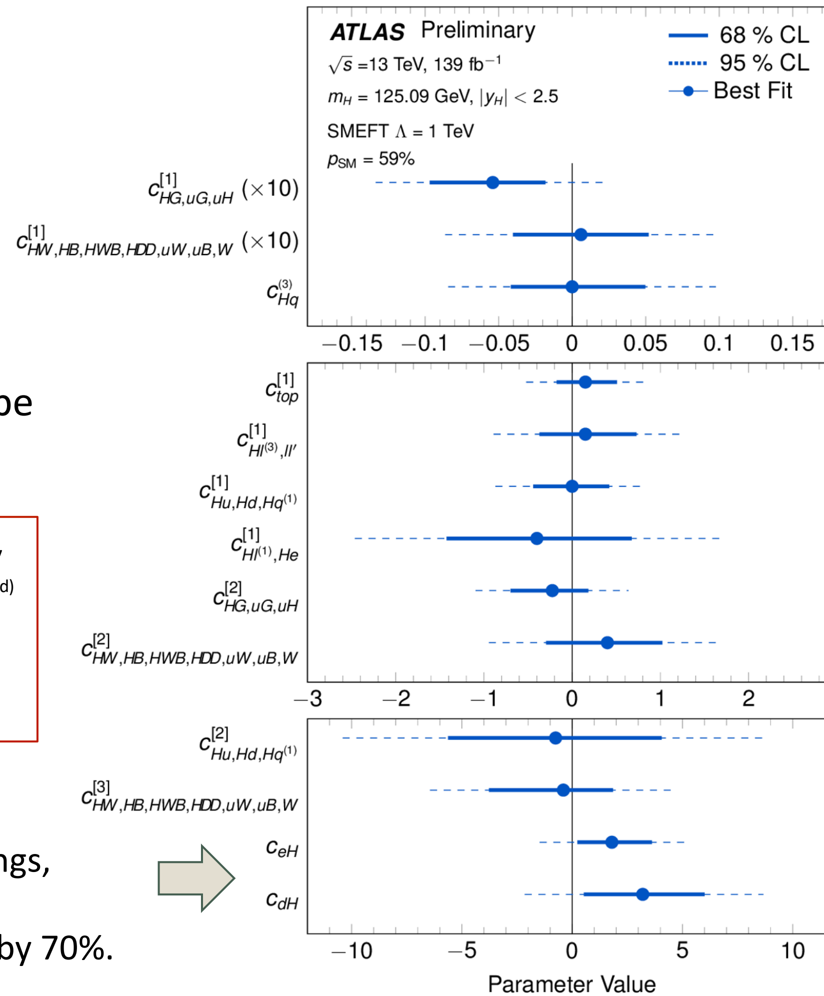
Well below the new physics scale Λ, the nature can then be described by an Effective Field Theory (EFT) Lagrangian:

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

Deviations from SM described by higher-dimensional operators $O_i^{(d)}$ suppressed by powers of Λ^{d-4}. Wilson coefficients $C_i^{(d)}$ can be constrained from data.

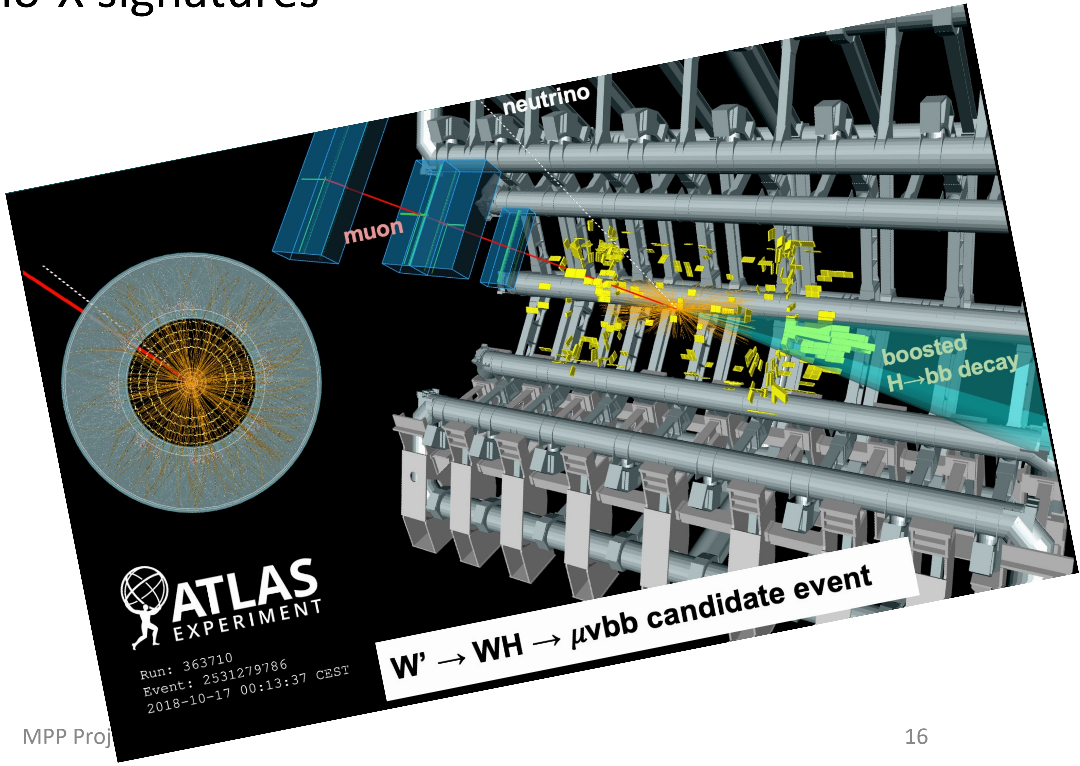
Fit to the latest Higgs cross section measurements:

- ✓ EFT parameters C_{eH} and C_{dH}, related to τ and b Yukawa couplings, constrained for the first time.
- ✓ Constraints on other Higgs-related EFT-parameters improved by 70%.



Direct searches for BSM physics

- Multiple approaches and signatures:
  - Searches for new heavy resonances
  - Dark Matter searches: Mono-X signatures
  - Supersymmetry



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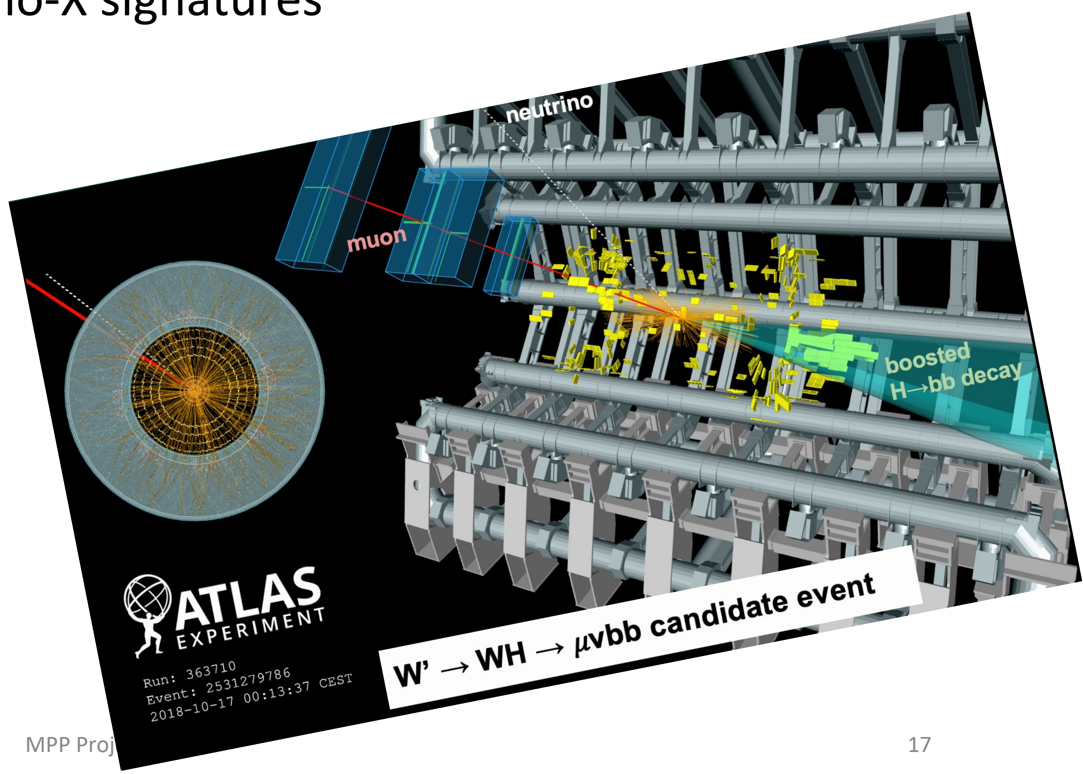
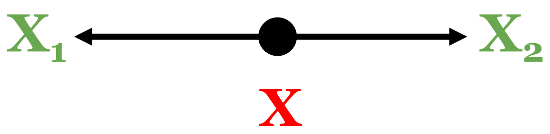


Searches for new heavy resonances

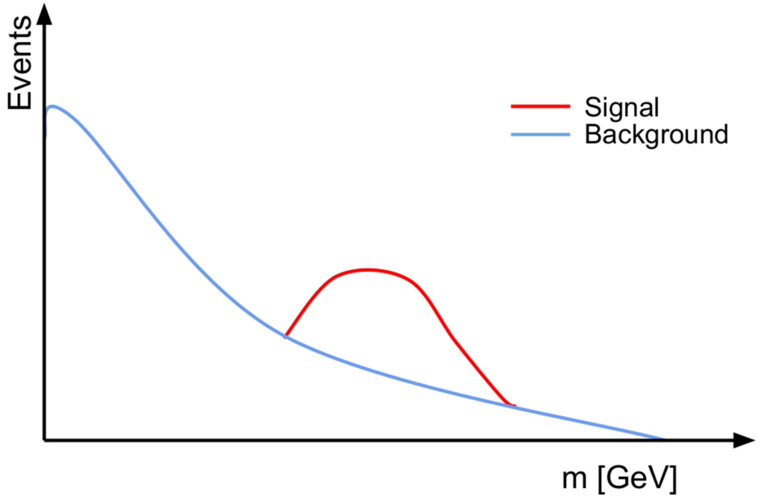
- A (heavy) resonance X decaying into SM particles X1 and X2.

- Multiple production and decay modes, targeting diverse sets of final states
  - Multi-lepton, Di-photon, Lepton + jets, Multi-jets



- Search for a bump in an otherwise smoothly falling mass spectrum.
  - (Quasi) Model-independent analyses

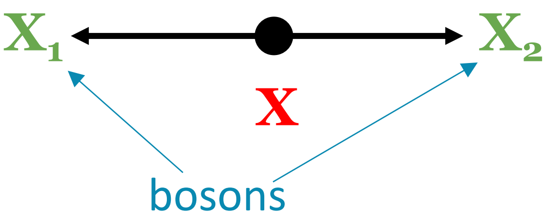
- Interpretations in generic frameworks
  - Extended Higgs sector:
    - Two Higgs Doublet Model (2HDM)
  - Other frameworks:
    - Heavy Vector Triplet (HVT) models
    - RS Extra-dimensional models
    - Leptoquarks

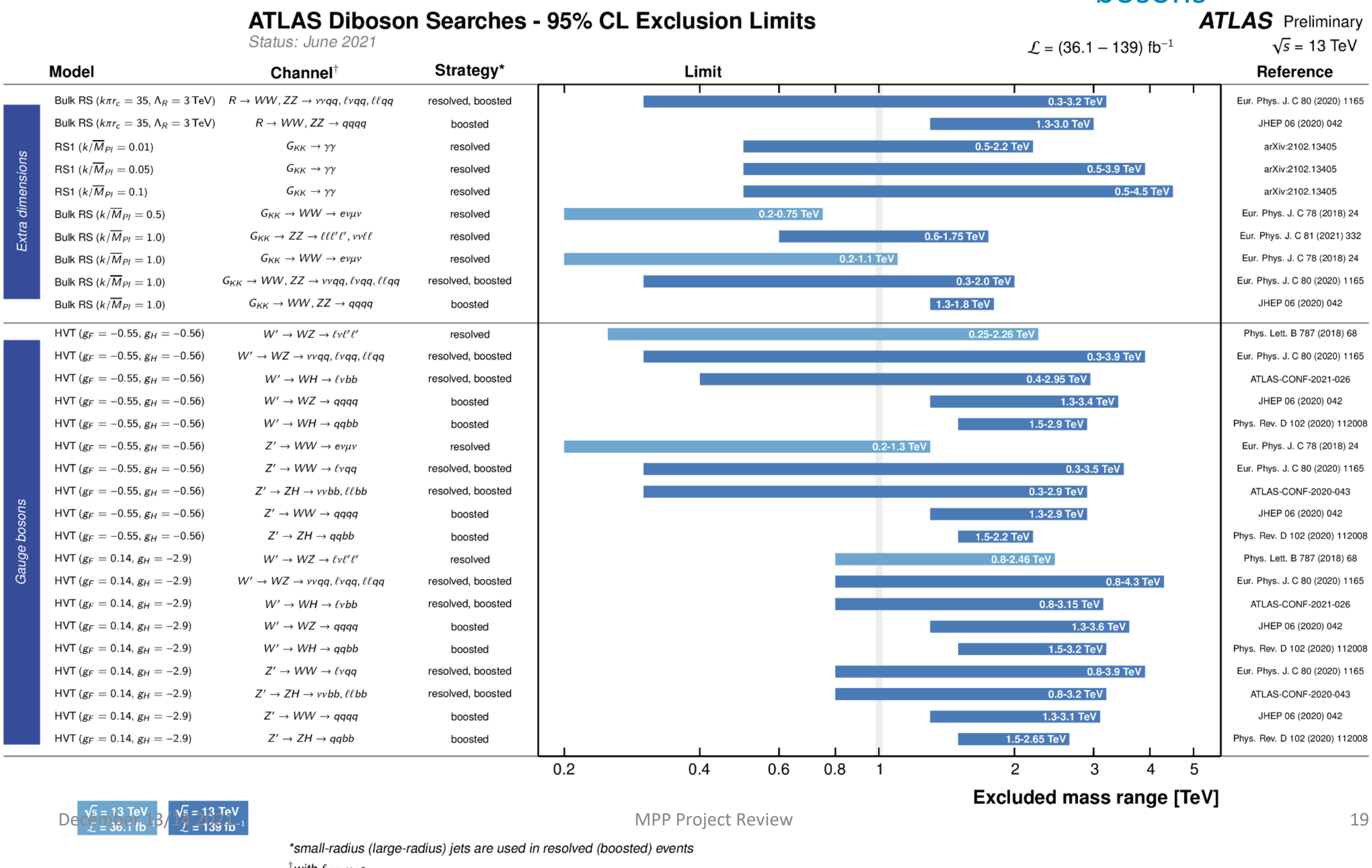


Searches for new heavy resonances:

diboson resonance searches

ATLAS-PHYS-PUB-2021-018





Searches for new heavy resonances:
diboson resonance searches

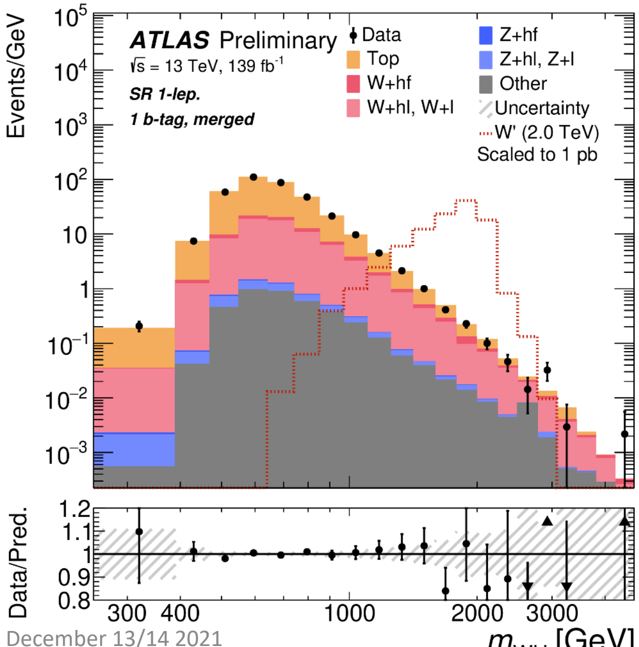
ATLAS-CONF-2021-026

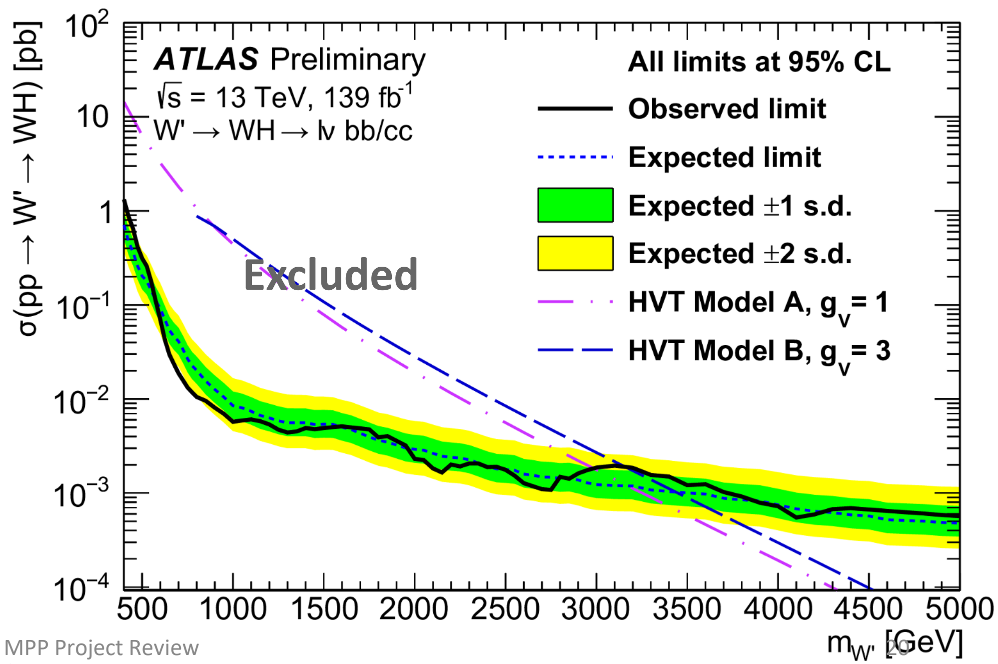
PhD Theses: A. Hönle, S. Maschek

Search for resonances in W'/ Z' → (WH, ZH) decays

- Probe ℓvbb, ℓℓbb and vvbb final states (ℓ = μ, e; boosted H decay)
- Analysis strategy:
  - Search for bumps in $m_{\ell vbb/\ell\ell bb/vvbb}$ spectra.
  - Simultaneous maximum likelihood fit to several non-overlapping signal and control regions.
  - Dominant systematic uncertainty: background modelling (top-quark), large-R jet mass resolution.

H: Higgs boson, m_H=125 GeV





Searches for new heavy resonances:

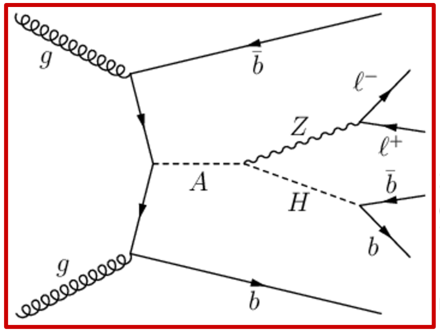
diboson resonance searches

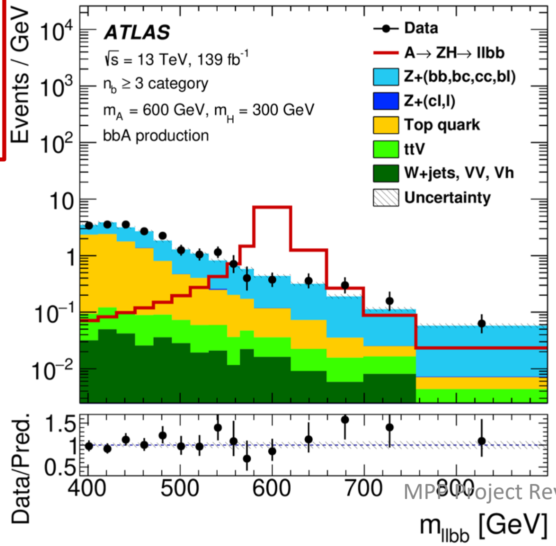
Eur.Phys.J. C81 (2021) 396

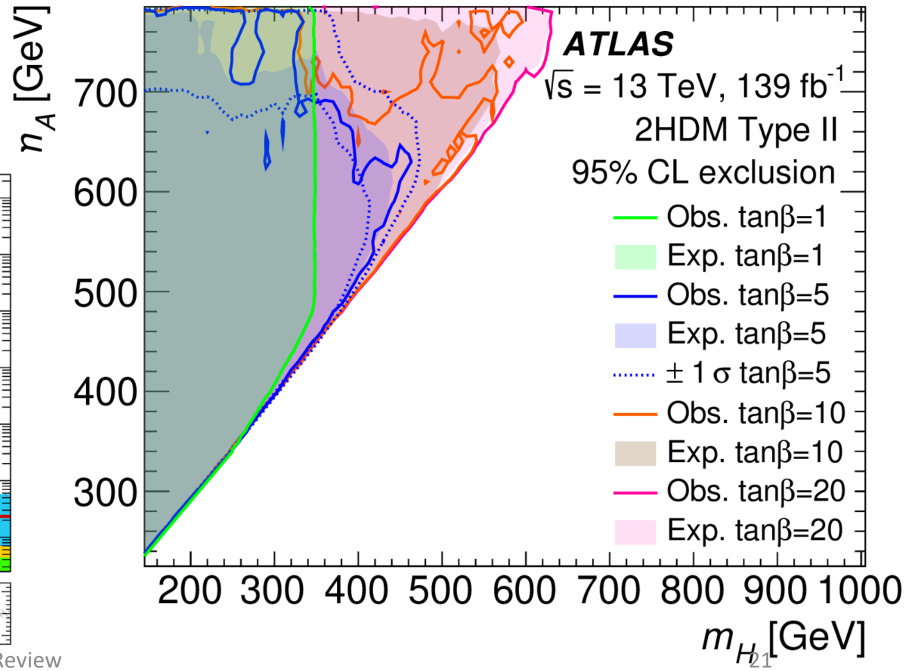
Search for new scalars in A → ZH decays

H: heavy Higgs boson, m_H>125 GeV

- Search for a pseudo-scalar decaying via A → ZH
  - Motivated by electroweak baryogenesis scenarios in the context of the 2HDM.
  - Probe gg → A and bbA production modes, with H → bb and H → WW → qqqq decays.
  - Scanning over different Higgs boson mass hypotheses.







Searches for new heavy resonances:

heavy charged Higgs bosons

Work in progress

Master Thesis: S. Grewe
PhD Thesis (in progress): S. Grewe

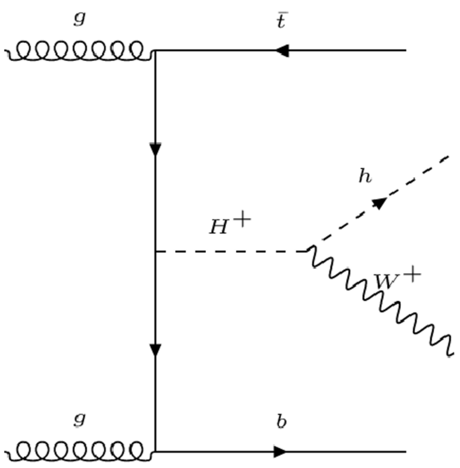
- Searches for an extended scalar sector are crucial:
  - can modify the electroweak phase transition and facilitate baryogenesis,
  - enhance vacuum stability,
  - provide dark matter candidate
  - possible solution to the strong CP problem
  - At least one set of charged Higgs bosons predicted by various extended scalar sector theories

- So far, ATLAS and CMS searches mainly focus on the $H^{\pm} \rightarrow tb$ and $H^{\pm} \rightarrow \tau\nu$ decay modes (motivated by MSSM)

- $H^{\pm} \rightarrow W^{\pm}\, h$ can have a significant branching ratio in models with three Higgs Doublets or at least one Higgs Triplet

- Expected dominant production mode of heavy charged Higgs bosons: in association with a top quark and a bottom quark

- We have to probe complicated final states such as ℓνjjbbbb
  - Use sophisticated machine learning algorithms for the classification and reconstruction of the candidate event



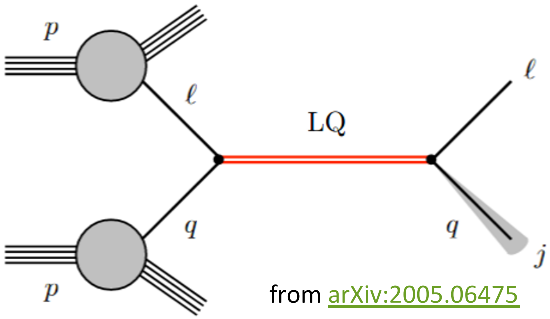
Searches for new heavy resonances:

Resonant Leptoquark Production

Work in progress

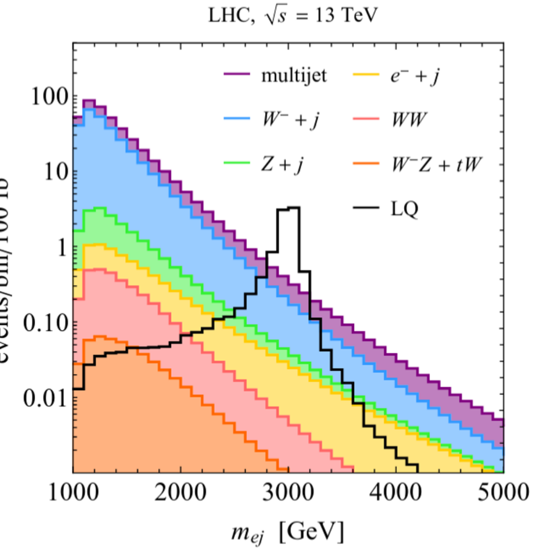
PhD Thesis (in progress): D. Buchin

- Leptoquarks (LQs)
  - particles with non-zero baryon and lepton number
    - carry color and electric charge
  - relate quark and lepton sector
  - promising solutions to e.g. muon g-2 and flavor anomalies



from arXiv:2005.06475

- LHC as Lepton-Proton Collider
  - Lepton content in proton due to quantum fluctuations[†].
    - allows resonant production of LQs
  - Phenomenological studies[‡] (Uli Haisch et. al) predict competitive sensitivity to current LQ searches.



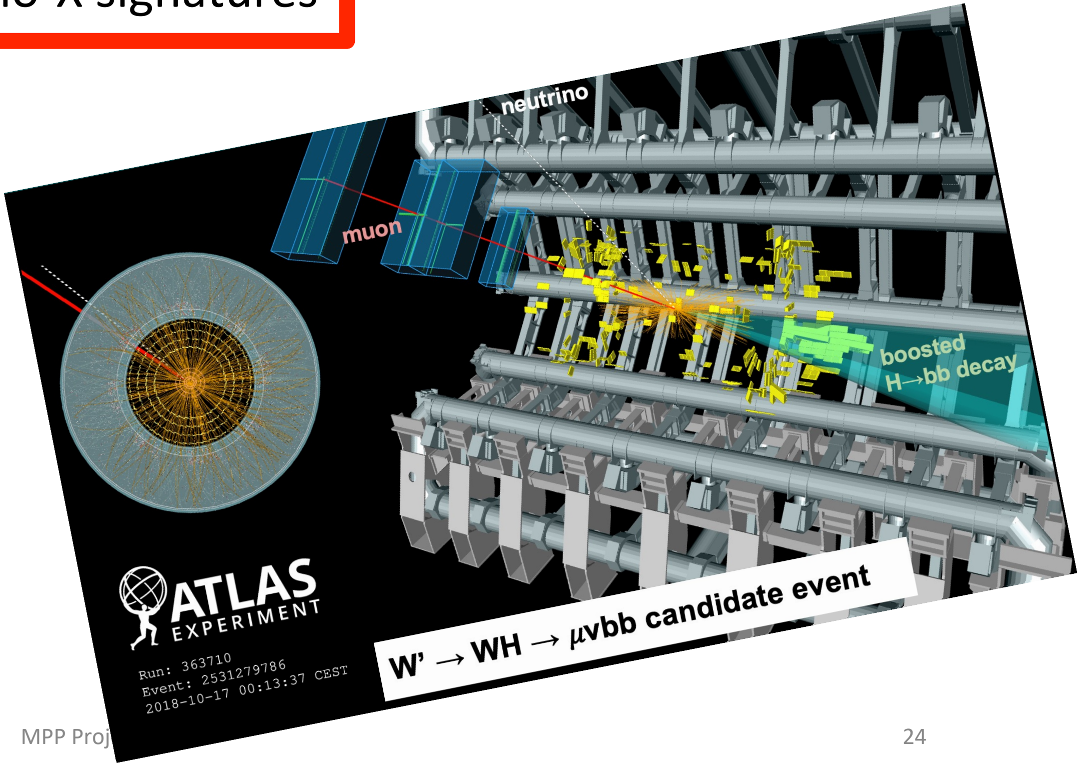
from arXiv:2005.06475

- Kicked-off search in lepon+jet final states following discussion with MPP theory group:
  - sensitivity via bump-hunt in invariant mass m(ℓ,j) spectrum
  - This is the first search for resonant LQ production in ATLAS.

[†] arXiv:2005.06477 [‡] arXiv:2005.06475, arXiv:2012.11474

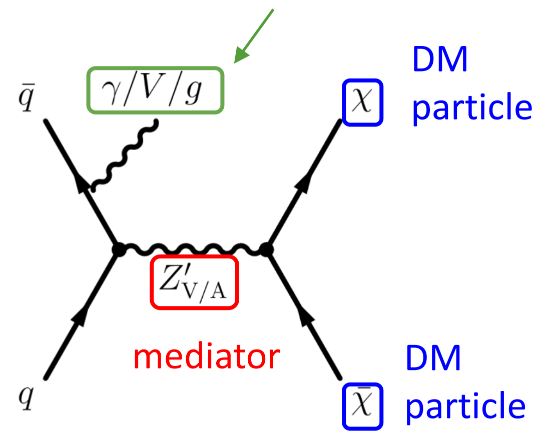
Direct searches for BSM physics

- Multiple approaches and signatures:
  - Searches for new heavy resonances
  - Dark Matter searches: Mono-X signatures
  - Supersymmetry

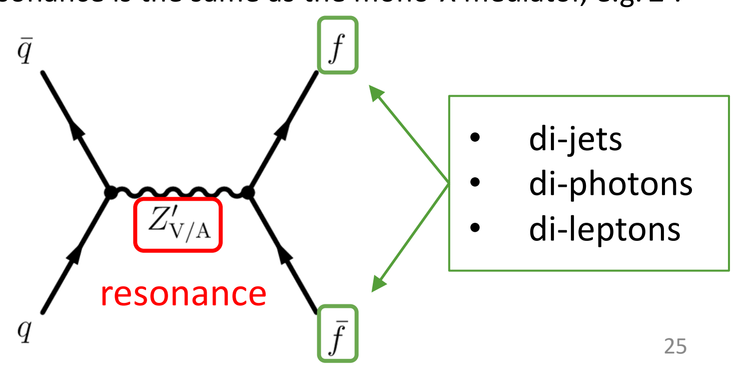


Dark matter searches

- Weakly interacting Dark Matter (DM) particles can be produced at the LHC.
- Observable only if produced in association with the visible SM particles: mono-X signatures.



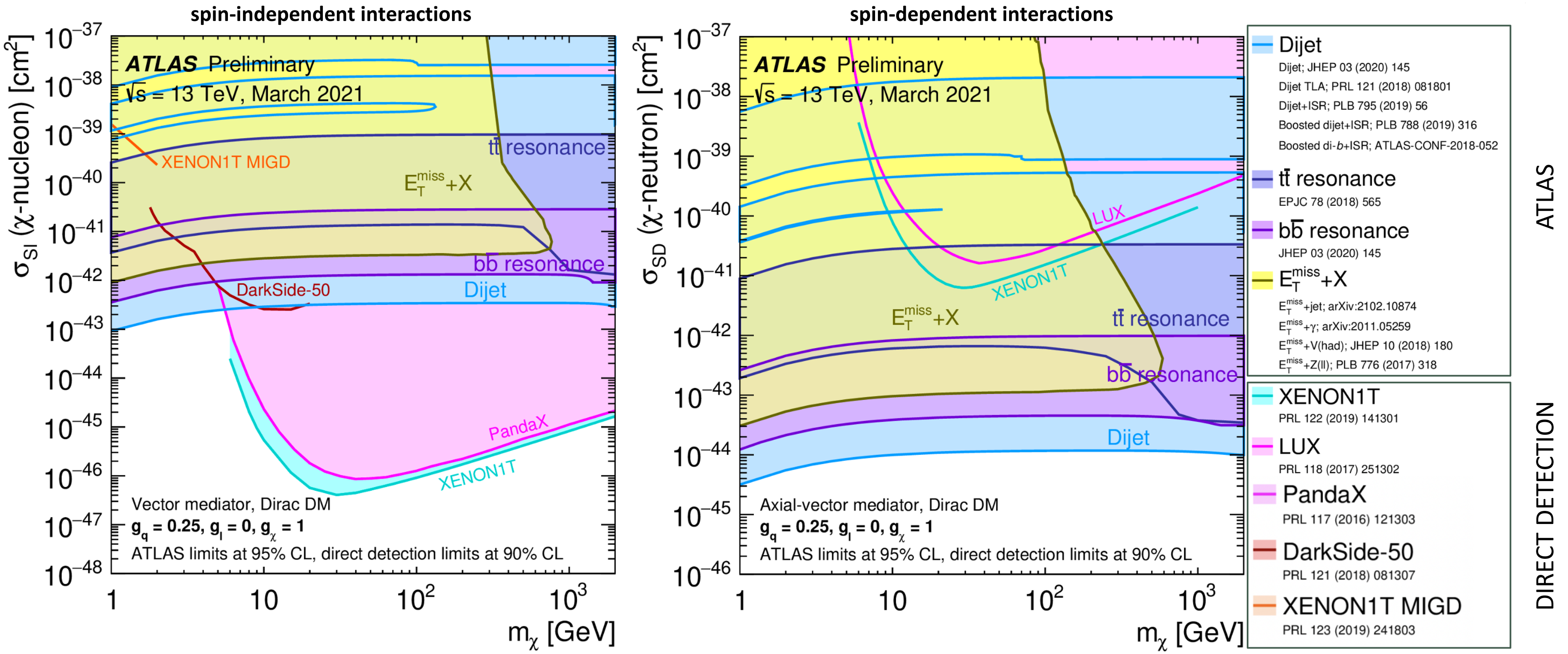
Complementary:
indirect DM constraints from the **resonance searches.**
Assuming that the resonance is the same as the mono-X mediator, e.g. *Z'*.



Dark matter searches:
Z' mediators

ATL-PHYS-PUB-2021-006

- Exclusion limits on the WIMP-nucleon scattering cross section
- Competitive and complementary to direct detection experiments
  - especially in case of a low-mass dark matter or spin-dependent interactions.

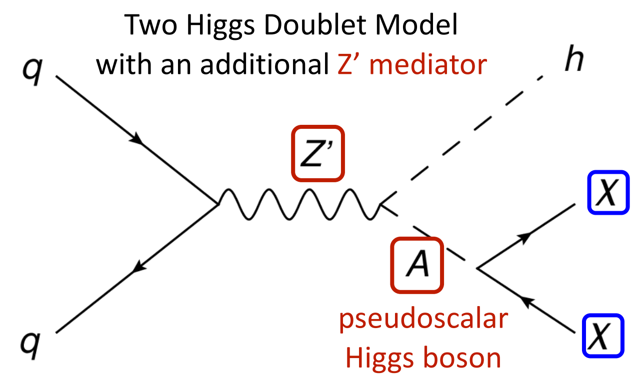


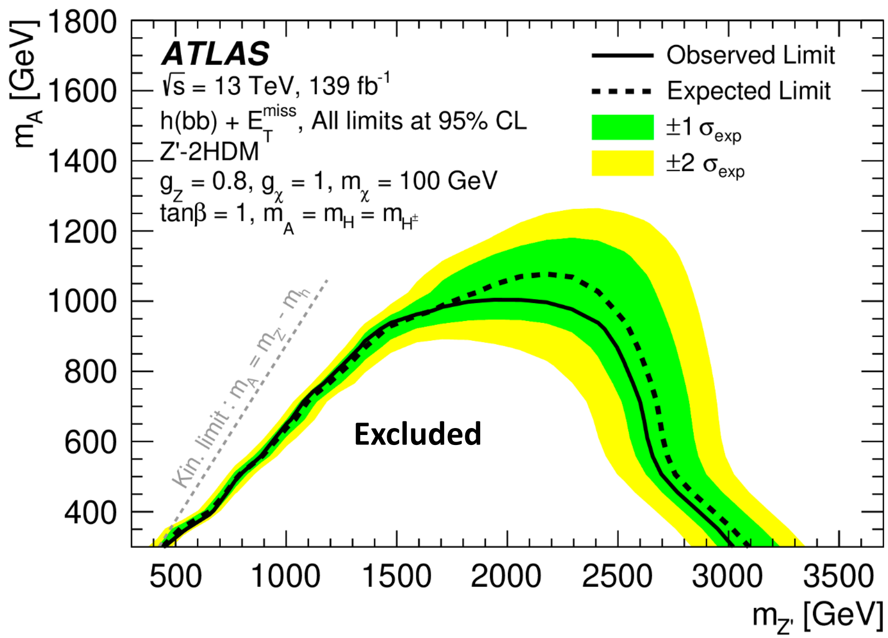
JHEP 11 (2021) 209

Dark matter searches:

mono-Higgs

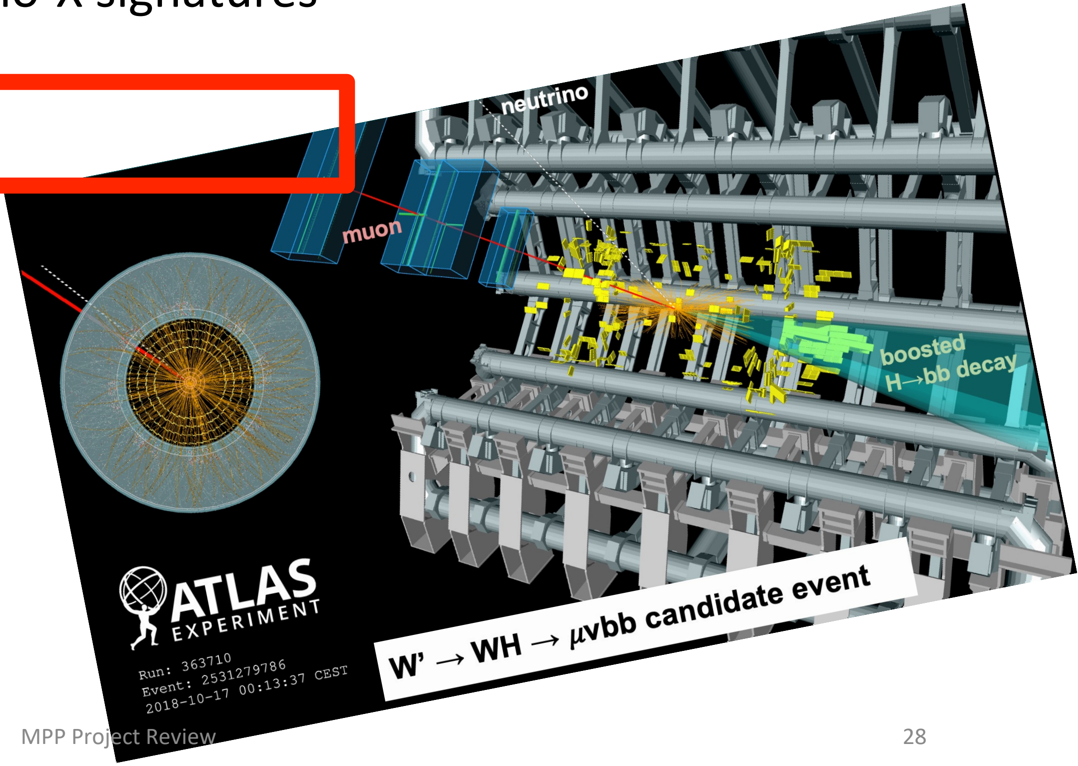
- Higgs sector is one of the most natural candidates to explain the origin of the Dark Matter mass.
- Direct interactions of DM with the Higgs bosons (DM has mass)
  - H production from the initial state is a minor contribution in this case
- Probed using the full Run 2 dataset.
- Constraints on several simplified models with an extended Higgs sector
  - Up to 30% improvement w.r.t previous analyses
- Model-independent exclusion limits also allow for interpretations in terms of future models.





Direct searches for BSM physics

- Multiple approaches and signatures:
  - New heavy resonance searches
  - Dark Matter searches: Mono-X signatures
  - Supersymmetry

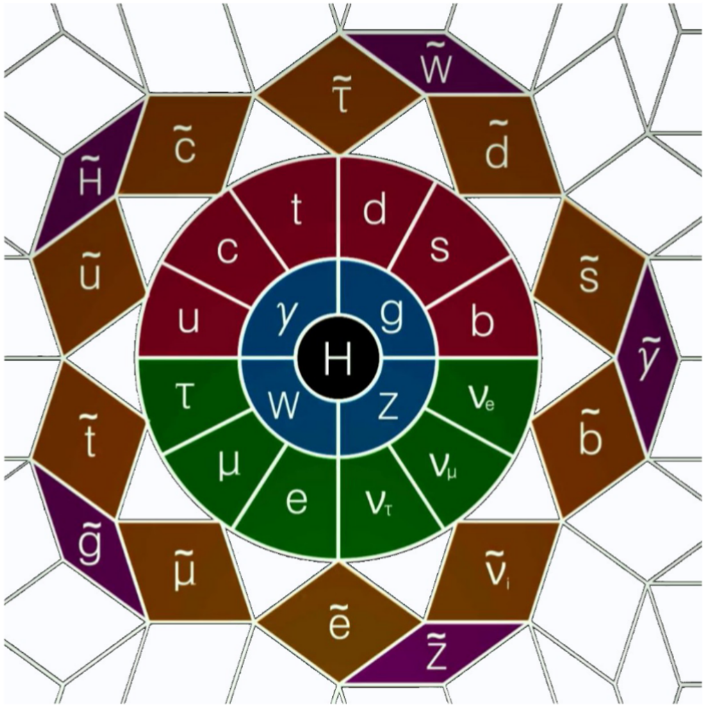


Supersymmetry

R-parity:

$$P_R = (-1)^{B-L+2s} = \begin{cases} 1 & \text{for SM particles} \\ -1 & \text{for their Superpartners} \end{cases}$$

- Supersymmetry (SUSY)
  - Predicts superpartner for each SM particle differing by spin ½
    - new, discrete quantum number R-parity



- Attractive Implications
    - lightest SUSY particle (LSP) sensible DM candidate, typically neutralino
    - possible (approx.) unification of gauge couplings
    - addresses why Higgs mass is much smaller than Planck scale (hierarchy problem)

- Searches performed in various final states
  - interpreted in specific SUSY scenarios

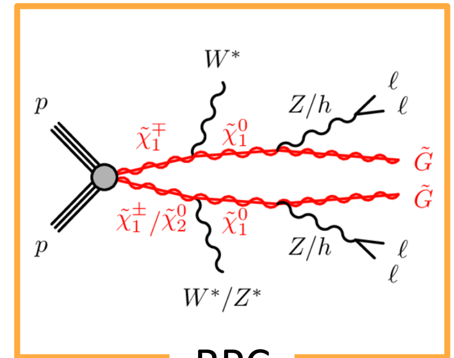
JHEP 07 (2021) 167

PhD Thesis (in progress): M. Rendel

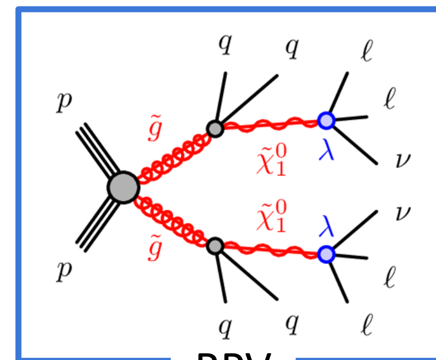
Supersymmetry:

Multi-Lepton Search

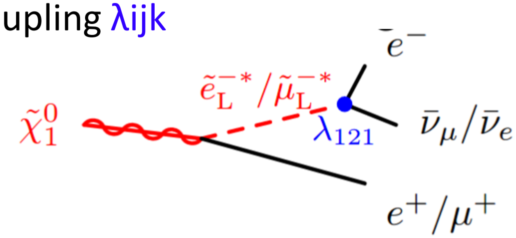
- Final states with four or more leptons: barely populated by SM backgrounds
  - Excellent phase space to probe for BSM physics
- Various SUSY models feature multi-lepton final states
  - in particular R-parity violating (RPV) scenarios
- R-parity:
  - assumed to be conserved in many models (RPC)
  - but can be violated:
    - yield leptonic decays of the lightest SUSY particle (LSP), governed by coupling λijk



RPC



RPV



- Search optimized for RPC as well as RPV SUSY models
  - Results for full Run 2 dataset

Supersymmetry:

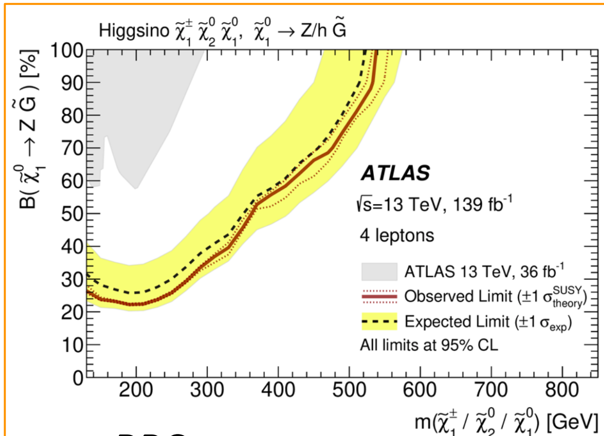
Multi-Lepton Search

JHEP 07 (2021) 167

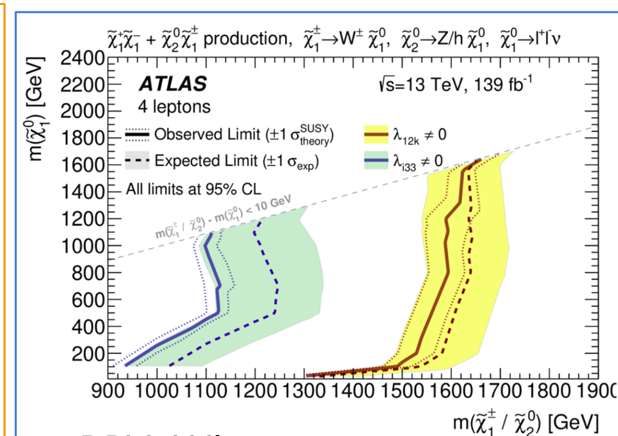
PhD Thesis (in progress): M. Rendel

- Data compatible with SM predictions
  - Exclusion limits significantly extended wrt previous analyses

- RPC Searches:
  - interpretation in simplified General Gauge Mediated SUSY model
  - exclusion of higgsino masses up to 550 GeV

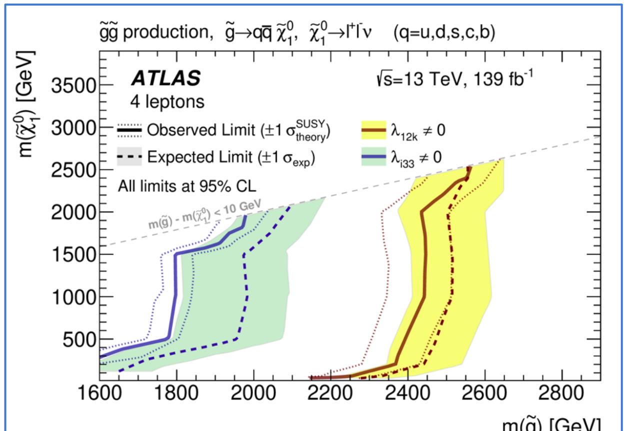


RPC

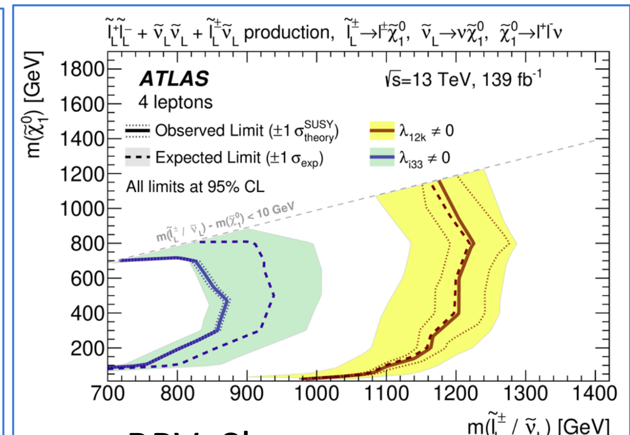


RPV Winos

- RPV Searches:
  - lower limits on several SUSY masses in simplified RPV models:
    - gluinos: up to 2.58 TeV
    - sleptons: up to 1.23 TeV
    - winos: up to 1.65 TeV



RPV Gluinos



RPV Sleptons

Supersymmetry:
search for Sleptons

Work in progress

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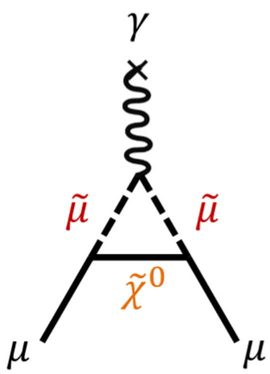
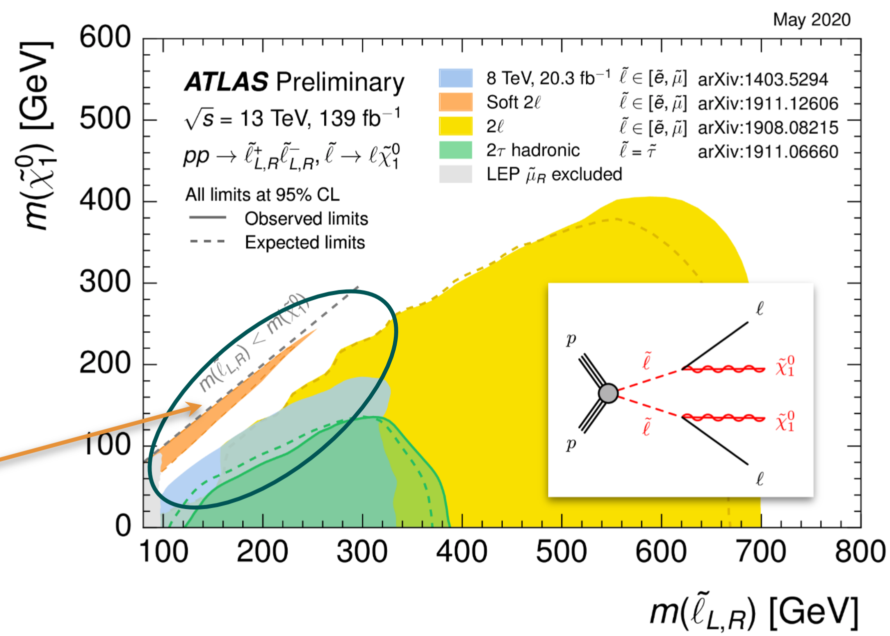


SUSY & Muon g-2

- potential SUSY contributions to muon g-2 via smuon-neutralino loops (and chargino-sneutrino loops)
- viable solutions to observed muon g-2 anomaly for light smuons ($\lesssim$ 1 TeV)

"Slepton-Gap"

- sensitivity gap in current exclusion reach for sleptons
- parameter scan verified gap is "home" to SUSY scenarios compatible with muon g-2
- revising 2L search based on initial-state radiation to tackle this gap



Conclusions

- ✓ **108** ATLAS publications in 2021
- ✓ 18 with direct MPP contributions
  - ✓ 10 of which in journals
    - ✓ 6 analysis-related
    - ✓ 4 detector-related

- Extensive analysis activity spanning a wide range of the ATLAS physics program

- Measurements of a number of top-quark and Higgs boson processes
    - Further improvements in precision and new channels being addressed
  - More stringent tests of higher order SM predictions
  - BSM constraints significantly improved, competitive with other LHC and non-LHC experiments.

- Direct searches for BSM signals
    - Diverse processes and final states
    - Approaches varying, from model-motivated to (quasi) model-independent
  - All results consistent with the SM
  - Significantly extended limits, often superior to other experiments

- Many analyses still ongoing and Run 3 data-taking starting next year: more results to come!