Latest Results from ATLAS

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全国第十八届重味物理和CP破坏研讨会

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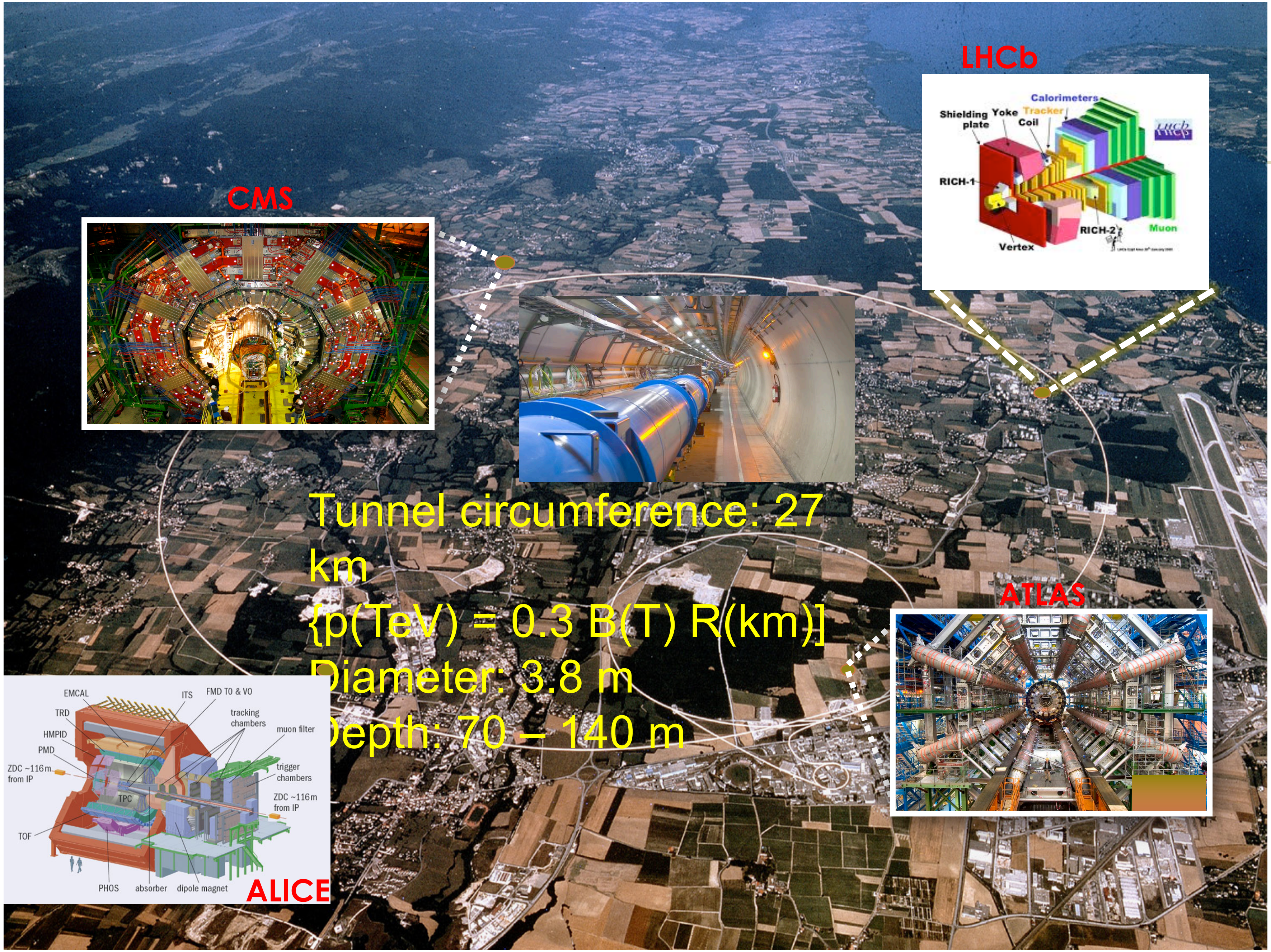
Experiments at Large Hadron Collider



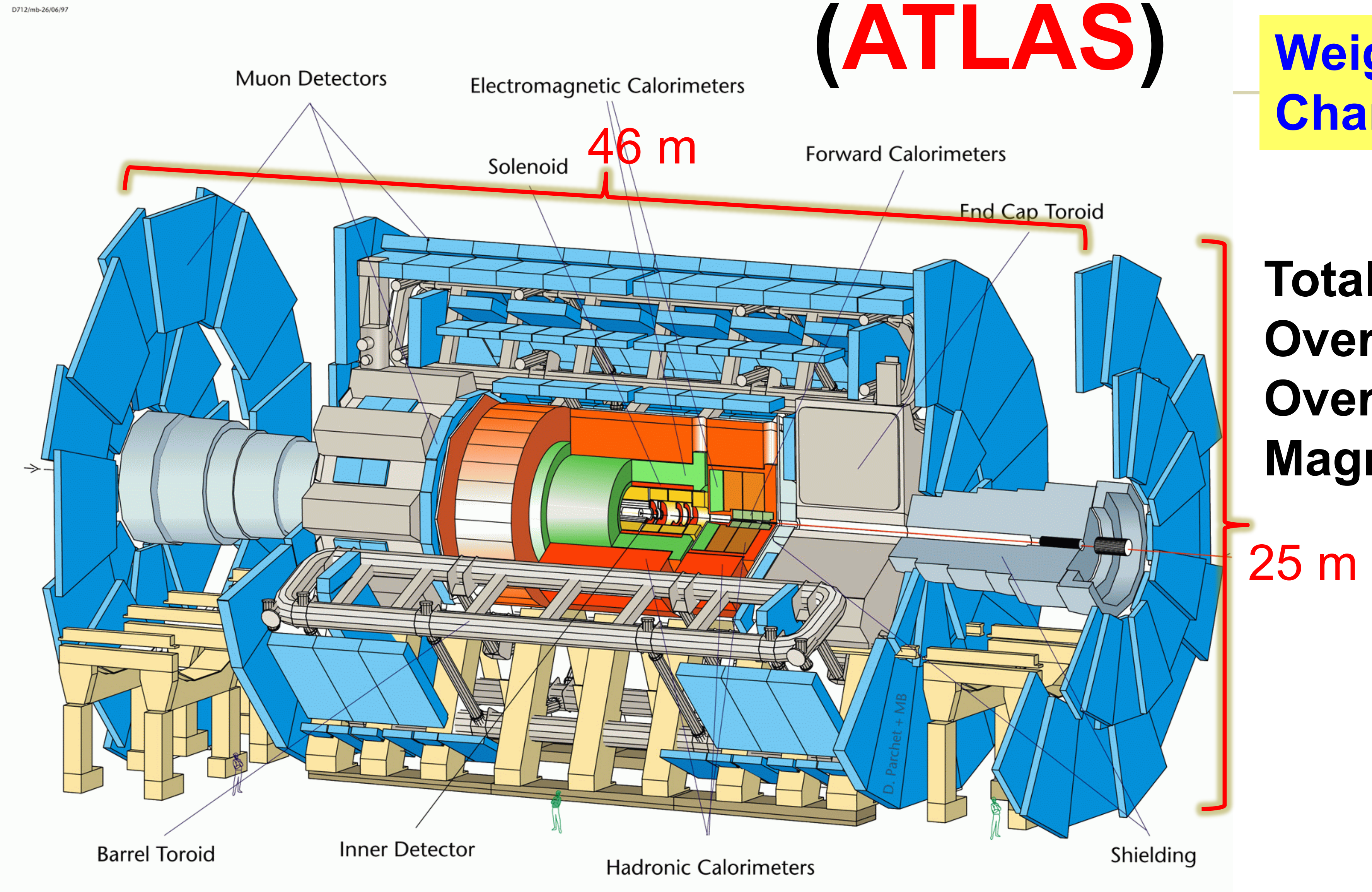
pp collider (also can collide heavy ion particles)

Run 1: 7, 8 TeV

Run 2: 13 TeV

Run 3: to start soon

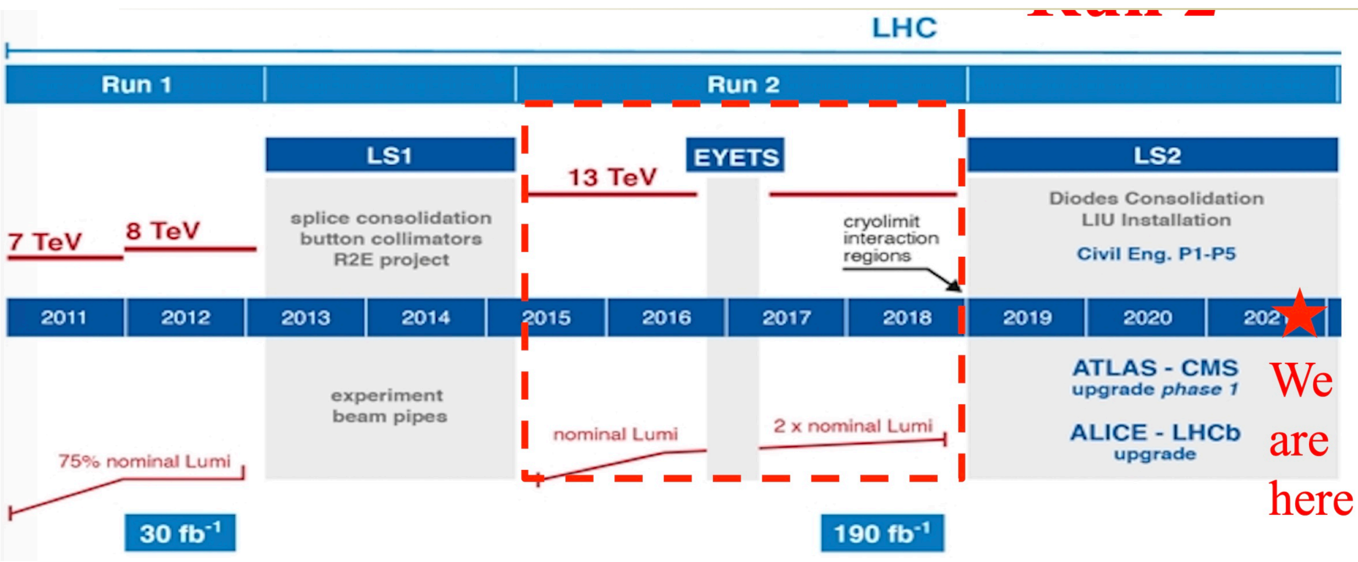
A Toroidal LHC ApparatuS (ATLAS)

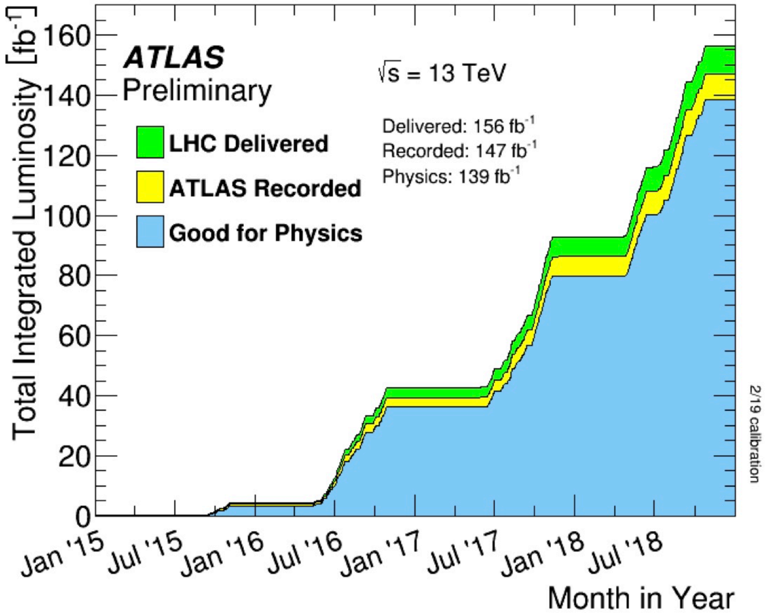


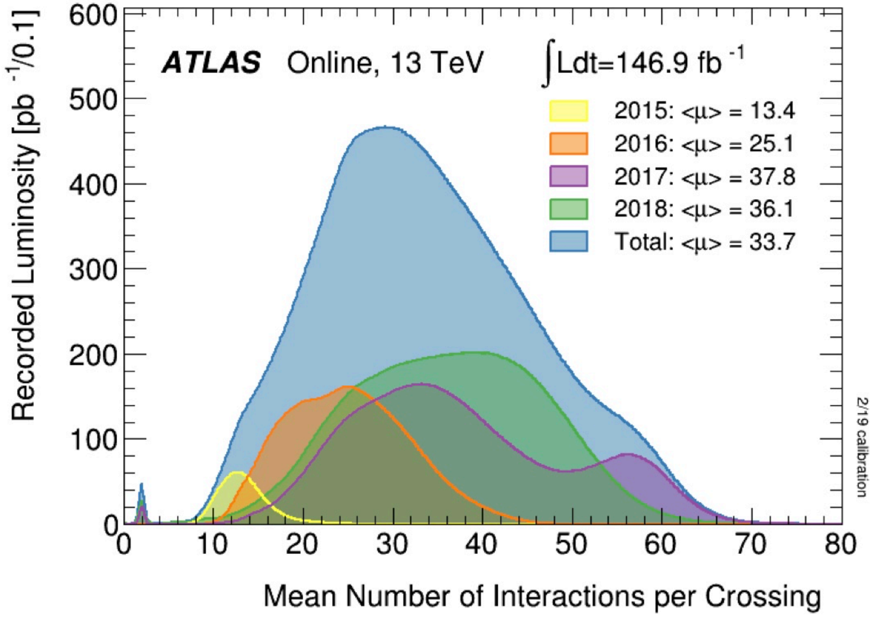
Weight : ~ 7000 tons
Channels: ~ 10^8

Total weight: 7900 T
Overall diameter: 25 m
Overall length: 46 m
Magnet filed: 2, 3-8 Tesla

ATLAS Run 2 Overview







- ✓ Run 2 at 13 TeV from year 2015 to 2018
  - ✓ 147 fb^{-1} pp collision data recorded. 139 fb^{-1} good for physics analysis (~95% efficiency)
  - ✓ Also heavy-ion collisions (Pb+Pb, p+Pb, Xe+Xe)
- ✓ Very good performance for object reconstruction. Major uncertainties for typical pT region (O(10)-O(100)GeV for leptons, O(100)-O(1000)GeV for jets)
  - ✓ Electron and muon identification < 1%, b-tagging < 2%, jet energy scale ~ 1% in central region

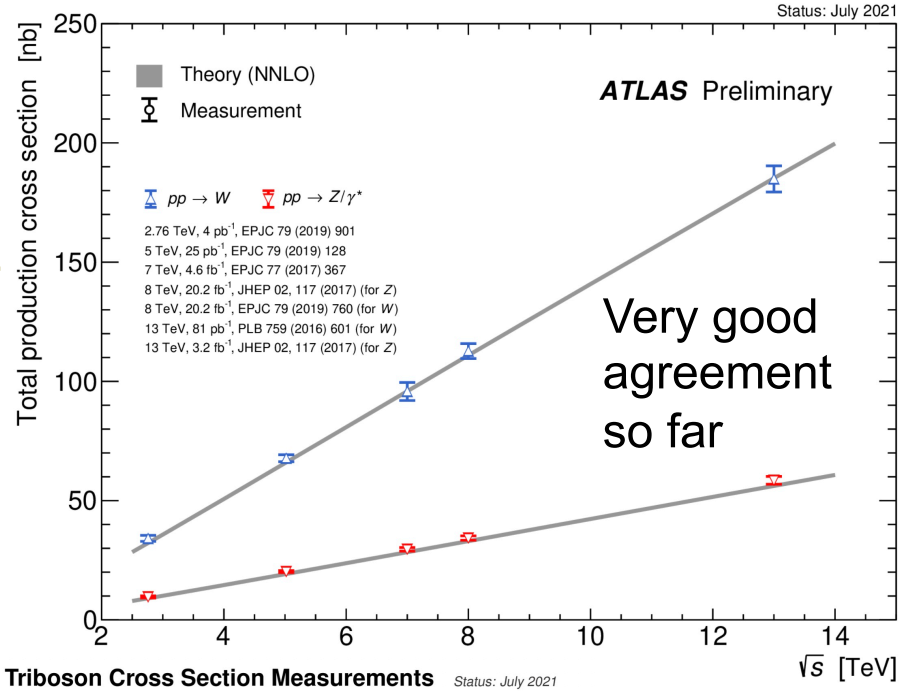
ATLAS Physics Results

- SM precision measurements and rare processes
- Higgs (and di-Higgs) measurements and searches
- Heavy flavor physics
- Searches for new physics beyond SM
- Heavy ion physics

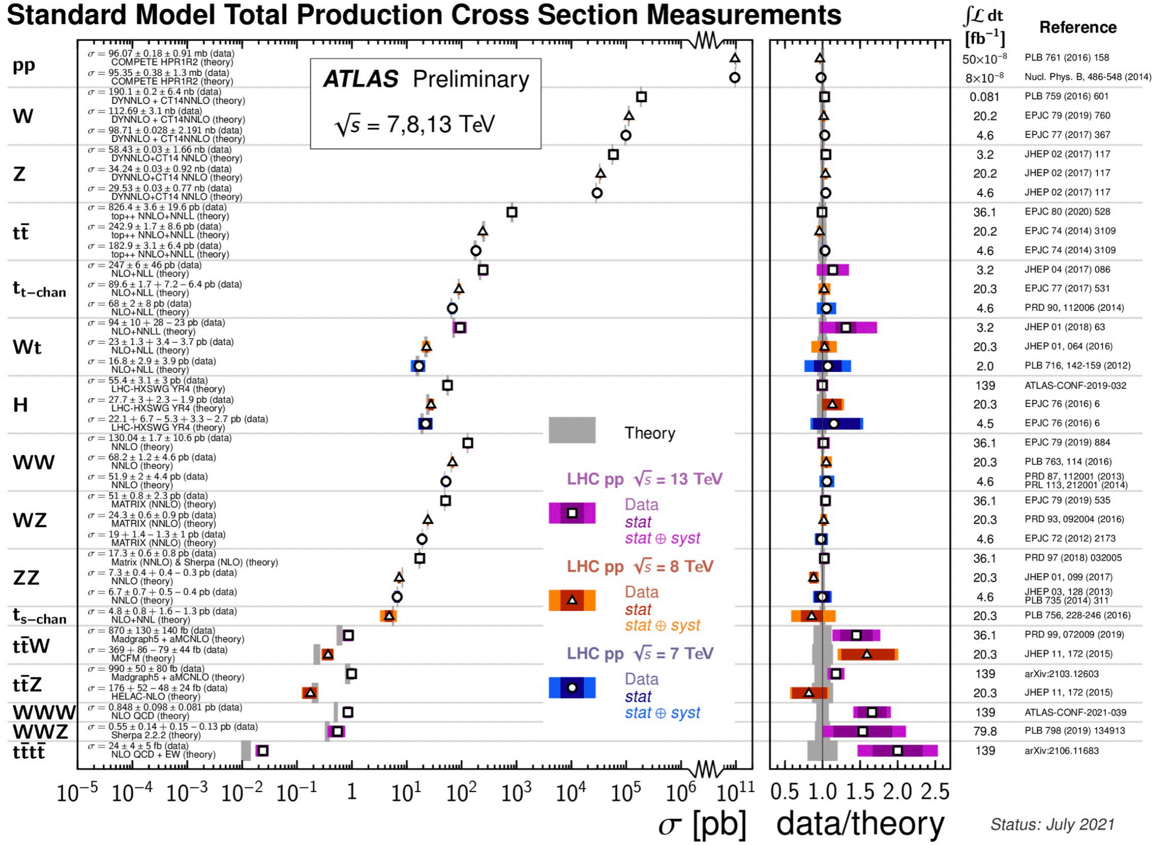
- Can only cover a few. Full lists are available here

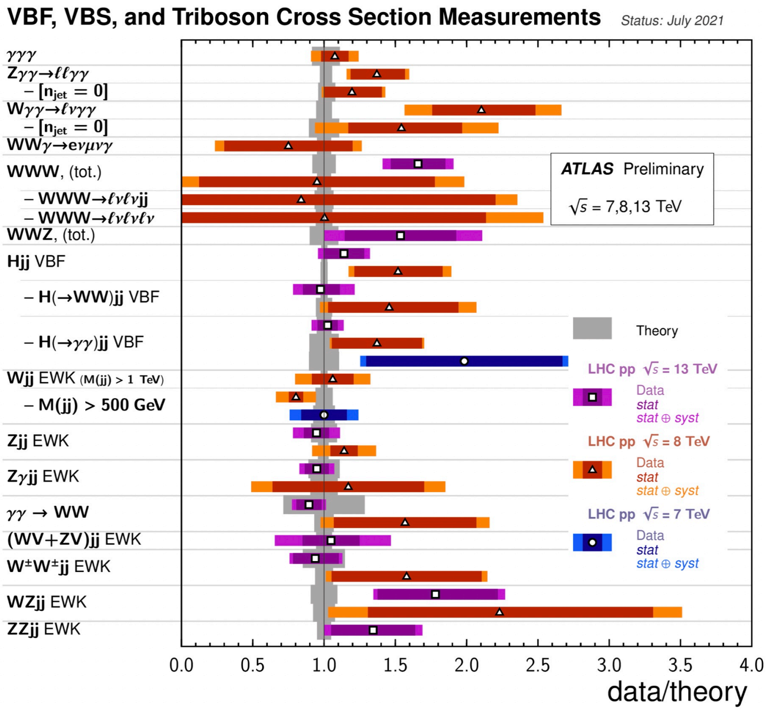
SM Measurements

- Key to test the SM in high energy frontier with high luminosity



Very good agreement so far



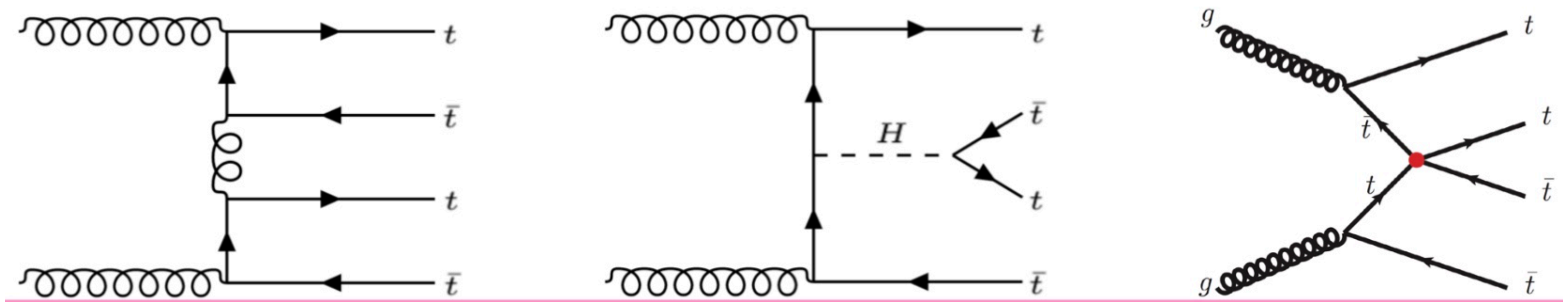


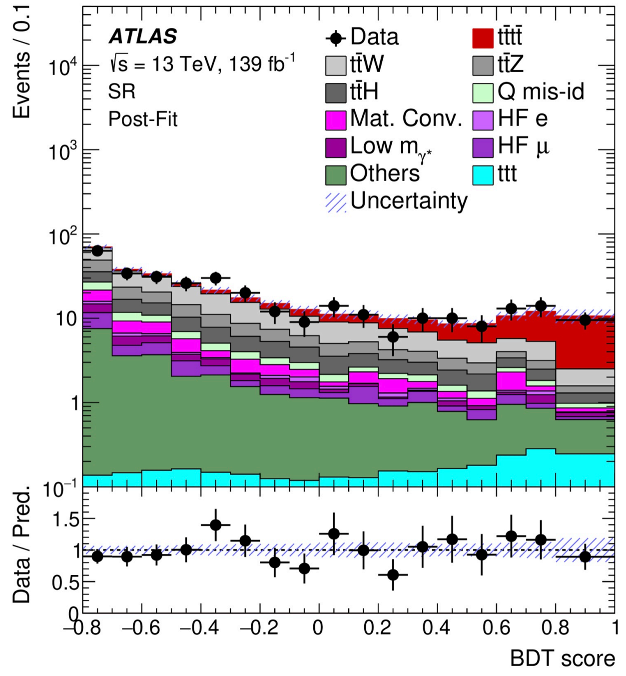
Starting to be able to probe rare SM processes like vector-boson scattering, triboson

Search for $t\bar{t}t\bar{t}$ production: Rare SM Process

Eur. Phys. J. C 80 (2020) 1085

- Sensitive to top Yukawa coupling with offshell Higgs
- Expect large contribution from BSM contributions





- Events selected in multi-lepton final states.
- MVA used with input features from jet multiplicity, jet flavor and event kinematics
- First evidence with 4.3σ
- Best fit signal strength: $\mu = 2.0 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst}) = 2.0\,^{+0.8}_{-0.6}.$

ATLAS-CONF-2021-039

Observation of WWW

- Triboson measurements directly probe the gauge boson self-coupling
- Any deviation would hint new physics at higher energy scale that is not accessible now
- Full Run 2 data used. Only events with 2 or 3 leptons are included (i.e. at least two Ws decay leptonically)

Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	**1.66 ± 0.28**

$$\sigma(pp \to WWW) = 850 \pm 100\ (\text{stat.}) \pm 80\ (\text{syst.})\ \text{fb.}$$

CERN Courier, November/December 2021

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ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

ATLAS

First observation of WWW production

The W boson was first directly observed in 1983 using the Super Proton Synchrotron proton–antiproton collider at CERN, resulting in a Nobel Prize the following year. Almost four decades later, the ATLAS collaboration has observed the simultaneous production of three W bosons for the first time.

The study of multi-boson processes involving boson self-interactions provides unique insight into the nature of electroweak symmetry breaking and therefore enables rigorous tests of the Standard Model (SM). Likewise, deviations from SM predictions could indicate hints of beyond-Standard Model physics through, for example, interactions that exist at energies beyond the current reach of the LHC which avoid the requirement to create the particle directly. These effects could potentially result from interactions with virtual particles in loops or new amplitudes generated by a tree-level exchange. In an effective field theory (EFT) approach, the possible new interactions are represented by operator terms with anomalous triple and quartic gauge couplings, both of which are present in WWW production.

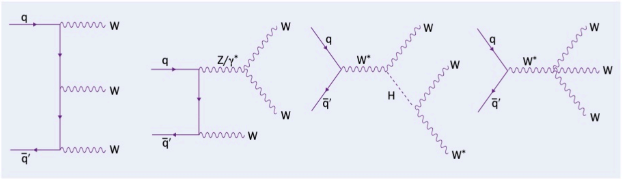


Fig. 1. *Example Feynman diagrams for the leading-order production of WWW events.*

Signal events

At leading order, the WWW signal is produced through the different mechanisms presented in the Feynman diagrams shown in figure 1. While there are many decay modes, ATLAS used four final-state channels where the signal-to-background ratio is big enough to observe the signal. The first three channels result from the decay of two of the Ws into charged lepton–neutrino pairs, with the same electric-charge sign of the charged leptons, and

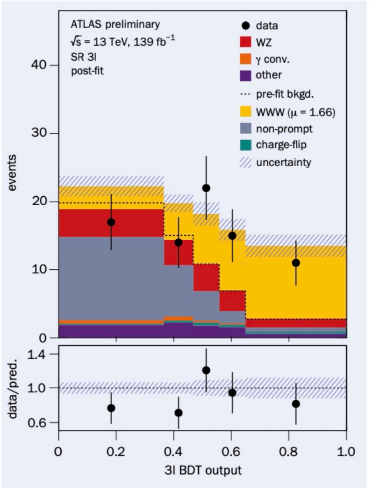
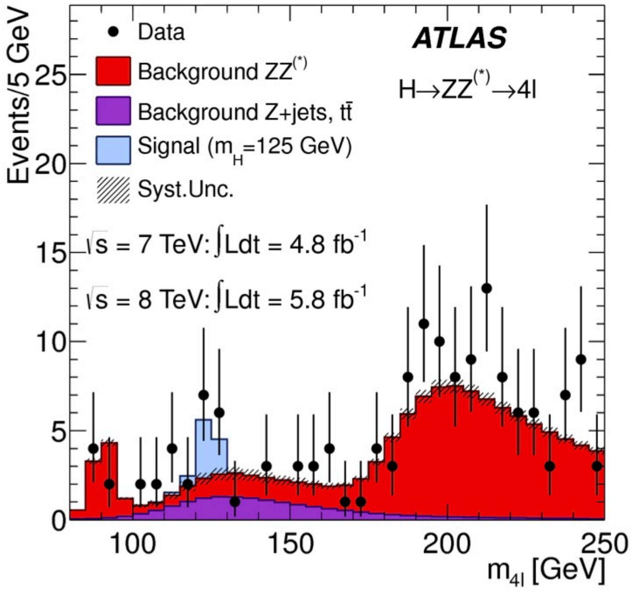


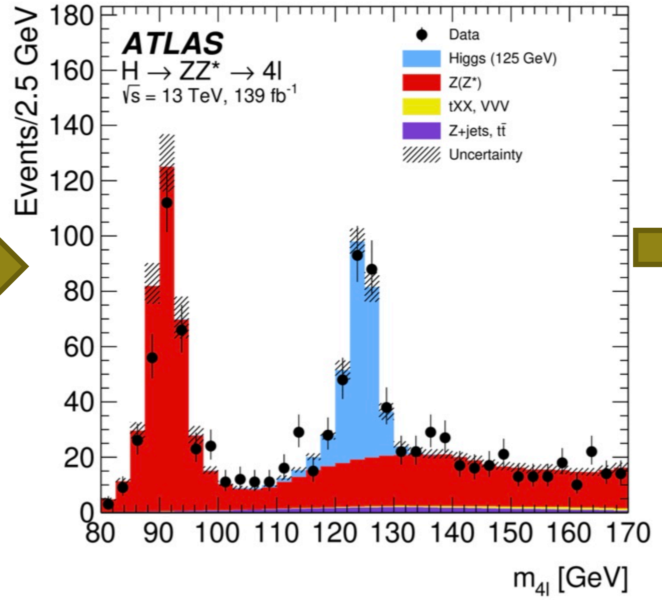
Fig. 2. *The BDT distribution of the WWW three-lepton channel.*

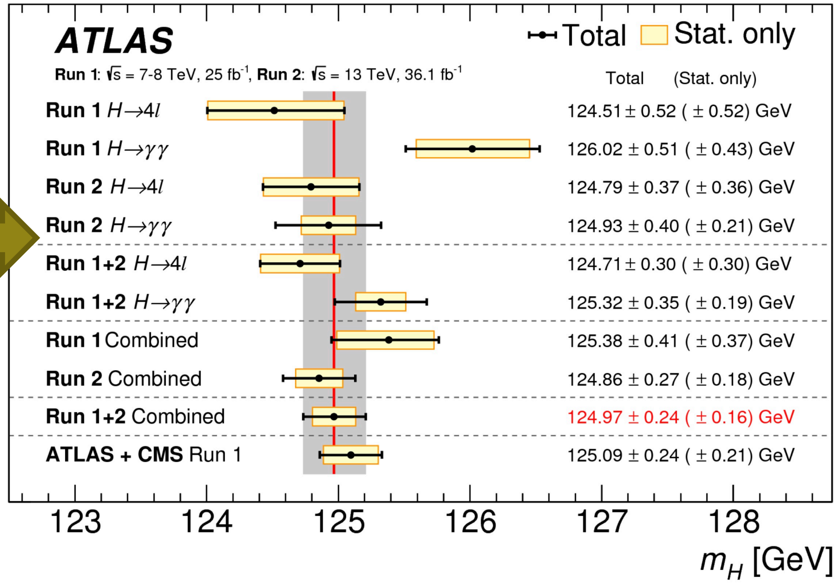
and three normalisation factors for the dominant WZ background. The BDT distributions were fitted in the four signal regions simultaneously with the trilepton invariant mass distribution in three WZ control regions (WZ plus 0, 1, ≥ 2 jets). The resulting BDT distribution for the 3l channel is shown in figure 2.

The large event samples (139 fb^{-1}) provided by the full Run-2 data set, the implementation of multivariate techniques, and an improved ATLAS detector and reconstruction performance enabled the observation and the cross-section measurement of this rare process. The observed (expected) significance of the measurement is 8.2 (5.4) standard deviations compared to the hypothesis with no WWW signal. The cross section is measured to be 850 ± 100 (stat.) ± 80 (syst.) fb, as derived from the observed signal strength (the ratio of measured to predicted yields) of 1.66 ± 0.28. The observed signal significance is within 2.4σ of the SM prediction. The full Run-3 data set is anticipated to more than double the number of signal events and will enable a more precise measurement of WWW production. Higher

Higgs







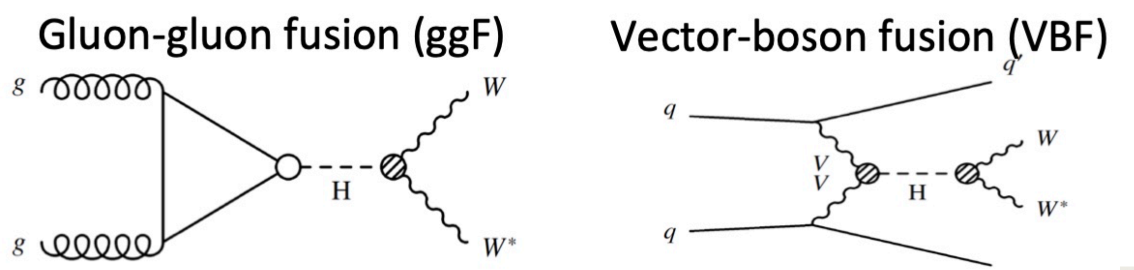
Higgs-like particle discovered at the LHC in Run 1

Since then, the major focuses have been on

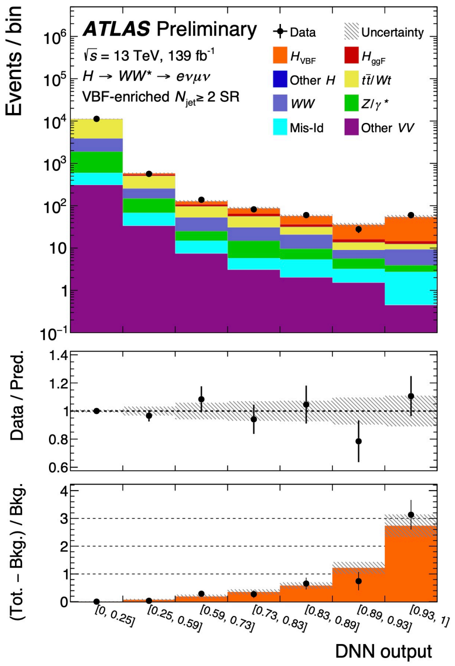
- ✓ Observation in major production (ggF, VBF, VH, ttH) and decay (WW, ZZ, γγ, bb/ττ) channels
- ✓ Searches in the rare decay channels (μμ/cc)
- ✓ Improved coupling and differential cross-section measurements
- ✓ Searches for new physics using Higgs boson (LFV, dark matter .etc)

Higgs → WW

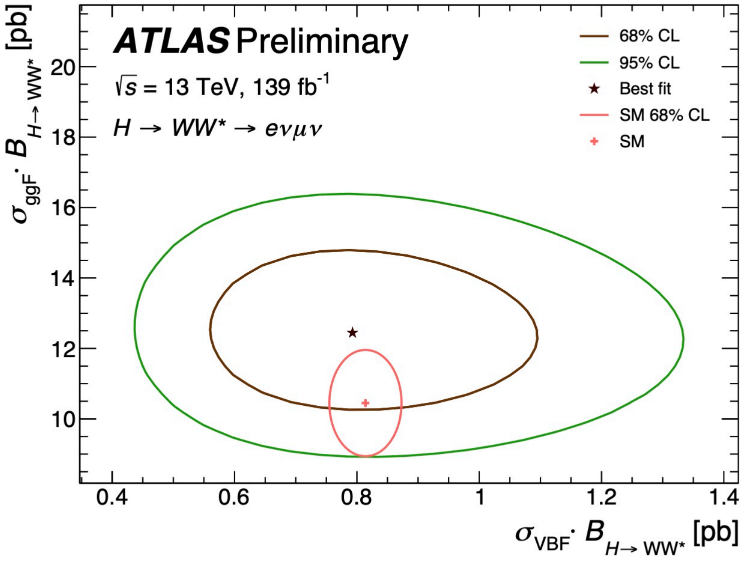
[ATLAS-CONF-2021-014]

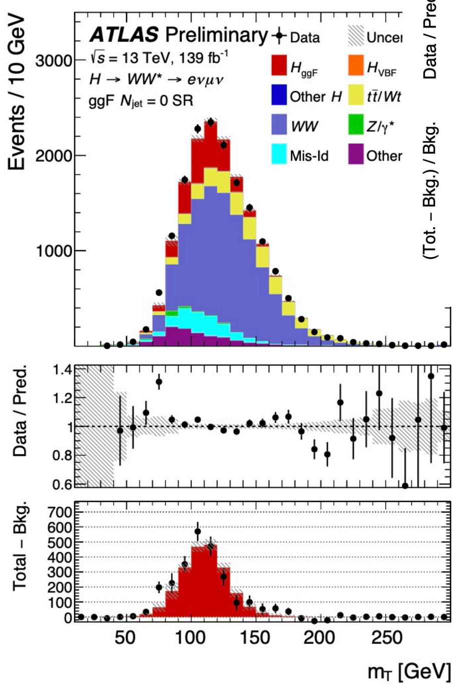


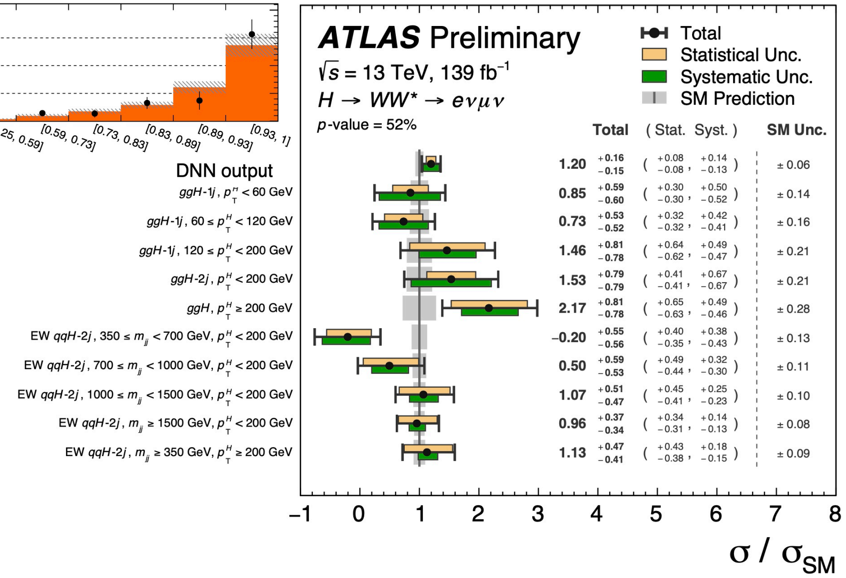
- Measured in different production modes
  - ggF: m_T used as final discriminant
  - VBF: 2 forward jets with large m_{jj} and dY_{jj}. DNN used as final discriminant
- Events are split into different jet multiplicity categories



- ✓ Cross section measured to 12% (22%) precision in the ggF (VBF) mode
- ✓ VBF observed at 6.6σ level



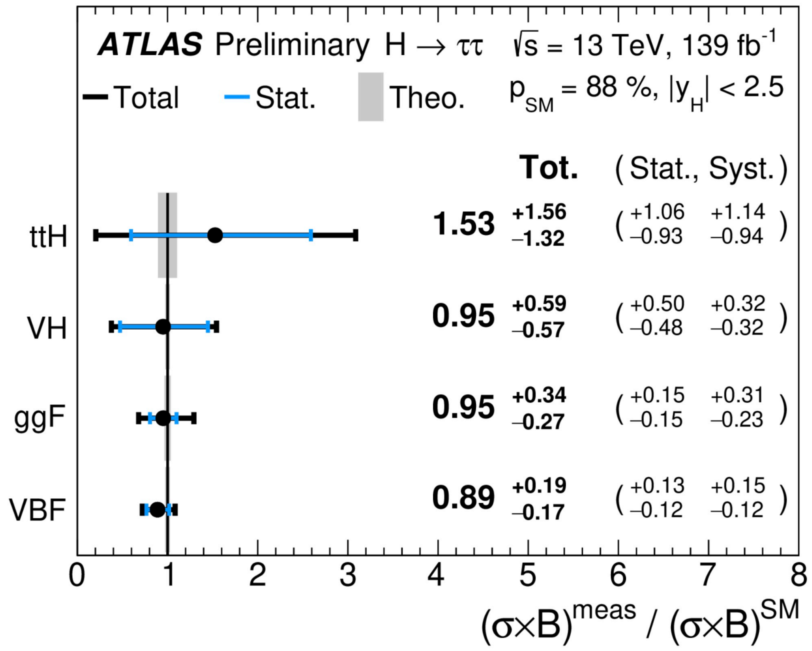


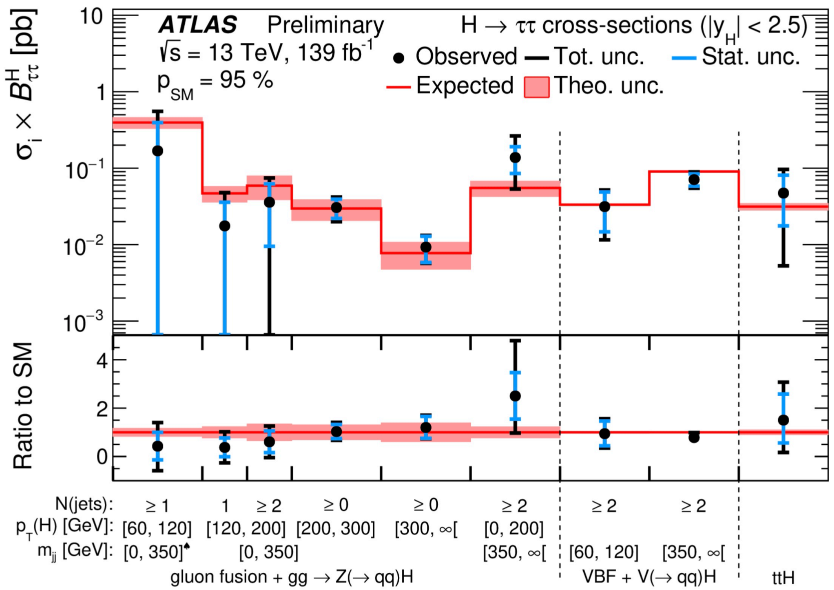


H → ττ

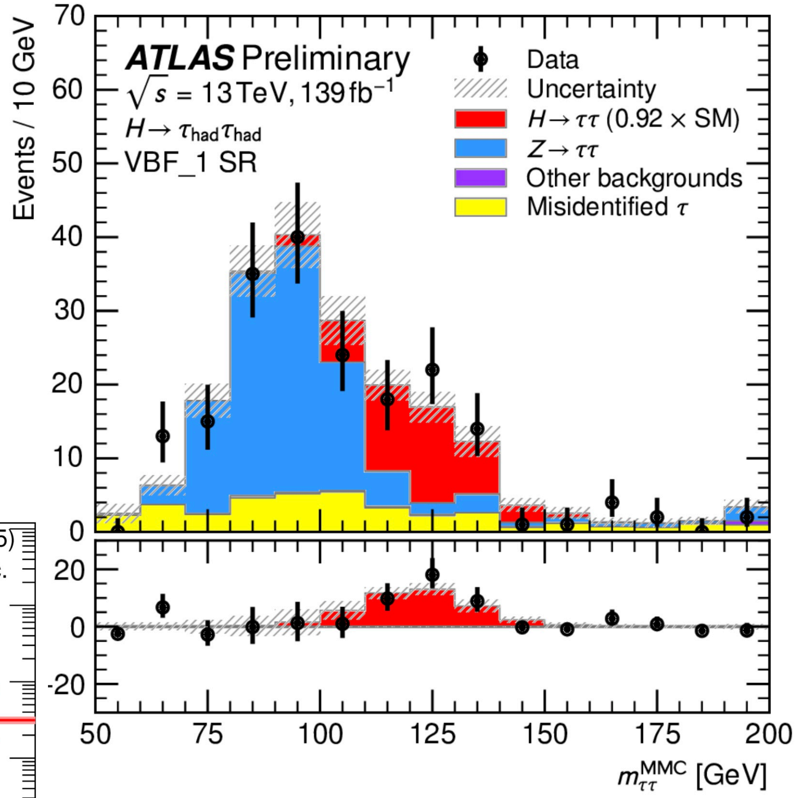
ATLAS-CONF-2021-044

- Relative high BR (~6.3%) allows to study Yukawa coupling with large statistic, in all four production modes
- Studies done in the fully(semi) ττ decay and eμ channels





First VBF H→ ττ observation with 5.3σ

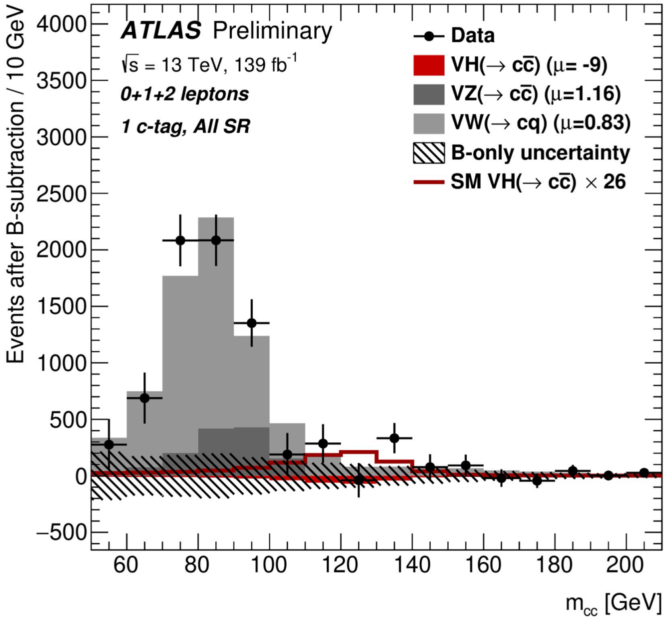


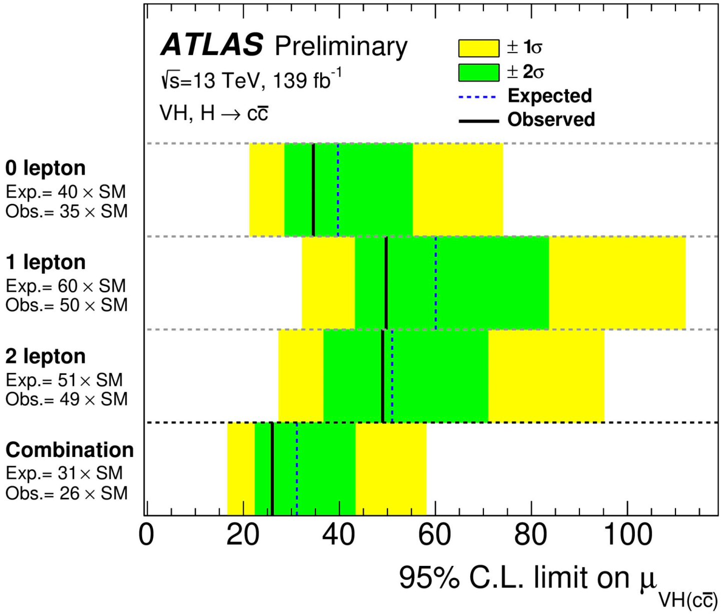
Cross section measured in 9 different STXS bins

ATLAS-CONF-2021-021

Searches for H → cc

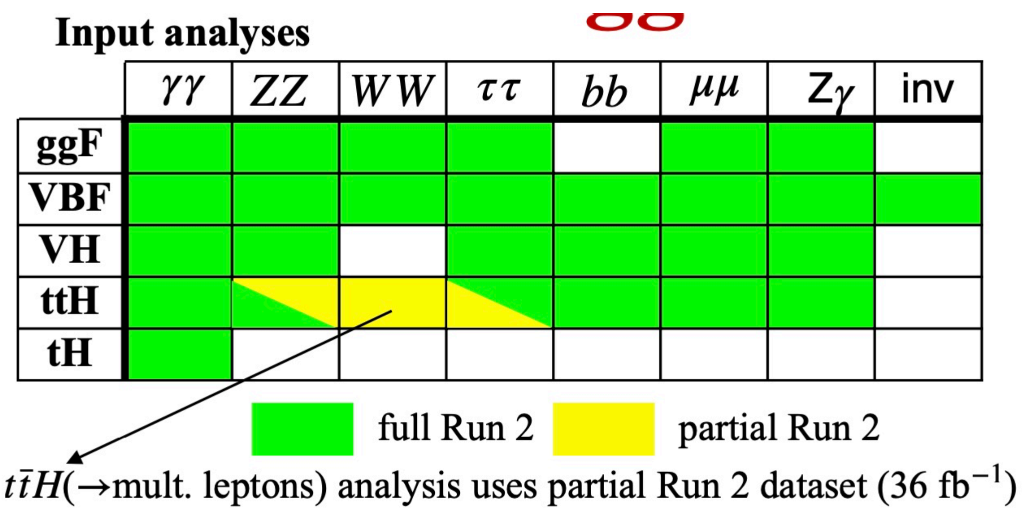
- Try to probe Higgs couplings to 2nd generation fermions
- Extremely difficult at hadron collider
  - Small BR ~2.9%, and large background
  - c-tagging is very challenging
- Developed dedicated c-tagger
  - To select ”intermediate” lifetime c hadrons between b and light flavor
  - 27% efficiency for c, 8% for b, 1.6% for light
- Searches done in VH channel with either large MET or 1/2 leptons



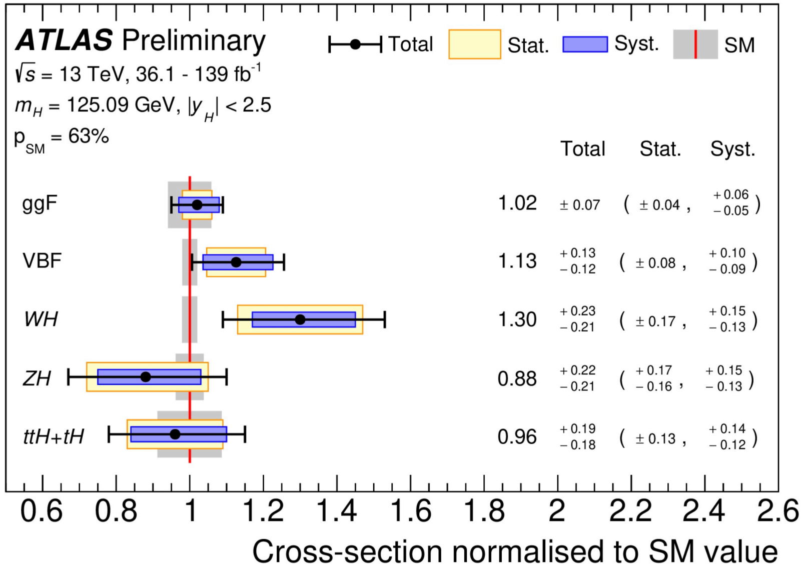


ATLAS-CONF-2021-053/

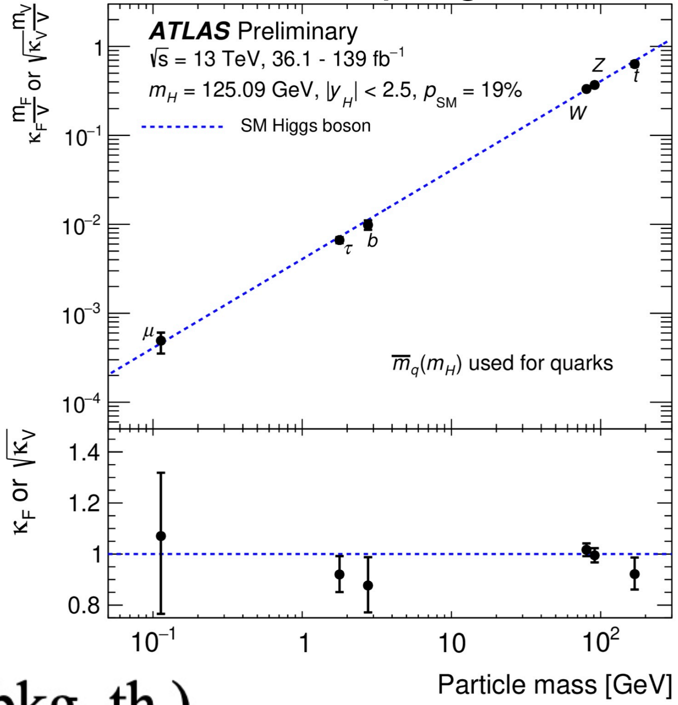
Higgs Combination



Production cross section



Coupling



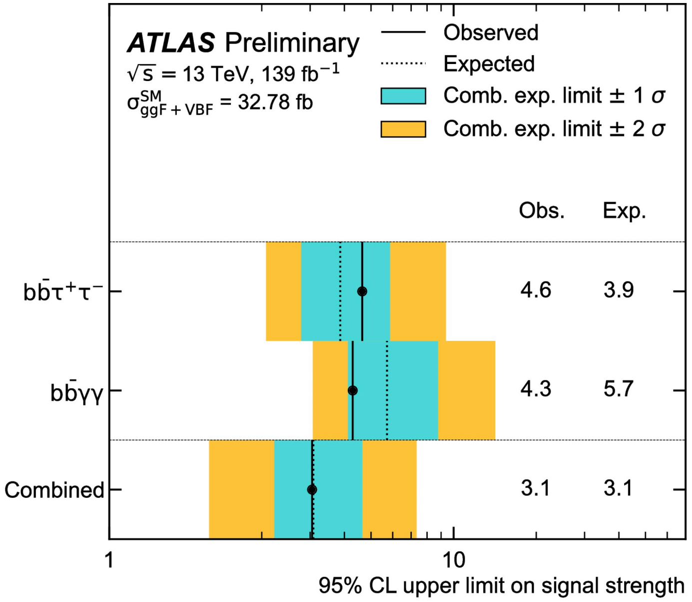
$$\mu = 1.06 \pm 0.06 = 1.06 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.})$$

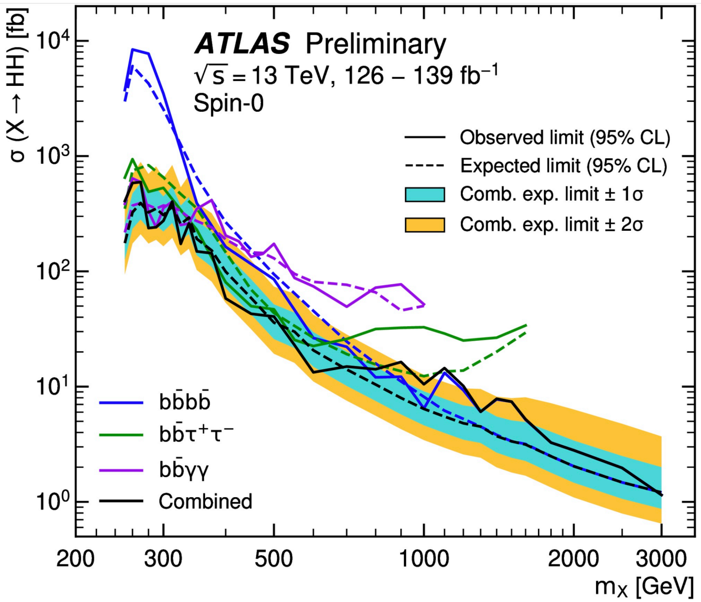
Theoretical uncertainty starts to dominant

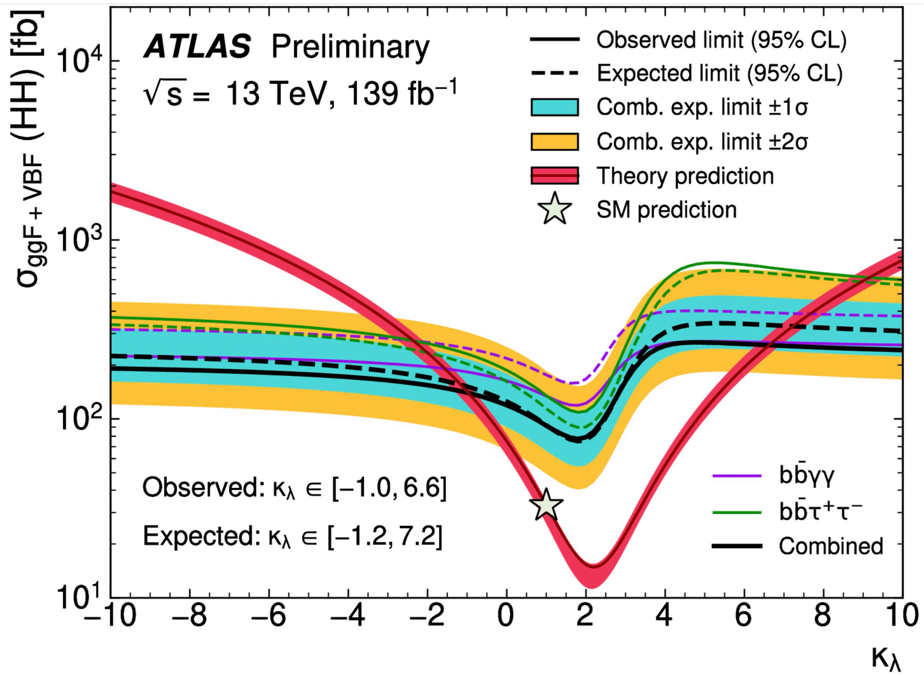
ATLAS-CONF-2021-052/

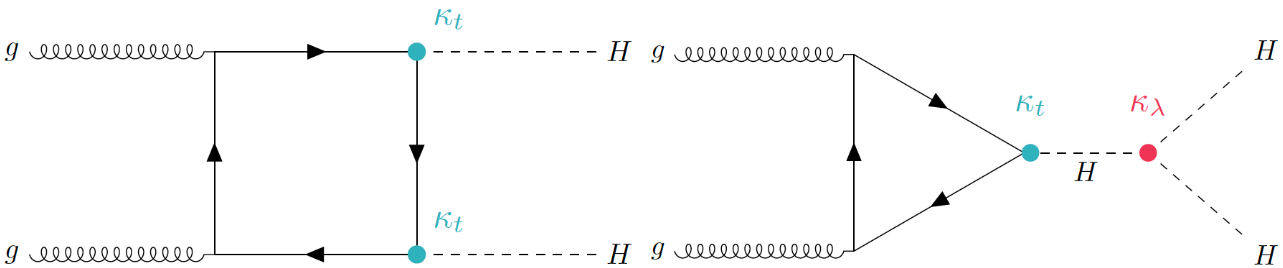
Di-Higgs Combination

- Direct probe of the Higgs self-coupling, as well as searching for new physics decays to HH in high mass.
- Combined using three channels
  - Resonant & non-resonant bbγγ: ATLAS-CONF-2021-016
  - Resonant & non-resonant bbττ: ATLAS-CONF-2021-030
  - Resonant bbbb: ATLAS-CONF-2021-035



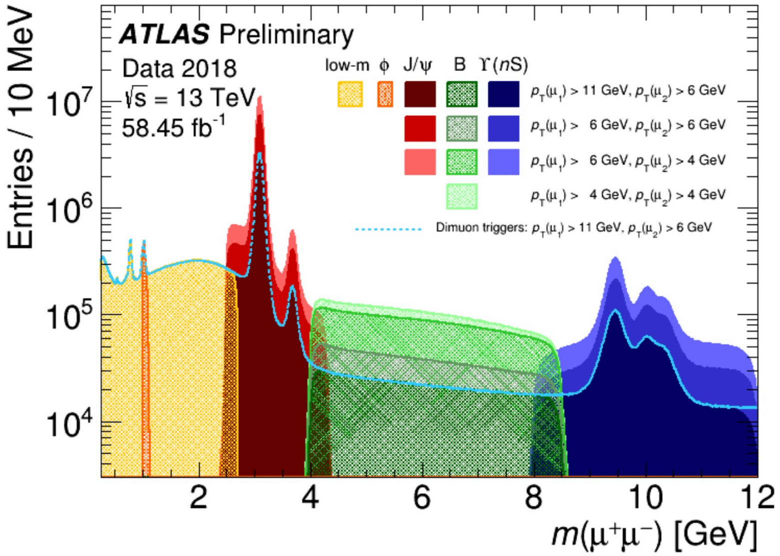




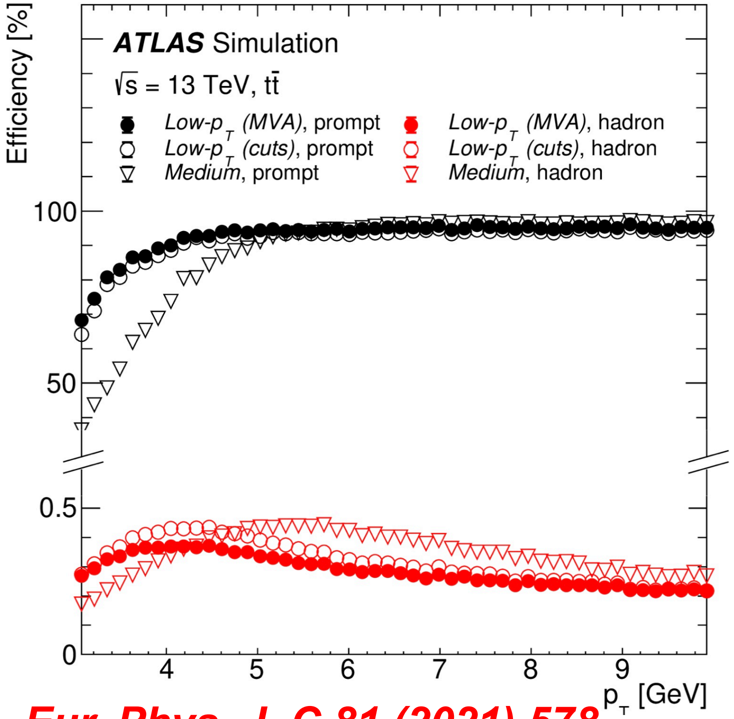


B Physics at ATLAS

- Possible deviations from SM in the B-related decays have captured more interest
- ATLAS has access to B, Bs, Bc, Λ_b, Y etc. Typical limitations are triggers, reconstruction and identifications etc.
- Due to experimental difficulties, mostly focus on muon final states
  - Typical triggers: di-muons with pT thresholds at 4, 6 and 11 GeV. Possible with some event topology cuts (dimuon mass, angular etc.)
  - In 2018, a di-electron high-level trigger has been implemented and being analyzed now
  - Improved muon identification down to 3 GeV. Machine learning widely used.



"Trigger" level di-muon mass distributions. Basic muon quality applied.



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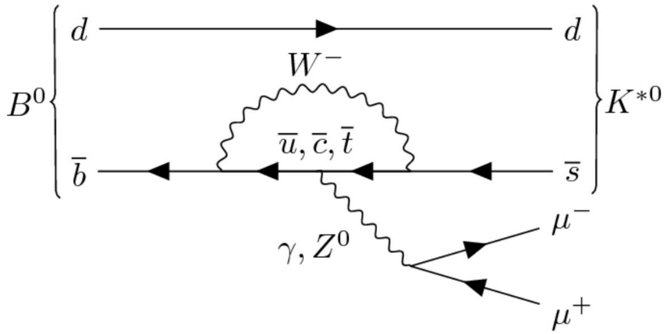
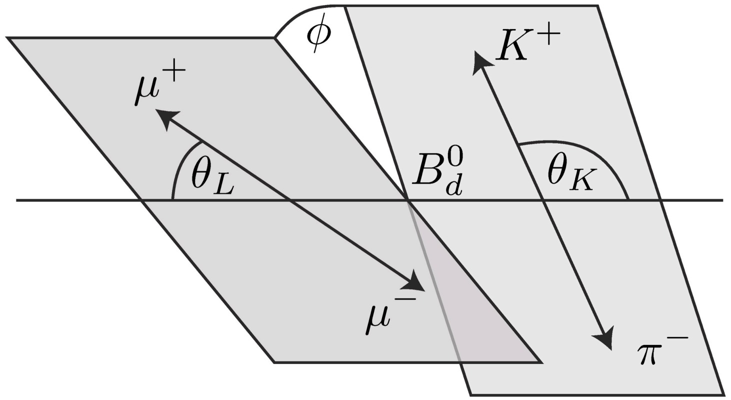
JHEP 10 (2018) 047

$B^0 \rightarrow K^*\mu\mu$ Angular Analysis

- Angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams
- Allows measuring a large set of angular parameters sensitive to Wilson coefficients
- Decays are described by three angular variables (θ_L, θ_K and ϕ) and dimuon mass squared (q^2)
- The angular distributions are measured in different q^2 bins
- LHCb reports a 3.4σ deviation from the SM

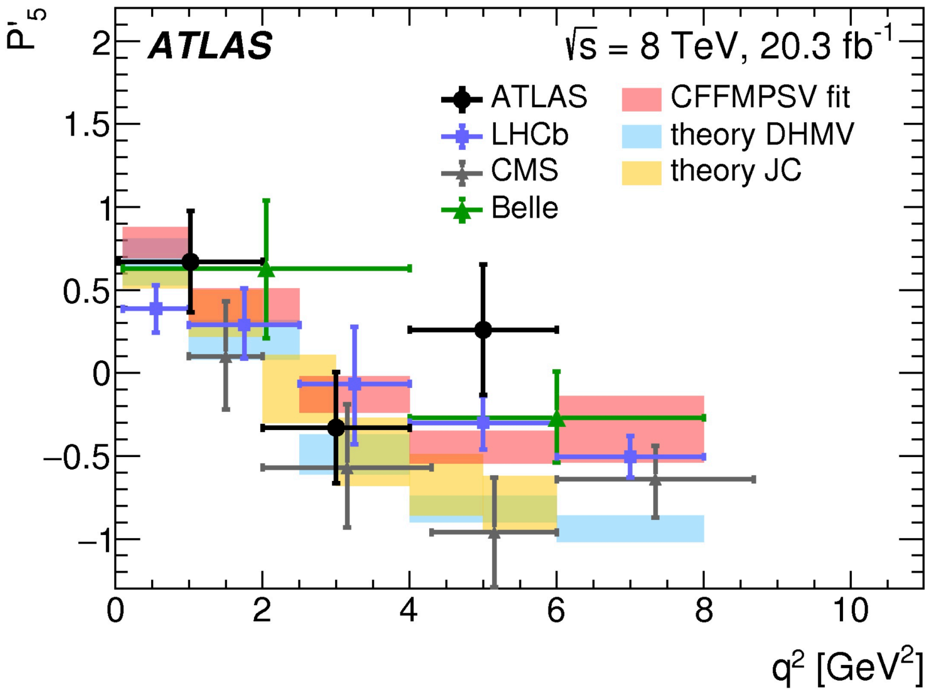




K*μμ Angular Analysis

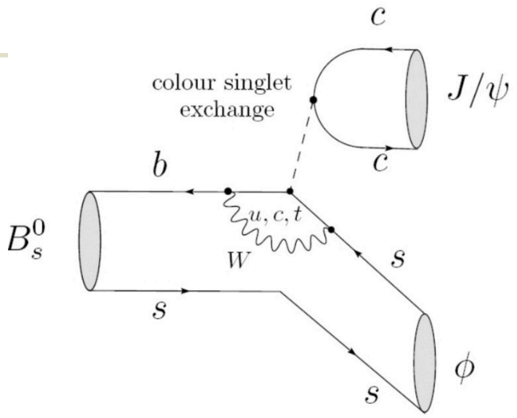
- Run 1 data at 8 TeV, 20.3 fb^{-1}. Selected with muon triggers starting at 4 GeV
- In total 787 events were selected in the $q^2 < 6$ GeV^2 region
- Extended unbinned maximum likelihood fits in each of the fit variants in each q^2 bin to extract FL and S(P) parameters
  - first fit of the invariant mass distributions
  - then fit of angular distributions
- Results are compatible with predictions
- Largest deviation seen in P'5 (2.7σ) between 4 to 6 GeV^2

q^2 [GeV^2]	n_{signal}	$n_{\text{background}}$
[0.04, 2.0]	128 ± 22	122 ± 22
[2.0, 4.0]	106 ± 23	113 ± 23
[4.0, 6.0]	114 ± 24	204 ± 26
[0.04, 4.0]	236 ± 31	233 ± 32
[1.1, 6.0]	275 ± 35	363 ± 36
[0.04, 6.0]	342 ± 39	445 ± 40

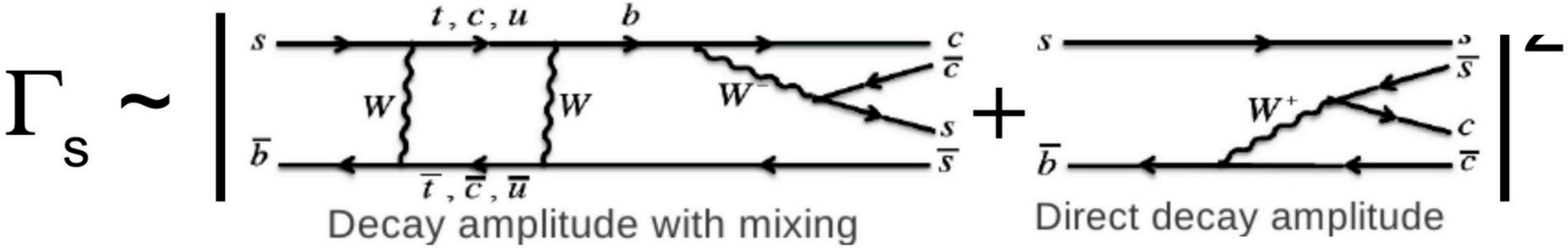


CP-violating phase φ_s in Bs → J/ψφ

Eur. Phys. J. C 81 (2021) 342



- Parameters of the B_s system:
  - Mixing → Decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_S$
  - $\Delta\Gamma_s = 0.087 \pm 0.021\ \mathrm{ps}^{-1}$ in the SM *[arXiv:1102.4274]*

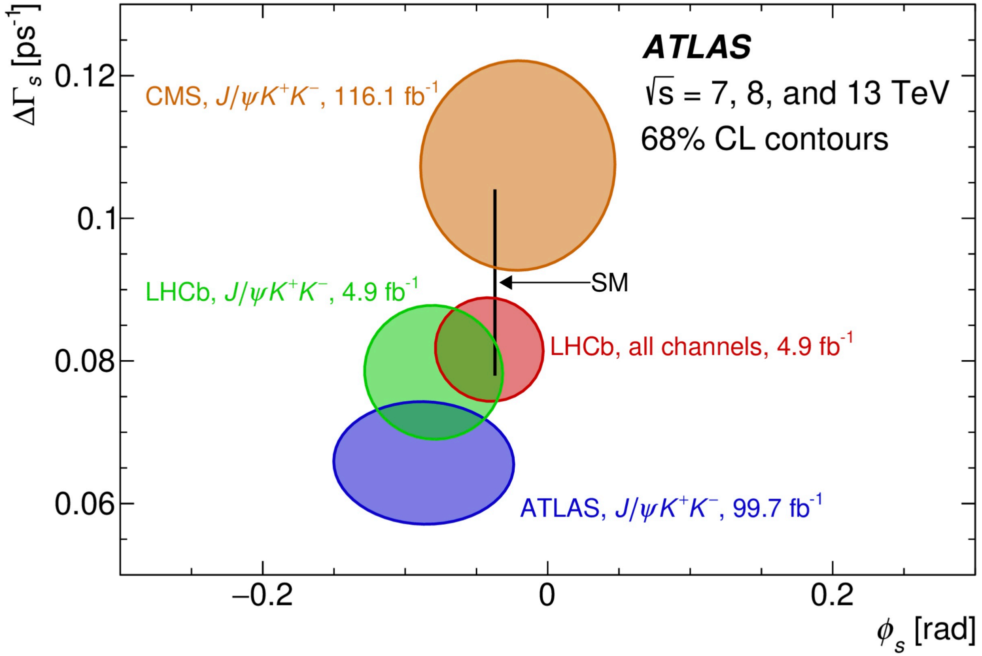


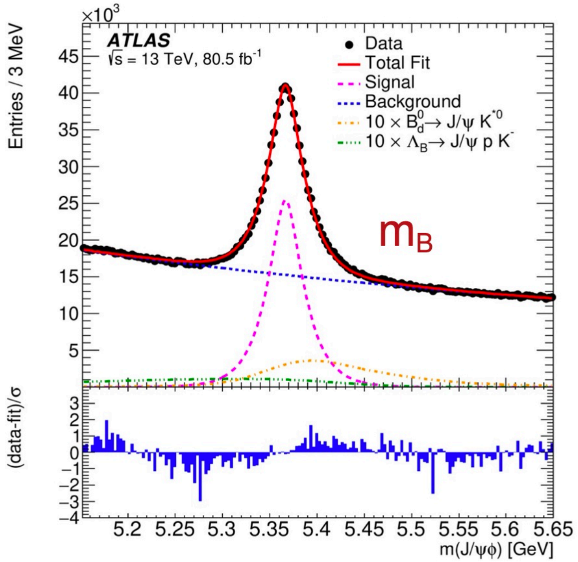
  - CPV phase φ_s → weak phase between mixing and b → ccs decay
  - $\varphi_s = -2\beta_s$ with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$
  - SM: $-2\beta_s = -0.0363 \pm 0.0016$ *[arXiv:1106.4041]*, 0.0370 ± 0.0010 *[UTfit18]*

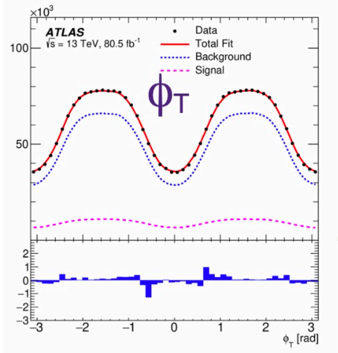
Slides taken from
Marcella Bona

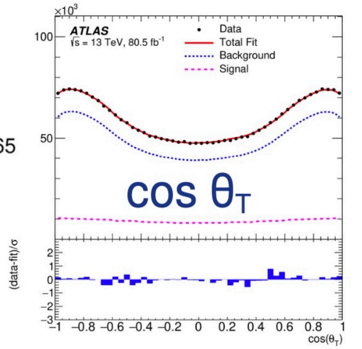
CP-violating phase φ_s in Bs → J/ψφ

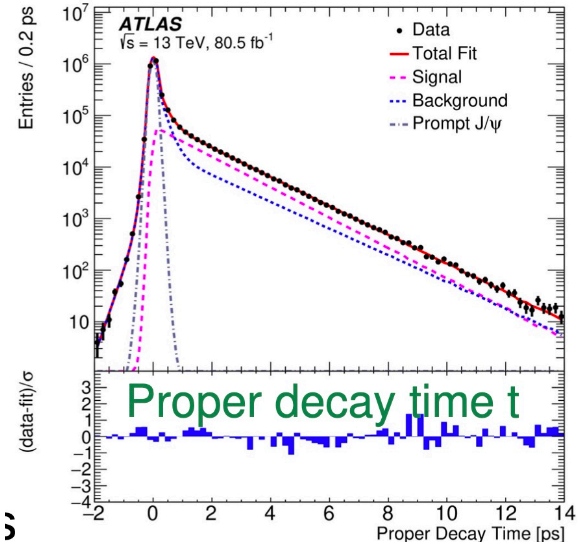
- Unbinned maximum-likelihood fit to extract the physics parameters
- Fitted variables
  - mass mB, proper decay time t and their error, tagging probability, angular

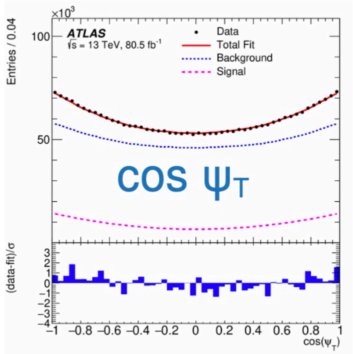












$$
\begin{aligned}
\phi_s &= -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.) rad} \\
\Delta\Gamma_s &= 0.0657 \pm 0.0043 \text{ (stat.)} \pm 0.0037 \text{ (syst.) ps}^{-1} \\
\Gamma_s &= 0.6703 \pm 0.0014 \text{ (stat.)} \pm 0.0018 \text{ (syst.) ps}^{-1}
\end{aligned}
$$

PhysRevLett.127.141801

bsll Contact Interaction

- Inspired by the B-meson decay anomalies, a four-fermion contact interaction between two quarks (b, s) and two leptons (ee or μμ) is used as a benchmark signal model
- Characterized by energy scale (Λ) and coupling (g_*)

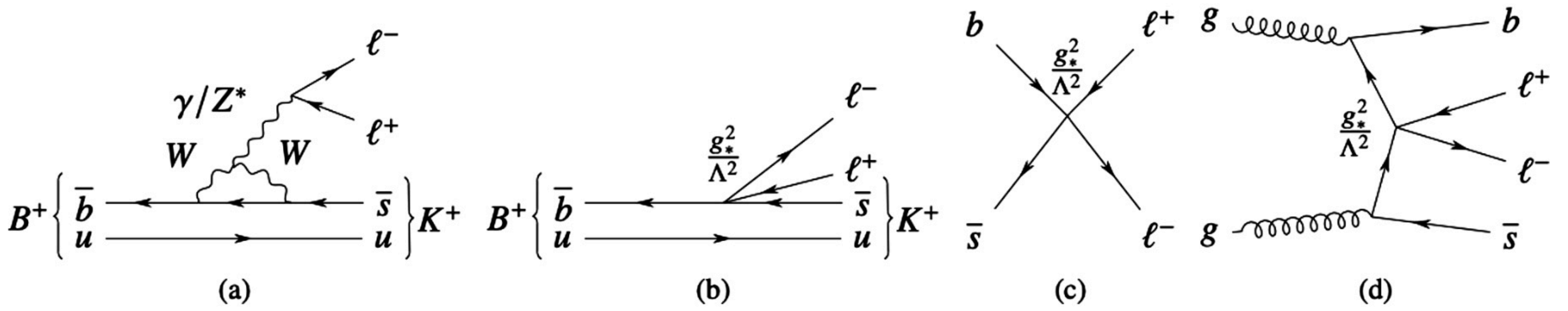
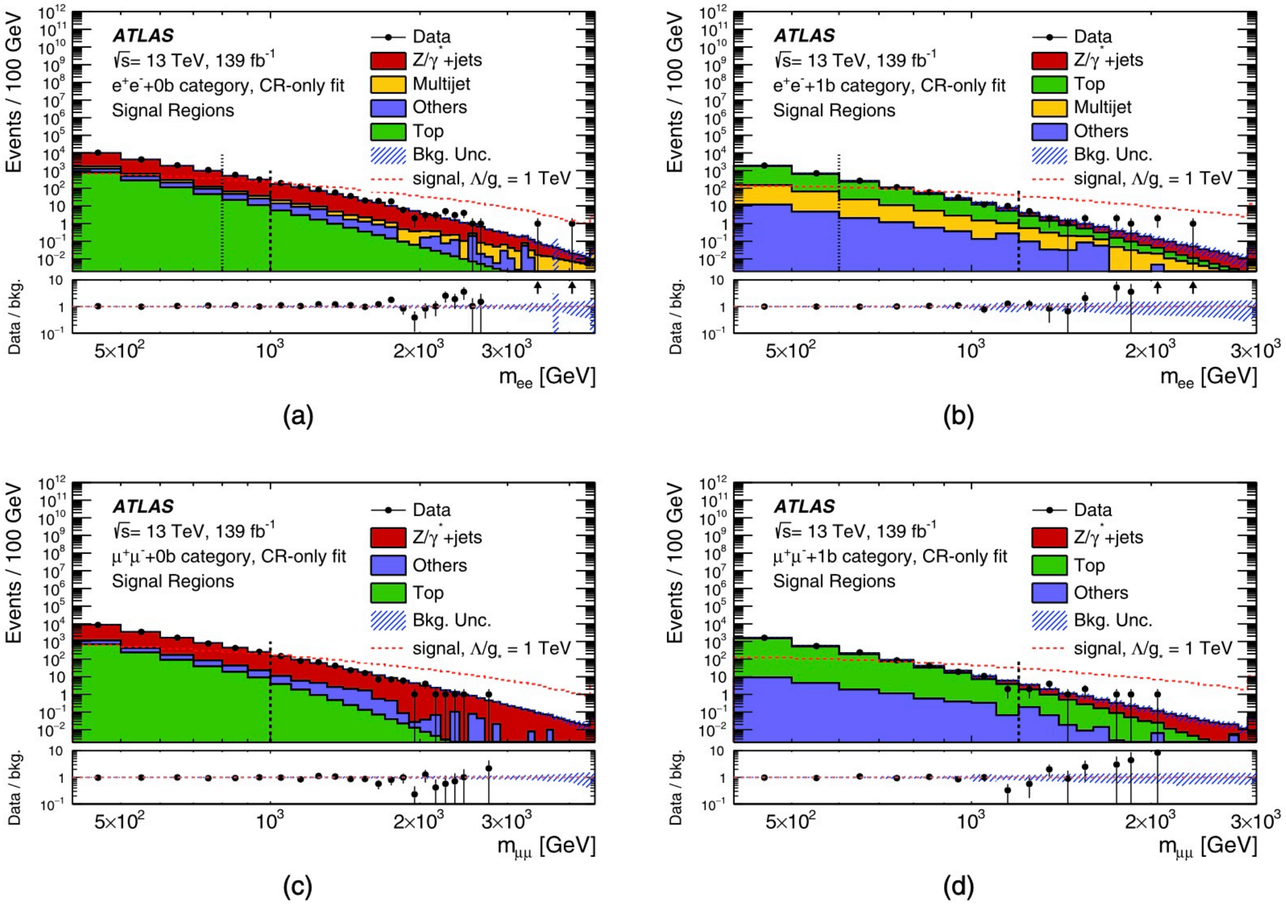


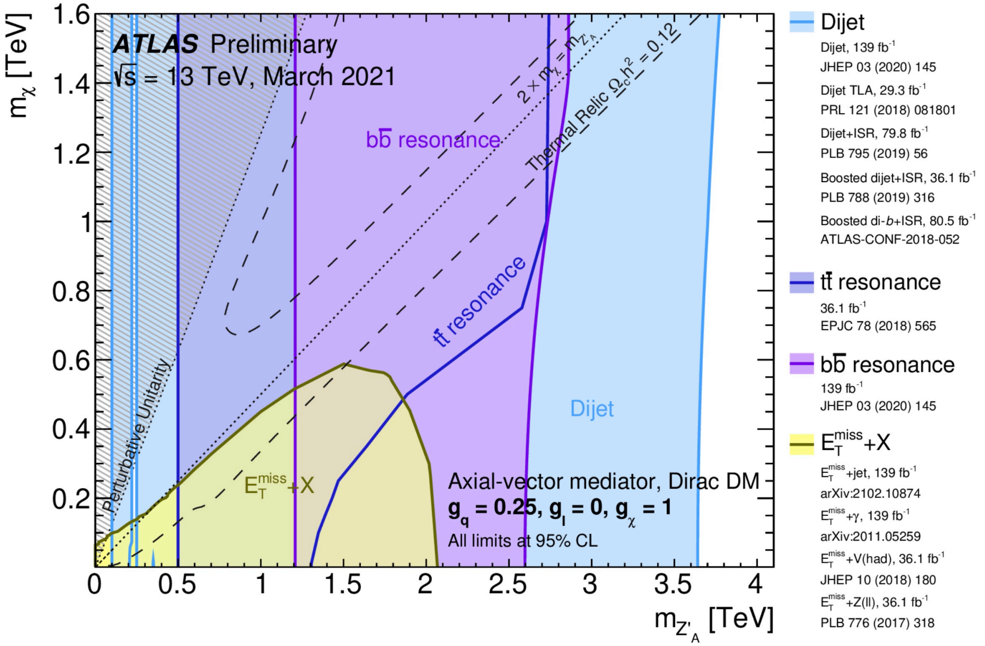
FIG. 1. Representative Feynman diagrams for the decay of a B^+ meson to a K^+ meson in association with two leptons (a) in the SM and (b) in the EFT approach and for production of two leptons via a $bs\ell\ell$ contact interaction in pp collisions (c) without and (d) with a b jet in the final state.

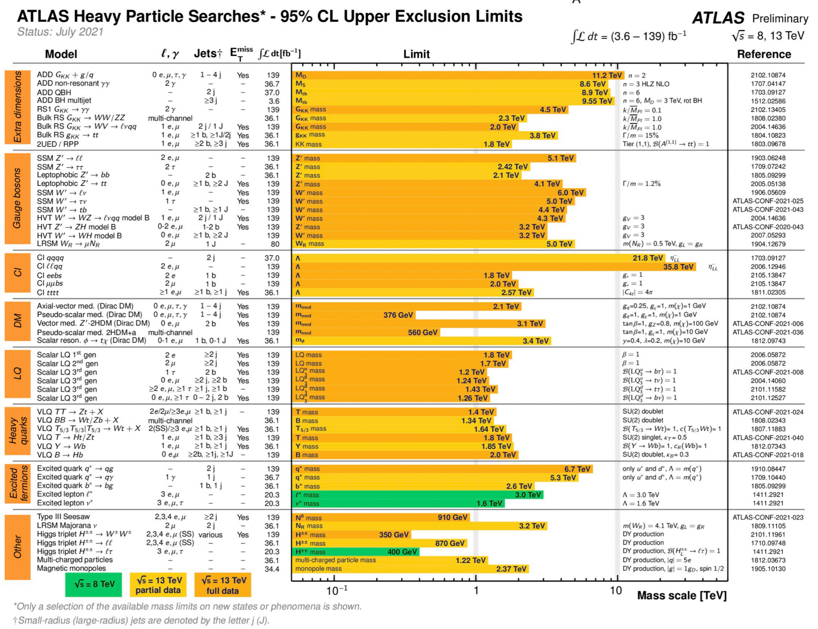
bsll Contact Interaction

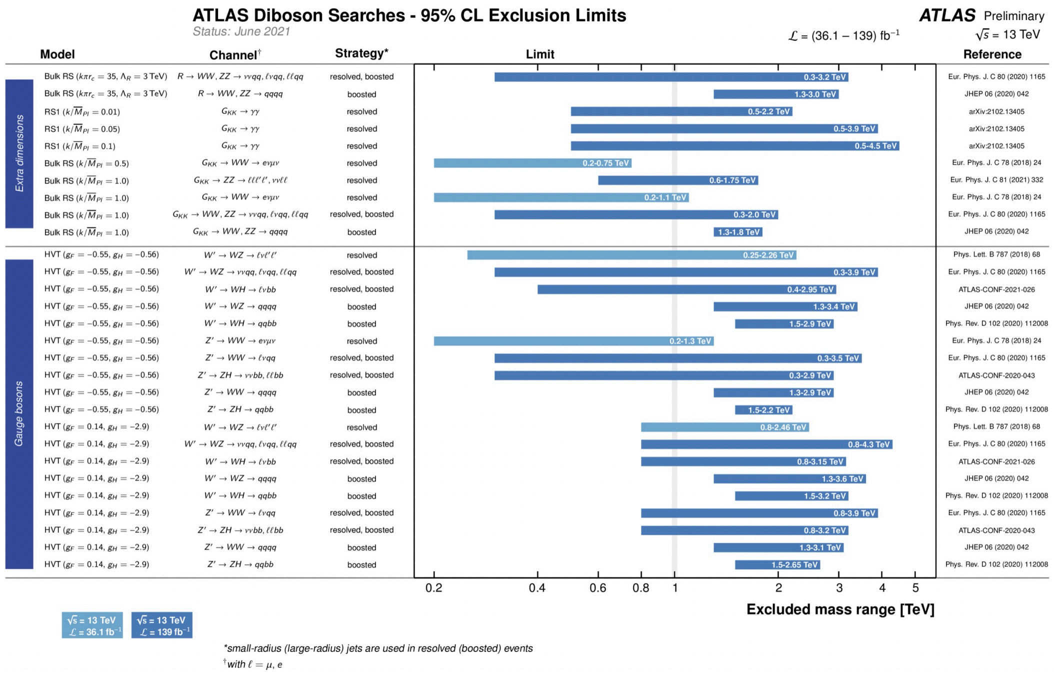
- Run 2 139 fb^{-1} data. Event selected with two leptons and 0/1 b-tagged jet
- Λ/g_* below 2.0 (2.4) TeV are excluded for electrons (muons)
- Still far below the value favored by B meson decay anomalies though (~3 TeV)



Other Searches





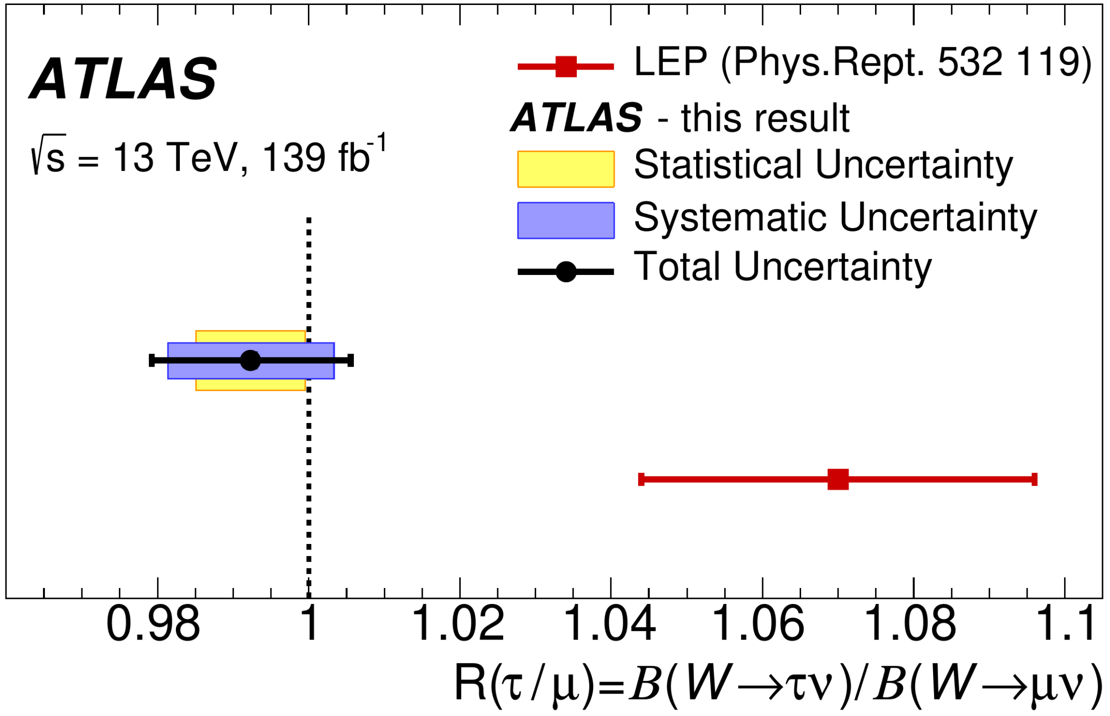


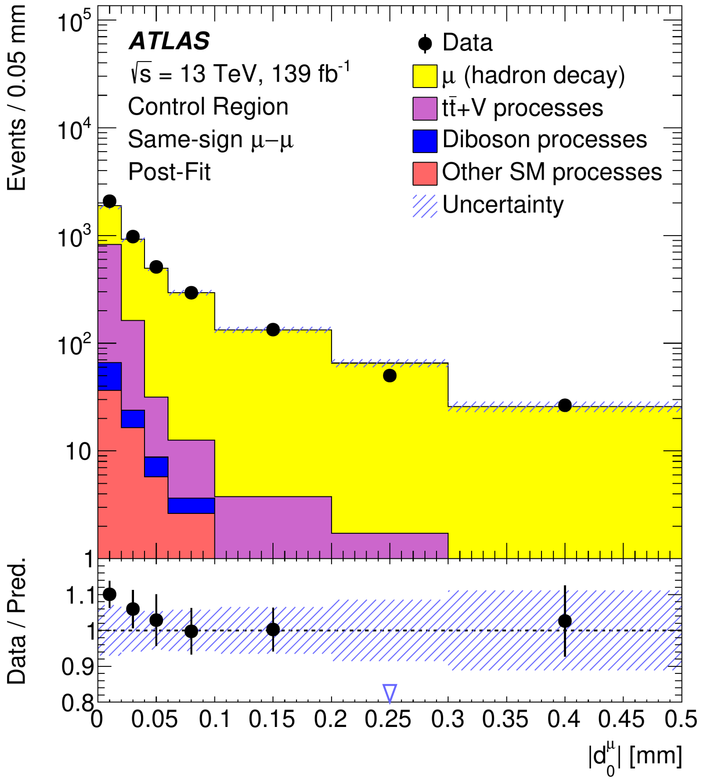
Dark matter, heavy particles, LFV, long-lived particles …

Nature Physics **volume 17**, pages 813–818 (2021)

LFV Using W from ttbar Decay

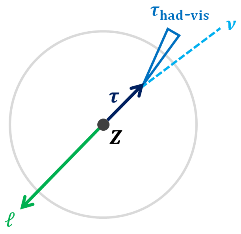
- Measure the ratio of W decay to tau/mu, from ttbar events (large statistic at LHC)
- Using full Run 2 data
- Using lifetime information to separate W to tau/mu decays





R(tau/m) = 0.992 +- 0.013

Most precise measurement of this ratio and the only such measurement at LHC

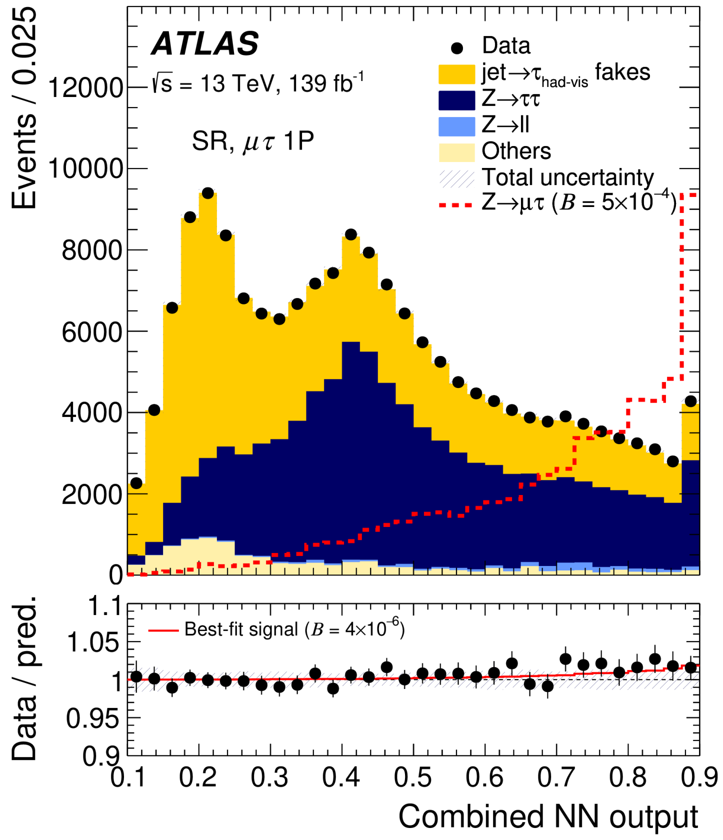


[Nature Phys. 17 (2021) 819](#)

LFV Using Z Decays

- Searching for LFV using Z decays to mutau or etau

Experiment, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ $[\times 10^{-6}]$ $e\tau$	$\mu\tau$
ATLAS Run 2, unpolarized τ	8.1 (8.1)	9.9 (6.3)
ATLAS Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
ATLAS Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
ATLAS Run 1, unpolarized τ		17 (26)
ATLAS Run 1+Run 2 combination, unpolarized τ		9.5 (6.1)
LEP OPAL, unpolarized τ	9.8	17
LEP DELPHI, unpolarized τ	22	12



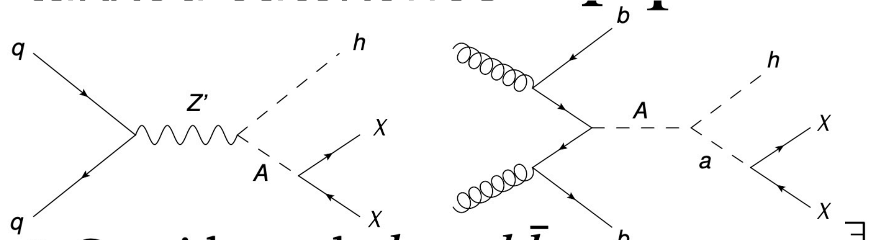
These results supersede the limits from the Large Electron–Positron Collider experiments conducted more than two decades ago.

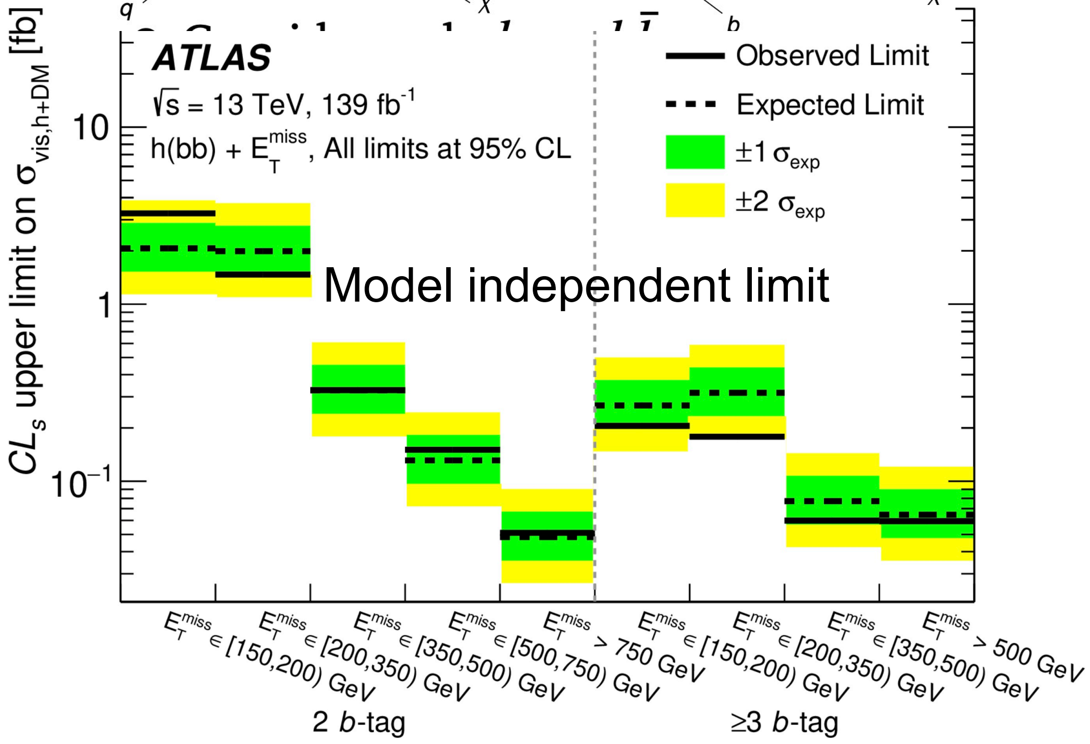
Major uncertainty still due to limited statistic
Systematic uncertainty dominant by tau reconstruction and calibration

arXiv:2108.13391

Searches for Dark Matter with h(bb) + MET

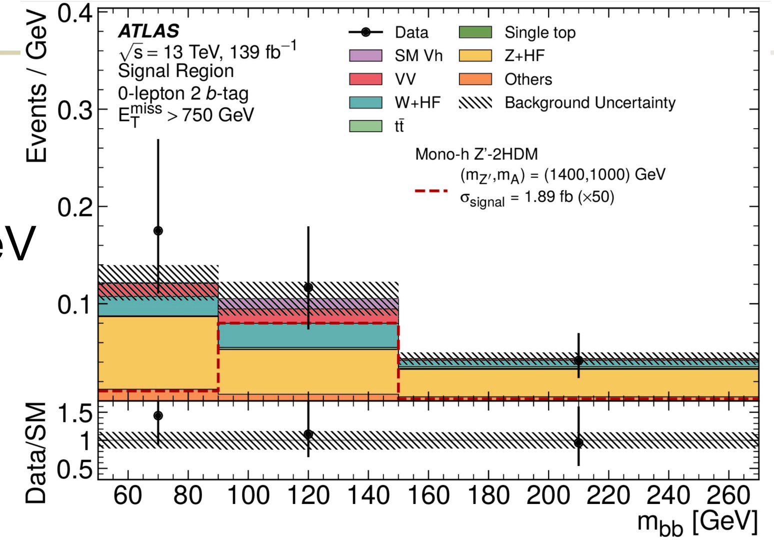
- Events split to 2 b-tagged and >= 3 b-tagged categories

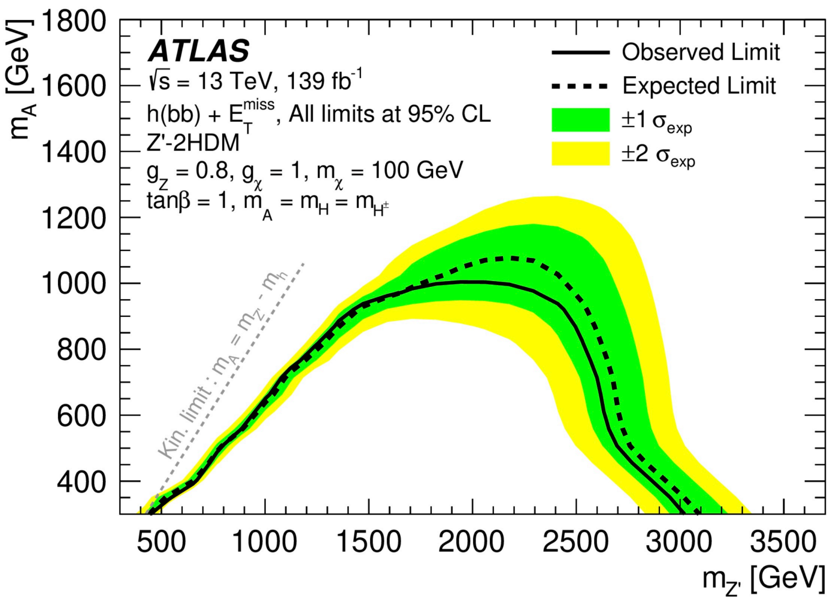




Model independent limit

MET > 750 GeV

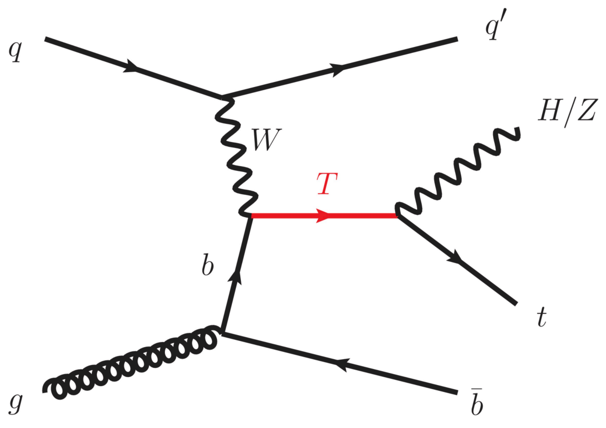


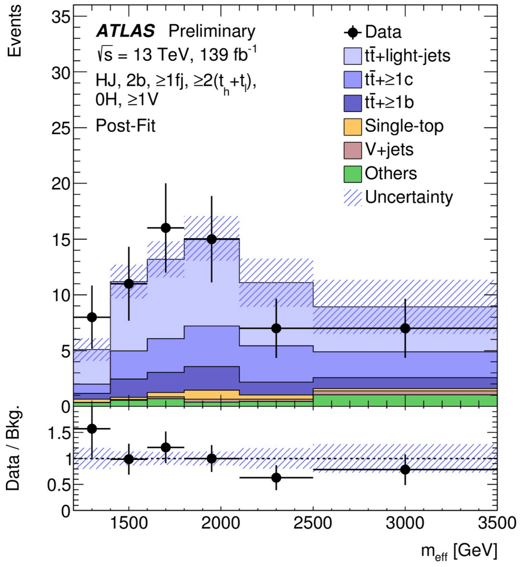


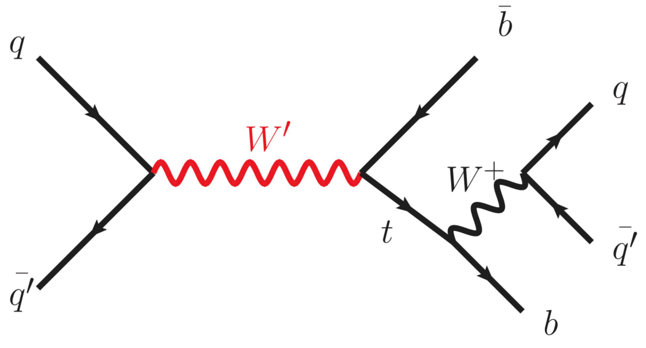
ATLAS-CONF-2021-040, ATLAS-CONF-2021-043

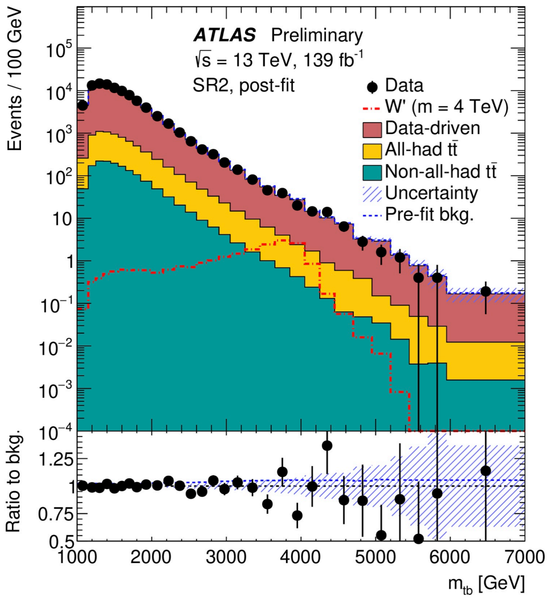
Searches for Heavy Resonance

- Multiple BSM theories predict new gauge bosons at TeV scale to address the hierarchy problem









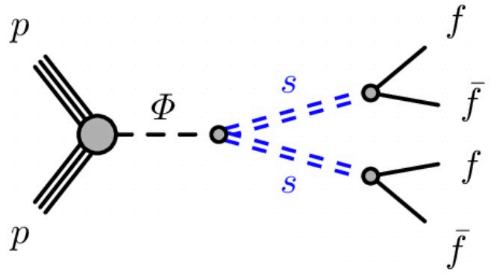
- ✓ Search for up-type vector-like quarks
- ✓ T mass below 1.8 TeV excluded

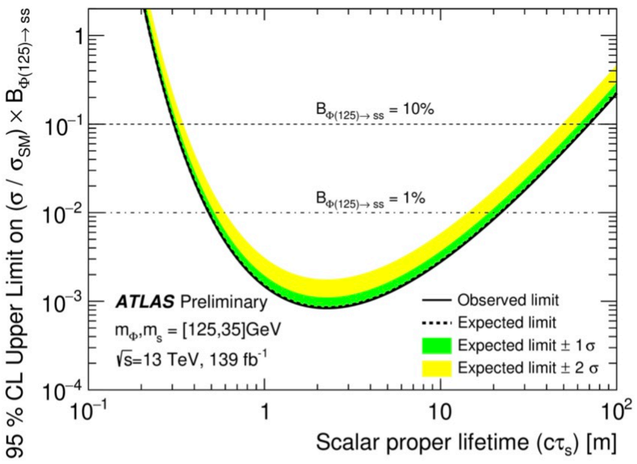
- ✓ Search for right-handed leptophobic W' with the same coupling strength as SM W
- ✓ Hadronic t identified from fat jets with DNN tagger
- ✓ W' mass below 4.4 TeV excluded

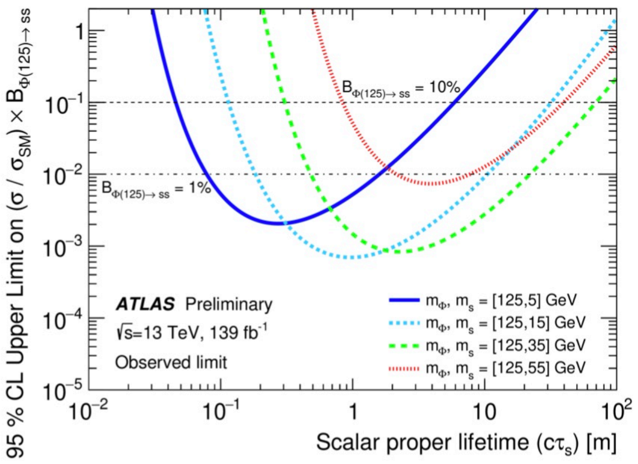
ATLAS-CONF-2021-032

Long-lived Particles From Displaced Vertex

- Several models (Higgs portal, hidden sector, SUSY) predict Higgs decays to long-lived particles decaying to jets
- In detector those events typically have 2 displaced vertex (DV)
- Use a dedicated Muon RoI cluster trigger. Reconstruct tracks and DV from in muon spectrometer







No events with 2 DV found
Expected background 0.32 +- 0.05

Summary

- Many new results from ATLAS
- Many works still ongoing to take full advantage of the Run 2 data
  - Improved CP. Rare SM processes. Searches for uncovered signatures
- Run 3 is also coming
- Stay tuned

backup

- B^0 flavour eigenstate can be identified through the $K^* \rightarrow K^- \pi^+$ decay
- angular distribution given by:

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\left[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$\left. +S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\right].$$

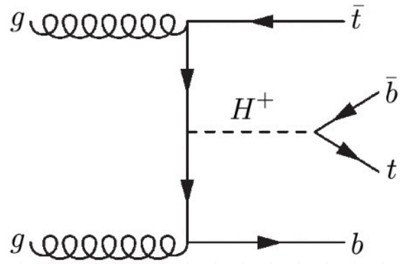
- the S parameters are translated into the $P^{(\prime)}$ parameters via

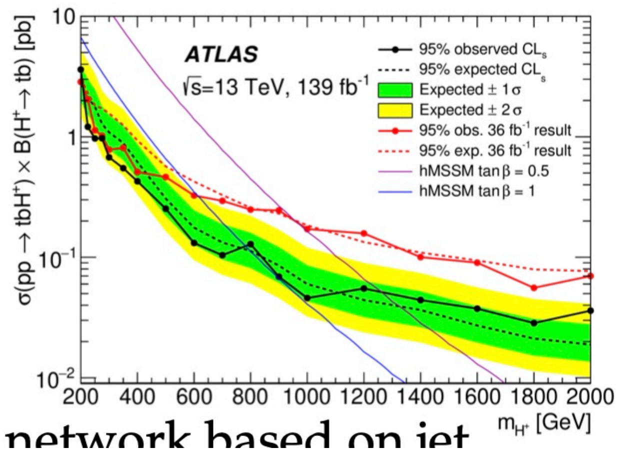
$$P_1 = \frac{2S_3}{1-F_L} \qquad P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

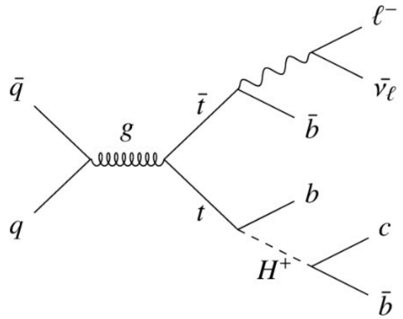
JHEP 06 (2021) 145, ATLAS-CONF-2021-037

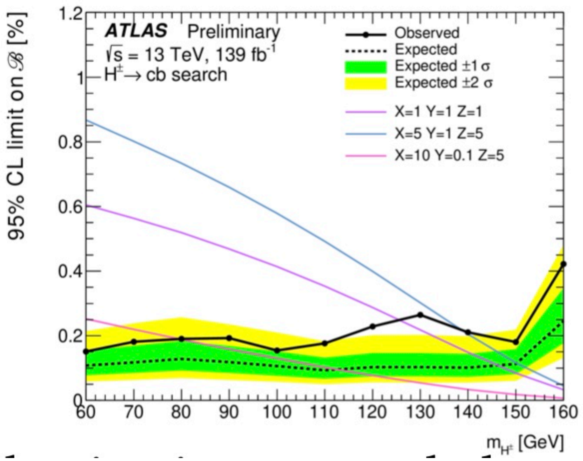
Charged Higgs

- Extended Higgs sectors with additional doublets or triplets









Analysis uses a neural network based on jet

Neural network used in both analyses

Analysis focus on high b-jet multiplicity region