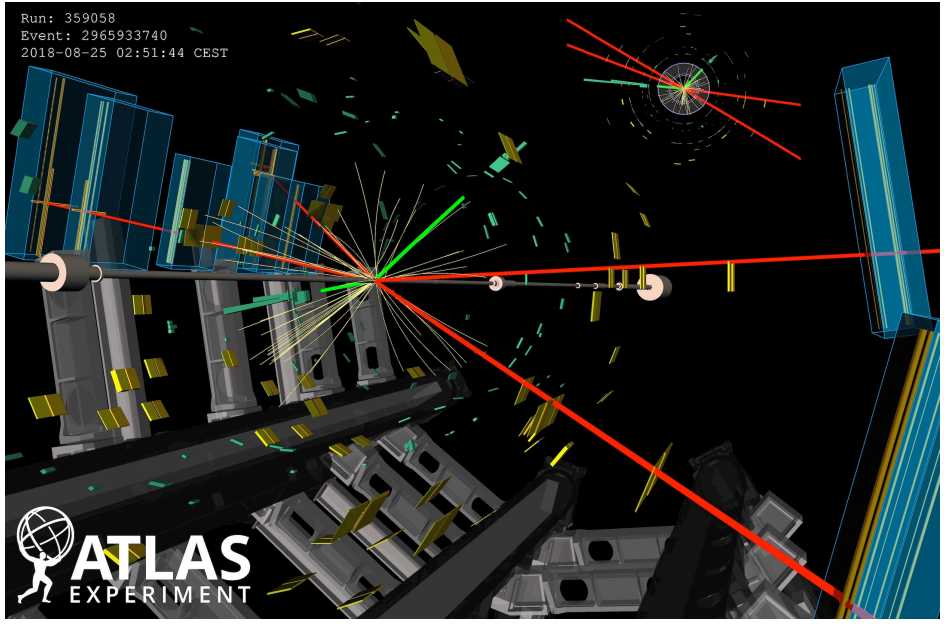
Physics Highlights from the ATLAS Experiment

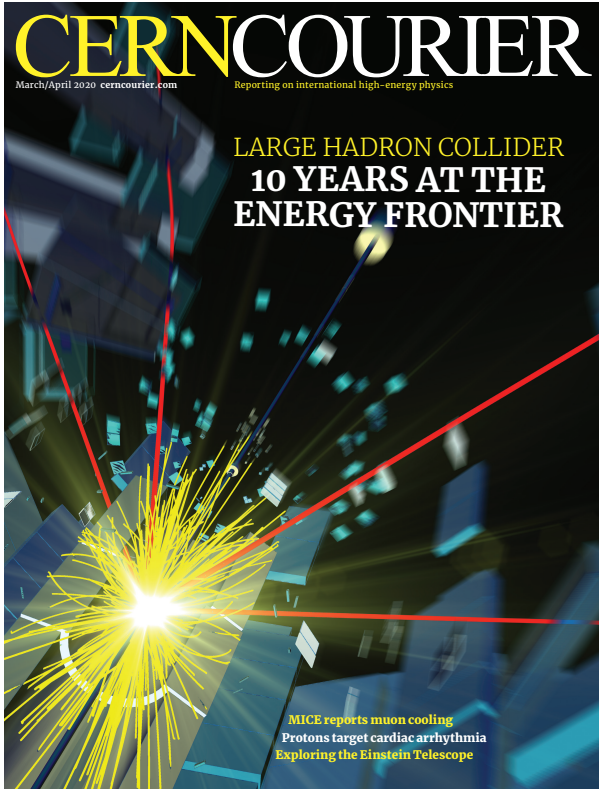


Karl Jakobs
For the ATLAS Collaboration

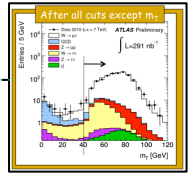
ICHEP 2020, Prague / Virtual Conference

UNI FREIBURG

10 Years at the Energy Frontier

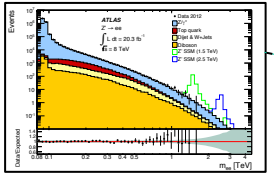


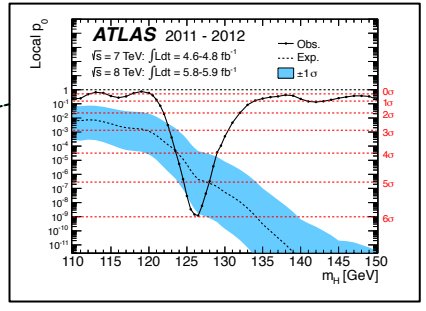
2010



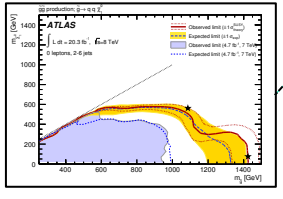
Fabiola Gianotti
ICHEP 2010, Paris

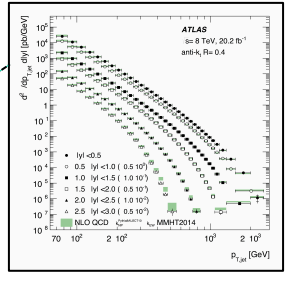
2012



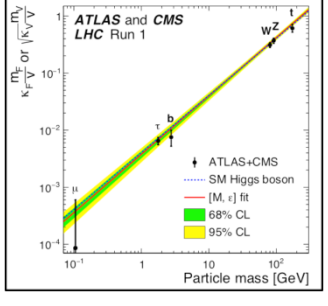


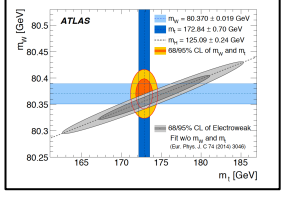
2014

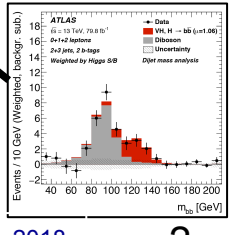




2016

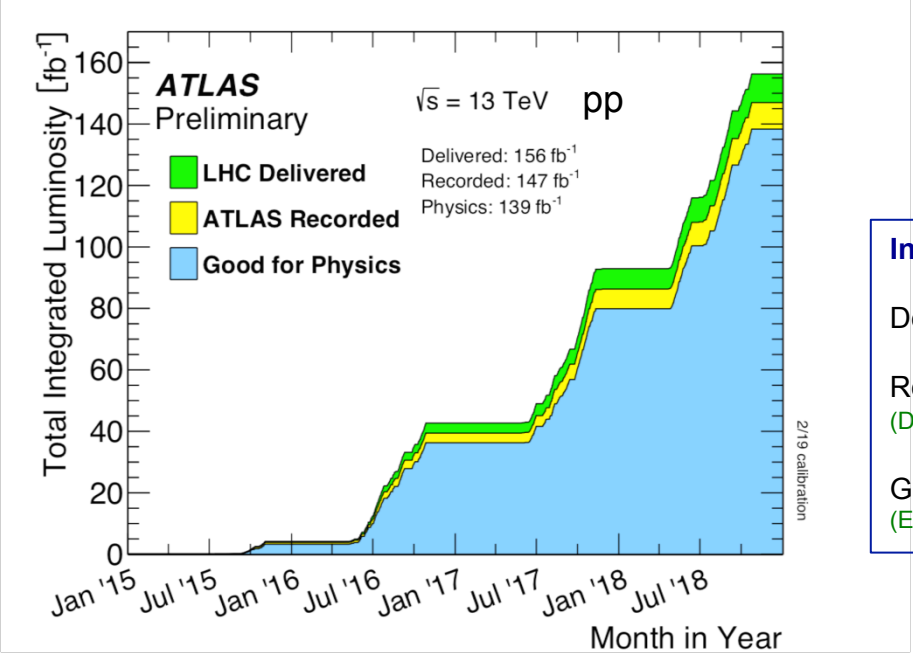






2018
ICHEP 2018, Seoul

LHC Run 2 (2015 – 2018)



In Run 2 (2015 – 2018):

Delivered: 156 fb^{-1}

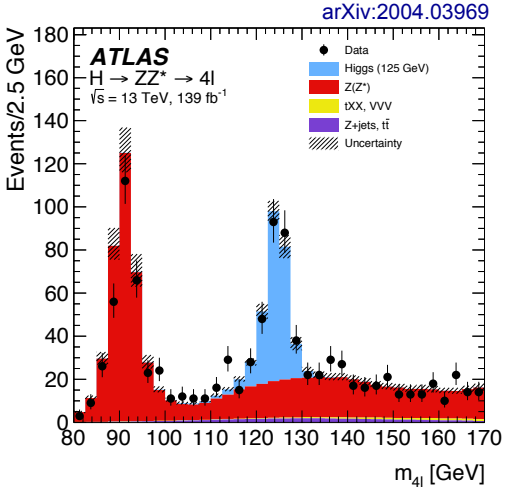
Recorded: 147 fb^{-1}
(Data taking efficiency 94.2%)

Good for Physics: 139 fb^{-1}
(Efficiency 94.6%, → high data quality)

- **94 public results (51 papers)** with complete Run-2 pp dataset, 139 fb^{-1}
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018
- **10 public results (2 papers)** incl. the 2018 Heavy Ion data, 1.7 nb^{-1}
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
- **35 ICHEP 2020 Conference contributions**
  https://atlas.cern/updates/atlas-news/summary-ichep-2020

Higgs Boson Physics

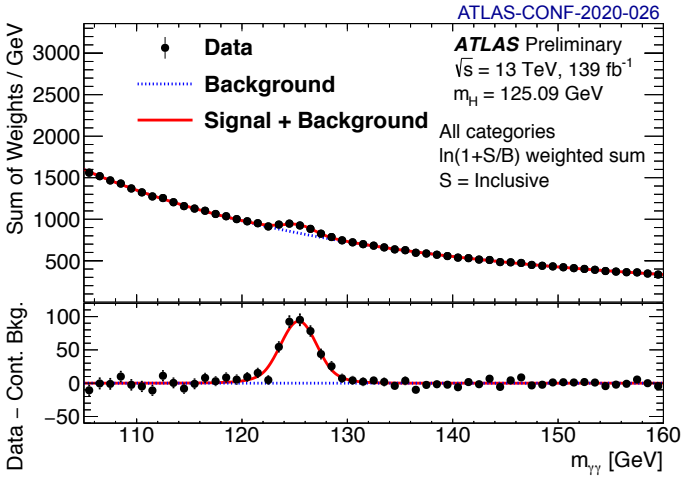
$H \to ZZ^* \to 4\ell$



σ = 53.5 ± 4.9 (stat) ± 2.1 (syst) pb

σ_{SM} = 55.7 ± 2.8 pb

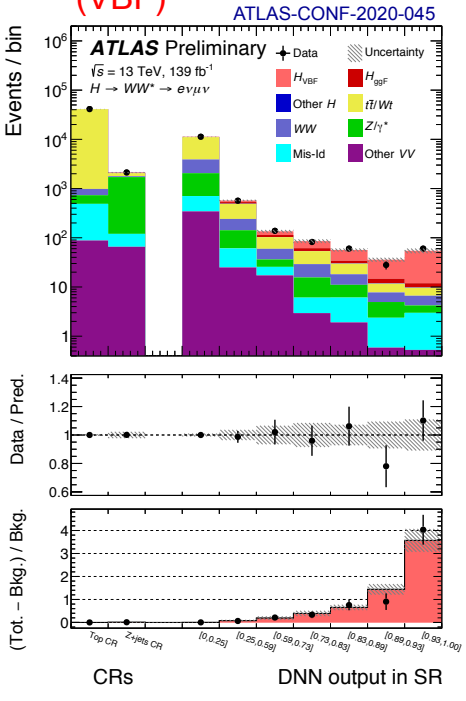
$H \to \gamma\gamma$



$\sigma \cdot BR_{\gamma\gamma}$ = 127 ± 7 (stat) ± 7 (syst) fb

$\sigma_{SM} \cdot BR_{\gamma\gamma}$ = 116 ± 5 fb

$H \to WW^* \to e\nu\,\mu\nu$ (VBF)



$\sigma^{VBF} \cdot BR_{WW}$ = 0.85 ± 0.10 (stat) $^{+0.17}_{-0.13}$ (syst) pb

$\sigma^{VBF}_{SM} \cdot BR_{WW}$ = 0.81 ± 0.02 pb

Obs. (exp.) significance: 7.0σ (6.2σ)

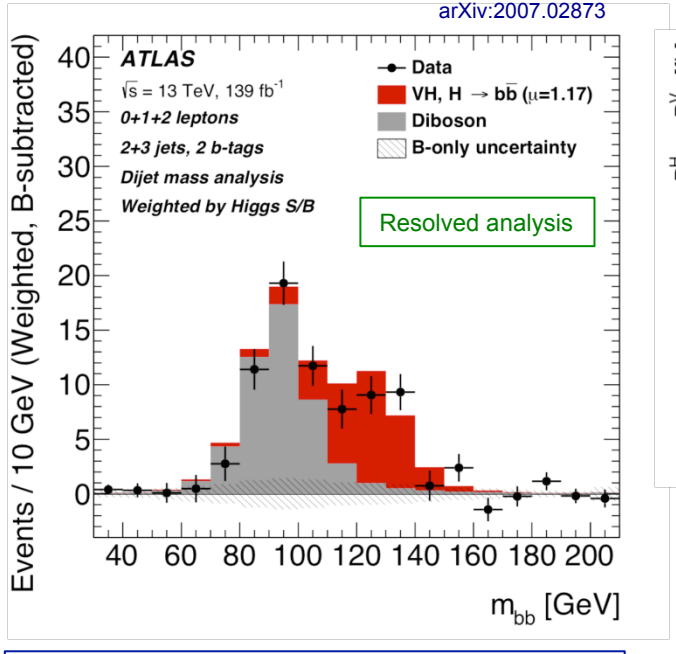
Large Run-2 dataset allows for more detailed measurements

- *Differential cross sections*
- *Search for rarer decay modes*

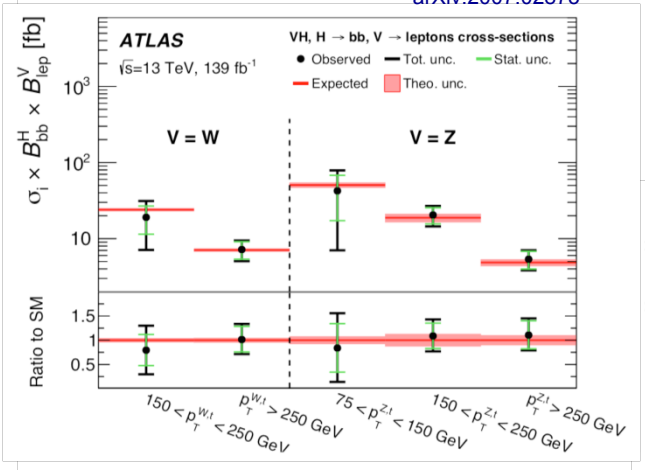
(i) Decays into Fermions: Run-2 results on VH, H → bb

Resolved analysis (standard)

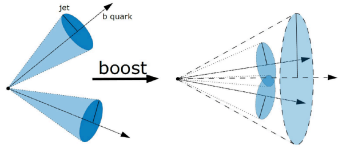
arXiv:2007.02873



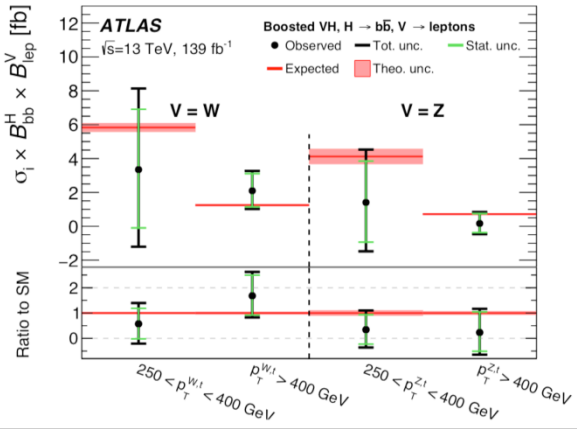
arXiv:2007.02873



Vector bosons at high p_T (boosted topology)



CERN-EP-2020-093



Signal strength: $\mu = \sigma_{obs} / \sigma_{SM}$

$\mu_{VH}(bb) = 1.02\ ^{+0.12}_{-0.11}\ (stat)\ ^{+0.14}_{-0.13}\ (syst)$

Obs. (exp.) significance: 6.7σ (6.7σ)

significance (ZH): 5.3σ (5.1σ)

Good agreement between measurements and SM predictions

Boosted analysis: measurement at high p_T → increased sensitivity to BSM physics

(ii) Decays into 2nd Generation Fermions?

- Important milestone: test of Yukawa sector

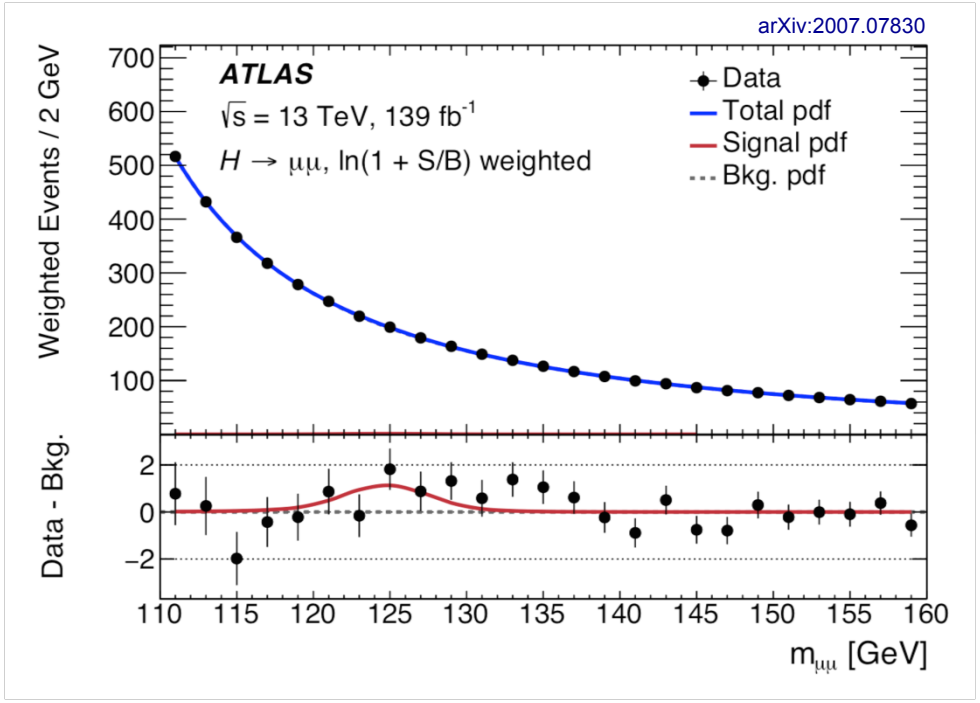
  H → μμ decays offer the most promising path to 2nd gen

- However: BR (H → μμ) ~ 2.2 • 10^{-4}, and huge background from Drell-Yan production of μ pairs

- Optimised analysis:
  - Exploit topological and kinematic differences between different Higgs production modes and the background
  - Use of multivariate techniques
    → Classify events in 20 mutually exclusive categories

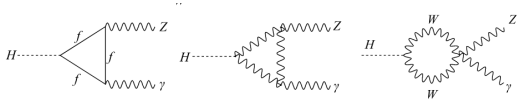
Best fit signal strength:	μ = 1.2 ± 0.6
Obs. (exp.) significance:	2.0σ (1.7σ)

Run 3 and beyond essential to increase sensitivity

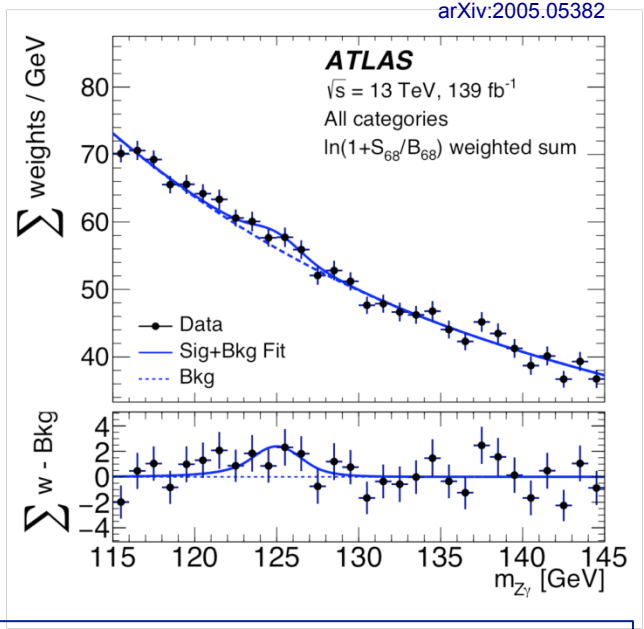


(iii) Search for **rare** and **invisible** decays

H → Zγ



arXiv:2005.05382



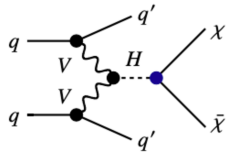
Background-only hypothesis: p-value of 1.3% (2.2σ)

Best fit signal strength: $\mu_{Z\gamma} = 2.0 \pm 0.9\,(\text{stat})\,^{+0.4}_{-0.3}\,(\text{syst})$

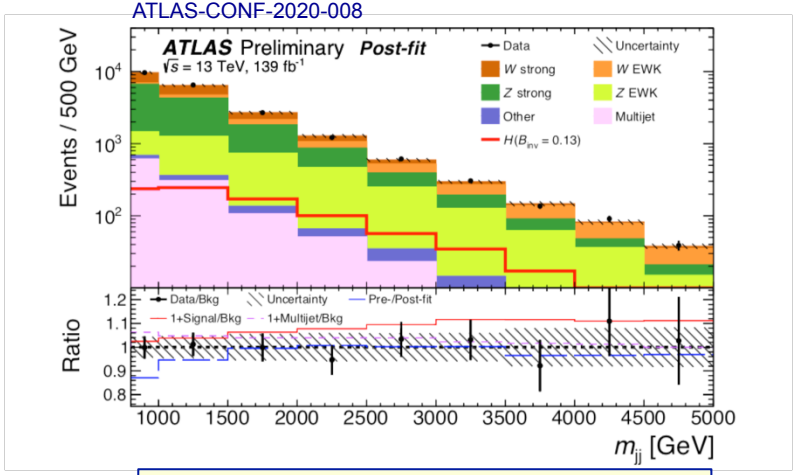
(exp. $\mu_{Z\gamma} = 1.0 \pm 0.8 \pm 0.3$ for a SM Higgs)

Run 3 and beyond essential to increase sensitivity

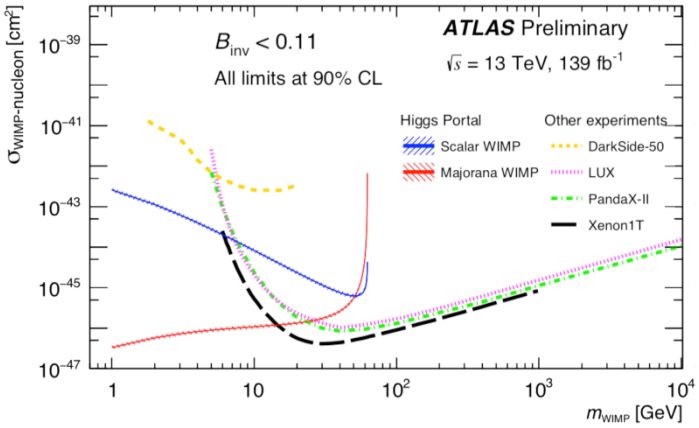
qqH → qq inv. (VBF)



ATLAS-CONF-2020-008



Limit on BR (H → inv.): < 0.13 (95% CL)



Dark Matter interpretation (Higgs portal models)

Combined Measurements of Higgs Boson production and decays

Channels included in the combination:

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

(i) Global signal strength

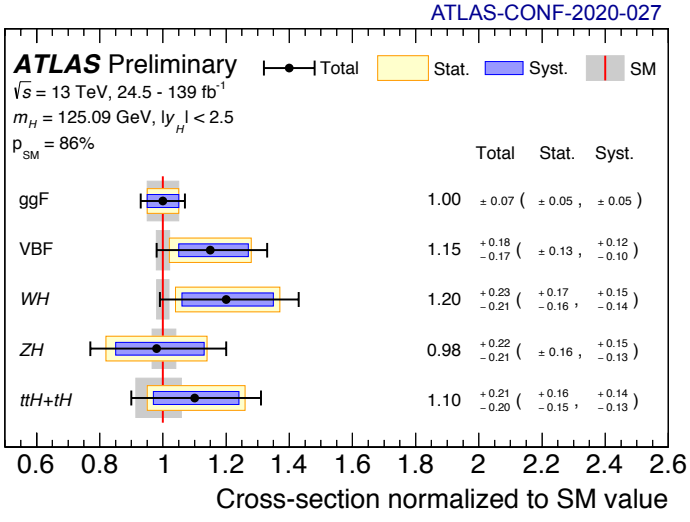
Describing a common scaling of the expected Higgs boson yields in all processes (σ x BR) (SM: μ = 1.0)

$$\mu = 1.06 \pm 0.07$$

$$[\pm 0.04\,(\text{stat}) \pm 0.03\,(\text{exp}) \,^{+0.05}_{-0.04}\,(\text{sig.th}) \pm 0.02\,(\text{bkg.th})]$$

(ii) Production Cross Sections

(assume SM branching ratios)



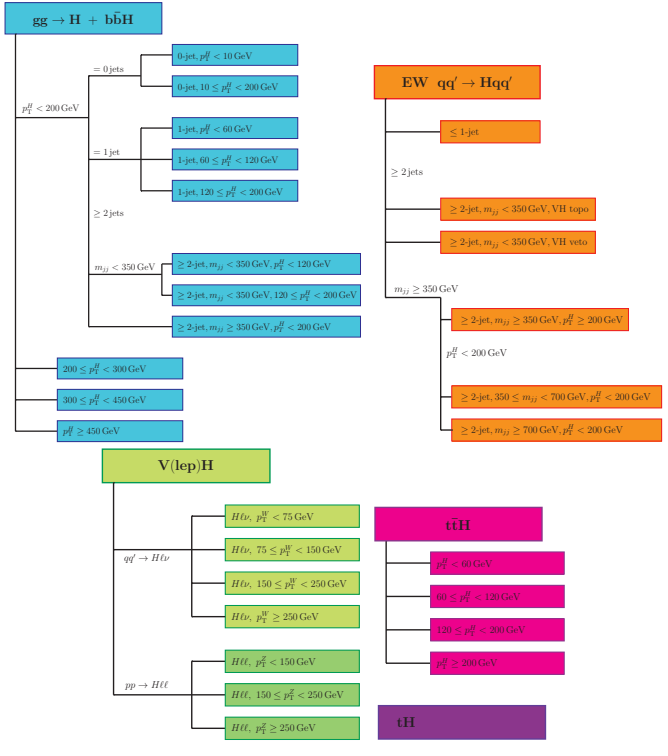
All major production processes observed
(significance > 5σ)

First observation of WH production: 6.3σ (5.2σ exp)

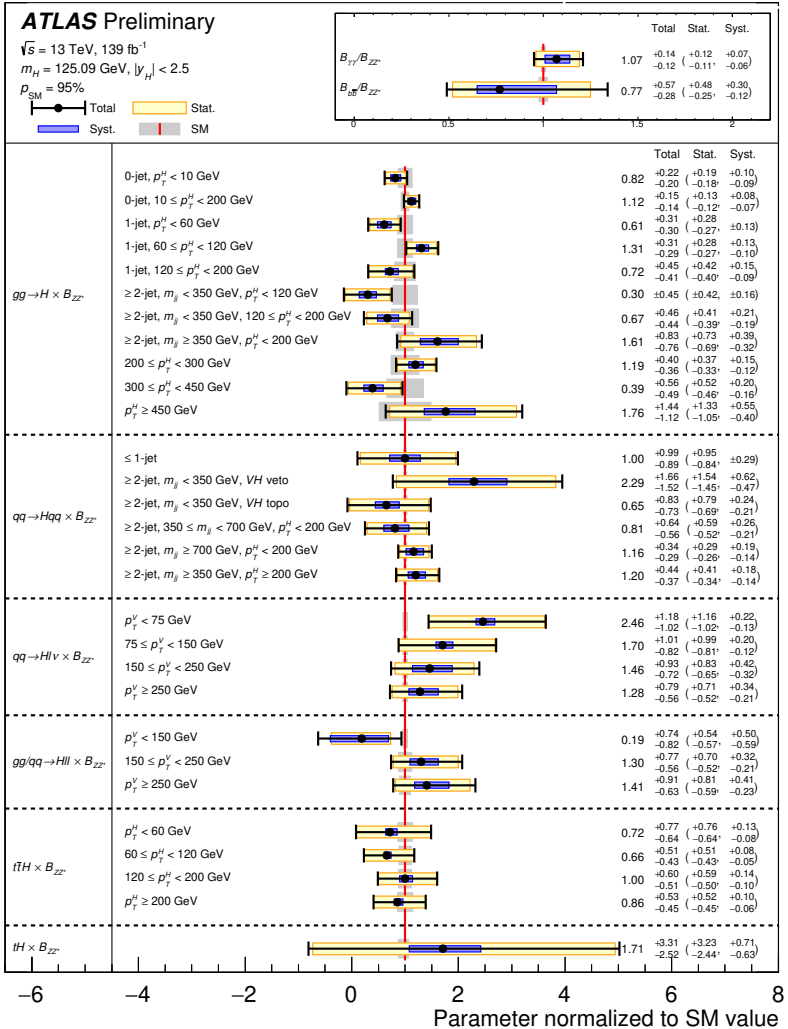
(iii) Measurements of **simplified template cross-sections (STXS)**

- *Partition phase space into a set of non-overlapping regions*
- *Defined in terms of kinematics of the Higgs boson, associated jets, W and Z bosons*

→ *Match experimental selections, avoid large theory uncertainties, sensitive to deviations from SM*



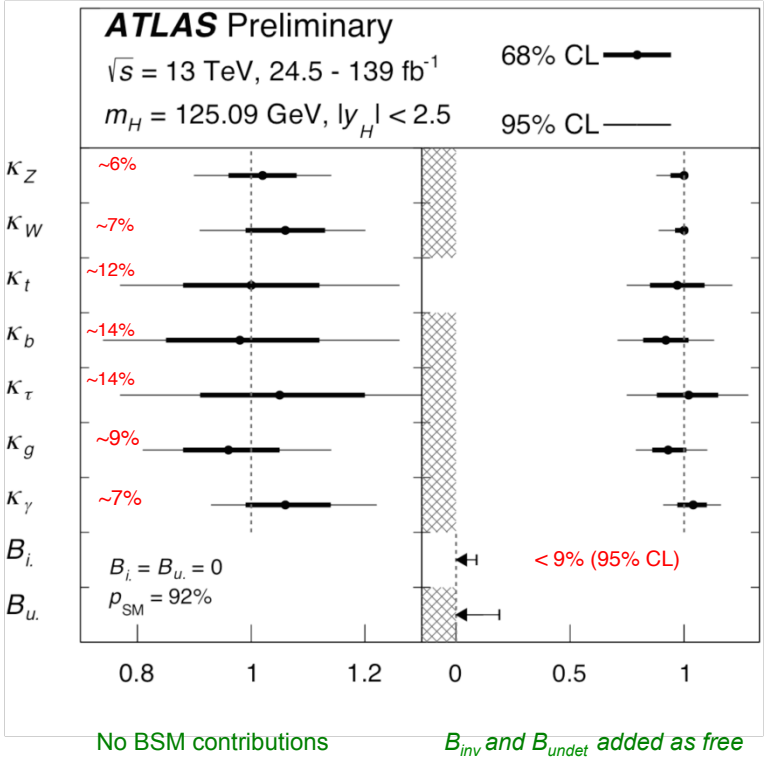
ATLAS-CONF-2020-027



(iv) Interpretation in the κ framework

- *Introduce **coupling scale factors κ** for each particle, including effective photon and gluon couplings*

ATLAS-CONF-2020-027



No BSM contributions ($B_{inv} = B_{undet} = 0$)

B_{inv} and B_{undet} added as free parameters with constraints $\kappa_W \leq 1$ and $\kappa_Z \leq 1$

Cross section times branching fraction of an individual channel σ(i → H → f) contributing to a measured signal yield:

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$

Definition of coupling strength modifier: $\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}}$ or $\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$

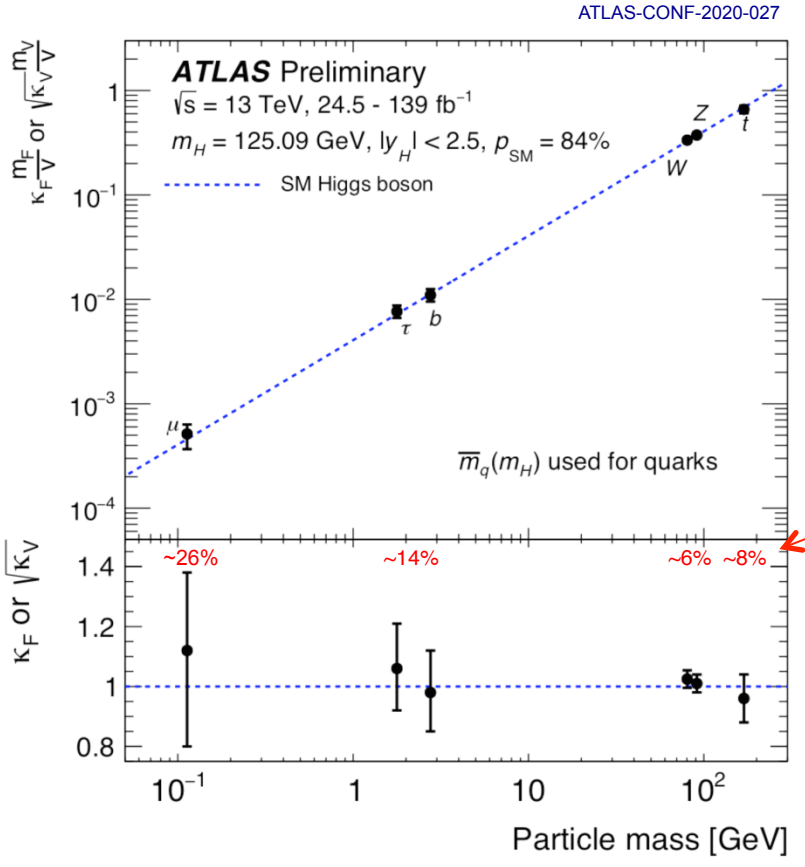
Scale factor of Higgs boson width: $\kappa_H^2(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \frac{\sum_j B_j^{\mathrm{SM}} \kappa_j^2}{(1 - B_{\mathrm{i.}} - B_{\mathrm{u.}})}$

Branching ratio of Higgs into invisible particles constrained to < 9% (95% CL) (<11% expected)

(VBF H → invisible, global fit)

Coupling strength versus mass

(assuming no new particle in loops and decays)

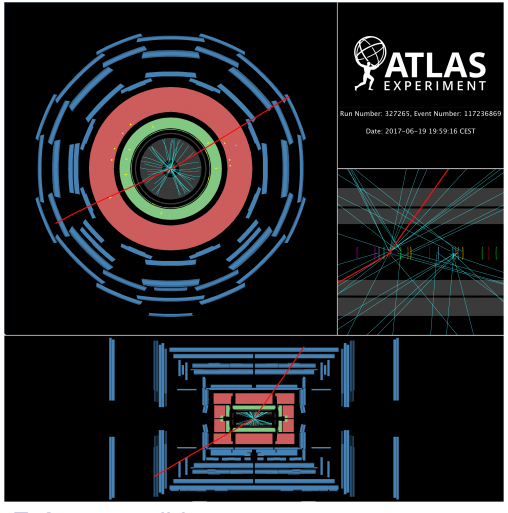


uncertainties on κ_i

Excellent agreement with SM predictions

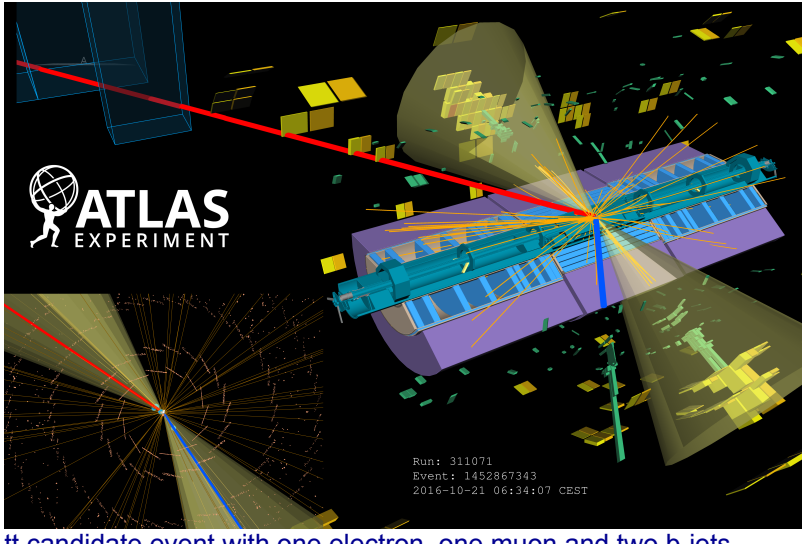
Coupling scaling ~mass over three orders of magnitude

(Precision) Tests of the Standard Model



Z → μμ candidate event

Expect **8 billion Z bosons** ...



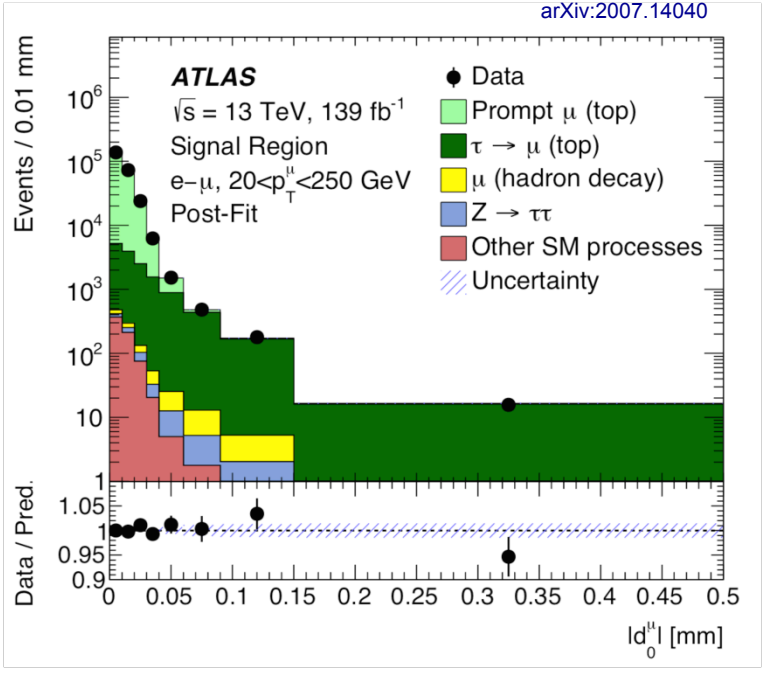
tt candidate event with one electron, one muon and two b-jets

... and **275 million top quarks** produced in 140 fb^{-1}

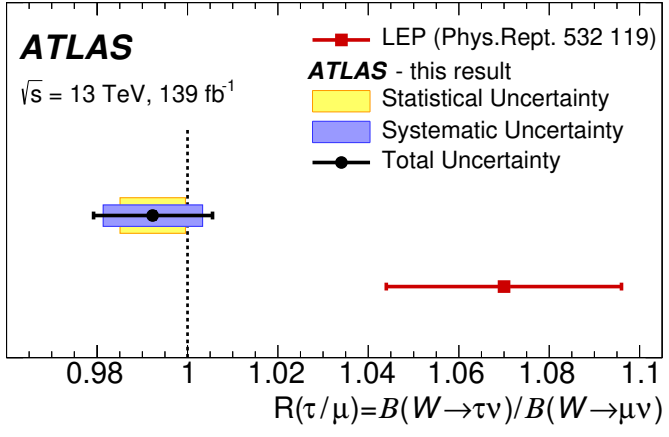
Lepton-Flavour Universality

- Use **large tt sample** as clean probe of W bosons (**di-leptonic decays**, ***tag(e,μ)–and–probe (μ)***)
- Measure ratio of prompt (W → μν) to softer, delayed muons from tau decays (W → τ ν → μνν ν)
- Also motivated by long-standing 2.7σ LEP deviation: R = BR(W → τν) / BR(W → μν) = 1.070 ± 0.026

arXiv:2007.14040



arXiv:2007.14040 (subm. Nature Phys.)



R = BR(W → τν) / BR(W → μν) = 0.992 ± 0.013

(factor two in precision compared to LEP)

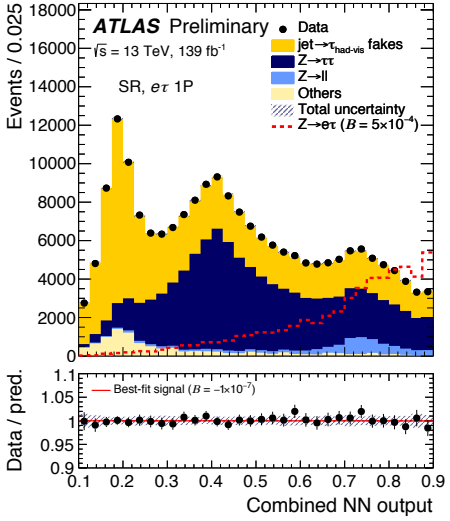
Consistent with Lepton-Flavour Universality

... like results based on τ lifetime and leptonic decays at low q^2 with precision at the level of ±0.14%

Lepton-Flavour Violation: Z → eτ / μτ decays

- Use **large sample of Z decays** to look for **Z → eτ / μτ decays** (would signal BSM physics)
- Use hadronic τ decays; major backgrounds: Z → ττ , W + jet (→fake τ) production
- Exploit kinematic differences ($p_T(\ell)$, $m_{vis}(\ell,\tau)$, m_T, ...) using neural networks

ATLAS-CONF-2020-035



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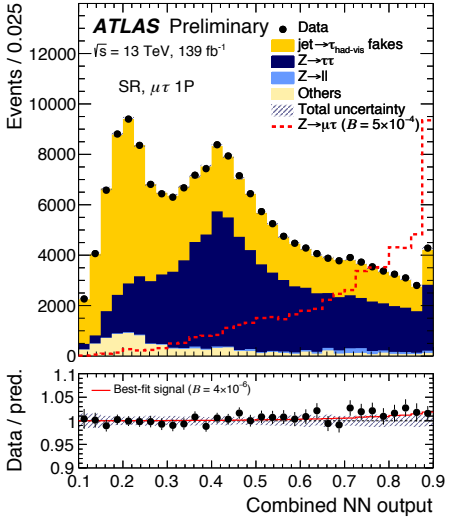


- Most stringent upper limits set on BR (Z → ℓτ)
  (unpolarised τ)

BR (Z → e τ) < 8.1•10^{-6} (95% CL) (exp. 8.1•10^{-6})
BR (Z → μ τ) < 9.5•10^{-6} (95% CL) (exp. 6.1•10^{-6})

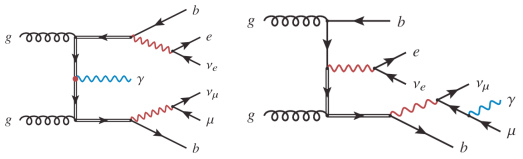
Limited by statistical uncertainty
→ significant improvements expected in Run 3 and HL-LHC

Overtakes previous limits from LEP:
BR (Z → e τ) < 9.8 10^{-6} (OPAL)
BR (Z → μ τ) < 12 10^{-6} (DELPHI)

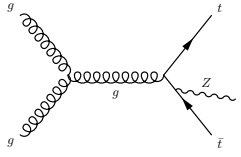
Associated (ttγ + tWγ) and ttZ production

- Direct access to **coupling of top quark to el.weak gauge bosons**
- Sensitivity to BSM physics (EFT approach) in differential cross-section measurements

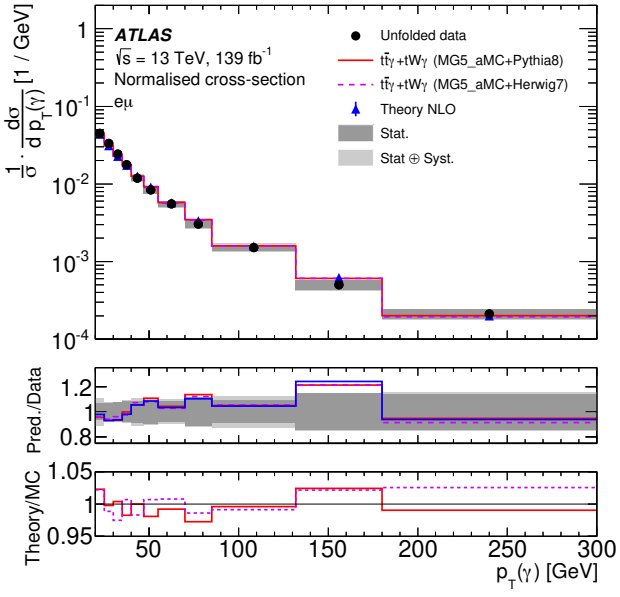
ttγ + tWγ



ttZ



arXiv:2007.06946



Select e, μ, γ final states

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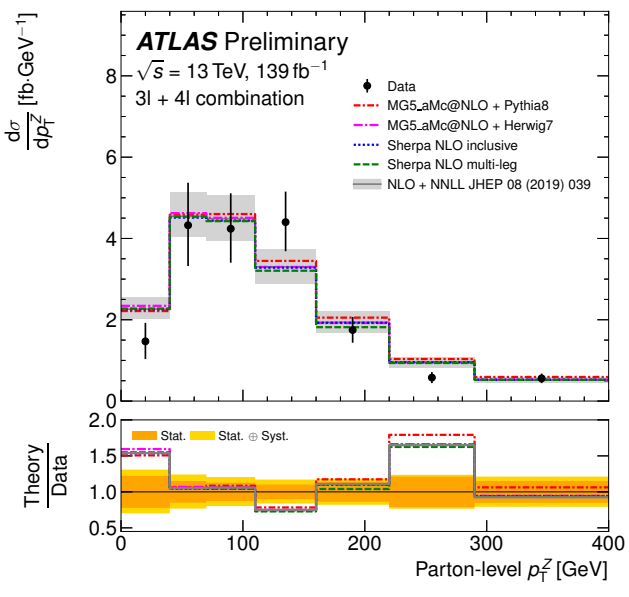
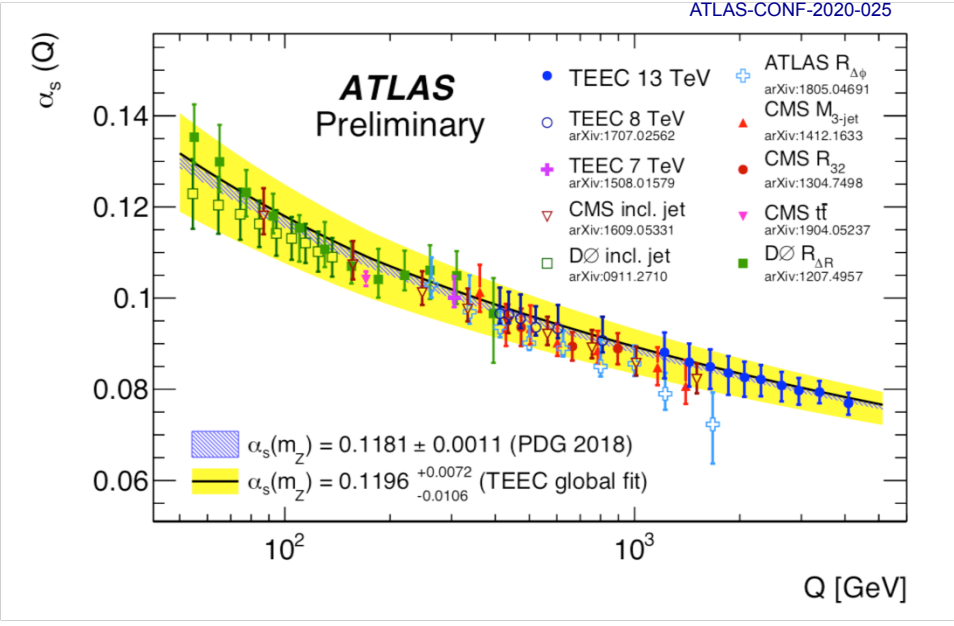


Select final states with 3 or 4 isolated leptons

Good agreement of the SM predictions with the measured inclusive and fiducial cross sections

Quantum Chromodynamics

ATLAS-CONF-2020-025

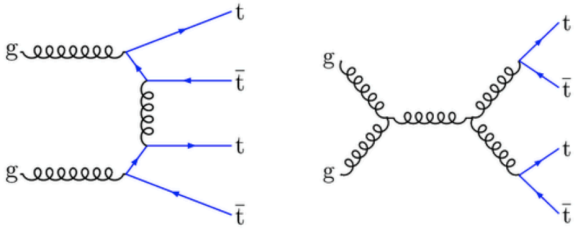


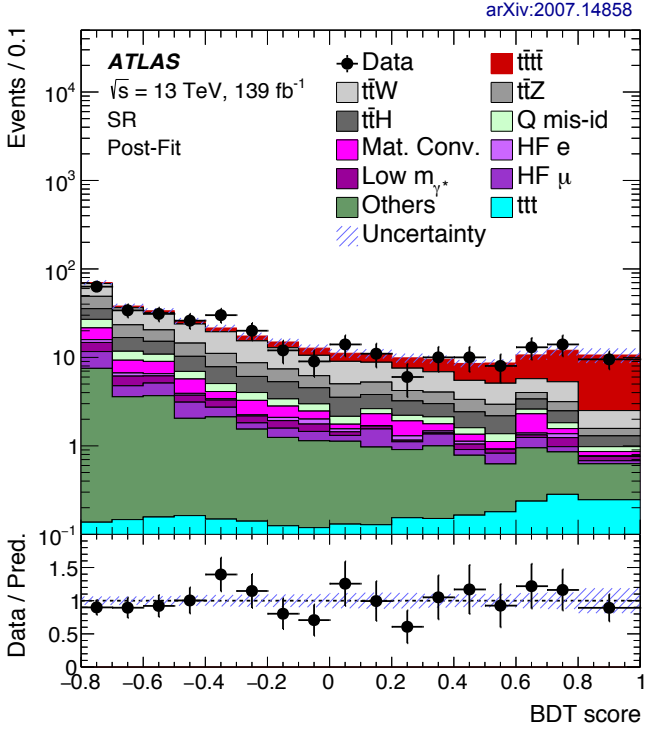
New measurement of α_s from Transverse Energy-Energy Correlations in multi-jet events (based on NLO calculations)

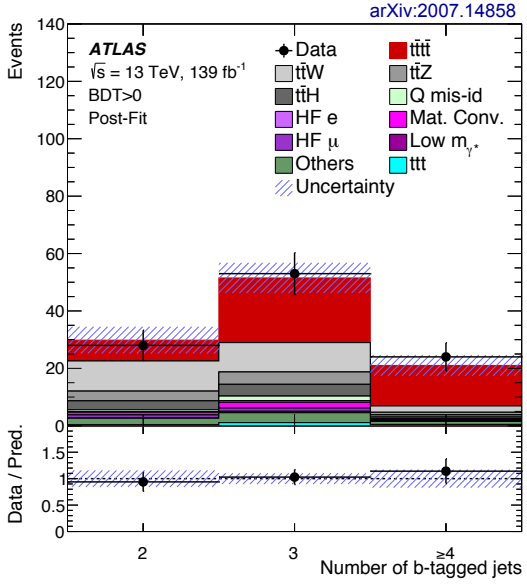
$\alpha_s = 0.1196 \pm 0.0004\ (\text{exp})\ ^{+\ 0.0072}_{-\ 0.0105}\ (\text{theo})$

Evidence for tttt production

- **Test of QCD** (rare process) and **sensitivity to BSM physics**
- Select final states with at least 3 leptons or 2 same-sign leptons (e,μ)
- Use multivariate techniques (jet multiplicity, jet flavour, event kinematics, …) to suppress backgrounds (ttW, ttZ, ttH, …)







Obs. (exp.) significance: 4.3σ (2.4σ)

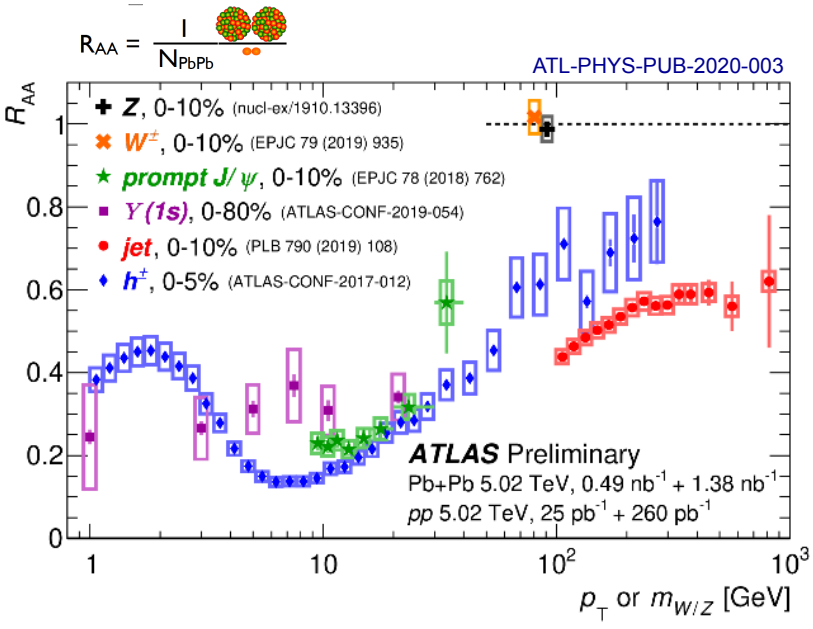
$\sigma_{tttt} = 24\ ^{+5}_{-5}\ (stat)\ ^{+5}_{-4}\ (syst)$ fb

(SM prediction: $\sigma_{tttt}^{SM} = 12 \pm 2$ fb)

Heavy Ion Physics

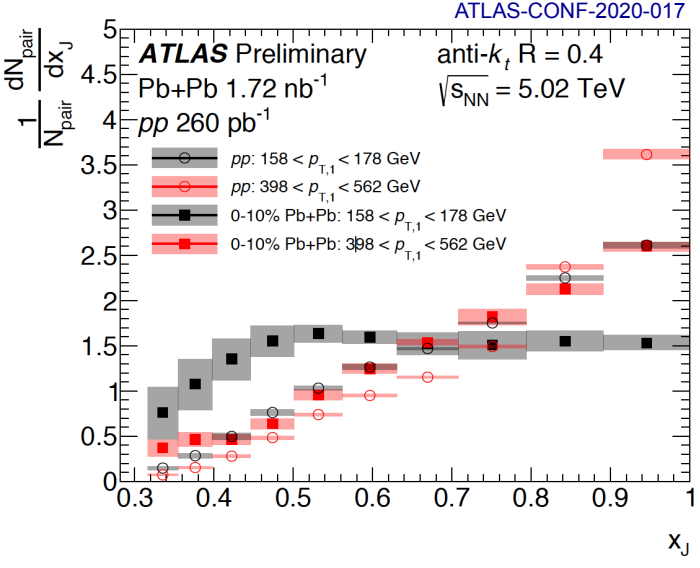
Suppression of strongly interacting probes in Pb-Pb collisions is uniformly observed
→ new results: more differential measurements

Suppression of several types of probes in Pb-Pb w.r.t. pp collisions



- Similar suppression for hadronic probes, production of W and Z bosons is unsuppressed

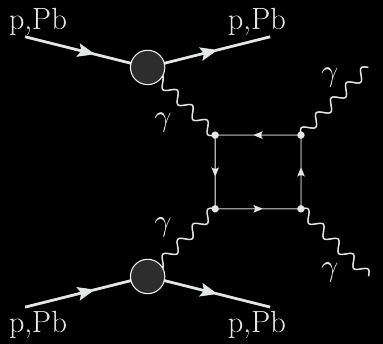
Differential di-jet momentum balance $x_J = p_{T,2} / p_{T,1}$

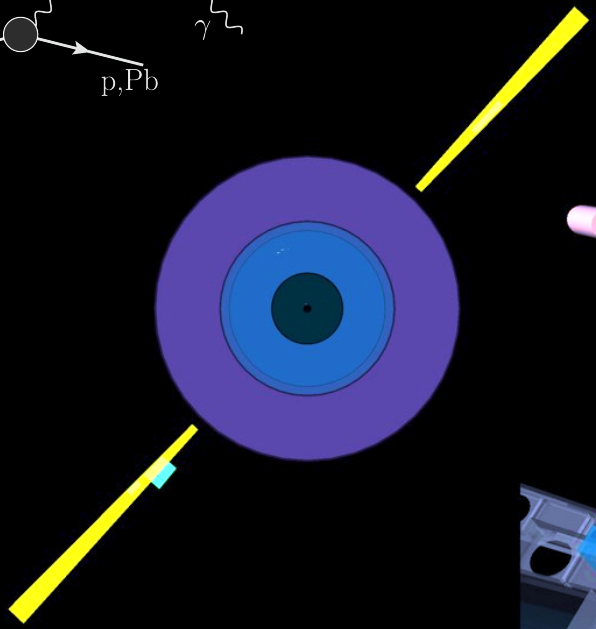


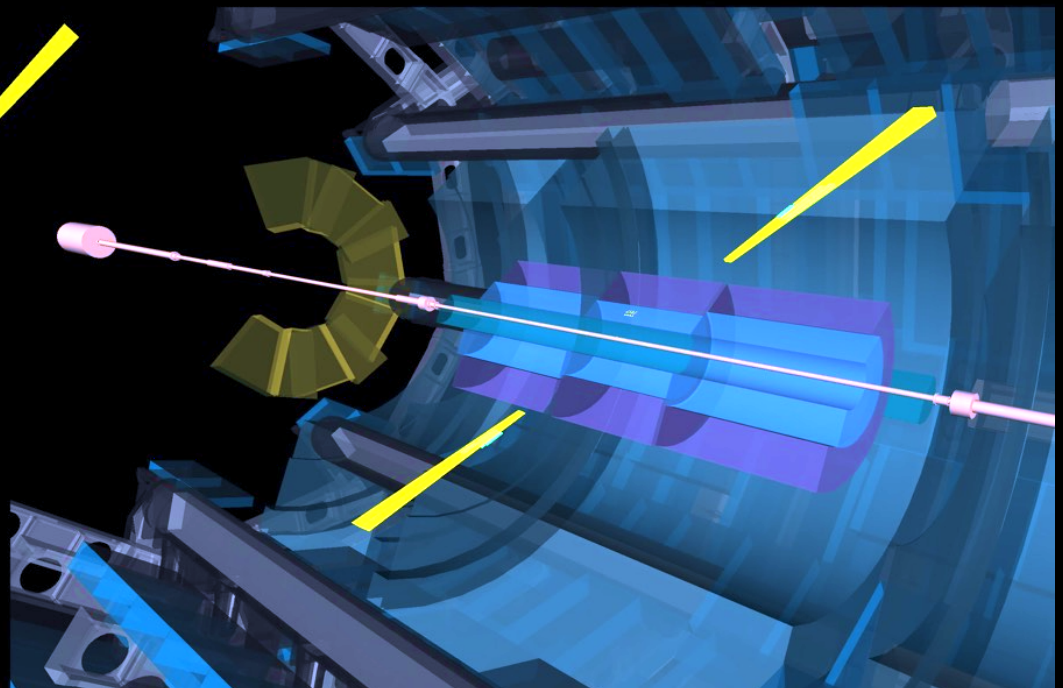
- Significant broadening observed in Pb+Pb collisions w.r.t. pp over large $p_{T,1}$ range;
- $p_{T,1}$ dependence
- Modifications observed in Pb+Pb decrease towards more peripheral events (not shown)

The LHC as a Photon-Photon Collider

Observation of light-by-light scattering in 5.02 TeV ultraperipheral Pb+Pb collisions (PRL 123 (2019) 052001)







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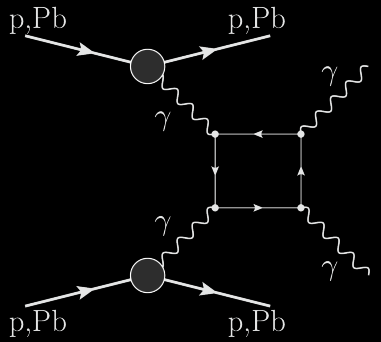
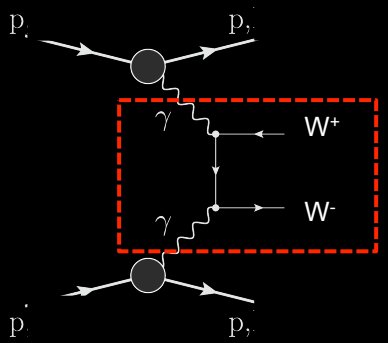
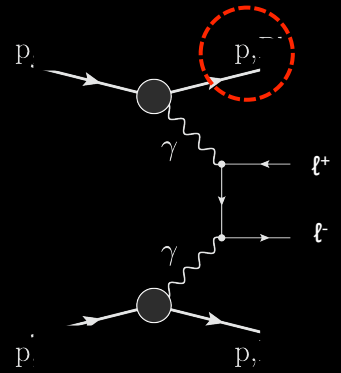
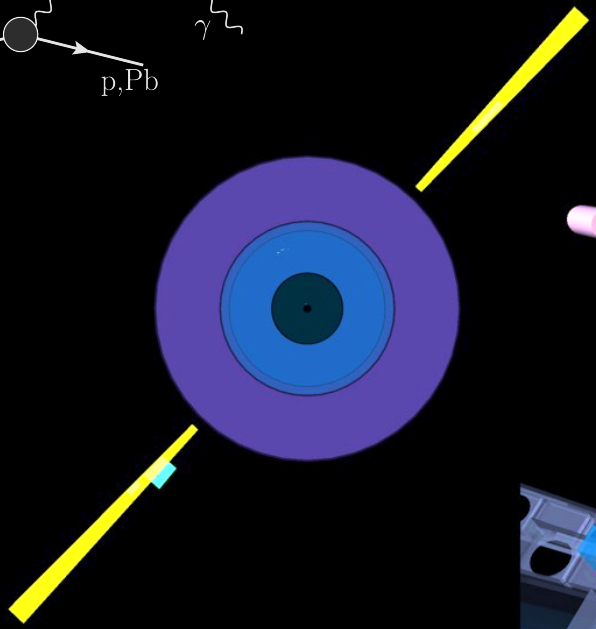
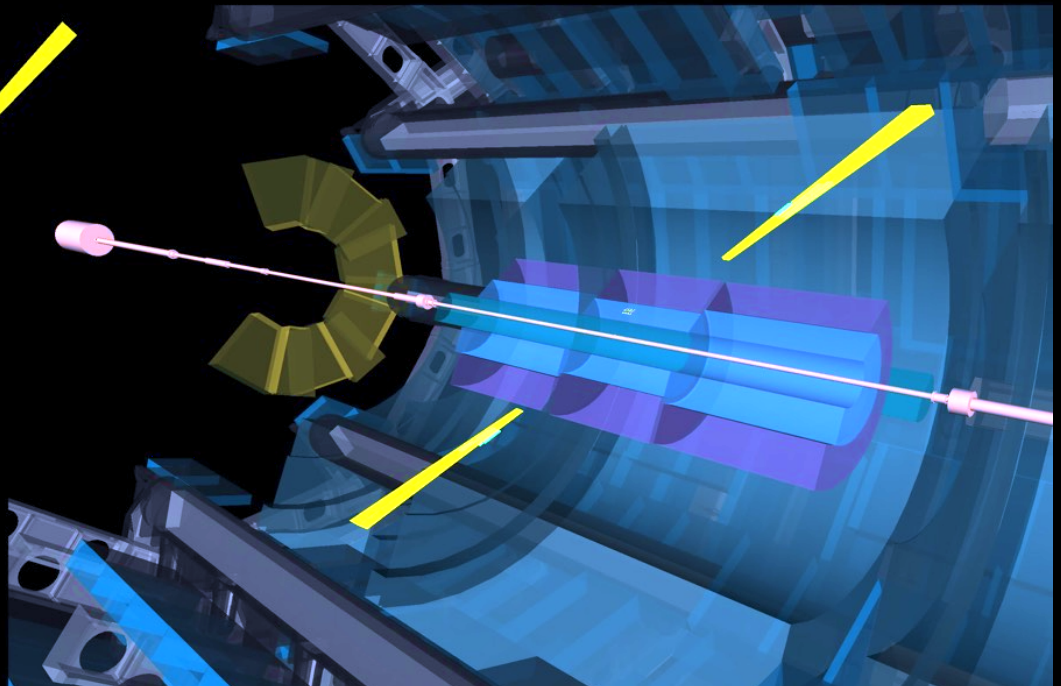








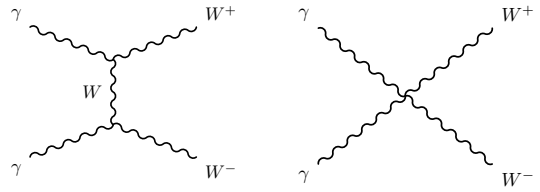


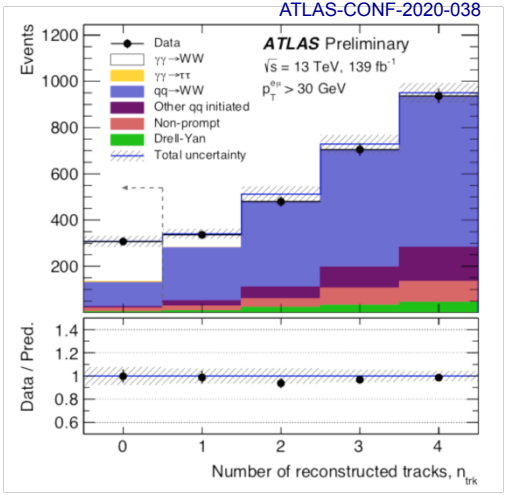
Observation of the γγ → WW process

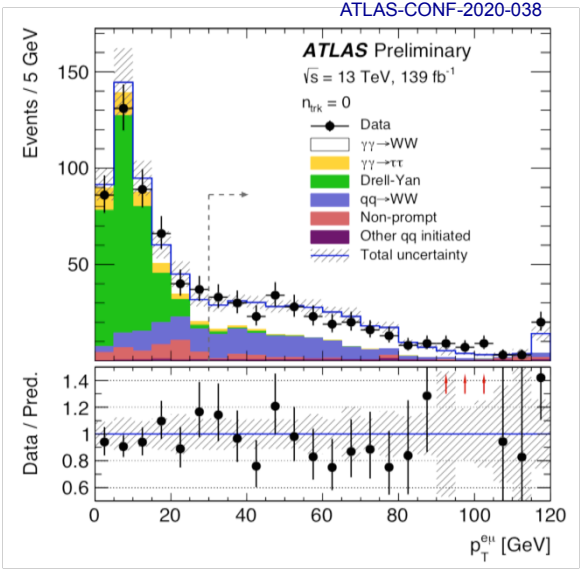
- Production through trilinear and quartic gauge-boson interactions (Born level)

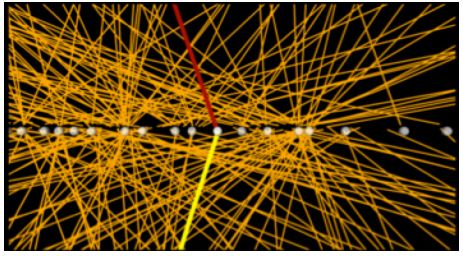
  → test of SM gauge structure, sensitive to anomalous gauge-boson interactions
- Search for **WW → eν μν signature**

  (e-μ vertex, $p_{T,\ell\ell} > 30$ GeV, no add. charged particle activity $N_{trk} = 0$)









σ_{fid} = 3.13 ± 0.31 (stat) ± 0.28 (syst) fb

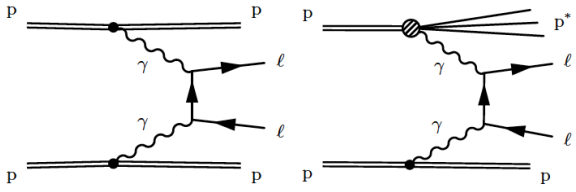
(σ_{fid}^{theo} = 2.1 ± 1.1 fb / 2.6 ± 1.3 fb)

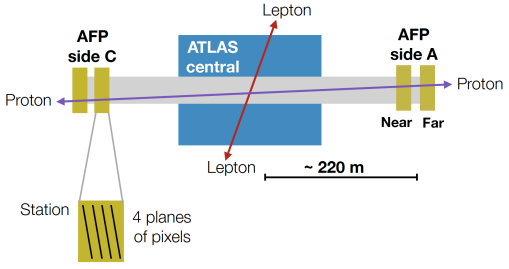
Obs. (exp.) significance: 8.4σ (6.7σ)

Run-1 evidence of photon-induced WW production in pp collisions has turned into observation

Observation of proton scattering in association with lepton pairs

- Forward scattering of incident protons is a hallmark prediction of photon fusion
- Measured in **ATLAS Forward Proton spectrometer (AFP)**



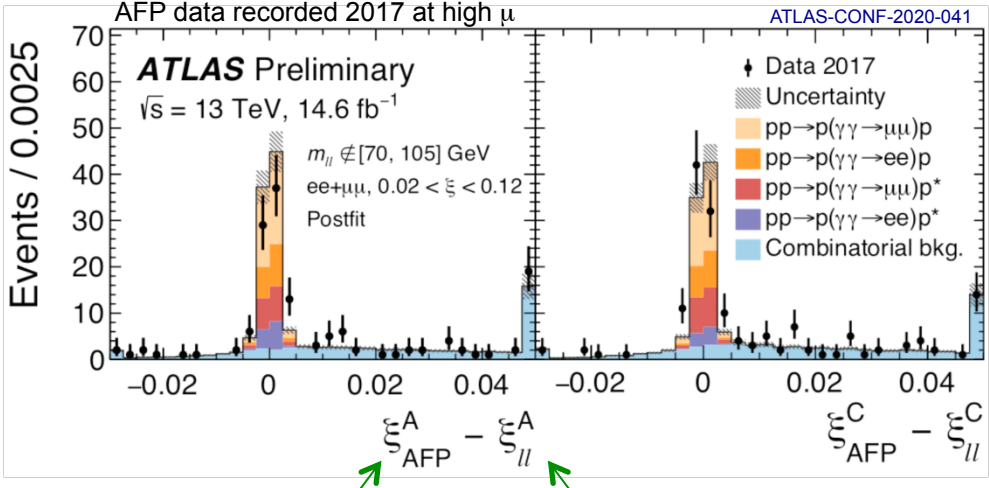


$\sigma_{\text{fid (ee+p)}}$ = 11.0 ± 2.6 (stat) ± 1.2 (syst) ± 0.3 (lumi) fb
$\sigma_{\text{fid (μμ+p)}}$ = 7.2 ± 1.6 (stat) ± 0.9 (syst) ± 0.2 (lumi) fb

Obs. significance: well above 5σ for both (ee) and (μμ)

Good agreement with SM expectations

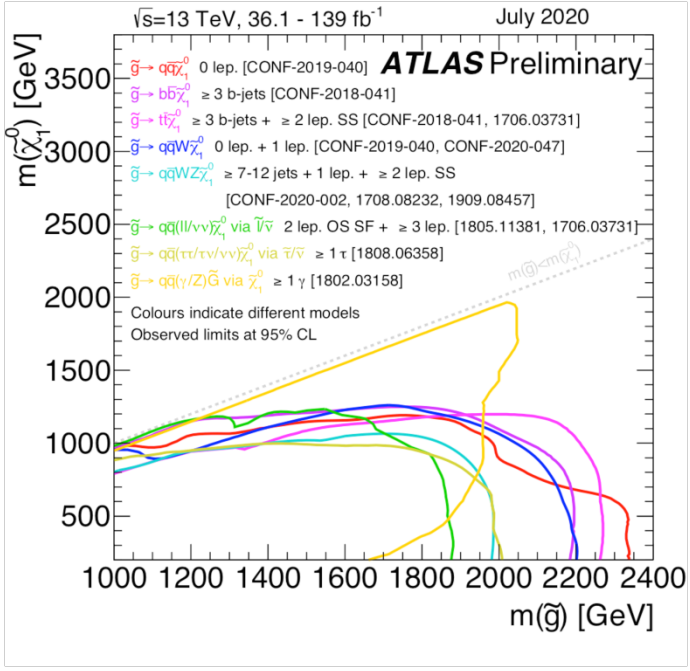
First cross-section measurement using proton-tagging in photon-fusion processes at the LHC

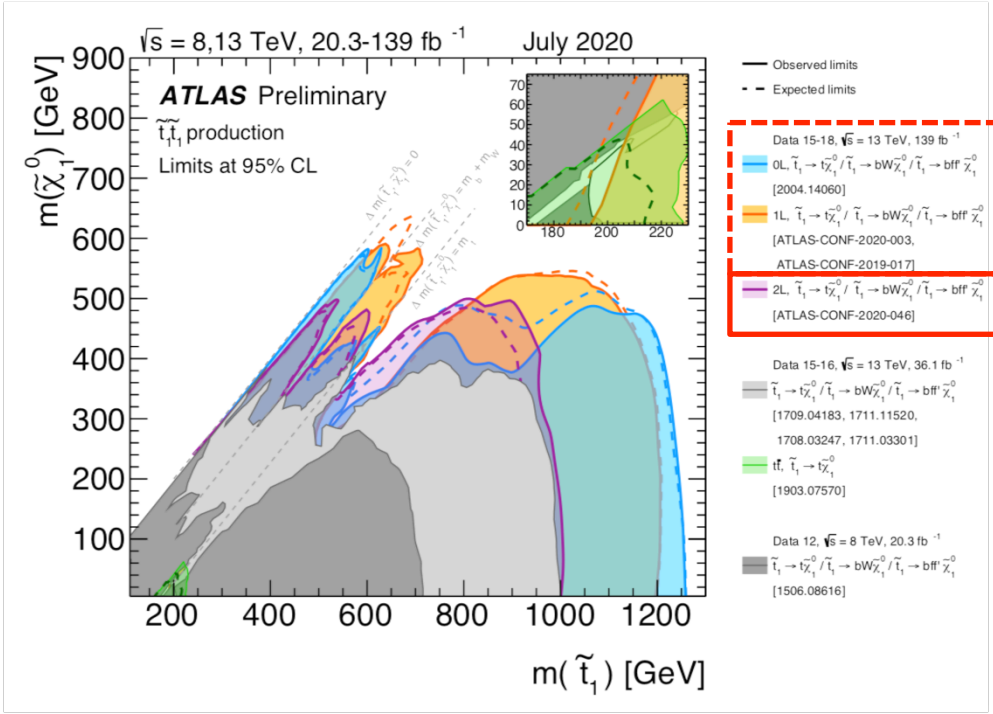


Fractional proton energy loss from scattered proton

Fractional proton energy loss from lepton kinematics

Search for Supersymmetry



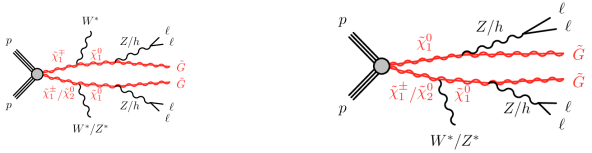


Strong limits for strongly produced SUSY particles, including top squarks:

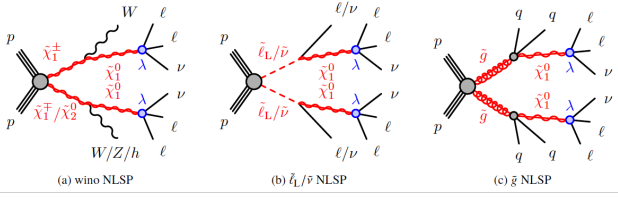
e.g. m_{gluino} < ~2.3 TeV excluded (for light neutralinos)
m_{stop} < ~1.25 TeV excluded (for light neutralinos) (Run-2 0-, 1-, and 2-lepton analyses)

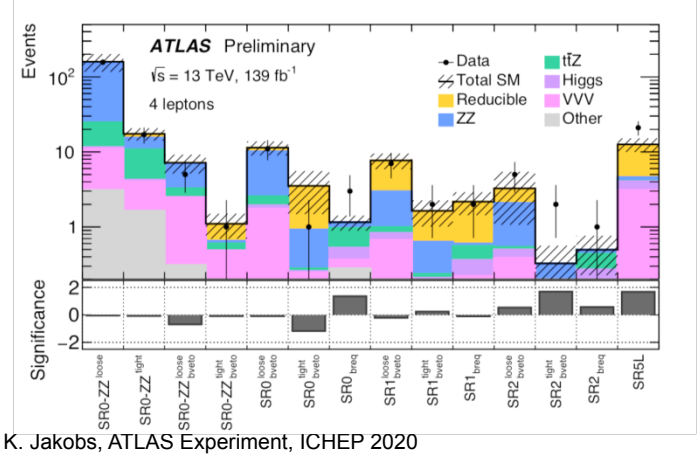
Search in events with four or more charged leptons

- **General Gauge Mediated (GGM)** SUSY models
  → **light higgsinos** without relying on low-momentum final states via decays $\tilde{\chi}_1^0 \rightarrow Z/h + \tilde{G}$



- **RPV scenarios** with a bino-like neutralino, decaying via RPV interactions $\tilde{\chi}_1^0 \rightarrow \ell_L^\pm \ell_{i/j}^\mp \nu_{i/i}$





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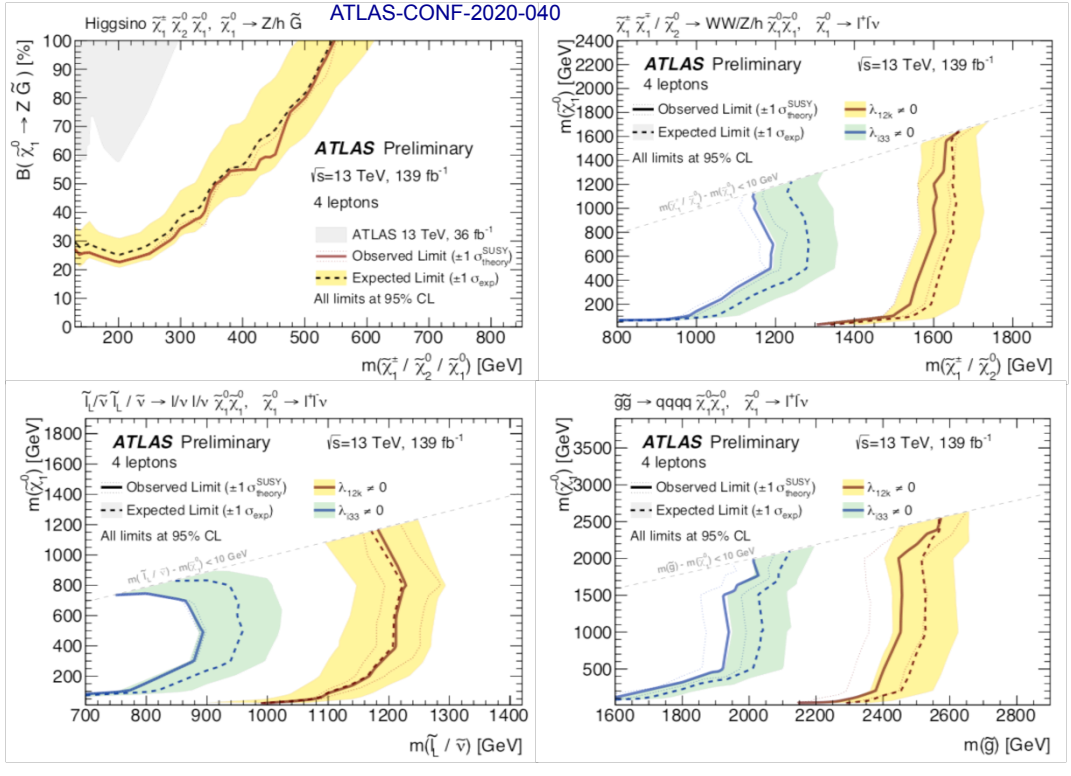


- GGM: Higgsino-like $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$ masses up to 550 GeV excluded (Substantial improvement w.r.t. analysis based on 36 fb^{-1})

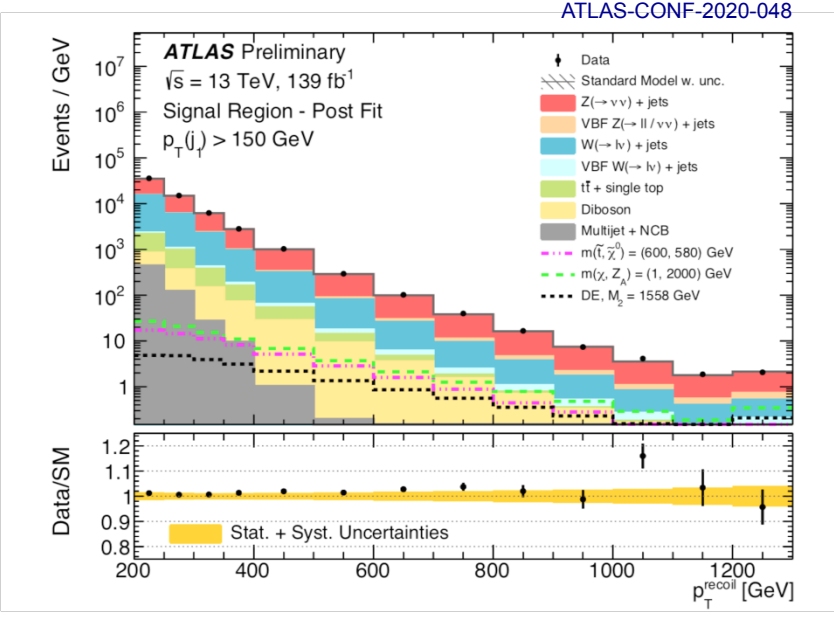
- In models with NLSP pair production with RPV LSP decays, $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$, $\tilde{\ell}_L/\tilde{\nu}$ and gluino masses up to 1.65, 1.23 and 2.58 TeV are excluded

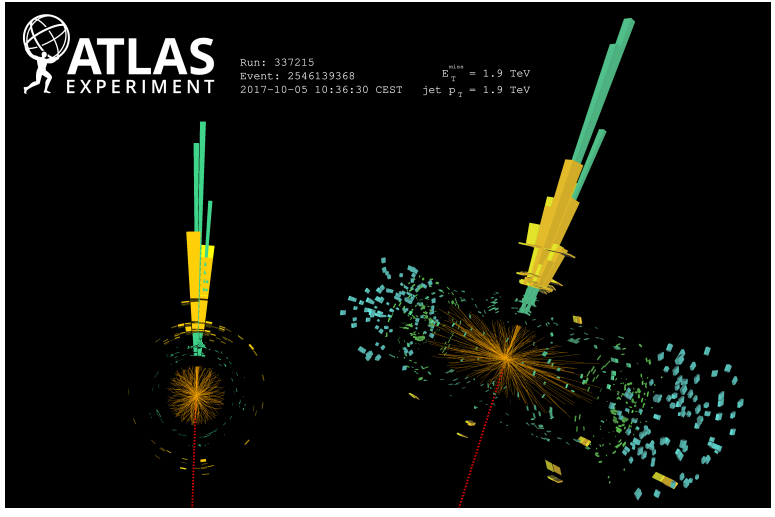
Mono-Jet Analysis

- Require at least one jet (E_T > 150 GeV) and E_T^{miss} > 200 GeV

- Enhanced sensitivity w.r.t. previous analyses
  (lower lepton p_T vetoes, τ and photon vetoes, lower jet and E_T^{miss} thresholds,
  improved theo. predictions for W/Z+jets [$NNLO_{QCD}$ + NLO_{EW}])

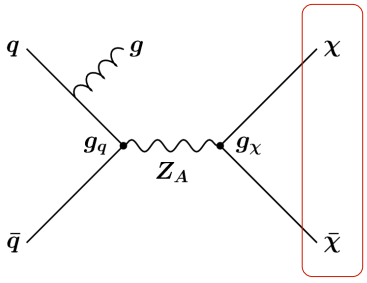
ATLAS-CONF-2020-048



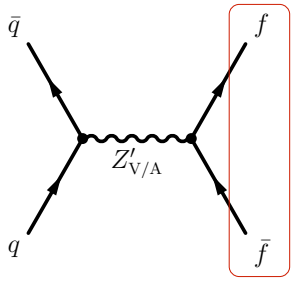


- Uncertainties at the level of a few percent
- Good agreement between data and SM expectations

Dark matter interpretation



Missing energy



Resonance

Model assumptions:

- Neutral, spin-1 particle acts as mediator
- DM assumed to be Dirac fermion

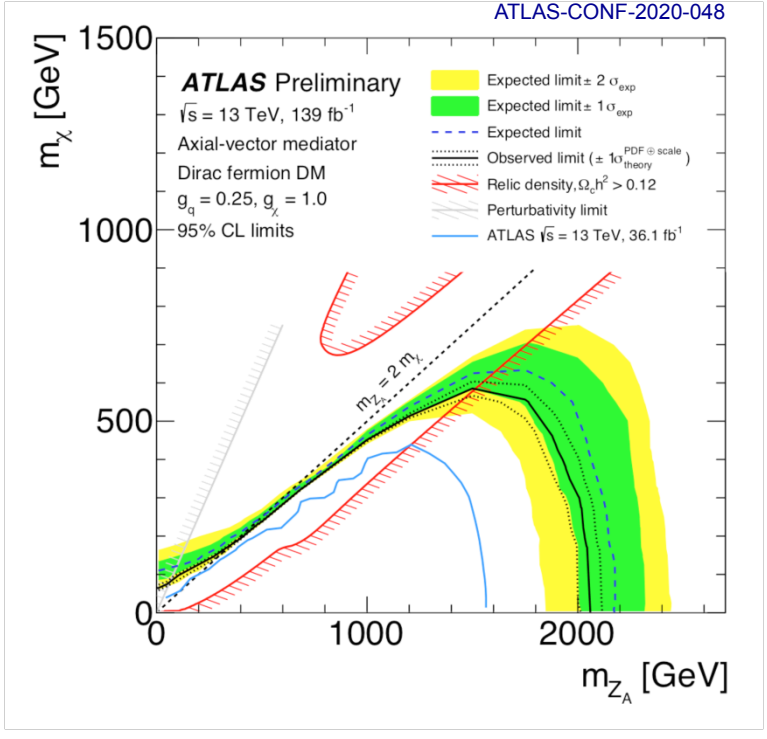
Five parameters:

- Masses of the mediator and DM particle
- g_l : coupling to all lepton-flavours
- g_X: coupling to DM
- g_q: flavour-universal coupling of Z' boson to all quarks

Signatures:

- **Mono: jet,** photon, W or Z, Higgs, top,..
- Resonances

ATLAS-CONF-2020-048



Axial-vector mediator

- Mediator masses up to 2 TeV excluded for low m_X (model dependent, here g_q = 0.25, g_x = 1.0)
- Significant improvement over previous limits

Summary

ICHEP 2020 ATLAS Physics Highlights:

- **Higgs boson profile**: consistent with Standard Model expectations

  - severe constraints on BSM contributions, e.g. BR (H → inv) < 9%
  - 2σ excess in search for H → μμ decays

- **Precision tests** in the Lepton Flavour sector and evidence for rare QCD process (tt tt production)

- Observation of the γγ → **WW** process, and of the γγ → **ℓℓ (p)** process with a **tagged forward proton** at the LHC

- More complex searches for BSM physics, e.g. mono-jet, SUSY

- The ATLAS Collaboration continues to exploit the rich Run-2 dataset …

  … and in parallel is preparing and looking forward to the exciting physics programme in the upcoming Run 3 and beyond

  https://atlas.cern/updates/atlas-news/summary-ichep-2020