Latest results on luminosity measurements with CMS

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on behalf of the CMS Collaboration

Physics motivations

Main parameters in particle colliders: center of mass energy ($\sqrt{s}$) and luminosity ($\mathcal{L}$).

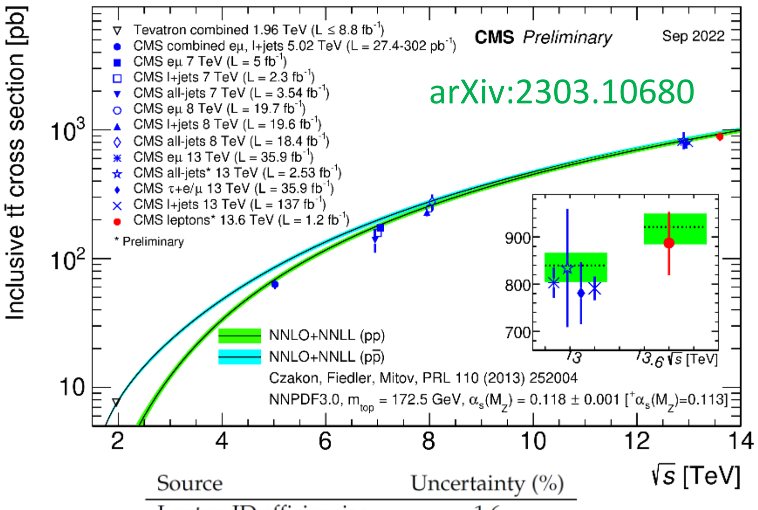
$\sqrt{s}$: available energy to produce new effects.

$\mathcal{L}$: ability to produce rare events (collision rate measurement).

Real time luminosity needed by experiments and colliders to optimize data taking conditions.

Cross section measurements directly related to integrated luminosity ($L_{int} = \int_0^T \mathcal{L}\, dt$).

Precise determination of luminosity needed to constraint Standard Model (SM) predictions or unveiling beyond SM physics.



Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3

arXiv:2303.10680

van der Meer method

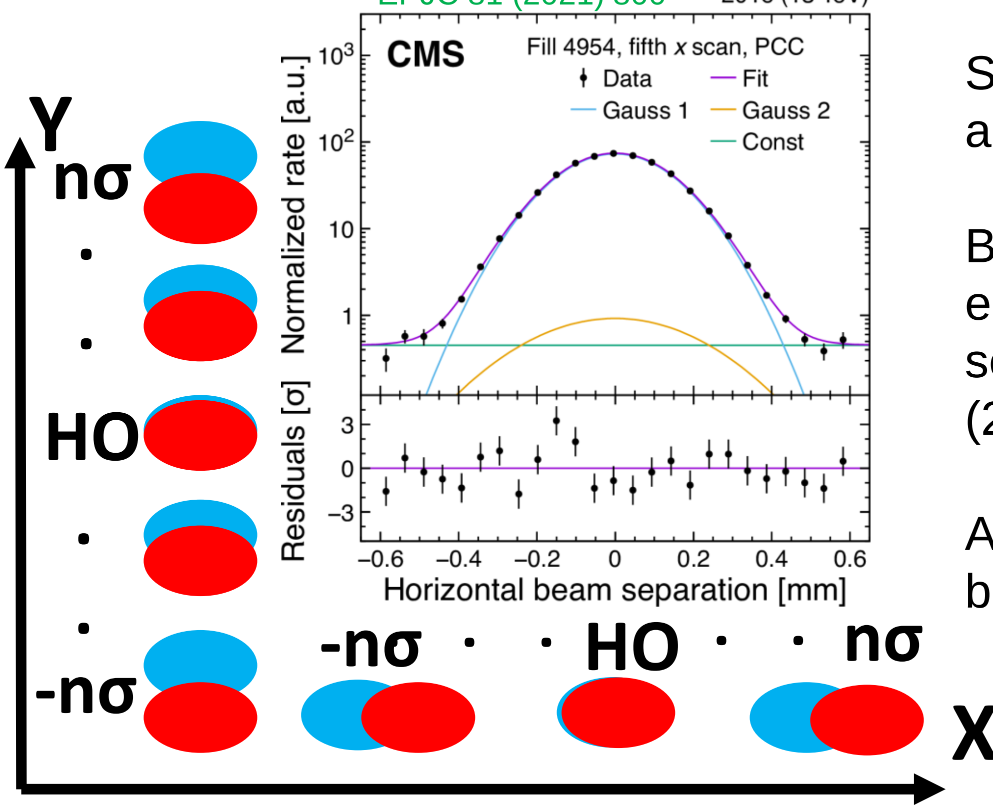
Experimentally, $\mathcal{L}$ is measured as a ratio of R_{peak} and σ_{vis}

$$\mathcal{L} = \frac{R_{peak}}{\sigma_{vis}}$$

Measured with van der Meer (VdM) scans

$$\sigma_{vis} = \frac{2\pi\Sigma_x\Sigma_y}{N_1 N_2 \nu} R_{peak}$$

EPJC 81 (2021) 800



Special beam conditions: low pile-up and small number of filled bunches.

Beams are collided transversely across each other. Rates as a function of separation provide the luminous area $(2\pi\Sigma_x\Sigma_y)$ A_{eff}.

Accelerator dependent parameters: beam currents (N_i) and frecuency (ν).

Assumption: X and Y independent.

Beam intensities

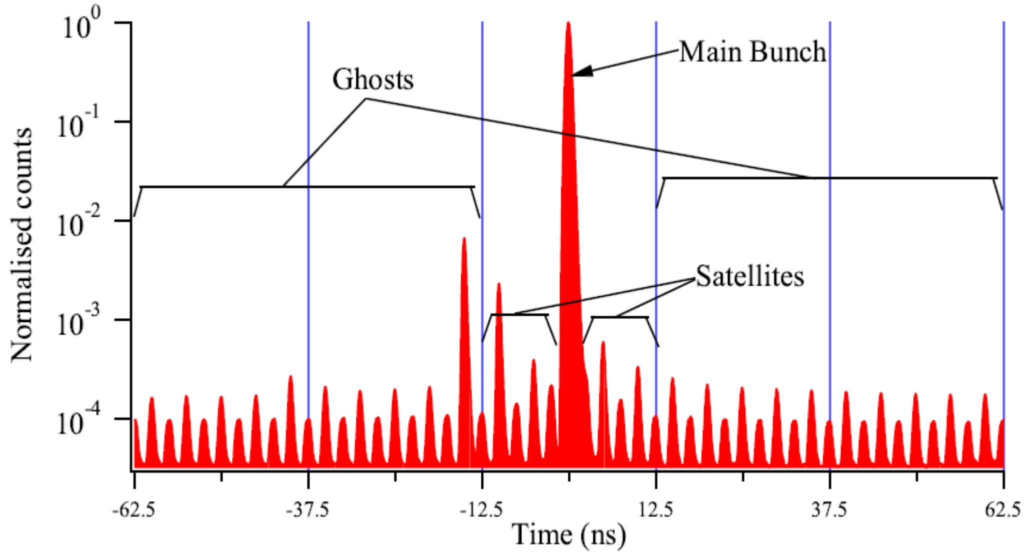
Several systematic effects, from detector or acelerator, can change the measurement of σ_{vis}

Beam intensities measured with DC current transformers while bunch currents with fast beam current transformer, both sensitive to charges outside colliding bunches that must be quantified and subtracted.

CERN-ATS-Note-2012-029 PERF

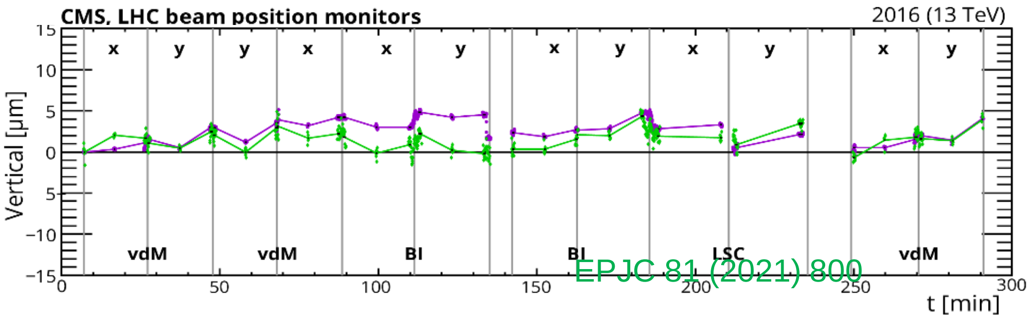
Ghosts: charge in nominally unfilled bunches

Satellites: charge in a nominally filled bunch but at least one RF period away the main bucket.



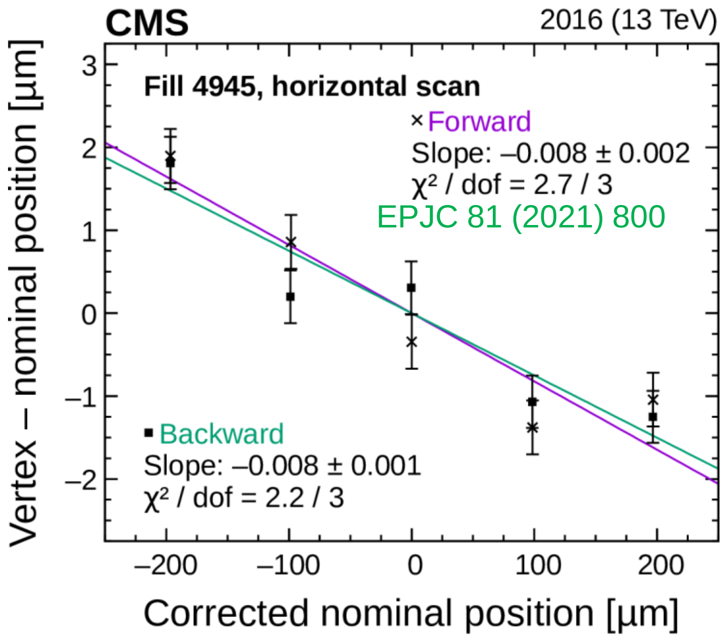
Beam position monitoring

Orbit Drift (OD): beam shifts from nominal position.



Measured with DOROS and LHC arc BPM.

Length scale (LS): actual beam displacement (and hence beam separation).



Produced by LHC steering magnets intended to produce a given nominal displacement.

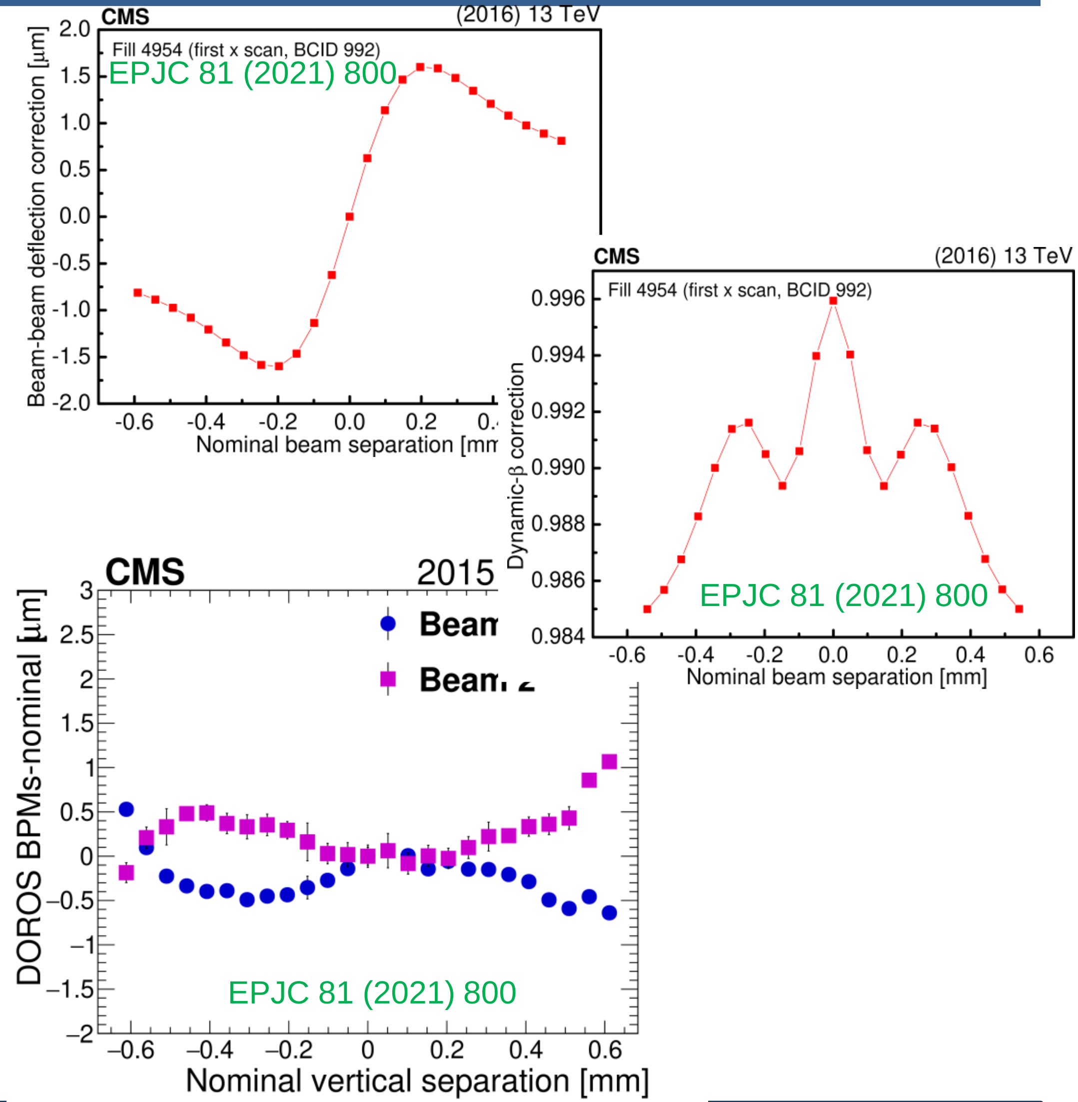
Linear fit to the difference between measured and nominal position.

Beam position monitoring

Electromagnetic repulsion between colliding bunches generates the so-called beam-beam (BB) effects.

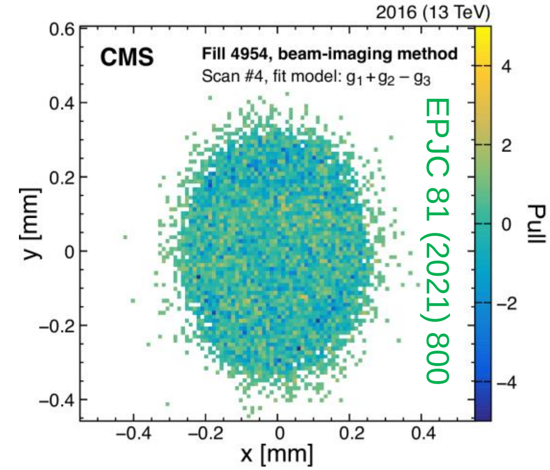
Defocusing of beams modifies the shape of transverse bunch profiles (dynamic β*)

Residual OD: difference between the nominal and corrected beam position after all known effects (BB, OD & LS) are taken into account.



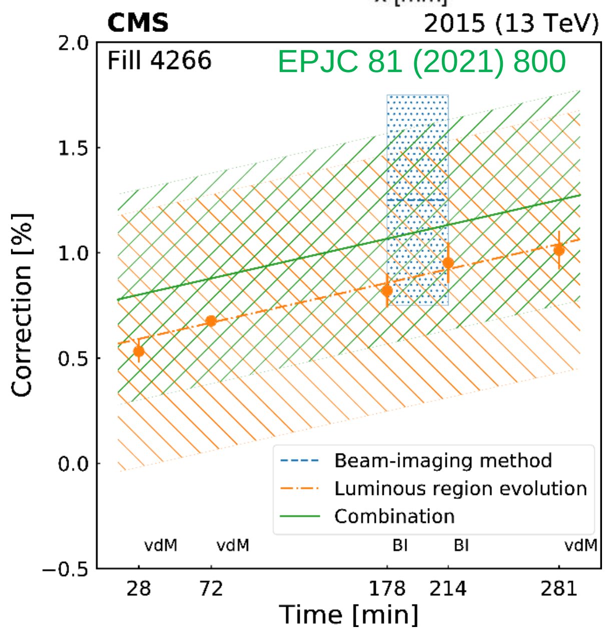
X-Y factorisation

VdM method assumes factorisation of bunch densities for A_{eff}.



BI method: reconstructed vertices used to obtain an image of the transverse bunch profiles (data driven).

Luminous región evolution: using luminous region and beam parameters, from 3D models of primary vertices distribution (bunch profiles are simulated).



Factorisation impact: compare luminosity from VdM to BI method and lumi region evolution.

Both methods provide consisten results.

Integration

Physics runs: collision rate maximized in order to produce large data sets.

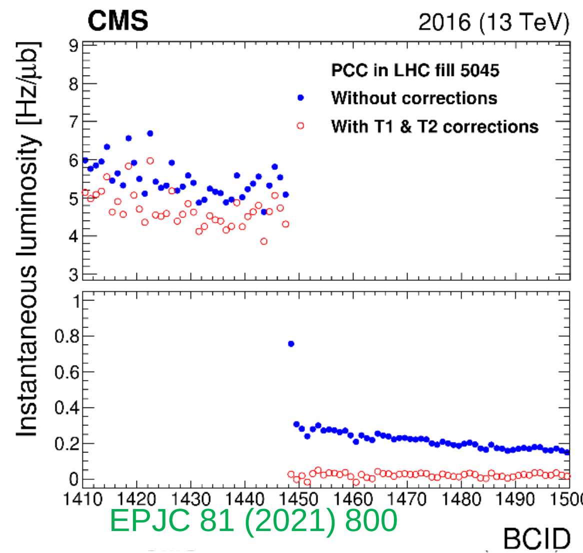
Further corrections to ensure long-term stability.

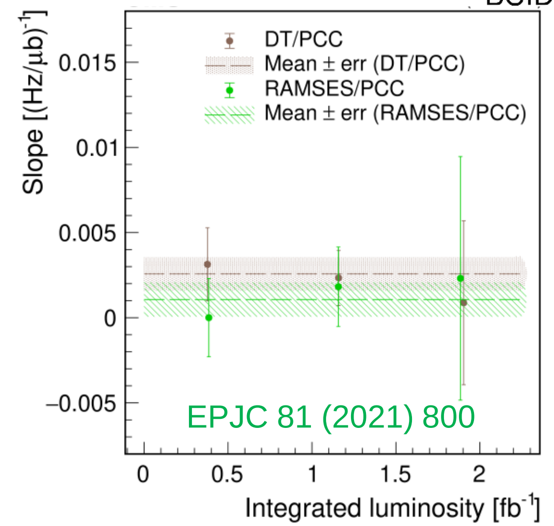
Out of time pile-up: contributions not arising from in-time collisions within the bunch crossing window.

Radiation damage: affect detector response by reducing efficiency or increasing noise.

Cross-detector comparison: ratios among luminometers to exhibit time variations.

Linearity: instantaneous luminosity ratio from luminometers. Slope of linear fit studied as a function of time.





Run 2 pp collisions at 13 TeV

Relative (%) systematic uncertainties in σ_{vis}

Source	2015	2016	2017	2018
Beam currents	0.2	0.2	0.3	0.2
Orbit drift	0.2	0.1	0.2	0.1
Length scale	0.2	0.3	0.3	0.2
Beam position	0.8	0.5	0.2	0.1
Beam-beam	0.5	0.5	0.6	0.2
X-Y correlation	0.5	0.5	0.8	2.0
Linearity	0.5	0.3	1.5	1.1
Stability	0.6	0.5	0.5	0.6
Total uncertainty	1.6	1.2	2.3	2.5
L_{int}(fb^{-1})	2.27	36.3	41.5	59.8

2015 & 2016: EPJC 81 (2021) 800

2017: CMS-PAS-LUM-17-004

2018: CMS-PAS-LUM-18-002

Summary

Precise luminosity measurements needed to constraint SM & beyond SM physics.

CMS relais on the VdM method to determine luminosity. Detailed study of different source of systematic uncertainties have been performed.

2015-2016: ~ 1.5% uncertainty, example of the astonishing performance of CMS

On going efforts to reduce 2017 & 2018 uncertainties.

Precisse heavy ion luminosity measurements to be realesed soon.

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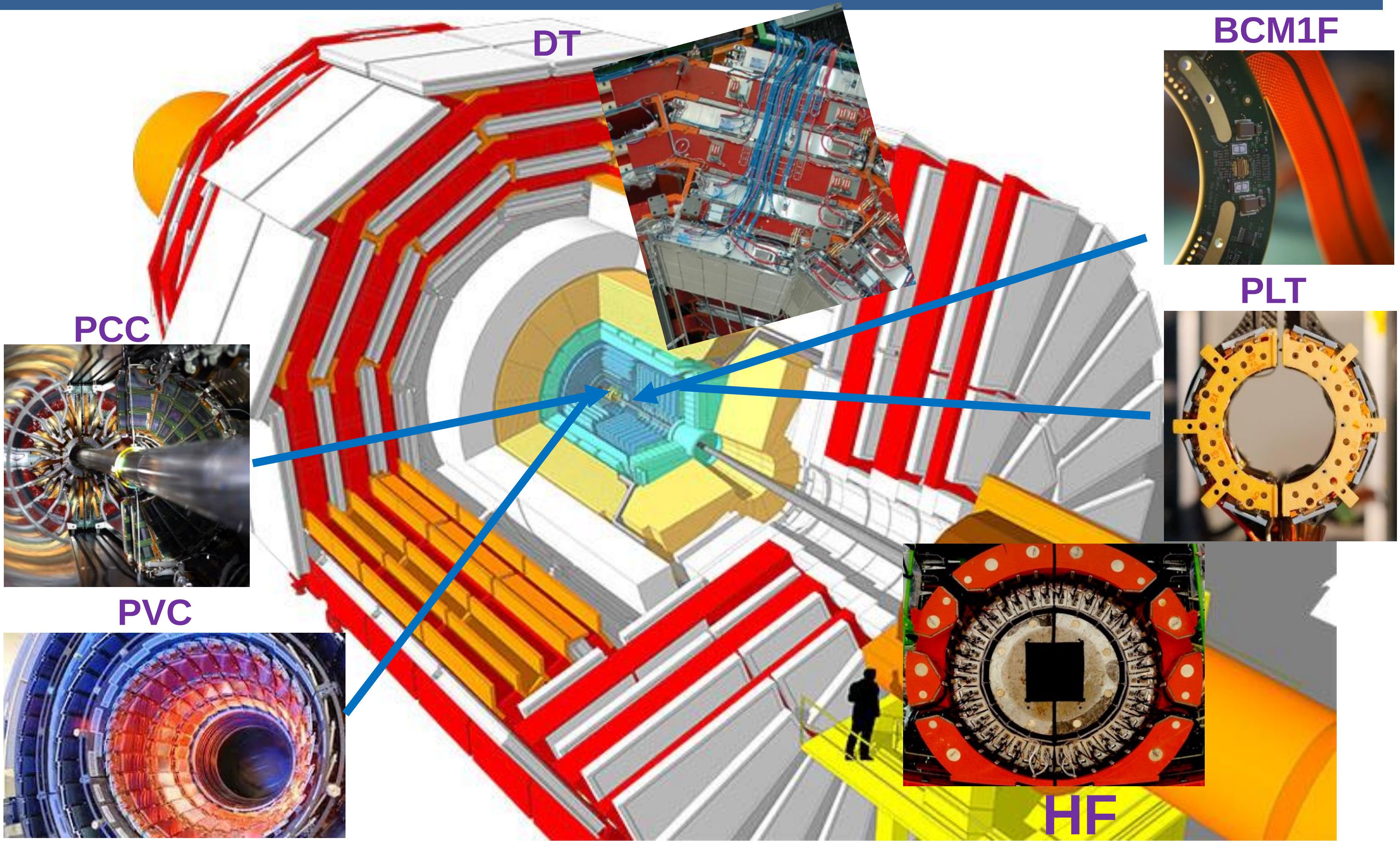
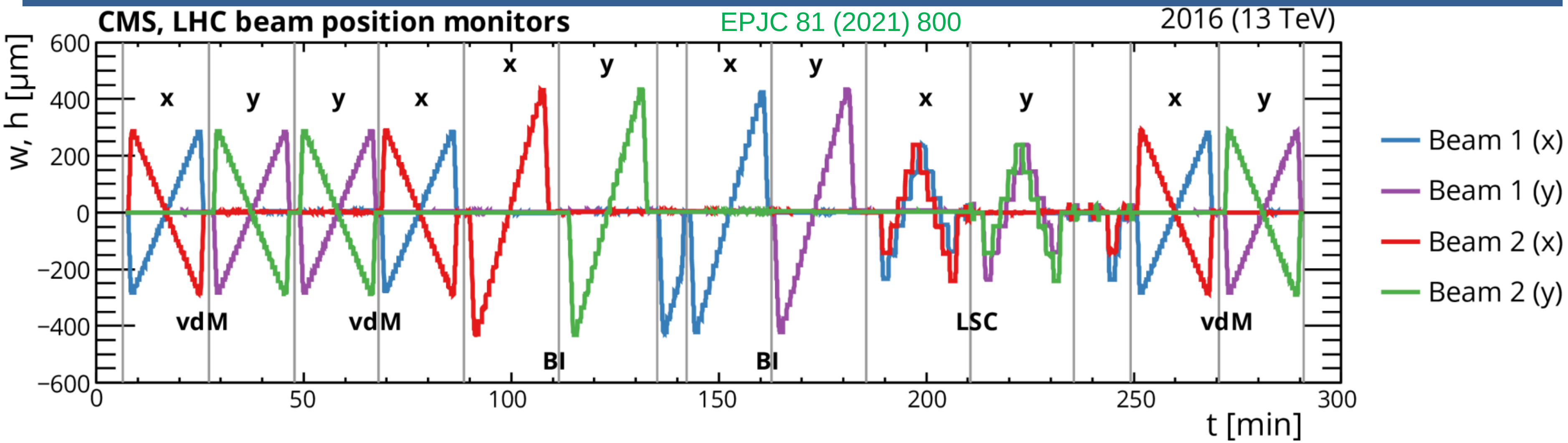
Thanks for your attention

Backup

Luminometers



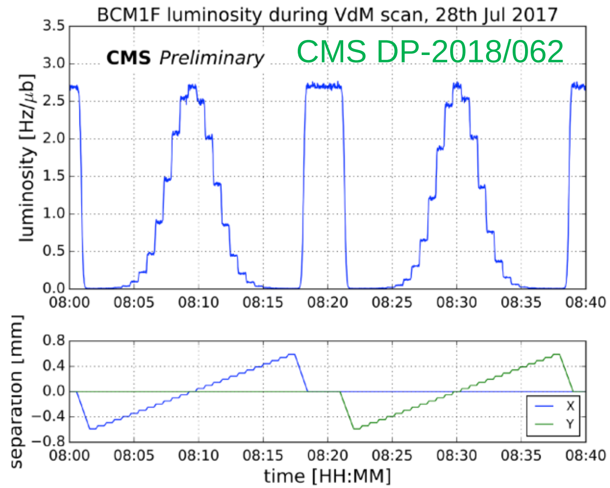
van der Meer scans: 2016 example



VdM scans: beams move 25 steps, 30 secs each, from $\pm 6\sigma_{beam}$.

Beam imaging (BI) scans: one beam fixed and the other moves 19 steps of 40 secs over $\pm 4.5\sigma_{beam}$.

Length Scale Calibration (LSC): both beams separated by $1\sigma_{beam}$ move together in $1\sigma_{beam}$ steps from $\pm 2\sigma_{beam}$ position and then repeat from $-1\sigma_{beam}$ separation. In total 5+5 steps of 60 secs each.



Luminosity using Z bosons

$Z \to \mu^+\mu^-$ clean experimental signature, large cross section, mass and width well known. Already used for calibrations and efficiencies. What about luminosity?

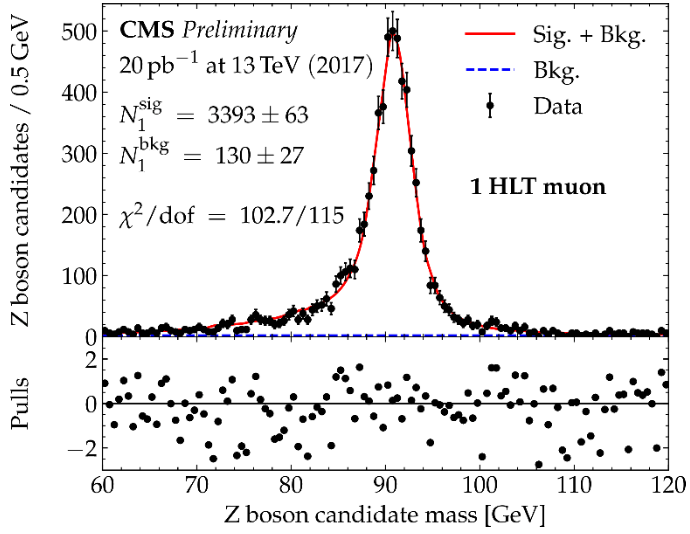
$\sigma_{\mathrm{fid}}^{Z} = N^{Z}/\mathcal{L}$ with $\sigma_{\mathrm{fid}}^{Z}$ identical for same $\sqrt{s}$ data sets. Ratio of N^Z used to transfer lumi. calibration from one data set to another. 2017 data sets: low and high PU.

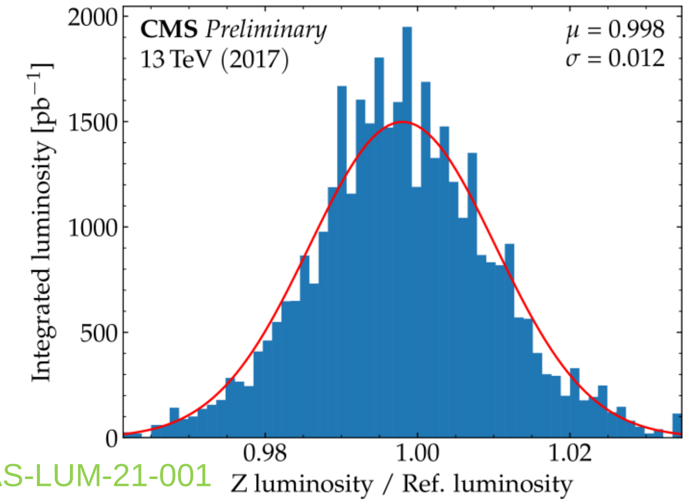
$$\mathcal{L}_{\mathrm{hPU}} = \frac{N^{Z}_{\mathrm{hPU}}}{N^{Z}_{\mathrm{lPU}}} \mathcal{L}_{\mathrm{lPU}}$$

Low PU luminosity uncertainty (1.7%) determined with VdM scan (CMS-PAS-LUM-17-004).

Agreement down to 0.2% realtive to the reference luminosity measurement.

CMS-PAS-LUM-21-001





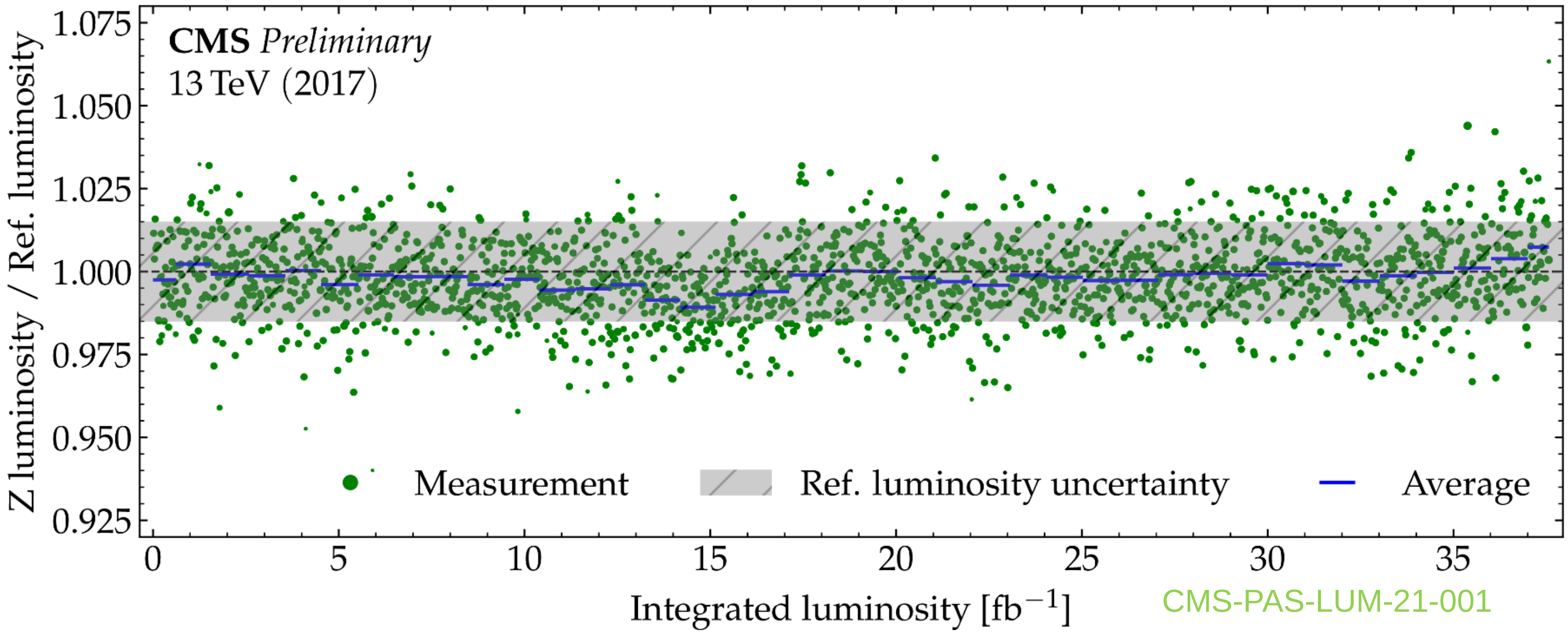
CMS-PAS-LUM-21-001

Luminosity using Z bosons

Stability of hPU luminosity well within reference uncertainties.

Transfer luminosity uncertainty of 0.4% ➔ total hPU uncertainty of 1.8%, to be compared to the 2.3% from ordinary measurement (CMS-PAS-LUM-17-004).

HL-LHC: up to 200 pp collisions per bunch crossing ➔ Z boson counting will provide significant improvement to the luminosity determination.



CMS-PAS-LUM-21-001