High-precision **luminosity** instrumentation for the **CMS detector** at the **HL-LHC**

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On behalf of the CMS collaboration

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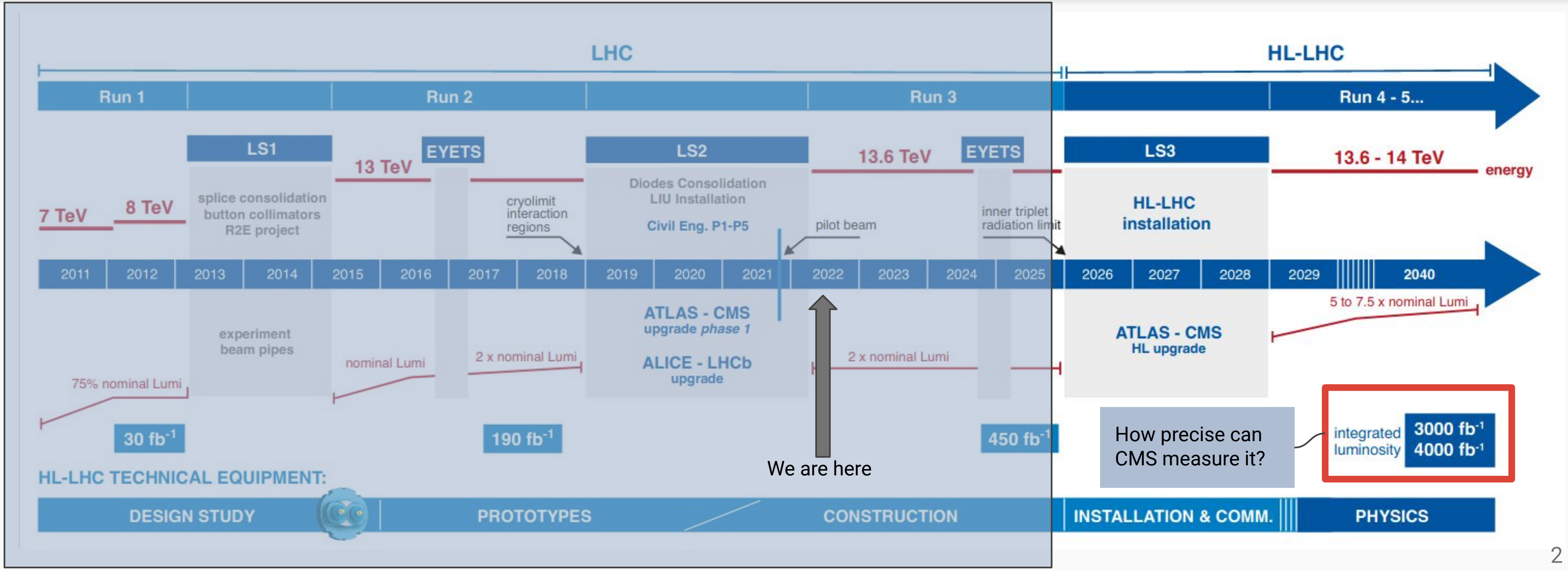
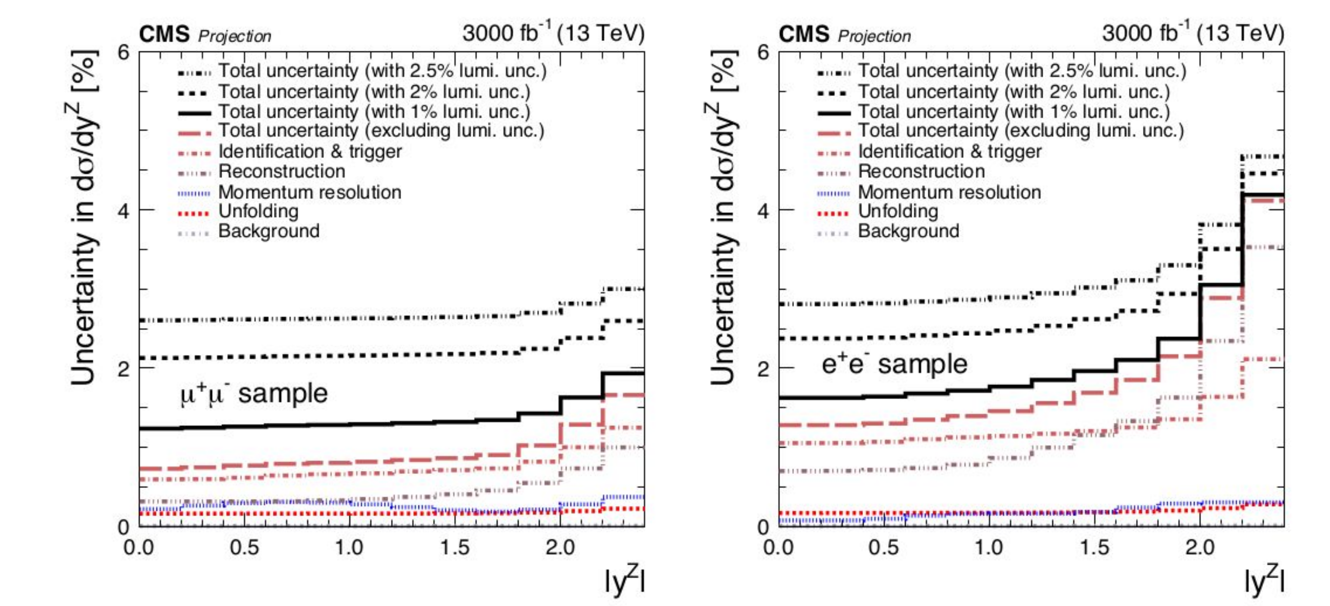
High Lumi LHC Program



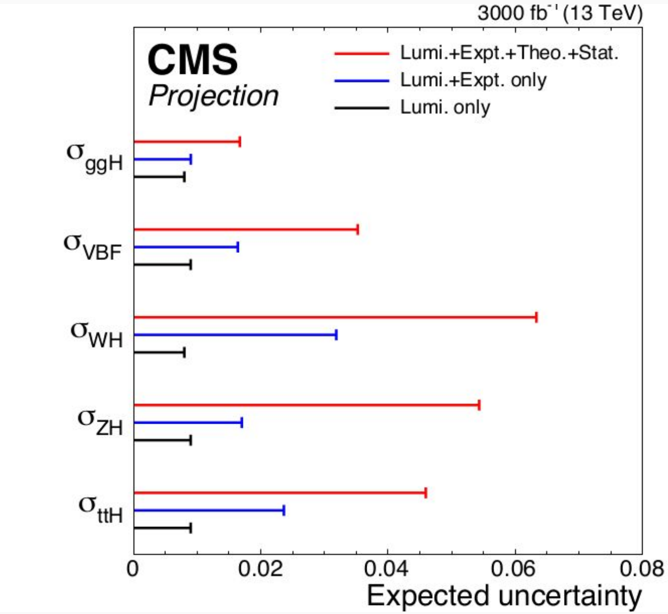
Why precise luminosity (I)?

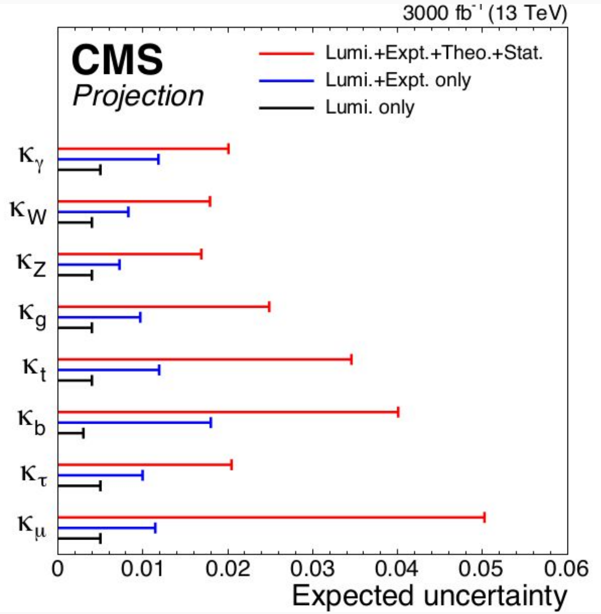
Projection of differential DY cross-section measurement



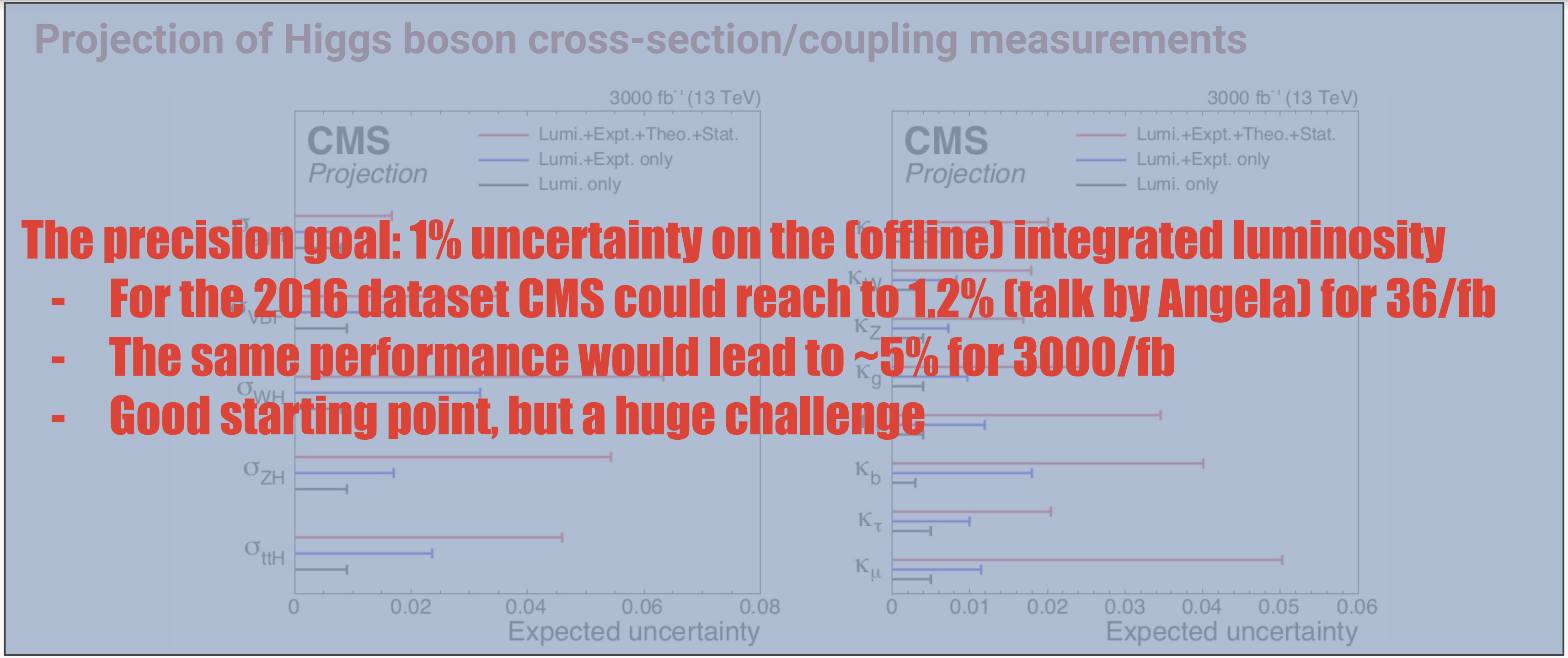
Why precise luminosity (II)?

Projection of Higgs boson cross-section/coupling measurements





Why precise luminosity (II)?



The precision goal: 1% uncertainty on the (offline) integrated luminosity

- **For the 2016 dataset CMS could reach to 1.2% (talk by Angela) for 36/fb**
- **The same performance would lead to ~5% for 3000/fb**
- **Good starting point, but a huge challenge**

Uncertainty sources

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

- Linearity
  - σ_{vis} is measured in VdM scans (very low rates)
- Stability
  - Integration over data-taking period
- Backgrounds
  - Understanding residuals and beam induced bkg.
- Redundancy and diversity of luminosity detectors
  - Cross checks/stability

Source	2015 (%)	2016 (%)	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.6	0.3	No
Integration uncertainty			
Out-of-time pileup corrections			
Type 1 corrections	0.3	0.3	Yes
Type 2 corrections	0.1	0.3	Yes
Detector performance			
Cross-detector stability	0.6	0.5	No
Linearity	0.5	0.3	Yes
Data acquisition			
CMS deadtime	0.5	<0.1	No
Total normalization uncertainty	1.3	1.0	–
Total integration uncertainty	1.0	0.7	–
Total uncertainty	1.6	1.2	–

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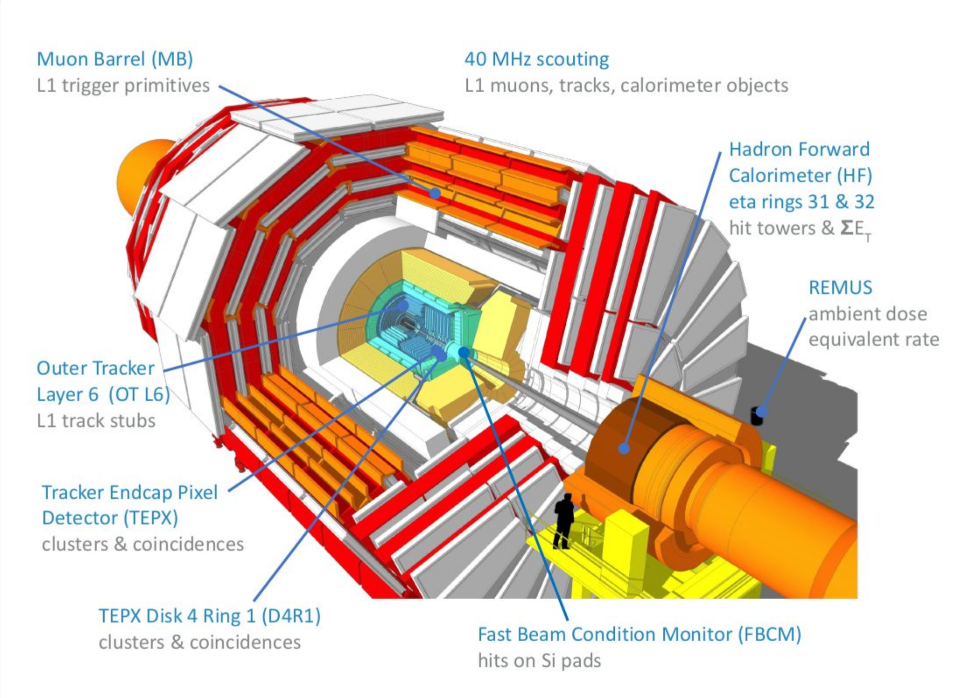
Strategy



Two lines:

- Exploiting the CMS sub detectors as much as possible for luminosity measurement
  - Tracker (Inner and Outer)
  - Muon System
  - Hadron calorimeter
  - 40 MHz scouting (L1)
  - REMUS
- Independent Luminometer
  - Fast Beam Condition Monitor (FBCM)

Phase-2 luminometers at a glance

	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 σvis (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	✗	✗	*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*

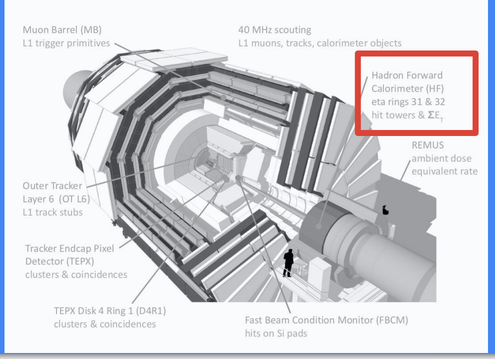
Precision luminometers

- Independent of central CMS DAQ
- Stability is essential

Back-end electronics
- Histogramming modules
- triggering (BRIL Trigger Board for Cluster finding in TEPX & D4R1)

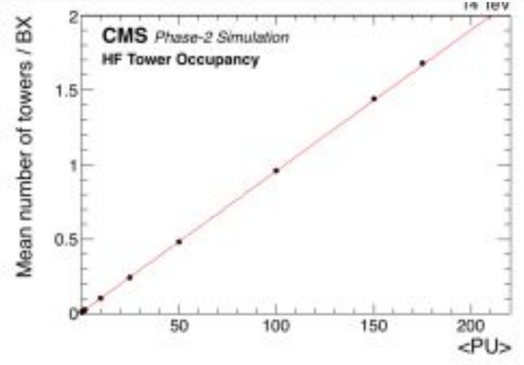
BRILDAQ:
- Independent from CMS DAQ
- Read out and process luminosity histograms from Histogramming modules
- Monitoring/Calibration
- Run control

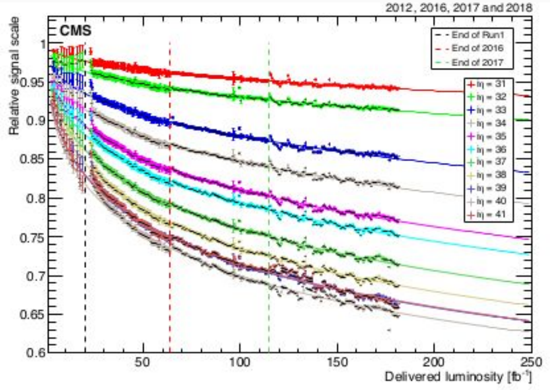
Hadron Forward Calorimeter



Already used in Runs I&II (3.15 < |η| < 3.5)

Aging and linearity is well studied

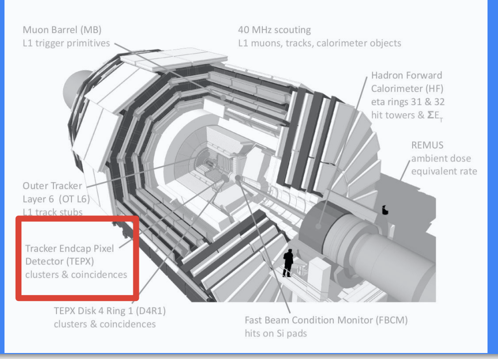


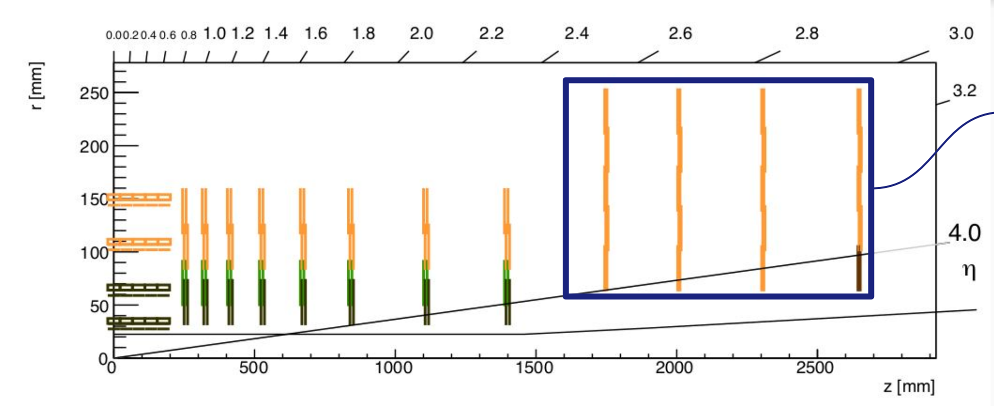


2 algorithms for lumi. measurement:

1. Tower Occupancy (HFOC)
2. Transverse Energy sum (HFET)

Inner Tracker Endcap Pixel Detector (**TEPX**)

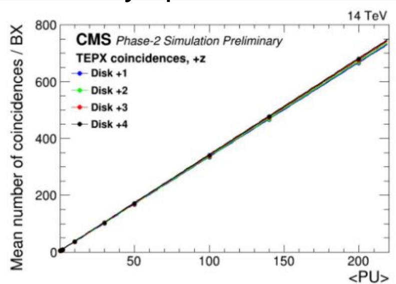


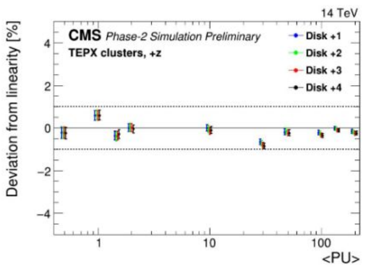


TEPX: 63 < r < 255 mm, 175 < |z| < 265 cm

- 800M Pixel / 2m^2
- Low occupancy

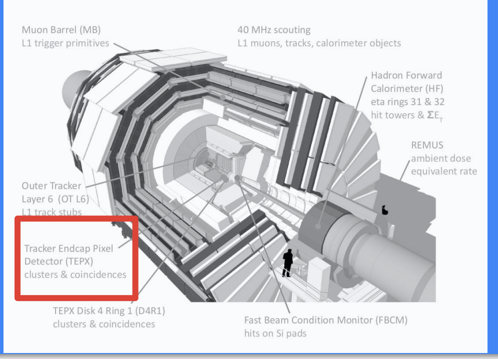
Linearity up to <PU>=200 is confirmed in simulation

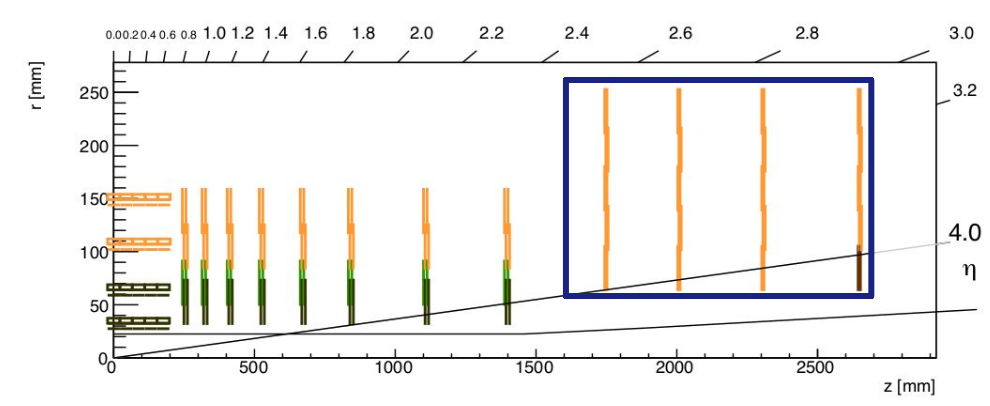




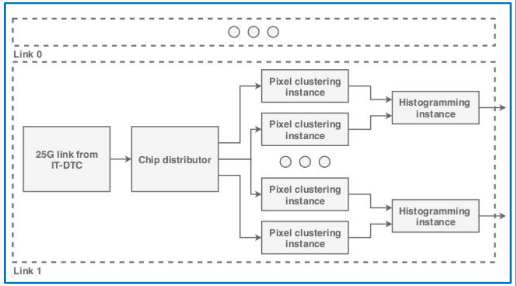
- Run-2 experience:
  - Linearity of “pixel cluster counts” with luminosity
- New in phase-2 upgrade:
  - FPGA to count “pixel clusters” in real time
  - based on dedicated unbiased trigger (75 kHz)

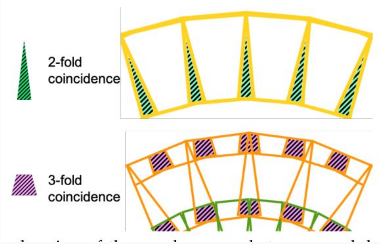
Inner Tracker Endcap Pixel Detector (**TEPX**)





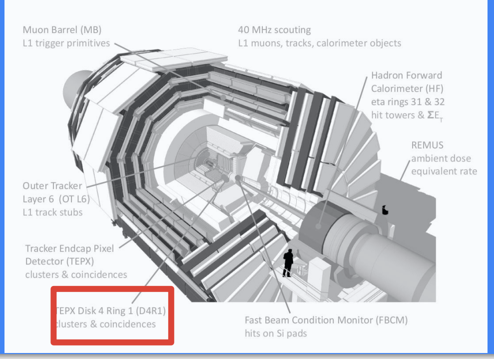
Schematic diagram of the luminosity processing firmware.

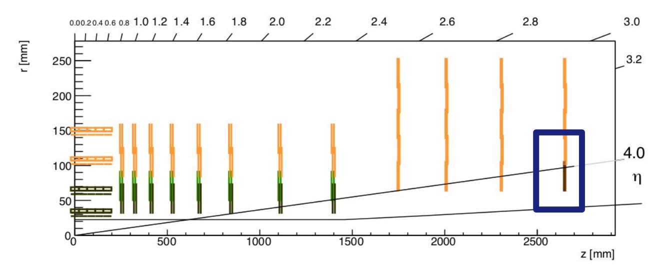




2/3-fold coincidences provides handles for further calibration and stability cross-checks

TEPX Disk 4 Ring 1 (D4R1)

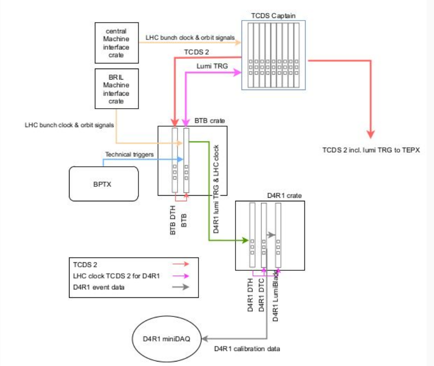




$|\eta| > 4$, $222 cm^2$

Is operated exclusively by BRIL

- Front-end optimization
- Dedicated back-end
- Dedicated timing and trigger

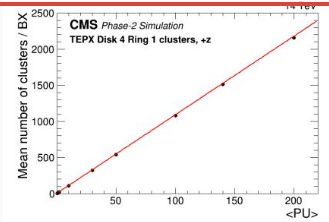


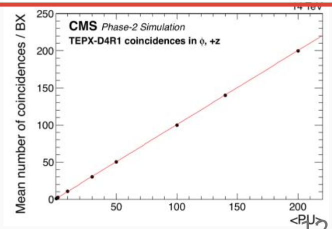
Beam induced background:

- Can be measured only for the first bunch in a train or unpaired bunches
- Background from activated materials (albedo) and out-of-time particles are dominant for other BXs

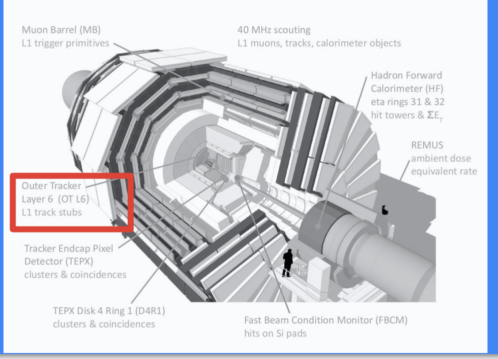
Luminosity

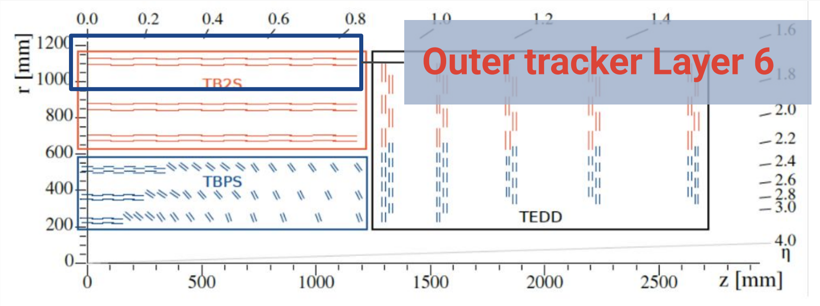
1. #clusters
2. #coincidences



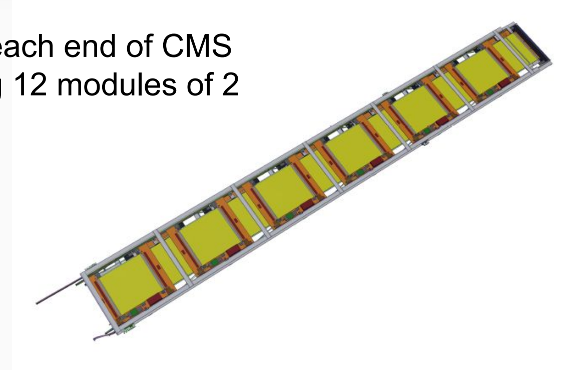


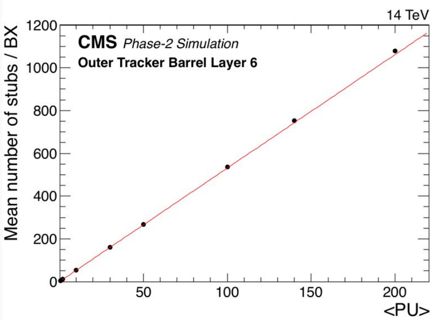
Outer Tracker



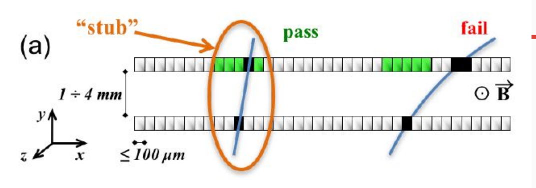


- 76 sensor ladders on each end of CMS
- Each ladder containing 12 modules of 2 Si-strip sensors

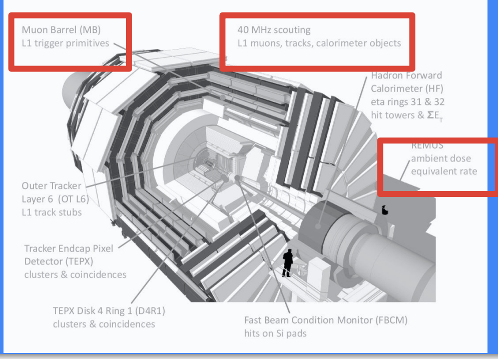




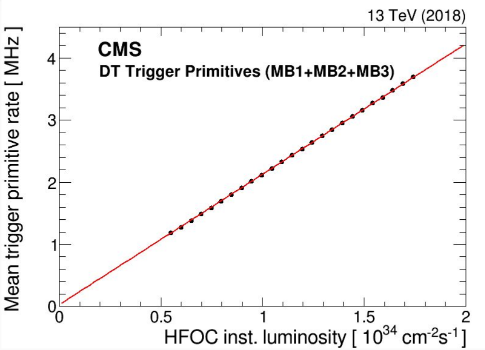
Simulation confirms the linearity of <number of stubs> and luminosity
track stub: reconstructed coincidences on the two sensors of the module @ 40 MHz

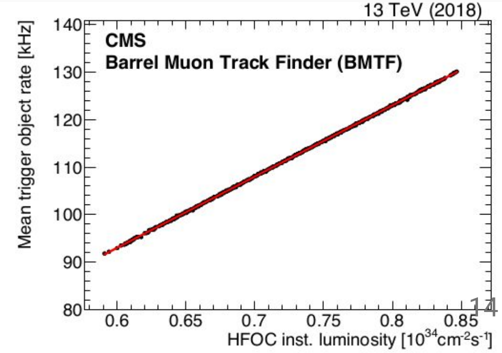


Other CMS based luminometers



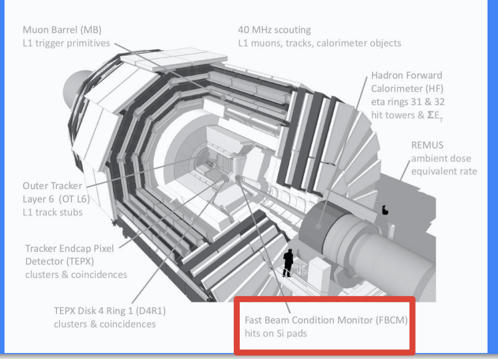
- **Muon barrel**
  - Counting of Muon tracks @L1
  - Hits from drift tube (+RPC) are combined to construct track segments for L1
  - Per bunch crossing
- **40 MHz scouting**
  - Part of the trigger data streams
  - Access to L1 trigger objects from all sources
  - Average number of objects is a measure of luminosity
- **REMUS**
  - CERN system to monitor radiation and environment
  - Radiation is expected to be proportional to luminosity



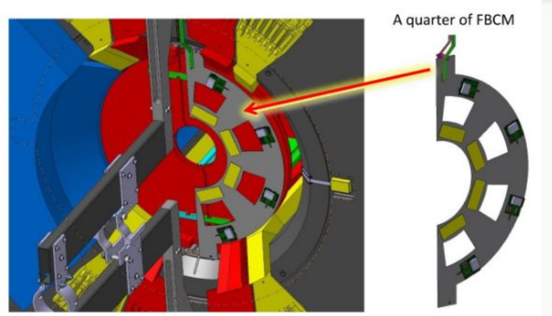


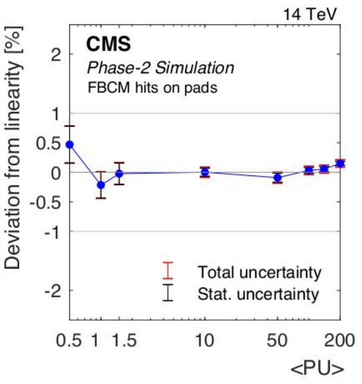
Independent Luminometer

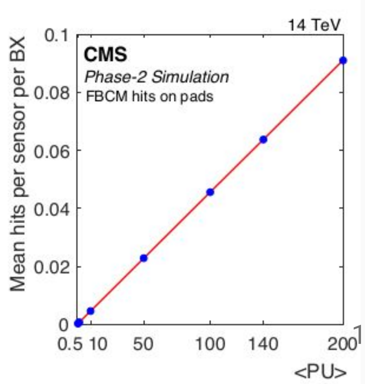
Fast Beam Condition Monitor (FBCM)



- **Location:** behind Disk4 of TEPX
  - r~14.5 cm, |z| ~ 285 cm
- **Silicon sensors:** 300μm thickness, ~3mm^2 area
  - 2 quarters per side, each with 84 sensors
- **Expected rate:**
  - 0.1 hit / sensor / BX @PU=200
- **GEANT Simulation**
  - Confirms the linearity of FBCM in the HL PU range







Independent Luminometer
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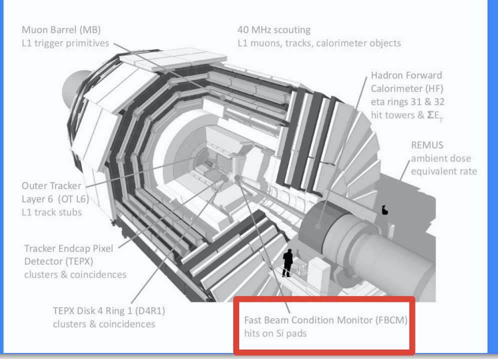
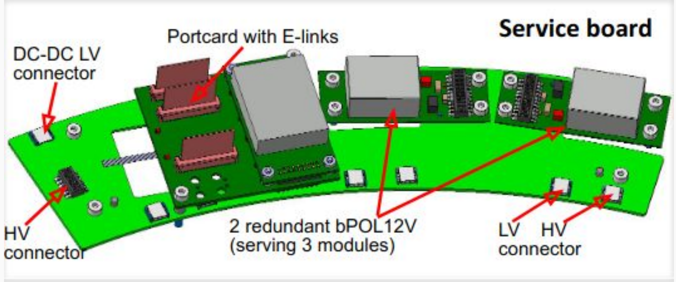
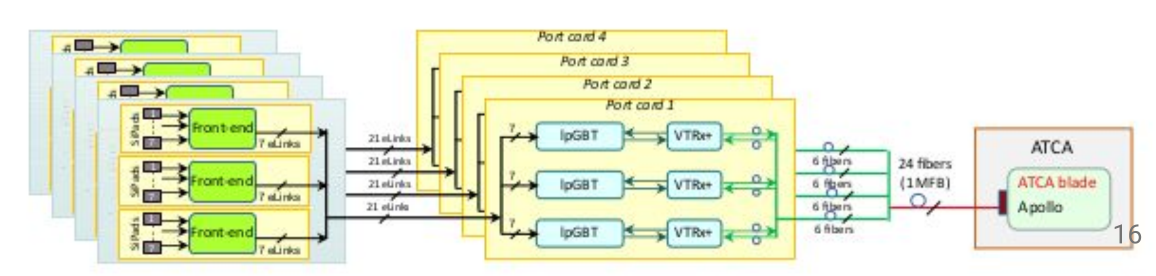


- **ASIC**
  - A dedicated 6 channel ASIC: under development
  - sub-ns time resolution: estimate BIB
  - Reuse of components from tracker
- **Service board**
  - At higher radius
  - 3 front-end modules
  - power/control/readout





Summary

This talk was based on the [CMS BRIL TDR]

- CMS has an extensive program to further improve the luminosity measurement in High-Lumi LHC era
  - The target of 1% uncertainty is essential to reach physics goals
- Subdetectors of the CMS (phase-2) will be exploited
  - Inner tracker (with a special role) + outer tracker + muon system + HF + …
- An independent luminometer (FBCM) is designed
  - Engineering development underway
- Run-3: Prime opportunity to test some of the ideas