Strategy for high-precision luminosity measurement with the CMS detector at the HL-LHC

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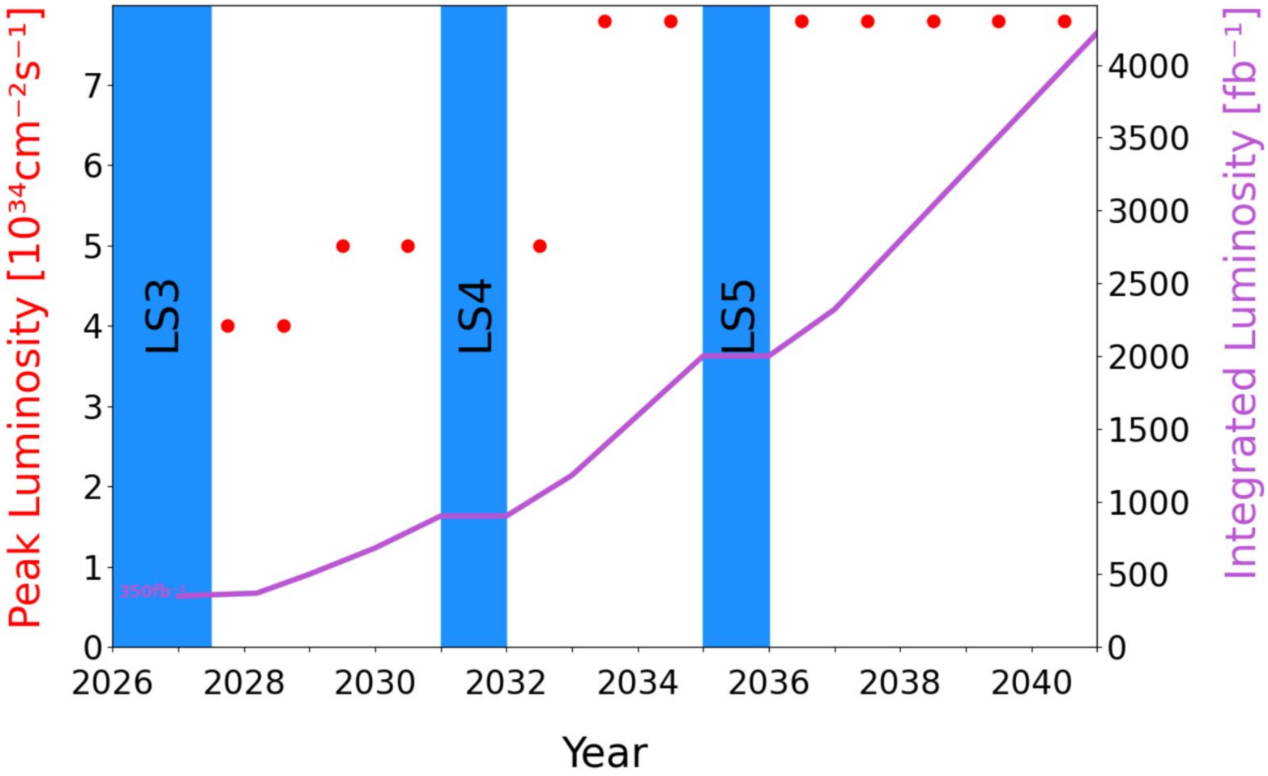
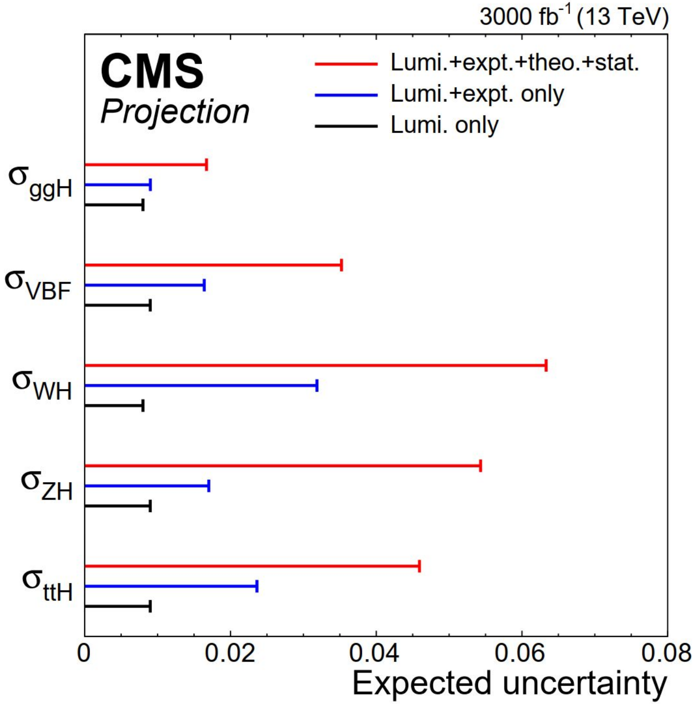
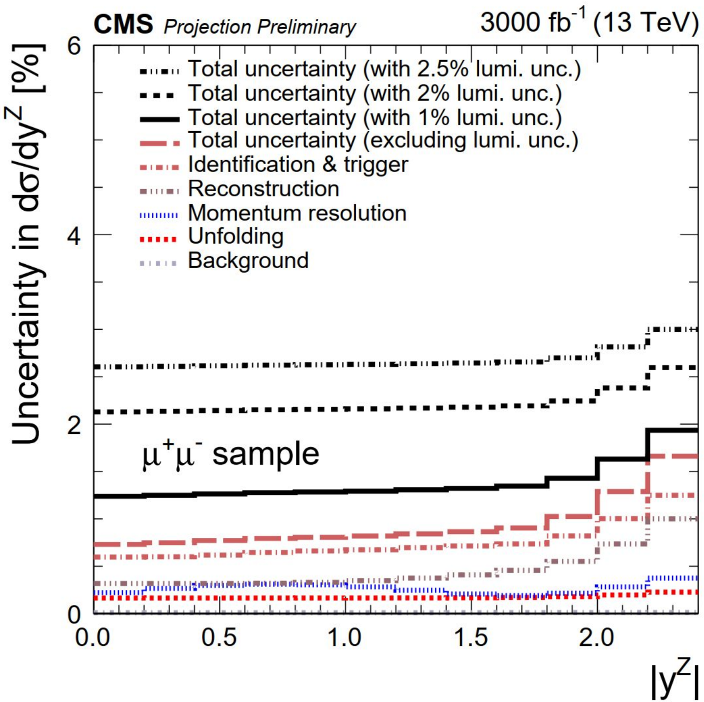
The HL-LHC luminosity



- Peak instantaneous luminosity of 5×10^{34} cm^{-2} s^{-1} (pileup≈140) - 7.5×10^{34} cm^{-2} s^{-1} (pileup≈200)
- Hardware must be designed to operate up to an integrated luminosity of 4000 fb^{-1}

Why high-precision luminosity measurement @ HL-LHC





Luminosity uncertainty will dominate the experimental systematic uncertainty at HL-LHC even with the target 1% precision and will remain significant even when including the expected theoretical uncertainties

From Run2 lumi uncertainty to HL-LHC lumi uncertainty

$$L = \int R(t)\, dt \;/\; \sigma_{vis}$$

Normalization (vdM scan)

Integration

	Systematic	Correction [%]	Uncertainty [%]
Normalization	Beam separation length scale	−1.3 to −0.4	0.2–0.3
	Linear orbit drift	+0.2 to +1.0	0.1–0.2
	Residual orbit drift	−0.6 to +0.4	0.5–0.8
	Transverse nonfactorization	+0.6 to +1.3	0.5–0.8
	Beam-beam deflection	+0.4 to +0.6	0.5
	Dynamic-β		
	Beam current calibration	+1 to +3	0.2
	Ghosts and satellites	+0.2 to +0.4	0.1
	Scan-to-scan variation	—	0.3-0.5
	Bunch-to-bunch variation	—	0.1
	Cross-detector consistency	—	0.5–0.6
	Background (detector specific)	0 to +0.8	0.1
Integration	Out-of-time effects (detector specific)	−17 to 0	0.3–0.4
	Cross-detector stability	—	0.5–0.6
	Linearity	—	0.3–1.5
	CMS dead time	—	<0.1

Phase-2 goal: 0.6% (~0.2% per source on average!)

Phase-2 goal: 0.8%

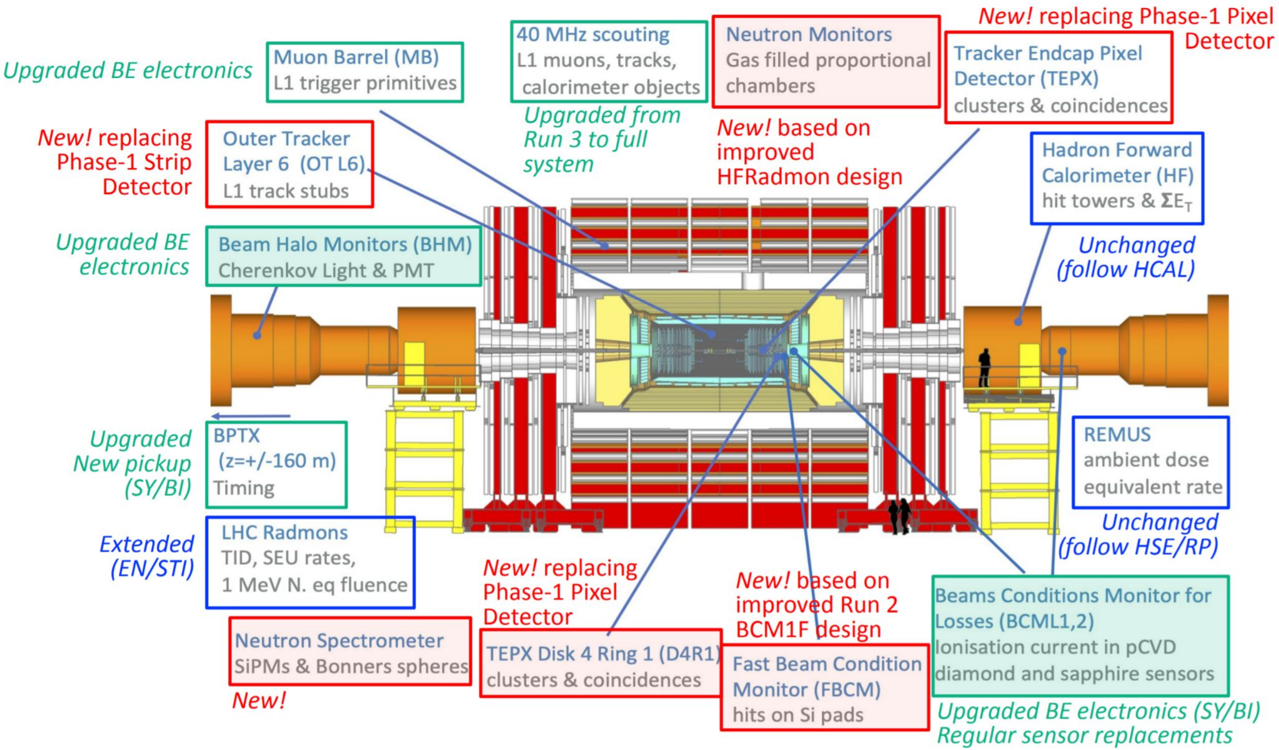
Critical to rely on detectors that exhibit excellent

- Linearity vs instantaneous luminosity, so that normalization through vdM scan valid at low/high PU
- Stability in response, to allow integration over extended data-taking periods d

→ Redundancy and diversity of the luminosity detector system very important. Target 1% (2%) offline (online) precision!

Best Run2 result so far (2016 data): 1.0 ⊕ 0.7 = 1.2% (LUM-17-003) [see Jingyu's poster]

Hardware evolution from Run3 to Phase 2



Central paradigm of maximum commonality

- Histogramming module, triggering (BRIL Trigger Board for TEPX & D4R1), readout back-end electronics,
- BRILDAQ (independent from CMS DAQ) for read out and process luminosity histograms, monitoring and calibration data, and run control system

Capabilities of the proposed luminosity systems

Diverse detector technologies and counting methods, orthogonal systematics, redundancy!

	Available outside stable beams	Independent of TCDS	Independent of foreseeable central DAQ downtimes	Offline luminosity available at LS frequency (bunch-by-bunch)	Statistical uncertainty in physics per LS (bunch-by-bunch)	Online luminosity available at ~1s frequency (bunch-by-bunch)	Statistical uncertainty in vdM scans for ovis (bunch-by-bunch)	Stability and linearity tracked with emittance scans (bunch-by-bunch)
FBCM hits on pads	✓	✓	✓	✓	*0.037%*	✓	*0.18%*	✓
D4R1 clusters (+coincidences)	✓	✓	✓	✓	*0.021%*	✓	*0.07%*	✓
HFET [sum ET] (+HFOC [towers hit])	✓	*if configured*	*if configured*	✓	*0.017%*	✓	*0.23%*	✓
TEPX clusters (+coincidences)	*if qualified beam optics*	✗	*if configured*	✓	*0.020%*	✓	*0.03%*	✓
OT L6 track stubs	*not anticipated*	✗	*if configured*	✓	*0.006%*	✓	*0.03%*	✓
MB trigger primitives via back end	✓	✗	✗	✓	*0.25%*	✓	1.2%	✓
40 MHz scouting BMTF muon	✓	✗	✗	✓	*0.96%*	✓	4.7%	✓
REMUS ambient dose equivalent rate	✓	✓	✓	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*

precision luminometers (FBCM, D4R1, HFET, TEPX, OT L6)

independent of any central CMS service (FBCM, D4R1, HFET)

at least one of them shall be available 100% of the time

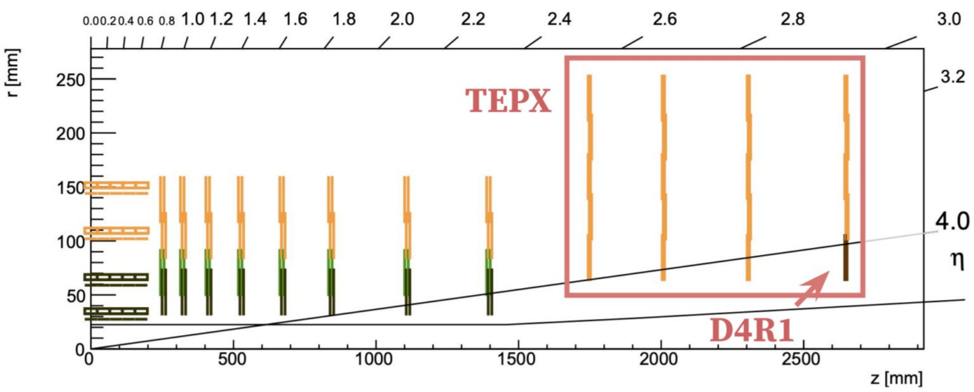
independent measurements (MB trigger primitives, 40 MHz scouting, REMUS)

Already used in Run 2

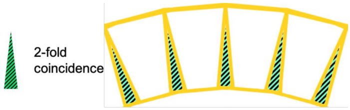
- Hadron Forward (HF) calorimeter (3.15 < |eta| < 3.5)
  2 algorithms for luminosity measurement: Tower Occupancy (HFOC) and Transverse Energy sum (HFET)

- Radiation and Environment Monitoring Unified Supervision (REMUS) monitors all around CERN. Radiation Monitoring System for the Environment and Safety (RAMSES) subsystem used for luminosity systematics

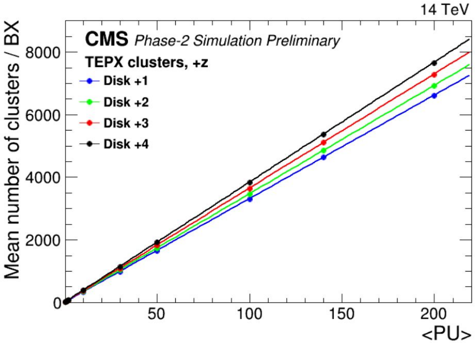
Tracker Endcap Pixel Detector (TEPX) [see Ashish's poster]

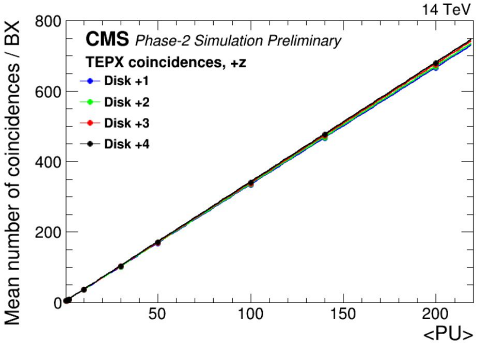


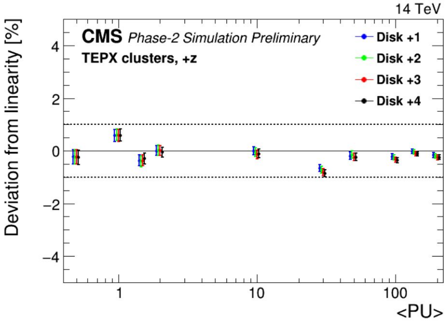
- TEPX 63 < r < 255 mm, 175 < |z| < 265 cm
  D4R1 lies beyond $|\eta| = 4$
- 800 M pixels over an area of 2 m^2
- Designed for 10^3 kHz vs 750 kHz → low occupancy
- TEPX luminosity using real time Pixel Cluster Counting on FPGA relying on dedicated unbiased trigger (75 kHz)

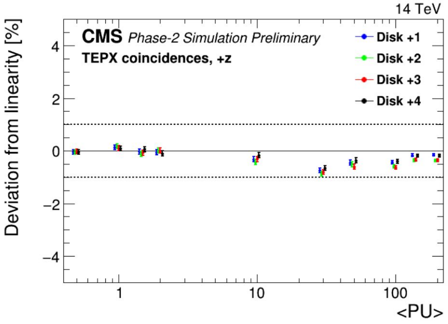


module geometry allows coincidence measurement (handle for calibration and systematics)



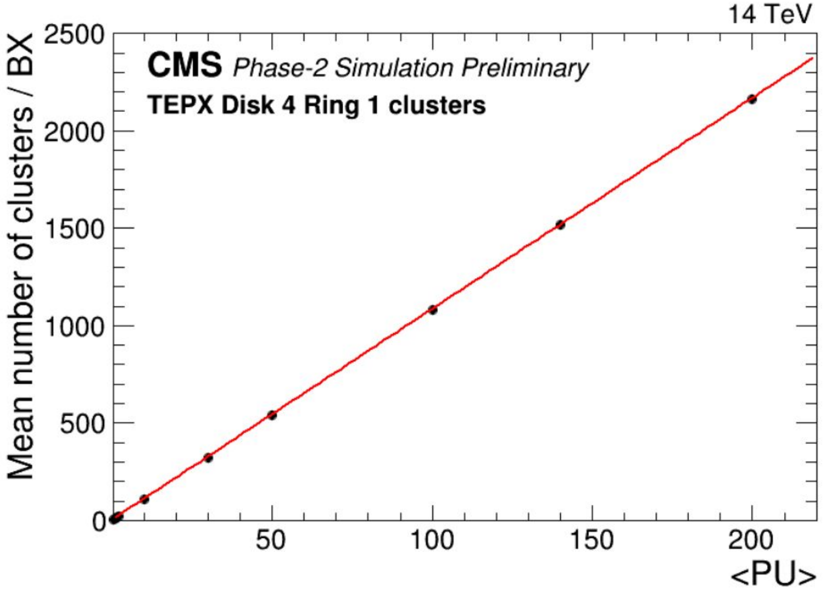


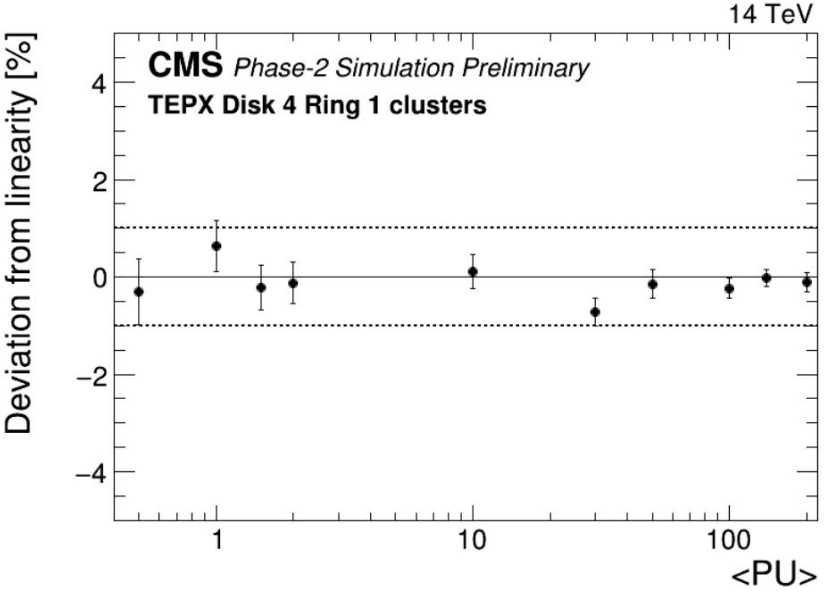




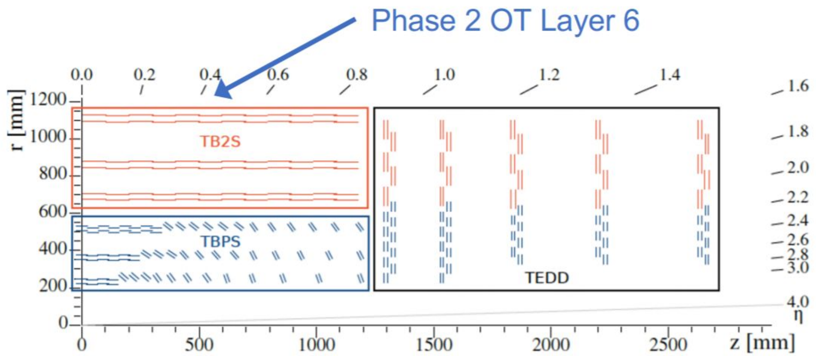
Disk 4 Ring 1 (D4R1) [see Ashish's poster]

- D4R1 operated exclusively by BRIL
- Higher trigger rate (750+75 kHz) and smaller surface (190 mm^2) → similar performance as TEPX
- Beam-induced background measurements needs at least 30 empty bunch crossings to decrease albedo and out-of-time particle contribution → only the first bunch in a train or unpaired bunches

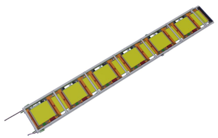


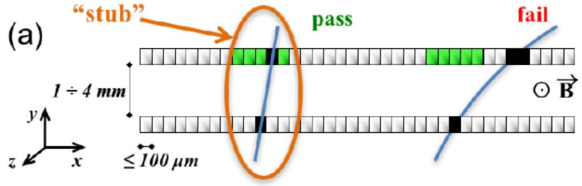


Outer tracker (OT)

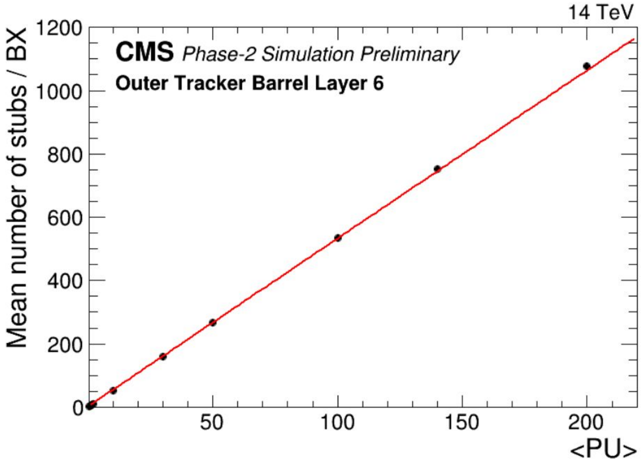


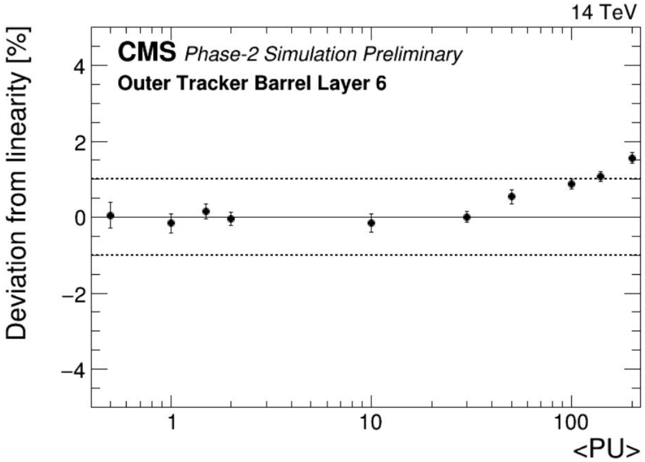
- Outermost barrel layer 6 in the TB2S part is used
- 76 sensor ladders on each end of CMS



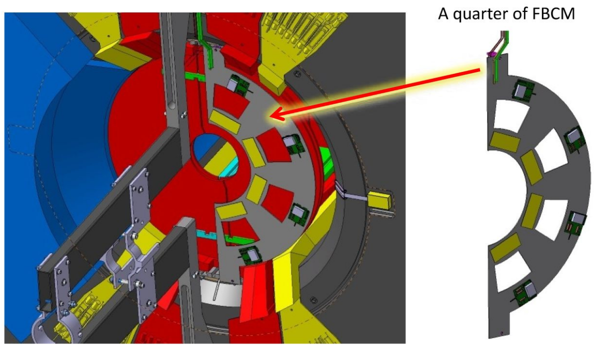


- Each ladder containing 12 modules of 2 Si-strip sensors
- The track stub reconstruction detects hit coincidences on the two sensors of the module @ 40 MHz

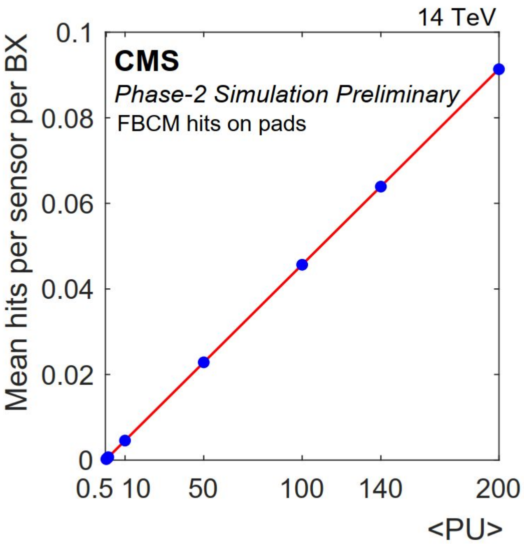


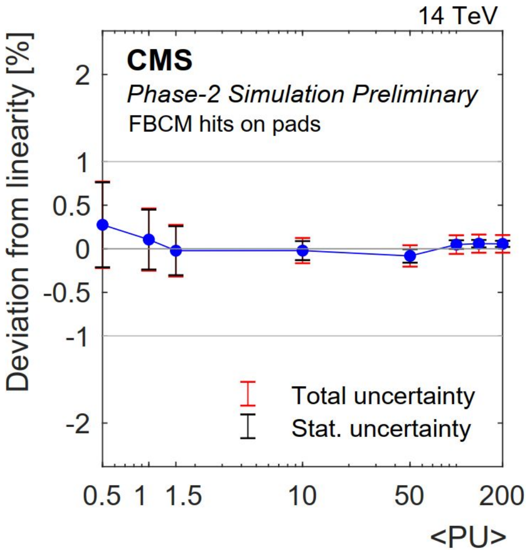


Fast Beam Conditions Monitor (FBCM) [see Joanna's poster]

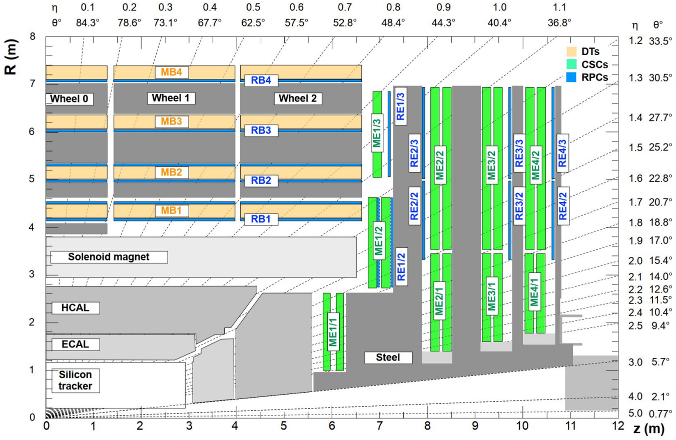


- Proposal to locate close to bulkhead (behind disk 4 of TEPX)
  $8 < r < 30$ cm, $277 < |z| < 290$ cm
- 4 quarters, 84 silicon-pad (expect 300um, 2.89 mm^2) sensors/quarter
- Luminosity measured using zero-counting algorithm
- BIB measurement exploiting info of the time-of-arrival (ToA) and time-over-threshold (ToT) of hits with a sub-ns resolution at the rate of 40 MHz



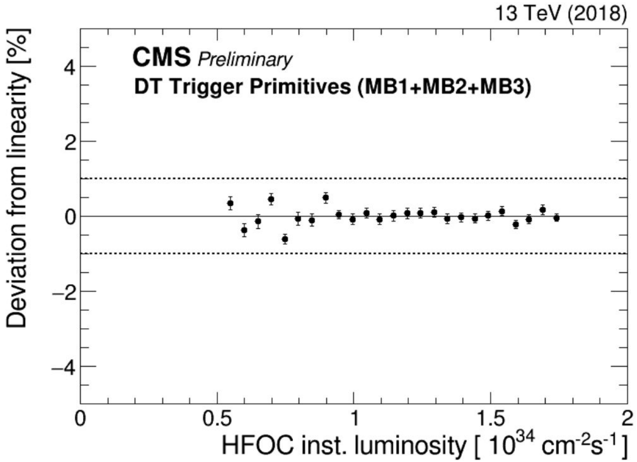


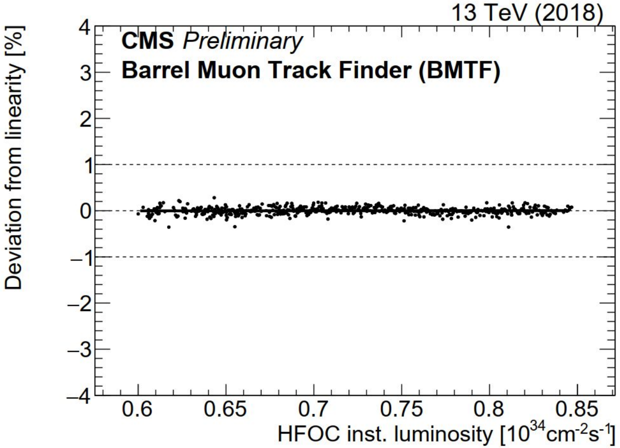
Muon barrel detector and 40 MHz scouting



- Counting of muon tracks @ L1 useful for excellent linearity and stability during Run2 → use upgraded system for Phase 2
- Hits from the DT (and RPC) detectors (including particles from jet punch-through) will be combined to reconstruct muon track segments (trigger primitives) as part of the L1 muon trigger system → use of BRIL firmware modules → From orbit-integrated (Run 2) to per bunch crossing (Phase 2)

- Scouting system (part or all of the trigger data streams) captures the L1 trigger objects (Barrel/Endcap muon track finder B/EMTF)
- Verification of the functionality of the existing trigger algorithms, as well as development of new algorithms without disturbing data taking with stable trigger algorithms
- 40 MHz demonstrator already tested in Run 2 and it will be extended for Run 3





Summary

- In High-Luminosity era we expect peak instantaneous luminosity of 5×10^{34} cm^{-2} s^{-1} (pileup≈140) - 7.5×10^{34} cm^{-2} s^{-1} (pileup≈200) and up to 4000 fb^{-1}
- Luminosity uncertainty will dominate the experimental systematic uncertainty at HL-LHC → aim to a precision of 1% (2%) offline (online).
  Best Run2 result (2016) with 1.2% precision (LUM-17-003) shows this is a feasible target.
- Estimation of beam-induced bkg important for data quality (and some new physics searches)

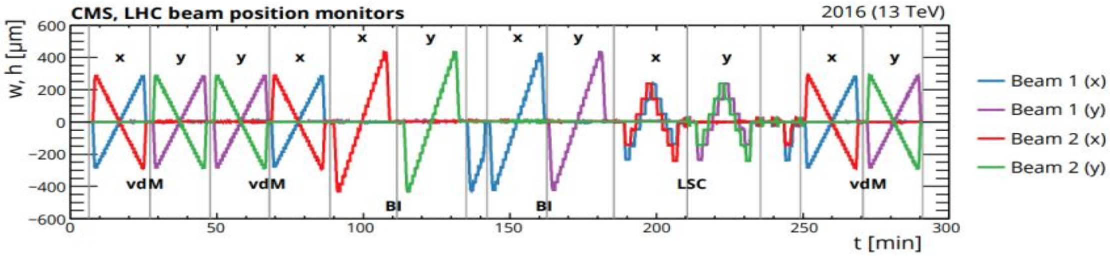
- CMS has a well defined upgrade plan (TDR submitted to LHCC end June) to fulfill these tasks
  - Exploiting redundancy and diversity of Phase 2 CMS detector systems
    - TEPX and BRIL-operated D4R1 with pixel cluster and coincidence counting
    - Strip Tracker OT L6 twofold coincidence counting
  - New dedicated luminometer
    - Fast Beam Conditions Monitor
  - Upgrade well established/demonstrated technology
    - Hadron Forward (HF) calorimeter with 2 algorithms
    - Muon Barrel (DT+RPC) backend
    - 40 MHz trigger scouting systems providing muon information
    - RAMSES
- Required excellent stability and linearity

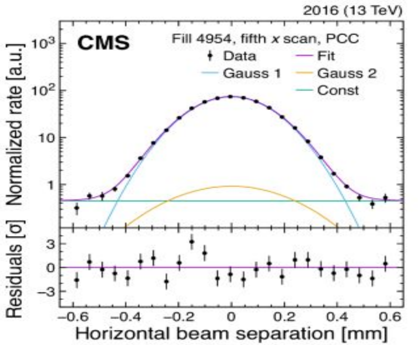
Backup

Precision Luminosity Measurement from CMS

Absolute luminosity scale measured for individual bunch crossings

beam-separation
van der Meer scans



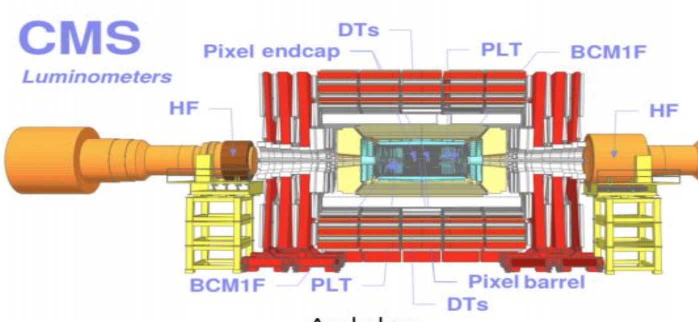


Obtained **relative precision**

- **1.6% in 2015** (2.2 fb^{-1})
- **1.2% in 2016** (36.3 fb^{-1})

Main sources of uncertainties

- differences between measured beam positions and the ones provided by the LHC
- factorizability of the transverse spatial distributions of proton bunches
- modelling of interactions among protons in the colliding bunches



PLT = *Pixel Luminosity Telescope*
BCM = *Beam Conditions Monitor*
HF = *Forward Hadron Calorimeter*
PCC = *Pixel Cluster Counting*

And also:

- 1.9% in 2017 at $\sqrt{s}$ = 5.02 TeV (302 pb^{-1}) → LUM-19-001

2104.01927, Physics briefings

Central paradigm: maximum commonality

Since conception of BRIL, **strengthen the use of common components in data acquisition and analysis of BRIL instrumentation**

Common

- triggering (BRIL Trigger Board: generate unbiased triggers for TEPX & D4R1, BPTX signal to CMS Global Trigger)
- readout back-end electronics (e.g., use Apollo and Serenity boards for BRIL luminosity systems)
- histogramming module for all luminometers
- data acquisition = BRILDAQ
    - Read out and process luminosity histograms, monitoring and calibration data
        - Luminosity data processed in ATCA back end with system-on-chip processors
        - Read out via control network through gigabit Ethernet
            - subsystems need to give sufficient bandwidth for (small) BRIL data volume
            - work with DAQ group to define architecture
        - Injected to BRILDAQ infrastructure
    - Independent run control system
    - Database providing all necessary information for physics analyses

Luminometer operation during LHC cycle

Different detectors will have different coverage depending on the agreed safety considerations with the subsystems