Measuring luminosity at the CMS experiment.

Concepts, uncertainties and systematics

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HEP Student Seminar
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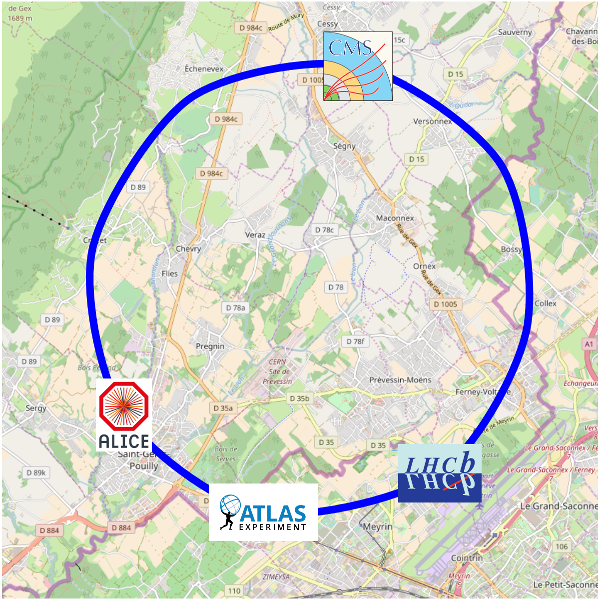
Large Hadron Collider (LHC)

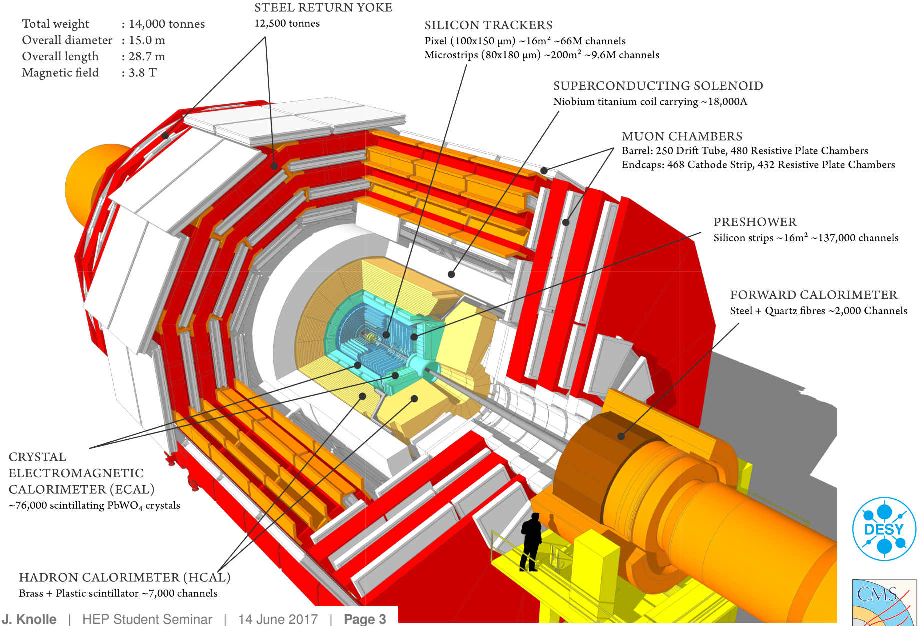


- circular tunnel in Switzerland and France (near Geneva)
- 27 km in circumference
- mean depth of 100 m

- 1232 dipole magnets
- 392 quadrupole magnets
- 9593 magnets in total
- 8 RF cavities per direction

- design energy: 7 TeV per beam
- design luminosity: $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Compact Muon Solenoid (CMS)



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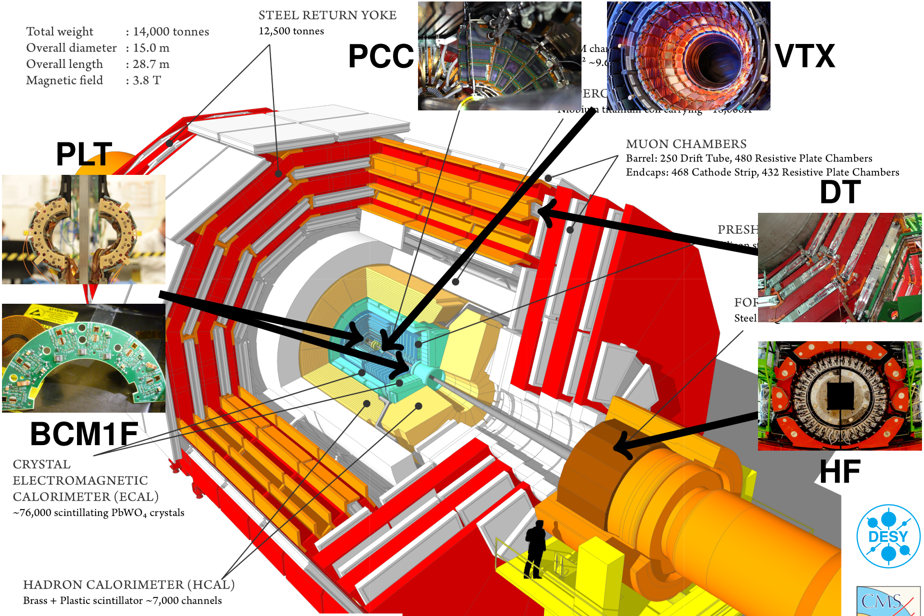


What is luminosity?

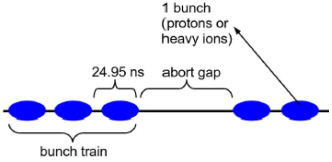
$$\frac{\mathrm{d}N}{\mathrm{d}t} = \mathcal{L} \cdot \sigma$$

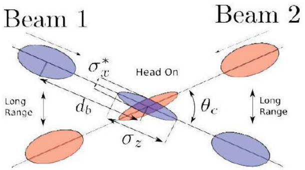
event rate

cross section

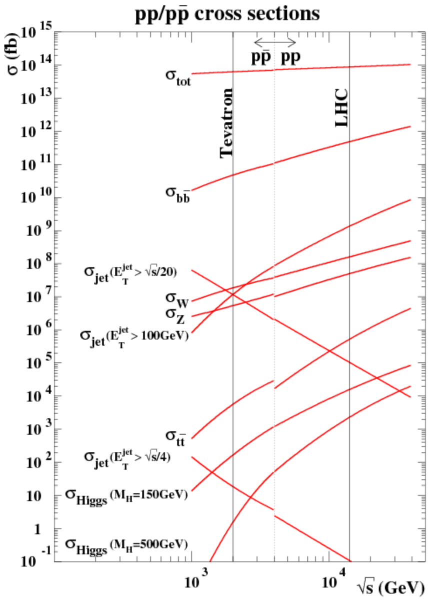
$$\mathcal{L} = \frac{f_\text{rev} N_1 N_2 n_b}{4\pi\sigma_x\sigma_y} F$$

- f_rev: revolution frequency (11245 Hz)
- n_b: number of bunches (up to 2808)
- σ_x, σ_y: beam widths ($\sim$ 15 µm)
- N_1, N_2: number of protons per bunch ($\sim 10^{11}$)
- F: correction factor (crossing angle, displacements)





Why is luminosity important?



Abstract

PAS TOP-16-006

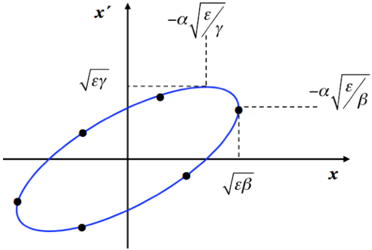
A measurement of the $t\bar{t}$ production cross section at $\sqrt{s} = 13$ TeV is presented using 2.3 fb^{-1} of proton-proton collision data acquired by the CMS detector. Final states including one isolated charged lepton (electron or muon) and at least one jet are selected and categorized according to the multiplicity of jets. From a likelihood fit to the invariant mass of the isolated lepton and a jet identified as stemming from the fragmentation and hadronization of b quark, the cross section is measured to be $\sigma(t\bar{t}) = 834.6 \pm 2.5\,(\text{stat}) \pm 22.8\,(\text{syst}) \pm 22.5\,(\text{lumi})$ pb in agreement with the standard model prediction. Using the expected dependency of the cross section on the top quark pole mass at NNLO+NNLL we determine the latter to be $m_t = 172.3^{+2.7}_{-2.3}$ GeV.

$$\sigma(t\bar{t}) = 834.6 \pm 2.5\,(\text{stat}) \pm 22.8\,(\text{syst}) \pm \mathbf{22.5\,(lumi)}\ \text{pb}$$

- We need high luminosity to get large number of events for processes with low cross sections.
- To measure cross section precisely, we need a precise knowledge of the luminosity.

How can we measure luminosity?

I. From machine parameters:



$$\mathcal{L} = \frac{f_{rev} N_1 N_2 n_b}{4\pi\sigma_x\sigma_y} F$$

- beam widths from machine parameters:
  - betatron function β^*: beam envelope, determined by beam optics
  - emittance ϵ: phase space volume occupied by the beam (beam property)
  - beam width: $\sigma = \sqrt{\beta^*\epsilon}$
- rather imprecise

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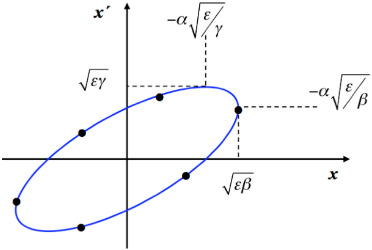

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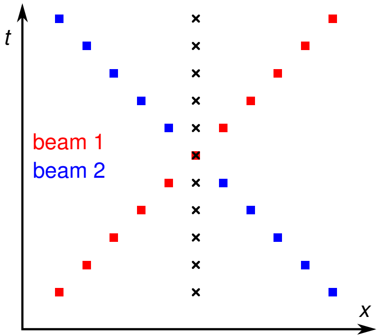
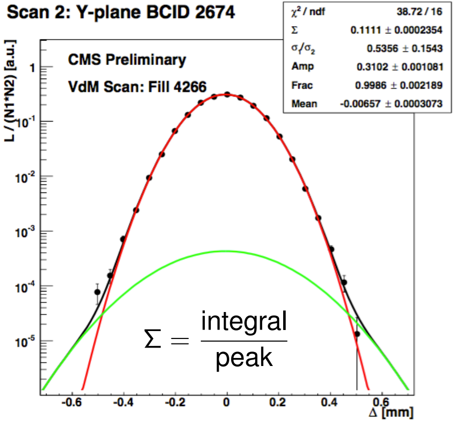
II. From rate measurements:

$$\mathcal{L} = \frac{1}{\sigma_{\text{vis}}} \frac{dN}{dt}$$

- σ_{vis}: cross section for general "hits" in a specific detector
- need to calibrate every detector used for luminosity measurements
- Van der Meer scans

Calibration: Van der Meer Scans

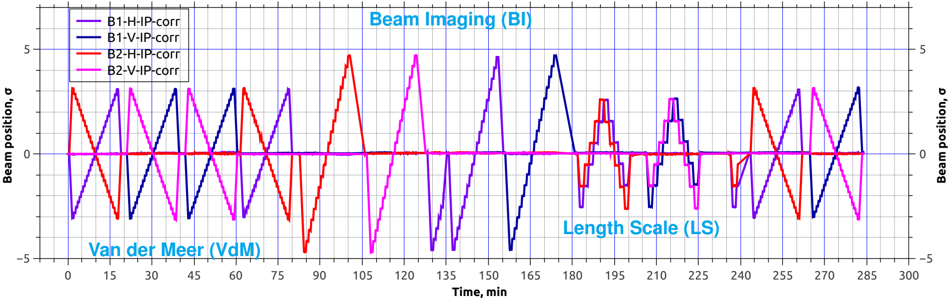




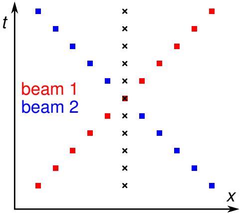
- special run: separate two beams in transverse plane, move them in steps through each other
- measure event rate as function of transverse distance
- for both transverse directions x, y

- $\sigma_{\text{vis}} = \dfrac{2\pi \Sigma_x \Sigma_y R_0}{N_1 N_2 f}$
- separately for every detector used to measure/monitor luminosity

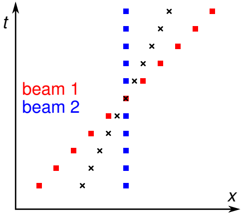
Calibration: 2016 Van der Meer Scan Campaign



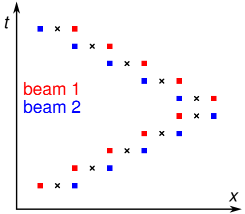
Van der Meer scans



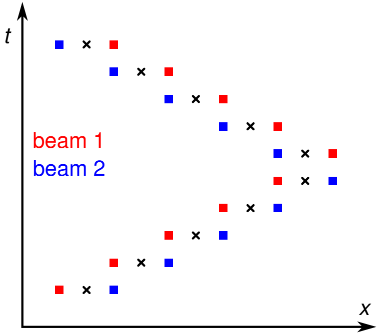
Beam Imaging scans



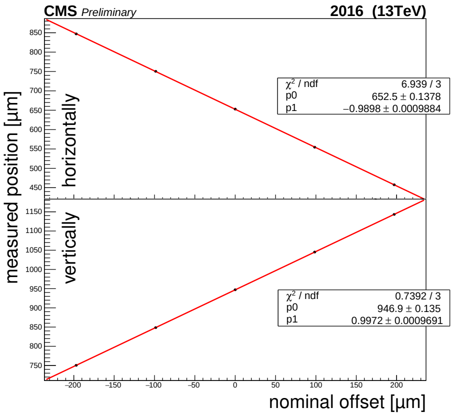
Length Scale scans



Calibration: Length Scale

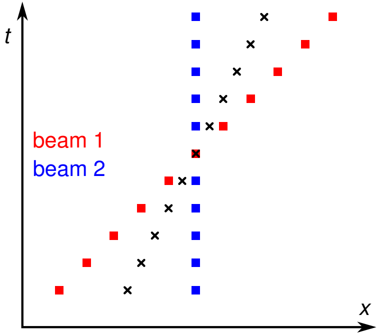


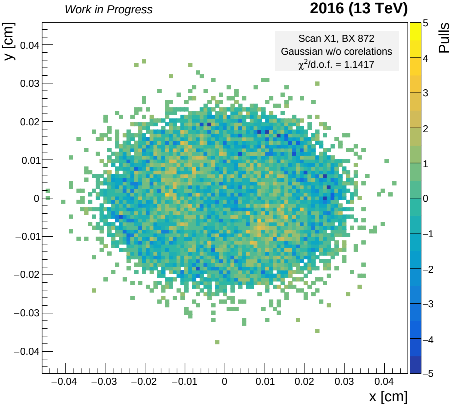
- put both beams at fixed transverse separation and move them across the detector
- measure vertex position as function of nominal position
- use slope of linear fit to correct nominal positions in VdM analysis



	correction	uncertainty
horizontally	-1.1 %	
vertically	-0.5 %	
total	-1.6 %	± 0.8 %

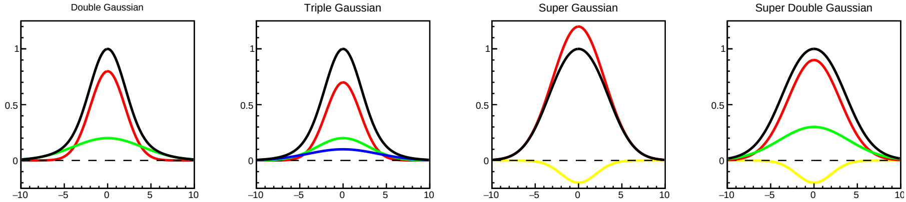
Calibration: Beam Imaging Scan

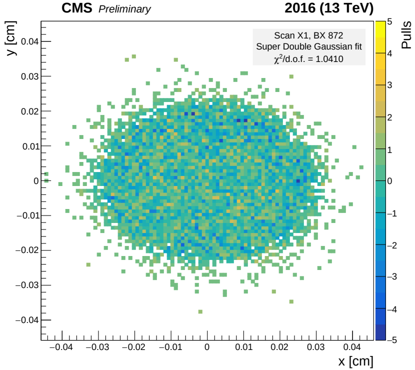




- keep one beam fixed and move the other beam across it
- measured vertex position form an image of the beam shapes
- simultaneously fit the four beam images with proton density model
- factorizable Gaussian model $\Rightarrow$ not a good description of data
- remember: $\sigma_{\text{vis}} \propto \Sigma_x \Sigma_y$ assumes factorizable beam shape

Calibration: XY Correlation Correction

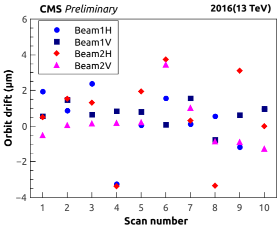


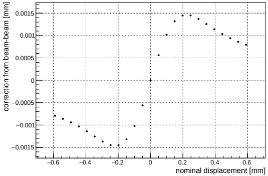


- fit models: normalized sums of Gaussians with positive or negative weights and non-zero correlation term
- best fit: "Super Double Gaussian"
- derive correction from comparing true overlap integral with simulated VdM scan result
- correction: +0.8 % with uncertainty $\pm$0.9 % (covering differences for different fit models and BCIDs)

Orbit drift

- beams may drift during scan steps
- beam positions measured with DOROS beam position monitors
- compare beam positions before and after each scan, estimate effect on Van der Meer calibration



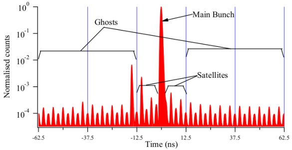


Beam-beam deflection

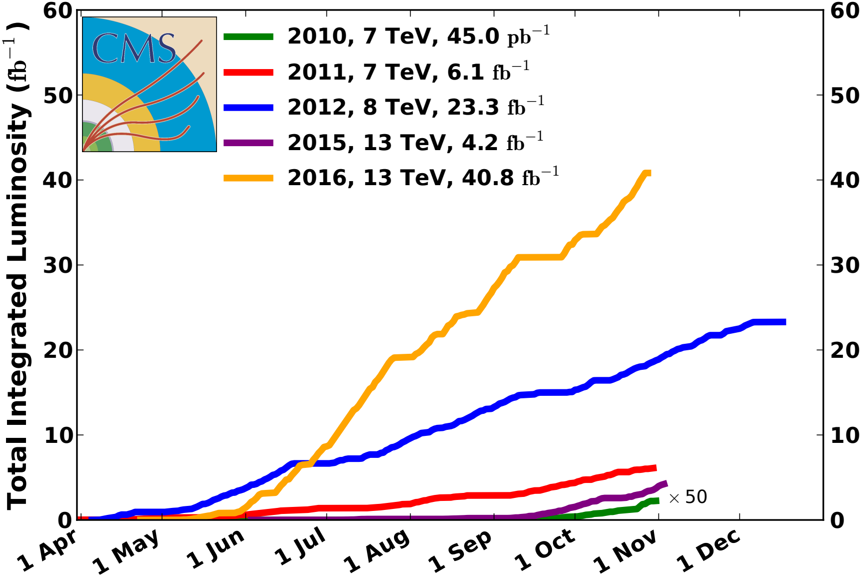
- proton beams repel each other, depending on their separation
- correct beam positions for this effect

Beam current measurements

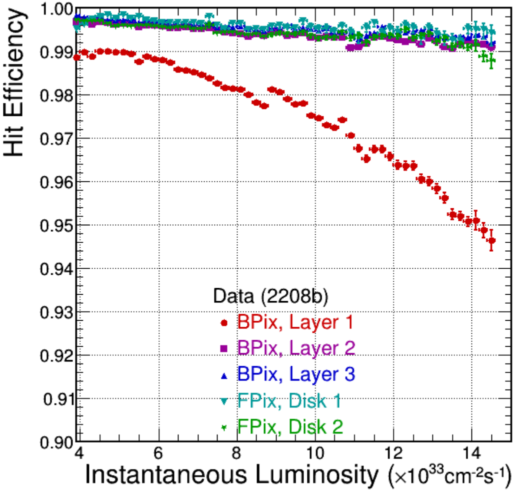
- several current measurement devices with different capabilities
- need to estimate spurious charges (ghosts and satellites)



Integration

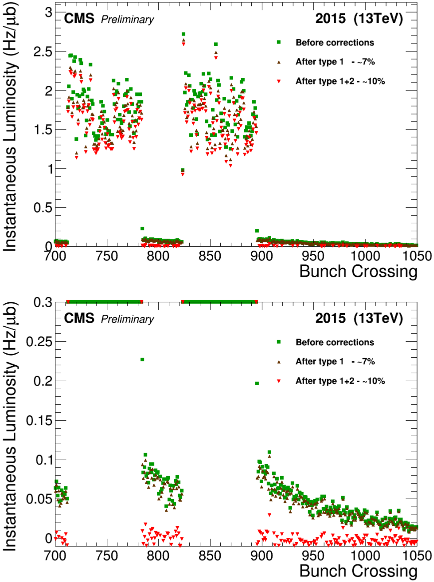


Integration: Pixel Cluster Counting



- use pixel cluster counts as main event rate
  - 66 million channels
  - occupancy < 0.1 % at design luminosity
  - very good stability over time
  - linear response up to high pile up
  - limited from maximum trigger rates
- use only modules that were operational during the entire year

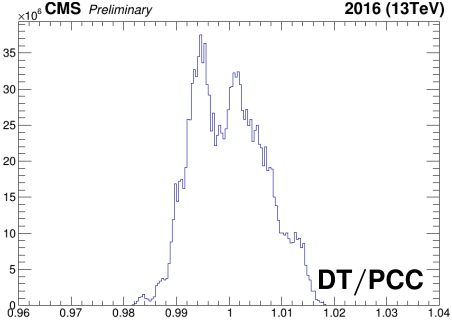
Integration: Out-of-Time Response Effects



- PCC biased by two out-of-time response effects
- type 1:
  - Spill-Over
  - electronic pixel signal leaking into next bunch slot
- type 2:
  - Afterglow
  - exponential decay of activated material surrounding the detector

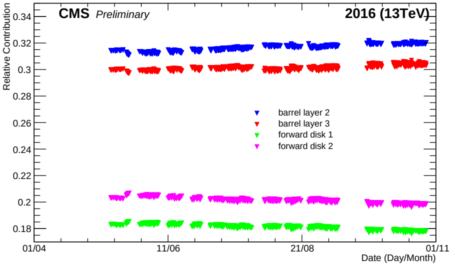
Integration: Stability and linearity

Cross-detector stability, linearity



- DT is assumed linear and stable
- linearity uncertainty of 0.6 % to cover PCC non-linearity
- stability uncertainty of 1.5 % to cover DT/PCC steps

Internal stability



- shown are relative contributions from pixel layer to total PCC
- per-layer contributions have drift throughout 2016 data-taking
- assign uncertainty of 0.5 %

⇒ total uncertainty: 1.7 % (2015: 1.0 %)

Overall uncertainty of 2016 luminosity

Systematic	**2015** (CMS-PAS-LUM-15-001)		**2016** (CMS-PAS-LUM-17-001)	
	Correction [%]	**Uncertainty [%]**	**Correction [%]**	**Uncertainty [%]**
INTEGRATION				
Internal stability			–	0.5
Cross detector stability	–	1.0	–	1.5
Linearity			–	0.6
Dynamic inefficiency	–	0.4	0 – 1	0.3
Type 1 corrections	7 – 9	0.6	7 – 12	0.7
Type 2 corrections	0 – 4	0.7	0 – 4	0.5
CMS deadtime	–	0.5	–	0.5
CALIBRATION				
XY correlations	1.1	1.5	0.8	0.9
Beam current calibration	–	0.3	–	0.3
Ghosts and satellites	–	0.2	–	0.4
Length scale	-0.5	0.5	-1.6	0.8
Orbit drift	–	0.4	–	0.4
Beam-beam deflection	1.8	0.4	1.5	0.4
Dynamic-β	–	0.5	–	0.5
TOTAL		2.3		**2.5**

Summary

- High luminosity important to achieve high statistics in rare events.
- Precise luminosity important to achieve high precision in cross section measurements.
- Luminosity at CMS is calibrated with Van der Meer scan method and measured using Pixel Cluster Counts.
- Preliminary 2016 result: Total integrated luminosity of $40.8\,\mathrm{fb}^{-1}$ with uncertainty of $2.5\,\%$

Thank you for your attention.