Standard Model Tests at the LHC

A. Salzburger, CERN on behalf of the ATLAS and CMS collaborations
LHC Run-1 and Run-2

main Run-1 dataset

Run-2 has started
LHC - The main experiments

**A Toroidal LHC Apparatus + ALFA**

length ~40 m, height ~22 m, weight ~7000 tons

Inner Tracker embedded in 2 T solenoid, sampling EM calorimeter,

MS tracker/spectrometer within a toroidal magnetic system

**Compact Muon Solenoid**

length ~ 22 m, height ~ 12.5 m, weight ~12500 tons

Full Silicon Inner Tracker embedded 5 T solenoid, crystal EM calorimeter

**A Large Ion Collider Experiment**

dedicated for Pb-Pb collisions,

high particle identification capability

**LHCb**

dedicated for studying properties of the B-mesons,

movable precision silicon pixel detector very close to the interaction region

**TOTEM**

roman pot detectors located 150/220 m from the CMS interaction point
Foundation - detector performance

- presented results rely on a very deep understanding and precise modelling of the experimental setups
  - impressive results from the performance/physics objects groups
  - in general, exceptional Monte Carlo detector modelling of the data

![CMS Tracker alignment](image1.png)

![ATLAS EM electron scale](image2.png)
Detector performance & data taking efficiency

- presented results would not have been possible without
  - excellent performance of the LHC
  - very high data taking efficiency and stable detector operation of the LHC experiments

- gives a lot of confidence for Run-2

**ATLAS Run-1 Detector Status (from Oct. 2012)**

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>95.0%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.3%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.5%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>99.9%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>98.3%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.6%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.8%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>96.0%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.1%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>98.2%</td>
</tr>
</tbody>
</table>

**ALICE dE/dx in TPC**

Very similar numbers for all experiments
the new kid
All spot-on - all done?

- Run-1 data has still a lot of interesting physics
  - **QCD** - become more and more precision measurements
    - Soft QCD: *minimum bias, underlying event measurements necessary in pp conditions*
    - Hard QCD: *test of high order pertubative QCD*
      (inclusive, multiple-jet production cross-sections V+jets production)
    - precision measurement of fundamental parameters $\alpha_s$
    - constraining the parton density functions (PDFs)
  - **EWK** observables and processes
    - $Z A_{fb}$
    - VBF/VBS results (observation and evidence)
      - precision measurements to come, such as $m_W$

- Run-2: 13 TeV measurements are on the way
  - back to the start, do it again and confirm (or not)
  - will show some hot-of-the-press results, many more to follow in the next months
Total inelastic cross section

- inelastic cross section measurements are essential
- very precise measurements for 7 TeV and 8 TeV
  - supplemented by TOTEM measurement
- first 13 TeV result from ATLAS
  - using Minimum Bias Scintillator detectors and extrapolated to total cross section
  - ratio measurement single sided counter/inclusive counters

73.1 ± 0.9 (exp.) ± 6.6 (lum.) ± 3.8 (extr.) mb.
Soft QCD - Minimum bias measurements

- Why measuring the charged particle multiplicities?
  - Pertubative QCD describes only hard-scatter partons, rest described by phenomenological models

- ND component
  - QCD motivated models with many parameters
  - These parameters have impact when extrapolated to high Q (e.g. color reconnection)

- SD & DD component not well constraint and little data available

- Measure primary charged particle distribution to constrain models
  - Model independent (e.g. no SD/DD/ND splitting), corrected to particle level

\[ \frac{dN_{\text{ev}}}{dn_{\text{ch}}}, \langle p_T \rangle \text{ vs. } n_{\text{ch}}, \frac{dN_{\text{ch}}}{d\eta}, \frac{d^2N_{\text{ch}}}{d\eta dp_T} \]
Minimum bias measurement - CMS/TOTEM

- charged particle measurement
  - track counting measurement with corrections
    track reconstruction efficiency (dominant)
    fake/ghost tracks (not an issue in \( \mu = 0 \))
    trigger, vertex, selection efficiency
    contamination of pile-up events
  - unfolding to particle level
    usually done using a Bayesian unfolding

- CMS combined with TOTEM
  - test model dependence up to \(|\eta| \sim 6.5\)
  - good modelling with QGSJetII-04 up to large pseudo-rapidity
Minimum bias measurement - ATLAS

- recent 13 TeV measurement of ATLAS
  - challenging due to newly installed innermost pixel detector (IBL)
  - many checks needed to understand the material budget of new detector
  - phase-space: \( N_{ch} \geq 1, p_{T} > 500 \text{ MeV}, |\eta| < 2.5 \)

- Good modelling by EPOS (LHC tune) and PYTHIA8 (A2 tune)
Soft QCD - Underlying event analyses

- Underlying event (UE) comprises all particles except those from the hard process of interest
  - performed within different azimuthal regions
  - Studying the UE at different processes and energies
- Modern tunes describe energy dependence very well
  - UE consistent between different processes within known selection biases

![Graphs and plots](image)
Soft QCD - particle production

- Measurement of particle spectra and species give additional input to understand/constraint the modelling
  - soft parton interactions
  - hadronisation process

- ALICE measurement of prompt hadrons ($\pi^\pm, K^\pm, p, \bar{p}$) at 7 TeV
  - combination of 5 techniques (sub-detectors) for particle identification

- Shapes of spectra are reasonably well described by most modules
  - no model can simultaneously describe the yield of the different particle types
Hard QCD - Jet production cross section

- Jet production cross section is a very good probe of QCD dynamics
  - over many orders of magnitudes, combines test of perturbative QCD with non-perturbative effects, LHC experiments cover 20 GeV to 2 TeV!
  - sensitive to $\alpha_s$, PDF and multi-parton interactions
  - accuracy of better than 5% achieved, very good agreement with NLO predictions

Jet $p_T$ range 20 GeV to 2 TeV, precision reaches ~5% level
Very good agreement with NLO QCD calculations
Complementary measurements of incl."jet," diPjet," 3Pjet" cross sections at HERA and LHC
Different sensitivity to underlying subprocesses and parton densities, e.g. gluon at high $x$
Full correlation across measurements allows for simultaneous use as inputs in QCD fits
Jet production cross section - ratios

- use different beam energies to build ratios
  - allows cancellation of certain systematic energies
  - results in a higher sensitive to PDFs

- new result of CMS at 2.76 TeV

\[ \text{Ratio 2.76/8 TeV} \]
- error range of 0.1 to 14 % with more precision at higher jet pT

**New measurement by CMS at 2.76 TeV**

CMS-SMP-14-017

Six $|y|$ bins (0.0-3.0), $p_T$ range 74-592 GeV

Precise test of QCD at different $\sqrt{s}$ and input to PDF fits

*e.g.* recently ATLAS $2.76$ TeV / $7$ TeV [EPJC (2013) 73 2509]
4-jet cross section measurement

- measured differentially w.r.t to different variables, e.g. angular distributions, jet momenta, event topologies
  test of PS and PS+ME
Jet production cross section - decorrelation

- Dijet azimuthal decorrelation measurement - complementary to multi-jet
  - insight on multi-jet production without measuring jets beyond leading two
  - experimental uncertainty on normalised distribution reach percent level for back-to-back jets

- Allows to test LO/NLO region
  - good agreement in NLO region (NLOJet++)
  - Multijet 2->4 provides best description (Madgraph + Pythia6)

\[ \Delta \phi_{\text{Dijet}} \approx \pi \]
\[ \Delta \phi_{\text{Dijet}} \approx 2\pi/3 \]
\[ \Delta \phi_{\text{Dijet}} \to 0 \]
Perturbative QCD - $V + \text{jets}$

- In general, very good agreement over many orders of magnitudes
- High accuracy of measurements allow to access discrepancies to predictions
- $V$+jets is a very good tool as it allows to test many processes

### Vector Boson + X Cross Section Measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\text{fid}}$</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+\ell+\nu$</td>
<td>$15.2 \pm 1.4 \pm 1.5$</td>
<td>$13.0 \pm 1.0 \pm 1.0$</td>
<td>$12.0 \pm 1.0 \pm 1.0$</td>
</tr>
<tr>
<td>$Z+\ell+\nu$</td>
<td>$10.0 \pm 0.5 \pm 0.5$</td>
<td>$7.0 \pm 0.5 \pm 0.5$</td>
<td>$6.0 \pm 0.5 \pm 0.5$</td>
</tr>
</tbody>
</table>

### ATLAS Preliminary

Run 1 $\sqrt{s} = 7, 8$ TeV
\( V + \text{jets} \)

- New results coming in with 13 TeV - good agreement with MC
  - using integrated luminosity of 85 pb\(^{-1}\)
  - MC: O and NLO matrix elements supplemented by parton showers
Strong coupling - $\alpha_s$ measurement

- $\alpha_s$ is a fundamental QCD parameter, many measurements are sensitive to it
  - measured via inclusive jet cross section, ratio 3-jet to 2-jet events ($R_{32}$), $t\bar{t}$ cross section, event shapes, etc.
  - CMS results demonstrate consistency of different processes
  - has sensitivity to new physics

Good agreement with 2-loop solution of RGE as function of the scale $Q$ up to TeV
Strong coupling - $\alpha_s$ measurement

- New measurement from ATLAS using event shapes

\[ \frac{1}{\sigma} \frac{d\Sigma}{d(cos \phi)} = \frac{1}{\sigma} \sum \int \frac{d\sigma}{dx_{T1} dx_{T2} d(cos \phi)} x_{T1} x_{T2} dx_{T1} dx_{T2} \]

\[ x_{Ti} = \frac{E_{Ti}}{E_T} \quad E_T = \sum_i E_{Ti} \]

\[ \alpha_s(m_Z) = 0.1173 \pm 0.0010 \text{ (exp.)} \pm ^{+0.0063}_{-0.0020} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0002 \text{ (NPC)} \]
EWK - Electroweak production of $W/Z$ : VBF $Z$

- Very complex and detailed analyses from ATLAS and CMS
  - First result from ATLAS, significance above $5\sigma$: observation of VBF production
  - Excellent agreement data/MC demonstrated – will be “VBF reference analysis”.

- Z+2-jet final state, separate EWK (t-channel exchange of $W/Z$) and non-EWK contributions. EWK dominantly VBF + $Z$-bremsstrahlung diagrams:

EWK

typical non-EWK
**EWK - VBF Z production**

- ATLAS analysis based on 5 fiducial regions
  - baseline, high-mass, search, control & high-\(p_T\)

- cut-based analysis, MC templates & control region to extract signal
  - SHERPA (LO multi-leg) and POWHEG (NLO) used for signal modelling

The “search” region (plot, \(m(jj) > 250\) GeV): EWK is 5% of total Z+jets signal.

\[
\sigma_{\text{EWK}} = 54.7 \pm 4.6^{+9.8}_{-10.4} (\text{stat}) \pm 1 (\text{lumi}) \text{ fb}
\]

\[
\sigma_{\text{Powheg}} = 46.1 \pm 1.0 \text{ fb}
\]

Similar agreement for \(m(jj) > 1000\) GeV region

Significance estimated using Toys for search and control regions.

Extract aTGC limits (compare to others)
EWK - VBF $W$ production

- CMS analysis
  - MVA based after cutting on BDT discriminant, likelihood fit to the $m_{jj}$ distribution to extract signal
  - Madgraph+PYTHIA used for signal modelling
  - data/MC agreement for distribution of BDT discriminant values not ideal
    -> results in systematic uncertainty
  - muon/electron channels very similar
    in terms of uncertainty & accuracy

- Well within prediction

<table>
<thead>
<tr>
<th>Event category</th>
<th>Measured cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu jj$</td>
<td>$0.43 \pm 0.04 \text{ (stat.)} \pm 0.10 \text{ (syst.)} \pm 0.01 \text{ (lumi.) pb}$</td>
</tr>
<tr>
<td>$ejj$</td>
<td>$0.41 \pm 0.04 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.01 \text{ (lumi.) pb}$</td>
</tr>
<tr>
<td>combined $\mu jj$ and $ejj$</td>
<td>$0.42 \pm 0.04 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.01 \text{ (lumi.) pb}$</td>
</tr>
</tbody>
</table>

predicted: $\sigma = 0.50 \pm 0.03 \text{ pb}$
EWK - production of $W$: VBS $ssWW$

- First evidence ($3\sigma$) of VBS reported by ATLAS in same-sign WW channel
  - QCD and EWK contribution about the same size

- 2-lepton with di-jet + MET final state
  - separate QCD with $O(\alpha_s^2\alpha_{EW}^4)$ contribution from EWK with $O(\alpha_{EW}^6)$
  - ATLAS signal modelling: Sherpa with Powheg for NLO normalisation

- Two analyses: inclusive $ssWW$ and the (subset) VBS EWK
Set first limits on anomalous quartic gauge couplings (aQGC) parameters relevant for WWWW couplings: $\alpha_4$ and $\alpha_5$

Use WHIZARD and K-matrix regularization and set limits using data in “EWK” analysis region.

\[\sigma(\text{incl}) = 2.1 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ fb}\]
\[\sigma(\text{pred}) = 1.52 \pm 0.11 \text{ fb}\]

\[\sigma(\text{EWK}) = 1.3 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (syst)} \text{ fb}\]
\[\sigma(\text{pred}) = 0.95 \pm 0.06 \text{ fb}\]
EWK - Di-boson production $WW$

- Remove $H \rightarrow WW$ contribution ($\sim 8\%$ effect)

- Evaluate limits for anomalous trilinear gauge couplings (aTGC)

- In this analysis only CP-conserving operators for aTGCs tested

<table>
<thead>
<tr>
<th>Coupling constant</th>
<th>This result ($\text{TeV}^{-2}$)</th>
<th>Its 95% CL interval ($\text{TeV}^{-2}$)</th>
<th>World average ($\text{TeV}^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{WWW}/\Lambda^2$</td>
<td>$0.1^{+3.2}_{-3.2}$</td>
<td>$[-5.7, 5.9]$</td>
<td>$-5.5 \pm 4.8$ (from $\lambda_\gamma$)</td>
</tr>
<tr>
<td>$c_W/\Lambda^2$</td>
<td>$-3.6^{+5.0}_{-4.5}$</td>
<td>$[-11.4, 5.4]$</td>
<td>$-3.9^{+3.9}_{-4.8}$ (from $g_1^2$)</td>
</tr>
<tr>
<td>$c_B/\Lambda^2$</td>
<td>$-3.2^{+15.0}_{-14.5}$</td>
<td>$[-29.2, 23.9]$</td>
<td>$-1.7^{+13.6}<em>{-13.9}$ (from $\kappa</em>\gamma$ and $g_1^2$)</td>
</tr>
</tbody>
</table>

$\sigma(\text{fid}) = 60.1 \pm 0.9 \text{ (stat)} \pm 3.2 \text{ (exp)} \pm 3.1 \text{ (theo)} \pm 1.6 \text{ (lumi)} \text{ pb}$

$\sigma(\text{NNLO}) = 59.8 \pm 1.2 \text{ pb}$
Forward-backward asymmetry $Z A_{fb}$

- ATLAS result from 7 TeV most precise of LHC
  - use 3 categories: $\mu\mu$, ee with central-forward (CF), ee with central-central (CC)
  - convert to $\sin^2\theta_{eff}^{lep}$ EWK mixing parameter
    - use PYTHIA (LO) to extract EWK contribution, POWHEG as a crosscheck
    - reasonable good modelling of $A_{fb}$ distribution
  
  Figure 1:

  Events / GeV
  
  $\sqrt{s} = 7$ TeV, 4.8 fb$^{-1}$
  - Data 2011
  - $Z\gamma^* \rightarrow ee$
  - Other backgrounds
  - Multijets

  $A_{FB}$

  $\sqrt{s} = 7$ TeV, 4.8 fb$^{-1}$
  - CF electron $p_T > 25$ GeV, $|\eta_c| < 2.47$
  - $2.5 < |\eta_\mu| < 4.9$

  $\Delta \sigma$

  $m_{ee}$ [GeV]

  ATLAS
  - $Z\gamma^* \rightarrow ee$
  - PYTHIA, $Z\gamma^* \rightarrow ee$
  - POWHEG, $Z\gamma^* \rightarrow ee$

EWK - Forward-backward asymmetry $Z A_{fb}$

- Overview table for $\sin^2 \theta_{\text{eff}}^{\text{lept}}$
  - Tevatron is reaching LEP precision
  - LHC not yet competitive (more statistics and more elaborated analyses needed)

- Preliminary CMS results using full 8 TeV dataset
  - excellent modelling with POWHEG
A first look on 13 TeV results

**Z+jets measurement**

\[ Z \to \ell^+\ell^- + \text{jets} \]

\[ p_T^{\text{jet}} > 30 \text{ GeV} \]

\[ |y| < 2.5 \]

**Isolated photon production**

**W cross section measurement**

**Jet cross section measurement**

**Ridge in p-p collisions**
A first look on 13 TeV results

Di-muon invariant mass spectrum

![Di-muon invariant mass spectrum](image)

**Di-jet invariant mass spectrum**

- Many more physics and performance studies in the pipeline
- Exciting times ahead with Run-2
  - SM tests at the new energy frontier

**Drell-Yan Z→μμ**

![Drell-Yan Z→μμ](image)

**CMS-DP-2015-001**

**CMS-DP-2015-015**

**CMS-DP-2015-017**
Conclusion & Outlook

- Run-1 data campaign was a very successful test of the SM

- This would not have been possible without the excellent modelling and understanding of the detectors

- In general very good agreement of the measurements with predictions

- More detailed Run-1 data analyses are on the way
  - e.g. $m_W$ precision measurements

- Run-2 data taking has started
  - first results are being prepared
BSM tests

- Testing the SM is testing beyond the SM

- Combined results of CMS and LHCb on $B^0_s \rightarrow \mu\mu$

\[ \mathcal{BR}(B_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9} \]

(Buras et al, JHEP 1009 (2010) 106)

- Branching ratio is sensitive to BSM effects

- Very rare decay
  - challenging analysis
All good - no tension at all?

- Overwhelming majority of measurements are consistent with SM model prediction
  - precision of the LHC measurements allow to test SM predictions over many orders of magnitudes
  - QCD measurements start turning into precision measurements

- Very little tension in SM measurements & EWK Higgs mechanism fits in like the perfect Cinderella shoe

- Or is there something we've missed?
  - ATLAS slight excess in high-mass di-boson production

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09:30 | Di-boson production at high transverse momenta beyond NLO QCD - Francisco Campanario (Karlsruhe Institute of Technology)