MPP project review ATLAS physics

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ATLAS EXPERIMENT

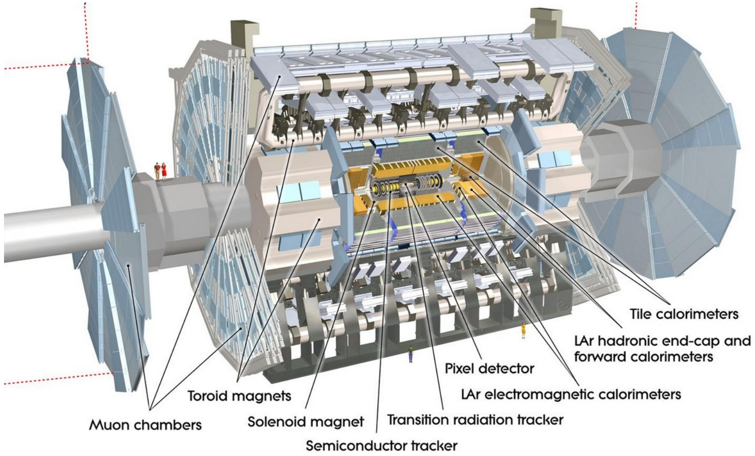
MAX-PLANCK-INSTITUT FÜR PHYSIK

ORIGINS Excellence Cluster

ATLAS

Run-2 data analyses with proton-proton collisions

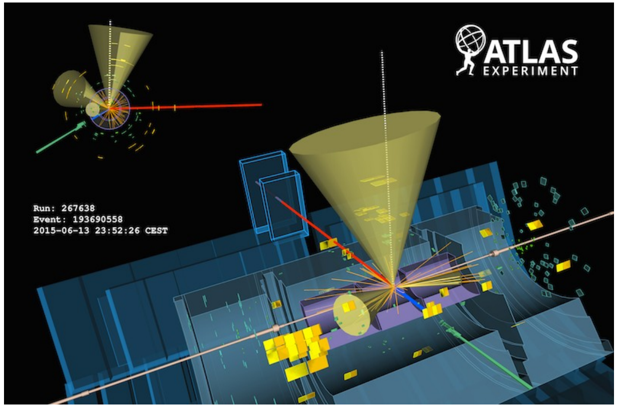
- Very successful data taking at $\sqrt{s}$ = 13TeV until end 2018
- Data taking efficiency 95.7%
- Integrated luminosity of about 140fb^{-1} was collected



MPP group members play a leading role in many important physics measurements and searches

- Top quark physics
- Higgs physics
- Searches for BSM physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



70 papers submitted to journals in 2020 so far

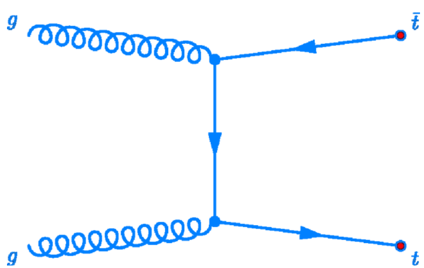
- This talk focusses on results with …
  … major contributions from MPP members
  … where MPP members are analysis (co-)coordinators

Top-quark physics and the top-quark mass

The *top-quark* is of great importance for all sectors of the Standard Model

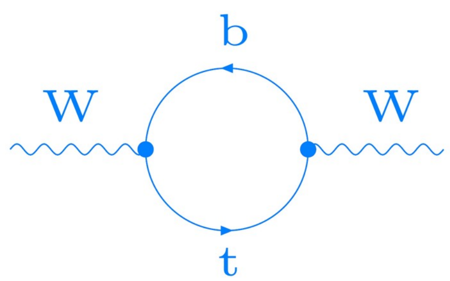
- The *top-quark* is the fermion with the highest mass, m_t~173 GeV
- Therefore it represents a very unique research subject
its mass is an outstanding and important parameter in all sectors of the Standard Model

top-quark pair production



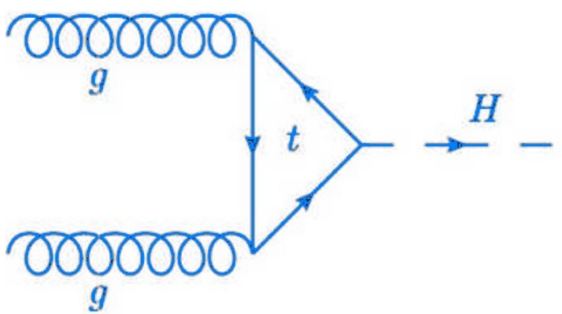
$$\mathcal{O}(\alpha_s^2)$$

Correction to muon-decay



$$\Delta\rho \sim \frac{3G_\mu m_t^2}{8\sqrt{2}\pi^2}$$

Higgs-production



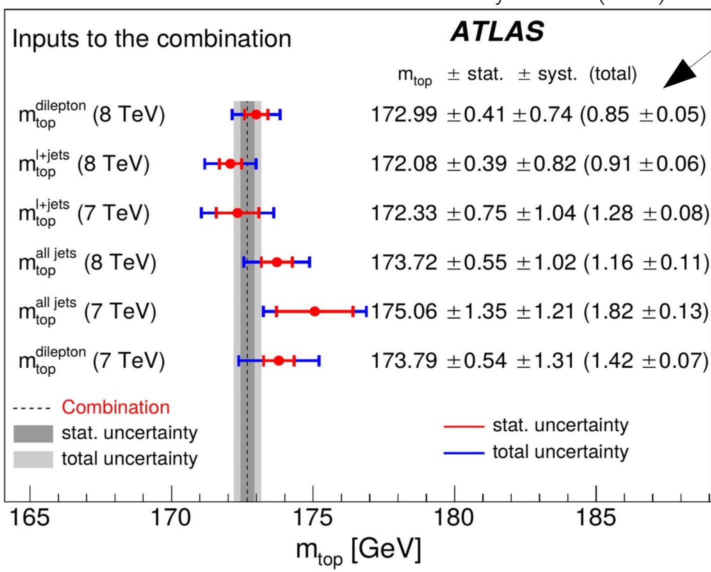
$$y_t \sim m_t$$

- The top-quark connects the strong, the electroweak and the Higgs sector
- Its precise knowledge is of crucial importance for indirect searches for BSM effects, e.g. through loop-induced insertions to SM predictions

Top-quark mass precision measurements

Reminder: top-quark mass measurements and the ATLAS combination

Eur.Phys.J. C79 (2019) 290



- Most precise single measurement: di-lepton channel
- ATLAS combination
  → m_{top}=172.69 ± 0.25 (stat) ± 0.41 (syst) GeV

Top-quark measurements nowadays 'systematically' limited

→ Important uncertainties associated to

- *tt* event modelling with MC event generators:
  tW-interference terms, color reconnection, parton shower, hadronization, background models, PDFs, …
- Jet energy scale, jet resolution, b-tagging, etc…

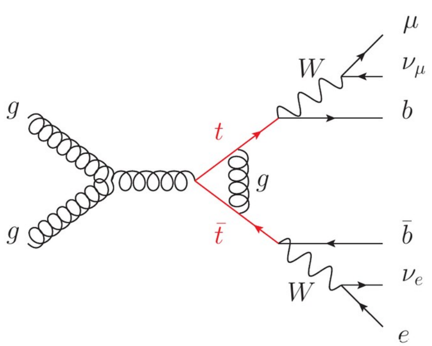
Ongoing work for improved top-quark mass determinations

- Combination of the results from ATLAS and CMS within the LHCTopWG
- Work on m_{top} in the dilepton and lepton+jets decay channels with Run-2 data
  Using deep neural networks: improve the efficiency for selecting the correct permutation of the decay products
  → Improvements of the top-quark mass measurement, and reductions of the systematic uncertainties

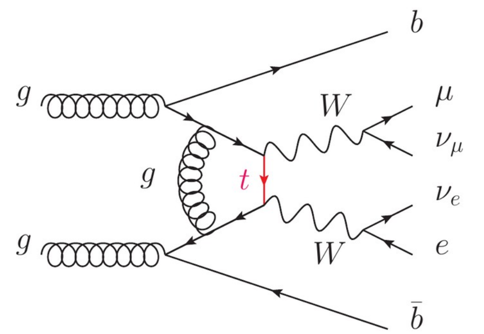
Measurements of: *pp → WWbb*

WWbb **represents the final state of top-quark pair events, but also includes…**

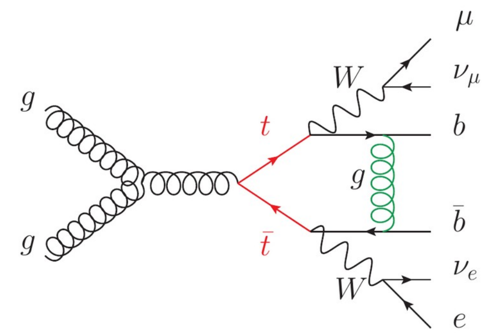
NLO correction to *tt* production



Non-doubly resonant diagram



Non-factorizing diagram



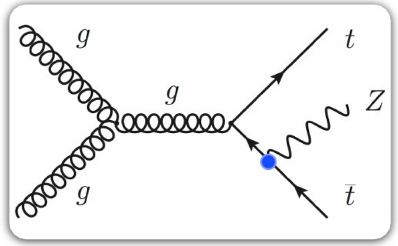
- Details on *WWbb* modelling are very relevant for *tt* & top-quark mass analyses, *SUSY* searches, etc..
  (Interference effects with single-top diagrams, narrow-width approximation, higher order correction in the top-quark decay, definition of the top-quark mass, NLO+PS matching, etc...)
- *WWbb* is an important process on its own
  - fixed order predictions, etc…
  - sensitivity to m_t, top-quark width Γ_t, α_s, PDFs, …

New measurements are performed

- di-lepton channel: *pp* → *bbll* + MET
  → Understand *tt*−*Wtb* interference
- l+jets channel: *pp* → *WWbb*
  → Measure *W*-boson kinematics
  → Determine SM parameters

top-quark pair in association with a *Z* boson

- *ttZ* is a comparatively rare and very interesting Standard Model process



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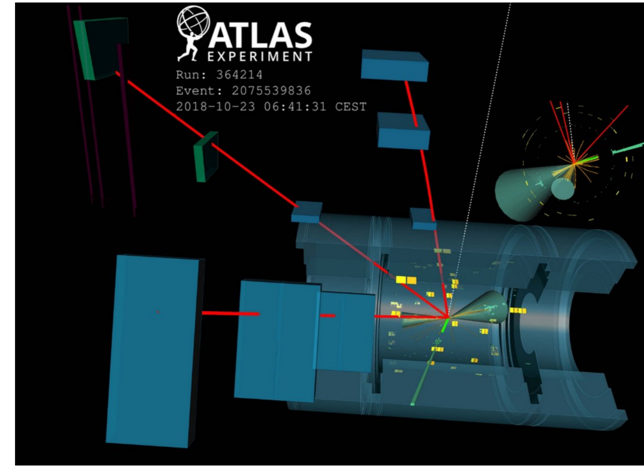

- measurements of *ttZ* offer stringent tests of the Standard Model

  → LO involves QCD & EW coupling

  → prominent background for searches
  (*tttt*,*tZq*, SUSY models, etc…)

- Combination of *3 lepton* and *4 lepton* final states
- Full run-2 dataset with 139 fb^{-1}

$$\sigma_{t\bar{t}Z} = 1.05 \ \pm 0.05 \text{ (stat.)} \ \pm 0.09 \text{ (syst.) pb}$$

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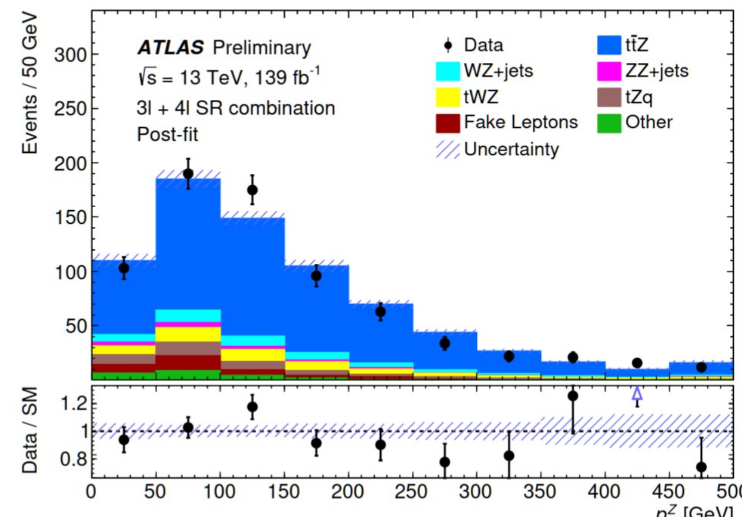


top-quark pair in association with a *Z* boson

ttZ – differential measurement performed as a function of 10 variables

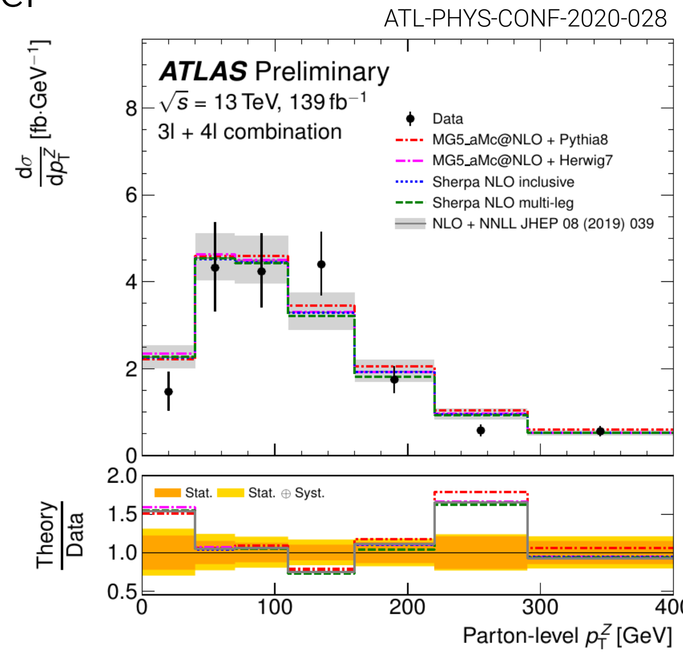
...in *3 lepton* and *4 lepton* channels

... with full Run-2 data

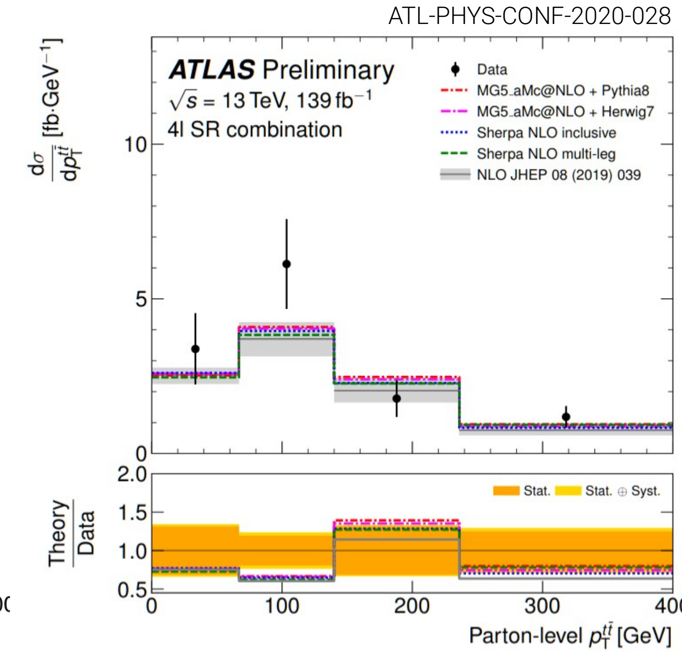
3ℓ	N_{jets}	$p_T^{\ell,\text{non-Z}}$	$\Delta\phi(Z, t_{\text{lep}})$	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$
4ℓ	N_{jets}	$p_T^{t\bar{t}}$	$\Delta\phi(Z, t\bar{t})$	$\Delta\phi(\ell_t^+, \ell_{\bar{t}}^-)$
$3\ell + 4\ell$	p_T^Z	$\lvert y^Z\rvert$		

- Data unfolded to parton level
- First differential *ttZ* measurement with full Run-2 data
- First measurements for variables probing the *tt*-system

Good agreement with Standard Model predictions



transverse momentum of *Z*-boson



transverse momentum of *tt*-system

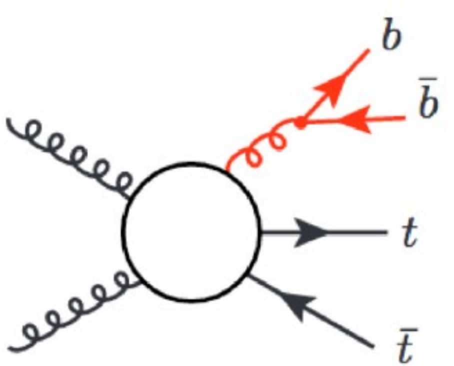
All-hadronic *ttbb* – Differential Cross Sections

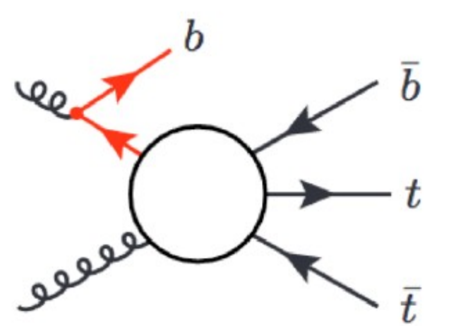
ttbb differential cross sections

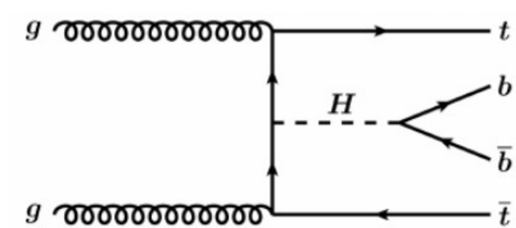
- Study heavy quark production
- Understand *ttbb* modelling
- Look for new physics,
  (e.g. charged Higgs (*gg* → *tbH⁺(tb)*))
- Very challenging to measure in the all-hadronic final state (8 *jets*)

ttbb cross sections are important for

- Present uncertainties on *ttbb* modelling: ~ 30%
- Sizeable background for many other measurements
  (e.g. all-hadronic *ttH(→bb)*, *tttt*, SUSY searches, etc...)
- Learn how to reconstruct all-hadronic *ttbb* events will help later: (e.g. for all-hadronic *tttt*, or *ttH, …*)
- analysis with Run-2 data ongoing...

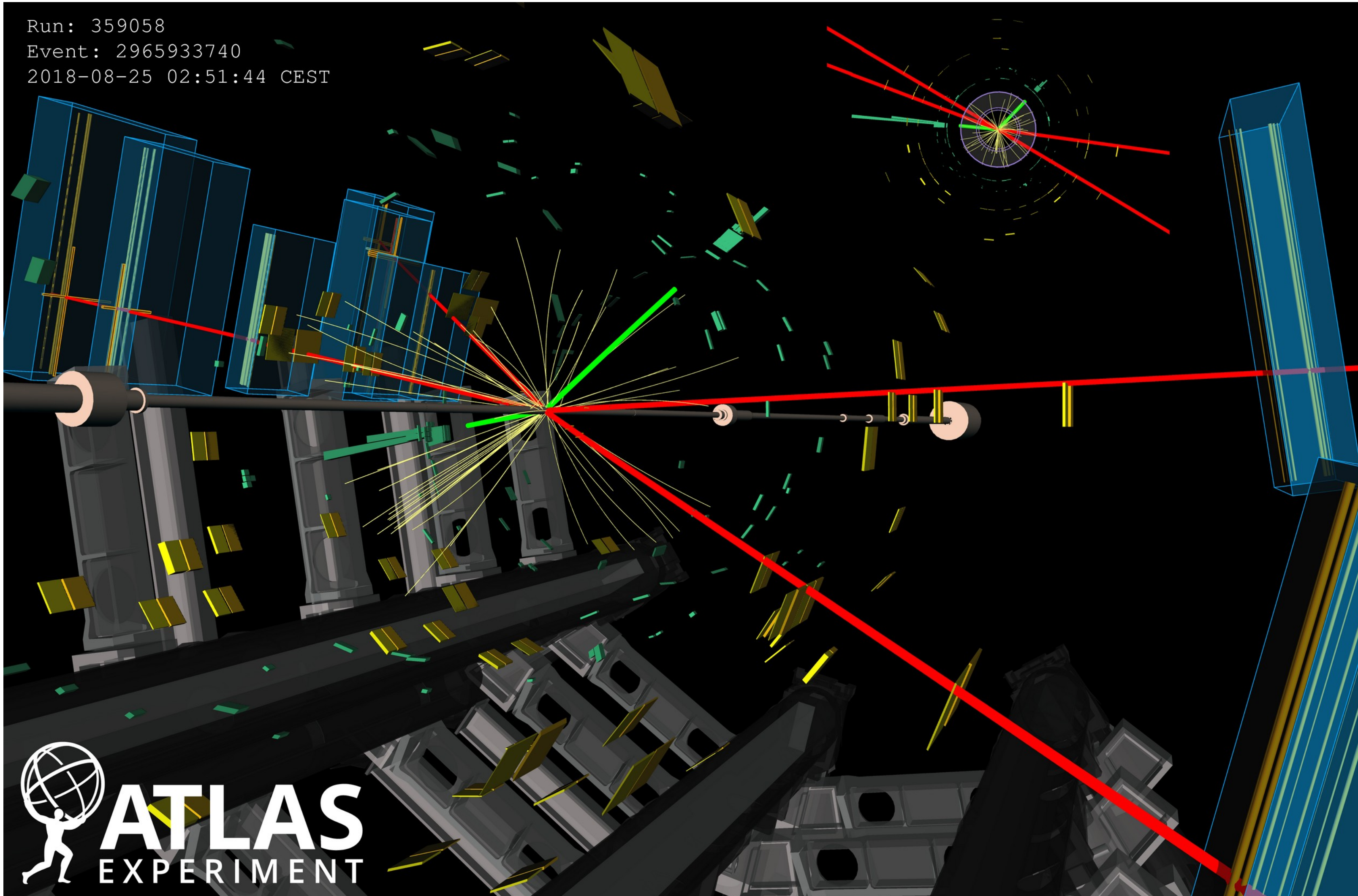






ttbb prediction: $\sigma \sim 12.1$ pb, expect ~ 1.5×10^5 events, new analysis techniques in development

Higgs physics



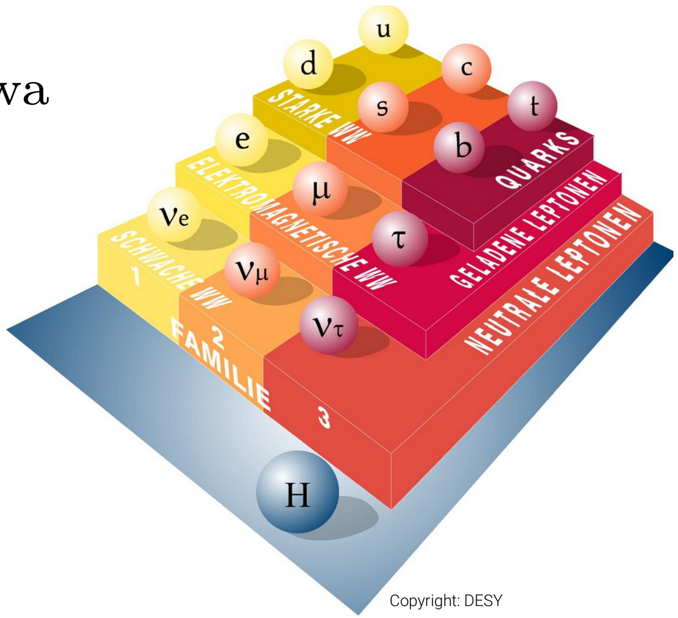
Higgs physics

The Higgs boson is a unique particle within the Standard Model

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_f + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{Yukawa}}$$

- A separate sector of the SM
- A unique particle which couples through mass terms
- The only SM one without spin
- The last particle discovered

  … and experimentally challenging to study



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The Higgs sector is a yet largely unexplored field

- The realization of the Higgs mechanism needs to be studied experimentally
- Numerous connections to possible physics beyond the Standard Model

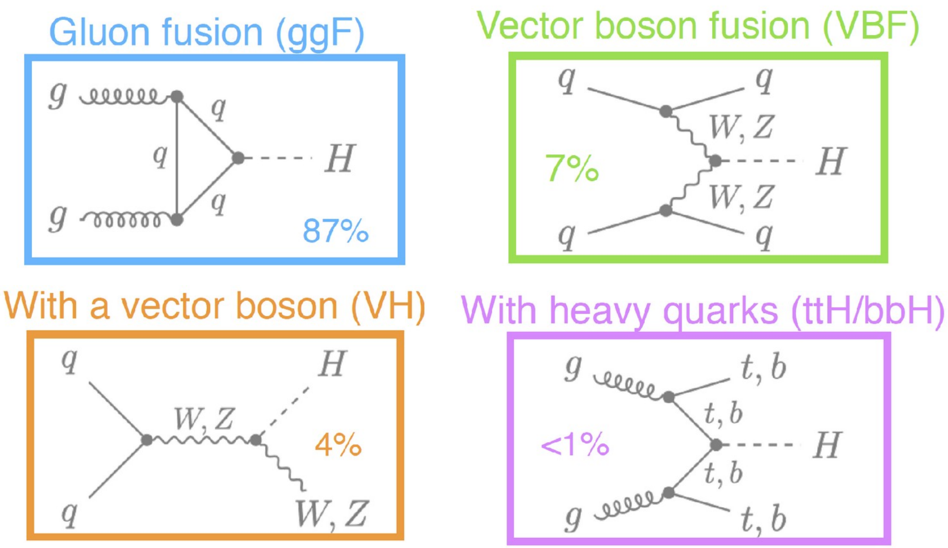
  (extended Higgs sectors, portal to Dark Matter, Supersymmetry...)

➙ The Higgs sector is a key physics research area for the decades to come.

Higgs production & decay

Higgs boson production

- Four key production modes



Higgs boson decay

- Five key decay channels

Decay Mode	Produced	Selected events
$H \to \gamma\gamma$	18 200	6 440
$H \to ZZ^*$	210 000	$(\to 4\ell)$ 210
$H \to WW^*$	1 680 000	$(\to 2\ell 2\nu)$ 5 880
$H \to \tau\tau$	490 000	2 380
$H \to bb$	4 480 000	9 240

MPP

- MPP contributes to *H→ZZ* and *H→WW*

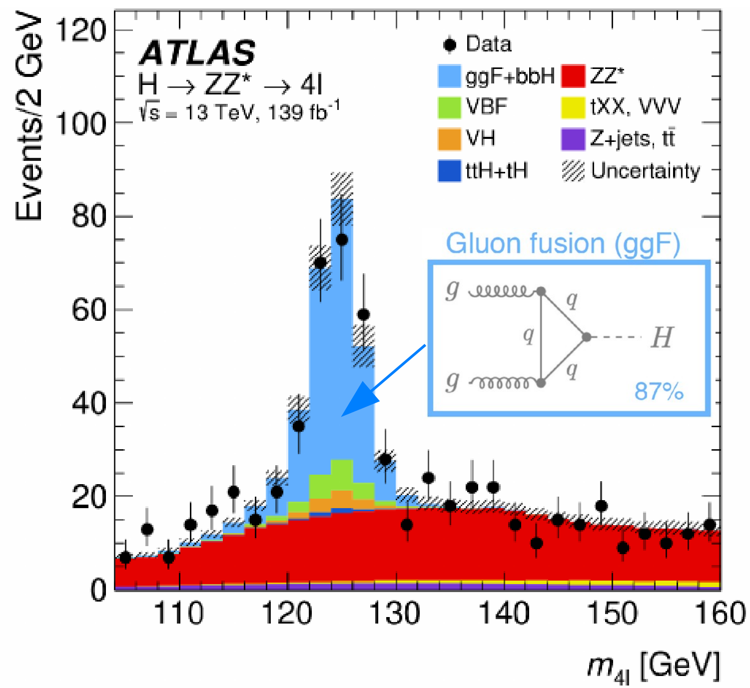
- About 8 Million Higgs bosons produced at ATLAS in Run-2
- About 25000 events selected for analysis after trigger acceptance and selection cuts

Higgs-boson production cross section

Higgs → ZZ → 4l*

- Small branching fraction, but low backgrounds
- Combination of various *ZZ** decay channels
- $\sigma_i^{H\to ZZ^*} = \sigma_i \times \mathcal{A}_i \times \mathcal{BR} = 1.34 \pm 0.12\mathrm{pb}$

Eur.Phys.J. C80 (2020), 957, PhD Thesis V. Walbrecht

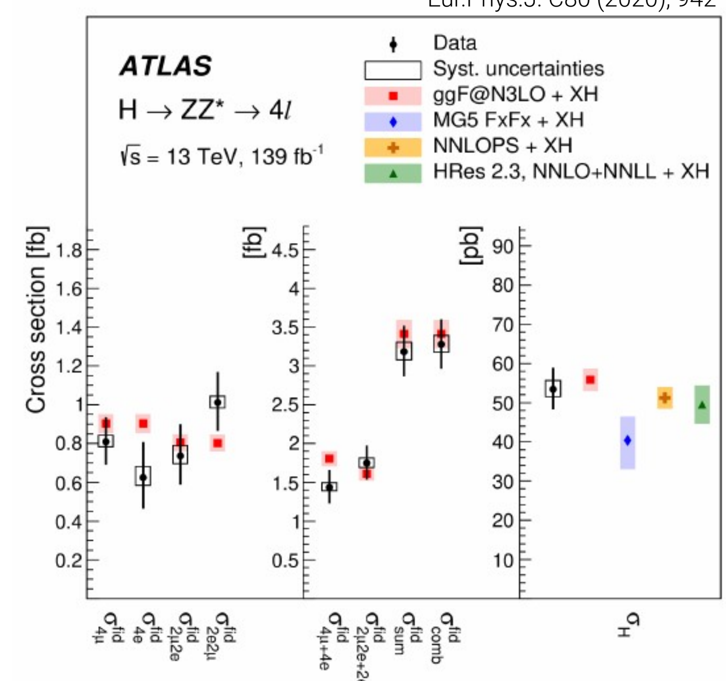


Total Higgs production cross section

$$\sigma_{\mathrm{tot}} = 53.5 \pm 4.9(\mathrm{stat.}) \pm 2.1(\mathrm{sys.})\ \mathrm{pb}$$

- Inclusive fiducial cross section *H→ZZ*→4l*

Eur.Phys.J. C80 (2020), 942



Fiducial and combined cross sections

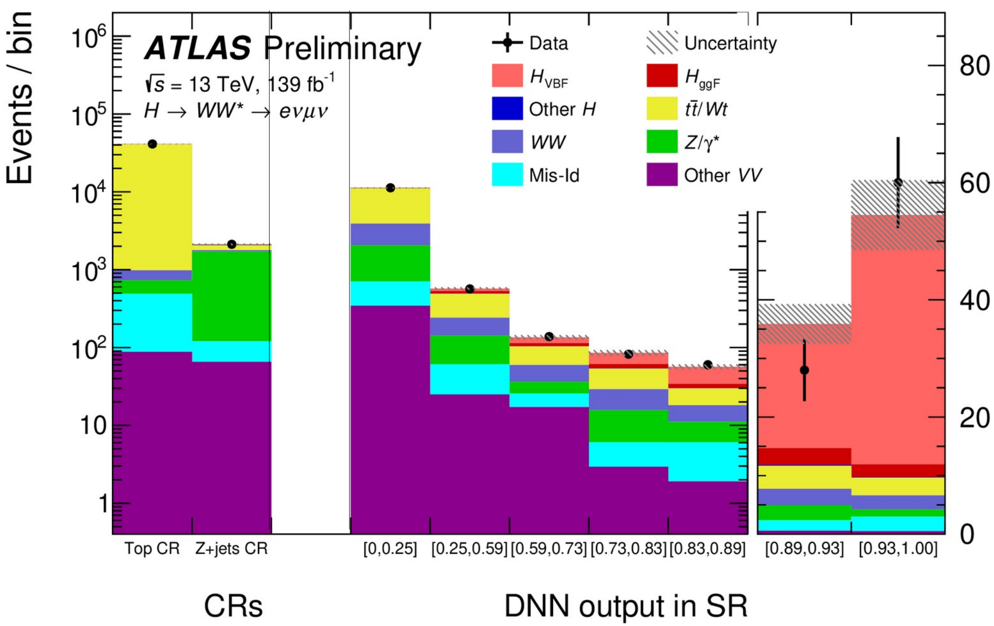
total σ_H

Higgs production

$H \rightarrow WW^* \rightarrow l l \nu \nu$

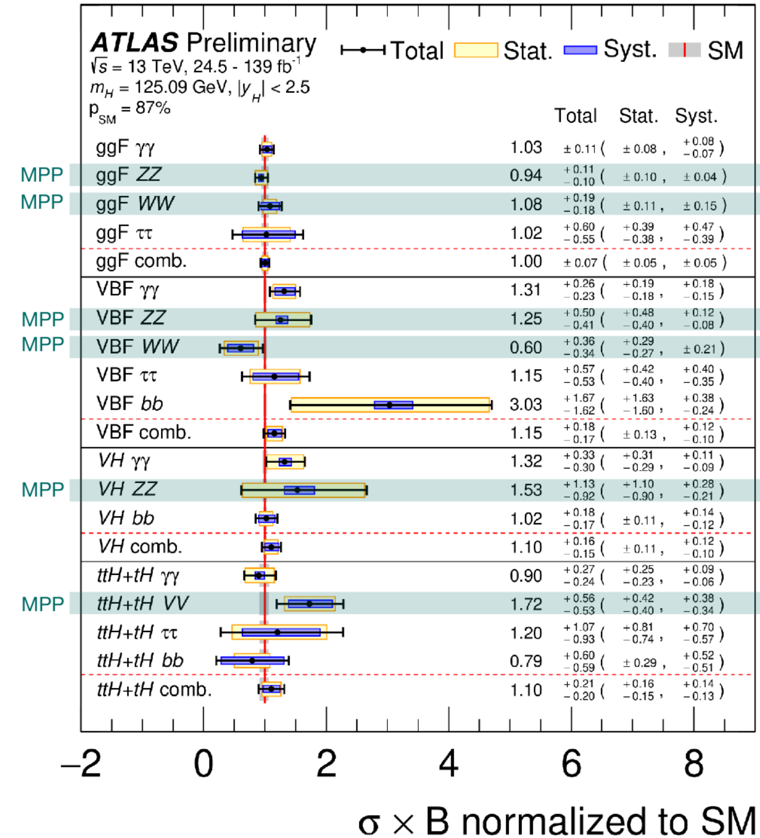
- VBF observed for the first time in a single decay channel
- Strong sensitivity enhancement via machine learning

ATLAS-CONF-2020-045



ATLAS Higgs cross section combination

ATLAS-CONF-2020-027



Global signal strength: $\mu = 1.06 \pm 0.07$

Differential and 'exclusive' Higgs cross sections

Differential Higgs cross sections

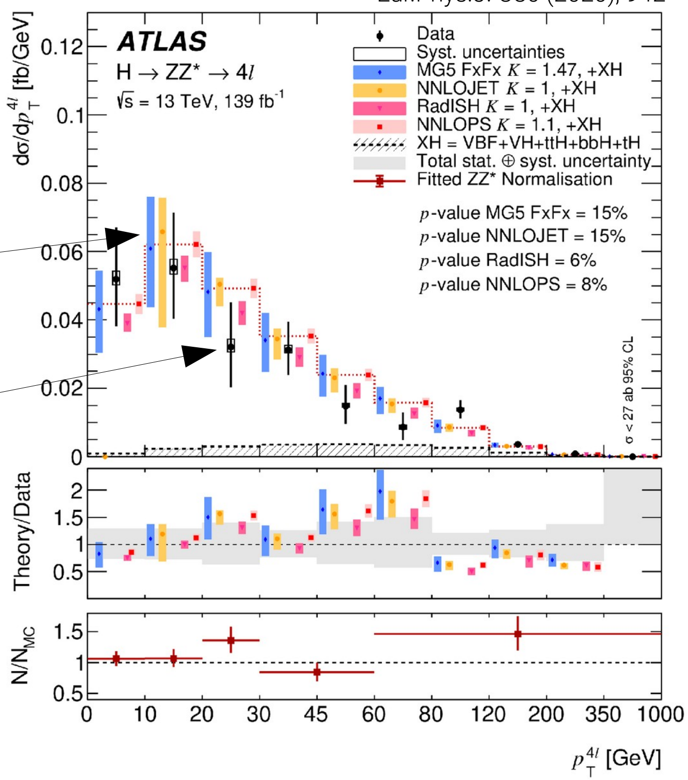
- Study Higgs boson dynamics

→ Sensitive to new physics

Eur.Phys.J. C80 (2020), 942

Various predictions

ATLAS data



Exclusive production cross sections

- Measurement of Higgs + additional activity

→ Sensitivity to Higgs-boson production mode

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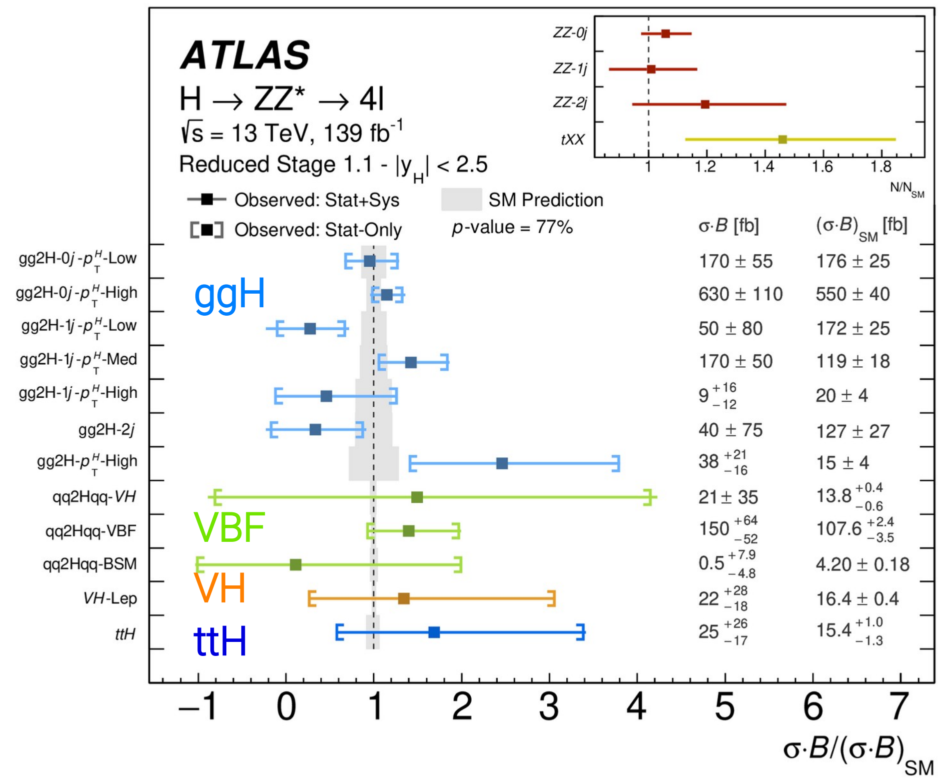


Higgs in a SM effective theory (*H→ZZ**)

SM could be just an effective theory (EFT) valid only below an energy scale Λ

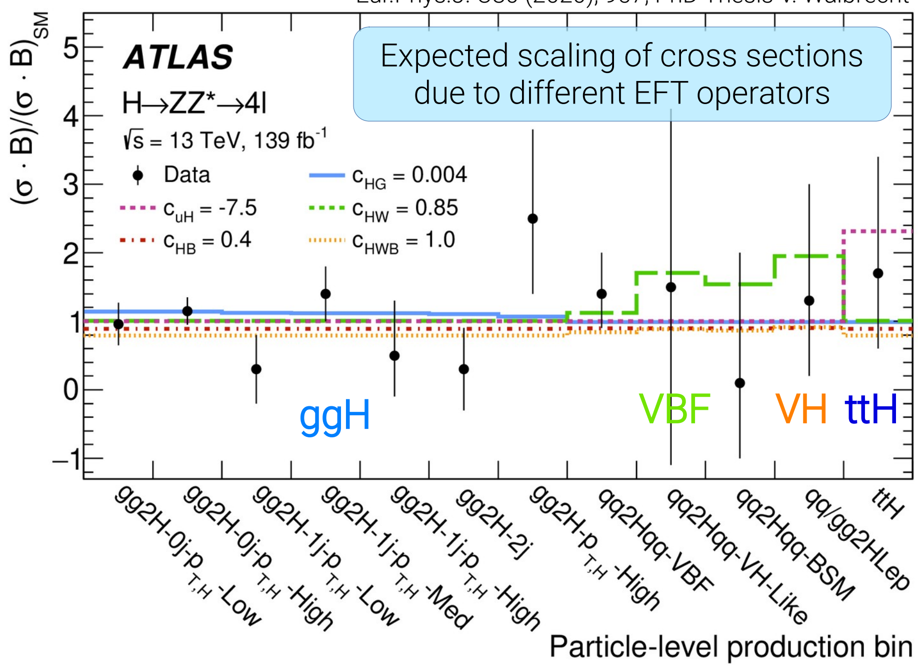
- Deviations from the SM are parameterized by higher-dimension operators

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{(5)} O_i^{(5)}}{\Lambda} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2} + \dots$$

Wilson coefficients $c_i^{(d)}$ can be constrained by the Higgs data.

- EFT interpretation of *H→ZZ*→4l* measurement

Eur.Phys.J. C80 (2020), 957, PhD Thesis V. Walbrecht



Affected production and decay vertices:

VBF, VH
H→ZZ
gg→H
gg→H, ttH

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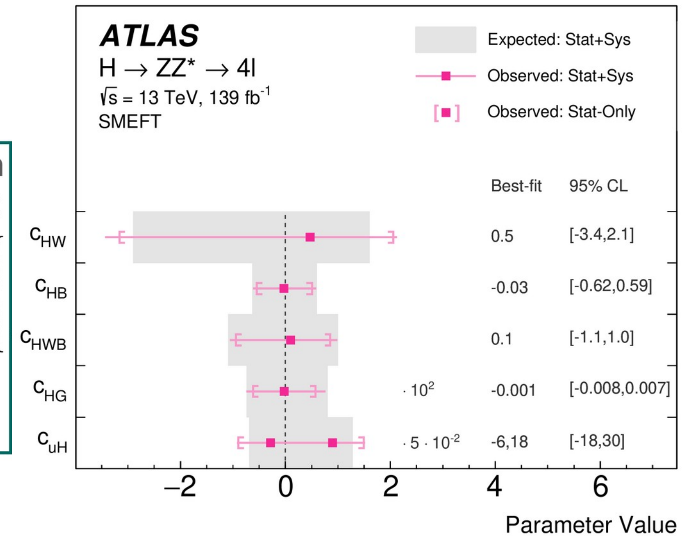


In preparation: combined EFT fit to ATLAS Higgs, electroweak and top-quark data

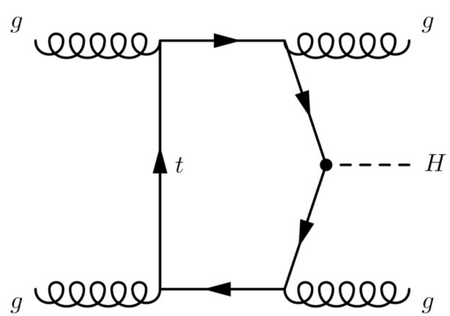
Higgs in a SM effective theory ($H \rightarrow WW^*$)

Standard Model could be an effective theory (EFT)

- Introduce an effective langrangian

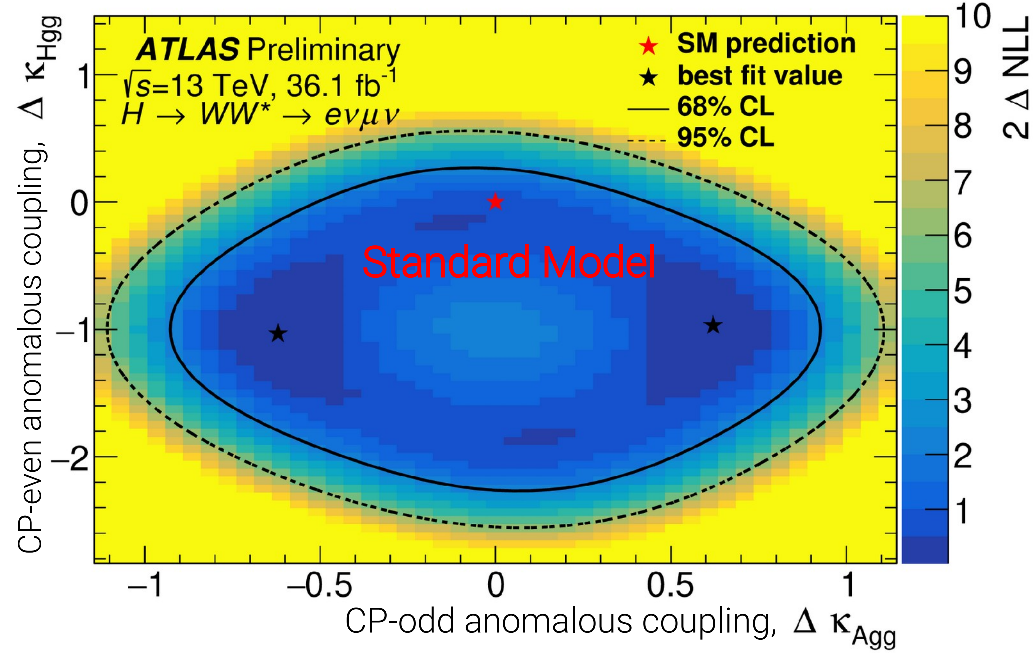
Direct search for CP-violation

- Effective $gg \rightarrow H$ vertex



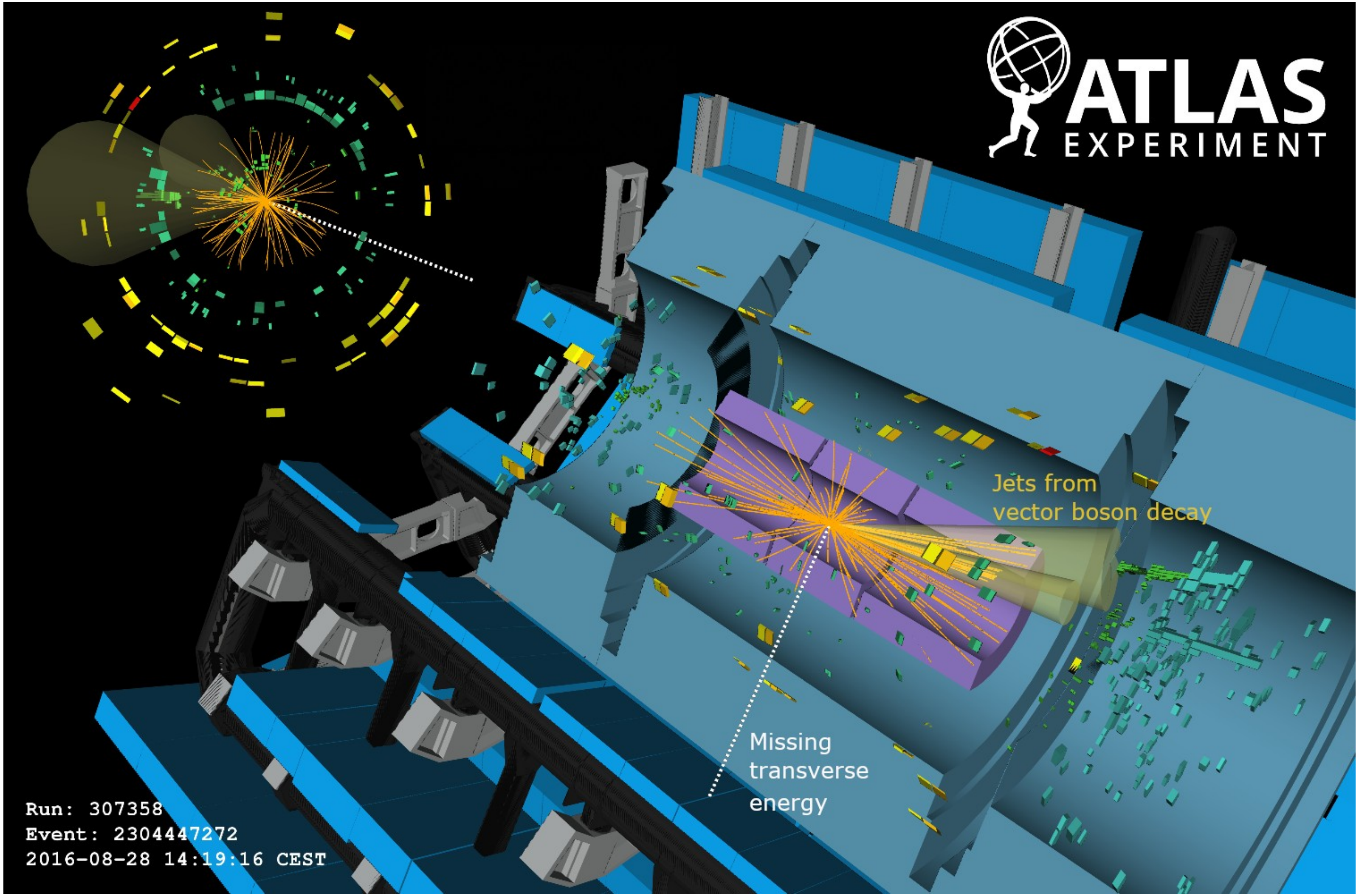
- Study azimuthal angle $\Delta\varphi_{jj}$ between the two jets in gluon fusion for $pp \rightarrow H(WW^*)+2jets$
- Constrain CP-violating terms: ideally avoid sensitivity to CP-even terms
- Similar studies ongoing in VBF using $pp \rightarrow ZZ^* \rightarrow 4l$

ATLAS-CONF-2020-055



Consistency with Standard Model expectations

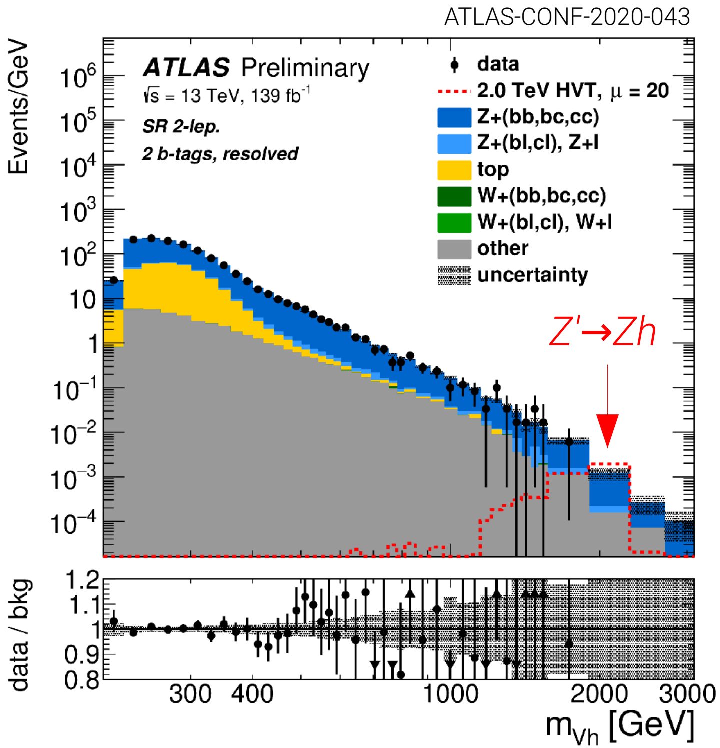
Direct searches for new particles

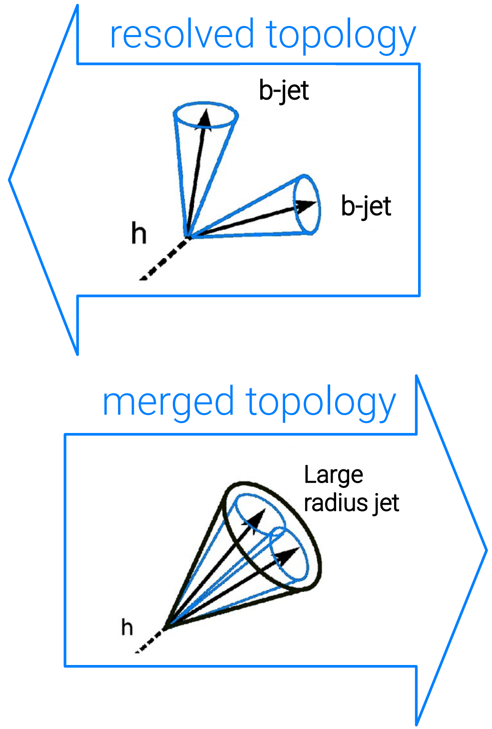


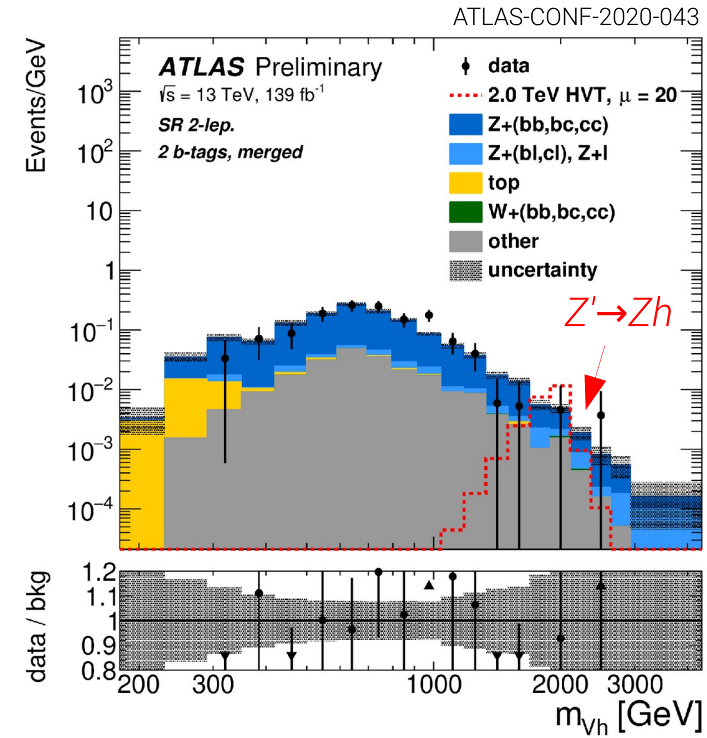
Search for di-boson resonances

Many SM extensions propose new heavy bosons (heavy Higgs, heavy vector bosons, gravitons, …)

- Generic search for 'bumps' in invariant di-boson mass spectra: *X*→ *Zh* → (*llbb*, *bbνν*)
- Resolved topology (*h*→*bb*)
- Merged: probe higher mass



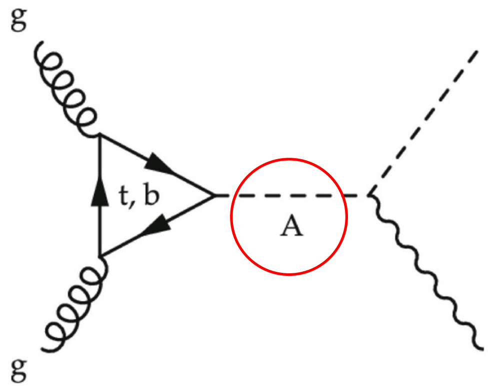




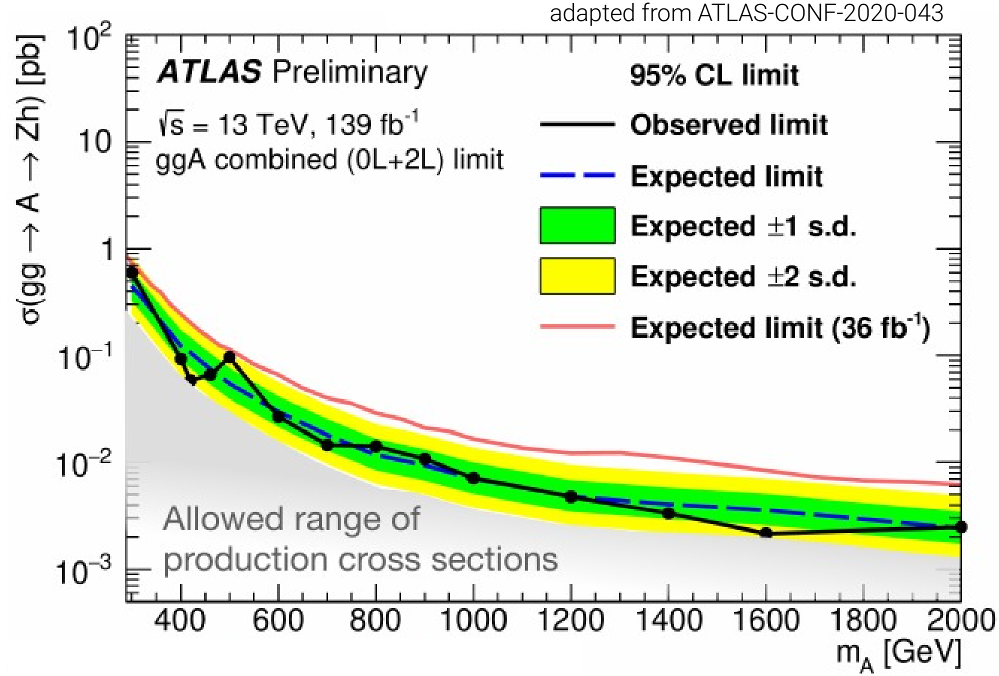
Search for di-boson resonances

Search for an extended Higgs sector – Two Higgs doublet fields (2HDM)

- 2HDM → predicts 5 physical Higgs bosons (*h*, *H*, *A*, *H*+, *H*-)



adapted from ATLAS-CONF-2020-043



- First result with full Run-II data
- Up to 3 times better constraints compared to previous results
- Ongoing:
  → Analysis optimization using machine learning techniques
  → First search for di-boson resonances produced via vector boson fusion

Dark matter searches

Higgs sector and Dark matter (DM) sector are closely related

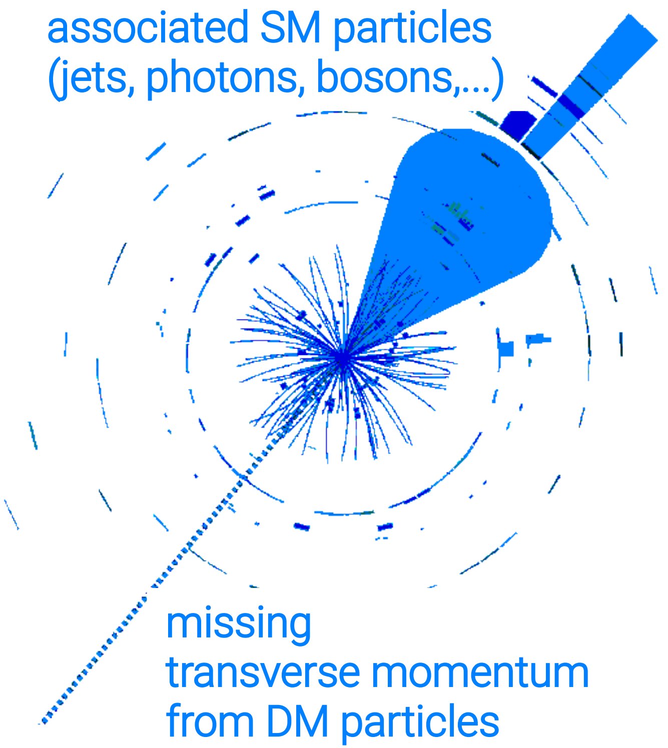
- Mass of Dark matter particles likely comes from some kind of Higgs mechanism

→ Probe direct interaction of DM and Higgs sector

- Observable signal if DM is produced in association with visible SM particles: mono-X signature

  Is there a Higgs mechanism in the Dark sector ?
  Could there be a dark Higgs boson ?
  Is there a Dark Higgs boson mixing with SM?

- Previous *MPP* searches:
  Mono-H(bb) (Phys.Lett.B 765 (2016) 11, PRL 119 (2017) 181804, ATLAS-CONF-2018-039)
  Higgs → invisible (JHEP 10 (2018) 180, PRL. 122 (2019) 231801)

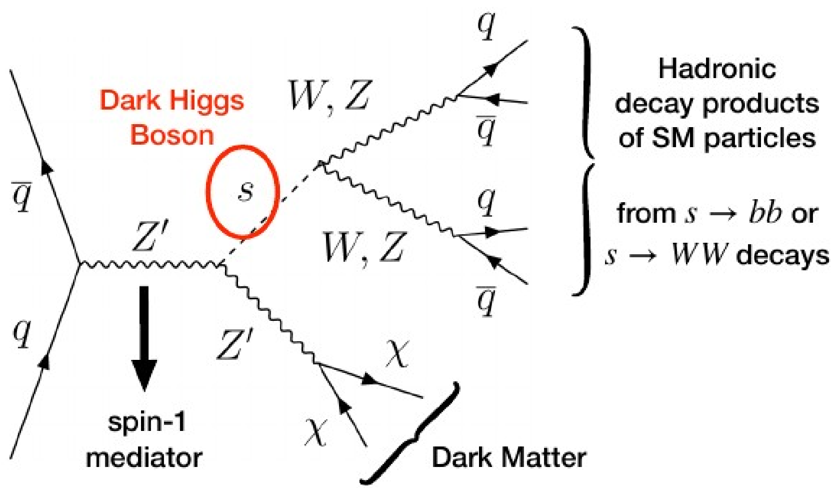


Higgs boson is one of the most obvious portals to DM

Dark matter searches

Weakly interacting DM particles

- Mono-X signature in weakly interacting DM model



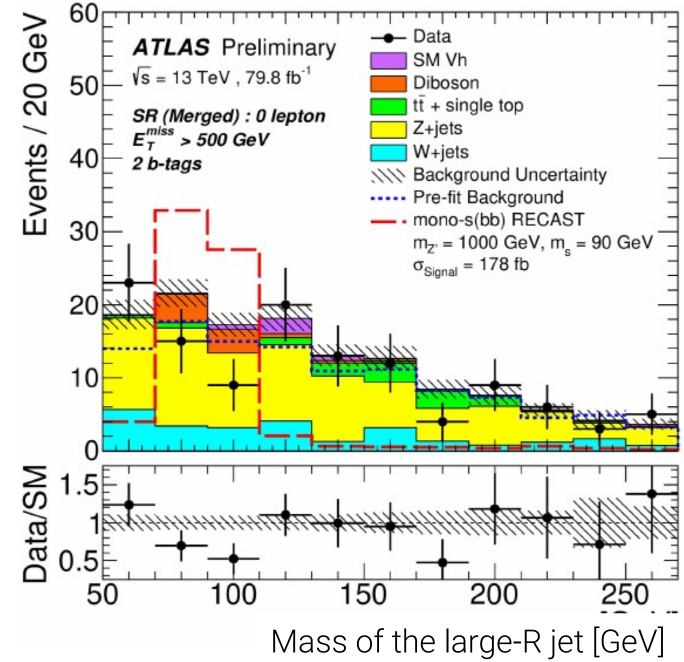
compare: M. Durr et al., JHEP 04 (2017) 143

- *s* → *bb*
  Reinterpretation of our Mono-*h*(*bb*) search in terms of *s*→bb Dark Higgs Boson decays
  (ATLAS-CONF-2018-039)

Mono-s(→bb)

- Reinterpret our previous Mono-H(*bb*) search
  (ATLAS-CONF-2018-039)
  → RECAST analysis preservation framework

ATLAS-PHYS-PUB-2019-032, PhD Thesis Ph. Gadow



Mediator masses up to 3.2 TeV are excluded

Dark matter searches – missing E_T + *VV*

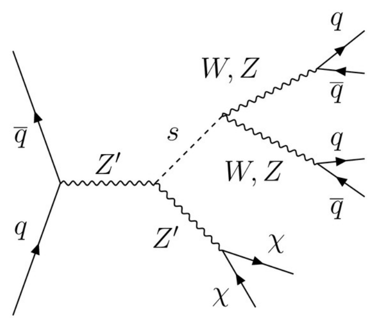
MET+*VV* hadronic channel

- Challenging signature

  s → WW → qqqq

- Novel track assisted reclustered jets

  (ATL-PHYS-PUB-2018-012)

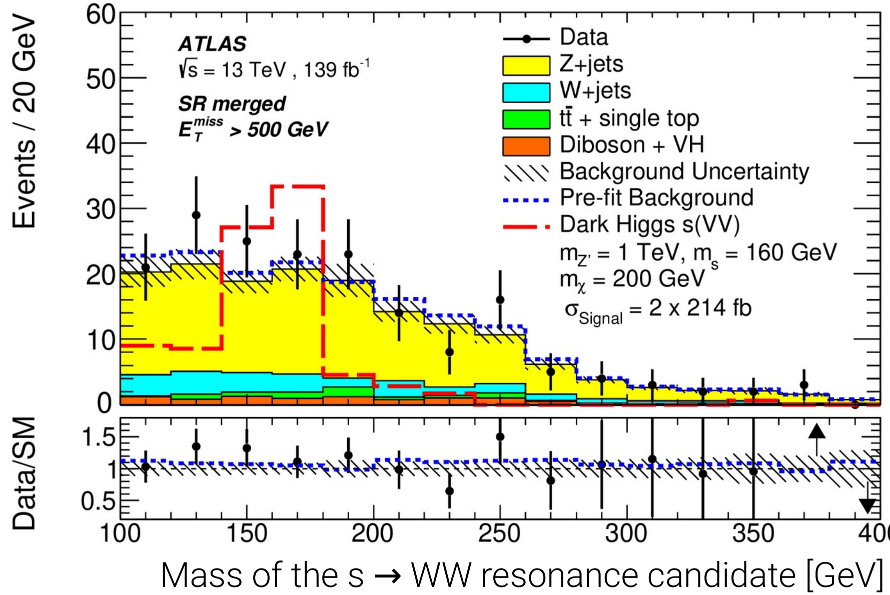


Limits on dark Higgs boson

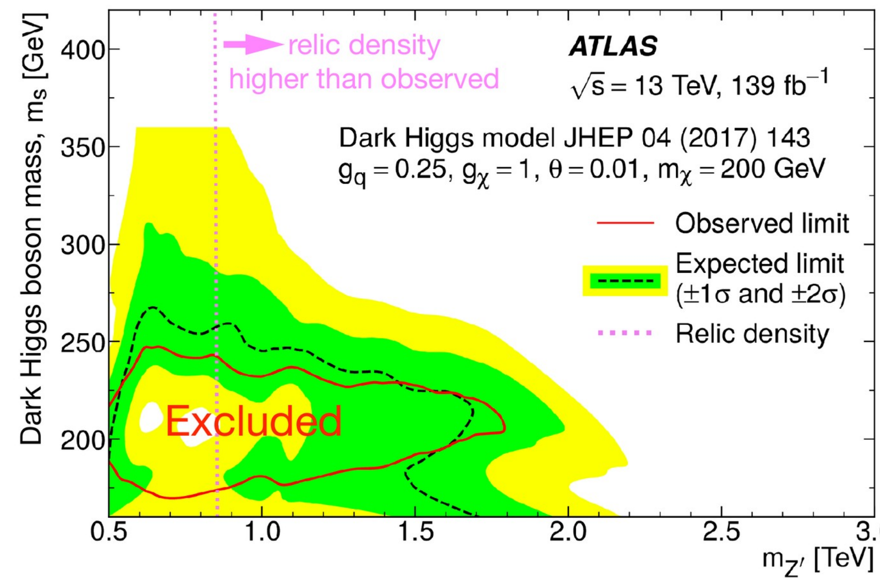
- First explicit search for dark Higgs decaying to *WW*/*ZZ* + MET
- mass reach beyond $m_s \sim 2m_W = 160$GeV

Setting limits on Dark Higgs Bosons for the first time at the LHC.

CERN-EP-2020-172, subm. to PRL, PhD Ph. Gadow



CERN-EP-2020-172, subm. to PRL, PhD Ph. Gadow



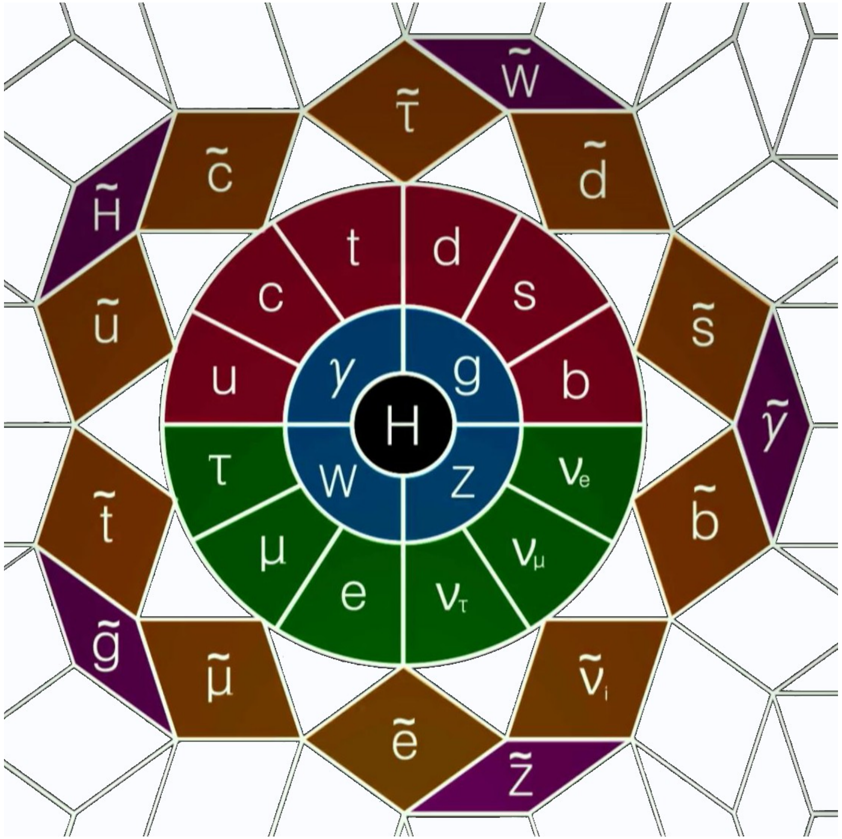
Supersymmetry

Supersymmetry (SUSY)

- An elegant and complete theory *beyond SM*
- Each SM particle gets a *superpartner* differing by spin ½
- New discrete *quantum number R*
  (1 for SM, -1 for SUSY particles)

Attractive implications

- Lightest SUSY particle (neutralino) reasonable DM candidate
- SUSY addresses why Higgs mass is smaller than Planck scale
- Naturalness arguments suggest that parts of SUSY particle spectrum would be accessible

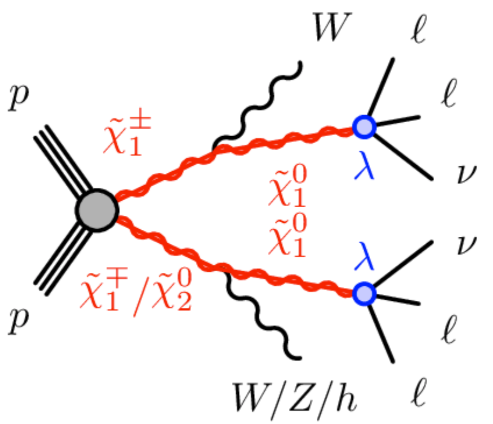


Searches are performed in various final state and interpreted in terms of specific SUSY scenarios

Supersymmetry – multi-lepton final states

Multi-lepton final states

- Clean experimental signature
- Sensitive to both R-parity conserving (RPC) and violating (RPV) scenarios



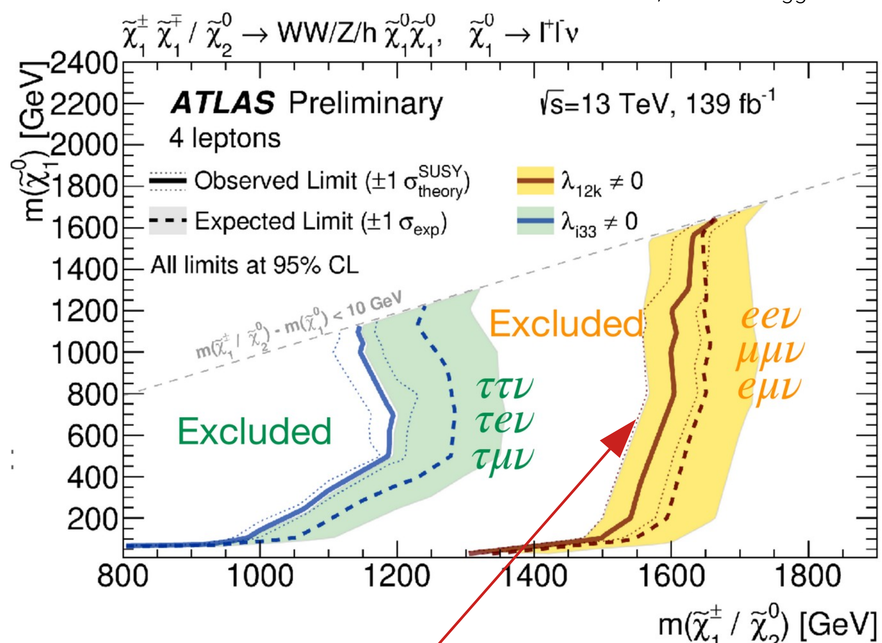
Example: *wino* NLSP pair production

Search with four or more charged leptons (e,μ,τ)

- Including leptonic and hadronic τ's
- Interpretation in terms of simplified RPV and RPC (inspired by General Gauge Mediatiation) models

- Observed exclusion limits (95%C.L.)

ATLAS-CONF-2020-040, PhD J. Junggeburth

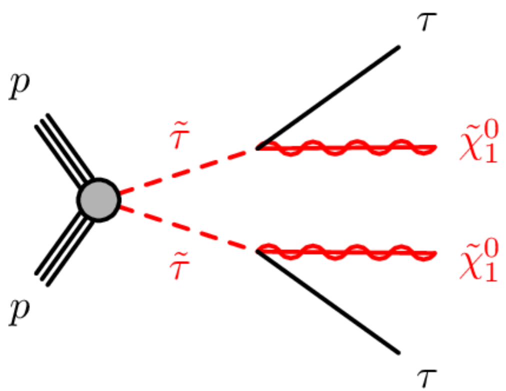


Exclude SUSY partice masses
winos up to 1.65 TeV
gluinos up to 2.58 TeV
sleptons up to 1.23 TeV
higgsinos up to 550 MeV

Supersymmetry – direct *stau* production

Direct production of light *stau* leptons

- Light stau-leptons may play a role in neutralino annihilation



- Would imply a DM relic density consistent with cosmological observations
- Current result considers $\tau_{had}\tau_{had}$ channel

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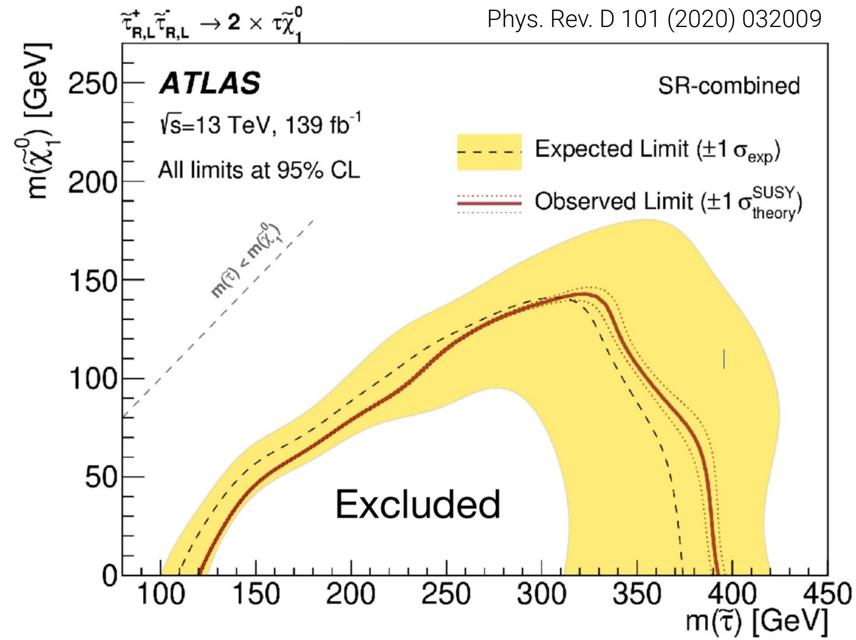


Ongoing: refine searches in $\tau\tau$ final states

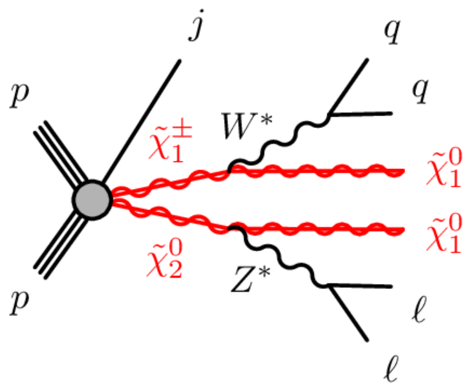
- Combine $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels
- Use machine learning techniques

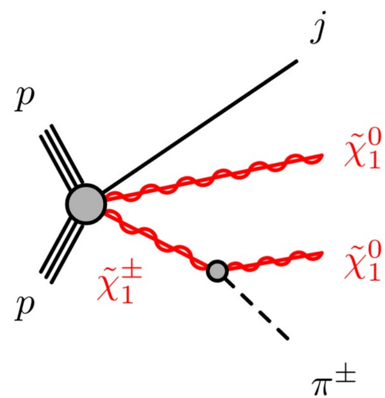
Exclusion sensitivity reached for the first time after analysing the full set of Run-2 data.

Compressed SUSY

Compressed SUSY mass spectra

- If neutralinos and charginos have nearly degenerate mass
- Compressed SUSY is challenging to constrain due to soft decay products

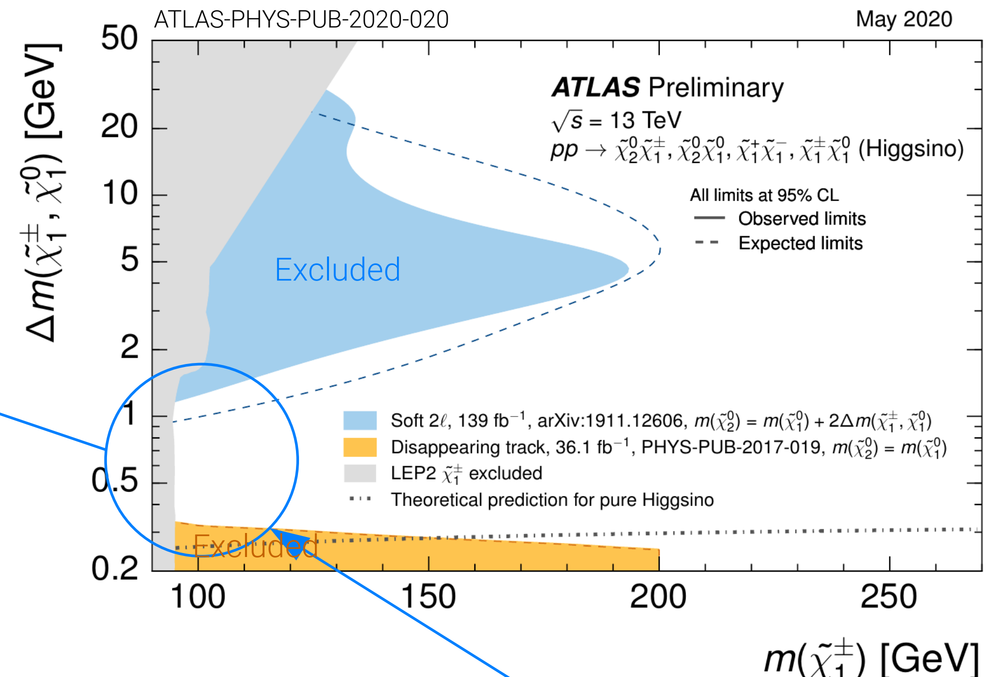




Cover the gap in sensitivity

- Measure soft displaced tracks (from charged higgsino decay)
- VBF topologies for higgsino production

(Summary of) ATLAS exclusion limits for higgsino pair production at 95% C.L.

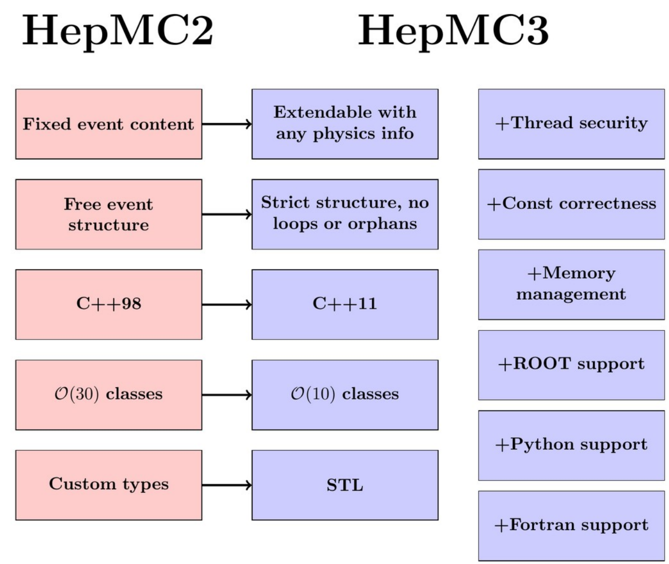


Ongoing work to cover gap by studying new signatures

Software-preparations for Run-3 and beyond

HepMC3 event record library

- Is a modern library to handle Monte Carlo event-records
- Version 3.2 was described in Comp.Phys.Comm. (2020)
- Implementation in ATLAS software (Athena) is ongoing



TheP8I library

- Is an interface of the Pythia8 String fragmentation model to ThePEG2/Herwig7
- Already in Athena&LCG
  → New option to get hadronisation modeling uncertainties in Run-3

Pseudorapidity of K_S^0 in $t\bar{t}$ events outside of jets

In ATLAS data (left)

In Herwig7 predictions (right) with native hadronisation(red) and TheP8I(blue).

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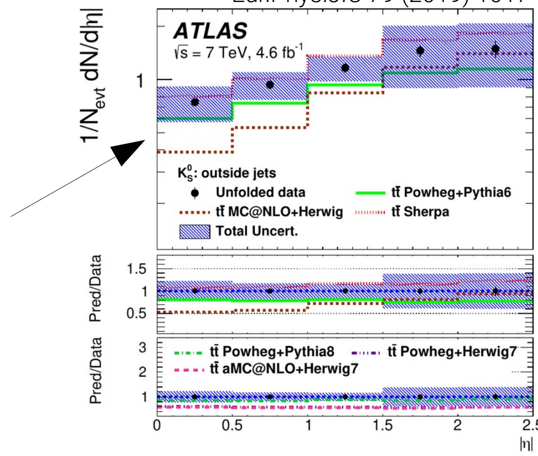
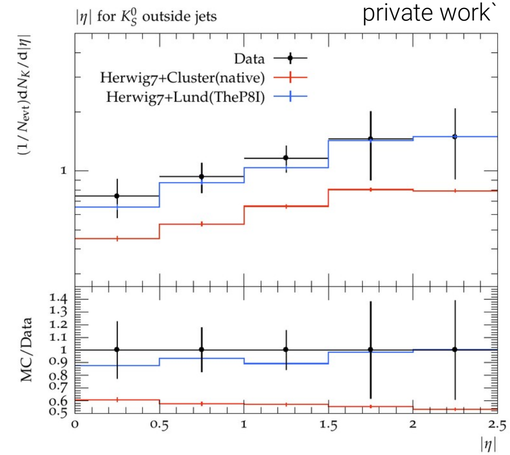


private work`



Summary

MPP group members are leading important ATLAS physics analyses

Top quark sector

- Precision analyses with full Run-2 data are ongoing
- Several complementary analyses to reduce backgrounds in other processes

Higgs sector

- Increased precision of cross section and coupling measurements
- Differential measurements

  → comprehensive EFT interpretations of Higgs-data

Searches for BSM physics (new resonances, dark matter, SUSY)

- Significant analysis improvements due to full Run-2 data set
- Novel analysis techniques extending the search range and new final states are explored

Plenty of work ahead of us…

- Systematics-sensitive analyses are still ongoing
- Preparation of Run-3 analyses is fully under way.