ATLAS Status Overview

A. Polini (INFN Bologna) on behalf of the ATLAS Collaboration

Outline:
• The ATLAS detector
• Run-2 Status and Performance
• Recent Physics Highlights*
• Upgrade Plans

August 6th 2018
Only few Highlights shown here: See dedicated presentations:

- Standard Model Physics Ludovica Aperio Bella
- New results on $W$ boson production with the ATLAS detector, Evelin Meoni
- Exotic Higgs, Nikolina Ilic
- Higgs boson decays to fermions with the ATLAS detector, Stanley Lai
- Measurement of Higgs boson production in association with top quarks with ATLAS, John Andrew Raine
- Searches for supersymmetry in signatures with long-lived particles with the ATLAS detector, Karri Folan Di Petrillo
- Searches for squarks and gluinos with ATLAS, Antonia Struebig
- Searches for electroweak production of supersymmetric particles with ATLAS, Sarah Williams
- Dark Matter searches at the LHC, Vasiliki Kouskoura
- Exotic Searches, Adriana Milic
- ATLAS Dark Matter searches: interpretation, Darren Price
- A search for Vectorlike Quarks Erich Varnes
ATLAS
- 25 meters high
- 44 meters long
- Weight 7000 tons
The ATLAS Detector in Run-2 (2015-2018)

New detectors in Run-2:

- Innermost pixel layer IBL, 3.4 cm from interaction point
- Muons: MDT in $1.1 < |\eta| < 1.3$, RPC in Barrel Feet Sectors
- Forward proton detectors, AFP (one/two arms in 2016/2017, 205+217m from IP)
- In addition, various consolidations provide improved running at high luminosities and rates (tracking, calorimetry, muon, luminosity measurement, etc.)
**The ATLAS Detector in Run-2 (2015-2018)**

**Trigger system (Run-2)**

- **L1** – hardware
  - output rate: 100 kHz latency: < 2.5 ms
  - New Central Trigger Processor
  - Improved resolution in calorimetry readout and trigger
  - Topological trigger at L1 (Calo+Muons)
- **HLT** – software
  - output rate: 1 kHz
  - proc. time: ~ 550 ms
- Wide upgrade to DAQ infrastructure

**Trigger**

- Menu consists of ~2000 triggers, covering a wide physics program
- Keep low threshold inclusive triggers
  - Single e/µ with $p_T>26$ GeV
  - $E_T^{miss} > 110$ GeV
Run-2 Data Taking

- Excellent machine performance running at about double of design luminosity
- Our biggest THANKS to the LHC!
- A big experimental challenge is pile-up (multiple p-p interactions in same bunch crossing) causing:
  - Multiple vertices, many low $p_T$ tracks
  - Underlying energy deposits in calorimeter
- Detector and data taking challenges:
  - Detector read-out with large occupancy, high rigger rates, data bandwidth, processing computing power

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**ATLAS Online Luminosity**

- $\sqrt{s} = 13$ TeV
- Peak Lumi: $21.4 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
- Limit from 2017 leveling

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**ATLAS Online, 13 TeV**

- $\int L dt = 108.3$ fb$^{-1}$
- 2015: $\langle \mu \rangle = 13.4$
- 2016: $\langle \mu \rangle = 25.1$
- 2017: $\langle \mu \rangle = 37.8$
- 2018: $\langle \mu \rangle = 38.3$
- Total: $\langle \mu \rangle = 33.3$

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August 6th 2018

A. Polini, Rencontres du Vietnam 2018, Qui Nhon
Two $Z\rightarrow \mu\mu$ candidates from different pp interactions, but in the same bunch-crossing, observed in 2017 data ... their production vertices are separated by 67 mm.
About a factor of 2 above LHC design luminosity. Expect $\mathcal{L} = 140 - 150$ fb$^{-1}$ for full 2015-2018 data-set.
Pileup mitigation techniques e.g. subtraction, correction continuously improving and getting mature
Physics Results

- $P_T(\tau^1_{\text{had}}) = 292 \text{ GeV}$
- $P_T(\tau^2_{\text{had}}) = 275 \text{ GeV}$
- $P_T(\text{b-jet}) = 47 \text{ GeV}$
- $E_{\text{miss}} = 33 \text{ GeV}$
- $m_{\text{tot}} = 591 \text{ GeV}$
Higgs → ZZ → 4 leptons

- Higgs boson discovered in July 2012 at LHC.
- Is the new particle the SM Higgs boson? → measure its properties
- Example for high purity but low branching fraction Higgs decay to four leptons (H→ZZ→4l):

**ATLAS**

\[ H \rightarrow ZZ^{(*)} \rightarrow 4l \]

L=4.8 fb\(^{-1}\) and 5.8 fb\(^{-1}\) at 7 and 8 TeV

- Data
- Background ZZ\(^{*}\)
- Background Z+jets, t\(\bar{t}\)
- Signal \(m_H=125\,\text{GeV}\)
- Syst.Unc.

\begin{align*}
L = 7\,\text{TeV}: & \int L dt = 4.8\,\text{fb}\(^{-1}\) \\
L = 8\,\text{TeV}: & \int L dt = 5.8\,\text{fb}\(^{-1}\)
\end{align*}

\[ m_{4l} \text{ [GeV]} \]

- 13 events 120 < \(m_{4l}\) < 130 GeV

\[ m_{4l} \text{ [GeV]} \]

- 195 events for 115 < \(m_{4l}\) < 130 GeV

**ATLAS** Preliminary

\[ H \rightarrow ZZ^{*} \rightarrow 4l \]

13 TeV, 79.8 fb\(^{-1}\)

- Data
- Signal \(m_H=125\,\text{GeV}\)
- ZZ\(^{*}\)
- Z+jets, t\(\bar{t}\), t\(\bar{t}\)+V, VVV
- Uncertainty

\[ m_{4l} \text{ [GeV]} \]

\[ 80 \quad 90 \quad 100 \quad 110 \quad 120 \quad 130 \quad 140 \quad 150 \quad 160 \quad 170 \]

August 6th 2018


**ATLAS-CONF-2018-018**
Differential cross-section using gauge boson decays

- Higgs decays to gauge bosons used for differential cross-section measurements.

- Differential cross-section becoming more and more precise with increasing statistics.
- Data well described by recent SM predictions.
Higgs mass measured in $H \rightarrow ZZ^* \rightarrow 4l(e,\mu)$ and $H \rightarrow \gamma\gamma$ channels with 36.1 fb$^{-1}$ @ 13 TeV

- Precision still limited by the available statistics. Prospects to determine the Higgs mass with more precision with full Run 2 data

arXiv: 1806.00242
Higgs sector: $H \rightarrow WW$ and $H \rightarrow \tau\tau$

Recent 13 TeV results (2015-2016 data)

$H \rightarrow WW$ ATLAS-CONF-2018-004

**Example of mass dist. in 1 out of 13 signal categories**

$H \rightarrow \tau\tau$ ATLAS-CONF-2018-021

**ATLAS**
- 13 TeV alone: $4.4 \sigma$ ($4.1 \sigma$ expected)
- 7/8/13 TeV combined: $6.4 \sigma$ ($5.4 \sigma$ expected)

**Signal significance ($\mu$)**
- ATLAS $\mu_{ggF} = 1.21^{+0.12}_{-0.11}$ (stat.) $^{+0.18}_{-0.17}$ (sys.) = $1.21^{+0.22}_{-0.21}$
- $6.3 \sigma$ ($5.2 \sigma$ exp.)
- $\mu_{VBF} = 0.62^{+0.30}_{-0.28}$ (stat.) $\pm 0.22$ (sys.) = $0.62^{+0.37}_{-0.36}$
- $1.9 \sigma$ ($2.7 \sigma$ exp.)

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- **$\tau_{\text{had}}\tau_{\text{had}}$**
  - Total: $2.49$ $^{+1.38}_{-1.17}$
  - SM exp.: $2.49$ $^{+0.77}_{-0.74}$ $^{+1.15}_{-0.91}$

- **$\tau_{\text{lep}}\tau_{\text{had}}$**
  - Total: $3.07$ $^{+1.49}_{-1.31}$
  - SM exp.: $3.07$ $^{+0.84}_{-0.83}$ $^{+1.22}_{-1.02}$

- **$\tau_{\text{lep}}\tau_{\text{lep}}$**
  - Combination: $6.76$ $^{+2.80}_{-2.78}$
  - SM exp.: $6.76$ $^{+1.45}_{-1.41}$ $^{+2.39}_{-2.40}$

- **$\sigma_{H \rightarrow \tau\tau}$ [pb]**
  - Total: $3.71$ $^{+1.06}_{-0.95}$
  - SM exp.: $3.71$ $^{+0.60}_{-0.59}$ $^{+0.87}_{-0.74}$
Associated $VH$ production and $H \rightarrow bb$

- $H \rightarrow bb$ highest branching ratio: $\text{Br}=58\%$ but huge background from heavy flavor production
- Need to use exclusive (rare) production mechanism to gain sensitivity $VH$, $H \rightarrow bb$
- Analysis:
  - Use high-$p_T$ boson region
  - Multi-variate analysis in 0, 1 and 2 lepton channels
  - Dijet mass analysis as cross-check

Example: One input to di-jet mass analysis global fit

Di-boson validation analysis $VZ(\rightarrow bb)$:
Observation of $H \rightarrow bb$ decay

**ATLAS** Preliminary

- $\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$
- 0+1+2 leptons
- 2+3 jets, 2 b-tags
- Weighted by Higgs S/B

**Dijet mass analysis**

- **VH alone:**
  - $4.9\sigma$ ($4.3\sigma$) obs (exp) (13 TeV)
- **Combined** (7,8,13 TeV) VBF, ttH, VH:
  - $5.4\sigma$ ($5.5\sigma$) obs (exp)

**Observation of Higgs decay to beauty quarks!**
Direct observation of top Higgs coupling. Confirmation of Yukawa coupling to fermions.

### Analysis

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated Luminosity [fb⁻¹]</th>
<th>Expected Significance</th>
<th>Observed Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>79.8</td>
<td>3.7 $\sigma$</td>
<td>4.1 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow \text{multilepton}$</td>
<td>36.1</td>
<td>2.8 $\sigma$</td>
<td>4.1 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>36.1</td>
<td>1.6 $\sigma$</td>
<td>1.4 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>79.8</td>
<td>1.2 $\sigma$</td>
<td>0 $\sigma$</td>
</tr>
<tr>
<td>Combined (13 TeV)</td>
<td>36.1–79.8</td>
<td>4.9 $\sigma$</td>
<td>5.8 $\sigma$</td>
</tr>
<tr>
<td>Combined (7, 8, 13 TeV)</td>
<td>4.5, 20.3, 36.1–79.8</td>
<td>5.1 $\sigma$</td>
<td>6.3 $\sigma$</td>
</tr>
</tbody>
</table>

### Inclusive ttH cross section (already 20% precision):

- @ 8 TeV $\sigma_{ttH} = 220 \pm 100$ (stat.) $+ 70$ (syst.)
- @ 13 TeV $\sigma_{ttH} = 670 \pm 90$ (stat.) $+ 105$ (syst.)

August 6th 2018
Spin correlation in top pair events

- Spin correlation for $pp \rightarrow tt \rightarrow e\mu bb$ measured between the top decay products and a spin axis.
- $\Delta \Phi(e\mu)$ is a sensitive variable.

Template fit on $\Delta \Phi(e\mu)$:
- $f_{SM}$ fraction of expected cross-section under the SM spin hypothesis
- No spin correlation template:
- top decay with spin correlation disabled

Stronger spin correlations observed than expected by NLO QCD

Fit result: $f=1.250\pm0.026\pm0.063$

$\Rightarrow$ 3.2$\sigma$ discrepancy with NLO QCD

Previous analyses also measured stronger spin correlations (with large uncertainties).

Similar results for fiducial particle-level and comparisons of ME generators.
Observation of same-sign $WWjj$

Higgs boson needed to restore unitarity of the WW scattering cross-section.
- Higgs boson leads to strong suppression via gauge cancellation of individual EW diagrams.
- Part of electroweak symmetry breaking studies.

$pp \rightarrow W^+/W^-\text{ jet jet}$ process:
- Large electroweak cross-section fraction ($\sigma_{\text{EW}}/\sigma_{\text{QCD}}$), and a strong background suppression.

**ATLAS**

**Events**

- $\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
- **Data**
- **W$^3$jj EW**
- **W$^3$jj QCD**
- **Non-prompt**
- **e/\gamma conversions**
- **WZ**
- **Other prompt**
- **Total uncertainty**

**Significance:**

6.9$\sigma$ (4.6$\sigma$) obs (exp)

**Fiducial cross-section:**

$$\sigma_{\text{fid}} = 2.91^{+0.51}_{-0.47} \text{(stat.)} \pm 0.27 \text{(syst.)} \text{ fb}$$

$$\sigma_{\text{Sherpa}}^{\text{fid}} = 2.01^{+0.33}_{-0.23} \text{ fb}$$

$$\sigma_{\text{Powheg}}^{\text{fid}} = 3.08^{+0.45}_{-0.46} \text{ fb}$$
**Electroweak production** of WZ boson in association with two jets pp → W±Z jet jet

Process sensitive to triple and quartic gauge couplings and anomalous couplings.

Observation of electroweak W/Z jet+jet process.

**Total fiducial WZ jet jet cross section:**

σ_{EW}(pp → W^±Z jet jet) = 0.57 ±0.15 fb

LO (Sherpa): 0.32 ±0.03 fb

**Also new results on inclusive WZ production:**

- Fiducial cross-section in agreement with NNLO QCD (inclusive and differential)
- Evidence of longitudinally W polarization (4.2σ)
- Measurement of Z polarization

ATLAS-CONF-2018-034
Inclusive Cross-Sections

Standard Model Total Production Cross Section Measurements

Status: June 2018

ATLAS Preliminary
Run 1,2 $\sqrt{s} = 7,8,13$ TeV

- LHC pp $\sqrt{s} = 7$ TeV
  - Data 4.5 – 4.9 fb$^{-1}$

- LHC pp $\sqrt{s} = 8$ TeV
  - Data 20.2 – 20.3 fb$^{-1}$

- LHC pp $\sqrt{s} = 13$ TeV
  - Data 3.2 – 36.1 fb$^{-1}$

August 15 2016 21 A. Polini, ISHBSM 2016, Weihai
Measurements of electroweak parameters

Measurement of electroweak mixing angle:
Drell-Yan cross-section $qq \rightarrow Z \rightarrow ll$ expanded as sum of 9 harmonic polynomials (NNLO QCD).
In LO QCD (Z-boson rest frame):

$$\frac{d\sigma}{dy^\ell dy^\ell dm^\ell d\cos\theta} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dy^\ell dy^\ell dm^\ell} \left\{ (1 + \cos^2 \theta) + A_4 \cos \theta \right\}.$$

$A_4$ measured using two leptons $|\eta|<2.4$ (cc) and at least one forward electron $2.5<|\eta|<4.6$ (cf).
Using 8 TeV data (2012).

$$\sin^2 \theta'_\text{eff} = 0.23140 \pm 0.00036$$

Uncertainty break-down
0.00021 (stat) $\pm$ 0.00024 (PDF) $\pm$ 0.00016 (syst)

Main limitation knowledge initial quark direction

Other recent electroweak measurements:
- W-mass: $80370 \pm 19$ MeV [EPJ C78 (2018) 110] $\sim 0.02\%$
- Higgs mass: $124970 \pm 240$ MeV [arXiv:1806.00242] $\sim 0.2\%$
- Top-mass: $172510 \pm 500$ MeV [ATLAS-CONF-2017-071] $\sim 0.3\%$

0.15\% precision
• Very active search program ... (SUSY, dark matter, new Higgs models...)
• In total, 62 search papers submitted (36 fb⁻¹).
• 8 new preliminary new physics searches with 80 fb⁻¹.
Di-boson resonance search

- Select large $p_t$ and large radius jet with boosted W-tag
- Recent improvements:
  - W and Z-boson tagging using angles from tracker and energies from calorimeter
  - Tagger working point optimization at high $p_t$
Search for new electro-weak boson

- New electro-weak gauge boson ($W'$) decaying in context of sequential SM benchmark model.
- $W' \rightarrow e\nu$; $W' \rightarrow \mu\nu$
- Assuming SM coupling

$\Rightarrow$ Masses below excluded at 95%CL: 5.6 TeV (80 fb$^{-1}$)

$\Rightarrow$ Need new techniques to increase further sensitivity.
July 2018 – 4 new results based on 80 fb⁻¹

- **gluino, multi-b search**
  - New update w.r.t. JHEP06(2018)107 with 2017 data. Earlier 2.4 sigma deviations disappeared.
  - New limits on the $m(\tilde{g}) > 2$ TeV at 95% C.L.

- **chargino decaying via W-bosons**
  - New limits $m(\tilde{\chi}^{\pm}_1) > 410$ GeV 95% CL.

- **bottom-squark pair production in final states Higgs**
  - Selection $\geq 6$ jets $> 4$ b jet, no leptons, $E_T^{miss} > 250$ GeV
  - Use Higgs mass tagging using two b jets
  - bottom-squarks with mass below 1400 GeV are excluded at 95% C.L.

- **Search for H+$E_T^{miss}$ signature in bb decay channel.**
  - Direct interaction of Higgs with DM sector.
  - New limits on $M_A$
Compressed spectrum squark degeneracy: squarks $O(500 \text{ GeV})$ gluinos $O(1 \text{ TeV})$

Longer decay chain more realistic models: sbottom $O(700 \text{ GeV})$ stop $O(700 \text{ GeV})$

Low rate, compressed: winos $O(\sim 100 \text{ GeV})$ sleptons $O(\sim 100 \text{ GeV})$ higgsino $O(\sim 100 \text{ GeV})$

Complexity, long-lived: gluinos $O(1 \text{ TeV})$ stop $O(500 \text{ GeV})$

Simplified signatures covered to high masses, but plenty of low mass unexplored model space.
Heavy Ions: not only Pb-Pb

Available data sets:

- Xe+Xe data:
  - 2017, $\sqrt{s_{\text{NN}}} = 5.44$ TeV
  - 3 $\mu$b⁻¹

- Pb+Pb data:
  - 2015, $\sqrt{s_{\text{NN}}} = 5.02$ TeV
  - 0.49 nb⁻¹

- pp data:
  - 2015, $\sqrt{s} = 5.02$ TeV
  - 25.0 pb⁻¹

ATLAS:
- $p_T > 0.1$ GeV;
- $|\eta| < 2.5$;
- full $\phi$ coverage

$R_{AA}$ relative yield of charged particles compared to pp collisions

ATLAS Preliminary
2015 Pb+Pb data, 0.49 nb⁻¹
2017 Xe+Xe data, 3 $\mu$b⁻¹

$R_{AA}$ distributions for events with same $N_{\text{part}}$
Heavy Ions: photon-jet correlations

- **Photon-jet correlations:**
  - To control over initial jet kinematics to see energy loss in jets
  - $x_{j\gamma}$, the transverse momentum balance between $\gamma$ and jet $x_{j\gamma} = \frac{p_{T,j}}{p_{T,\gamma}}$
  - For Pb+Pb collisions, the $x_{j\gamma}$ distribution is modified with increasing centrality, consistent with the picture of parton-energy loss in the hot nuclear medium.

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**ATLAS** Preliminary
- $pp$ 5.02 TeV, 25 pb$^{-1}$
- Pb+Pb, 0.49 nb$^{-1}$

$p_T^{\gamma} = 100-158$ GeV

- $pp$ (same each panel)
- Pb+Pb
• **Detector challenges:**
  - Higher radiation \(\sim 10^{16} \text{ 1MeV neq/cm}^2 ; 10 \text{ MGy}\)
  - Higher pile-up:
    - Run-1
    - HL-LHC

  \[\mu = 20 ; \langle n_{\text{PU jets } p_T > 30 \text{GeV}} \rangle \sim 0.04\]
  \[\mu = 200 ; \langle n_{\text{PU jets } p_T > 30 \text{GeV}} \rangle \sim 7.4\]

• **Upgrade goal:**
  - Keep performance (tracking, b-tag, jet/\(E_T^{\text{miss}}\), ...)
  - Trigger rates acceptable with low \(P_T\) thresholds
  - Pile-up mitigation up to large \(\eta\) is needed
**Main Target:**

- Better trigger capabilities (efficiency, fake rejection)
- Maintain same acceptance/$p_T$ thresholds with higher pileup.

**Fast Track Trigger (FTK)** *(ATLAS-TDR-021-2013)*

- HW based tracking of Si-tracking layers at “Level 1.5”
- Commissioning ongoing in Run-2

**High Granular L1 Calorimeter Trigger** *(ATLAS-TDR-022-2013)*

**Status/Plans:**
- 2014: Installed FE demonstrator
- 2015: Successful data taking
- On-going: FE-BE prototype and production
- 2019: Installation

**Muons: New Small Wheel (NSW)** *(ATLAS-TDR-020-2013)*

- sTGC + MicroMegas (trigger & precise tracking)

**Trigger/DAQ Phase I Upgrade** *(ATLAS-TDR-023-2013)*

- **L1Calo**: improved lepton triggering, feature extractors for e/γ, jets, MET...
- **L1Muon**: new/improved sector logic (and information to central trigger), NSW
**ATLAS Phase II Upgrades (2024-2026 → HL-LHC)**

**ITK Inner Tracker:** (ATLAS-TDR-025 -030 2017)
- Pixel + Strip
- $|\eta| < 2.7 \rightarrow |\eta| < 4.0^*$

**Path and Status:**
- **6 Technical Design Reports released**
- **1 Technical proposal (High Granularity Timing Detector)**

**Muons:** (ATLAS-TDR-026 2017)
- Inner Barrel Layer (thin-gap RPC + μMDT)
- New electronics
- Muon Tag $|\eta| < 2.7 \rightarrow |\eta| < 4.0^*$

**Calorimeters:** (ATLAS-TDR-026 -027 2017)
- FE, BE Electronics LAr/Tilecal
- sFCAL w/ better granularity*

**Trigger & DAQ**
(ATLAS-TDR-029 2017)
- L0 (Calo+Muon): 1 MHz
- L1 (Calo+Muon+ITK): 400 KHz
- HLT/EV: 10 KHz

**HGTD (LHCC-2018-023)**
- silicon low-gain aval.det.
- 30ps resolution. $2.4 < |\eta| < 4$
Conclusions

- The LHC has gone beyond its design and is now in full production phase
- ATLAS detector and trigger system working very well
  - ATLAS coping well with pileup levels approaching twice design
- Wealth of measurements already from 13 TeV data
  - A more refined picture of the Higgs:
    - All main Higgs decays ($H \rightarrow bb$) are now observed.
    - Direct observation of Higgs coupling to top quark (via $ttH$).
    - Yukawa coupling to fermions established ($ttH, H \rightarrow bb, H \rightarrow \tau\tau$)
  - ... and much more
- Extensive and active search program for full run-2 (>150 fb⁻¹ achievable).
- Moreover an intense program of upgrade will allow ATLAS to run at its best as LHC and HL-LHC will deliver up to 3000 fb⁻¹ of luminosity
- Huge thanks to the LHC and injector teams for the excellent performance
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Thank You!