Standard Model Measurements with CMS

Norbert Neumeister

On behalf of the CMS Collaboration
Outline

• Introduction
• QCD
  – Inclusive jet cross sections
  – Di-jet cross sections
  – PDF constraints
  – Measurement of $\alpha_s$
  – 2-, 3-, 4-jet azimuthal correlations
• Electroweak
  – Inclusive Z/W production
  – Z/W + jets
  – Differential cross sections and PDFs
  – Di-boson production
  – aTGC and aQGC
• Summary
Introduction

- **SM precision measurements are important at the LHC**
  - test a wide range of QCD and EW predictions to the highest energies available
  - tune theoretical calculations and MC generators
  - provide precise modeling of backgrounds to many searches

- any deviation from the SM expectation may be a sign of new physics!

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**CMS Preliminary**

August 2017

Test of the SM over ~10 orders of magnitude

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 13 TeV CMS measurement ($L \leq 35.9 \text{ fb}^{-1}$)

Theory prediction

CMS 95%CL limits at 7, 8 and 13 TeV

All results at: http://cern.ch/go/pNj7

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LHC Performance

• About 40 fb\(^{-1}\) has been delivered by the LHC in 2016, exceeding the integrated luminosity accumulated in all years before 2016 and expectations.

• The CMS detectors has been working spectacularly with virtually no degradation in performance over the 3 years of Run 1 and 2 years of Run 2.

• 7 TeV: 6 fb\(^{-1}\) (2010-11)
• 8 TeV: 23 fb\(^{-1}\) (2012)
• 13 TeV: 4 fb\(^{-1}\) (2015) + 40 fb\(^{-1}\) (2016)
Inclusive Jet Production

- Double and triple-differential jet cross section measurements at 8 TeV and 13 TeV
  - Use anti-$k_T$ clustering algorithm with $R = 0.7$ or 0.4 → test radiative and non-perturbative effects
  - 7 orders of magnitude, for jet $p_T$ up to ~ 2 TeV and $|y|=4.7$
  - Good agreement with NLO QCD predictions + NLO EW + non-perturbative calculations
Di-Jet Production

• Triple differential cross sections \( (p_{T, \text{avg}}, y^*, y_b) \), sensitive to different subprocesses and overlapping \((x,Q)\) regions in PDFs

• Compared to NLOJet++ (with non-perturbative and EW effects)
  – in agreement with NLO predictions
  – used to constraint PDFs
  – used to extract \( \alpha_s \)

\[
y^* = \frac{1}{2} |y_1 - y_2|
\]

\[
y_b = \frac{1}{2} |y_1 + y_2|
\]
Jet Mass Measurement

- Jet mass is sensitive to internal structure of jets
- Double-differential jet cross section measured as a function of the jet mass and jet $p_T$ in events with a dijet topology
  - with and without a jet grooming algorithm applied that removes low-energy portions from a jet.
  - for ungroomed jets, all Monte Carlo event generators are found to predict the jet mass spectrum within uncertainties in the data for intermediate masses of about 10-30% of the jet transverse momentum.
PDF Constraints

- Considering high $|y_1 + y_2|$, high $p_T$ allows access to high $x$ values
  - Constrain PDF at high $x$ (theory uncertainties are larger than experimental)
  - Reduces PDF uncertainties, specially the gluon PDF, in the boosted regime (high $|y_1+y_2|$, high $p_T$), where large $x$ are probed
  - It also changes the gluon PDF shape for low $Q^2$

![PDF Constraints Diagram](image-url)
Measurement of $\alpha_s$  

- Use ratio of inclusive two- and three-jet event cross sections ($R_{32}$) to extract $\alpha_s$ at $M_Z$

  - Minimize $\chi^2$ of the fit of theoretical predictions to data

$\alpha_s(M_Z) = 0.1150 \pm 0.0010 \text{ (exp)} \pm 0.0013 \text{ (PDF)} \pm 0.0015 \text{ (NP)} - 0.0000 \pm 0.0050 \text{ (scale)}$
2-3-4-Jet Azimuthal Correlations

- Normalized differential cross-section in $\Delta \phi_{1,2}$ of the two leading $p_T$ jets in inclusive 2-, 3-, 4- jets, and in $\Delta \phi_{2j\text{min}}$, the minimum azimuthal angular separation between any two jets in 3-, 4- jet topologies.
  - Sensitive to the radiation of additional jets.
  - Probes the dynamics of multijet production.
  - Results compared to LO and NLO MC generators with various PS tunes.
Improved description from NLO

Herwig7 describes the $\Delta\phi_{1,2}$ cross sections best, while PH2J (POWHEG matched to Herwig++ or Pythia8) describes the $\Delta\phi_{2j}^{\text{min}}$ data best.
Inclusive W/Z Production

• **W and Z decays are special final states:**
  – They are theoretically well understood, unique signatures and have high rate
  – Experimentally the $W \rightarrow l\nu$ and $Z \rightarrow ll$ channels are among the cleanest final states that we can exploit at hadron colliders
  – They are used to understand and calibrate the detector response (trigger, identification, resolution, efficiencies)
  – They are dominant signal and/or background in many searches for new particles

• **Constraints for Parton Distribution Functions**
  – Key ingredient to make theoretical predictions at hadron colliders
  – LHC probes gluons and sea quarks

• **With W/Z we can probe different aspects of QCD calculations**
  – Tests of perturbative QCD and parton emission in a new energy regime
  – Tune Monte Carlo generators in order to better describe the data
Inclusive W/Z Production

- W and Z production at LHC proceeds at the hard scattering level and at first order via collisions of a valence quark (u,d) and a sea anti-quark (Q ≈ 100 GeV):
  \[ u + \overline{d}(s) \rightarrow W^+ \quad u + \overline{u} \rightarrow Z \]
  \[ d + \overline{u}(c) \rightarrow W^- \quad d + \overline{d} \rightarrow Z \]

- Since parton fractions in this process are typically \(10^{-3} < x < 10^{-1}\), sea-sea qq contributions are also important.

- Provide access to central parameters for global EWK fit (masses, couplings, asymmetries).

- Provide powerful constraints for non-perturbative part (PDFs, tunes).

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W and Z Production

- Inclusive W and Z cross section measurements at 7, 8, and 13 TeV
  - Good agreement with NNLO
- Building blocks for a number of physics analyses
  - V+b/c, differential cross sections and many others

CMS-PAS-SMP-15-004
arXiv:1612.03016
Inclusive W Cross Section

- Inclusive W/Z cross sections are measured at $\sqrt{s} = 13\text{ TeV}$, $\int L = 43\text{ pb}^{-1}$
- Electron ($E_T > 25\text{ GeV}$, $|\eta| < 2.5$) and muon ($p_T > 25\text{ GeV}$, $|\eta| < 2.4$) used
- MET fit is used for $W^+$ and $W^-$ signal extraction, respectively
  - Main background is QCD
  - $W \rightarrow \tau\nu$, Drell-Yan, diboson and top-pair production

\[
\sigma(pp \rightarrow W^+ X) \times \mathcal{B}(W^+ \rightarrow \ell^+\nu) = 11370 \pm 50(\text{stat}) \pm 230(\text{syst}) \pm 550(\text{lumi}) \text{ pb}
\]
\[
\sigma(pp \rightarrow W^- X) \times \mathcal{B}(W^- \rightarrow \ell^-\bar{\nu}) = 8580 \pm 50(\text{stat}) \pm 160(\text{syst}) \pm 410(\text{lumi}) \text{ pb}
\]
Inclusive Z Cross Section

- Z signal extraction is estimated using counting method in 60<M(Z)<120 GeV
- Almost background free
- Both total and fiducial cross sections

\[ \sigma(pp \to ZX) \times \mathcal{B}(Z \to \ell^+\ell^-) = 1910 \pm 10\text{(stat)} \pm 40\text{(syst)} \pm 90\text{(lumi)} \text{ pb} \]

- Updated result \( Z \to \mu\mu \) with full dataset and new luminosity:
  \[ \sigma(pp \to ZX) \times \mathcal{B}(Z \to \mu^+\mu^-) = 1870 \pm 2\text{(stat)} \pm 35\text{(syst)} \pm 51\text{(lumi)} \text{ pb} \]

**FEWZ (NNLO, NNPDF3.0) = 1870 \pm 50 \text{ pb}**

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Inclusive W/Z Cross Section

- Measured cross sections agree with next-to-next-to-leading order QCD and next-to-leading order EW calculations.

- Predictions of cross sections calculated for 5 PDF sets:
  - PDFs show differences depending on which data are used in the fit

- Systematic uncertainties:
  - Dominant uncertainty: luminosity (significantly reduced with full statistics)

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<thead>
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<th>Source</th>
<th>W^+</th>
<th>W^-</th>
<th>W^+</th>
<th>W^-</th>
<th>W^+</th>
<th>W^-</th>
<th>Z</th>
<th>Z</th>
<th>W/Z</th>
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<td>1.7</td>
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<td>Total experimental [%]</td>
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<td>1.9</td>
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</table>

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Inclusive W & Z Production

- The experimental precision is already comparable with theoretical uncertainties
  - With current statistics can challenge state-of-the-art theoretical predictions: <1% scale variation at NNLO
- Measure the W/Z, W⁺/W⁻ ratios test pQCD
- Good overall agreement with theory predictions at NNLO

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Lepton Universality

- Ratio of electron- and muon channel $W^\pm$ and $Z$ boson production fiducial cross sections
- $R_Z$ fully dominated by LEP result $0.9991 \pm 0.0024$
Differential Z Cross Section

- Differential $Z \rightarrow \mu\mu$ cross sections measured at $\sqrt{s} = 13$ TeV, $\int L = 2.3$ fb$^{-1}$ (full 2015 dataset)
- Differential cross sections as function of: $p_T(Z)$, $y(Z)$, $p_T(\text{lepton})$, $\phi^*$
  - Low $p_T$: governed by initial-state radiation and intrinsic $p_T$ of initial-state parton inside proton
    - Modeled using soft gluon resummation or parton shower models
  - High $p_T$: dominated by quark-gluon scattering, described by perturbative QCD
- Comparison with aMC@NLO, POWHEG (NLO) and FEWZ (NNLO)
  - FEWZ gives good agreement for $p_T > 25$ GeV
  - POWHEG and aMC@NLO show small deviations
  - Soft gluon resummation is needed to overcome divergences
- Define \( \phi_\eta^* = \tan\left(\frac{\pi - \Delta \phi}{2}\right) \cdot \sin(\theta_\eta^*) \) where \( \cos(\theta_\eta^*) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right) \)

- Probes Z boson \( P_T \), but depends on direction of muon → smaller exp. uncertainty

- POWHEG shows good agreement in very low \( \phi^* \) region
\( \text{d}\sigma/\text{d}p_T^\mu \)

- \( p_T \) distribution of Z boson
  - Muons with \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.4 \)
  - Relative isolation in a cone of radius \( \Delta R = 0.4 \) with an isolation selection requirement of less than 15%
  - \( 60 \text{ GeV} < M_Z < 120 \text{ GeV} \)

- No generator is able to describe the data in all of the studied phase-space

![Data, aMC@NLO, POWHEG, FEWZ comparison](image)

CMS-PAS-SMP-15-011
Drell-Yan $d\sigma/dm$

- Differential Drell-Yan cross section measured at $\sqrt{s} = 13$ TeV with $\int L = 2.8$ fb$^{-1}$ of data
- Only $\mu\mu$ final states; Muons with $p_T > 22$ (10) GeV and $|\eta| < 2.4$
- $d\sigma/dm$ in range $15 < M < 3000$ GeV (43 bins)
- Apply all corrections to get FSR-corrected results in full acceptance
- Data-driven background estimation for $t\bar{t}$, $tW$, $\tau\tau$, $W$+jets, QCD $d\bar{d}$

![Graphs showing Drell-Yan cross section data and theoretical predictions](image-url)
• Measured differential cross section compared with aMC@NLO and FEWZ predictions
  – FEWZ prediction is NNLO theoretical values calculated with NNPDF3.0 PDF
  – Generally good agreement with the prediction within uncertainties

![Drell-Yan dσ/dm](image)

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Electroweak Mixing Angle

- Forward-backward asymmetry near Z peak is sensitive to leptonic $\sin^2\theta_{\text{eff}}$
- Use combined ee and $\mu\mu$ data samples
- Fit $A_{FB}$ distribution in 12 bins of $m$ and 6 bins in $|y|$ with different $\sin^2\theta_{\text{eff}}$ templates

$$\sin^2\theta_{\text{lept}}^{\text{eff}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

$$\sin^2\theta_{\text{lept}}^{\text{eff}} = 0.23101 \pm 0.00052.$$
W/Z + Jets

• W/Z + jet production is sensitive to gluon content of the proton:
  \[ u + g \to W^+ + q \text{ jet} \]
  \[ d + g \to W^- + q \text{ jet} \]

• When associated to specific jet flavors, there is sensitivity to other PDFs too:
  \[ s + g \to W^- + c \]
  \[ b + g \to Z^0 + b \]

• Accurate modeling of V+jets is importance for many measurements at the LHC
  – W/Z+jets is dominant background for precision top quark measurements
  – Important for precision Higgs physics (background modeling)
  – Important for modeling of SM background in searches of new physics

• With W/Z+jets we can probe different aspects of QCD calculations
• Test QCD fixed-order calculations and MCs, sensitive to higher order effects but also soft QCD effects (particle emission, PS).
  - Compared to predictions: LO(≤4j) and NLO(≤2j) MadGraph5_aMC@NLO; NNLO for one inclusive jet
  - Measured: Excl./Incl. jet multiplicities, jet $p_T$, jet $\eta$, and $H_T$ up to ≥ 3 jets
  - Good agreement with predictions, but overall LO MadGraph5_aMC@NLO slightly underestimates data on the observables
Similarly to W+jets, the measurements are sensitive to higher order corrections and radiative effects.

Compared to predictions: MadGraph5_aMC@NLO with NLO for 0, 1 and 2 jets

- Good agreement although the third jet $p_T$ is decreasing more rapidly in simulation than data.
W/Z + b Jets

- Sensitive to gluon splitting, can probe b-quark PDF, important background to Higgs and BSM searches.

- W+b\(\bar{b}\)
  - Cross section obtained by fitting \(M_T\)
  - Compared to LO (4FS/5FS) and NLO
  - In agreement with predictions

- Z+(b)b
  - Fiducial \(Z+\geq 1b, \geq 2b\) cross sections and ratio
  - Differential in jet \(p_T\) and \(Z\) \(p_T\)
  - Compared to LO (4FS/5FS) and NLO
  - 20% discrepancy for 4FS LO
  - 5FS LO overestimates data at low b-jet \(p_T\)

![Graph showing cross section data and predictions](image-url)
• Test of QCD predictions, sensitive to charm content in the proton. Test modeling of Z+HF in searches (e.g. FCNC top decays).

• Signal isolated with:
  – Selection with a muon from decay of a HF quark, participating in a displaced vertex
  – Selection of exclusive final states from D meson resonant peaks (either $D^\pm$ or $D^{*\pm}$)
**EW Z + 2 Jets**

- Signal is defined as $lljj$ final state with $p_T(j) > 25$ GeV, $m(jj) > 120$ GeV, $m(ll) > 50$ GeV

$$\sigma_{LO}(\text{EW } lljj) = 0.50 \pm 0.02 \text{ (QCDscale)} \pm 0.02 \text{ (PDF)}$$

- Pure EW:
  - non-VBF diagrams that lead to identical final states and cannot be neglected
  - these diagrams have important negative interferences with the VBF productions

![Signal Diagram](image)

![Background Diagram](image)
Multivariate analysis techniques are used to optimize S/B
Binned maximum likelihood fit with strength modifiers for all MC components
10% precision:

$\sigma(\text{EW } \ell\ell jj) = 552 \pm 19(\text{stat}) \pm 55(\text{syst}) = 552 \pm 58(\text{total}) \text{ fb}$
Electroweak $W$ Production

- **Vector boson fusion (VBF) characteristic signature**
  - 2 jets at high $|\eta|$  
  - high dijet invariant mass $m_{jj}$  
  - large rapidity separation $\Delta \eta$  
  - little hadronic activity in the central part of the detector  
  - multivariate analysis to increase background discrimination

- **Fiducial cross section from fits to $m_{jj}$ distributions, using parametric models for all processes**
  \[ \sigma_{\text{fid}} = 0.42 \pm 0.04 \text{ (stat)} \pm 0.09 \text{ (syst)} \pm 0.01 \text{ (lumi)} \text{ pb} \]

- **Consistent with LO prediction**
  \[ \sigma_{\text{LO}} = 0.50 \pm 0.02 \text{ (scale)} \pm 0.02 \text{ (PDF)} \text{ pb} \]
Di-Boson Production

- Important test of EWSB
- Large amount of measurement variety of final states
- Sensitive to BSM contributions
- Good agreement with the SM

**March 2017**

### CMS Preliminary

<table>
<thead>
<tr>
<th>System</th>
<th>Production Cross Section Ratio: $\sigma_{exp} / \sigma_{theo}$</th>
<th>7 TeV CMS measurement (stat,stat+sys)</th>
<th>8 TeV CMS measurement (stat,stat+sys)</th>
<th>13 TeV CMS measurement (stat,stat+sys)</th>
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<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$1.06 \pm 0.01 \pm 0.12$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
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<tr>
<td>$W\gamma$, (NLO th.)</td>
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<td>$5.0 \text{ fb}^{-1}$</td>
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<tr>
<td>$Z\gamma$, (NLO th.)</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
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<tr>
<td>$Z\gamma$, (NLO th.)</td>
<td>$0.98 \pm 0.01 \pm 0.05$</td>
<td>$19.5 \text{ fb}^{-1}$</td>
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<td>$WW+WZ$</td>
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<td>$ZZ$</td>
<td>$1.10 \pm 0.04 \pm 0.05$</td>
<td>$35.9 \text{ fb}^{-1}$</td>
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All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)
• First diboson measurement with 13 TeV data
• Main channel: \( ZZ \rightarrow 4\ell \), clean signature and background to \( H \rightarrow 4\ell \)
• Differential cross sections (with and w/o jets) to test higher order effects (NNLO QCD and NLO QED)
• Cross section agrees well with NNLO prediction
• Measure differential cross section as function of $p_T^{ZZ}$
• Possible indication for a softer $p_T^{ZZ}$ than what is predicted by both POWHEG+MCFM and MG+MCFM
**ZZ + 2 Jets**

- Vector boson scattering and constraints on anomalous quartic gauge couplings from events with two Z bosons and two jets
- The electroweak production of two Z bosons in association with two jets is measured with an observed (expected) significance of 2.7 (1.6) standard deviations

![Graphs showing data and theoretical predictions for ZZ + 2 Jets](image-url)
**WW + 2 Jets**

- EWVV+2 jets production (VBS) probes EWSB
- Characterized by 2 forward jets separated in rapidity, with low hadronic activity in between
- $W^\pm W^\pm$ same sign lepton selection, two jets with large $y$ separation and $m_{jj}$ leads to first observation of EWVV at 13 TeV (5.5$\sigma$)

![Plots showing event distributions for $m_{jj}$ and $m_{ll}$ with CMS Preliminary data and theoretical predictions.](image-url)
Anomalous Vector Boson Couplings

- New physics at higher scales can lead to modified couplings → probe for increase in cross section
  - aTGC constrained with inclusive diboson (WWZ vertex)
  - aQGC constrained with EW VVjj and triboson

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Anomalous Vector Boson Couplings

- Sensitivity depends on the channel
  - Boosted topology with hadronic final states usually has best sensitivity
  - Large gain in sensitivity with \( \sqrt{s} \)
- Limits on aQGC

Dimension-8 transverse parameters \( f_{\lambda,i} \)

Dimension-8 mixed transverse and longitudinal parameters \( f_{\lambda,i} \)

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Summary

- Known QCD and EW processes continue to be studied in greater detail
  - Results benefit from (and drive) the advancements in theoretical calculations and MC generators
  - Differential measurements with uncertainties below 1%

- Enough statistics to see EW production of diboson processes: path toward $W_L W_L$ scattering
  - Development of data analysis tools (boosted techniques, using jet substructure for hadronic $W$ and $Z$ decays etc.)

- Expect a significant increase in sensitivity to anomalous gauge boson self-interaction couplings
  - Await for a suite of new results

- No significant deviations from the SM observed to date
  - Increasingly more precise and complex SM measurements will continue to play a complementary role to direct searches in probing for new physics