MEASUREMENT OF ELECTROWEAK GAUGE BOSON PRODUCTION IN ASSOCIATION WITH JETS IN ATLAS

QCD@LHC 2023

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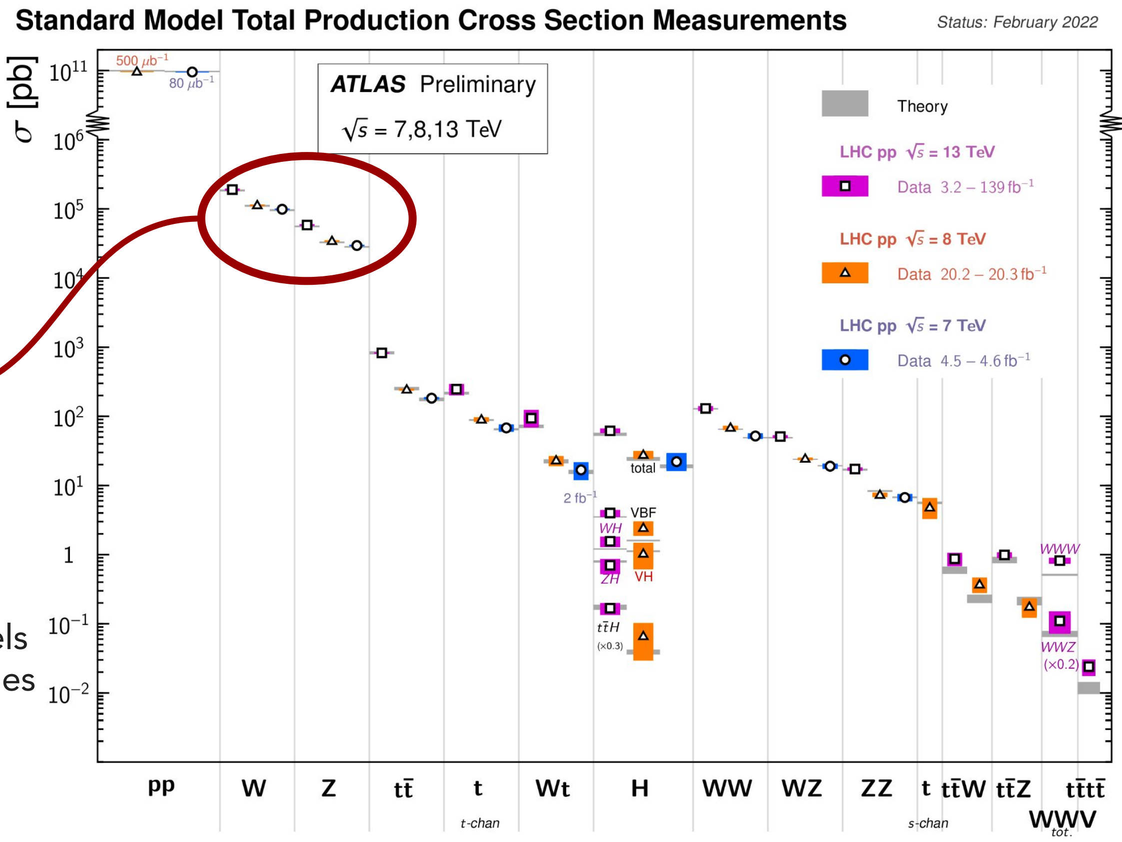
WHY STUDY W AND Z BOSON AT THE LHC

We are sensitive to a wide range of cross-sections at the LHC

W and Z production have (relatively) high cross-section

Enables us to probe a wide variety of interesting physics!

Ideal tools to probe electroweak and QCD models
Important backgrounds to Higgs and BSM searches
Help us understand our detectors better!



This talk with focus on 3 results

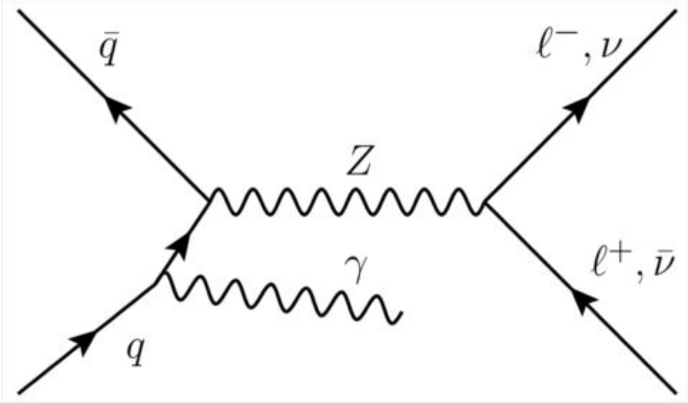
MEASUREMENT OF THE Z BOSON INVISIBLE WIDTH ATLAS CONF NOTE

MEASUREMENT OF $Z\gamma$+JETS DIFFERENTIAL CROSS-SECTION JHEP 07(2023) 72

PRODUCTION OF W BOSON IN ASSOCIATION WITH A CHARMED HADRON Phys. Rev. D 108 (2023) 032012

MEASUREMENT OF THE Z BOSON INVISIBLE WIDTH

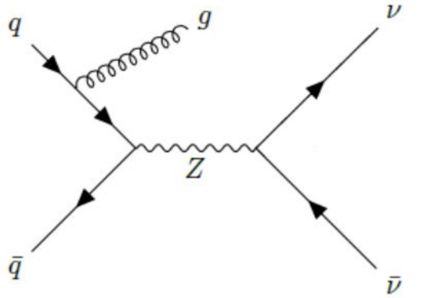
ATLAS CONF NOTE
PAPER COMING SOON!
2015-2016 dataset 37 fb^{-1}

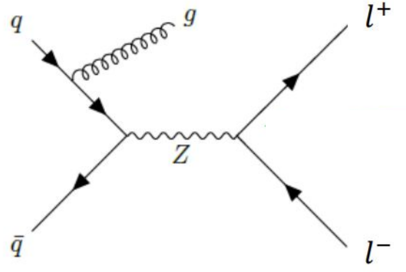


MOTIVATION and STRATEGY

- Measurement of invisible width of the Z boson reveals number of light neutrinos that couple to the Z boson and potential BSM contributions

$$R^{\mathrm{miss}}(p_{\mathrm{T,Z}}) \equiv \frac{\frac{d\sigma(Z(\rightarrow \mathrm{inv}) + \mathrm{jets})}{dp_{\mathrm{T,Z}}}}{\frac{d\sigma(Z(\rightarrow \ell\ell) + \mathrm{jets})}{dp_{\mathrm{T,Z}}}} = \frac{\frac{d\sigma(Z + \mathrm{jets}) \times BR(Z \rightarrow \mathrm{inv})}{dp_{\mathrm{T,Z}}}}{\frac{d\sigma(Z + \mathrm{jets}) \times BR(Z \rightarrow \ell\ell)}{dp_{\mathrm{T,Z}}}}$$



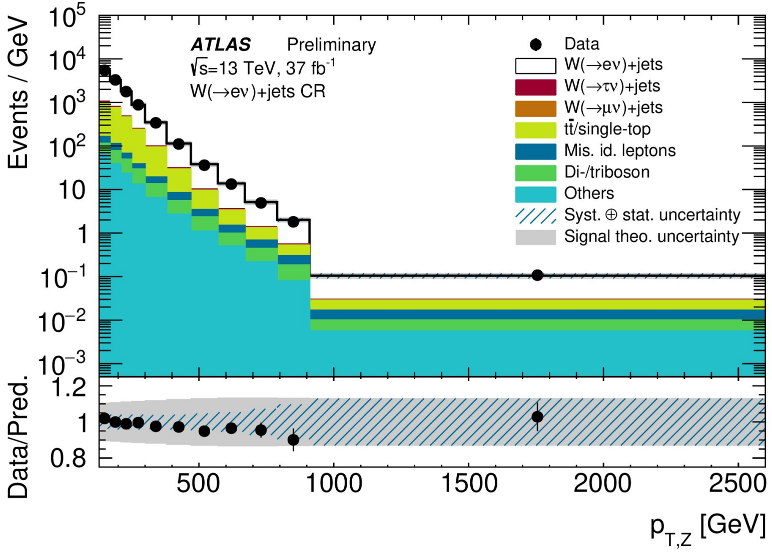


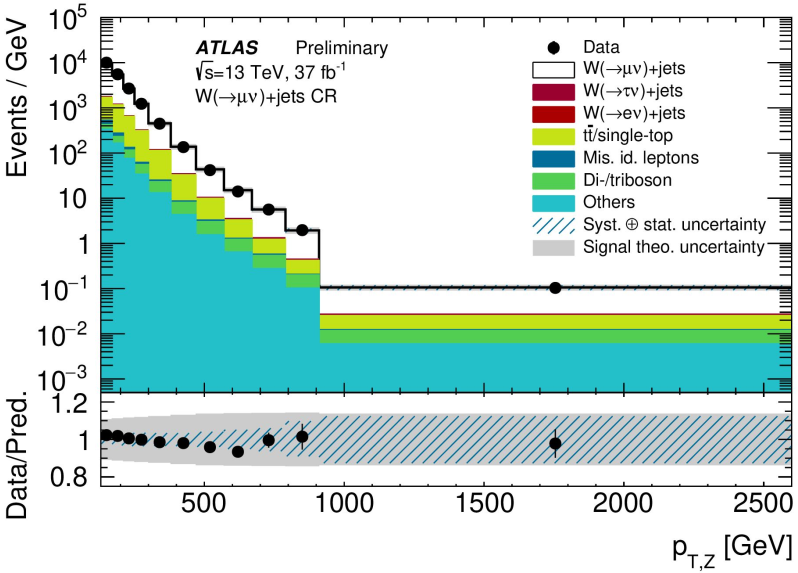
- Many dominant systematic uncertainties cancel in the ratio
- Fit $R^{\mathrm{miss}}_{(pT,\, Z)}$ to constant function and determine:
  $\Gamma\,(Z \rightarrow \text{invisible}) = R^{\mathrm{miss}} \times \Gamma\,(Z \rightarrow ll)$

- Require at least one jet with pT > 110 GeV and $|\eta| < 2.4$
- $Z \rightarrow$ invisible + jets: E_T miss > 130 GeV
- $Z \rightarrow ll$ + jets: E_T miss + pT (leptons) > 130 GeV
- Dominant background: W+jets

BACKGROUND ESTIMATION

- W+jets dominant background to Z → invisible process
  - estimated using simulations and constrained via dedicated CRs enriched in those processes
  - W→μ**v** and W→e**v** CRs
  - W→e**v** (W→μ**v**) simulations in the Z→ inv region scaled by ratio of data to simulations obtained in W→e**v** (W→μ**v**) enhanced CR in each bin of $p_{T, Z}$





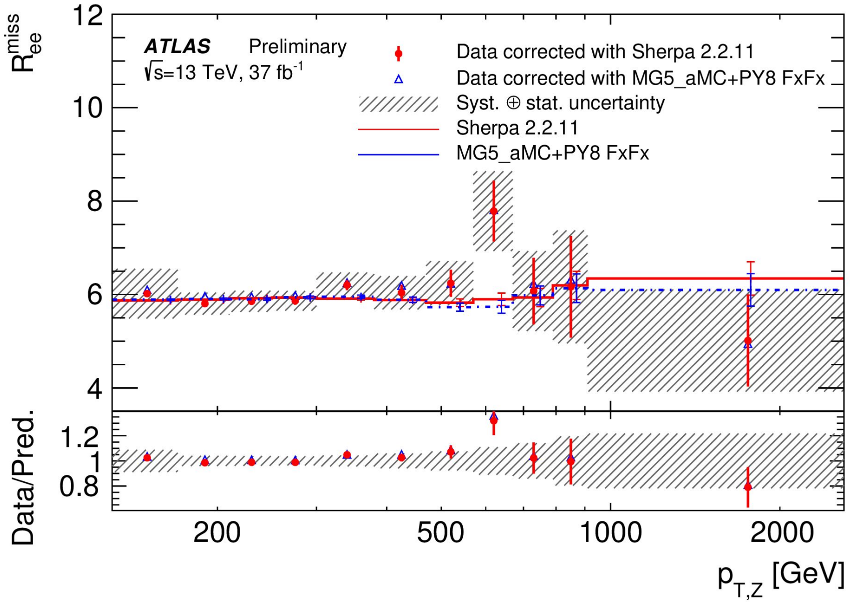
  - data to prediction comparisons in W(→μ**v**) + jets and W(→e**v**) + jets events as a function of $p_{T, Z}$ CRs

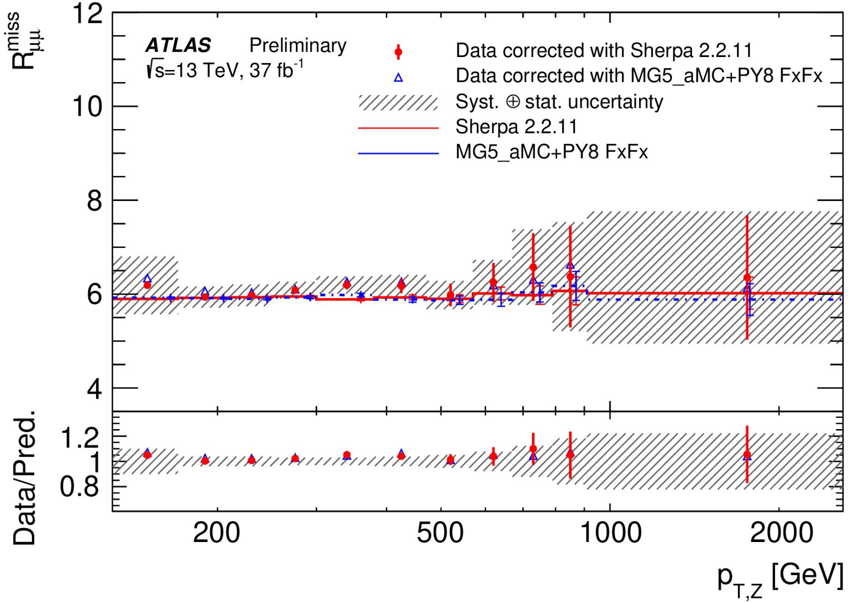
- Other backgrounds include multi-jet, top production, diboson production, Z→ ll, non-collision events

RESULTS: R^{miss}

$$R^{\text{miss}}(p_{\text{T,Z}}) \equiv \frac{\frac{d\sigma(Z(\rightarrow \text{inv})+\text{jets})}{dp_{\text{T,Z}}}}{\frac{d\sigma(Z(\rightarrow \ell\ell)+\text{jets})}{dp_{\text{T,Z}}}} = \frac{\frac{d\sigma(Z+\text{jets})\times BR(Z\rightarrow \text{inv})}{dp_{\text{T,Z}}}}{\frac{d\sigma(Z+\text{jets})\times BR(Z\rightarrow \ell\ell)}{dp_{\text{T,Z}}}}$$

- Both, numerator and denominator, extrapolated to common phase space
  - At least one jet, with pT > 110 GeV, eta < 2.4
  - $p_{T,Z}$ > 130 GeV





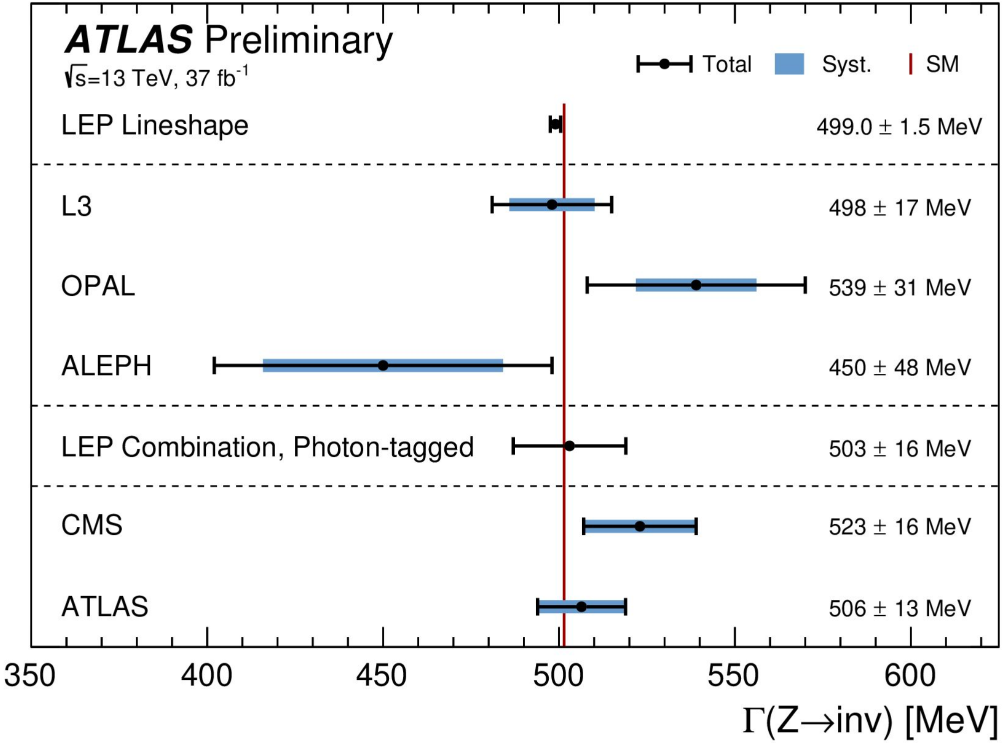
- Measured R^{miss} of electrons and muons as a function of $p_{T,Z}$ in the corrected phase space

RESULTS: Γ(Z → inv)

- Comparison of **Γ**(Z → inv) by LEP experiments: L3, OPAL, ALEPH, CMS and ATLAS

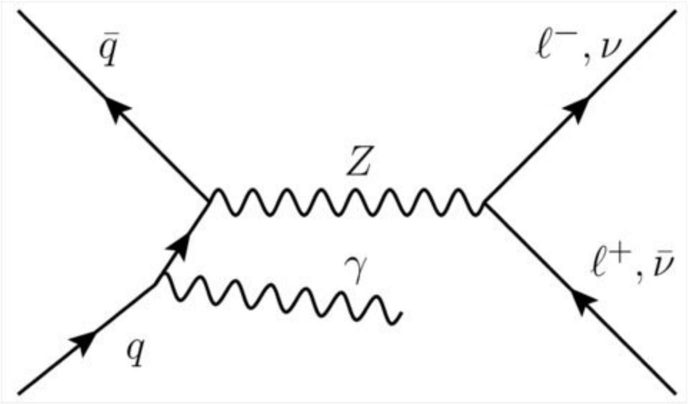
- ATLAS result:
  Γ(Z → inv) = 506 ± 2(stat.) ± 12(syst.) MeV
  - Most precise result for recoil based final states
  - Dominated by systematic uncertainties
    - Lepton uncertainties

- Good agreement b.w LHC and LEP results as well as good compatibility with SM



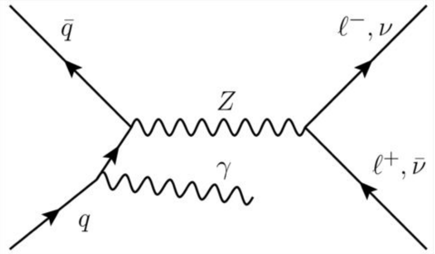
MEASUREMENT OF Zɣ+JETS DIFFERENTIAL CROSS-SECTION

Published in JHEP 07(2023) 72
Full run 2 dataset 139 fb^{-1}

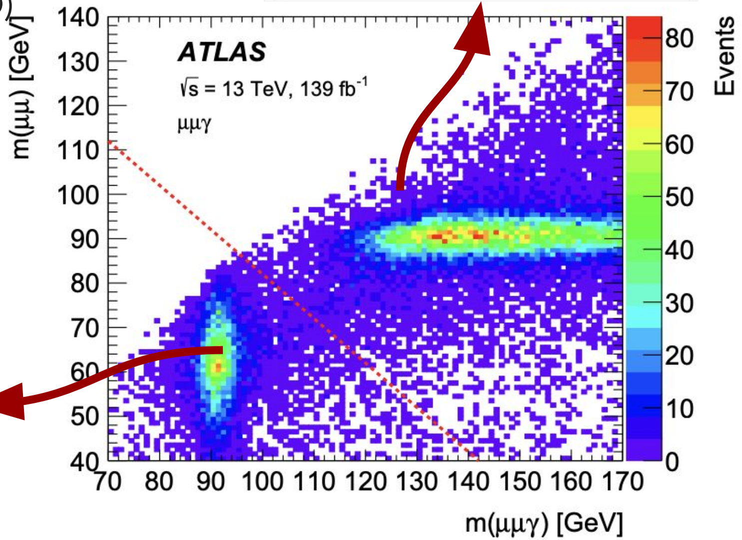


MOTIVATION and STRATEGY

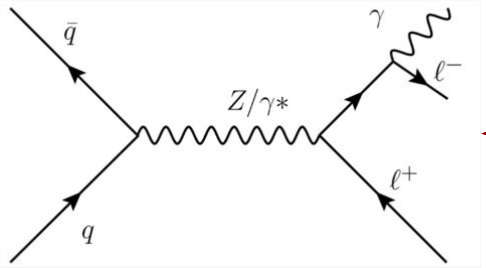
- Precision measurement of cross-section plays crucial role in studying SM and have sensitivity to BSM physics
  - differential cross-sections for $Z\gamma$+ jets can help to test fixed-order perturbative QCD
  - sensitive to PDFs and can help validate PDFs extracted from global analyses
  - constrain MC models
  - constrain ALPs couplings to Z boson and photon
  - presence of jets in final state allows for study of EFTs



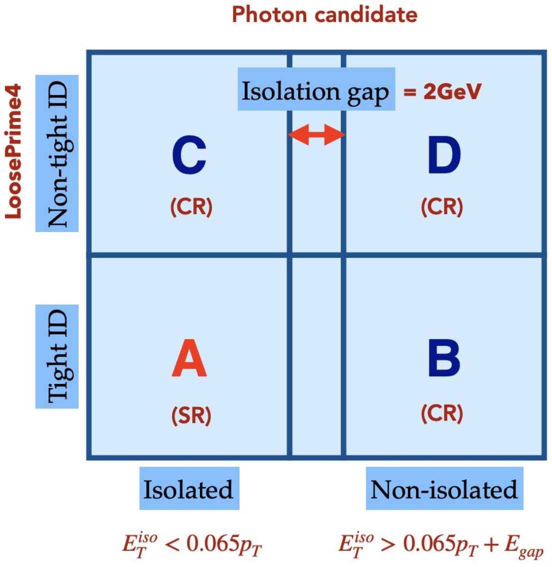
- Measurements of differential cross sections as functions of QCD-related observables
  - hard variables: hard scale of the process (non-zero @LO)
    - H_T, p_T ll, etc
  - resolution variables: sensitive to QCD variations
    - $p_T^{ll\gamma} / m_{ll\gamma}$ in slices of $m_{ll\gamma}$ etc



Only consider Z bosons decaying into l^+l^- (l=e,μ)
p_T $l_1(l_2)$ > 20(25) GeV
m_{ll} > 40 GeV
m_{ll} + $m_{ll\gamma}$ > 182 GeV
SR: 2 OSSS leptons



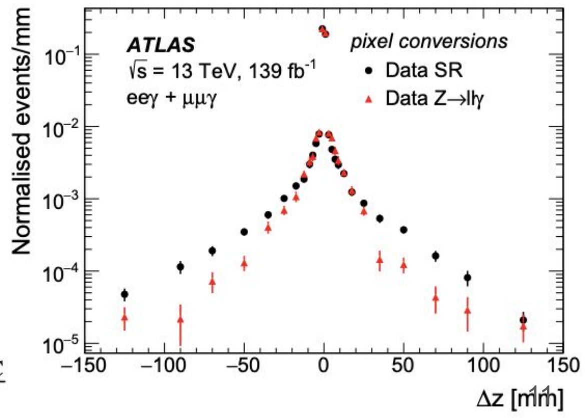
BACKGROUNDS: DATA DRIVEN



- Z+jets
  - dominant background - one of the jets is misidentified as a photon
  - 3 Z+jets CR's constructed by inverting photon isolation and/or ID criteria
  - Signal leakage fraction estimated using simulation
  - correlation factor: $R = \dfrac{N_A^{Z+jets} \times N_D^{Z+jets}}{N_B^{Z+jets} \times N_C^{Z+jets}}$
  - fake estimate: $N^{Z+jets} = (N_A^{data} - N_A^{bkg}) \text{ X } \dfrac{(1 - N_A^{sig})}{N_A^{data} - N_A^{bkg}}$

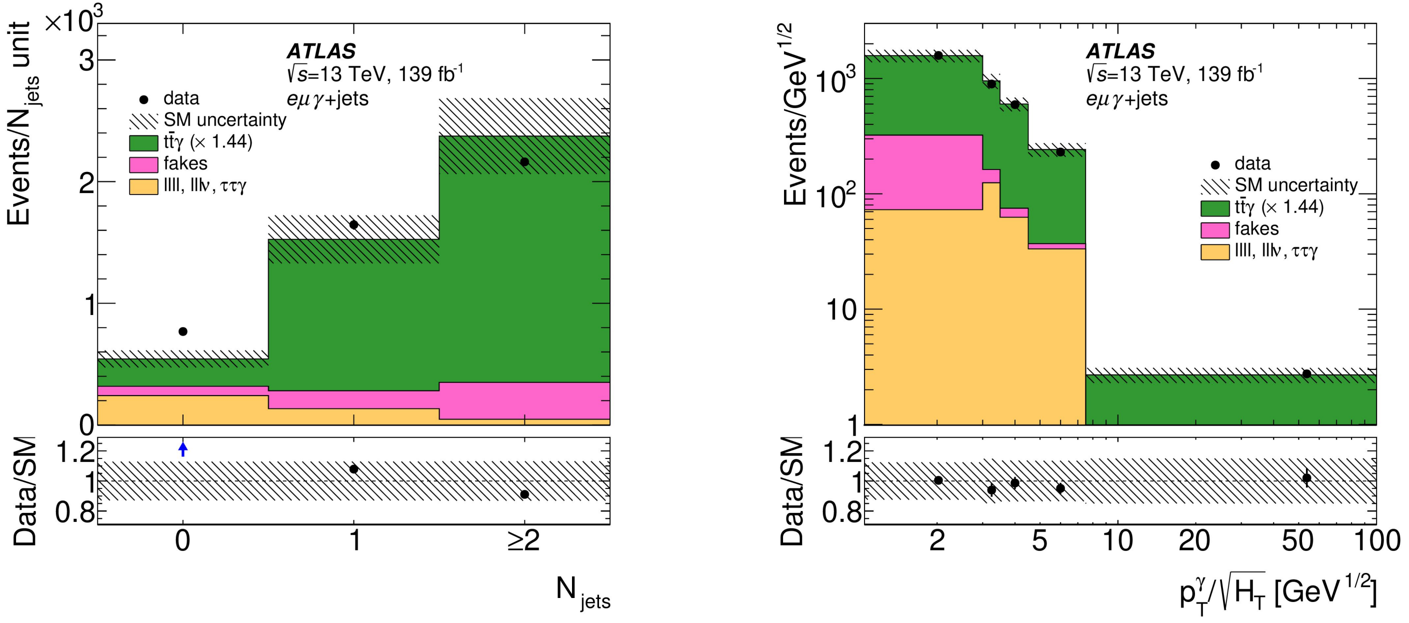
- Pileup
  - selected photons may originate from different pp collisions in the same bunch crossing
  - photons come from a vertex different from leptons
  - $\Delta Z = Z_{PV} - Z_{\gamma}$ wider in pileup events than in signal pp events
  - estimated through pileup fraction: $N_{PU} = f_{PU} * N_{data}$

$$f_{\mathrm{PU}} = \frac{1}{N_{\mathrm{data}}} \cdot \frac{N_{\mathrm{data}}^{\mathrm{PU}} - N_{\mathrm{MC}}^{\mathrm{PU}}}{P_{\mathrm{PU}}}$$



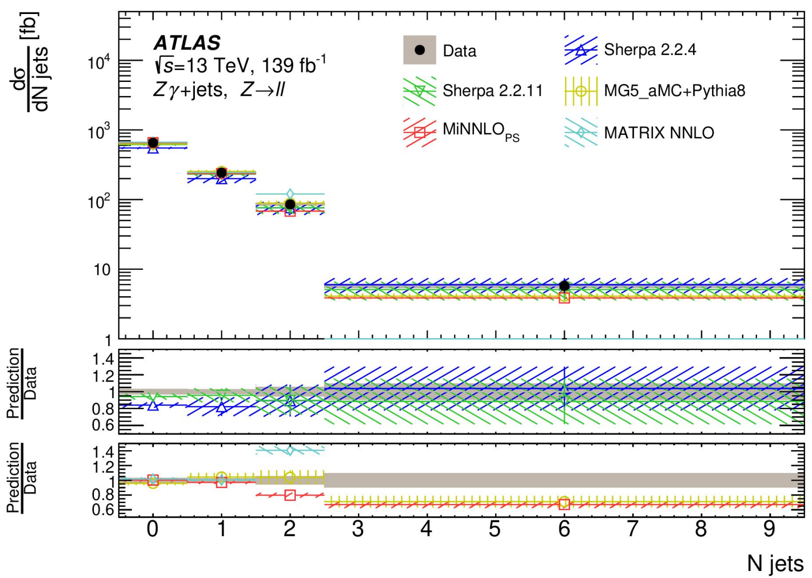
BACKGROUND ESTIMATION: SIMULATION

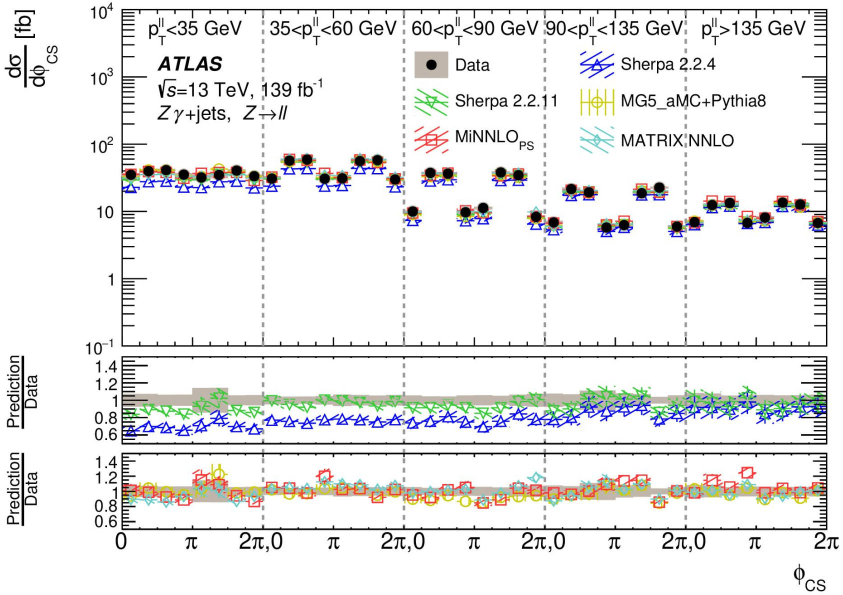
- ttγ, triboson, diboson background estimated using simulation
- ttγ estimated using dedicated CR
  - construct eμγ channel as CR (no contribution from Z)
  - Dominated by ttɣ contribution
  - Evaluate fake photon estimation
  - General good agreement observed b.w data and MC in the ttɣ CR



RESULTS: COMPARISON OF UNFOLDED RESULTS W. THEORY

- Compare results of unfolding with theoretical predictions from
  - Calculations of Sherpa 2.2.4, Sherpa 2.2.11, MadGraph
  - NNLO prediction of MiNNLO_{PS}
  - NNLO fixed order calculation MATRIX





- Sherpa and MadGraph generally describe the data well
  - Sherpa 2.2.11 agreement better than Sherpa 2.2.4
  - Sherpa underestimates total cross-section

PRODUCTION OF W BOSON IN ASSOCIATION WITH A CHARMED HADRON

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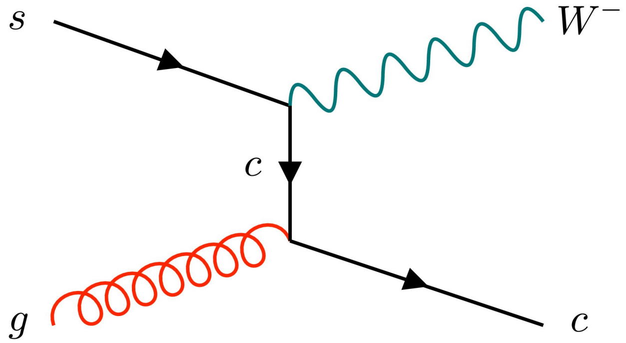
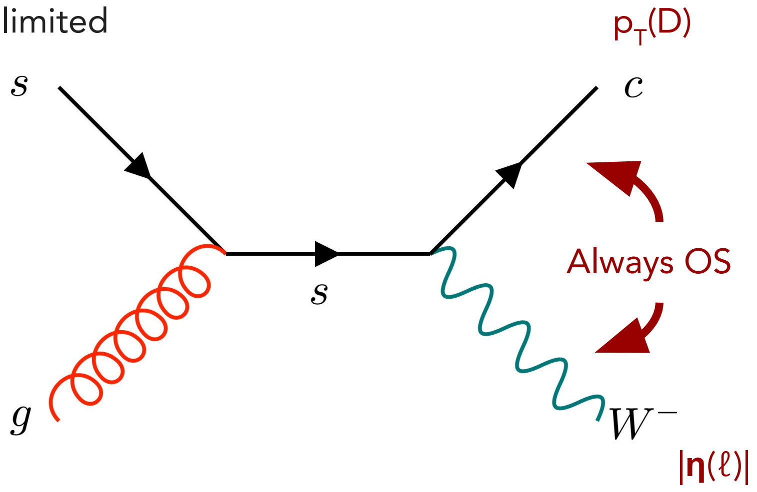
Full run 2 dataset 139 fb^{-1}



MOTIVATION and STRATEGY

- Current information about strange quarks in the proton is limited
- gs → Wc is the dominant production mode
  - sensitive to s-quark PDF
- Crucial for constraining PDF uncertainties



- Reconstruct $D^+ \to K^-\pi^+\pi^+$ and $D^{*+} \to K^-\pi^+\pi^+$ with a secondary vertex fit (Kalman filter)
  - D candidates reconstructed from 3 displaced vertices
- Signal produces W + D of opposite charge
- Background mostly symmetric in charge
- Extract signal from OS - SS candidates

- Extract differential cross-sections with multiple likelihood fits: 5 bins in $p_T(D)$ and 5 bins in $|\boldsymbol{\eta}(\ell)|$
- Fit invariant mass $m(D^+)$ $m(D^{*+} - D_0)$ in each differential bin
  - Complex likelihood fit with 10 POIs and > 300 NPs

BACKGROUND ESTIMATION

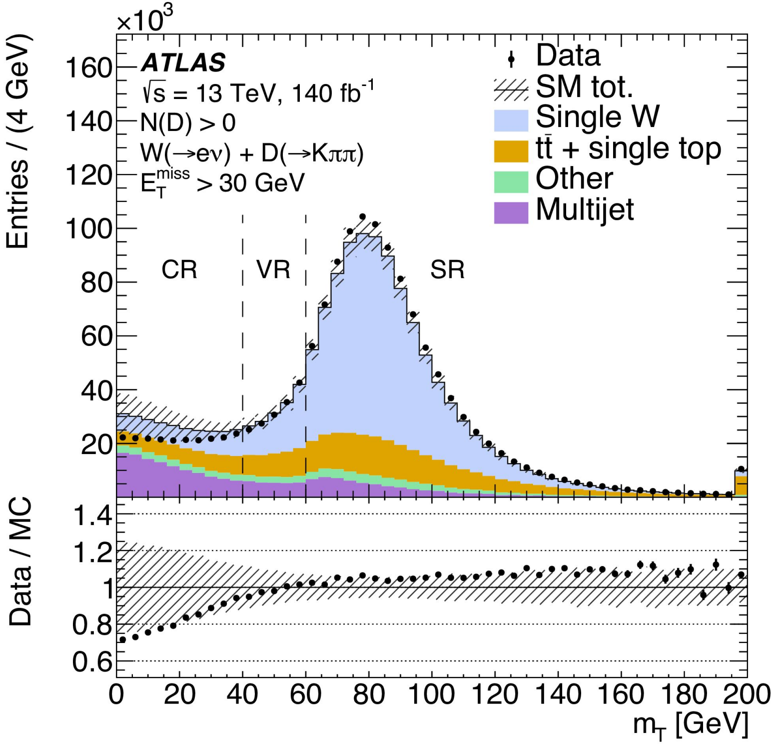
- tt, single-top Wt, single-top s-channel, t-channel, tt+V , VV
  - Estimated using simulation

- Multijet backgrounds arise if one or more jet constituents mis-reconstructed as prompt lepton

- Electron channel: mis-ID hadrons, converted photons, semi-leptonic heavy-flavor decays
- Muon channel: muons from heavy-flavor hadron decays

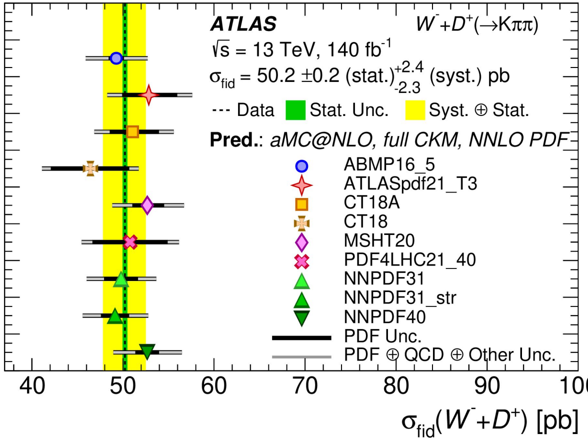
- Matrix method: measure fake/real lepton efficiencies and estimate multi-jet estimation from Anti-Tight data
- Fake CR to measure fake lepton efficiency
  - Inverted W selection: MET < 30 GeV, mT < 40 GeV
  - Select anti-tight leptons by inverting isolation requirement

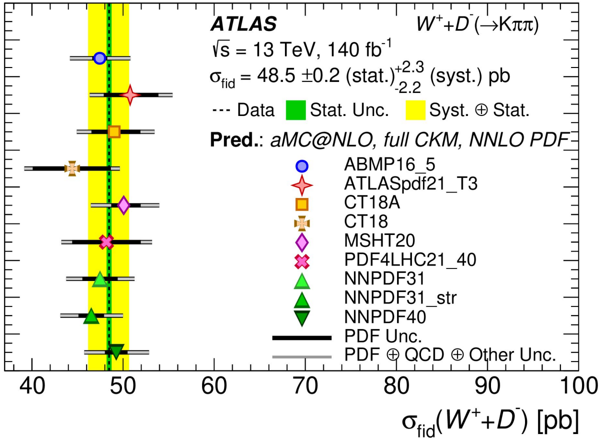
- Fake efficiency depends on MET
  - Additional CR defined with MET > 30 GeV, mT < 40 GeV
- Validation region: MET > 30 GeV, 40 < mT < 60 GeV
- Extrapolated into SR: MET > 30 GeV, mT > 60 GeV



RESULTS: INTEGRATED CROSS SECTION and R_C

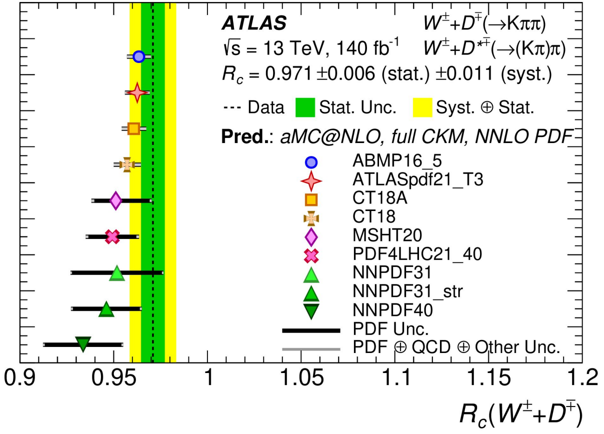
Channel	$\sigma_{\text{fid}}^{\text{OS-SS}}(W{+}D^{(*)}) \times B(W \to \ell\nu)$ [pb]
$W^-{+}D^+$	50.2 ± 0.2 (stat.) $^{+2.4}_{-2.3}$ (syst.)
$W^+{+}D^-$	48.5 ± 0.2 (stat.) $^{+2.3}_{-2.2}$ (syst.)
$W^-{+}D^{*+}$	51.1 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
$W^+{+}D^{*-}$	50.0 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
	$R_c^{\pm} = \sigma_{\text{fid}}^{\text{OS-SS}}(W^+{+}D^{(*)}) / \sigma_{\text{fid}}^{\text{OS-SS}}(W^-{+}D^{(*)})$
$R_c^{\pm}(D^+)$	0.965 ± 0.007 (stat.) ± 0.012 (syst.)
$R_c^{\pm}(D^{*+})$	0.980 ± 0.010 (stat.) ± 0.013 (syst.)
$R_c^{\pm}(D^{(*)})$	0.971 ± 0.006 (stat.) ± 0.011 (syst.)





- Measured fiducial cross-section times the single-lepton-flavor W branching ratio compared with different NNLO PDF predictions

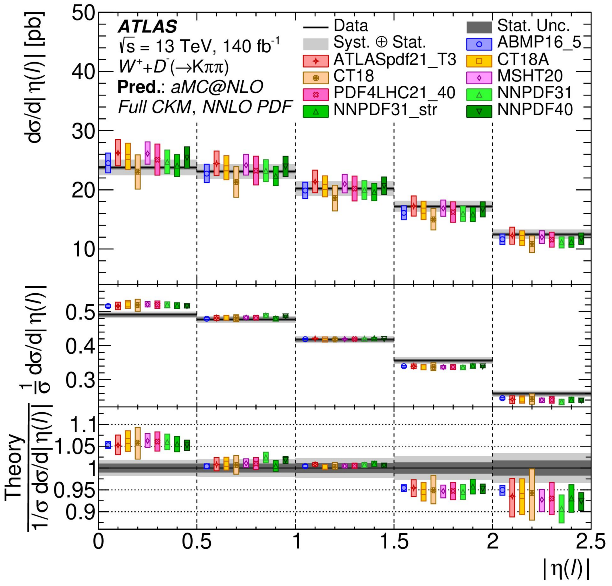
- Ratio between charge-configurations also measured
    - consistent with symmetric strange sea
    - comparable precision

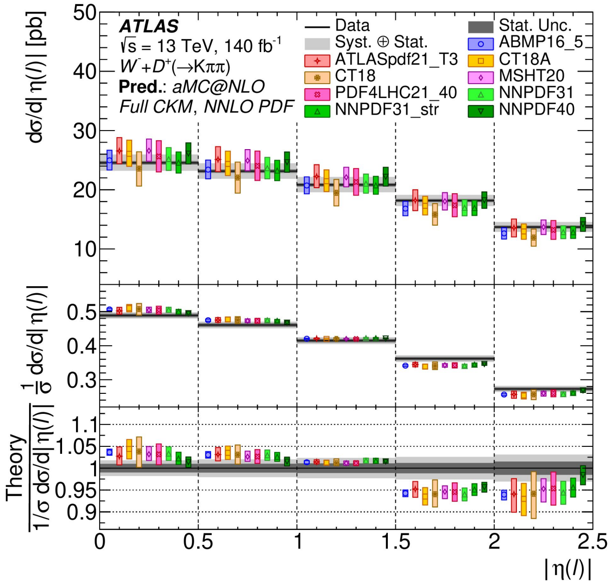


RESULTS: DIFFERENTIAL CROSS SECTION

- 8 differential cross-sections:
  [W-, W+] **×** [D+, D*] **×** [pT(D), **η**(lep)]

- Absolute cross-section matches well with data, but shape difference in **η**(lep) can be observed!





- Same trends in W- and W+ channels and D+ and D* channels
- Data **η**(lep) less central than predictions

LHC HAS DELIVERED A LARGE AND HIGH QUALITY ***pp*** COLLISIONS DATASET

ATLAS HAS ENORMOUS AND WIDE VARIETY OF WORK TO UNDERSTAND THE W AND Z BOSON PRODUCTION AND OBTAIN INTERESTING RESULTS

RUN-2 ANALYSES STILL IN PROGRESS AND RUN-3 EFFORTS HAVE STARTED

STAY TUNED FOR MORE RESULTS!