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

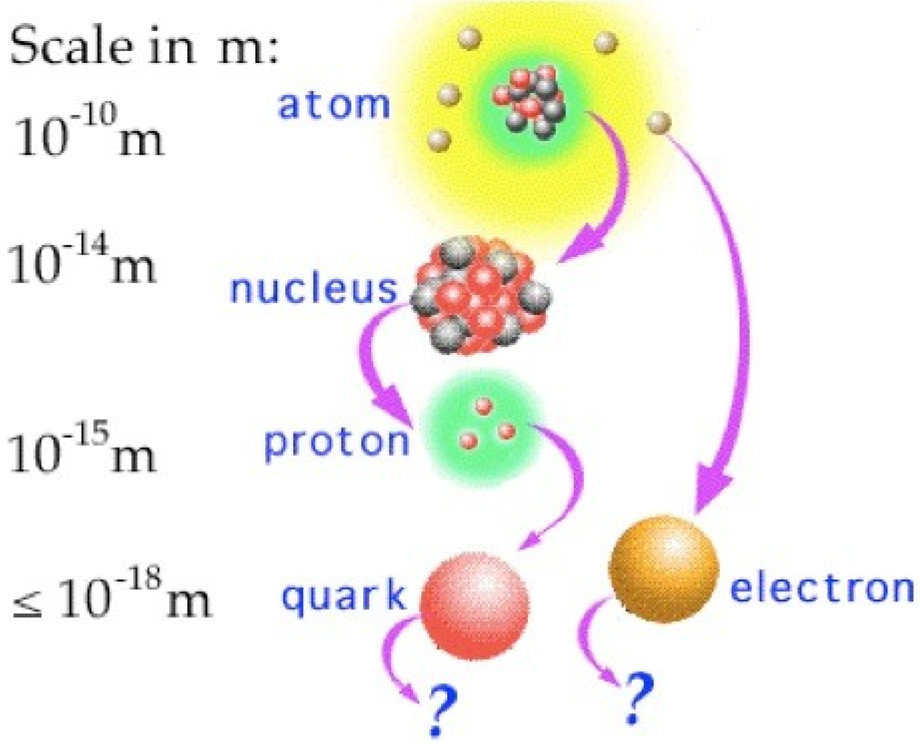
Tomáš Davídek,
Institute of Particle and Nuclear Physics,
Faculty of Mathematics & Physics,
Charles University

ATLAS EXPERIMENT

# Introduction (1)

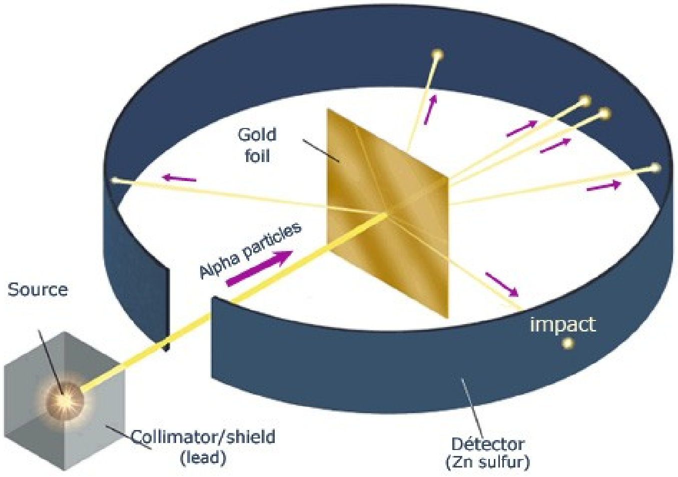
## Particle physics investigates elementary objects the matter is built of and their mutual interactions

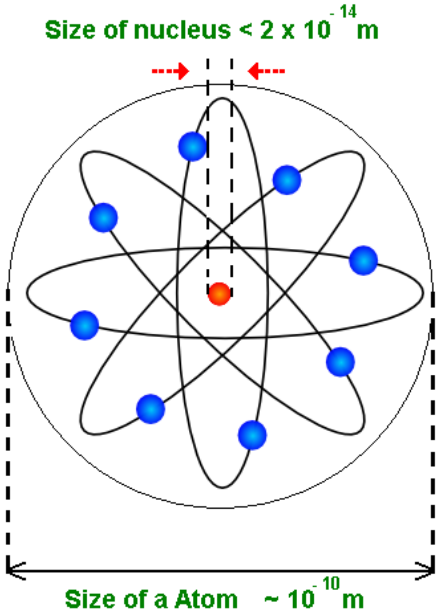
- What are the elementary objects?
  - atom → nucleus → anything yet smaller?



# 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)



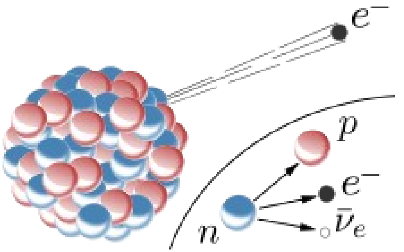

  - similarly, the proton structure was discovered much later in e-p collisions

The same principle is also used nowadays – but we collide particles at much higher energies

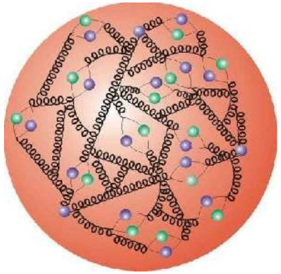
# Forces in nature

- **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



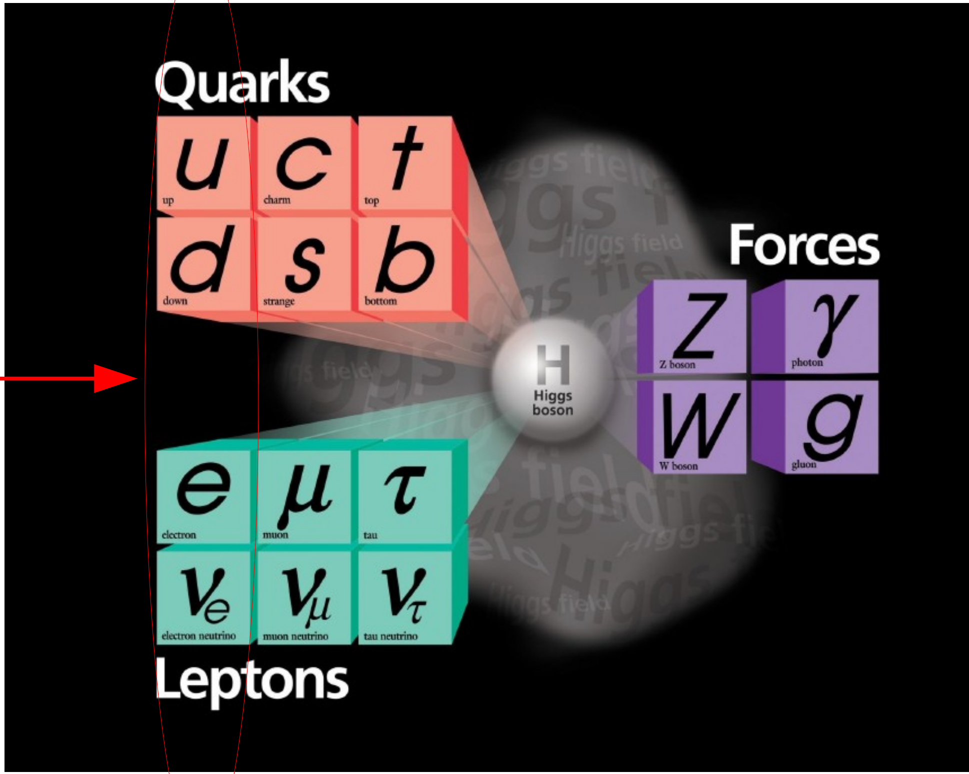

- **Strong force**
  - interaction between quarks in hadrons (protons, neutrons, ...)
  - as a „residual" effect it binds protons and neutrons in nuclei



Forces are mediated by exchange particles – photon (elmg), W/Z bosons (weak), gluons (strong)

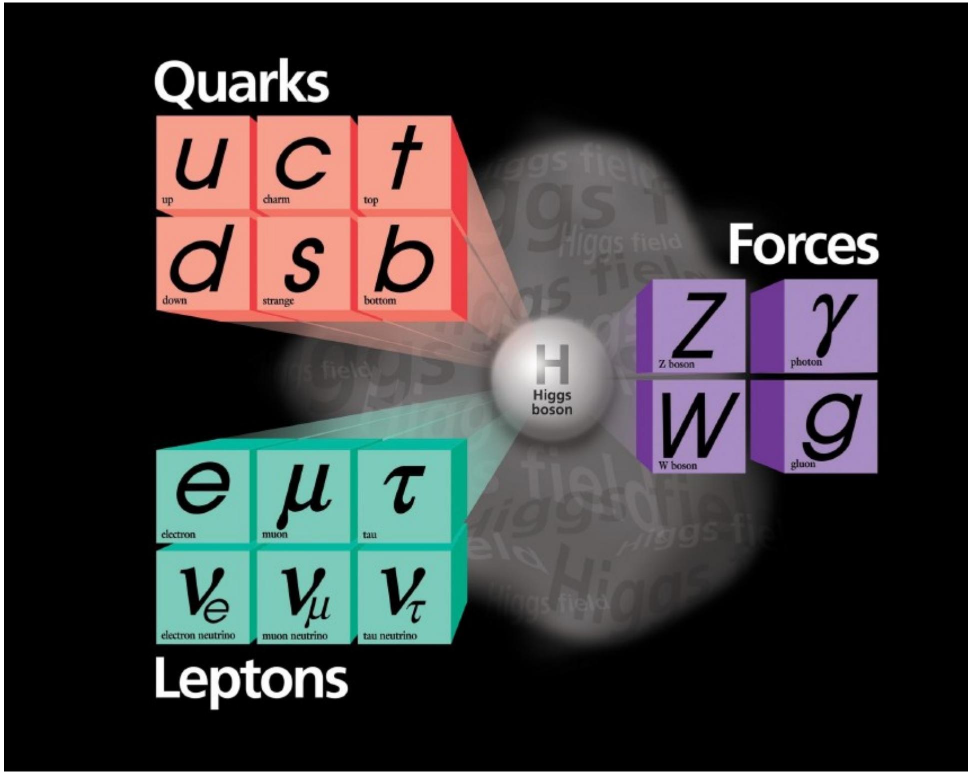
# Standard Model (1)

- 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



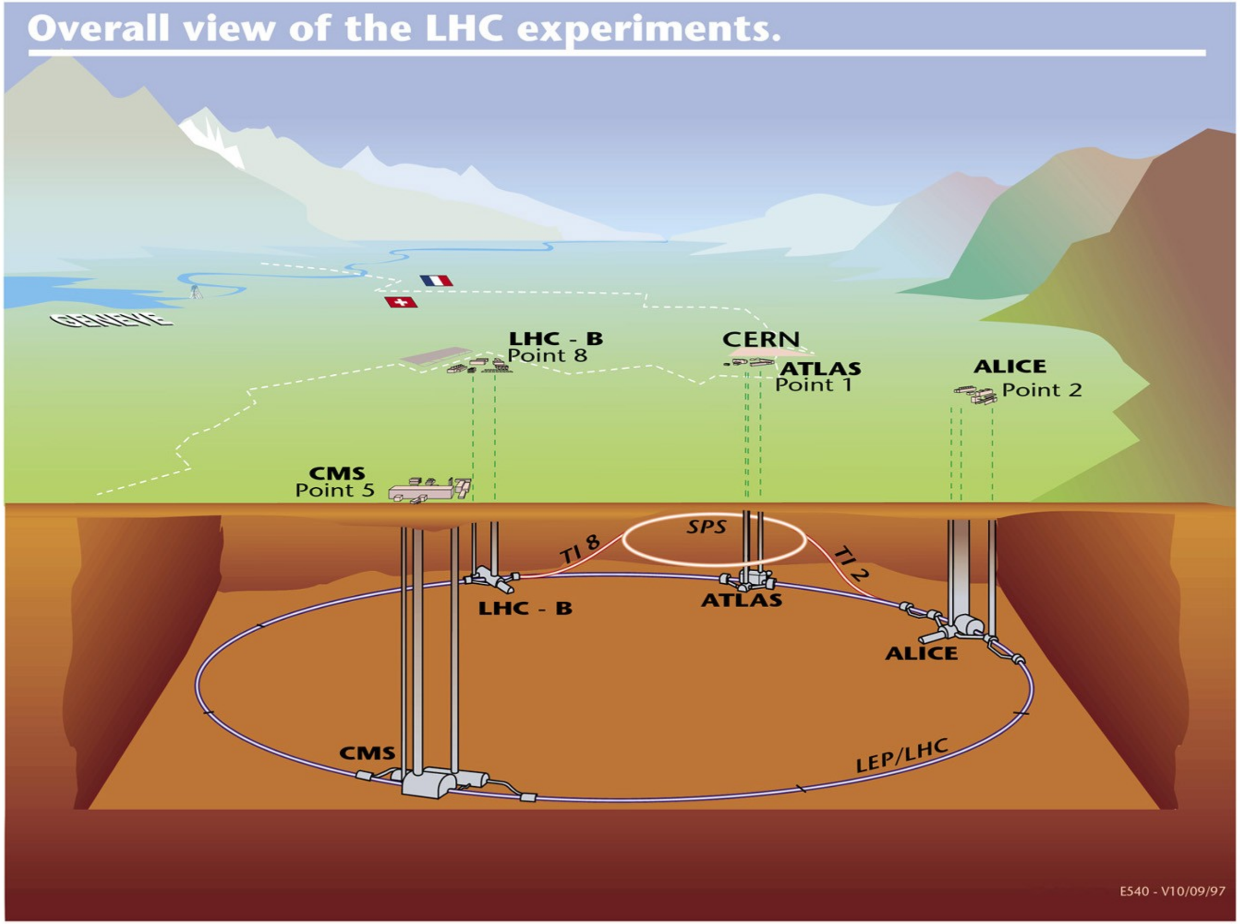
# Standard Model (2)

- 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

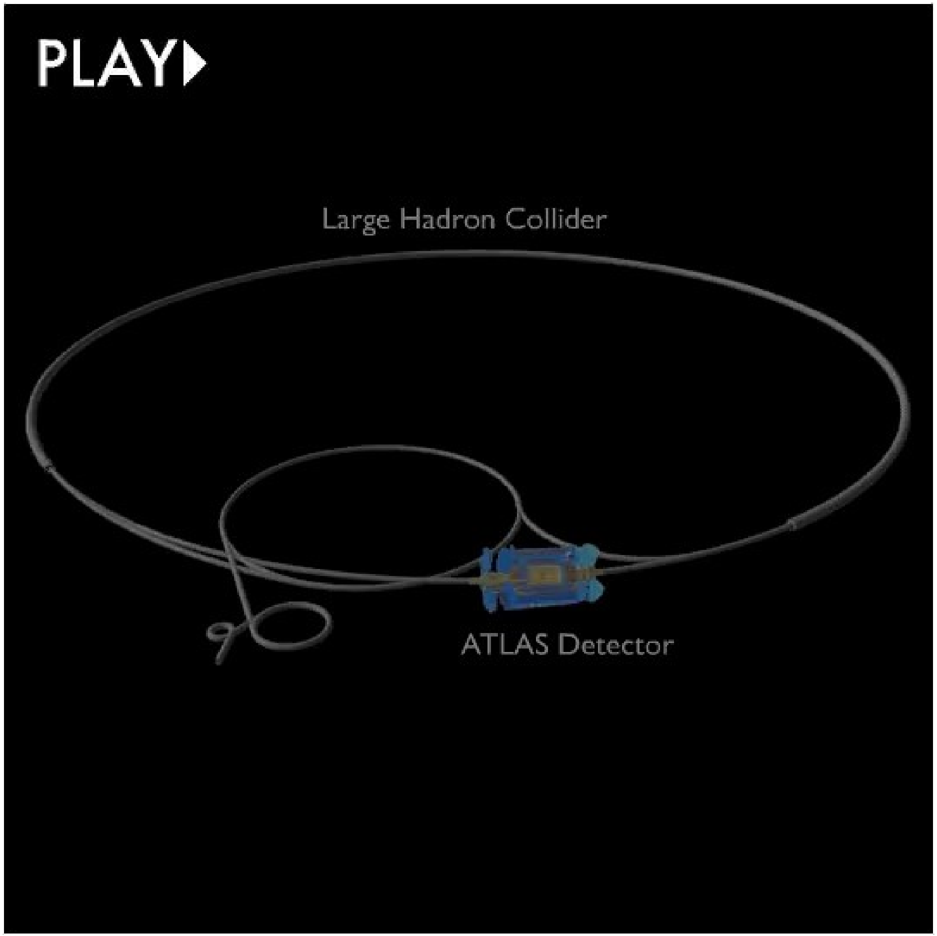


# ATLAS & LHC (1)

- 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, ...)

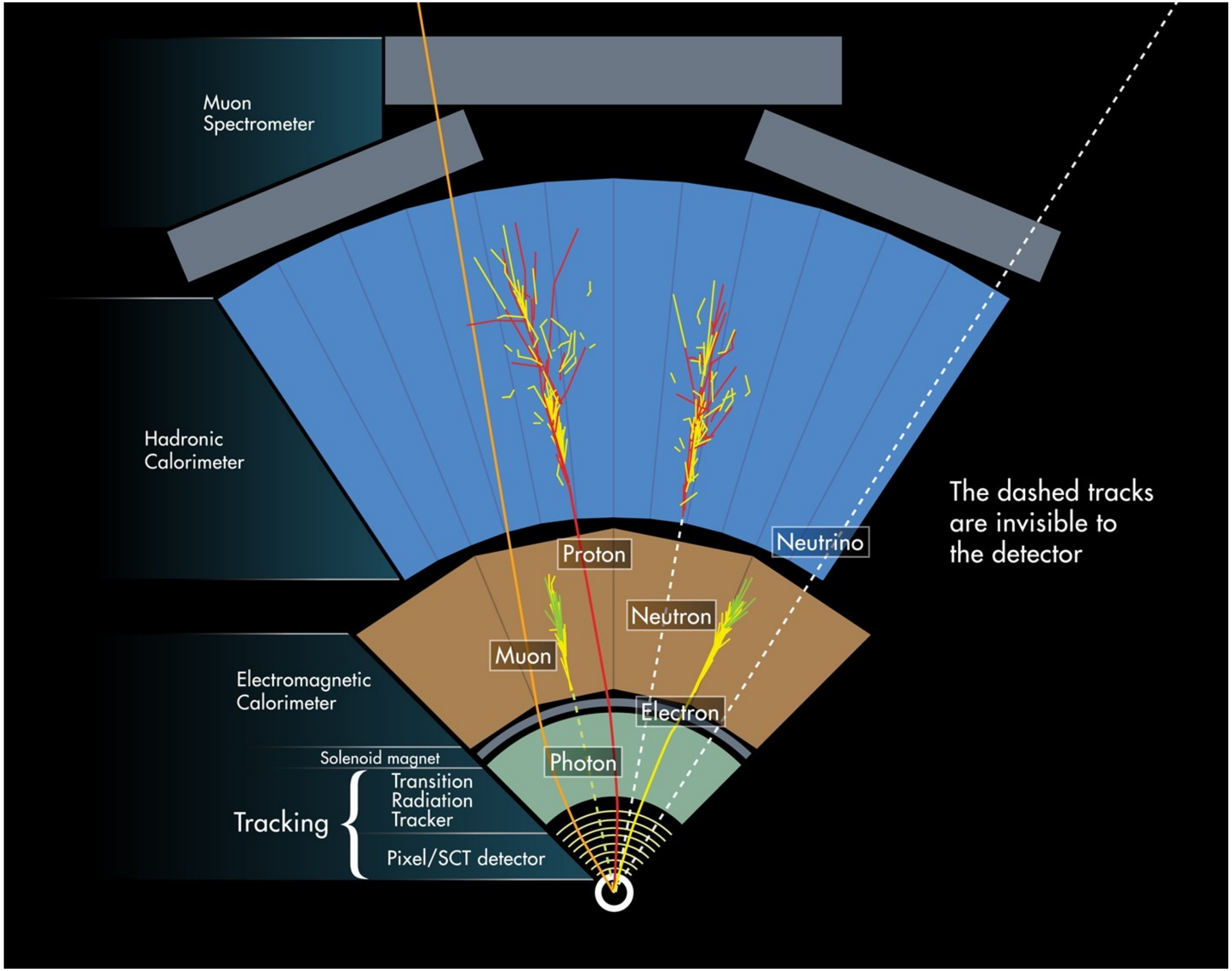


# ATLAS & LHC (2)



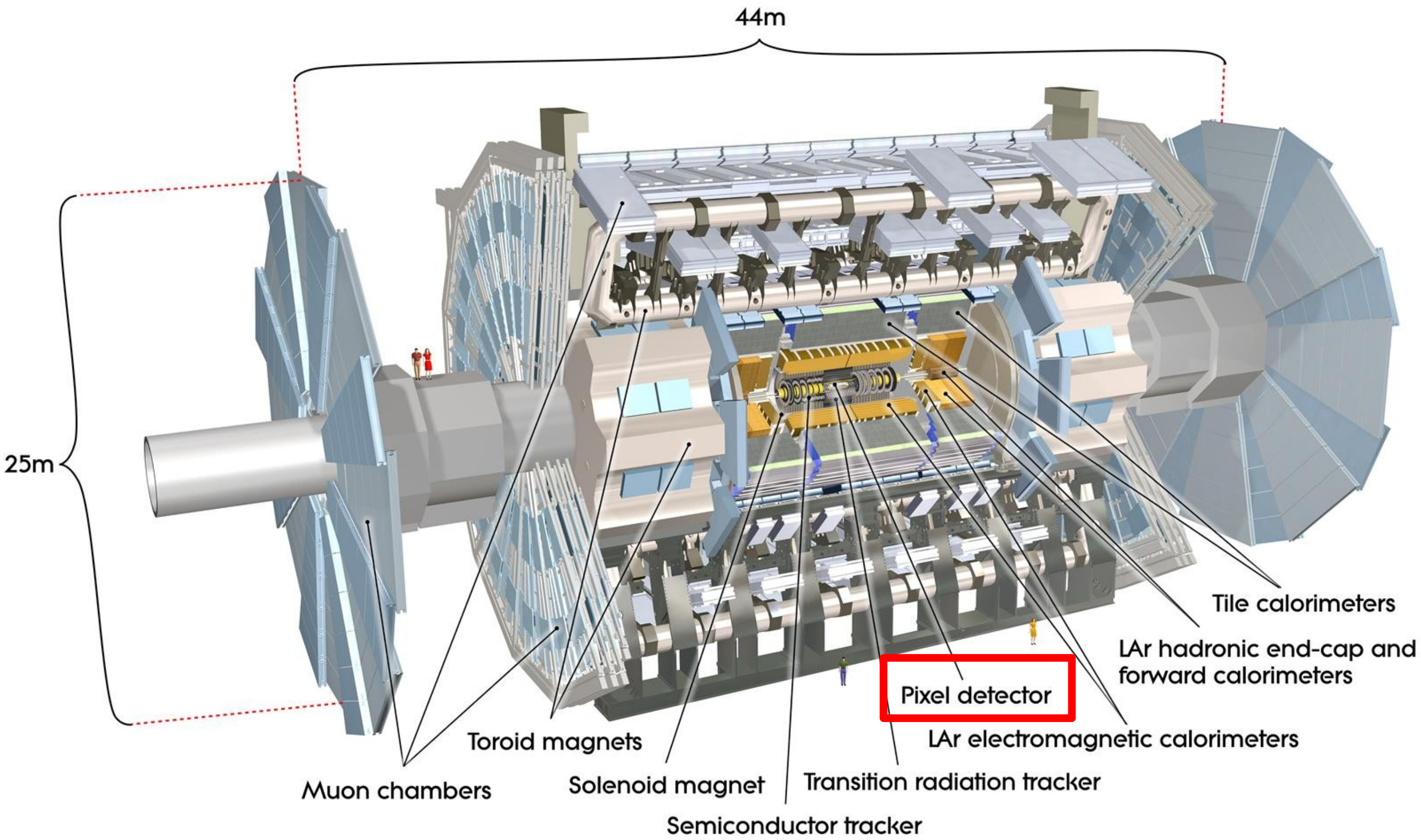
# ATLAS & LHC (3)

- 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



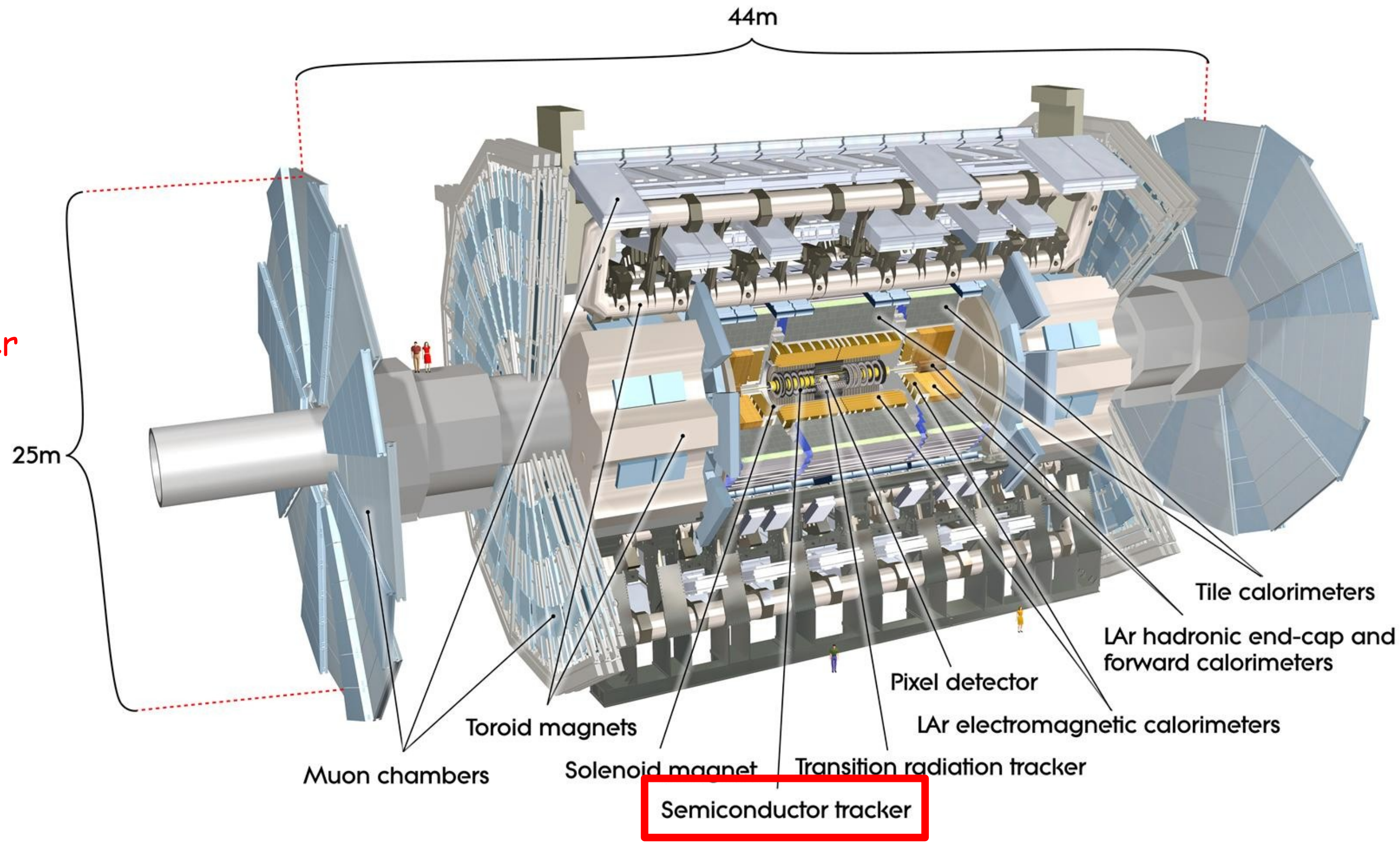
# ATLAS & LHC (4)

- The ATLAS experiment
  - Czech and Slovak teams involved in several sub-detectors:
    - Pixel detector



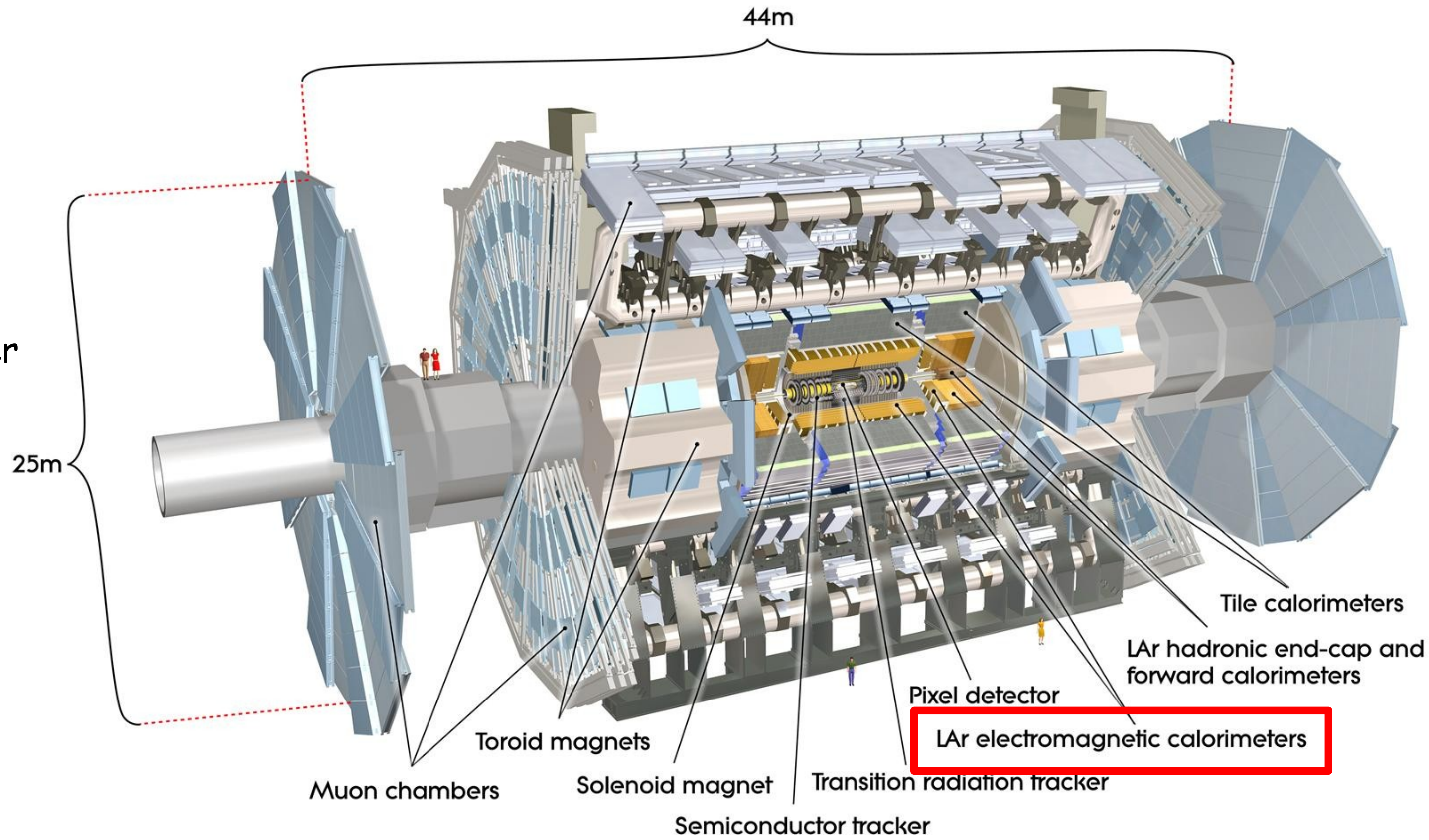
# ATLAS & LHC (4)

- The ATLAS experiment
  - Czech and Slovak teams involved in several sub-detectors:
    - Pixel detector
    - Semiconductor Tracker



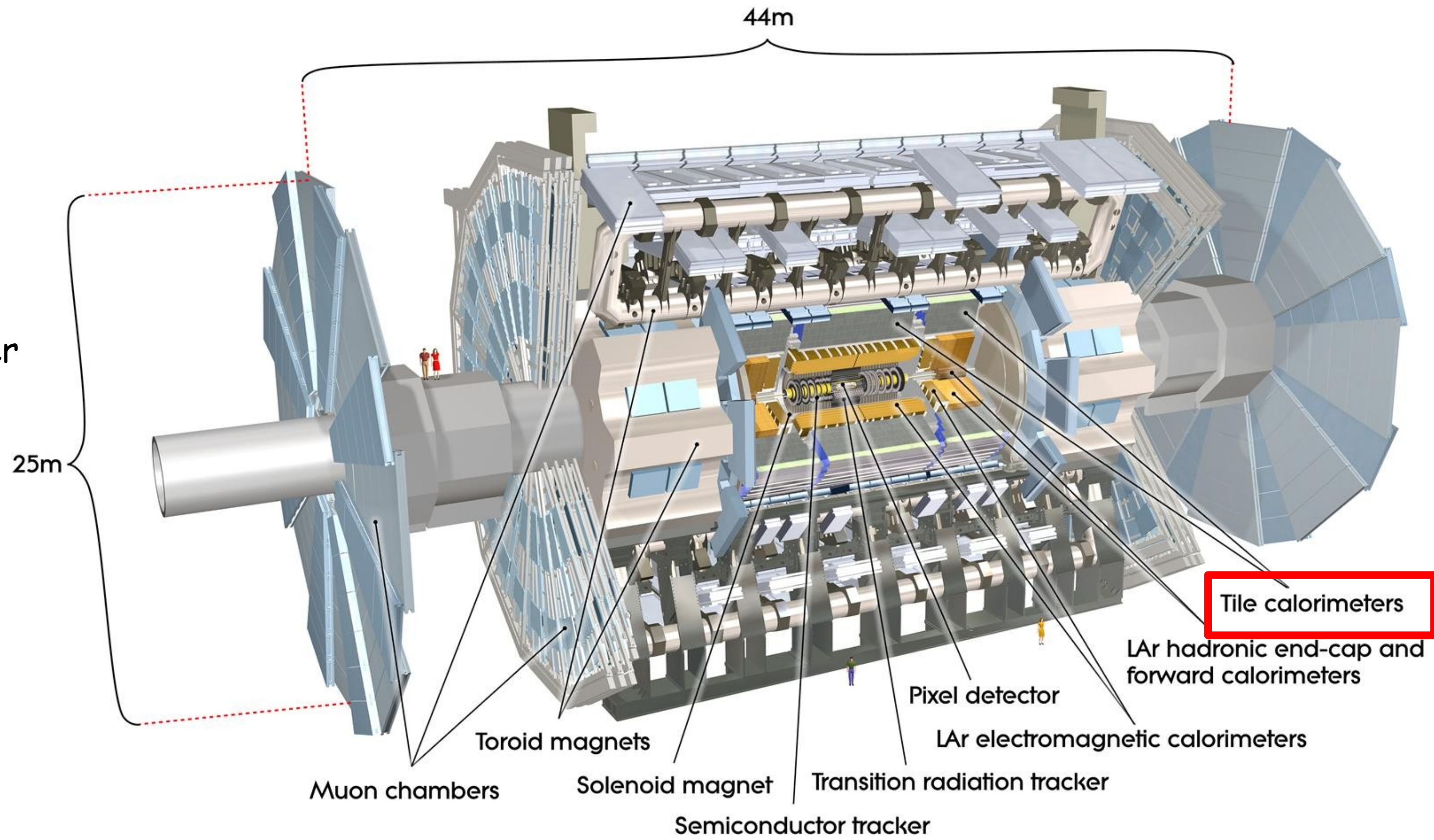
# ATLAS & LHC (4)

- The ATLAS experiment
  - Czech and Slovak teams involved in several sub-detectors:
    - Pixel detector
    - Semiconductor Tracker
    - LAr elmg calorimeter



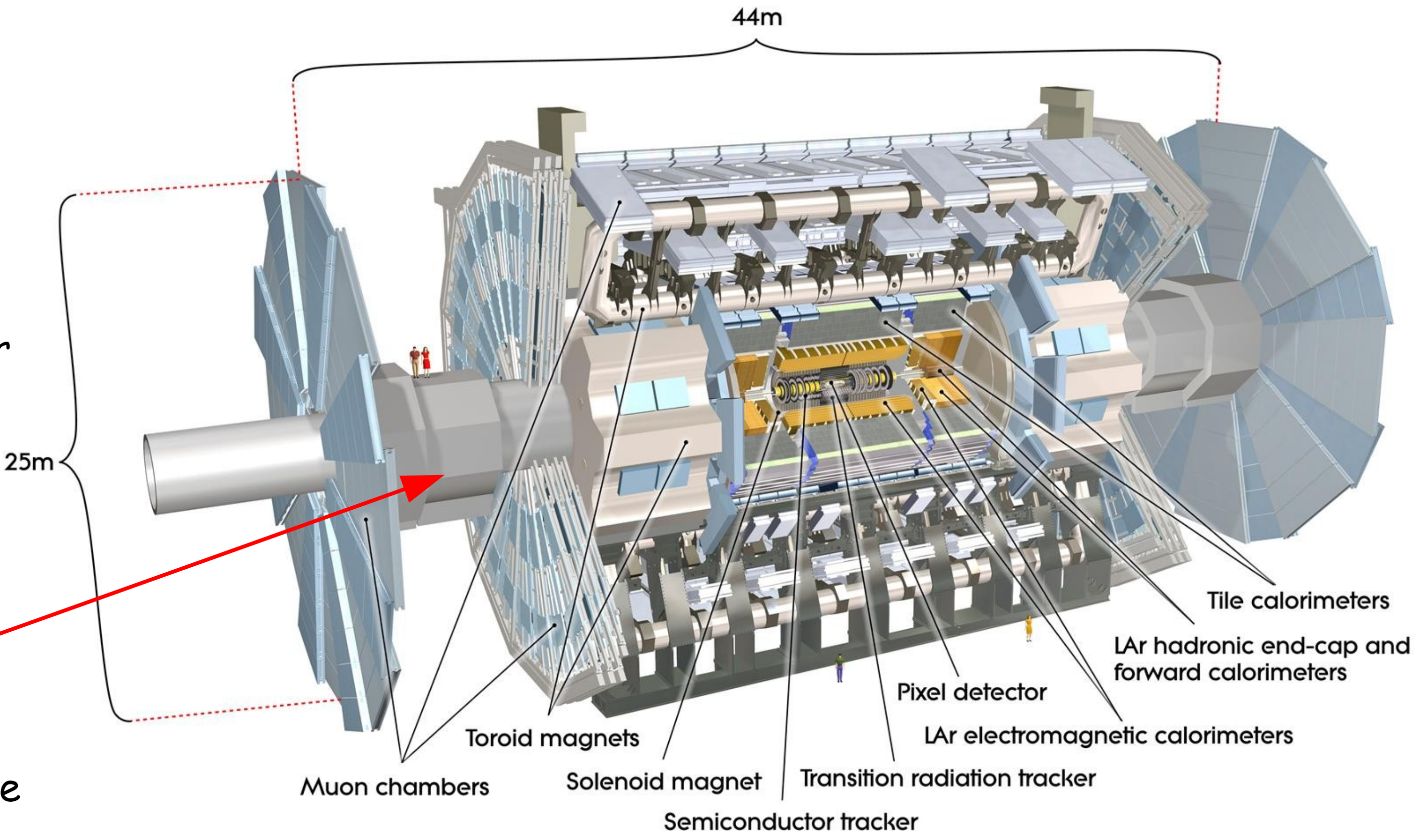
# ATLAS & LHC (4)

- The ATLAS experiment
  - Czech and Slovak teams involved in several sub-detectors:
    - Pixel detector
    - Semiconductor Tracker
    - LAr elmg calorimeter
    - Tile Calorimeter



# 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



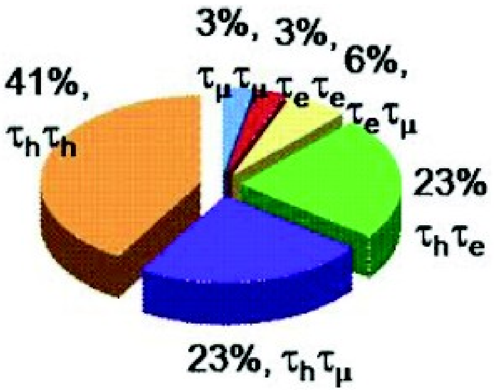
# ATLAS physics programme

- 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

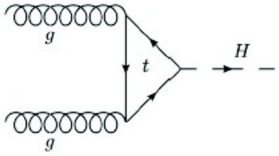
- Czech and Slovak physicists are involved in many analyses
- Few examples are given in next slides
  - cross-section measurement of $H \to \tau\,\tau$
  - various top-quark measurements
  - $B^0_s \to J/\psi\,\varphi$ CPV phase measurement
  - measurement of $\gamma\,\gamma \to W\,W$
  - heavy ions physics

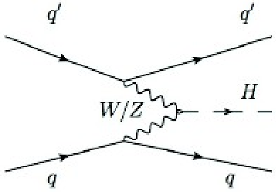
# $H \to \tau\,\tau$ (1)



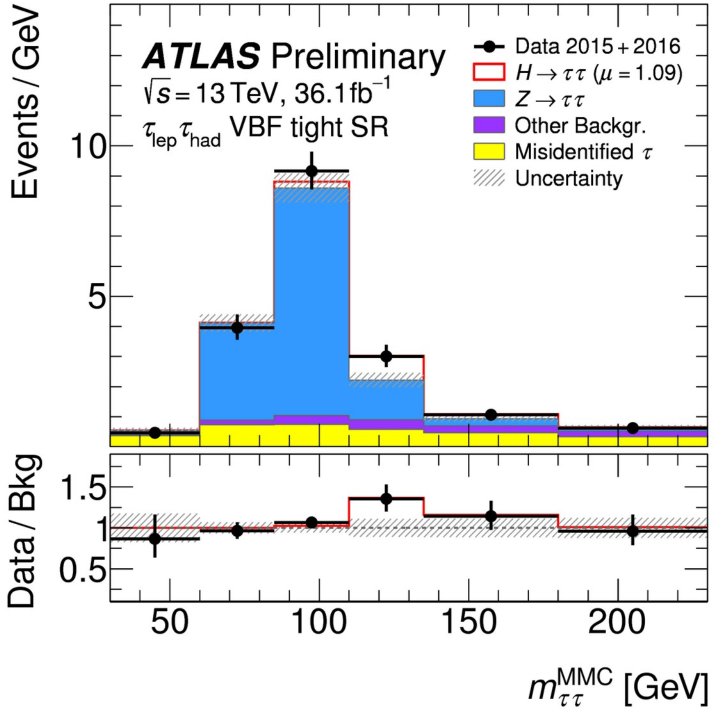

- Difficult measurement since τ-leptons further decay, either $\tau \to e/\mu + 2\nu$ or $\tau \to$ hadrons $+ \nu$. Neutrinos in the final state represent another challenge for the event reconstruction.
  - Higgs boson mass needs to be approximated (MMC)

- Analysis deals with multiple categories, targetting
  - two main Higgs production mechanisms (ggH, VBF)



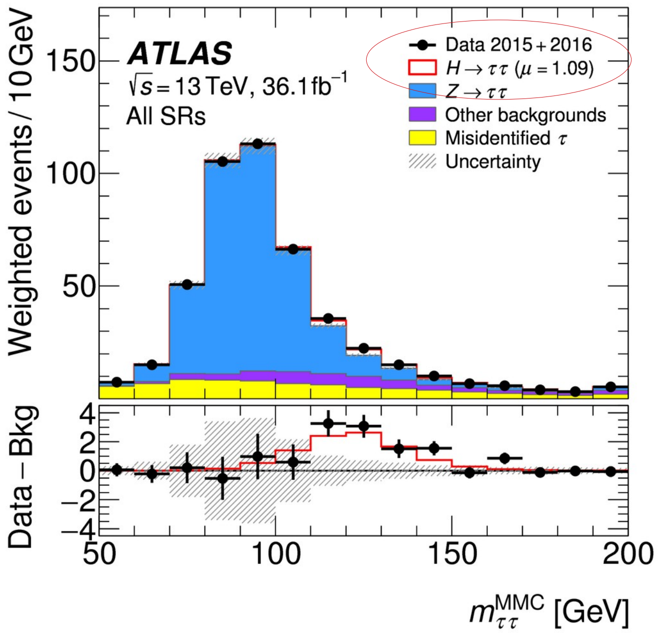




  - different final states ($\tau_{e/\mu}\tau_{e/\mu}$, $\tau_{e/\mu}\tau_h$ , $\tau_h\tau_h$)
    - example in one category



# H → τ τ (2)

- 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 τ-leptons is observed with a significance of 6.4σ
  - 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.

# $t\bar{t}$ charge asymmetry (1)

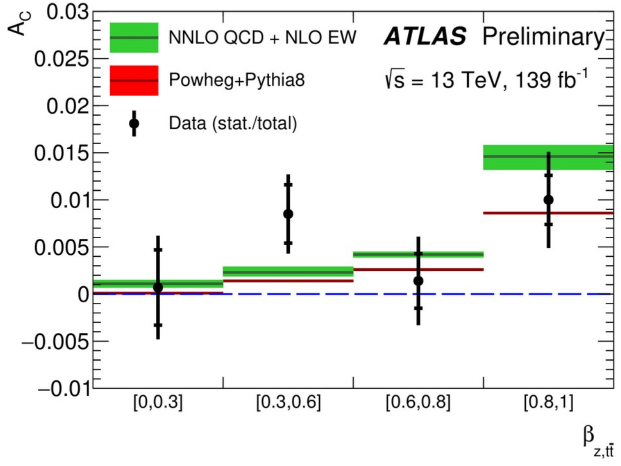
- In the pp collisions, the top-quark pair production ($t\bar{t}$) is dominated by fully symmetric $gg \to t\bar{t}$ process, smaller contributions come from $q\bar{q}$ or $qg$ processes.
  - due to parton distribution functions, top-quarks tend to be produced in the forward direction, while antitop-quarks 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

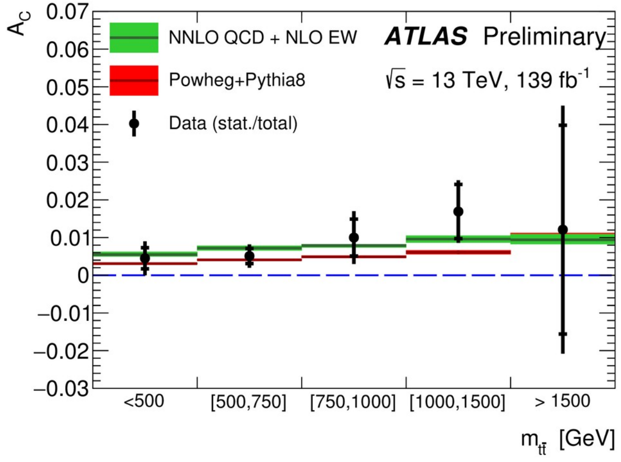
$$A_c \equiv \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}, \text{ where } \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$

- Analysis in a nutshell:
  - semi-leptonic $t\bar{t}$ events ($t\bar{t} \to WbW\bar{b} \to \ell\nu bq\bar{q}'\bar{b}$) 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 $\Delta|y|$ for acceptance and detector resolution effects

# $t\bar{t}$ charge asymmetry (2)

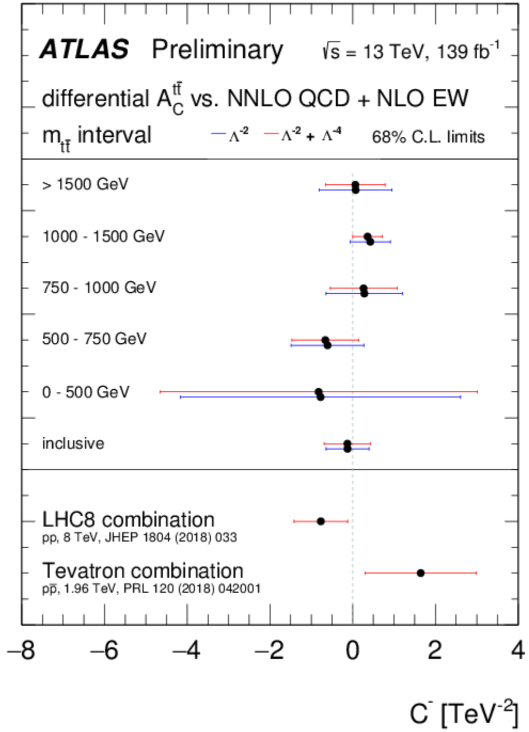
- Differential measurements as a function of velocity and invariant mass of $t\bar{t}$ system



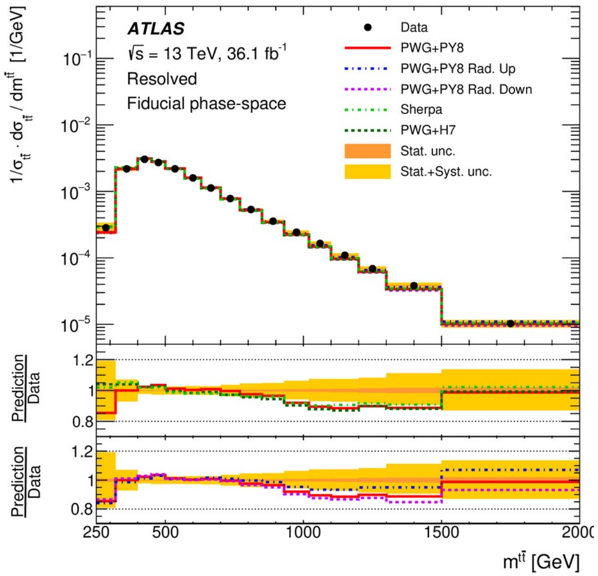

- Interpretation in EFT: limits are imposed on dim-6 Wilson operators and compared to forward-backward asymmetry measurements @Tevatron

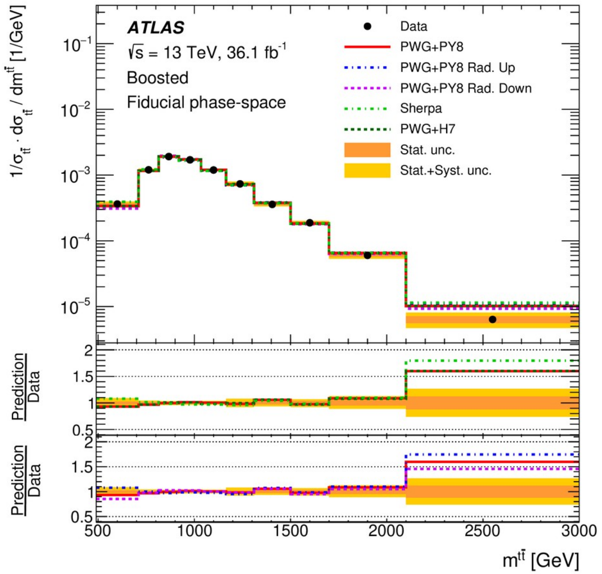
- More details in press release and/or ATLAS-CONF-2019-026



# $t\bar{t}$ differential cross-sections (1)

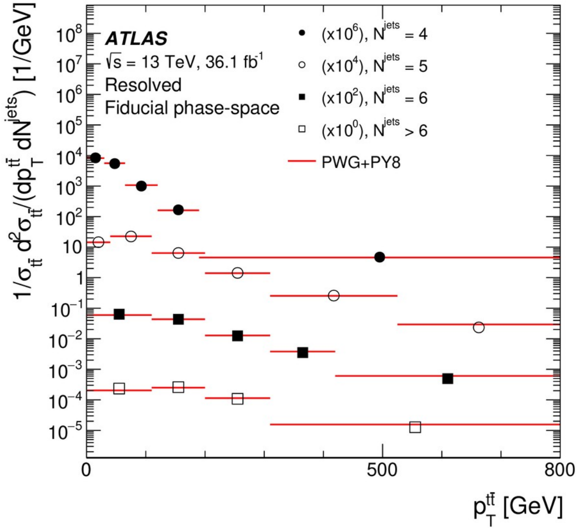
- **Motivation**: another test of the theory & models – constrain higher-order QCD calculations and parton distribution functions, tunning MC generators, sensitivity to new physics
- Analysis performed in semi-leptonic channel ($t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}'\bar{b}$), 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

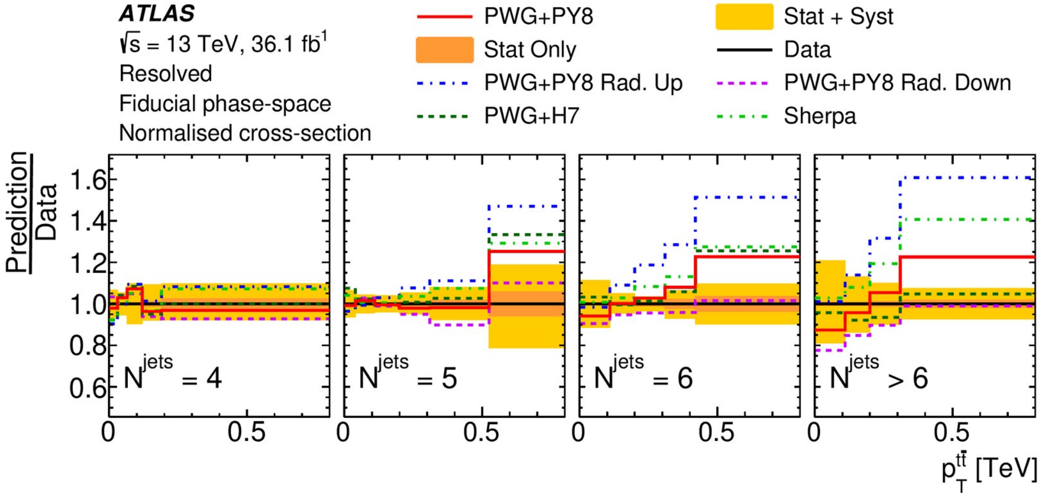


# $t\bar{t}$ differential cross-sections (2)

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



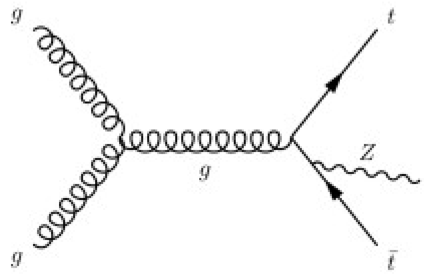




- In general, Powheg+Pythia8 (resolved) and Powheg-Herwig7 (boosted) provide good description of the largest fraction of the investigated variables

- 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)

- See Eur. Phys. J. C 79 (2019) 1028 for more details

# $t\bar{t}Z$ cross-section measurement (1)

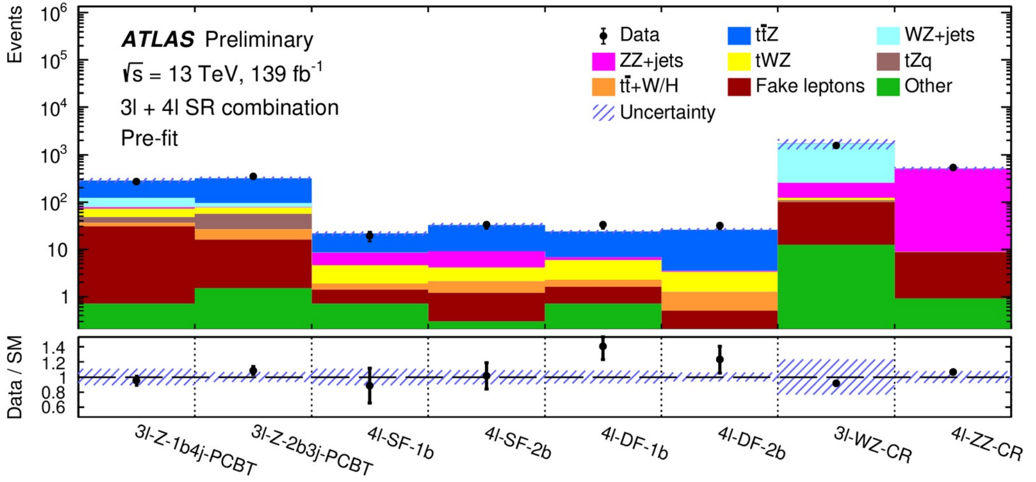



- Provides information about $t\bar{t}Z$ coupling, possible deviations from SM prediction might indicate new effects in EW symmetry breaking

- Both inclusive and differential cross-sections are measured in final states with 3ℓ and 4ℓ ($Z \to \ell\ell$ and $t\bar{t} \to WbW\bar{b}$, 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)

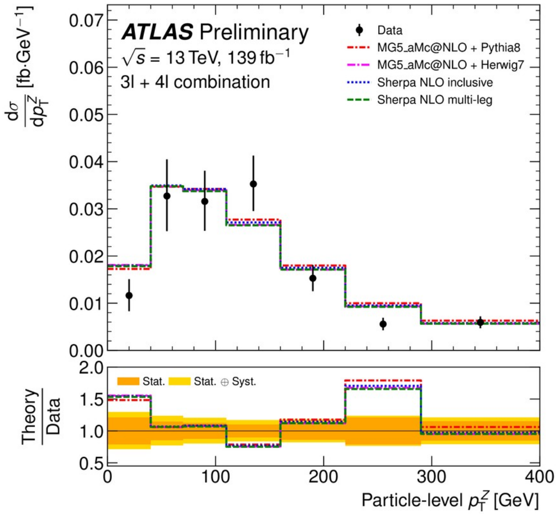


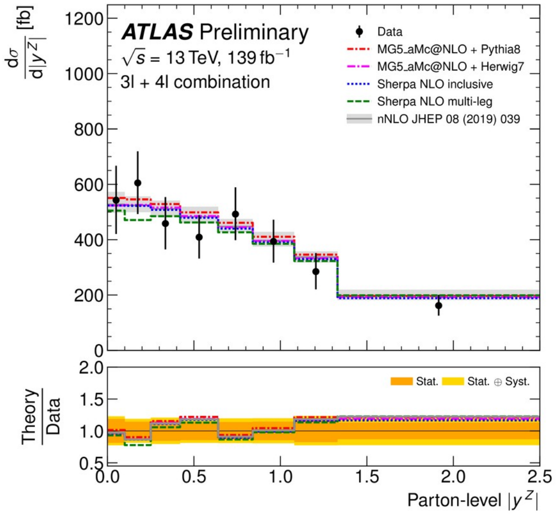

$$\sigma(pp \to t\bar{t}Z) = 1.05 \pm 0.05(\text{stat}) \pm 0.09(\text{syst})\,\text{pb}$$

$$\sigma(\text{SM})^{\text{NLO+NNLL}} = 0.86^{+0.07}_{-0.09}(\text{scale}) \pm 0.03(\text{PDF}+\alpha_s)\,\text{pb}$$

# $t\bar{t}Z$ 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



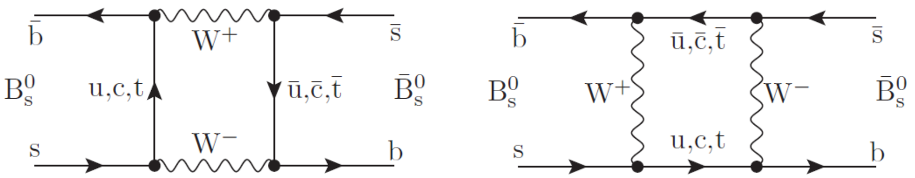




  - all differential measurements limited by available statistics, differences between various predictions are smaller than the uncertainties

- More details in ATLAS-CONF-2020-028

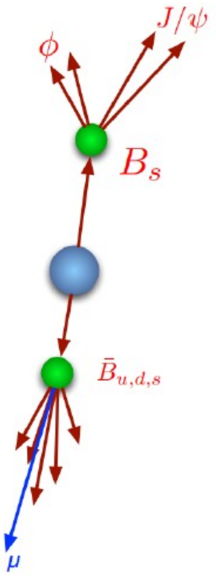
# $B^0_s \rightarrow J/\psi\ \varphi$ (1)

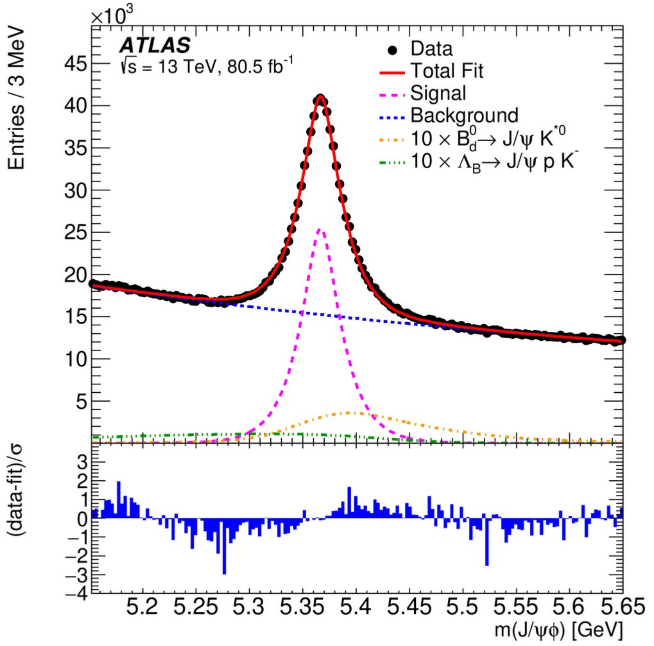
- CP violation occurs due to the interference between the direct decay and the decay with $B^0_s$ – $\overline{B}^0_s$ mixing




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

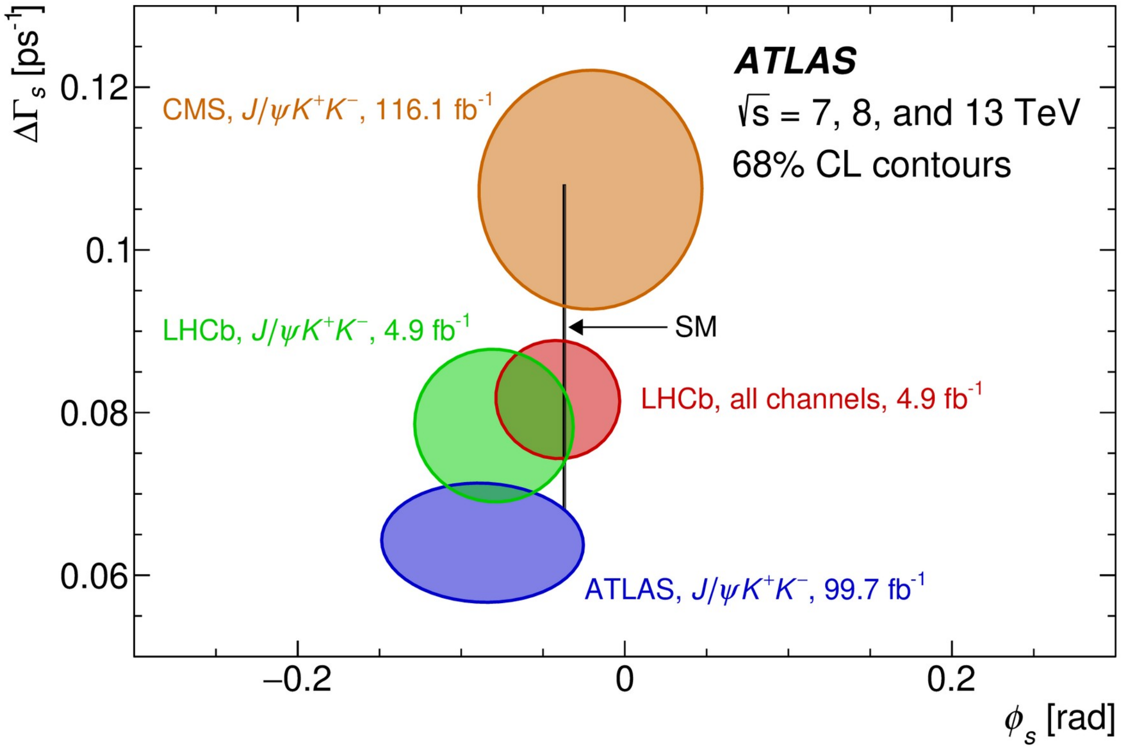
- Crucial analysis ingredients:
  - identification of the final state
    $B^0_s \rightarrow J/\psi\ \varphi \rightarrow \mu^+\mu^-K^+K^-$
  - flavour tagging of the opposite B-meson
  - proper life time measurement



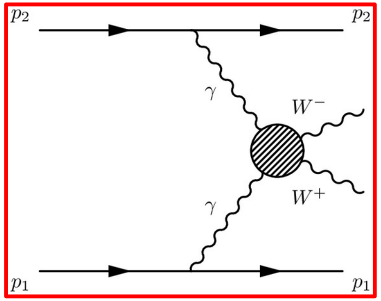
# $B^0_s \to J/\psi\ \varphi$ (2)

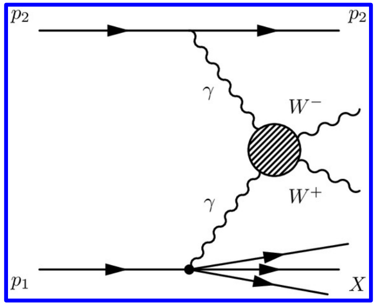
- ATLAS recently published results combining 2015+2016+2017 and Run 1 data – arXiv:2001.07115
- Results still compatible with SM predictions, but there is some tension between the results of individual experiments

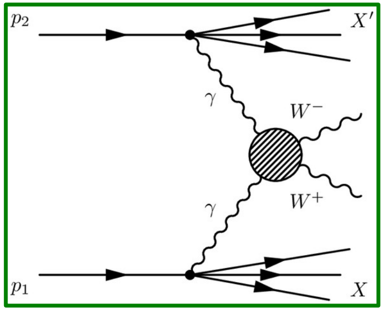


# $\gamma\,\gamma \rightarrow W\,W$ (1)

- **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 μ, $p_T(e\mu) > 30$ GeV, $m_{e\mu} > 20$ GeV
  - no further tracks from that vertex ($n_{trk} = 0$)

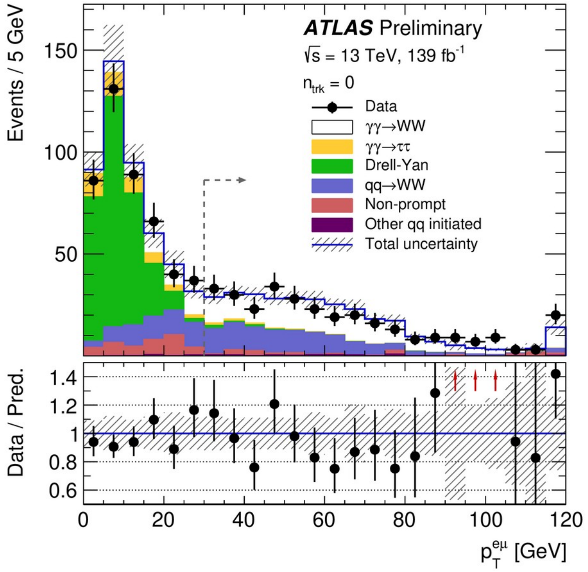


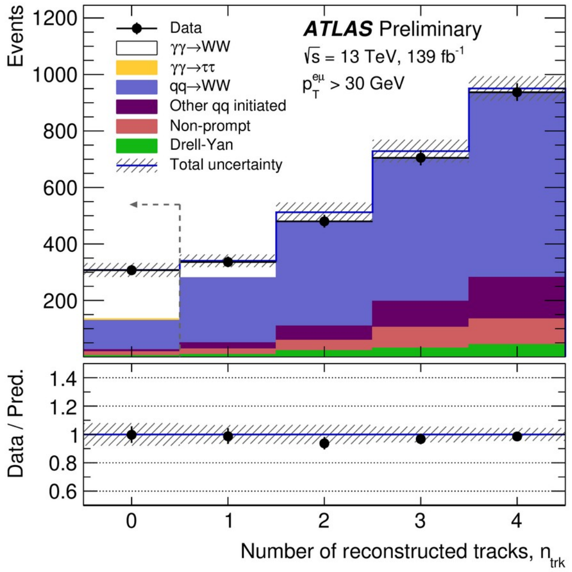



# γ γ → W W (2)

- 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



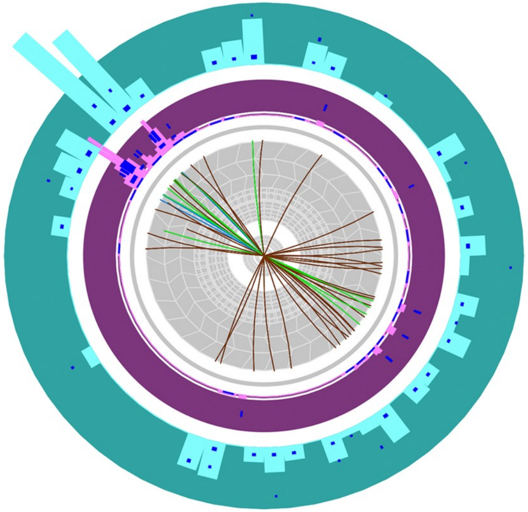

- Observation established at 8.4σ, measured fiducial volume cross-section

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

- More details in press release and ATLAS-CONF-2020-038

# Heavy ion collisions (1)

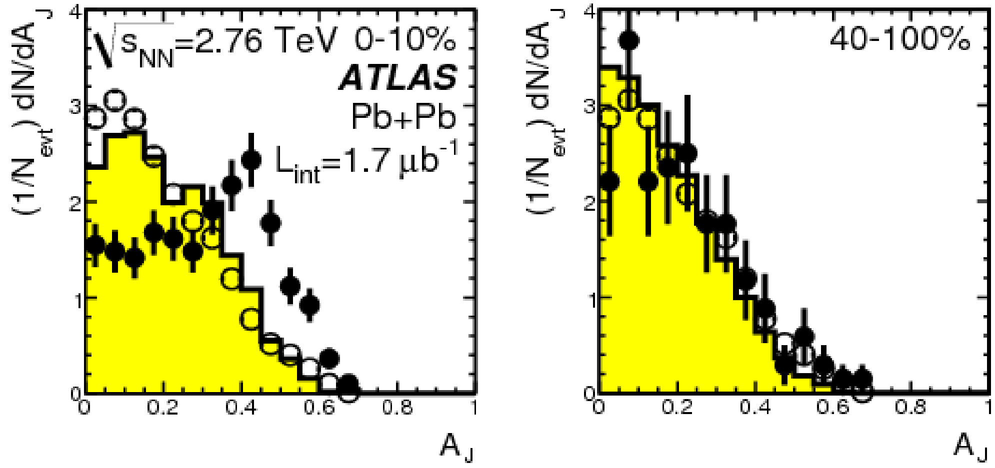
- In ultrarelativistic collisions of nuclei, QGP is created in the central collisions. Energy of quarks/gluons propagating through QGP is modified, leading to energy asymmetry in di-jet events (Phys. Rev. Lett. 105 (2010) 252303)



$$A_J \equiv \frac{E_{T,1} - E_{T,2}}{E_{T,1} - E_{T,2}}$$

jet quenching

central collisions peripheral collisions

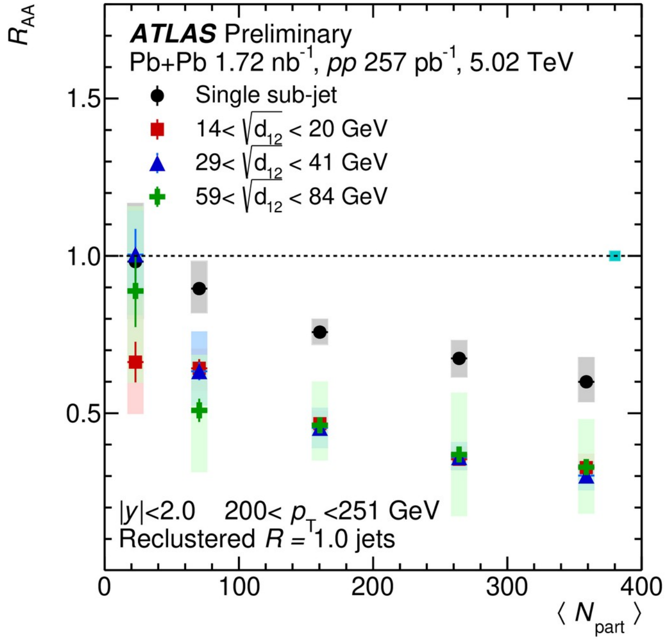



- The jet yields are compared between the Pb-Pb and p-p collisions at the same centre-of-mass energy per nucleon using nuclear modification factor $R_{AA}$

$$R_{AA} \equiv \frac{d^2 N_{AA} / d p_T d y}{\langle T_{AA} \rangle d^2 \sigma_{pp}^{inel} / d p_T d y} = \frac{1}{\langle N_{AA} \rangle} \cdot \frac{\text{yield in AA}}{\text{yield in pp}}$$

# 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 $N_{part}$ 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 → jets with hard internal splitting loose more energy in QGP medium
  - more details in press-release and ATLAS-CONF-2019-056



# 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

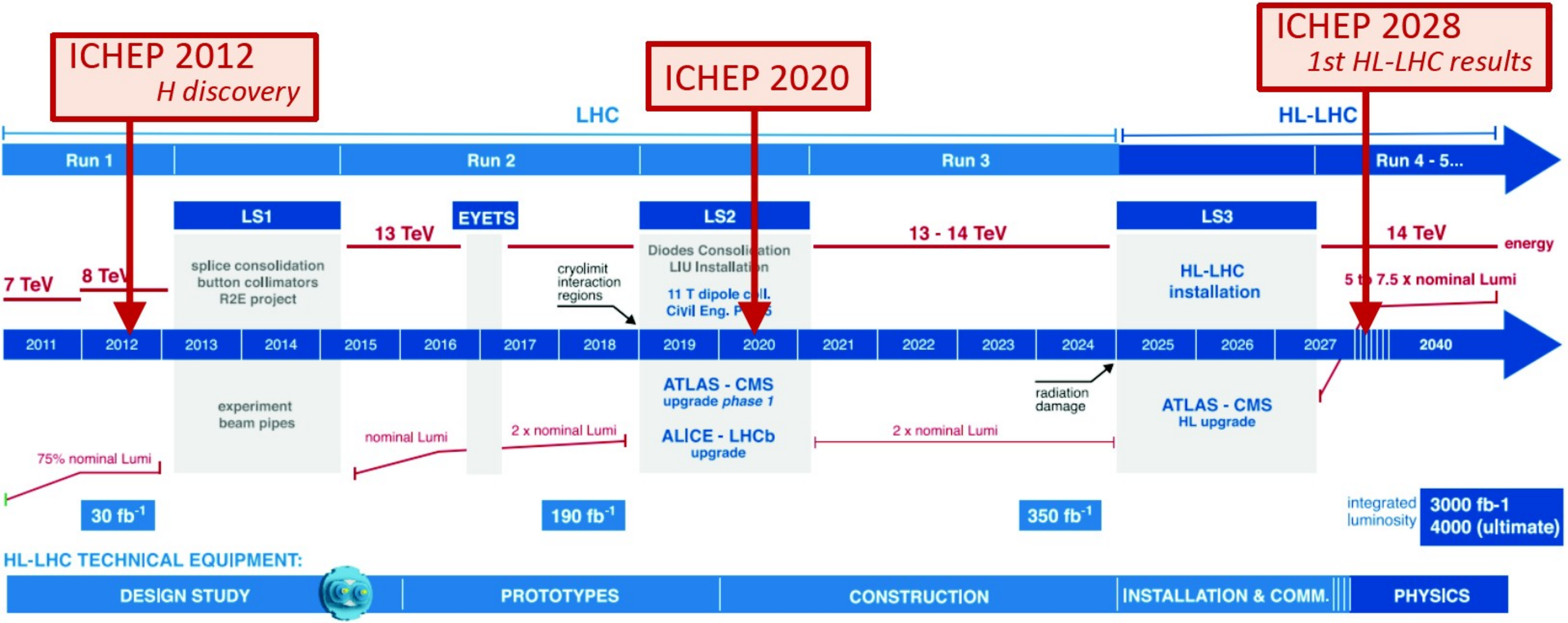
→ **need more data**

# 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




slide by J. D'Hondt, ICHEP 2020, Prague

# $H \to e\tau$, $H \to \mu\tau$ (1)

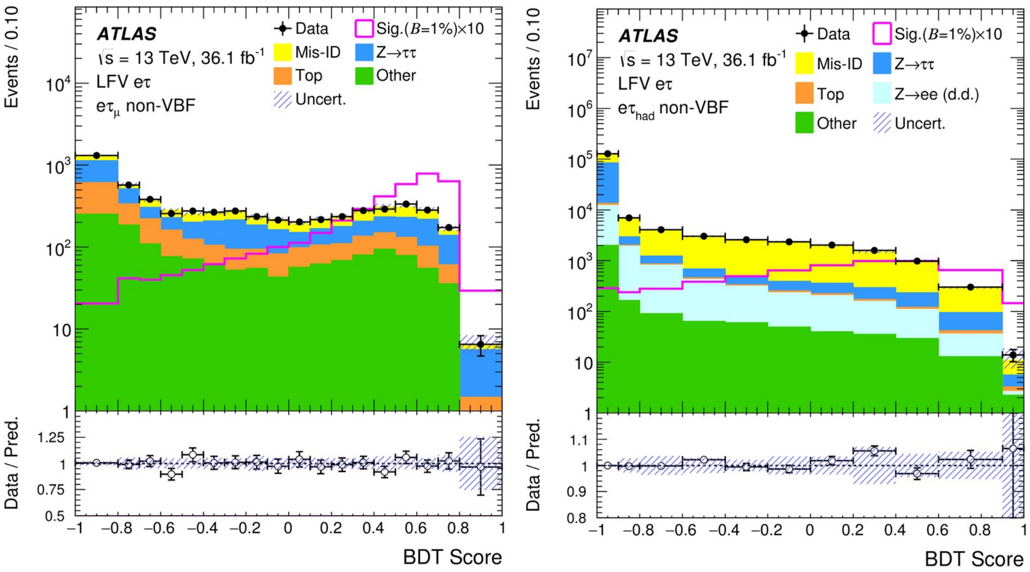
- Both experiments published the results on partial Run-2 dataset (36 $fb^{-1}$)
- Both leptonic and hadronic τ-decay modes explored, for $\ell\tau_{lep}$ channel only different-flavour leptons considered in the final state to avoid large $Z \to \ell\ell$ background
- Background: normalization and validation in CRs
  - irreducible $Z \to \tau\tau$, reducible $t\bar{t}$, diboson, SM H decays (ττ, WW)
  - fakes (ℓ or $\tau_{had}$ is mimicked by a jet or a lepton) from W+jets, multijet, $Z \to \ell\ell$
- Event selection & categorization in SR
  - 2 different-flavour isolated leptons ($\ell\tau_{lep}$) or an isolated lepton and $\tau_{had}$ of opposite charges ($\ell\tau_{had}$)
  - angular separation ℓ-τ, b-veto (except of $H \to e\tau_{had}$ in CMS)
  - categories: non-VBF and VBF (**ATLAS**); 0-jet, 1-jet, 2-jets ggH and 2-jets VBF (**CMS**)

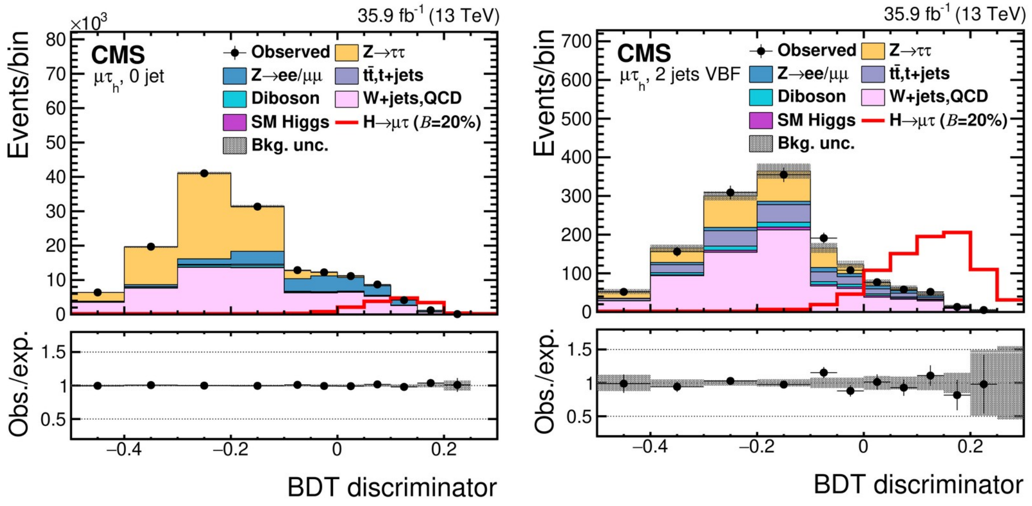
# H → eτ, H → μτ (2)

- 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 → eτ)

CMS (H → μτ)



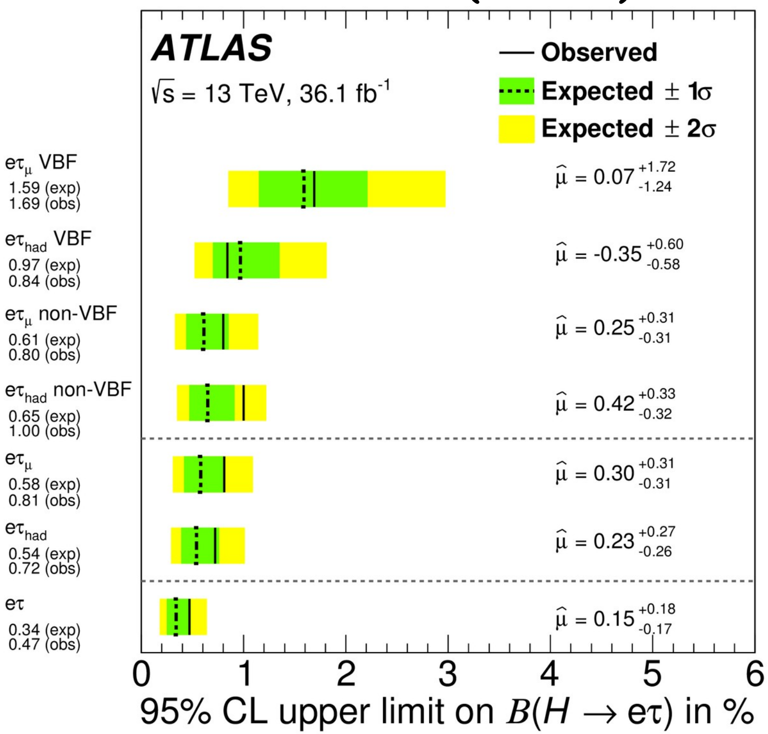




Phys. Lett. B 800 (2020) 135069

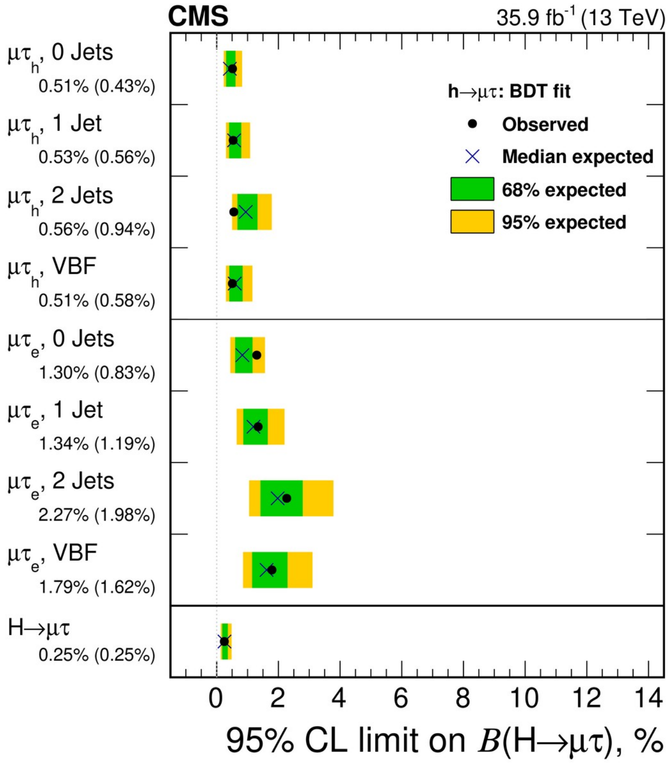
JHEP 06 (2018) 001

# H → eτ, H → μτ (3)

## ATLAS (H → eτ)




## CMS (H → μτ)



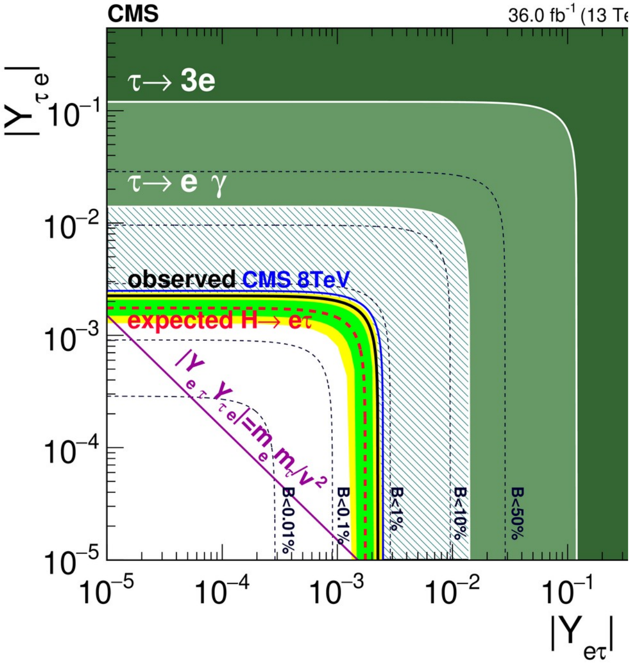

- Combined upper limits on LFV branching fractions (Phys. Lett. B 800 (2020) 135069, JHEP 06 (2018) 001)

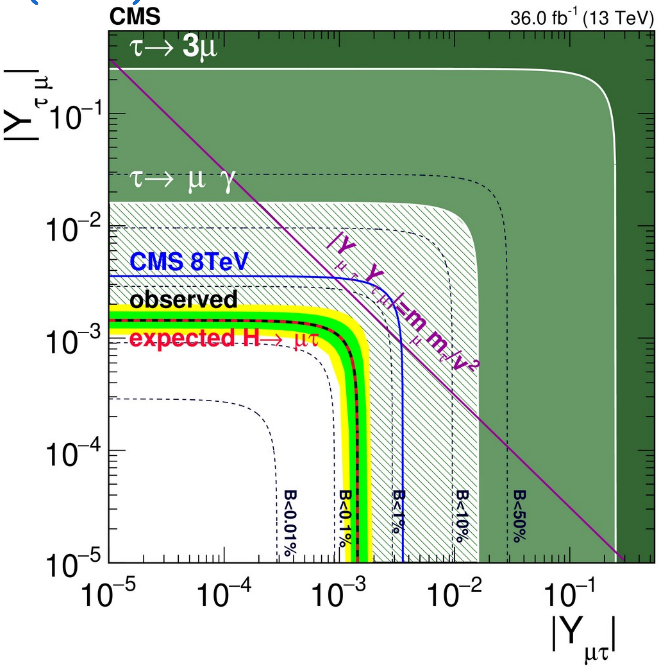
| | ATLAS | CMS |
|---|---|---|
| B(H → eτ) | < 0.47% | < 0.61% |
| B(H → μτ) | < 0.28% | < 0.25% |

# Yukawa LFV couplings

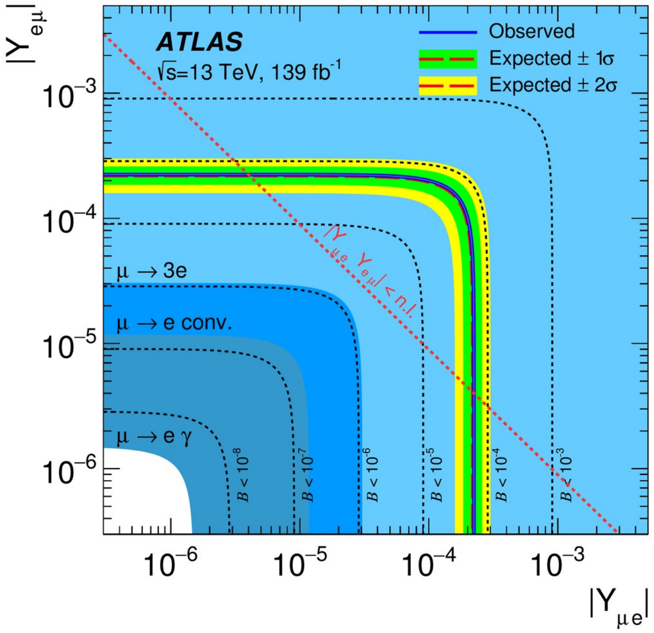
- The results on LFV Higgs decays are interpreted in terms of non-diagonal Yukawa couplings and compared to other LFV searches ($\tau \to \ell\gamma$, $\tau \to 3\ell$, $\mu \to e\gamma$, $\mu \to 3e$)

JHEP 06 (2018) 001

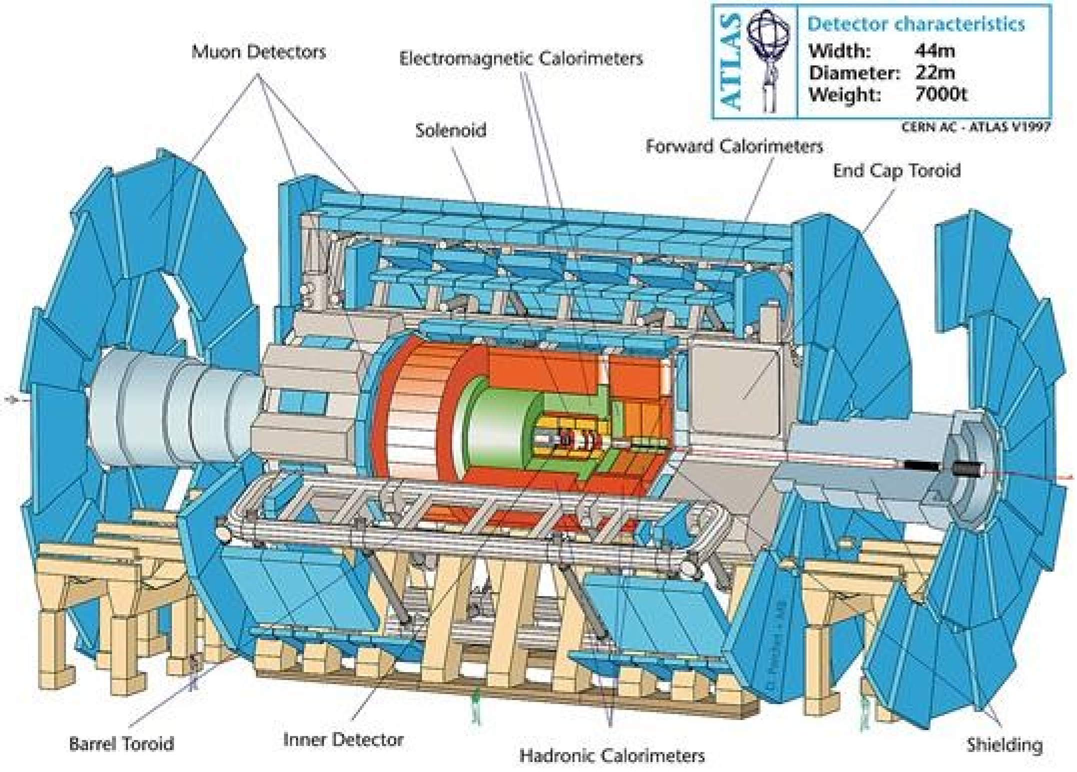



Phys. Lett. B 800 (2020) 135069




- both ATLAS and CMS limits are more stringent than those coming from $\tau \to \ell\gamma$, $\tau \to 3\ell$ measurements


Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding