Recent Standard Model Results From ATLAS

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Kruger 2022: Discovery Physics at the LHC
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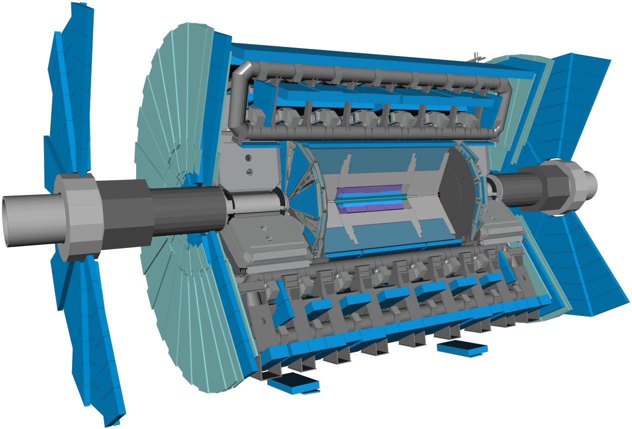
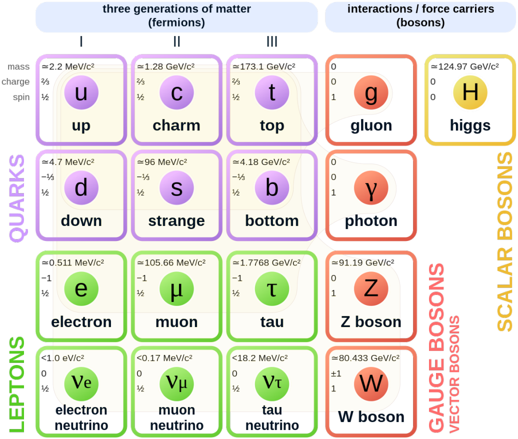


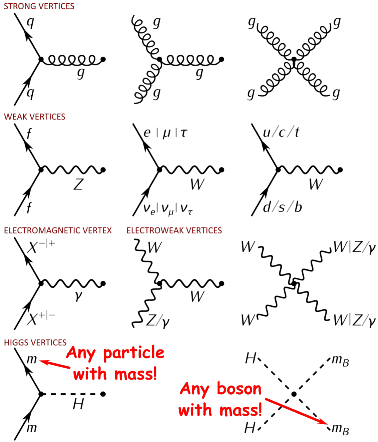
Introduction

- The Standard Model represents our current best understanding of particle physics.
- However, we know that it is not complete – there has to be something more...
- ATLAS has a large program of **direct searches** for new physics – *Mohamed's talk!*
- Then we have **Standard Model Measurements!** – why do we do them?
  - Measure a fundamental Standard Model parameter (eg. masses, couplings...)
  - Test a fundamental property (eg. *lepton flavour universality*)
  - Observe/study a new process or phenomena
  - Precisely test a theory calculation
  - Search for hints of new physics through data/MC discrepancies
  - Provide inputs to tune non-perturbative processes
  - Test MC modelling eg. parton shower implementations
  - Measure the proton PDF
  - And more...!
- There are a *very large* number of ATLAS results each of which could have a whole talk so I will be selective (with personal bias on recent/important) on what I show...
- I will focus on the measurements of more fundamental physics rather than those used for tuning, but the latter are obviously essential for future LHC precision measurements to be possible! *(also see George's and Ethan's talks!)*

The Standard Model

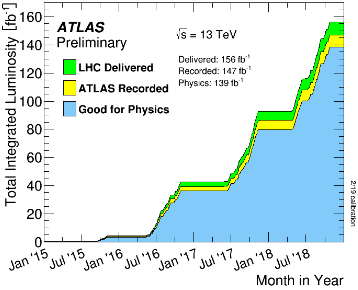
- The Standard Model is defined by its particles and their interactions.
- We look to measure the properties of the particles and their interactions.

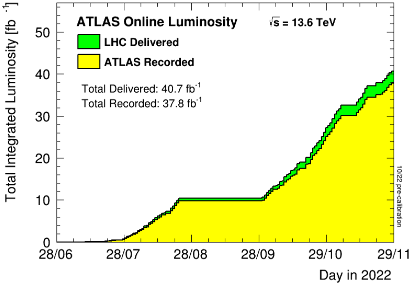




The Dataset

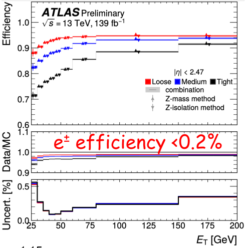
- In Run 2 we successfully recorded 139 fb^{-1} for physics analysis.
- This corresponds to 8.4 billion $W \to \ell\nu$, 813 million $Z \to \ell\ell$, 115 million $t\bar{t}$ and 7.7 million Higgs events!
- This is a huge dataset to probe many aspects of the Standard Model
- For reference, LEP had 1.7 million $Z \to \ell^+\ell^-$ events and ~50 thousand WW events across the 4 experiments.
- Run 3 will bring another 250(?) fb^{-1} at a 13.6 TeV, and we already have 37.8 fb^{-1} recorded this year!

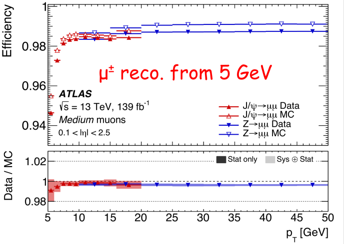


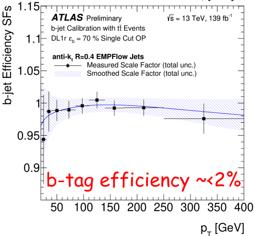


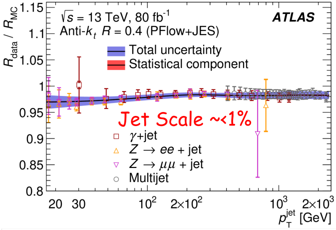
Detector & Performance [EGAM-2022-02] [2012.00578] [FTAG-2021-001] [2007.02645]

- None of the measurements I will present would be possible without the excellent precise calibrations and uncertainties on the different physics objects: $e^{\pm}$, $\mu^{\pm}$, $\tau_h^{\pm}$, γ, jets, b/c-tagging & $E_{\mathrm{T}}^{\mathrm{miss}}$!









Outline

1. Inclusive Cross-Sections
2. Differential Cross-Sections
3. Fundamental couplings (α_S)
4. Particle Masses
5. Particle Decay Branching Ratios
6. Spin/Helicity Properties
7. Asymmetry measurements
8. Studying QCD
9. Beyond the current reach / looking forward
10. Conclusions & Outlook

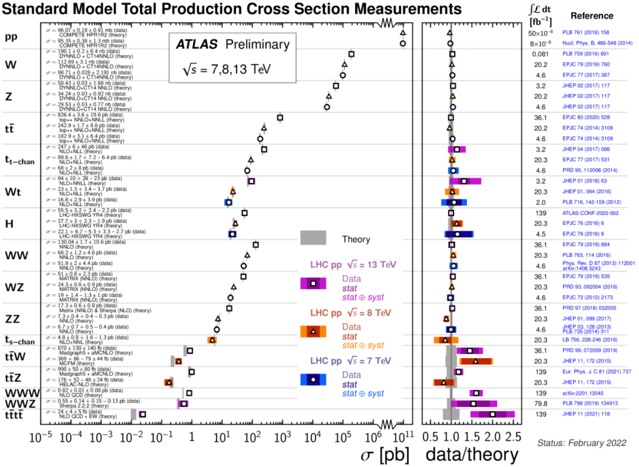
For each I will just show examples and a global summary – many more results can be found on the ATLAS website

1. Inclusive Cross-Sections

The simplest thing we can measure is
how often we see a particle being produced
or how often we observe a particular process!

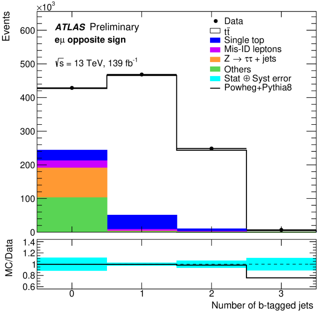
Inclusive cross-sections

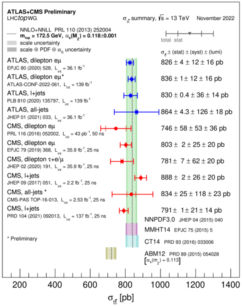
- Measuring the rate of production of different processes is a key SM measurement.
- Processes measured over 7 orders of magnitude!
- Huge success of the Standard Model to predict all these different processes!



Inclusive $t\bar{t}$ cross-sections @ 13 TeV [ATLAS-CONF-2022-061]

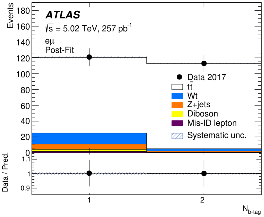
- The LHC produces a huge number of top-pair events, and they are quite distinctive.
- At 13 TeV we're not statistics limited so we use the purest channel; $e-\mu$
- By counting events with 1 and 2 b-tagged jets we can extract: the *cross-section*, $\sigma_{t\bar{t}}$ and *probability of a b-jet falling in the detector, being reco. & tagged*, ϵ_b.
- Main systematics; $t\bar{t}$ theory+PDF - affects how often ℓ in acceptance, ℓ $\epsilon_{\text{iso.}}$, & Wt.
- The cross-section is: $\sigma_{t\bar{t}} = 836 \pm 1(\text{stat.}) \pm 12(\text{syst.}) \pm 16(\text{lumi.}) \pm 2(\text{beam})\text{pb}$ $\rightarrow$ a **total relative uncertainty of 2.3%** and in excellent agreement with prediction.

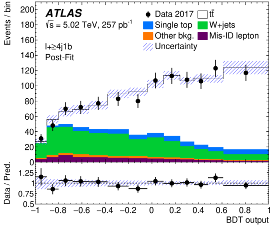


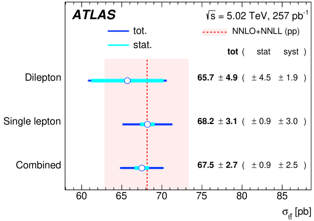


Inclusive $t\bar{t}$ cross-sections @ 5 TeV [2207.01354]

- The LHC did a short run at $\sqrt{s} = 5.02$ TeV where we collected 257 pb^{-1}.
- Cross-section at this energy is ∼12 times smaller than 13 TeV - now stat. limited!
  → need to use all channels - same flavour di-lepton and ℓ+jets.
- Di-lepton channels follow same methods as @ 13 TeV, but now very stat. limited.
- ℓ+jets suffers from large W+jets background.
- Events are separated into 6 regions based on jet and b-tagged jet multiplicity.
- *Boosted Decision Trees* are used to enhance signal (different BDTs for low/high nJet). Cross-section extracted from a likelihood fit of BDT outputs.
- Combined result: $\sigma_{t\bar{t}} = 67.5 \pm 0.9(\mathrm{stat.}) \pm 2.3(\mathrm{syst.}) \pm 1.1(\mathrm{lumi.}) \pm 0.2(\mathrm{beam})\mathrm{pb}$
  → a **total relative uncertainty of 3.9%** and in excellent agreement with prediction.

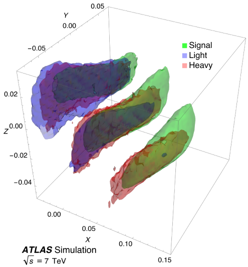


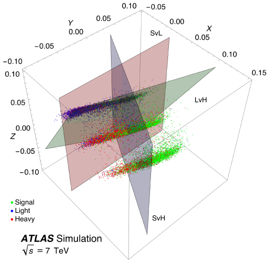


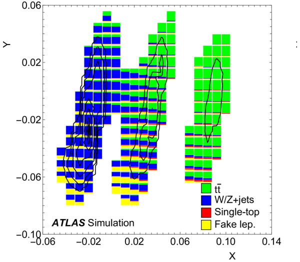


Inclusive $t\bar{t}$ cross-sections @ 7 TeV & 8 TeV [1406.5375] [2212.00571]

- The cross-section at 7 TeV and 8 TeV was measured with the same di-lepton method with Run 1 data, and good agreement with the Standard Model was found.
- The relative uncertainties are **3.9%** and **4.3%**.
- The statistical components are **1.7%** and **0.7%**.
- Therefore it is also intersting to look at the 1-lepton channel in 7 TeV data – **and we have a new result!**
- Support vector machines are used to separate the large $W + jets$ backgrounds separately treating processes with $b-$jets (eg. $Wb\bar{b}$, Wt, etc.) and those without.
- The resulting cross-section is $\sigma_{t\bar{t}} = 168.5$ pb $\pm$**4.1%** – competitive with 2ℓ!



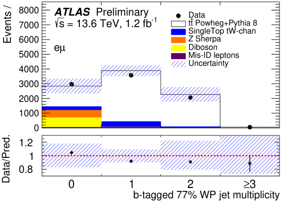


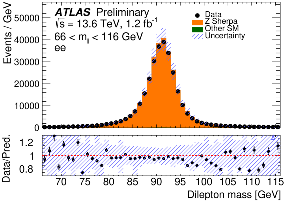


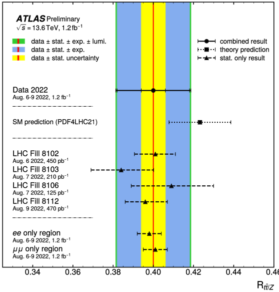
Inclusive $t\bar{t}$ cross-sections @ 13.6 TeV – Run 3 Result!

[CONF]

- This year we started running at 13.6 TeV.
- Obviously we don't yet have the same level of understanding.
- Large luminosity uncertainty means we measure $\sigma_{t\bar{t}}/\sigma_Z$.
- $\sigma_{t\bar{t}} = 830 \pm 12(\text{stat.}) \pm 27(\text{syst.}) \pm 86(\text{lumi.})$ pb
  – relative uncertainty of 11%
- $\sigma_{t\bar{t}}/\sigma_Z = 0.400 \pm 0.006(\text{stat.}) \pm 0.017(\text{syst.}) \pm 0.005(\text{lumi.})$ **– δR of 4.7%**
- In agreement with the Standard Model!

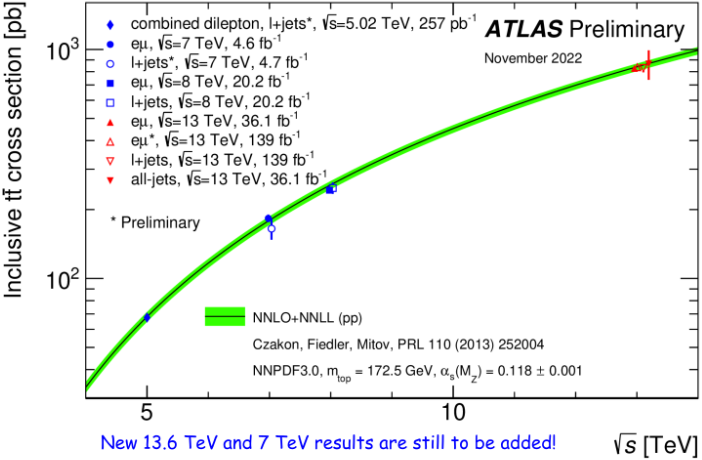






Inclusive $t\bar{t}$ cross-sections

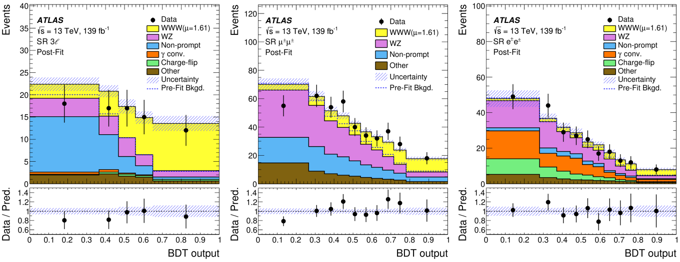
- We see excellent agreement across all collision energies and achive uncertainties as low as 2.4% – dominated by luminosity measurement.
- Fantastic test of the SM and can be used to tune PDFs and measure $m_{\text{top}}^{\text{pole}}$.

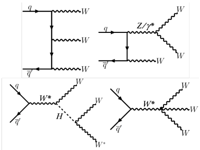


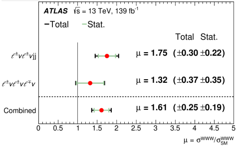
New 13.6 TeV and 7 TeV results are still to be added!

WWW cross-section [2201.13045]

- A more rare process: WWW production was observed for the 1st time in 2022!
- Predicted cross-section 511±18 fb - only 71,000 events in Run 2 dataset!
- Purest selection is $3\ell^{\pm}$ ($e^{\pm}$ or $\mu^{\pm}$) and $E_{\mathrm{T}}^{\mathrm{miss}}$ – but low stats.
- Add channels with 2 same-sign charged $\ell^{\pm}$ + 2 jets (no b-jets) + $E_{\mathrm{T}}^{\mathrm{miss}}$
- Events with additional $\ell^{\pm}$ are rejected to reduce ZZ and WZ backgrounds.
- A fit of BDT outputs to enhance the signal finds $\sigma/\sigma_{SM} = 1.61 \pm 0.25$
- Main uncertainties: stats. (12%), non-prompt bkg. (6%) and WZ modeling (3%).
- **8σ observation of WWW**, (only) 2.6σ above SM prediction.





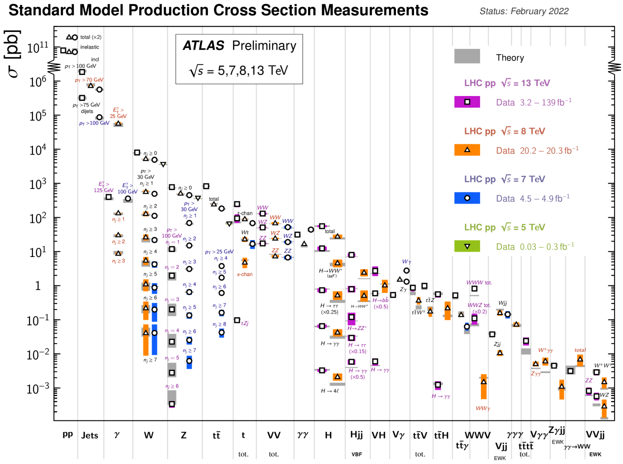


2. Differential Cross-Sections

As we have lots of data we can measure cross-sections differentially!

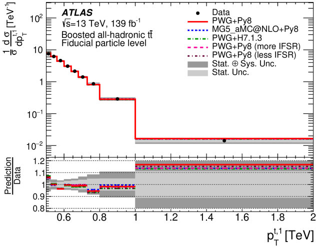
Differential Cross-Section Introduction

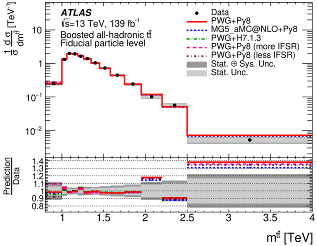
- With the large dataset we are able to perform many of the measurements in several kinematic bins defined by *truth level selections*.
- To extract the cross-sections the data distributions are unfolded to the truth level.

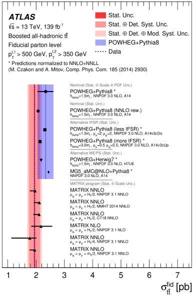


$t\bar{t}$ Differential Cross-Section (all-had) [2205.02817]

- 45% of the time $t\bar{t}$ decay all-hadronically - the single largest branching fraction.
- This therefore gives access to the highest p_{T} and mass.
- Large radius jets are used to reconstruct the two top candidates.
- A *Deep Neural Network* is used to "tag" hadronic top quarks.
- Distributions are unfolded to both a particle level fiducial definition as well as a parton level fiducial definition.
- NLO models generally describe the data well across all distributions, for the high p_{T} fiducial volume at parton level NNLO calculations provide a better description than NLO $\rightarrow$ **analysis sensitive to NNLO effects!**

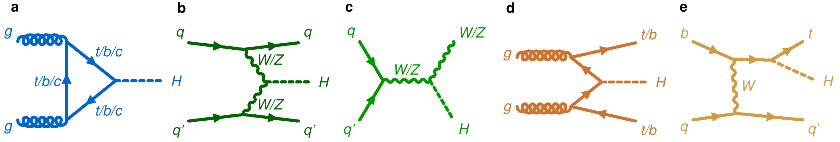






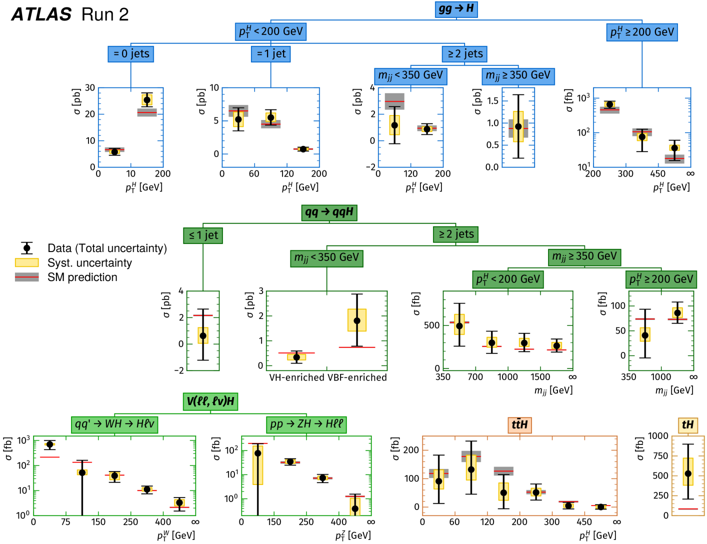
Higgs STXS Measurements [2207.00092]

- The Higgs boson was discovered at the LHC in 2012 – discovering all of its properties is an essential part of the LHC physics program.
- To study Higgs production differentially the *Simplified Template X-Section* (STXS) is used.
- We separate QCD and electro-weak production, then study different bins of jet multiplicity, di-jet mass and Higgs p_{T}.
- To extract the cross-sections with the best precision a combination of the analyses of the different decay channels is performed: $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$, $H \to \tau\tau$, $H \to b\bar{b}$, $H \to Z\gamma$, $H \to \mu\mu$, $H \to c\bar{c}$, $H \to \mathrm{invisible}$.
- The $\gamma\gamma$ and ZZ dominate inclusive and low p_{T} measurements, with WW and $\tau\tau$ channels essential for VBF production, and $b\bar{b}$ is important for VH production and also reaches the highest p_{T}.



Higgs STXS Measurements [2207.00092]

- Good agreement seen across all kinematic categories.



3. Fundamental Couplings

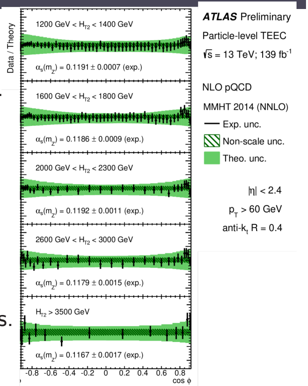
We can extract fundamental couplings from our differential measurements!

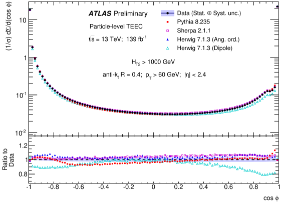
α_S from Jets (A/TEEC) [ATLAS-CONF-2020-025]

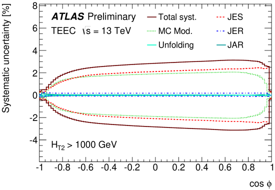
- The strong coupling constant, α_S, is a fundamental parameter in the Standard Model.
- It runs with energy so it typically extracted at $\alpha_S(M_Z)$.
- But an additional measurements as a function of Q^2 test QCD theory.
- Transverse energy correlators are used to extract α_S.

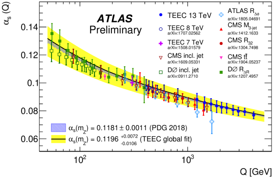
$$\alpha_S(M_Z) = 0.1196 \pm 0.0004(\text{exp.})^{+0.0072}_{-0.0105}(\text{th.})$$

- Measurements as a function of Q^2 also show good agreement with extrapolation from other measurements.







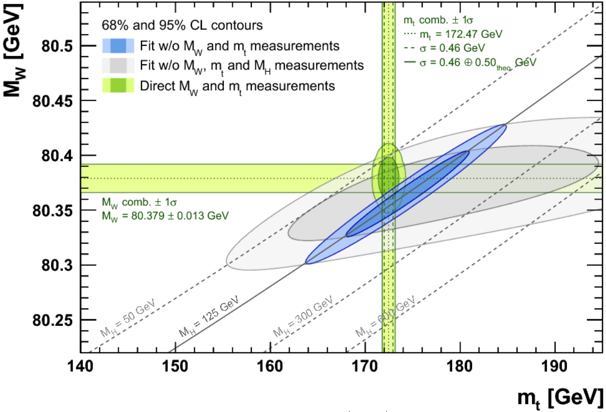


4. Particle Masses

The masses of the particles are
fundamental inputs to the Standard Model
$\rightarrow$ *we need to measure them precisely!*

Masses of Particles

- We focus on Higgs, W-boson and Top quark as the others are not really measurable[1,2] at the LHC.
- Also they have largest uncertainties, and the biggest impact on the Electroweak Fit!

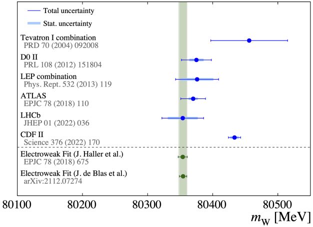


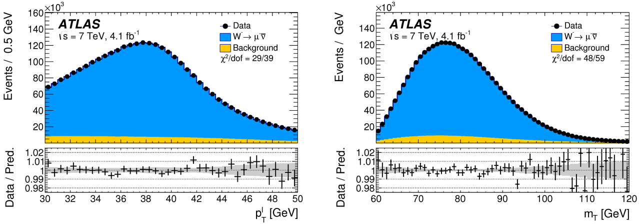
[1] We have lots of Z-bosons but we use the Z mass peak to calibrate $e^{\pm}$, $\mu^{\pm}$

[2] m_{τ}, $m_b(m_H)$ and $m_c(m_H)$ are technically measured through their coupling to the Higgs but not with high precision.

W mass [1701.07240]

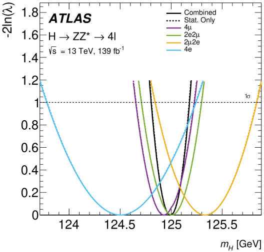
- This isn't a new result but this year there was a new result from CDF [link] & C. Hays' talk.
- CDF measured 80433±9 MeV
- ATLAS measured 80370±19 MeV (0.023%)
- A difference of 63 MeV – so there is some tension
- The ATLAS measurement was based on 2011 data $\rightarrow$ analysis is highly affected by *pile-up* such that the lower *pile-up* smaller dataset was preferred, over the 2012 and Run 2 datasets.
- W-mass is extracted from p_{T}^{ℓ} and m_{T} separately showing good agreement.
- In Run 2 there were low-μ runs at 13 TeV – good prospects for future results...

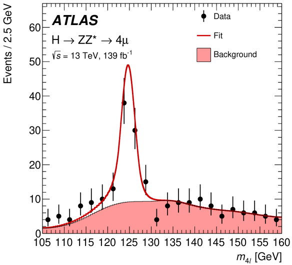


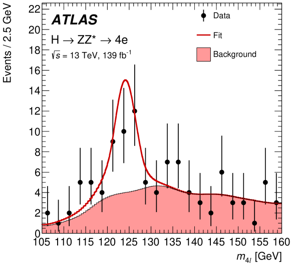


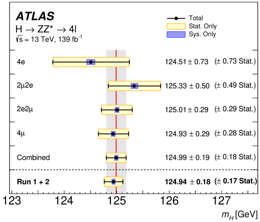
Higgs mass [2207.00320]

- The channels that are best for measuring the Higgs mass are $\gamma\gamma$ and $ZZ \rightarrow 4\ell$.
- Both analyses highly dependent on the precise reconstruction and calibration of physics objects.
- Recent analysis of $ZZ \rightarrow 4\ell$ with full Run 2
- A deep feed-forward neural network (NN) is employed and another network estimates the event-level $m_{4\ell}$ resolution, σ_i.
- **A precision of $\pm 0.14\%$ is achieved!** (stat. dominated)



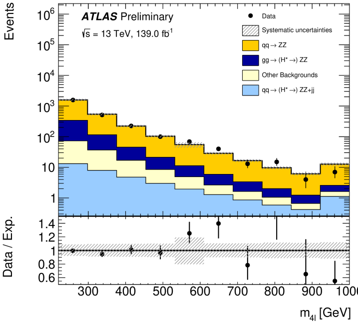


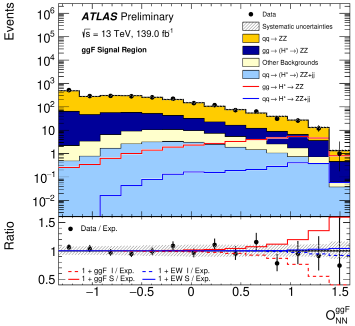




Higgs width [ATLAS-CONF-2022-068]

- The total width is another fundamental property which we want to measure!
- The on-shell Higgs cross-section is $\propto 1/m_H\Gamma_H$
- Off-shell Higgs cross-section is $\propto 1/m^2_{H*}$
- Looking at $H \to ZZ \to 4\ell$ and $H \to ZZ \to \ell\ell\nu\nu$ we can measure the off-shell cross-section and get width from the ratio!
- $\Gamma_H = 4.6 \pm 2.6$ MeV – in agreement with the SM $\Gamma_H^{SM} = 4.1$ MeV.



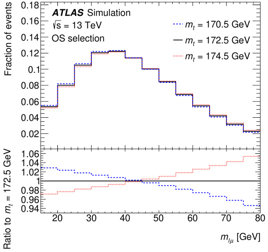


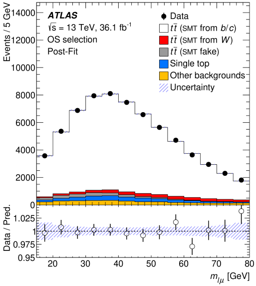
Top mass (soft-μ) [2209.00583]

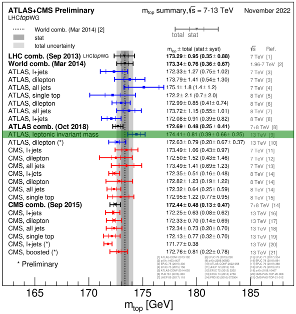
- Top mass traditionlly extracted from m_{bjj} template and $m_{\ell b}$ in the di-lepton channel.
- New analysis uses semi-lep. $t\bar{t}$ where one B-hadron decays semi-leptonically to a μ.
- The mass of the two leptons; one from $W \to \ell\nu$, the other from the B-hadron, is used to extract the top mass.
- This is sensitive to fragmentation, but not hadronic uncertainties which affect the other methods, **a largely uncorrelated measurement!**

$$m_t = 174.41 \pm 0.39(\text{stat.}) \pm 0.66(\text{syst.}) \pm 0.25(\text{recoil.})\text{GeV}$$

("recoil" is a change in the recoil scheme for gluons in the parton shower).





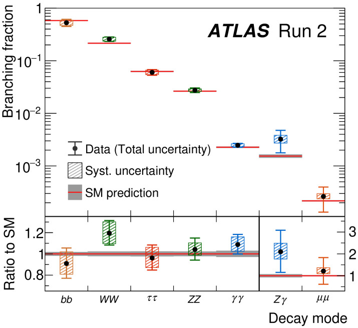


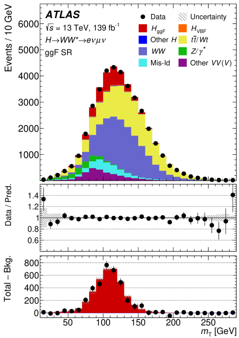
5. Particle Decay Branching Ratios

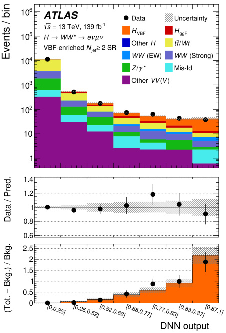
How do the particles decay?
Does it agree with expectation?

Higgs Decays [2207.00092] [2207.00338]

- The Higgs branching ratios are measured for all the different decay channels assuming SM Higgs production cross-sections.
- 7 channels are assessible with 5 measured with a **precision better than 20%**!
- Each channel is a complete analysis; eg. *WW* is measured in both ggF and VBF.
- In ggF a fit of $m_T = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 + |\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$ is performed.
- In VBF the fit is the the output of a *Deep Neural Network* (DNN).

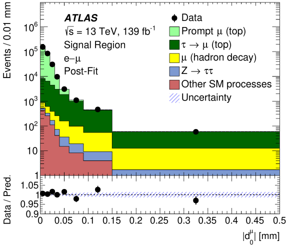


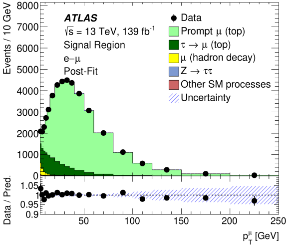


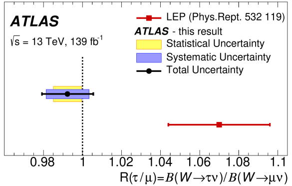


W Couplings and testing LFU [2007.14040]

- *Lepton Flavour Universality* means the BRs of W/Z should be the same for all ℓ.
- At LEP they found $R_{\tau/\mu} = BR(W \to \tau\nu)/BR(W \to \mu\nu) = 1.070 \pm 0.026$
- Using W-bosons from $t\bar{t}$ this has been tested at ATLAS.
- One W-boson is used to trigger and select the event, the other to measure the BR.
- $\tau \to \mu\nu$ decays are used to avoid hadronic τ reco. efficiency uncertainties.
- A 2-D fit of the transverse impact parameter d_0 and the lepton p_{T} is used to separate $W \to \mu\nu$ and $W \to \tau(\to \mu\nu\nu)\nu$.
- Measured ratio; $R_{\tau/\mu} = 0.992 \pm 0.013[\pm 0.007(\mathrm{stat}) \pm 0.011(\mathrm{syst})]$
  $\rightarrow$in agreement with the Standard Model and refutes the LEP discrepancy.

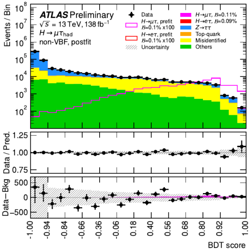


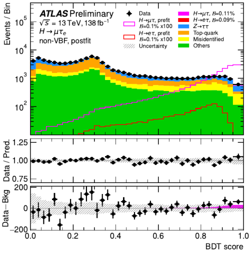


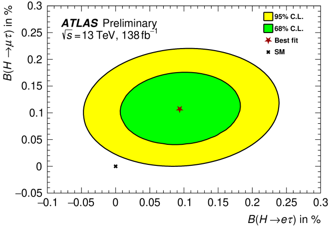


Lepton Flavour Violation in Higgs [ATLAS-CONF-2022-060]

- In the Standard Model there should be no Lepton Flavour Violation so decays like $Z \to e\mu, e\tau, \mu\tau$, $H \to e\mu, e\tau, \mu\tau$ are forbidden.
- New result looking at $H \to e\tau$ and $H \to \mu\tau$.
- Two methods used - a MC-based method, and one which exploits the symmetry in the backgrounds to measure BR($H \to \mu\tau$)-BR($H \to e\tau$).
- Both utilize both leptonic and hadronic tau-decays, and use machine learning to form the final discriminant.
- Upper limits are set of BR($H \to e\tau$)$<$ 0.19% and BR($H \to \mu\tau$)$<$ 0.18%.
- **Best fit result is compatible with the SM at the level of 2.2σ.**







6. Spin/Helicity Properties

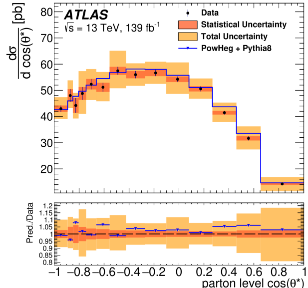
We can predict the spin/helicity
of the produced particles...
Does this match expectation?

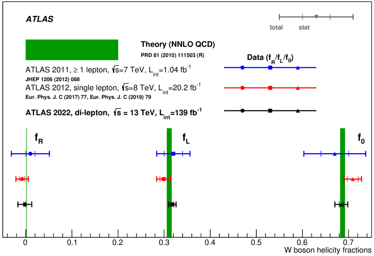
Top helicity [2209.14903]

- In top decay to $b + W$ we expect the W-boson helicity to have well defined fractions - eg. f_R will be small as W couples to left-handed particles.
- By reconstructing the system and measuring the angle between the lepton and the b-quark in the W-boson rest frame, $\cos\theta^*$, the fractions can be measured.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)f_0 + \frac{3}{8}(1-\cos\theta^*)^2 f_L + \frac{3}{8}(1+\cos\theta^*)^2 f_R.$$

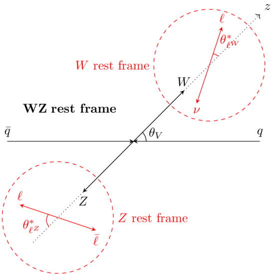
- Fit to unfolded normalized data used to extract the three helicity fractions.
- Systematics dominated by jet reconstruction and $t\bar{t}$ modeling.
- **1st ATLAS Run 2 measurement, and more precise!**

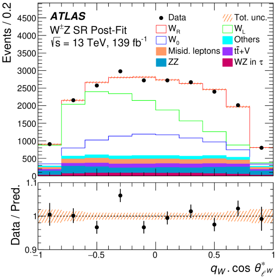


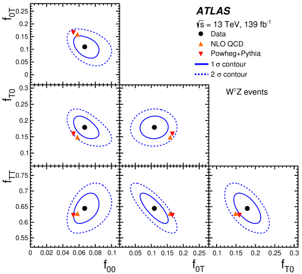


WZ Polarization [2211.09435]

- Similarly in WZ production the helicity of the two bosons is encoded into the distributions of the leptons that they decay into.
- By measuring the angle of the leptons in the W and Z rest frames the fractions of longitudinal, left and right transverse helicities can be extracted.
- The measurement extracts the fractions where both bosons are longitudinal f_{00}, both are transverse f_{TT}, and mixed states.
- The measurements are in agreement with the NLO QCD calculation.
- **This is the first observation of WZ production where both bosons are longitudinally polarized!**

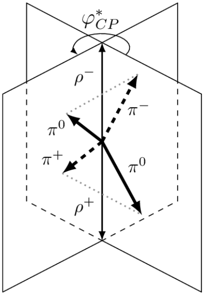


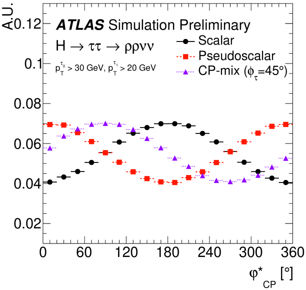


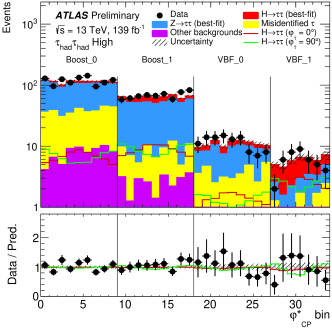


$H \rightarrow \tau\tau$ and CP violation [ATLAS-CONF-2022-032]

- The transverse spin correlations of the τ leptons encode the CP nature of the Higgs decay vertex; $H \rightarrow \tau\tau$.
- The spin properties are translated into kinematics of the τ decay products.
- ϕ^*_{CP} is formed from these reconstructed decay products and is sensitive to the CP nature. A fit is then performed across categories enhanced in Higgs signal.
- The CP-mixing angle, ϕ_τ is measured to be 9 ± 16^o (with $\phi_\tau = 0^o$ in the SM).







7. Asymmetry measurements

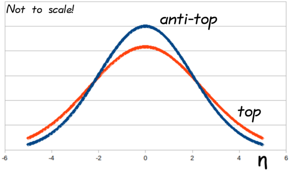
With large uncertainty cancelations small effects can be probed!

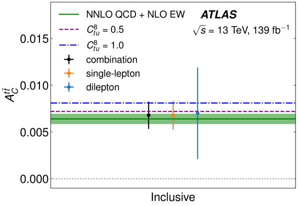
Charge Asymmetry in $t\bar{t}$ [2208.12095]

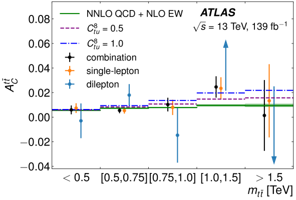
- To find new physics we want to be sensitive to effects beyond tree level ie. to interference/loop effects.
- The forward-central charge asymmetry is defined by;

$$A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

- For gg production $A_C = 0$ to all orders, for $q\bar{q}, qg$ $A_C = 0$ at LO, but interference beyond LO gives a small SM asymmetry – also sensitive to new physics!
- Combination of resolved and boosted channels in 1-lepton and 2-lepton channel.
- $A_C = 0.0068 \pm 0.0015$, **differs from zero by 4.7σ!**





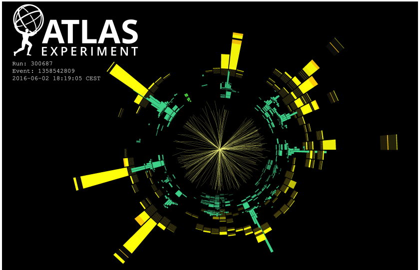


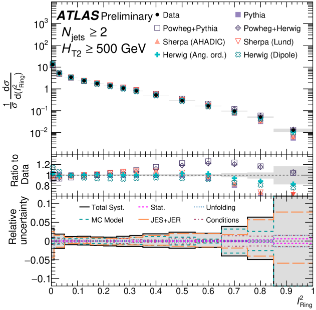
8. Studying QCD

QCD dominates events at the LHC
We can study the shapes of events to
tune MC and compare to predictions.

Event isotropies using optimal transport [ATLAS-CONF-2022-056]

- *Optimal transport* quantifies the energy required to move the vectors in an event to a given configuration.
- For I^2_{ring} this is the energy required to make the jet a perfect di-jet.
- This distribution is unfolded to show how well different generators can model complex states found in the tails of QCD distributions.
- The parton shower generators are generally unable to capture the full shape of the distribution showing how this is useful for future tuning of parameters.





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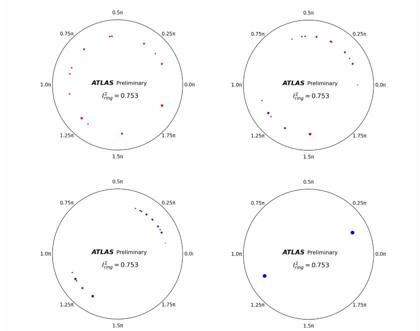

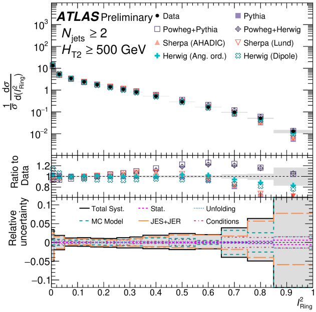

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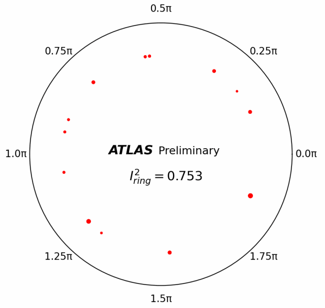
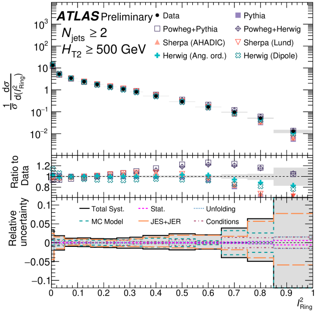
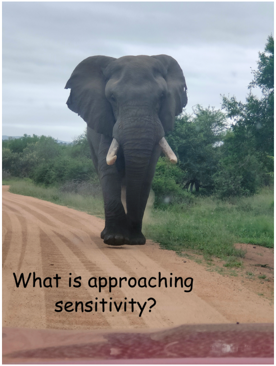




9. Beyond the current reach / looking forward

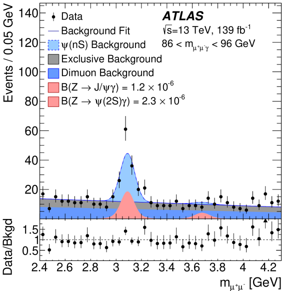
Some things we haven't managed to see yet...
What could be round the corner? (in the Standard Model)

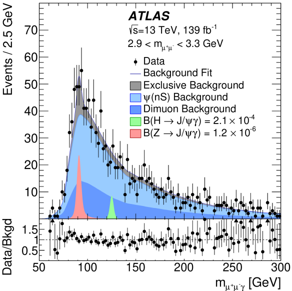


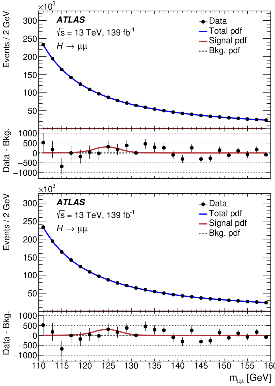
Rare decays: eg. $Z \to J/\psi + \gamma$ & $H \to \mu\mu$ [2208.03122] [2007.07830]

- A recent search for rare Z and H decays involving meson+γ eg.BR($Z \to J/\Psi + \gamma$).
- 2D unbinned likelihood in $m_{\mu\mu}$, $m_{\mu\mu\gamma}$ used to search for signals.
- Limit of 1.2×10^{-6} on BR($Z \to J/\Psi + \gamma$), with SM prediction of $\sim 1 \times 10^{-7}$.

- Observing $H \to \mu\mu$ would indicate that the Higgs provides mass to muons!
- Small signal on top of large Drell-Yan background.
- Multiple categories targetting ggF, VBF, VH and ttH.
- Best fit signal strength: $\mu = 1.2 \pm 0.6$

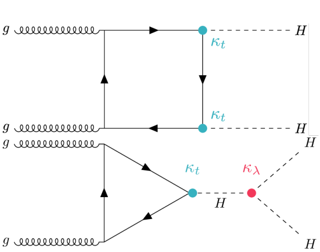


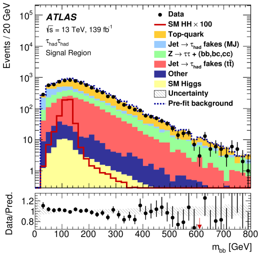


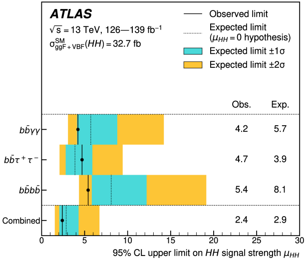


Di-Higgs [2211.01216]

- The production of two Higgs bosons is yet to be observed.
- This is particularly interesting as it is sensitive to the self-coupling of the Higgs $\rightarrow$ **this is us beginning to explore the shape of the Higgs potential!**
- The cross-section is very small $\sim$ 1700 times smaller than single Higgs - need to exploit channels where we can reconstruct the mass of both Higgs, and have significant branching ratio.
- Recent combination of $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ gives an upper limit on the HH cross-section of 2.4 times the Standard Model x-sec.
- We also extract limits on the Higgs self coupling; $-0.4 < \kappa_\lambda = \lambda_{\text{HHH}}/\lambda_{\text{HHH}}^{\text{SM}} < 6.3$

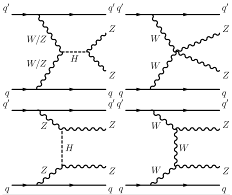


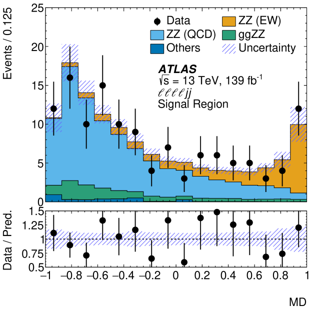


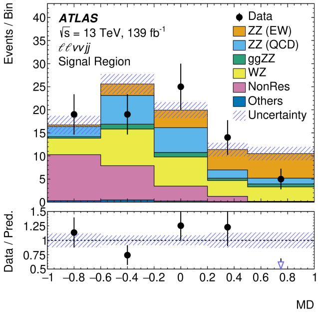


VBS and Polarization [2004.10612]

- Earlier I discussed the measurement of the polarization in WZ events.
- One of the key motivations for the LHC is to investigate EW-symmetry breaking in vector boson scattering - specifically in the longitudinally polarized case.
- We have now observed vector boson scattering of ZZ (5.5σ), $W^{\pm}Z$ (5.3σ), $W^{\pm}W^{\pm}$ (6.5σ) and $Z\gamma$ (6.3σ).
- An exciting prospect for Run 3 and the HL-LHC is to start to study the polarisation of scattering bosons!







10. Conclusions & Outlook

Conclusions & Outlook

- I've shown a large number of results in the last 49 minutes!
- But this was just a snapshot of the ATLAS measurement program.
- Overall the Standard Model is performing fantastically, and the predictions and data generally agree within the uncertainties
  – there are no clear signs of new physics *(currently...)*
- We will be:
  - taking more data
  - improving analysis techniques
  - reducing uncertainties by understanding our detector better
- We will see if the current small discrepancies grow or shrink, or other disagreements appear!
- Run 3 is only just beginning, and there are many other results which are still being carried out with the Run 2 dataset – doing careful, precise measurements takes time!

Sorry if I omitted your favourite measurement or topic – there wasn't time to cover everything so large (and important) areas of our physics program are missing from my slides...