# TIMING DETECTORS AT THE HL-LHC

**Learning to Discover : Advanced Pattern Recognition**
Institut Pascal, Orsay
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Corentin Allaire

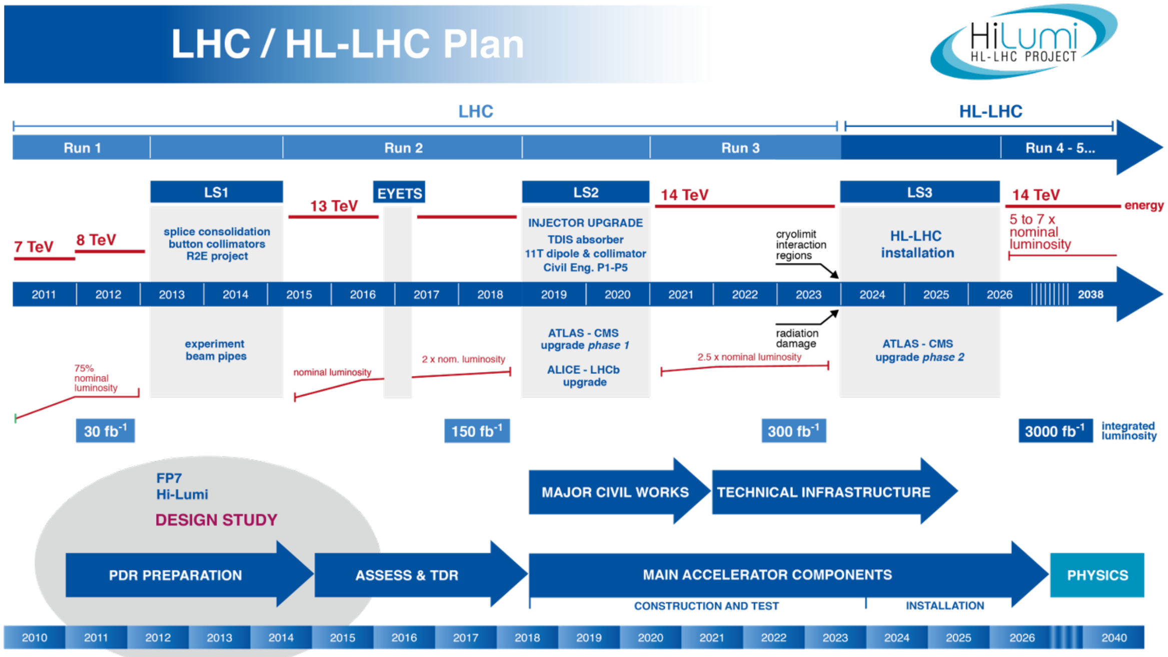
# The High Luminosity LHC

- End of Run 3 (2023) : 300 $fb^{-1}$
- With current luminosity, 10 extra year need to halve statistical errors
- Plan to increase the instantaneous luminosity from $(1\text{-}2)\times10^{34}cm^{-2}s^{-1}$ to $7.5\times10^{34}cm^{-2}s^{-1}$
- A total integrated luminosity of 4000 $fb^{-1}$ at the end of the LHC in 2037

$$\mathcal{L} = \frac{n_1 n_2 f N_b F}{4\pi\sigma_x\sigma_y}$$

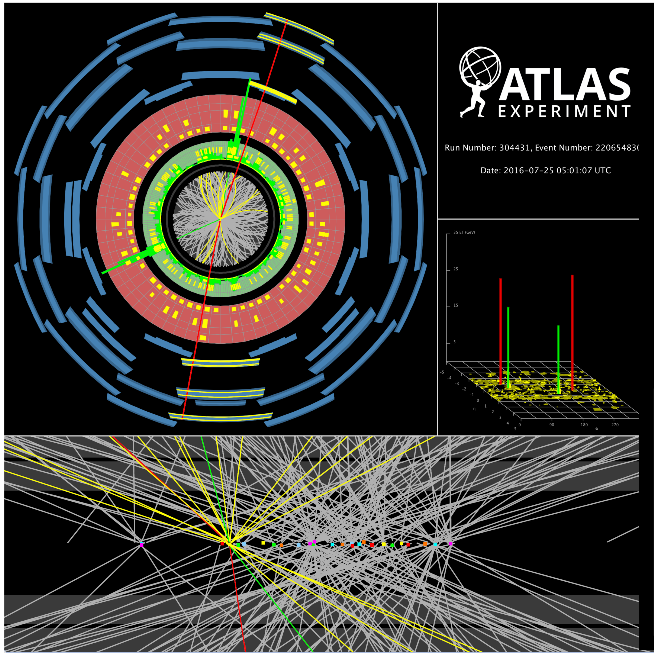
**LHC Upgrades :**

- Smaller bunches with more protons -> larger density of proton -> larger luminosity
- Improved insertion magnet (squeeze the bunches pre-collision)
- Crab cavities to improve geometrical factor of the collision
- Luminosity levelling

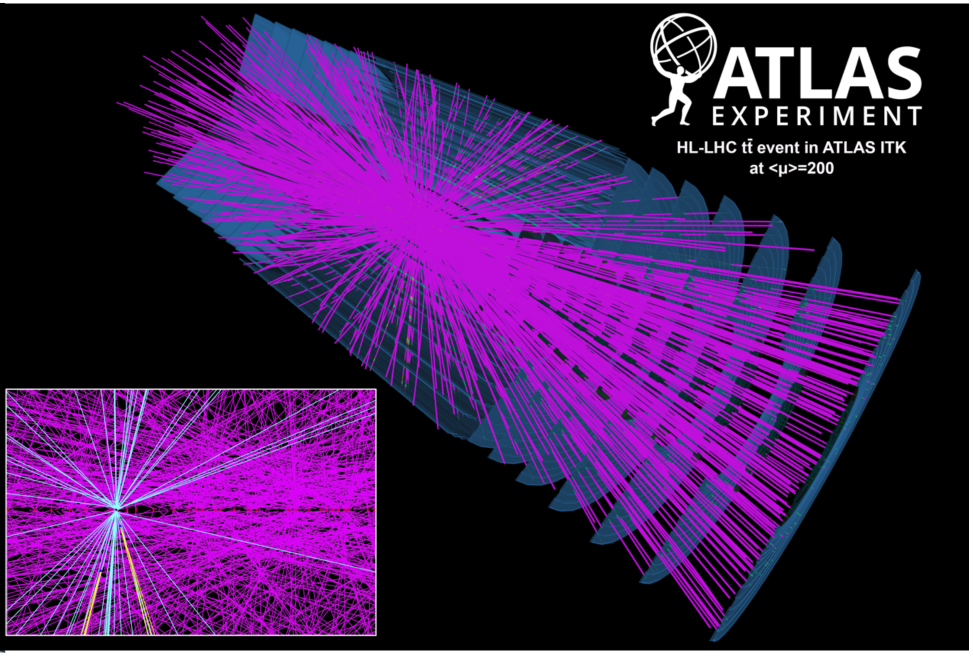


# Pile-up at the HL-LHC

- Pile-up increase with the luminosity : $\mu = \frac{\mathcal{L} \times \sigma_{inel}}{\mathrm{N}_b f}$
- Large PU increase at the HL-LHC :
  - Harder object reconstruction
  - Large radiation dose deposited in the detector
- From <μ>=25 to <μ>=200, larger PU density



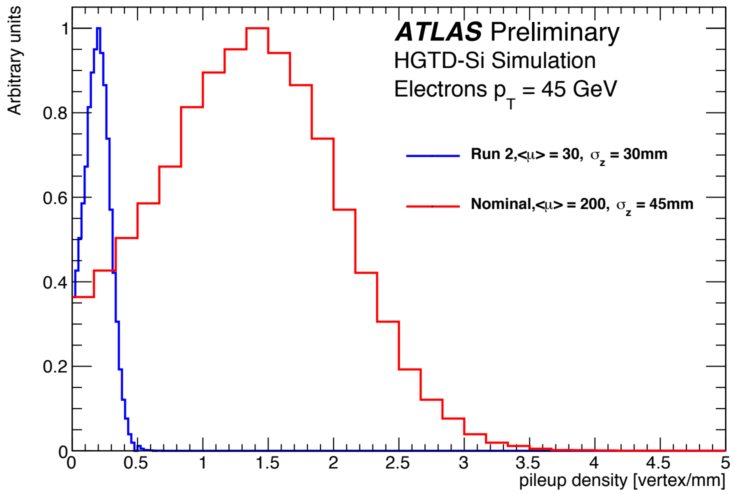

H->eeμμ, <μ>=25




Simulation $t\bar{t}$, <μ>=200

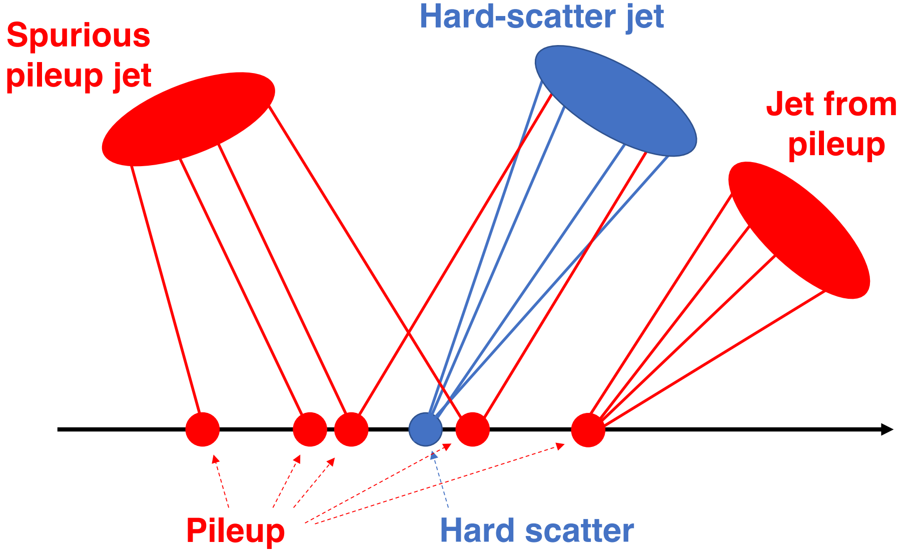
# Pile-up at the HL-LHC

- The pile-up (PU) increase with luminosity
- Same size beamspot -> larger PU density
- Close by vertices might not be differentiated by the tracker -> merged vertices
- Result in additional PU jets and contamination of hard scatter (HS) objects

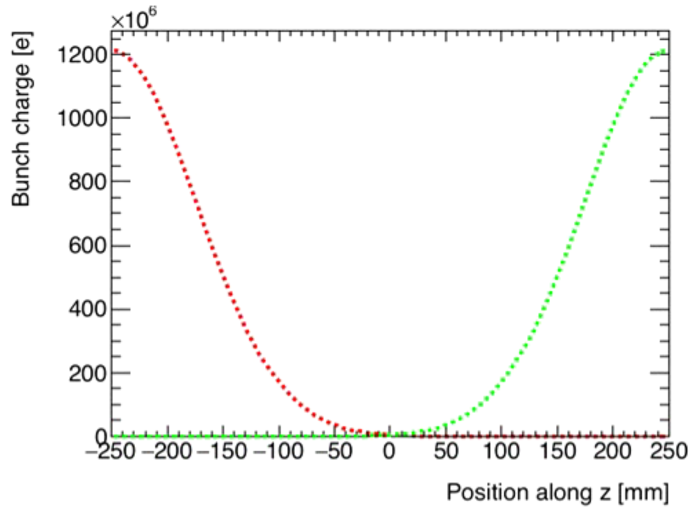


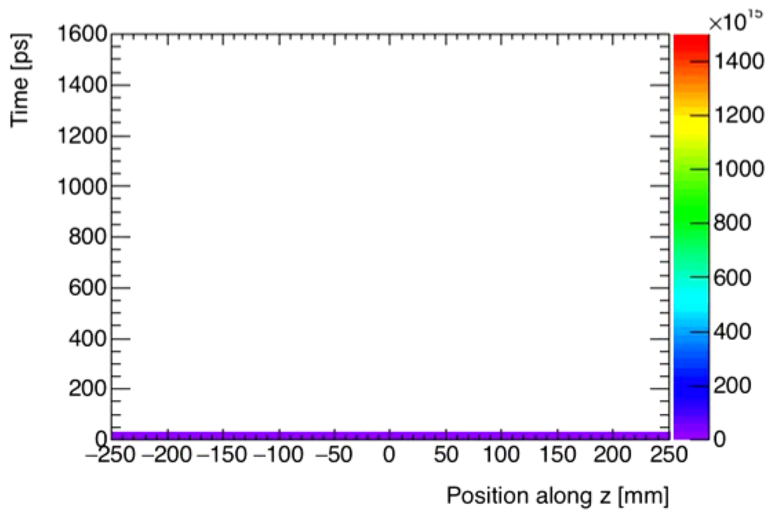

**Example with jets:**

- Pile-up can contaminate HS jets
- Pile-up jet can appear to come from the HS vertex
- Pile-up particle can be combine and create jets

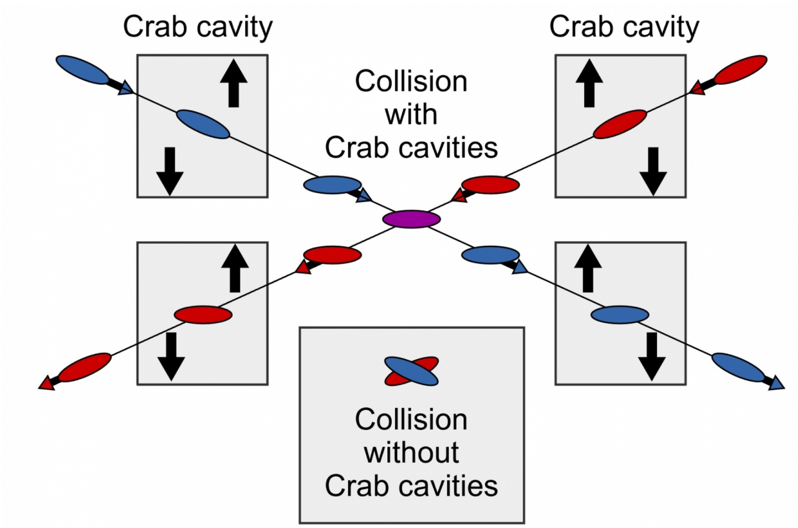


# ATLAS Beamspot




- Proton bunches -> gaussian density
- Crab cavities maximize the overlap of the bunch
- Bunch length of 90 mm
- Crossing non-instantaneous : interaction spread in time



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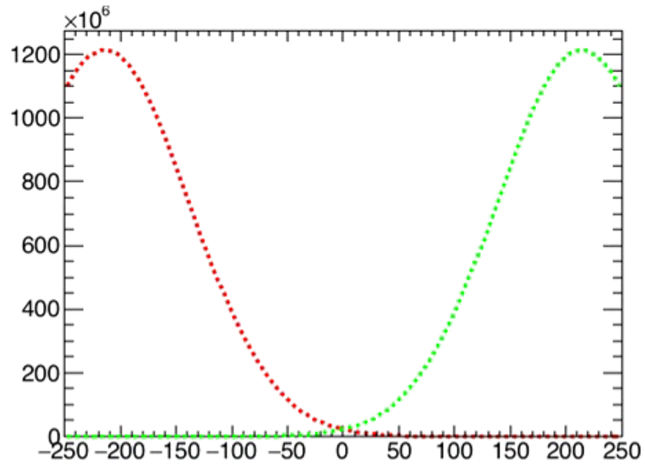


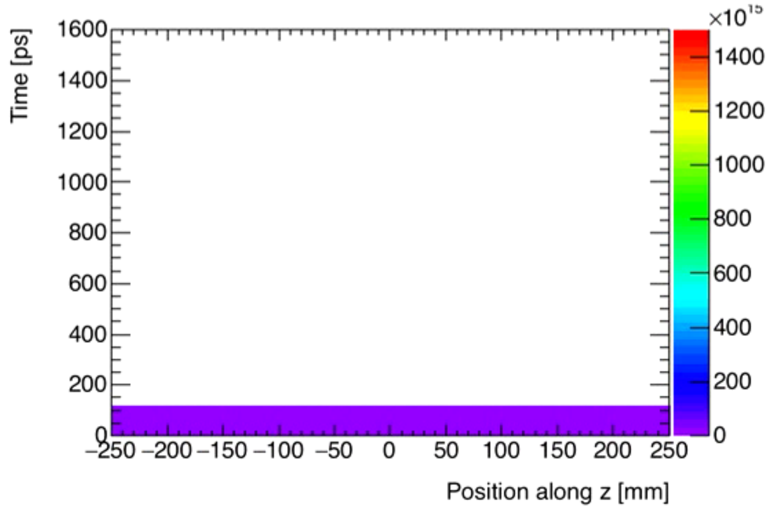


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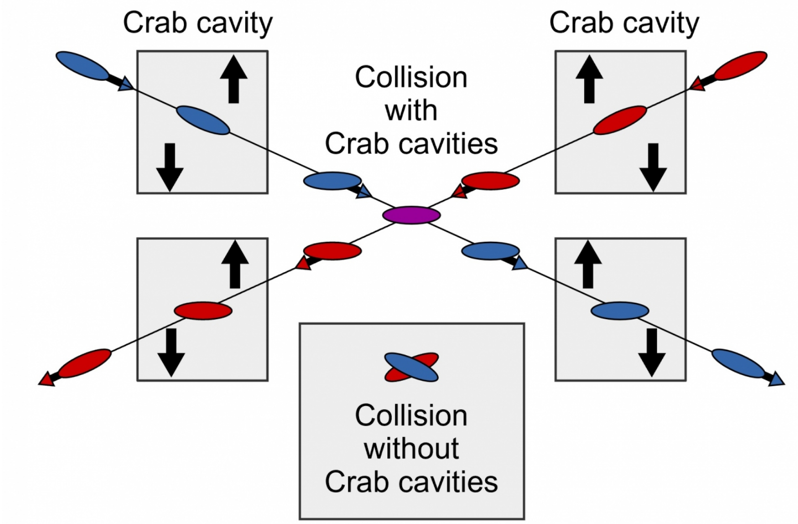

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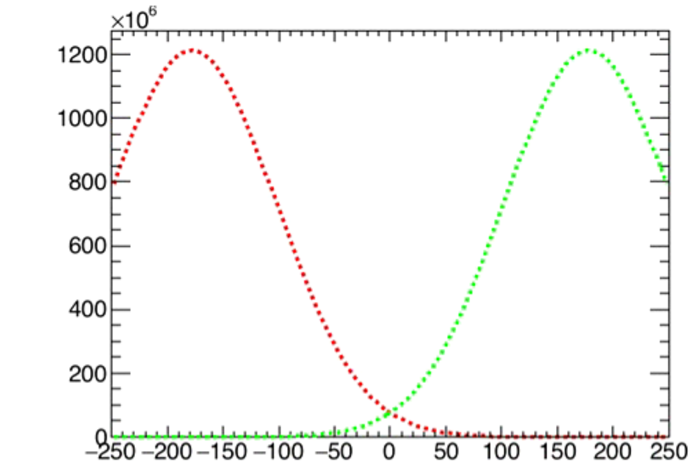


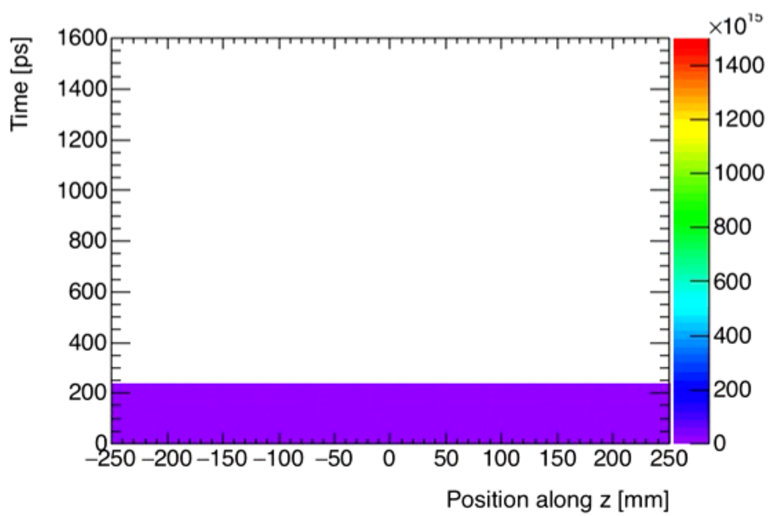


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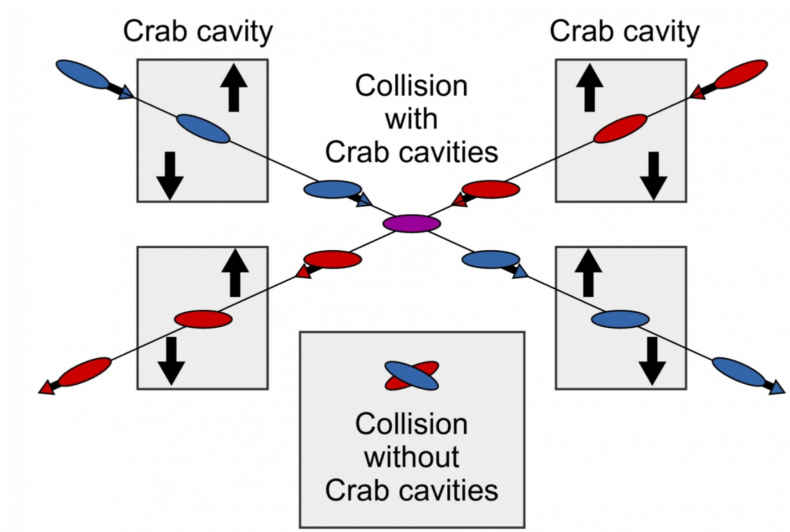

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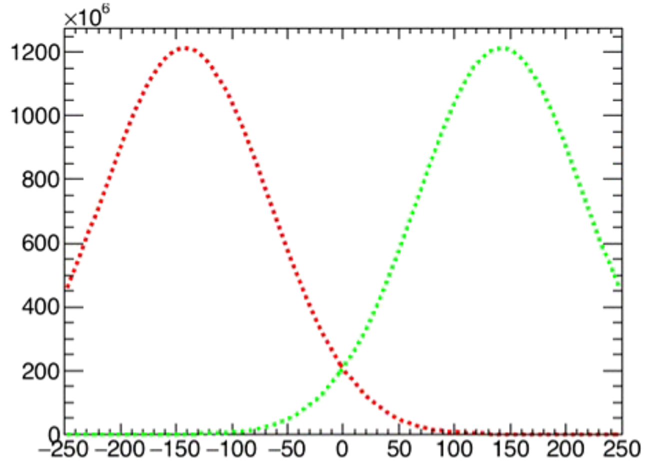


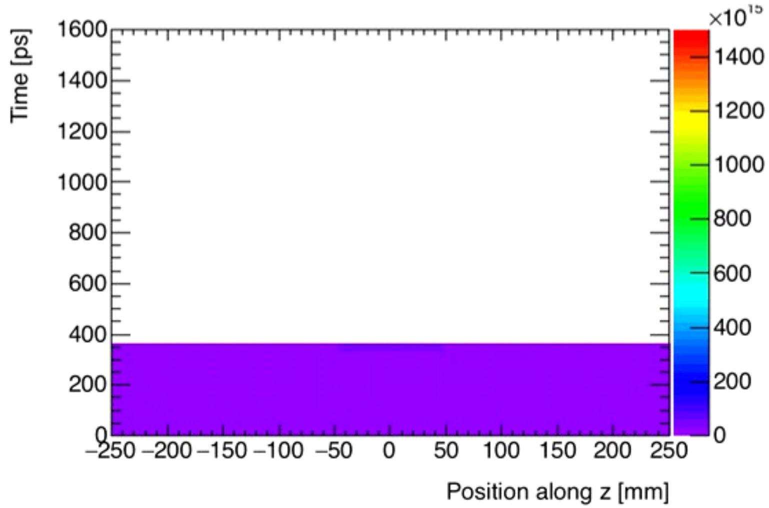


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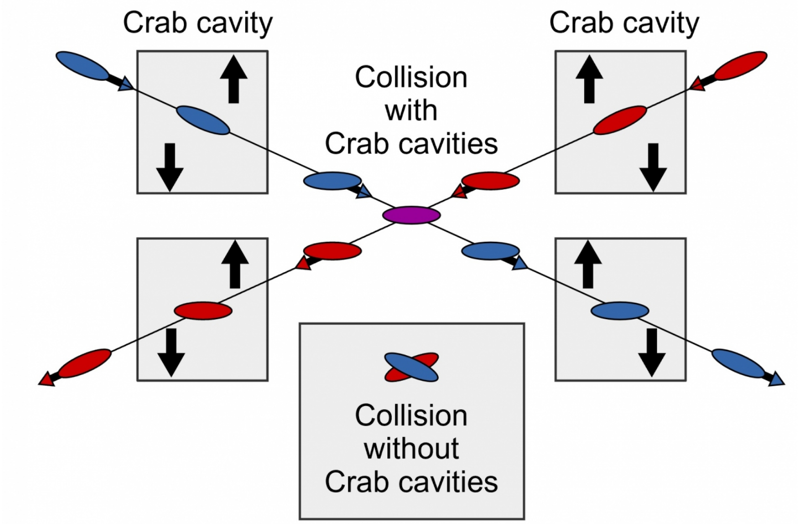

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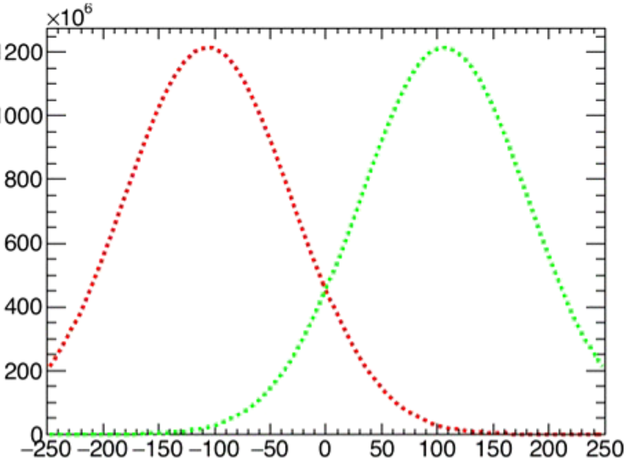


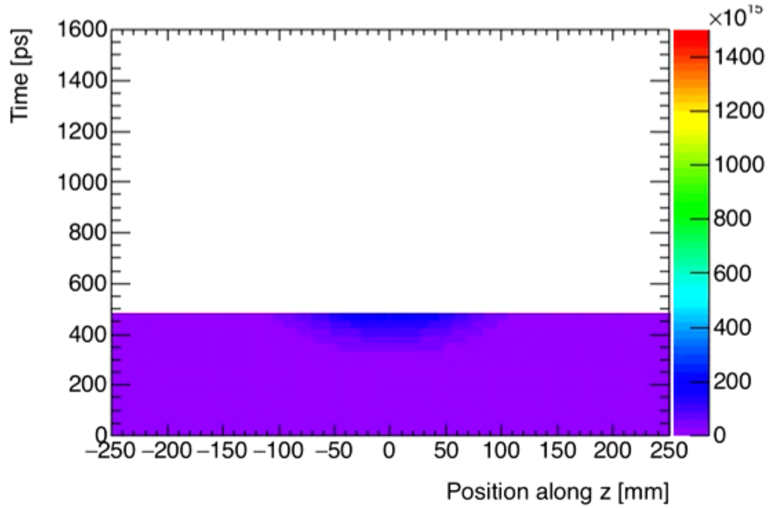


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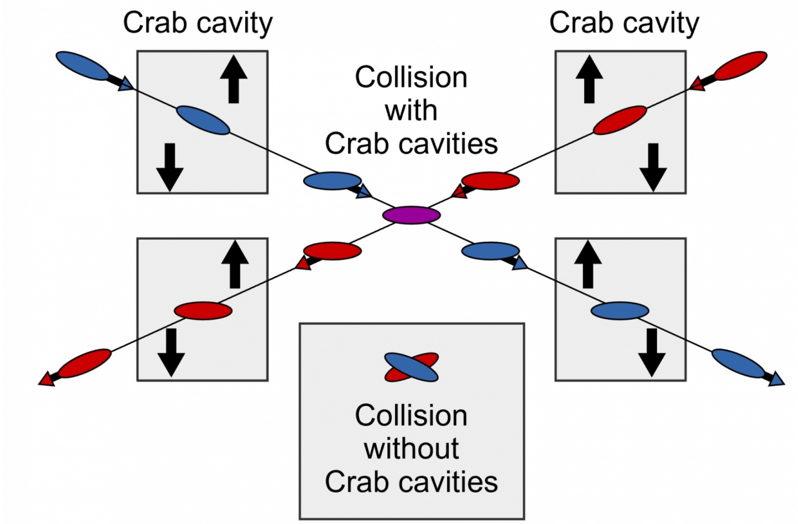

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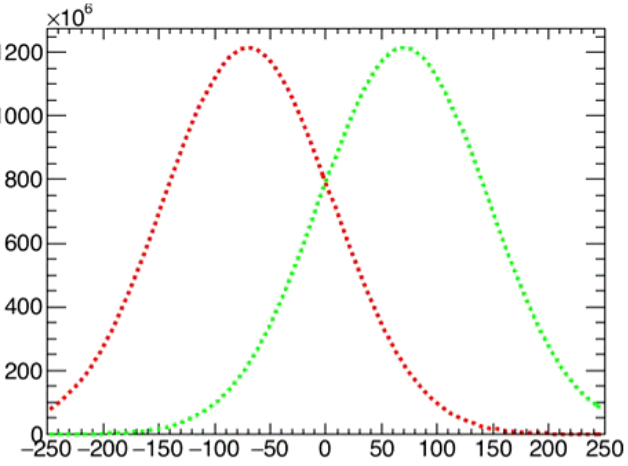


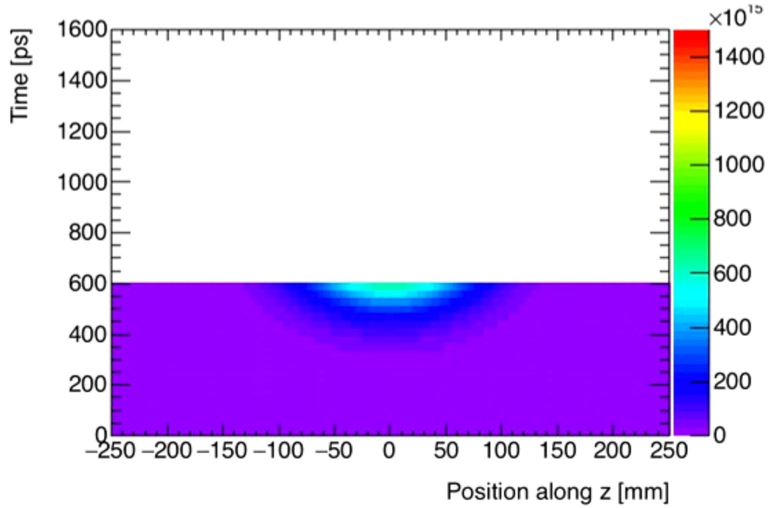


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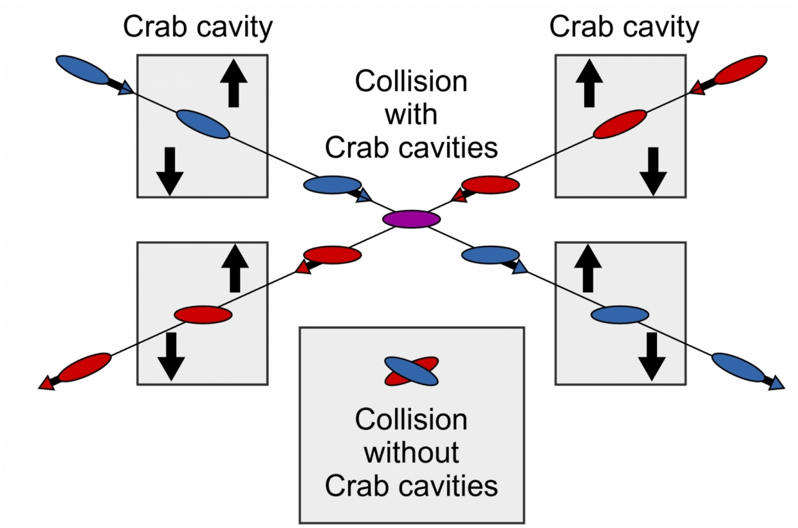

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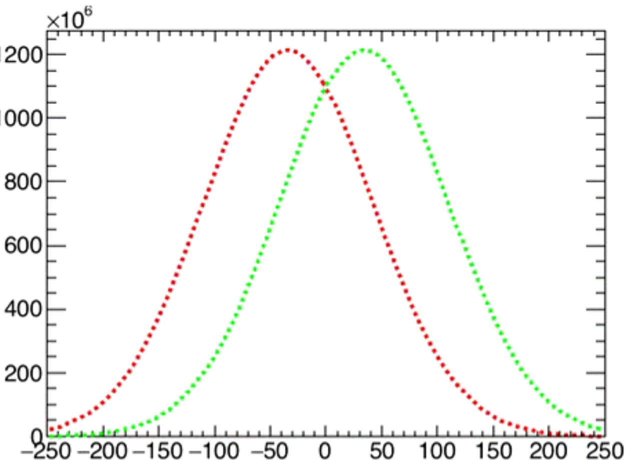


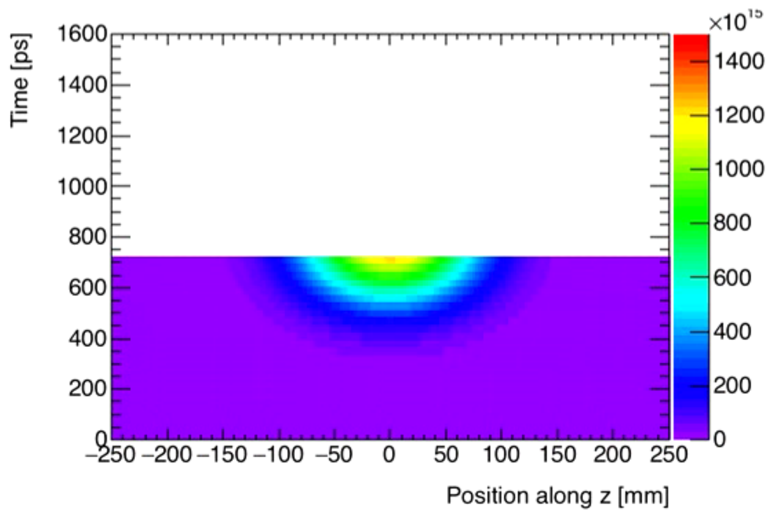


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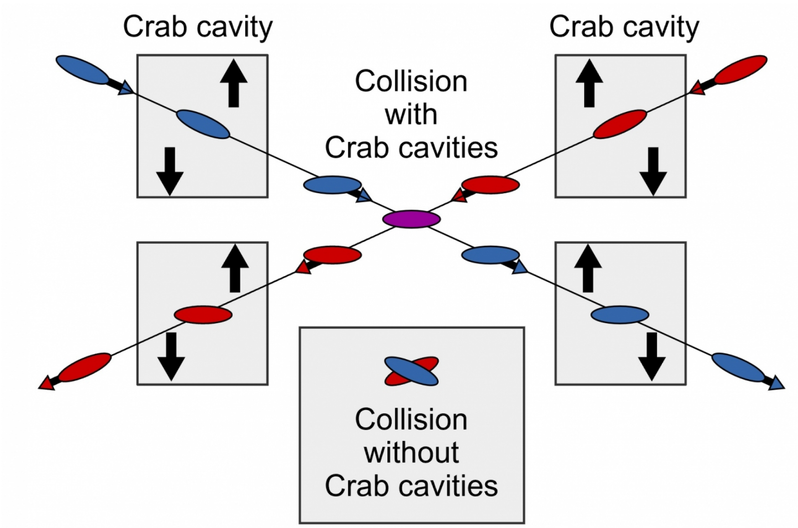

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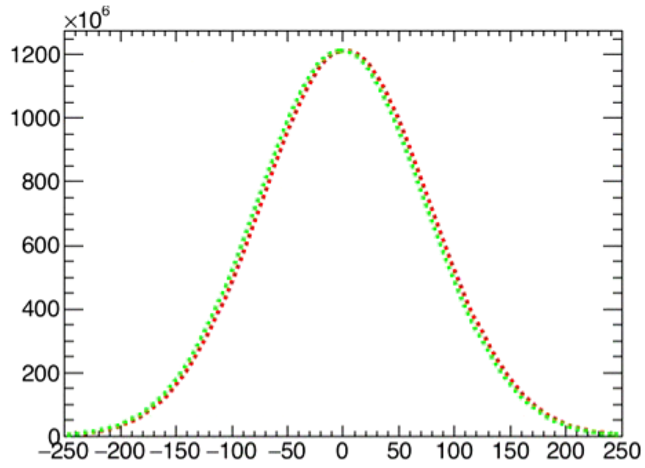


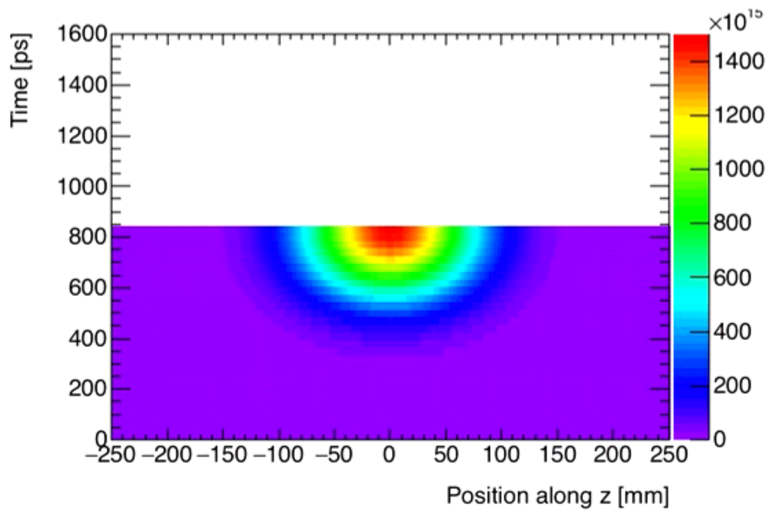


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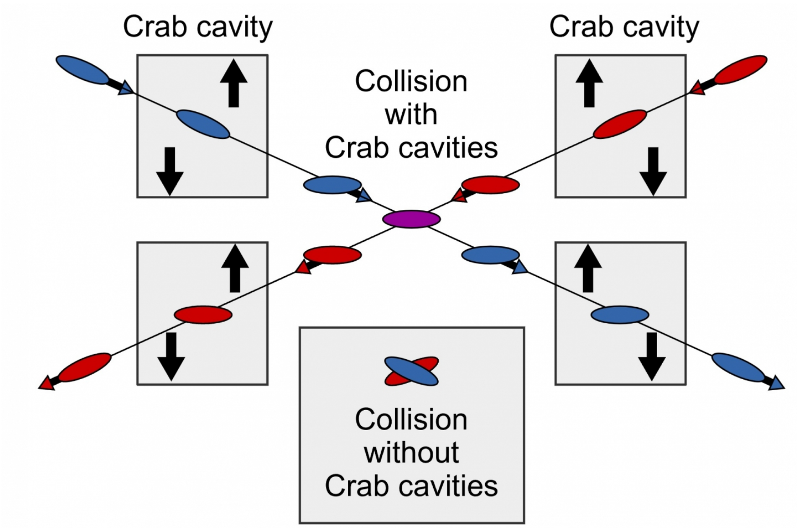

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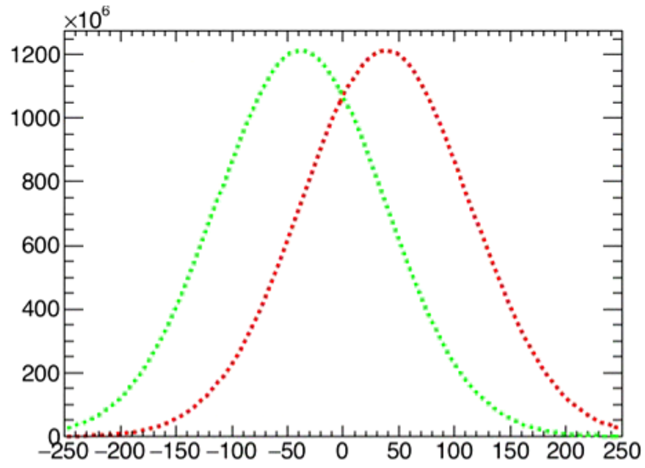


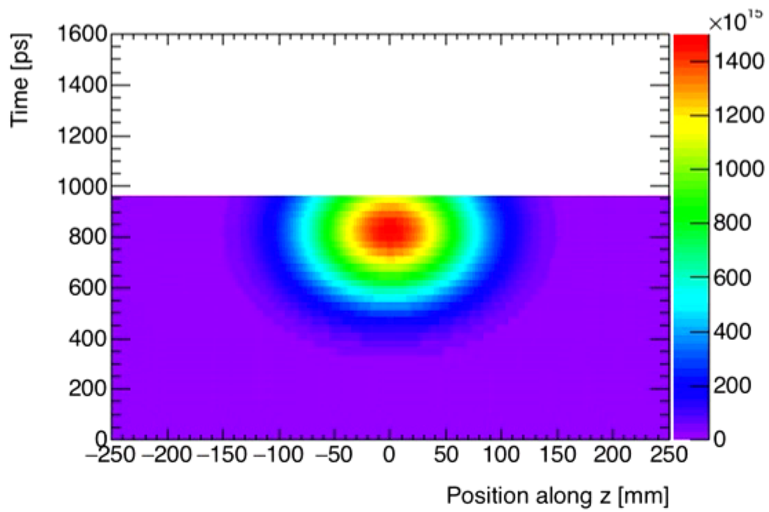


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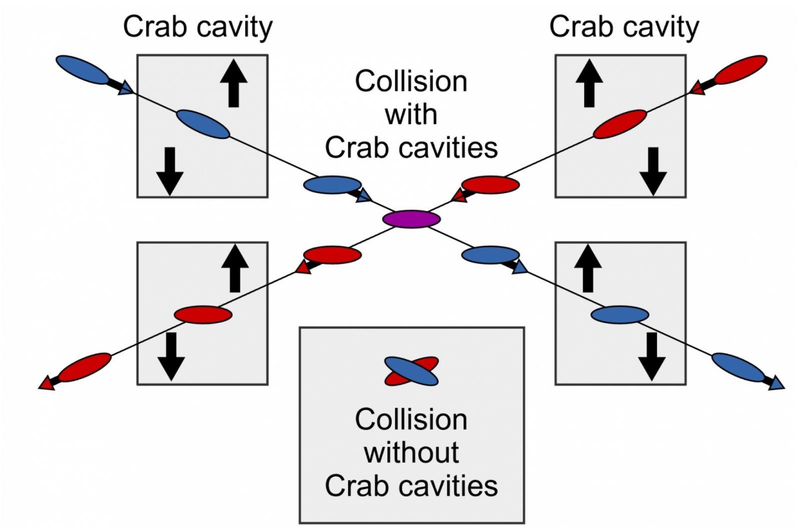

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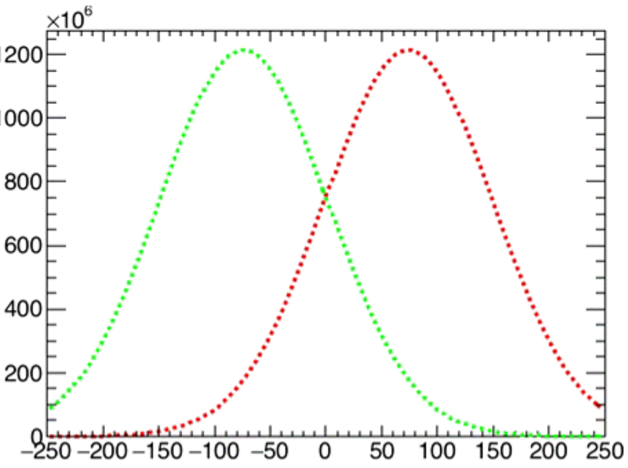


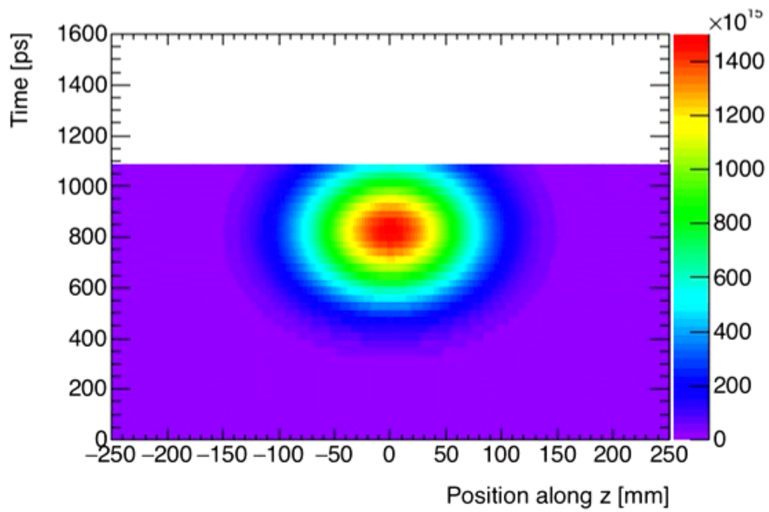


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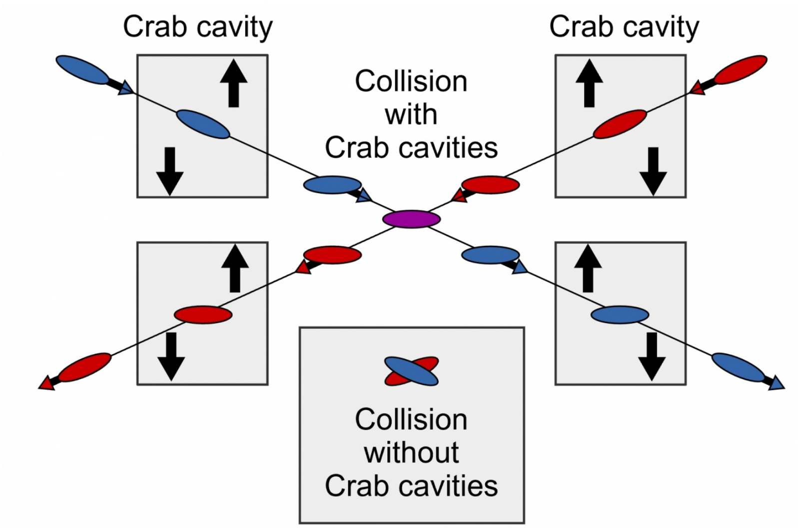

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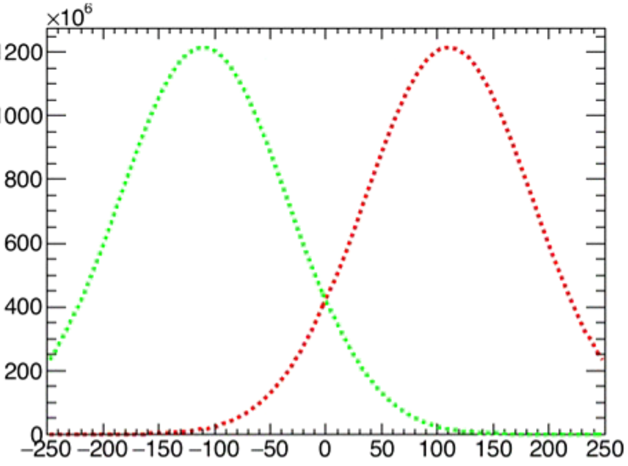


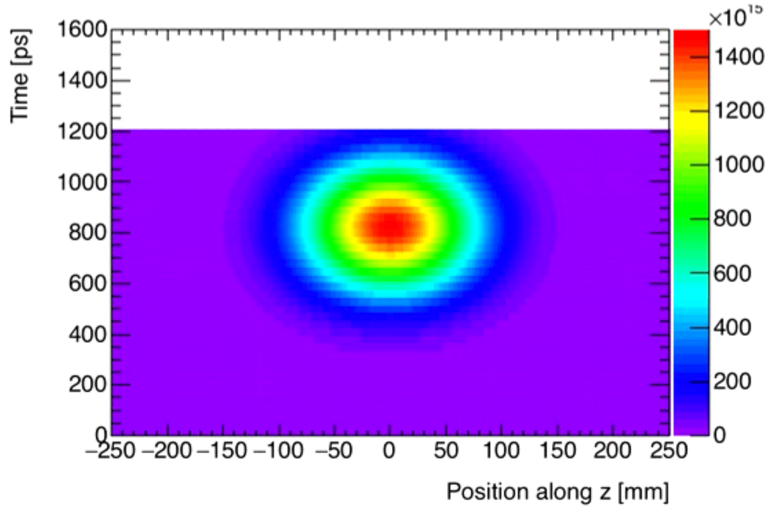


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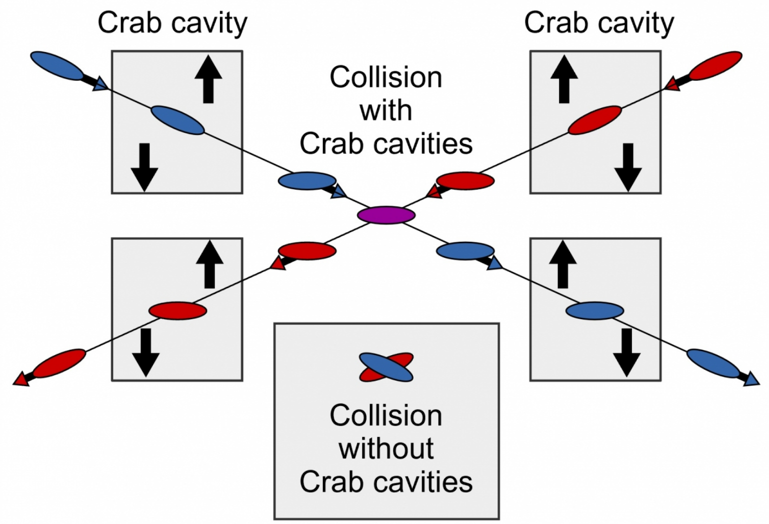

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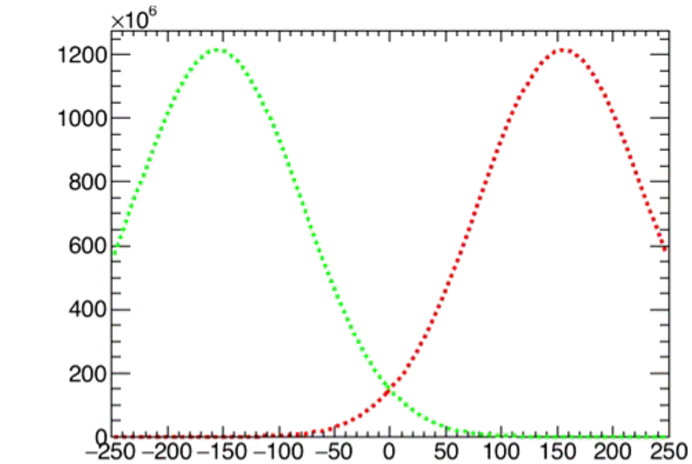


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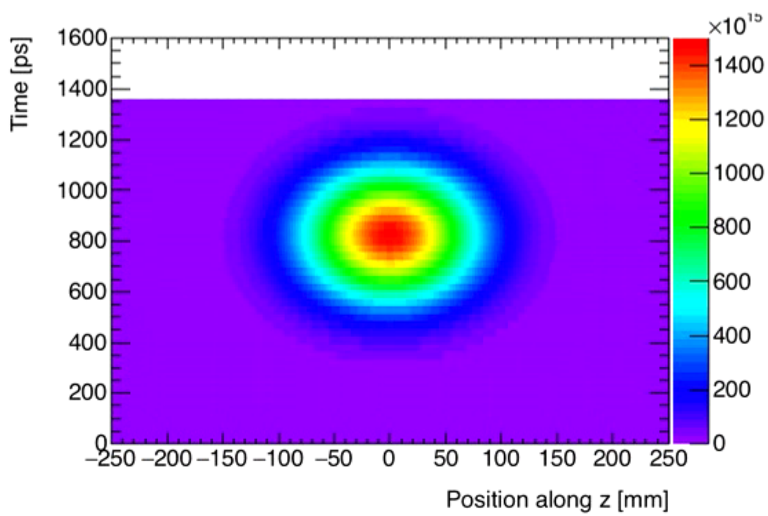


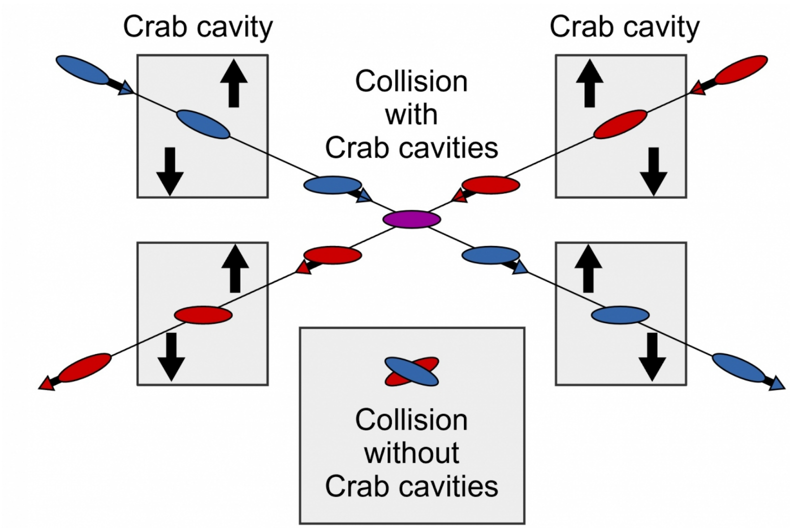

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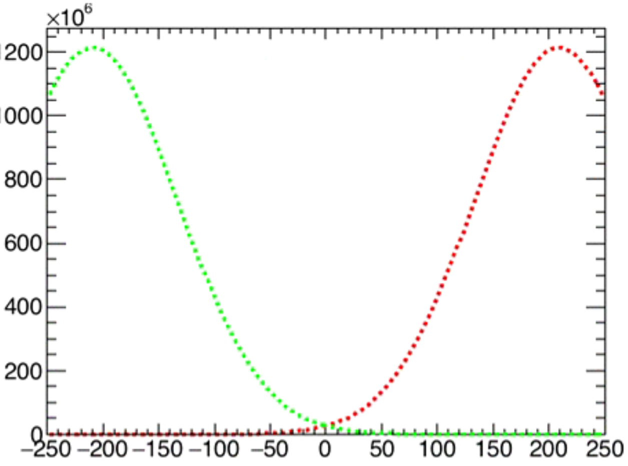


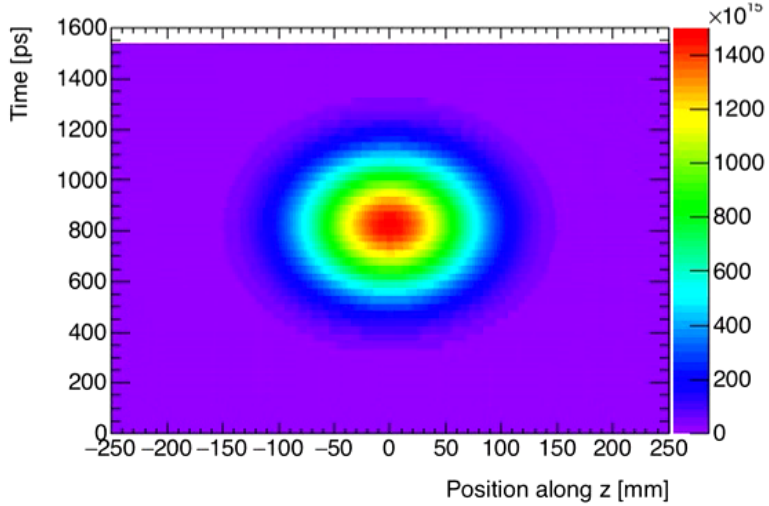


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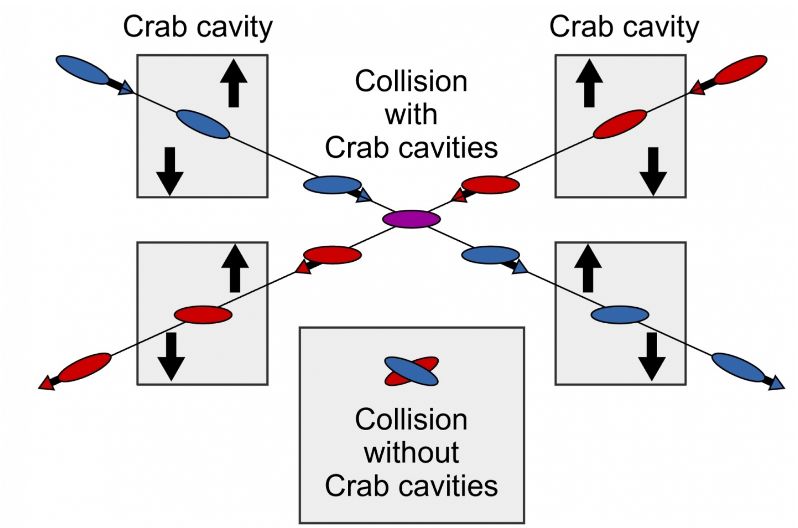
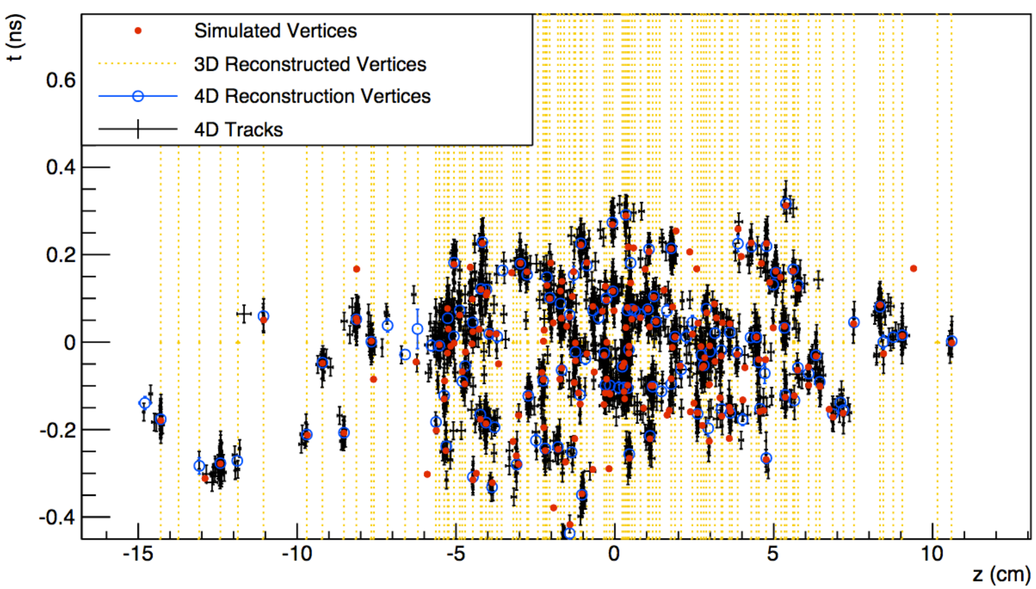
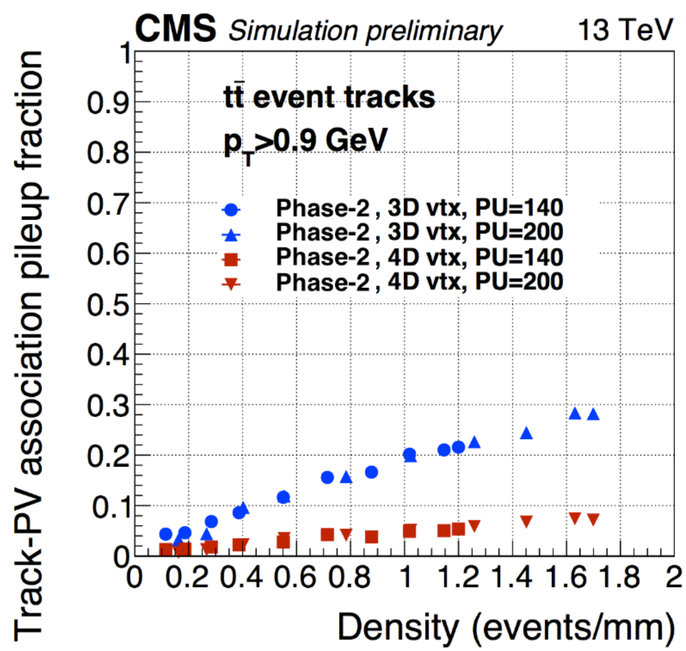


# Removing Pile-up vertices

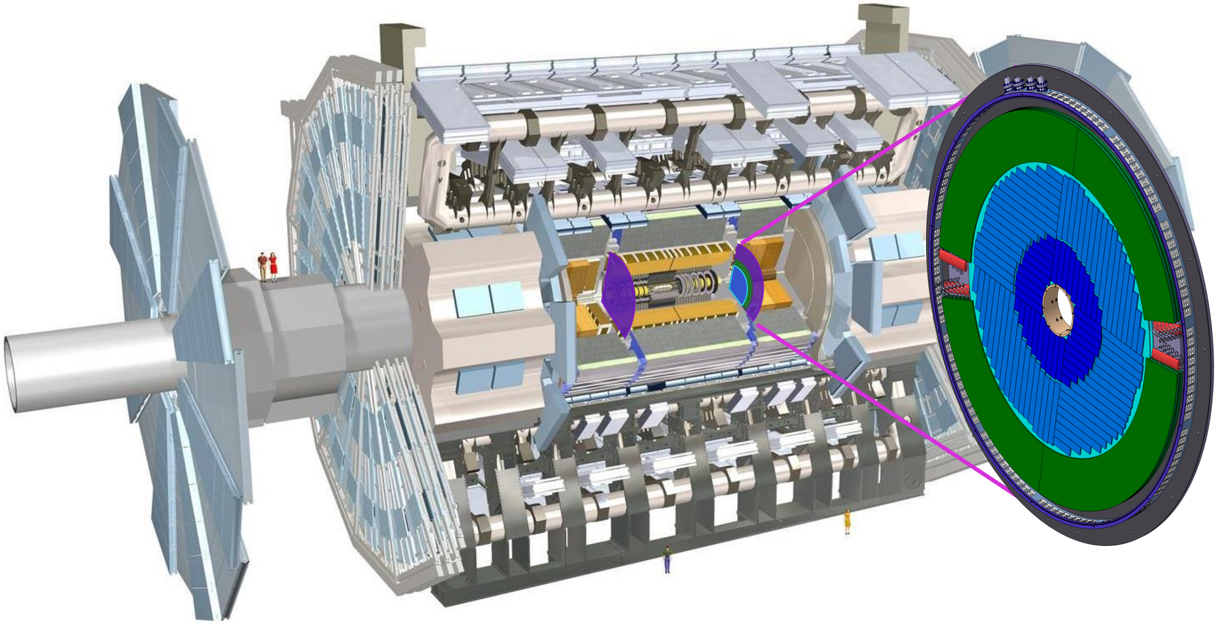
- Vertices are spread in position and time :
  - $\sigma_z$ = 45 mm (≈ 150 ps)
  - $\sigma_t$ = 175 ps
- Some pile-up interaction are merged with the hard scatter one by the tracker

- The use of timing information can be used to separate pile-up and hard scatter
- Limited by the timing resolution and the timing association capability



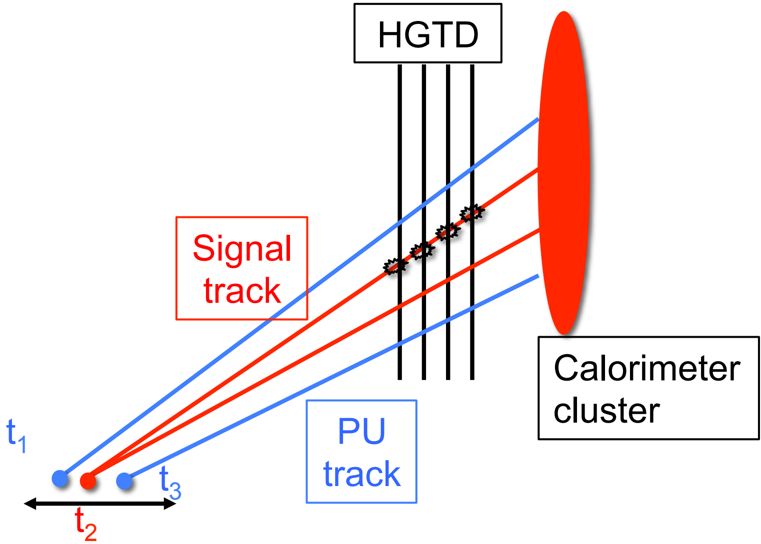



# The High Granularity Timing Detector



**Principle :**

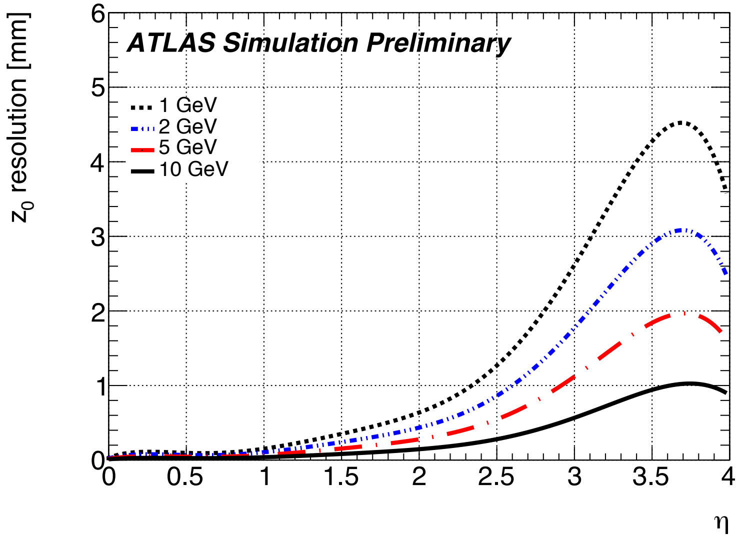
- Tracks extended to the HGTD
- Associated with Hits (time)
- The more hits the better the resolution : $Track_{res} = \frac{Hit_{res}}{\sqrt{N}}$
- 30 ps resolution per track before irradiation
  50 ps at the end of life




**HGTD :**

- In both endcap of ATLAS (z= ±3.5 m)
- Cover : 120 < r < 640 mm (2.4 < |η| < 4)
- 2 double sided-layer per endcap
- $1.3 \times 1.3$ mm$^2$ LGAD sensor

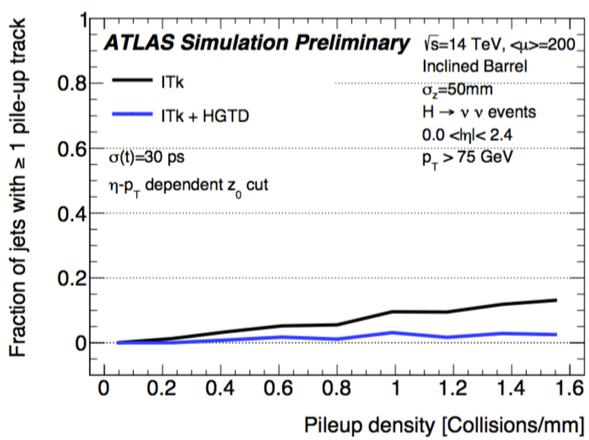
# HGTD motivation

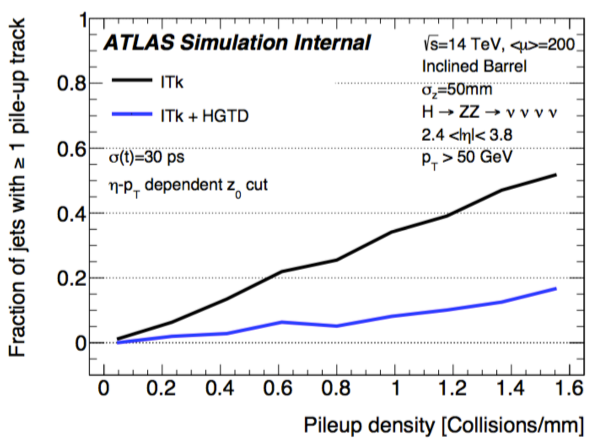



- Resolution of the tracker worst in the forward region (order of the mm)
- High PU density (1.4 vertices/mm)
- High likelihood of having a PU vertices merged with the signal vertex
- Could be complemented by time information to separate PU track from signal one
- Negligible impact in the forward region

$$\frac{z_0 - z_{vertex}}{\sigma_{z_0}} < 2$$

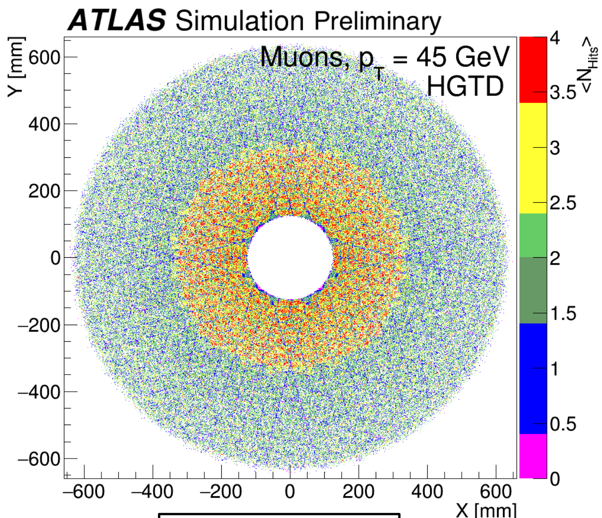
$$\frac{t - t_{vertex}}{\sigma_t} < 2$$

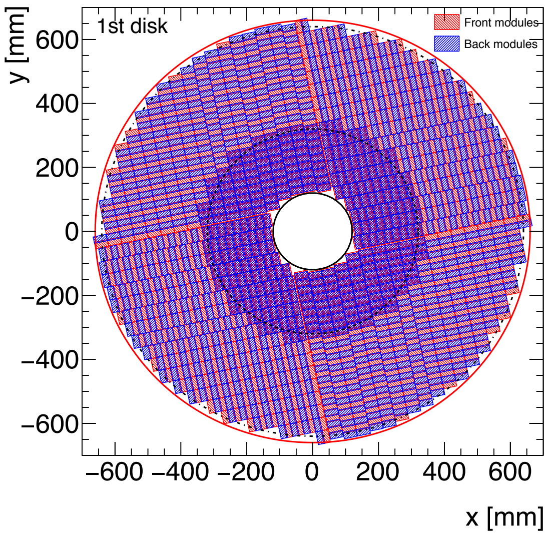


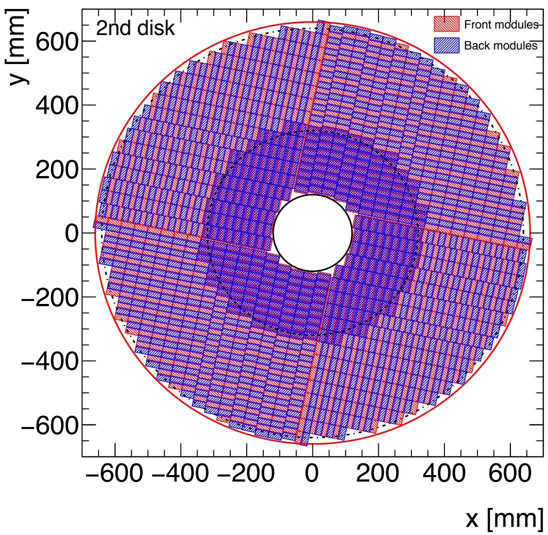



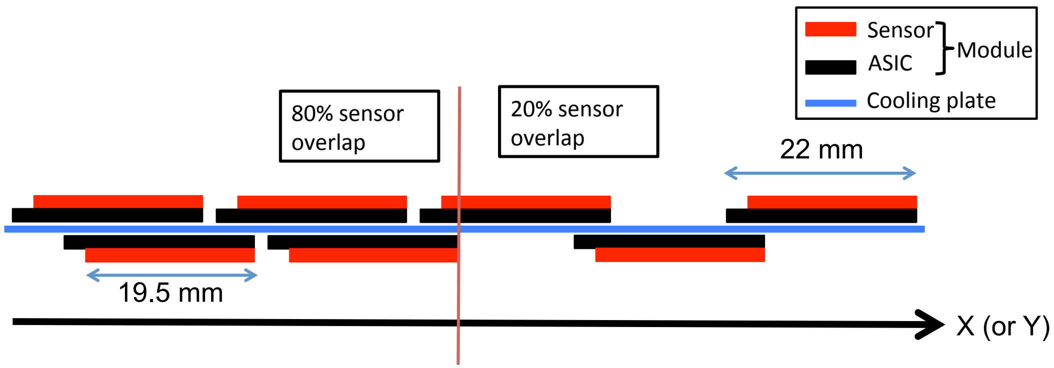
# HGTD layout

- To maximise the resolution of the HGTD the number of hit associated to each track need to be maximize
- 2 double sided-layer per endcap : from 0 to 4 hit per track
- More module in the inner region to compensate the larger radiation
- Layout optimised to maximise the efficiency

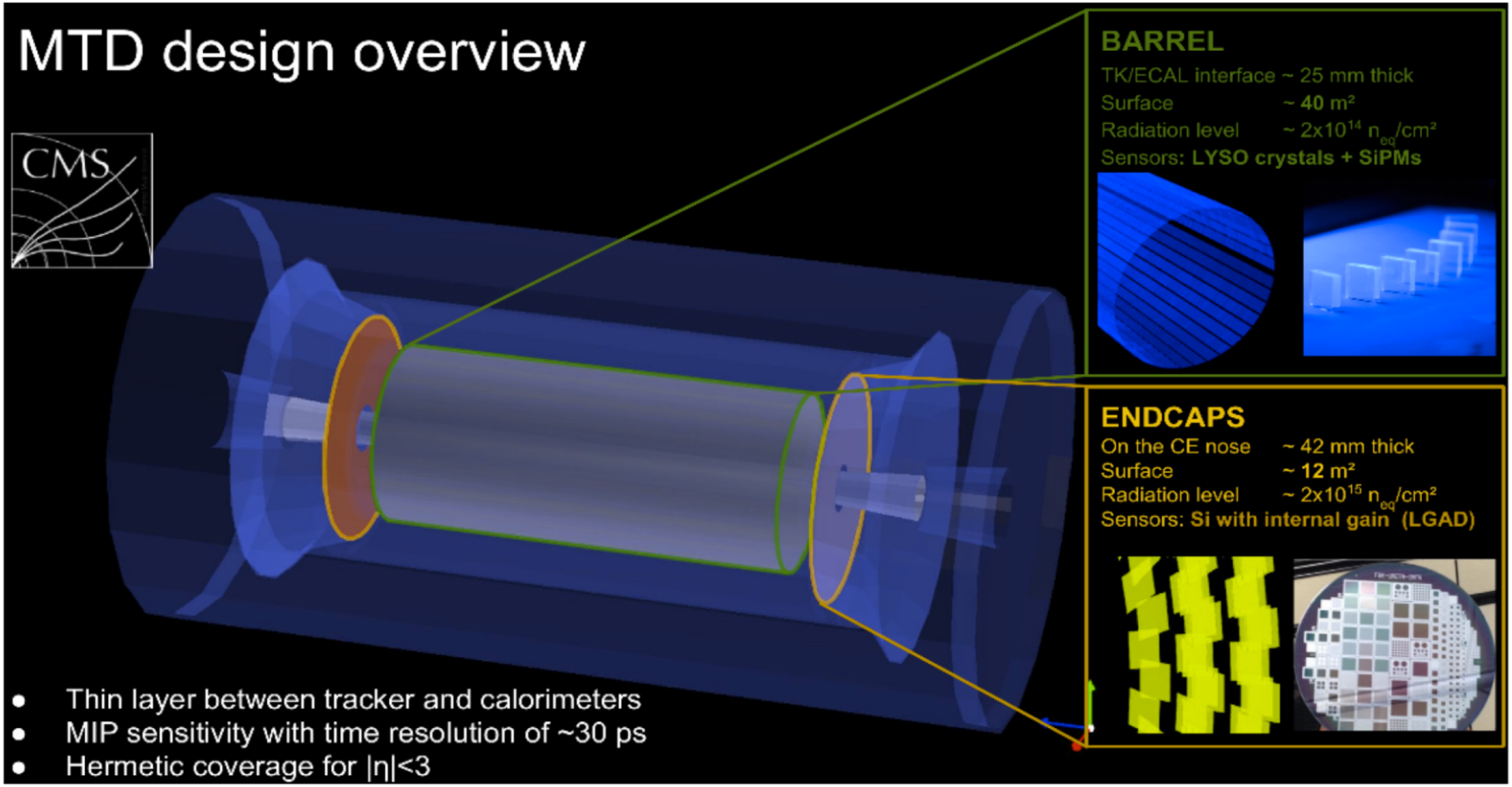


# MIP Timing Detector



# MIP Timing Detector

**Barrel :**

- LYSO crystal + SIPM (similar to calorimeter)
- Layer built at the end of the tracker
- Less radiation than the forward region

**Endcap :**

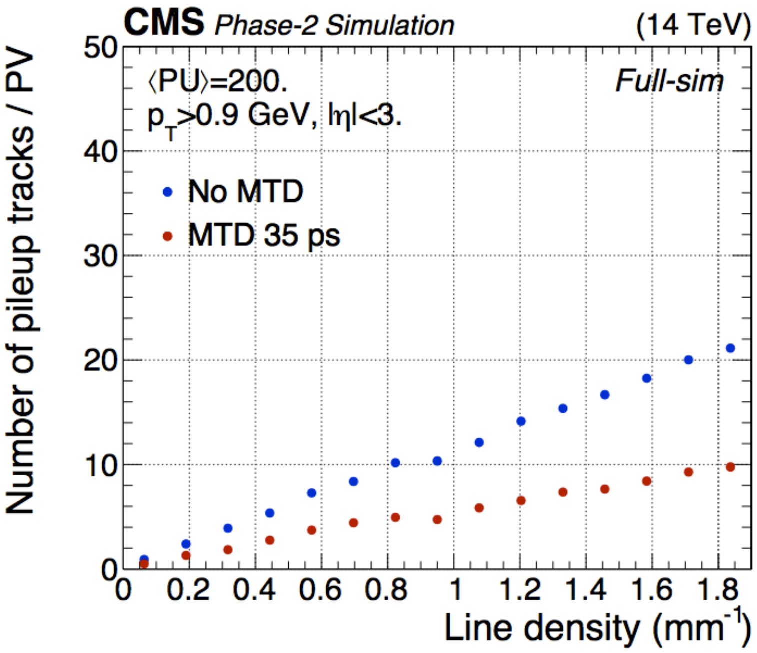
- LGAD (similar to ATLAS HGTD)
- Single layer between the tracker and calorimeter
- High radiation dose

- Fewer layers : worst timing resolution and efficiency
- Full timing coverage : Easier to reconstruct vertices times

| | Barrel<br>LYSO+SiPM | Endcap<br>LGAD |
|---|---|---|
| Coverage | $\|\eta\| < 1.5$ | $1.5 < \|\eta\| < 3.0$ |
| Surface Area | $\sim$ 40 $m^2$ | $\sim$ 12 $m^2$ |
| Power Budget | $\sim$0.5 kW/$m^2$ | $\sim$1.8 kW/$m^2$ |
| Radiation Dose | $\leq$ 2e14 neq/$cm^2$ | $\leq$ 2e15 neq/$cm^2$ |
| Installation Date | 2022 | 2024 |

# MTD motivation

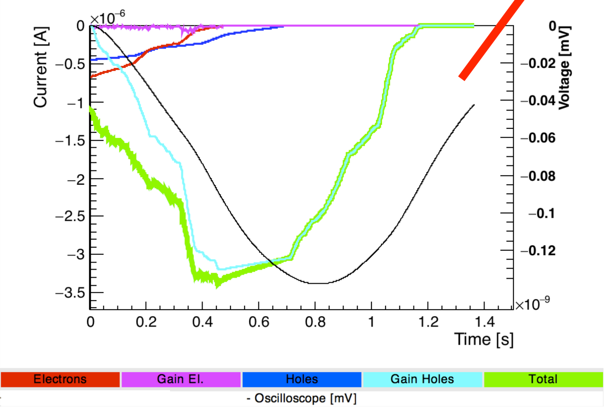
- CMS rely on a Particle flow algorithm : information from the different subdetector are combined to fully reconstruct the events
- Time information significantly improve such algorithm by providing a way to determine if track are from PU or HS
- CMS calorimeter is also capable of achieving a time resolution of the order of 100-150 ps, the timing can thus help associate tracks to calorimeter cluster



# Time resolution

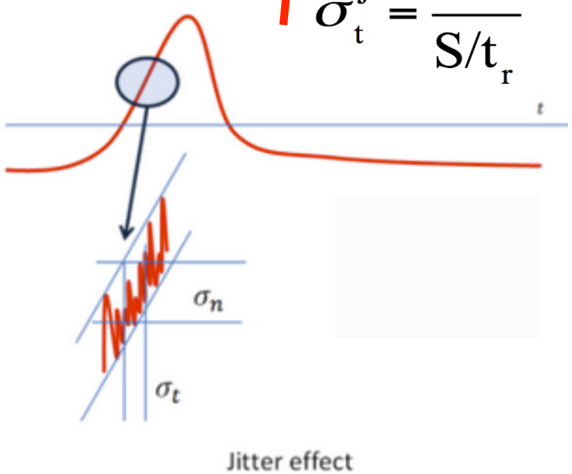
$$\sigma^2_{\text{det}} = \sigma^2_{Landau} + \sigma^2_{jitter} + \sigma^2_{TW} + \sigma^2_{TDC}$$

Binning of the electronic



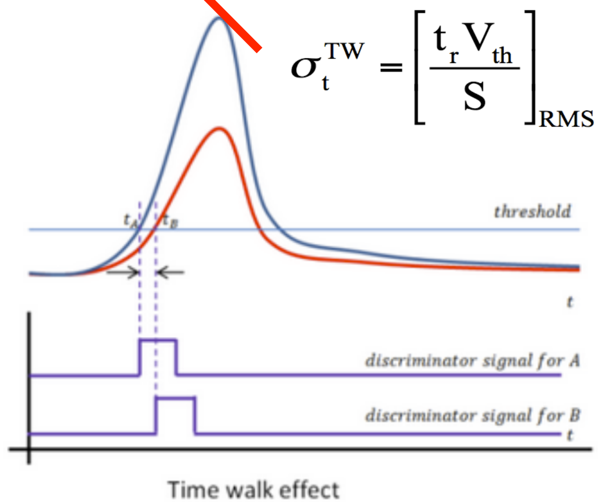

- Energy deposit in the sensor change the pulse shape
- Uncertainty on the reconstructed time

$$\sigma_t^J = \frac{N}{S/t_r}$$




Noise affect the reconstructed time

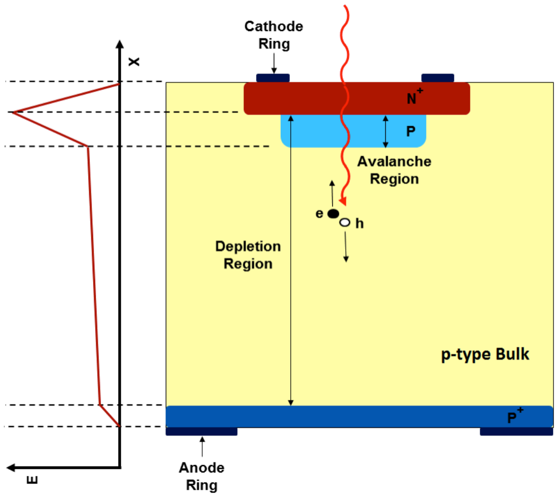
$$\sigma_t^{TW} = \left[\frac{t_r V_{th}}{S}\right]_{RMS}$$




Reconstructed time change with the amplitude of the pulses

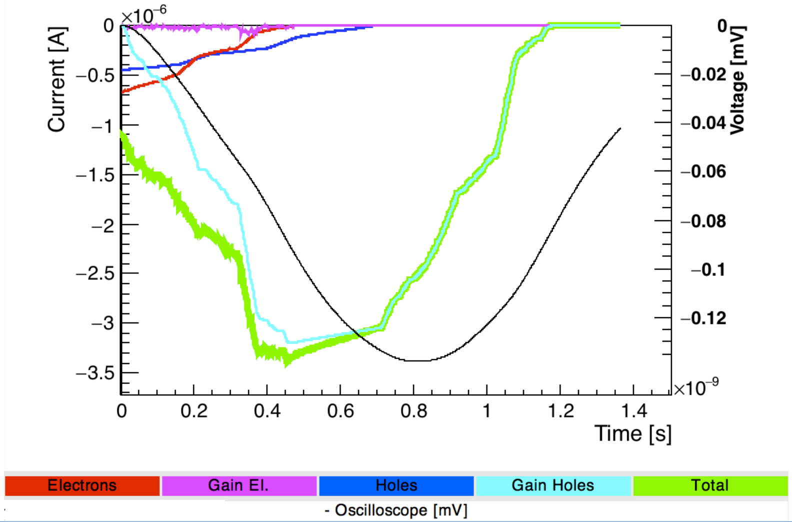
# Technology to measure time

## Gain -> Good timing resolution




LGADs : ATLAS and CMS forward timing

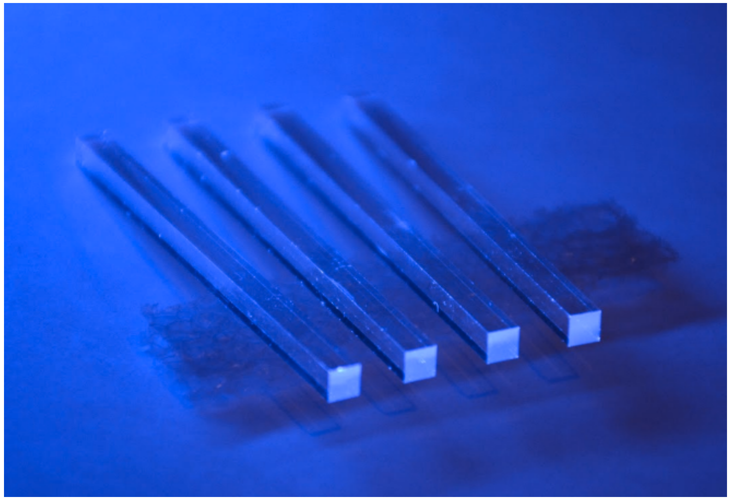
- Relatively new technology
- Lots of R&D still on going
- Si sensors : particle create $e^-$ / hole pairs, they drift through the sensor
  **->** signal
- LGAD sensors : Same but the $e^-$ go through a high E field -> showering -> **gain**




- Gain of the order of 10-15 -> time resolution of ~30 ps
- Good radiation resistance, loss of resolution with the dose received

# Technology to measure time

## Gain -> Good timing resolution

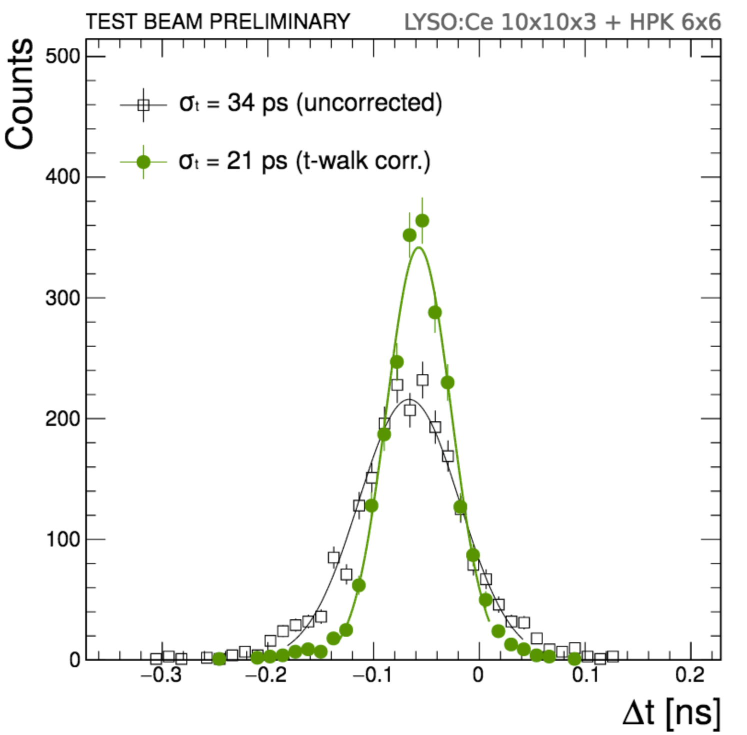


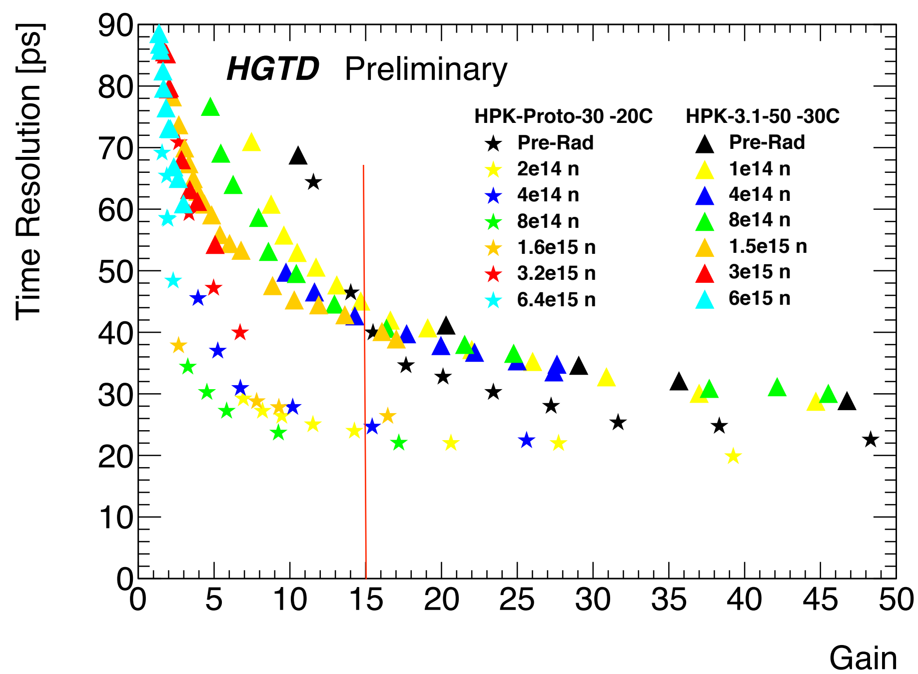
LYSO crystal + SIPM

- Crystal : produce photons when particles go through them
- SIPM : Multiply the number of photon (gain) and collect them to create a signal
- Already used in CMS calorimeters
- Can provide a resolution of ~40 ps
- Less radiation resistant

# Resolution

- ATLAS and CMS have study extensively the resolution of their sensor in different test beam campaign
- Good resolution of 30 ps have been shown to be achievable pre-irradiation
- After irradiation the resolution worsen up to 50-60 ps



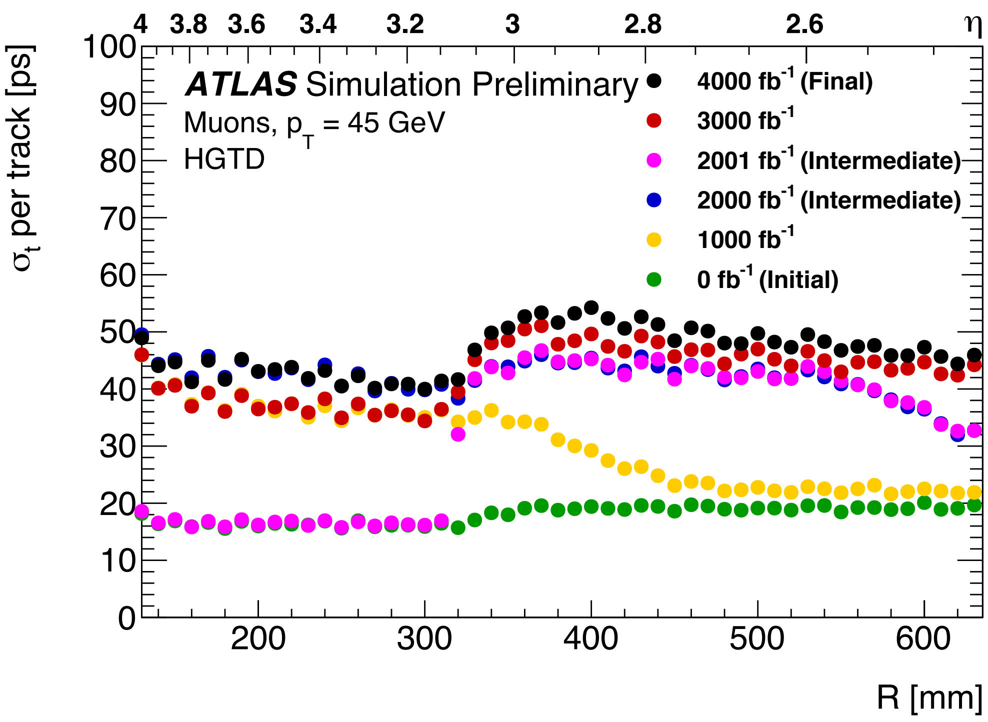



# Resolution in the detector

- The more hits from the timing detector associated with the track the better the resolution of the tracks
- The reconstruction algorithm used to associate the hits to the tracks thus has a major impact on the performances

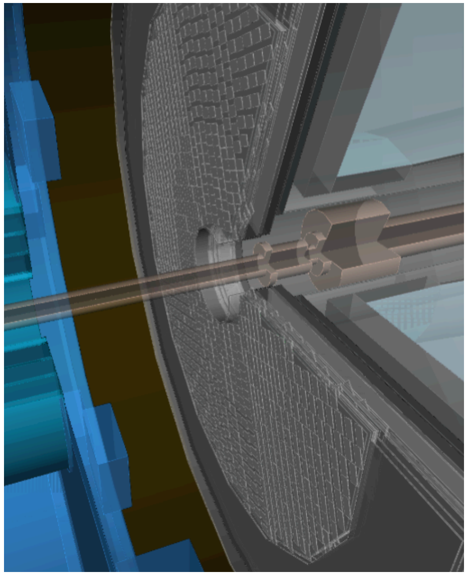
**Two approaches :**

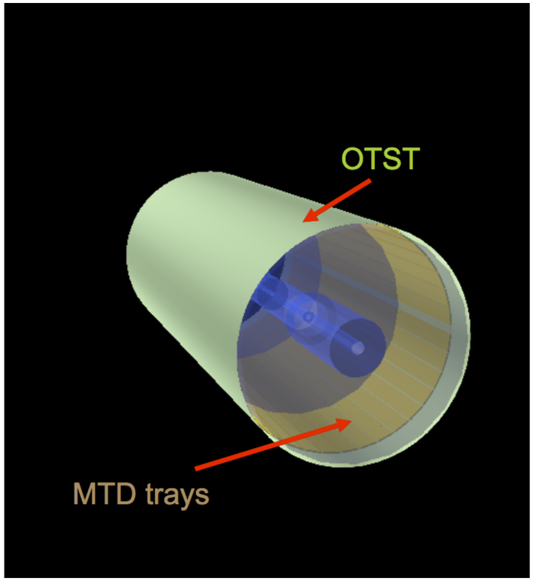
- The times of the tracks can be compared with each other (track to track)
- Tracks can be used to reconstruct global $t_0$ time (vertex to track)

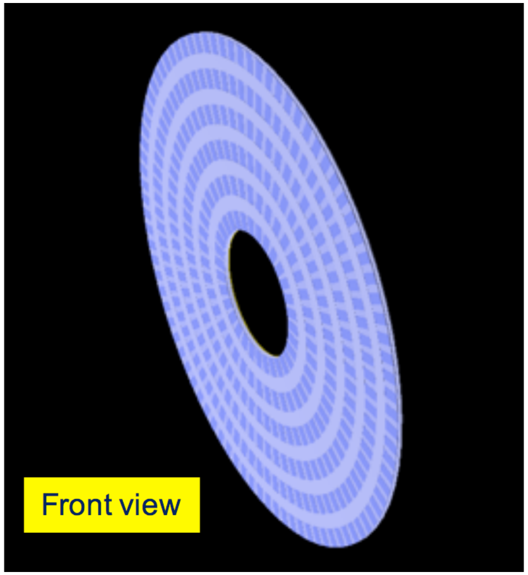


# Impact of the timing detector

- Both ATLAS and CMS studied the impact on such detector on the performances using simulation
- Most reconstruction algorithms were not reoptimized for those studies better improvement could be expected with smarter algorithm





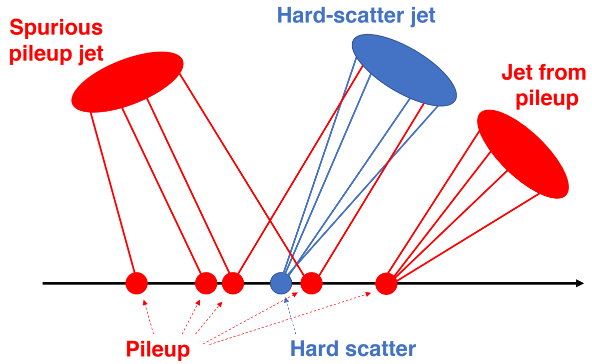



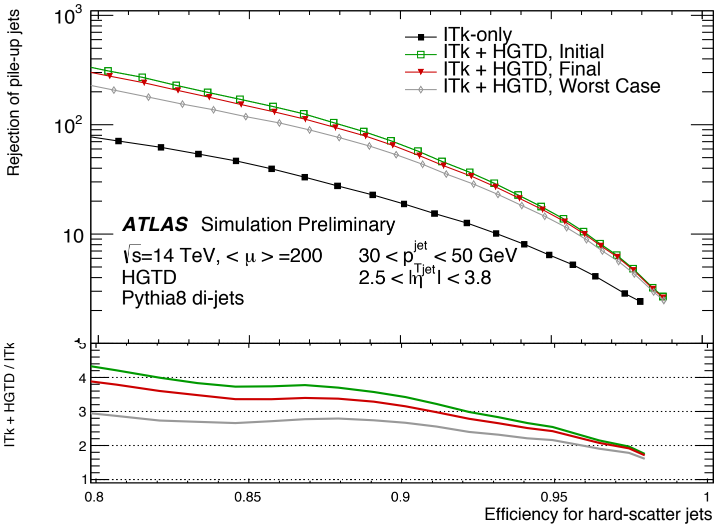
# Pile-up jet rejection

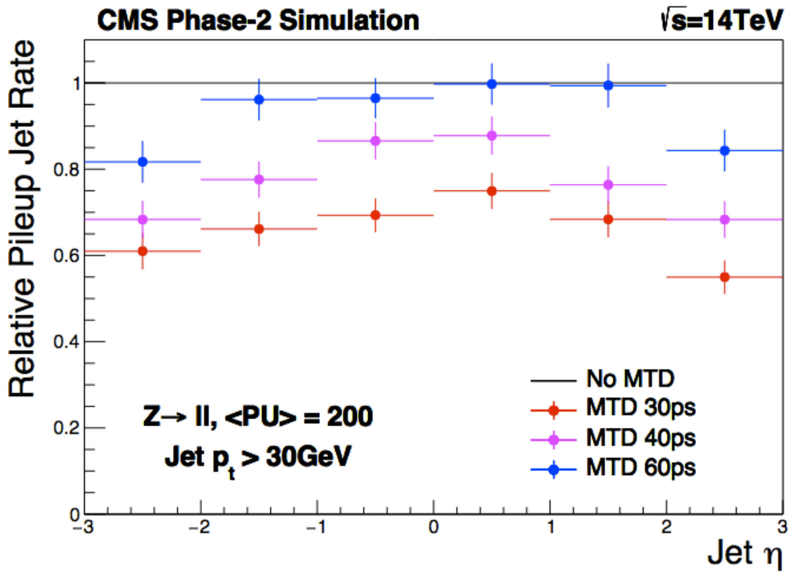
- Improved by the time information

- ATLAS : Rejection of PU jets based on ratio of $p_T$ (tracks) and $p_T$ (jet)
- Removing out of time tracks improve the algorithm

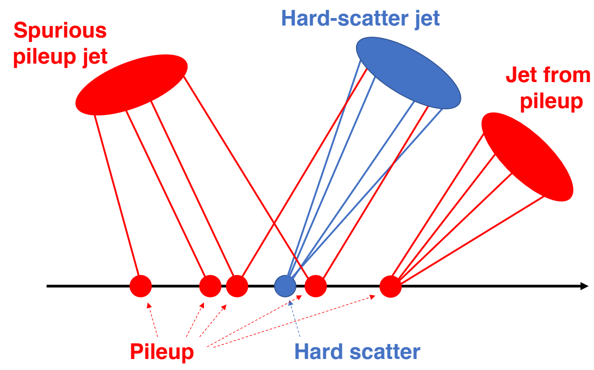
- In CMS track out of time are removed from the particle flow algorithm
- This also result in a reduction of the number of PU jets

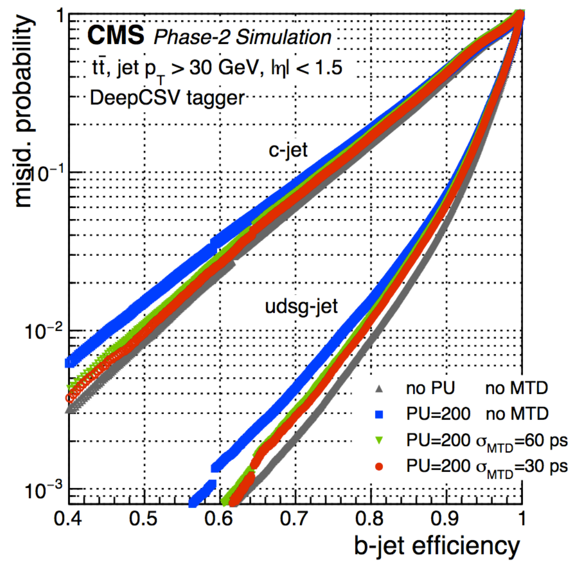


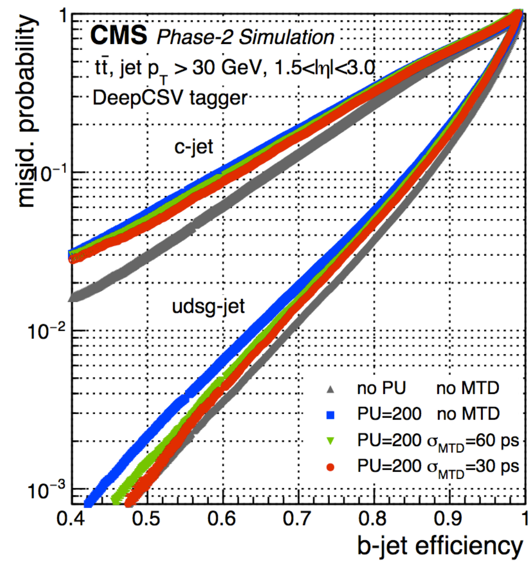



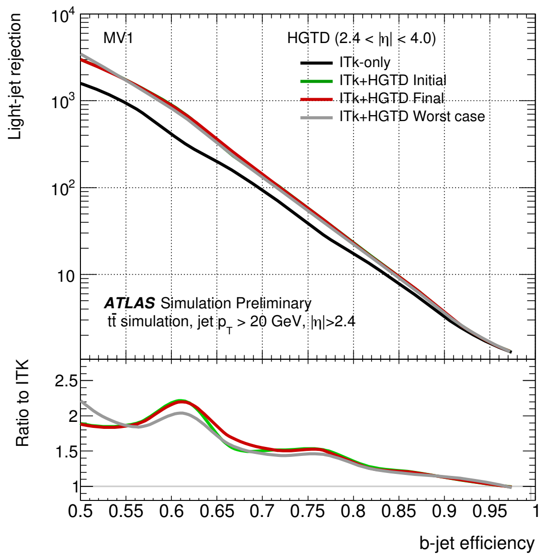
# Heavy flavor tagging



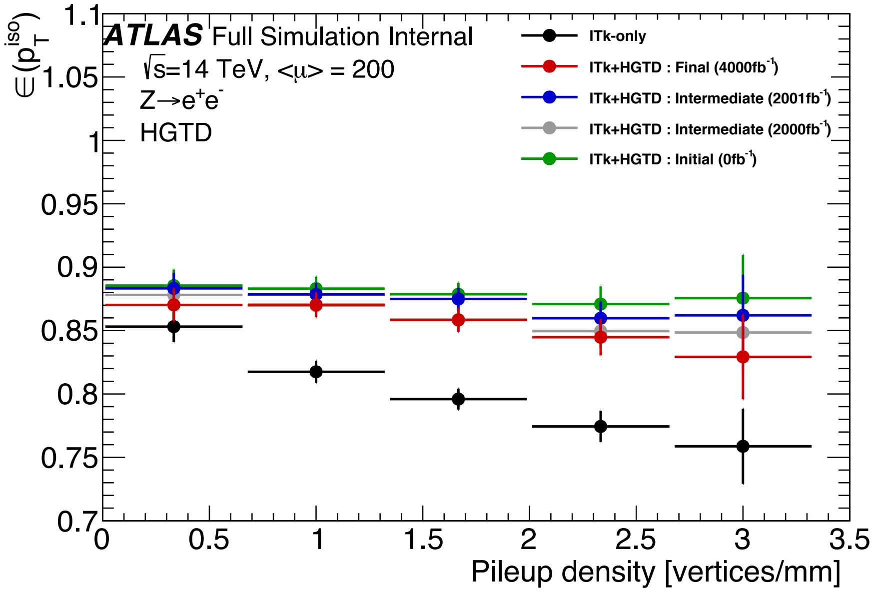




- Identification of heavy flavor quarks improved by time information
- When reconstructing such jets more track are accepted due to the longer lifetime of the b hadron -> more PU jet contamination
- Time help keep the PU contamination low and improve the reconstruction

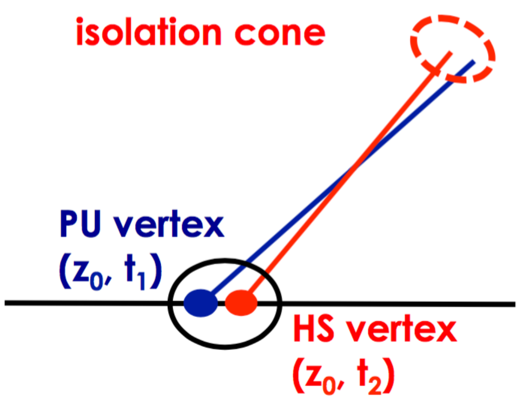


# Electron Isolation




- Track isolation used in many analyses with leptons to fight QCD background
- Isolated lepton -> Lepton that come from the studied process (and not from showering)
- Isolated : with no other track with $p_T > 1$ GeV in $\Delta R < 0.2$

- PU can reduce the Isolation efficiency
- A time compatibility of the close track with the electron track can be added
- Improve the efficiency of such algorithm



# Conclusion

- Time information can greatly improve the performances of the detectors in high pile up environments
- The performance of such detector greatly depend on the reconstruction algorithm
- Different experiment can use timing in different way depending on their needs
- The technology is evolving quiete quickly : Smaller granularity (pixel like), better resolution (1 ps)
- Currently part of their own subdetector but will probably be in the future part of most trackers