Luminosity determination using Z boson production at the CMS experiment

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[CMS-PAS-LUM-21-001]

$Z \to \mu\mu$ events are produced at the LHC at a high rate and have a clean signature
- Unique features for luminosity determination
- Completely complementary to traditional luminometers

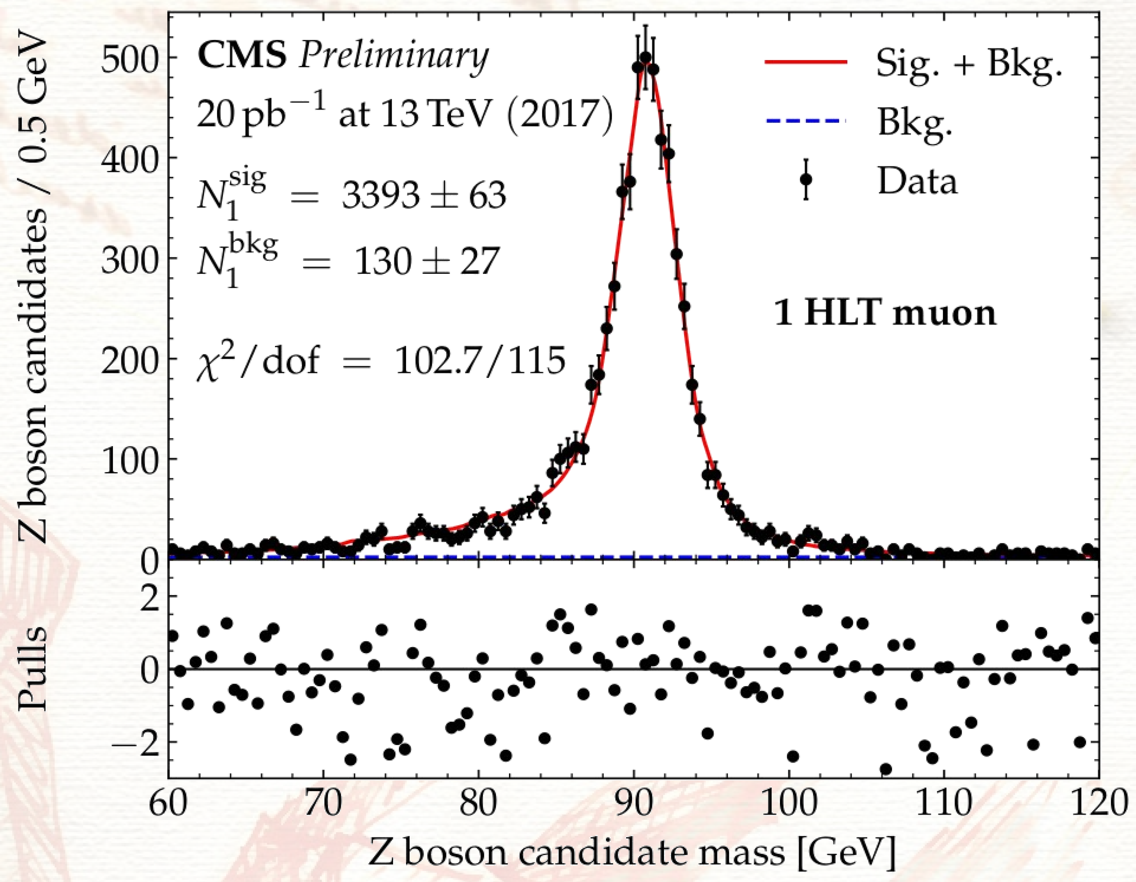
Simultaneous extraction of Z boson yield and efficiency
- Mutually exclusive categories for correct statistical treatment

$$\mathcal{L} = \frac{N^{Z}}{\sigma^{Z}_{\mathrm{fid}}\epsilon^{Z}}$$

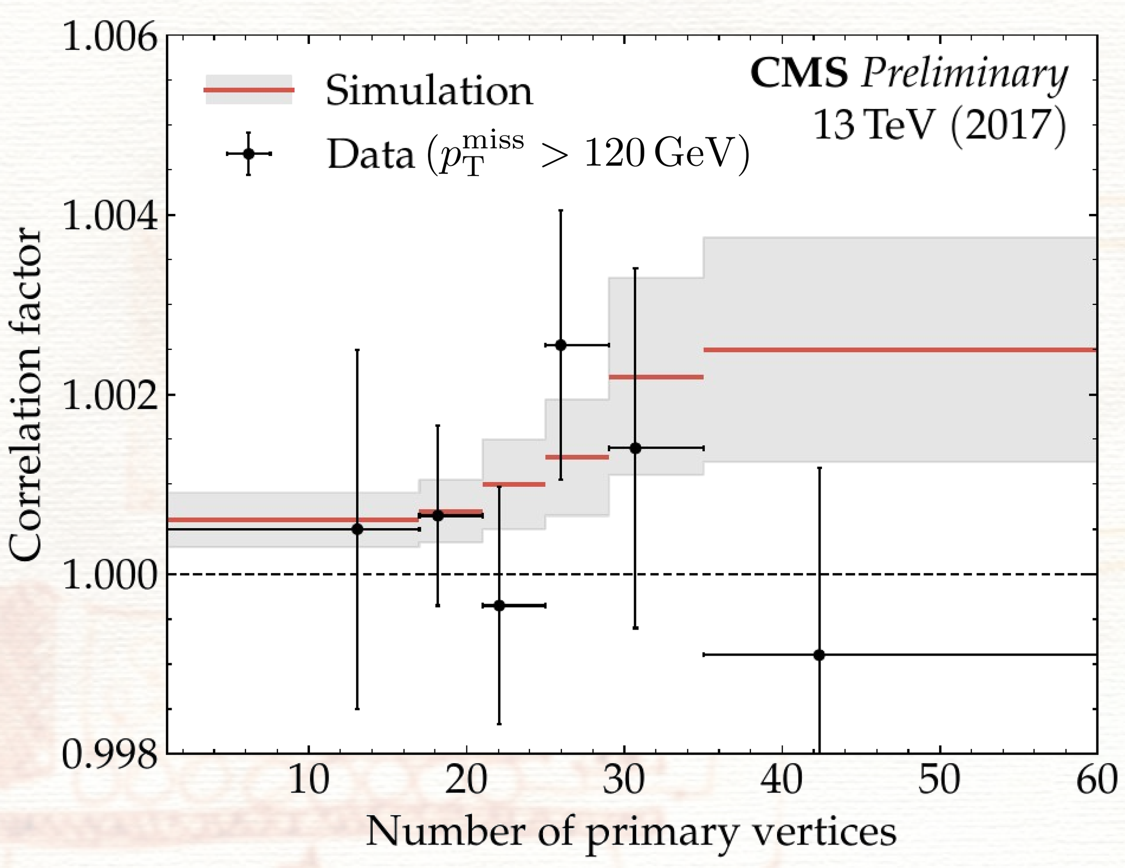
$$N_1 = 2\epsilon^{\mu}_{\mathrm{HLT}}\,(1 - C_{\mathrm{HLT}}\epsilon^{\mu}_{\mathrm{HLT}})\,\epsilon^{Z}_{\mathrm{ID}}N^{Z} + N^{\mathrm{bkg}}_{1}$$

$$N_2 = C_{\mathrm{HLT}}\,(\epsilon^{\mu}_{\mathrm{HLT}})^2\,\epsilon^{Z}_{\mathrm{ID}}N^{Z} + N^{\mathrm{bkg}}_{2}$$

Subtraction of background through fits to invariant mass of di-muon pairs



Di-muon correlation at trigger level C_{HLT}
- Mainly caused by online trigger isolation
- Correction from simulation – validated in data



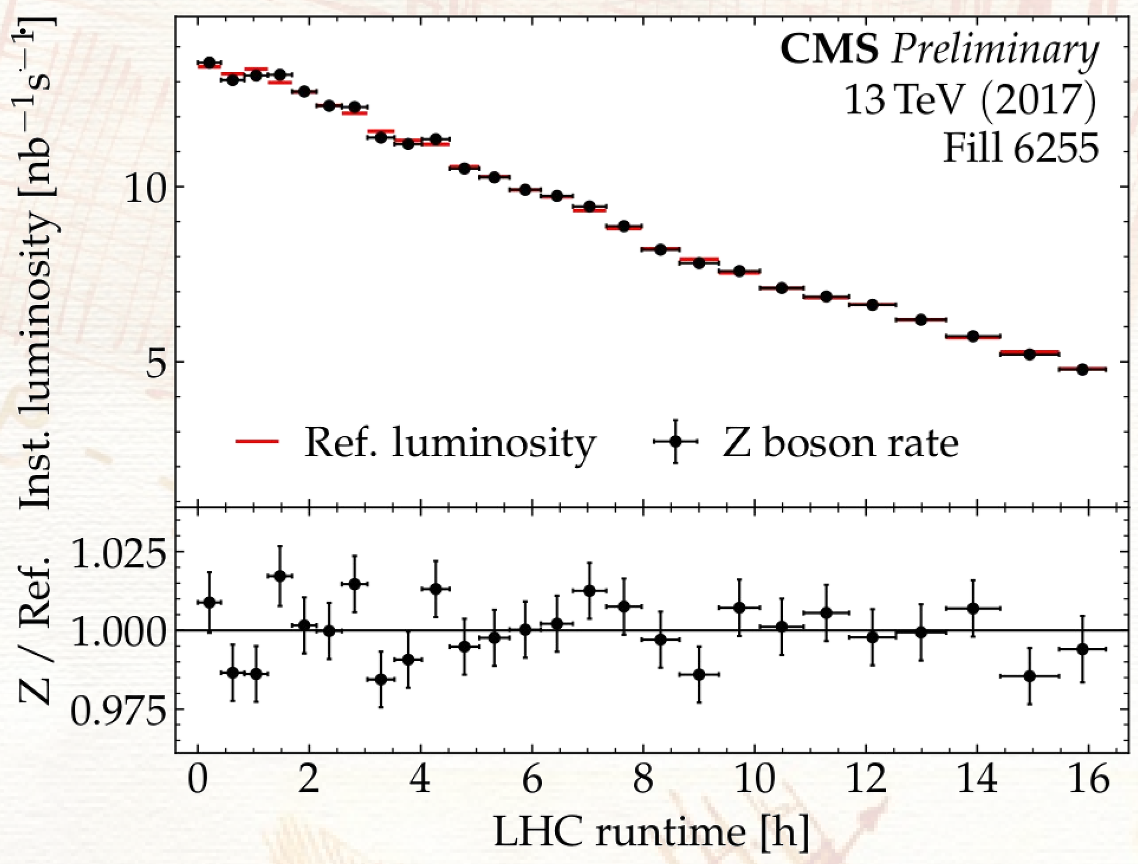
Muon trigger, identification, and reconstruction efficiencies measured in situ
- Two independent muon momentum measurements to obtain full absolute efficiency

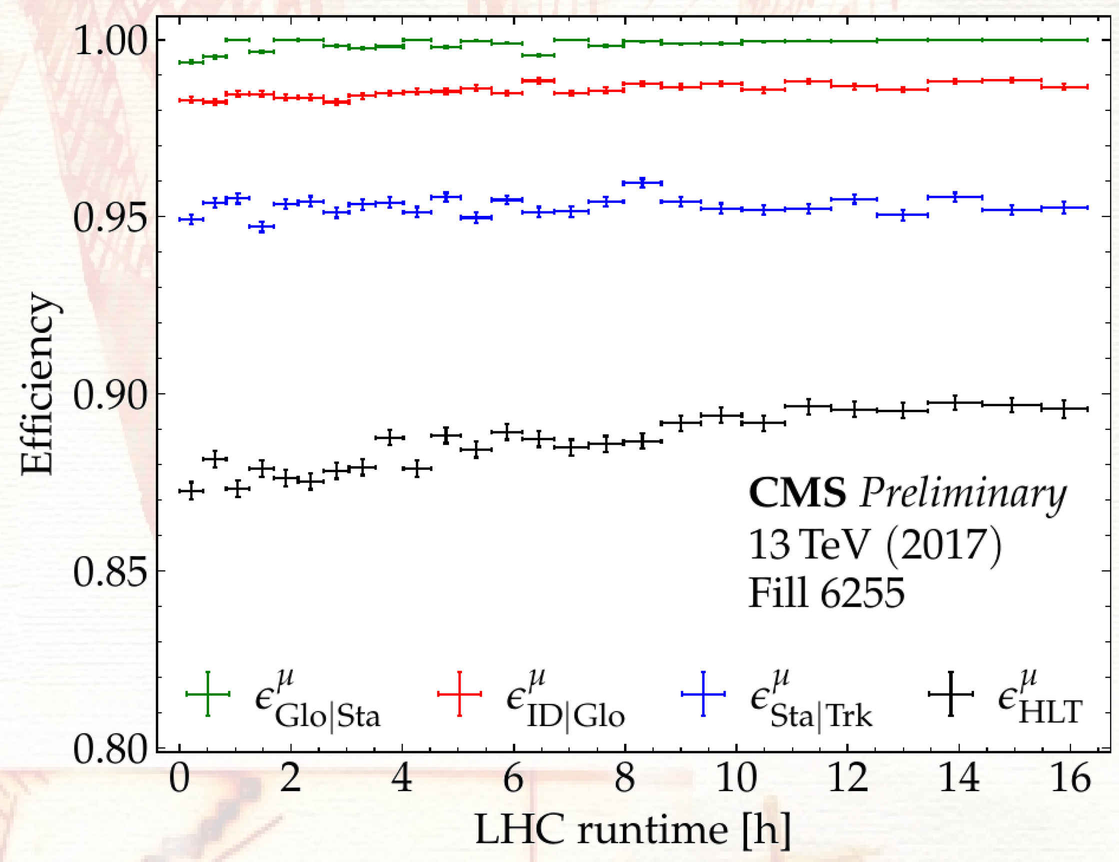
$$\epsilon^{\mu}_{\mathrm{ID}} = \epsilon^{\mu}_{\mathrm{ID|Glo}} \cdot \underbrace{\epsilon^{\mu}_{\mathrm{Glo|Sta}}}_{\text{inner track}} \cdot \underbrace{\epsilon^{\mu}_{\mathrm{Sta|Trk}}}_{\text{outer track}}$$

Muon efficiencies measured via tag and probe

$$\epsilon^{\mu}_{x|y} = \frac{n^{\mathrm{p}}}{n^{\mathrm{p}} + n^{\mathrm{f}}}$$

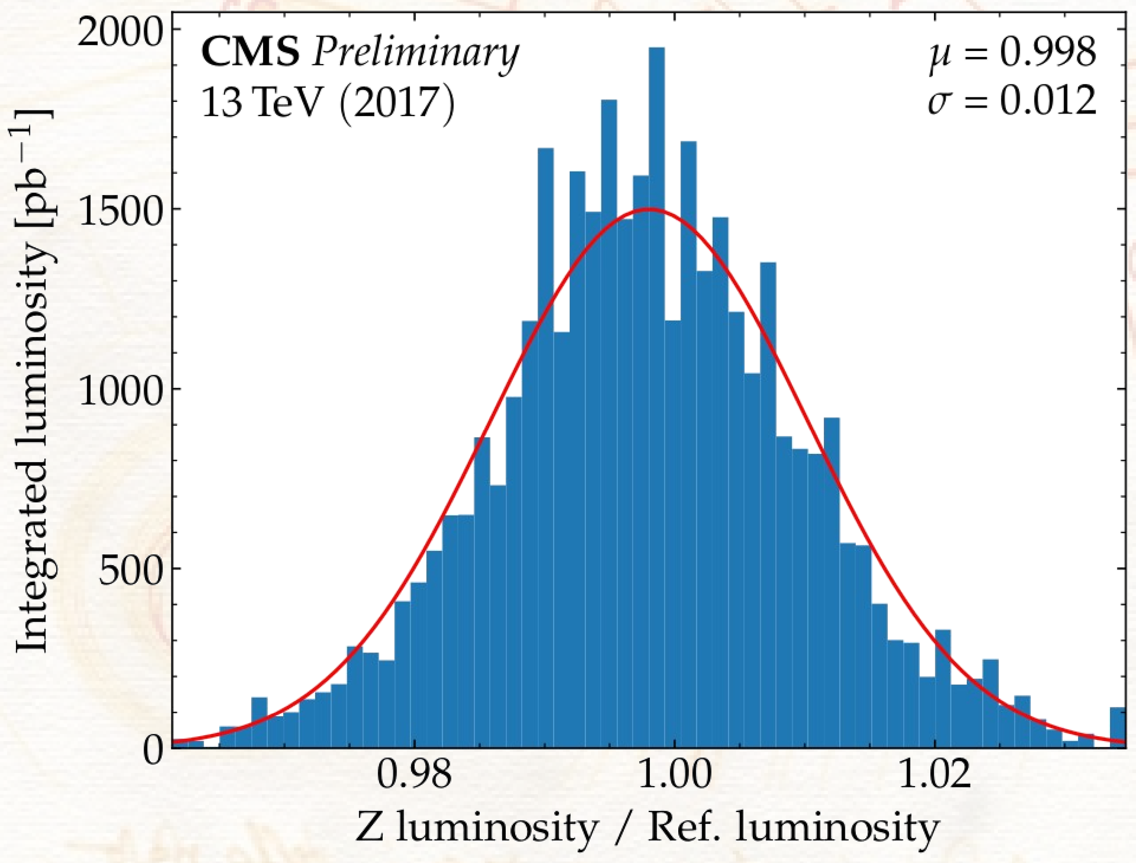
Measurements performed in short time intervals
- Track time dependent detector conditions





Absolute scale from low pileup data
- Correlated uncertainties cancel in ratio

$$\mathcal{L}_{\mathrm{highPU}} = \frac{N^{Z}_{\mathrm{highPU}}}{N^{Z}_{\mathrm{lowPU}}}\mathcal{L}_{\mathrm{lowPU}}$$



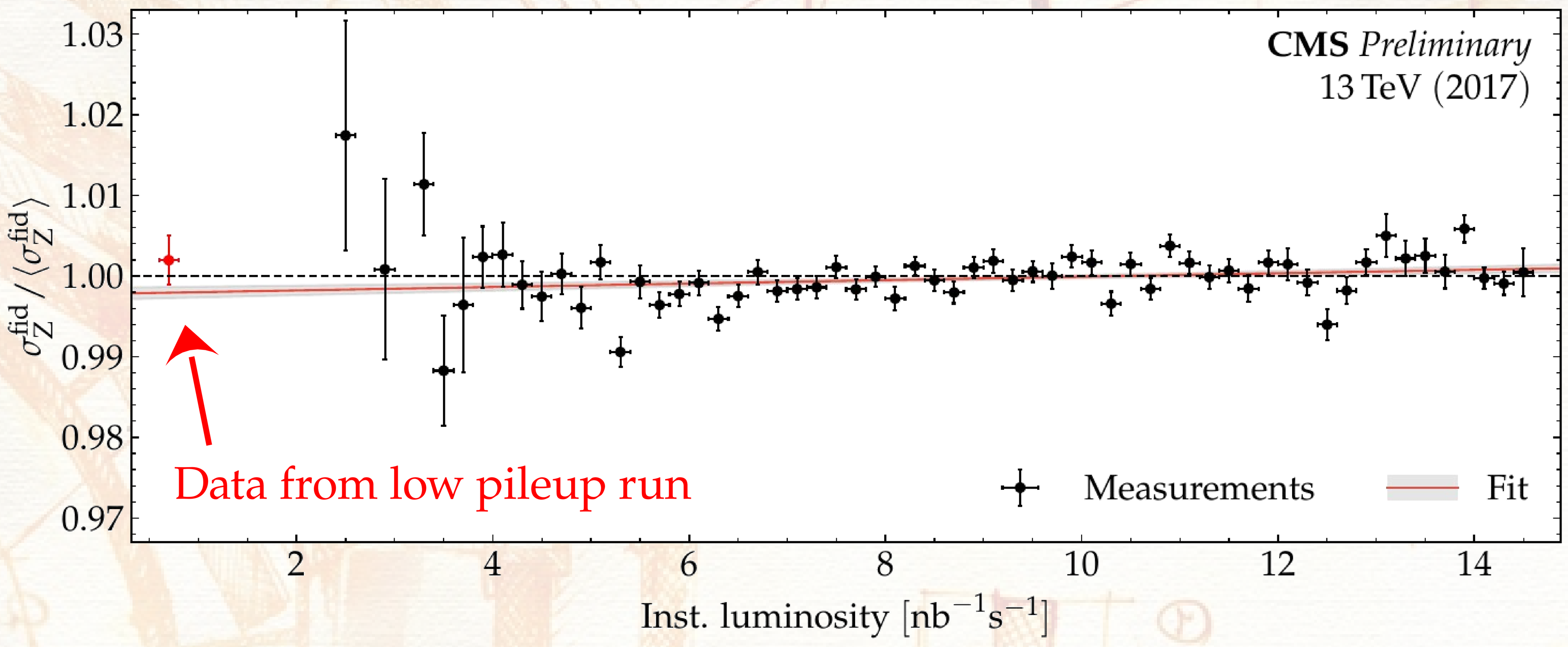
Both measurements agree to a level of 0.2%

First time study of complete set of systematic uncertainties

$$\delta r = \delta(N^{Z}_{\mathrm{highPU}}/N^{Z}_{\mathrm{lowPU}}) = {}^{+0.42\%}_{-0.40\%} = {}^{+0.31\%}_{-0.28\%}(\mathrm{syst}) \pm 0.29\%(\mathrm{stat})$$

Leading systematic uncertainties
- Muon momentum scale resolution
- Signal and background modeling
- L1 muon/ ECAL prefiring

Extrapolation from low to high pileup studied from 1-14 $\mathrm{nb}^{-1}\mathrm{s}^{-1}$ combining full 2017 data
- Both measurements agree to a level of 0.2%



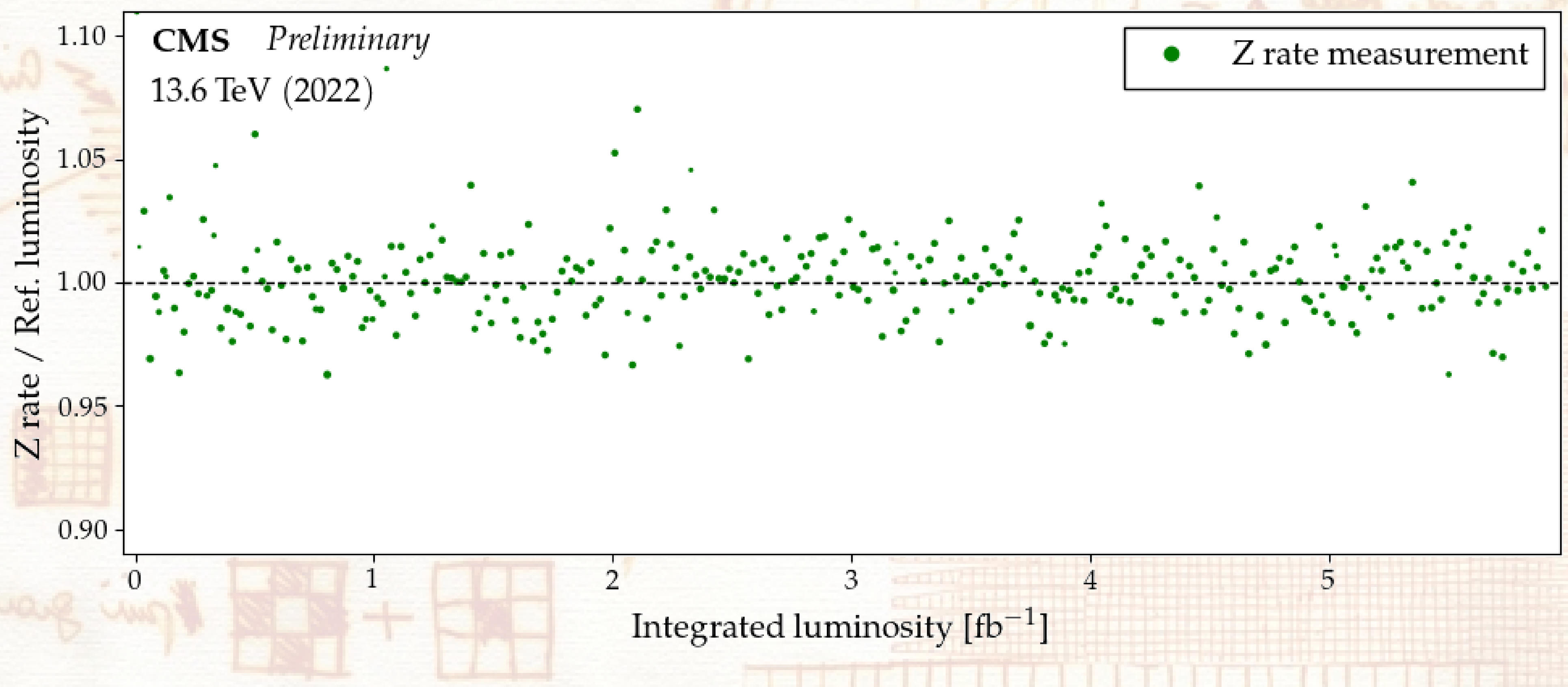
Outlook & discussion:

Given $\delta\mathcal{L}_{\mathrm{lowPU}} = 1.7\%$ we can extract $\delta\mathcal{L}_{\mathrm{highPU}} = \delta\left(\frac{N^{Z}_{\mathrm{highPU}}}{N^{Z}_{\mathrm{lowPU}}}\mathcal{L}_{\mathrm{lowPU}}\right) = 1.73\%$

Also interesting to transfer calibration between data sets of different years
- Dedicated studies of systematic effects between data sets necessary

Extrapolation uncertainty will become more important in the future
- At high luminosity LHC $\langle\mu\rangle \approx 200$!

Without further ado applied in Run 3! See: [CMS-DP-2023-003]



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