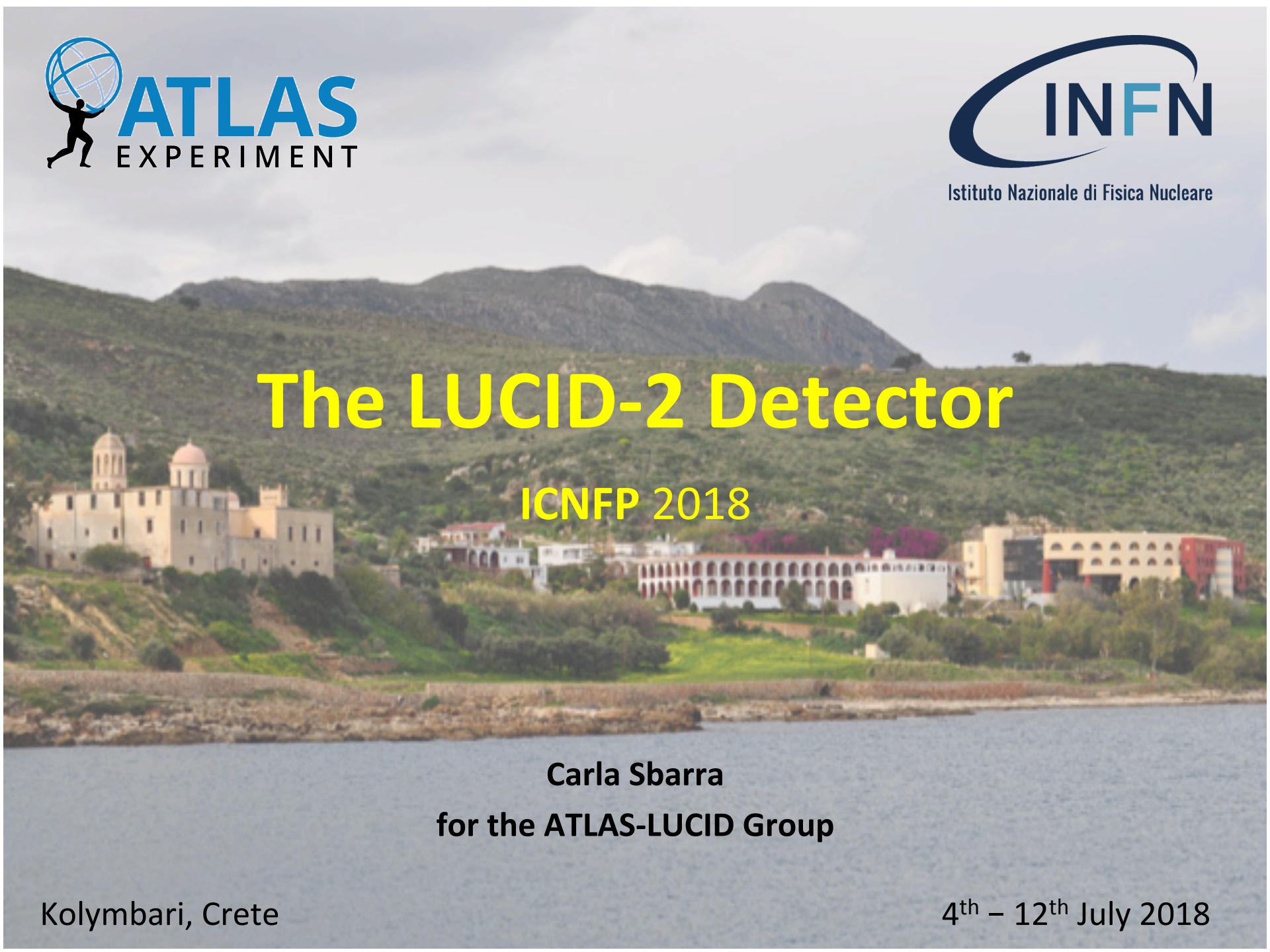


The LUCID-2 Detector

ICNFP 2018

Carla Sbarra

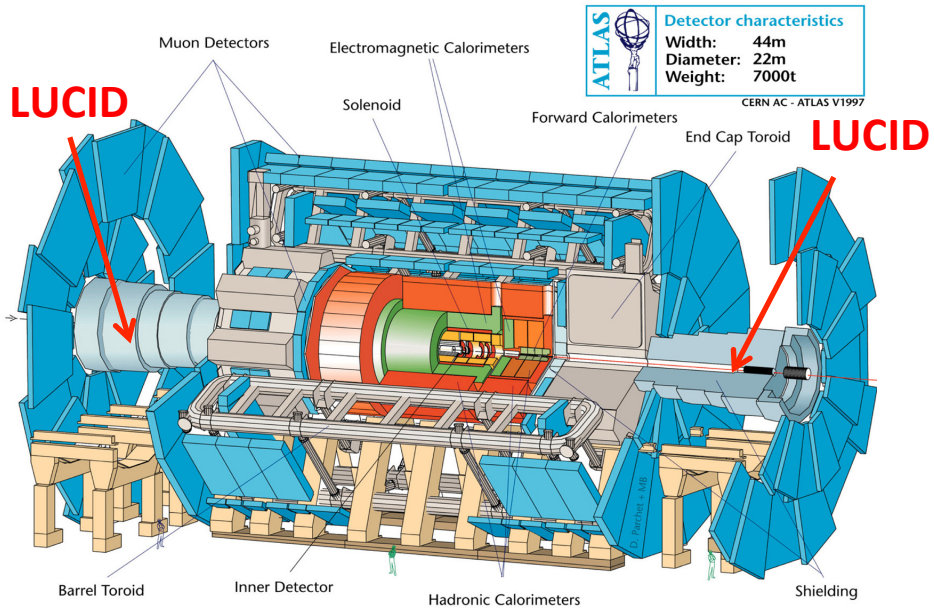
for the ATLAS-LUCID Group

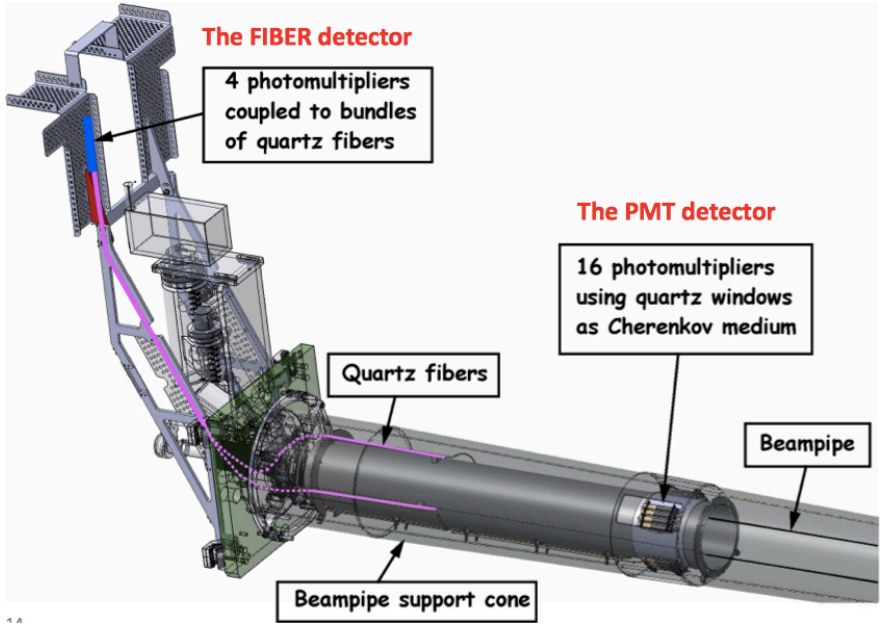
Kolymbari, Crete

4^{th} – 12^{th} July 2018

LUminosity Cerenkov Integrating Detector-2

- ATLAS detector dedicated to luminosity measurements and monitoring
- Two identical modules at ~ 17 m from ATLAS Interaction Point and ~ 125 mm from beam line





Luminosity monitoring at LHC

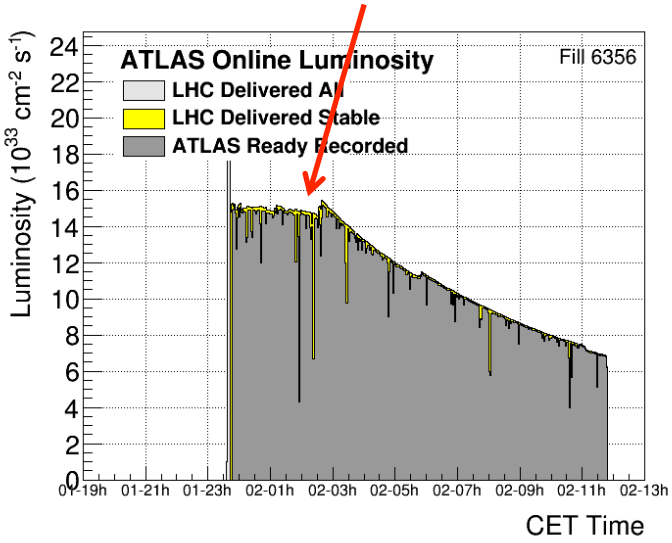
- Measure / put limits to any cross section σ once N events are observed: integrated Recorded luminosity L (σ = N/L)

  LHC data grouped in "luminosity blocks" of typically 1 min for data analysis
- Trigger optimization → Delivered luminosity for individual bunches
- Beam Optimization → Delivered instantaneous luminosity $\mathcal{L}$ to machine operators every few seconds
- Luminosity **Leveling** → Delivered instantaneous luminosity $\mathcal{L}$ to machine operators every few seconds
  - Needed to optimize accelerator performance when in excess of capabilities of readout and storage infrastructures of experiments
  - Realized by beam separation
  - Expected to be "normal operation" at HL-LHC

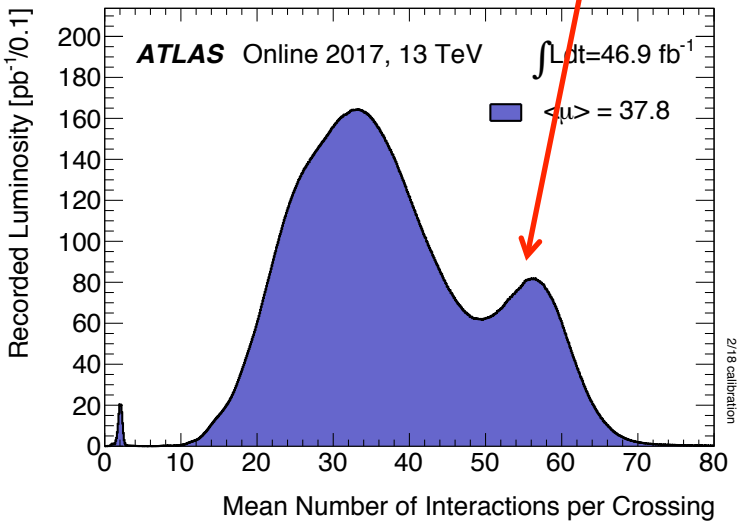
Luminosity Leveling in 2017

More than 50% of 2017 data taken in runs with luminosity leveling.
LHC able to reach a **number of pp interaction per bunch crossing μ** > 80
Both ATLAS and CMS readout system saturated at <μ> ≈ 60

Delivered Instantaneous luminosity leveled at 1.5 10^{34} cm^{-2} s^{-1}

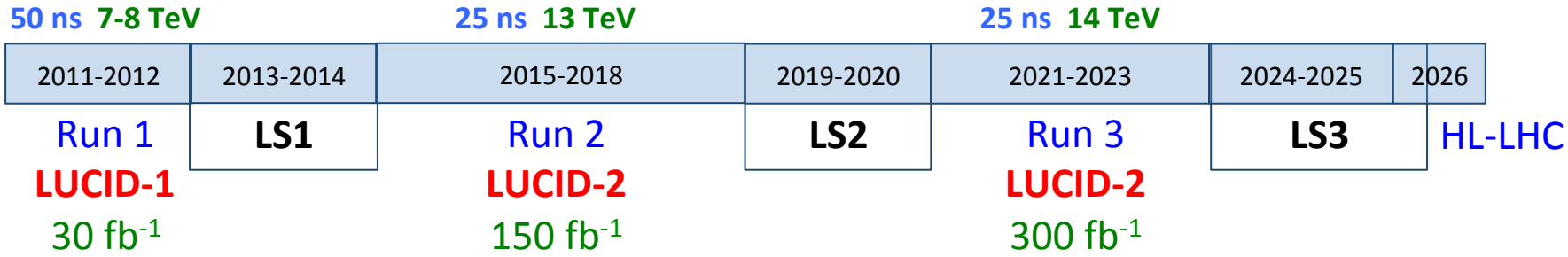


constant <μ> below 60



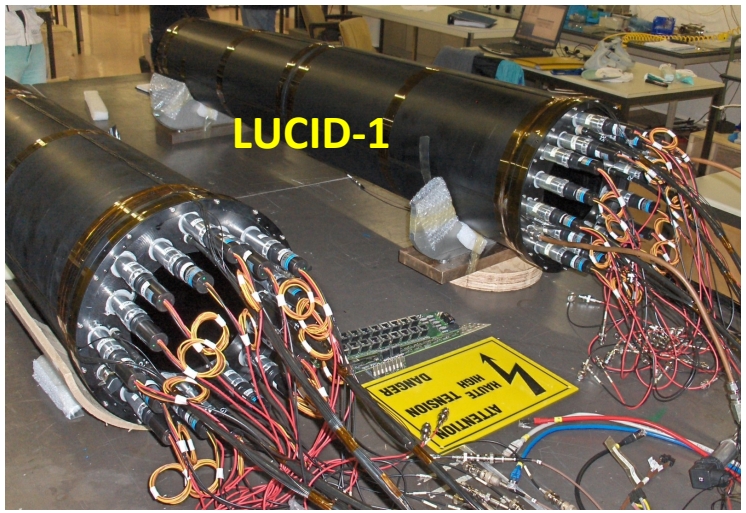
Needed to maximize physics reach

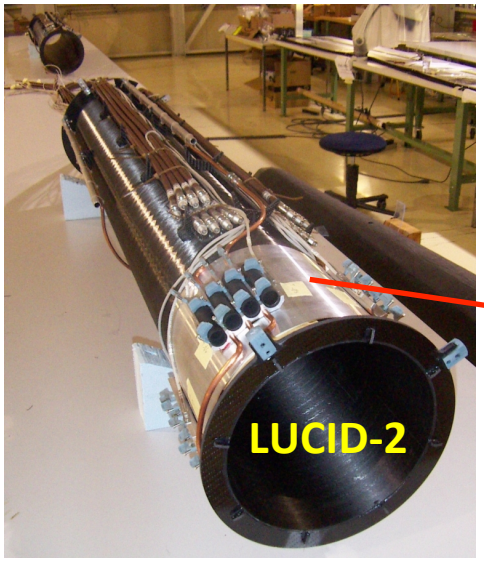
LHC timeline & LUCID-2 requirements

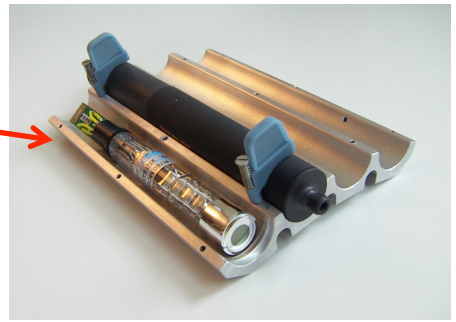


- Bunch crossing every 25 ns → Faster: early signal digitisation
- Few calibration fills/year → Stable: robust PMT-gain control
- Luminosity changes by orders of magnitudes between calibration fills and standard operations → Large dynamic range: small acceptance
- # of pp interactions per bunch crossing (μ) from 10^{-3} in calibration fills to more than 60 → Capability to handle different pileup conditions: many algorithms
- LUCID close to the beam pipe → Radiation hard: quartz

LUCID-1 & LUCID-2



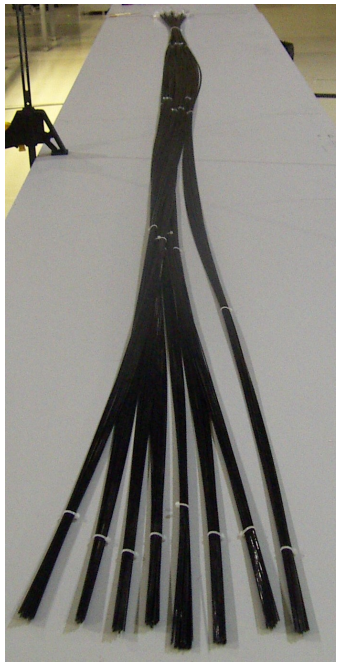




- 20 Al tubes/ module, immersed in C4F10 Cherenkov radiator gas:
  - 16 directly coupled with quartz-window PMTs
  - 4 end in a cone coupled to quartz fiber bundle + PMT
- Analog signals to electronics cavern about 100 m away
- PMT-gain calibration via LED

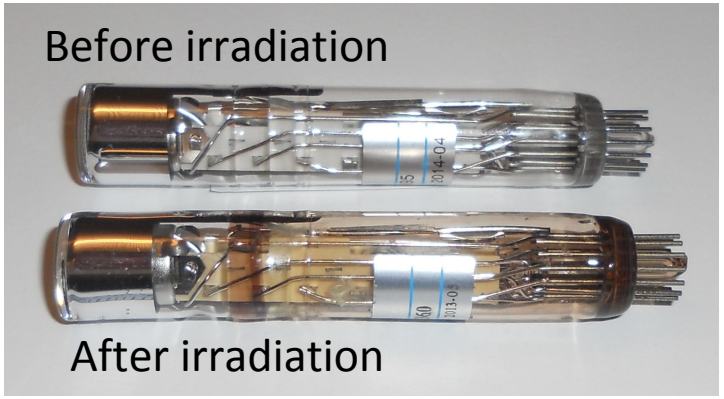
- No gas radiator :
  - 16 PMTs with quartz window (12+4 spares)
  - 4 quartz fiber bundles
- Smaller PMT size: 10/7 mm diameter
- Mu-metal case
- Early signal digitization (≈15 m)
- New calibration systems & improved old one
- New algorithms (charge)

Sensitive elements



Bundles of
37 quartz fibers

Hamamatsu R760
with reduced
acceptance



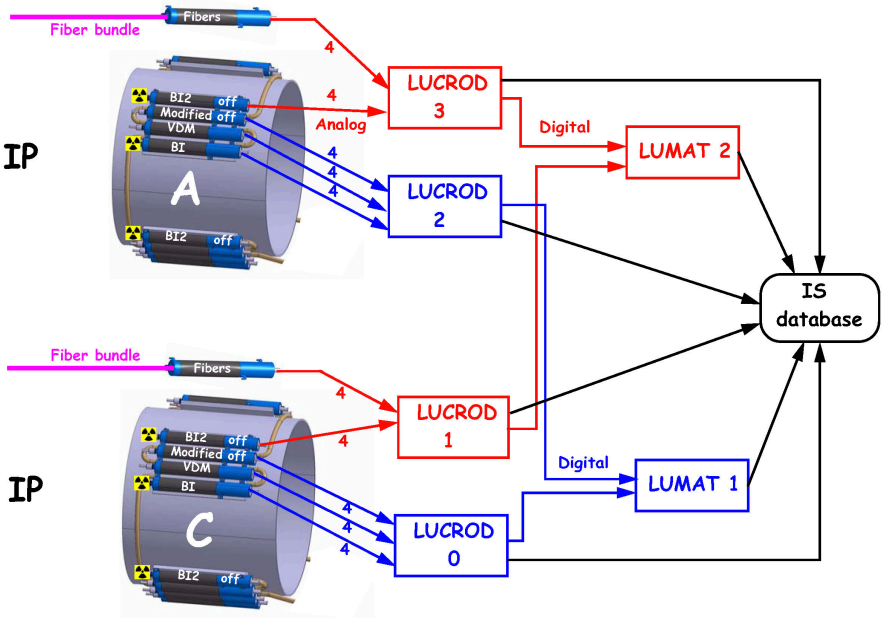
Tested against radiation:
200 kGray ^{60}Co @ Calliope
2.6 10^{14} n/cm^2 @ Tapiro
→ dark current increase
→ negligible effects on gain

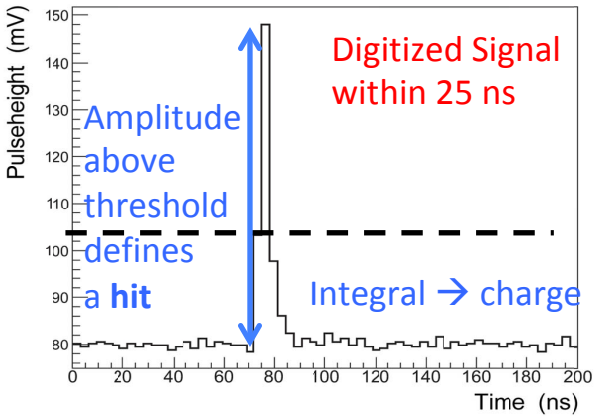
Borosilicate glass: 80% SiO_2 +4% Na_2O+13% B_2O_3+3% Al_2O_3

Fused Silica: 100% SiO_2

200 kGray actually reached by end of 2017

Electronics





- PMT signal amplified, digitized, discriminated
- Hits to modified LUMAT (optical links)
- Signal integrated over 25 ns intervals
- Hits & charges accumulated in FPGA
- Digitized signal readout via VME for monitoring and calibration purposes
- Occasional SEU automatically recovered

Luminosity algorithms

- **Hit and Event counting (^{207}Bi calibrated PMTs)**
  - Provide visible number of interactions per bunch crossing μ_{vis} via Poisson Statistics where hit/event probability $P = 1\text{-}e^{-\mu vis}$
  - pileup of signals below threshold → spurious hits (migration). Most relevant for fibers and PMTs with reduced acceptance
  - event algorithms saturate at pileup ≥ 30
  - Hit counting fine up to μ ≈ 100 (individual sensors as well as any combination of them to reduce position dependence)

f_{LHC}= Orbit frequency
L = Bunch Inst. Luminosity
σ = Inelastic Cross section

$$L = f_{LHC}\frac{\mu}{\sigma} = f_{LHC}\frac{\mu_{vis}}{\sigma_{vis}}$$

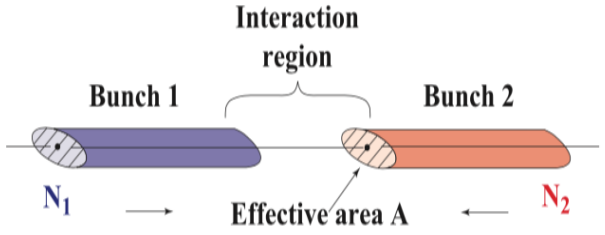
$\mu_{vis} = \varepsilon\mu$
$\sigma_{vis} = \varepsilon\sigma$
ε = detection efficiency

algorithm-dependent calibration constant

- **Total charge (fibers and "modified" PMTs)**
  - directly proportional to luminosity
  - directly affected by PMT-gain fluctuations
  - does not saturate

Luminosity Calibration

Special runs known as *Van der Meer* scans: low intensity beams are separated in x and y while luminosity monitors measure rates

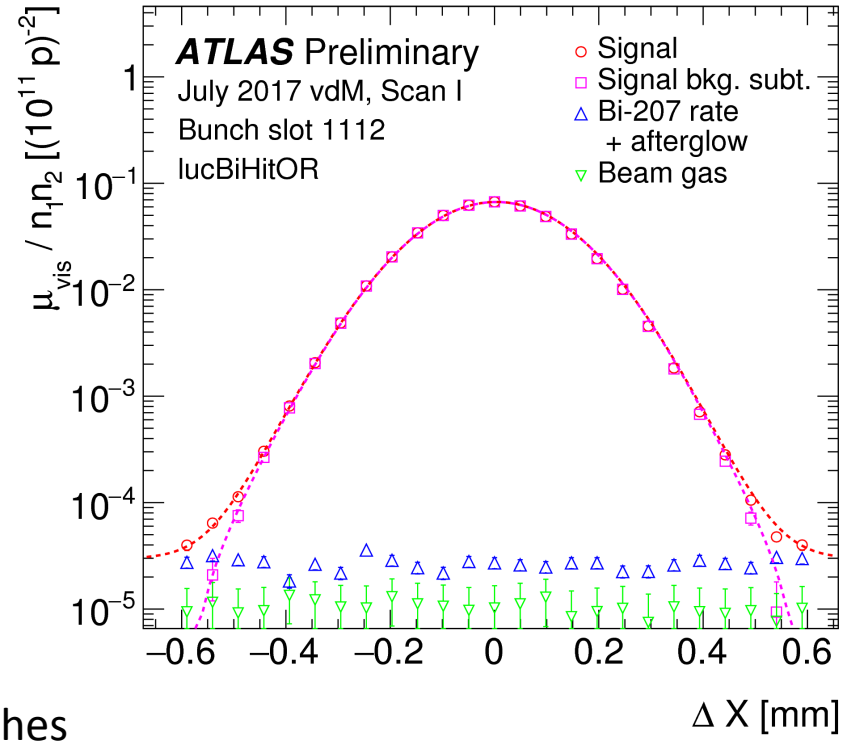


$$\sigma_{vis} = 2\pi \frac{\mu_{vis} \Sigma_X \Sigma_Y}{N_1 N_2}$$

μ_{vis}^{peak} peak value of scan curve

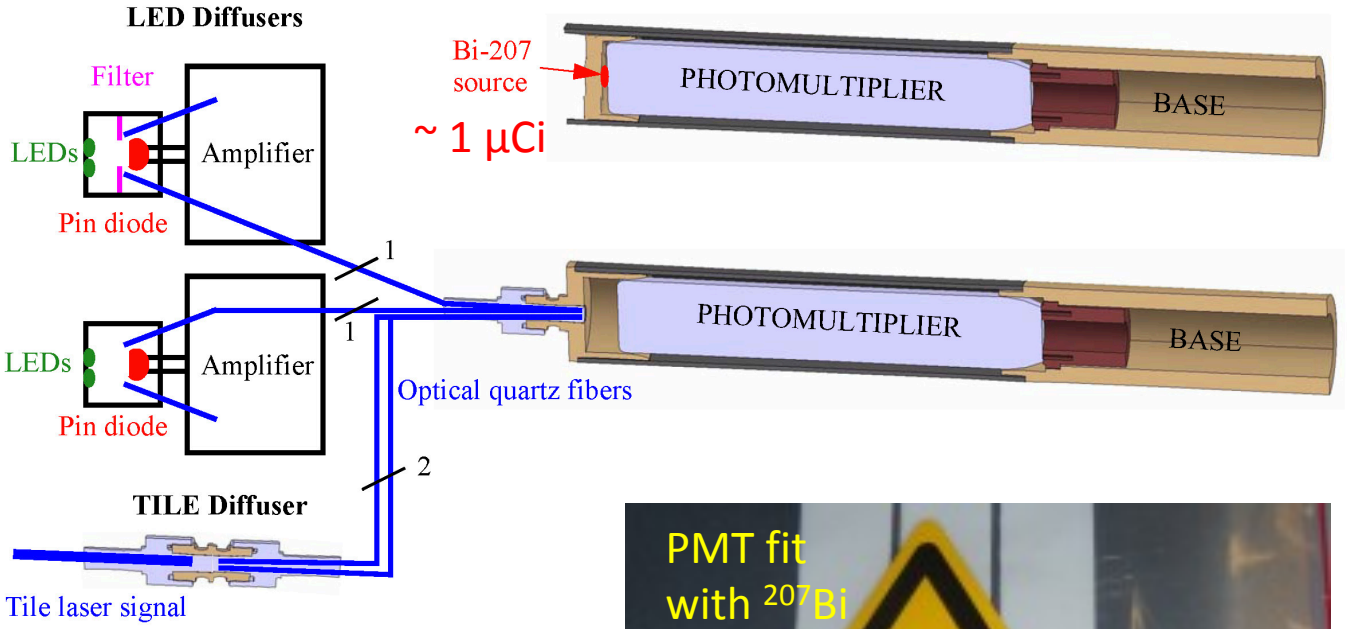
$\Sigma_X \Sigma_Y$ widths of scan curves

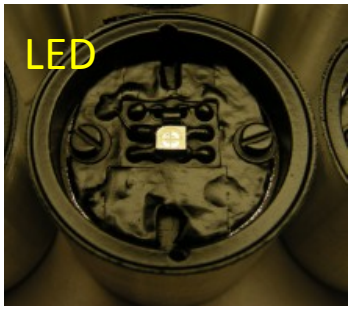
$N_1 N_2$ number of protons per bunches

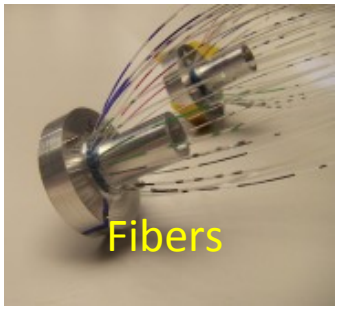


PMT-Gain Calibration Systems

Three Independent Systems



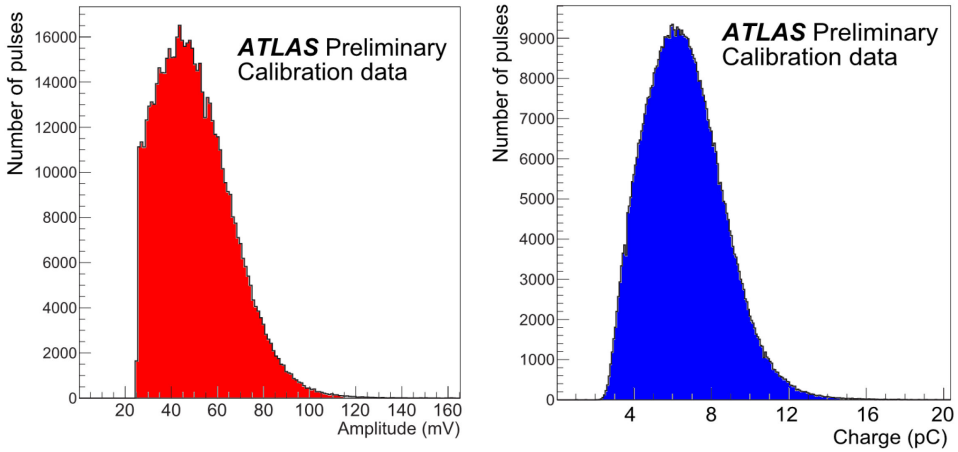




^{207}Bi signal monitoring

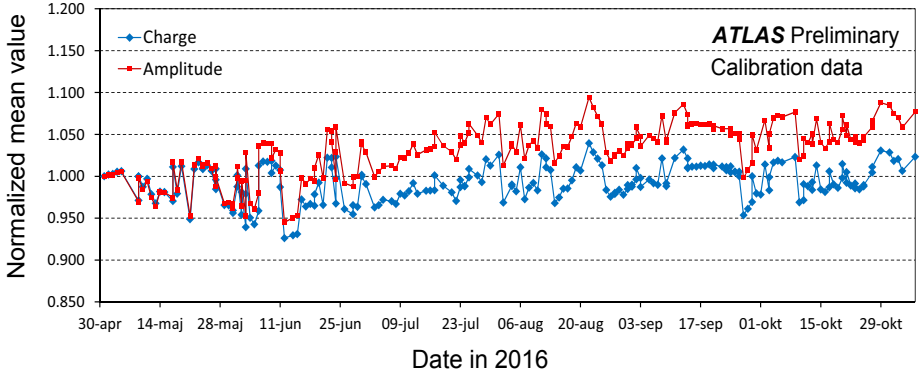
Calibration sessions at each inter-fill. HV adjusted to keep PMT gain constant (~ 10^5)

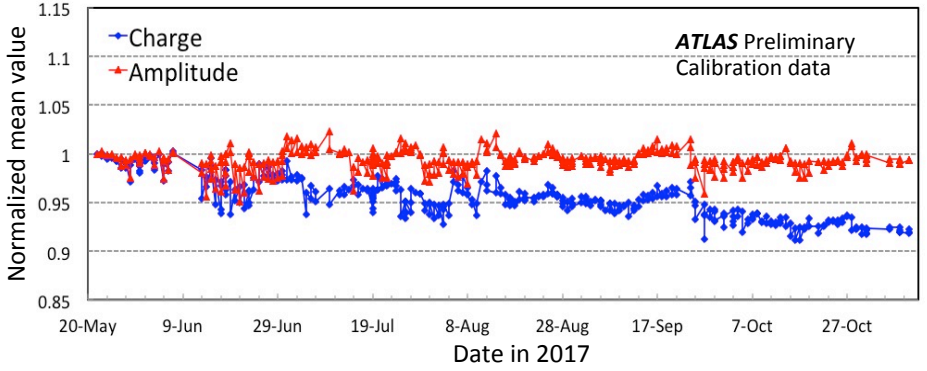
Constant <amplitude> is not the same as constant <charge>



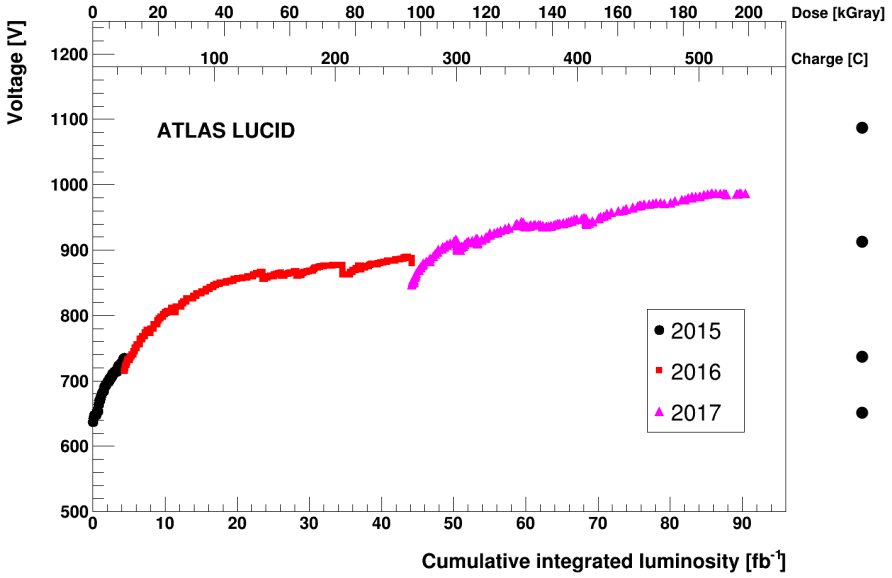
Self-triggered ^{207}Bi signal Amplitude & Charge distributions

since 2017: Amplitude for hit counting, charge for total charge

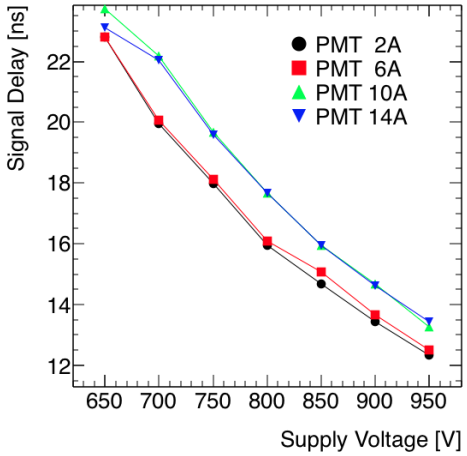


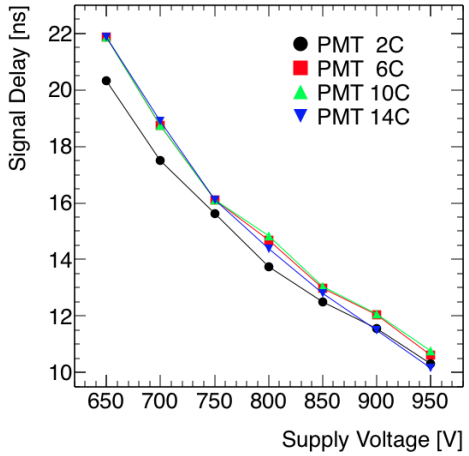


PMT Voltage Evolution



- Maximum HV Hamamatsu R760 can sustain is 1250 V
- Started in 2015 at average HV ≈ 650V for a gain G ≈ 10^5
- Additional 350 V by end of 2017
- Charge produced by PMTs in excess of 500 C



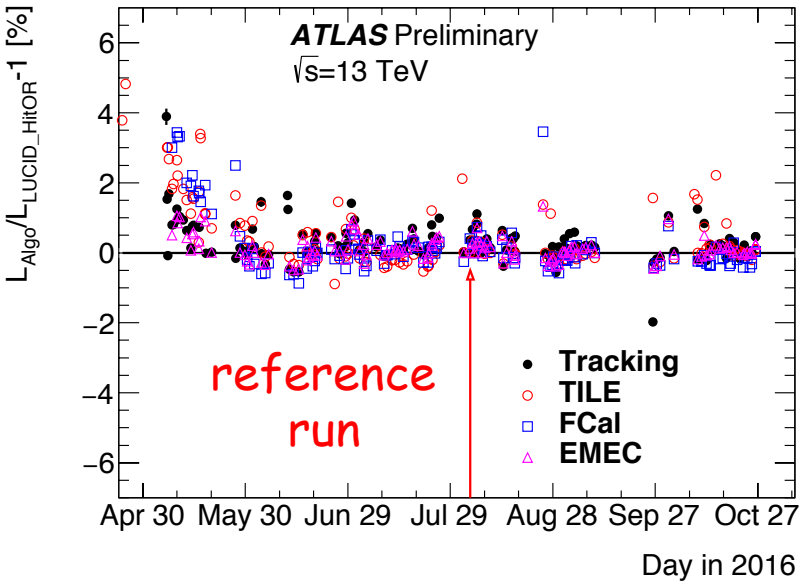


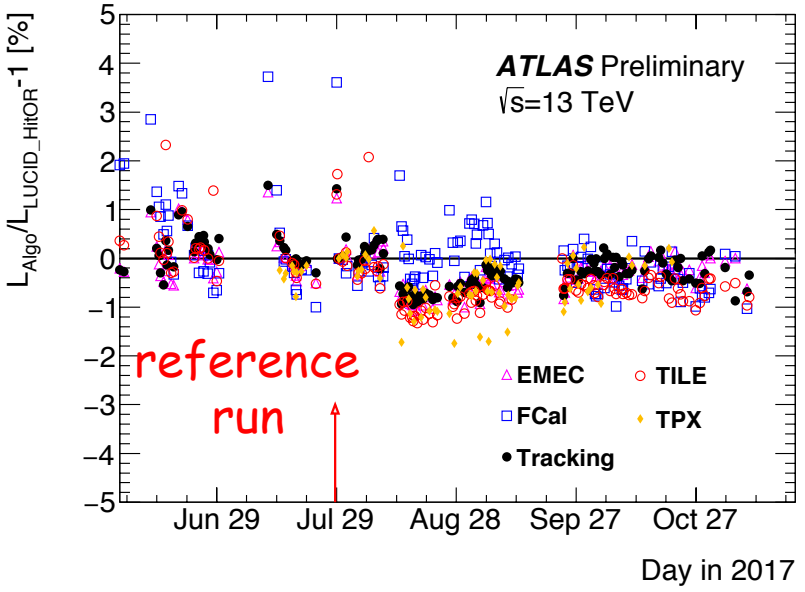
HV-dependent transit-time in PMT affects Q/A ratio

Luminosity measurement accuracy

- Preferred algorithm (hit counting) corrected offline for migration (μ dependence) using track counting
- Other detectors (without individual bunch granularity) used to assess overall stability

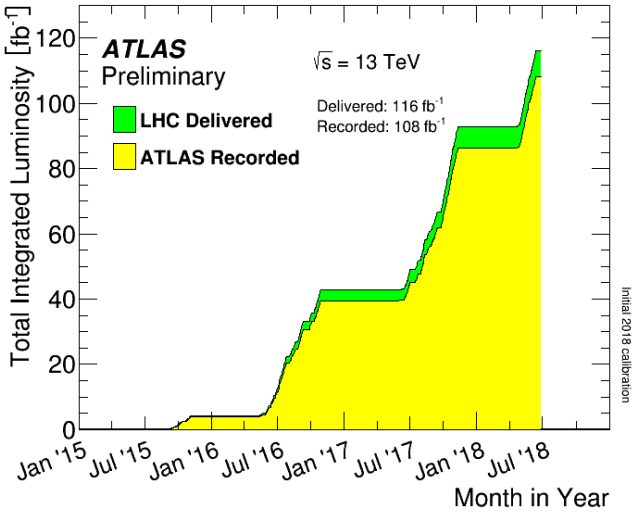
Year	Precision (%)
2015	2.1
2016	2.2
2017	2.4* preliminary

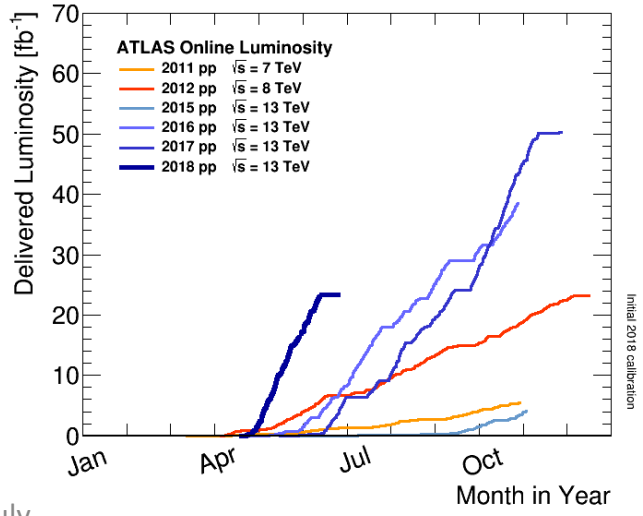




Status and Perspectives

- LUCID-2 is again providing luminosity to LHC and ATLAS in 2018
- First signs of PMT aging: gain losses, few deaths (using spares)
- Redundancy provides safety margin: each individual PMT can be used as an individual detector, combination of several to minimize sensitivity to beam crossing angle
- Run 3 will be challenging as far as PMT lifetime is concerned (additional 150 fb^{-1} in just few years)
- Total charge algorithms to be finalized
- Thinking about HL-LHC (expected $\langle\mu\rangle\approx200$): Run 3 good place for prototypes





Summary

- LUCID-2 is the only detector in ATLAS able to measure the Luminosity delivered by LHC for each individual bunch, both online and offline
- It is as well the only detector providing instantaneous luminosity as needed for luminosity leveling
- LUCID-2 has been providing the official ATLAS luminosity since 2015, with precisions better than 2.5% despite pileup values in excess of 60
- Other detectors are however needed to correct for μ-dependence and assess long term stability, which dominate the overall precision
- LUCID operations demonstrate that a conceptually simple detector can be extremely effective when fit with proper electronics and robust monitoring
- The full potential of LUCID is still to be exploited (optimization of charge measurements)
- LHC Run 3 and HL-LHC in the future