Recent SM EW results from LHC

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December 21, 2018

Introduction

- SM is a relativistic renormalizable quantum theory of 12 fermions with 3 forces mediated by spin-1 gauge bosons
- $SU(2) \times U(1)$ gauge symmetry is spontaneously broken
  $\rightarrow$ massive $W^{\pm}$ and Z bosons

- All SM parameters are measured experimentally (except for some of neutrino parameters):
  - α_{QCD}
  - fermion masses and mixing
  - m_H, m_Z, G_F, fine structure constant
- SM predictions $\sim$agree with data
- **SM is self-consistent but not complete**

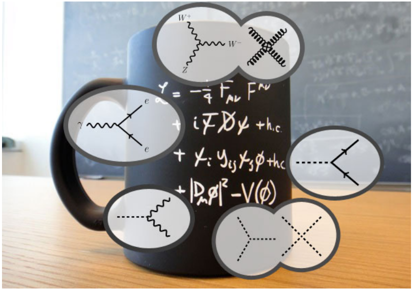
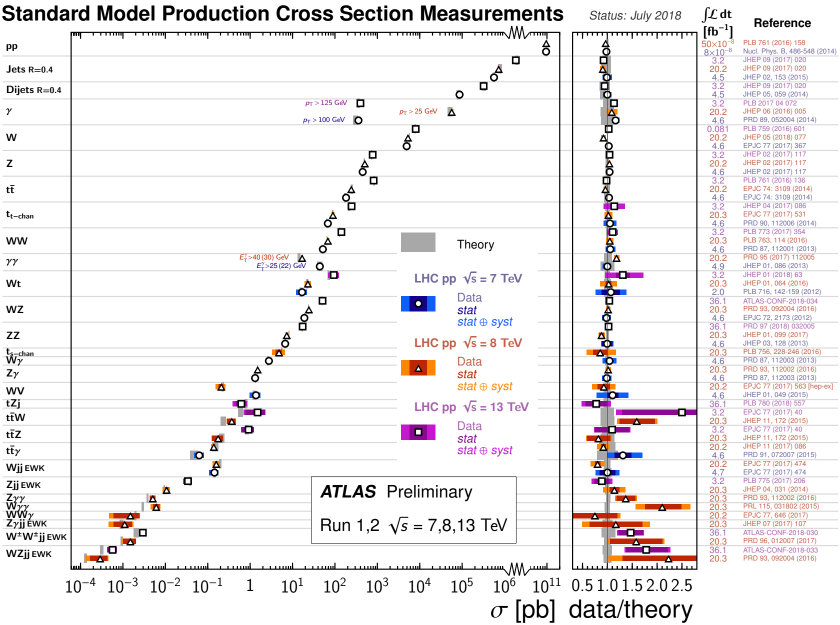


Image by Flip Tanedo

SM EW measurements

- Long history of EW measurements at colliders:
  - SPS, SLC, LEP, Tevatron
  - LEP still provides most precise measurements of W and Z parameters
- Some of LHC unique capabilities:
  - Higgs boson properties
  - More precise measurements of top quark properties
  - *Observation of rare processes in pp collisions*
  - *Test perturbative SM calculations at the EW scale*
- This presentation:
  - Highlights of recent ATLAS and CMS EW measurements
  - Focus on new results released since the previous CLHCP

N(experimental observables) >> N(SM parameters)



Outline of this presentation

Di-boson production measurements

- Probe gauge structure of SM with high precision
- Sensitive to gauge boson triple coupling
- **Results at 13 TeV: $Z\gamma$ and WZ cross sections**

Vector Boson Scattering

- Sensitive to gauge boson quartic coupling
- **Results at 13 TeV: electroweak production of WZ and same sign WW**

Z boson differential cross sections

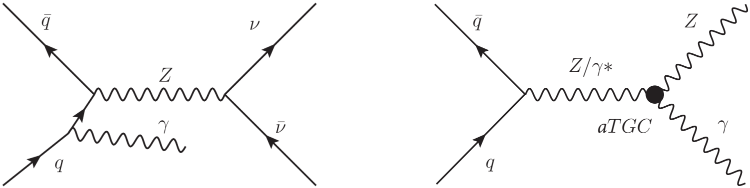
- **Effective leptonic weak mixing angle sin$\theta^{l}_{\mathrm{eff}}$ with 8 TeV data**

Neutral gauge boson self-couplings are absent at tree level in SM:

- $ZZ\gamma$, ZZZ, $ZZ\gamma\gamma$, $ZZZZ$...

$Z\gamma \rightarrow \nu\nu\gamma$ production at LHC is possible via initial state radiation

- Measure $Z\gamma \rightarrow \nu\nu\gamma$ cross section to probe for neutral self-couplings

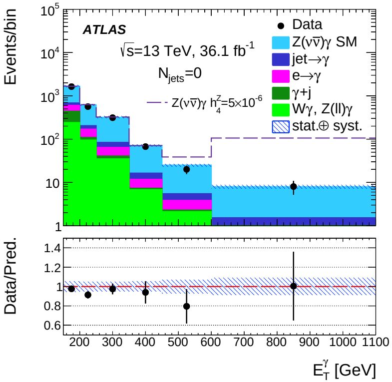


Experimental final state:

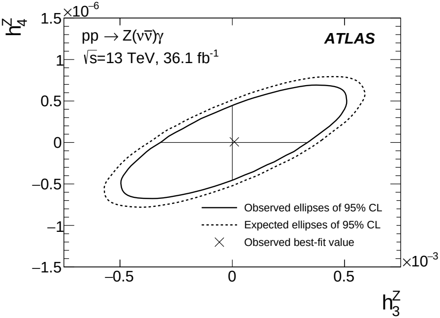
- Photon with $p_T > 150$ GeV plus high missing transverse momentum greater than 150 GeV
- $\mathcal{B}(Z \rightarrow \nu\nu) = 20\%$ - more events at high p_T^Z compared to $Z\gamma \rightarrow l^+l^-\gamma$

$Z\gamma \to \nu\nu\gamma$ cross section

- Measured fiducial cross section: $\sigma^{\text{ext.fid.}}_{Data} = 83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.) fb
  - NNLO in QCD MCFM prediction: $\sigma^{\text{ext.fid.}}_{MCFM} = 78.1 \pm 0.2 \pm 4.4$ fb
  - Dominant uncertainty due to mismodelling of photon efficiency and energy scale
  - Presented yesterday by Dimitrii Krasnopevtsev
- Also measured differential cross sections: inclusive and $N_{\text{jet}} = 0$
- Set limits on anomolous $ZZ\gamma$ ($h^Z_{3,4}$) and $Z\gamma\gamma$ ($h^\gamma_{3,4}$) couplings - factor of 3-7 improvements

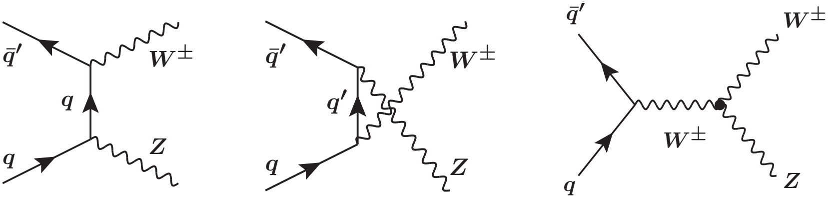


[New ATLAS results submitted to JHEP](#)



Charged gauge boson self-couplings are present at tree level in SM:

- Quartic couplings: $WWZZ$, $WWWW$, $WWZ\gamma$, $WW\gamma\gamma$
- Triple couplings: WWZ, $WW\gamma$



$W^{\pm}Z$ cross section and gauge boson polarisation

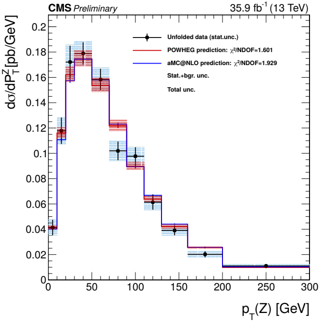
- Sensitive to anomalous triple gauge boson couplings
- Select leptonic decays for clean experimental detection: $W^{\pm}Z \to l^{\pm}\nu l^{+}l^{-}$

$W^{\pm}Z$ cross section

- $W^{\pm}Z$ total cross section measured by CMS:
  - Measured: $\sigma_{W^{\pm}Z} = 48.09^{+1.00}_{-0.96}(\mathrm{stat})^{+0.44}_{-0.37}(\mathrm{theo})^{+2.39}_{-2.17}(\mathrm{syst}) \pm 1.39(\mathrm{lumi})$ pb
  - MATRIX: $\sigma_{W^{\pm}Z} = 49.98^{+1.1}_{-1.0}$ pb (NNLO in perturbative QCD)
- Also measure precise fiducial and differential cross sections
- Experimental uncertainty is reduced for $W^{+}Z/W^{-}Z$ ratio - comparable to NNLO accuracy

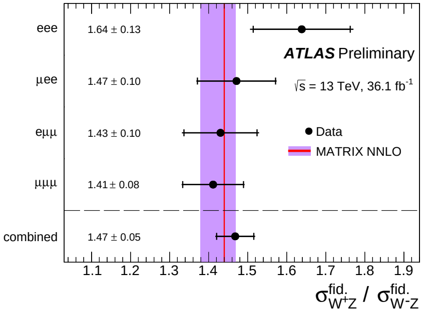
Differential p_Z cross section

CMS-PAS-SMP-18-002



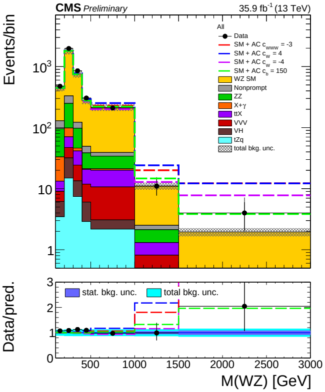
Measure $W^{+}Z/W^{-}Z$ ratio

ATLAS-CONF-2018-034



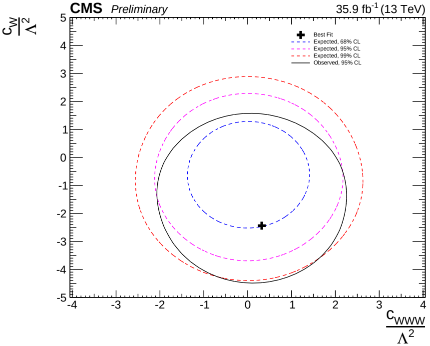
$W^{\pm}Z$: limits on anomalous couplings

- CMS set limits on anomalous couplings using Effective Field Theory approach:
  $\delta\mathcal{L}_{\mathrm{AC}} = c_{WWW} \times Tr[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + c_W \times (D_\mu H)^\dagger W^{\mu\nu}(D_\nu H) + c_b \times (D_\mu H)^\dagger B^{\mu\nu}(D_\nu H)$
- Test m_{WZ} distribution for deviations from SM predictions

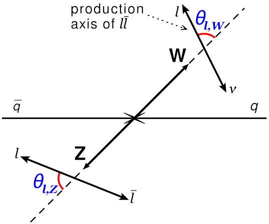


Anomalous coupling limits

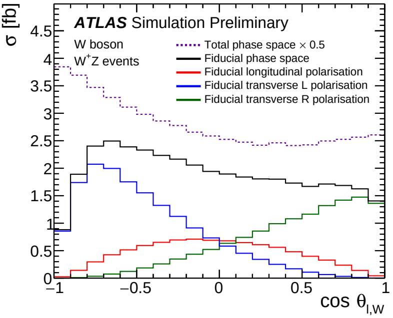
CMS-PAS-SMP-18-002

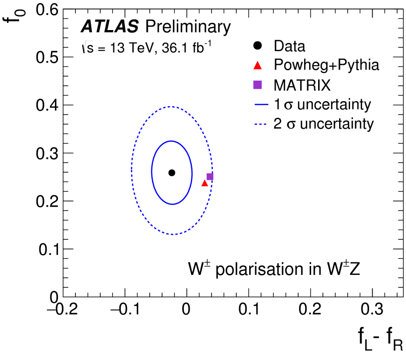


W and *Z* polarisation measurement

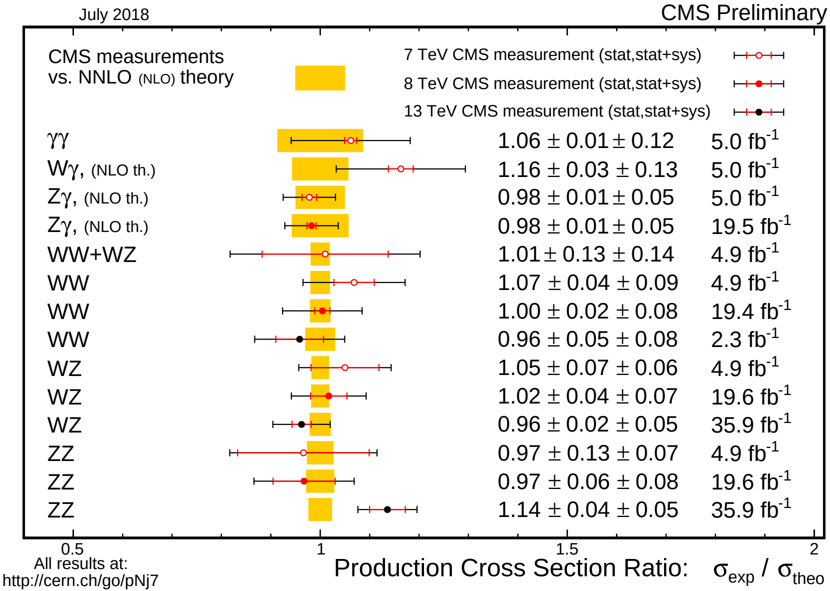


- Measure W/Z polarisation using lepton angular distributions
- f_0, f_L and f_R define the longitudinal, transverse-left handed and transverse-right handed helicity fractions at Born level
- Observed (expected) significance of 4.2σ (3.8σ) for longitudinally polarised W bosons
- Sensitive to new broad resonances not seen by direct searches



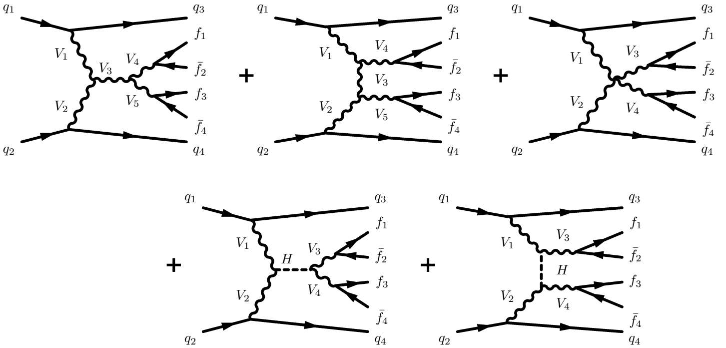


Di-boson measurements from both experiments agree with SM predictions



Electroweak production of $W^{\pm}Z$ and same sign $W^{\pm}W^{\pm}$ bosons

- Also referred to as Vector Boson Scattering
- Sensitive to self-interactions of gauge bosons
- Unitarity at high energies requires presence of the SM Higgs boson



Vector Boson Scattering experimental signature:

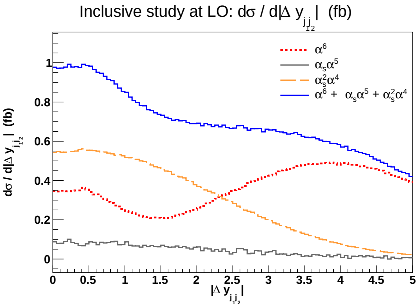
- 2 jets with rapidity gap and large di-jet invariant mass

– Summary of VBS analyses at LHC presented yesterday by Elena Yatsenko

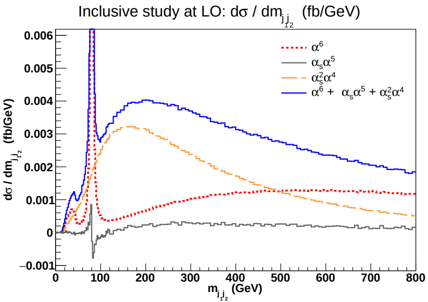
Phenomenology highlights for $W^\pm W^\pm jj$ VBS

- $W^\pm W^\pm jj$ electroweak production at LO - α^6: VBS signal
  - 2 jets with rapidity gap and large invariant mass
  - Same sign requirement suppresses high rate SM background processes
- $W^\pm W^\pm jj$ QCD production at LO - $\alpha^4\alpha_S^2$: dominant background
- Interference between VBS and QCD processes at LO - $\alpha^5\alpha_S$: ∼percents in VBS signal region
- $W^\pm W^\pm jj$ has the largest electroweak to strong production cross section ratio
  - Complete NLO correction in signal region is -17.1% 1708.00268
  - At NLO, cannot unambiguously separate EW VBS and QCD background processes

Di-jet rapidity difference 1803.07943



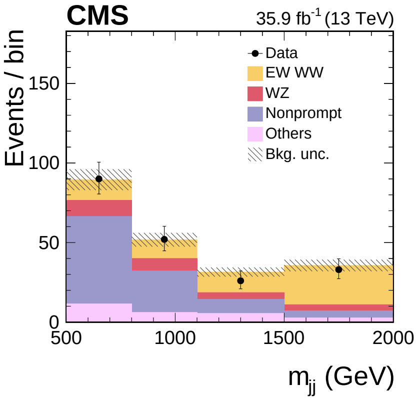
Di-jet invariant mass 1803.07943



Observation of $W^{\pm}W^{\pm}jj$ electroweak production

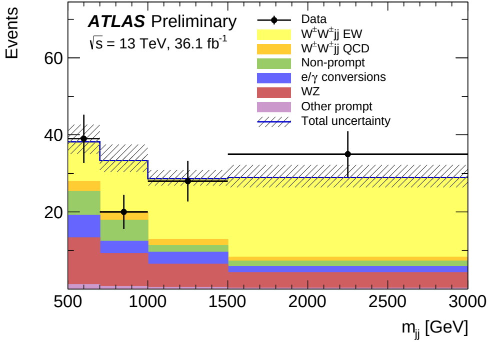
- Both experiments reported observation of $W^{\pm}W^{\pm}jj$ electroweak production
  - Enhancement of data events at high m_{jj} values - classical VBS signature
  - Measurement uncertainty is dominated by statistical data uncertainty
  - Mis-identified leptons are important experimental background

Observed significance 5.5σ



Observed significance 6.9σ

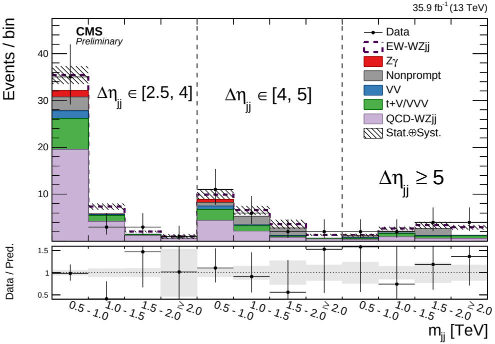
Presented yesterday by Liqing Zhang



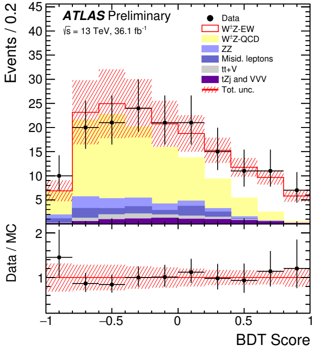
Measurements of $W^{\pm}Zjj$ electroweak production

- CMS performs 2d fit using m_{jj} and $\Delta\eta_{jj}$ variables
  - $W^{\pm}Zjj$ QCD background process normalised from data: $\mu^{QCD}_{W^{\pm}Zjj} \sim 1$
- ATLAS performs multi-variate analysis - 15 kinematic variables to select $W^{\pm}Zjj$ VBS signal
  - $W^{\pm}Zjj$ QCD background process normalised from data: $\mu^{QCD}_{W^{\pm}Zjj} = 0.60 \pm 0.25$

Obs. (exp.) significance 1.9σ (2.7σ)



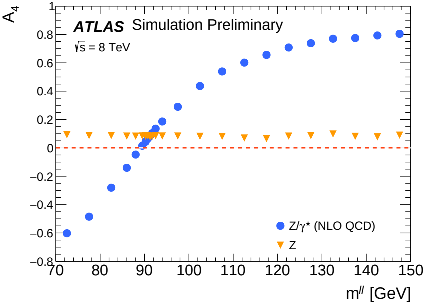
Obs. (exp.) significance 5.6σ (3.3σ)

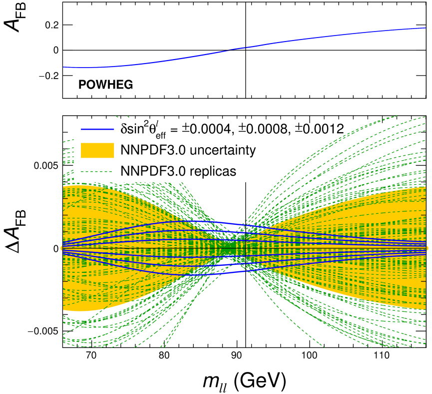


Effective leptonic weak mixing angle

- Measure $sin^2\theta^f_{eff}$ via fermion spin correlations in $q\bar{q} \to Z/\gamma^* \to l^+l^-$ process
  - $sin^2\theta^f_{eff} = \kappa_f \times sin^2\theta_W$, where κ_f includes EW corrections
- Experiments measure **Forward-Backward** asymmetry: $A_{FB} = \frac{3}{8}A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F - \sigma_B}$
  forward and backward hemispheres defined in Collins-Soper frame of the dilepton system
- At LO for given m_{ll} value: $\frac{d\sigma}{d(cos\theta^*)} \propto 1 + cos^2\theta^* + A_4 cos\theta^*$
- Different u/d quark PDF contributions and couplings to EW bosons generate A_{FB}

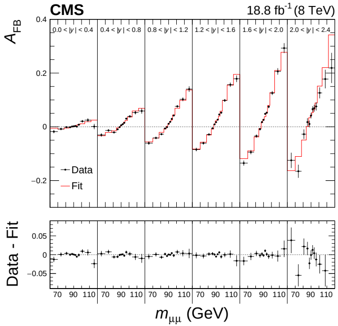
Strong dependence of A_{FB} on m_{ll} is due to axial and vector interference

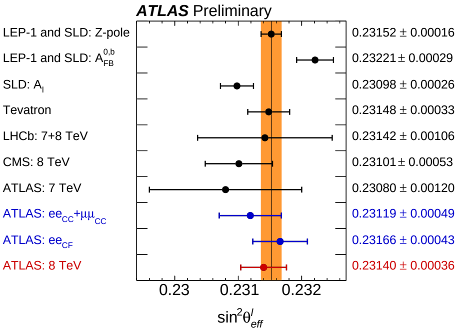




Effective leptonic mixing angle: results

- **Perform measurements using two dimensional bins of dilepton rapidity and invariant mass**
  - CMS fit constrains systematic uncertainty due to Parton Density Functions
  - ATLAS includes forward electrons with $2.5 < |\eta| < 4.9$ that enhance sensitivity
  - ATLAS result is checked with triple-differential Z/γ^* cross section measurements
- PDF is dominant systematic uncertainty - comparable to statistical uncertainty
- Using $\sim$20 fb^{-1} recorded at 8 TeV - factor of $\sim$7 more data recorded at 13 TeV
  Z differential measurements at 13 TeV were presented yesterday by Qun Wang





ATLAS: $\theta^l_{eff} = 0.23140 \pm 0.00021\ (\text{stat.}) \pm 0.00024\ (\text{PDF}) \pm 0.00016\ (\text{syst.})$

CMS: $\theta^l_{eff} = 0.23101 \pm 0.00036\ (\text{stat.}) \pm 0.00031\ (\text{PDF}) \pm 0.00018\ (\text{syst.}) \pm 0.00016\ (\text{theo.})$

Summary and conclusions

- Presented recent LHC results probing EW sector of the SM
  - $Z\gamma \to \nu\nu\gamma$ cross section measurement and anomalous coupling tests
  - $W^{\pm}Z$ cross section and gauge boson polarisation measurements
  - Measurements of electroweak production of same-sign WW
  - Measurements of electroweak production of WZ bosons
  - Measurements of effective leptonic mixing angle
- So far, measurements agree with SM predictions at NNLO or NLO
- These and other measurements will be improved with full Run 2 dataset
- More measurements in pipeline - other diboson states, triboson, etc
- Thank you and stay tuned for more results!