Selected results of the ATLAS experiment with significant contribution of Czech and Slovak physicists

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Introduction (1)

Particle physics investigates elementary objects the matter is built of and their mutual interactions

- What are the elementary objects?
  - atom $\rightarrow$ nucleus $\rightarrow$ anything yet smaller?
Introduction (2)

- How can we figure out the internal structure?
  - shooting a projectile on the investigated objects and measure deviations from the point-like structure
  - Rutherford experiment (discovery of nucleus in 1912)

- similarly, the proton structure was discovered much later in e-p collisions

The same principle is also used nowadays - but we collide particles at much higher energies
Forces in nature

- **Gravity** - too weak in the world of elementary particles, forget...

- **Electromagnetic force**

- **Weak force**
  - radioactive β-decay of neutrons or nuclei: $^A_Z X \rightarrow ^{A}_{Z+1} Y + e + \nu$
  - p-p cycle in the Sun

- **Strong force**
  - interaction between quarks in hadrons (protons, neutrons, ...)
  - as a „residual“ effect it binds protons and neutrons in nuclei

Forces are mediated by exchange particles - photon (elmg), W/Z bosons (weak), gluons (strong)
Standard Model (1)

- Theory describing our current knowledge of particles and their interactions
- Matter is built of fermions
  - 6 quarks and 6 leptons
  - all stable matter is built of 1st generation fermions
- Forces are mediated by spin-1 bosons
- Higgs boson (spin 0) "gives masses" to all elementary particles
Is that all? No, there are several phenomena that cannot be explained within Standard Model (SM), e.g.

- abundance of matter over anti-matter in the Universe?
- origin of dark matter?
- pattern of fermion masses and mixings?
- dynamics of EW symmetry breaking?

Searches for new physics beyond SM

- precise measurements of known particles & processes, deviations hint on physics beyond SM
- direct search for new particles and/or new phenomena
**ATLAS & LHC (1)**

- **Large Hadron Collider**
  - circular collider built at CERN in a tunnel of 27 km circumference, 100 m underground
  - provides proton-proton (and p-Pb, Pb-Pb) collisions at very high energies and intensities in 4 interaction points
  - 2 large general-purpose experiments (ATLAS, CMS) plus dedicated experiments (ALICE, LHCb, ...)

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*Overall view of the LHC experiments.*
ATLAS & LHC (2)
ATLAS & LHC (3)

- Most particles are unstable, we detect only their decay products
- Measurement methods depend on the particle's type
- Large experiments consist of several sub-detectors allowing to combine multiple types of simultaneous measurements
The ATLAS experiment

Czech and Slovak teams involved in several sub-detectors:

- Pixel detector
• The ATLAS experiment
  • Czech and Slovak teams involved in several sub-detectors:
    - Pixel detector
    - Semiconductor Tracker
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    - LAr electromagnetic calorimeter
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  - Tile Calorimeter
ATLAS & LHC (4)

- The ATLAS experiment
  - Czech and Slovak teams involved in several sub-detectors:
    - Pixel detector
    - Semiconductor Tracker
    - LAr elmg calorimeter
    - Tile Calorimeter
    - detector of forward protons AFP
    - neutron shielding
  - they also participate in preparing upgrade of some sub-detectors
**ATLAS physics programme**

- **Covers many domains of particle physics**
  - **Higgs physics**: as precise as possible determination of couplings to other particles, (differential) cross-section measurements, search for very rare and/or exotics decays not predicted by SM, search for other Higgs-like particle(s)
  - **top-quark physics**: top-quark mass & width, decays, (differential) cross-sections including four top-quark production etc
  - **flavour physics**: quarkonia, processes involving heavy mesons (B, D) and their (rare) decays, CP violation processes, etc
  - precise measurements of **electroweak processes** involving W, Z
  - **QCD and jet physics**, measurement of **diffractive processes** („forward“ physics)
  - search for **Supersymmetry** (SUSY)
  - **exotics** - search for new physics phenomena including dark matter, new resonances, excited quarks & leptons, processes with lepton flavour violation etc
  - **heavy ions** - investigation of phenomena in strongly interacting medium (QGP)
CZ/SK involvement

- Czech and Slovak physicists are involved in many analyses.
- Few examples are given in next slides:
  - cross-section measurement of $H \rightarrow \tau \tau$
  - various top-quark measurements
  - $B^0_s \rightarrow J/\psi \phi$ CPV phase measurement
  - measurement of $\gamma \gamma \rightarrow W W$
  - heavy ions physics
**H → τ τ (1)**

- Difficult measurement since τ-leptons further decay, either $\tau \rightarrow e/\mu + 2\nu$ or $\tau \rightarrow$ hadrons $+ \nu$. Neutrinos in the final state represent another challenge for the event reconstruction.
  - Higgs boson mass needs to be approximated (MMC)

- Analysis deals with multiple categories, targeting
  - two main Higgs production mechanisms (ggH, VBF)
  - different final states ($\tau_{e/\mu}T_{e/\mu}$, $\tau_{e/\mu}T_h$, $T_hT_h$)
    - example in one category

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**ATLAS Preliminary**

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

$H \rightarrow \tau\tau$ ($\mu = 1.09$)

- Data 2015 + 2016
- $Z \rightarrow \tau\tau$
- Other Backgr.
- Misidentified $\tau$
- Uncertainty
Combining all categories, the analysis of 2015+2016 data determines the cross-section for the two main production mechanisms:

- $\sigma^{ggh} = 3.1 \pm 1.0 \,(\text{stat})^{+1.6}_{-1.3} \,(\text{syst}) \,\text{pb}$
- $\sigma^{VBF} = 0.28 \pm 0.09 \,(\text{stat})^{+0.11}_{-0.09} \,(\text{syst}) \,\text{pb}$

When combining the results with earlier data of Run 1 (2010-2012), the Higgs boson decay to pairs of $\tau$-leptons is observed with a significance of $6.4\sigma$.

- for more details, see the press release and/or the paper Phys. Rev. D 99 (2019) 072001

An improved analysis of the full Run 2 data (2015-2018) is currently ongoing, results should soon be updated.
In the pp collisions, the top-quark pair production ($\bar{t}t$) is dominated by fully symmetric $gg \rightarrow \bar{t}t$ process, smaller contributions come from $qq$ or $qg$ processes.

- due to parton distribution functions, top-quarks tend to be produced in the forward direction, while antitop-quarks tend to be more central ($|y_t| > |y_{\bar{t}}|$)
- measurement of charge asymmetry $A_c$ provides another stringent test of SM, possible contribution from „new physics“ processes would lead to different asymmetry

$$A_c \equiv \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}, \text{where } \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

Analysis in a nutshell:

- semi-leptonic $\bar{t}t$ events ($\bar{t}t \rightarrow Wb\bar{W}b \rightarrow \ell v b q \bar{q} b$) selected, two topologies are considered
  - resolved topology (four small-R jets in the final state) - multivariate technique (BDT) is exploited for correct assignments of jets to individual partons, b-tagging
  - boosted topology (hadronically decaying top is reconstructed as one large-R jet instead of 3 small-R jets)
- fully Bayesian unfolding is then used to correct $\Delta|y|\text{ for acceptance and detector resolution effects}
tt charge asymmetry (2)

- Differential measurements as a function of velocity and invariant mass of $t\bar{t}$ system

- Interpretation in EFT: limits are imposed on dim-6 Wilson operators and compared to forward-backward asymmetry measurements @Tevatron

- More details in press release and/or ATLAS-CONF-2019-026

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**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

**Differential $A_0^c$ vs. NNLO QCD + NLO EW**

- $m_V$ interval
  - $\Lambda^2$
  - $\Lambda^2 + \Lambda^4$
  - 68% C.L. limits

- $m_V$ intervals:
  - $> 1500$ GeV
  - 1000 - 1500 GeV
  - 750 - 1000 GeV
  - 500 - 750 GeV
  - 0 - 500 GeV

- Inclusive

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LHCb combination

- pp 8 TeV, JHEP 1804 (2018) 033

Tevatron combination

- pp 1.96 TeV, PRL 120 (2018) 042001

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$C$ [TeV$^2$]
**Motivation**: another test of the theory & models – constrain higher-order QCD calculations and parton distribution functions, tuning MC generators, sensitivity to new physics

**Analysis performed in semi-leptonic channel** ($\ttbar \rightarrow Wb\bar{W}b \rightarrow ℓvbq\bar{q}b$), separately for resolved and boosted topology

- **single-differential cross-sections** the MC description is usually good in resolved topology, while some mismodelling is observed in boosted topology
\( \bar{t}t \) differential cross-sections (2)

- worse description of double-differential cross-sections, all event generators have problems when \( p_T(\bar{t}t) \) is a probed observable

- In general, Powheg+Pythia8 (resolved) and Powheg-Herwig7 (boosted) provide good description of the largest fraction of the investigated variables

- Results are also unfolded to the parton-level in order to compare with state-of-the-art QCD predictions (general improvement wrt NLO+PS MC generators)

**ttZ cross-section measurement (1)**

- Provides information about **ttZ coupling**, possible deviations from SM prediction might indicate new effects in EW symmetry breaking
- Both inclusive and differential cross-sections are measured in final states with 3ℓ and 4ℓ (Z → ℓℓ and tt → WbW̄b, where 1 or both W decay to ℓ'ν)
- Analysis is split into several categories depending on 3 or 4ℓ, 1 or 2 b-tagged jets, different vs opposite flavour ℓ (→ 6 regions)
- **Inclusive cross-section** is derived from profile likelihood fit to 6 signal regions and 2 control regions (WW+light jets, WZ+light jets)

\[ \sigma(pp \rightarrow ttZ) = 1.05 \pm 0.05\text{(stat)} \pm 0.09\text{(syst)} \text{pb} \]

\[ \sigma(\text{SM})^{\text{NLO+NNLL}} = 0.86^{+0.07}_{-0.09}\text{(scale)} \pm 0.03\text{(PDF+ } \alpha_s \text{)} \text{pb} \]
\( \bar{t}tZ \) cross-section measurement (2)

- **Differential cross-section measurements** performed at detector, particle and parton level
  - iterative Bayesian procedure used for unfolding
  - \( p_T(Z) \) and \(|y(Z)|\) are sensitive to MC modelling and various BSM effects, respectively

- all differential measurements limited by available statistics, differences between various predictions are smaller than the uncertainties

- More details in ATLAS-CONF-2020-028
$B_s^0 \rightarrow J/\psi \varphi$ (1)

- CP violation occurs due to the interference between the direct decay and the decay with $B_s^0 - \bar{B}_s^0$ mixing

- Although SM predicts non-zero CP-violating phase $\phi_s$, possible contribution from new physics may significantly enhance this phase

- Crucial analysis ingredients:
  - identification of the final state $B_s^0 \rightarrow J/\psi \varphi \rightarrow \mu^+ \mu^- K^+ K^-$
  - flavour tagging of the opposite $B$-meson
  - proper life time measurement

Results still compatible with SM predictions, but there is some tension between the results of individual experiments.
\( \gamma \gamma \rightarrow W W \) (1)

- **Motivation**: only diagrams with gauge bosons contribute at the tree level, the process is sensitive to anomalous gauge boson interactions (EFT with dim-6 and dim-8 operators)

- Looking for the process \( p p (\gamma \gamma) \rightarrow p(*) W W p(*) \rightarrow e \nu \mu \nu \)
  - photons are radiated off the whole proton or off a parton
  - elastic vs single-dissociative vs double-dissociative events

- Main background comes from Drell-Yann process, \( q\bar{q} \rightarrow WW \) and \( \gamma \gamma \rightarrow \tau \tau \)

- Event selection
  - OS e and \( \mu \), \( p_T(e\mu) > 30 \text{ GeV}, m_{e\mu} > 20 \text{ GeV} \)
  - no further tracks from that vertex (\( n_{\text{trk}} = 0 \))
Global fit using 1 signal region and 3 control regions (with inverted criteria on $p_T(e\mu)$ and $n_{trk}$) to constrain main background components.

Observation established at 8.4σ, measured fiducial volume cross-section

$$\sigma(pp(\gamma\gamma) \rightarrow p(*)WWp(*) \rightarrow e\nu\mu\nu) = 3.13 \pm 0.31\text{(stat)} \pm 0.28\text{(syst)} \text{fb}$$

More details in press release and ATLAS-CONF-2020-038
Heavy ion collisions (1)

- In ultrarelativistic collisions of nuclei, QGP is created in the central collisions. Energy of quarks/gluons propagating through QGP is modified, leading to energy asymmetry in di-jet events (Phys. Rev. Lett. 105 (2010) 252303)

\[ A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} - E_{T,2}} \]

Jet quenching

- The jet yields are compared between the Pb-Pb and p-p collisions at the same centre-of-mass energy per nucleon using nuclear modification factor \( R_{AA} \)

\[ R_{AA} = \frac{d^2N_{AA}}{dT_{AA}dp_Tdy} \frac{dT_{pp}d^2\sigma_{pp}^{inel}}{dT_{pp}dp_Tdy} = \frac{1}{\langle N_{AA} \rangle} \cdot \frac{\text{yield in AA}}{\text{yield in pp}} \]
Heavy ion collisions (2)

- Recent studies measure large-radius jets with sub-jets and look at the (weighted) distance between two leading sub-jets

\[ d_{12} \equiv \min(p_{T,1}^2, p_{T,2}^2) \cdot (\Delta \phi_{12}^2 + \Delta \eta_{12}^2) \]

- \( R_{AA} \) scales with number of nucleons participating in the collision \( N_{\text{part}} \), as expected

- moreover, the yield of large-radius jets consisting of several sub-jets is more suppressed than those containing a single small-radius jet \( \rightarrow \) jets with hard internal splitting loose more energy in QGP medium

Conclusions & plans (1)

• After the discovery of the Higgs boson in 2012 the Standard Model seems completed, but
  • still need to improve precision to verify whether all properties of the new particle agree with
    SM predictions (rare decays, self-coupling etc), since Higgs might be a portal to new physics
  • precision tests of many other SM features/parameters are carried out, discrepancies should
    hint on new physics, too
• We know that Standard Model cannot be the final theory, we are looking for hints for new
  physics in many corners of the phase space
  • search for new particles, no evidence for any so far
  • precision measurements did not provide clear evidence for new physics yet, but some tensions
    between experiment(s) and theory/models exist

→ need more data
Conclusions & plans (2)

- Czech and Slovak teams are very active in the ATLAS experiment, contributing significantly to several domains of detector construction/operation/upgrade as well as physics data analysis.

- The detector currently undergoes maintenance and phase-1 upgrade, while many analyses using full Run-2 (2015-2018) data are still ongoing:
  - In parallel, upgrade works/studies for High-Luminosity LHC ramping up.

- Looking forward to new results, Run-3 data (expected start of data-taking in 2022) and HL-LHC (from ~2027 onwards).
BACKUP
From the LHC to the High-Luminosity LHC @ CERN

ICHEP 2012
H discovery

ICHEP 2020

ICHEP 2028
1st HL-LHC results

HL-LHC TECHNICAL EQUIPMENT:

HL-LHC TECHNICAL EQUIPMENT:

slide by J. D’Hondt, ICHEP 2020, Prague
Both experiments published the results on partial Run-2 dataset (36 fb$^{-1}$).

Both leptonic and hadronic $\tau$-decay modes explored, for $\ell T_{\text{lep}}$ channel only different-flavour leptons considered in the final state to avoid large $Z \rightarrow \ell \ell$ background.

Background: normalization and validation in CRs

- irreducible $Z \rightarrow \tau \tau$, reducible $t \bar{t}$, diboson, SM $H$ decays ($\tau \tau$, $WW$)
- fakes ($\ell$ or $\tau_{\text{had}}$ is mimicked by a jet or a lepton) from $W$+jets, multijet, $Z \rightarrow \ell \ell$

Event selection & categorization in SR

- 2 different-flavour isolated leptons ($\ell T_{\text{lep}}$) or an isolated lepton and $\tau_{\text{had}}$ of opposite charges ($\ell T_{\text{had}}$)
- angular separation $\ell$-$\tau$, b-veto (except of $H \rightarrow e T_{\text{had}}$ in CMS)
- categories: non-VBF and VBF ($\text{ATLAS}$): 0-jet, 1-jet, 2-jets $ggH$ and 2-jets VBF ($\text{CMS}$)
$H \rightarrow e\tau$, $H \rightarrow \mu\tau$ (2)

- BDT trained to enhance signal/background separation, BDT score used as discriminating variable in the final fit. Examples of two categories in each search

**ATLAS ($H \rightarrow e\tau$)**

**CMS ($H \rightarrow \mu\tau$)**


JHEP 06 (2018) 001
H → eτ, H → μτ (3)

- Combined upper limits on LFV branching fractions

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<th>ATLAS</th>
<th>CMS</th>
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<tr>
<td>B(H → eτ)</td>
<td>&lt; 0.47%</td>
<td>&lt; 0.61%</td>
</tr>
<tr>
<td>B(H → μτ)</td>
<td>&lt; 0.28%</td>
<td>&lt; 0.25%</td>
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Yukawa LFV couplings

- The results on LFV Higgs decays are interpreted in terms of non-diagonal Yukawa couplings and compared to other LFV searches (τ → ℓγ, τ → 3ℓ, μ → eγ, μ → 3e)

- both ATLAS and CMS limits are more stringent than those coming from τ → ℓγ, τ → 3ℓ measurements