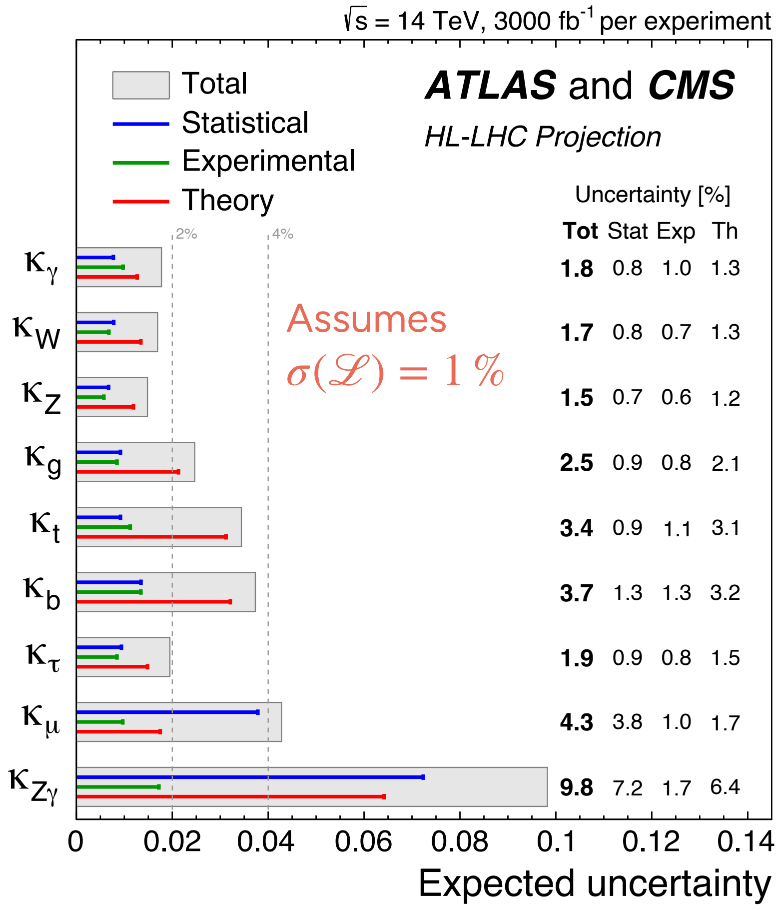
Towards an ATLAS luminosity measurement at HL-LHC

42nd International Conference on High Energy Physics, Prague, July 18-24, 2024

Christian Ohm (KTH), on behalf of the ATLAS Collaboration

Importance of precise luminosity measurements at HL-LHC

High-precision measurements key goal, e.g.
Higgs sector (ATLAS & CMS Snowmass report)



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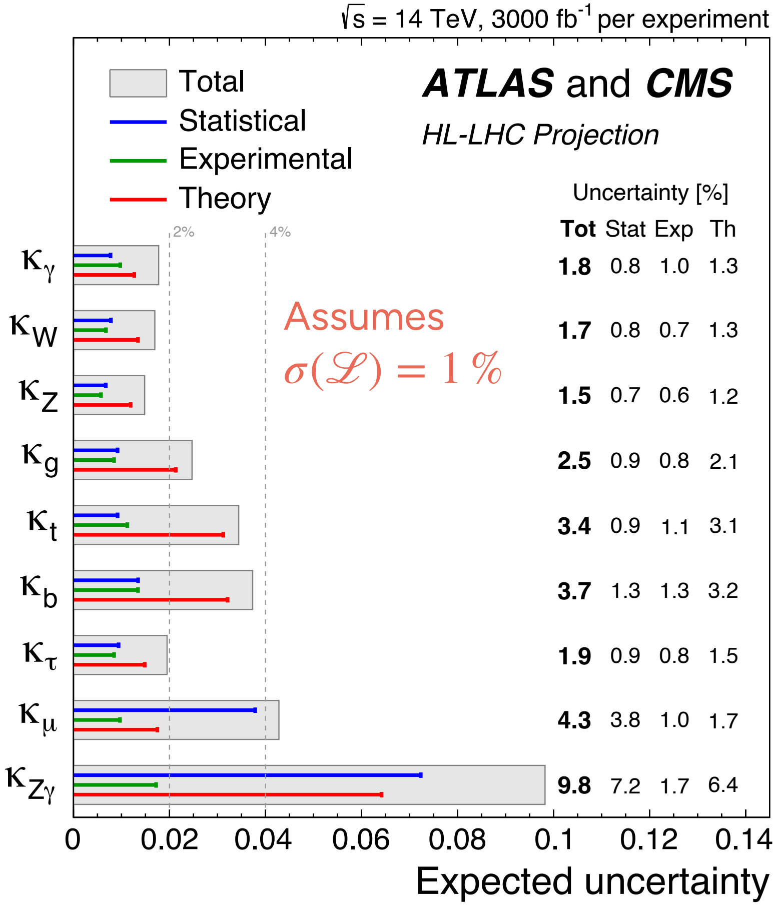
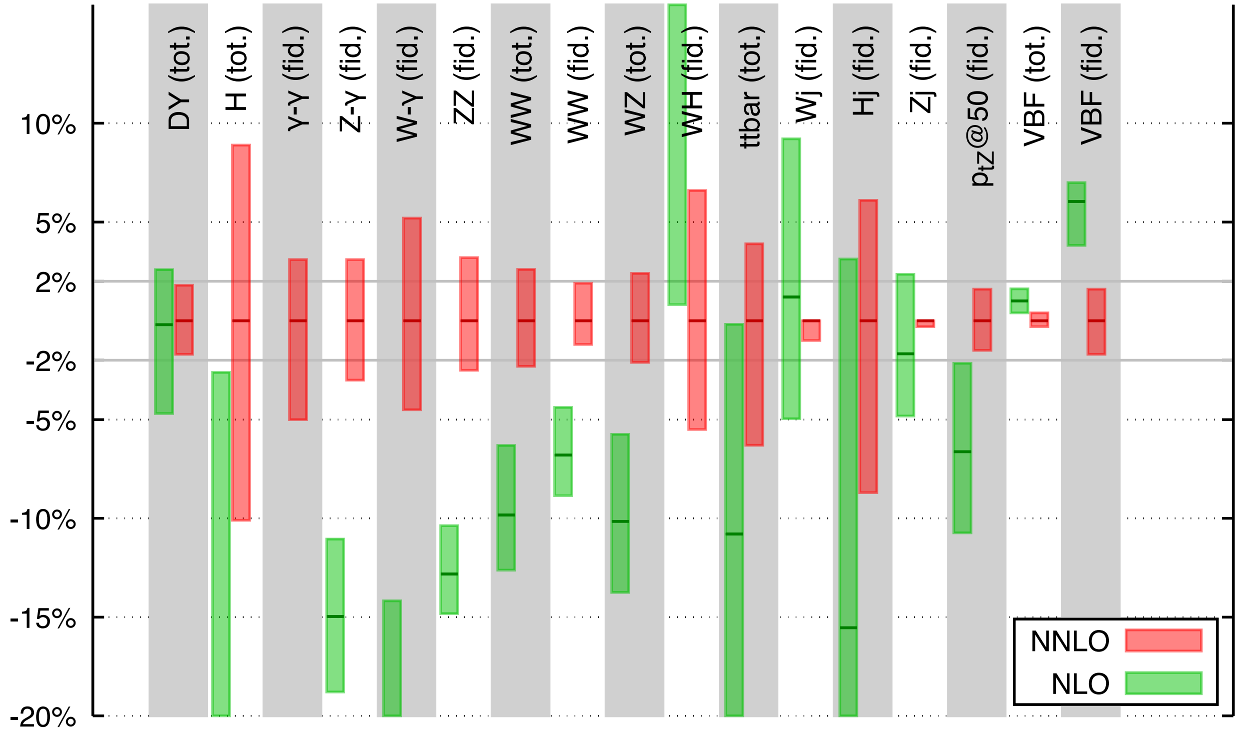


	Tot	Stat	Exp	Th
κ_γ	1.8	0.8	1.0	1.3
κ_W	1.7	0.8	0.7	1.3
κ_Z	1.5	0.7	0.6	1.2
κ_g	2.5	0.9	0.8	2.1
κ_t	3.4	0.9	1.1	3.1
κ_b	3.7	1.3	1.3	3.2
κ_τ	1.9	0.9	0.8	1.5
κ_μ	4.3	3.8	1.0	1.7
$\kappa_{Z\gamma}$	9.8	7.2	1.7	6.4

Comparison of LHC xsecs for SM processes at NLO and NNLO

⇒ Need precise measurements to match progress in theory!



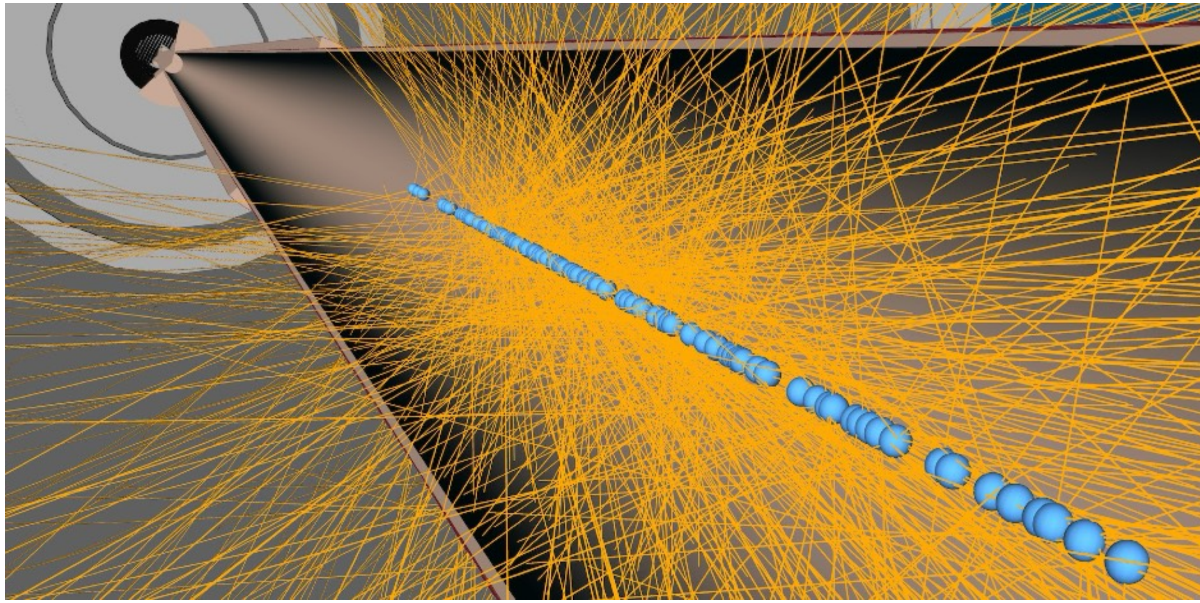
"luminosity is potential keystone measurement for LHC precision programme" - G. Salam, LHCP 2016

Challenges for precise HL-LHC luminosity measurements

- The HL-LHC will deliver *much higher instantaneous luminosity*, need to prepare to be able to handle
  - Up to $7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ ⇔ average number of interactions/crossing $\langle\mu\rangle \sim 200$
  - Dramatically increased detector activity ⇒ *harsher radiation environment*

  ⇒ *Very challenging* to reach goal of measuring luminosity with $\leq 1\ \%$ uncertainty

- Absolute calibration will still be done through annual *van der Meer scans at low $\langle\mu\rangle$*
  - Critical to understand LHC beams, associated uncertainties can be significant at this level (e.g. non-factorization and beam-beam unc.)
- Longer extrapolation vdM → physics conditions, need *precise calibration transfer* to high pileup!
- More radiation, need to *understand stability of luminometer response* with time/dose



MC simulation with $\mu \approx 200$ (link)

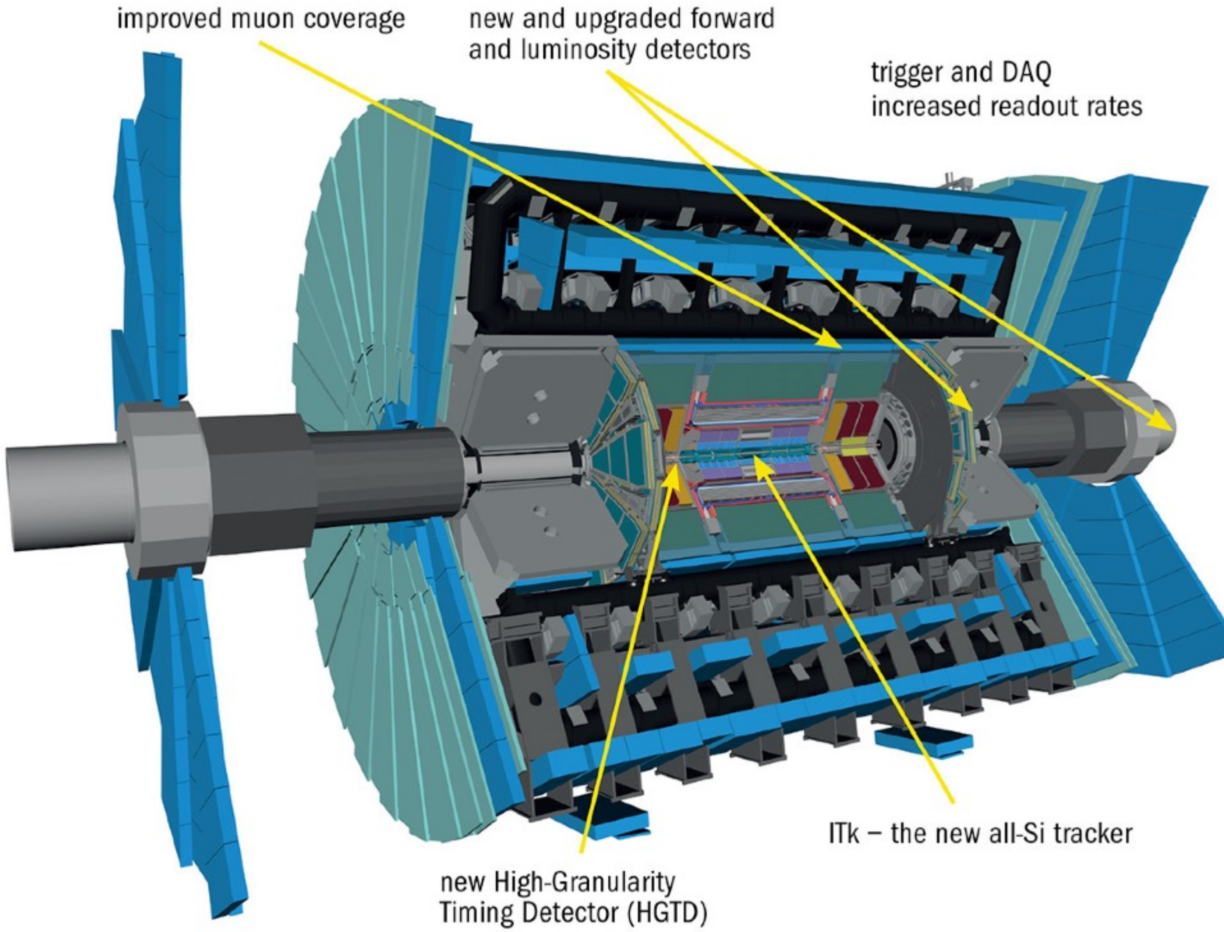
Requirements for precise HL-LHC luminosity measurements

ATLAS wants to reach 1% uncertainty on the yearly calibrated (offline luminosity):

- Need *several robust, redundant and complementary luminometers and methods*
- At least *three* detectors fulfilling each of these critical capabilities:
  - Bunch-by-bunch measurements
  - $< 1\,\%$ statistical uncertainty in ~ 30 s
  - Low (or accurately subtractable) backgrounds, e.g. so-called “afterglow” due to activation
  - Large dynamic range: $\mu \sim 10^{-4} \rightarrow 200$
  - Available outside stable beams, dedicated/independent DAQ
- Also desirable to have radiation-hard detectors with $< 1\,\%$ non-linearity wrt μ, not significantly affected by out-of-time pileup, and excellent long-term stability over months/years
- Precise calibration requires *person-power and experience*

Upgraded and new detectors in ATLAS for HL-LHC

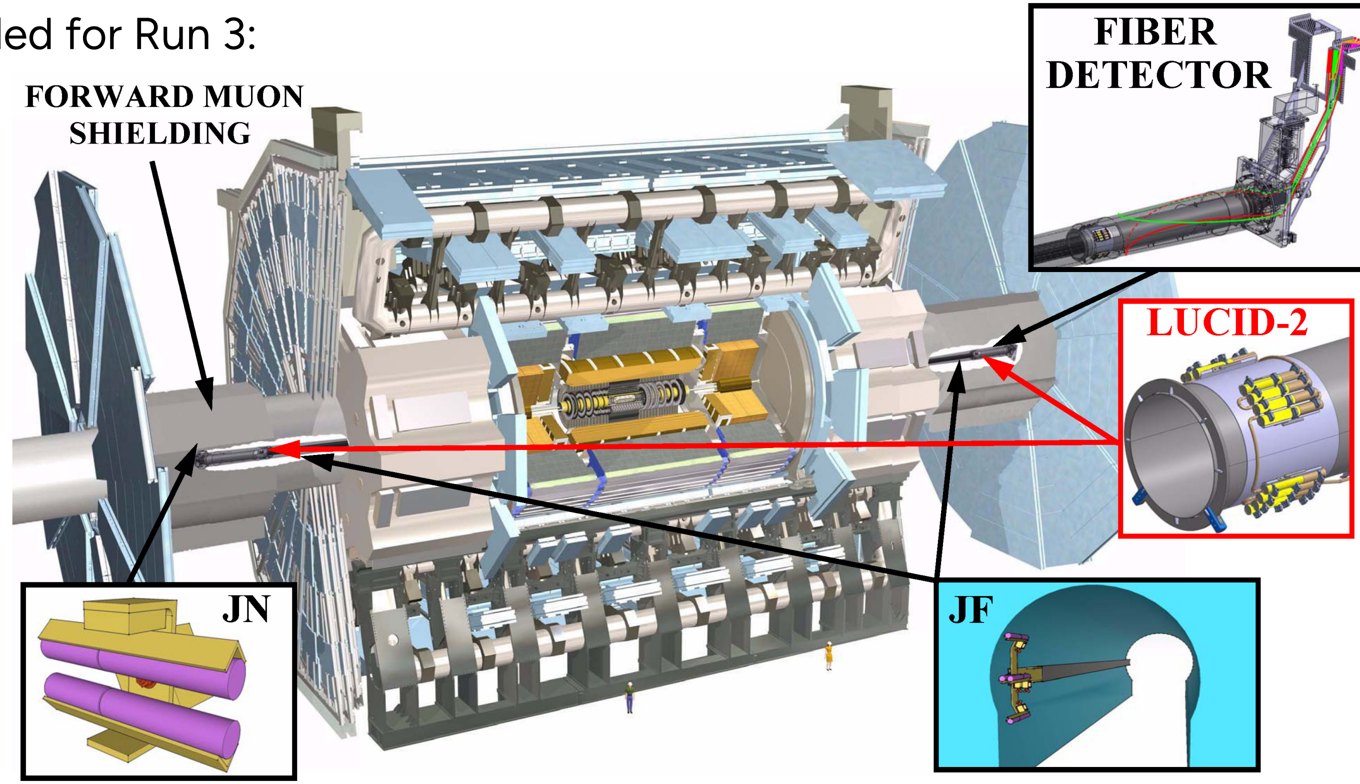
- Comprehensive Phase-II detector upgrades, many which provide key improvements for luminosity:
  - New Luminosity Cherenkov Integrating Detector — LUCID-3
  - High-Granularity Timing Detector (HGTD)
  - New all-silicon Inner Tracker (ITk)
  - BCM' - updated Beam Conditions Monitors
  - Additional systems considered
    - BMA - Beam Monitoring for ATLAS
    - Pixel Luminosity Rings
  - Improved trigger & data acquisition increases the capacity for offline readout



LUCID-3

- Full replacement of LUCID-2, key workhorse for ATLAS lumi determination in Run 2:
  - Based on Cherenkov emission from charged particles in quartz in front of PMTs ($|\eta| \gtrsim 4$)
  - Uses radioactive source (Bi coating) for calibration to ensure stability
- Three prototypes with different acceptances installed for Run 3:
  - **JF:** PMT-based detector with quartz windows, placed at $z \approx \pm 16$ m and $R = 30$ cm (cf. $R = 12$ cm in LUCID-2)
  - **JN:** A lower-rate PMT detector, located in the shadow of ATLAS shielding, at $z = \pm 18.7$ m, $R = 40$ cm
  - **Fiber:** bundles of quartz fibers used as Cherenkov-light emitter and transmitter, calibrated with innovative LED (fibers) and radioactive-source (PMTs) system
- More info in Technical Proposal

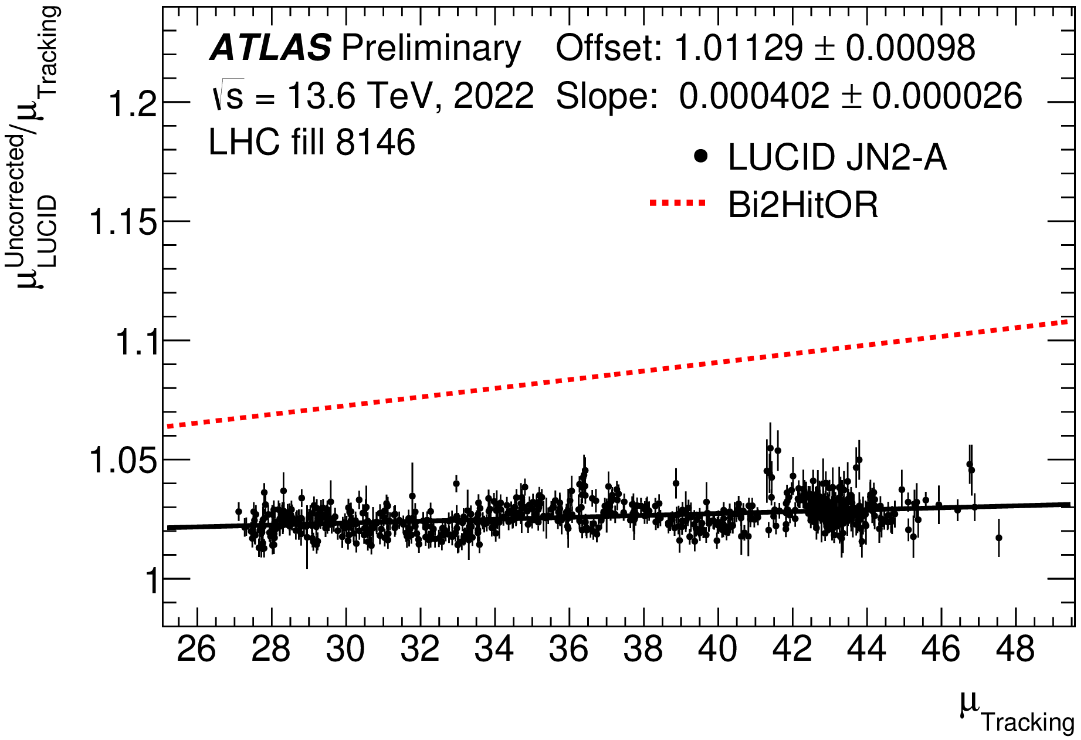
See J. Lindon's poster for more details!



LUCID-3 - results from prototypes with 2022 *pp* data

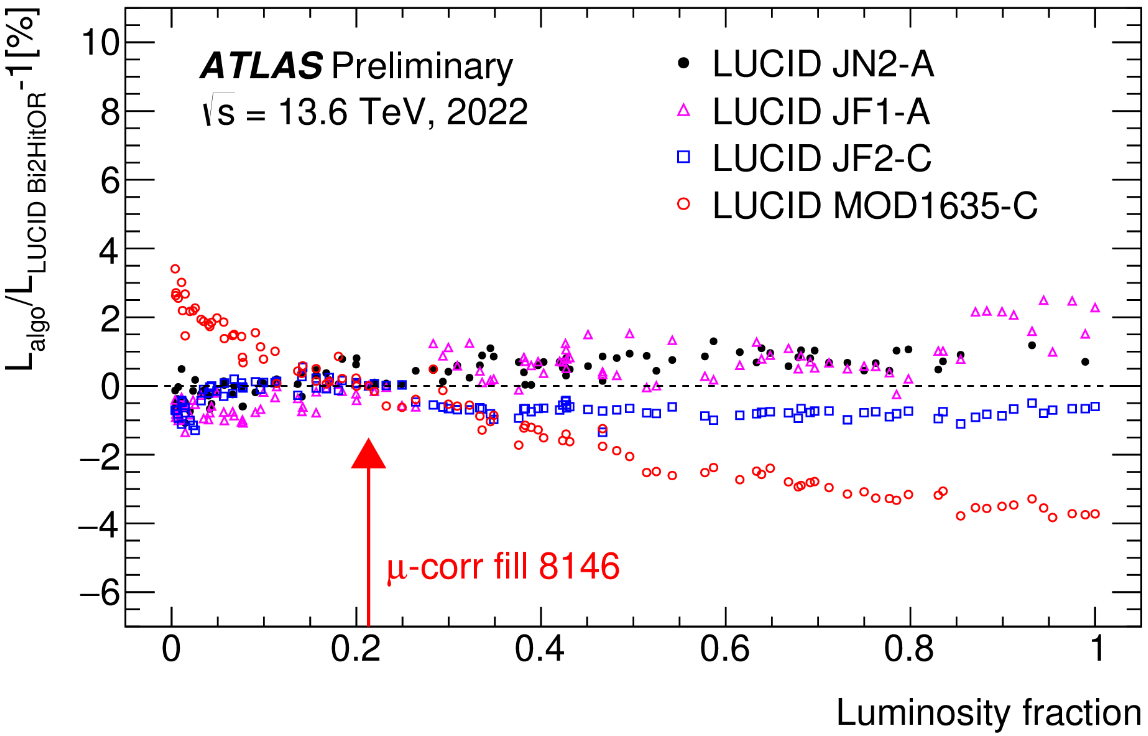
JINST 19 C03053

Linearity of response with $\langle\mu\rangle$, compared to LUCID-2 with track-counting as reference



Slope shows reduced μ-dependence (0.04% per unit of μ) for JN prototype compared to current LUCID-2 (Bi2HitOR)

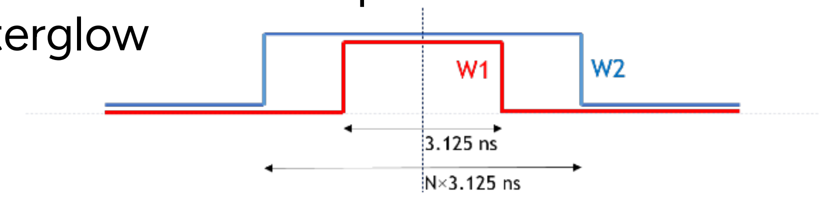
Long-term stability of detector response

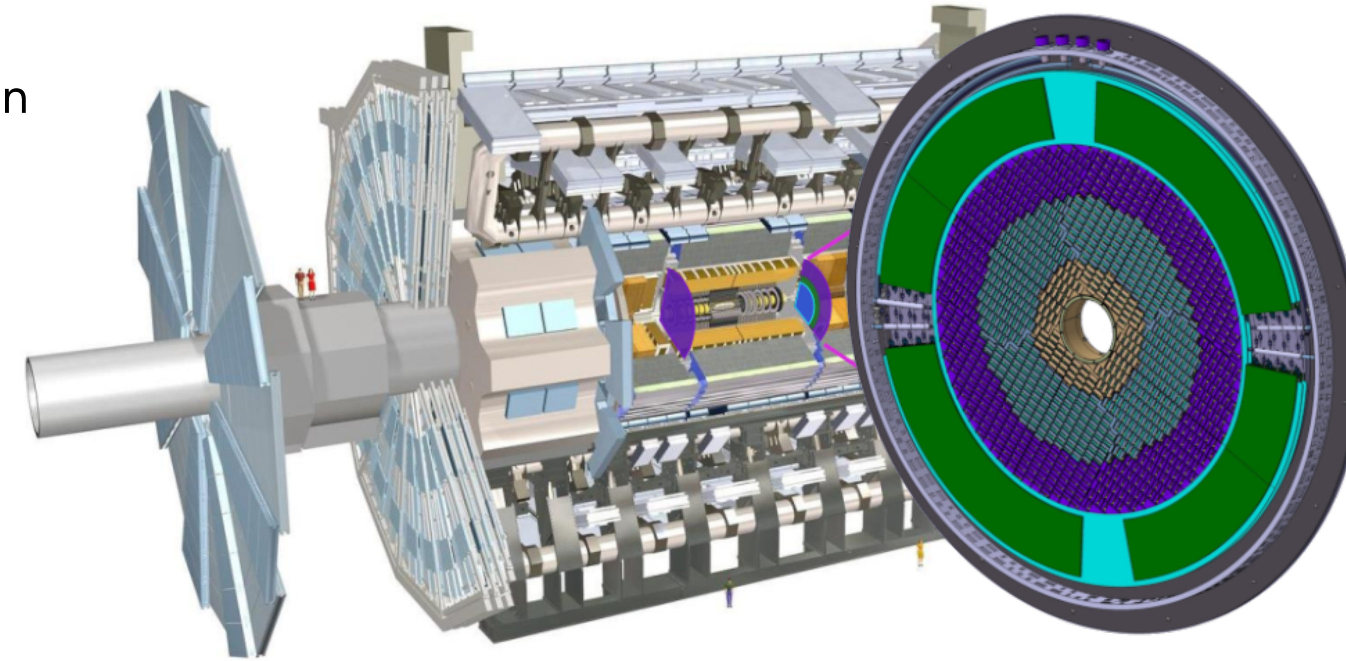


JN and both JF2-C stable well within 1% over 2022

High-Granularity Timing Detector (HGTD)

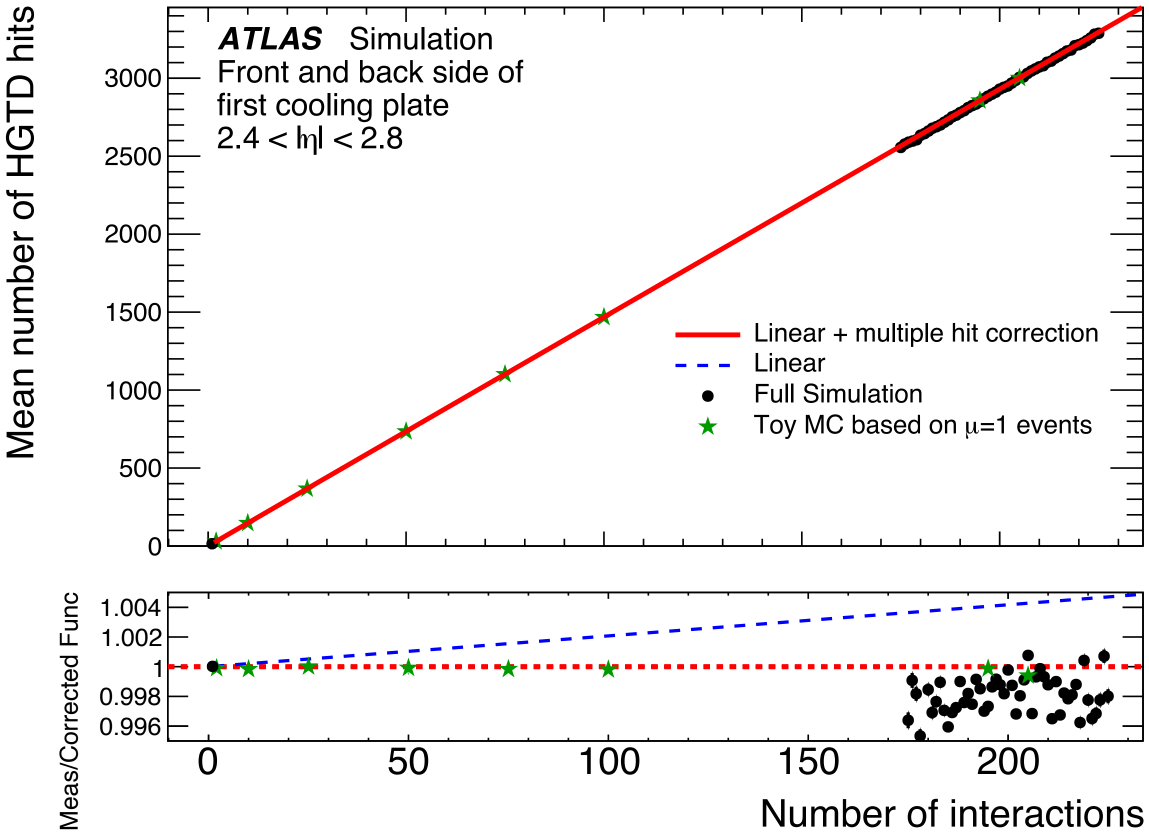
- High-precision timing detector introduced to separate collisions from the same bunch crossing *in time*
  - Time spread of beam spot has $\sigma(t) = 180\ \mathrm{ps}$, HGTD gives $30 - 50\ \mathrm{ps/track}$
  - Uses novel Low Gain Avalanche Detector (LGAD) silicon technology
  - Covers $2.4 < |\eta| < 4.0$ at $z = \pm 3.5\ \mathrm{m}$
- High-granularity device $(1.3 \times 1.3\ \mathrm{mm}^2$ pixels) in forward region ⇒ expect very linear response as function of $\langle\mu\rangle$
- Equipped with dedicated lumi readout path
  - Sends sum of hits per ASIC (225 pixels) *every BCID*, independent of trigger
  - Two time windows provide handle on afterglow





See TDR and talk by A. Leopold (yesterday…)

HGTD - linearity and statistical uncertainty from simulations



Linearity within 0.5% out of the box for $0 < \mu < 200$ range, correction for multiply-hit pixels make it negligible

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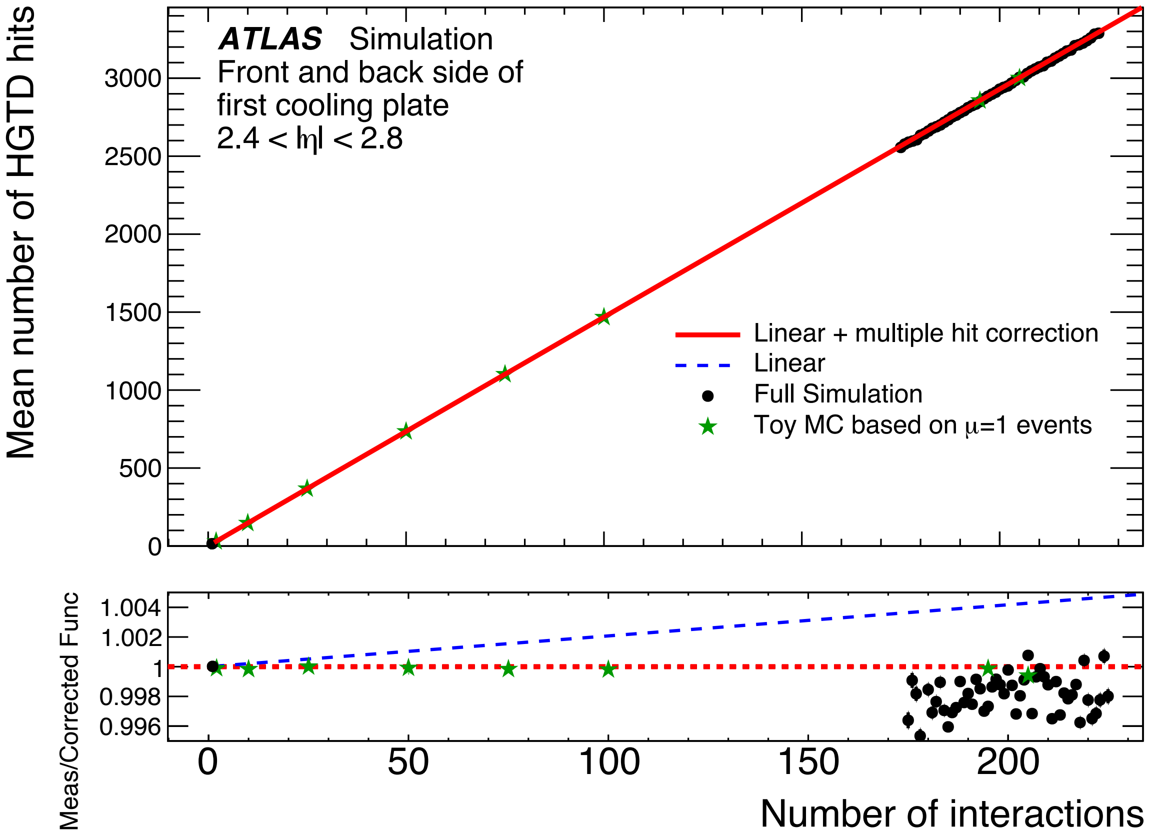

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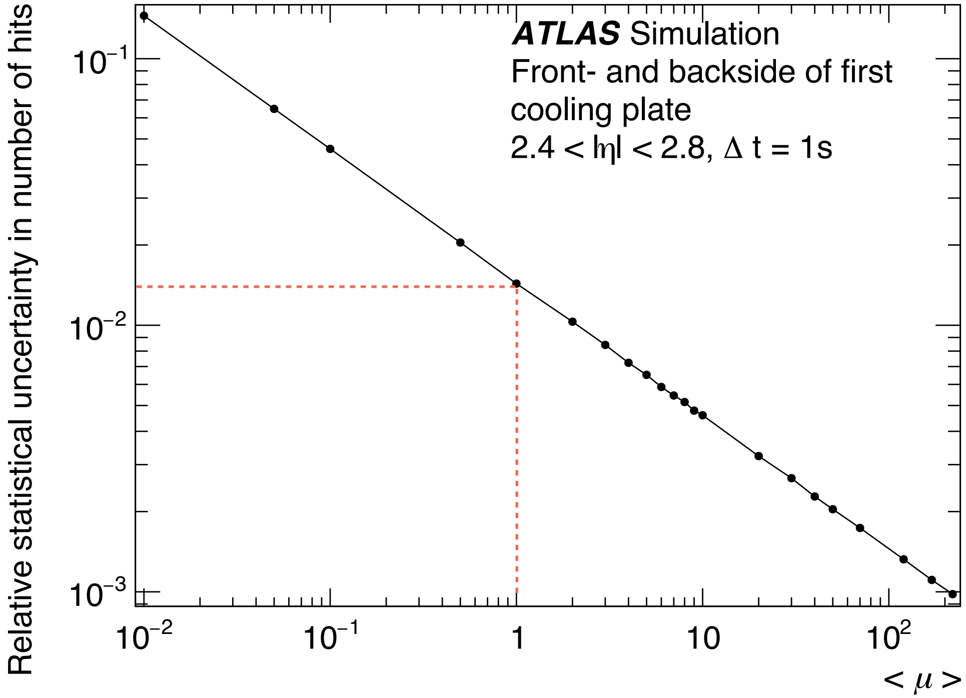
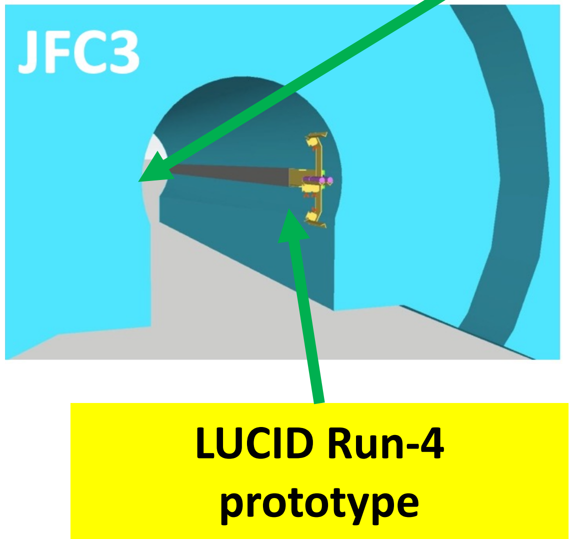


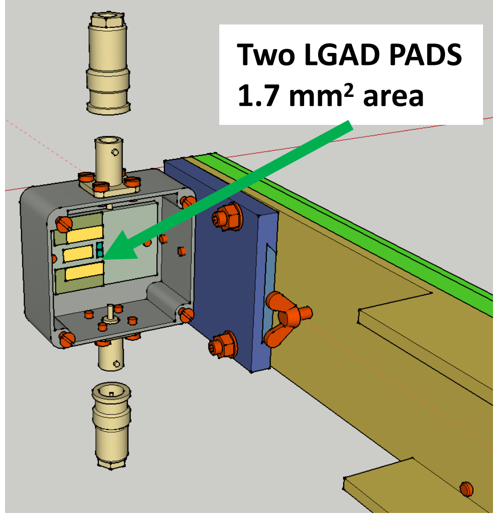
Statistical uncertainty $\sim 1\,\%$ with only 1 second of data at $\langle\mu\rangle \sim 1$, per BCID

(NB! This is only simulations, but…)

Beam Monitors for ATLAS (BMA)

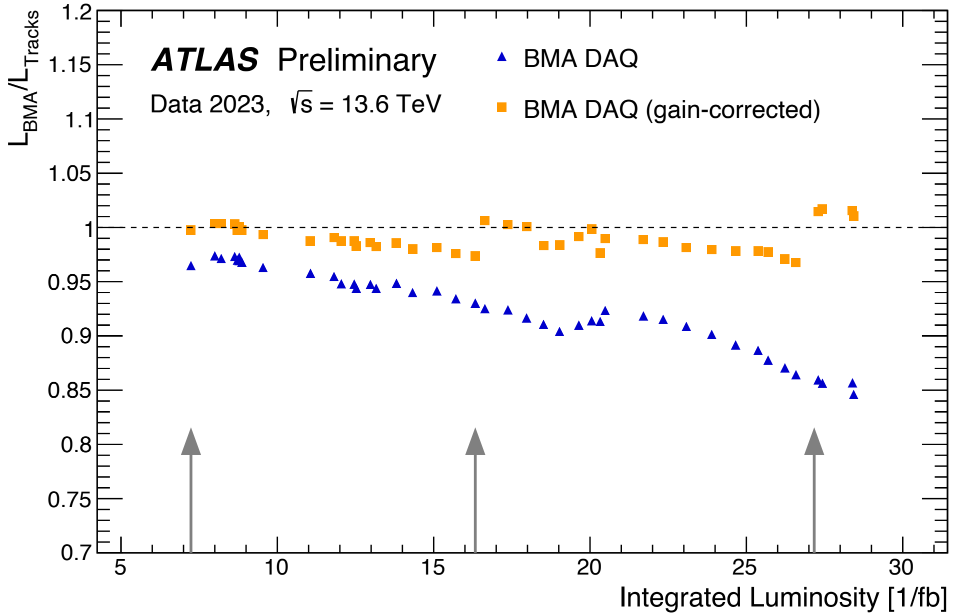
- Additional luminometer proposed for Run 4
- Prototypes installed since 2022, also based on LGADs, uses HGTD prototype sensors — already providing operational experience of this technology
  - $1.3 \times 1.3\ \mathrm{mm}^2$ pixels mounted on forward shielding gives very small geometric acceptance
    - Very good linearity
    - To calibrate during vdM scans, many more pixels than in current prototype are needed
  - Prototypes installed in 2022, replaced sensors with updated ones in 2023 and 2024
  - Read out by current Run-2 LUCID electronics (LUCROD), with fixed and variable gains





(See TIPP2023 proceedings for more info)

BMA - results from 2023 *pp* collision data



Luminosity measured by BMA wrt track-counting vs. integrated luminosity in 2023 (arrows indicate manual gain adjustments for reduced response due to radiation damage of older LGAD prototypes)

Public plots from May, see LUMI-2023-10

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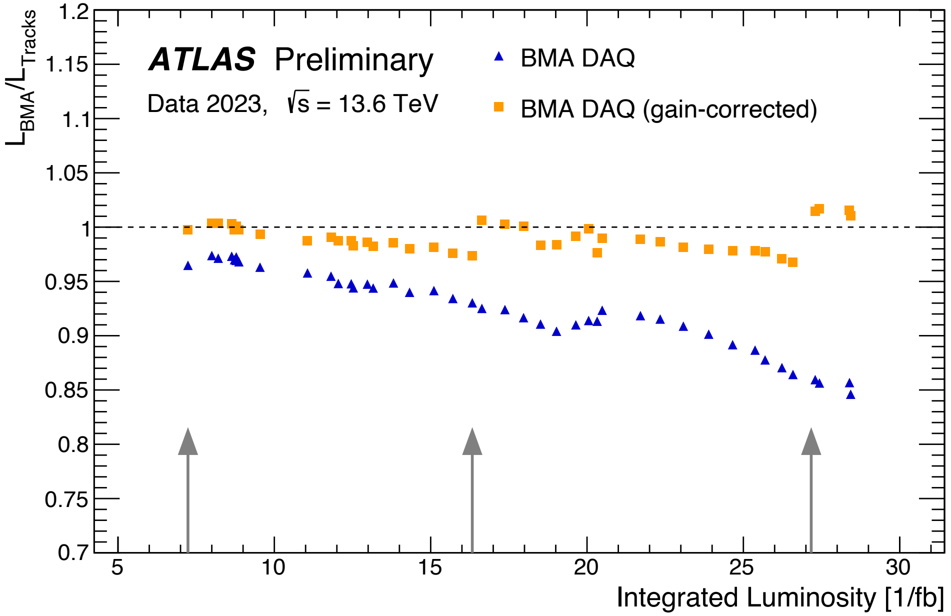

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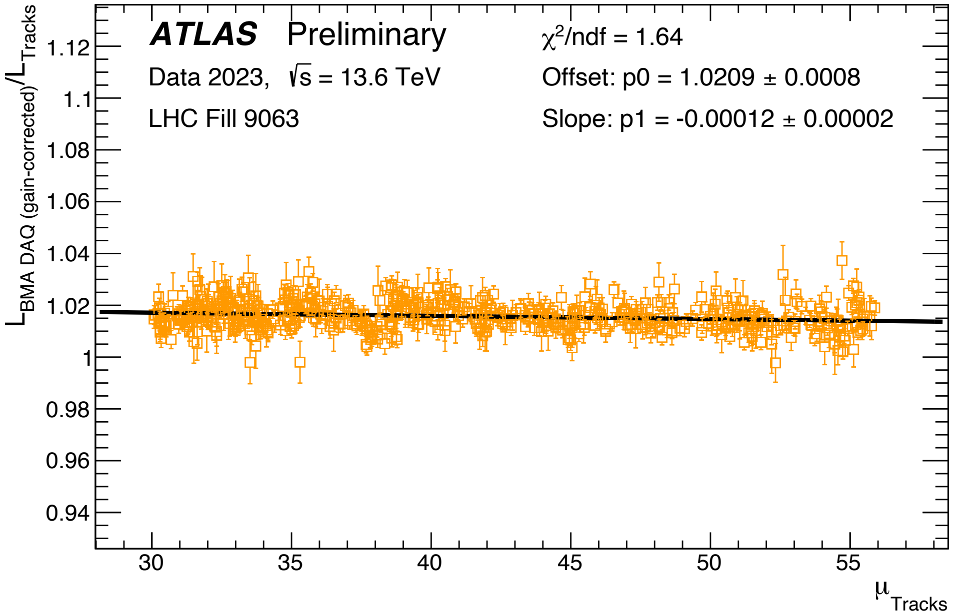

Linearity in $\langle\mu\rangle$ with track-counting as reference, for one specific LHC fill

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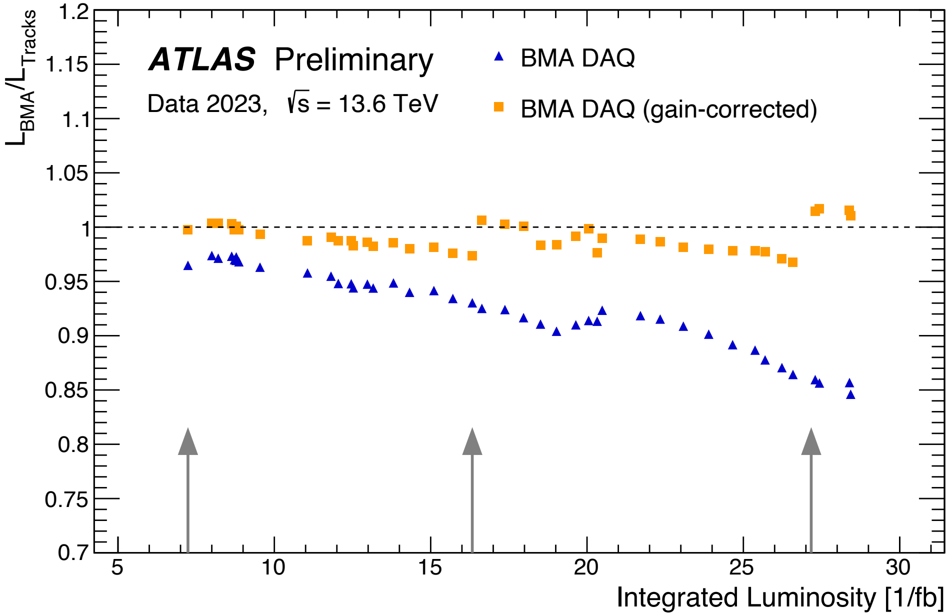

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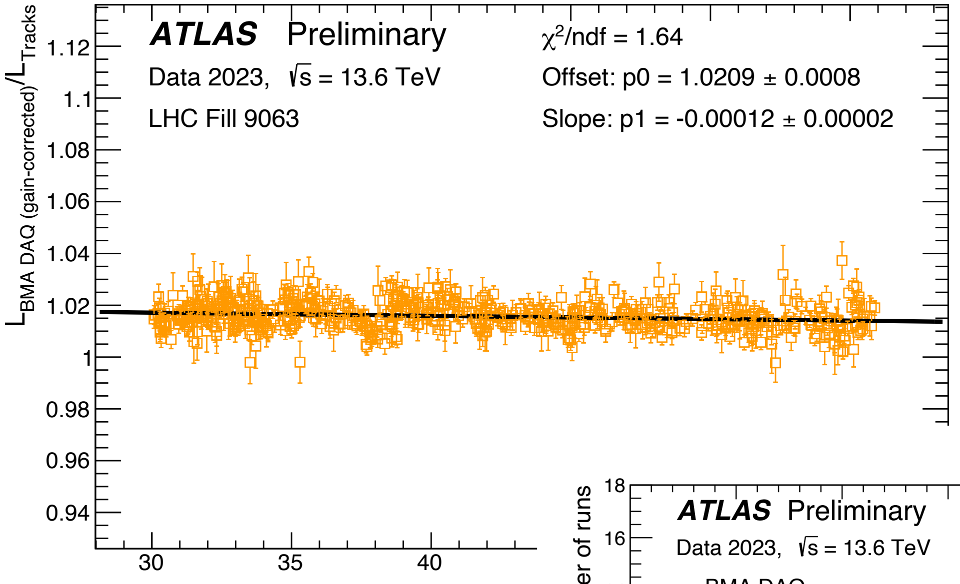
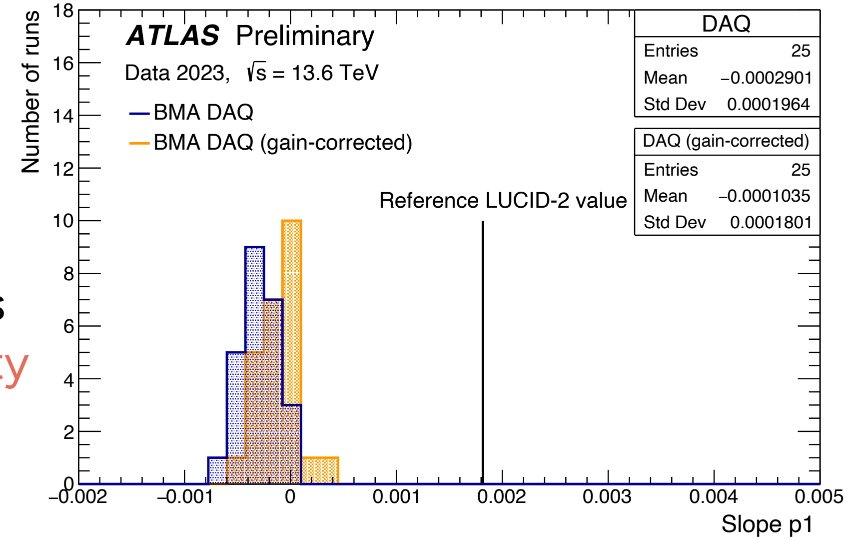


Linearity in $\langle \mu \rangle$ with track-counting as reference, for one specific LHC fill

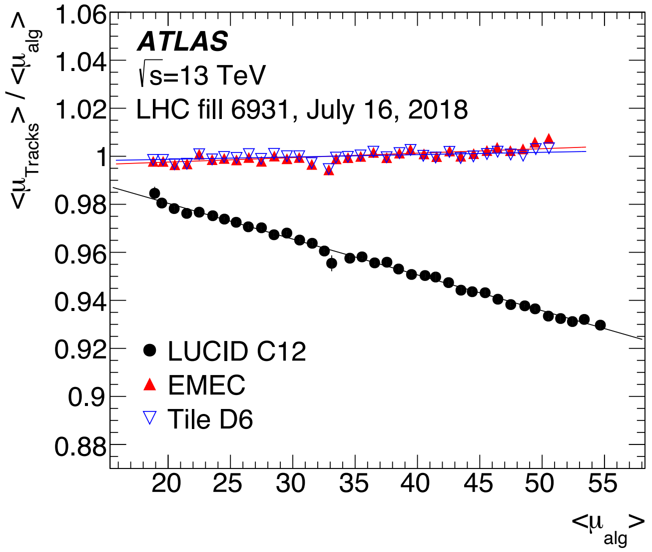
Values of slope p1 for many runs

⇒ better linearity than LUCID-2



Calorimeters and counting tracks and pixel clusters

- **Calorimeters** play an important role for luminosity measurements, and will continue to do so:
  - **EM endcap, FCAL** (based on liquid-argon) as well as **hadronic Tile calorimeter** measure bunch-averaged luminosity stably via current drawn due to detector activity during collisions
    $\Rightarrow$ excellent for linearity and long-term stability studies
  - Readout electronics will be upgraded, which may provide additional handles for luminosity measurements



Calos linear with tracks, cf. LUCID before μ corr.
(Eur. Phys. J. C 83 (2023) 982)

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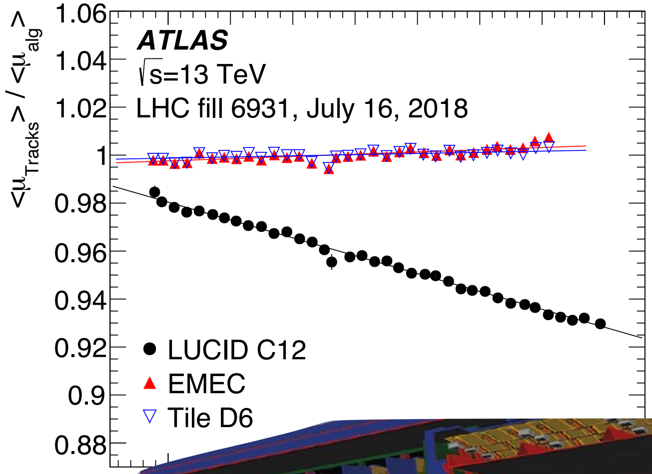
    ⇒ excellent for linearity and long-term stability studies
  - Readout electronics will be upgraded, which may provide additional handles for luminosity measurements
- **ITk** will provide improved offline luminosity capabilities
  - **Track counting** critical reference due to excellent linearity, (current methods suffer from increasing fake rates at high μ)
  - **Pixel-cluster counting** currently being developed in Run 3, will likely be critical for Run 4

  Both techniques rely on randomly triggered (partial) events
  ⇒ Increased readout rate could provide more stats



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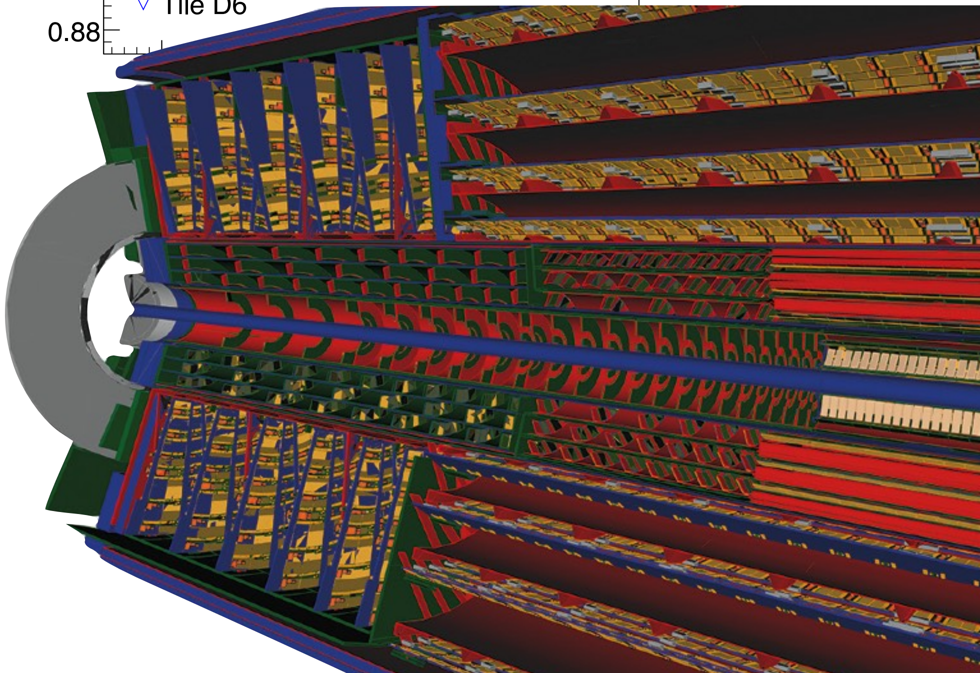
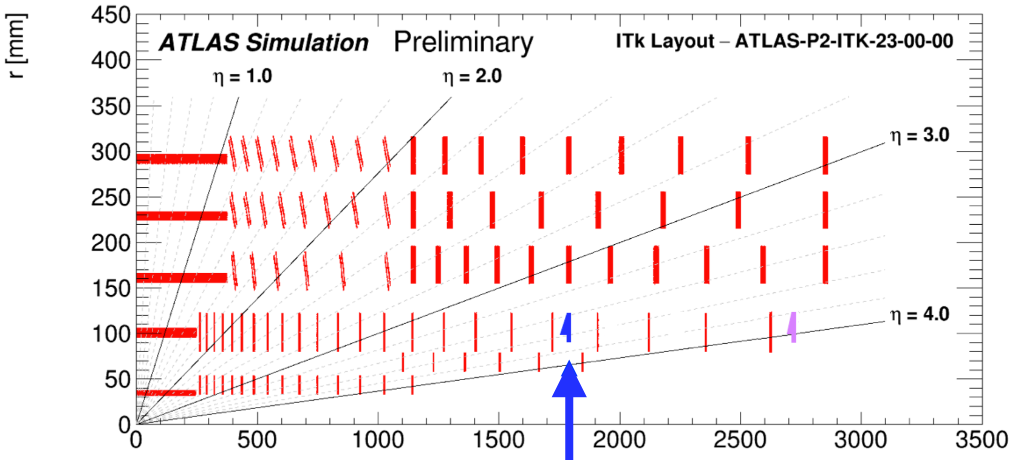
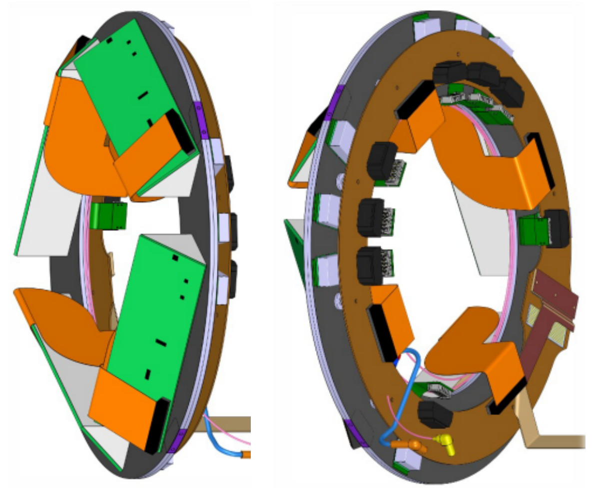


New **Beam Conditions Monitor (BCM′) & Pixel Luminosity Rings (PLR)**

Two detector systems in the ITk pixel volume

- **BCM′** replacing current BCM detector providing *beam protection and luminosity capabilities*
    - Modern pCVD diamond sensors (less aging, improved noise and charge collection)
    - Good timing resolution and single-MIP sensitivity ⇒ lumi via event counting





BCM′ (more here)

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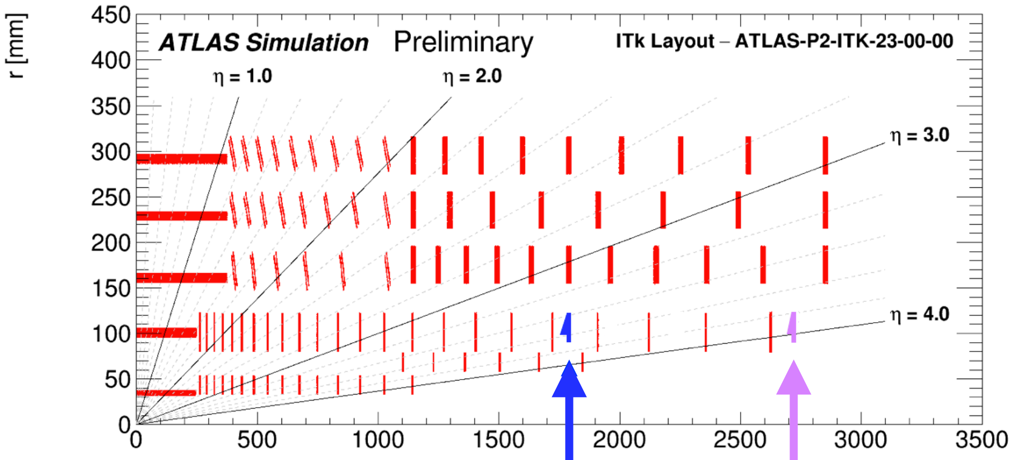
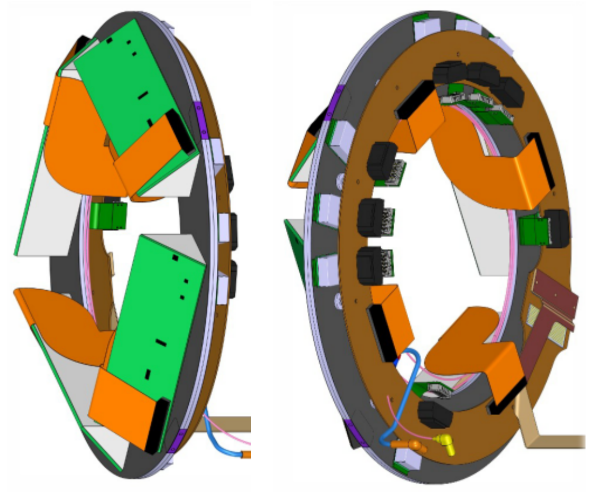
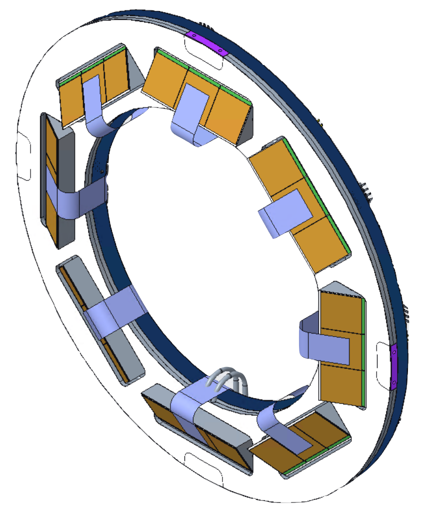
  - Modern pCVD diamond sensors (less aging, improved noise and charge collection)
  - Good timing resolution and single-MIP sensitivity ⇒ lumi via event counting
- **PLR**
  - Proposed additional ITk Pixel endcap rings dedicated to luminosity, 8 modules per side
  - Sensors tilted by $30°$ to get longer clusters ⇒ improved background rejection
  - Up to 2-8 MHz readout, depending on occupancy, independent of trigger





BCM’ (more here)



PLR

Summary & conclusions

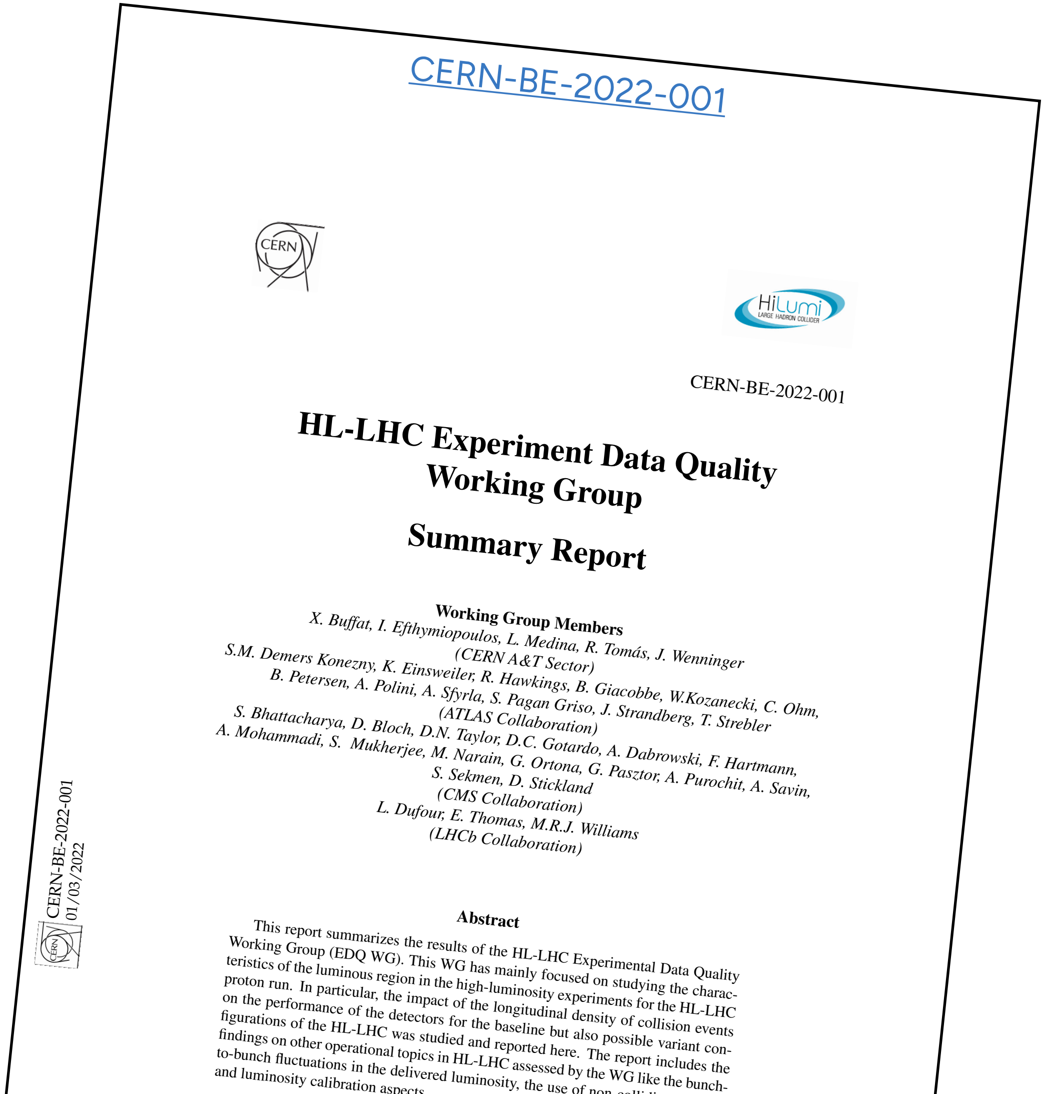
- Ambitious goal of 1% uncertainty on luminosity set by the physics program, demanding measurement
    - Requires a combination of luminosity detectors with complementary capabilities, and redundancy
- Several new and upgraded detector systems dedicated to luminosity measurements under development
    - **LUCID-3, HGTD and BCM'** being constructed, can operate in full mu range (vdM $\rightarrow \mu \sim 200$)
    - **ITk** will provide improved tracking and higher-rate readout for offline track/cluster measurements
    - Studies ongoing for additional **BMA** and **PLR** luminometers
    - **Calorimeters** in ATLAS will continue to offer complementarity and play important role for long-term stability
- Final analysis of ATLAS Run-2 luminosity reached an uncertainty of 0.83% — reaching below 1% will be much more challenging at the HL-LHC, and will require **long-term effort, person-power, and dedication**

KTH
VETENSKAP
OCH KONST

Requirements for precise HL-LHC luminosity measurements

Report from HL-LHC EDQ WG:

- Offline: "targeting a systematic *uncertainty of 1% on the annual integrated luminosity* after final calibration"
- Online:
  - Highly stable bunch-by-bunch measurement with sufficient redundancy to operate in all LHC conditions
  - Approximately 2% absolute precision in real time


CERN-BE-2022-001

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HL-LHC Experiment Data Quality Working Group

Summary Report

Working Group Members

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CERN-BE-2022-001
01/03/2022

Abstract

This report summarizes the results of the HL-LHC Experimental Data Quality Working Group (EDQ WG). This WG has mainly focused on studying the characteristics of the luminous region in the high-luminosity experiments for the HL-LHC proton run. In particular, the impact of the longitudinal density of collision events on the performance of the detectors for the baseline but also possible variant configurations of the HL-LHC was studied and reported here. The report includes the findings on other operational topics in HL-LHC assessed by the WG like the bunch-to-bunch fluctuations in the delivered luminosity, the use of non-colliding ... and luminosity calibration aspects