CZ and SK contributions to the ATLAS experiment

Alexander Kupčo

Institute of Physics of the CAS

30th anniversary of the accession of the CSFR to CERN

12 October 2022, Prague

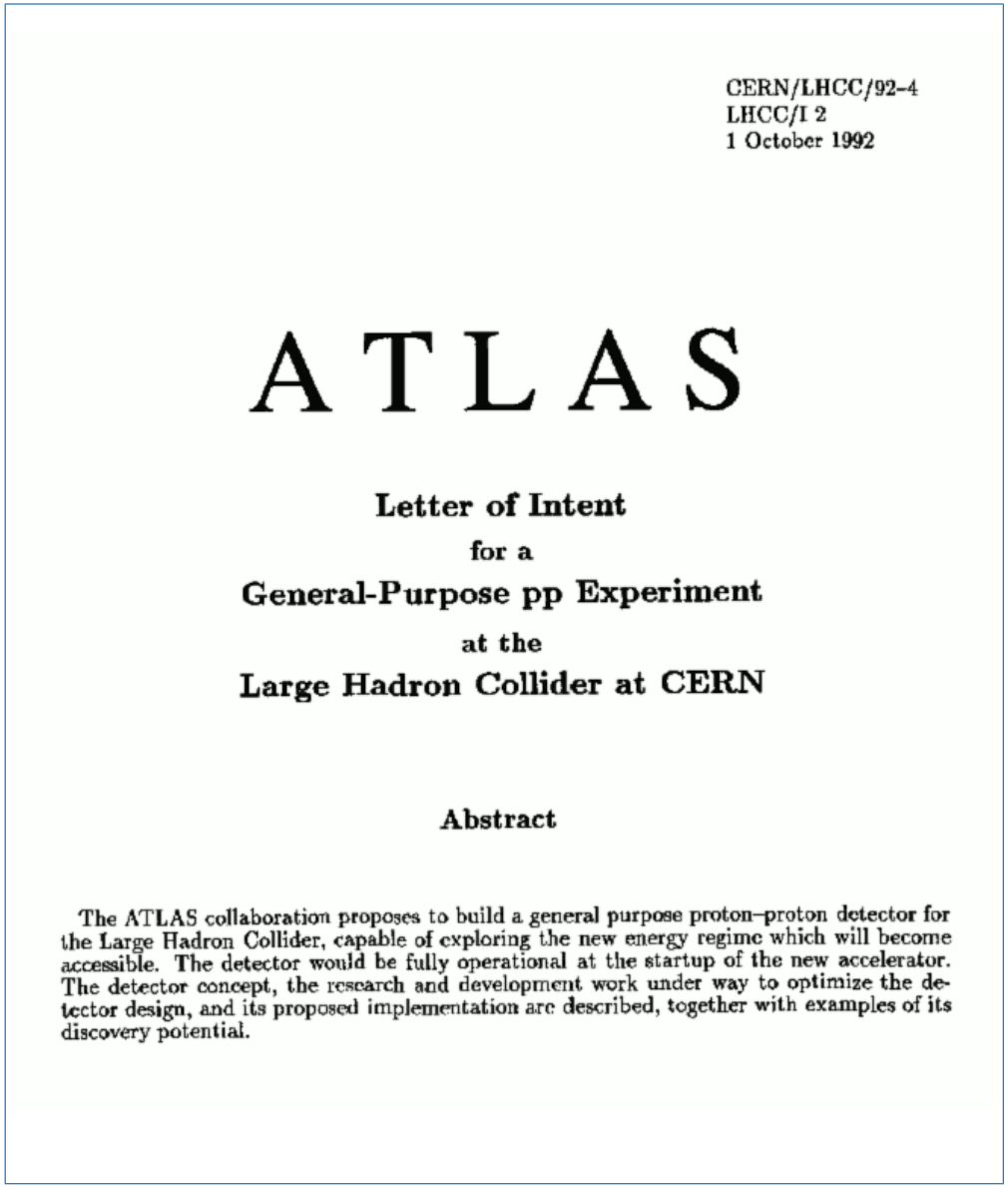
With contributions from: T. Davídek (CU), Z. Hubáček (CTU), J. Chudoba (FZU), O. Kepka (FZU), J. Kroll (FZU), J. Kvita (PU), R. Leitner (CU), M. Mikeštíková (FZU), P. Stríženec (IEP), S. Tokár (CU Bratislava)

CZ and SK ATLAS groups

- **Charles University** (CU)
  - Faculty of Mathematics and Physics
- **Czech Technical University in Prague** (CTU)
  - Faculty of Nuclear Sciences and Physical Engineering
  - Faculty of Mechanical Engineering
  - Institute of Applied and Experimental Physics
- **Institute of Physics of the CAS** (FZU)
- **Palacký University Olomouc** (PU)
  - Faculty of Science (since 2008)
- **University of West Bohemia** (UWB)
  - Faculty of Electrical Engineering (technical associate since 2019)

- **Comenius University Bratislava** (CU Bratislava)
  - Faculty of Mathematics, Physics and Informatics
- **Institute of Experimental Physics of the SAS** (IEF)

ATLAS is celebrating 30 years



CERN/LHCC/92-4
LHCC/I 2
1 October 1992

ATLAS

Letter of Intent
for a
General-Purpose pp Experiment
at the
Large Hadron Collider at CERN

Abstract

The ATLAS collaboration proposes to build a general purpose proton–proton detector for the Large Hadron Collider, capable of exploring the new energy regime which will become accessible. The detector would be fully operational at the startup of the new accelerator. The detector concept, the research and development work under way to optimize the detector design, and its proposed implementation are described, together with examples of its discovery potential.

Members of the ATLAS Collaboration

University of Bratislava, Bratislava, Czechoslovakia
P.Chochula, M.Grendar, V.Hlinka, K.Holy, R.Janik, P.Kubinec, P.Lichard, L.Luchan, J.Masarik, M.Pikna, P.Povinec, B.Sitar, P.Strmen, I.Szarka, S.Tokar, J.Vanko

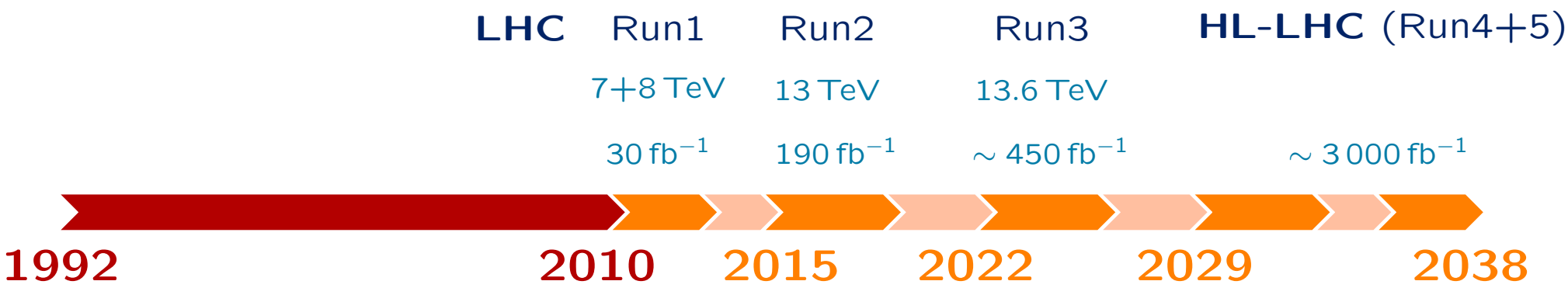
Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Czechoslovakia
J.Ban, D.Bruncko, E.Kladiva, I.Kralik, L.Sandor

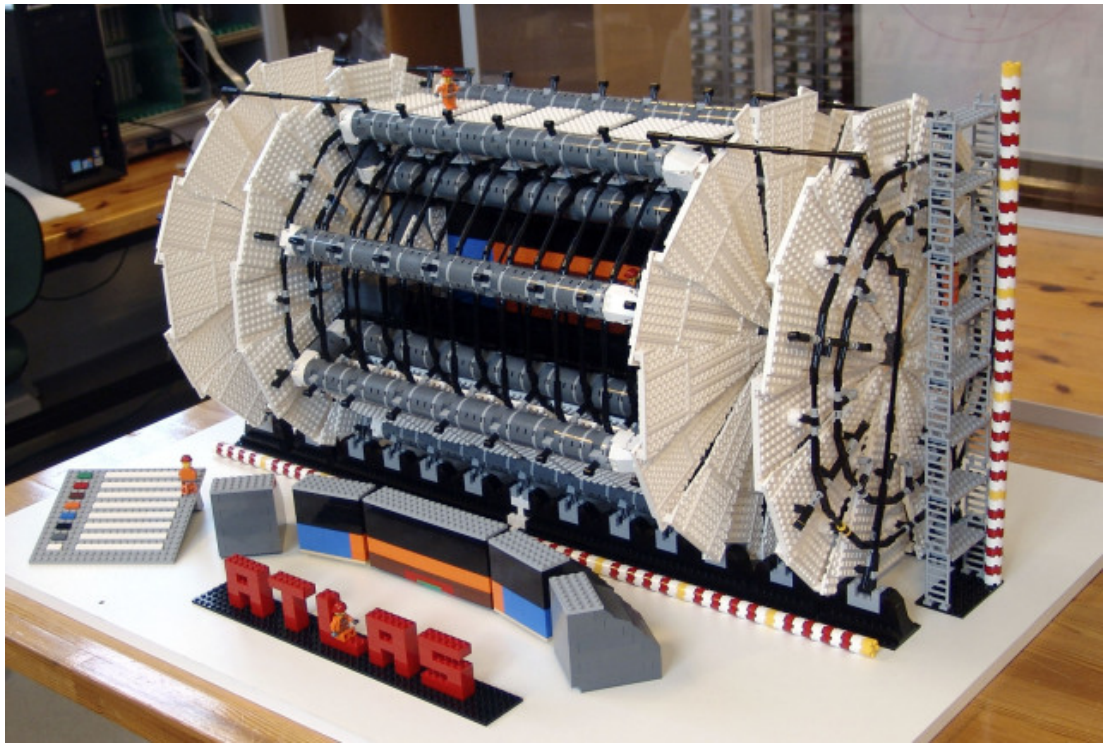
Institute of Physics CSAV and Nuclear Centre of Charles University, Prague, Czechoslovakia
J.Bohm, Z.Dolezal, J.Hrivnac, R.Leitner, M.Lokajicek, S.Nemecek, S.Pospisil, V.Simak, M.Smizanska, M.Suk, P.Tas, Z.Trka, S.Valkar, M.Vecko, V.Vrba, I.Wilhelm

Five Czechoslovak institutes among founding members of ATLAS

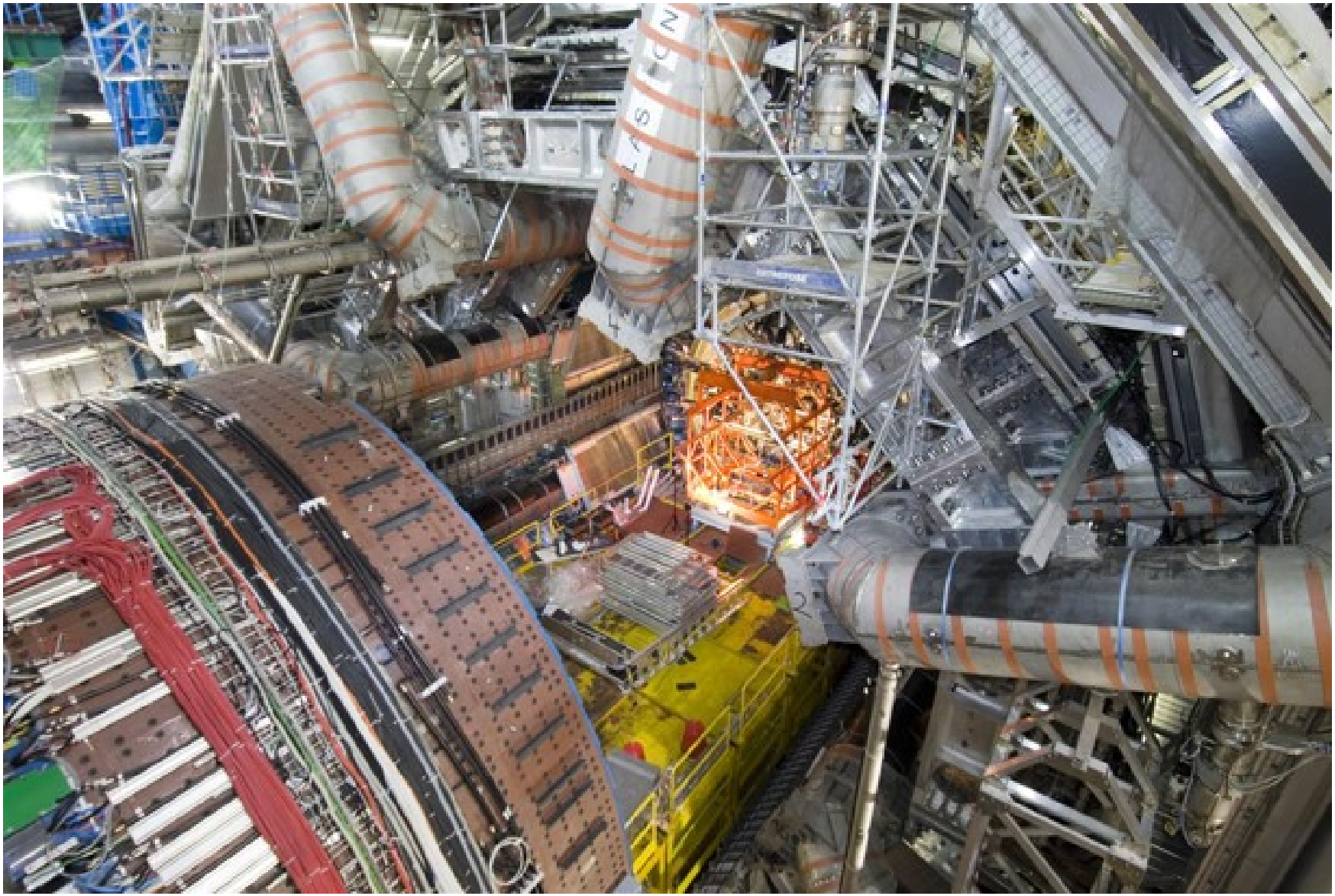
- CTU not mentioned explicitly but there are people from CTU on the authorlist

Construction period



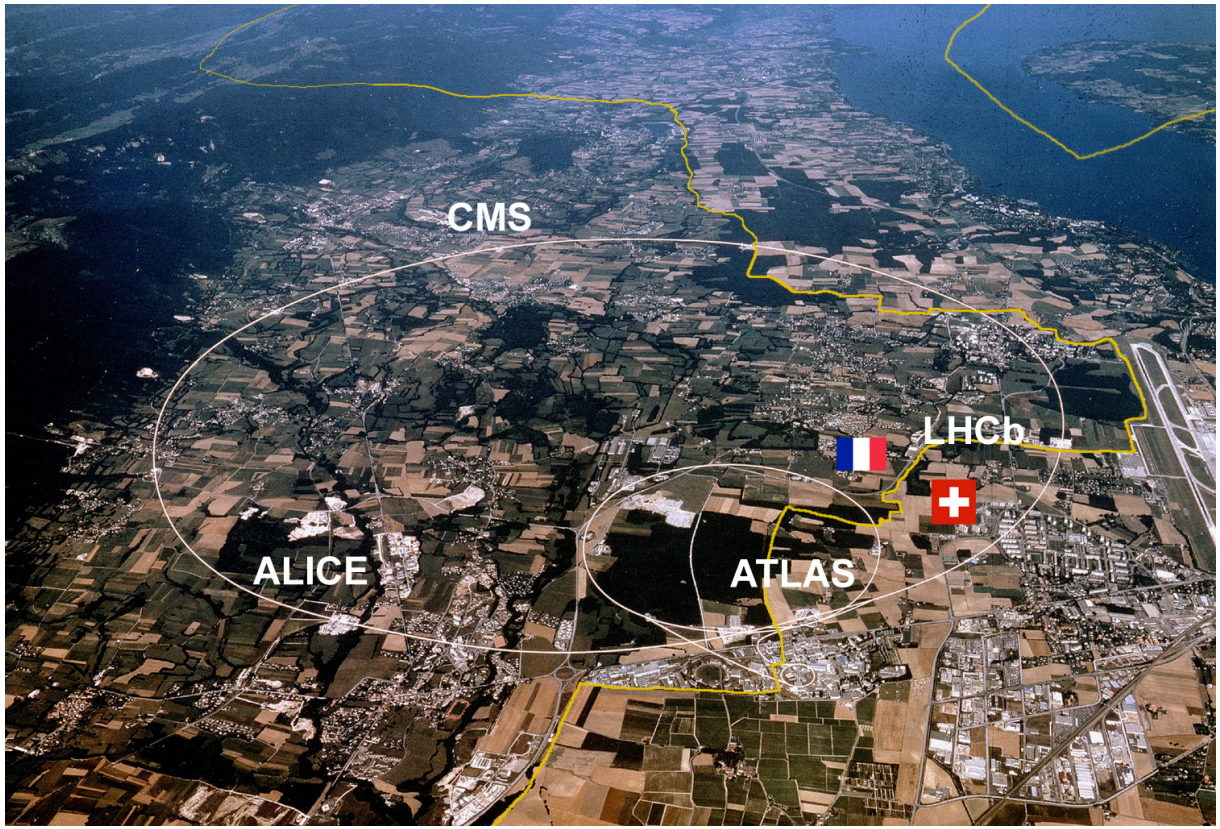


ATLAS detector

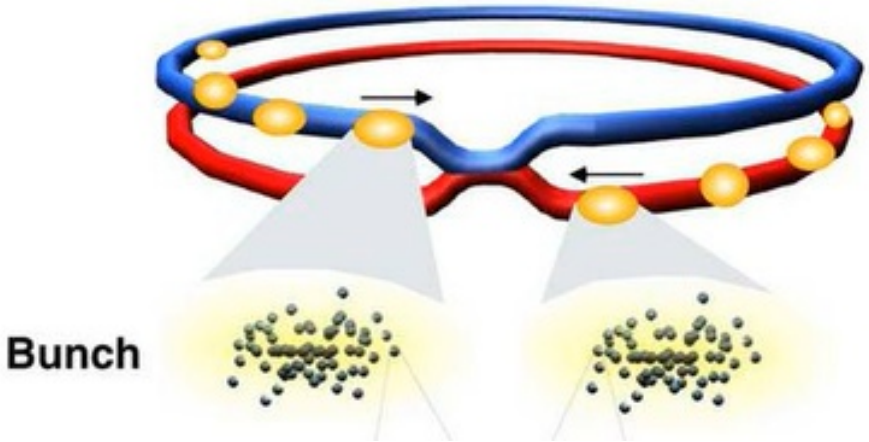


One of the most complex scientific instruments ever built

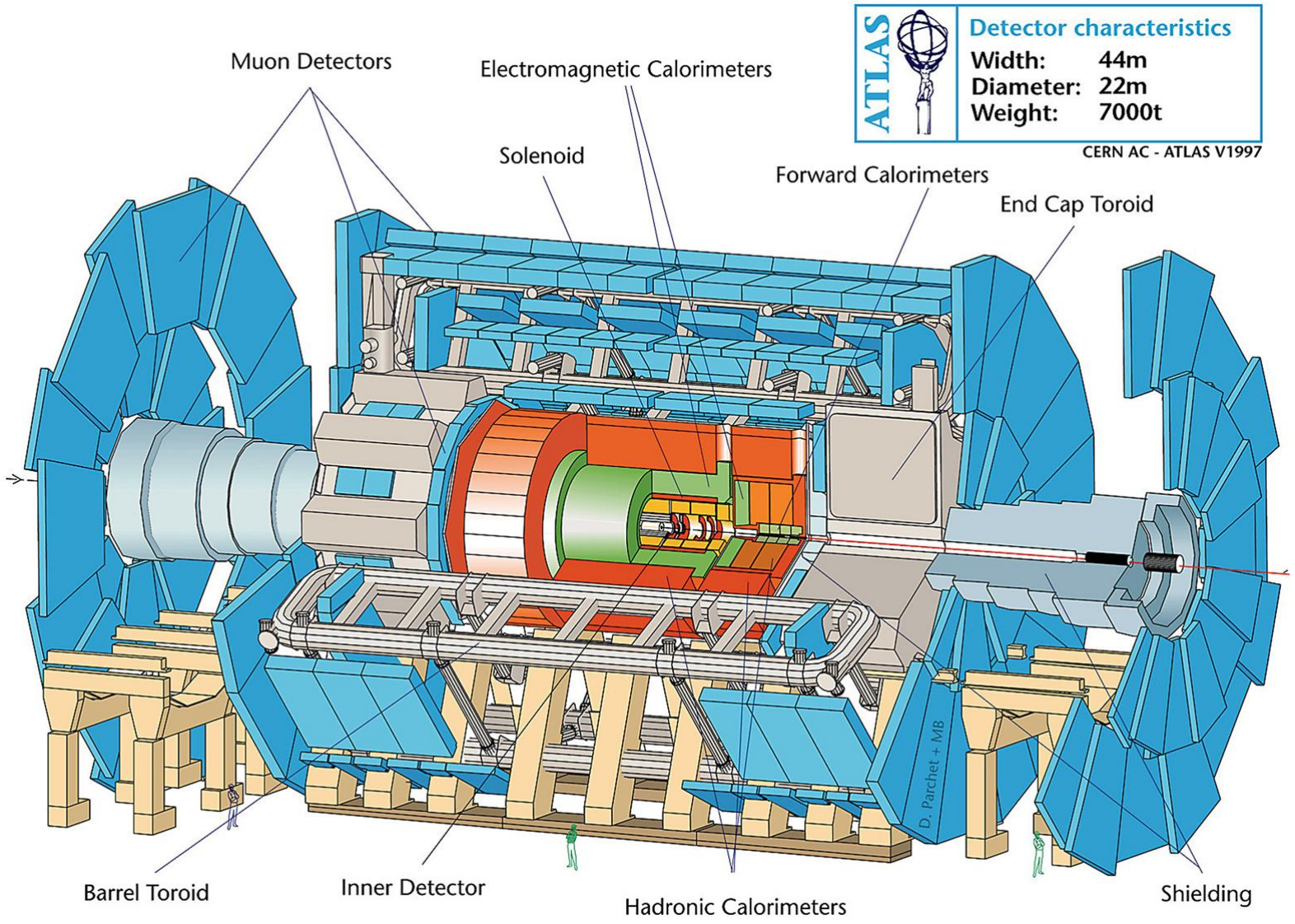
LHC



- **L**arge
  - built in LEP tunnel
  - circumference of $27\,\mathrm{km}$
- **H**adron
  - $6.8\,\mathrm{TeV}$ proton beams
  - $1040\,\mathrm{TeV}$ lead beams
- **C**ollider
  - two beams colliding at 4 points
  - bunch crossing rate of $40\,\mathrm{MHz}$
  - 70 p–p interaction per bunch X-ing



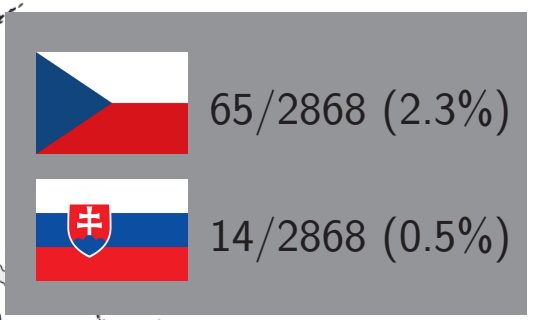
ATLAS detector



General purpose detector built to fully exploit LHC discovery potential

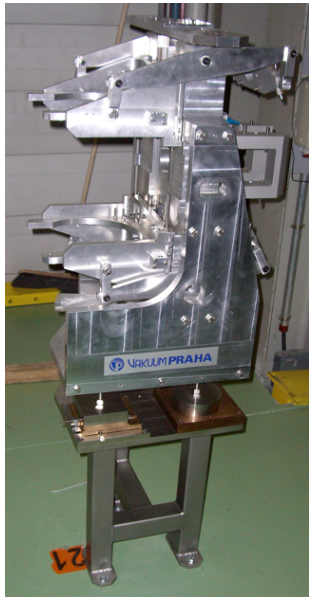
ATLAS Collaboration

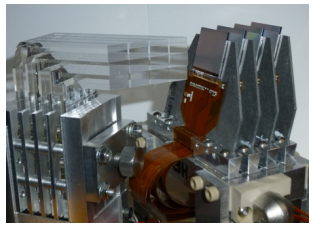
- 3000 physicists from 181 institutions from 42 countries



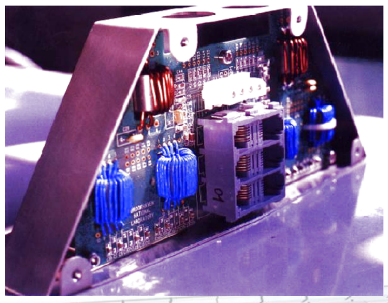
CZ and SK contributions to ATLAS construction

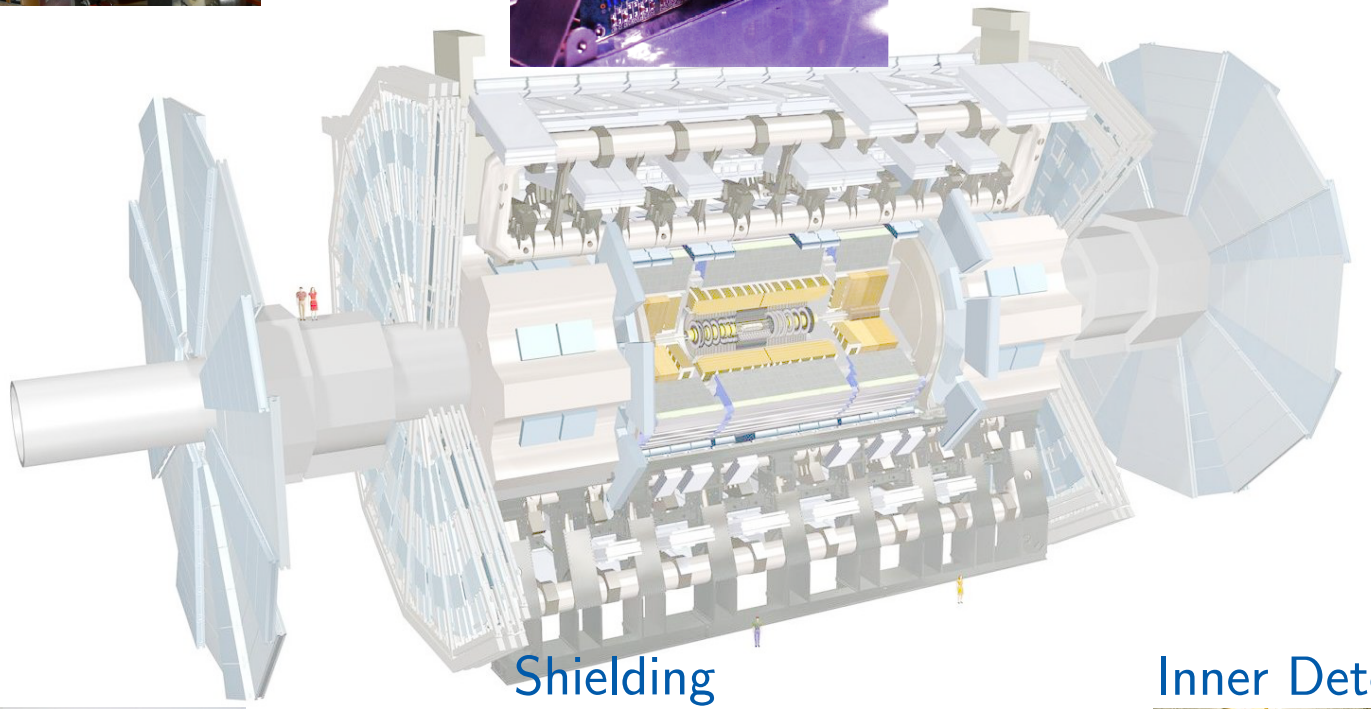
ALFA+AFP forward detectors



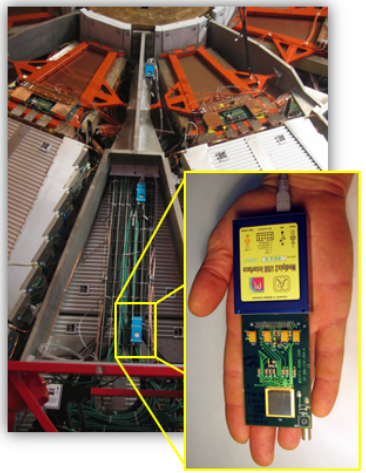


LAr Calorimeter

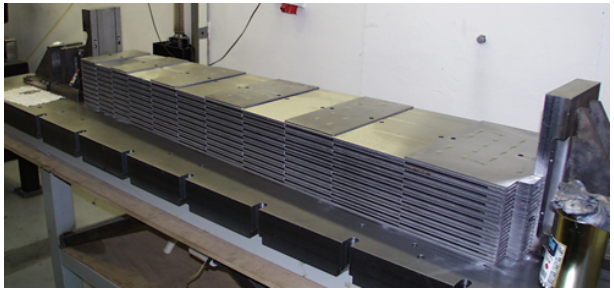




MPX Radiation Monitors

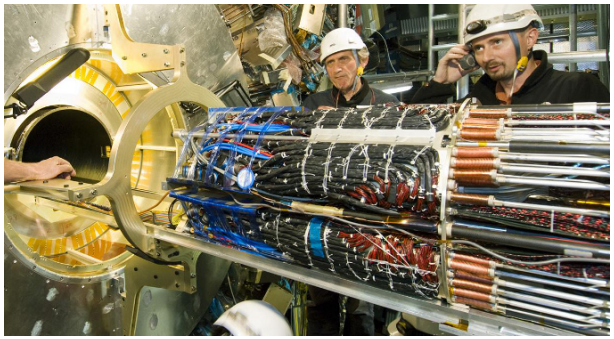


Tilecal



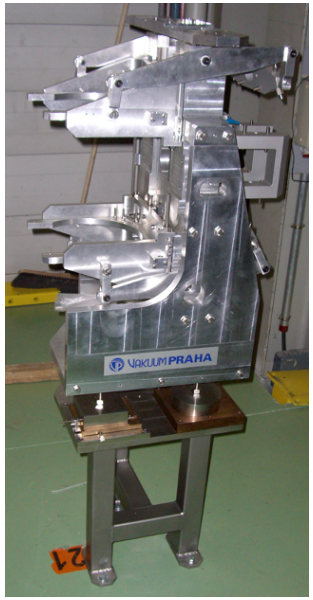
Shielding

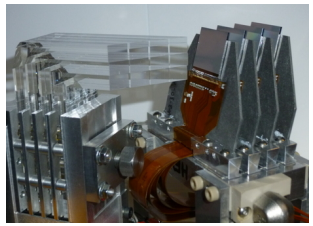
Inner Detector



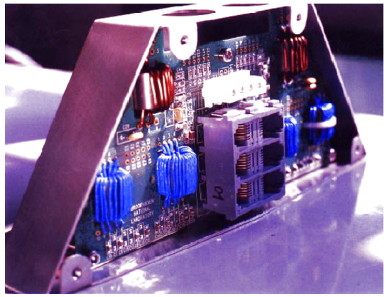
CZ and SK contributions to ATLAS construction

ALFA+AFP forward detectors



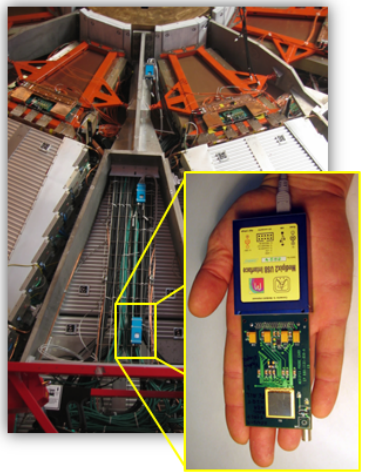


LAr Calorimeter

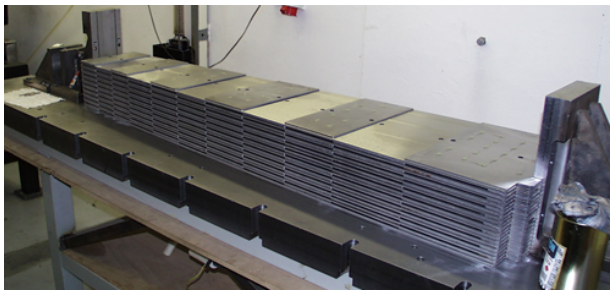


	CU	CTU	FZU	PU	WBU	CUB	IEF
Tilecal	×	×	×			×	
LAr cal.							×
Inner Det.	×	×	×				
FWD det.	×	×	×	×	×		
MPX		×					×
Shielding	×	×					

MPX Radiation Monitors

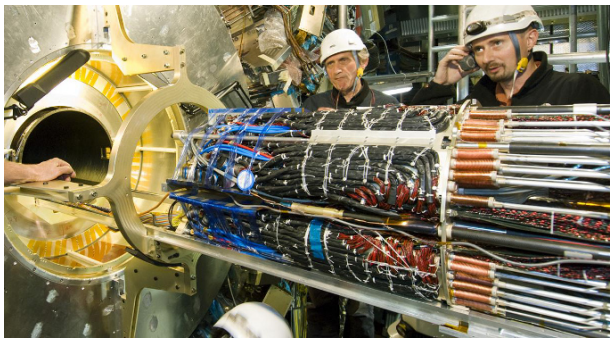


Tilecal



Shielding

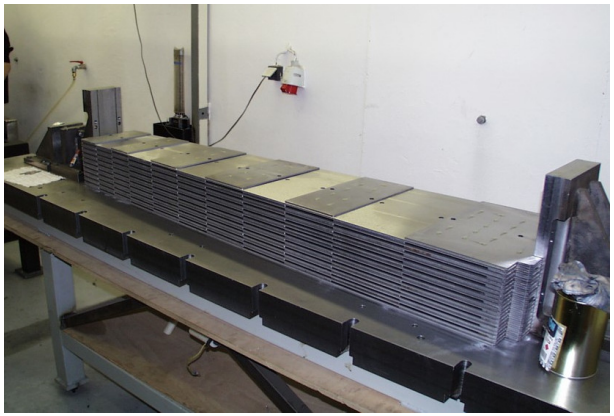
Inner Detector



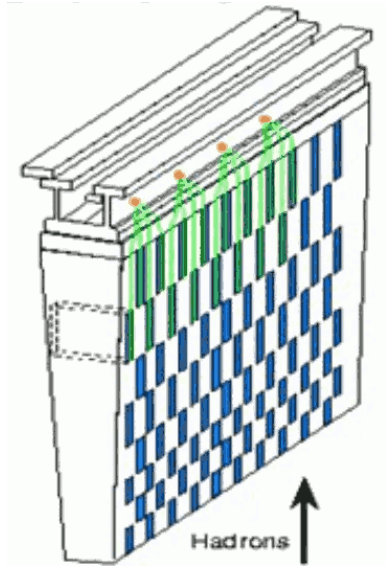
Tilecal

(CU, CTU, FZU, CU Bratislava)

Tiles assembly at FZU



- submodules for 1/8 of Tilecal
- 3000 t of low carbon steel (Válcovny Dvůr Králové)

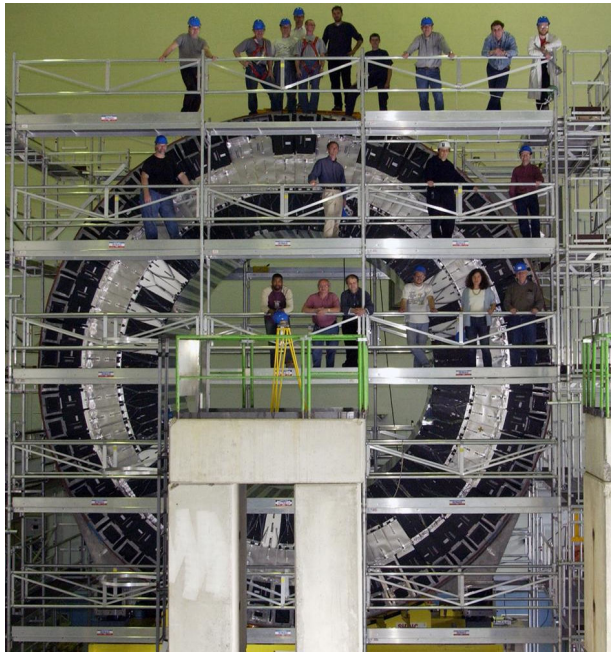


Light mixers at CU

- production of 10 000 light mixers

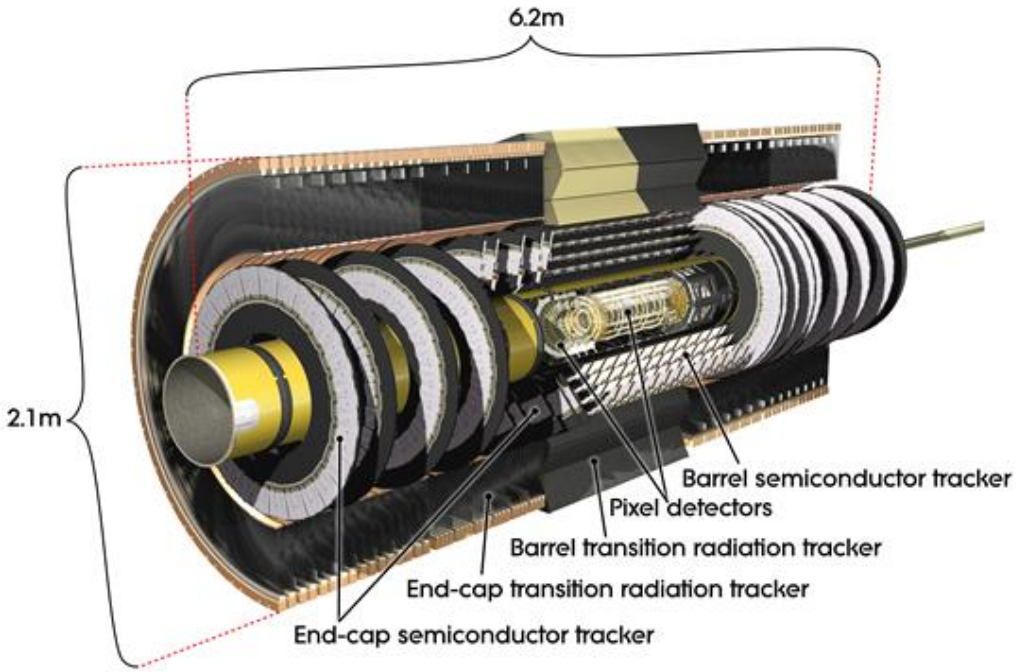
LV and HV Power Supplies

- delivered by Tesla Hloubětín



R. Leitner - ATLAS Tilecal project manager 2001-2005

Inner Detector - Pixel detector



- Pixel Detector
- Semiconductor Tracker (SCT)
- Transition Radiation Tracker

Pixel Detector at FZU

- production technology of pixel sensors
- half of sensors delivered by ON Semiconductor
  ATLAS Supplier Award for ON Semiconductor (2007)
- sensor mass production testing at FZU
- assembly at Dortmund, Genova, Bonn, and CERN


ATLAS Supplier Award for ON Semiconductor

Supplier of Silicon Sensors for the ATLAS Pixel Detector

Design of the sensor

The ON Semiconductor Czech Republic foundry of Roznov, Czech Republic has supplied a total of 515 production sensor wafers containing a total of 1177 production sensor tiles within the technical specifications for the ATLAS Pixel Detector. These sensors were delivered on schedule and within budget.

The requirements of the ATLAS Pixel Detector were very demanding. It is the first large-scale silicon detector to combine such a complex sensor layout (46080 individual pixel implants arranged as a two-dimensional array within a 10 cm² active area) with extreme radiation requirements (reliable operation to a total dose of 10^{15} cm^{-2} neutron-equivalent, roughly ten times higher than for typical strip sensors). Achieving these requirements led to the first commercial implementation of several new sensor technologies. The high-dose sensor requirement led to the use of a low-dose boron implantation (so-called "p-spray" isolation) which allowed breakdown-free operation of the sensors at bias voltages above 600V after the full radiation dose. The silicon bulk material was specially processed using the DOFZ technique (diffusion oxygenation at very high temperature to embed significant Oxygen in the Silicon lattice and improve the depletion behavior of the material after high radiation doses). In addition, the need to achieve high quality and yield in volume production required a new testing capability, implemented as a "bias grid" which allows a complete I/V characterization of the sensor tile with a single set of measurements.

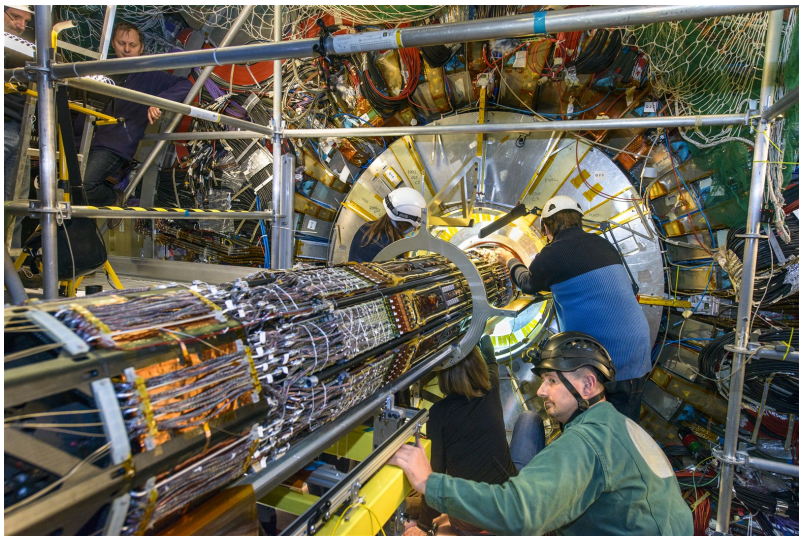
ON Semiconductor, in its Roznov foundry, has produced wafers satisfying all of these requirements with excellent yield. As there are three sensor tiles per wafer, and the full wafer must be bump-bonded, high yield is essential to control the overall cost. The average yield achieved by ON Semiconductor was 2.3 good tiles per wafer, well above our acceptance requirement.

The ATLAS Collaboration greatly appreciates the efficient cooperation and the excellent performance of the ON Semiconductor Czech Republic foundry, which has contributed significantly to the success of ATLAS.

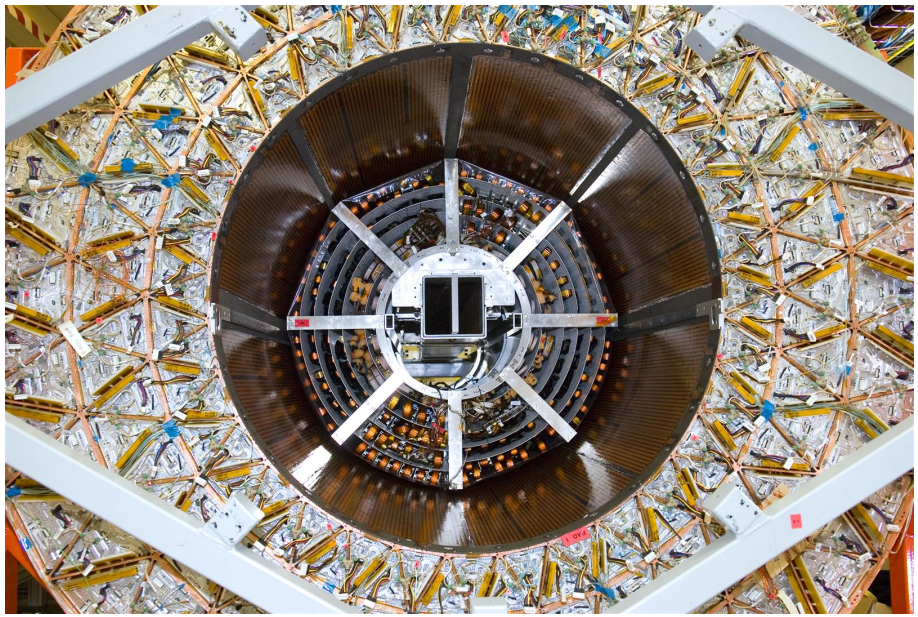
Geneva, November 2007

Dr. Peter Jenni
ATLAS Spokesperson

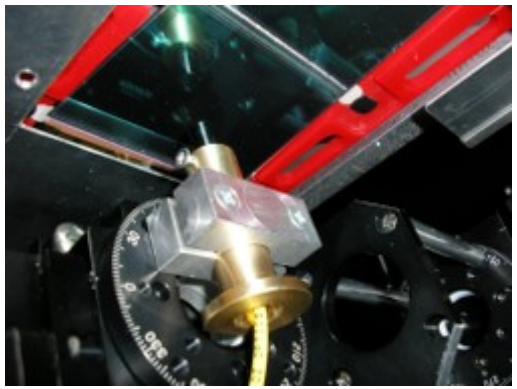
Dr. Maximilian Metzger
CERN Secretary-General



Inner detector - SCT



- sensor mass production testing (CU, CTU, FZU)
- irradiation tests of strip sensors (FZU)



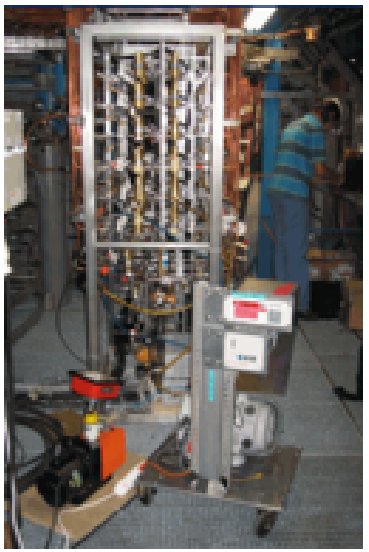
laser setup at CU

testing box at CTU

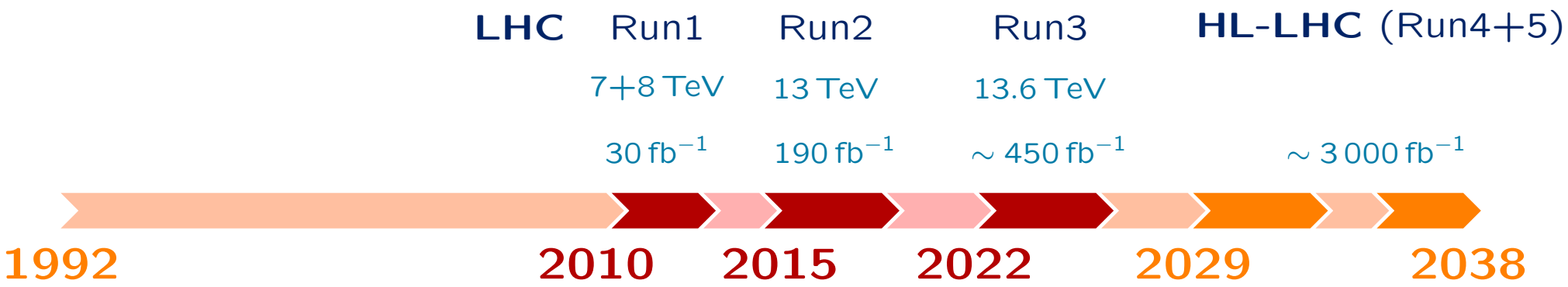
- development of LV cards (FZU)

1158 cards delivered by TTC Prague

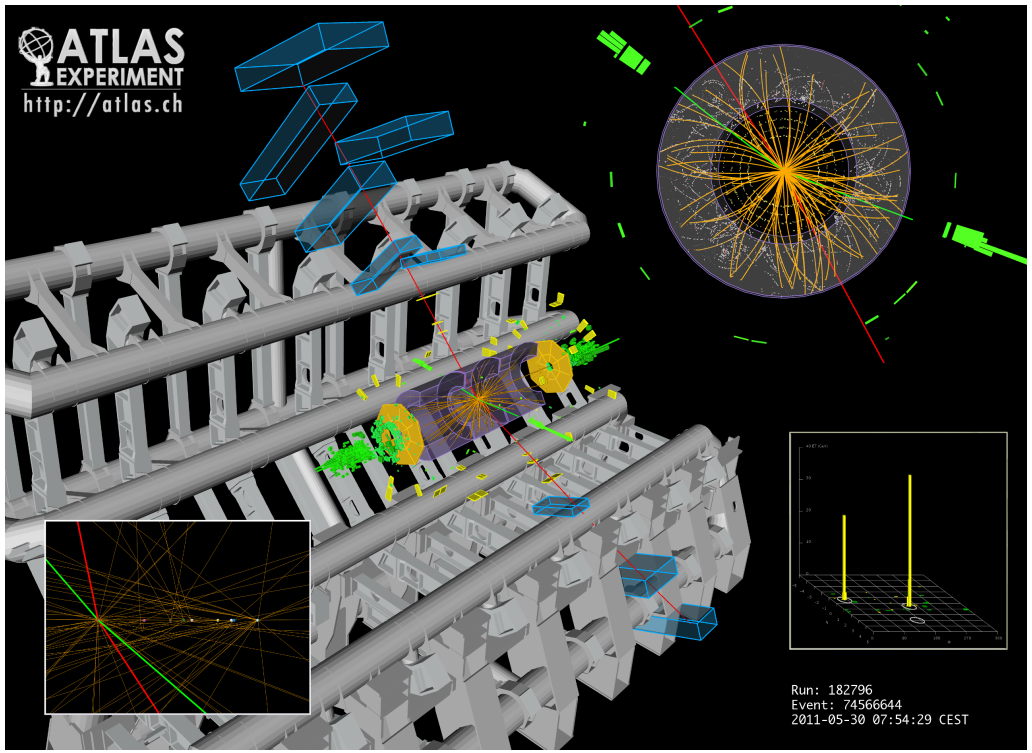
- development of ID cooling system (CTU)



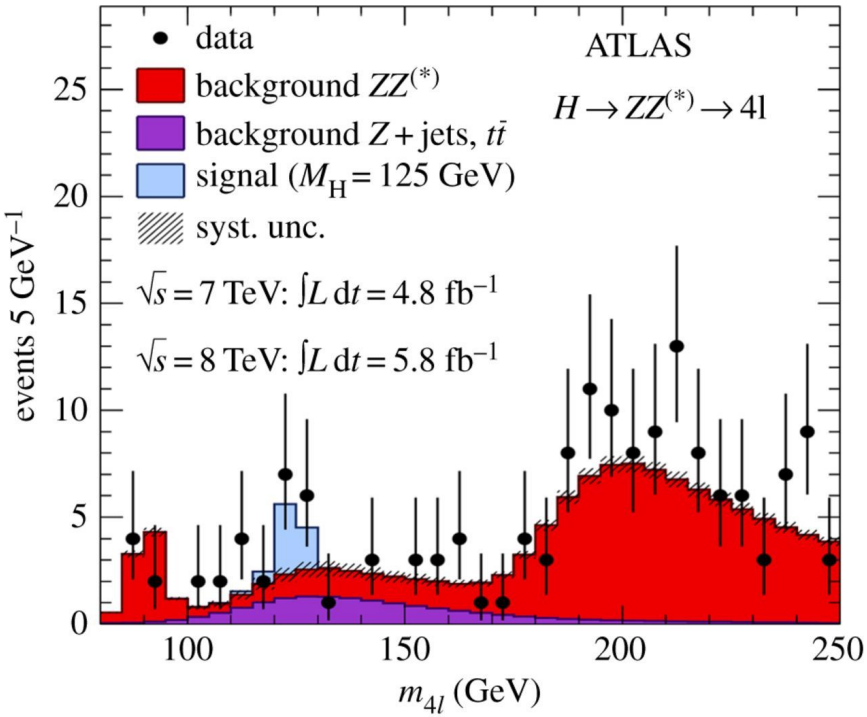
Data taking and physics analyses



$H \to ZZ^{(*)}$ candidate from 2011



H boson discovery in 2012



Operation

CZ/SK ATLAS operation and upgrade in 2020

- 332/220 shifts in control room or as experts on call
- 15.1/3.8 FTE of additional technical support
- 1.7/0 FTE at local Tier 2 computing center
- 19.2/0.4 FTE for HL-LHC ATLAS upgrade
- in total 37/5 FTE of work recognized by ATLAS

2015 ATLAS Award
for Tilecal maintenance
for S. Němeček

Computing

- ATLAS generates petabytes data per year

10/2022: 300 PB on disk, 260 PB on tapes
650 000 simultaneous jobs

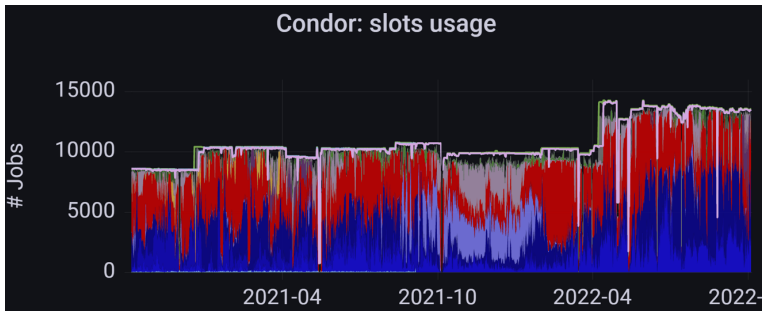
- hierarchical distributed model for computing
  - Tier2 sites provide about half of capacity

CZ Tier2 center (FZU,CU,NPI)

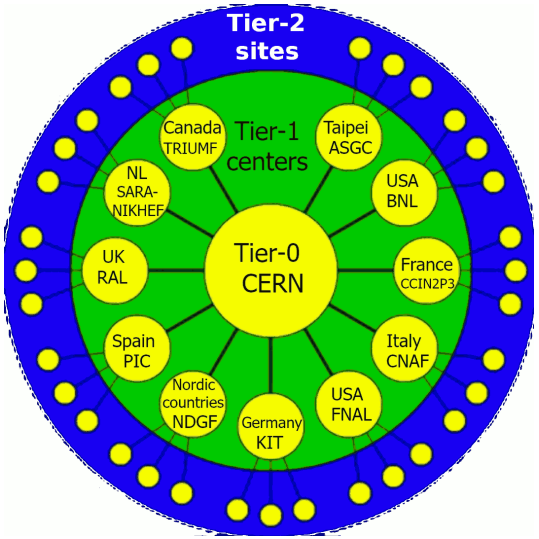
- part of the first LCG mash in 2003
- supports ATLAS, ALICE, Auger, CTA, DUNE
- disk capacity 11 PB and 13 600 CPU cores

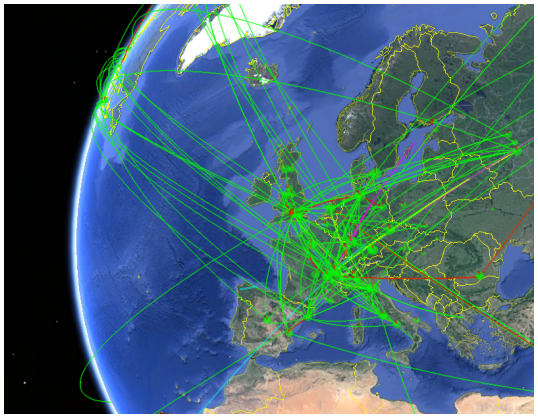
SK Tier2 center (CU Bratislava, IEP)

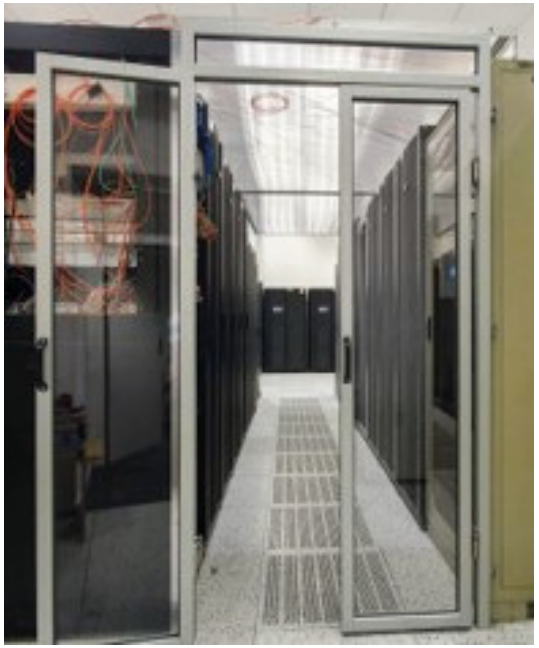
- supports ATLAS, ALICE
- disk capacity 5 PB and 2 000 CPU cores



Condor cluster usage at Prague Tier2




WLCG Google Earth


Prague Tier2 (FZU,CU,NPI)


CU Bratislava - IEP Košice Tier2

Contributions to Physics Program

	CU	CTU	FZU	PU	CUB	IEF
Soft QCD	×	×	×	×	×	
Jets	×	×	×			
Heavy Ion (HI)	×					
EWK			×		×	
B-physics	×	×	×			
Top physics	×		×	×	×	×
Higgs physics	×	×				
BSM	×					

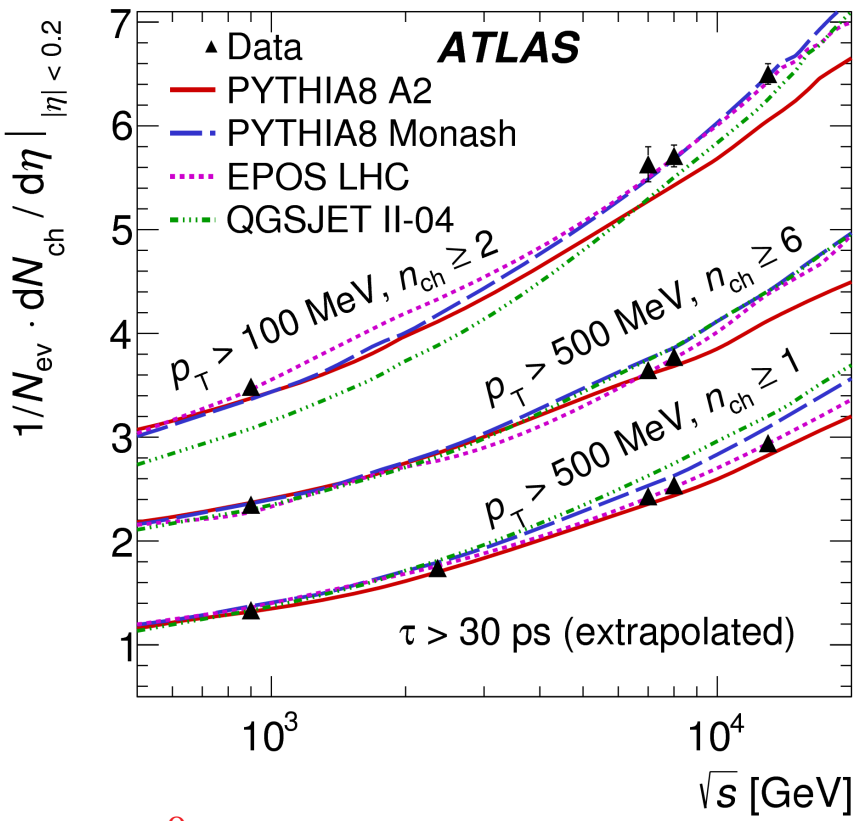
Soft processes induced by strong interaction

Minimum bias events (FZU, PU)

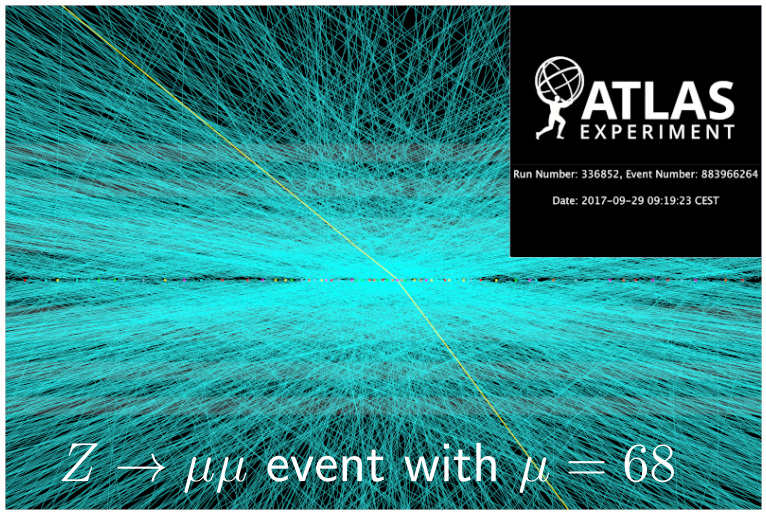
- in most collisions protons are just softly touched
- we observe a spray of soft (low p_T) particles
- at LHC, essential to understand their properties

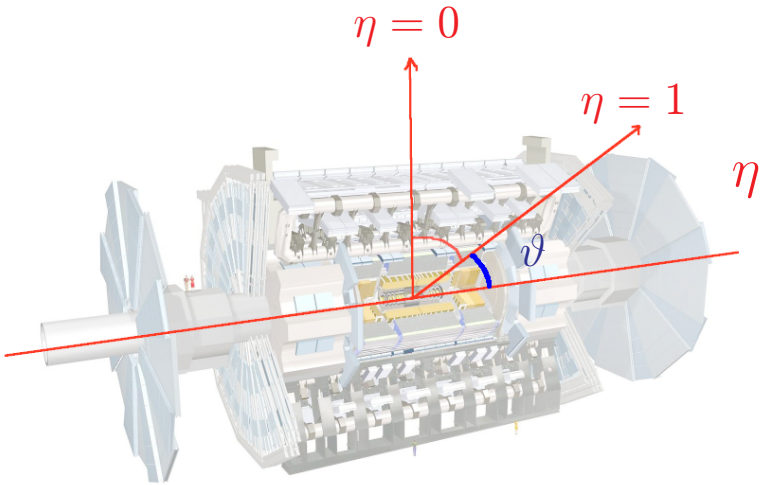
  up to about 70 p-p collisions per bunch crossing
- hard to model, they need to be measured
- first ATLAS measurement paper (March 2010)

  Charged particle multiplicities at $\sqrt{s} = 900$ GeV PLB 688 (2010) 21
- we contributed to all ATLAS minbias measurements



EPJ C76 (2016) 602

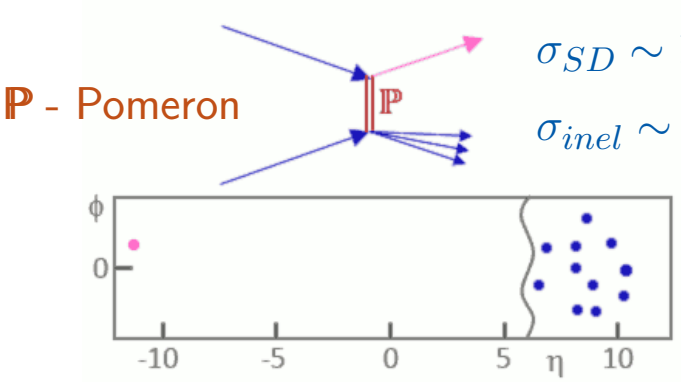




$$\eta = -\ln\tan(\vartheta/2)$$

Soft QCD - Diffractive events

- quite often proton at LHC survives the collision

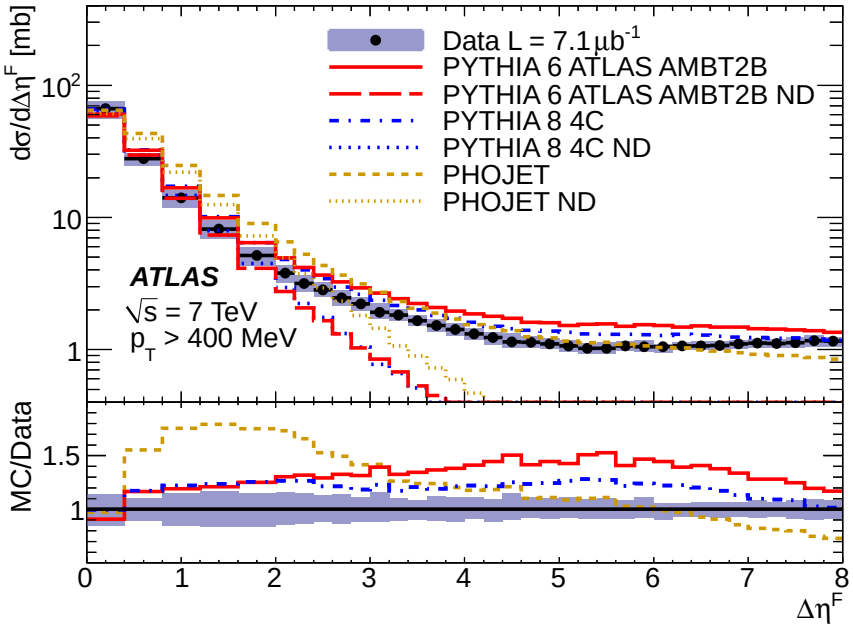


arXiv:1312.3803

Rapidity Gaps

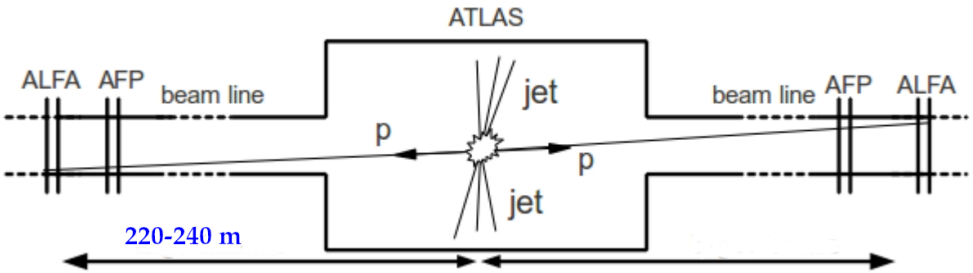
- authors of first diffractive analysis (FZU)

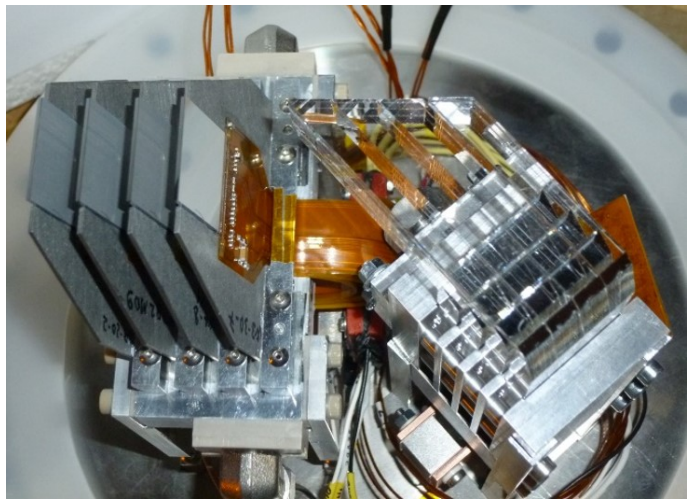
Rapidity Gap cross section at $\sqrt{s} = 7$ TeV



EPJ C72 (2012) 1926

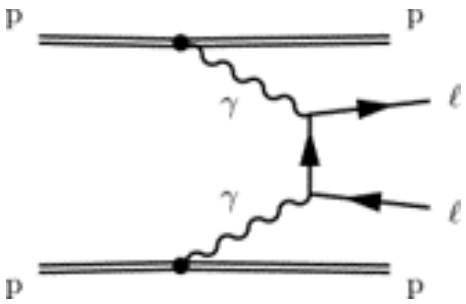
Detection of forward protons (ALFA/AFP)





- strong HW contribution (CU, CTU, FZU, UP, WBU)
  including timing detector reaching 20 ps resolution
- ALFA p-p total cross section PLB 761 (2016) 158 (CU, PU)

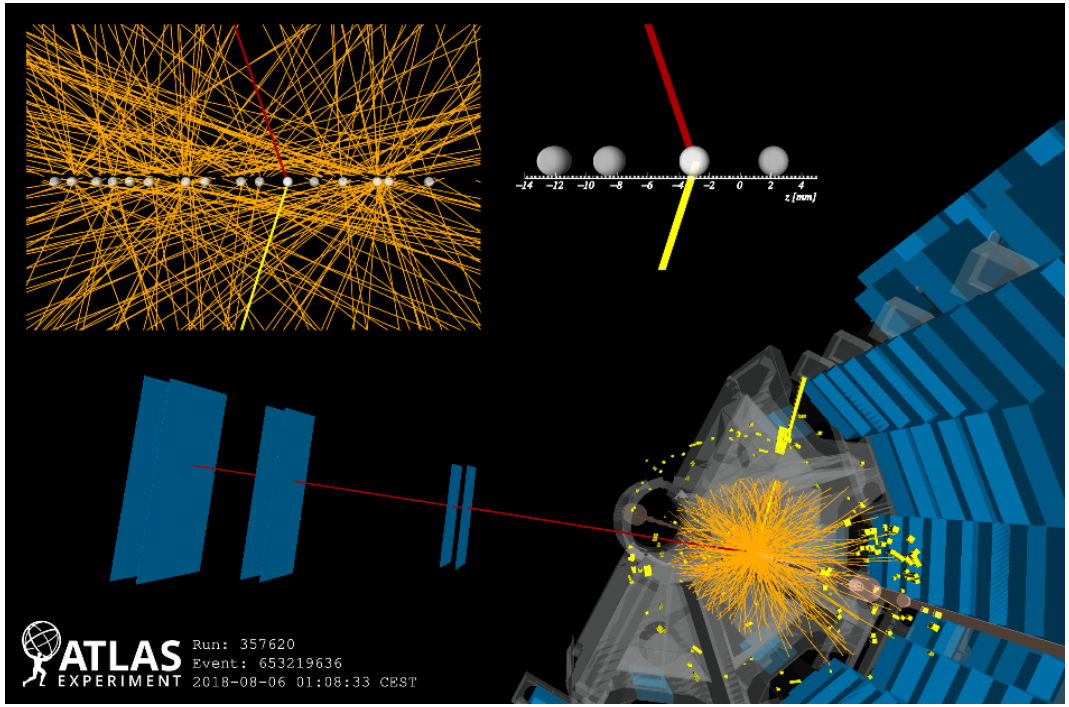
Photon induced processes



- $\gamma\gamma \to \mu\mu$ differential measurement

  PLB 777 (2018) 303 (FZU)

- first observation of $\gamma\gamma \to WW$ PLB 816 (2021) 136190 (FZU)
- based on rapidity gap technique



PLB 816 (2021) 136190 (FZU)

CERNCOURIER | Reporting on international high-energy physics

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HIGGS AND ELECTROWEAK | NEWS

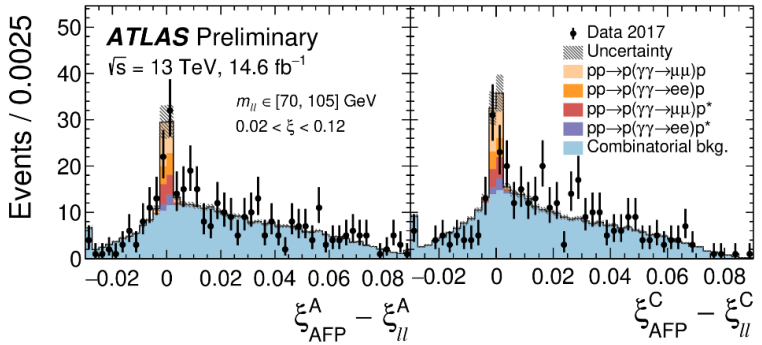
The LHC as a photon collider

15 August 2020

A report from the ATLAS experiment

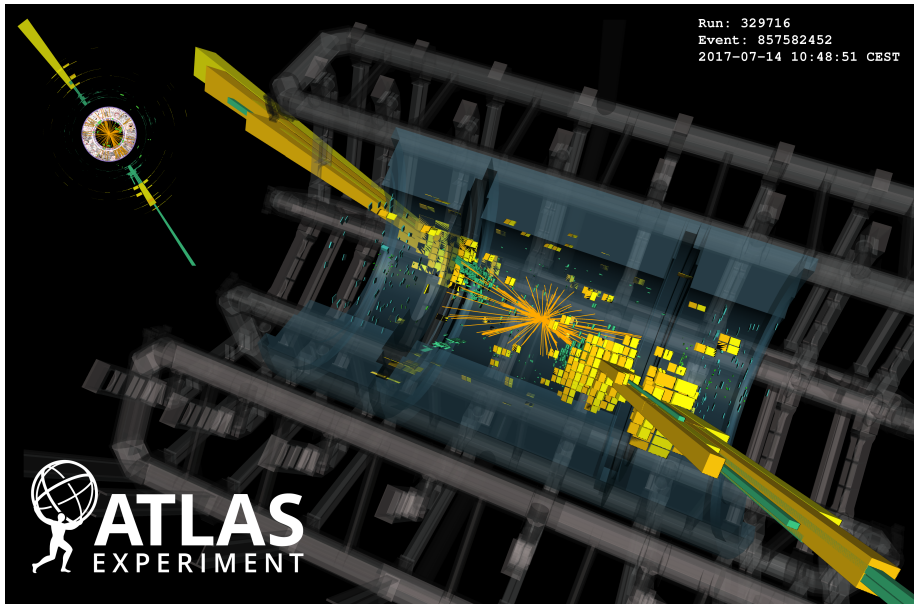
Future forward Part of the ATLAS forward-proton spectrometer. Credit: ATLAS collaboration

- 1st observation of $\gamma\gamma \to ll$ with forward protons tagged by AFP



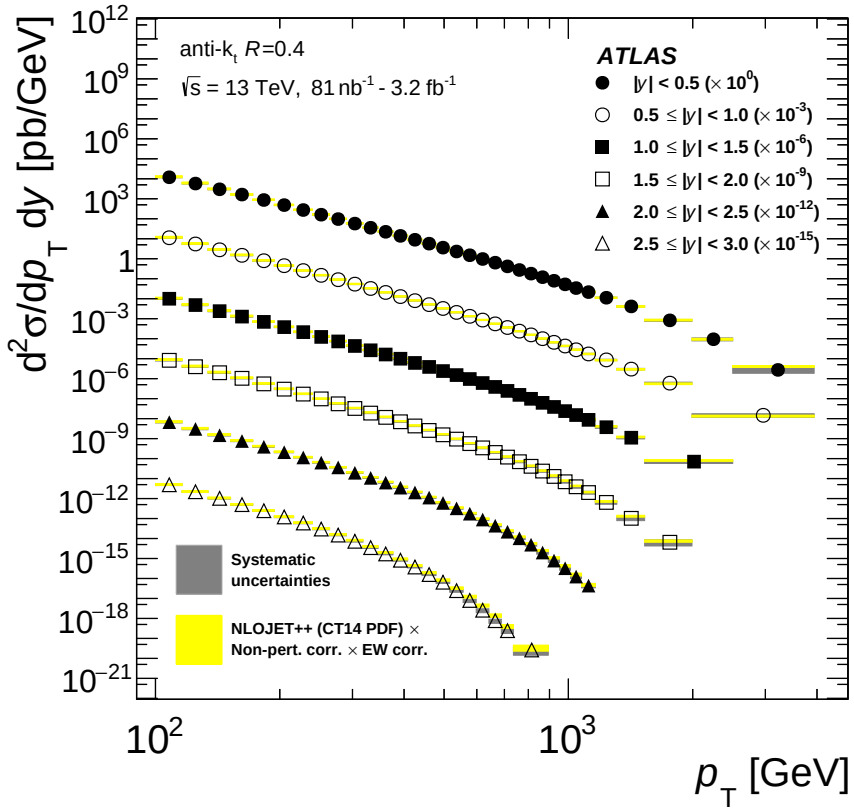
PRL 125 (2020) 261801 (CTU, FZU)

Jet physics



- jets - collimated spray of particles
  fingerprints of quarks/gluons kicked out from protons
- most violent events produced by LHC
- jet transverse momenta (p_T) up to ~ 3 TeV
  $\Delta x \cdot \Delta p \sim \hbar \Rightarrow$ we reach scale of 10^{-20} m

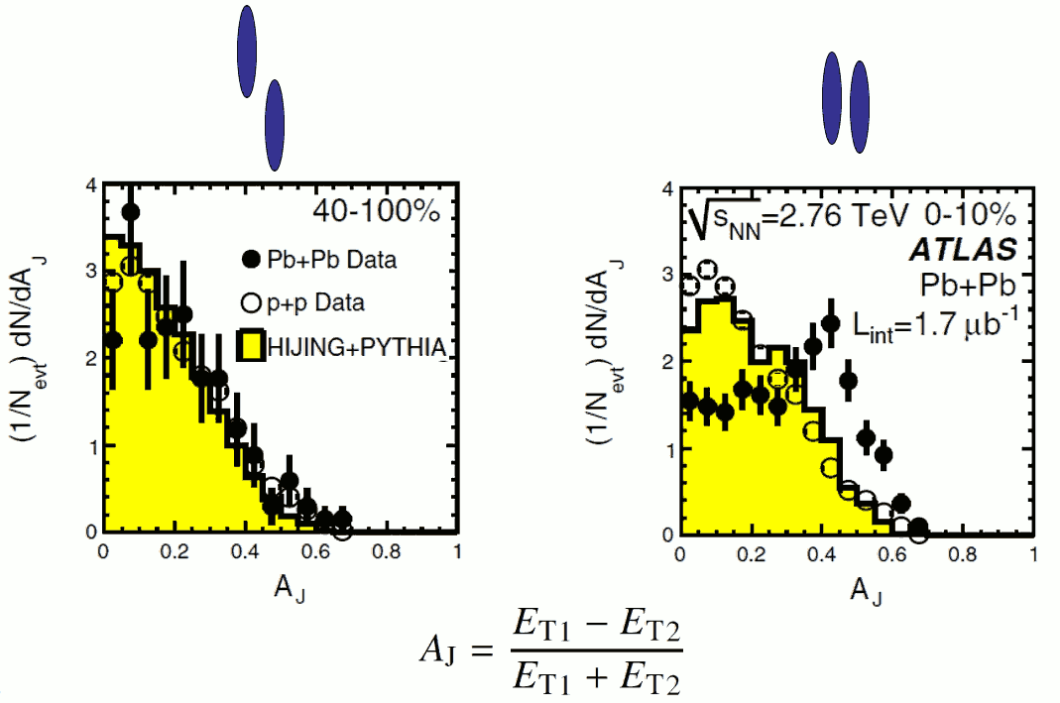
- strong contribution to high p_T jet measurements at $\sqrt{s} = 8$ and 13 TeV (CU, CTU)
  JHEP 09 (2017) 020 JHEP 05 (2018) 195
- results in good agreement with QCD
- quarks are point-like at least at 10^{-20} m scale



Heavy Ion Physics

- very active HI group at CU
- goal is to understand properties of ultra dense and hot matter created in ultra-relativistic HI collisions
- jets as probes of dense and hot medium properties

1st observation of jet quenching at LHC



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

PRL 105 (2010) 252303

- most cited ATLAS paper before Higgs discovery

- Inclusive jet suppression

PRL 114 (2015) 072302, PLB 790 (2019) 108

- jet sub-structure and fragmentation

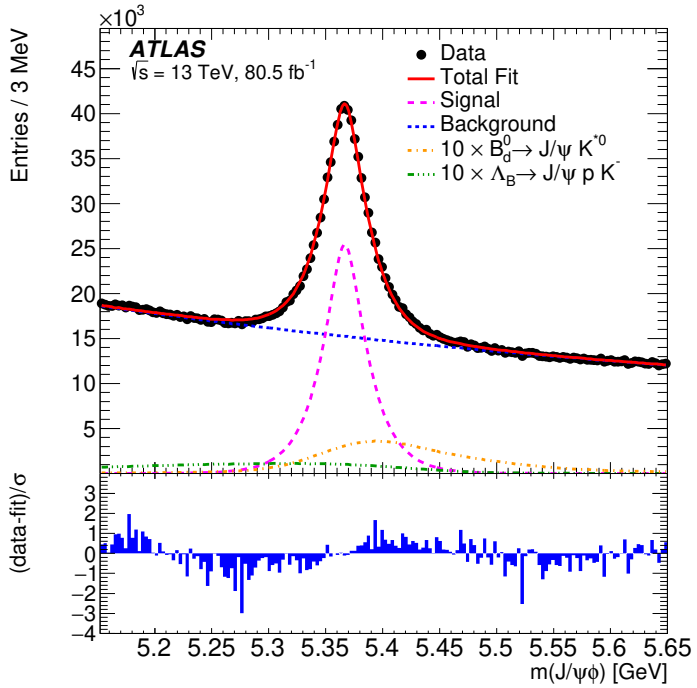
PLB 739 (2014) 320-342, PLB 751 (2015) 376-395

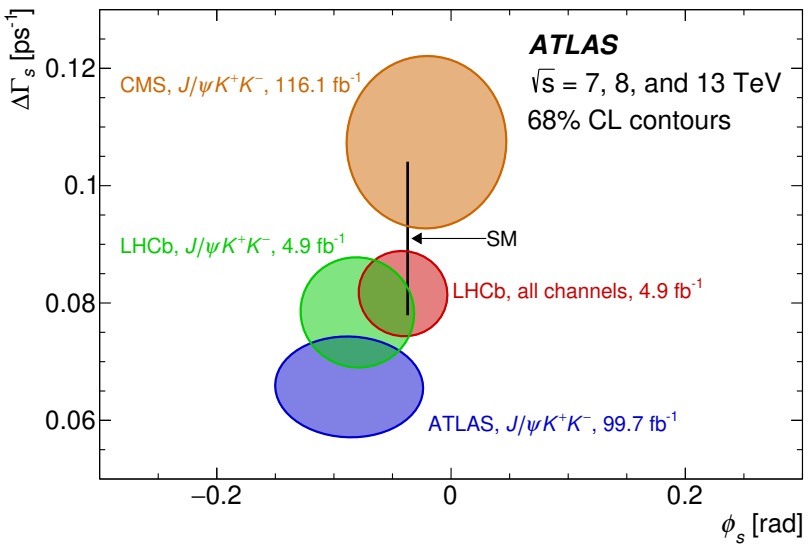
B-hadron physics

- very active groups (CU, CTU, FZU)
- plenty of contributions

$B_s^0 \to J/\psi + \phi$ channel

- great dedication from the start of LHC
- $B_s \to J/\psi + \phi$ observation ATLAS-CONF-2011-050
- lifetime ATLAS-CONF-2011-092
- CP-violating weak phase ϕ_s and width difference $\Delta\Gamma_s$
  - 2011 data without tagging JHEP 12 (2012) 072
  - 2011 with tagging PRD90 (2014) 052007
  - 2012 (tagged) data JHEP 08 (2016) 147
  - 2015-2017 (tagged) data EPJ C81 (2021) 342
  - ATLAS competitive with LHCb!
- more topics
  - Oscillations also in the B_d^0 system ($\Delta\Gamma_d$)
  - (Semi)-muonic rare B-decays analyses ($B_s \to \mu\mu$, $B_d \to K^\star\mu\mu$)
  - Polarization of Λ baryons (Λ_0, Λ_b)
  - Spectroscopy and b-hadron production ($X(5568)$, b-pair prod.)





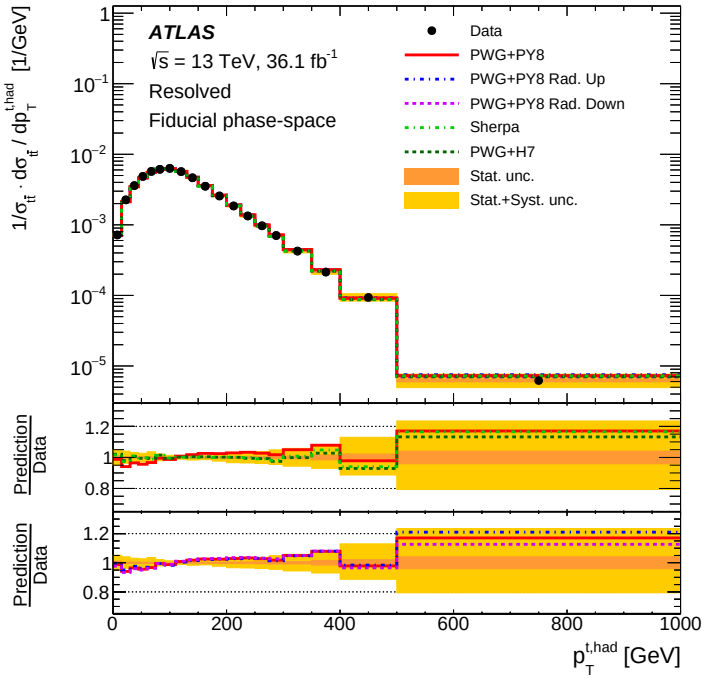
EPJ C81 (2021) 342

Physics of top quark

- top quark - the most massive fermion
- promising window for BSM physics
- cooperation between CZ and SK groups

top production

- $t\bar{t}$ production in $l+$jets at $13\,\text{TeV}$ (CUB) PLB 810 (2020) 135797
- differential cross section in $l+$jets (PU) EPJ C79 (2019) 1028
- diff. X-sect. in all-hadronic boosted (PU) PRD98 (2018) 012003
  - Data so precise that NNLO is needed!



EPJ C79 (2019) 1028

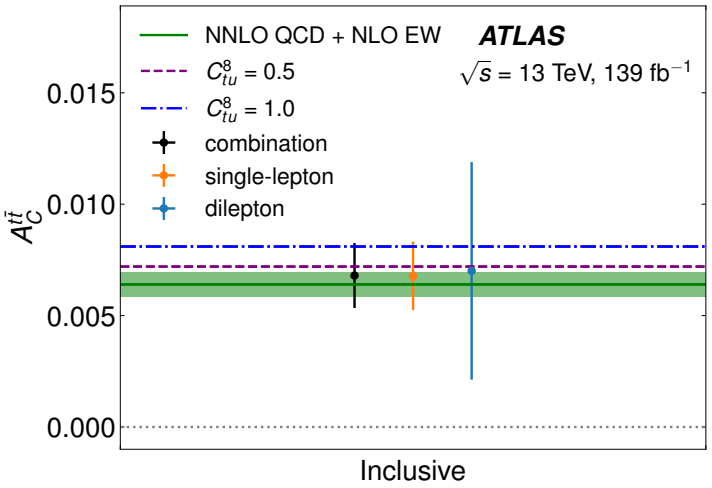
$t\bar{t}$ charge asymmetry

- t slightly wider in rapidity (y) than $\bar{t}$

$$A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}, \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

- tiny effect in SM
- early analyses at 7 and $8\,\text{TeV}$ (FZU) JHEP05 (2015) 061 PRD94 (2016) 032006
- up to first evidence in full Run2 dataset (CUB) arXiv:2208.12095

$A_C^{t\bar{t}} = 0.0068 \pm 0.0015 \qquad 4.7\sigma$ evidence



Physics of top quark

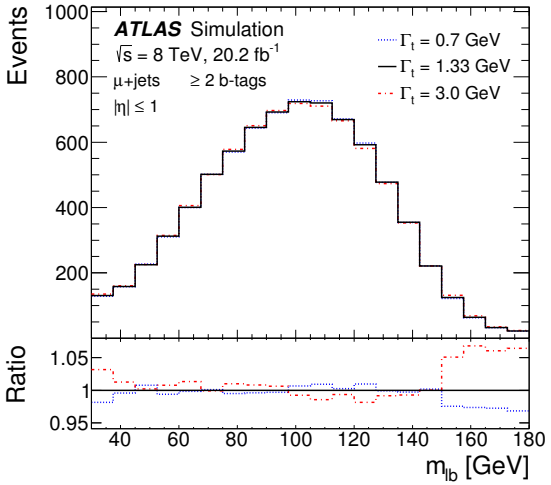
- top quark - main subject of study of CUB group

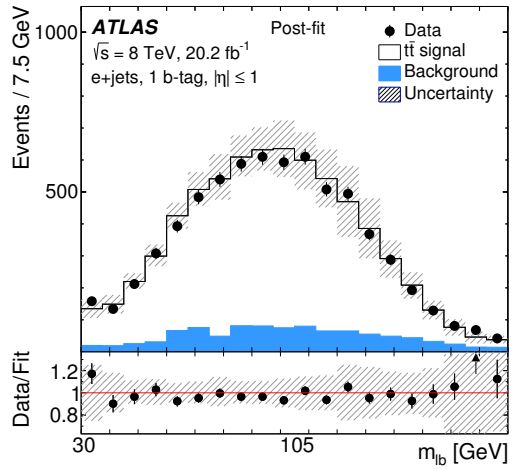
top quark properties

- top charge JHEP11 (2013) 03
- **decay width** Γ_{top} EPJC78 (2018) 129

$$\Gamma_{\text{top}} = 1.76 \pm 0.33(\text{stat})^{+0.79}_{-0.68}(\text{sys})\ \text{GeV}$$

(the most accurate direct Γ_{top} measurement)





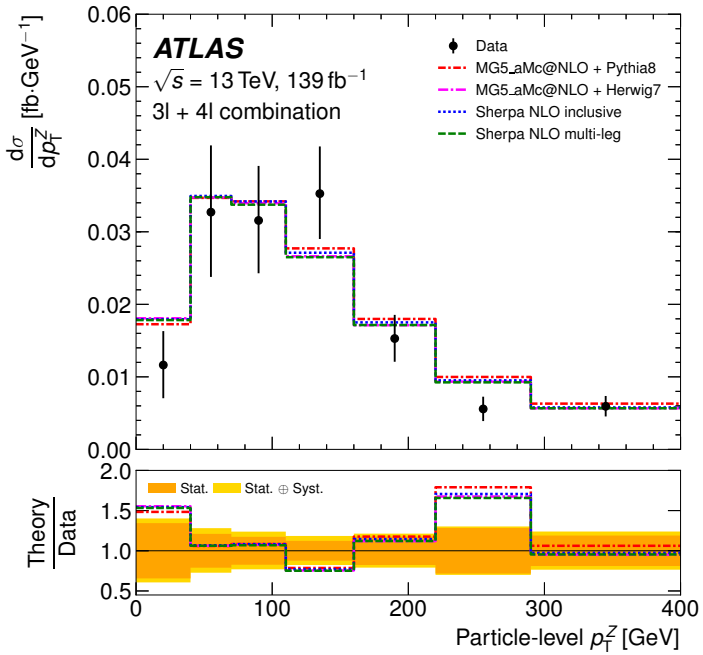
EPJ C78 (2018) 129

coupling to EWK gauge bosons

- associated production of $t\bar{t}$ and Z EPJ C81 (2021) 737
- first full Run2 measurement
- achieved 9.9% precision in inclusive cross section

top quark and W boson tagging

- study of various taggers for boosted top and W topologies (EPJ C79 (2019) 375)



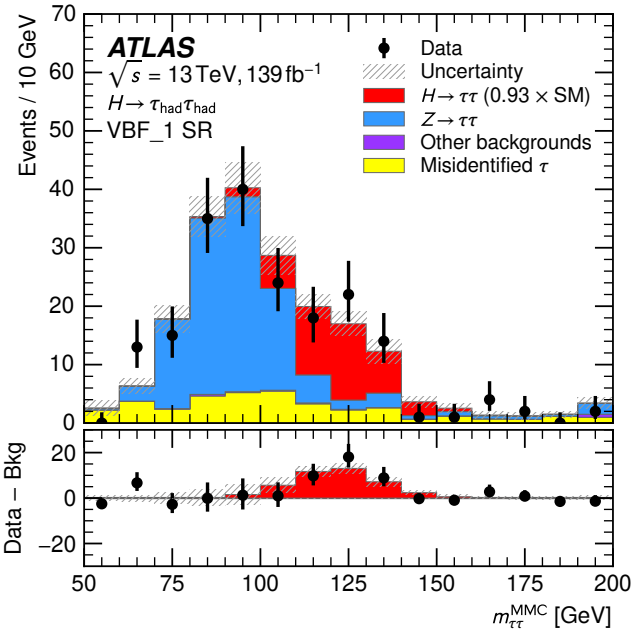
EPJ C81 (2021) 737

Physics of Higgs Boson

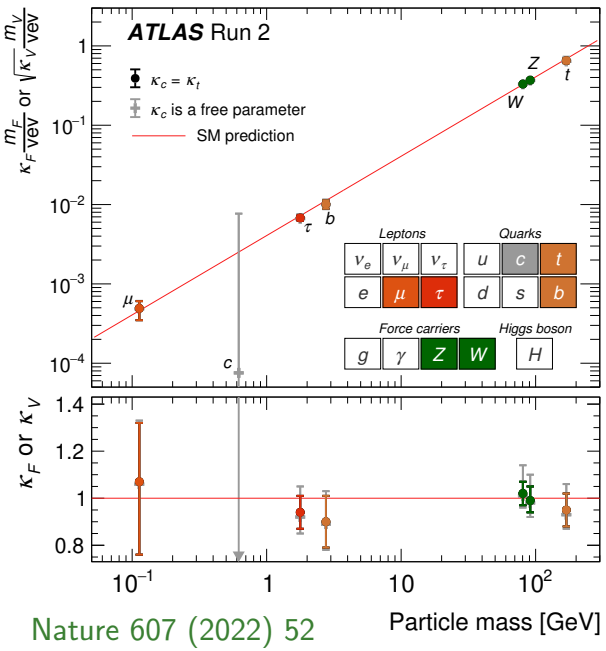
H coupling to fermions

- $H \to \tau\tau$ channel
  - evidence in Run1 data (CU) JHEP 04 (2015) 117
  - precise measurement with full Run2 data sample (CU) JHEP 08 (2022) 175

$$\sigma_{H\to\tau\tau} = 2.94 \pm 0.21(\text{stat})^{+0.37}_{-0.32}(\text{syst})$$



- search for ttH to multilepton final states (WW, ZZ, $\tau\tau$) (CTU) PLB 749 (2015) 519
  - direct test of Yukawa coupling between H and t
  - observed later in full Run2 data sample with 6.3σ significance PLB 784 (2018) 173
- Yukawa couplings proportional to fermion masses
- fundamental prediction of SM
- confirmed by ATLAS measurements



Nature 607 (2022) 52

Our roles in ATLAS Physics management

Oldřich Kepka (FZU)
Standard Model (SM)

Pavel Řezníček (CU)
B-physics (2013–2015)

Martin Spousta (CU)
Heavy Ion (2017–2019)

Martin Rybář (CU)
Heavy Ion (HI)

SM Soft QCD and Diffraction
- K. Černý (PU), S. Todorová (CU), M. Taševský (FZU), O. Kepka (FZU)

SM Jet and Photon Physics - Z. Hubáček (CTU)

B-physics - Rare Decays
- T. Jakoubek (former FZU), P. Řezníček (CU)

B-physics - Physics with $B \to J/\psi$
- R. Novotný (former CTU)

HI Jet Physics
- M. Rybář (CU), M. Spousta (CU)

HI Correlations and Global Physics
- P. Balek (CU)

Top Reconstruction
- O. Majerský (CU Bratislava), T. Dado (former CU Bratislava)

Top Combination - T. Dado (former CU Bratislava)

Top Properties - S. Tokár (CU Bratislava)

Contributions to ATLAS management II

ATLAS Construction

- Tilecal project manager – R. Leitner (CU)
- AFP installation Coordinator – P. Sicho (FZU)

Operation & Maintenance

- Pixel Run & DAQ Coord. – O. Kepka (FZU)
- Pixel P1 Infrastr. Coordinator – P. Šícho (FZU)
- Tilecal Maintenance & Infrast. – S. Němeček (FZU)
- Tilecal Data Prep. & Perform. – T. Davídek (CU)
- LAr Software & Data Prep. – P. Stríženec (IEP)

HL-LHC Upgrade

- ITk Strip Irradiation Tests Coordinatior

  J. Kroll (FZU)
- ITk Strip Resource Manager – Z. Doležal (CU)
- ITk Pixel Off-detector Services Coordinator

  P. Šícho (FZU)
- Tilecal Upgrade Software & Performance

  T. Davídek (CU)

Software and computing

- DDM Central Services Coordinator – T. Kouba (FZU)
- FastCalo Simulation Group Conv. – Z. Hubáček (CTU)

Collaboration matters

- FWD IB chair – M. Taševský (FZU), V. Vorobel (CU)
- LAr IB chair – P. Stríženec (IEP)
- chair of speakers committee

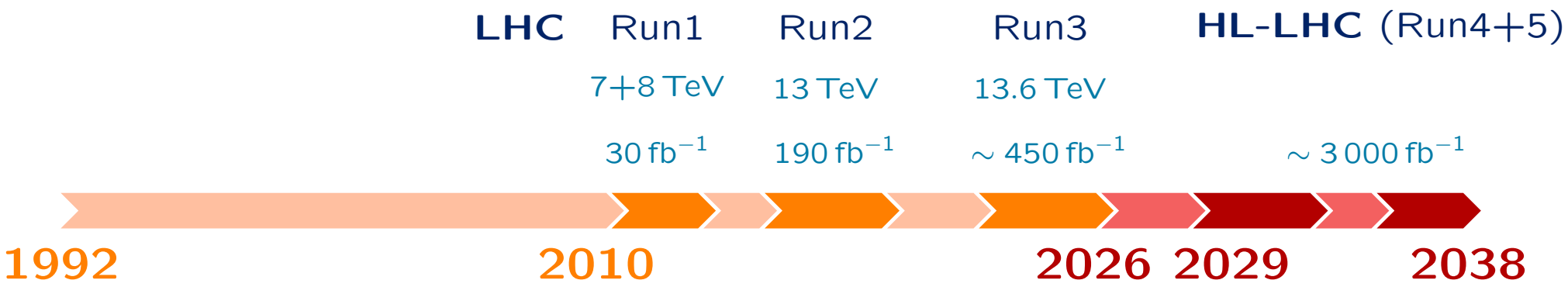
  M. Taševský (FZU), Z. Doležal (CU)
- chair of Tilecal speakers committee

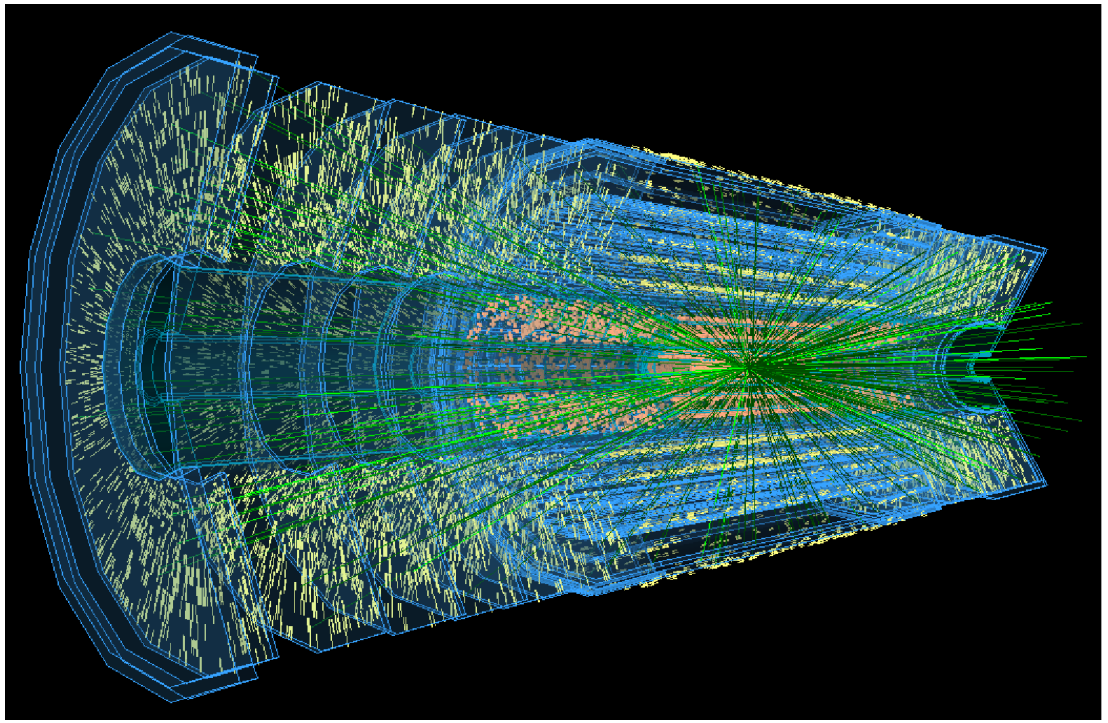
  J. Faltová (CU),T. Davídek (CU)
- chair of LAr speakers committee – P. Stríženec (IEP)

P. Stríženec (LAr DAQ)

P. Šícho (AFP+Pixels)

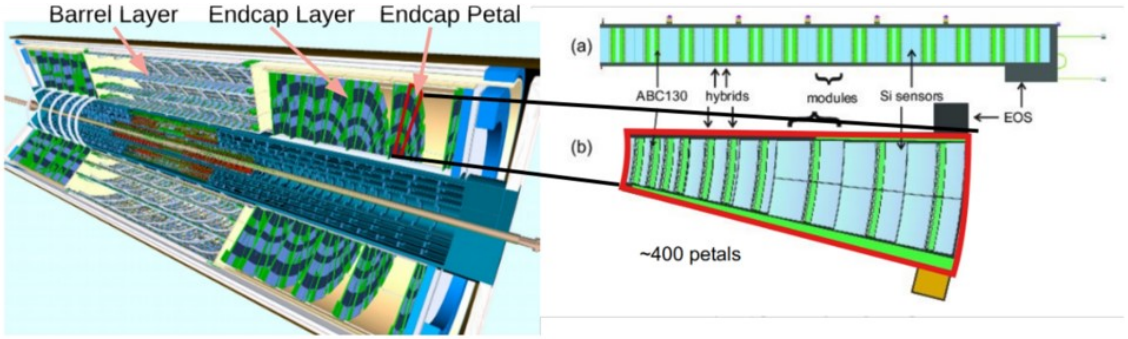
Future - HL-LHC Upgrade





ATLAS HL-LHC Upgrade

- Estimated cost 280 MCHF (1/2 of ATLAS cost)
- CZ/SK share 5.7/0.9 MCHF
- CZ major contribution (5.1 MCHF) to new tracker (ITk)
  - testing 4500 sensors for one Endcap detector
  - assembly of 750 modules for one Endcap disc



- SK major contributions
  - Tilecal (CU Bratislava)
    production of auxiliary control boards
  - LAr calorimeter (IEP) - software development

Joint Clean Lab for ITk Strip at FZU

(CU,CTU,FZU,PU)

- clean room: $52\,\mathrm{m}^2$
- cleanliness ISO 7
- temperature stability 1°C
- humidity control $\pm 10\%$
- ESD safe lab equipment
- 2 probe stations
- metrology station
- wire-bonding machines
- dry storage cabinet
- flow boxes, . . .

- site fully qualified for sensor testing in Oct 2020

^{60}Co Terabalt, ÚJP Praha

- cooperation with industry
  - ITk production database (Unicorn U)
  - module assembly (Argotech)
  - ^{60}Co irradiation (UJP Praha)

Organization of ATLAS Meetings

ALTAS CZ+SK workshops

- Keeping CZ and SK communities together

  ⋮

  - 2015, PU in Olomouc
  - 2016, University of Žilina
  - 2017, FZU in Prague
  - 2018, IEP in Košice
  - 2019, CTU in Prague

UP, Olomouc 2015

FZU, Prague 2017

IEP, Košice 2018

ATLAS Overview Weeks

- Prague 2003
- Bratislava 2017

\+ many more dedicated ATLAS Workshops

Summary

- ATLAS represents for CZ and SK particle physics community an opportunity to participate in the world leading experiment that pushes the field forward
- The community uses this opportunity very well
  - Strong contribution of young physicists to ATLAS scientific program and results
  - Strong contribution to the detector construction, operation, and upgrades
  - Related R&D programs bring opportunities to our engineers and technically oriented universities
  - This involvement generates opportunities for our industry
  - Science made by ATLAS is attractive to general public

    and it attracts students - 39 defended ATLAS PhD. thesis: 27 (CZ) / 12 (SK)
- CZ and SK groups are well recognized within ATLAS - vital contributors
- We are doing our best to continue to be vital contributors during the HL-LHC era