The ATLAS Experiment at the LHC Collider
Selected Results and a Short Look Back to the Last 25 Years

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On behalf of the ATLAS Collaboration

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Lomonosov Conference is 25
ATLAS too...
In 1992...

- No top quark.
- No $\nu_\tau$.
- No neutrino oscillations.
- No dark energy.
- No CP violation in B mesons.
- No Higgs boson.
- No gravitational waves.

- LEP was running at the Z peak.
- SLC started with polarized beams.
- PEPII in construction.
- Tevatron was just starting its Run 1.
- HERA starting.
- COBE satellite just measured the first map of CMB anisotropy.
Outline

• A brief history of ATLAS
• Sub-detectors, reconstructed objects and performance

• The Higgs boson discovery and measurement of its properties
• Top physics
• Electroweak and QCD measurements
• SUSY searches
• Exotic searches
• Heavy ions
• Many other measurements and searches

• Conclusions
A Brief History of ATLAS Before Collisions...

• 1992: Letter of Intent.
• 1995: First Memorandum of Understanding.
• 1996: ATLAS approved.
• 1999: Construction started.
• 2004: First components in the pit.
• 2005: First recorded cosmic ray.
• 2008: Construction completed.
• 2009: First LHC collisions...
A Brief History of ATLAS Since Collisions...

Run 1:

50 pb\(^{-1}\) at \(\sqrt{s} = 7\) TeV (2010)
5 fb\(^{-1}\) at \(\sqrt{s} = 7\) TeV (2011)
23 fb\(^{-1}\) at \(\sqrt{s} = 8\) TeV (2012)

**LS1 (2013-2014):**
Installation of the IBL, a new innermost pixel layer, at 3.5 cm from the beam.

Run 2:

61 fb\(^{-1}\) at \(\sqrt{s} = 13\) TeV (2015 + 2016 + ongoing 2017)
Inner Tracking

- Precise inner tracking: High resolution hits from silicon pixel and microstrip (SCT) detectors for impact parameter determination and vertex reconstruction.
- Continuous outer tracking: TRT for pattern recognition and momentum measurement.
- Immersed in a 2 T solenoidal magnetic field.
- 103 M channels, including new innermost pixel layer installed in 2013.
- Precise tracking up to $|\eta| < 2.5$.

IDTR-2017-004  IDTR-2015-007  IDTR-2016-003
Electrons and Photons

• Benefit from high performance of the liquid argon with accordion geometry calorimeter.
• Hermetic (accordion), $|\eta| < 3.2$.
• Fine granularity (easy to achieve, see figure).
• Very fine first sampling (discriminate $\pi^0$), up to $|\eta| < 2.4$.
• Bipolar response (reduce pile-up response).
• 173 k channels (including presampler).

• Pseudorapidity is drawn on electrodes like graduation marks on a ruler.
• Bonus: Add longitudinal sampling.

EGAM-2017-003

EGAM-2017-004

EGAM-2017-006
Jets and Missing $E_T$

- Jet reconstruction uses calorimeter energy measurements and charged tracks.
- This includes hadronic calorimeters (19 k channels, $|\eta| < 4.9$).
- Jet energy calibration uses MC and data-driven methods.
- Systematic error on the jet energy scale is one of the most important uncertainties for many measurements and searches.
- Missing transverse energy uses all reconstructed objects, without double-counting between tracker and calorimeters.
ATLAS muon spectrometer is based on 3 air-core toroid magnets.
- Toroids are instrumented with detection chambers (1 M channels, $|\eta| < 2.7$).
- Bending power between 2 and 6 Tm.
- Momentum measurement uses Inner tracking and muon spectrometer.

**Muons**
B-Jets

• B jets are tagged by exploiting the long lifetime of b hadrons, which gives large impact parameters and secondary vertices.
• B tagging relies on the performance of silicon pixel detector.
• B tagging used in a large fraction of physics analysis (top physics, susy searches...).
• Light-jet rejection typically 4 times better than in Run 1 (IBL and better algorithms).
Higgs boson: 20 years of simulation before discovery...

1992 Letter of Intent
$\sqrt{S} = 16$ TeV
$100 \text{ fb}^{-1}$
$M_{top} = 140$ GeV!

1994 Technical Proposal
$\sqrt{S} = 14$ TeV
$100 \text{ fb}^{-1}$

1999 Physics TDR
$\sqrt{S} = 14$ TeV
$100 \text{ fb}^{-1}$

2008 Expected Performance
$\sqrt{S} = 14$ TeV
$10 \text{ fb}^{-1}$

2012 Discovery
$\sqrt{S} = 7$ TeV and 8 TeV
$10.7 \text{ fb}^{-1}$
**Measured Decay Channels for Higgs Boson**

**2012**

*ATLAS*  
Measured Decay Channels for Higgs Boson  
*Phys. Lett. B 716 (2012) 1-29*

**2012**

*ATLAS*  
Comparison of measured decay to $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ rates to SM predictions  
*JHEP 04 (2015) 117*

**2017**

*ATLAS*  
$\mu = 0.90 \pm 0.18$ (stat) $^{+0.21}_{-0.19}$ (syst.)  
*arXiv:1708.03299*

**2015**

*ATLAS*  
Comparison of $H \rightarrow \tau \tau$ rates to SM predictions  
*JHEP 04 (2015) 117*

See talk by Dj. Boumédiene
Not observed yet

- Decay channels: $H \rightarrow \mu^+ \mu^-$ and $H \rightarrow Z\gamma$.
- Production modes: $ttH$, important for top quark Yukawa coupling.
Higgs Boson Mass

See talk by Dj. Boumédiene

On-going efforts to reduce the Run 2 systematic errors.
Higgs Boson Cross Section and Production Modes

- This analysis uses $\gamma\gamma$ and $Z^*Z$ decay channels.
- Production modes cross sections are fitted assuming SM branching fractions.
- SM prediction in the ggF-VBF contours has a $p$ value of 3 %, with respect to measurement.

See talk by Dj. Boumédiene
Top Quark Mass

- Top quark mass: The best known quark mass.
- Extracting $m_{\text{top}}^{\text{pole}}$ comes with larger theoretical errors (QCD scales, PDF’s).
- Main experimental error: jet energy scale.
Top Quark Production Associated with Z Boson

- First observation of this channel.
- Allows to investigate WWZ and tZ couplings.
- tZq production is a background to tH.

ATLAS-CONF-2017-052
Measurement of W Boson Mass

- $M_W$ depends on $M_{\text{top}}$ and $M_H$ through loops.
- A precise measurement of $M_W$ is a test to the SM.
- ATLAS achieved a very competitive measurement.
- No evidence of any deviation from SM.

$M_W = 80.370 \pm 0.019 \text{ GeV}$
W/Z Physics

Example: Z + jets production, a test for perturbative QCD:

\[ \sigma(Z/\gamma^{*} \rightarrow l^+l^- + n_{\text{jets}}) \] [pb]

\[ p_T^{\text{jet}} > 30 \text{ GeV}, |y^{\text{jet}}| < 2.5 \]

**ATLAS**

13 TeV, 3.16 fb^{-1}

anti-k_{T} jets, R = 0.4

**Z/\gamma^{*} → l^+l^- + jets**

- Data
- BLACKHAT + SHERPA
- SHERPA 2.2
- ALPGEN + Py6
- MG5_aMC+Py8 CKKW
- MG5_aMC+Py8 FxFx

\[ \frac{d\sigma}{dp_T^{\text{jet}}} \] [pb/(GeV)]

\[ p_T^{\text{jet}} > 30 \text{ GeV}, |y^{\text{jet}}| < 2.5 \]

**ATLAS**

13 TeV, 3.16 fb^{-1}

anti-k_{T} jets, R = 0.4

**Z/\gamma^{*} → l^+l^- + 1 jet**

- Data
- BLACKHAT + SHERPA
- SHERPA 2.2
- ALPGEN + Py6
- MG5_aMC+Py8 CKKW
- MG5_aMC+Py8 FxFx

\[ \frac{\text{Prod.}}{\text{Data}} \] []
Triboson Production: A Tool to Investigate BSM Physics

WWW production:
Sensitive to WWWWWW coupling

WWγ production:
Sensitive to WWγγ coupling

See talk by E. Soldatov


arXiv:1707.05597

Many more Run 2 multiboson final state analysis are coming...
Supersymmetry Searches

- Most Popular BSM Model.
- Large number of searches, using all varieties of objects reconstructed by ATLAS.
- Large number of parameters: Searches interpreted within specific SUSY versions: pMSSM, mSUGRA, GMSB...

Readable summary table at: ATLAS-SUSY-SUMMARY
Searches for New Heavy Objects

**ATLAS**

13 TeV, 36.1 fb⁻¹

\[ Z' \rightarrow \ell \ell \]

**ATLAS**

13 TeV, 36.7 fb⁻¹

\[ W \rightarrow l\nu \]

95% CL

\[ \sigma(pp \rightarrow W) \times BR(W \rightarrow l\nu) \text{ [pb]} \]

\[ m_W \text{ [TeV]} \]

\[ \sigma_B \text{ pp} \]

\[ M_Z \text{ [TeV]} \]

\[ m_{Z'} \text{ [GeV]} \]

\[ \chi^2/DOF = 9.3/7 \]

\[ \text{Events} / 0.1 \text{ TeV} \]

\[ m_{Z'} \text{ [TeV]} \]
Light by Light Scattering in Pb-Pb Collisions

• $\gamma \gamma \gamma \gamma$ vertex forbidden in Standard Model.
• But $\gamma \gamma \rightarrow \gamma \gamma$ scattering occurs via box diagrams:

\[ \alpha (\alpha_{EM})^4, \text{very rare...} \]
• At LHC with HI: Simple topology.
• Produced in ultra peripheral collisions.
• Initial state photons emitted by ions ($\propto Z^2$, $Z = 82$).
• Observed with a significance of 4.4 $\sigma$. 
Anticipated Future

Run 2 (2015-2018):
120 fb\(^{-1}\) at $\sqrt{s} = 13$ TeV expected (61 fb\(^{-1}\) delivered up to now).

LS2 (2019-2020):
• Upgrade of the calorimeter trigger.
• Replacement of inner endcap muon chambers.

Run 3 (2021-2023):
150 fb\(^{-1}\) at $\sqrt{s} = 14$ TeV expected.

LS3 (2024-2025):
• Installation of a new inner tracker, with a coverage up to $|\eta| = 4$.
• Replacement of calorimeters and muon chambers electronics.
• Upgrades of trigger and data acquisition.

HL-LHC era (2026-2037)
3000 - 4000 fb\(^{-1}\) at $\sqrt{s} = 14$ TeV expected.
Conclusions

• ATLAS was born 25 years ago, while the general picture of particle physics was totally different from nowadays.

• A few original ideas were proposed to build ATLAS subdetectors. Ideas were validated by almost 10 years of R&D efforts, followed by the construction of the experiment.

• The discovery of the Higgs boson and measurement of its couplings validated the mass generation mechanism in the Standard Model.

• EW, QCD and top quark measurements are constraining SM, and could give indirect access to new physics.

• Searches benefit from the increase of LHC energy in Run 2.

• We are hoping for some nice surprises from Nature...

• ATLAS is preparing actively the HL-LHC era, both in detector R&D and physics prospective: Higgs couplings known at the level of < 10 %, Higgs self-coupling, rare decays, etc.
Backup
• **Two trigger levels:**
  - **Level 1:** Hardware, uses calorimeters and muon chambers.
  - **High Level Trigger:** Software, uses optimized offline-like code.
• During LHC Run 2, typical rates were of 75 kHz and 1 kHz for LVL1 and HLT respectively.
• Trigger menus are optimized depending on luminosity.
• Thresholds are a compromise between physics and the readout capabilities of the detector and the data acquisition.

Higgs Boson Spin and Parity

- All studies support the $0^+$ hypothesis.
- Other hypothesis ruled out at 99.9 % CL.
Measurement of the Full Spin Density Matrix in $t\bar{t}$ Events

- Top pairs are not polarized at LHC (weak production is negligible).
- But the two spins are correlated.
- New Physics could alterate SM predictions.
- Results: No deviation from SM predictions.

### ATLAS

**Spin Correlations**

- $C(k,k)$: $0.296 \pm (0.072) \pm (0.057)$
- $C(n,n)$: $0.304 \pm (0.038) \pm (0.047)$
- $C(r,r)$: $0.086 \pm (0.075) \pm (0.122)$

**Cross Correlations**

- $C(n,k)+C(k,n)$: $-0.012 \pm (0.089) \pm (0.087)$
- $C(n,k)-C(k,n)$: $-0.040 \pm (0.065) \pm (0.058)$
- $C(n,r)+C(r,n)$: $0.117 \pm (0.082) \pm (0.102)$
- $C(n,r)-C(r,n)$: $-0.006 \pm (0.082) \pm (0.070)$
- $C(r,k)+C(k,r)$: $-0.261 \pm (0.112) \pm (0.135)$
- $C(r,k)-C(k,r)$: $0.073 \pm (0.122) \pm (0.148)$

### JHEP 03 (2017) 113
Single Top Quark Production

**s-channel:** Sensitive to a $W'$

**t-channel:** Measurement of $V_{tb}$

**Wt channel:** Sensitive to b-quark pdf

See talk by F. Fabbri

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**ATLAS Preliminary**

Single top-quark production

Top Sum. Pl.
Jet Physics: A Window to QCD

- Example: Measurement of $\alpha_s$ running with jet Energy-Energy correlations.
- Idea: Gluon radiation jets are not back-to-back with their original jet, while their emission probability depends on $\alpha_s$.

**ATLAS**

\[ \alpha_s (Q) \]

\[ Q \, [\text{GeV}] \]

\[ 10^2 \, \text{to} \, 10^3 \]

\[ i \= s \, 8 \, \text{TeV}; 20.2 \, \text{fb}^{-1} \]

\[ \alpha_s^{\text{partial}} (m_Z) = 0.1186 \]

\[ H_{12} > 1400 \, \text{GeV} \]

\[ \text{arXiv:1707.02562} \]
One of the Recent SUSY Results: Search for Third Generation Super Partners in an MSSM Scenario

**ATLAS Preliminary**

- **Observed limit (±1 σ_{SUSY})**
- **Expected limit (±1 σ_{exp})**

**f_{S}=13 TeV, 36.1 fb^{-1}**

**Best b0L SR**

**ATLAS Conf-2017-038**
Jet Quenching in Pb-Pb Collisions

- Azimuth dependence of jet energy loss in PQG found to be consistent with the elliptic shape of interaction region.
- A softer fragmentation in central collisions has been measured.
- Measurements are in qualitative agreement with models on energy loss inside PQG.

__arXiv:11706.09363__
And Many More...

Search for dark matter

See talk by P. Czodrowski

Diffractive physics

Search for exotic Higgs decay

See talk by F. Prokoshin

B physics

See talk by P. Czodrowski

Search for dark matter

Diffractive physics