LUCID-3: the upgrade of the ATLAS Luminosity detector for High Luminosity LHC

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for
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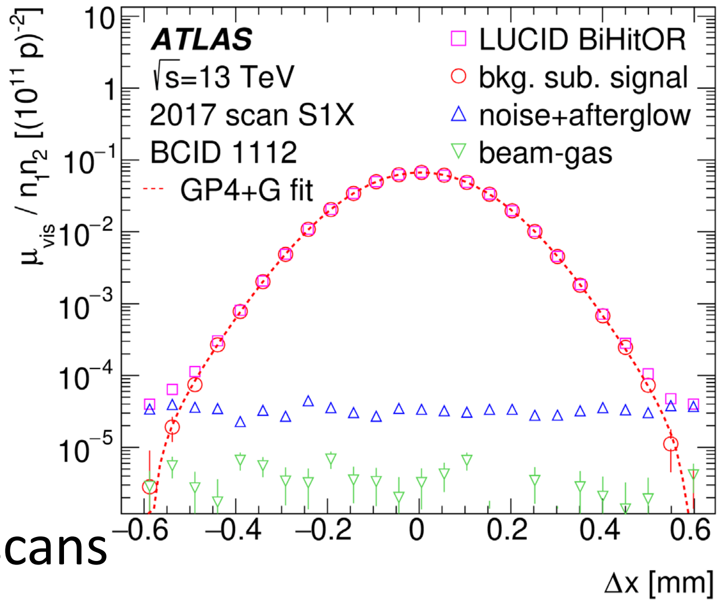
Outline

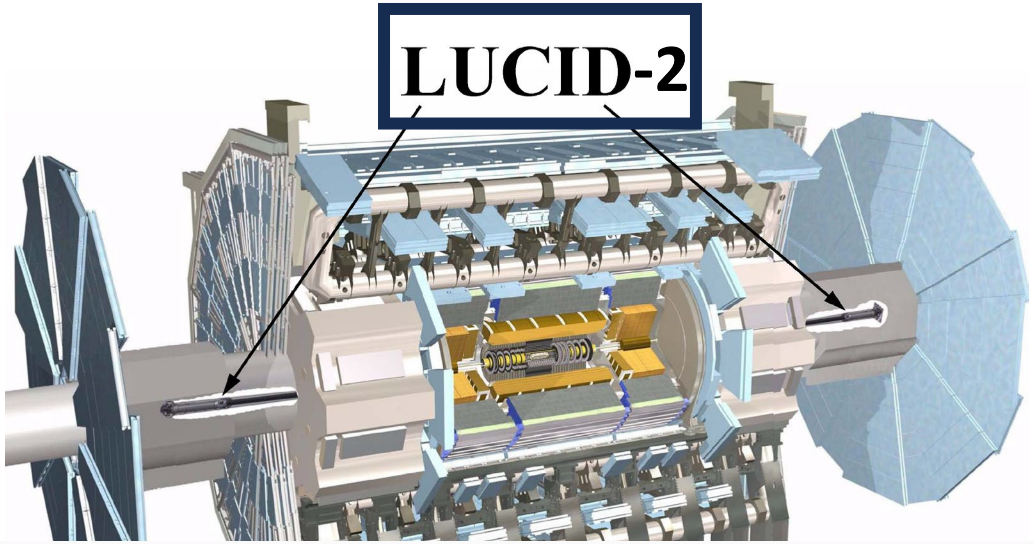
- The importance of the luminosity measurement
- LUCID-2 in LHC Run-2/3
- The challenge of the luminosity measurement in HL-LHC
- The LUCID-3 upgrade for HL-LHC
  - The strategy
  - The LUCID-3 design
  - Prototypes performance in Run-3
- conclusions

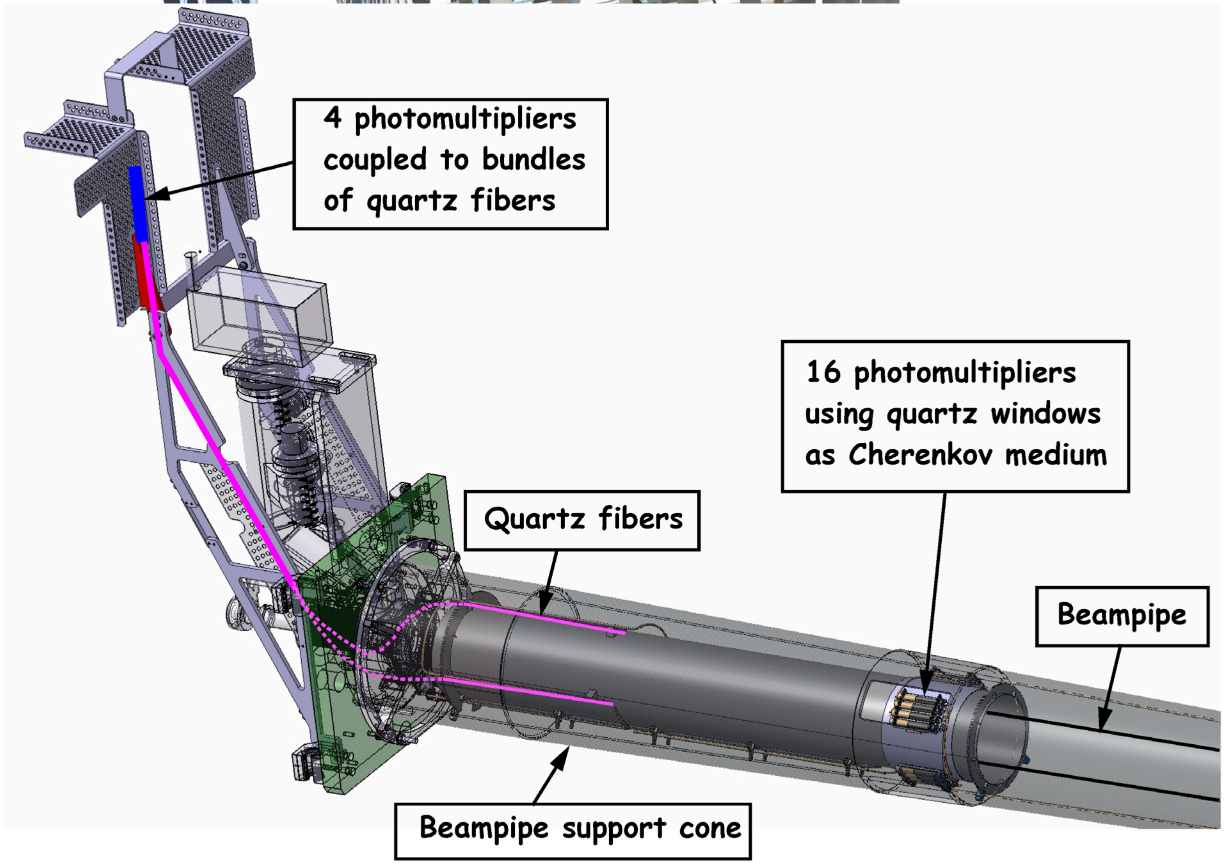
Importance of the luminosity measurement

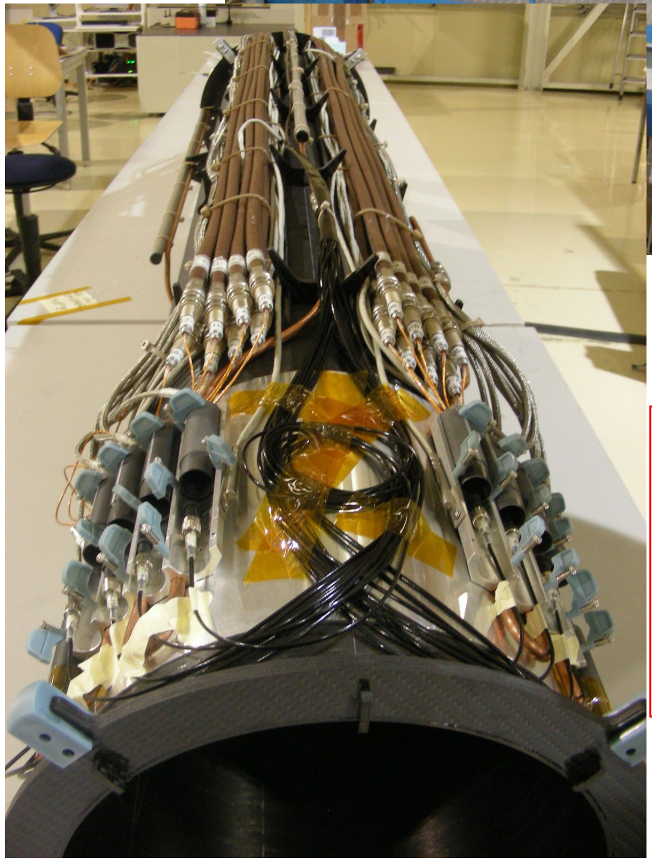
- A precise measurement of the luminosity at a collider is fundamental for:
  - The physics program (cross sections determination, limits for New Physics, etc)
    - Luminosity systematics directly enter into the final systematics
  - Monitoring of the beam conditions (crucial for HLC):
    - Beam operation optimization, lumi-levelling, correct operation in different IPs
  - Efficient data taking of the experiments
    - Vary trigger pre-scales with luminosity



- The luminosity measurement can be sub-divided into 2 steps:
  - absolute calibration, performed at very low luminosity (in ATLAS ~10^{30} $cm^{-2}s^{-1}$) and controlled conditions in dedicated vdM scans
  - The measurement in standard physics at L ~ 10^{34} cm^{-2} s^{-1}
- LUCID-2 provided the ATLAS luminosity measurement in Run-2 with 0.83% precision
  - unprecedented result in a hadron collider







LUCID-2

2 modules symmetric wrt IP

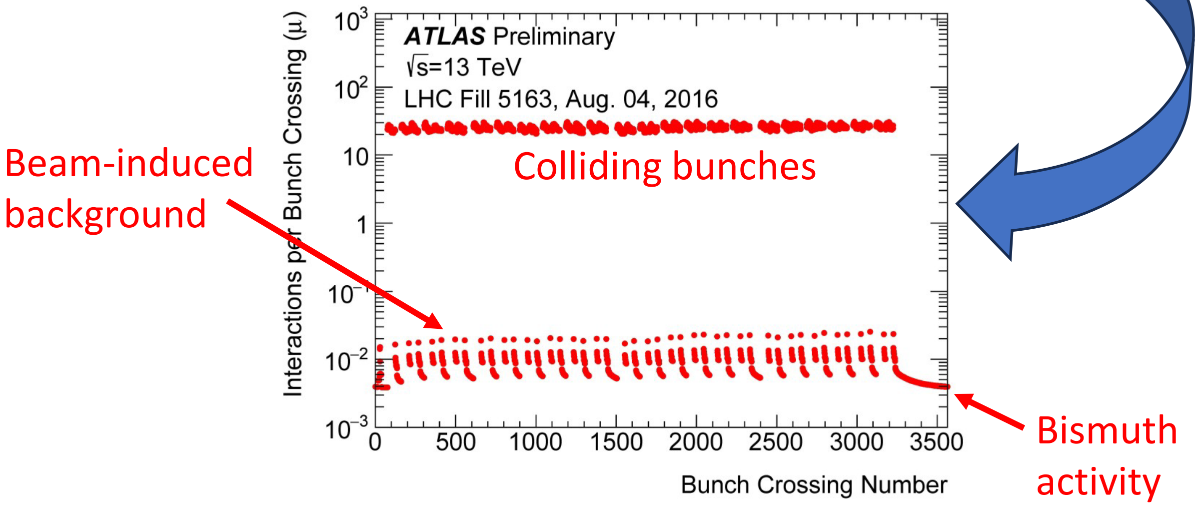
R ~ 12.5 cm

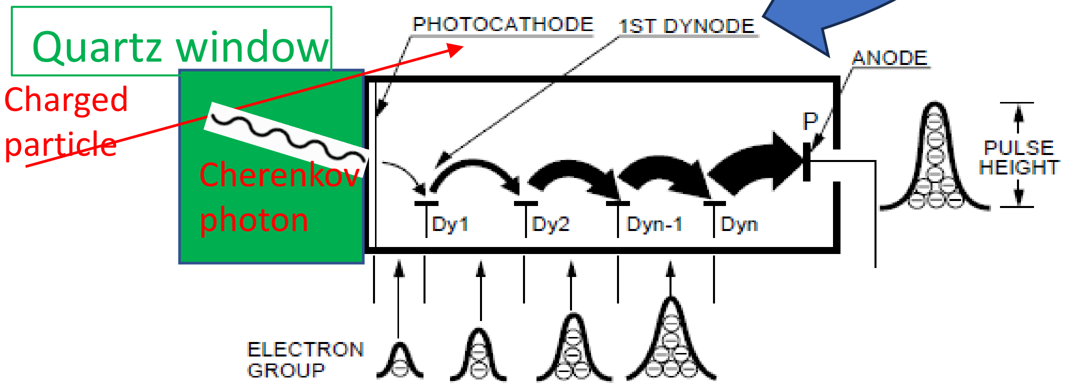
|z| ~ 17 meters from IP

$|\eta| \in [5.56\text{-}5.64]$

How can a PMT detector be innovative ?

1. PMTs measure <u>directly</u> charged particles (no scintillator or similar)
   - Through Cherenkov light produced by charged particles in the PMT quartz window
2. Each PMT measure at ~ 40 MHz rate
   - Bunch-by-bunch measurement

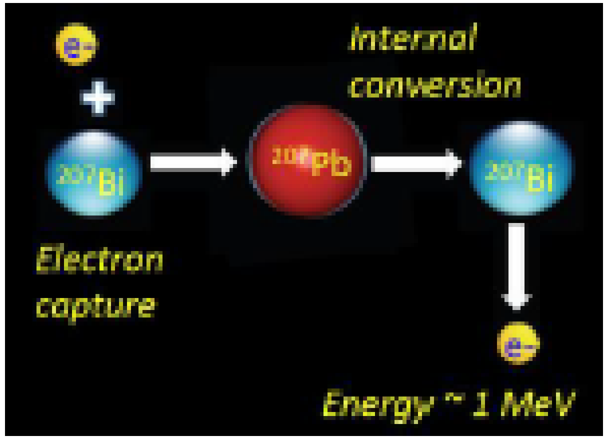


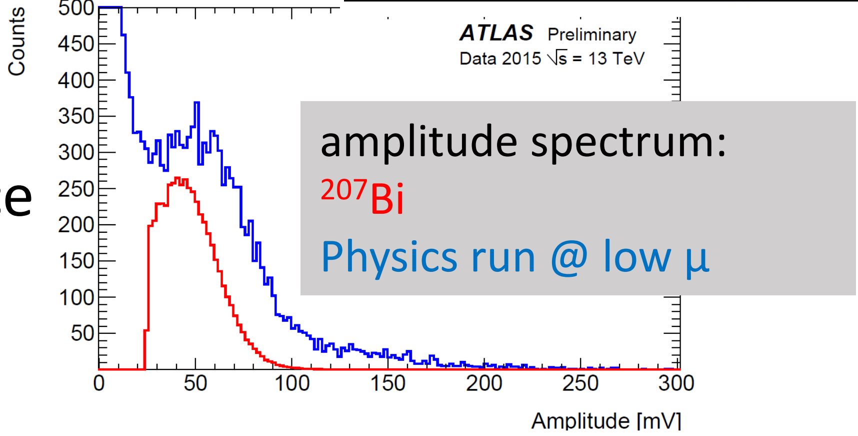


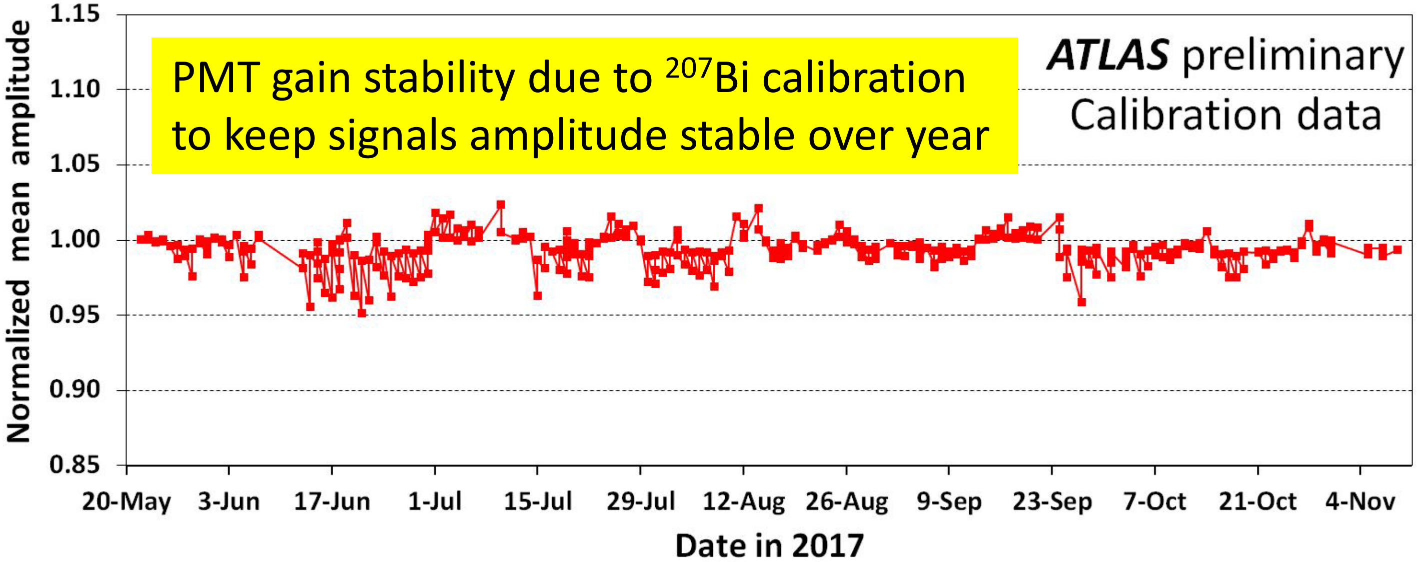
3. Gain is monitored through a ^{207}Bi radioactive source deposited constantly on the PMT window
   - Activity of ~50 kBq does not interfere with luminosity measurement

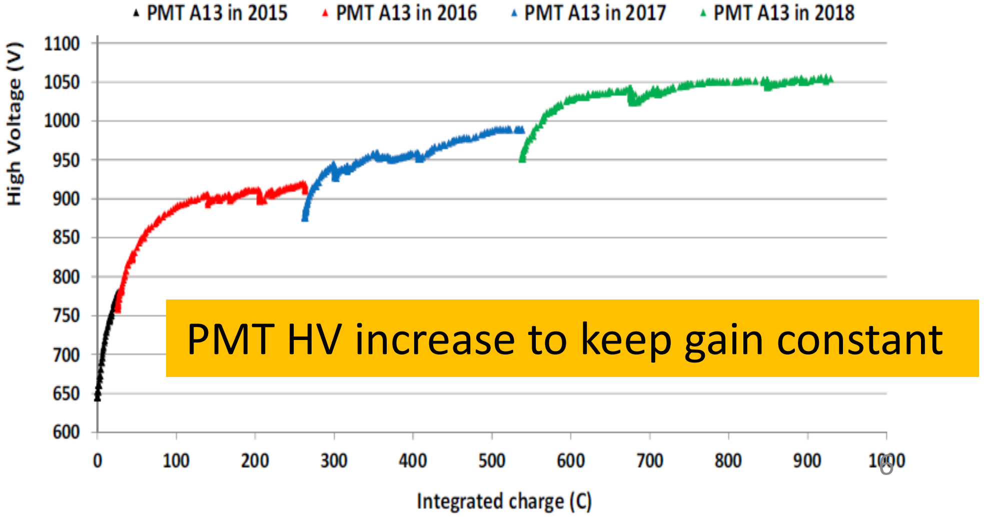
The ^{207}Bi monitoring system

- Large PMT gain losses due to large current produced
  - Would result in increasingly underestimation of L
- Innovative monitoring system based on ^{207}Bi source deposited onto the PMT window
  - Internal conversion monochromatic electrons produce same Cherenkov light (amount & wavelength) as particles from IP





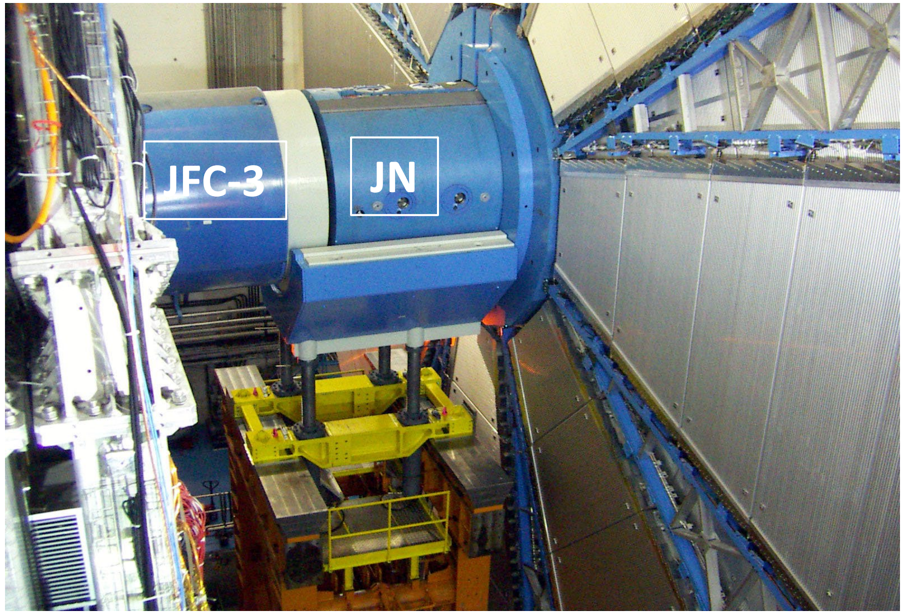


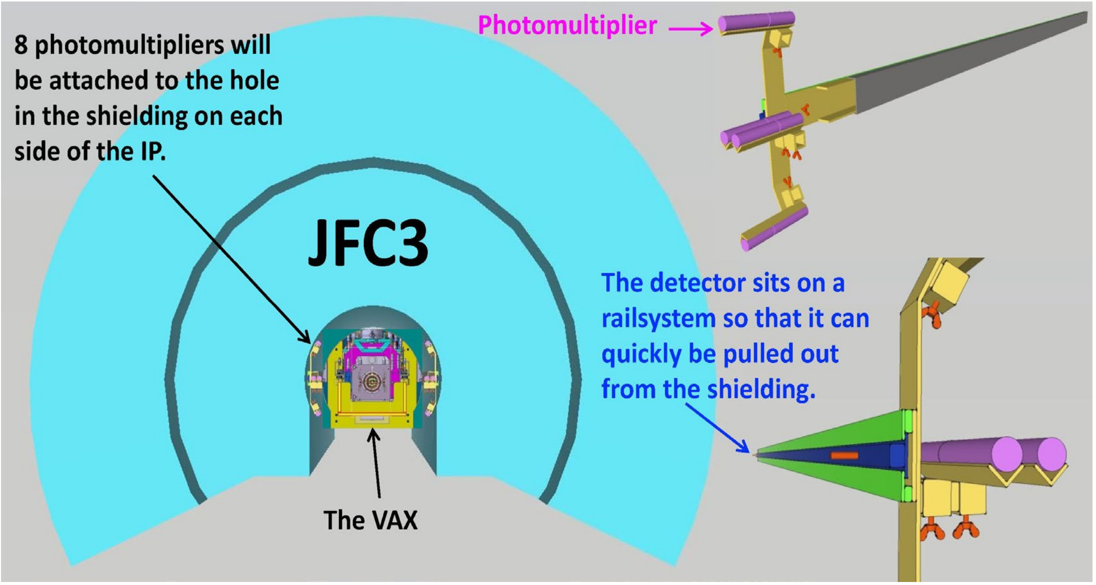


HL-LHC: the challenges

- The Physics challenge: precision analyses call for a ~1% luminosity systematic
  - All systematic sources (vdM, linearity, stability,..) at sub-% level
  - In Run-2 we made it, but HL-LHC conditions much harsher
- The LHC challenge: number of simultaneous interactions per bunch-crossing (μ) ~140 (200 in ultimate scenario)
- The LUCID challenges:
  - Saturation of hit-counting algorithms => move away from beam-pipe, limit PMT acceptance
    - Zero-starvation leads to saturation
  - Radiation hardness & safe maintenance => limit particle flux, use rad-hard components
  - Stability => exploit monitoring/correction tools to mitigate ageing (^{207}Bi)
  - Modularity => independent sub-detectors/algorithms to avoid glitches
  - Avoid interference with new LHC vacuum equipment

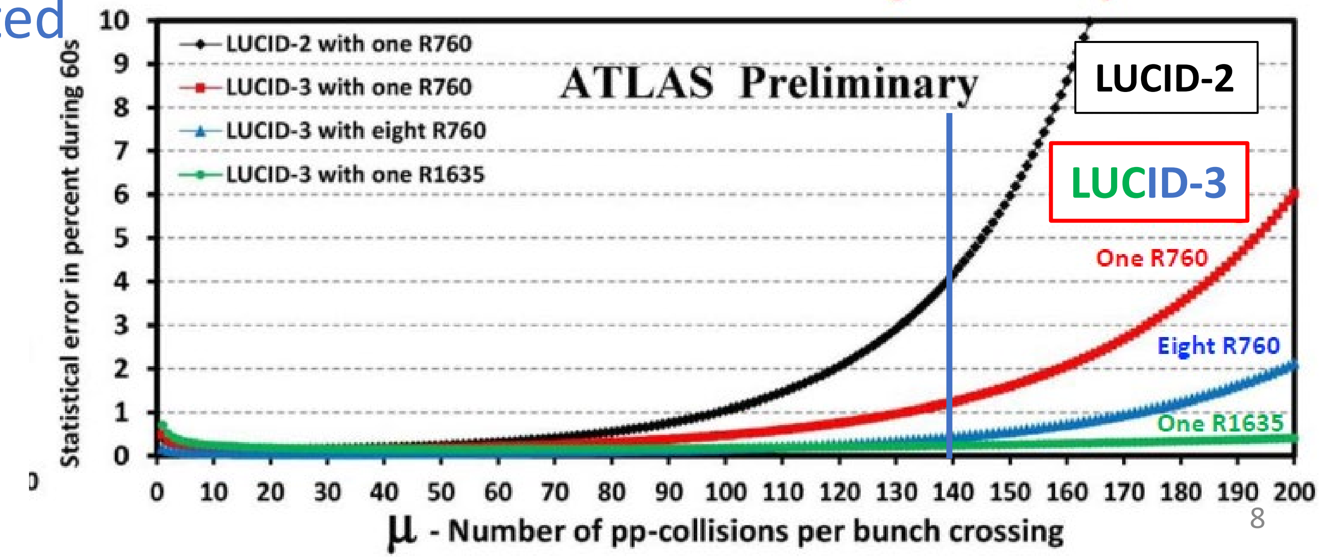
How to limit the acceptance: change location





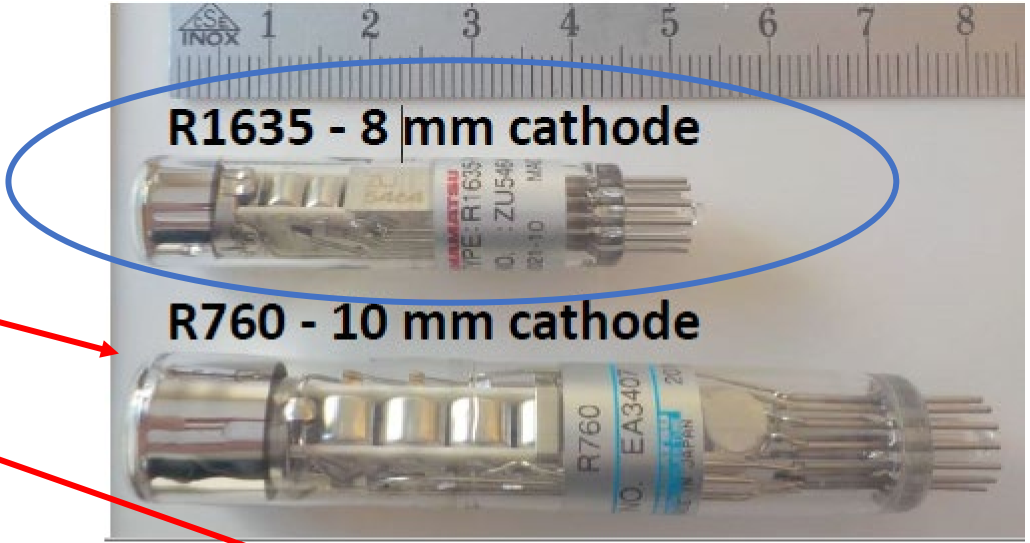
- 30% lower acceptance wrt LUCID-2 predicted by MC at R~ 30 cm in the JFC-3 absorber
- Statistical uncertainty in single bunch luminosity measurement <1% up to μ ~ 140 (200) depending on PMT acceptance

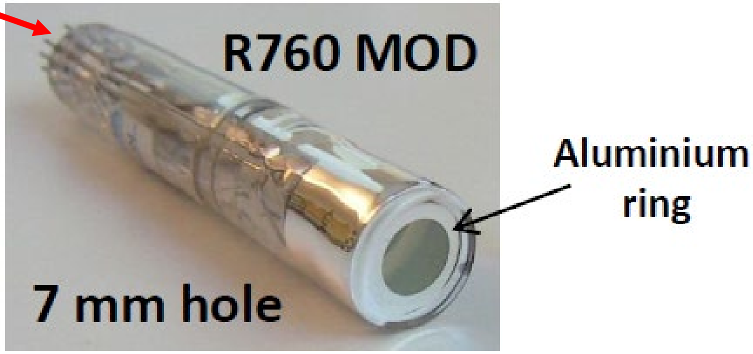
Offline measurements of single bunch-pairs.



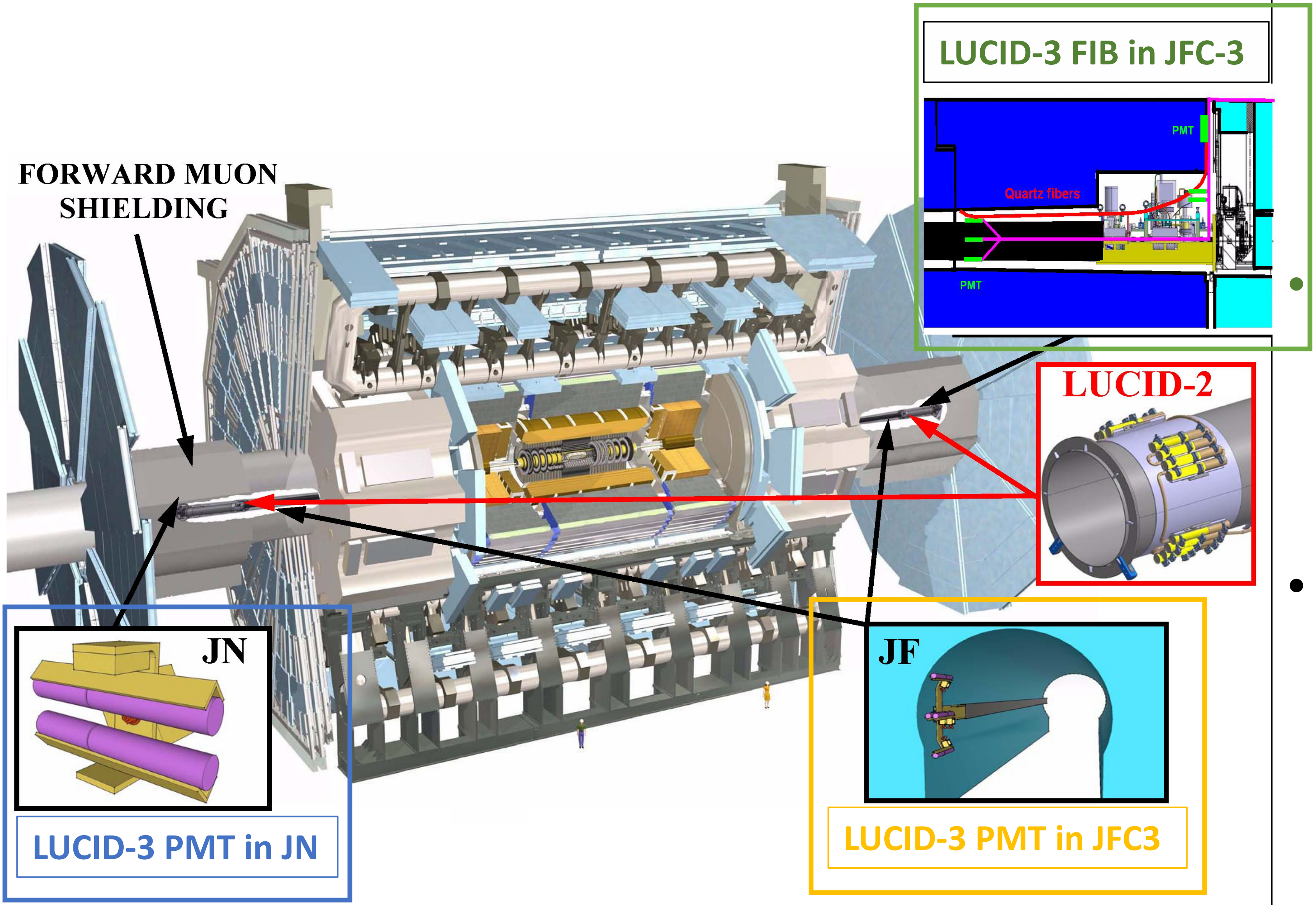
How to limit the acceptance: reduce PMT acceptance

- Additional to increasing distance from the beam-pipe, reducing the PMT acceptance (cathode diameter) is the other handle
- Pure quartz window needed for radiation hardness and Cherenkov light production
- LUCID-2 baseline: Hamamatsu R760
- LUCID-2: first attempt to reduce acceptance
  - Custom modified R760 with Al masking effective but increases non-linearity
- LUCID-3: custom made Hamamatsu R1635 with quartz window produced for LUCID-3
  - Thinner window expected to *slightly* reduce non-linearity
  - Acceptance reduced by ~35% wrt R760
  - Critical: max anode current limited to 30 µA (vs 100 µA of R760)
    - Will it work ?



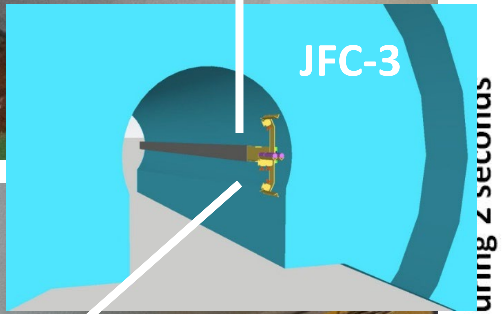


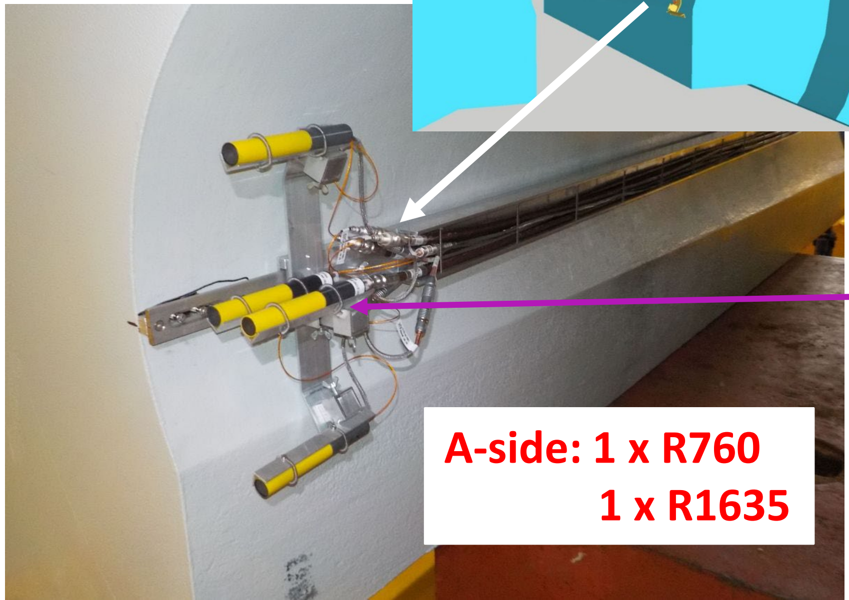
The LUCID-3 project



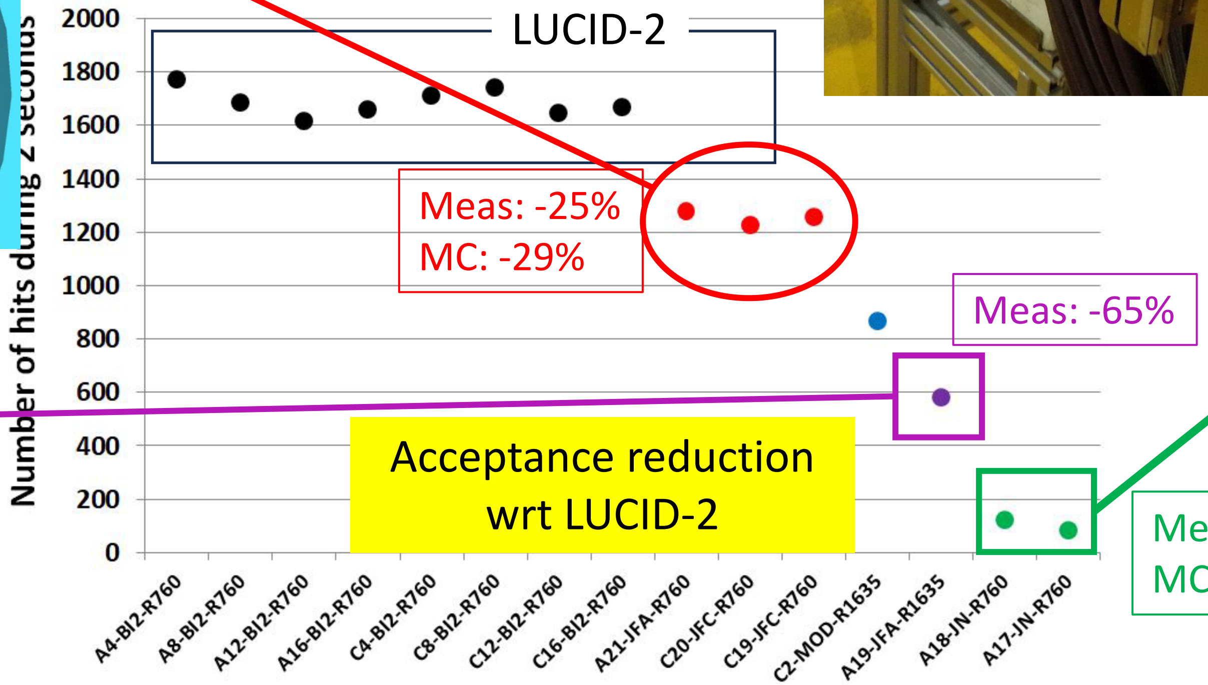
- Baseline detector: PMT detector located in the JFC-3 shielding
  - plus a set of PMTs located in the shadow of the JF shielding to further reduce the acceptance (JN PMTs)
- Complementary detector: Cherenkov-light fiber radiators read-out by PMTs in low radiation area
- All this work if:
  - Acceptance as predicted by MC
  - R1635 performance ok
  - Fiber stability under control
  - In summary: if Luminosity measurement optimal

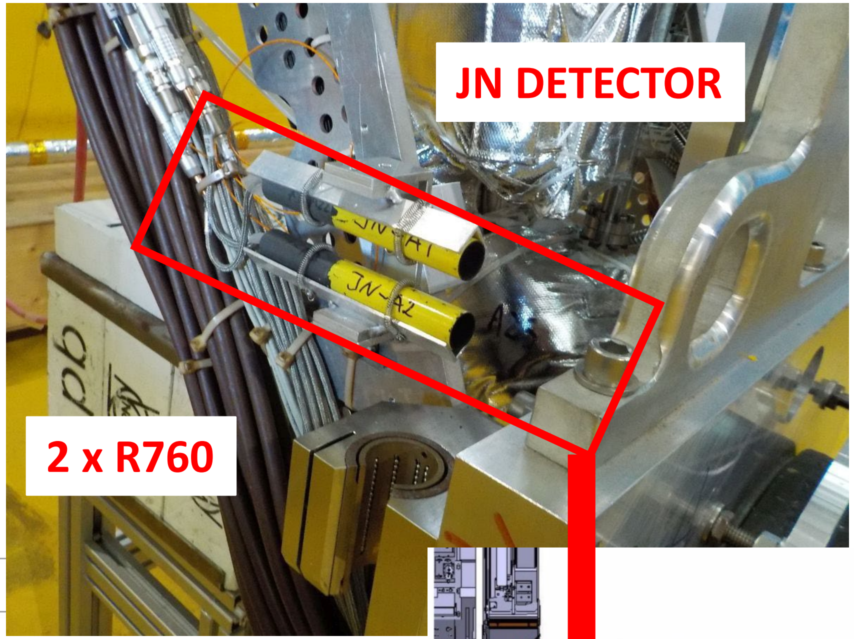
LUCID-3 PMT prototypes in LHC Run-3

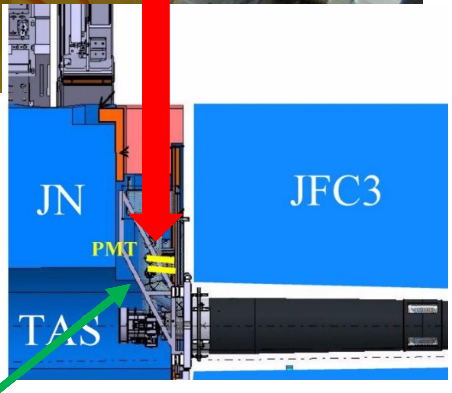




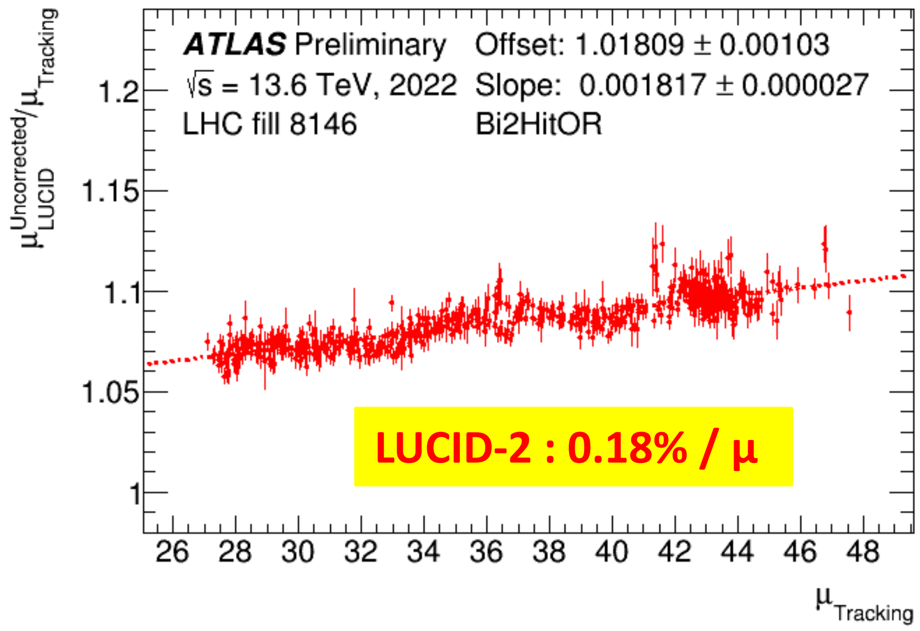
- MC acceptance prediction confirmed by data
  - No saturation and statistical uncertainty confirmed !



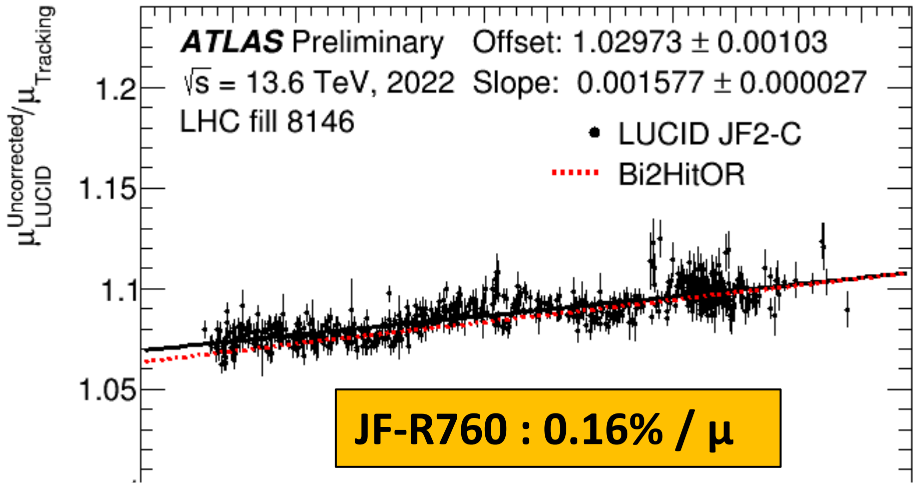


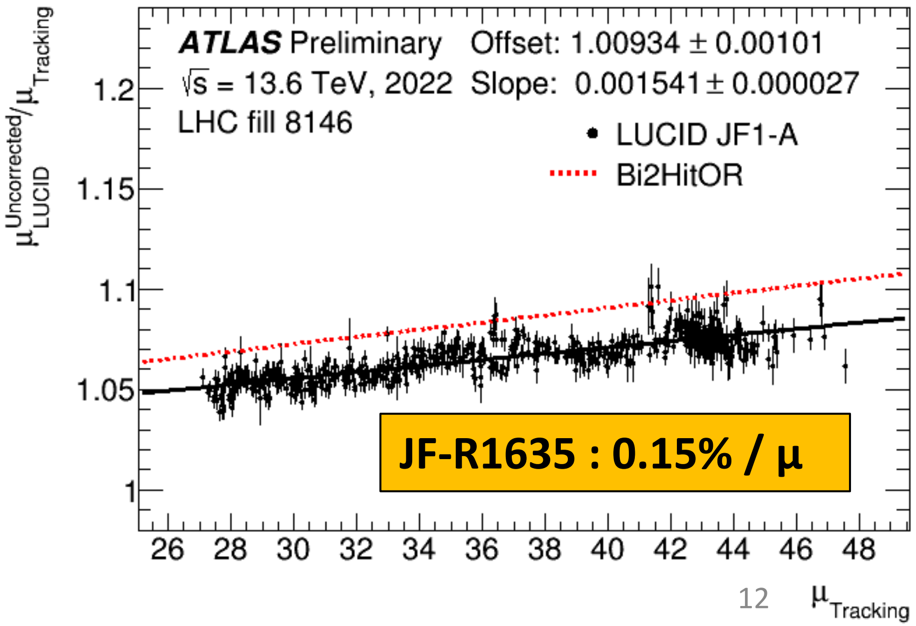


Performance of the JF detector: linearity

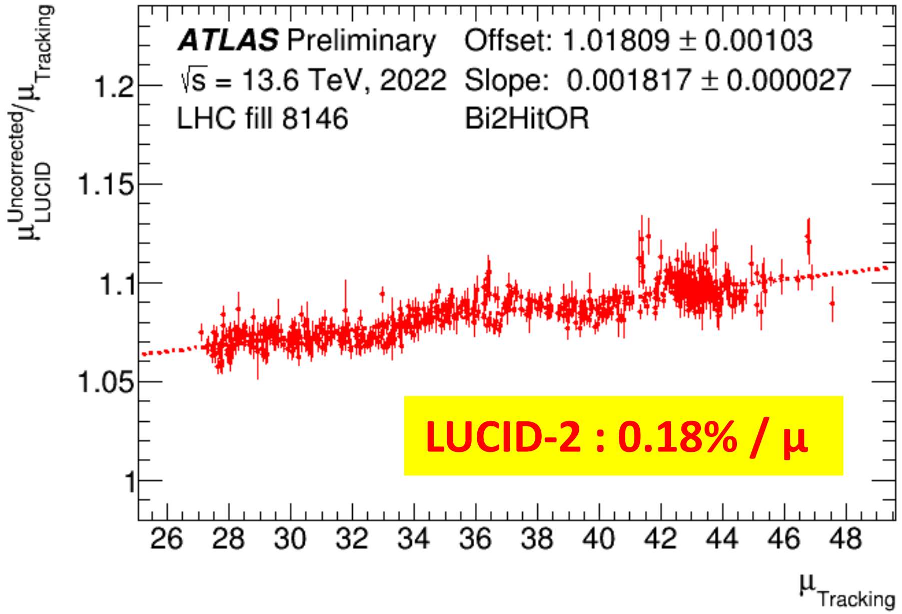


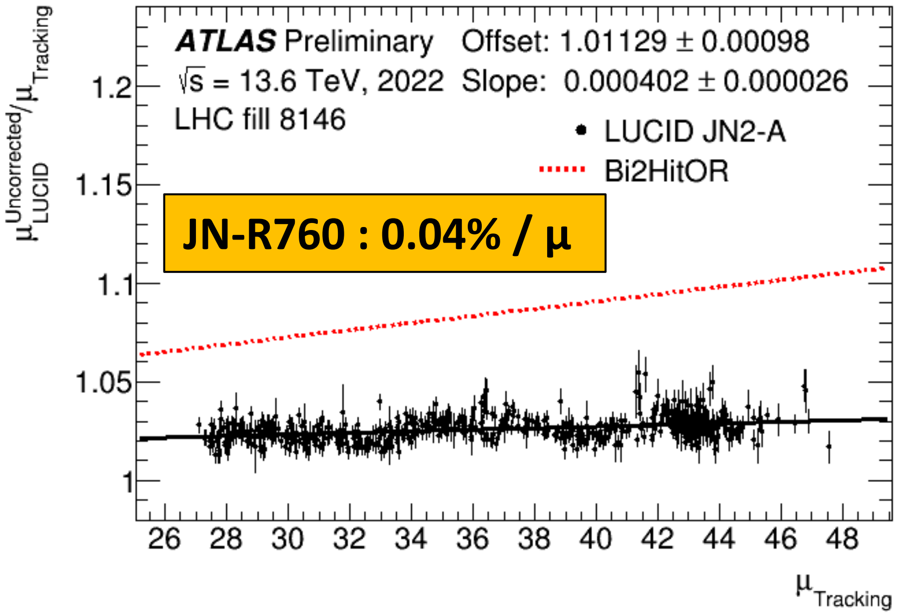
- Sligthly lower non-linearity wrt to LUCID-2 in JF-detector
  - Probably due to lower occupancy
- No difference between R760 and R1635 in the same location
  - But R1635 much more linear than MOD-PMT previously attempted
- JF-PMTs will still need a large non-linearity correction by tracking and/or calorimeters





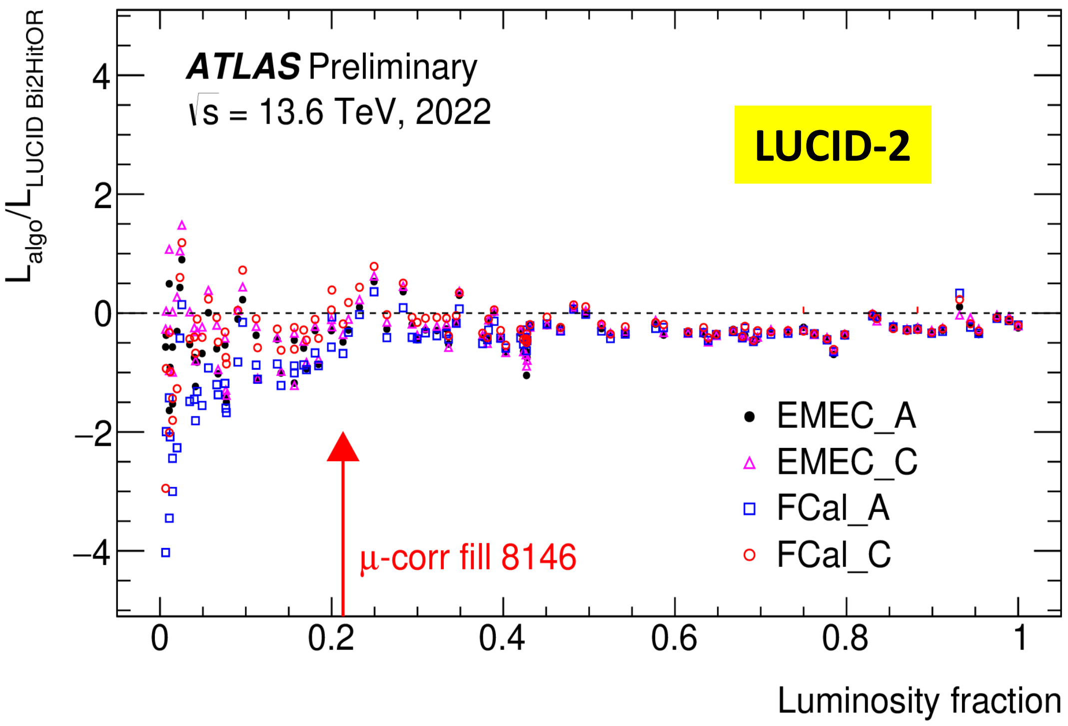
Performance of the JN detector: linearity

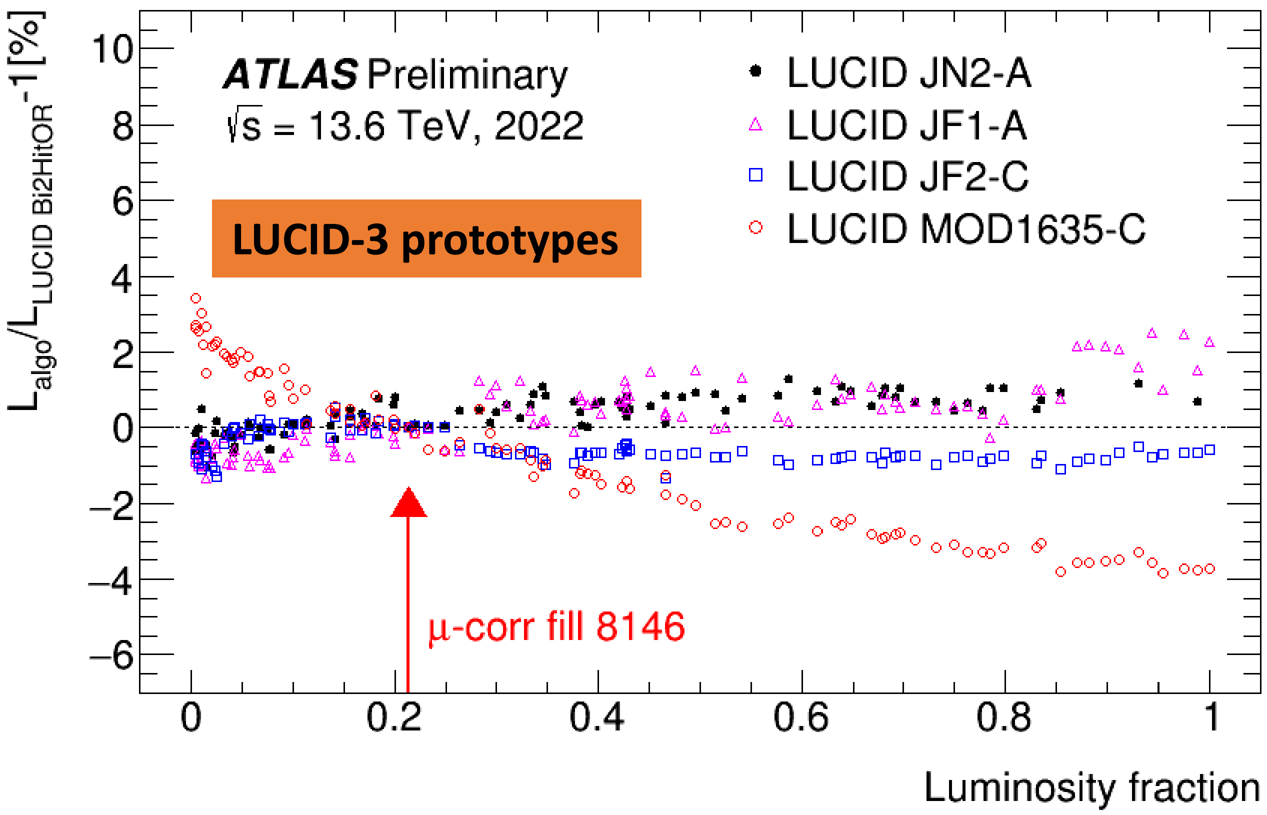




- JN-PMT have 4 times lower non-linearity than LUCID-2
  - due to lower occupancy
- JN-PMTs will still need a non-linearity correction
- by tracking and/or calorimeters
  - same size as LUCID-2 in Run-2 but in 4 times larger μ-range
- No vdM calibration possible due to reduced sensitivity to vdM tails
  - But cross-calibration to JF-detector possible in vdM runs

Performance of the PMT prototypes: stability

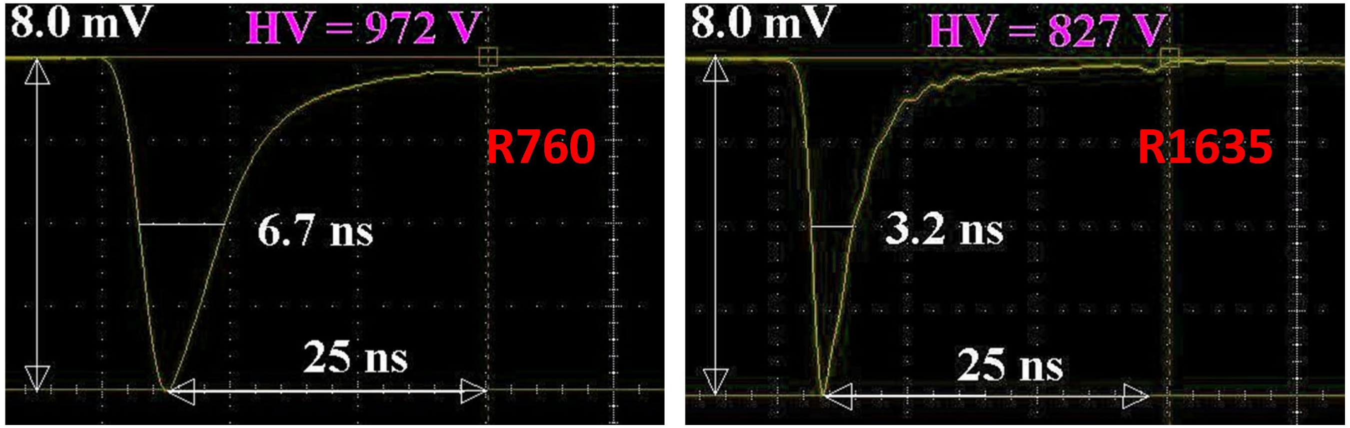


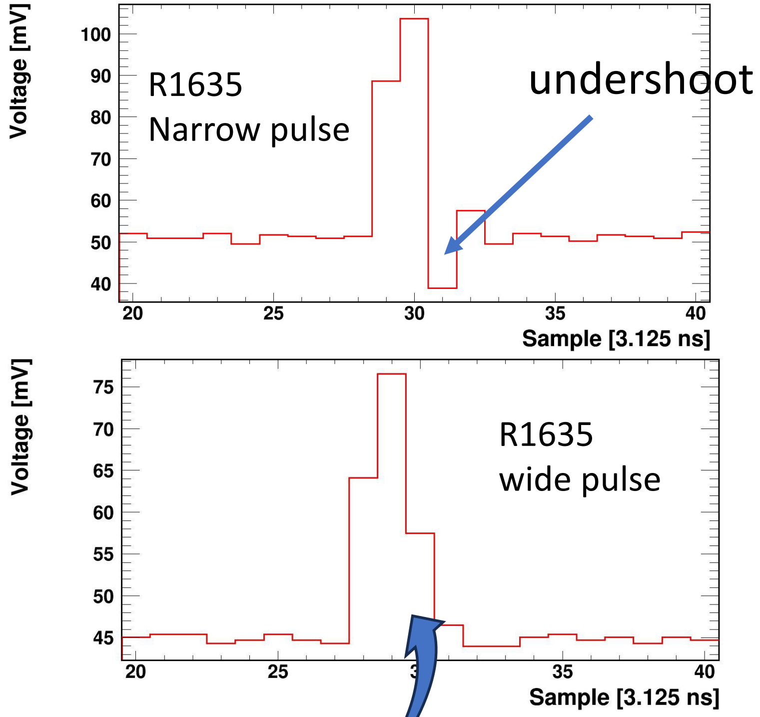


- JF (R760) shows a similar stability and run-to-run fluctuations as present LUCID-2
- JF (R1635) shows overall good stability but larger fluctuations => see next slide
- JN detector shows good stability but with larger fluctuations (small acceptance)
- MOD-1635 is a R1635 located in LUCID-2 region => see next slide

Experience with R1635 PMTs

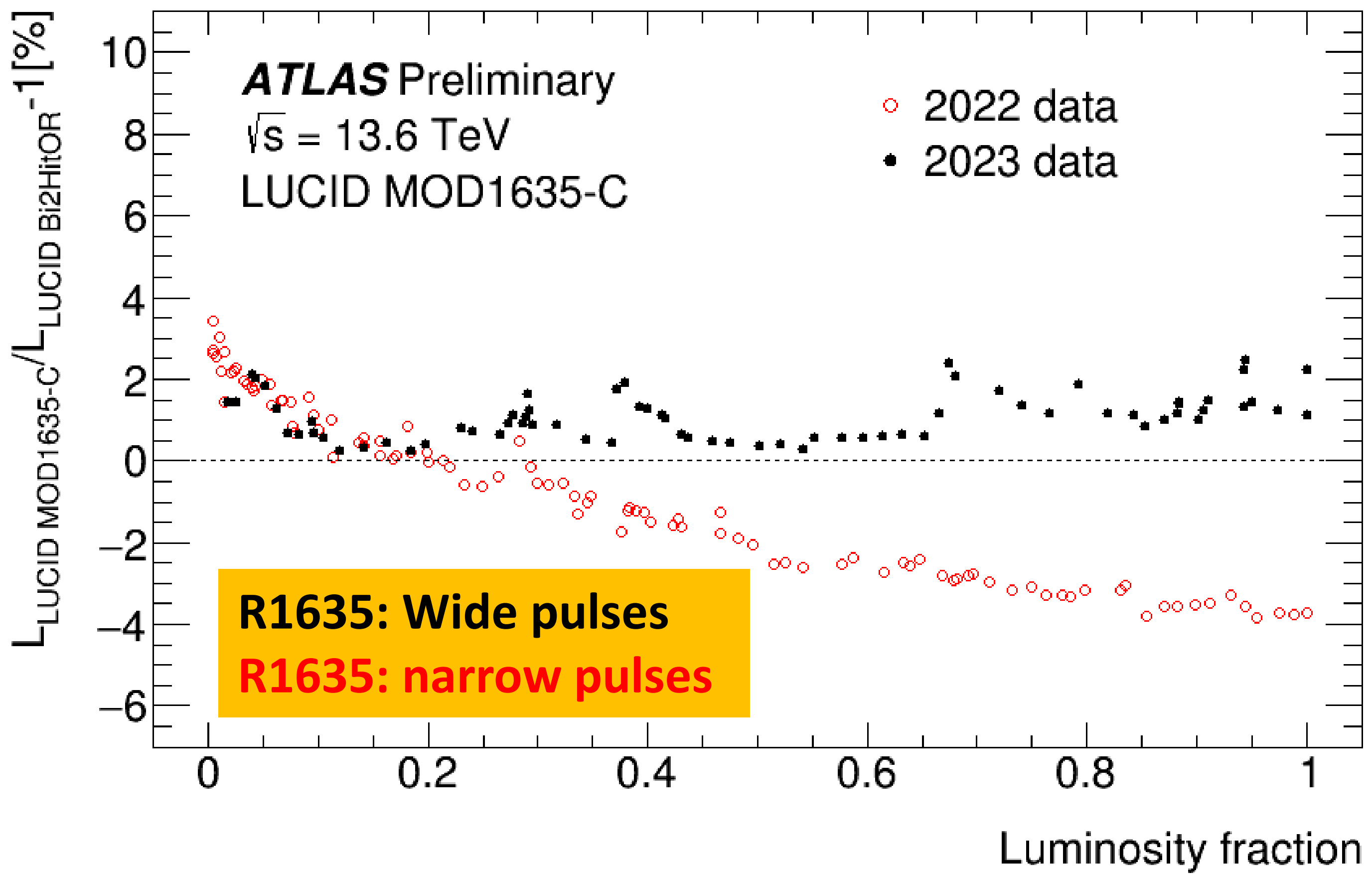
- Two R1635 used in 2022: one in JF and one in LUCID-2 location (C2 PMT)
  - LUCID-2 region characterized by 30% larger particle flux
  - C2 PMT works at the limit or out of current specs (I > 30 µA)
- Signals from R1635 narrower than R760





- The present RO electronics (LUCROD) has 320 MHz sampling FADC
  - Too slow for R1635 signals precise sampling
  - Temporary solution was to add capacitors to widen R1635 signals
  - RO electronics for HL-LHC will have to have double frequency sampling FADCs (see backup)

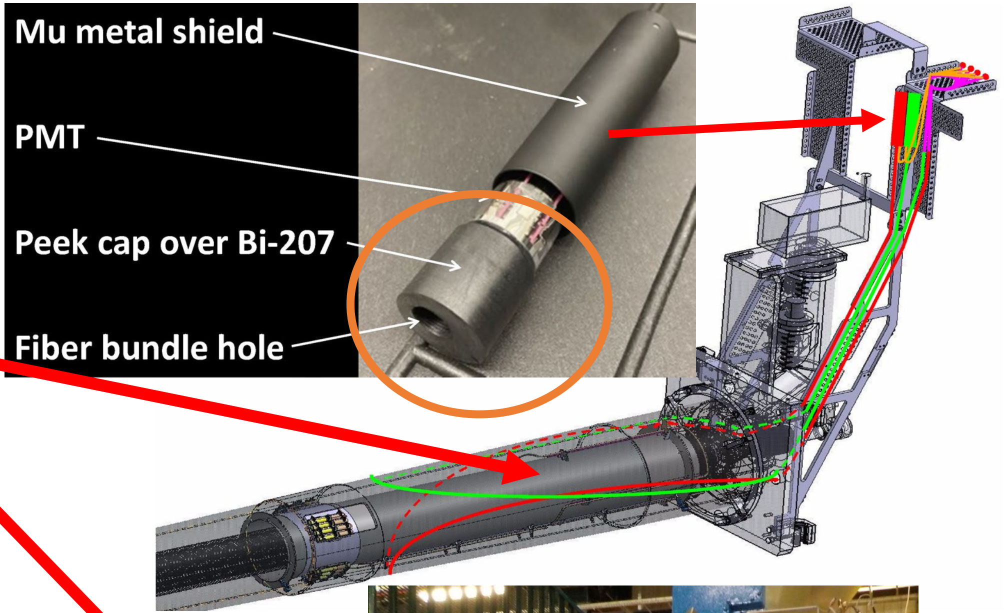
R1635: from narrow to “normal” pulse width

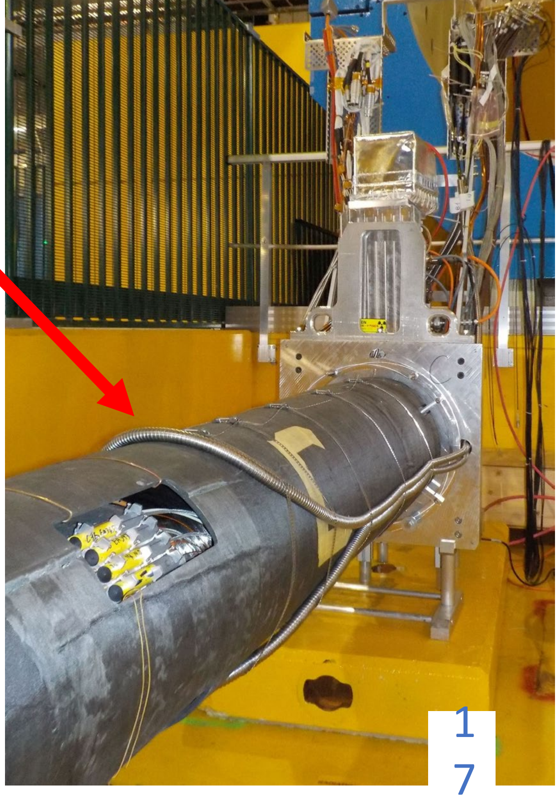


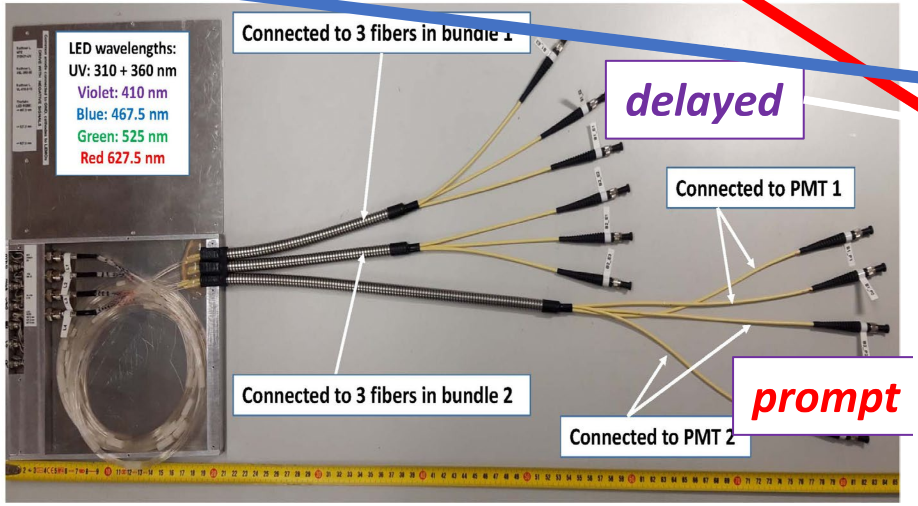
- After signals made as R760, C2 stability significantly improved
  - C2 works at the limit/out of specifications
  - Used as test bench for PMT resistance
- Same intervention foreseen in next end-of-year shutdown also for JF R1635 PMTs
  - Expected to improve time-stability and possibly non-linearity

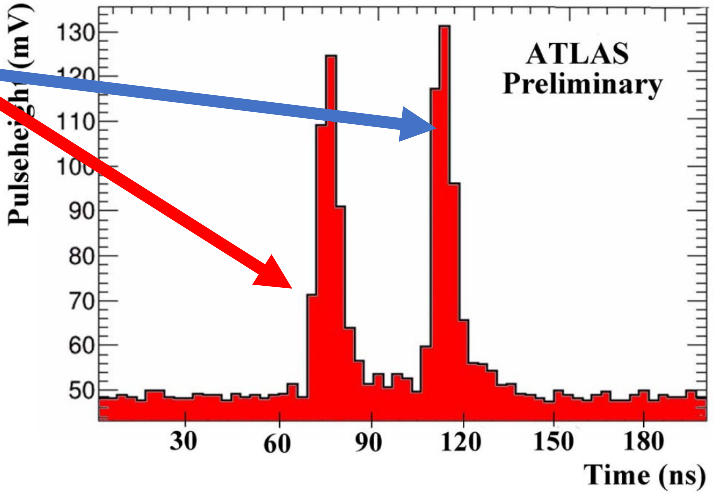
Prototypes: the fiber detector

- 2 fiber bundles built and installed in Side-C
  - Made of about 50 new rad-hard quartz fibers
  - Read-out by R7459 PMTs (ϕ=28 mm)
- Equipped with a new monitoring system:
  - ^{207}Bi for PMT gain-monitoring/HV-adjustment
  - LED light of different wavelengths from UV to green: injected directly (***prompt***) and through the fiber (***delayed***) to monitor fiber degradation (see backup)









conclusions

- LUCID-2 provided an exceptional measurement of the luminosity in Run-2 but needs an upgrade to cope with HL-LHC conditions
- The proven PMT-technology will be preserved, but a new location and smaller PMTs will be deployed to cope with the increase of μ
- A complementary fiber detector will be built if its performance will prove to be suitable
- Prototypes for both technologies have been installed in Run-2 and are taking data
  - Results from the PMT prototypes confirm that the detector will cope with the HL-LHC physics program needs
  - The analysis of the fiber prototypes is ongoing
- a redesign of the readout electronics is ongoing, to match with the R1635 signals and to be consistent with the ATLAS TDAQ in HL-LHC

backup

LUCID-2 in LHC Run2/3

- LUCID-2 provided the ATLAS luminosity measurement
  - Both online and offline, in all beam conditions, luminosity ranges, filling schemes, pp and HI collisions
- In Run-2 a luminosity precision of 0.83% was achieved
  - unprecedented result in a hadron collider

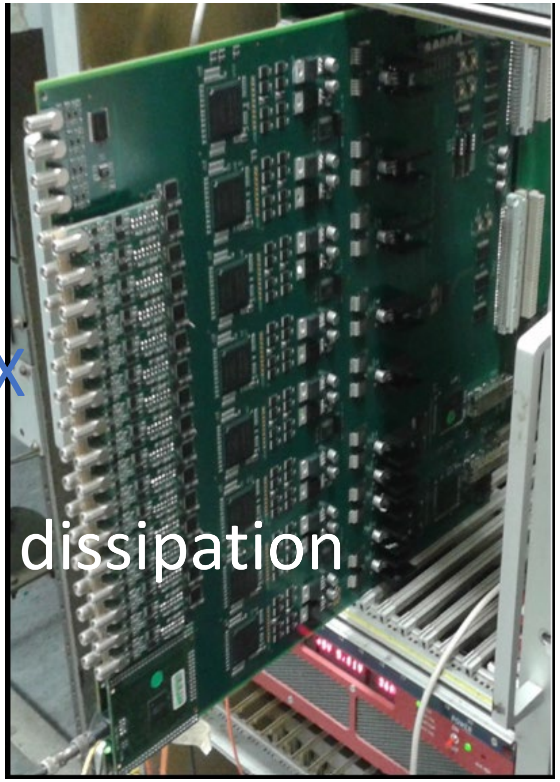
Data sample	2015	2016	2017	2018	Comb.
Integrated luminosity [fb^{-1}]	3.24	33.40	44.63	58.79	140.07
Total uncertainty [fb^{-1}]	0.04	0.30	0.50	0.64	1.17
Total uncertainty [%]	1.13	0.89	1.13	1.10	0.83

- Cannot be regarded as a LUCID-alone measurement:
  - LUCID non-linearity up to 10% between the vdM and physics needed a correction using track-counting based algorithms
  - The LUCID long-term stability has been checked using the calorimeters measurement
- In the next slides a description of the present LUCID-2 as many of its features will also apply to the upgrade for HL-LHC

Criteria for the LUCID-3 design

- PMT detector on JF-shielding:
  - Increased distance from beam-pipe to reduce acceptance by 30% (50%) for R760 (R1635)
  - Mitigation of radiation and charge-induced ageing
  - Easy yearly maintenance:
    - JF brought to surface in end-of-year shutdowns
    - PMTs mounted on sliding rails to operate at ~1 meter from JF activated surface
    - PMTs can be substituted in 1 minute each => ~20 µSi dose for full detector replacement
- PMT detector behind JF (JN detector)
  - Predicted acceptance <5% of LUCID-2
  - Background-induced non-linearity should be dramatically reduced
  - No ageing foreseen (survive full HL-LHC)
- Fiber detector:
  - Construction depending on:
    - Need of complementarity wrt to PMTs (algorithms, hit-counting saturation)
    - Proof of full functionality (not satisfying in Run-2): monitoring of PMT and fiber ageing
- All solutions need test on beam

LUCID-3 electronics



- The LUCID-3 electronics will be an evolution of the Run-2/3 based on the LUCROD* board sending data directly to the FELIX
  - Integrated in the Run-4 TDAQ infrastructure
- Decision on VME vs ATCA depends on power delivery and heat dissipation
- Main modifications:
  - FADCs to sample at 640 MHz (vs present 320 MHZ)
  - Upgraded version of FPGAs under study
  - Optical interface through 2 lpGBT links and 1 VTRx+ transceiver
- Under study implementation of algorithms combining SideA & SideC
  - Idea is to abandon the LUMAT card and perform combinations at the FELIX software

* *LUCROD board is a custom board designed, produced and commissioned by INFN-Bologna and is currently used also by ZDC in Run-3 thanks to firmware/software developments done in Bologna*.

R760 vs R1635: gain monitoring and HV adjustment

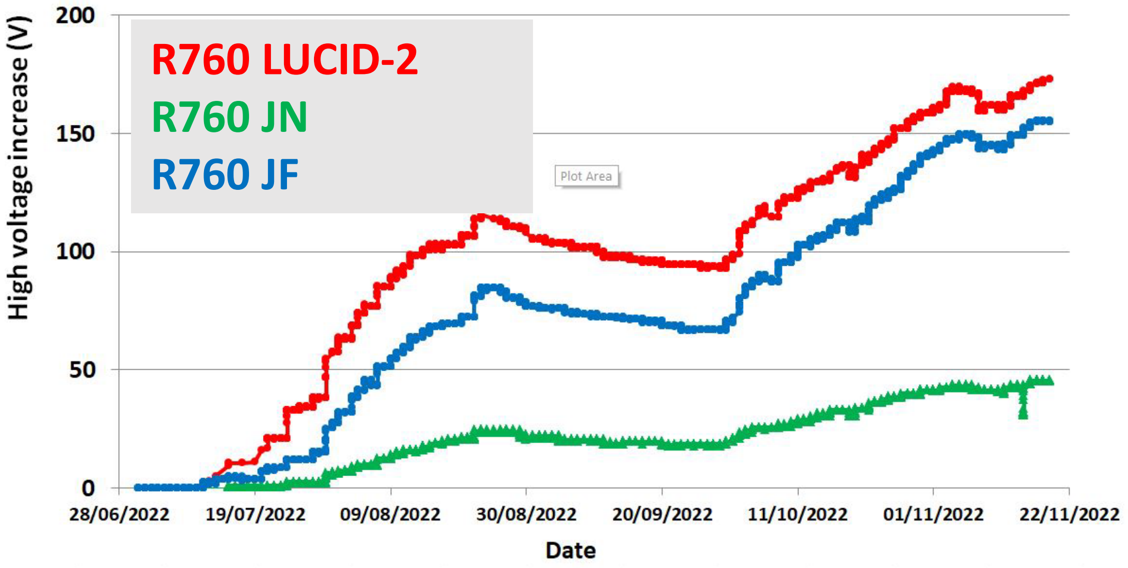
- HV adjusted after each LHC fill to keep gain constant (^{207}Bi calibration)
- After an integrated luminosity of ~ 40 fb^{-1} (year 2022)

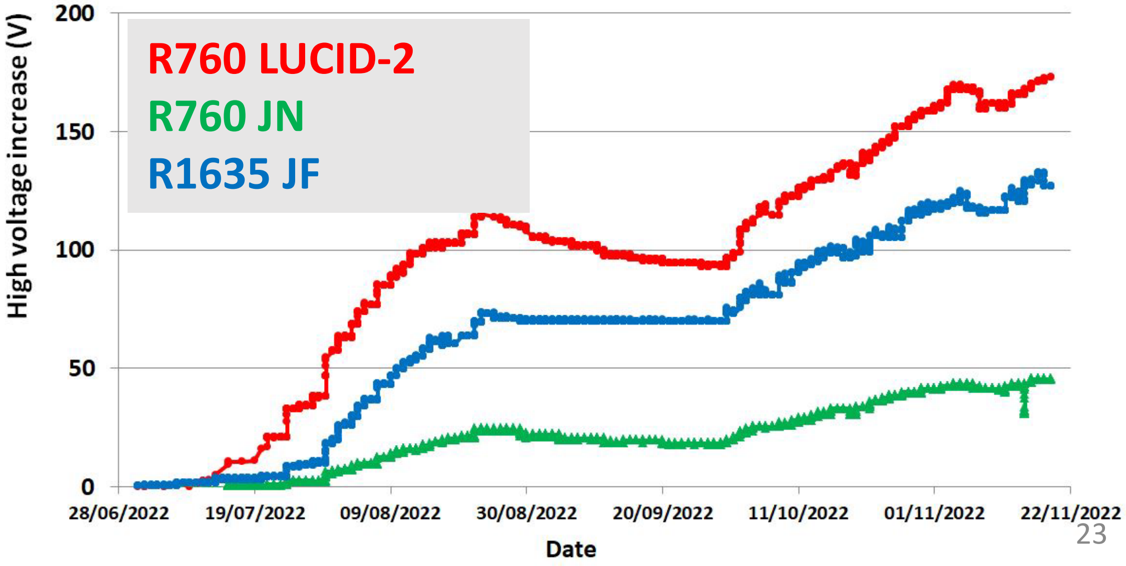
R760

- 180 V increase for a typical LUCID-2 R760
- 150 V increase for R760 in JF (lower particle flux)
- < 50 V increase for R760 in JN location (very small flux ➔ ageing drastically reduced)

R1635

- 120 V increase for R1635 JF





Fiber ageing with radiation

- Fibers irradiated with γ's at ENEA with total dose corresponding to 3 years of Run-3
- Online monitoring of the fiber's opacification as a function of wavelenght
  - 6 wavelengths (285-627 nm) cycled during irradiation
- Large losses observed in UV range
  - Much lower effect at larger λ
  - filter inserted in one of the 2 prototypes to compare the long-term behaviour w/wo UV component
- Ratio between prompt and delayed signal to be used to correct offline the luminosity measurement
  - Analysis ongoing