Lecture: ATLAS Physics

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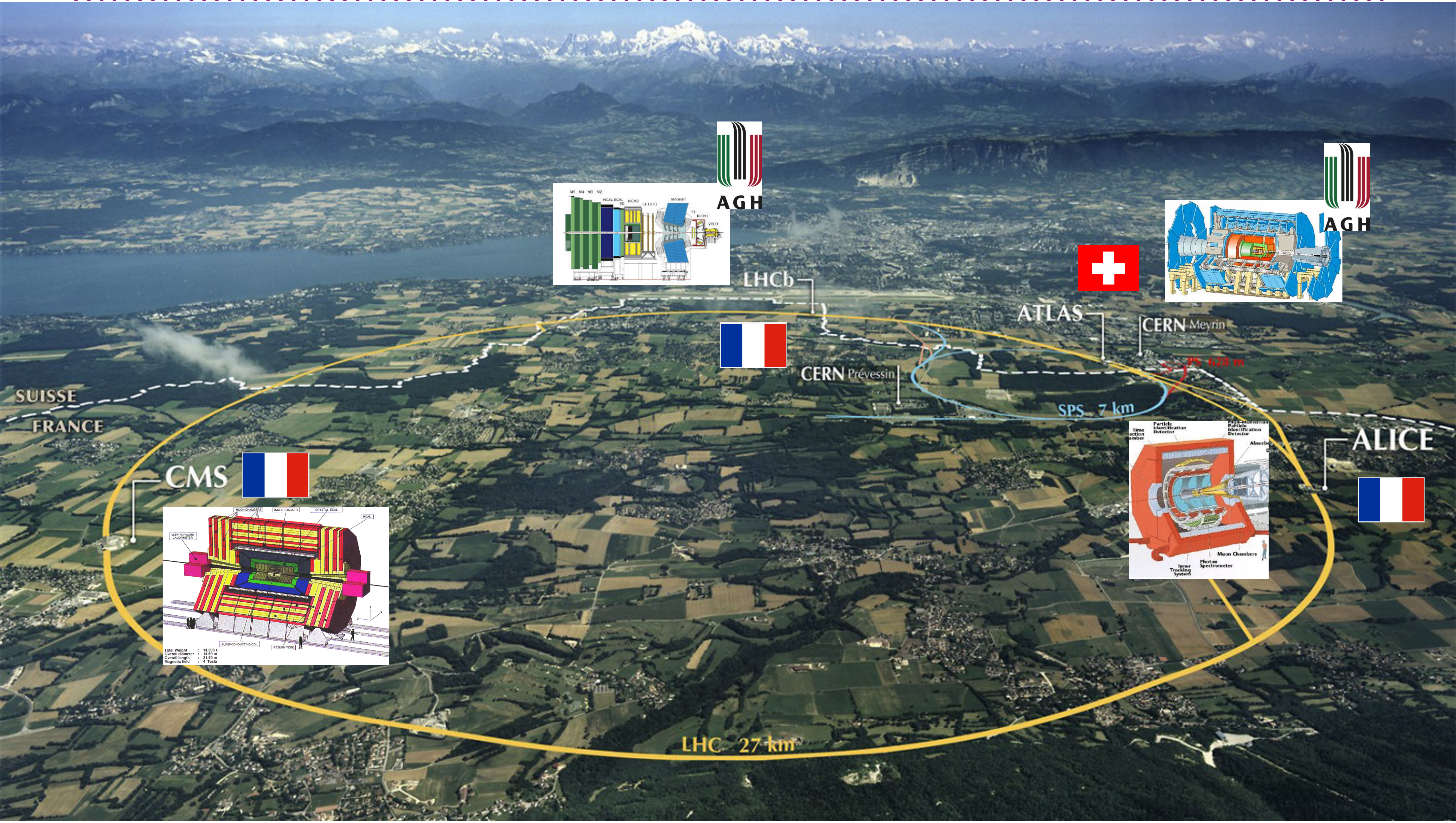
CONTENT

1. ATLAS experiment at the LHC
2. Physics at ATLAS
   - God Particle: Higgs boson
   - Searches for New Physics
   - Heavy-ion physics in a nutshell
   - Ultra-peripheral collisions
   - Future of ATLAS

I. ATLAS EXPERIMENT

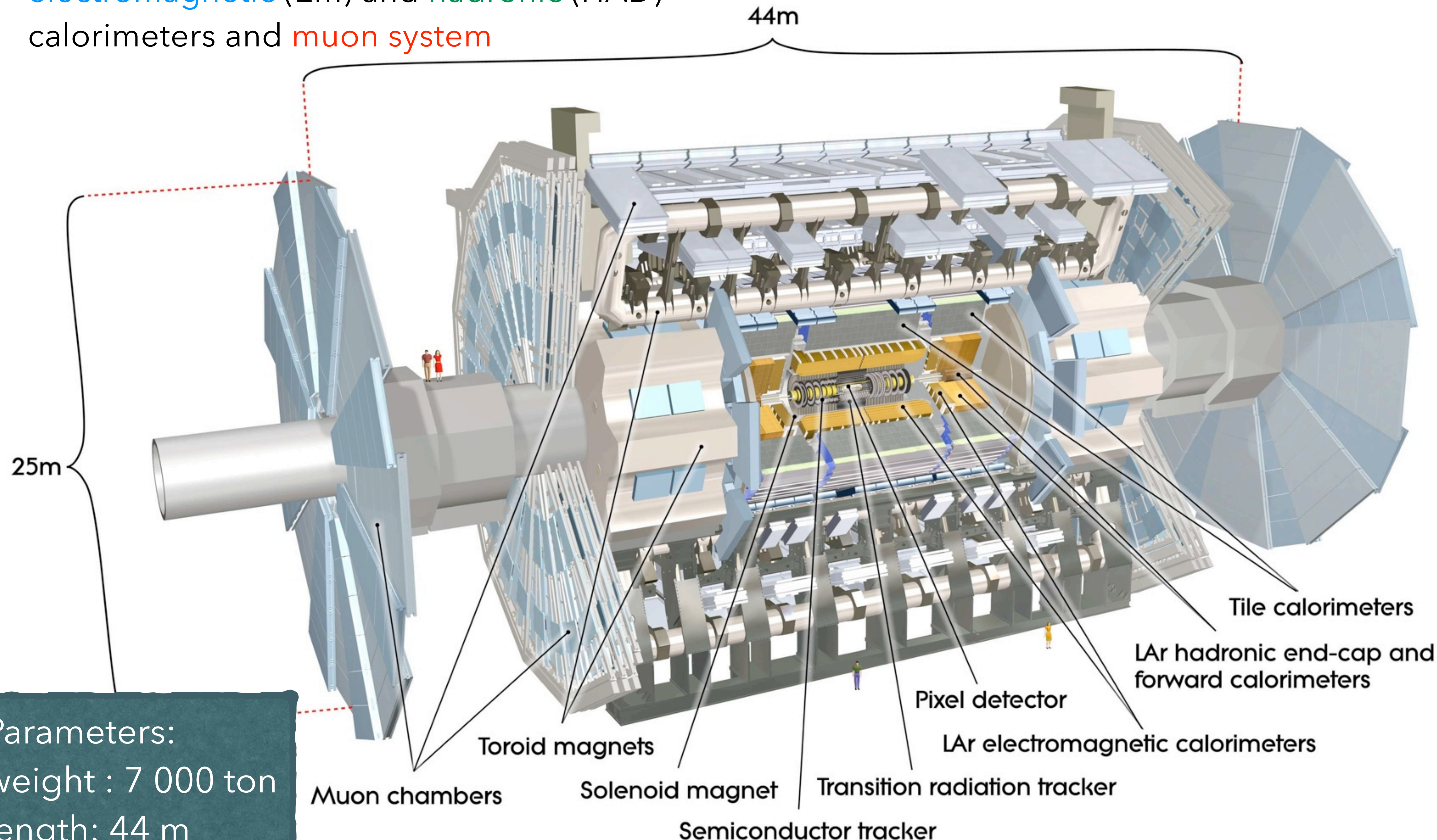
LARGE HADRON COLLIDER



- Large Hadron Collider (LHC) is a machine of 27 km in circumference
- Most of the time proton-proton collisions at **0.9, 5, 7, 8** (2009-2013) and **13 TeV** (2015-2018)
- 4 weeks per year dedicated to heavy-ion collisions: lead-lead at **2.76 TeV** (2010, 2011) and **5.02 TeV** (2015 and 2018)

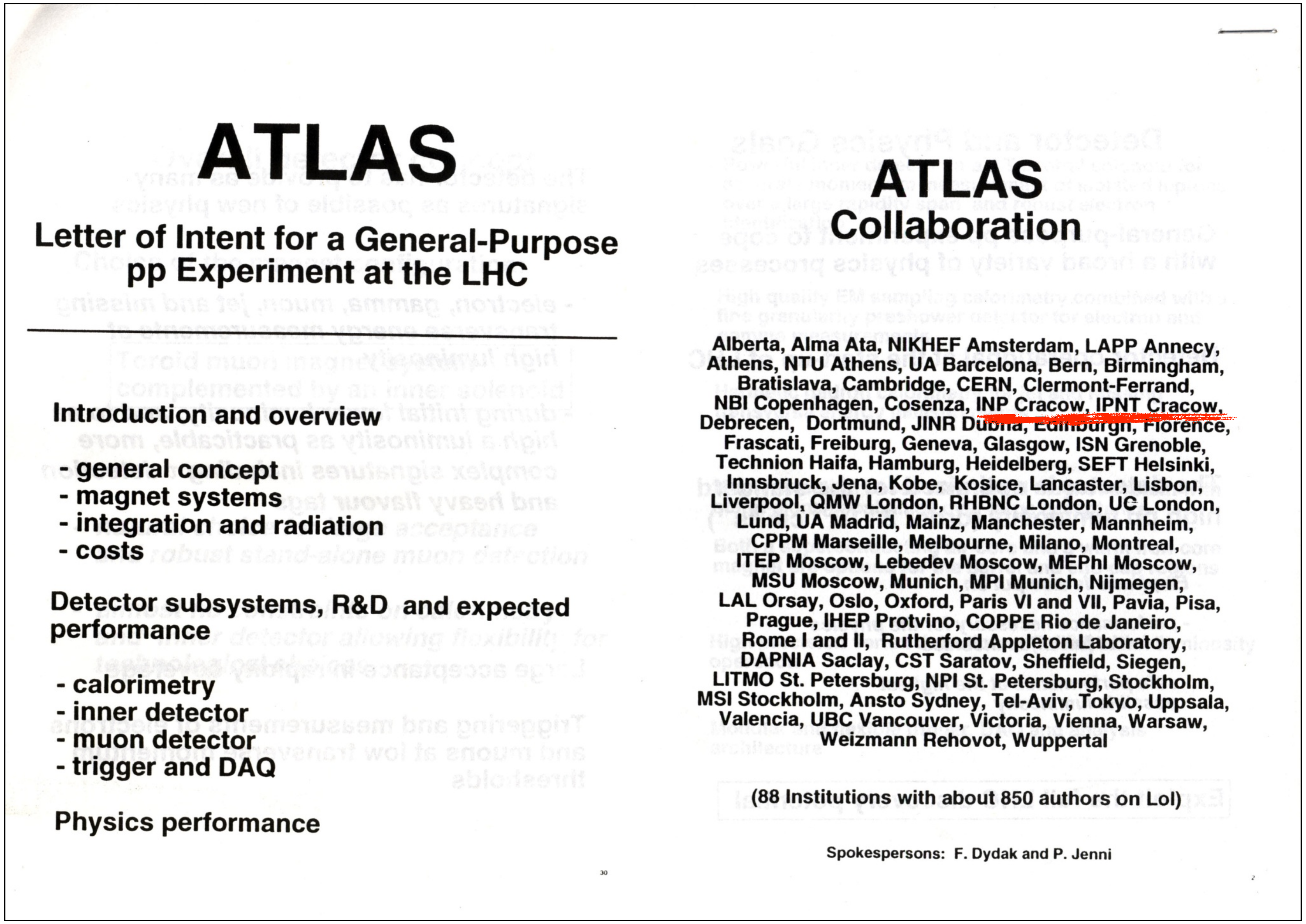
ATLAS DETECTOR

Three main subsystems: inner detector, electromagnetic (EM) and hadronic (HAD) calorimeters and muon system



Parameters:
weight : 7 000 ton
length: 44 m
height: 25 m

BIRTH OF EXPERIMENTS AT THE LHC: YEAR 1992



ATLAS

Letter of Intent for a General-Purpose pp Experiment at the LHC

Introduction and overview

- general concept
- magnet systems
- integration and radiation
- costs

Detector subsystems, R&D and expected performance

- calorimetry
- inner detector
- muon detector
- trigger and DAQ

Physics performance

ATLAS Collaboration

Alberta, Alma Ata, NIKHEF Amsterdam, LAPP Annecy, Athens, NTU Athens, UA Barcelona, Bern, Birmingham, Bratislava, Cambridge, CERN, Clermont-Ferrand, NBI Copenhagen, Cosenza, INP Cracow, IPNT Cracow, Debrecen, Dortmund, JINR Dubna, Edinburgh, Florence, Frascati, Freiburg, Geneva, Glasgow, ISN Grenoble, Technion Haifa, Hamburg, Heidelberg, SEFT Helsinki, Innsbruck, Jena, Kobe, Kosice, Lancaster, Lisbon, Liverpool, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Melbourne, Milano, Montreal, ITEP Moscow, Lebedev Moscow, MEPhI Moscow, MSU Moscow, Munich, MPI Munich, Nijmegen, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pisa, Prague, IHEP Protvino, COPPE Rio de Janeiro, Rome I and II, Rutherford Appleton Laboratory, DAPNIA Saclay, CST Saratov, Sheffield, Siegen, LITMO St. Petersburg, NPI St. Petersburg, Stockholm, MSI Stockholm, Ansto Sydney, Tel-Aviv, Tokyo, Uppsala, Valencia, UBC Vancouver, Victoria, Vienna, Warsaw, Weizmann Rehovot, Wuppertal

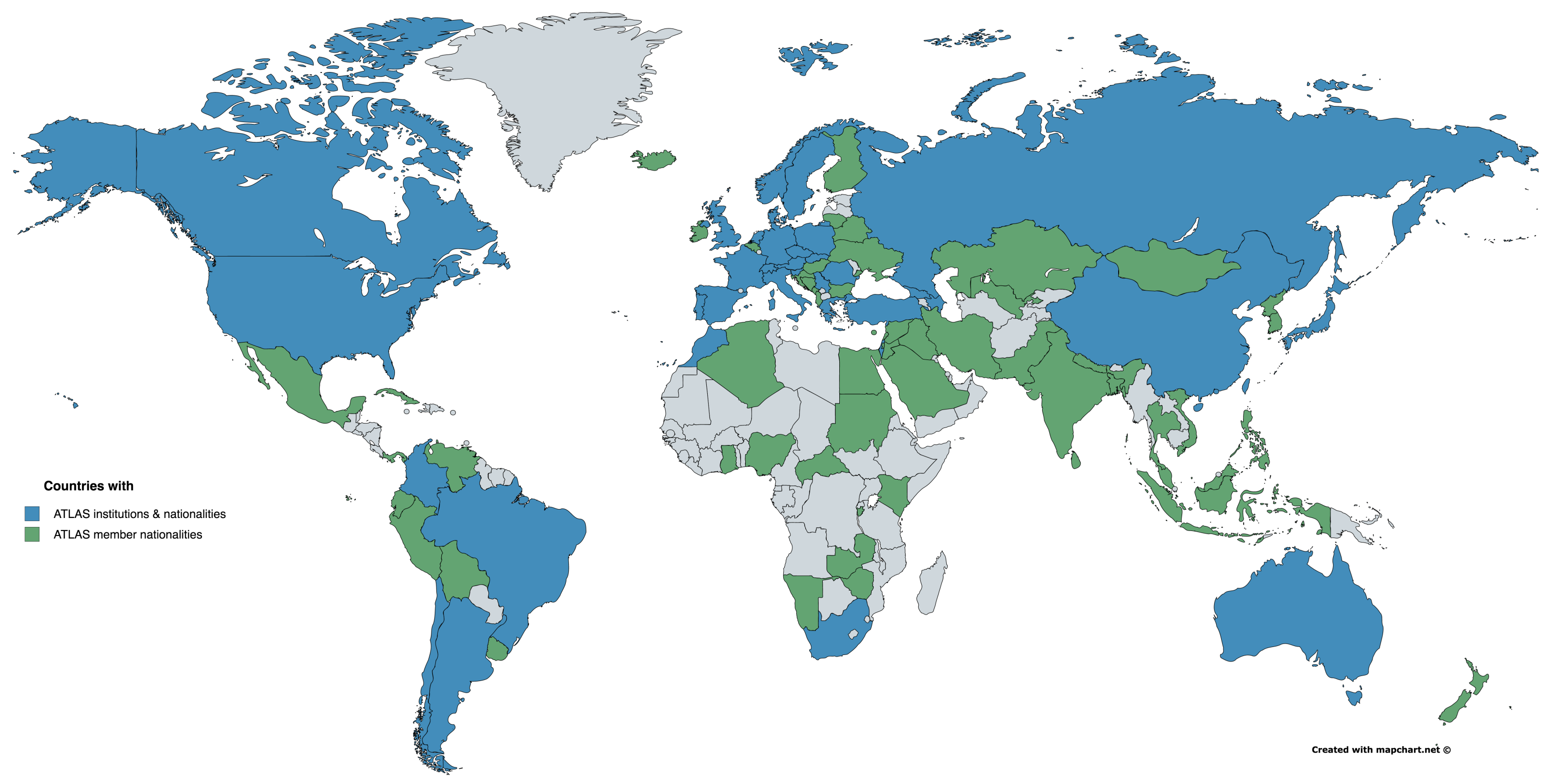
(88 Institutions with about 850 authors on LoI)

Spokespersons: F. Dydak and P. Jenni

- ➤ Two institutions from Kraków signed the letter of intent in 1992
  - ➤ Institute of Nuclear Physics (**INP Cracow**) and
  - ➤ Faculty of Physics and Nuclear Techniques (**IPNT Cracow**) founded in 1991 by Senat AGH UST
    - ➤ A team leader is **prof. Danuta Kisielewska, honorary professor of AGH UST** since 2019

ATLAS COLLABORATION

- **38** countries
- About **180** institutes
  - **Poland is a founding member since** 1992
  - Polish institutes: **AGH+UJ** and **IFJ** in Kraków
  - 1 ATLAS member per 1 M habitants
- **3 000** scientists with about **1 000** students



Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

ATLAS AT AGH UST

Staff:

prof.dr hab. inż. Władysław Dąbrowski

prof. dr hab. inż. Danuta Kisielewska

prof. dr hab. inż. Mariusz Przybycień

dr hab. inż. Tomasz Bołd, prof. AGH

dr hab. inż. Iwona Grabowska-Bołd, prof. AGH

dr hab. inż. Tadeusz Kowalski

dr hab. inż. Bartosz Mindur, prof. AGH

dr inż. Leszek Adamczyk

dr inż. Stefan Koperny

Assistant/assistant professors (adiunkt):

dr inż. Klaudia Maj

dr inż. Mateusz Dyndał

dr inż. Rafał Sikora

PhD students:

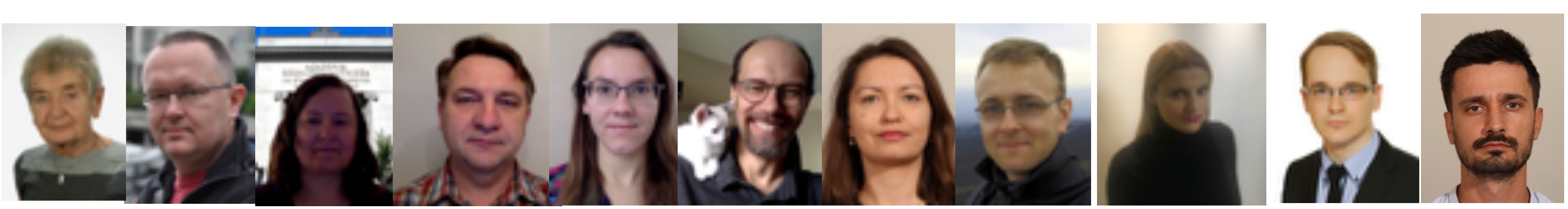
mgr inż. Agnieszka Ogrodnik

mgr inż. Inga Łakomiec

mgr inż. Krzysztof Janas

mgr Alexander Kevin Gilbert

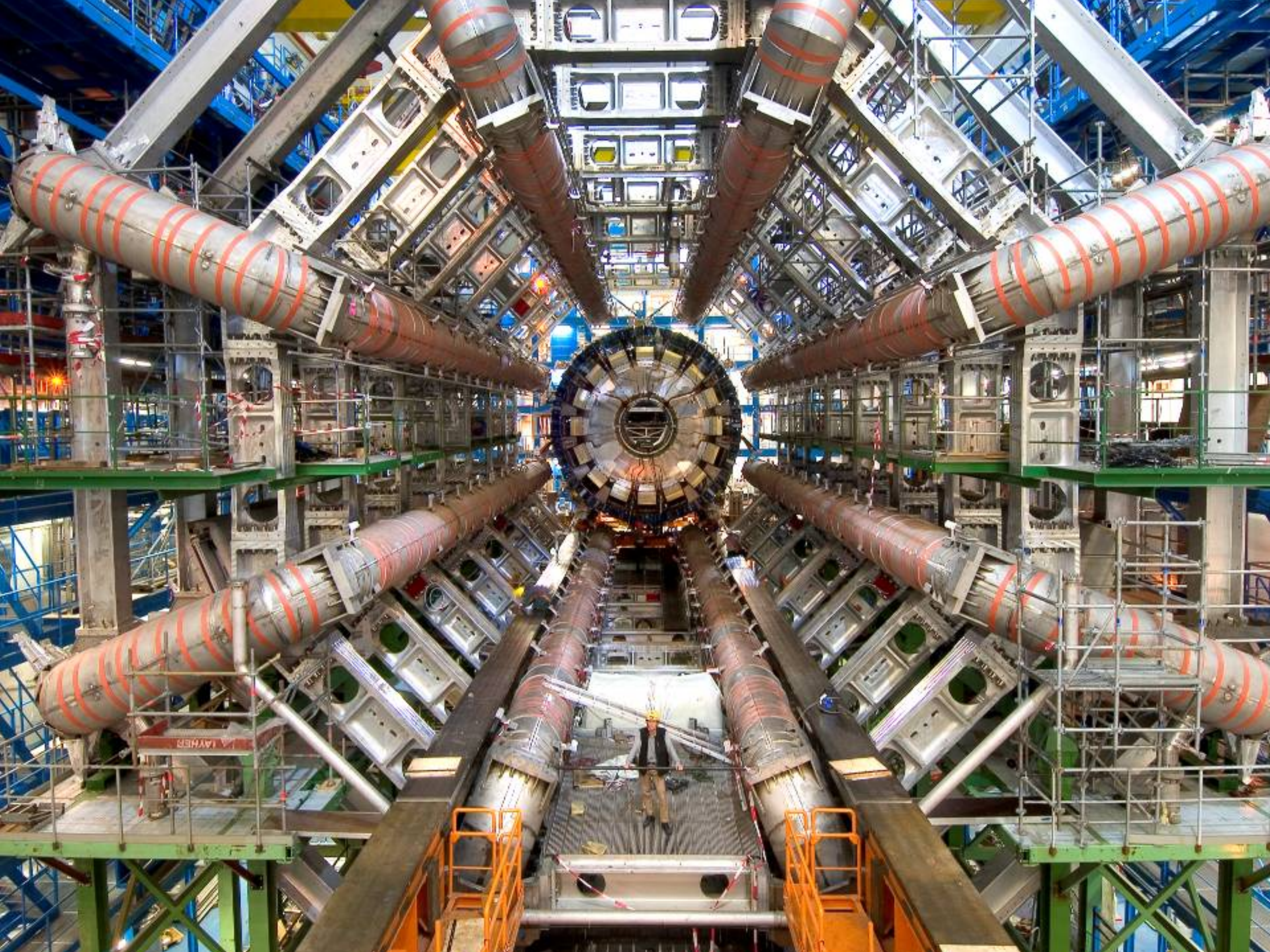
DK BM IGB LA AO TB KM RS IŁ KJ MD



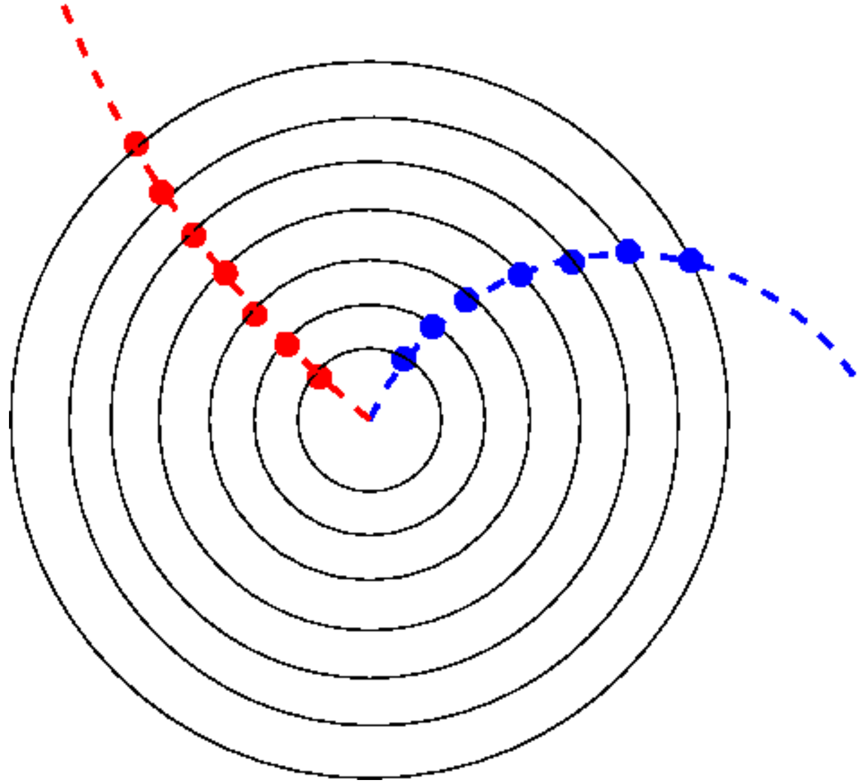
16 team members + 4 master/diploma students + 9 engineering students

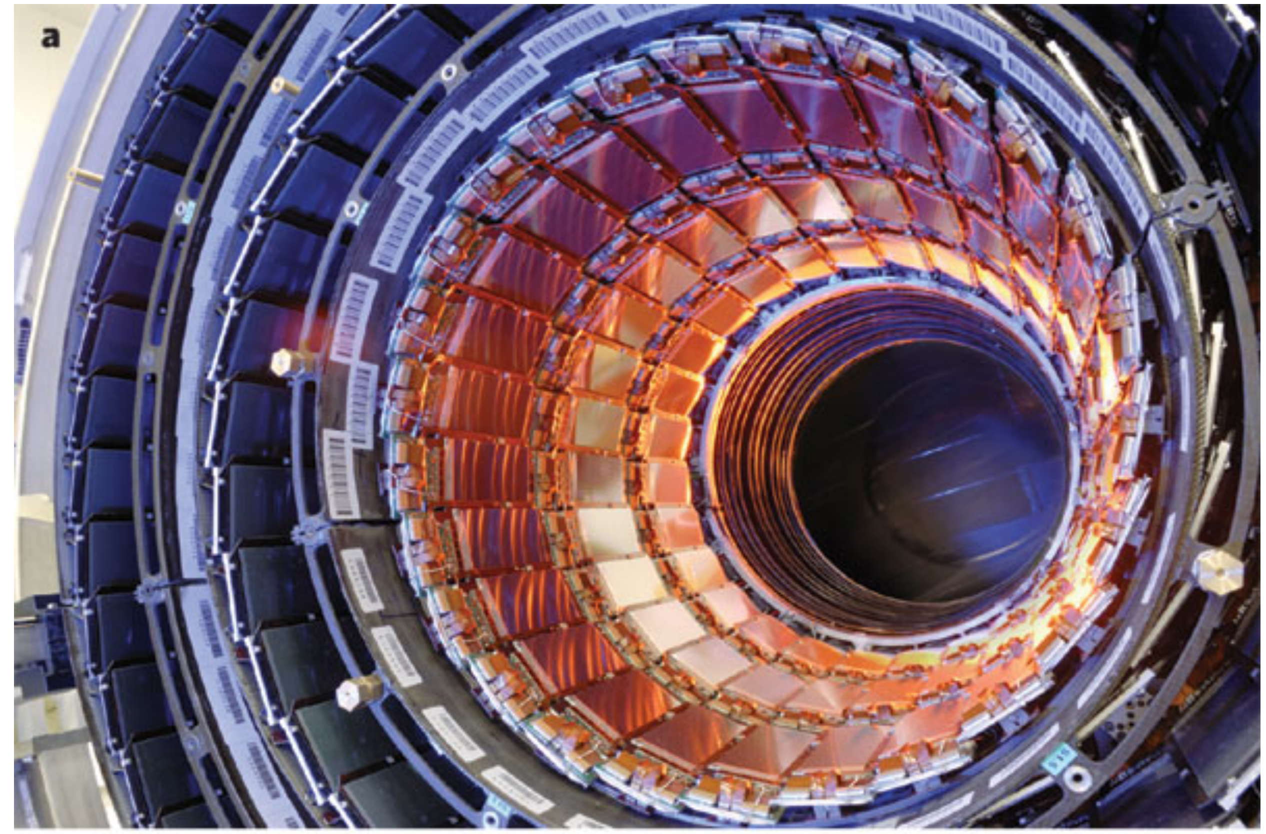
25 YEARS OF ATLAS COLLABORATION

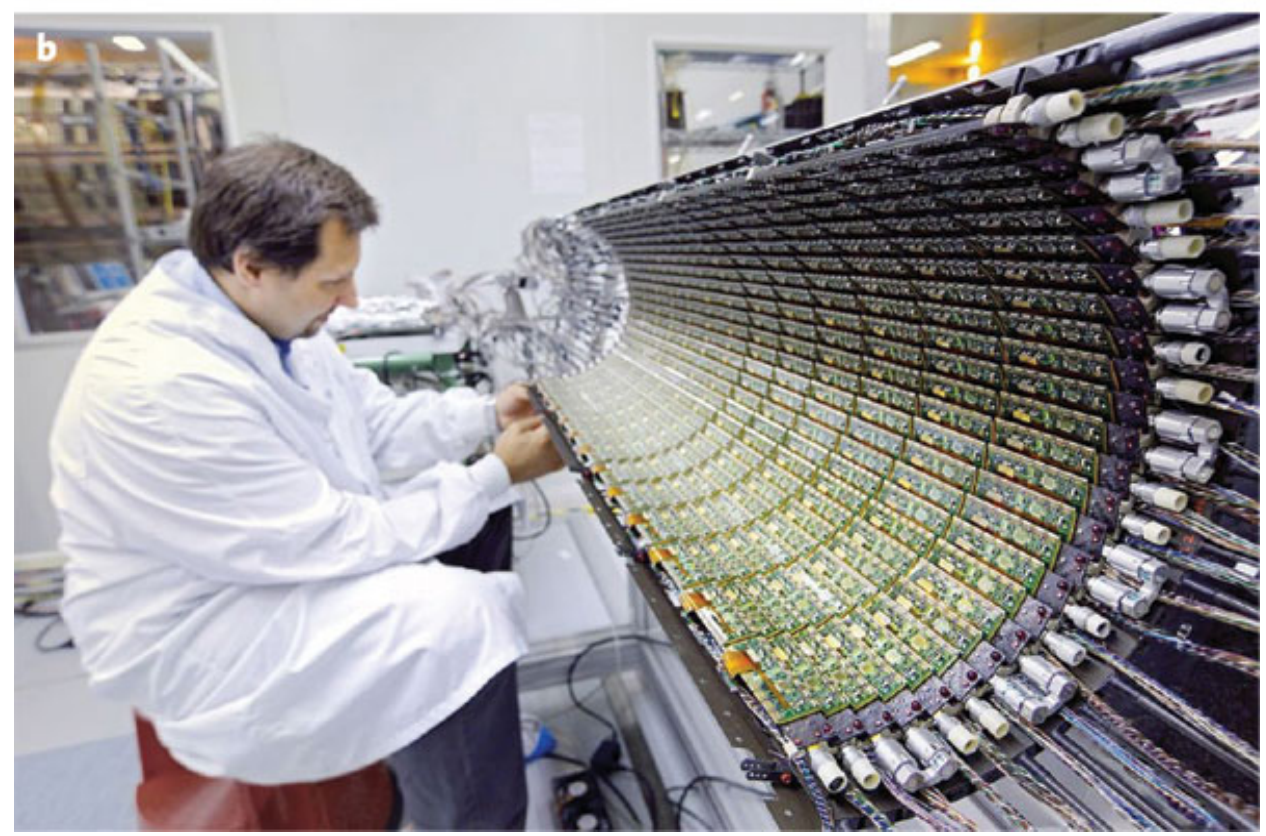
- Gala to celebrate 25th anniversary in 2017, ATLAS Week, Bratislava



INNER DETECTOR

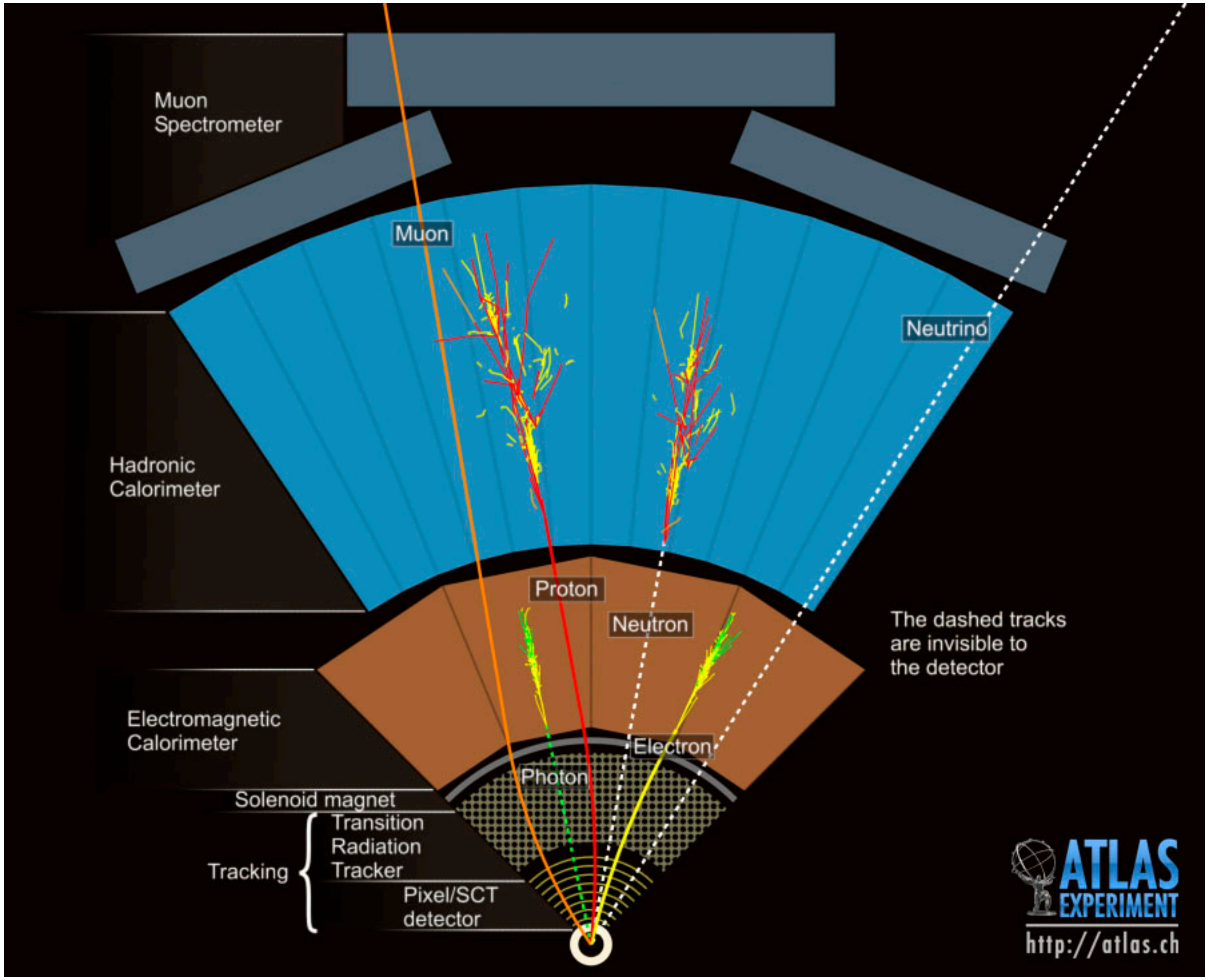






- Charged particle traverses gas or silicon
  - Ionisation process: measured charge allows to reconstruct its energy and position
  - Typical resolution is **15 µm**
- Detector is immersed in a magnetic field of **2 T**
  - Curvature if the trajectory gives us information on momentum
- Active hits give us information about a trajectory
- **Team from AGH UST contributes to the ID system (SCT, TRT)**

PARTICLE IDENTIFICATION IN A NUTSHELL

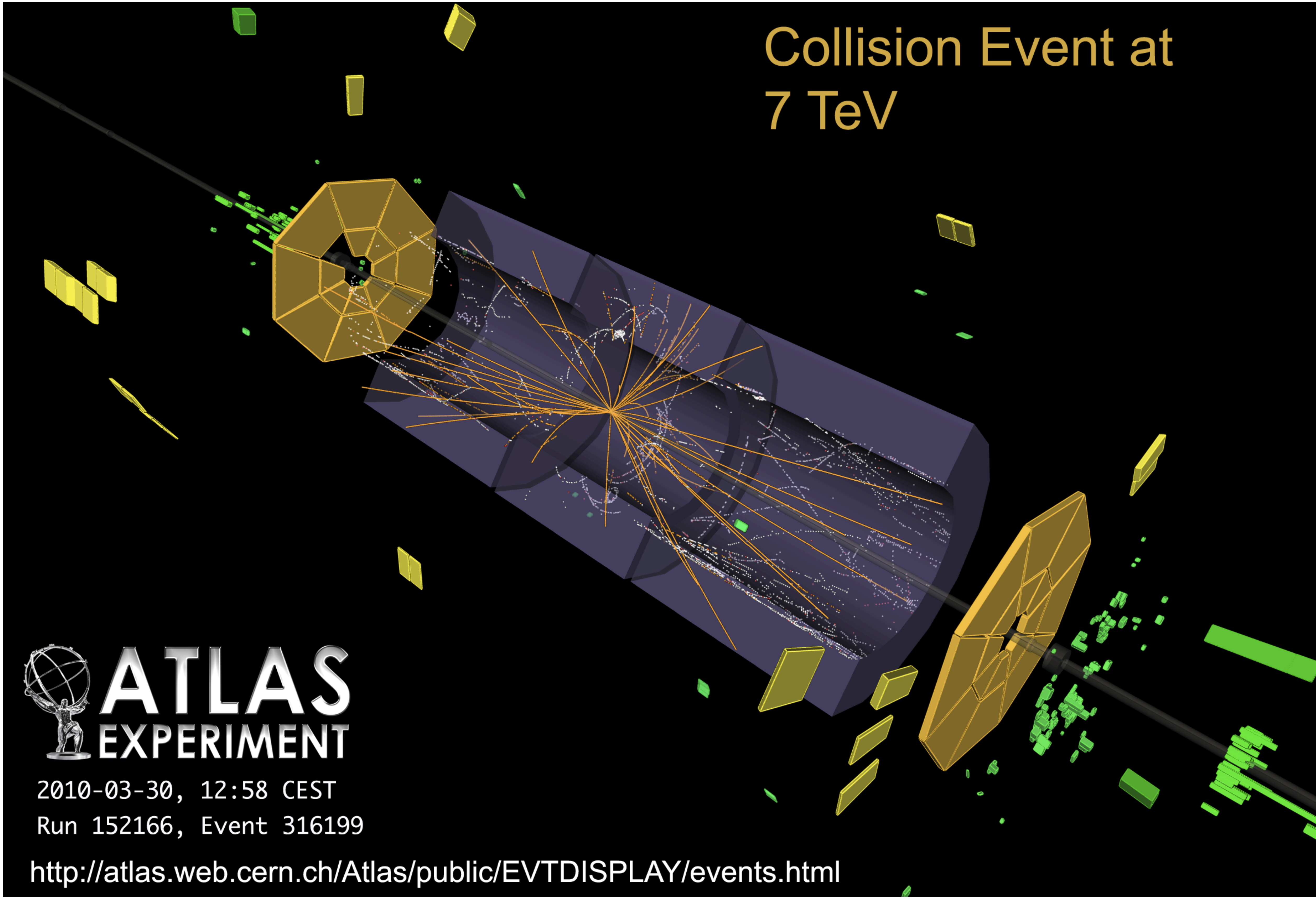


Each subsystem aims at detecting a certain group of particles:

- Electrons (e+): a track in the Inne Detector and a cluster in the EM calorimeter
- Photons (ɣ): only a cluster in the EM calorimeter
- Muons (μ+): a track in the Inne Detector and a track in the Muon System

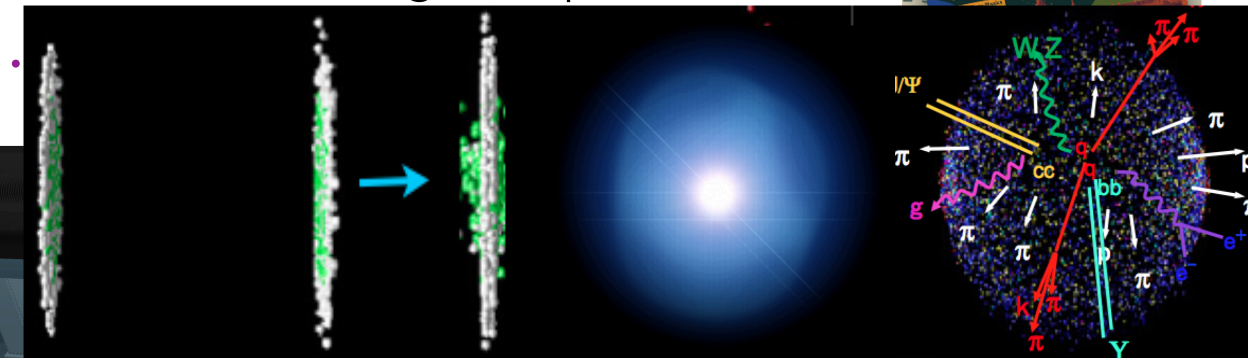
11 YEARS OF PHYSICS AT THE LHC IN 2021

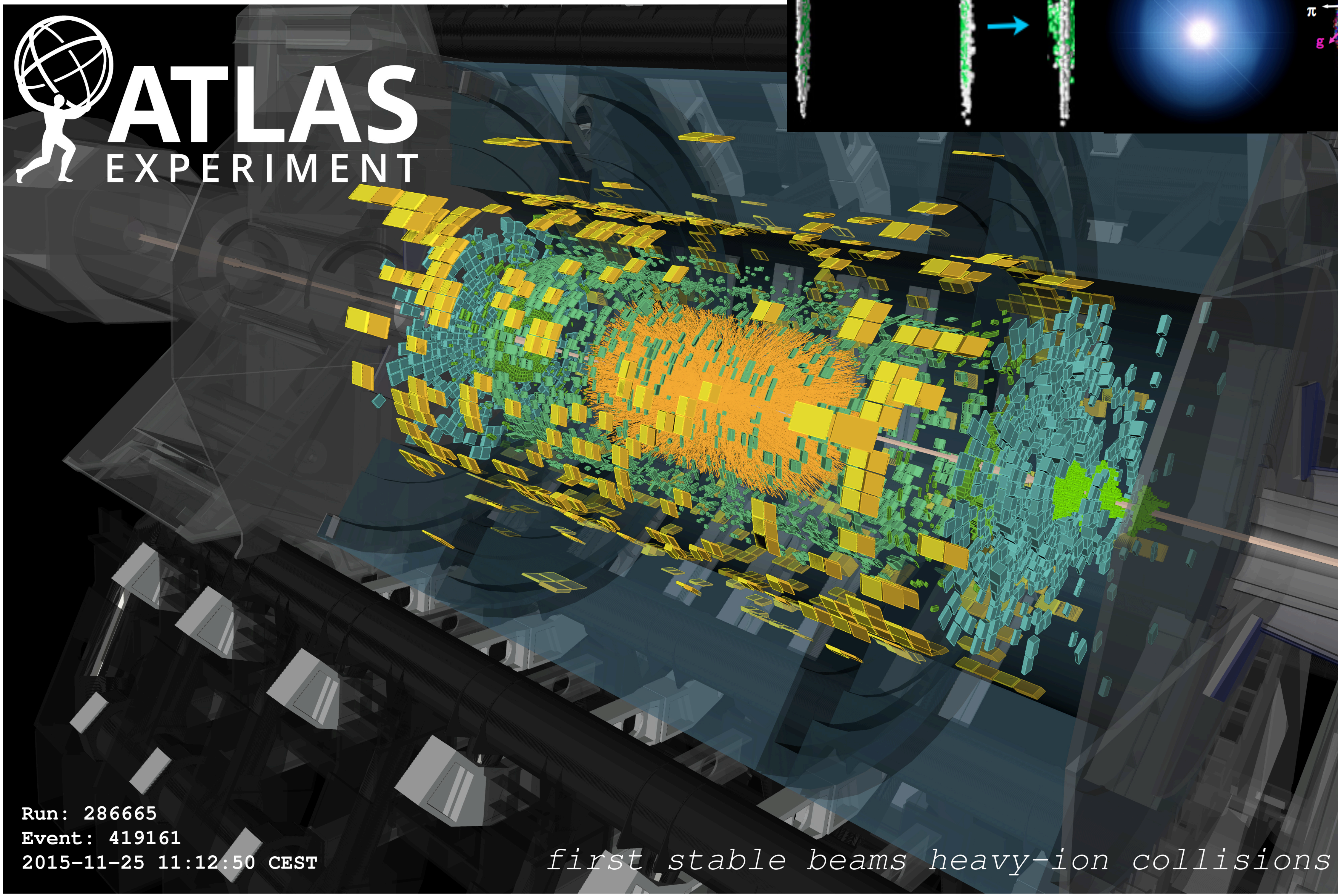
FIRST PROTON-PROTON COLLISIONS IN 2010



LEAD-LEAD COLLISIONS

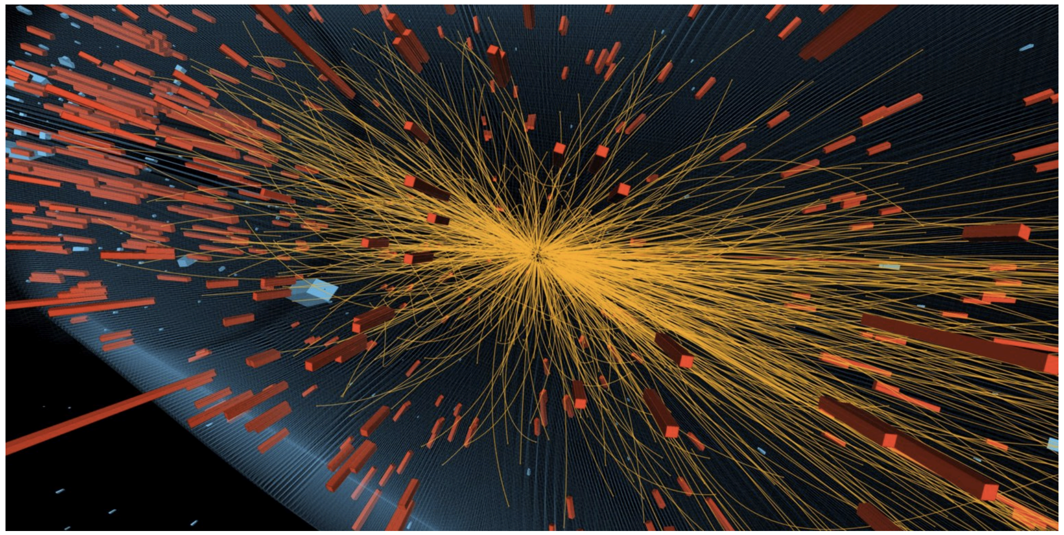
Droplet of quark-gluon plasma





- A lot of activity in the entire detector
- Challenge to reconstruct and identify particles in the collision
- **Group of scientists from the AGH UST is working on physics of heavy-ion collisions**

NEEDLE IN THE HAYSTACK

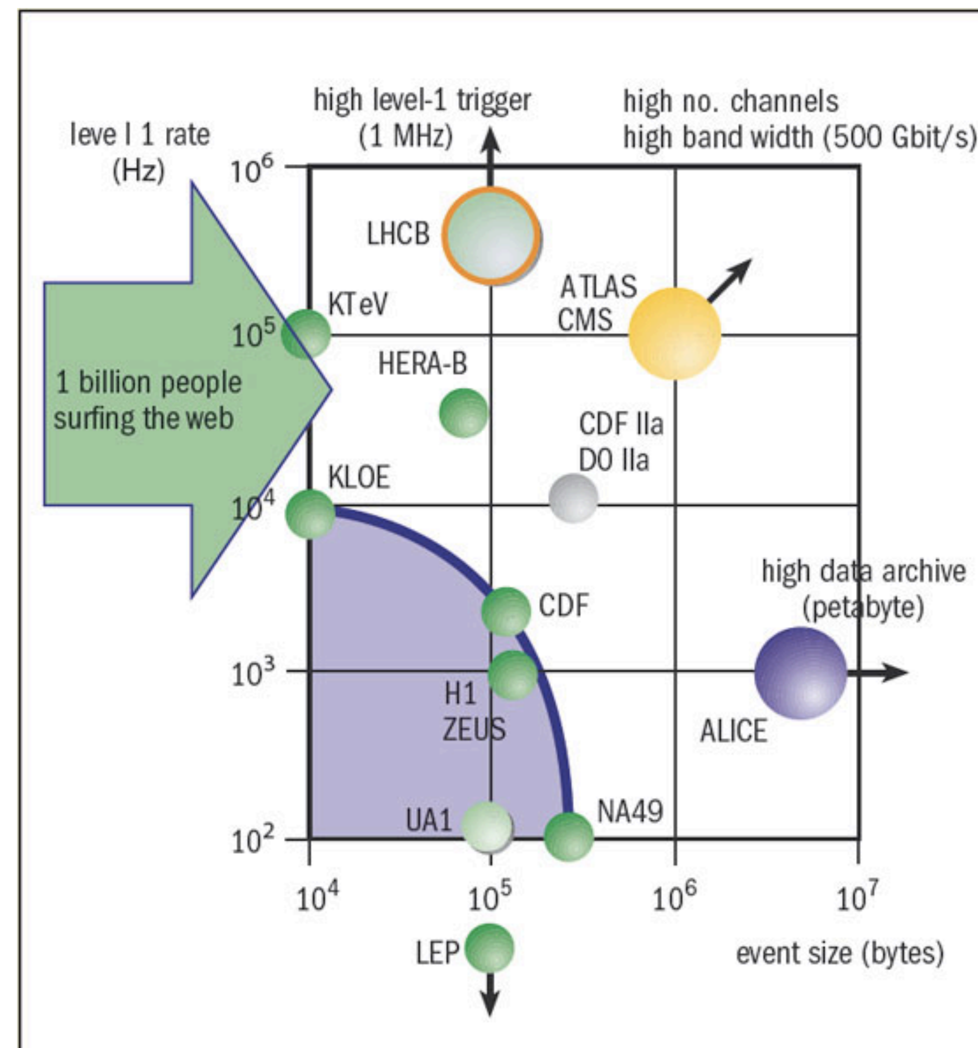


Bunch-crossing rate **40×10^6 Hz**

Proton-proton interactions **10^9 Hz**

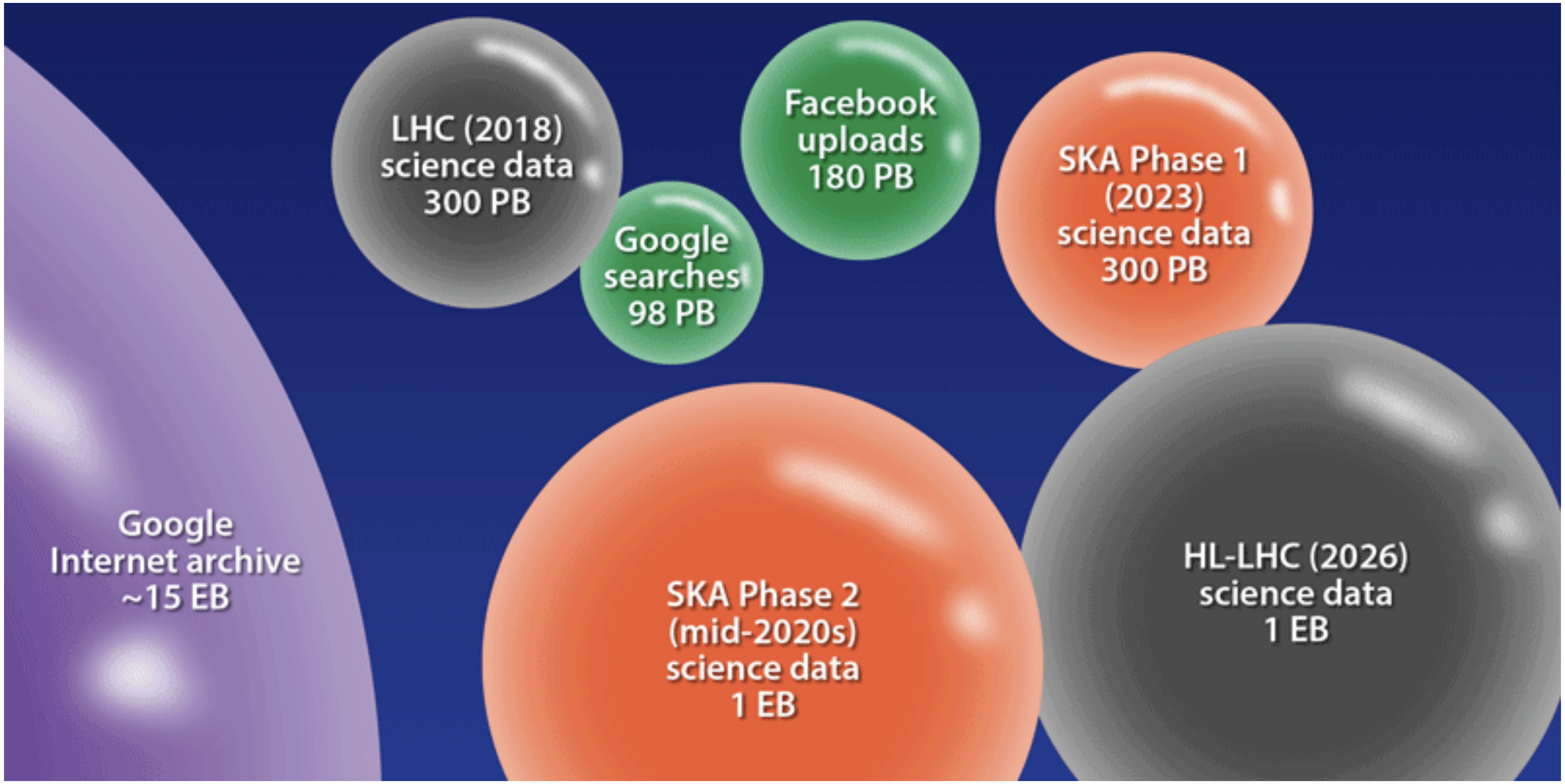
Expected production of new particles **10^{-5} Hz**

Selection of 1 collision out of 10 000 000 000 000



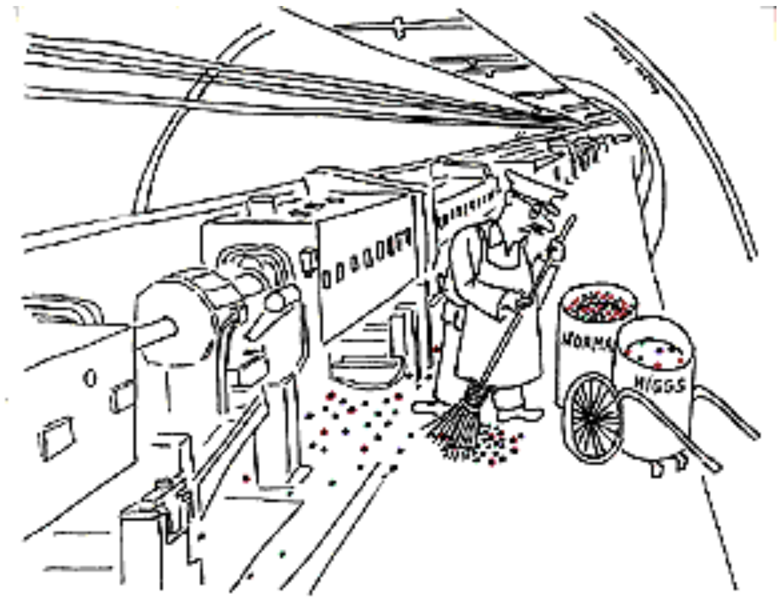
- ➤ Collisions need to be filtered out in real time: trigger system (TDAQ)
- ➤ Team from AGH UST is part of the TDAQ project of ATLAS

BIG DATA SCIENCE

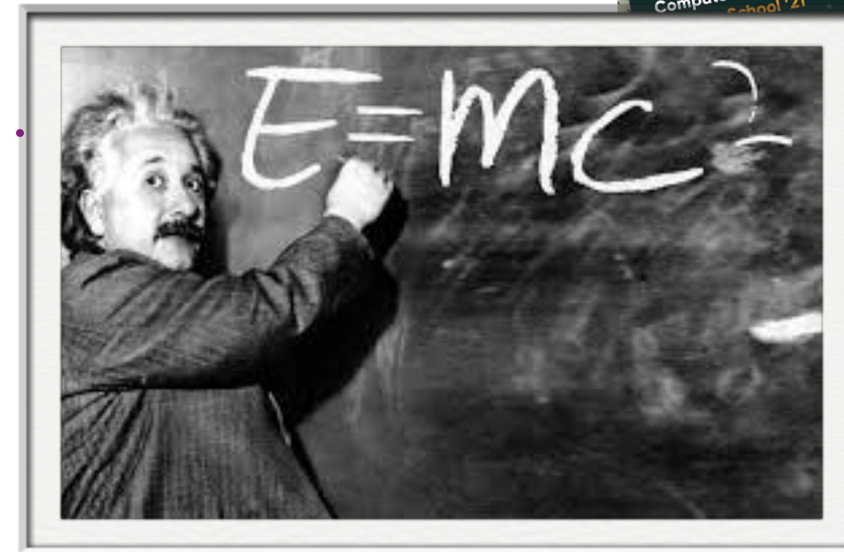


- Comparison of the yearly data volumes of current and future projects, where PB stands for petabyte (10^{15} bytes) and EB stands for exabyte (10^{18} bytes)

II. PHYSICS AT ATLAS



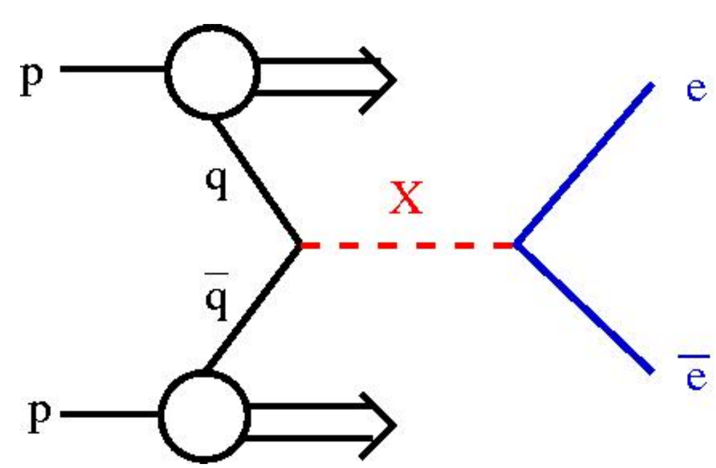
GENERAL PRINCIPLE



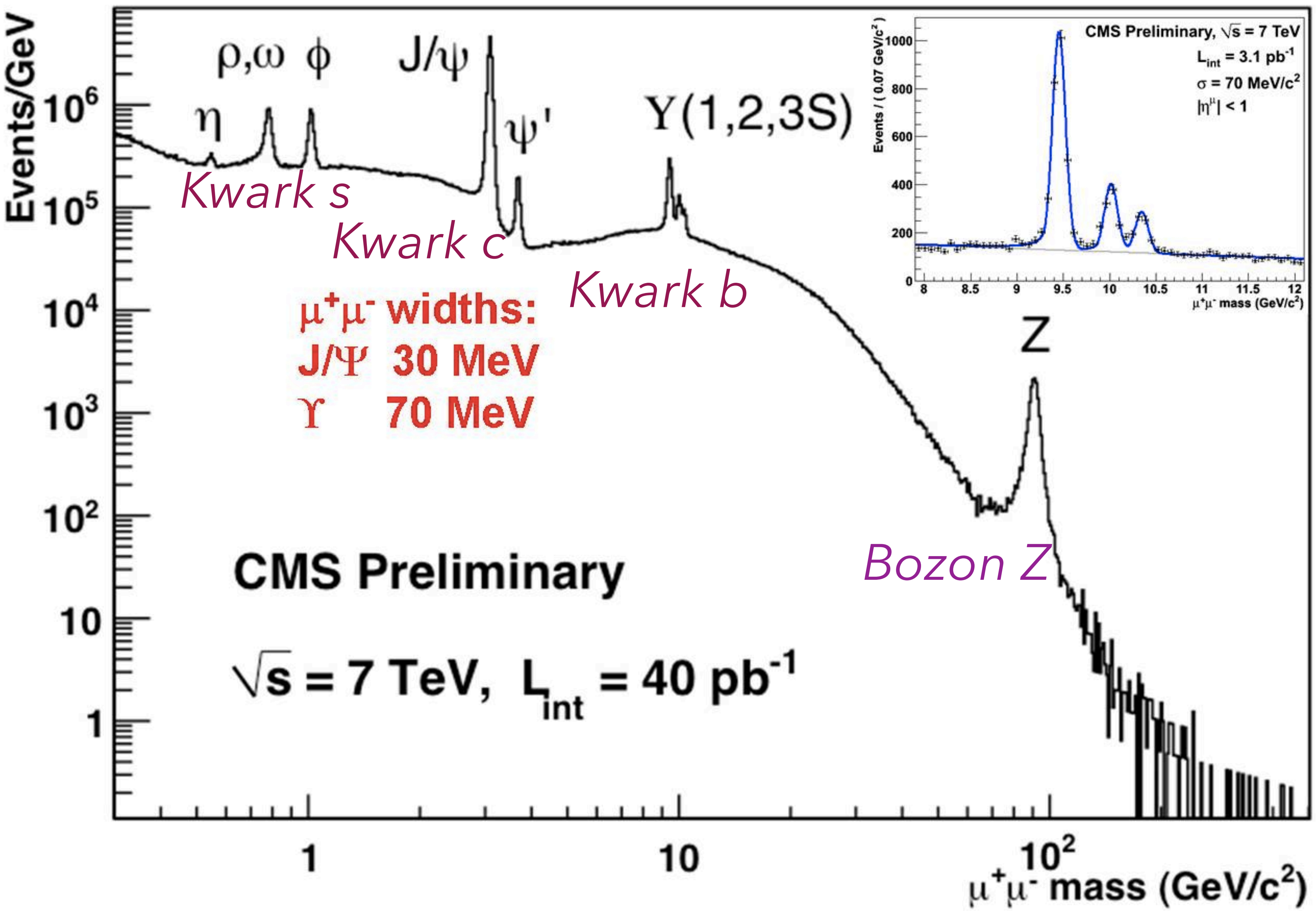
- Energy and mass are equivalent

$$E = mc^2$$

  - where E - energy, m - mass, c - speed of light
- At the LHC proton beams are collided with energy of 6.5 TeV each
  - Total collision energy: **13 TeV**
  - Production of particles with mass $m_X < 13$ TeV is possible
    - In practice quark and gluons may interact which carry part of proton's energy
    - Most of produced particles is **short lived** (<< 1s), **they decay** and one can observe them indirectly via decay products



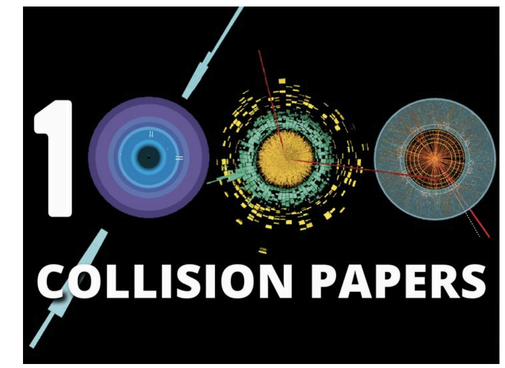
DISCOVERY OF NEW PARTICLES IN EXPERIMENTS

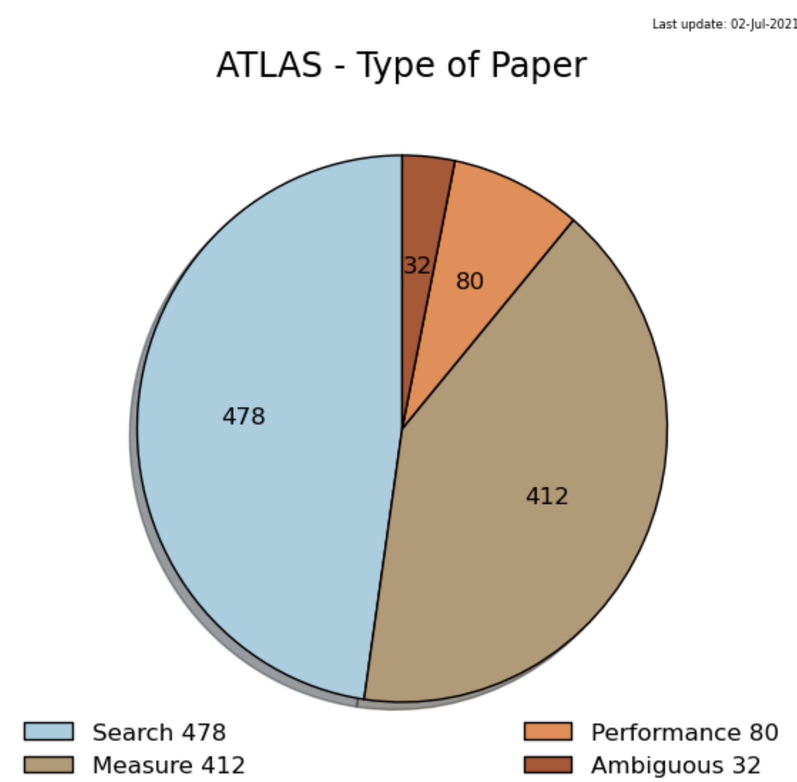


- Physicists can explore quarks and other elementary particles
- Search for peaks in the mass spectrum

DATA ANALYSIS IN ATLAS

- Data analysis is organised in 8 physics groups:
  - Standard Model
  - B Physics & Light States
  - Top: the heaviest elementary particle
  - Higgs: discovered in 2012 at the LHC: 1st example
  - Heavy Ions: 2nd example
  - Higgs and Diboson Searches
  - Exotics: 3rd example
  - Supersymmetry

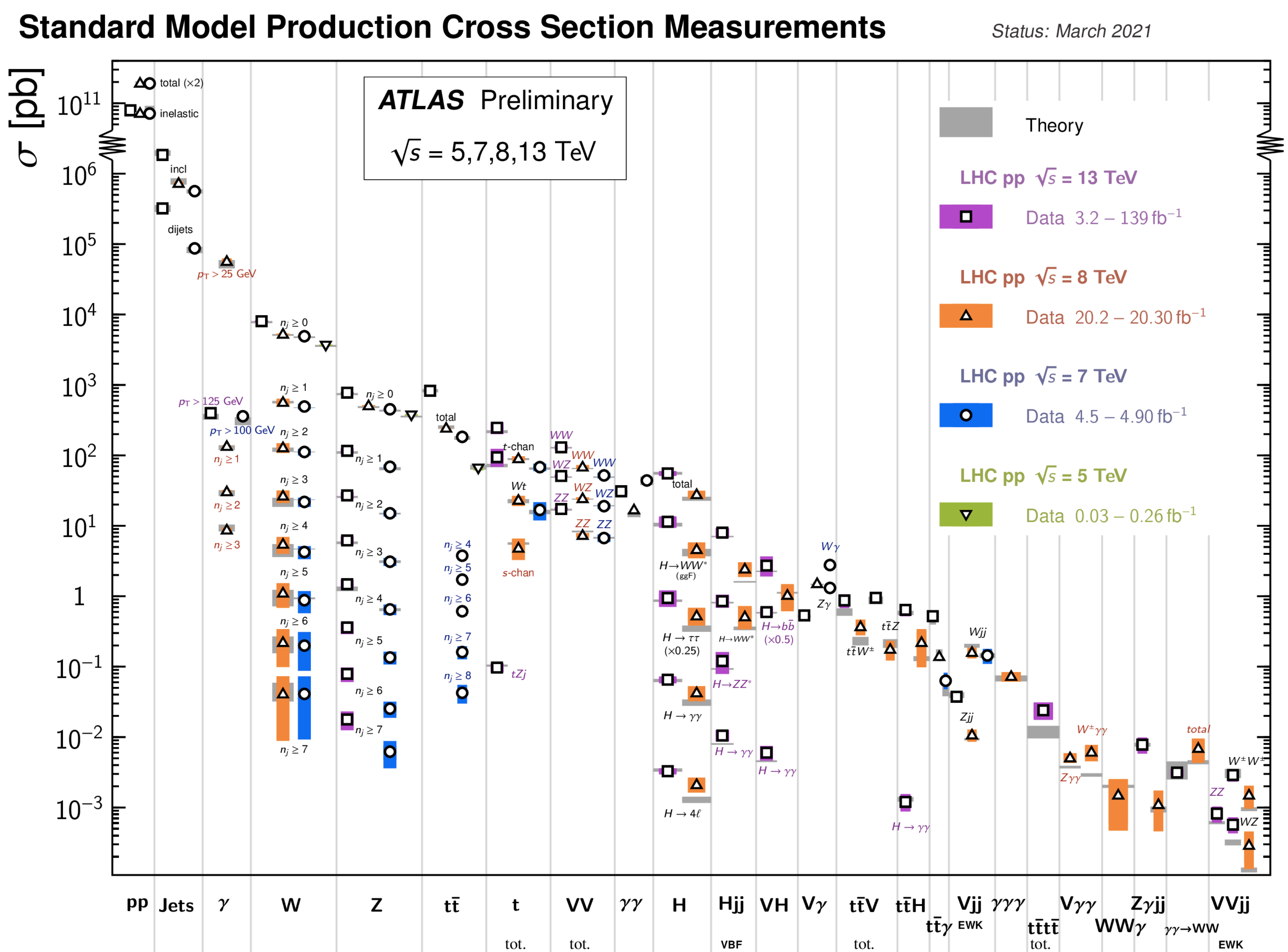




  - 1 002 scientific publications

Read more: https://atlas.cern/updates/news/1000-collision-papers

STANDARD MODEL AS OF TODAY



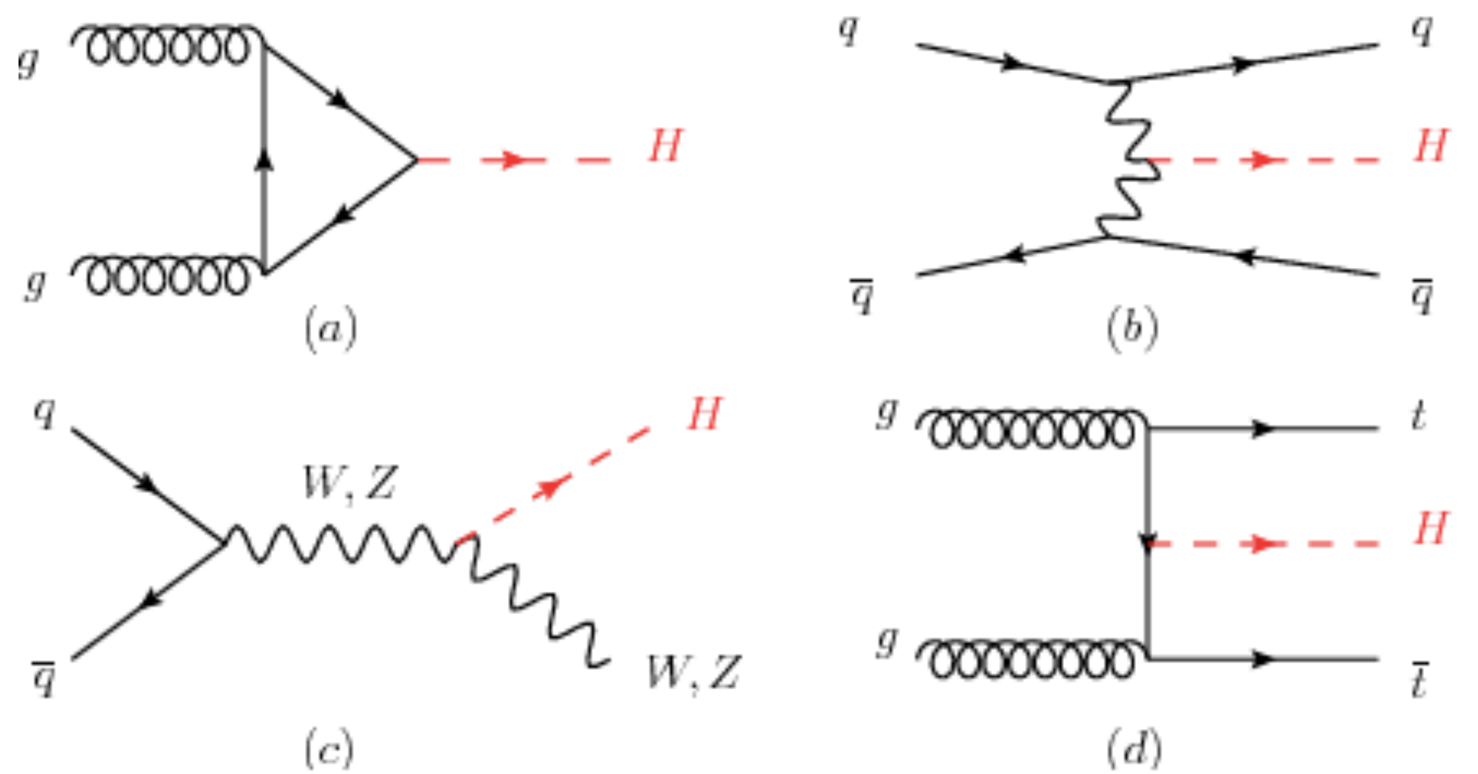
- ➤ Particle production at energies of **5, 7, 8 and 13 TeV**
- ➤ Measurements cover 14-15 orders of magnitude
- ➤ Fantastic agreement with Standard Model predictions
- ➤ Measurements of W and Z bosons at 5 TeV were done at the AGH UST

IIA. HIGGS BOSON

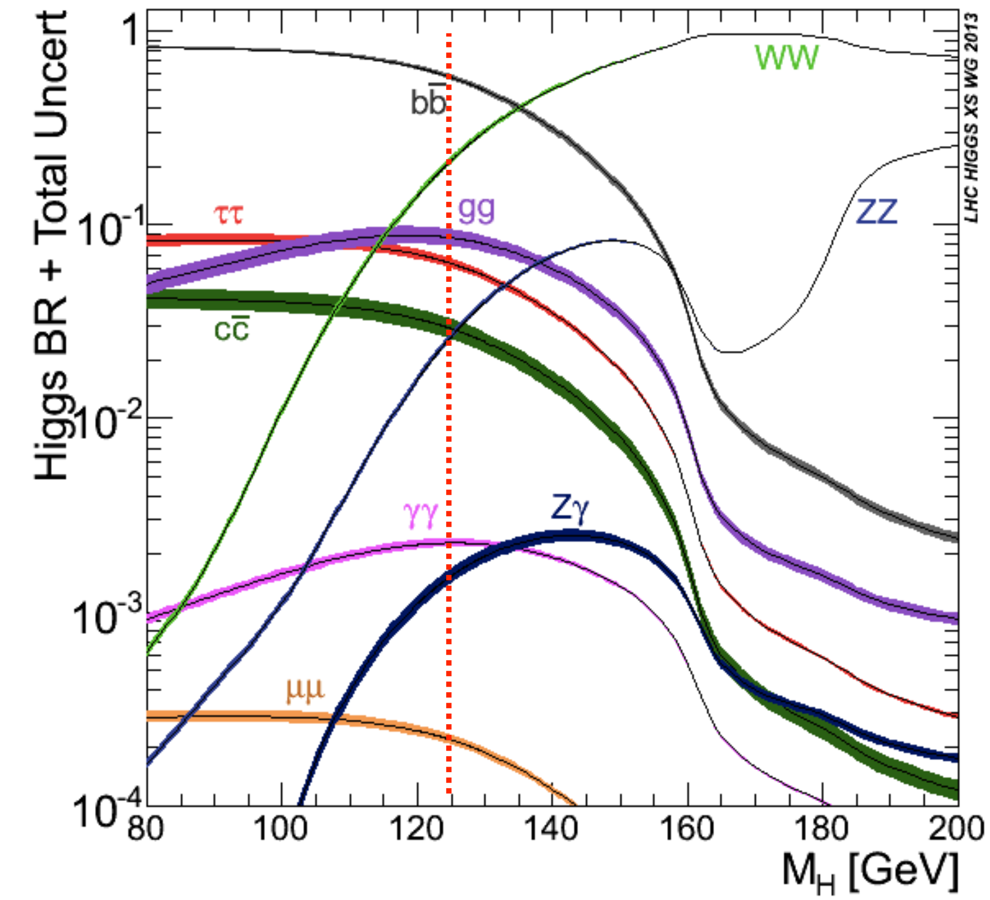
“I think I’ve found the Higgs boson!”

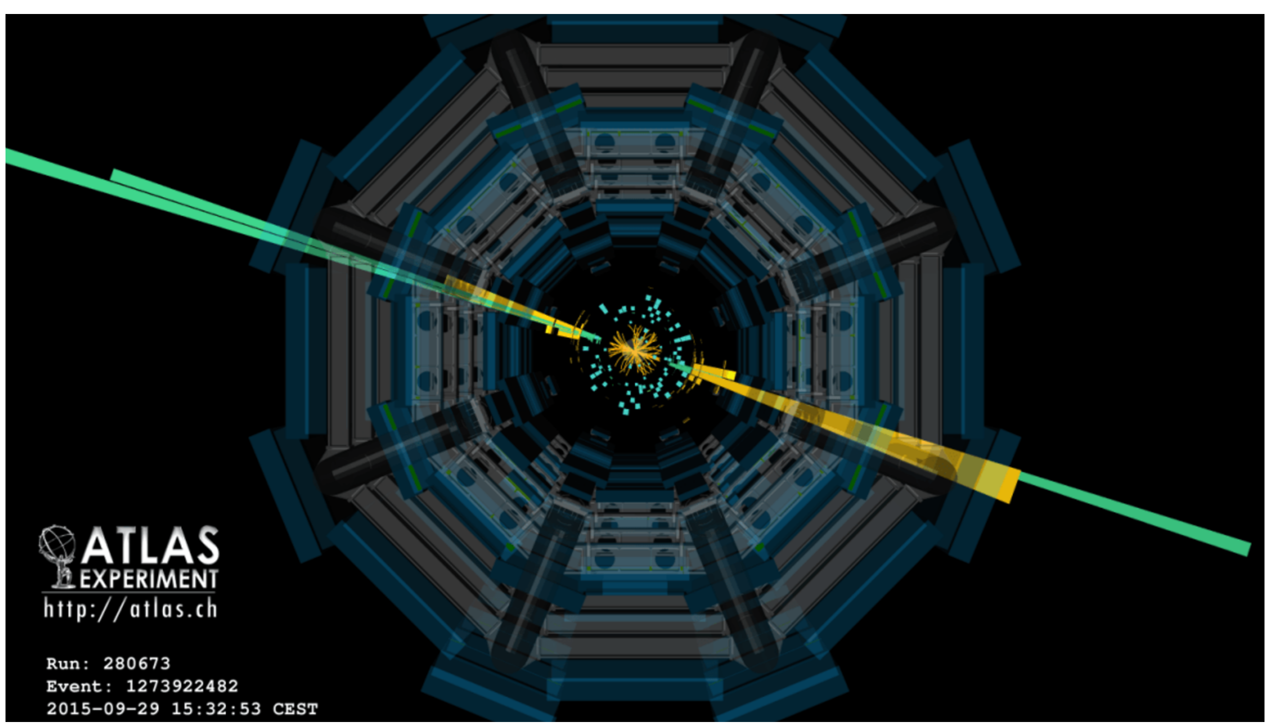
HIGGS PRODUCTION AND DECAY

gluon-gluon fusion vector-boson fusion



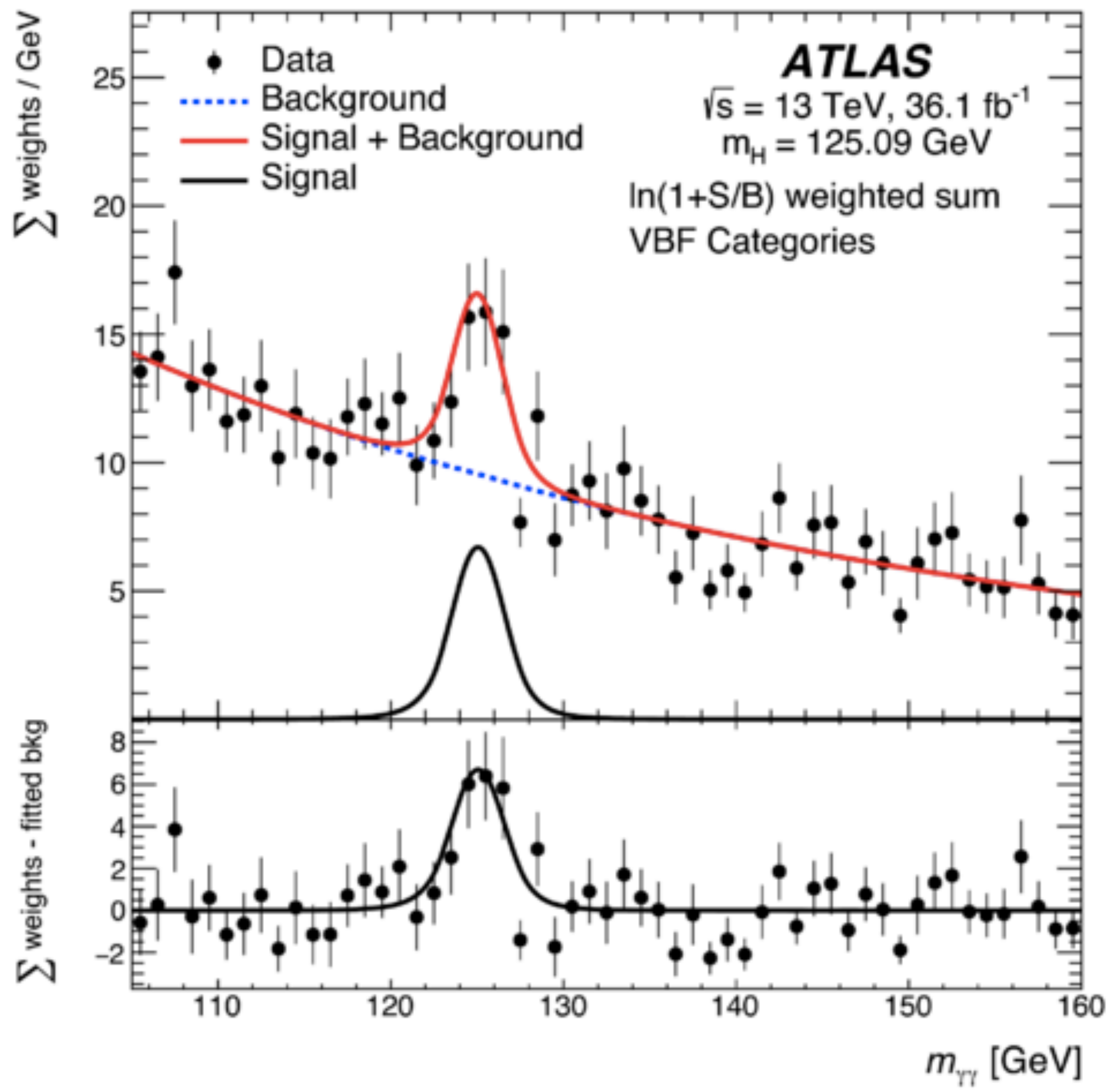
Higgs strahlung in association with $q\bar{q}$

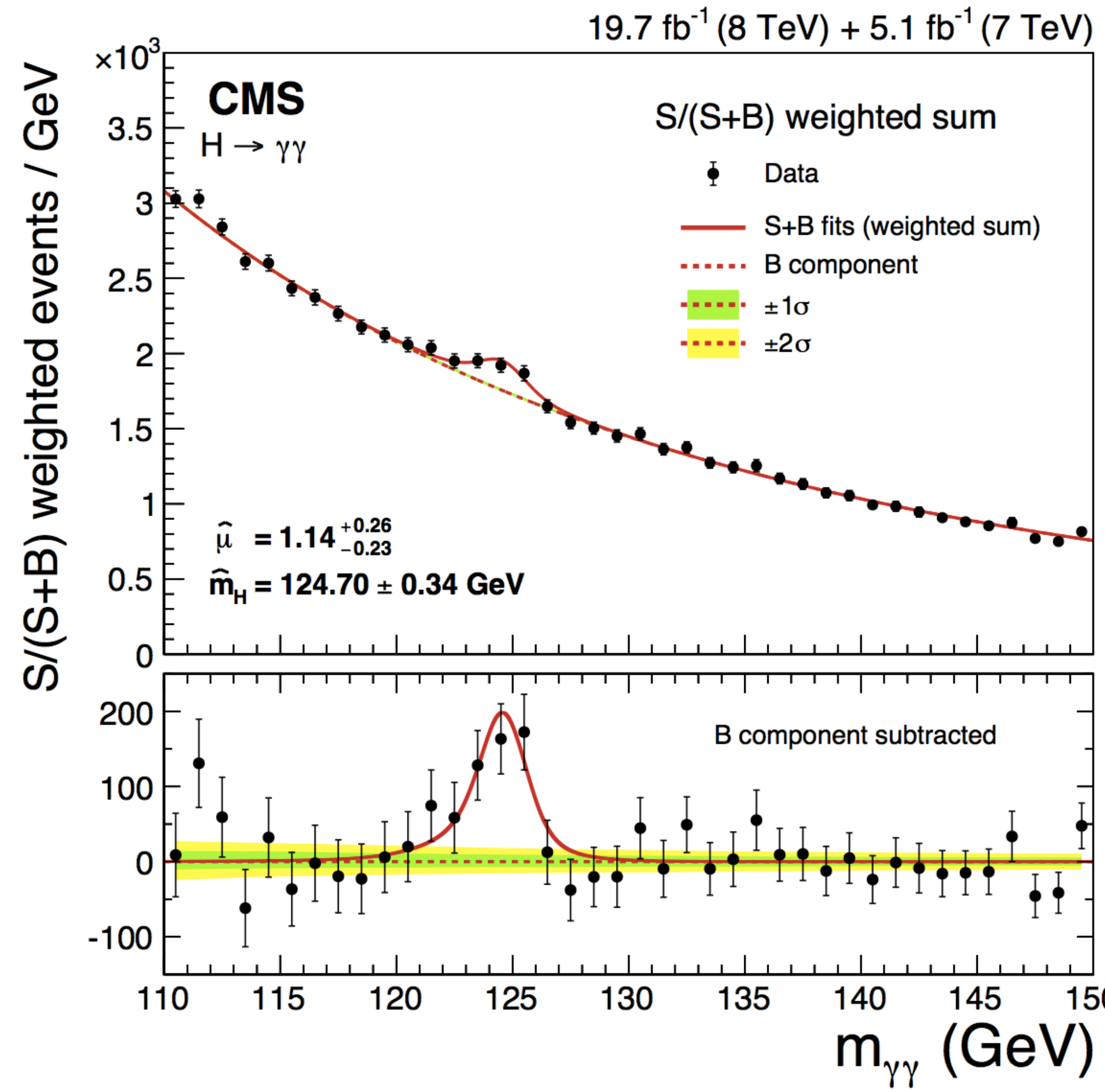




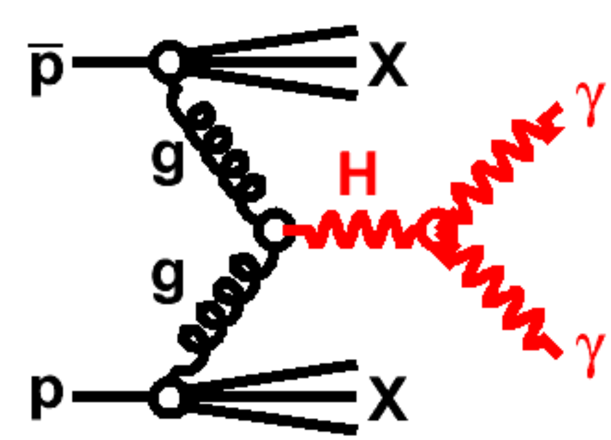
- Higgs boson is an unstable particle which decays shortly after it is produced
  - **0.2% in two photon channel**
  - 0.014% in 4 electrons or muons
  - 99.8% decays are very difficult to measure

HIGGS BOSON

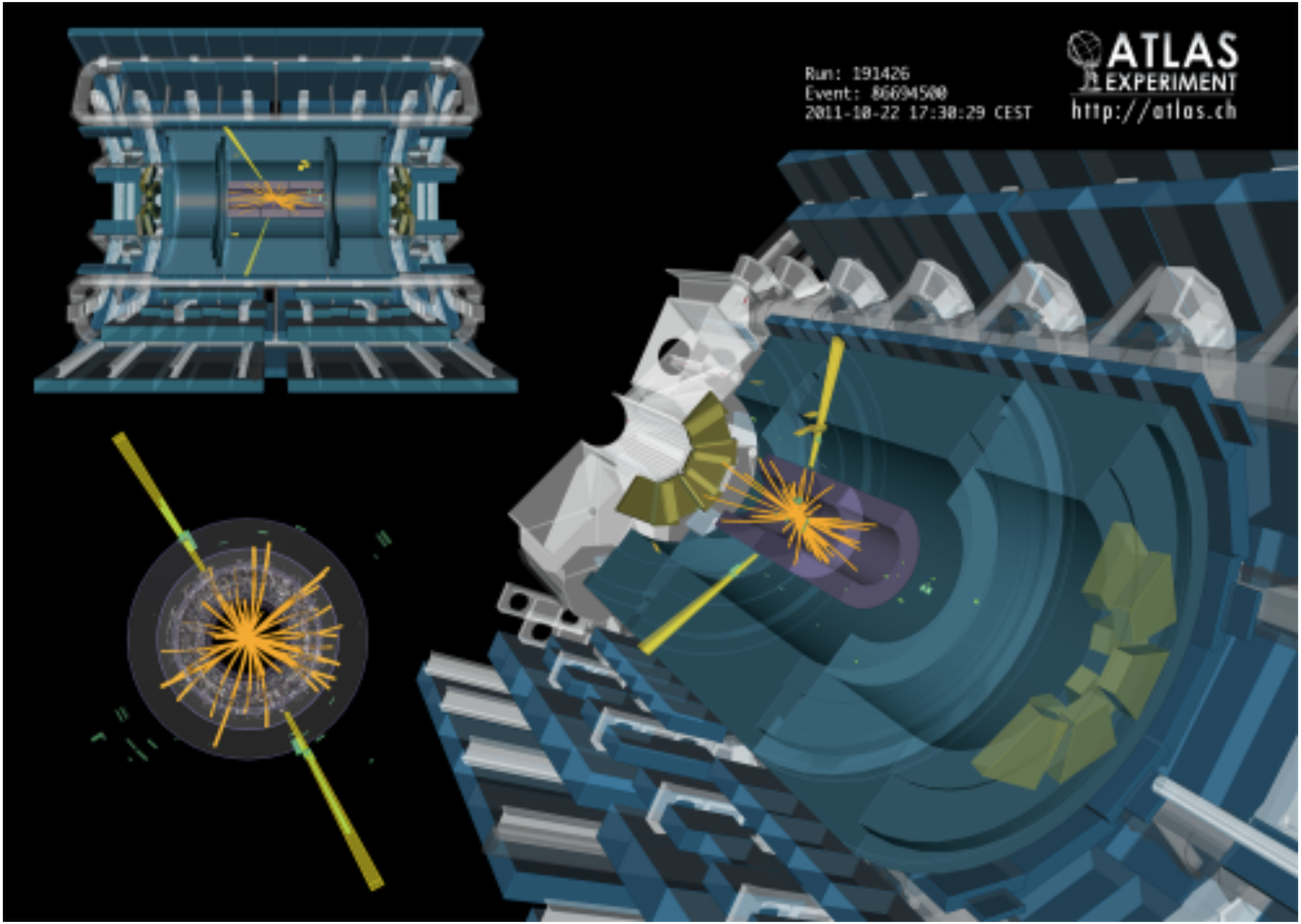




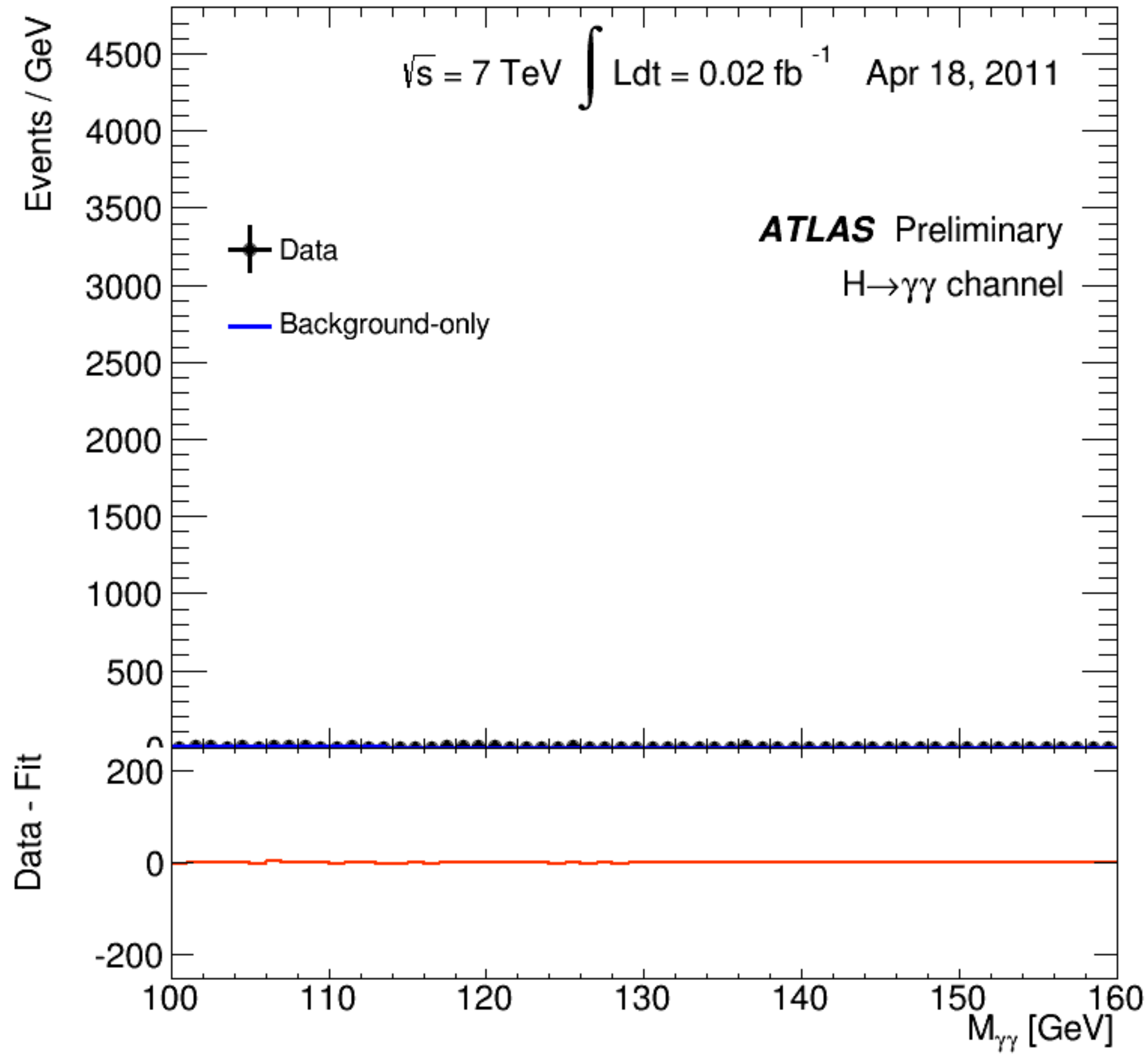
- Two independent experiments (ATLAS and CMS) see a peak in the mass of two-photon system distribution at 125 GeV



EVENT CANDIDATE WITH THE HIGGS BOSON



MANY COLLISIONS NEEDED: DATA FROM 2011–2012



- A number of collected events has been growing with time since 2011
- Events added in 2012 made a difference
  - Peak in the mass distribution originating from Higgs boson gradually became visible
  - Conclusion: data taking is a long, long process

HIGGS BOSON DISCOVERY

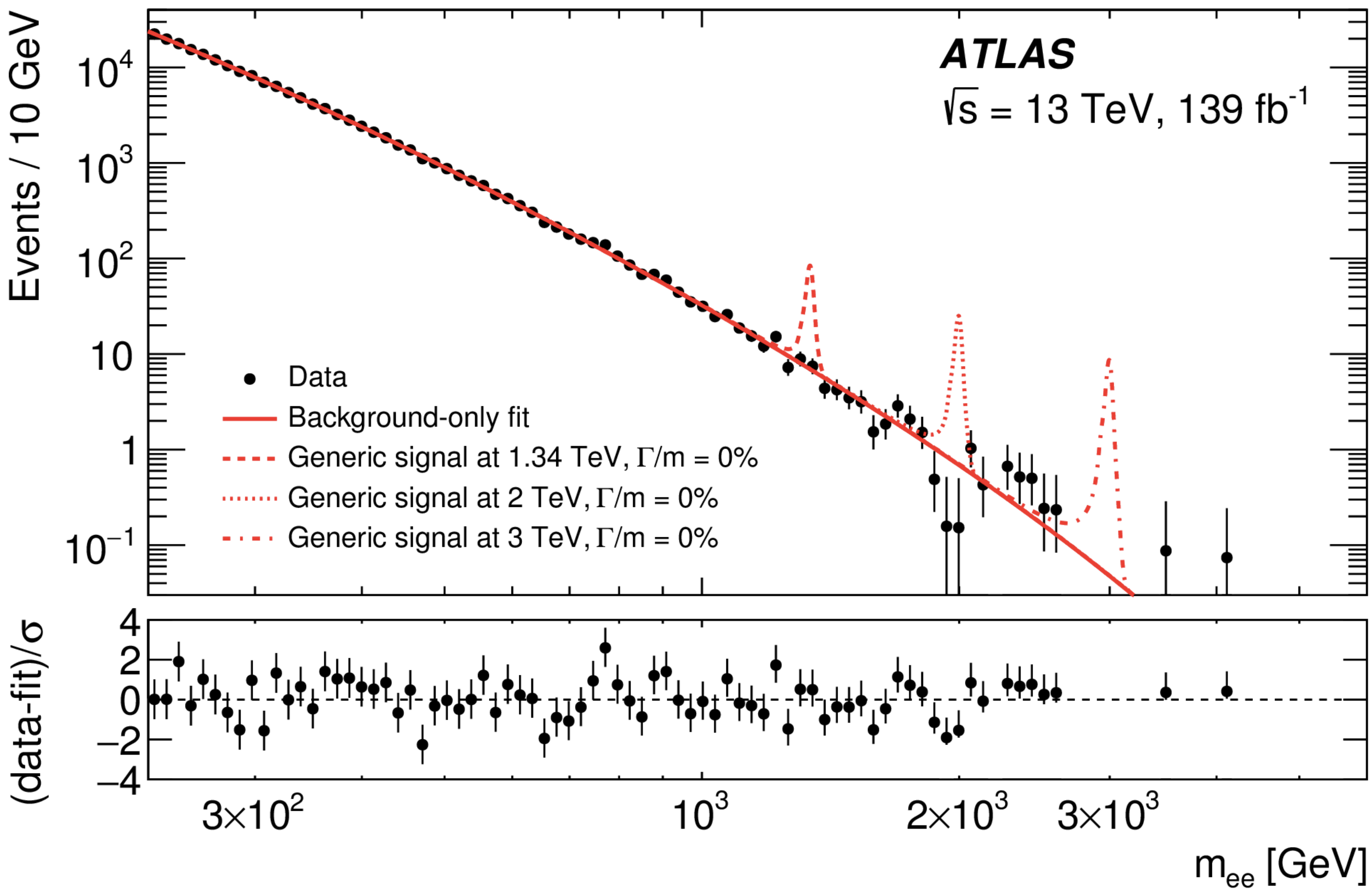
Fabiola Gianotti

(ATLAS spokesperson in 2012)

Peter Higgs

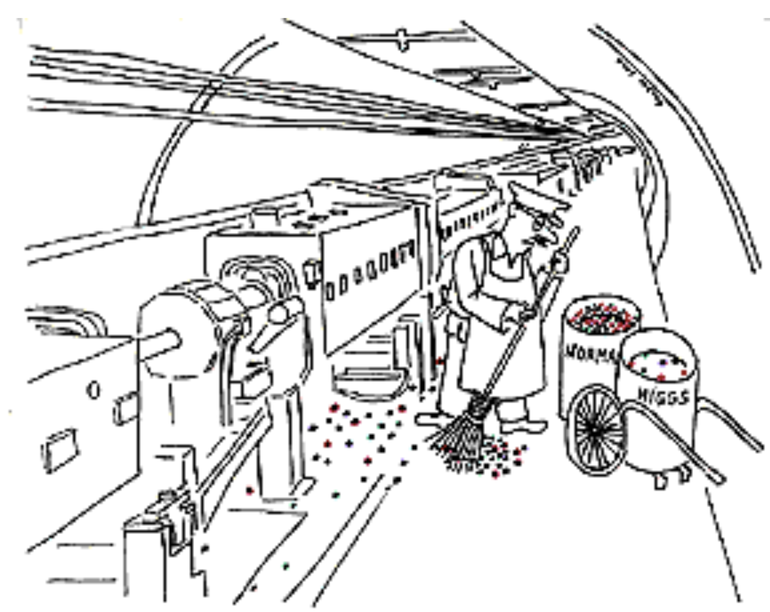
- Year **1964**: theoretic concepts for the Higgs boson
  - Solves the origin of mass in Standard Model
- Year **1992**: ATLAS (and CMS) collaborations started their work on experiments
- Year **2012**: discovery of the Higgs boson (**July 4th:** 9th anniversary yesterday)
- Year **2013**: Noble Prize for Peter Higgs and Francois Englert "*for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider*"

BUT WHAT ABOUT NEW PHYSICS?

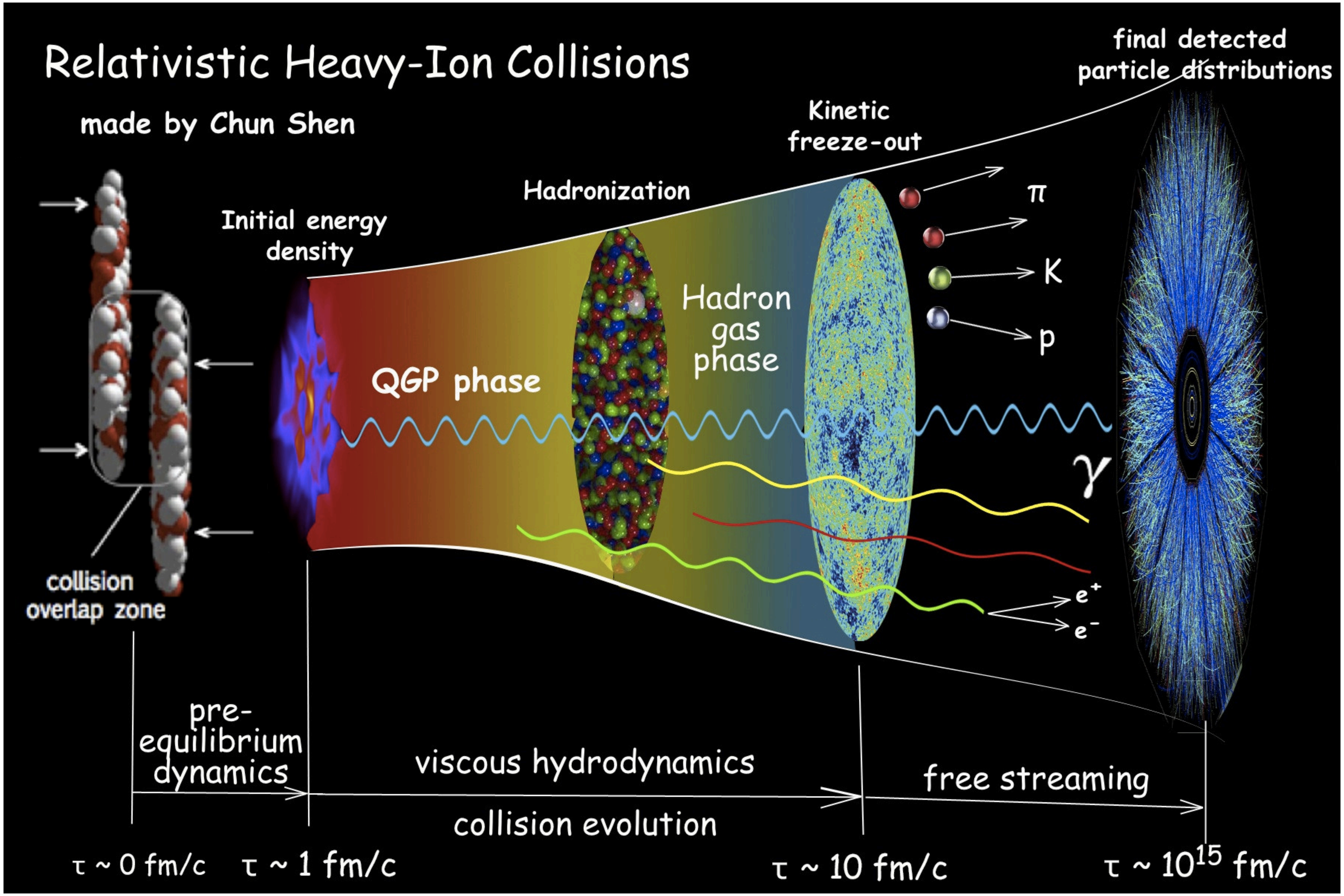


- Mass distribution for e^+e^- pairs for proton-proton collisions collected in years 2010-2018
  - **No deviation** from **Standard Model** is observed

IIB. HEAVY-ION PHYSICS

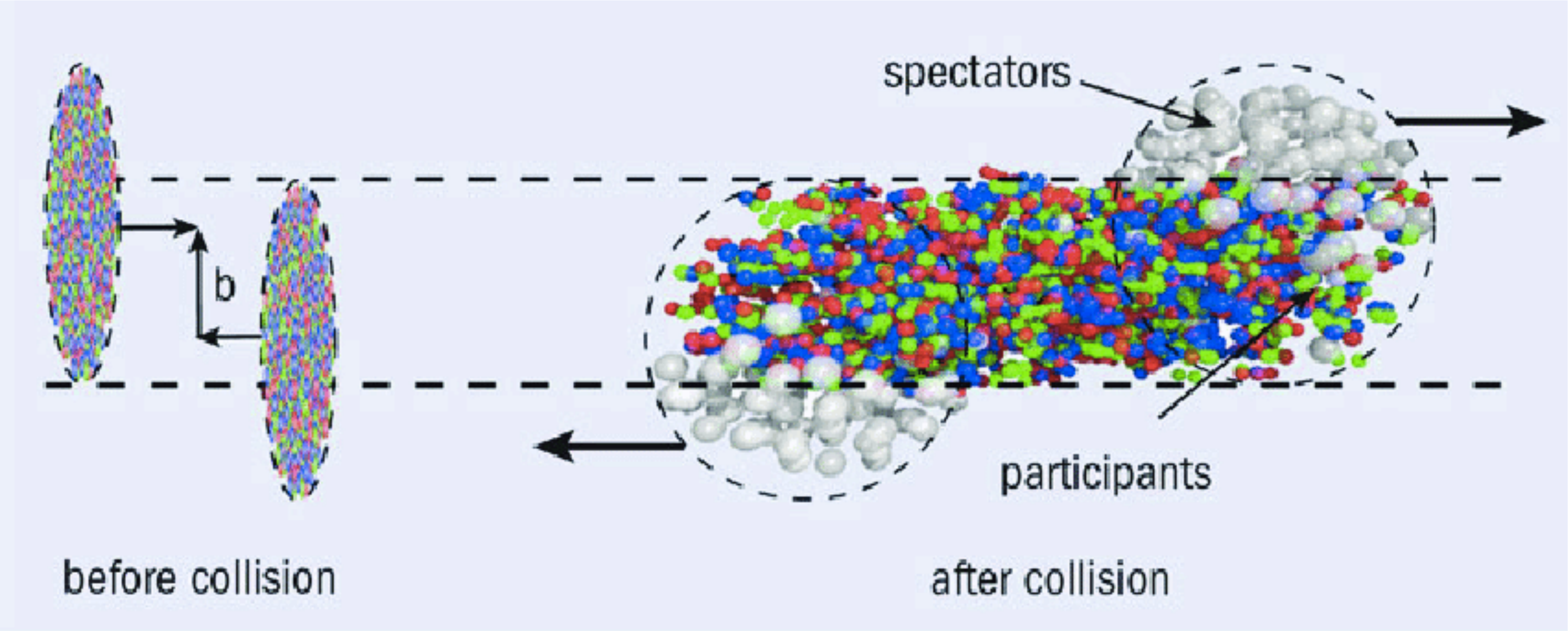


HEAVY-ION PHYSICS IN A NUTSHELL



- New state of matter called **Quark-Gluon Plasma** (QGP) is produced in heavy-ion collisions: quark and gluons are deconfined
  - QGP existed shortly after **Big Bang**
- Its properties can be measured based on final detected particle distributions

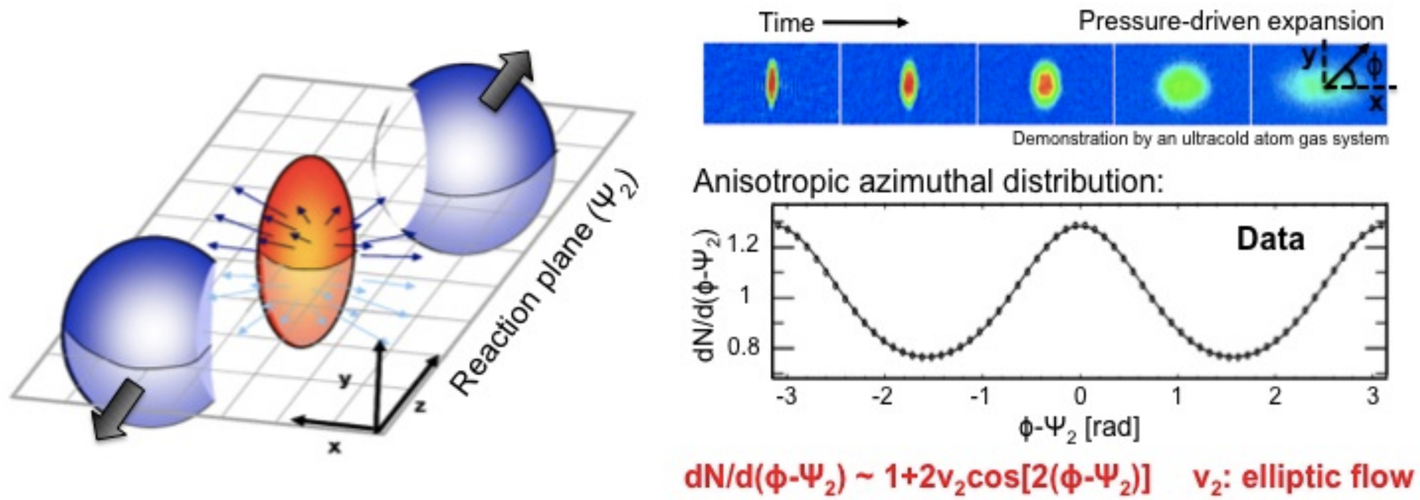
NUCLEUS-NUCLEUS COLLISIONS



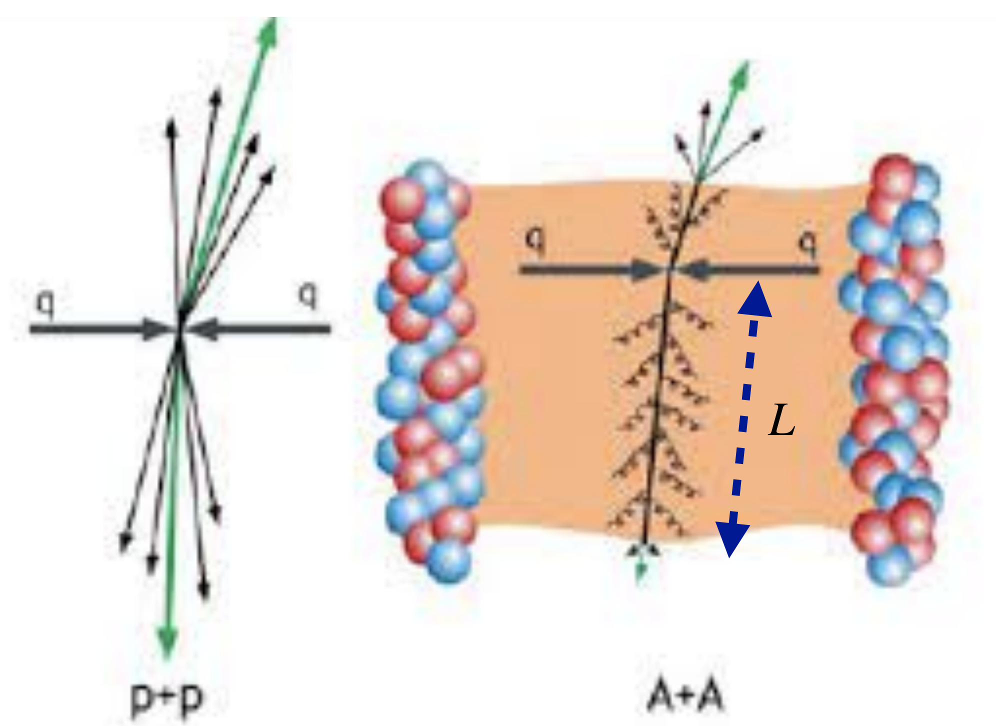
- To first order, a heavy-ion collision is just O(A) p+p collisions at the same time but huge variations event-to-event
- **Impact parameter b**
  - **Small b** - **central** collisions, **large b** - **peripheral** collisions
  - Cannot be measured directly
  - Use a proxy and a model to get access to information on participants, $N_{\rm part}$ and collisions, $N_{\rm coll}$
- As centrality grows QGP is likely to be produced

SIGNATURES OF QGP

- **Collective phenomena**
  - Initial spatial anisotropy is converted to momentum anisotropy of final-state particles



- **Jet quenching**
  - Energy loss of high-p_T patron due to the interactions with the QGP medium

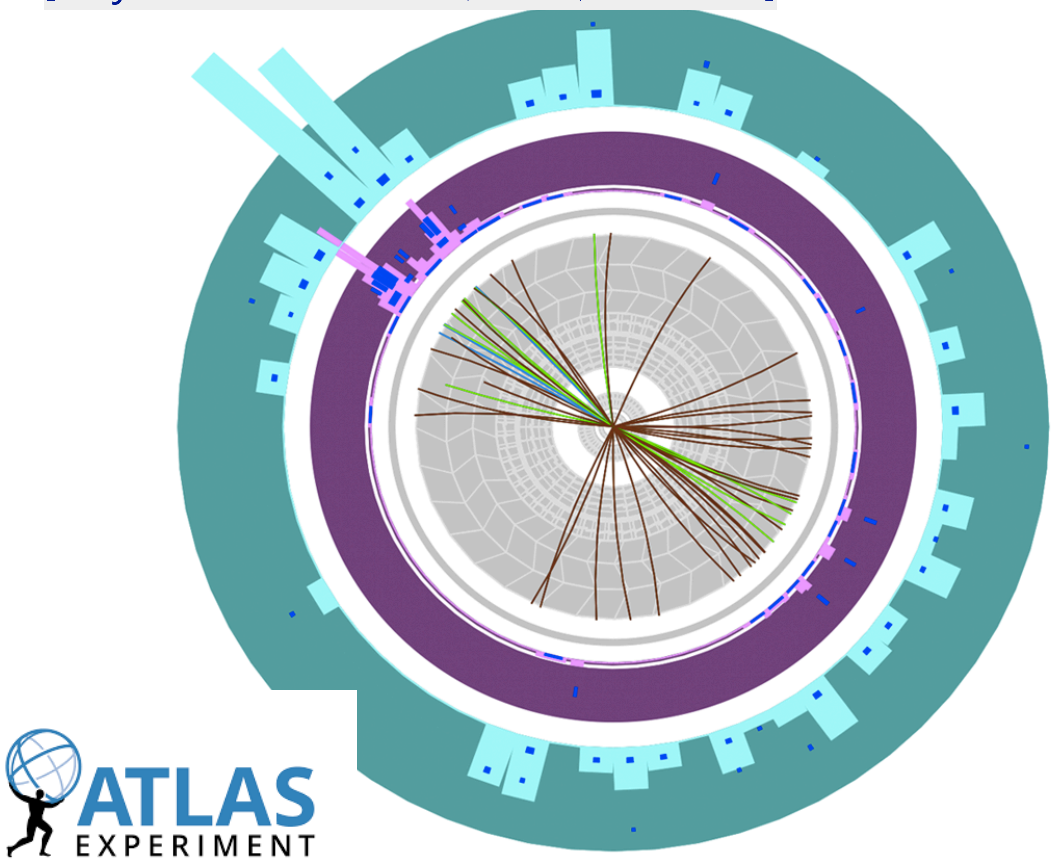


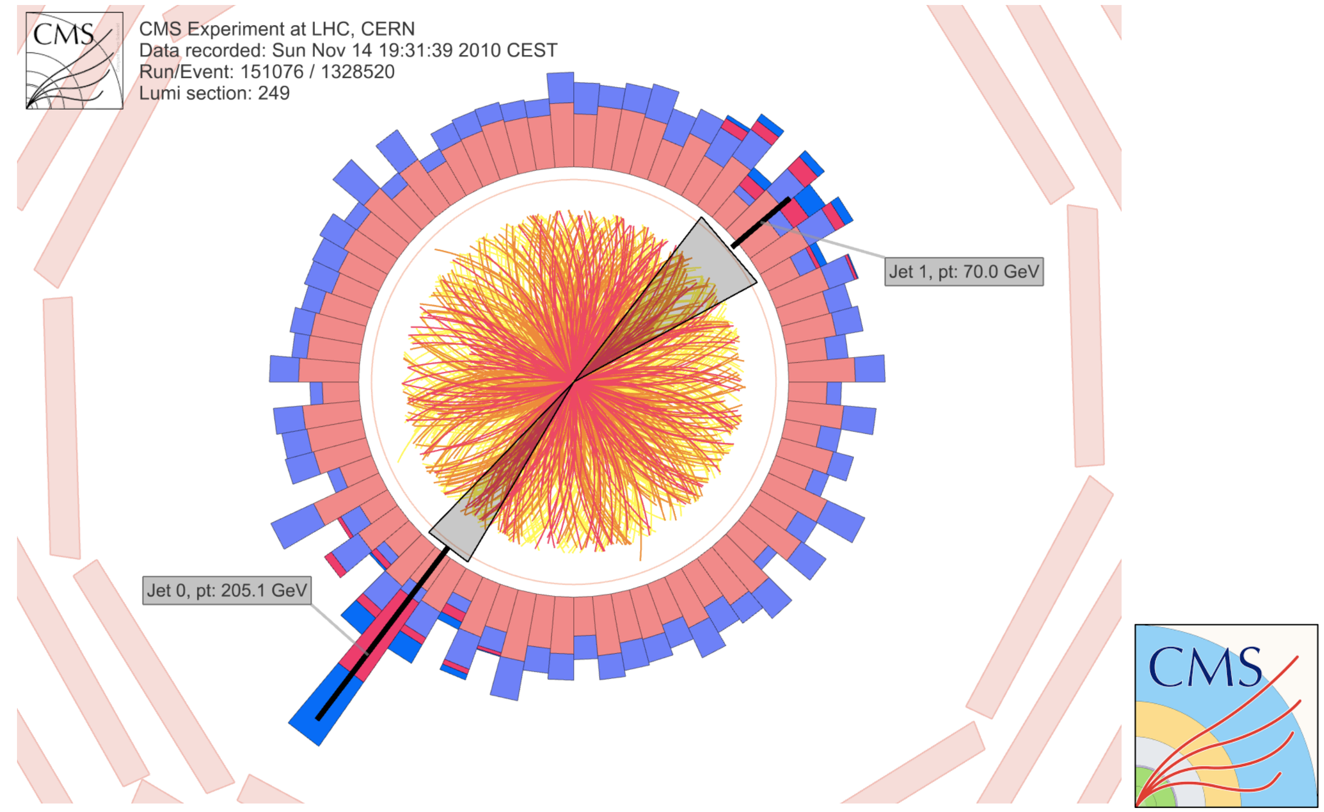
$$\langle \Delta E \rangle \sim \alpha_s C_R \hat{q} L^2$$

C_R (Casimir factor) = 4/3 for quarks
3 for gluons
$\hat{q}$ medium transport coefficient ~ gluon density and momenta
L path length

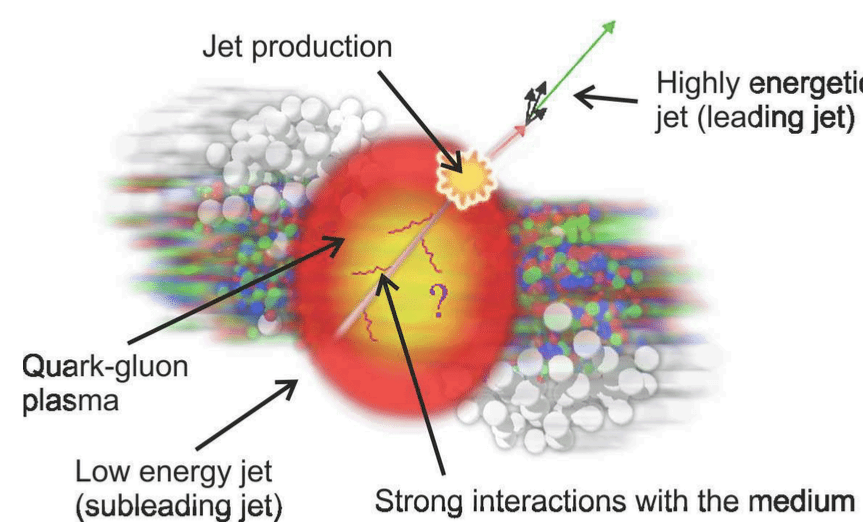
JET QUENCHING IN 2010

[Phys.Rev.Lett. 105 (2010) 252303]



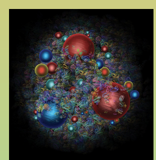
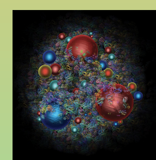


- Partons traversing the QGP are affected by the medium
- Most spectacular observable is a **dijet suppression**
  - **First direct** observation in the 2010 HI run
  - Phenomenon of **jet quenching**: suppression of jets in the hot and dense QGP



COLLISIONS IN RUN 1 AND RUN 2

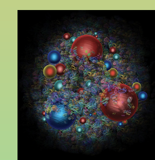
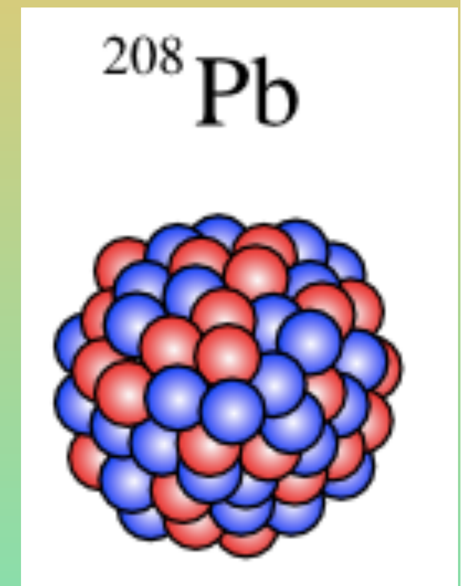
proton-proton

900 GeV (2009)
2.76 TeV (2013)
7 TeV (2010-11)
8 TeV (2012)

5.02 TeV (2015)
13 TeV (2015-18)
5.02 TeV (2017)

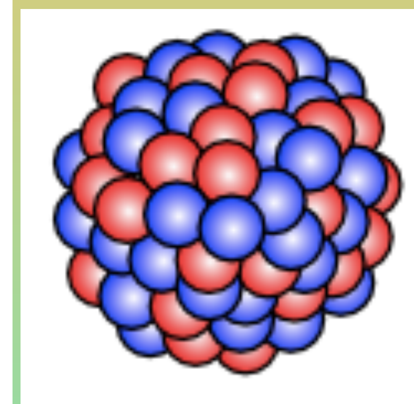
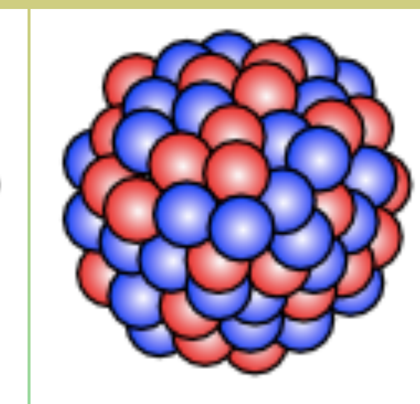
proton-lead

5.02 TeV (2012-13)

5.02 TeV (2016)
8.16 TeV (2016)

lead-lead

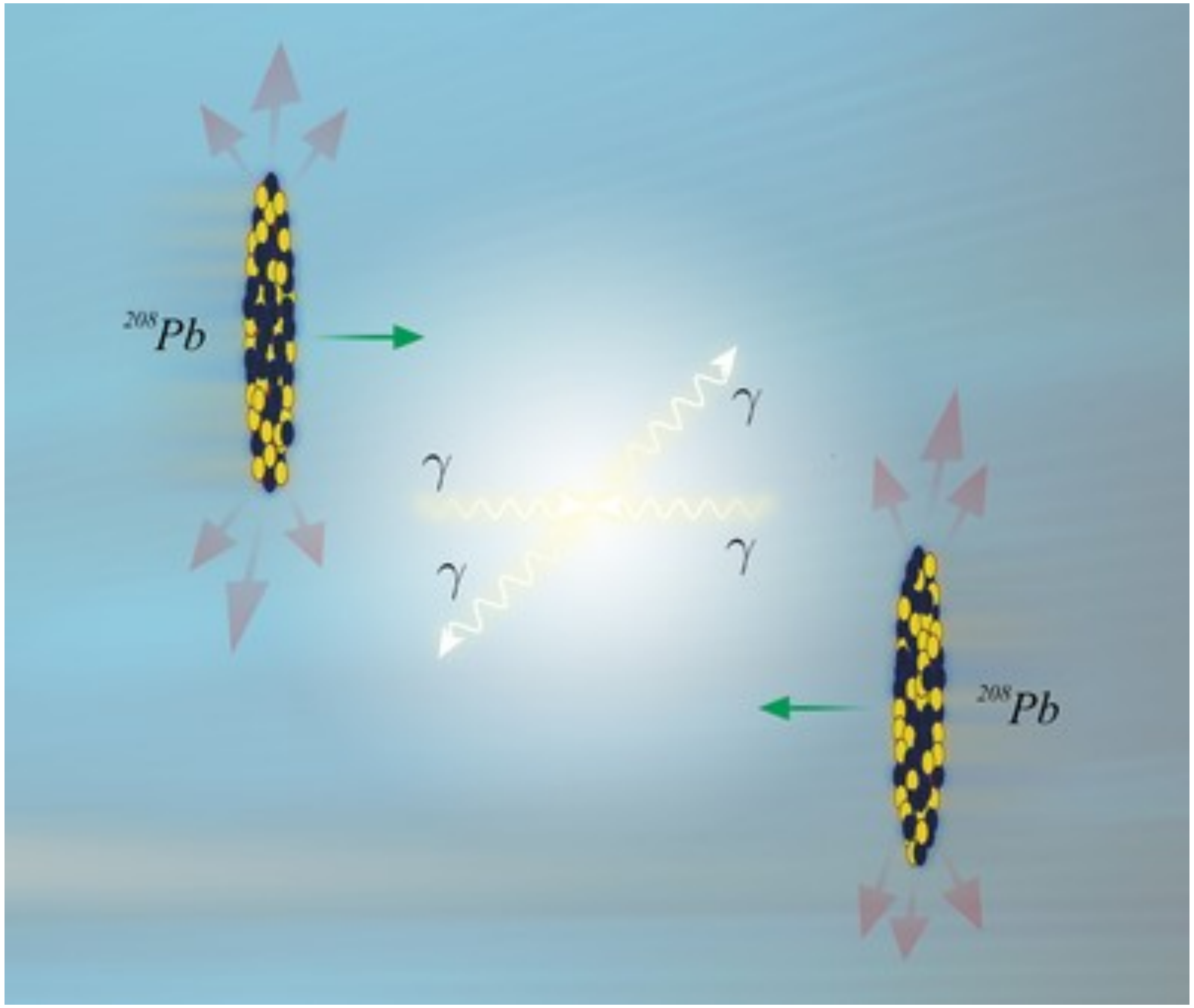



2.76 TeV (2010-11)

5.02 TeV (2015)
5.02 TeV (2018)

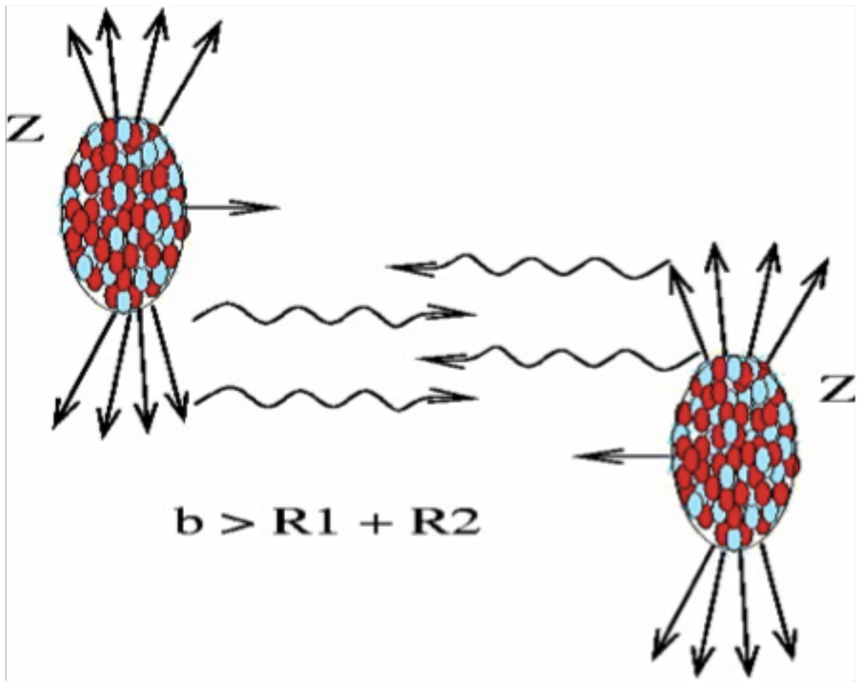
Bonus: Xe-Xe run 5.4 TeV (2017)

TWO-PHOTON COLLISION AT THE LHC



- When two charged particles pass next to each other at the LHC, accompanying electromagnetic fields are huge
- They are equivalent to intense photon fluxes
- Therefore, eventually an elastic collision of two photons may occur at the LHC

ULTRA-PERIPHERAL COLLISIONS AT THE LHC



Ultra-peripheral collision (UPC): $\gamma\gamma$ or γA

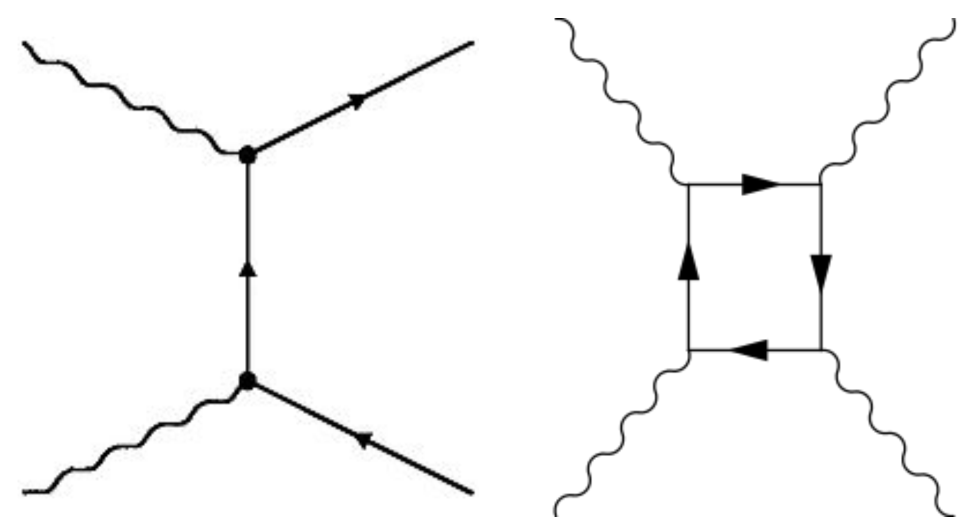
- Basis for photon-photon physics by
  - Fermi, Nuovo Cim. 2 (1925) 143
  - Weizsacker, Z. Phys. 88 (1934) 612
  - Williams, Phys. Rev. 45 (10 1934) 729
- Led to formulation of Weizsacker-Williams Approximation or **Equivalent Photon Approximation** (**EPA**)

- Cross section for processes AA(γγ) → AA(X) are calculated using:
  - Number of equivalent photons (EPA) by integration of relevant EM form factors

$$n(b,\omega) = \frac{Z^2\alpha_{em}}{\pi^2\omega}\left|\int dq_\perp q_\perp^2 \frac{F(Q^2)}{Q^2} J_1(bq_\perp)\right|^2$$

$$Q^2 < 1/R^2 \qquad \omega_{\max} \approx \gamma/R$$

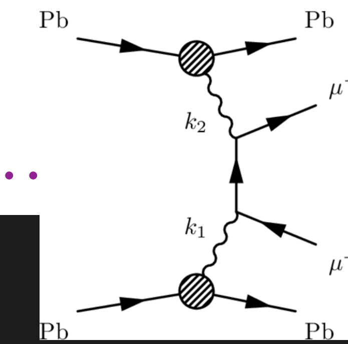
Z^4 **enhancement in Pb+Pb** over pp

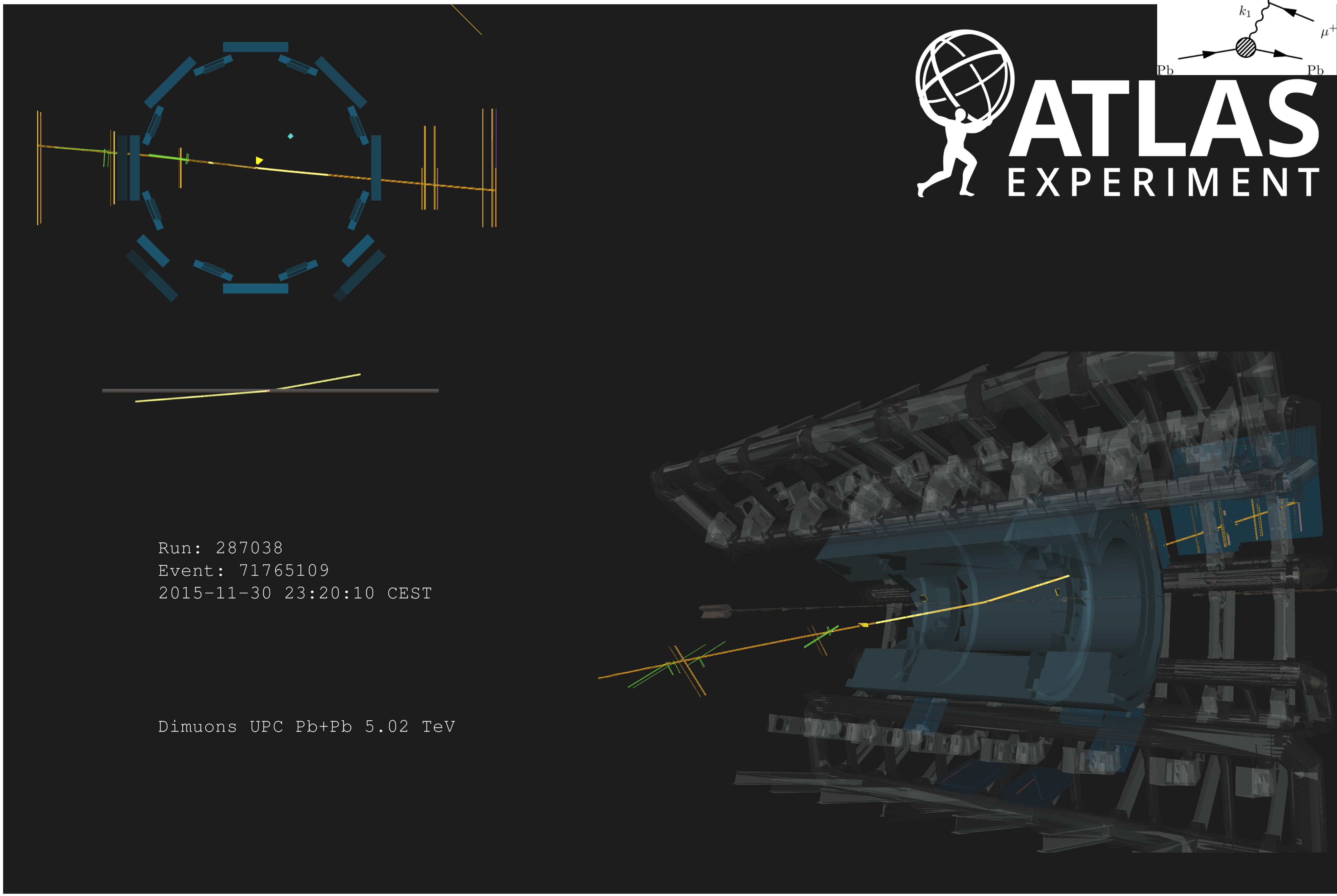


  - Elementary cross section of γγ → X:

$$\sigma^{\mathrm{EPA}}_{\mathrm{A_1A_2}(\gamma\gamma)\to\mathrm{A_1A_2X}} = \int\int d\omega_1 d\omega_2 n_1(\omega_1) n_2(\omega_2) \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})$$

EXCLUSIVE DIMUON EVENT IN UPC

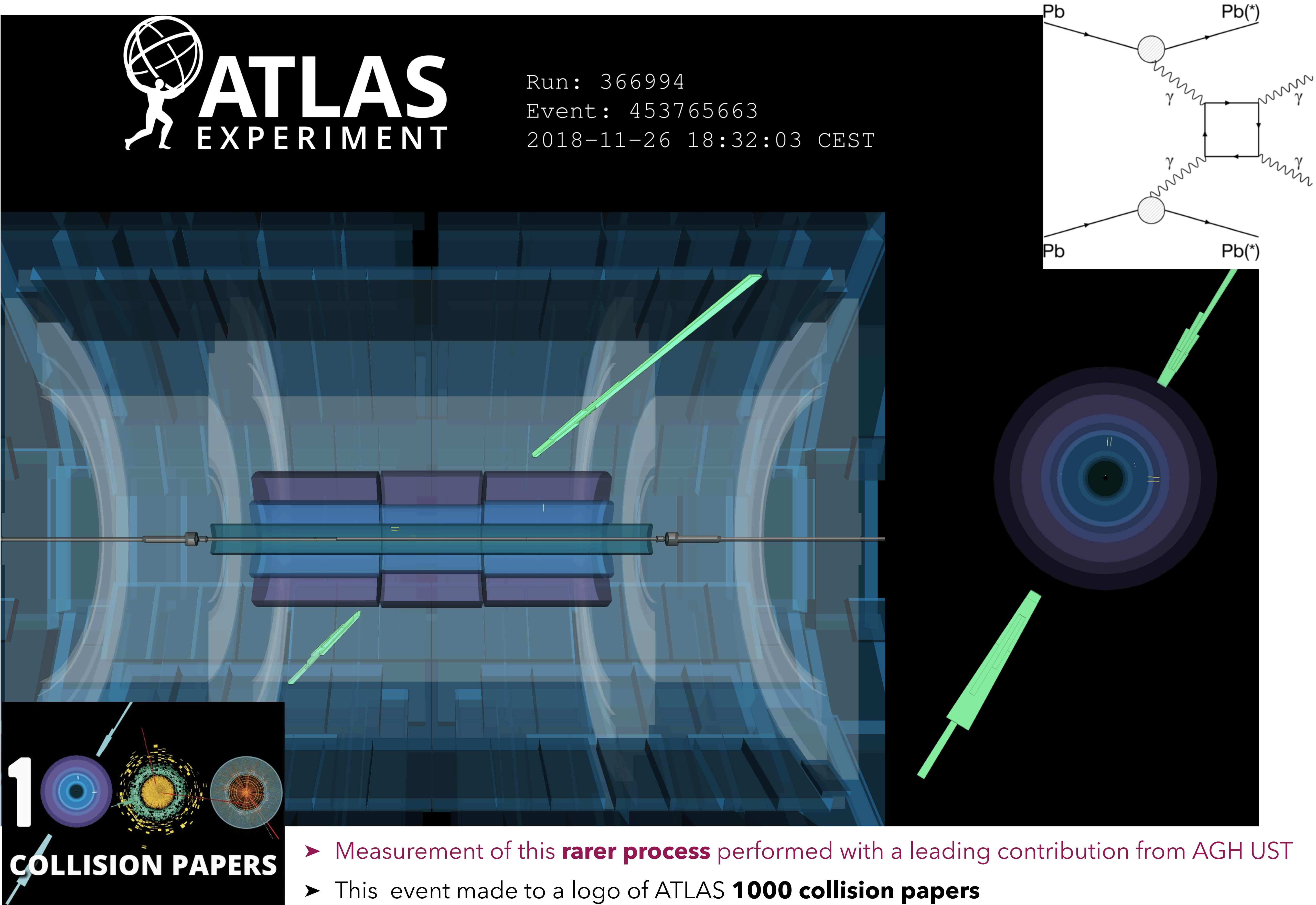




Only two back-to-back muons, otherwise the detector is empty

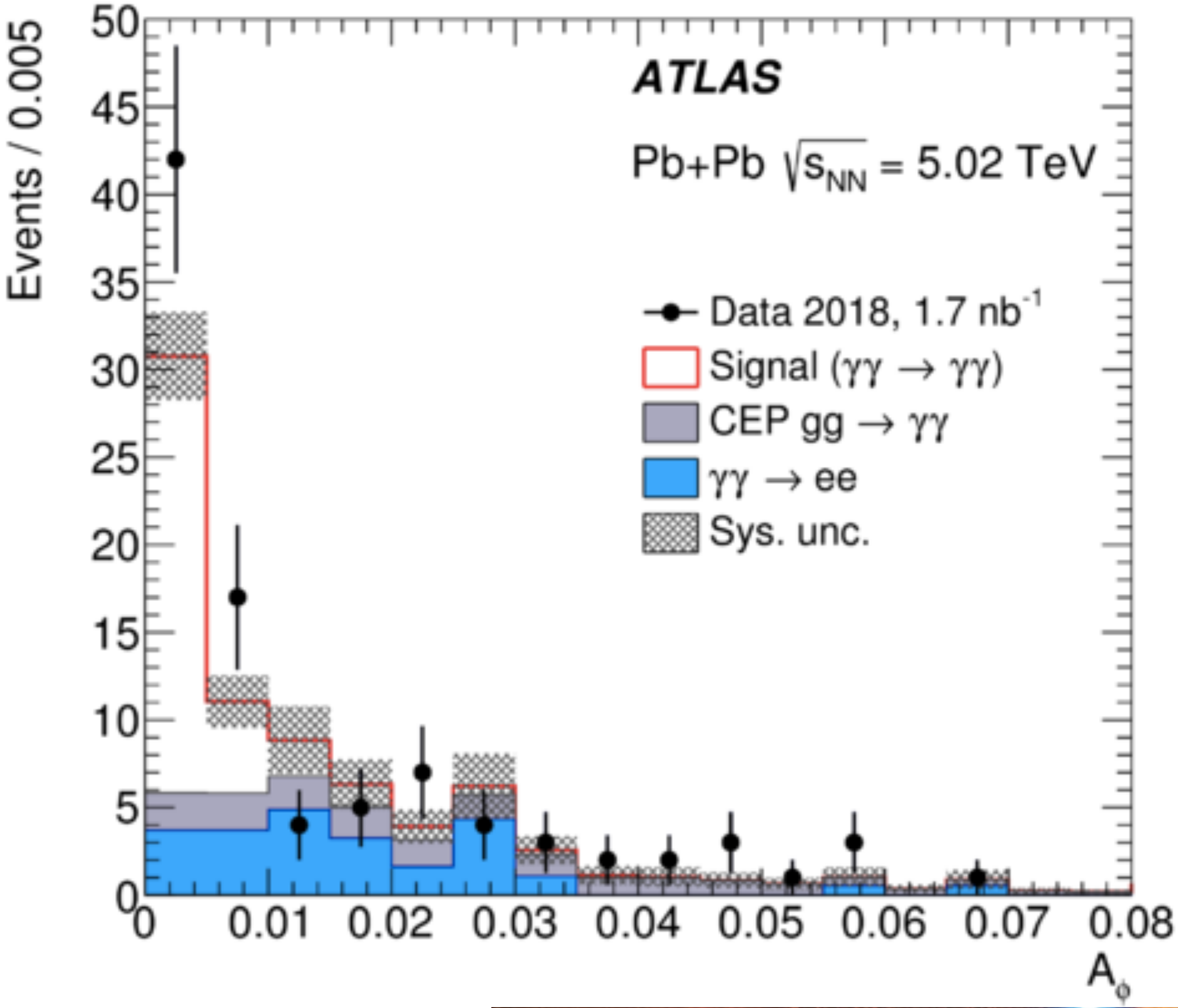
Ongoing analysis of $\gamma\gamma \rightarrow e^+e^-$ process at the AGH UST

LIGHT-BY-LIGHT SCATTERING AT THE LHC



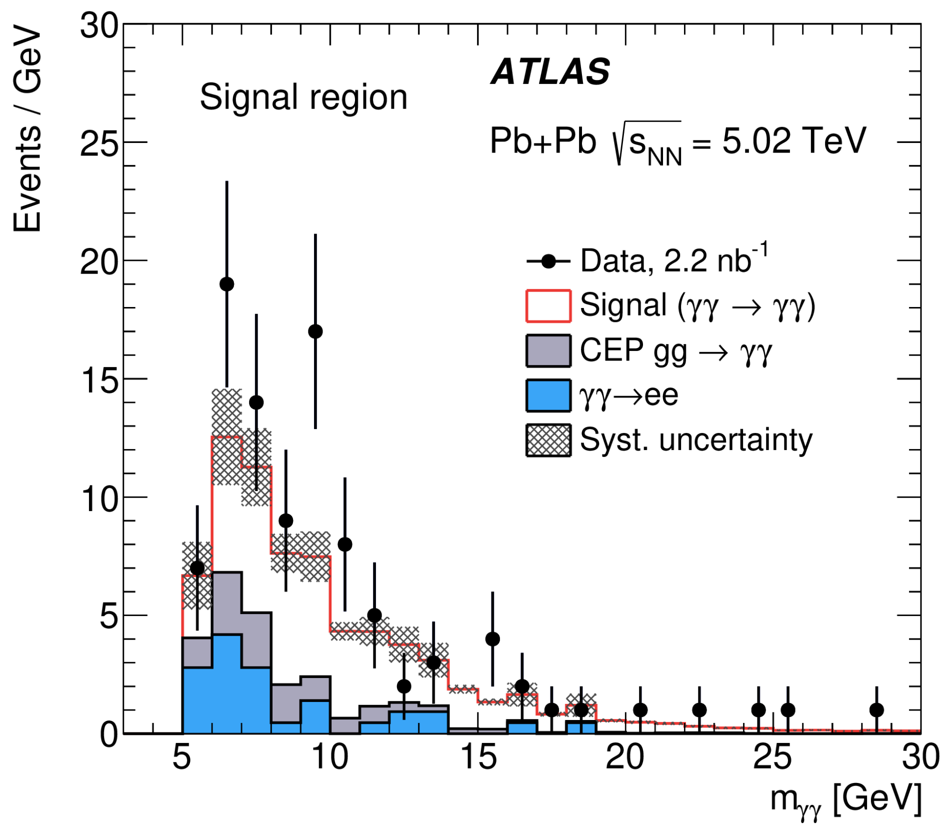
- Measurement of this **rarer process** performed with a leading contribution from AGH UST
- This event made to a logo of ATLAS **1000 collision papers**

FIRST DIRECT OBSERVATION

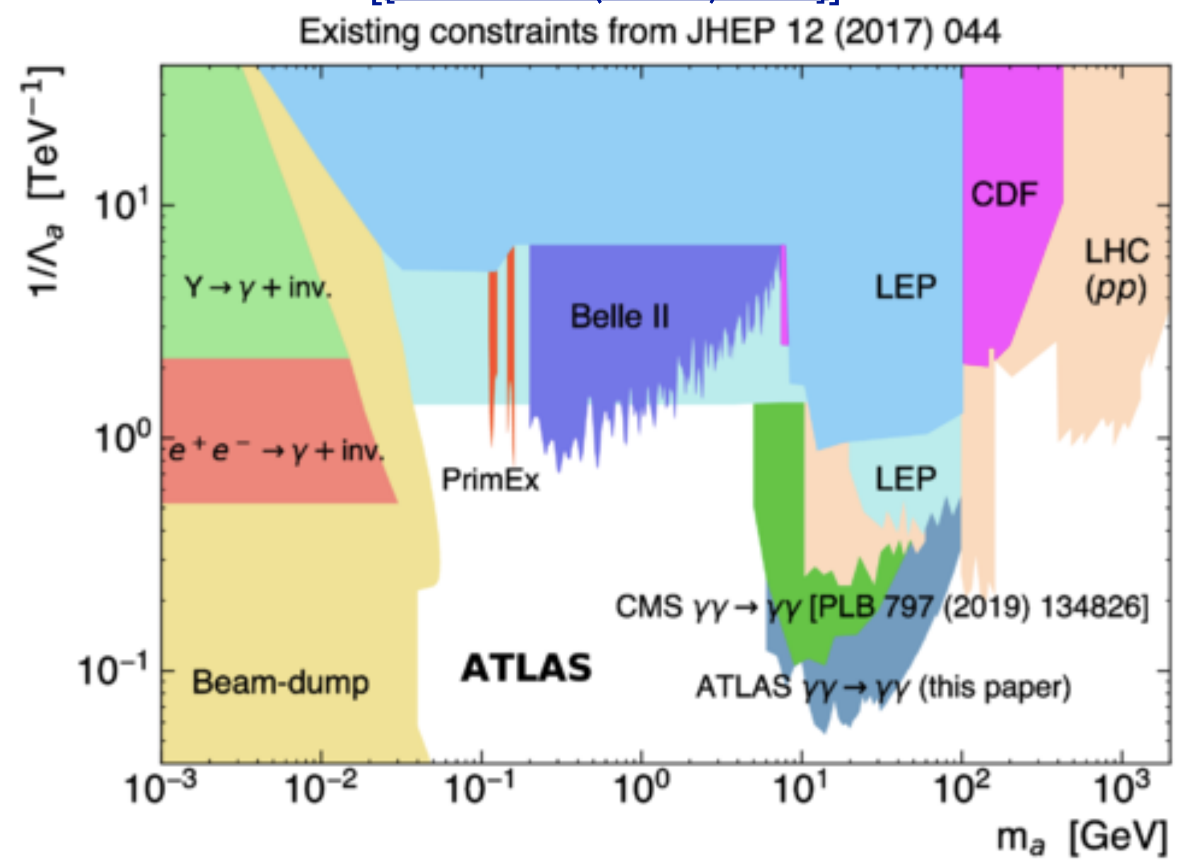


- In **14 bilion collisions** of lead-lead nuclei about **59 candidates** for photon-photon scattering observed
- Significance of **8.2 sigma**
- This process is the only one which can explain a mechanism which is behind light interactions of two lightsabers

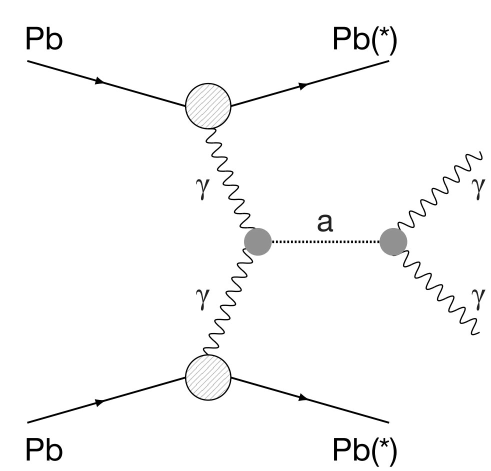
SEARCH FOR AXION-LIKE PARTICLES

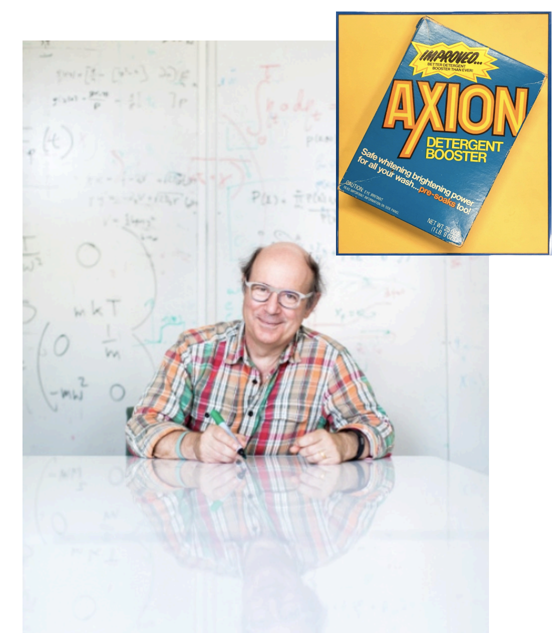


[[JHEP 03 (2021) 243]]



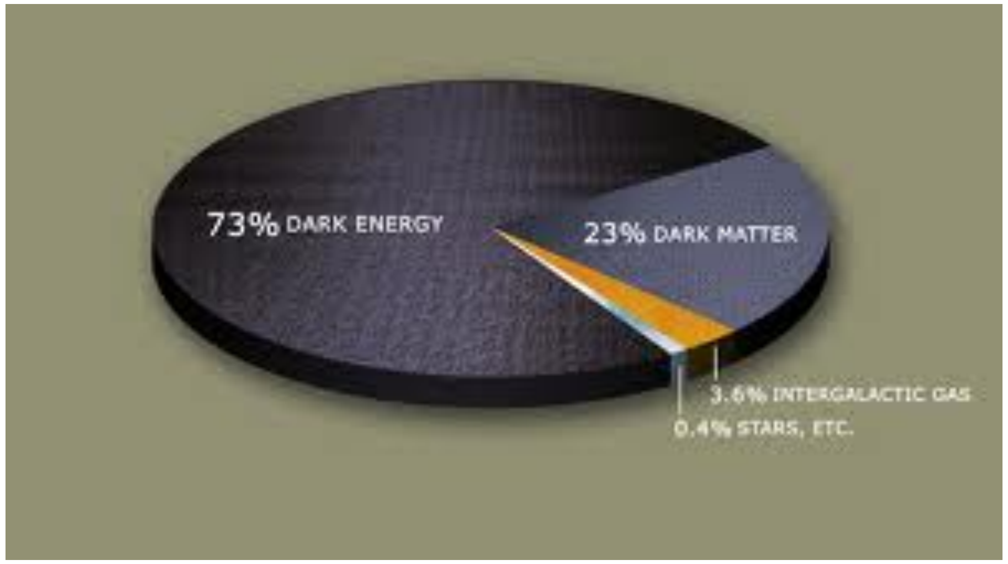
- Search for new particles (axions) decaying to two photons
- If they exist they would show as a peak in the $m_{\gamma\gamma}$ distribution
- No evidence for signal
- Establish the most stringent limits on ALP production for masses between 5-100 GeV
- AGH UST contributed to the search

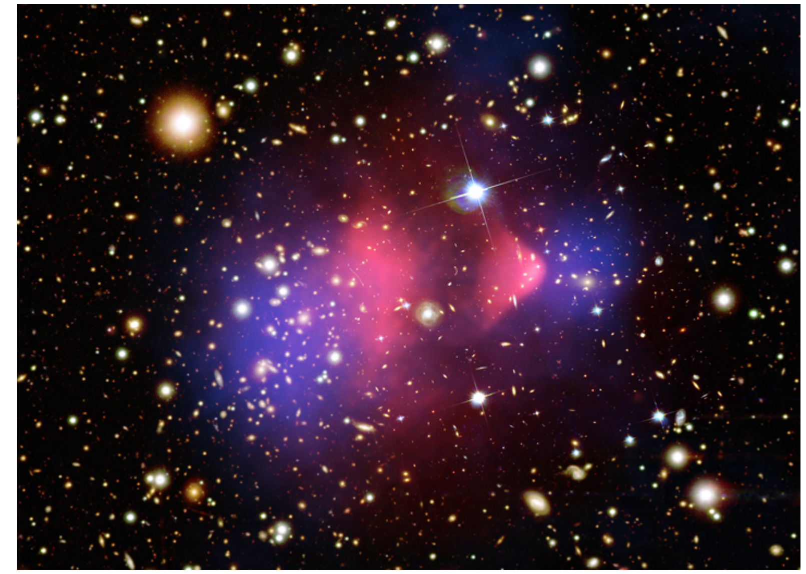




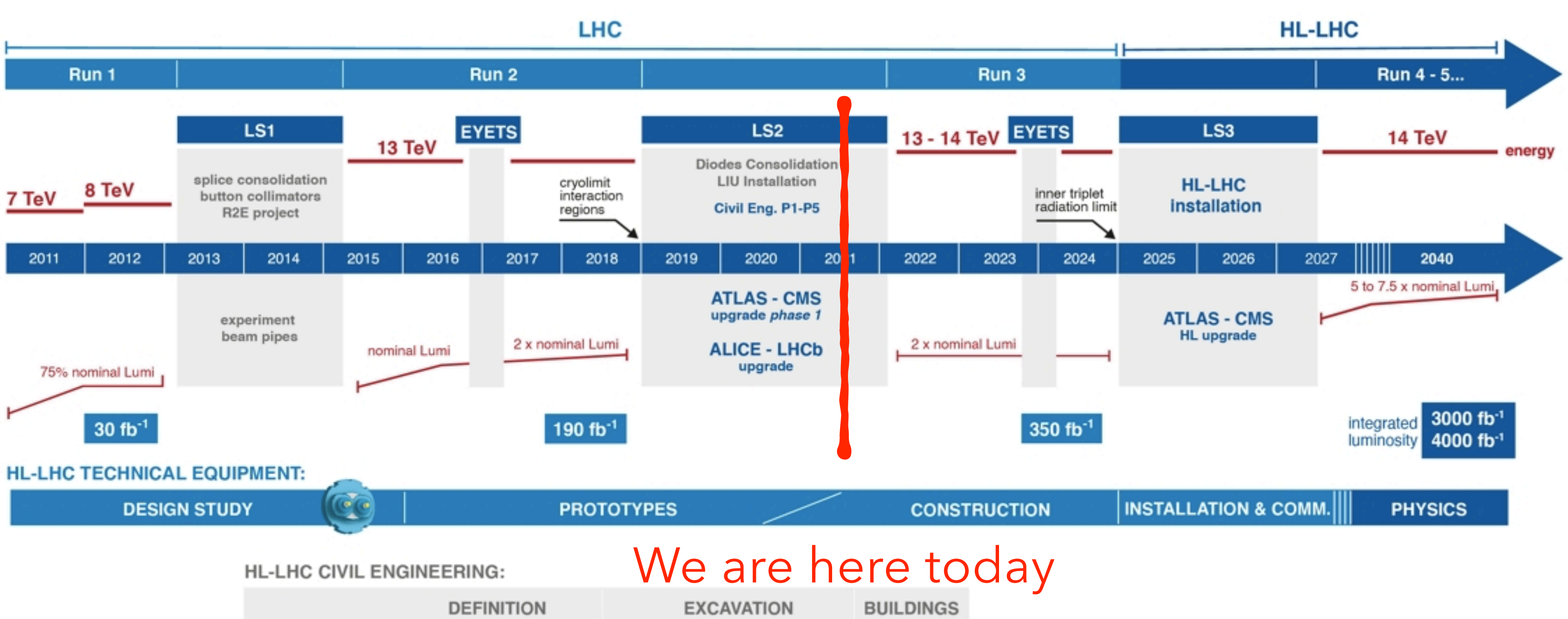
Prof. Frank Wilczek

WHAT NEXT?





- **Standard Model** describes our microcosm but it is not complete
  - It does not explain the origin of dark matter
  - It does not explain what happened to antimatter
  - It does not describe gravity …
  - ….



LHC physics programme will run until **2040**

Still many opportunities to contribute to science

THANK YOU FOR YOUR ATTENTION

PROJEKTY, W KTÓRYCH BIERZE UDZIAŁ WFIIS AGH

- Fizyka zderzeń ciężkich jonów
  - Pomiary bozonów W i Z
  - Pomiary z kwarkami t
  - Badanie korelacji między cząstkami naładowanymi
  - Pomiar rozpraszania foton-foton
- Fizyka zderzeń proton-proton
  - Procesy dyfrakcyjne
- Oprogramowanie systemu trygera, optymalizacja trygerów
- Optymalizacja identyfikacji elektronów
- Detektor wewnętrzny śladów (hardware i oprogramowanie)
- Detektor AFP i jego oprogramowanie

ZAPRASZAMY DO WSPÓŁPRACY

BACKUP SLIDES

IN THE PHYSICS BRIEFING

ATLAS

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Updates

Latest News, Briefings, Press Statements, Feature Articles, Collaboration Portraits and Blog Entries from ATLAS

Physics Briefing

Tags: HION group, Heavy Ion, Physics Results, LHCP 2020, LHCP

ATLAS measures light scattering on light and constrains axion-like particles

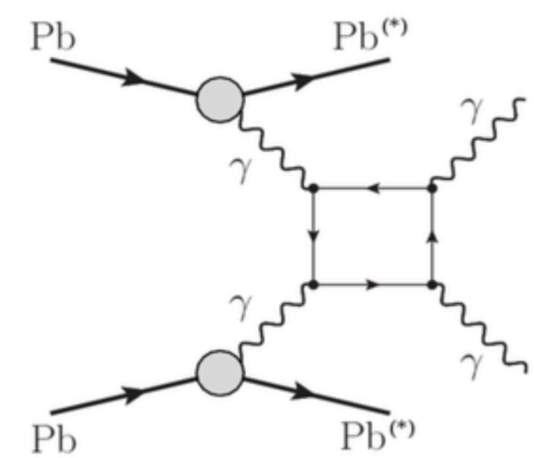
By ATLAS Collaboration, 25th May 2020

Light-by-light scattering is a very rare phenomenon in which two photons – particles of light – interact, producing another pair of photons. Direct observation of this process at high energy had proven elusive for decades, until it was first seen by the ATLAS Collaboration in 2016 and established in 2019. In a new measurement, ATLAS physicists are using light-by-light scattering to search for a hyped phenomenon beyond the Standard Model of particle physics: axion-like particles.

➤ The updated result made to the physics briefing for an online LHCP conference in May 2020

DIRECT MEASUREMENT OF LIGHT-BY-LIGHT SCATTERING

- Very rare QED process which has just been measured in HI collisions for the first time
- By **ATLAS** (evidence: 2017, observation: 2019, combination: 2021) and **CMS** (evidence: 2019)
  - Involves photons with $p_T > 2.5$ GeV
- Excess consistent with the LbyL signal from SM
  - ATLAS: **97 event candidates**, about 27±5 events from background
  - CMS: **14 event candidates**, about 3 events from background

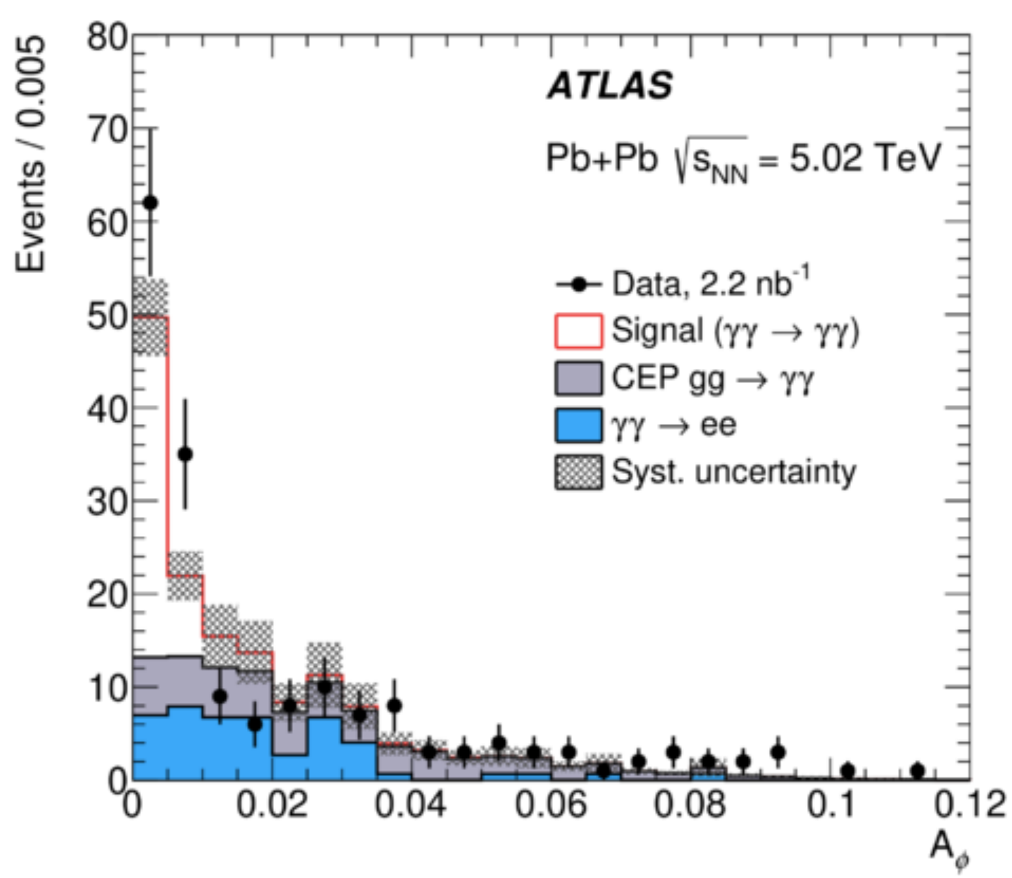


Measured cross sections:

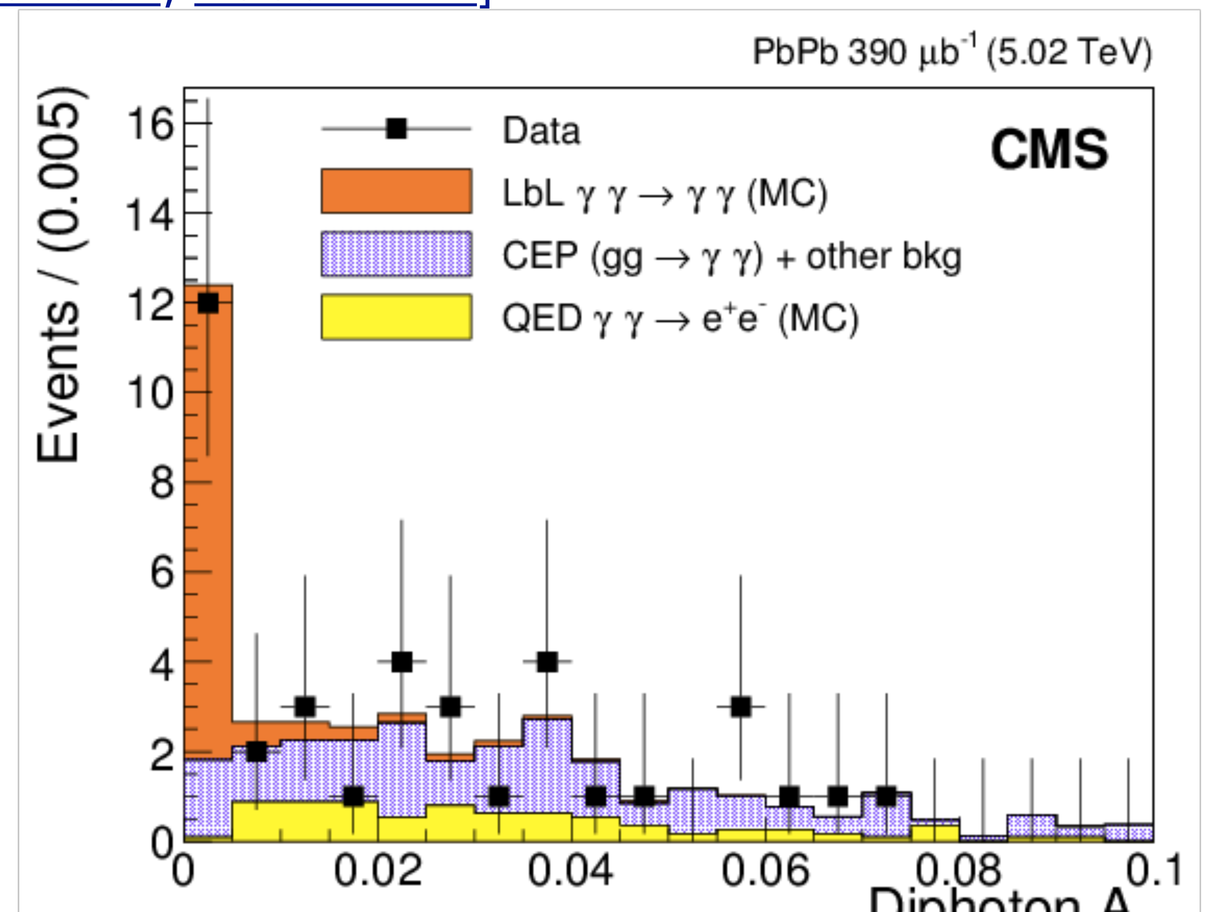
ATLAS - σ_{fid}=120 ± 17 (stat) ± 13 (syst) ± 4 (lumi) nb

CMS - σ_{fid}=120 ± 46 (stat) ± 28 (syst) ± 4 (th) nb

In agreement with SM predictions [arXiv:1601.07001, 1305.7142]

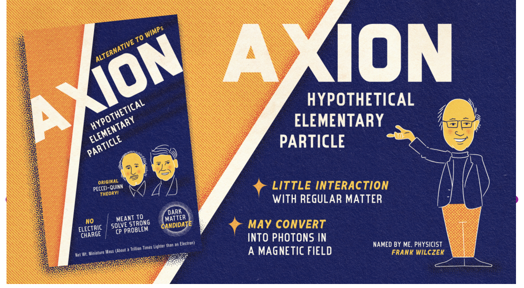


[JHEP 03 (2021) 243]

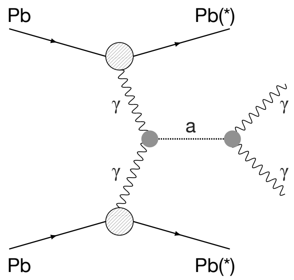


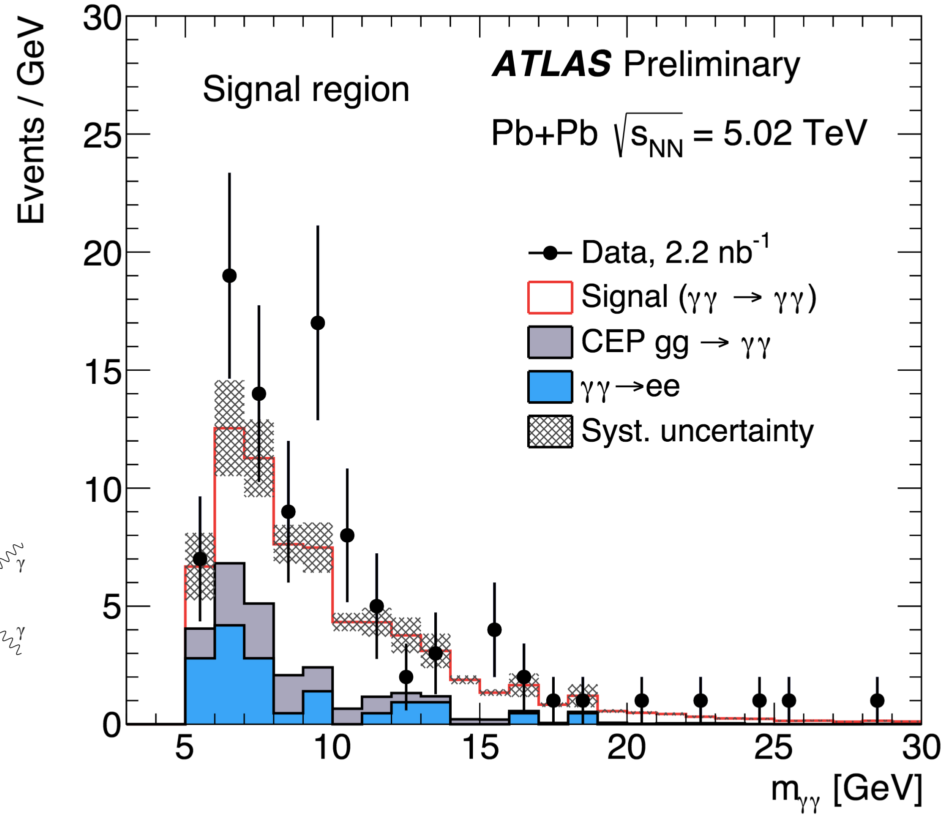
[Phys. Lett. B 797 (2019) 134826]

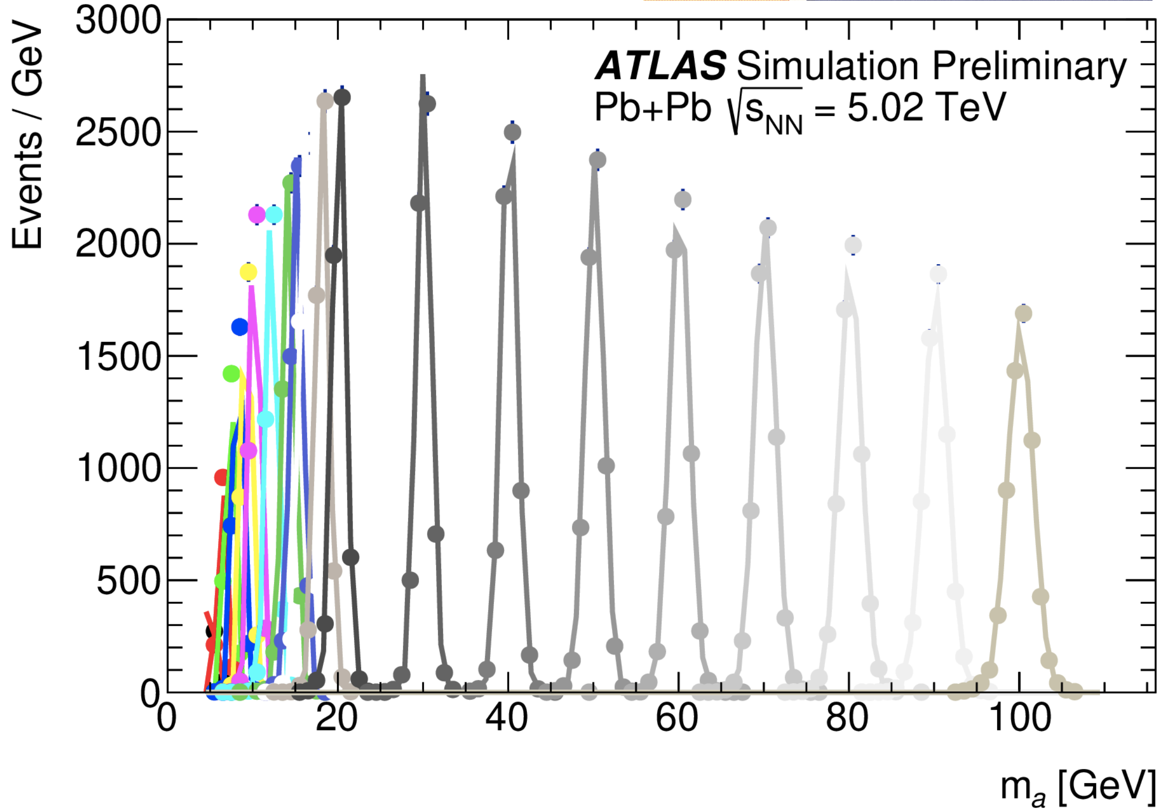
SEARCH FOR AXIONS



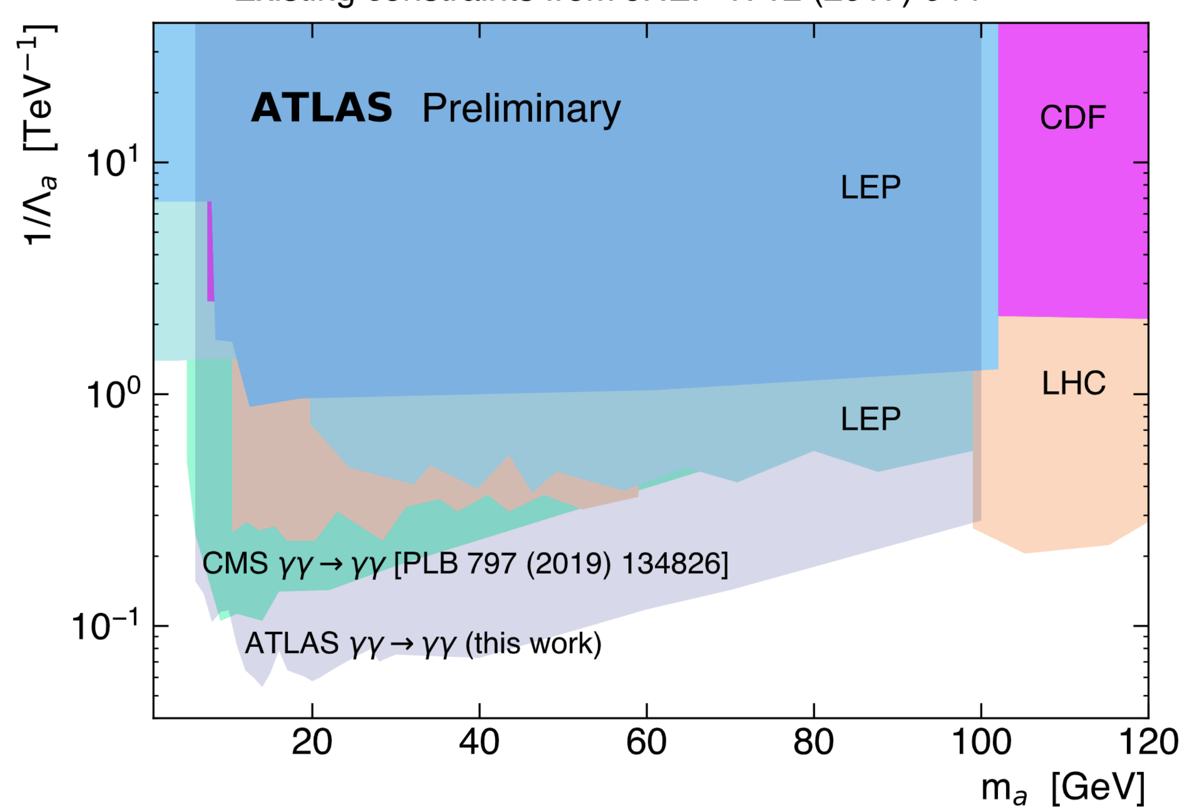
New [ATLAS-CONF-2020-010]







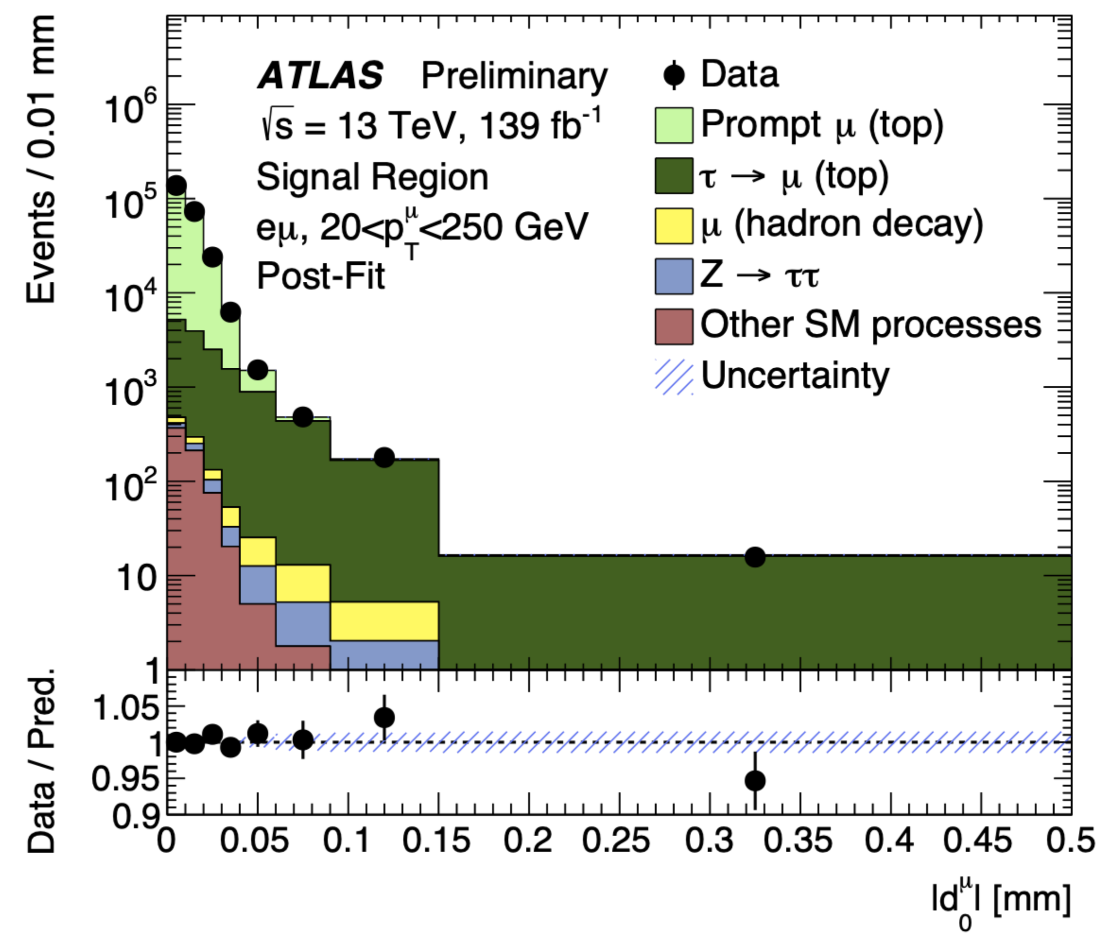
Existing constraints from JHEP 1712 (2017) 044



- Distribution of $m_{\gamma\gamma}$ used to **search for ALP** in $6 < m_{\gamma\gamma} < 100$ GeV range using a cut-and-count method
  - Signal: $\gamma\gamma \to a \to \gamma\gamma$, $\mathrm{BR}(a \to \gamma\gamma) = 100\%$
  - Background: LbyL, $\gamma\gamma \to e^+e^-$, central exclusive production of $gg \to \gamma\gamma$
- 95% CL limits on σ and coupling $1/\Lambda_a$
  - Largest deviation of 2.1σ at $m_{\gamma\gamma} \sim 10$ GeV
  - **The most stringent limit** established for ALP masses between 6-100 GeV

LEPTON UNIVERSALITY

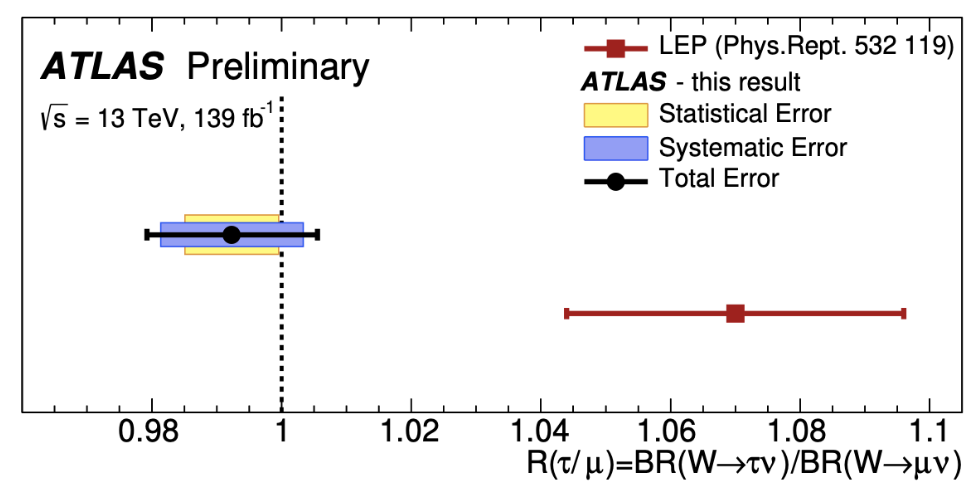
- Measure a difference between tau and muon leptons in a ratio $R = \dfrac{W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau X}{W \to \mu\nu_\mu}$
- Standard Model prediction: R=1
- Long-standing discrepancy between data and theory at LEP
- **Data is consistent with unity**
- Excellent precision of the ATLAS measurement released in May 2020 (LHCP)



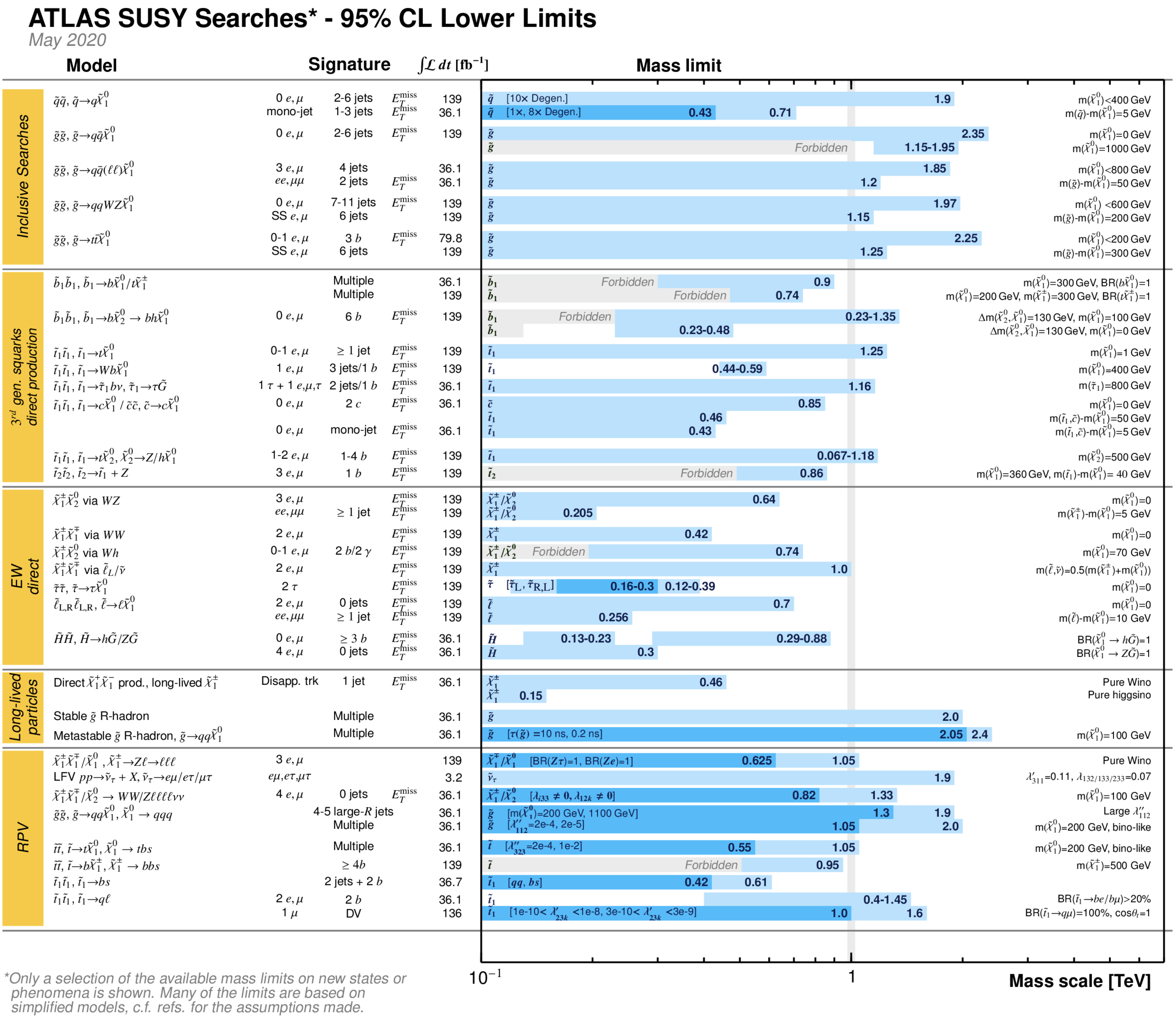
New ATLAS result addresses long-standing tension in the Standard Model

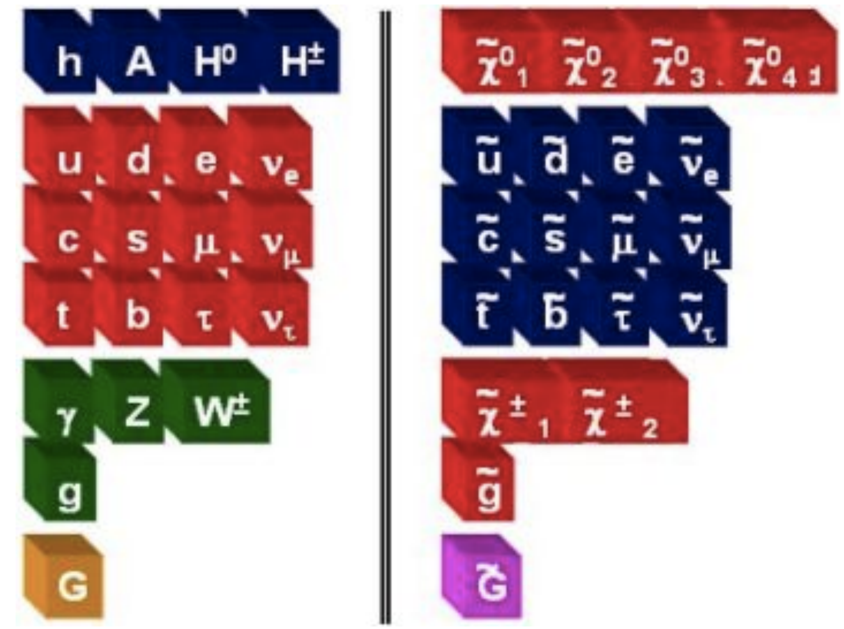
By ATLAS Collaboration, 28th May 2020

Perhaps the best-known particle in the lepton family is the electron: a key building block of matter and central to our understanding of electricity. But the electron is not an only child. Electrons are accompanied by heavier siblings, the muon and tau-lepton, to give three lepton *flavours*. According to the Standard Model of particle physics, the only difference between these siblings should be their mass: the muon is heavier than the electron, and the tau-lepton is heavier than the muon. It is a remarkable feature of the Standard Model that each flavour is equally likely to interact with a W boson; this is known as *lepton flavour universality*.



AND SUPERSYMMETRY?



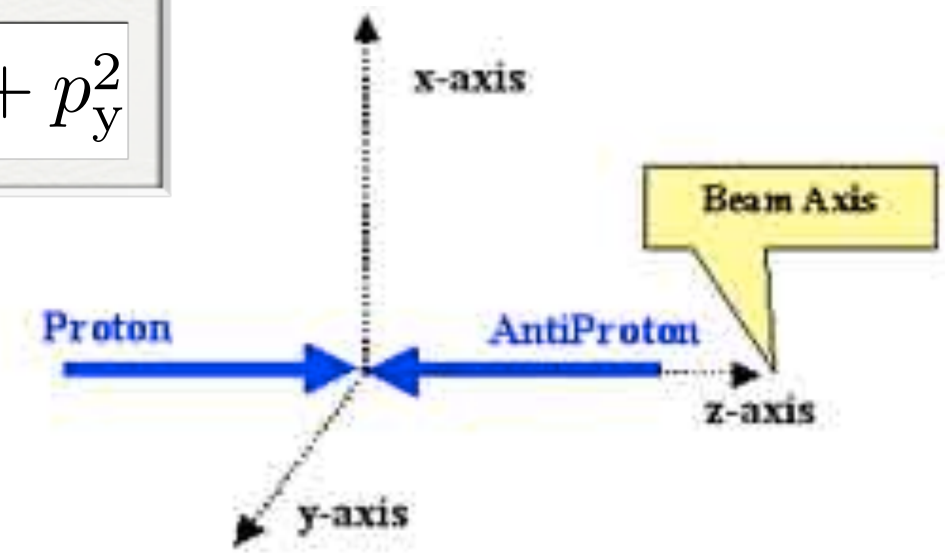


- ➤ No evidence of supersymmetry (SUSY) at the LHC so far

DEFINITIONS

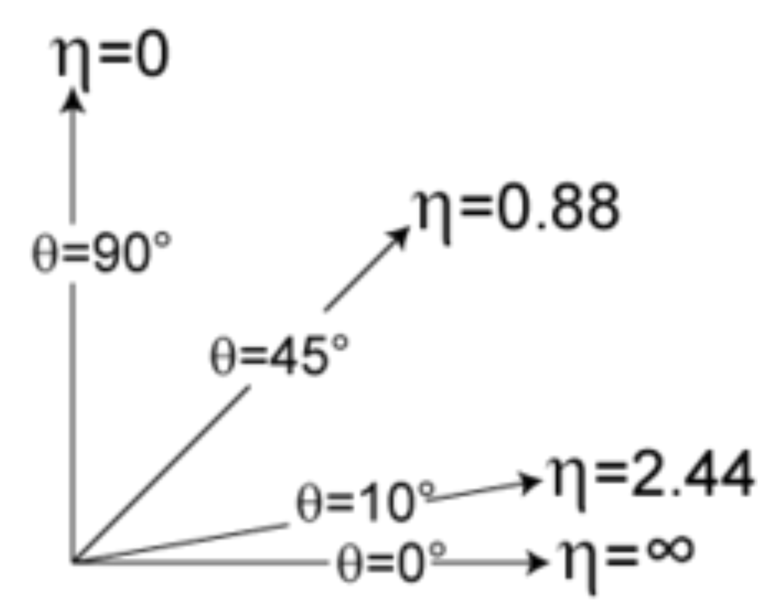
- Transverse momentum, p_T

$$p_{\mathrm{T}} = \sqrt{p_{\mathrm{x}}^2 + p_{\mathrm{y}}^2}$$

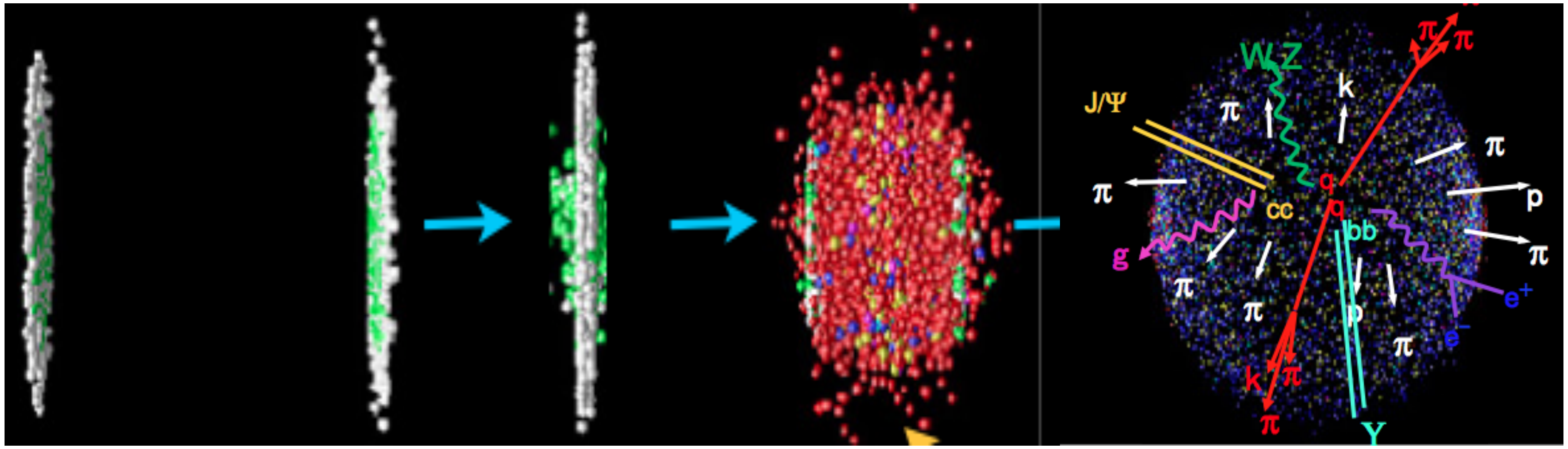


- Azimuthal angle, ϕ
- Polar angle, θ
- Pseudorapidity, η

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$



HEAVY-ION PHYSICS PROGRAM IN ATLAS



One of the main goals of heavy-ion (HI) physics is to study the QGP

- ➤Use variety of final states to provide insight into properties of the QGP
  - ➤ **Hard probes**
    - ➤Color objects e.g. **jets**, hadrons – insight into partonic energy loss in the QGP
    - ➤Colorless objects e.g. **electroweak bosons** – standard candles in the medium, look for nuclear effects on PDFs
  - ➤ **Bulk particle production**
    - ➤Sensitivity to initial geometry, initial conditions, collective behaviour, etc
    - ➤ Understand the origin of ridge in small systems
  - ➤ **Ultra peripheral collisions**
    - ➤ Use gamma-gamma or gamma-nucleus interactions to study initial state, explore QED, also a potential window for BSM physics