EUROPEAN PHYSICAL SOCIETY HEP2025 MARSEILLE

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Raw Data Reduction in the CMS Experiment for Run-3 and Phase-2

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On behalf of the CMS Collaboration

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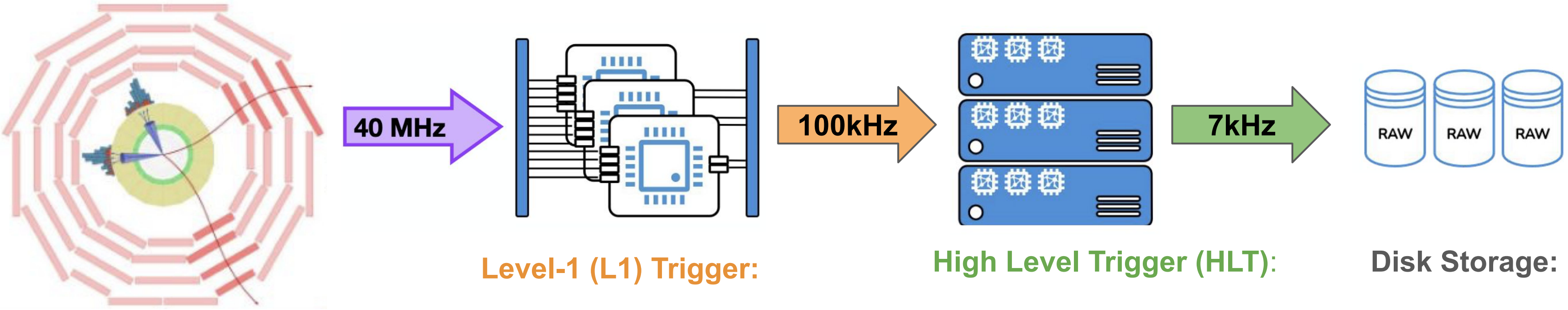
CMS trigger system: Run3

- LHC bunch crossing happens with 25ns gap
  - Rate of collision 40MHz
  - Not feasible to store all the events
- CMS utilizes two level trigger system to select interesting events



Level-1 (L1) Trigger:

Hardware-based, using custom electronics (FPGAs), only calorimeter and muon detectors are used. Latency 3.2μs

High Level Trigger (HLT):

Software based, full detector read-out, offline like reconstruction. Latency 1s

Disk Storage:

Offline reconstruction

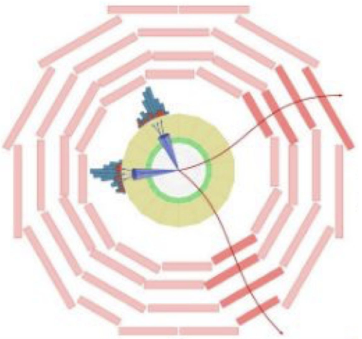
CMS trigger system: plan for Phase-2

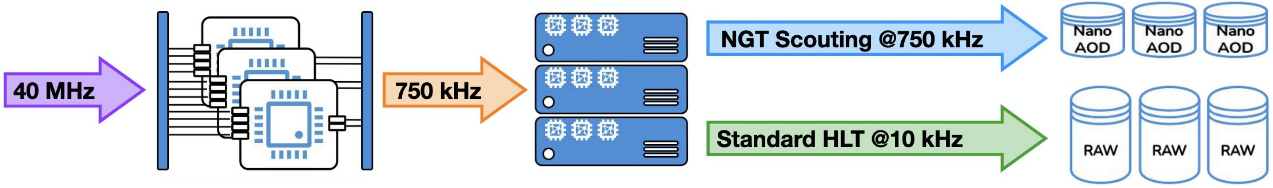
- LHC bunch crossing will happen with 25ns gap
  - Rate of collision 40MHz
  - Not feasible to store all the events

Same as Run-3

- CMS will utilize two level trigger system to select interesting events

Thanks to the NGT scouting (See Novel ideas, Triggering discoveries in high energy Physics)





Level-1 (L1) Trigger:

Hardware-based, using custom electronics (FPGAs), **Tracker**, calorimeter and muon detectors will be used. **Latency 12.5μs**

High Level Trigger (HLT):

Software based, full detector read-out, offline like reconstruction

Same concept as Run-3

Disk Storage:

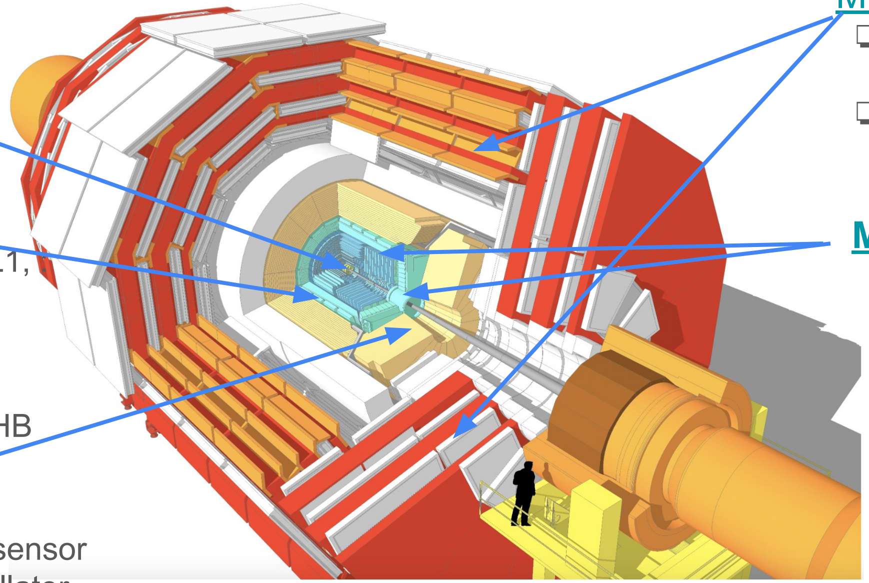
Offline reconstruction

CMS detector: Phase-2

Tracker:
- **Increased granularity,**
- Less material
- **Extended |η| < 4**

Barrel Calorimeter:
- Single crystal information at L1, better matching of tracks and shower, improved isolation
- Replacement of backend electronics for both EB and HB

Endcap Calorimeter:
- CE-E: Pb absorber+Silicon sensor
- CE-H: Stainless Steel+scintillator
- 3D showers, timing information



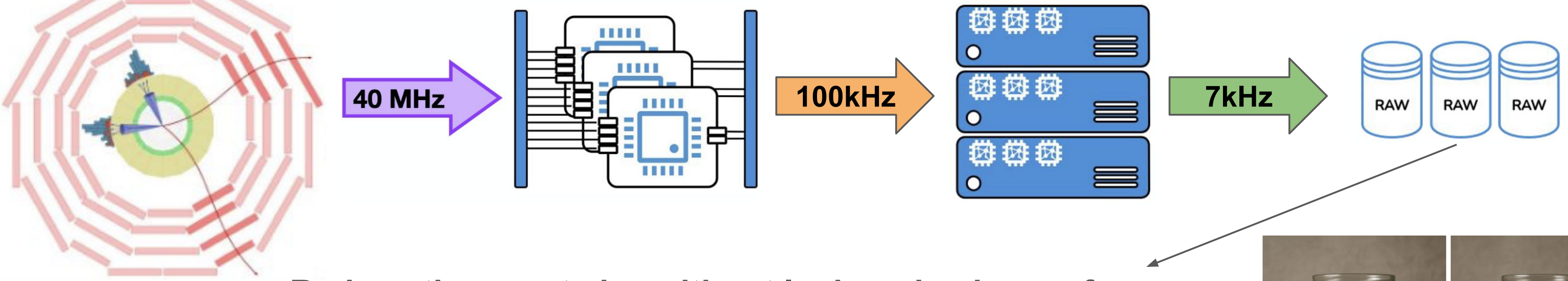
Muon detector
- Upgrade of electronics in CSC, RPC, DT
- **New RPC, GEM chambers with extended |η| upto 2.8**

MIP Timing Detector:
- Timing information of charged tracks with 30-40 PS precision
- **BTL:crystal scintillator+SiPM**
- **ETL: Low Gain Avalanche Diodes**

New detector and increased granularity will increase the Phase-2 event size significantly !

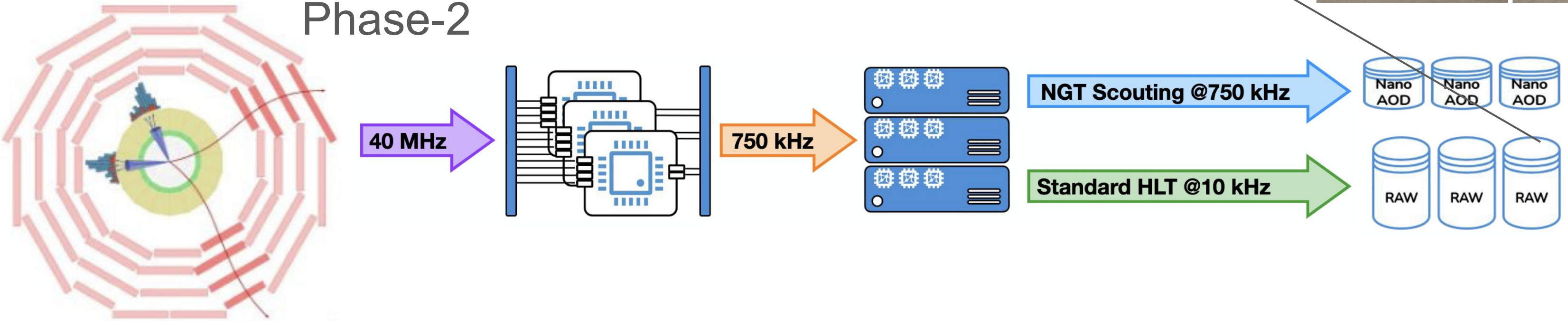
Our goal

Run-3



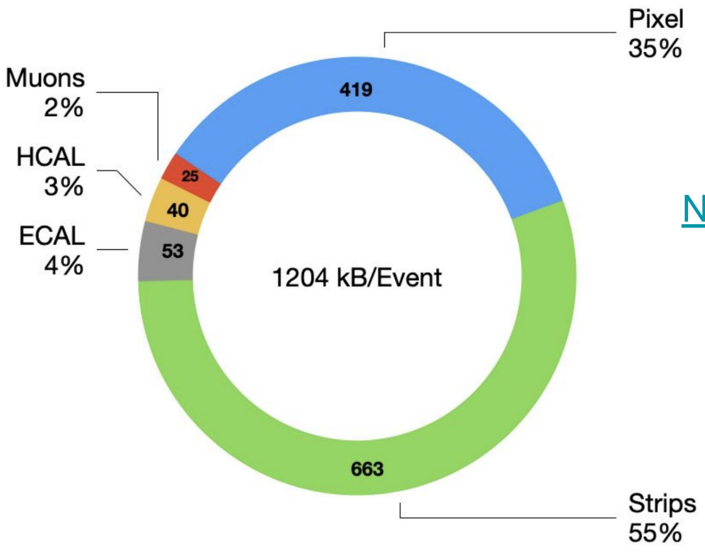
Reduce the event size without losing physics performance: store more events with limited bandwidth ~80GB/s

Phase-2



Detector contribution to the event size at HLT: Run3

- Event size ~ 1.2 MB at pile-up ~ 60
  - Main contribution comes from the silicon strip tracker detector



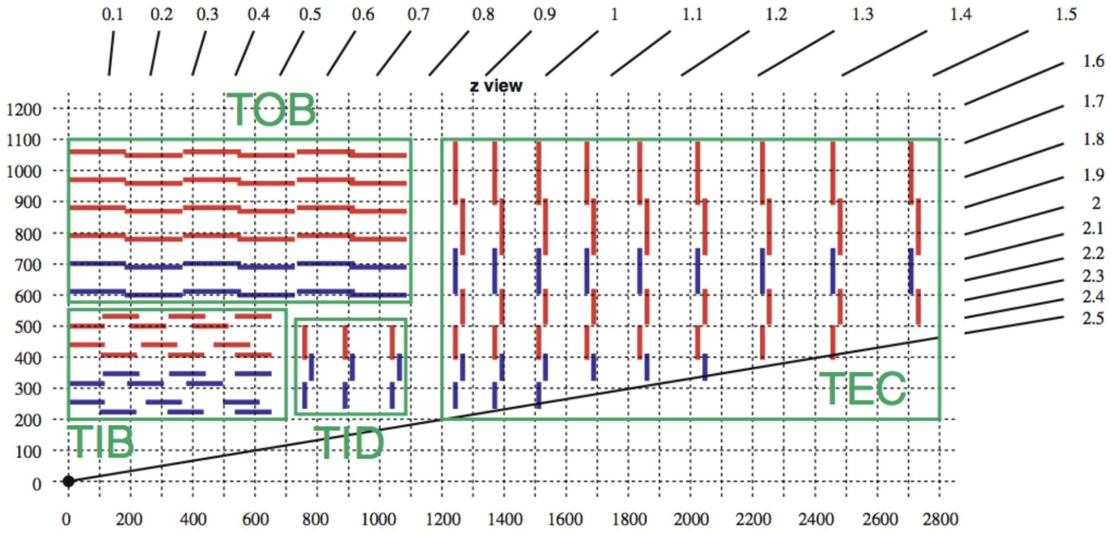
NGT workshop

- **Our attempt is to reduce the size of Strip detector data**
  - **without losing physics performance significantly → Lossy compression**

Strip detecor in CMS Tracker

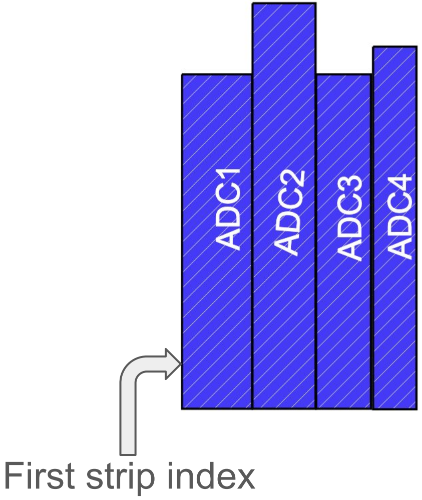
- Total active area of strip detector around 200m^2
  - ~ 9.6 M read-out channels in total

- Silicon strip modules:
  - p-on-n sensors, 320/500 µm thickness
  - 512/728 strips per module (4-6 APV25 chips)



Strip Cluster

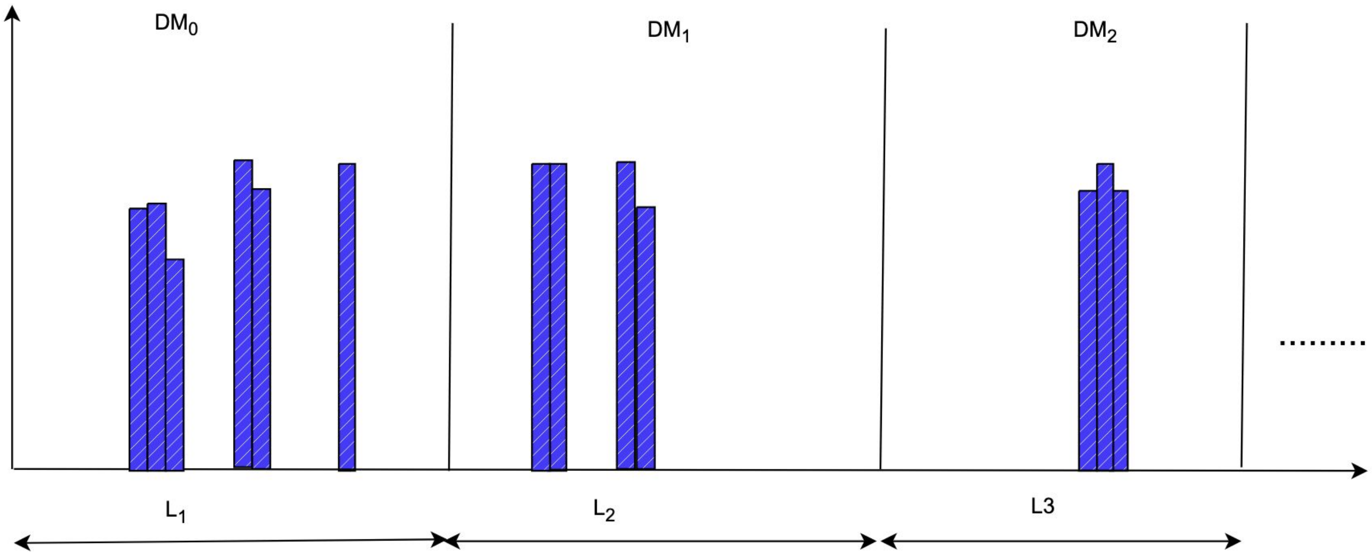
- Strip cluster is a set of consecutive strips satisfying some thresholds to avoid the detector noise.
- At the HLT step, **raw information** about the individual strip cluster is stored:
  - Index position of the first strip belonging to the cluster, stored as 16 bit integer.
  - The analog-to-digital counter (ADC) value for each strip within a cluster, stored as 8 bit integer.



First strip index	16 bit
ADC value	8*4= 32 bit
Total	48 bit

Strip Cluster collection

- A strip-cluster collection is a set of clusters that belongs to a particular detector module.
- The following information about the strip cluster collection is stored:
  - A unique identification number of a detector module (detId) containing at least one cluster
    - 369120277, 369120278, 369120281, 369120282… **large number!**



DM_i: ith detector module

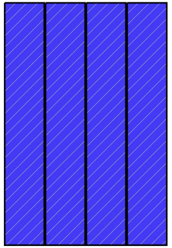
L_i: Length of DM_i in terms of number of silicon strips present

  - The position of the first cluster within the cluster collection for each detector module
    - 0,3,5,........... 290244, 290262, 290271….. **large number!**

Measures taken to reduce the strip cluster size in Heavy Ion analysis: HI_raw’

- The event size in HI collision is higher than pp collision
  - ~ 6% higher in compressed event size

- Explored unique approach to reduce the size of strip cluster in Run-3: approximated raw’, CERN-CMS-DP-2024-007
  - Store size of the cluster: 8 bit integer
  - Store average charge (total ADC value / size): 8 bit integer
  - Store barycenter position, ADC-weighted strip index center: 16 bit integer



Barycenter position: ∑ i*adc_i / ∑ adc_i	16 bit
Average charge: ∑ adc_i / ∑ i	8 bit
size	8 bit
Total bit	32 bit

Reduced event size by ~ 50%

Can we reduce the strip cluster size further?

CMS DP-2025/031

Use fewer bits to encode barycenter and average charge information: raw'

- Currently in HI, the barycenter information is stored with 10% precision

$$std :: round(\text{ barycenter's value} \times \boxed{10})$$

- Generalize the things in such a way that any bit configurations can be used to store barycenter/average charge (variable) information using the following formula:

$$std :: round(\text{ variable's value} \times \boxed{\frac{\text{pow(2,maximum bit) - 1}}{\text{variable's maximum value}}})$$

Resolution of variable is controlled by these terms

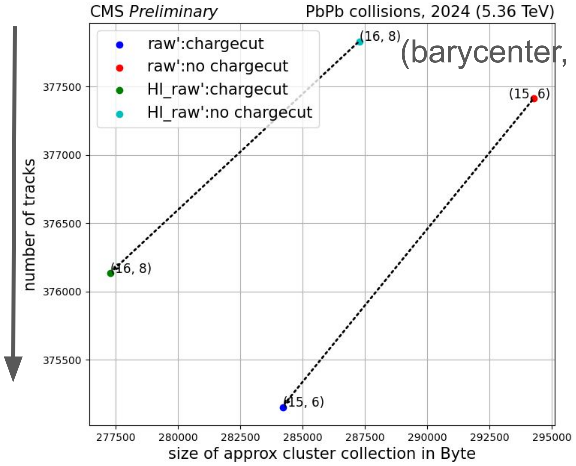
Apply tight charge cut on strip cluster

- Apply tight charge cut on strip cluster at the HLT level
  - ADC value per cm of detector module > 1945.
  - strip clusters failing this cut, are not not saved at the HLT output
  - Reduce the contribution coming from pile-up

- This cut reduces the size of strip cluster collection significantly without affecting track reconstruction.

PbPb

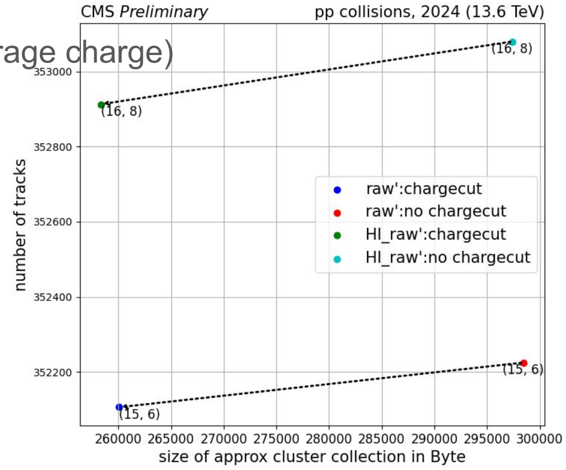
Negligible reduction



3% reduction

pp

(barycenter, average charge)

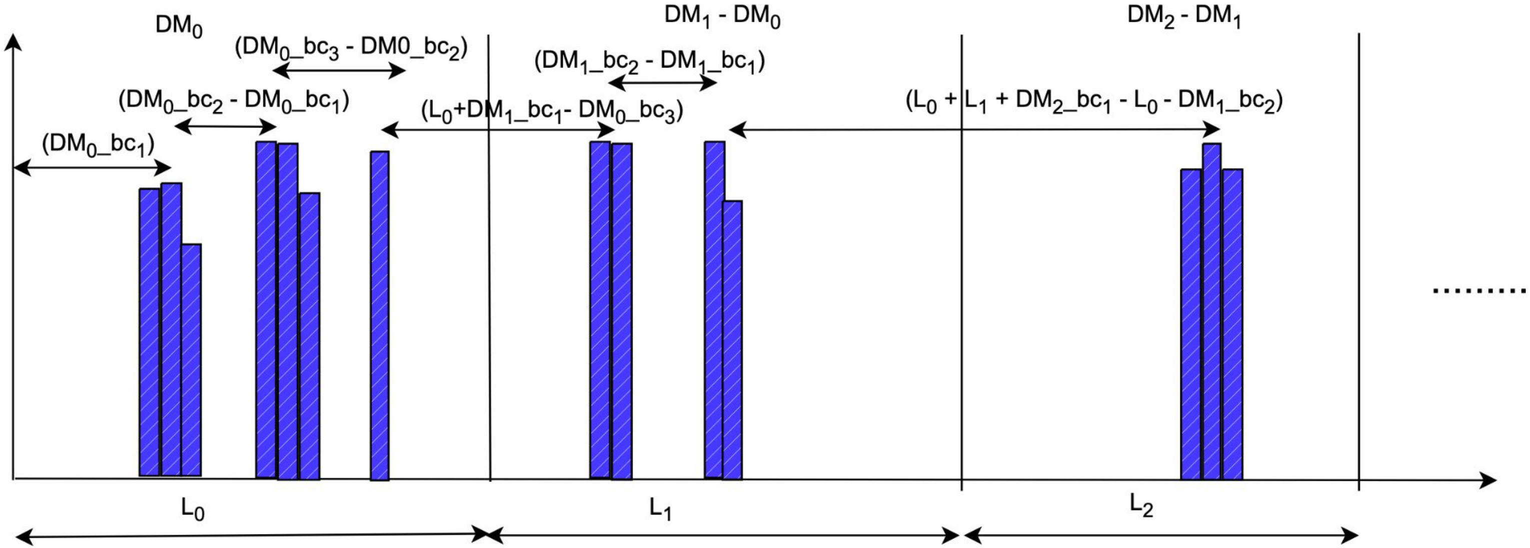


13% reduction

Can we do better than this?

Save difference of barycenter position: v2

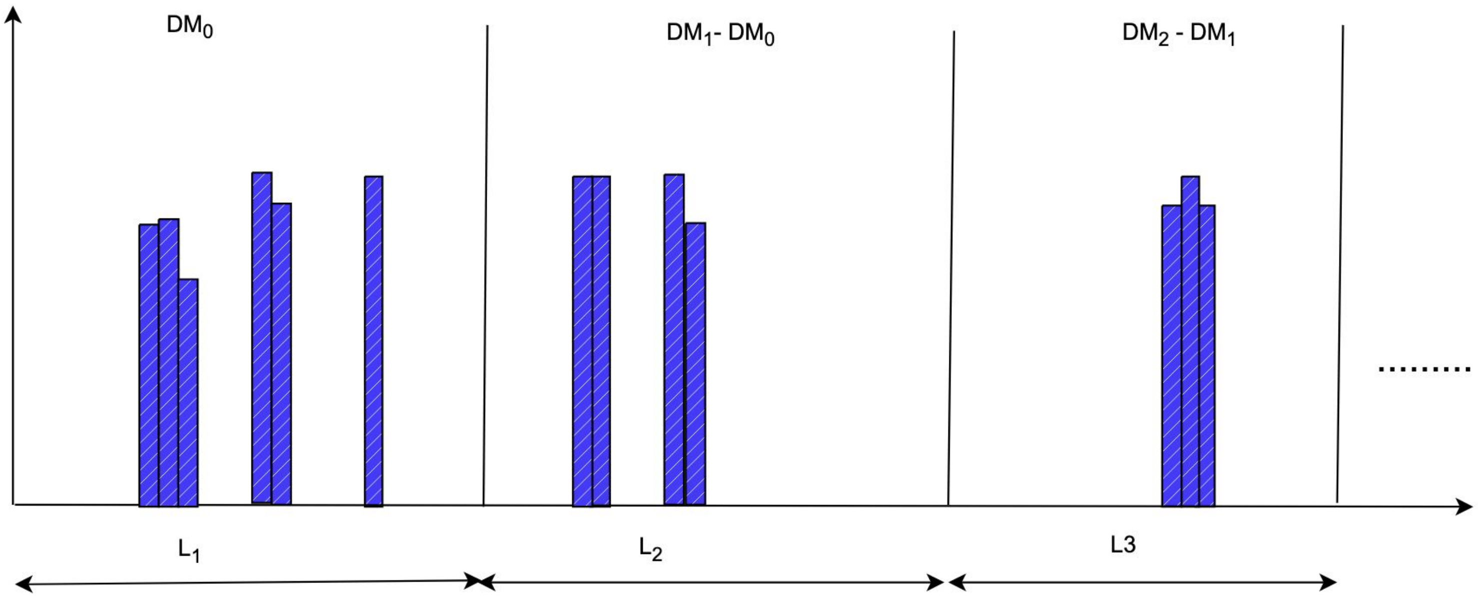
- Save difference of actual barycenter position
  - 283, 1363, 3487, 4200, 4657……… → 283,1080, 2124,713,457…… ❌ ✅
- Consider length of the detector modules in terms of number of total strips present in the detId
  - Remove the variable containing the position of first cluster
    - 0,3,5,……….. 290244, 290262, 290271….. ❌



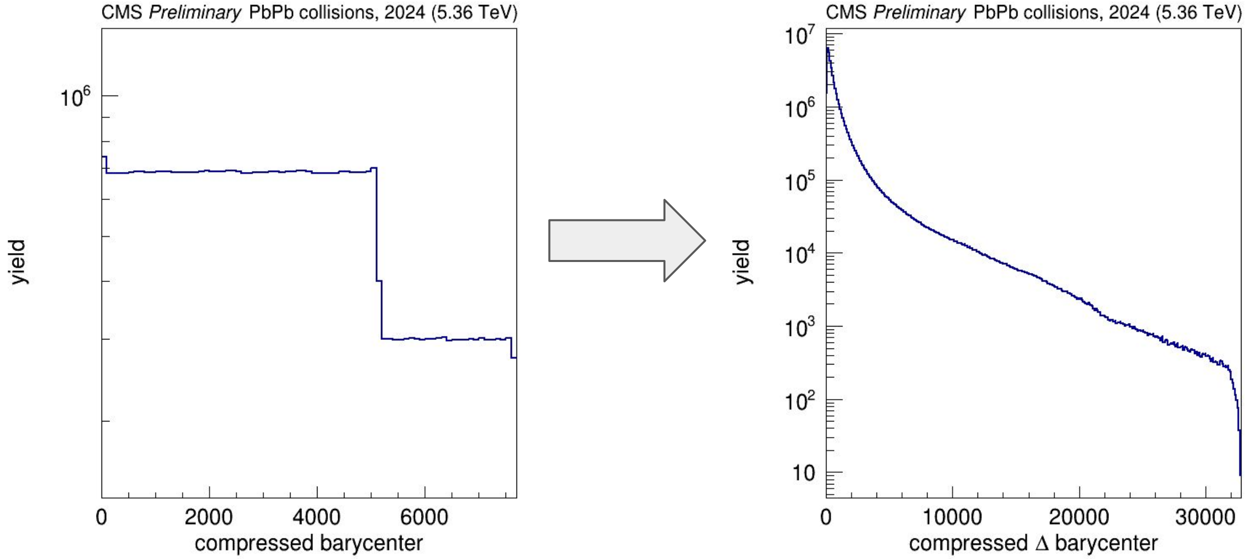
$DM_i\_bc_j$: jth barycenter position in ith detector module

Save difference of detId: version-2 (v2)

- Instead of saving detId, save difference of detId
  - 369120277, 369120278, 369120281, 369120282 … → 369120277,1, 3,1,1…..
    ❌ ✅



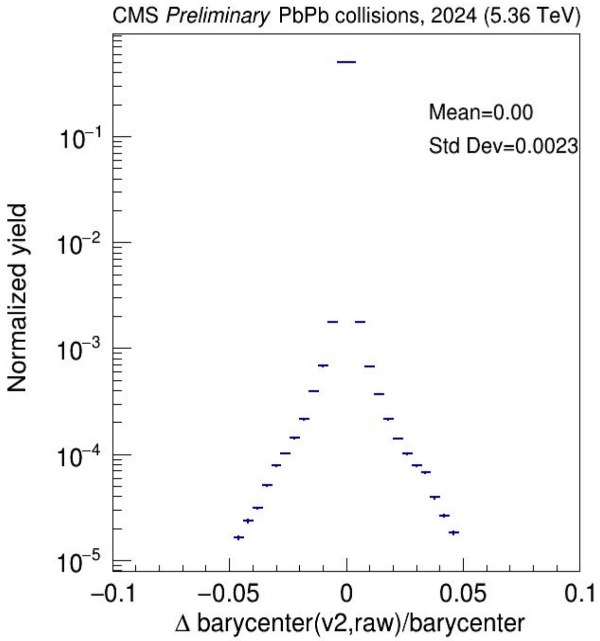
Compressed, barycenter vs difference of barycenter distribution

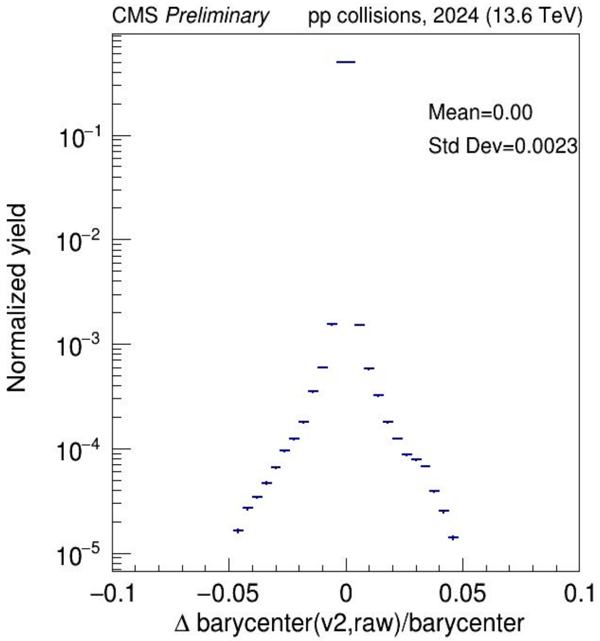


- ❑ Barycenter distribution becomes sharply falling for v2 → reduces entropy of the variable.
  - ❑ Less bits to represent for more frequent values while more bits for larger values with less frequency.
    - ❑ Compression algorithm becomes more efficient.

Resolution of barycenter position: v2

- Matching of the barycenter position between raw and v2 is good.





Absolute delta in the barycenter position is below 0.05 strips.

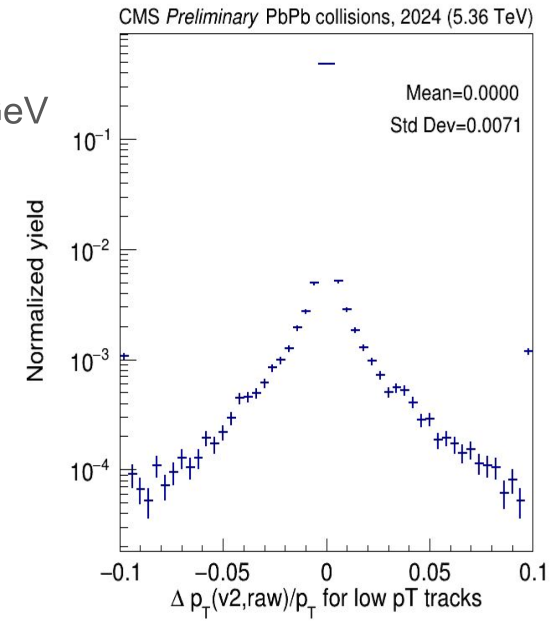
Effect on track reconstruction: v2

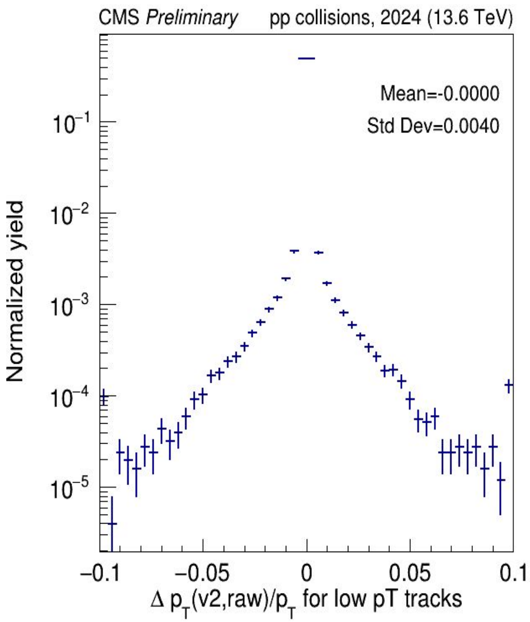
- Tracks are reconstructed with raw clusters and clusters with v2 and selected with
  - normalized $\chi^2 < 2$, $|\Delta p_T / p_T| < 0.10$, total number of hits in tracker > 11
- Tracks between raw and v2 are matched with the closest ΔR, with maximum ΔR < 0.5

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Good matching is observed

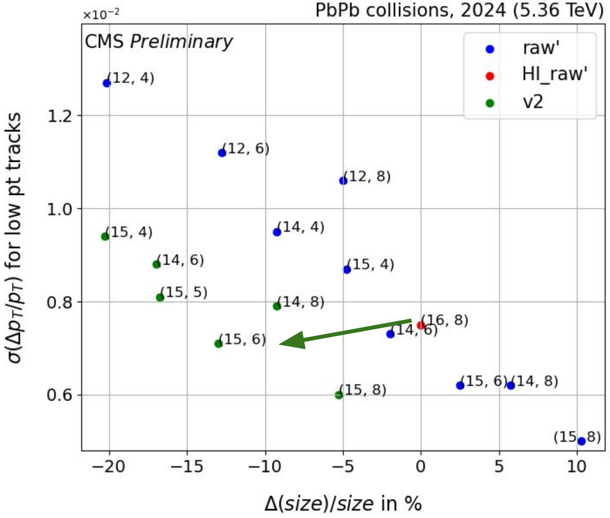
$p_T < 1$ GeV

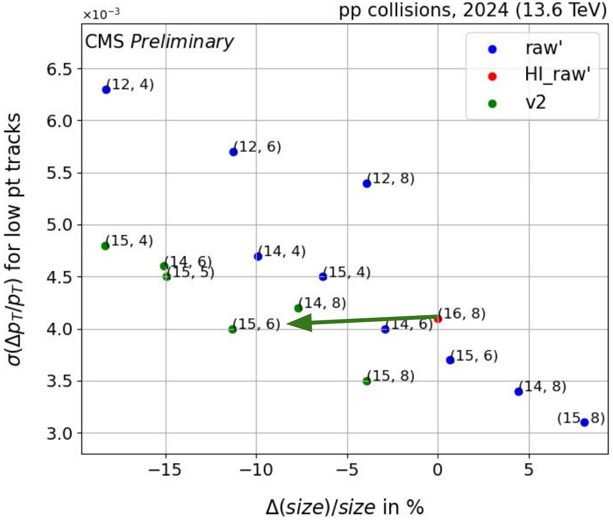




Comparison among different bit configurations and methods

p_T < 1 GeV



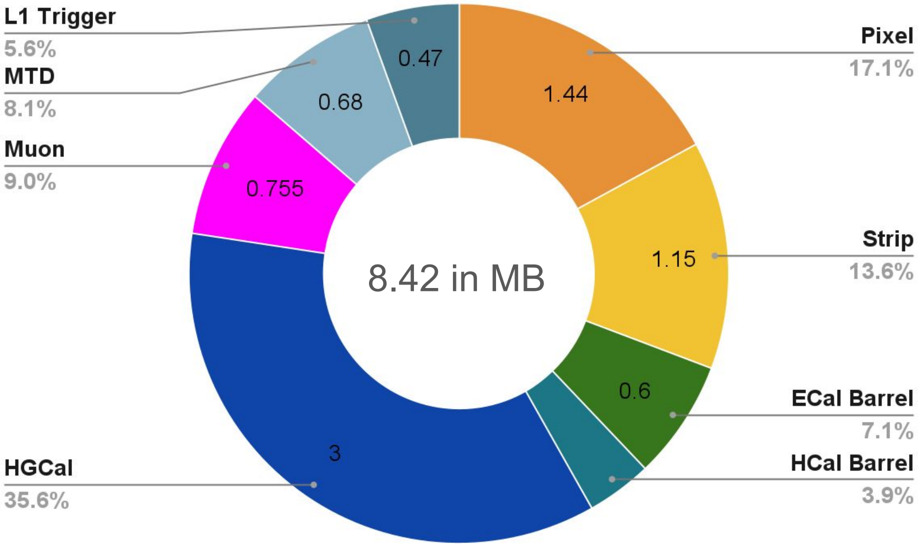


- The configuration for barycenter, and average charge (15,6) in v2 gives reduction in strip cluster collection's size > 10% with respect to current method, while keeping similar performance in track reconstruction.

CMS DP-2025/031

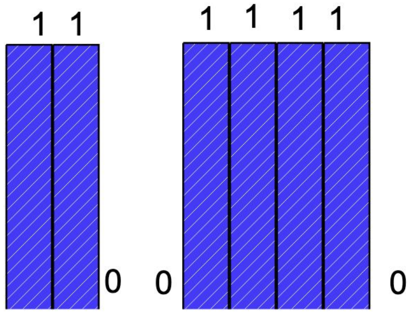
Detector contribution to the event size at HLT: Phase-2

HLT TDR



- ❑ Maximum contribution comes from HGCal followed by Pixel.

- ❑ Strip cluster will be binary completely



- ❑ It might be still useful to save the difference of barycenter position in phase-2 as well.

- ❑ Size of HGCal can be reduced following the same method as strip detector.

Conclusion

- CMS is approaching to the High-Luminosity Phase-2 scenario.
- Event size is the main bottleneck to store interesting events at the HLT with limited bandwidth.
- In Run-3 HI collision, the raw strip cluster was replaced by approximate raw' strip cluster which reduced the event size by around factor 2.
- Attempt is made to reduce the strip cluster size further by extending the approximate raw' cluster method
  - Strip cluster collection's size is reduced significantly by applying tight charge cut on strip cluster, using fewer bits to save the difference of barycenter position, and average charge.
    - Total reduction is ~16% for HI and ~23% for pp.
  - This method will be implemented for next HI collision run and, in Phase-2, the plan is to use the method in both pp and HI collisions.
- Same method can be propagated to other sub-detectors like HGCal for Phase-2.
- Work is ongoing!

Stay tuned !!!!

Back up

CERN-EP-2025-036

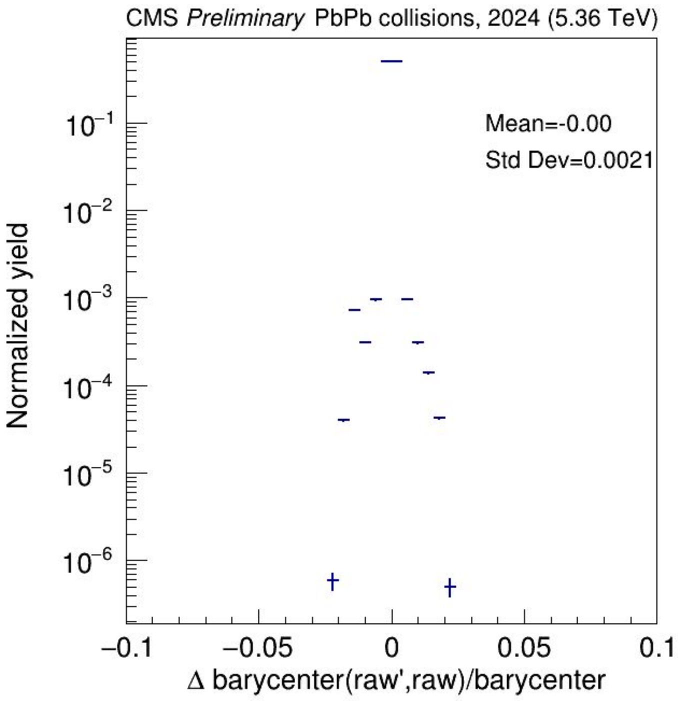
Sub-detector	Layer	No. of APV25s	Pitch [μm]
TIB	1, 2	6	80
TIB	3, 4	4	120
TOB	1–4	4	183
TOB	5, 6	6	122

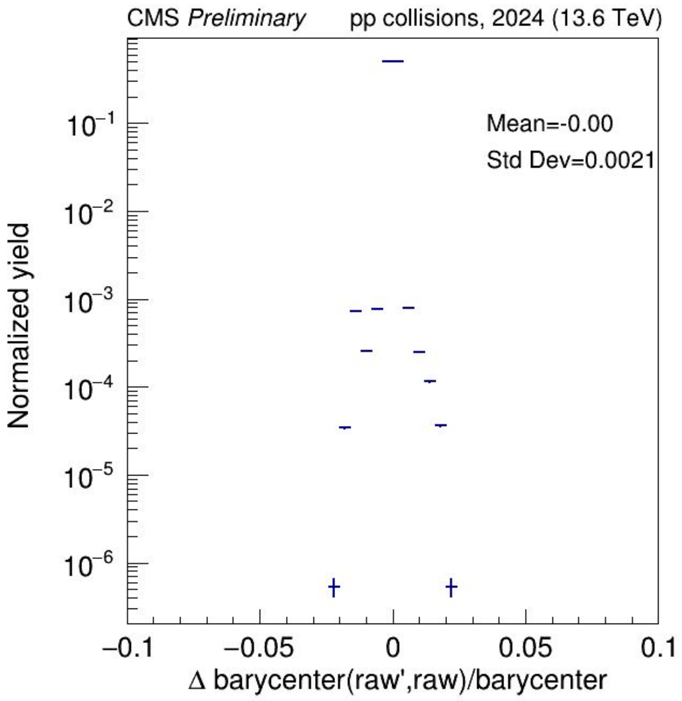
Sub-detector	Ring	No. of APV25s	Pitch range [μm]
TID	1	6	80.5–119
TEC	1	6	81–112
TID/TEC	2	6	113–143
TID/TEC	3	4	123–158
TEC	4	4	113–139
TEC	5	6	126–156
TEC	6	4	163–205
TEC	7	4	140–172

2009, JINST, 4 P05004

1. *Cluster reconstruction.* The cluster reconstruction groups adjacent strips whose associated charges pass a set of thresholds. The thresholds depend on the noise levels characterizing the strips of the cluster. Clusters are reconstructed by searching for a seed strip with a signal-to-noise ratio (S/N) greater than 3. Neighboring strips are attached to the cluster if their signal-to-noise ratio exceeds 2. The total signal size of the cluster must exceed five times the quadratic sum of the individual strip noises. The cluster reconstruction algorithm is referred to as *3-Threshold* algorithm. The signal of a cluster is based on the sum of the ADC counts of all associated strips. In the most recent reconstruction pass a correction for the variations in the electronic gain was applied. These corrections had been derived from the height of digital synchronization signals [2].

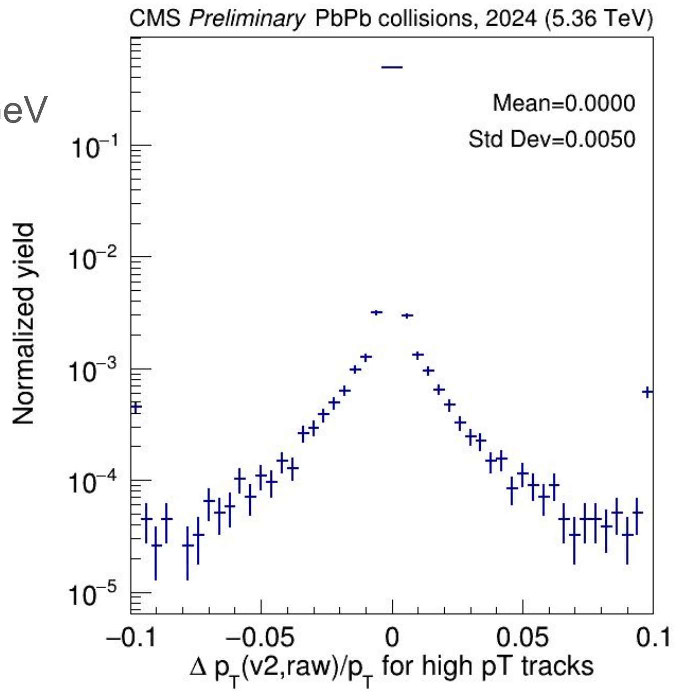
Resolution of barycenter position: raw’

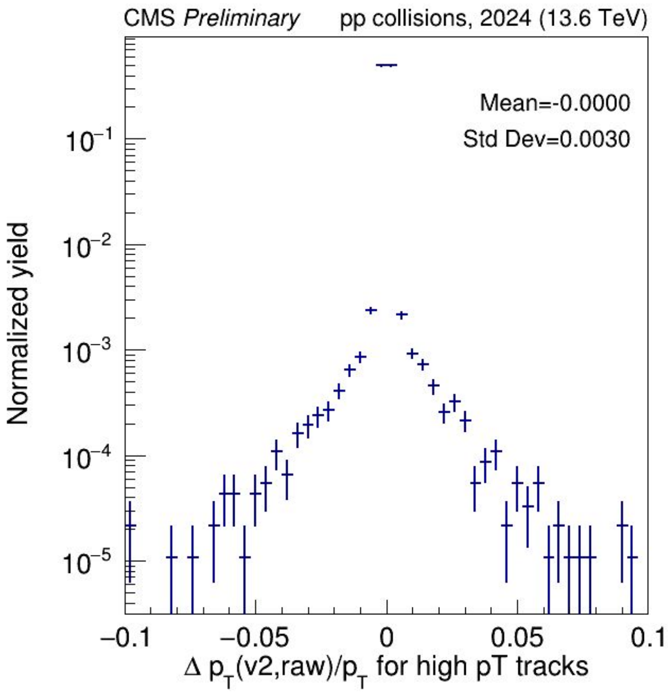




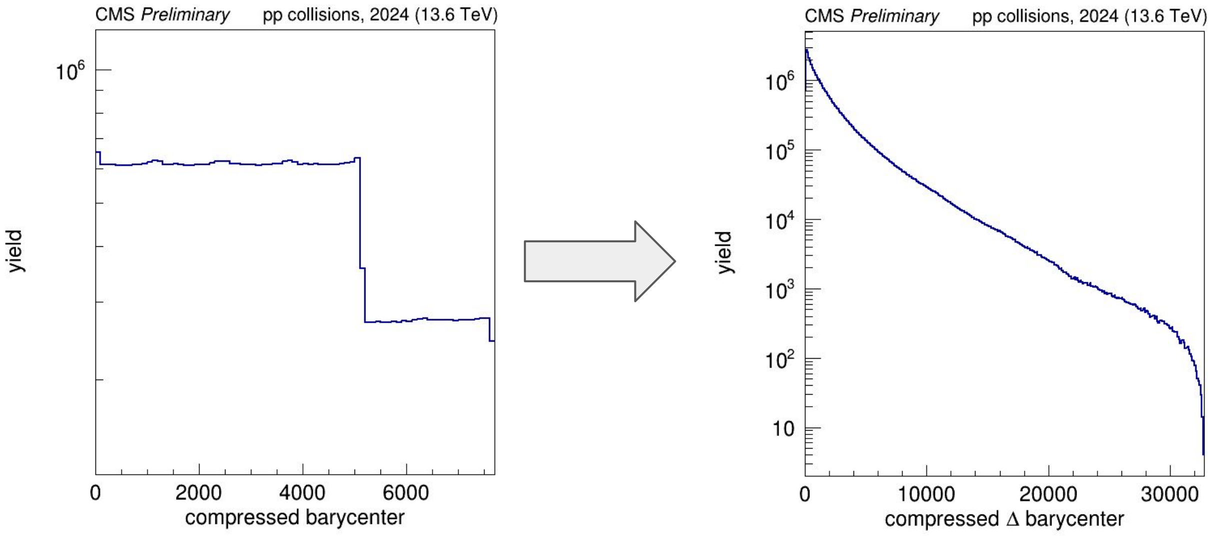
Effect on track reconstruction

p_T > 1GeV



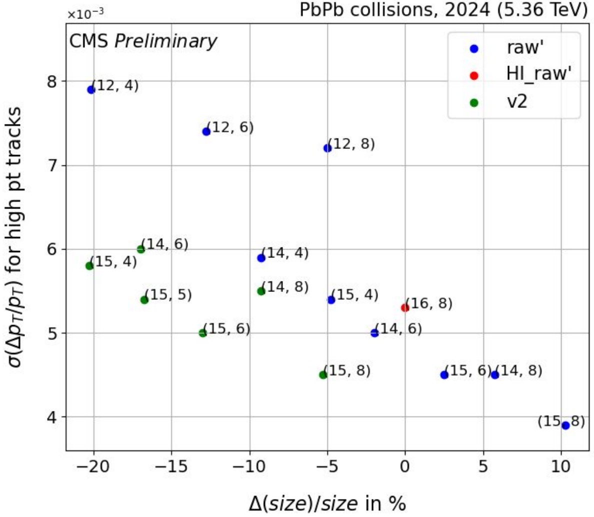


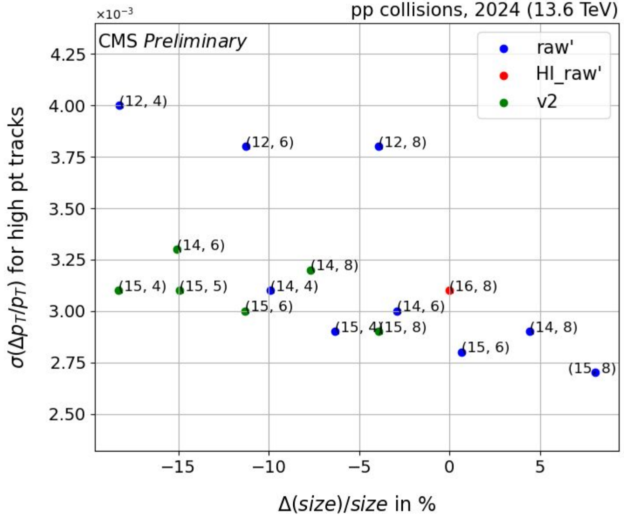
Compressed, barycenter vs difference of barycenter distribution



Comparison among different bit configurations and methods

p_T > 1 GeV





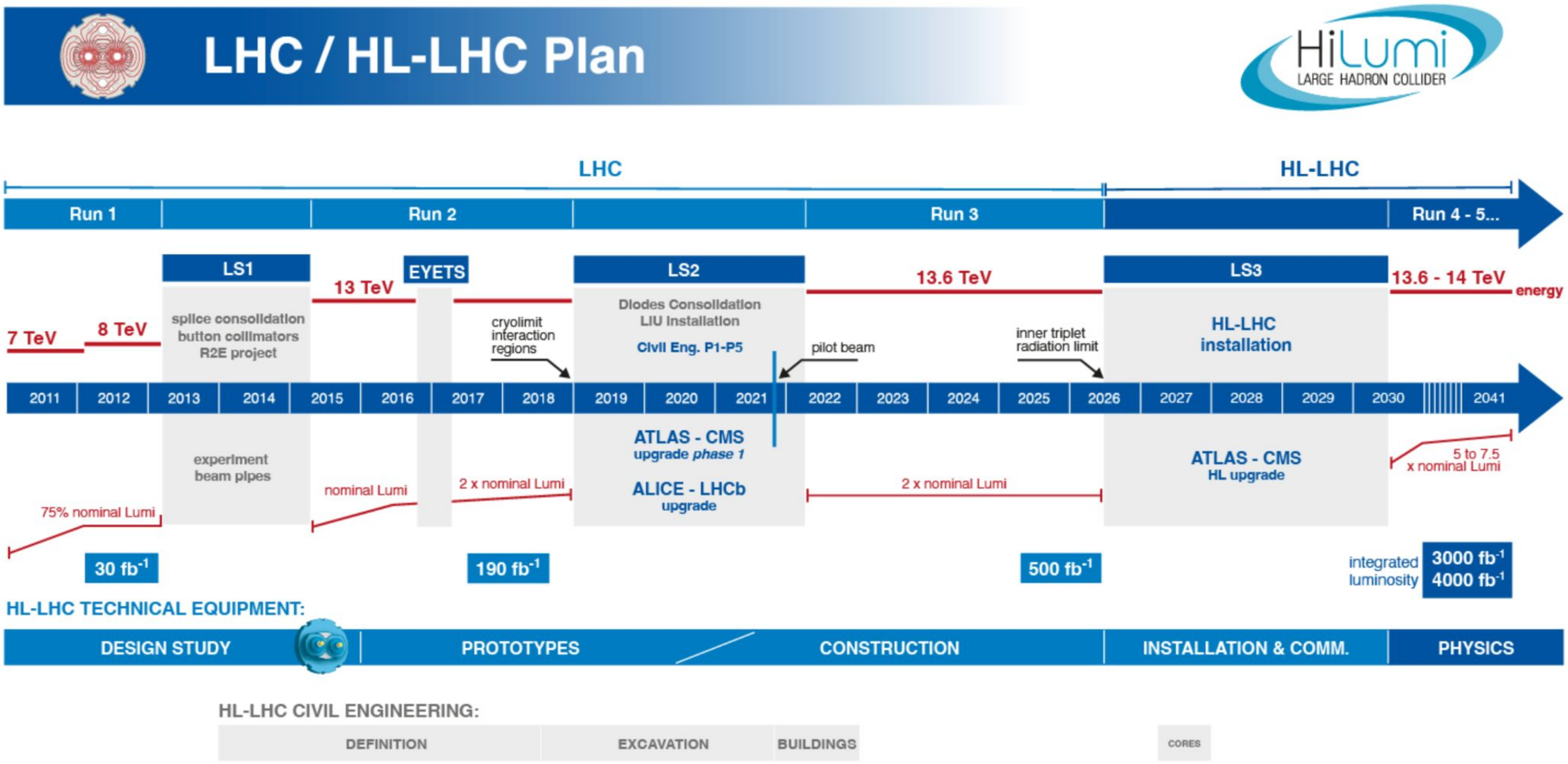
HLT TDR

Table 3.2: CMS Phase-2 detector readout and ATCA back-end (BE) electronics characteristics and event size summary. Two scenarios for HL-LHC are considered: Run-4 with peak $\langle PU \rangle = 140$ and a L1 rate of 500 kHz, and Run-5 with peak $\langle PU \rangle = 200$ and a L1 rate of 750 kHz. Columns 11–12 denote the average throughput (Thru) per sub-system back-end board and back-end crate for the ultimate scenario of Run-5.

Sub-system	Back-end platform	Back-end FPGA	BE boards	BE crates	Front-end lpGBT links[a]	Subevt size (MB) $\langle PU \rangle = 140$	Subevt size (MB) PU=200	Thru (Tb/s) PU=140 500 kHz	Thru (Tb/s) $\langle PU \rangle = 200$ 750 kHz	Av thru per BE board (Gb/s)	Av thru per BE crate (Gb/s)	Notes
Inner Tracker	Apollo	2xVU13P	28	4	1260	1.01	1.44	4.03	8.64	309	2160	
Outer Tracker - PS.	Serenity	1xVU13P	108	9	5592	0.50	0.72	2.01	4.31	40	479	([b])
Outer Tracker - 2S.	Serenity	1xVU13P	108	9	7608	0.30	0.43	1.21	2.58	24	287	([b])
Track Finder TPG	Apollo	2xVU13P	180	18		0.01	0.01	0.04	0.06	1	1	
MIP Timing Det. - BTL	Serenity	2xKU15P	8	2	864	0.17	0.24	0.67	1.44	180	720	
MIP Timing Det. - ETL	Serenity	2xKU15P	14	2	1600	0.31	0.44	1.23	2.64	189	1320	
ECAL Barrel	BCP	1xVU13P	108	12	9792	0.42	0.60	1.68	3.60	33	300	
HCAL Barrel	BCP	1xVU13P	18	2	other	0.24	0.24	0.96	1.44	80	720	
HCAL HO	BCP	1xVU13P	9	1	legacy	0.03	0.03	0.12	0.18	20	180	
HCAL HF	BCP	1xVU13P	9	1	other	0.06	0.06	0.24	0.36	40	360	
HGCAL	Serenity	2xKU15P	84	12	8000	2.10	3.00	8.40	18.00	214	1500	
HGCAL TPG Stage1	Serenity	2xVU7P	72	8	9000	0.11	0.15	0.42	0.90	13	113	
HGCAL TPG Stage2	Serenity	2xVU9P	54	6		0.04	0.05	0.14	0.30	6	50	
Muon DT	BMT	1xVU13P	84	8	2400	0.11	0.15	0.42	0.90	11	113	
Muon CSC	APX	1xVU13P	10	2	other	0.33	0.47	1.32	2.82	282	1410	
Muon GEM - GE1/1	APX	1xVU13P	8	1	GBTX	0.002	0.003	0.01	0.02	2	18	
Muon GEM - GE2/1	APX	1xVU13P	8	1	GBTX	0.001	0.002	0.01	0.01	1	9	
Muon GEM - ME0	APX	1xVU13P	18	2	1728	0.08	0.12	0.34	0.72	40	360	
Muon RPC	Serenity	UltraScale+	18	3	other	0.01	0.01	0.03	0.07	3	22	
Level-1 Trigger	various	UltraScale+	280	28		0.26	0.26	1.04	1.56	6	60	([c])
Total			>1226	>130	50k	6.08	8.42	24.3	50.5			

[a]Count of links based on lpGBT-VL+ (see Appendix A), "Other" links include the use of VL(+) components with radiation-tolerant FPGA at the front-end.
[b]The Outer Tracker uses the same links to multiplex trigger and DAQ data. The proportion of trigger data is expected to be roughly 80%.
[c]The Level-1 trigger comprises 5 sub-systems using the APX, BMT, X2O and Serenity platforms.

LHC/HL-LHC plan



HL-LHC schedule