Luminosity measurement at the HL-LHC

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on behalf of the ALICE, ATLAS, CMS, LHCb Collaborations

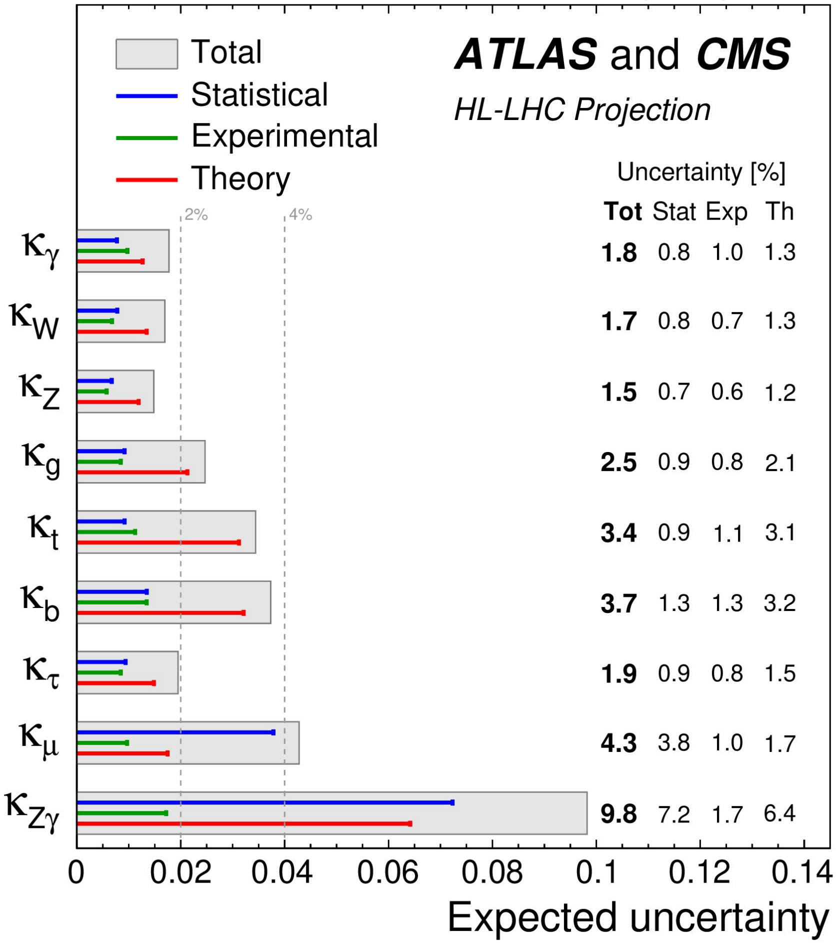
Boston, June 7th 2024
LHCP 2024

The 1% challenge

Huge HL-LHC dataset: precision measurements at the % or sub-% level

ATL-PHYS-PUB-2022-018

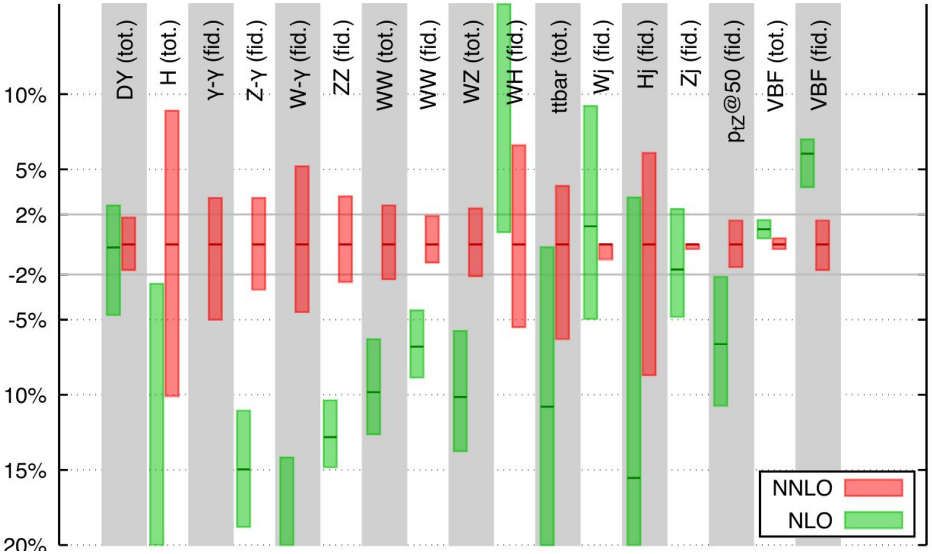
$\sqrt{s}$ = 14 TeV, 3000 fb^{-1} per experiment



Uncertainty [%]

	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

G. Salam, 2016



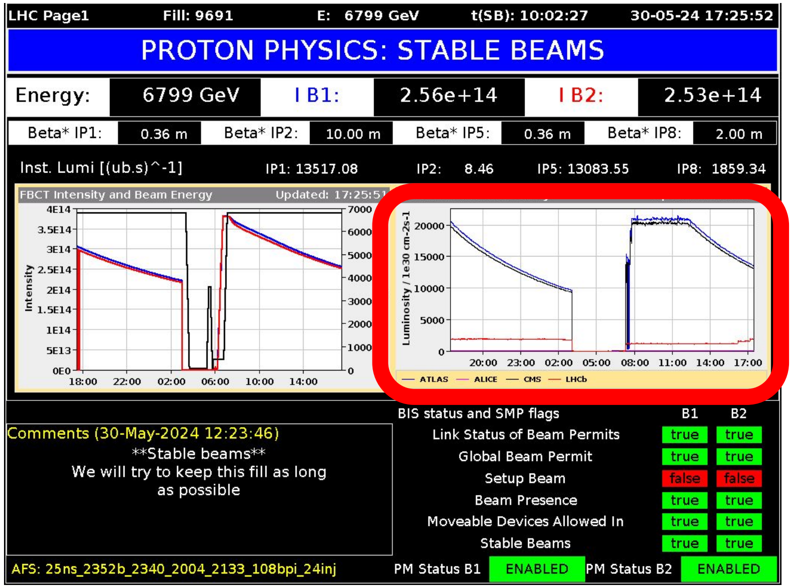
$$\sigma = N/\mathcal{L}$$

The absolute value of delivered luminosity needs to be known **at the 1% accuracy or better**!

Real-time luminosity information

Real-time monitoring of per-bunch luminosity for fast feedback to the accelerator:

- luminosity delivered at each interaction point (and how they compare)
- evolution within a fill for luminosity-leveling (max pile-up)
- profile within a train of bunches



LHC Page1 Fill: 9691 E: 6799 GeV t(SB): 10:02:27 30-05-24 17:25:52

PROTON PHYSICS: STABLE BEAMS

Energy:	6799 GeV	I B1:	2.56e+14	I B2:	2.53e+14

Beta* IP1:	0.36 m	Beta* IP2:	10.00 m	Beta* IP5:	0.36 m	Beta* IP8:	2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 13517.08 IP2: 8.46 IP5: 13083.55 IP8: 1859.34

Comments (30-May-2024 12:23:46)
Stable beams
We will try to keep this fill as long as possible

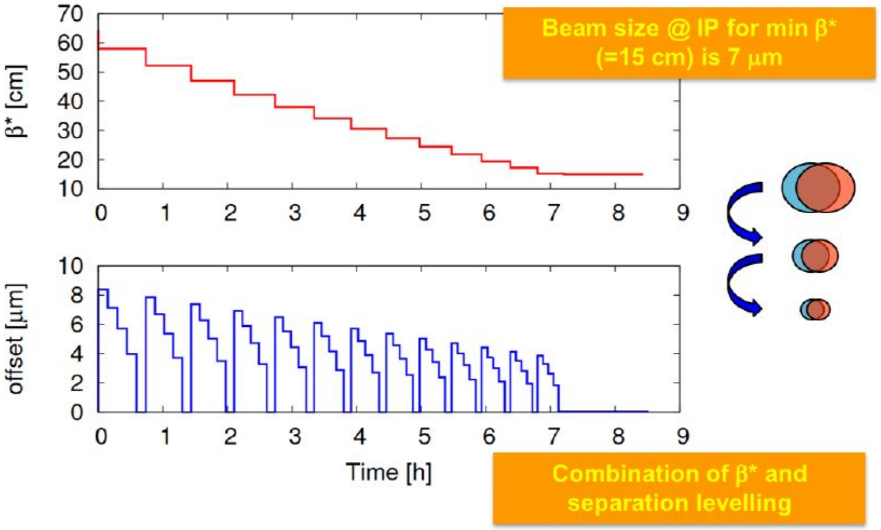
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_2352b_2340_2004_2133_108bpi_24inj

PM Status B1 ENABLED PM Status B2 ENABLED

LHC Online Page 1

HL-LHC Luminosity leveling, CMS-NOTE-2019-008



Beam size @ IP for min β* (=15 cm) is 7 μm

Combination of β* and separation levelling

This information is continuously needed, also outside stable beams, with an accuracy **better than ~5% and a granularity of a few seconds**.

Luminosity measurements

$$\mathcal{L} = \frac{\mathcal{R}}{\sigma_{\text{inel}}} = \frac{\mu}{\sigma_{\text{inel}}} \cdot n_b f_r$$

n_b = number of bunches
f_r = revolution frequency

Relate the rate of a given process with its cross-section

- e.g. inelastic p-p collisions
- on a per-bunch basis can be written as a function of number of interactions per bunch-crossing (μ)

Luminosity measurements: visible count

$$\mathcal{L} = \frac{\mathcal{R}}{\sigma_{\text{inel}}} = \frac{\mu}{\sigma_{\text{inel}}} \cdot n_b f_r = \frac{\boxed{\epsilon\mu}}{\epsilon\sigma_{\text{inel}}} \cdot n_b f_r$$

Each luminosity detector/algorithm (luminometer) has a specific efficiency to detect each inelastic pp collision (ε).

- **μ_{vis} = εμ** is the visible counting rate

Three classes of algorithms:

- **Object Counting**: count of “hits” in each event, sum over events
    - number of cells/pixels/fibers, tracks, number of Z bosons, …
    - strongly relies on well-verified Poisson-statistics assumption

- **Particle Flux**: “continuous” observable proportional to μ
    - current in PMTs of calorimeters, ...

- **[Event Counting]**: infer from 0-count rate (R0) & Poisson statistics
    - low pile-up datasets, won’t scale well for HL-LHC

Luminosity measurements: absolute calibration

$$\mathcal{L} = \frac{\mathcal{R}}{\sigma_{\text{inel}}} = \frac{\mu}{\sigma_{\text{inel}}} \cdot n_b f_r = \frac{\epsilon\mu}{\boxed{\epsilon\sigma_{\text{inel}}}} \cdot n_b f_r$$

σ_{vis} = $\epsilon\sigma$ is called visible cross-section

- Ideally constant in time and conditions

Measured in dedicated fills (van-der-Meer scans) where luminosity can be computed independently.

- low pile-up, low number of bunches, larger beam size (emittance)

Beam separated progressively. Rate relates to beam parameters

bunch currents

$$\mathcal{L} = \frac{n_1 \cdot n_2}{2\pi\Sigma_x\Sigma_y} \cdot n_b f_r$$

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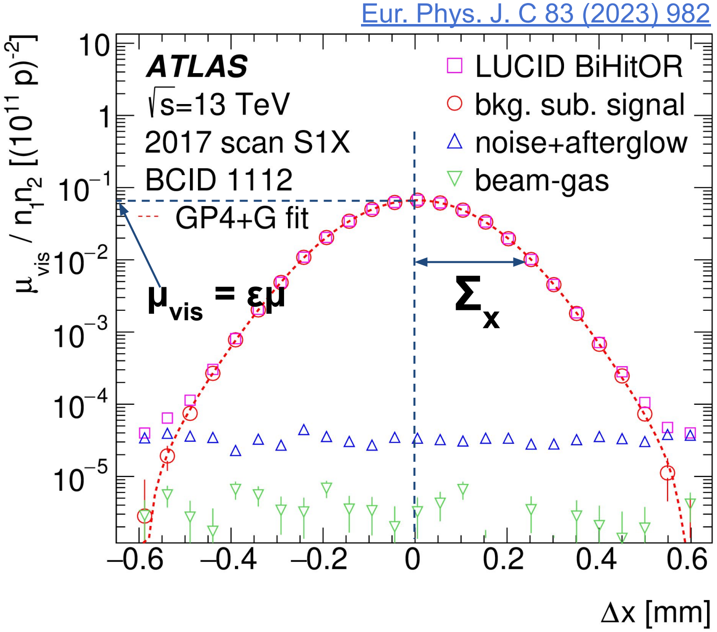

Luminosity measurements: extrapolation

Calibration Transfer

From vdM scan conditions to physics

- pile-up, bunch trains, …

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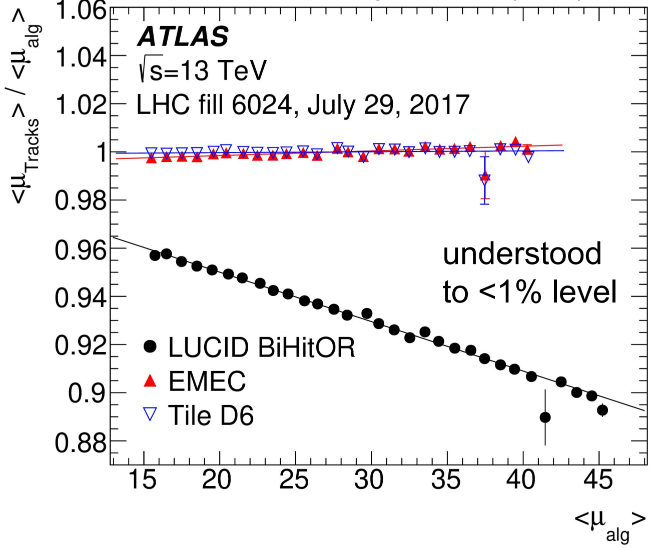


understood to <1% level

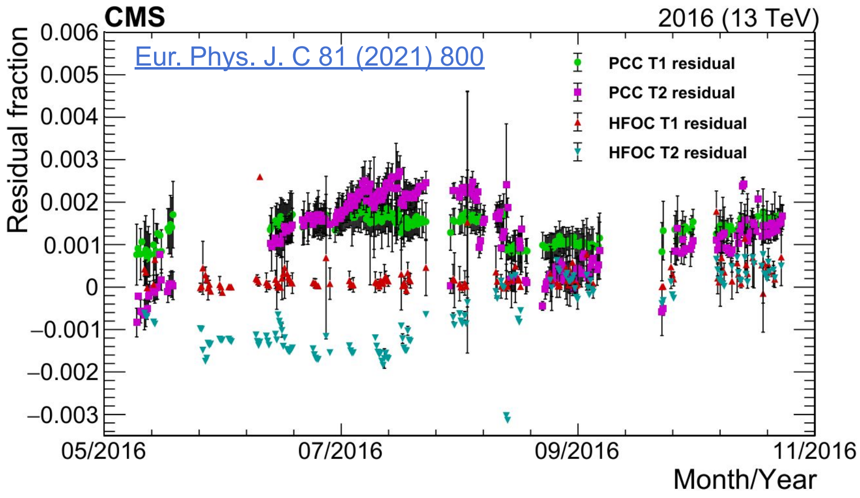
Much larger extrapolation needed for HL-LHC, μ ~ 1 → ~ 140.

- high dynamic range, insensitive to pile-up effects, bunch structure, …

Long-term stability

Throughout data-taking periods.

- varying fill-by-fill conditions



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Sensitive to detectors' aging, operational conditions, beam conditions, …

Run 2 Luminosity and HL-LHC expectations

Run-2 uncertainty already < 1%

- after lots of experience and refinements, here as example using ATLAS

Absolute calibration (vdM) ~ 0.65%

- expected to be very similar to nowadays
- x/y correlations effects play a key role
  - e.g. for Run-3 much larger, dominant

Calibration transfer ~ 0.50%

- much larger extrapolation needed for HL-LHC
- expected to be the dominant contribution to the total uncertainty at HL-LHC

Long-term stability ~0.14%

- only possible via multiple methods that can be compared and investigated
- Need to design robust, redundant and complementary luminometers and methods (person-power!)

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HL-LHC Requirements

Need a redundant set of luminometers with complementary strengths
- at least three independent that should have critical requirements satisfied
- many others that are instrumental in cross-calibrating and track stability

Some of the key requirements:
- bunch-by-bunch measurement
- < 1% statistical uncertainty in ~30s
- low or accurately subtractable (beam-induced) backgrounds
- large dynamic range: $\mu \sim 10^{-5}$ to 200
- available outside stable beams
- dedicated/independent DAQ
- < 1% non-linearity with in-time and out-of-time pile-up
- Excellent long-term (months/years) stability

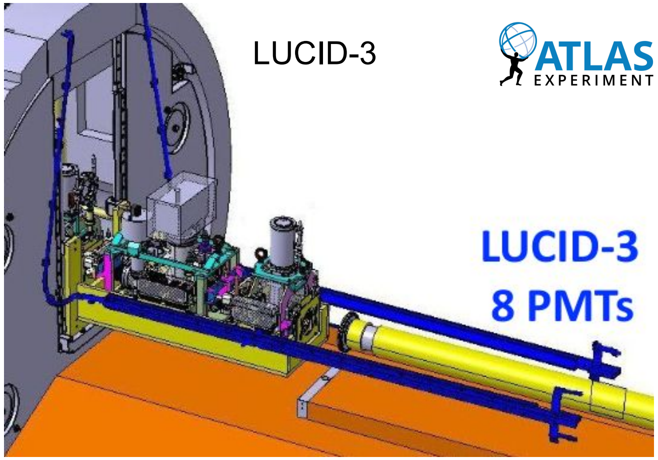
Experiments have planned various upgrades to satisfy these requirements with multiple detectors. I will show a sample of them next.

Cherenkov-based luminometers: PMT and Fibers

Cherenkov radiation from Quartz (SiO_2)

- Photomultiplier tubes (PMT) with quartz window
- Quartz fibers

Positioned far-forward ($\eta \gtrsim 4$) in the detectors on both sides.


LUCID-3

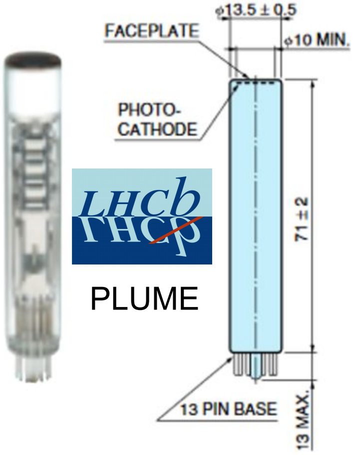
ATLAS EXPERIMENT

Technology already well tested in previous runs, but major changes to adapt acceptance to expected HL-LHC particle multiplicity.

- ATLAS has installed a prototype already in Run 3 data-taking

Some key common characteristics:

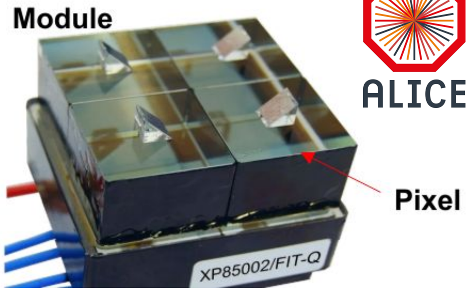
- per-bunch readout @ 40 MHz;
- independent readout, always available;
- good statistical uncertainty, quickly;
- large dynamic range (multiple sizes).
- some non-linear pile-up response,
  - improvements mitigate effects;
- some long-term stability effects,
  - mitigated with continuous active monitoring.



PLUME

FT0

ALICE



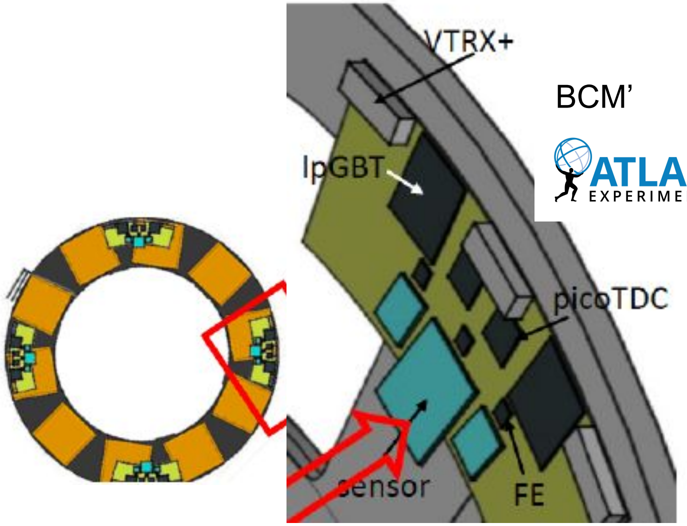
Solid-state detectors as luminometers

Two main technologies:

- diamond sensors (multiple-sized sensors)
- silicon sensor pads on dedicated forward rings
- LGAD fast timing detector

Some also used as beam protection systems.

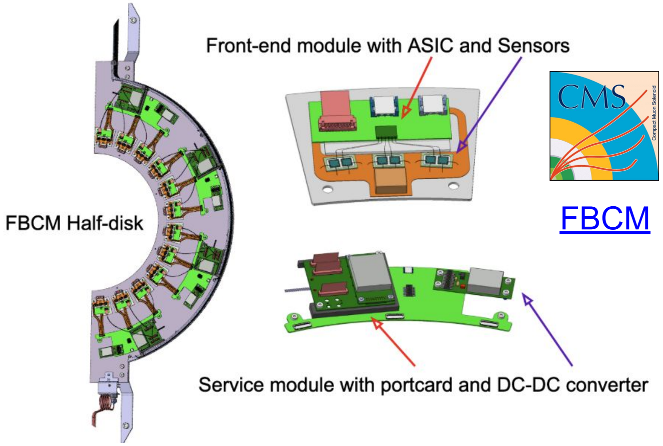
Fast-timing: in-situ background subtraction in timing.



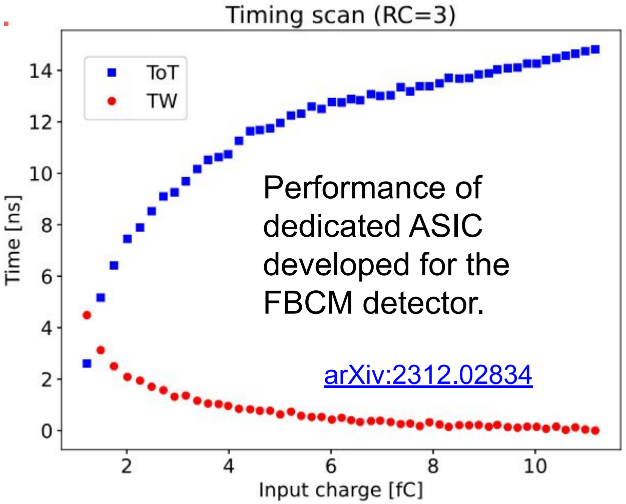
BCM’

Some key common characteristics:

- independent readout, always available;
- good statistical uncertainty, quickly;
- large dynamic range (multiple sizes).
- some non-linear in/out of time pile-up response;
- some long-term stability effects.

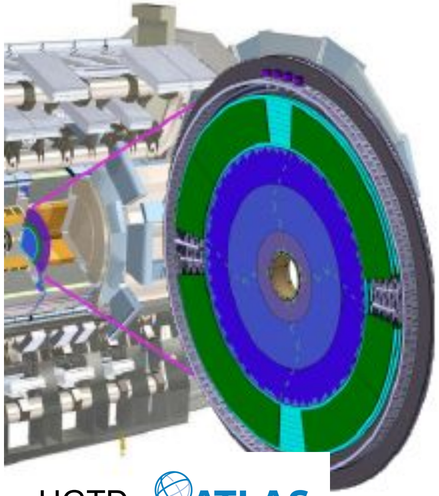


FBCM



Performance of dedicated ASIC developed for the FBCM detector.

arXiv:2312.02834



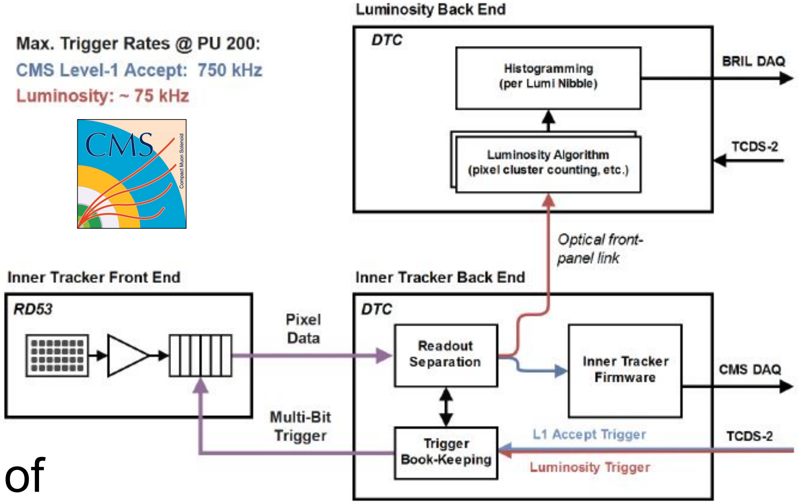
HGTD

Pixel detector as luminometer

Pixel detectors offer a great linearity and stability, with multiple algorithms possible, from counting cluster of hits (PCC) to short tracks.

- CMS foresees dedicated readout for forward pixel endcaps (TEPX, 2 m^2 of Si)
- ATLAS proposed dedicated ring (PLR), but not yet approved

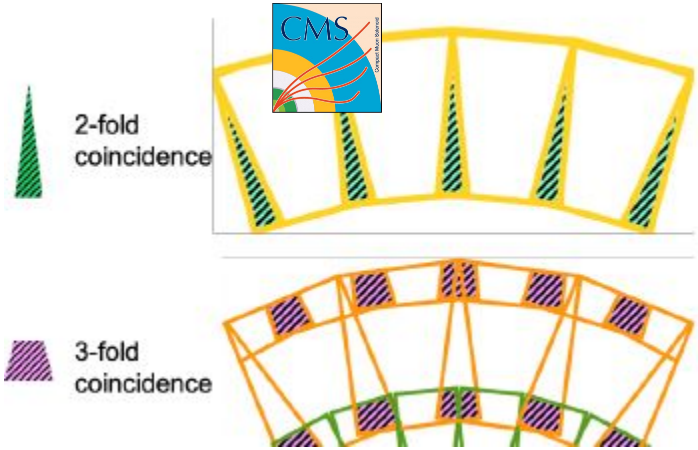
Max. Trigger Rates @ PU 200:
CMS Level-1 Accept: 750 kHz
Luminosity: ~ 75 kHz

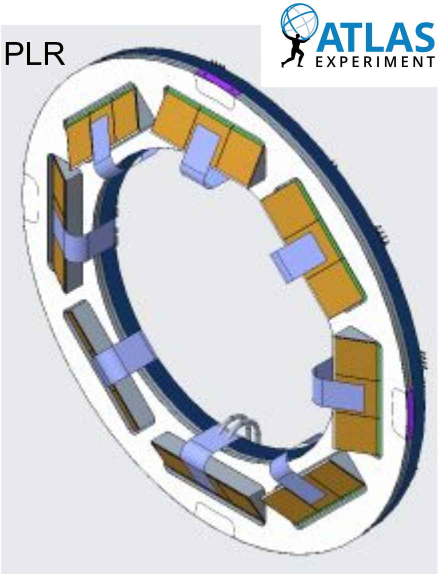


PCC / Track-based measurements are workhorse of current luminosity strategy.

- dedicated readout, if foreseen per-bunch readout (sampling)
- excellent background rejection
- large dynamic range
- excellent pile-up independence
- long-term stability (redundancy)
- a bit slower for small statistical uncertainty
- partially available outside stable beams

TEPX





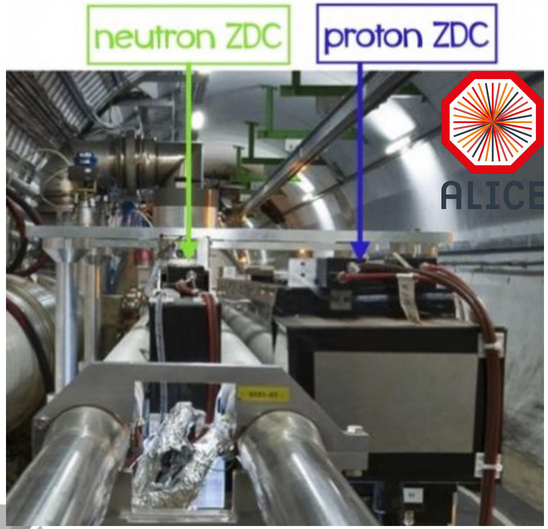
Calorimeter-based luminometers

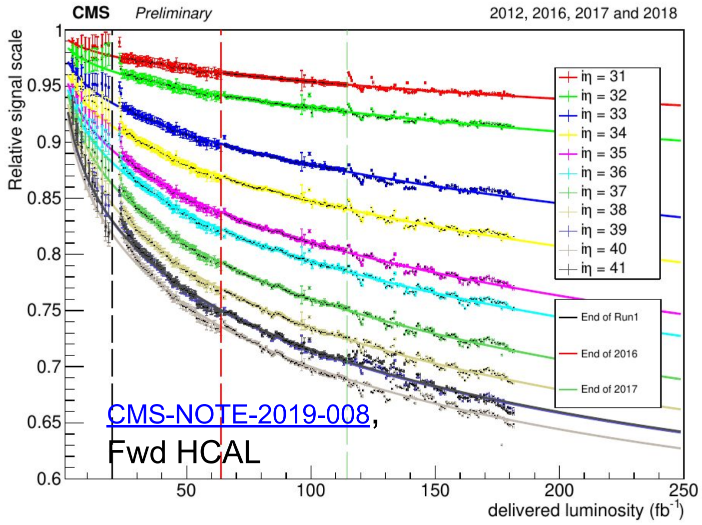
Hadronic (forward) calorimeters (some with dedicated readout) have been proven to be excellent in dynamic range, critical to vdM to physics extrapolation.

- dedicated readout for CMS forward hadronic calorimeter
- Zero-degree calorimeter (ZDC, ALICE)

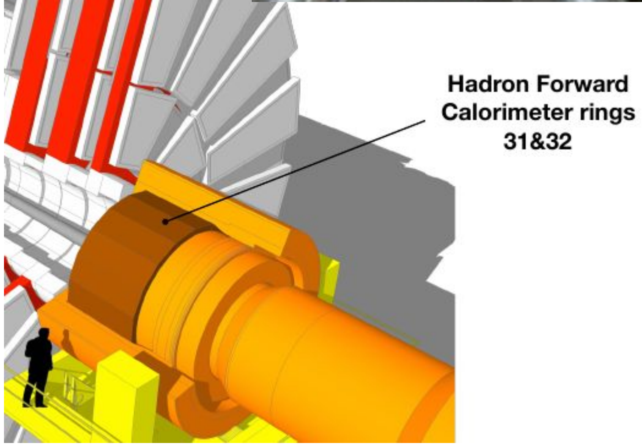
Demonstrated critical role in calibration transfer.
Focus on having them as fully-calibrated luminometers.

Detector aging needs proper corrections.





CMS-NOTE-2019-008, Fwd HCAL



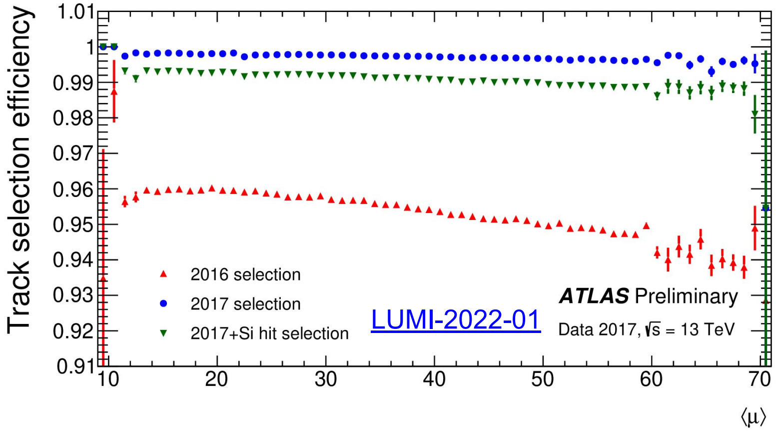
Higher-level objects as luminometers

A large spectrum of offline algorithms are crucial in the calibration transfer and long-term stability studies, for the ultimate 1% accuracy on integrated luminosity.

Two great examples that use higher-level objects from multiple detectors

- robustness due to redundancy in object reconstruction

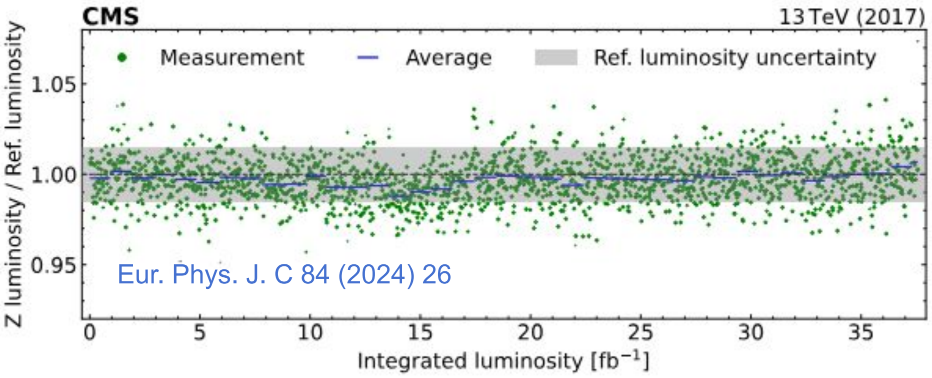
Track Counting



LUMI-2022-01

- dedicated stream and reconstruction for fast processing and large statistics

Z-boson Counting



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- larger luminosity ensures large statistics even for “rare” processes (e.g. Z)
  - also proposed for calibration transfer
- Z→μμ offers in-situ calibration of efficiency and detector response

Redundancy and Complementarity

Each experiment will have at least three or more independent luminometers

- each capable of working from vdM to nominal conditions

Several methods will be used to cross-calibrate their response.

	Stability		*Statistics, Dynamic Range*					*Availability*	*Dedicated DAQ*	
CMS	Stability tracked with emittance scans (bunch-by-bunch)	Linearity measured and tracked with scans (bunch-by-bunch)	Statistical uncertainty in Σ in vdM scans satisfactory (bunch-by-bunch)	Statistical uncertainty in luminosity in physics satisfactory (bunch-by-bunch)	Online bunch-by-bunch luminosity available at 4LN frequency	Online orbit-integrated luminosity available (at 4LN frequency)	Offline luminosity available at LS frequency (bunch-by-bunch)	Available outside stable beams	Independent of foreseeable central DAQ downtimes	Independent of TCDS
TEPX D4R1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓1
TEPX	✓	✓	✓	✓	✓	✓	✓	✓2	✓3	✗
HF	✓	✓	✓	✓	✓	✓	✓	✓	✓4	✓4
OT layer 6 stubs	✓	✓	✓	✓	✓	✓	✓	✗5	✓3	✗
Muon trigger stubs	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗
HFRadmon	✓6	✓6	✗	✗	✗	✓	✓6	✓	✓	✓
RAMSES	✓6	✓6	✗	✗	✗	✓	✓6	✓	✓	✓
Dedicated BRIL BCM1F-like device	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

CMS-NOTE-2019-008

Conclusions

The HL-LHC demands and accurate luminosity measurement

Multiple factors need to be controlled exquisitely well to achieve those targets

- the transfer of calibration from dedicated to physics fills will play a key role

The LHC experiments have designed a set of upgrades to meet these challenges, including increasing the redundancy of independent luminometers available.

Only a sustained effort and an ambitious upgrade program can achieve the equally ambitious physics goals we have set for HL-LHC!

BACKUP

Luminosity measurements: absolute calibration

$$\mathcal{L} = \frac{\mathcal{R}}{\sigma_{\text{inel}}} = \frac{\mu}{\sigma_{\text{inel}}} \cdot n_b f_r = \frac{\epsilon\mu}{\boxed{\epsilon\sigma_{\text{inel}}}} \cdot n_b f_r$$

σ_{vis} = $\epsilon\sigma$ is called visible cross-section

- Ideally constant in time and conditions

Key hypothesis: uncorrelated luminous region distribution in transverse directions

- direct 2D scans (time consuming)
- beam imaging (dedicated detectors)
- indirect effects on luminous region shape

Sub-dominant for full Run 2 calibration, dominant for preliminary Run 3 results.

While expected to be similar for HL-LHC, it's hard to predict a-priori, **a key possible challenge in the HL-LHC era**!

JINST 9 P12005 (2014)