Precision Luminosity Measurement with the CMS Detector for HL-LHC

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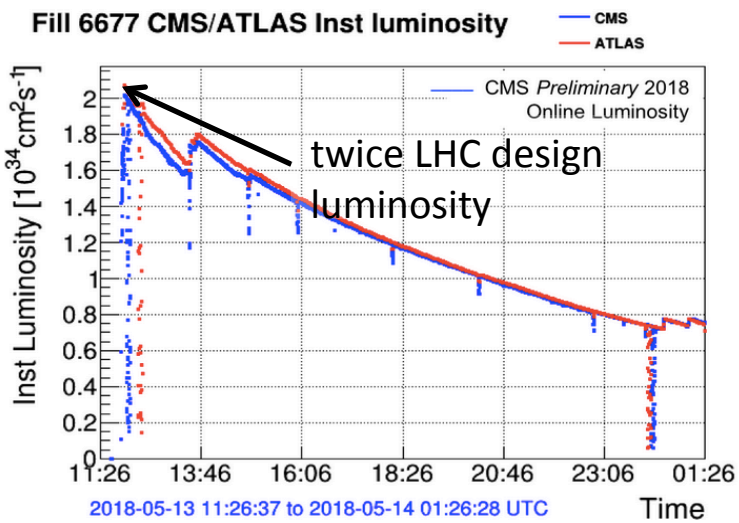
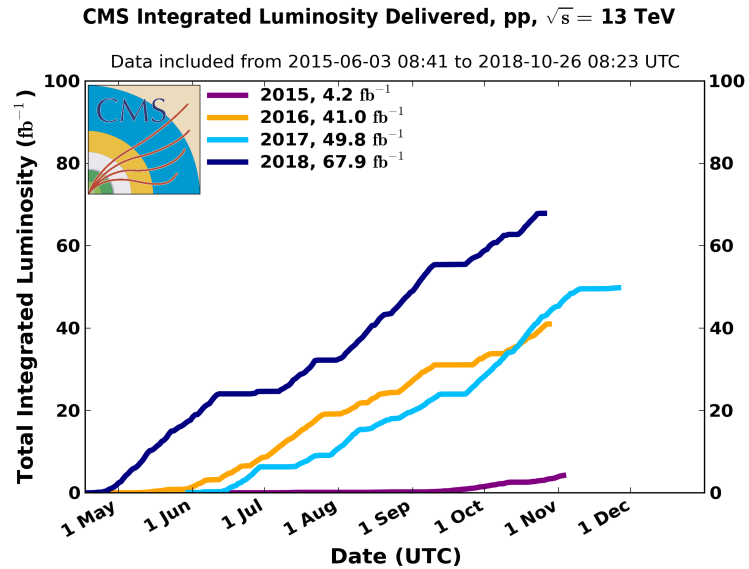
Luminosity L is one of the most important parameters for a collider :

- the precision of physics process's cross-section depends critically on the accuracy of the luminosity.
- The luminosity is the figure of merit the collider's operation day by day efficiency.





$$L = \frac{R}{\sigma}$$

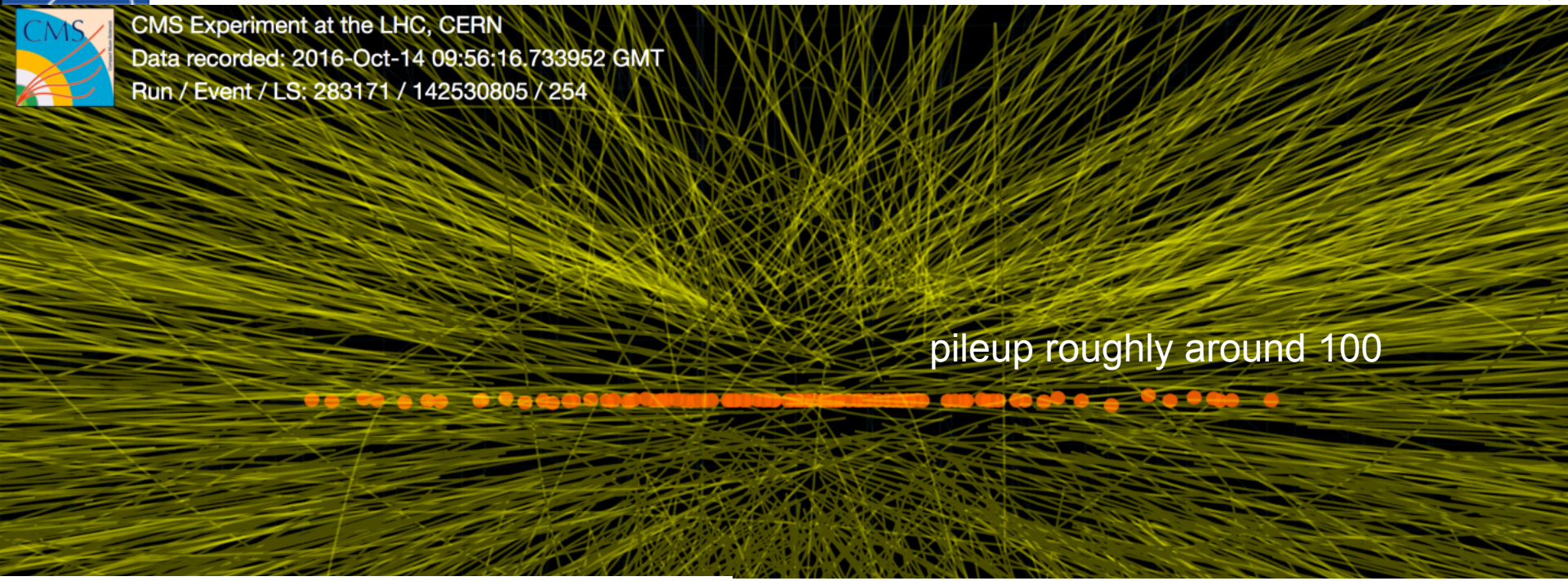
R-event rate
σ – process cross-section

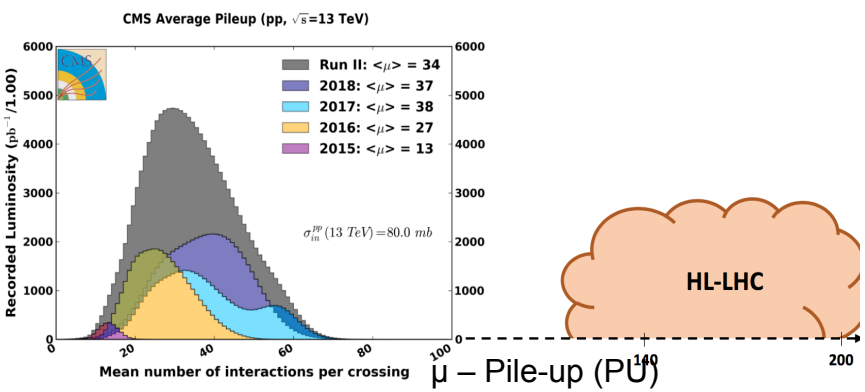
$$L = \frac{N_1 N_2 f_r n_b}{2\pi \Sigma_x \Sigma_y}$$

N1, N2 – number of protons in bunch
N_b –number of colliding bunch pairs
fr = 11246 Hz is the LHC orbit frequency
$\Sigma_{x,y}$ beam overlap widths

In the CMS experiment The Beam Radiation Instrumentation and Luminosity (BRIL) project is responsible for luminosity measuring

High-Luminosity LHC





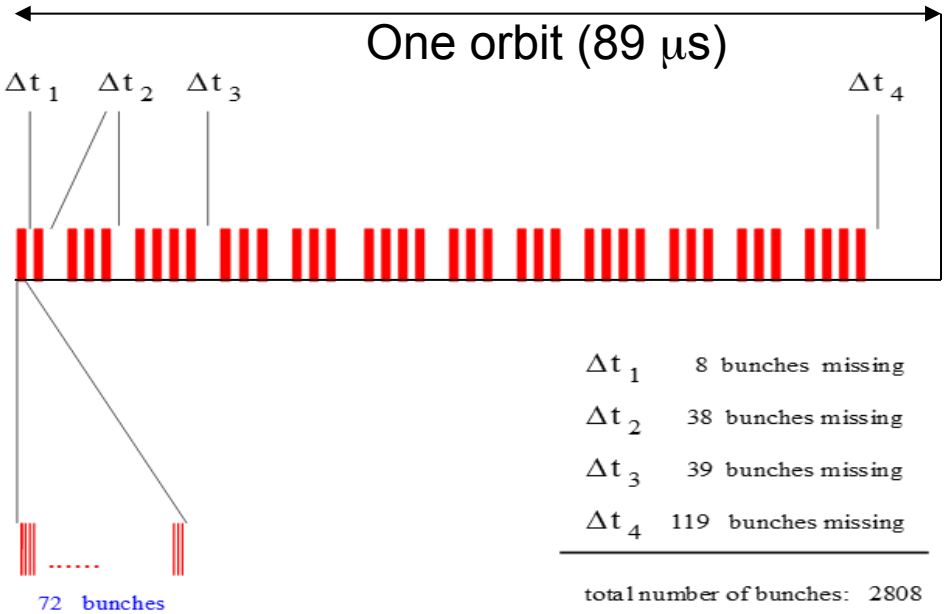
Pile-up of 140 baseline, of 200 ultimately

√s = 14 TeV,

Expected integrated luminosity in CMS>3000 fb^{-1}

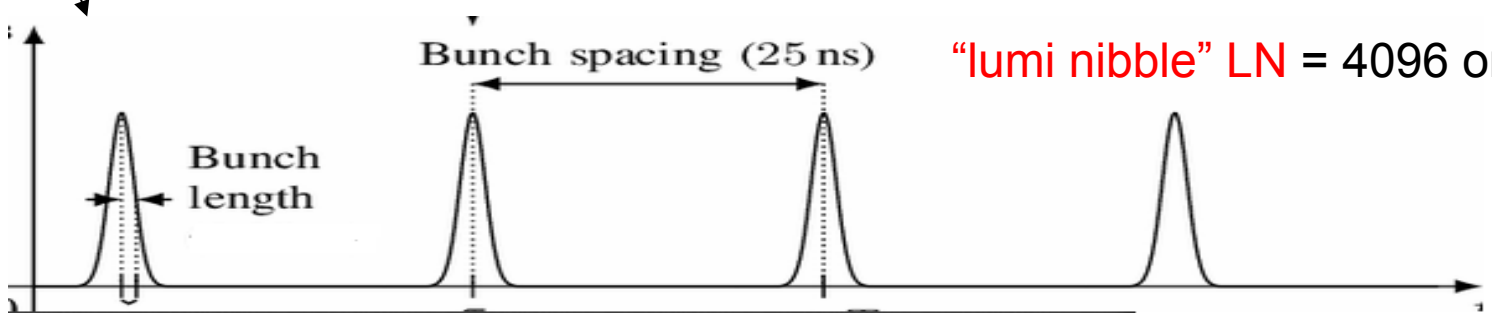
New highly granular and radiation hard detector technology required

HL-LHC beam structure (the nominal filling scheme)



https://cds.cern.ch/record/2319396/files/CERN-THESIS-2018-051.pdf

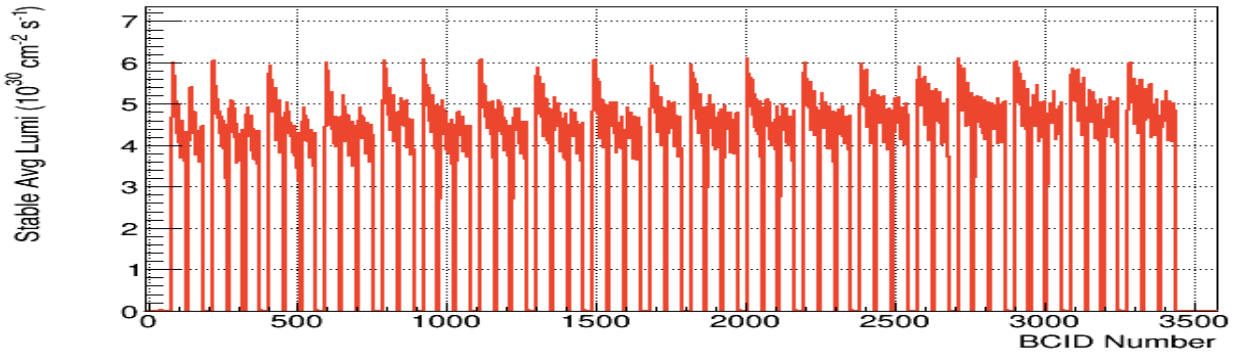
- Bunch-by-bunch luminometer provides PU value for every single bunch crossing (BX)
- But statistical accuracy of the single BX measurement is low
- Since bunches are circulating with f_r we can measure BX signal for the selected bunch pair many times, for many orbits and perform histogram accumulation



"lumi nibble" LN = 4096 orbits or 0.36 s

Online Instantaneous Luminosity *for machine performance:*

lumi levelling, PU distribution & beam monitoring.



Histogramming and readout
4LN = 1.46s

Bunch crossing ID

Offline Luminosity *for CMS Physics*

For offline CMS physics analyses, data are provided in units of "lumi sections" (LS), corresponding to 64LN or 23.3 s.
Sometimes days or years of latency are needed for the minimizing of luminosity uncertainties

Uncertainties in the CMS luminosity measurement for Run 2 2.3-2.5%

2015/2016 - Expect significant improvement in the Luminosity uncertainties

HL-LHC offline Luminosity Precision Target

Integrated Luminosity uncertainty is the **dominant systematic uncertainty** for precision cross-section measurements with well-controlled systematic - **leptonic Z and W bosons, and top quark decays**

The measured inclusive fiducial cross sections in the dimuon and dielectron final states.
The combined measurement is also shown.
B is the Z→ll branching fraction.

Cross section	$\sigma\,\mathcal{B}$ [pb]						
$\sigma_{Z\to\mu\mu}$	694	±	6	(syst)	±	17	(lumi)
$\sigma_{Z\to ee}$	712	±	10	(syst)	±	18	(lumi)
$\sigma_{Z\to\ell\ell}$	699	±	5	(syst)	±	17	(lumi)

arXiv: 1909.04133

- Most HL-LHC standard model analyses
  - Luminosity uncertainty typically becomes subleading *only if* at the ~1% level
- Theorists formulate at HL-LHC the target for luminosity is a ~1% precision in the Report on the Physics at the HL-LHC and Perspectives for the HE-LHC (arXiv: 1902.10229)
- **Overall, CMS are going to push for absolute Luminosity to 1.0% precision to fully exploit HL-LHC physics potential**

How is possible to measure precisely the absolute Luminosity?

Major challenge is the determination of the absolute calibration scale

"standard candle"
(Example of "standard candle" in e+e- colliders - Bhabba scattering cross section
But for LHC situation is much more sofisticated – Z ➔μμ is under investigation)

OR

•By using information from **LHC instrumentation**

For the LHC, it was proposed to use the special **Van der Meer (VdM)** method to provide a luminosity calibration based on machine parameters for the physics experiments

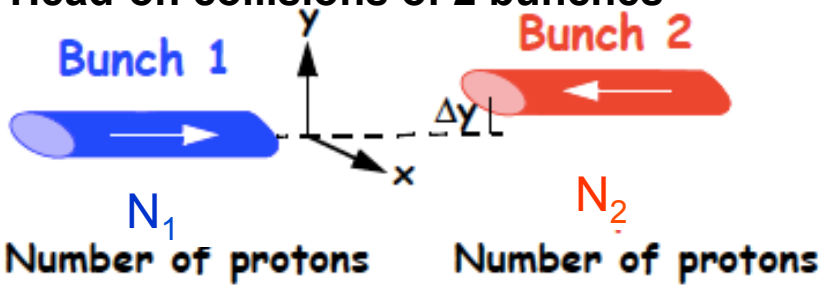
VdM separation scans first pioneered by Simon van der Meer at CERN's Intersecting Storage Ring accelerator (ISR) in the 1960s.

Calibration involves scanning the LHC beams through one another to determine the size of the beams at their point of collision.

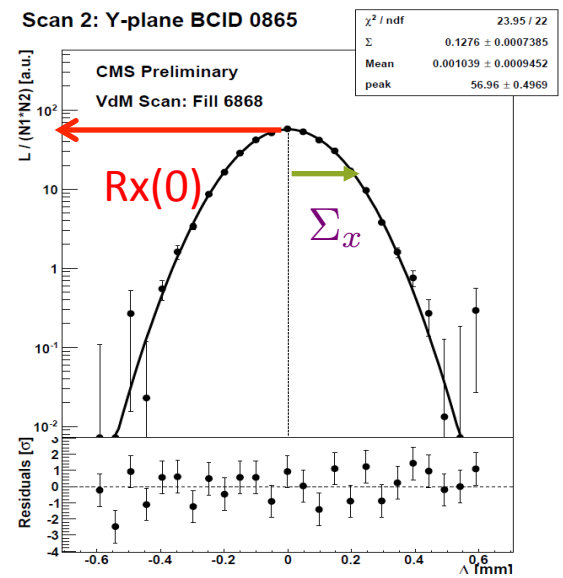
These VdM scans allow for determination of the absolute luminosity as a function of beam parameters and so can be used to develop a calibration for the individual luminometers.

Van der Meer (VdM) scan

Head-on collisions of 2 bunches



Interaction rate $R_x(\delta)$ versus beam-beam separation



$$L = \frac{R_x(0)}{\sigma_{vis}}$$

, **R – interaction rate , σ_{vis}-cross section- needs to be defined**

It was shown by Van der Meer that if the density distributions of protons in the horizontal and the vertical planes are **uncorrelated and stable**, for Gaussian distributions of protons:

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\delta)\mathrm{d}\delta}{R_x(0)}$$

$$\sigma_{vis} = \frac{2\pi R_x(0)\Sigma_x\Sigma_y}{N_1 N_2 n_b f_r}$$

N1, N2 – number of protons
n_b –number of bunches
fr = 11246 Hz is the LHC orbit frequency

} **machine parameters**

If we assume that

σ_{vis} is a constant over 4- 5 orders of magnitude of intensity

- **Linearity of luminometers & algorithms**
- **Long term stability of luminometers (harsh radiation conditions)**

Then we can measure luminosity **--> by independent CMS subdetectors**!

VdM scan and Physics mode HL-LHC conditions

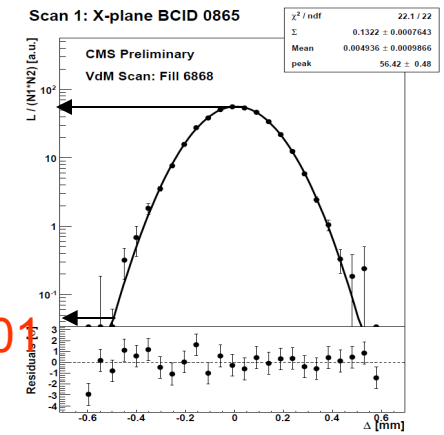
VdM scans are performed during a special LHC fill once per year with specific conditions to reduce systematics

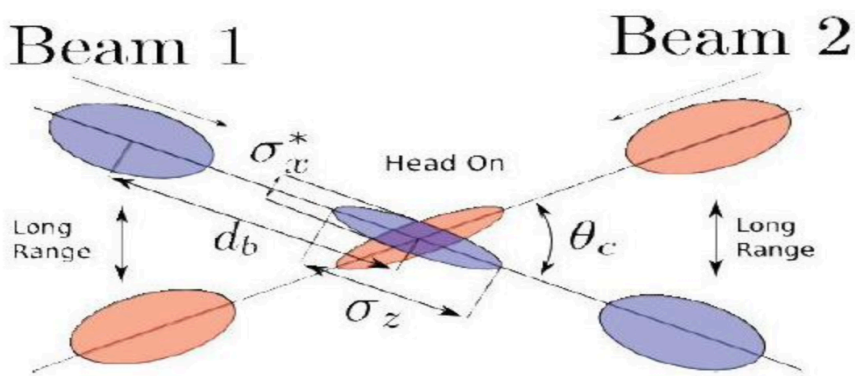
	vdM scan	Physics mode
Number of bunches	< 150	up to 2656 (all bunches of the fill)
Bunch current	0.8×10^{11} protons	1.15×10^{11} protons
Beam optics	$\beta^* = 1917\,\mathrm{cm}$	$\beta^* = 30\,\mathrm{cm}$
Beam overlap width	$\approx 120\,\mu\mathrm{m}$	10–$15\,\mu\mathrm{m}$
Crossing angle	0	range of crossing angles decreasing from $280\,\mu\mathrm{rad}$
Pileup (μ)	0.001-0.5 interactions	140-200 interactions

VdM scan

0.5

0.001





For HL-LHC conditions for BbB

$$Dynamic\_Range = \frac{200}{0.001} = 2*10^5$$

The larger is the crossing angle, θc , the smaller is the area of overlap and therefore smaller is the possibility of collision.

σ_z is constant over the machine ~7.5 cm,

σ_x varies and squeezed its minimum in the Interaction Points

Uncertainties in the CMS Run2 Luminosity measurement

Year	Total [%]	Normalization [%]	Integration [%]
2015	**2.3**	1.8	1.5
2016	**2.5**	1.5	2
2017	**2.3**	1.5	1.7
2018	**2.5**	2.1	1.3

Driving uncertainties: X/Y-correlation, stability, linearity

M. Guthoff "Overview of the CMS Run-2 luminosity determination and calibration methodology" LHC Lumi Days 2019
https://indico.cern.ch/event/813285/timetable/

2015: CMS PAS LUM 15 001, 2016: CMS PAS LUM 17 001, 2017: CMS PAS LUM 17 004, 2018: CMS PAS LUM 18 002

Normalization Absolute scale from beam-separation scans (VdM scan)
Integration (detector stability throughout the year, linearity over four orders of magnitude in luminosity, redundancy between luminometers, BX-dependent corrections, in- and out-of-time pileup …)

What is the BRIL strategy to reach 1.0% precision in absolute Luminosity for the HL LHC?

BRIL Strategy for Phase II Luminosity

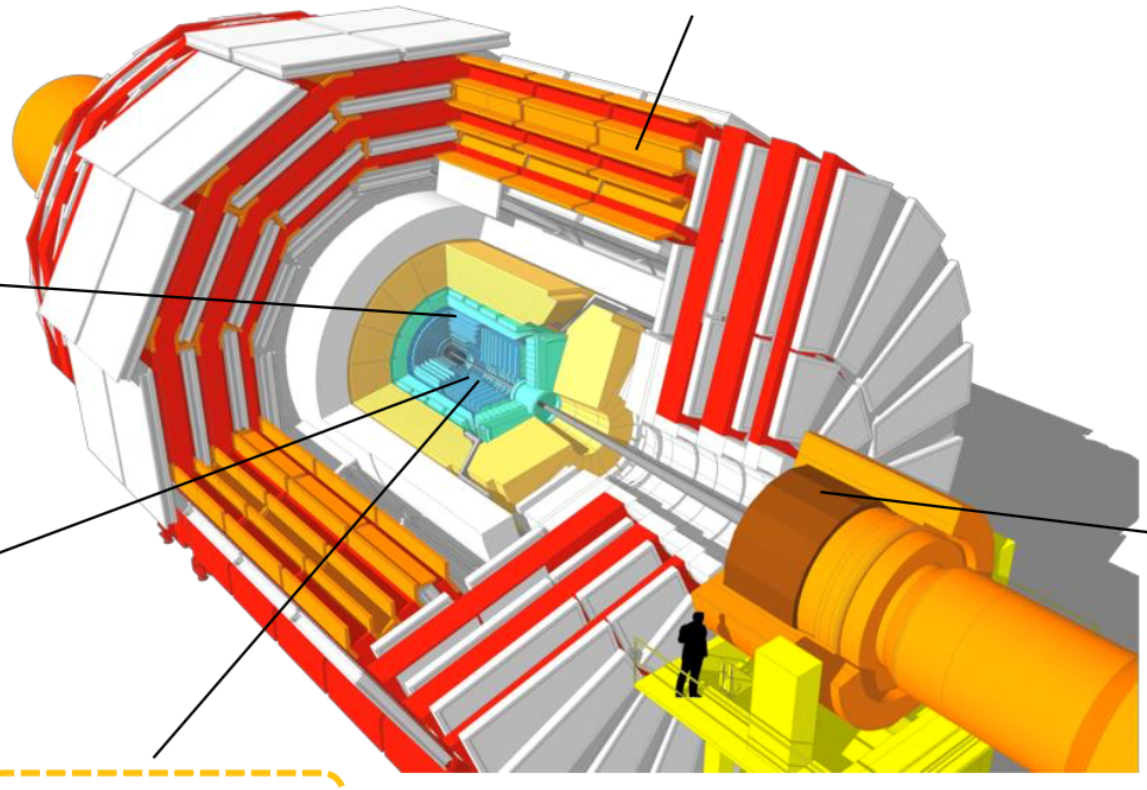
BRIL has decided to use multiple measurements of luminosity to evaluate a systematic error & maintain redundancy

- to extend / exploit the functionality of a different CMS subsystems to measure luminosity

- CMS subdetectors have to be operated outside of global data taking (with minor adaptations of the system architecture)
  - this has been proven by using the HF detector with a dedicated lumi readout

- to develop dedicated BbB luminometer:
  - Independent readout
  - additional BbB luminosity measurements in special beam conditions
  - orthogonal systematics to other CMS subsystems
  - stability
  - linearity, calibration transfer

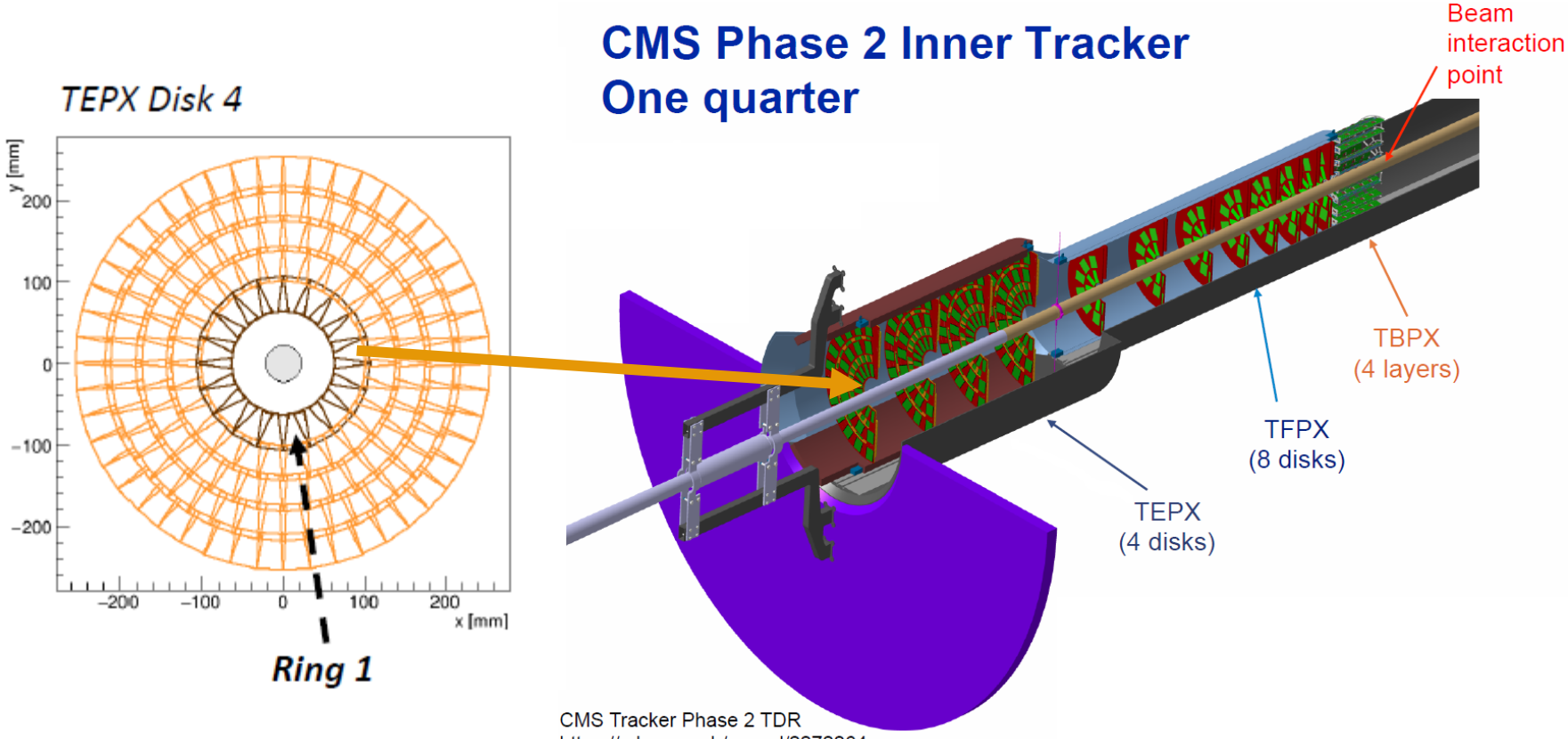
HL-LHC Prospects



The Inner Tracker (IT) Endcap

The *location* and *technology* of the Inner Tracker Endcap Pixel Detector **(TEPX)** make it a potentially suitable instrument for:

- Online Luminosity measurement in all of TEPX
- Beam Induced Background measurements in Disk 4 Ring 1 (D4R1)



CMS Tracker Phase 2 TDR
https://cds.cern.ch/record/2272264

Advantageous characteristics of the TEPX

- **Geometry**: ~2m^2 of active area with large fraction of overlapping area

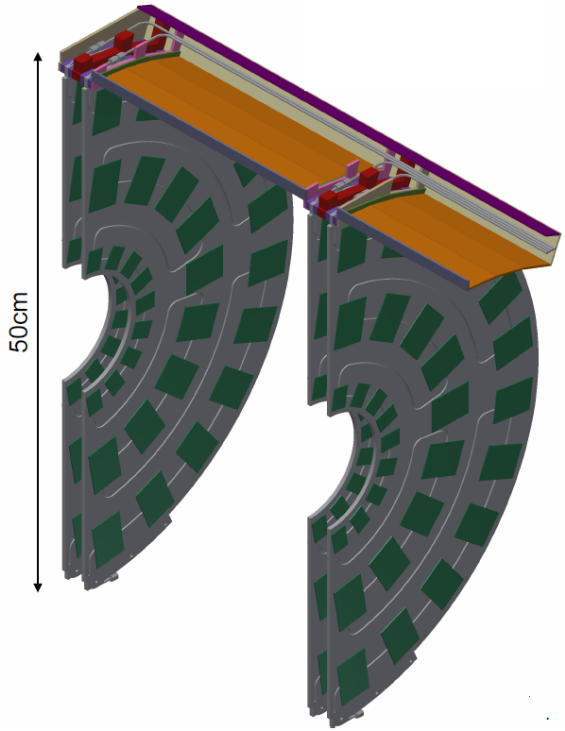
- **Location**: Higher z-positions allow for good separation between collisions and incoming background products, low occupancy region

- **Technology**: Radiation hardness (~10MGy), high granularity (25x100μm^2 pixels)

- **Disk 4 Ring 1**: Dedicated for luminosity and beam-induced-background only (under full BRIL control)

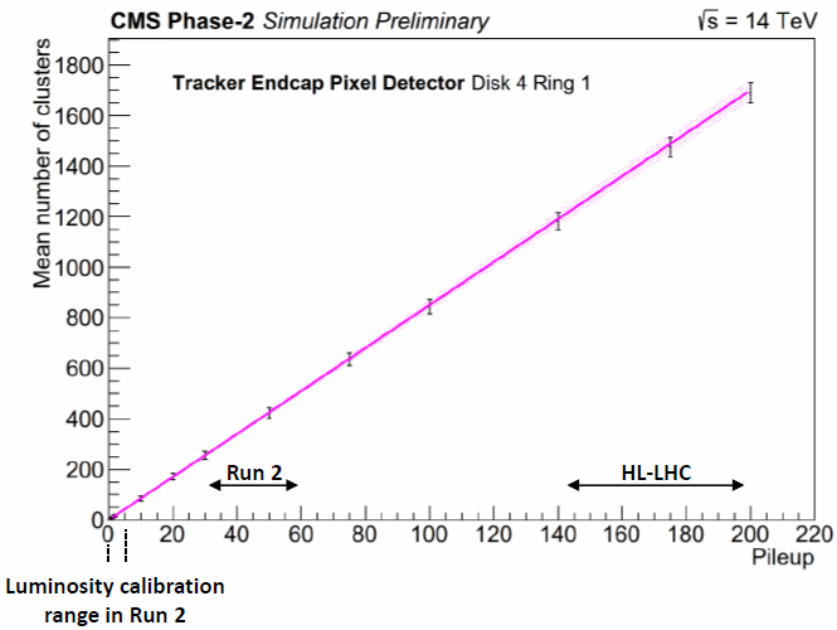
- 2 disks (double Dee) with modules on front and back side form one "z position"

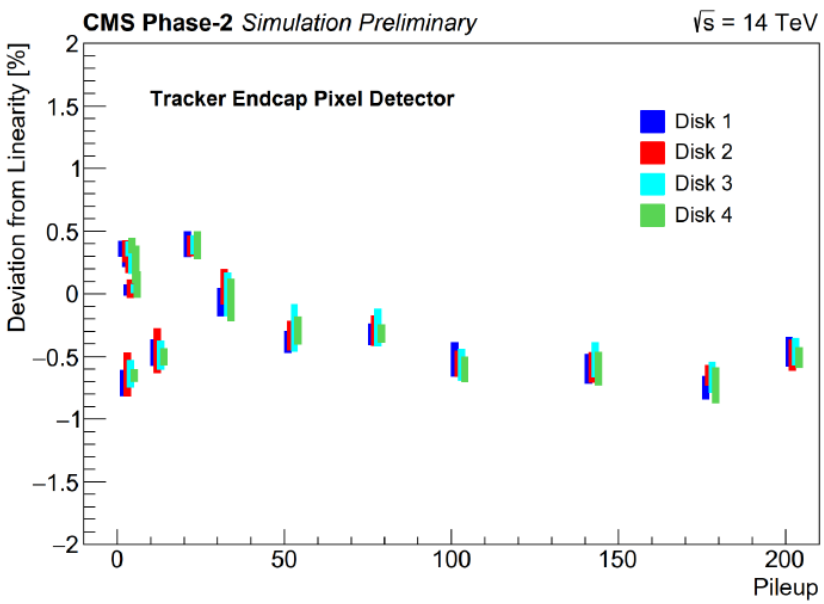
- Modules arranged in 5 rings on double Dee



TEPX Linearity Simulations

- Linearity studies in release *CMSSW_10_4_0_pre2* and *Inner Tracker geometry v. 6.1.3*
- Potentially interesting observables: ***hits, clusters and coincidences***
- Observation: Excellent linearity of number of cluster over whole pileup range





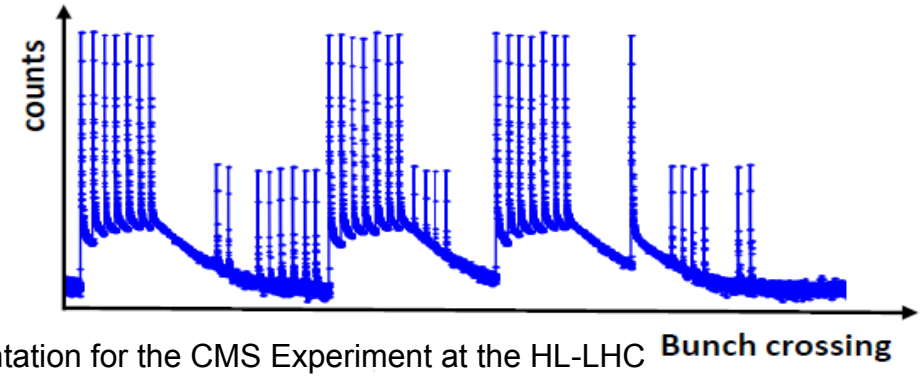
High presicion Luminosity Instrumentation for the CMS Experiment at the HL-LHC
A.Ruede et al, TWEPP 2019

CMS DP-2019

Service Requirements

- *TEPX as principal luminometer:* High availability of services – even outside of "global" CMS data taking
- Independence of Disk 4 Ring 1:
  - Operation as luminosity detector only
  - Standalone, dedicated triggers (~750+75 kHz)
- Implementation of two different triggers required for rest of TEPX: Physics triggers (750 kHz) & Lumi trigger (~75 kHz)
- Triggers will be a mix of: Random, zero-bias, filling-scheme-based
- Adjustable trigger rates to achieve high precision in special runs
- No throttling of luminosity triggers without a hard requirement to do so

Exemplary histogram of a generic algorithm



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TEPX – will be the main BbB luminometer of CMS collaboration for HL-LHC

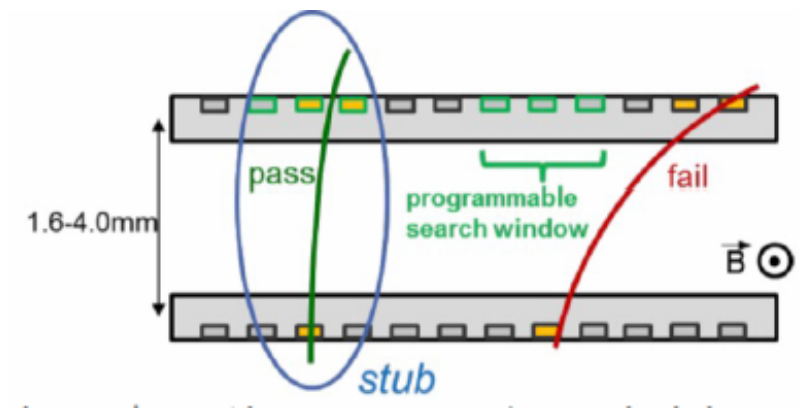
The Outer Tracker (OT)
outermost layer 3 TB2S stub counting

OT is designed to send 2-fold hit coincidences at the module level (stubs) at 40 MHz for L1 Track finder:

•**Simulations** indicate that the **number of stubs** in TB2S L3 is **highly linear** as a function of pileup (based on standard CMSSW digitiser w/o detailed FE model)

- OT can provide **redundant and independent BbB lumi** measurements
- high availability for luminosity could dramatically improve the BbB measurements
- OT could provide a lumi measurements **outside of global data taking/between runs** (provided that tracker has no needs for calibration procedure)

A pair of hits in the 2 sensors from 1 particle passing the correlation criteria is called 'stub'



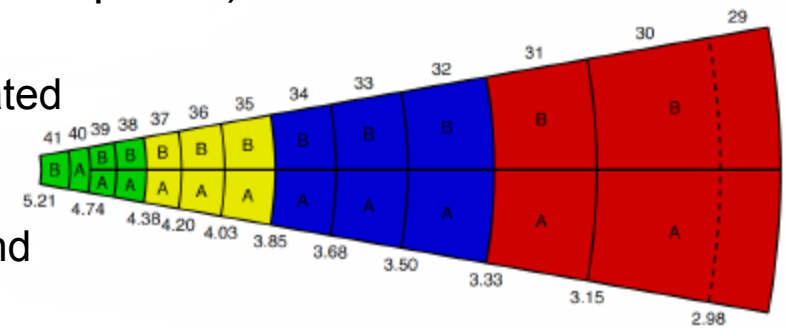
Memory and bandwidth estimations indicate that histogramming could be accomodated in the OT back-end system

readout over the control network seems feasible

The forward calorimeter HF luminosity

HF collects Cherenkov radiation in quartz fibres embedded in steel absorber
BRIL is using data from η-rings 31&32 (3.15< η<3.50)

•2 algorithms: BbB occupancy (**HFOC**) and E_t sums (**HFET**) are calculated in the HF back-end using dedicated BRIL lookup tables



•Double buffered **BbB histograms** are accumulated and readout via control network

•HFOC shown to be **highly linear** up to peak Run 2 pileup

HF often served as main CMS online luminometer in the past

Phase II

•HF is considering to follow the other calorimetry systems with an upgrade of the back-end to the new **ATCA architecture** – would require **porting of the BRIL specific data** processing (independent LUTs, histogramming)

•Need to kick-of **simulations of HF at Phase II** pileup to carefully study linearity including fibre ageing/degradation effects

•Need to investigate use of **higher η-rings to improve sensitivity at very low luminosity**

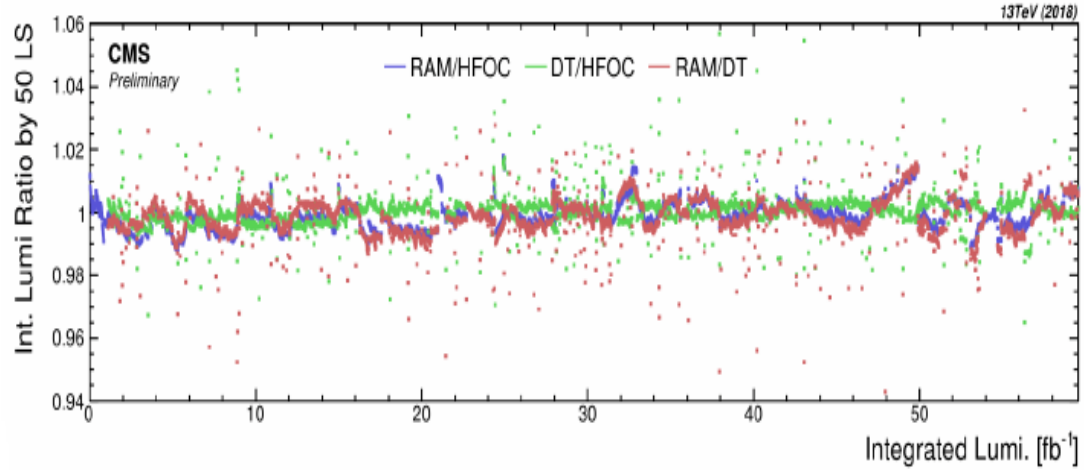
Muon barrel chambers
Drift tubes (DT) luminosity

So far using barrel muon track-candidate sorter from the BMTF* at **lumisection (LS)** granularity- **Offline luminometer**

•Shows **good linearity** but **no BbB** Information

•Only suitable for **stability** and **linearity** monitoring

•Track-candidates include DT&RPCs – unstable due to RPC pressure and BMFT FW changes



CMS PAS LUM-18-002

Phase II

•Lower level objects (only DT stubs) **histogrammed BbB (40 Mhz)** at the FW level should provide much better statistical error and faster readout interval for true **online muon luminosity**

•Not sensitive to L1 FW evolution if branched-of directly at the DT back-end

*Barrel Muon Track Finder

Summary

At least three independently calibrated, stability and linearity tracked luminometers

- allow to identify the misbehaving measurements
- diverse technologies to avoid common biases

Statistically significant BbB measurements in VdM and in physics conditions with 4LN (1.46s) granularity

Reliable, able to measure luminosity in the presence of beam independently of central DAQ

Additional dedicated BRIL luminometers offering long-tem stability and linearity >4 orders of magnitude

- Allow cross-calibration of luminometers in case of problems and further insight to systematic uncertainties

Implement novel techniques like luminosity determination from fiducial Z boson production rates

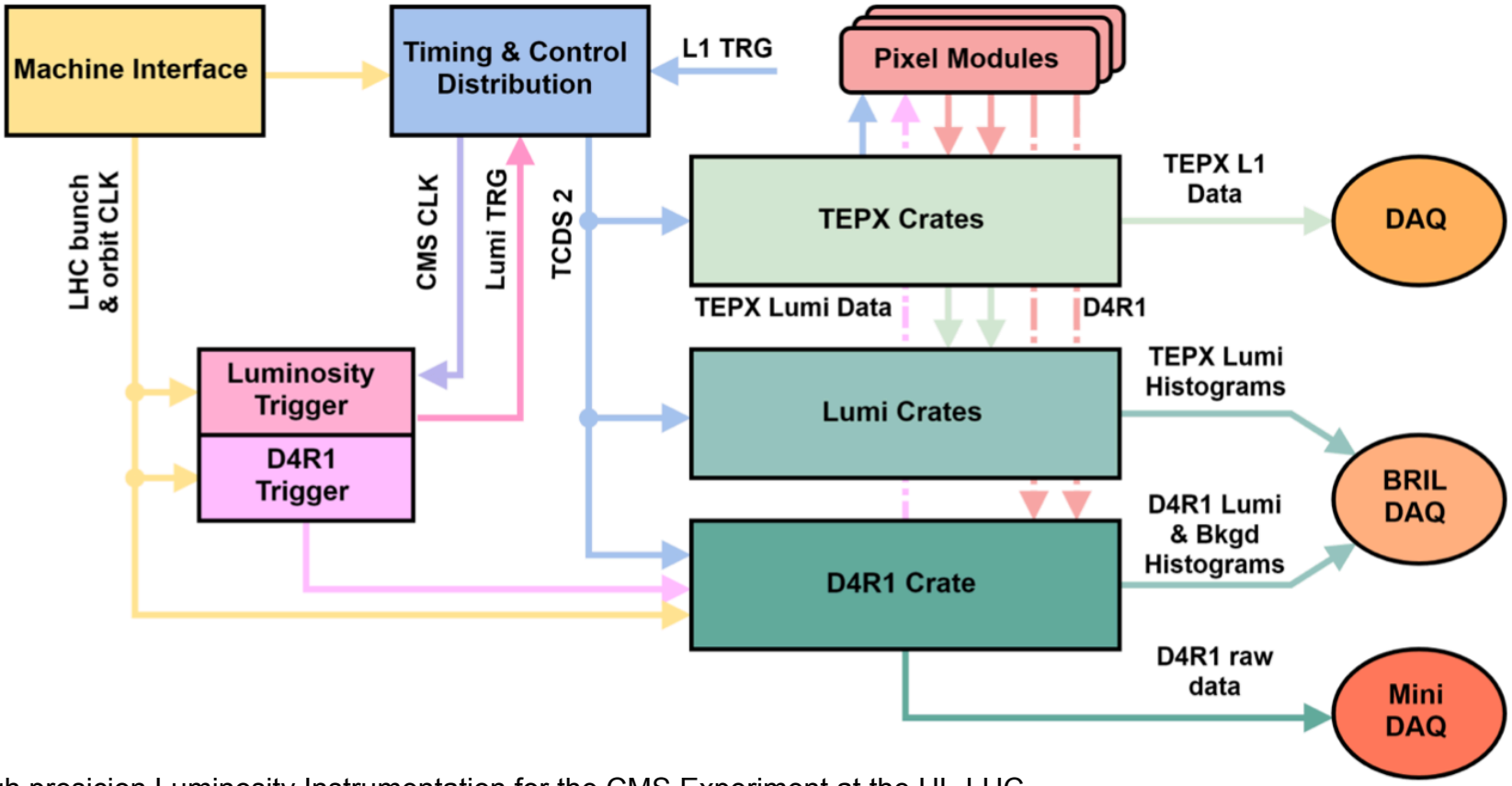
- Backup slides

Summary of the systematic uncertainties entering the CMS luminosity measurement for $\sqrt{s} = 13$ TeV pp collisions collected in 2018. When applicable, the percentage correction is shown.

	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	−0.8	0.2
	Orbit drift	0.2	0.1
	x-y nonfactorization	0.0	2.0
	Beam-beam deflection	1.5	0.2
	Dynamic-β^*	−0.5	
	Beam current calibration	2.3	0.2
	Ghosts and satellites	0.4	0.1
	Scan to scan variation	—	0.3
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	—	0.5
	Background subtraction	0 to 0.8	0.1
Integration	Afterglow (HFOC)	0 to 4	$0.1 \oplus 0.4$
	Cross-detector stability	—	0.6
	Linearity	—	1.1
	CMS deadtime	—	<0.1
	Total		2.5

CMS PAS LUM-18-002

System Architecture



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Bandwidth Estimations

*Estimations for **histograms** of **one** generic algorithm per quarter of IT and a histogramming granularity of per-quarter-of-rings:*

Memory: $3564\ bins \cdot 20\frac{bit}{bin} \cdot 2x4x5\frac{quarter\ rings}{Crate} \cdot 2\ (buffer) \approx 5.7\ Mbit$

Readout Bandwidth for LN4: $\frac{5.7\ Mbit}{1.46\ s} \approx 3.9\ Mbps$

With 3 Algorithms and 4 crates → **~46.8 Mbps** for *pure histograms* of IT Lumi

Not taken into account yet:

- Header frames (ring number, algorithm ID etc.) → *not significant*

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