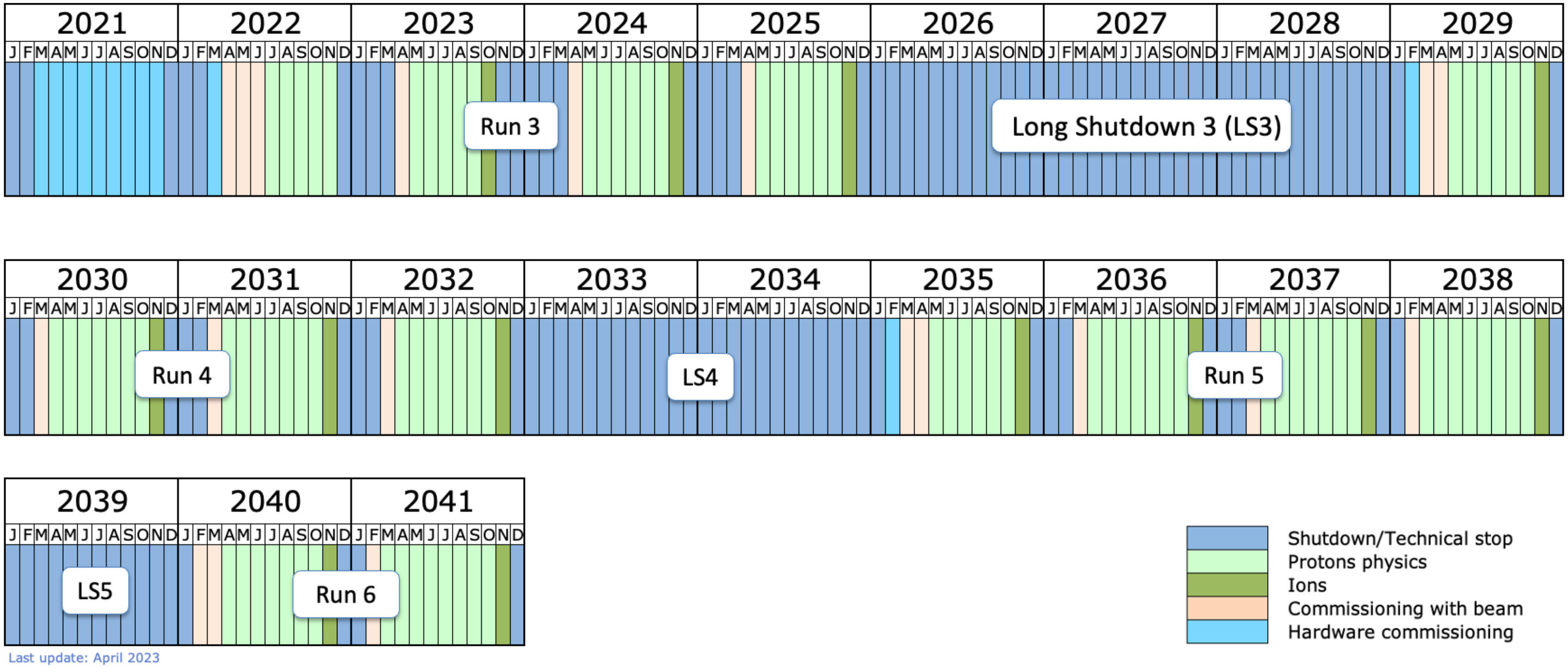
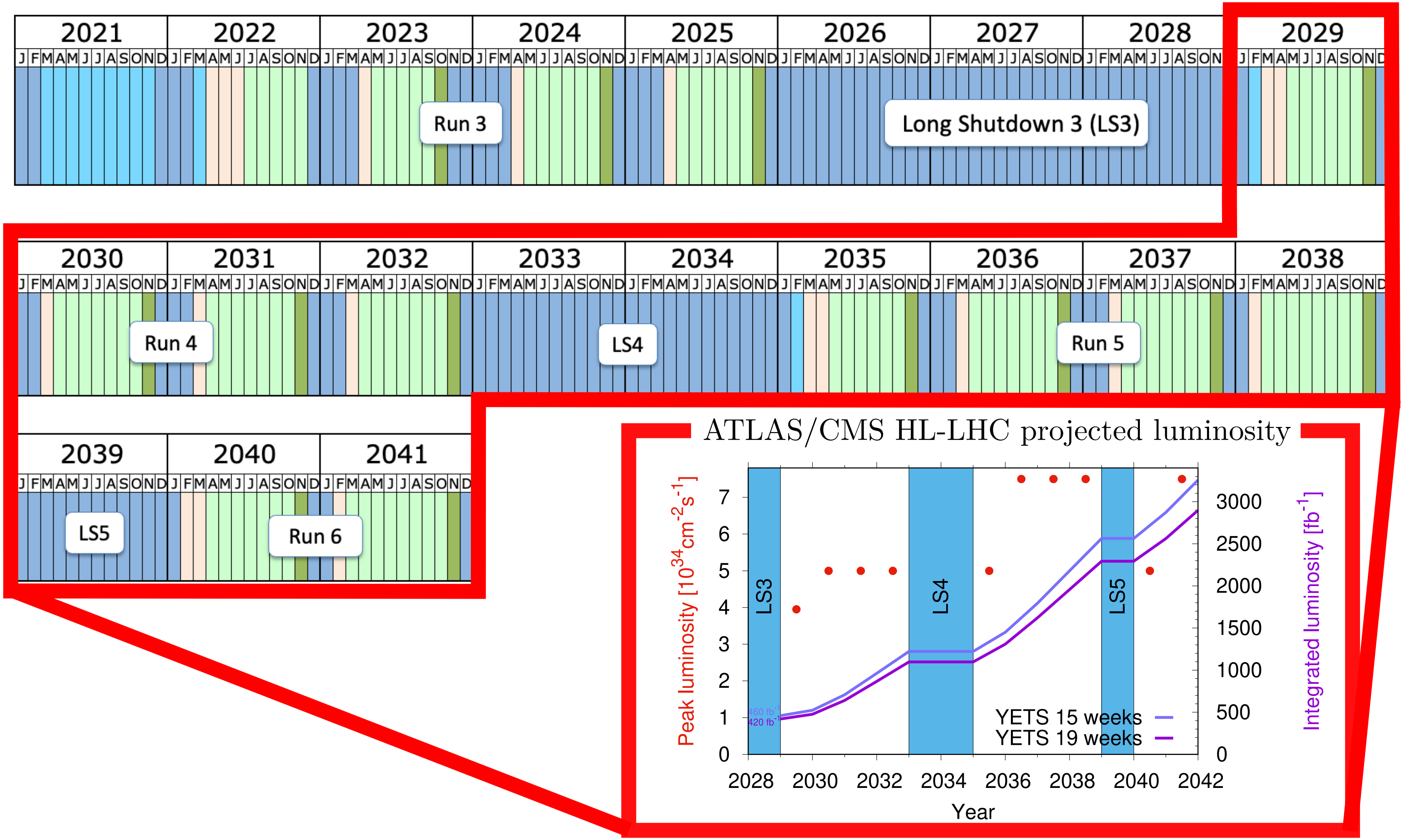
4D tracking and vertexing for future detectors at HL-LHC

Vertex 2023 - 32nd International Workshop on Vertex Detectors

Tim Evans, on behalf of ATLAS, ALICE, CMS & LHCb collaborations


2021 2022 2023 2024 2025 2026 2027 2028 2029
Run 3
Long Shutdown 3 (LS3)
2030 2031 2032 2033 2034 2035 2036 2037 2038
Run 4
LS4
Run 5
2039 2040 2041
LS5
Run 6
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning
Last update: April 2023


2021
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2036
2037
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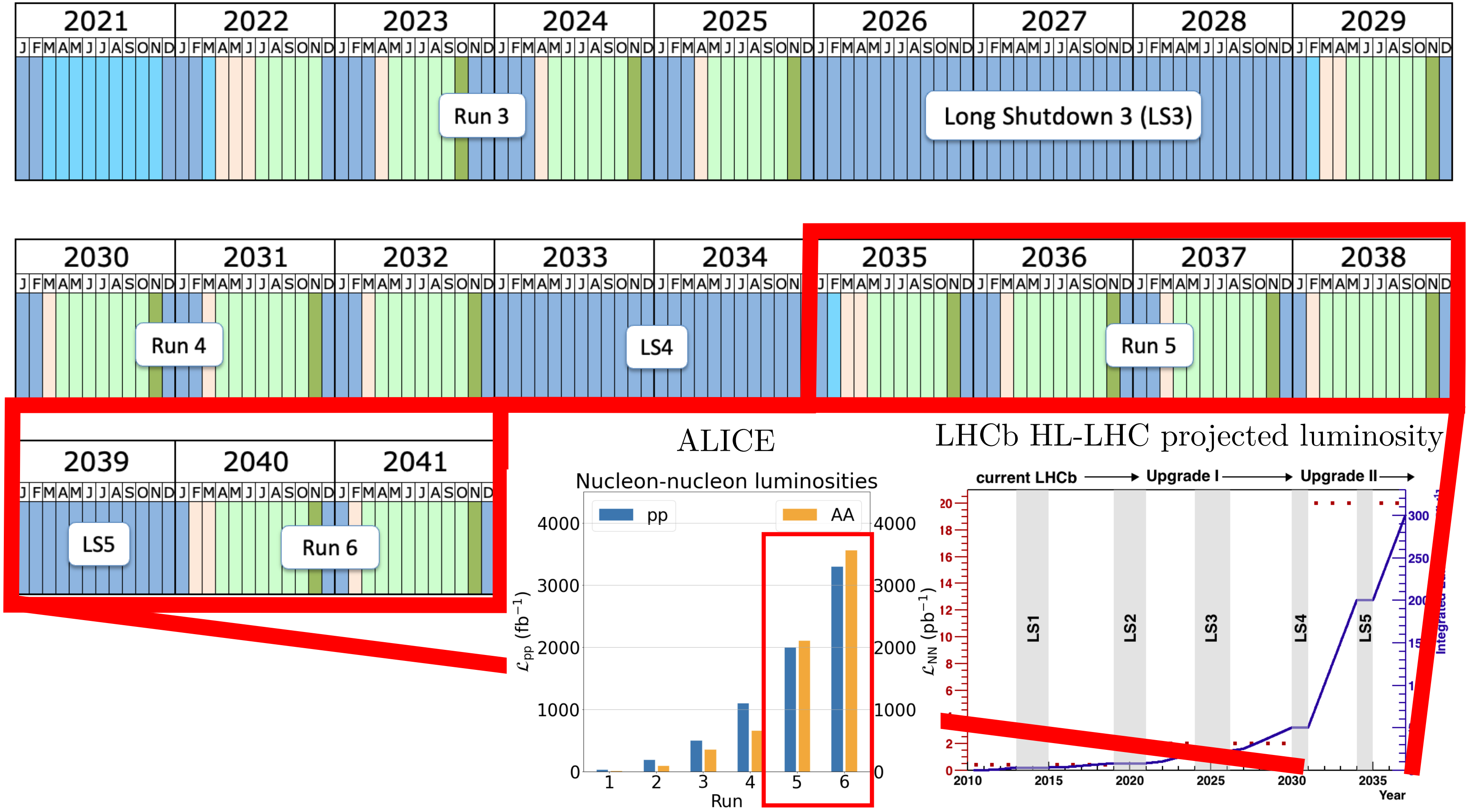
Run 4
LS4
Run 5
2039
2040
2041
LS5
Run 6
ATLAS/CMS HL-LHC projected luminosity
Peak luminosity [10^34 cm^-2 s^-1]
Integrated luminosity [fb^-1]
LS3
LS4
LS5
YETS 15 weeks
YETS 19 weeks
Year



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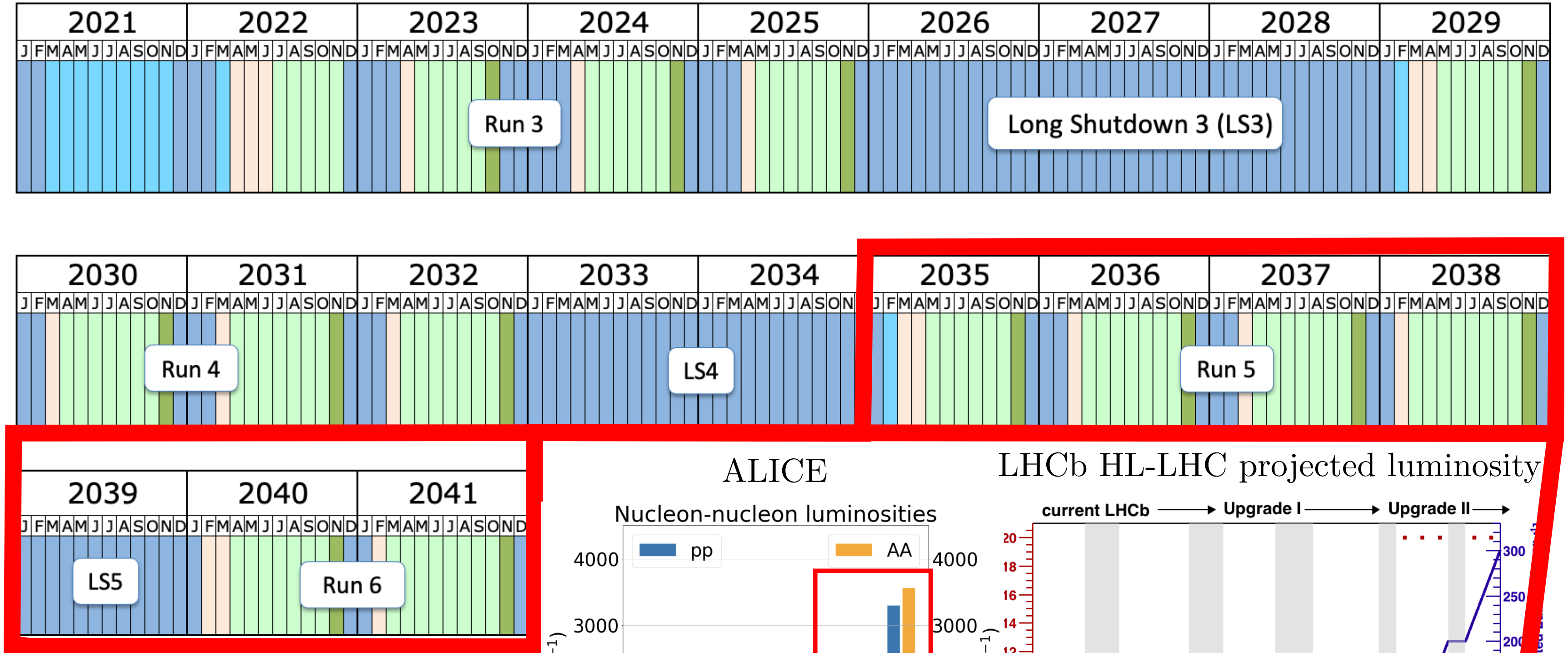
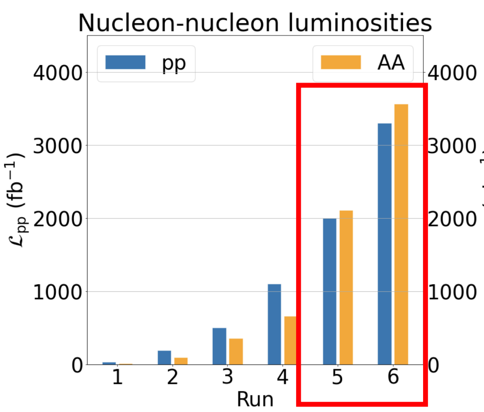
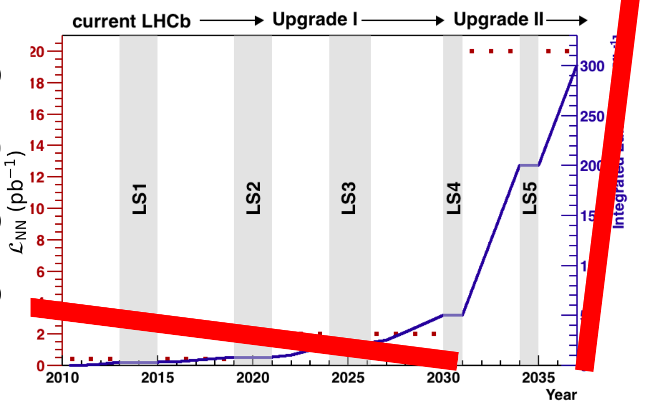
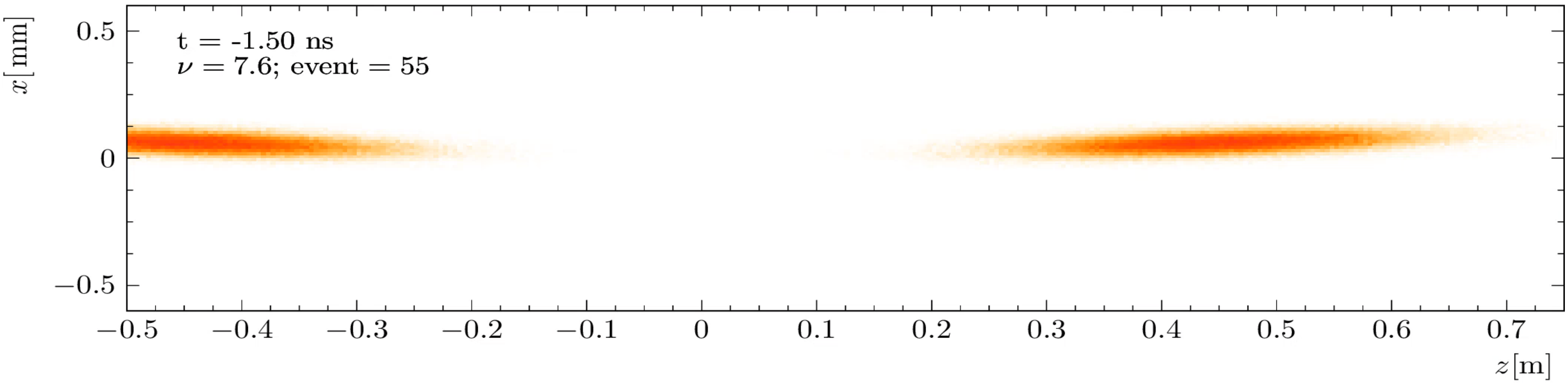
ALICE
Nucleon-nucleon luminosities
pp
AA
Run
LHCb HL-LHC projected luminosity
current LHCb
Upgrade I
Upgrade II
LS1
LS2
LS3
LS4
LS5
Year



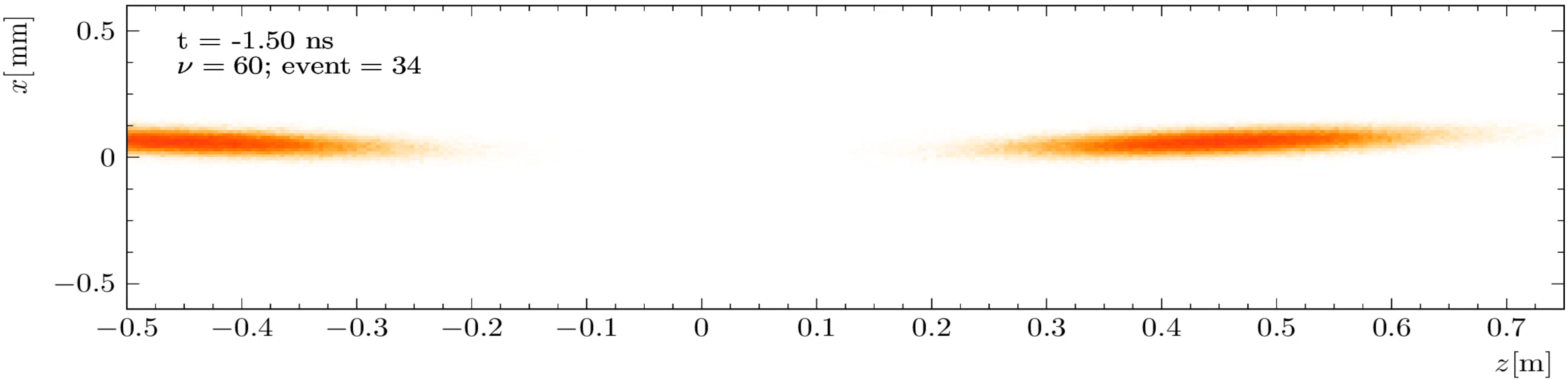




- $N_{\text{pp}}(\text{ATLAS, CMS})/\text{BX} :\sim 60 \rightarrow 200$
- $N_{\text{pp}}(\text{LHCb})/\text{BX} :\sim 7 \rightarrow 60$
- $N_{\text{AA}}/\text{BX} :\sim 0.01$



pions (π^+)
strange ($K^+, K^0_s, \Lambda^0, ...$)
charm ($D^0, D^+, \Lambda_c^+, ...$)
beauty ($B^0, B^+, B^0_s, ...$)
leptons (μ^-, e^-)
protons



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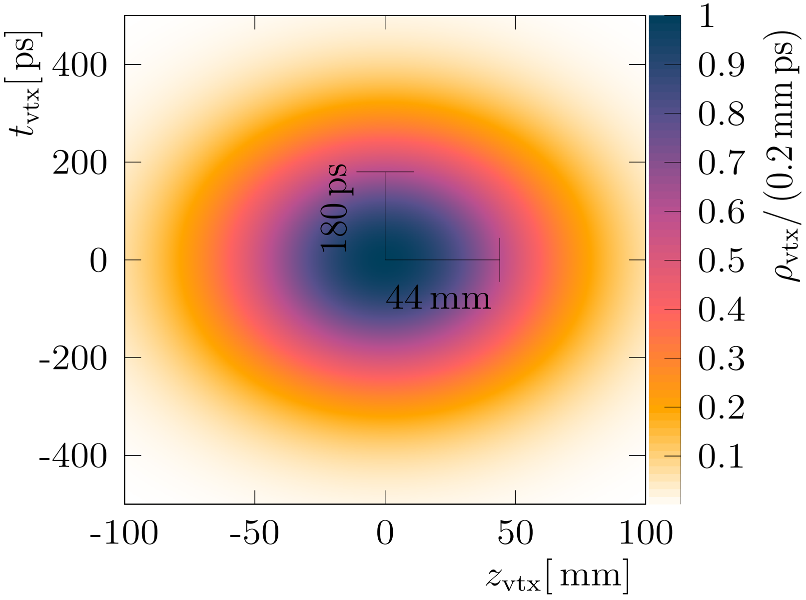
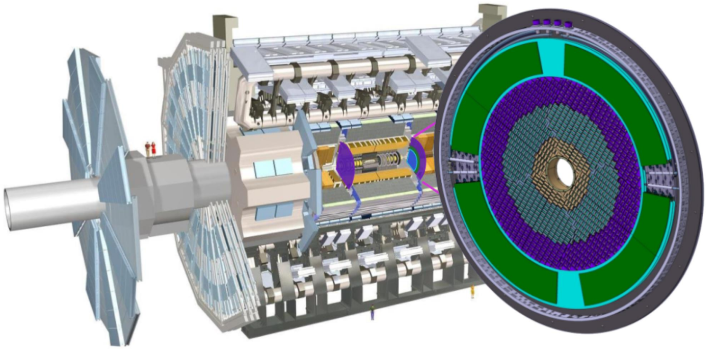


- *pp* collisions separated in time as well as space
- Crucially the two are uncorrelated
- Separation in time essentially time-of-flight for the length of a bunch ($\sigma_t = \sigma_{RMS}/\sqrt{2}c \sim 180\,\mathrm{ps}$)
  - Implies detectors with time resolution $<< \sigma_t$ $\implies$ 10s of picoseconds

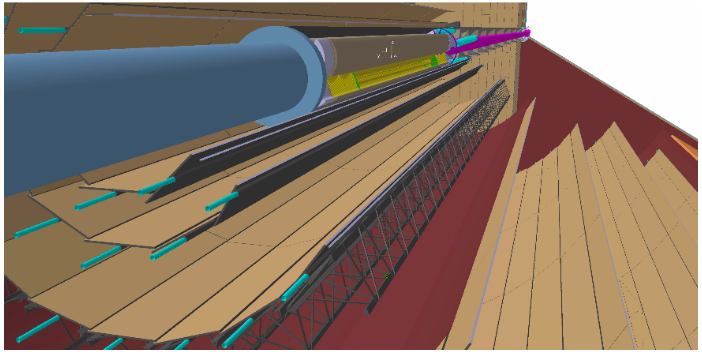
Two approaches:

Dedicated timing detectors



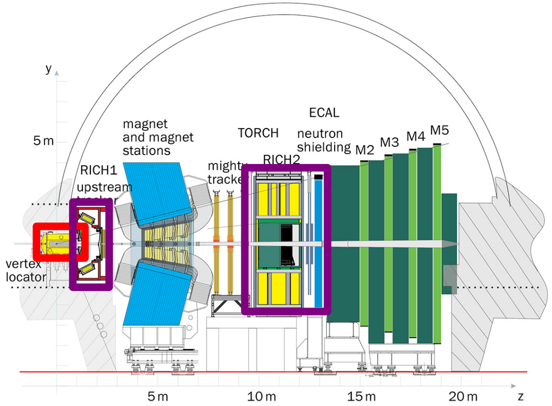
Design and construction of the ATLAS High-Granularity Timing Detector

Precision Timing with the CMS MIP Timing Detector for High-Luminosity LHC

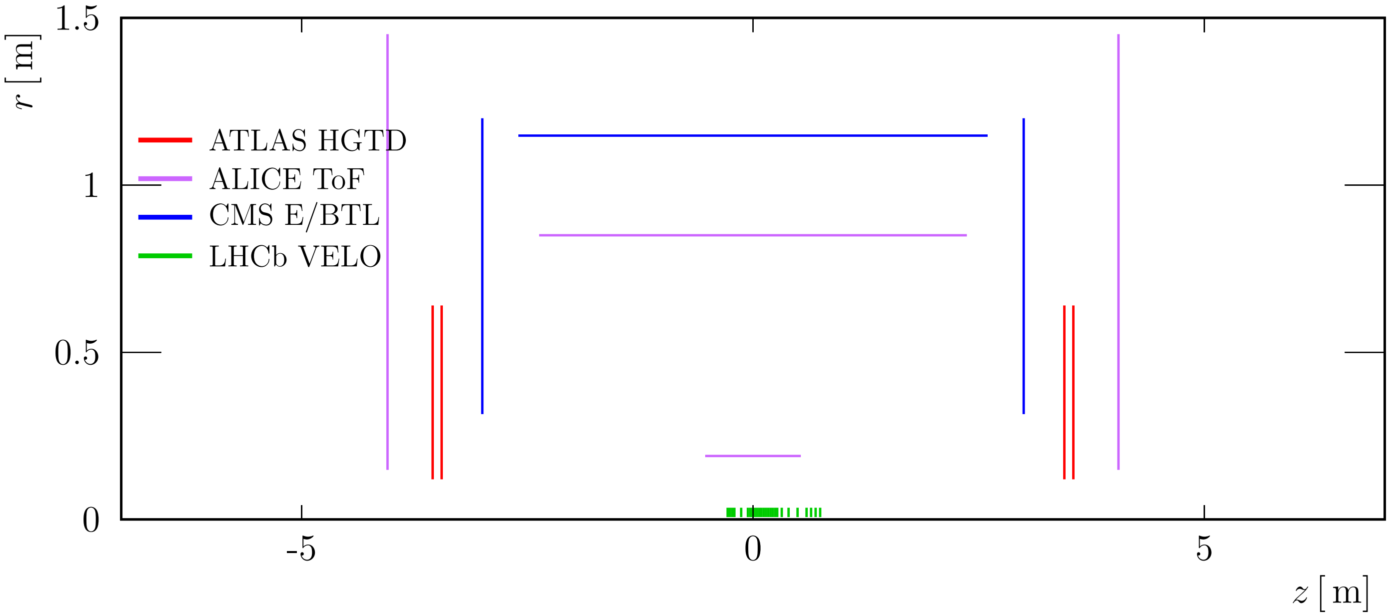


ALICE3 Time-of-flight system

Integrating timing into existing detector concepts



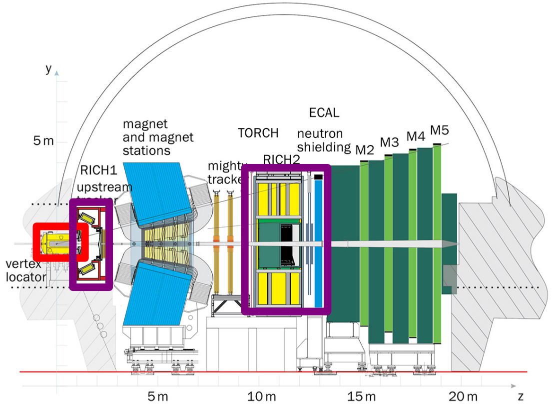
The plans of the future upgrade LHCb Tracker (Velo)



Detector	Acceptance	Technology	Pitch	Layers	Documentation
HGTD	$2.4 < \|\eta\| < 4.1$	Silicon/LGAD	1.3 mm	4+4	ATLAS-TDR-031
Barrel TOF	$\|\eta\| < 1.75$	Silicon	$1 \rightarrow 5$ mm	1+1	ALICE LoI
Forward TOF	$1.75 < \|\eta\| < 4$	Silicon	$1 \rightarrow 5$ mm	1+1	
BTL	$\|\eta\| < 1.45$	LYSO+SiPM	~ 3 mm	1	CMS-TDR-020
ETL	$1.6 < \|\eta\| < 3.0$	Silicon/LGAD	1.3 mm	4+4	
VELO	$2 < \eta < 5^*$	Silicon	$\leq 55\,\mu$m	> 26 ?	LHCB-DP-2021-008-001

* Some acceptance in $\eta < -1, 1 < \eta < 2$

Integrating timing into existing detectors



The plans of the future upgrade LHCb Tracker (Velo)

4D tracking in LHCb's Vertex Locator

VELO tracking can exploit two useful facts:

- No magnetic field $\implies$ tracks are $\sim$ straight lines
- (Approximately) constant in azimuthal angle ϕ

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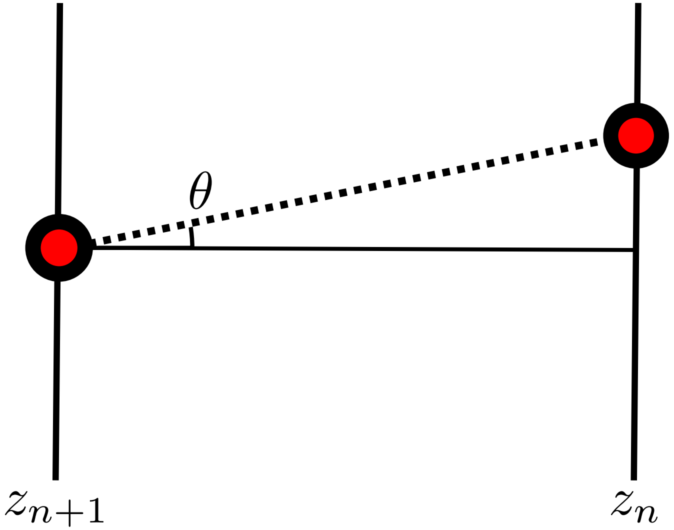
Going to 4D:

- Assume 50 ps measurement per layer
- Can place requirements on Δt when constructing the track



$$|\Delta t_{tof}| = \frac{z_n - z_{n+1}}{v \cos\theta} \sim \frac{z_n - z_{n+1}}{c \cos\theta}$$

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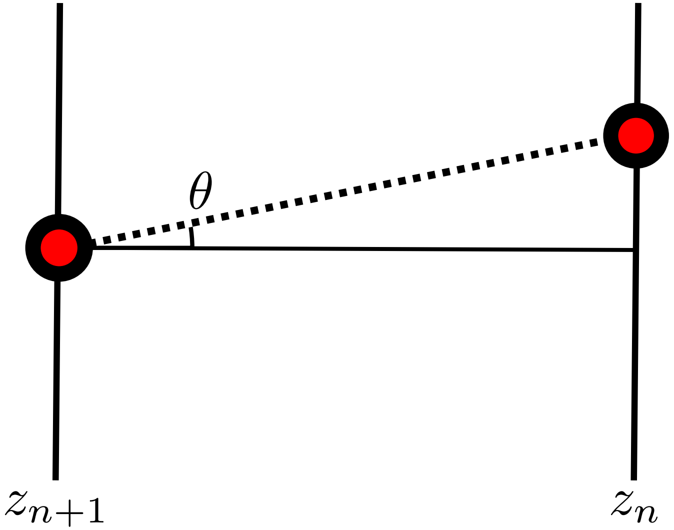
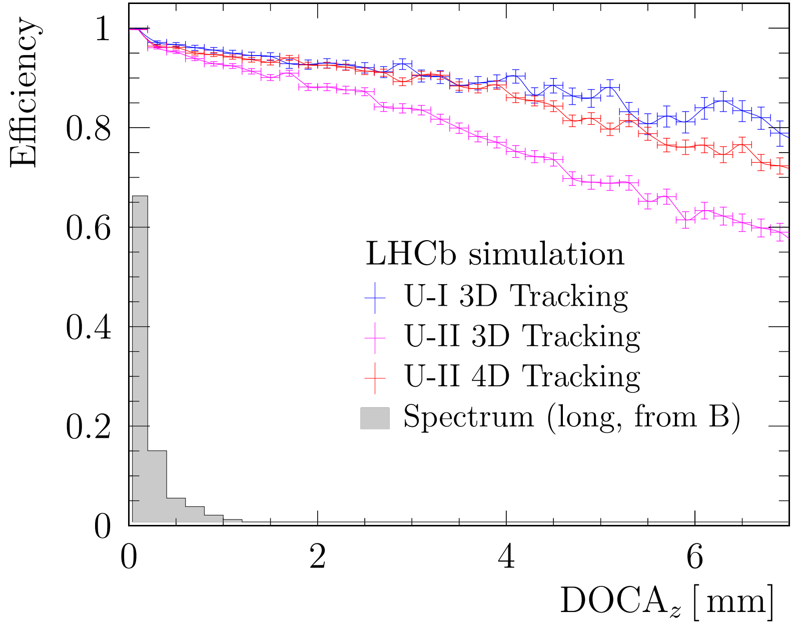
- Assume 50 ps measurement per layer
- Can place requirements on Δt when constructing the track
- For 99% efficiency, implies 180 ps window between first two hits
  - Reduces fraction of wrong hits by $\mathcal{O}(50\%)$
  - Benefits from averaging measurements as hits are added*

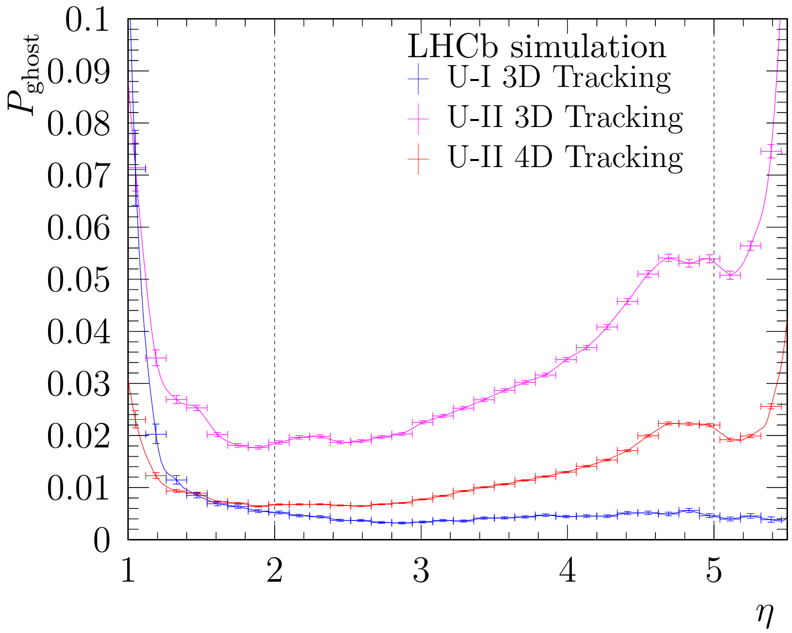


$$|\Delta t_{tof}| = \frac{z_n - z_{n+1}}{v\cos\theta} \sim \frac{z_n - z_{n+1}}{c\cos\theta}$$

* different to spatial measurements where scattering is far more important

Some performance metrics

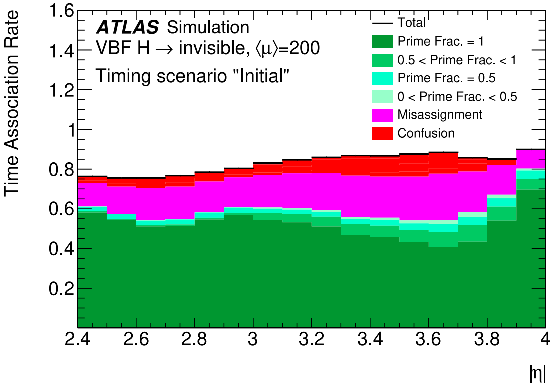


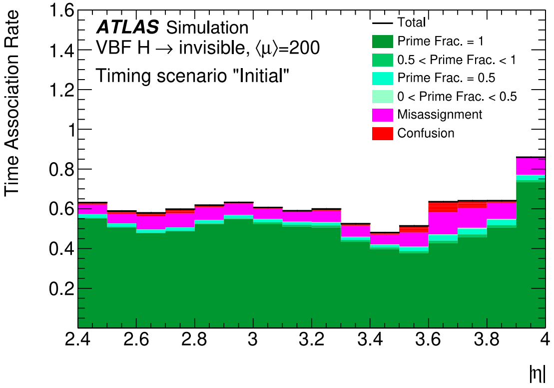


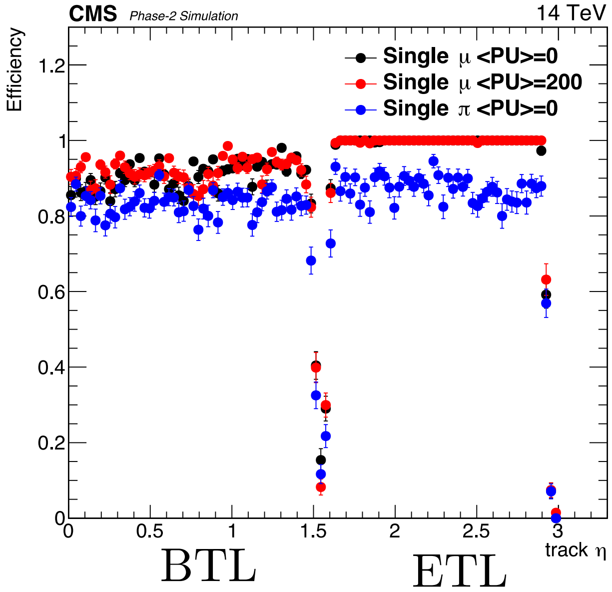
- 4D tracking is more robust: improves efficiency vs track geometry and fake track rates
- Ongoing work on more sophisticated approaches on FPGAs, GPUs etc.

4D tracking @ ATLAS/CMS

- HGTD / ETL have $\sim 1\,\text{mm}^2$ pads $\implies$ not tracking detectors
- Match timestamps from these detectors with tracks from the tracking system



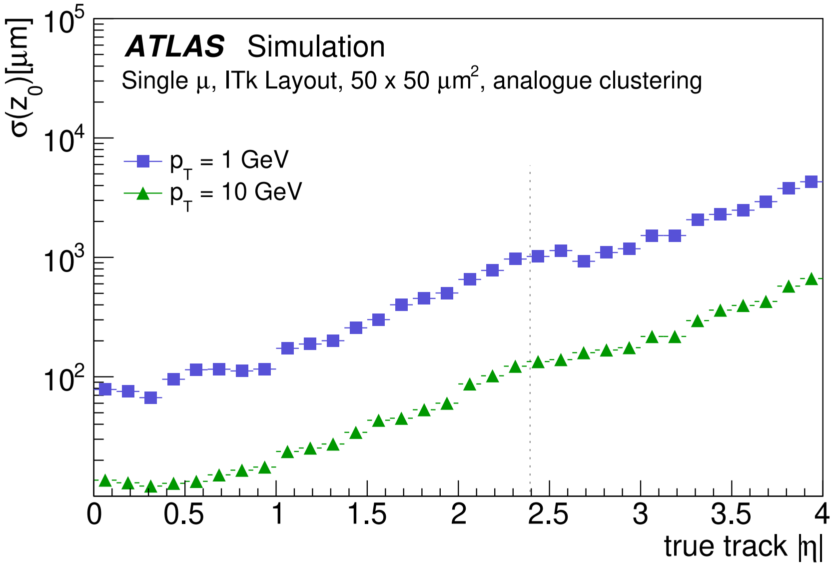


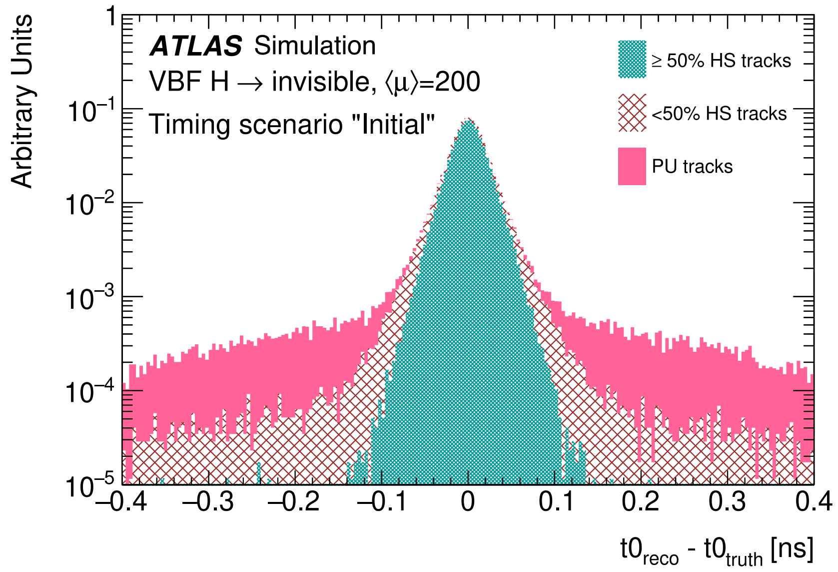


HGTD hit association efficiency (before/after cleaning)

4D Vertexing @ ATLAS

1. Make (3D) vertices using tracking system
2. Find tracks matched to the HGTD compatible with these vertices
3. Use to fit for vertex time



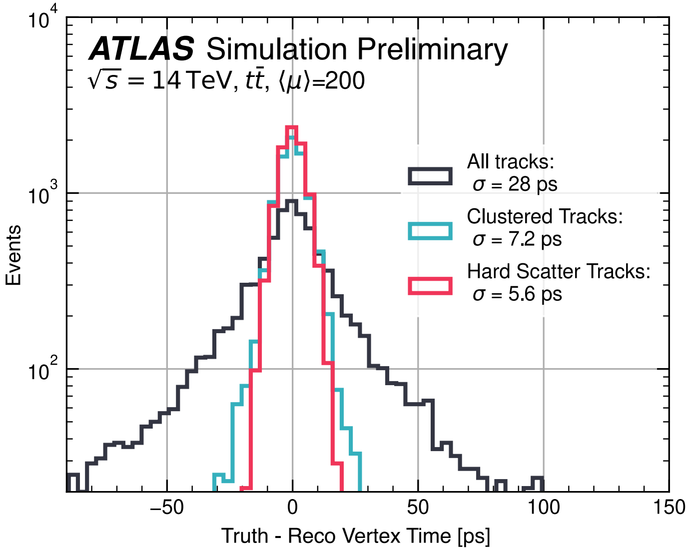


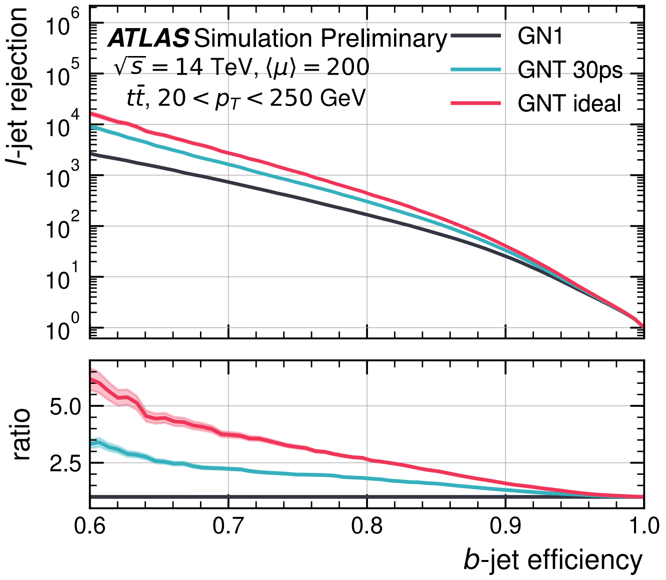
- Around 60% of HS vertices have enough tracks to be timestamped
- For purity $> 50\%$, can get to a $\sigma_{vtx} \sim 20\,\mathrm{ps}$
- Can use this vertex time to reject tracks from other vertices

Proposal to add timing layer(s) to ITK

ATLAS-PHYS-PUB-2023-023

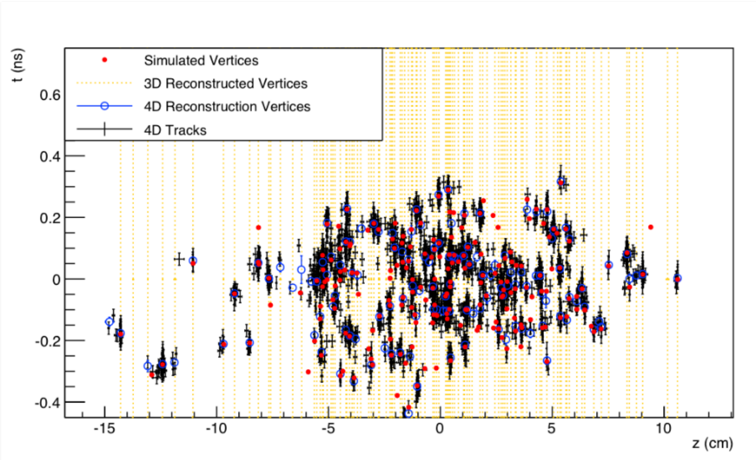
- Beyond Run-4 enhancement to replace 2 layers of ITK with 4D detectors
- Targeting $\sim 30\,\mathrm{ps}/$ layer
- Would improve vertex resolution by giving coverage of low η region
- Improve b-tagging, searches for LLPs etc..

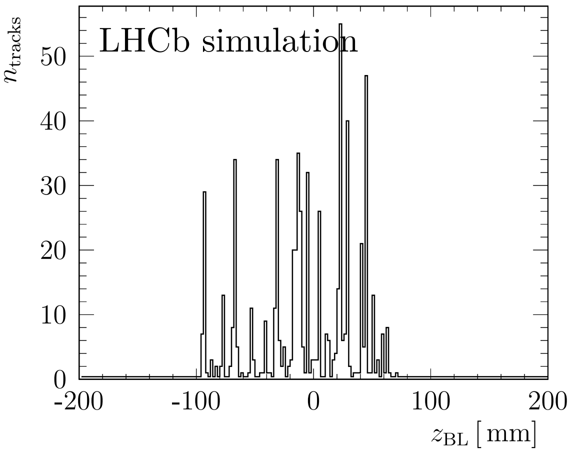


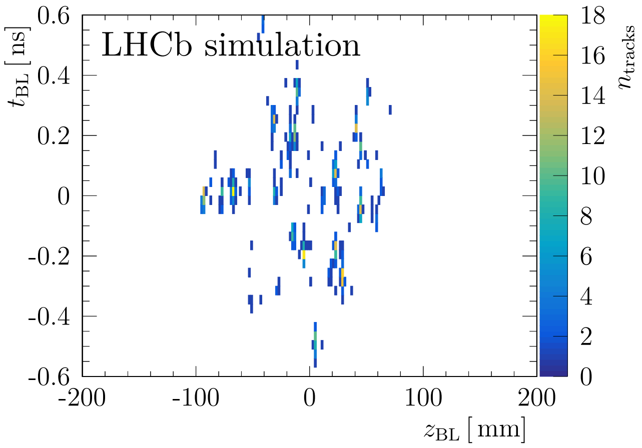


4D Vertexing @ CMS / LHCb

- Because of the much wider η coverage, can do true '4D' vertexing
- Project tracks onto (z,t) plane at the beam axis
- Cluster in 2D (CMS: deterministic annealing, LHCb: seed-and-merge)

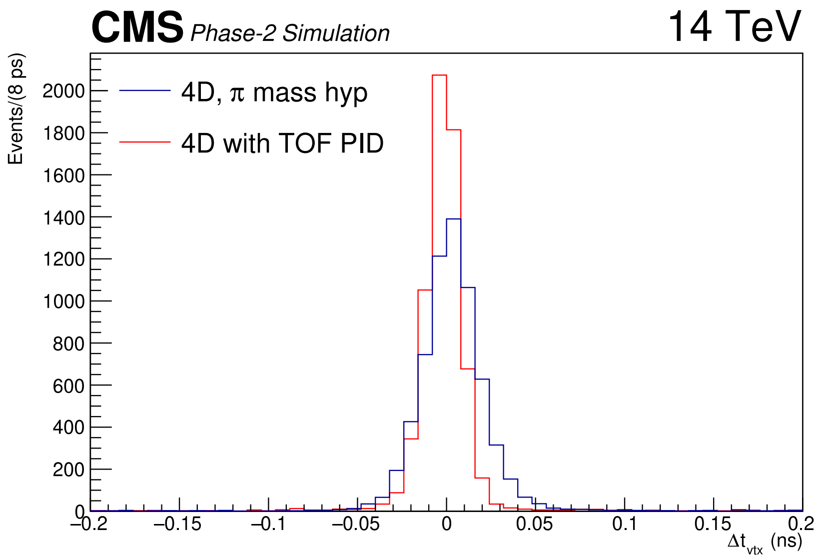


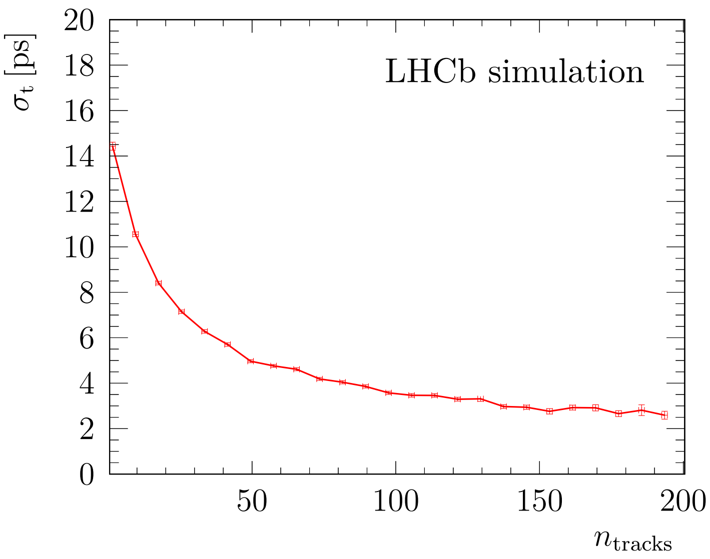




4D Vertexing @ CMS / LHCb

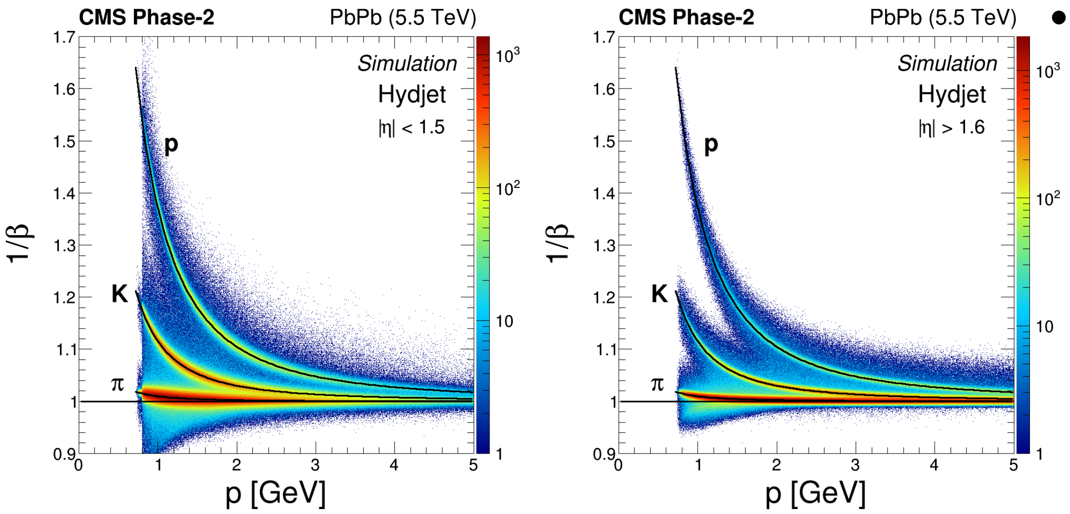
- $> 90\%$ efficiency for "interesting" PVs
- Can achieve resolution of a few ps on the PV





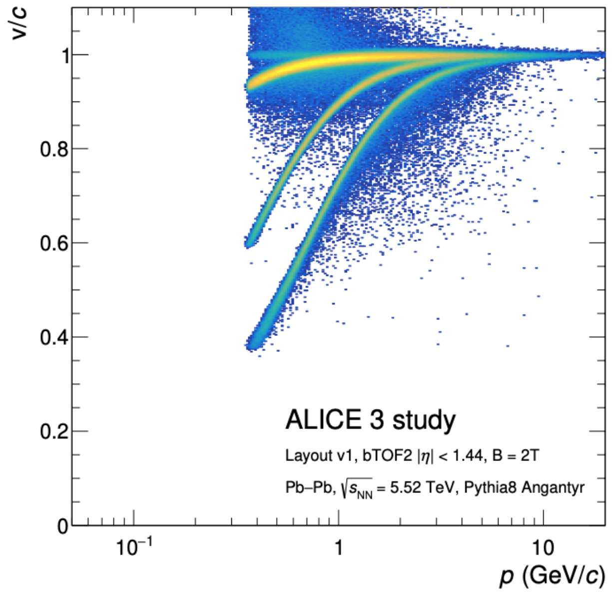
- Less than 1% merging at 200 pileup
- Resolutions below 10 ps, but need correct PID hypothesis

PID with timing at CMS & ALICE



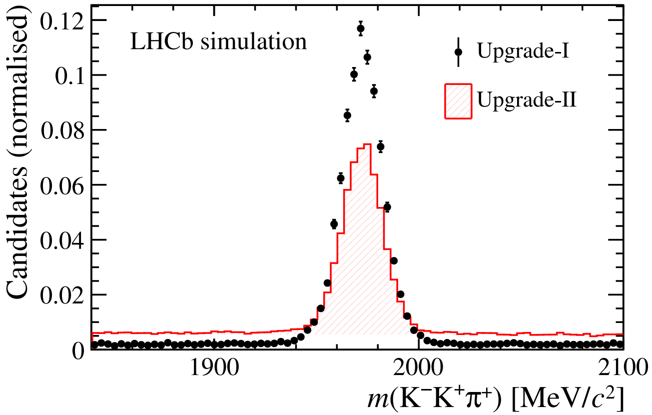
- Can provide PID capacity in HI collisions!
- Up to $\sim 5\,\text{GeV}$ for $p - \pi$ separation

- For ALICE3, similar detectors planned (LGAD / CMOS-LGAD*) to provide TOF PID
- Targeting $\sim 20\,\text{ps}$ resolution

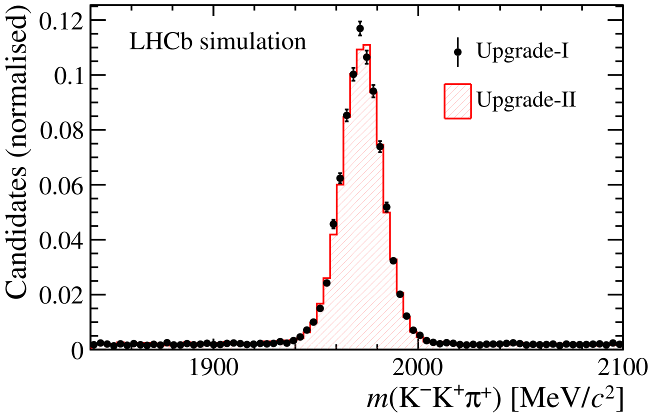


Reproduced from:
The studies for the ALICE3 detector

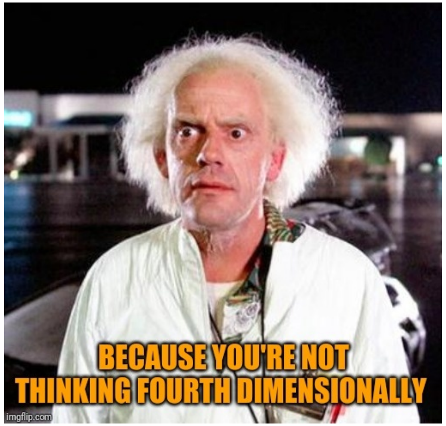
Beyond 4D tracking and vertexing @ LHCb



(without timing)



(with timing)

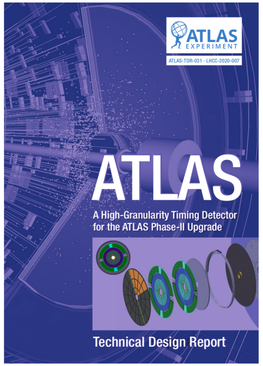


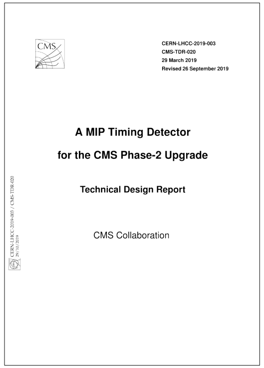
$$(x, y, t_x, t_y, q/p)(z) \rightarrow$$
$$(x, y, t_x, t_y, q/p, t)(z)$$

- Timing also key to reconstructing higher-level quantities
- Pictured: Impact of timing on charm meson reconstruction
- Key: consider reconstruction in 4D (when and where) rather than in terms of timing windows

Conclusions

- Timing detectors are **the** key technology to enable particle physics at ultra high pileup
- Different solutions adopted based on target acceptance of each experiment
- LHCb's Upgrade 2 VELO will be the first true 4D tracker at the LHC
- Same detectors can also bolster PID performance
  - For CMS, gaining the capability "for free"
  - For ALICE3, dedicated TOF with higher granularity




CERN-LHCC-2019-003
CMS-TDR-020
29 March 2019
Revised 26 September 2019

A MIP Timing Detector
for the CMS Phase-2 Upgrade

Technical Design Report

CMS Collaboration