CTD/WIT 2019

Connecting the Dots and Workshop on Intelligent Trackers

Valencia, April 2 - 5, 2019

LHCb Upgrade II

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on behalf of the LHCb collaboration

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Motivation

Main goal of LHCb: search for physics "Beyond Standard Model"

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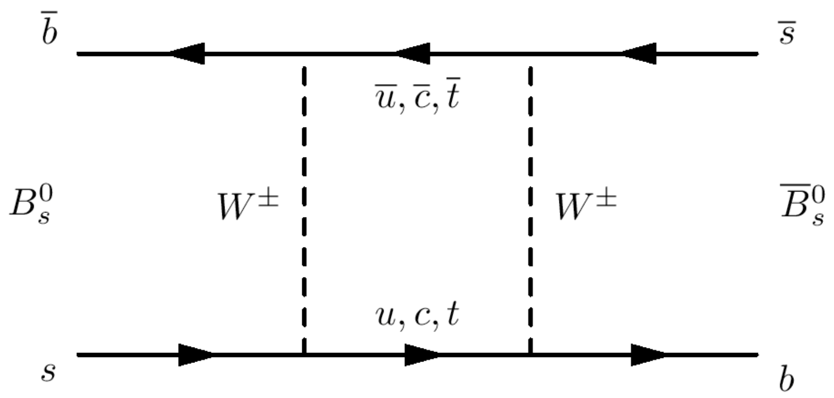
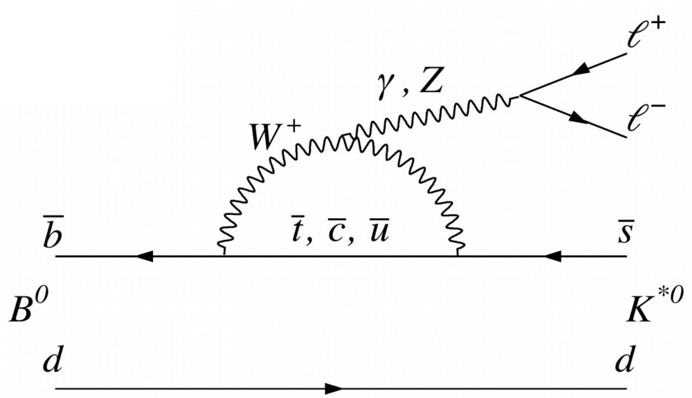
→ most BSM physics models predict additional heavy particles

→ can cause additional amplitudes in processes with internal loops





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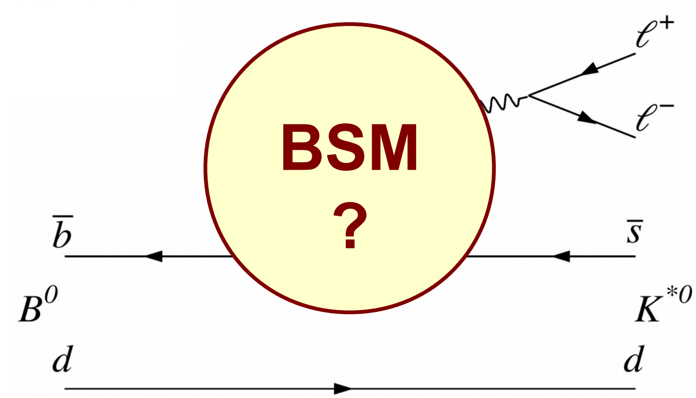
→ can lead to sizeable modifications of observables
(rates, angular distributions, *CP* violating phases)



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→ most BSM physics models predict additional heavy particles

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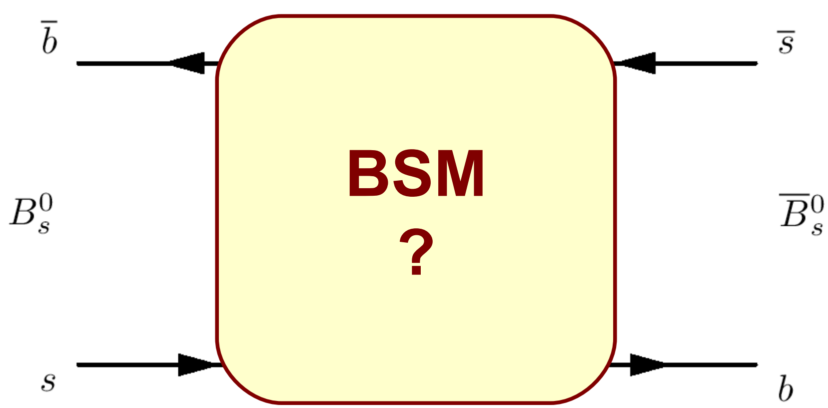
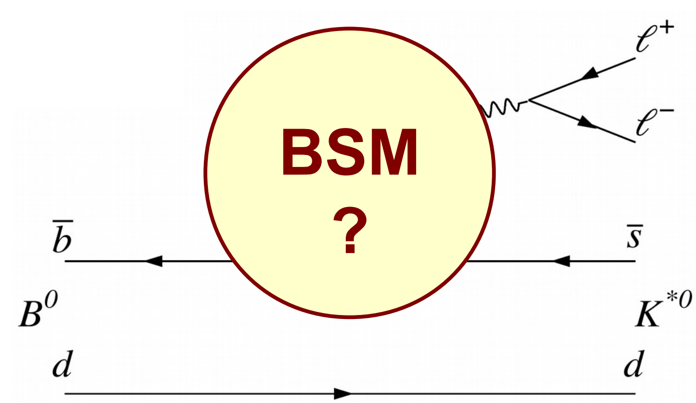
Uncover deviations from Standard Model expectations
by comparing its predictions with precision measurements





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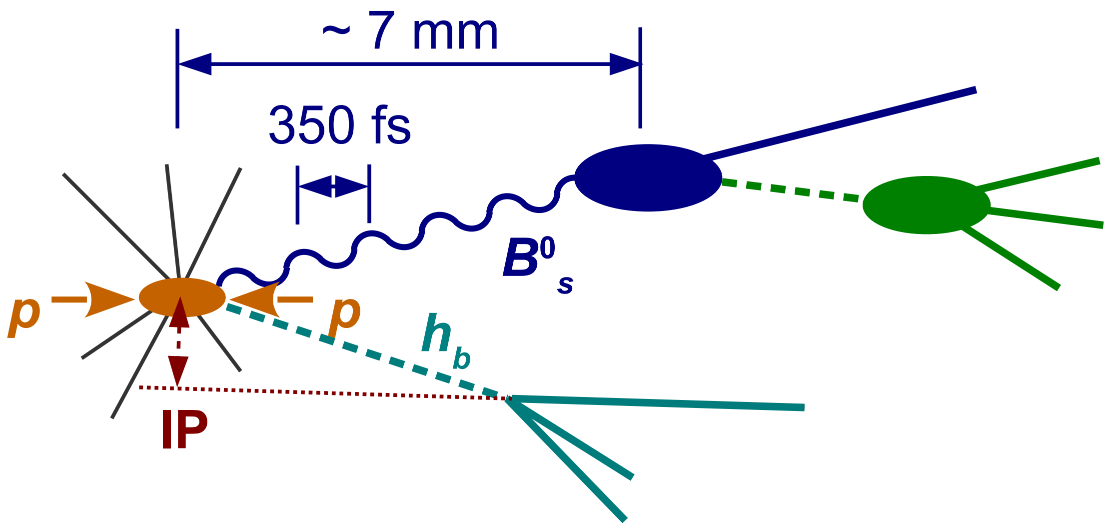


Efficient and precise track reconstruction vital for LHCb physics

→ identify primary and secondary vertices

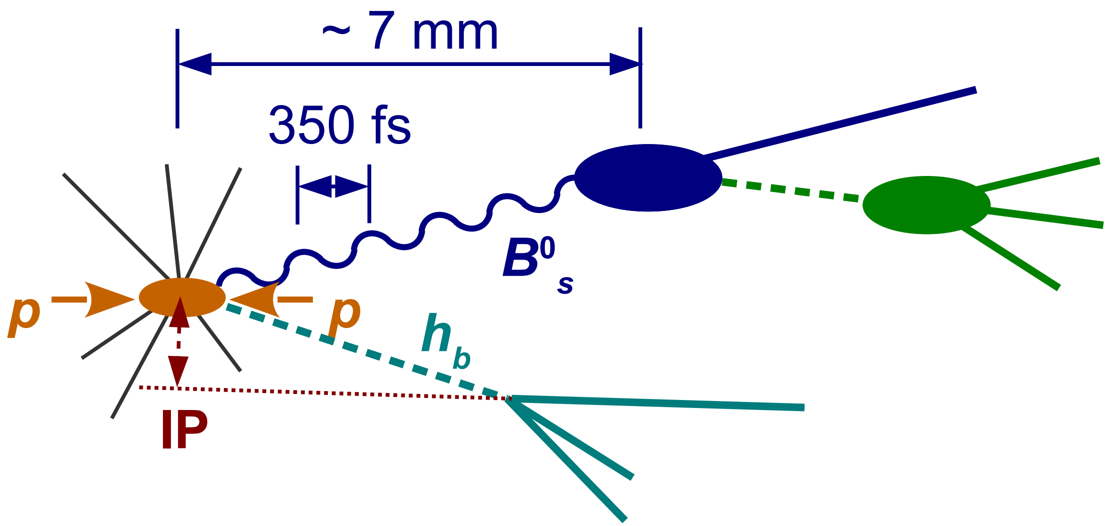
→ measure impact parameters (trigger)

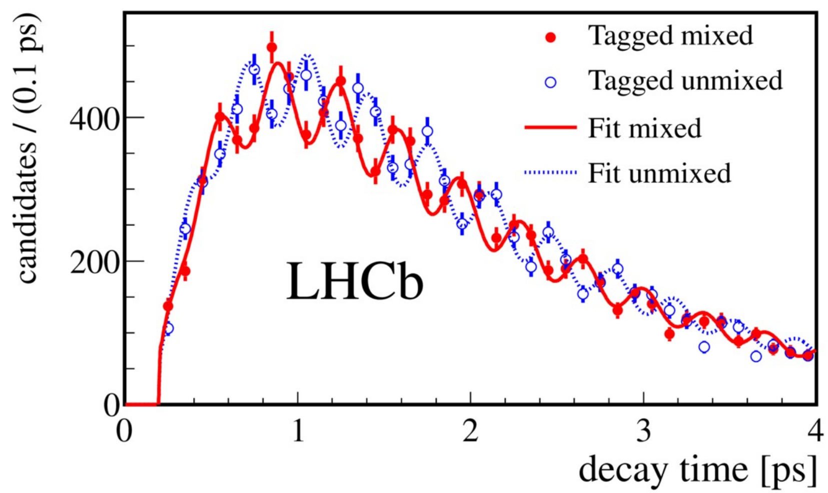
→ measure decay time of *b* and *c* hadrons

→ resolve fast B_s^0–$\overline{B}_s^0$ oscillations

→ momentum resolution & invariant mass resolution

Motivation





[NJP 15 (2013) 053021]

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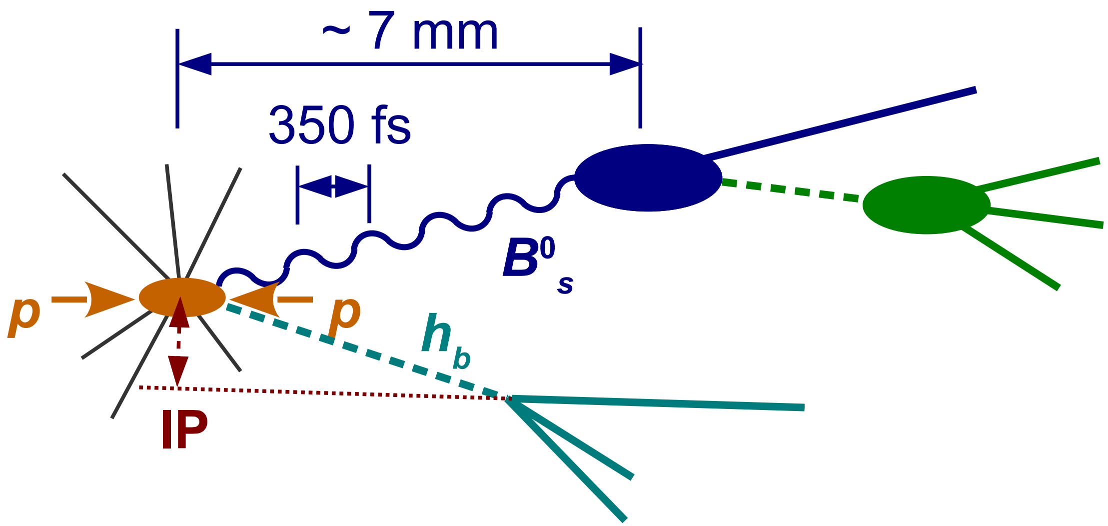

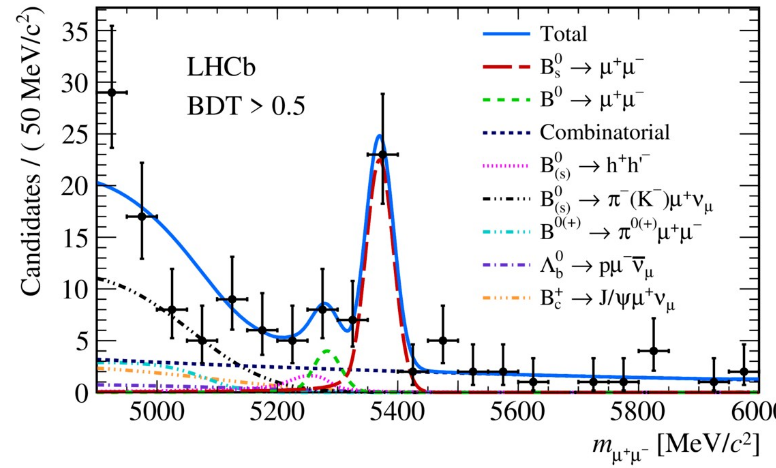

[PRL 118 (2017) 191801]

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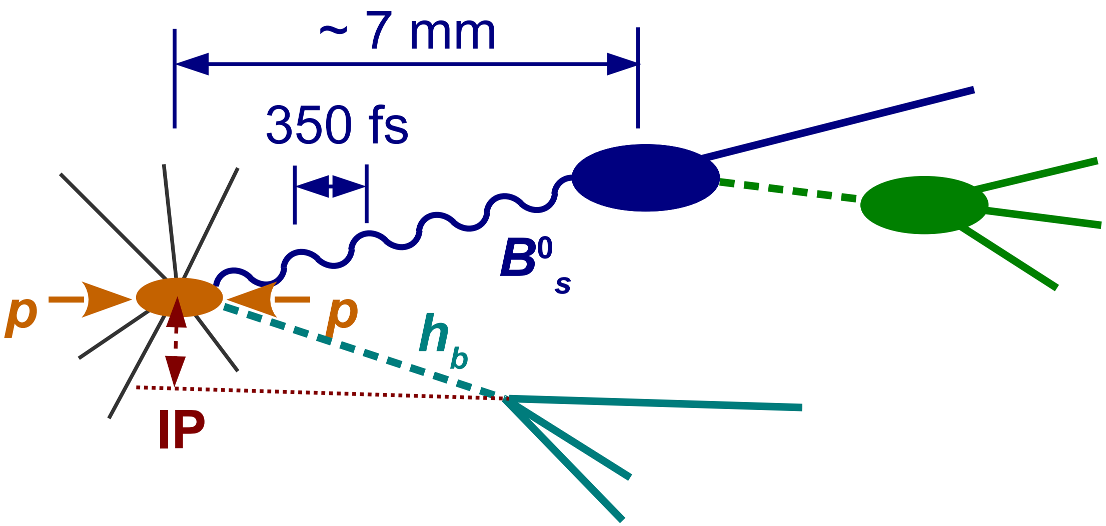

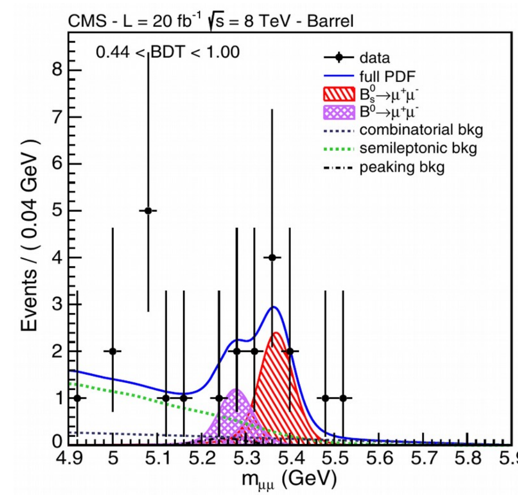

[PRL 111 (2013) 101804]

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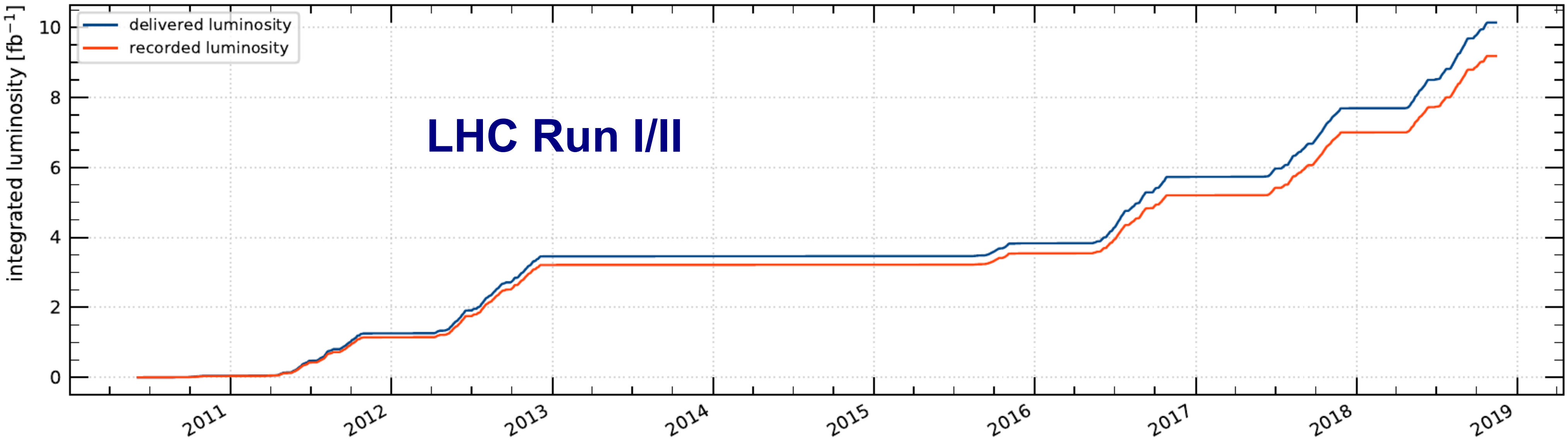
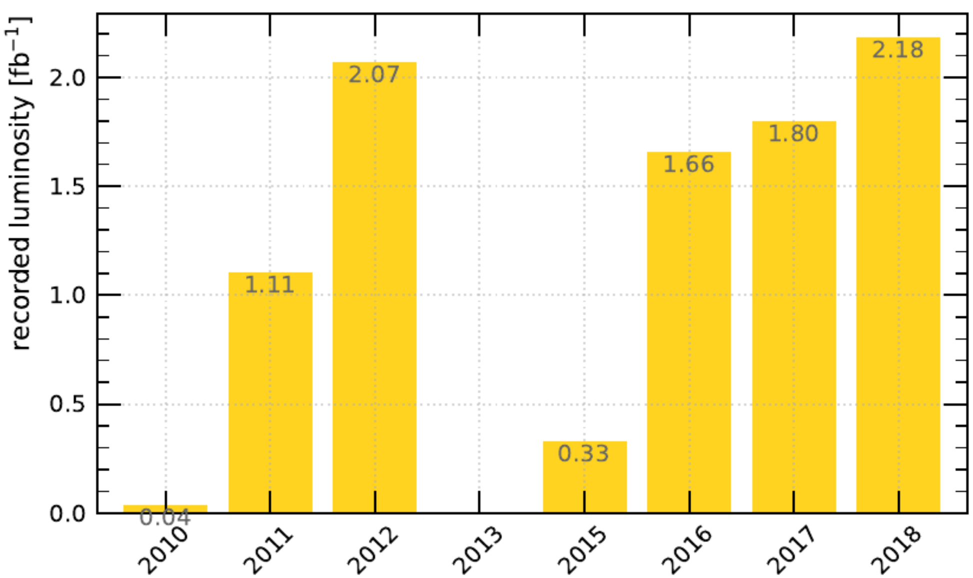
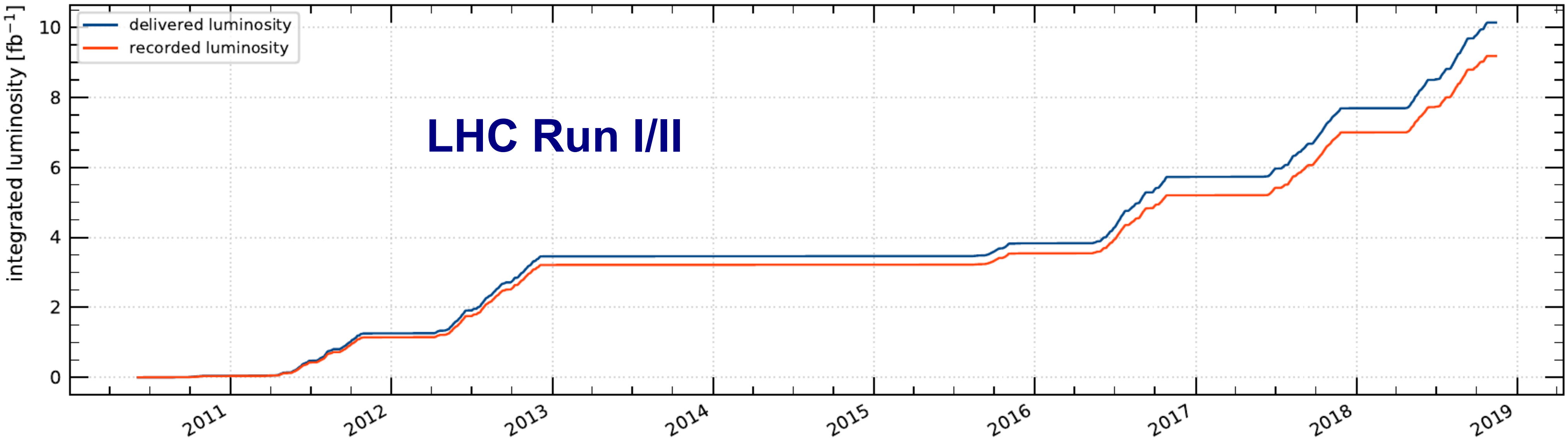


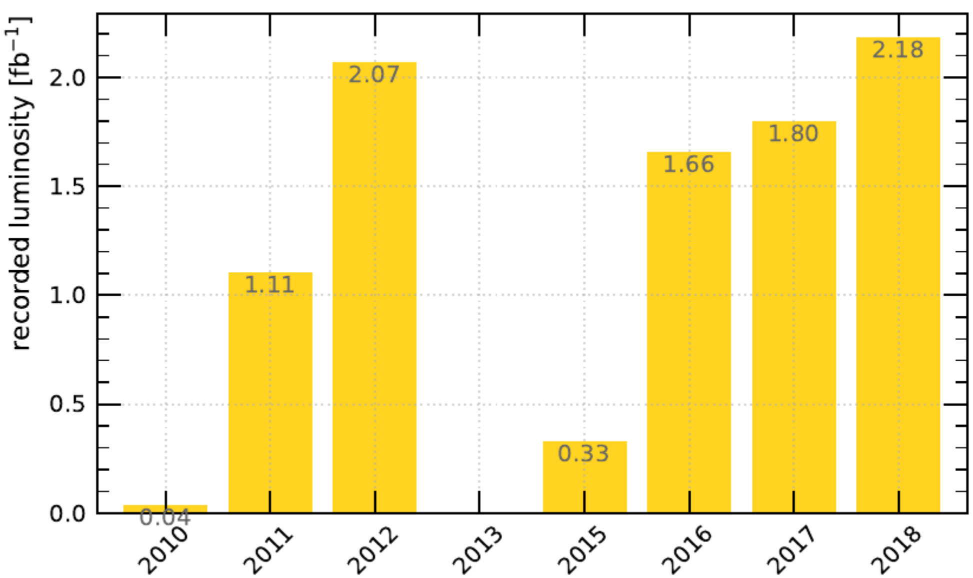


9.18 fb^{-1} recorded

in *pp* collisions

Motivation



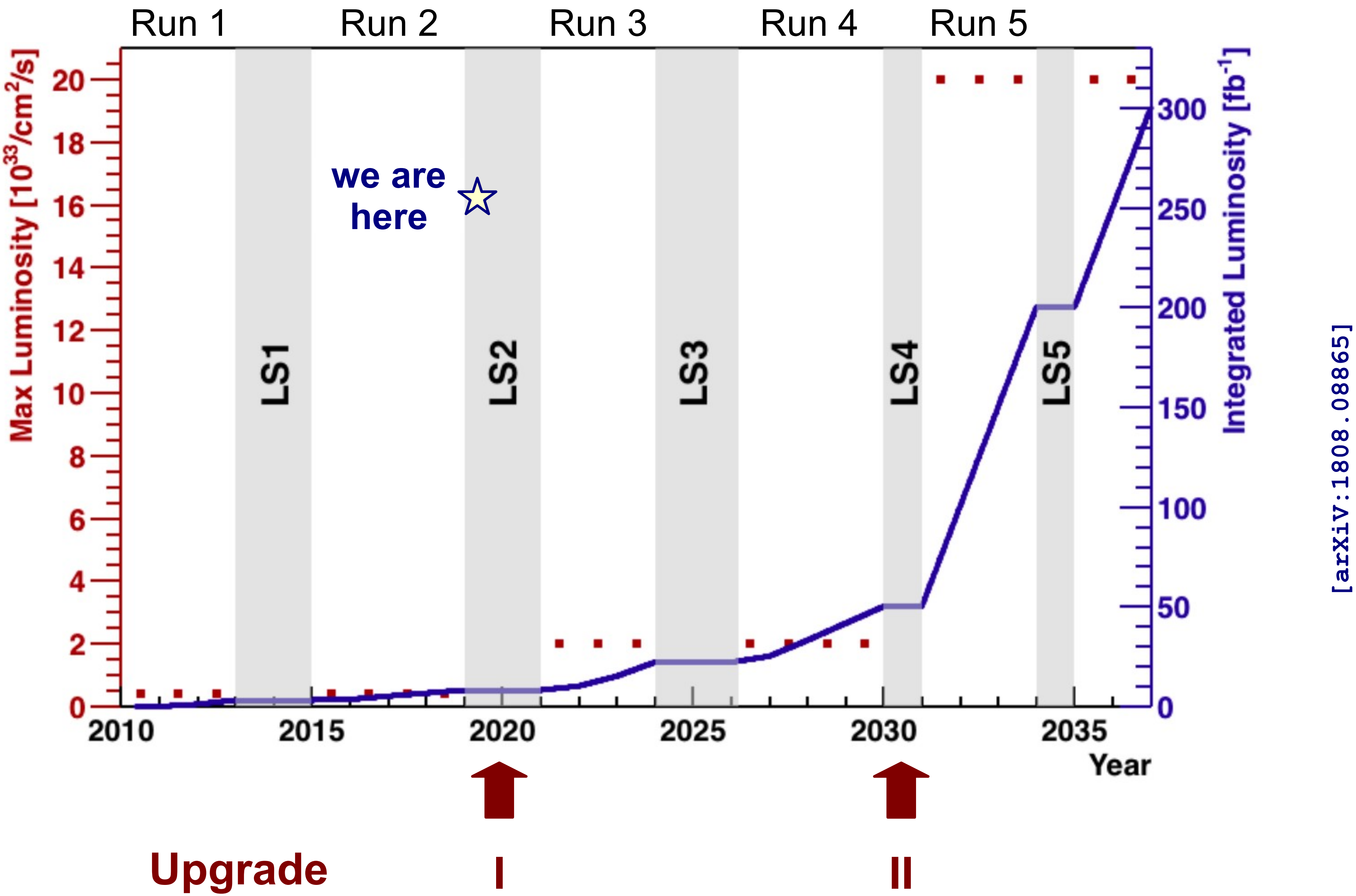


Most results limited by statistical uncertainty

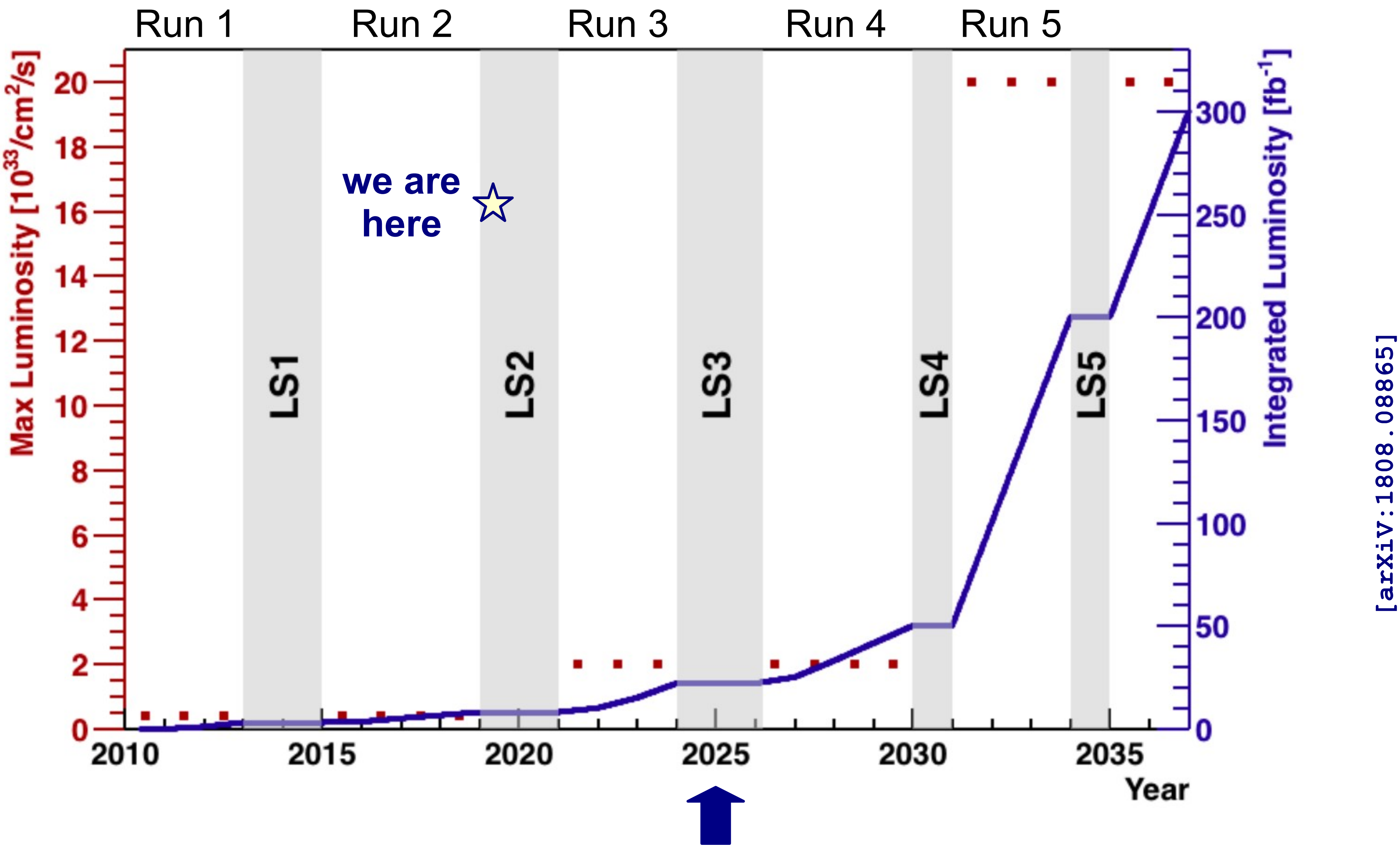
→ will need 4 × statistics to improve by another factor 2

→ 15 years of data taking at current conditions

Scenario

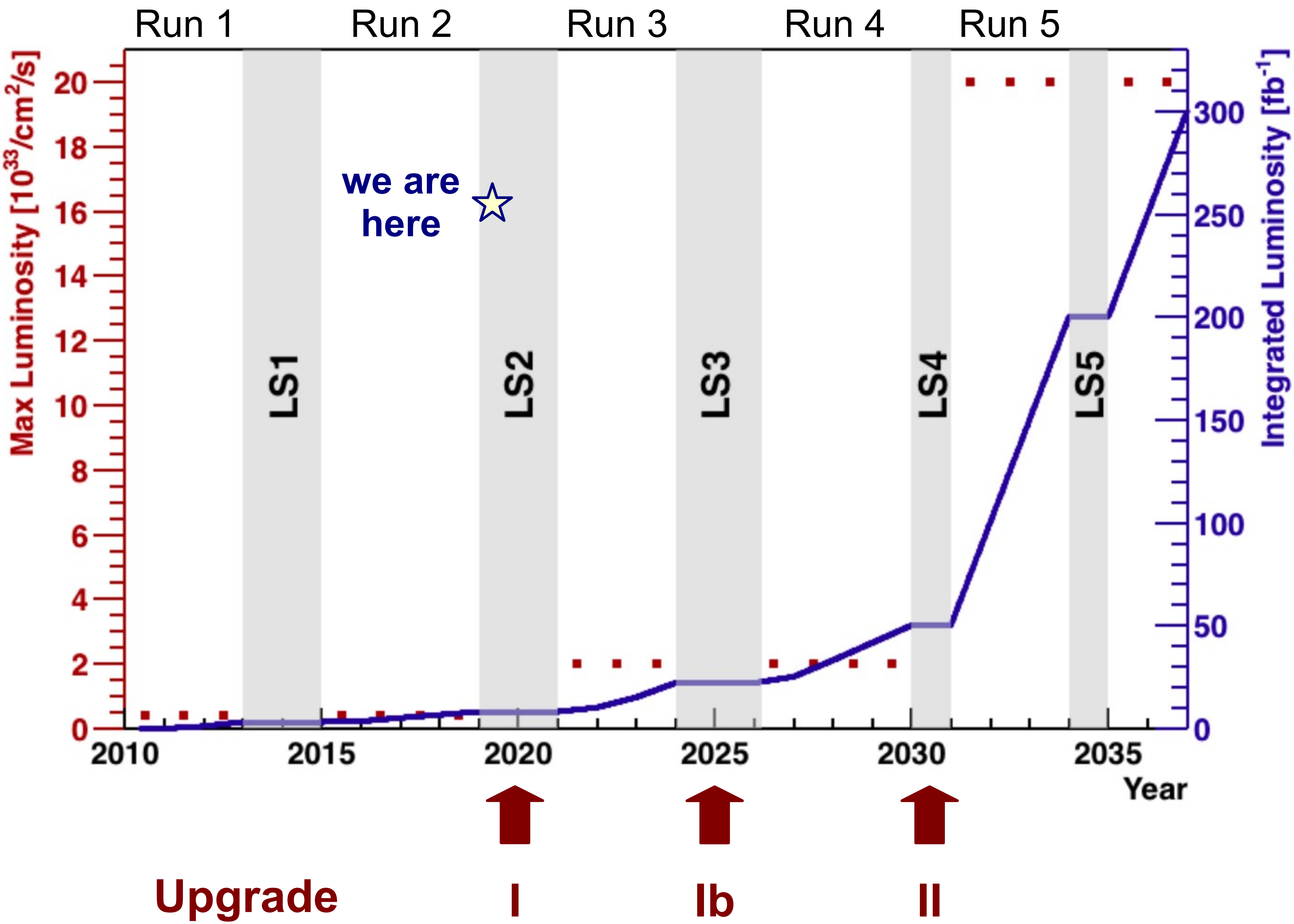

Run 1
Run 2
Run 3
Run 4
Run 5
Max Luminosity [10^33/cm^2/s]
20
18
16
14
12
10
8
6
4
2
0
LS1
LS2
LS3
LS4
LS5
we are here
2010
2015
2020
2025
2030
2035
Year
300
250
200
150
100
50
0
Integrated Luminosity [fb^-1]
[arXiv:1808.08865]
Upgrade
I
II

Scenario



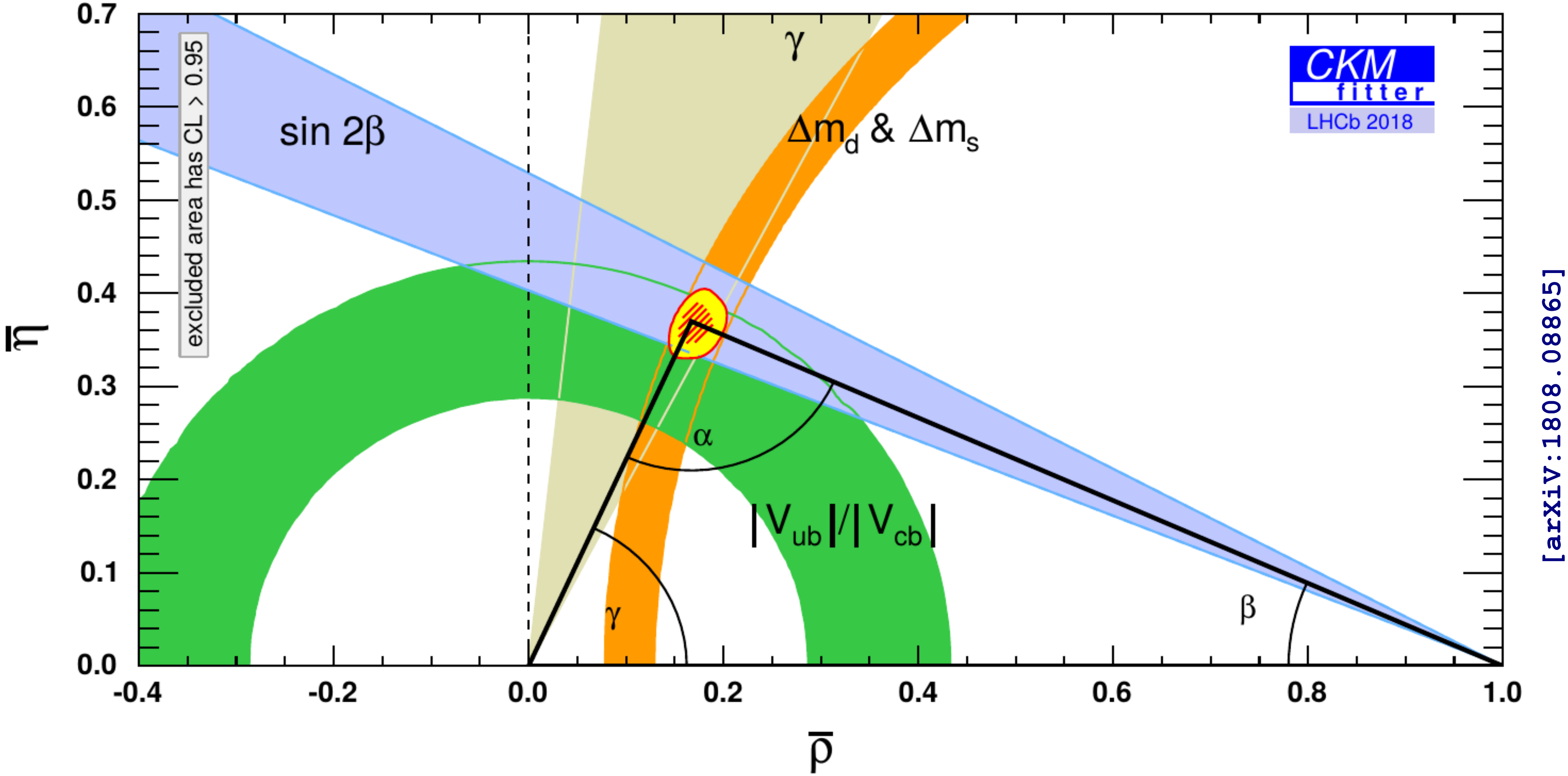
HL-LHC, ATLAS / CMS upgrades

Scenario



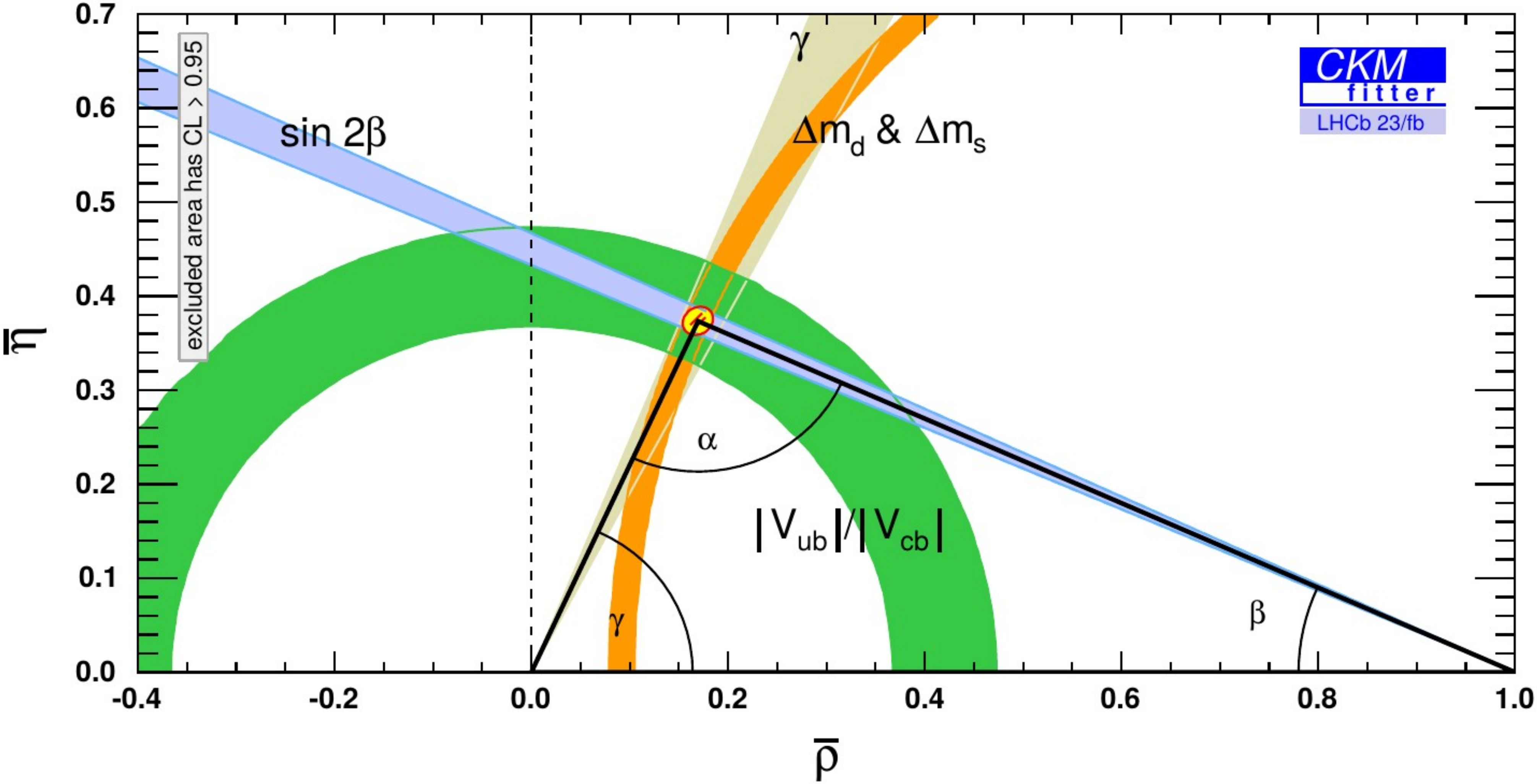
[arXiv:1808.08865]

Physics Reach



LHCb now

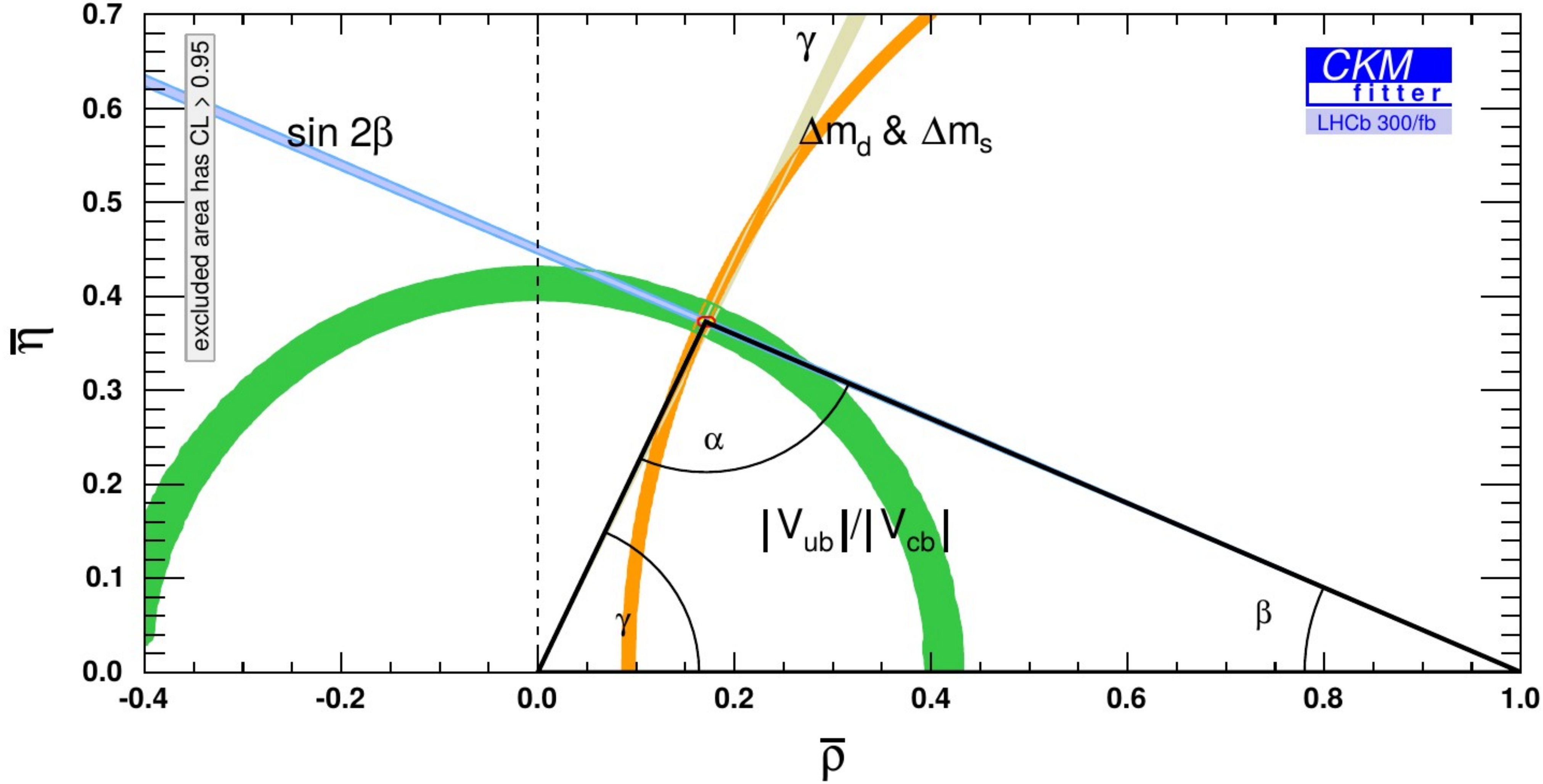
Physics Reach



[arXiv:1808.08865]

LHCb ~ 2025

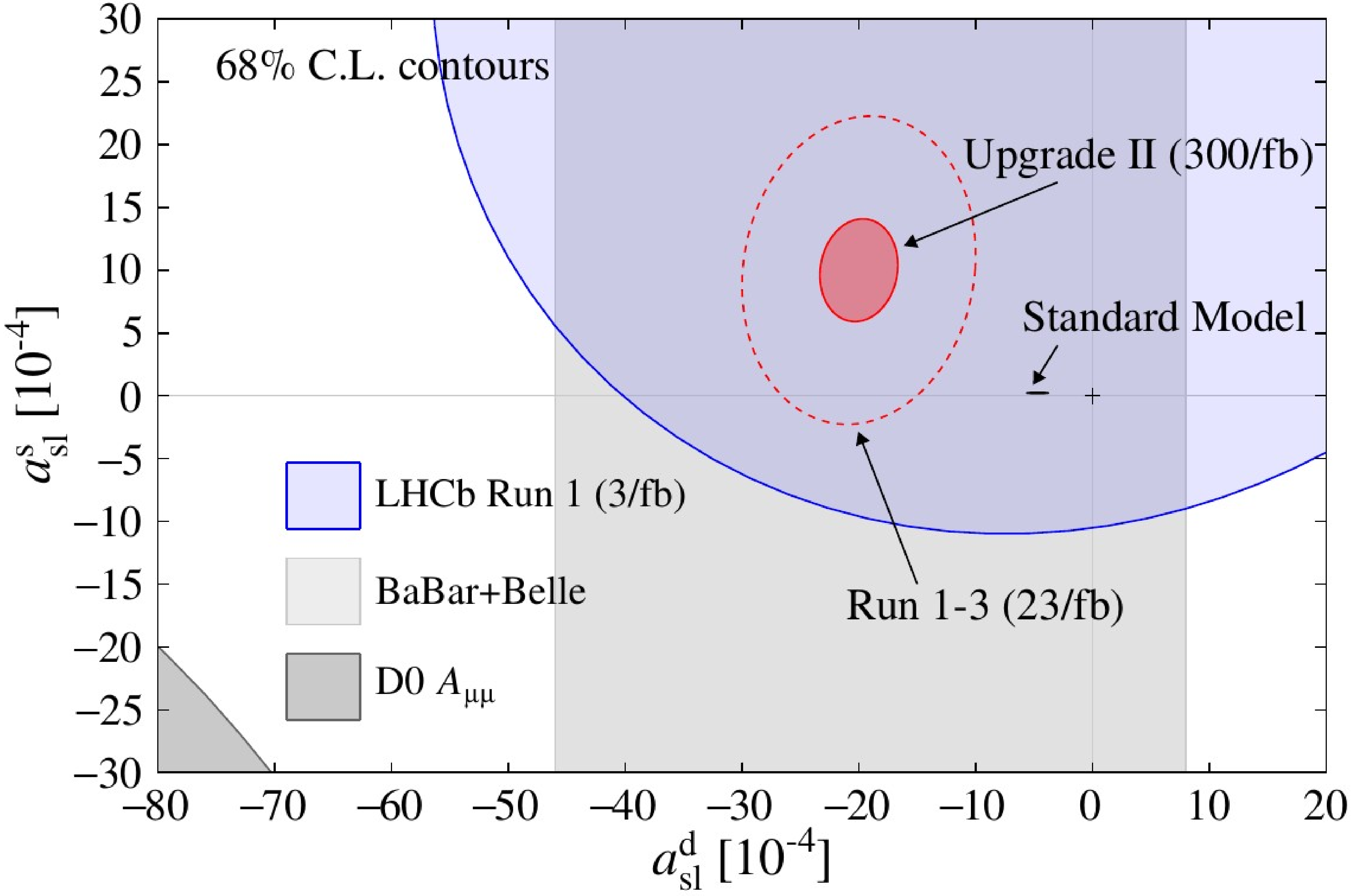
Physics Reach



[arXiv:1808.08865]

LHCb Upgrade II reach

Physics Reach



[arXiv:1808.08865]

Physics Reach

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projec LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0\to\mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x\sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

$\leq 9\ \mathrm{fb}^{-1}$ **$23\ \mathrm{fb}^{-1}$** **$300\ \mathrm{fb}^{-1}$**

[arXiv:1808.08865]

Status

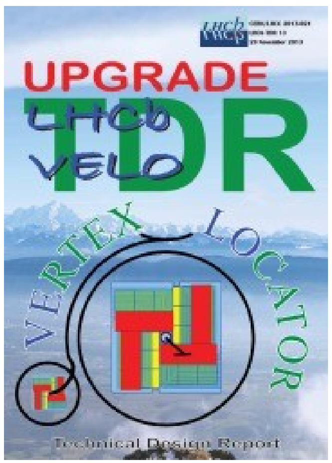
Upgrade I: 2019/2020

→ Technical Design Reports
→ construction underway

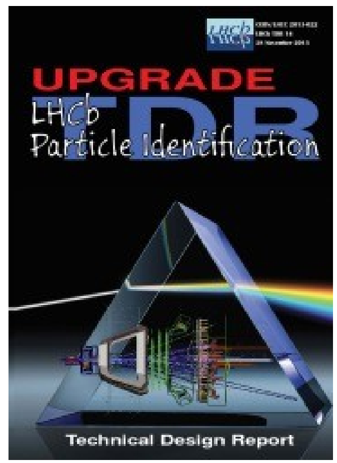
Upgrade II: 2030

→ EoI, Physics Case
→ approved to proceed to TDR

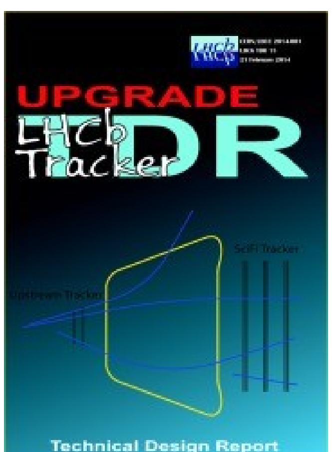
[CERN-LHCC 2013-021]



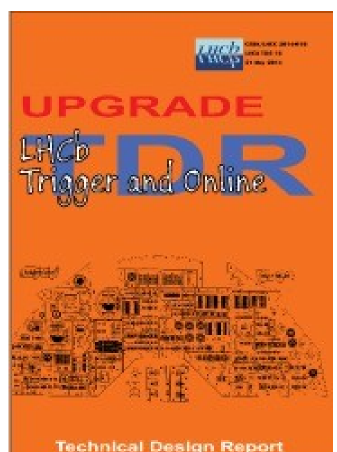
[CERN-LHCC 2013-022]



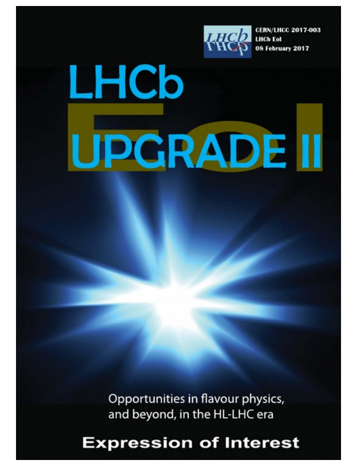
[CERN-LHCC 2014-001]



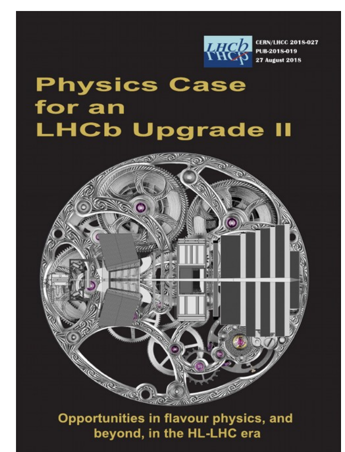
[CERN-LHCC 2014-016]



[CERN-LHCC-2017-003]



[CERN-LHCC-2018-027]



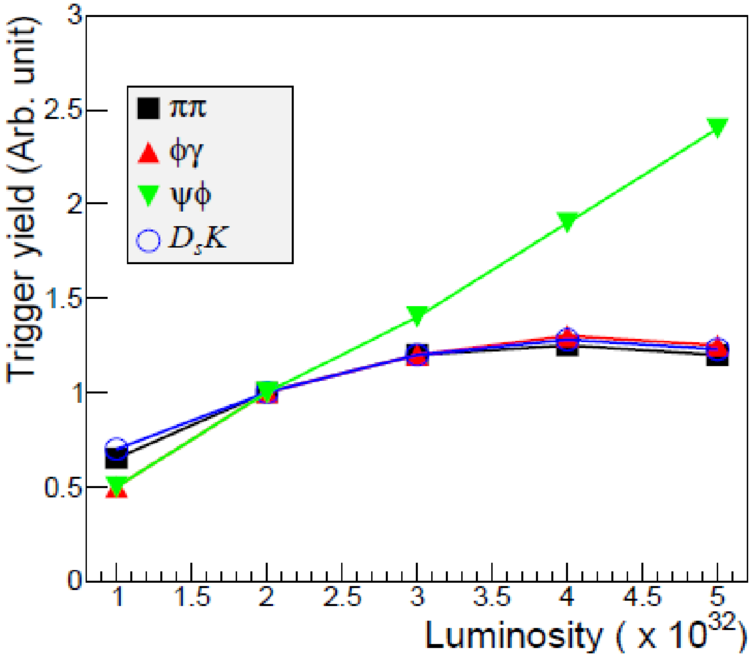
Upgrade I

Increase instantaneous luminosity
$4 \times 10^{32} \rightarrow 2 \times 10^{33}$ cm^{-2} s^{-1}

Abolish hardware trigger stage
to fully exploit higher collision rate

→ read out full detector at 40 MHz

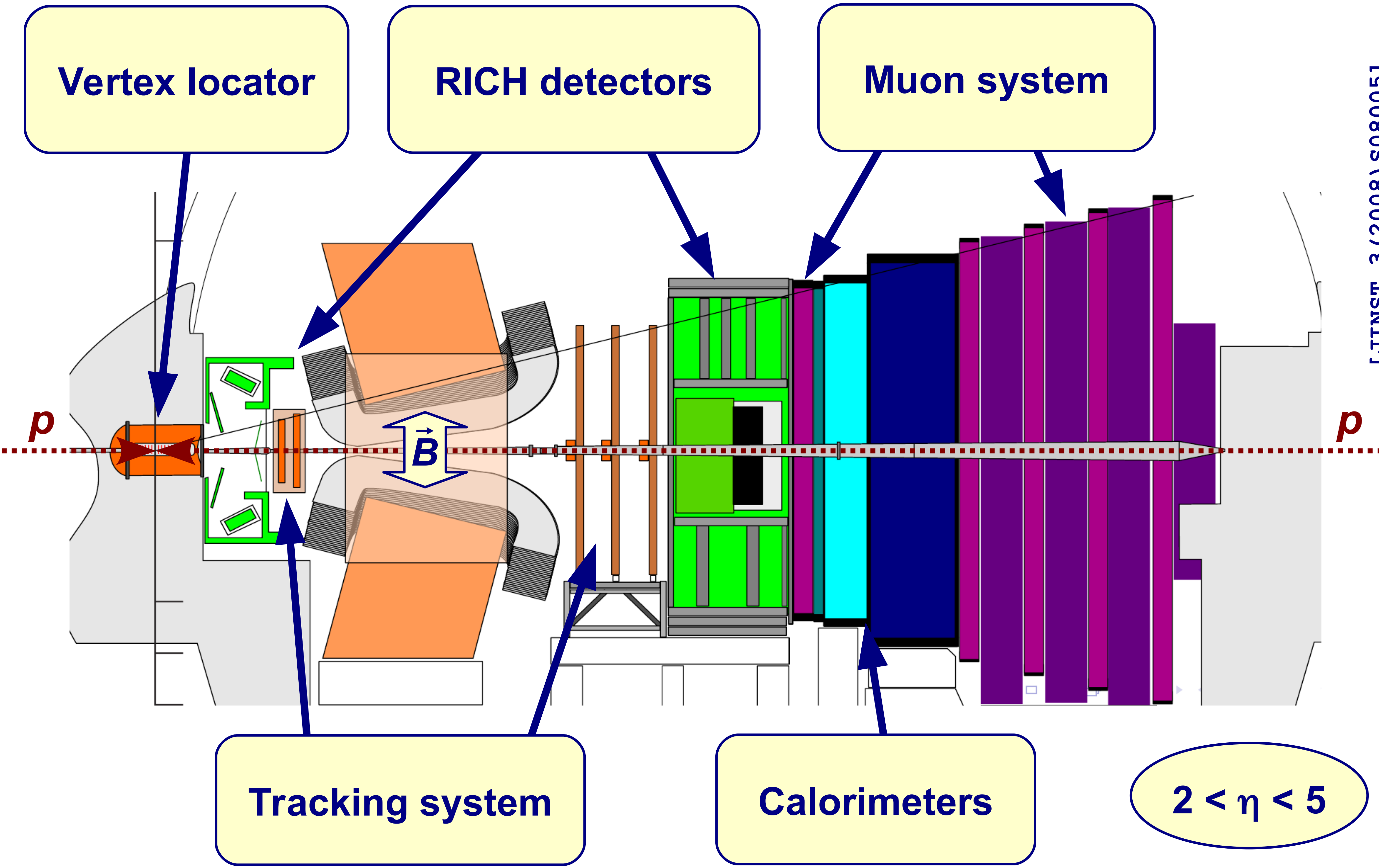
→ operate software trigger
at 40 MHz input rate !



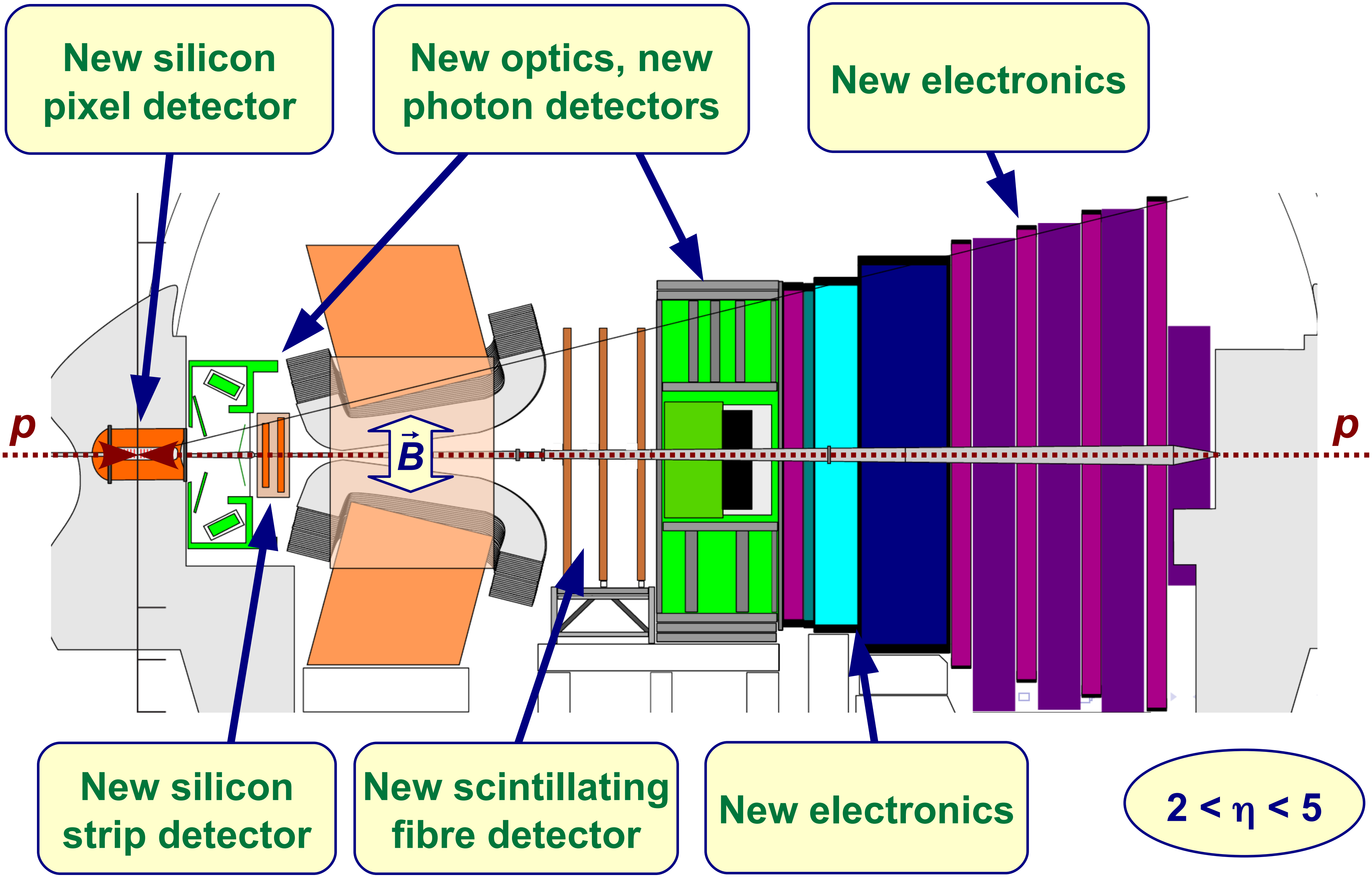
Replacement of tracking detectors
→ finer granularity to cope with higher particle density
→ new front-end electronics compatible with 40 MHz readout

Track reconstruction at collision rate !

LHCb Run I/II


Vertex locator
RICH detectors
Muon system
p
B
p
Tracking system
Calorimeters
2 < η < 5
[JINST 3 (2008) S08005]

LHCb Upgrade I

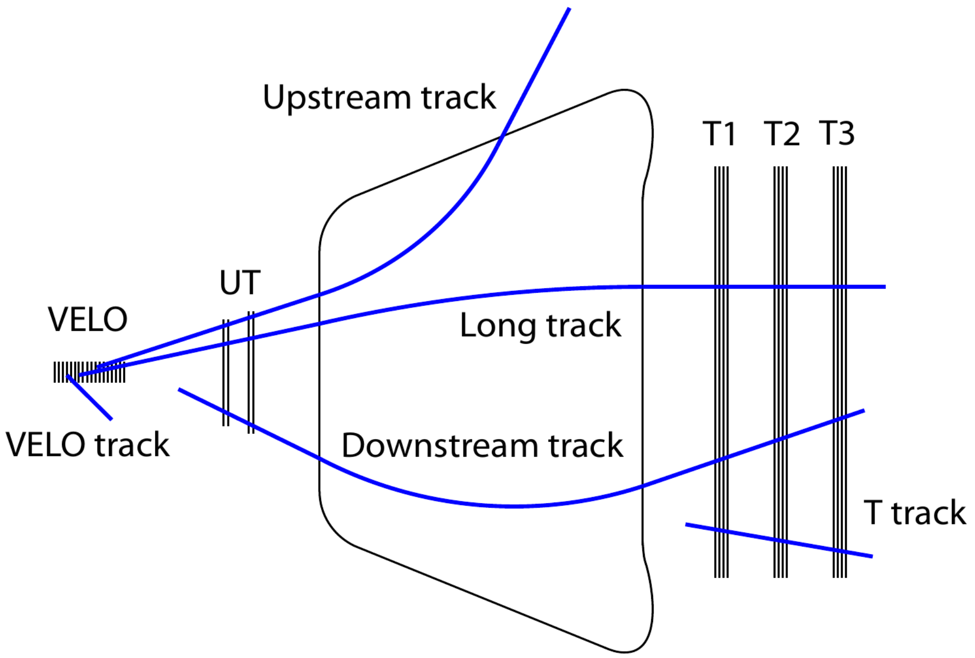


Track Reconstruction

"Long tracks" most useful for physics analyses

→ precise vertex and impact parameter

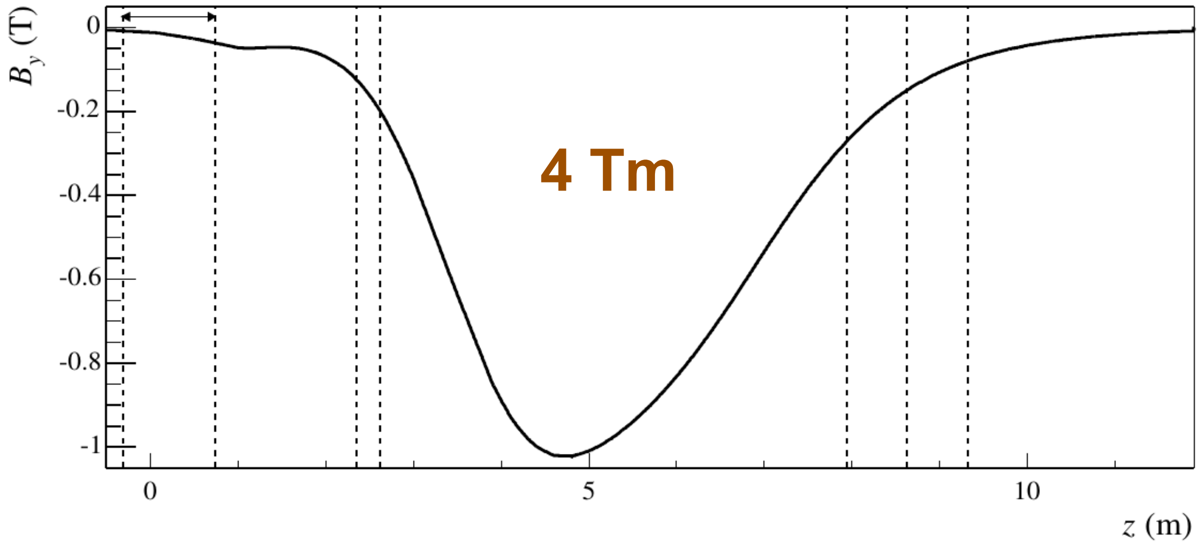
→ precise momentum



Challenge for pattern recognition:

→ sparse hit information

→ 5.5 m and 4 Tm in between UT and T stations



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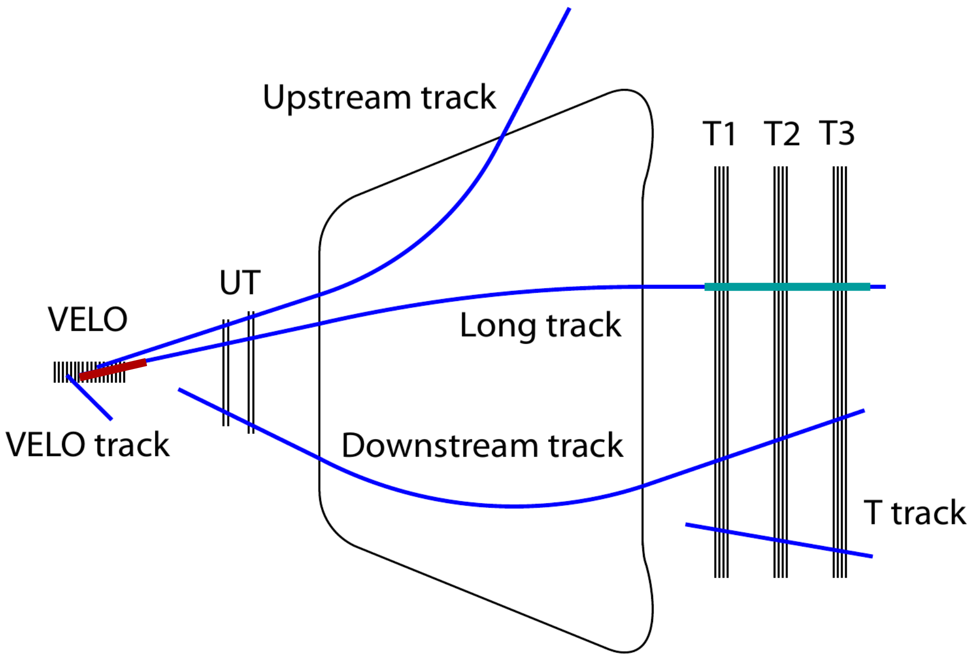
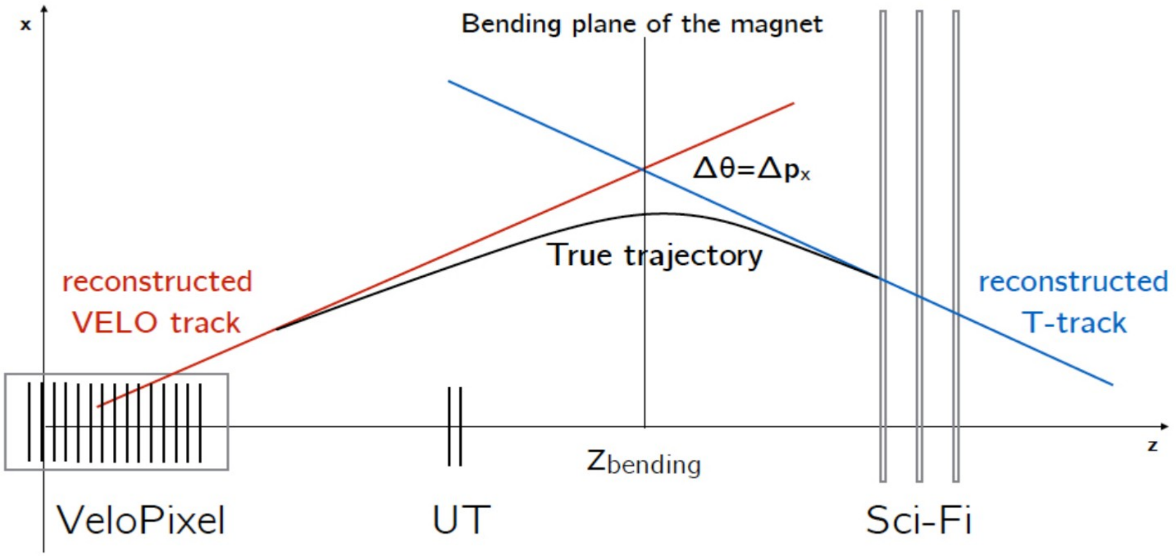


"Track matching"

→ extrapolate upstream and T tracks to middle of magnet

→ look for matches



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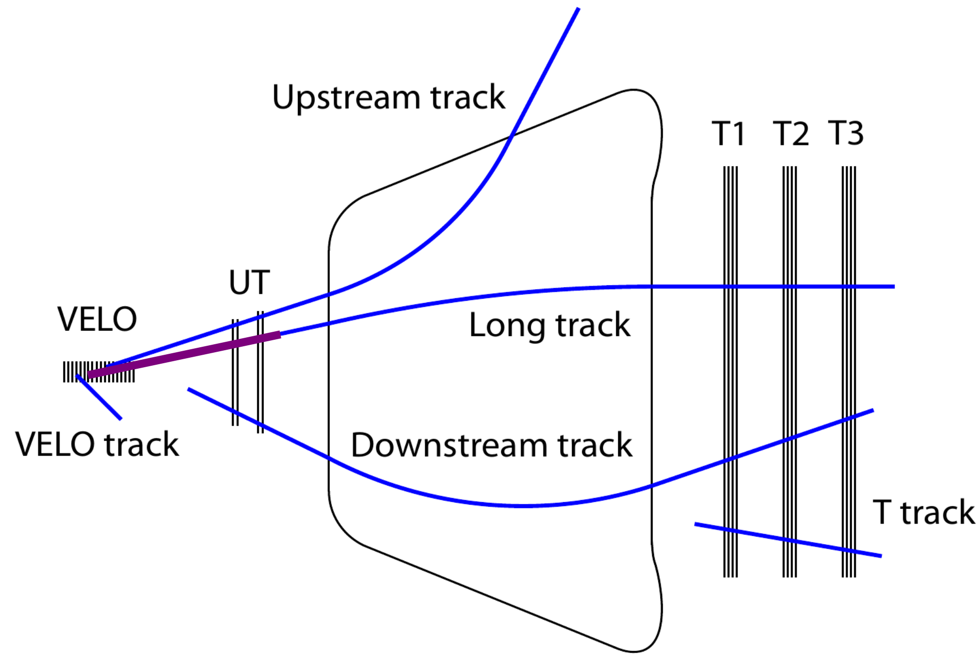
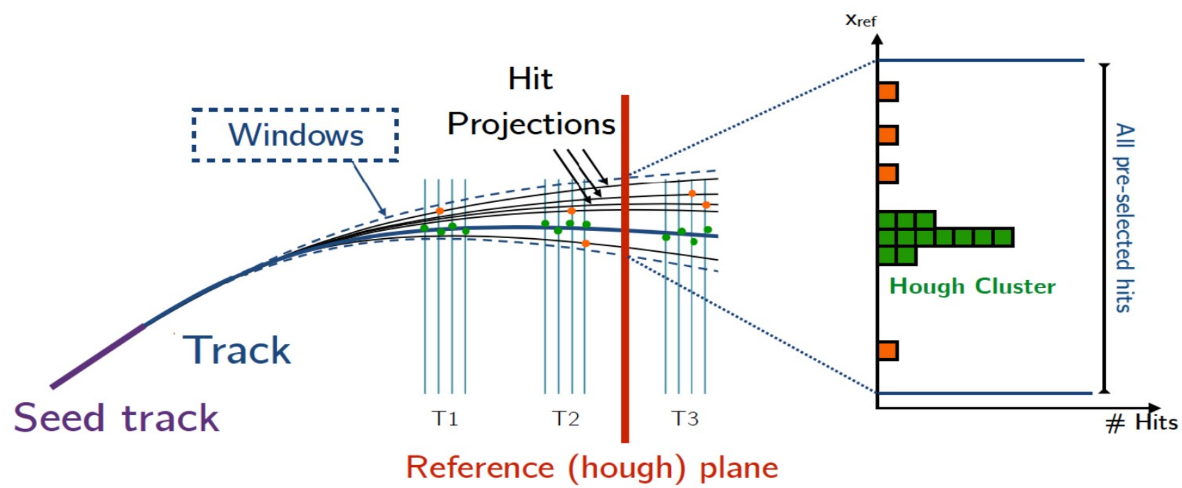


"Forward tracking"

→ extrapolate upstream track to T stations

→ open search window (momentum dependent!)

→ search for clusters of hits



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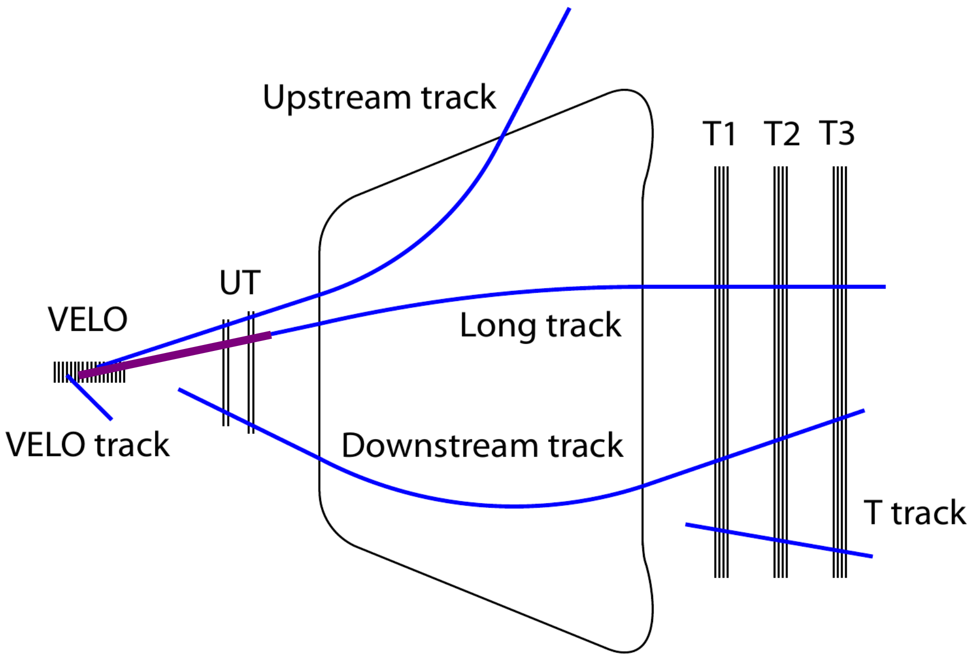
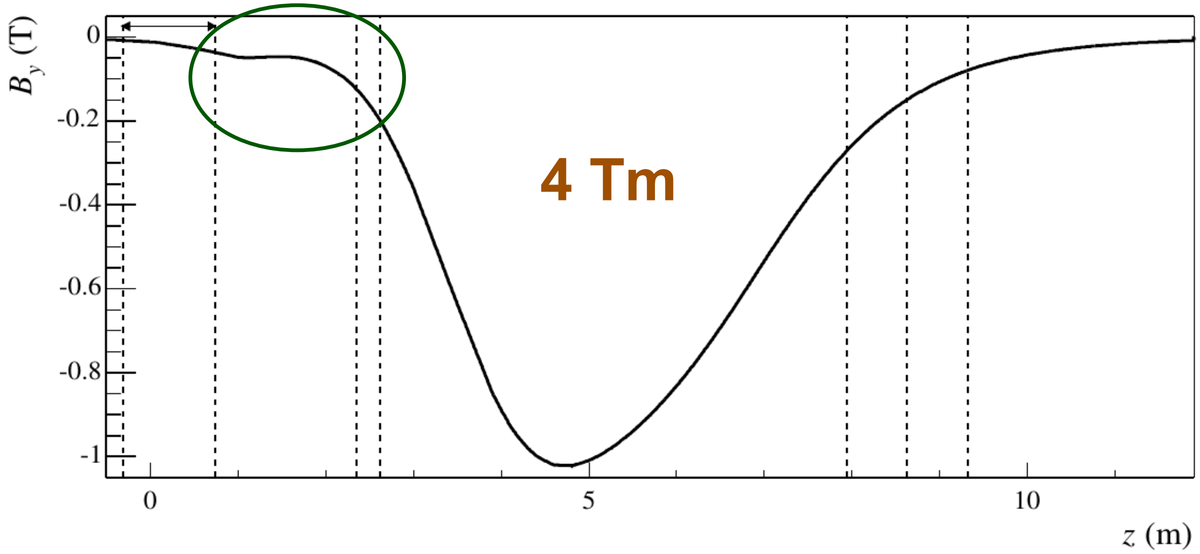


Fringe field in between VELO and UT:

→ determine charge

→ determine momentum to 15 – 30 % precision



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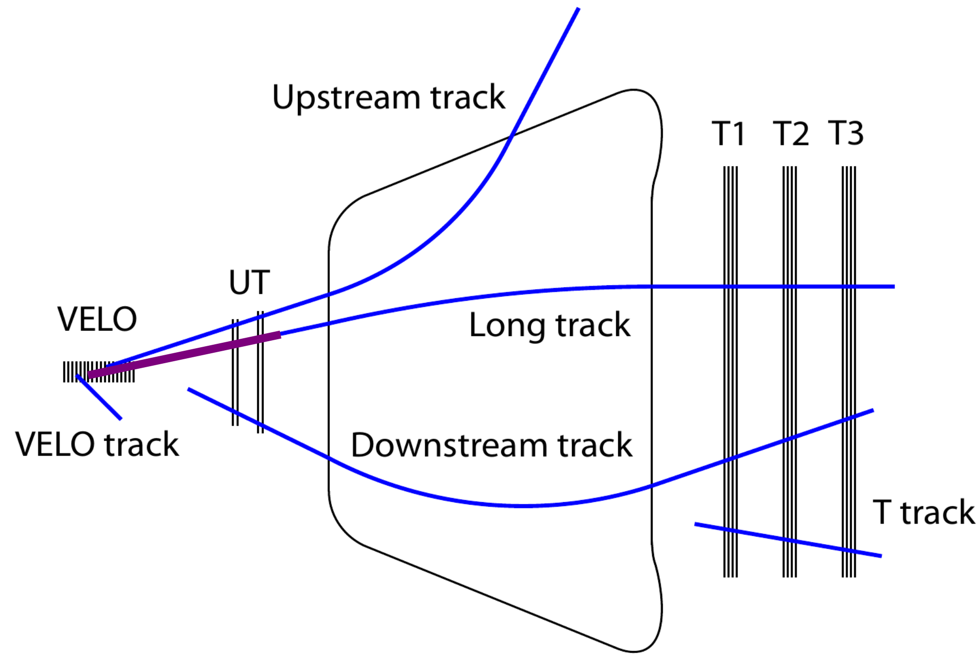
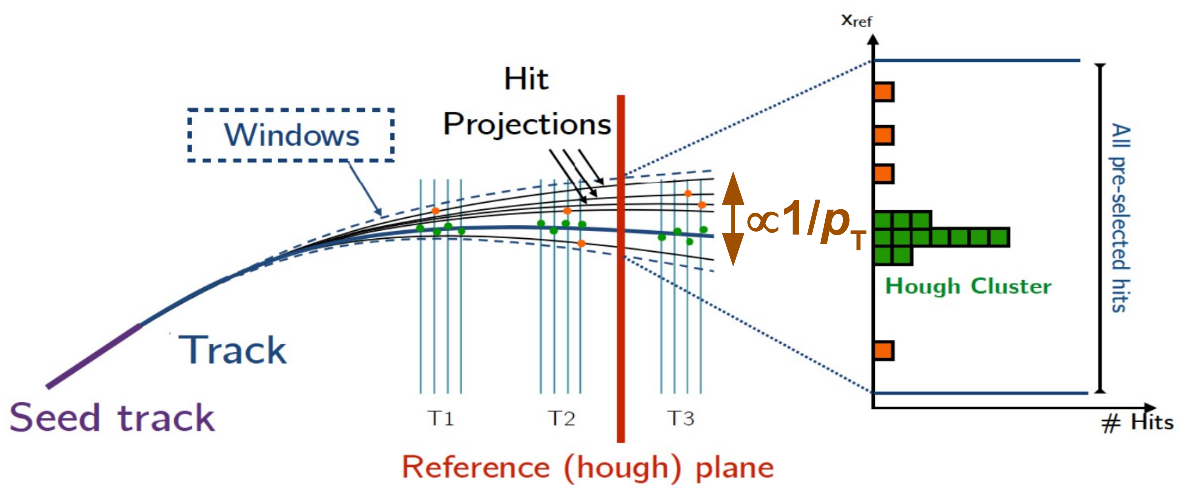


→ smaller search windows in downstream stations

→ fewer combinatorics

→ faster algorithm



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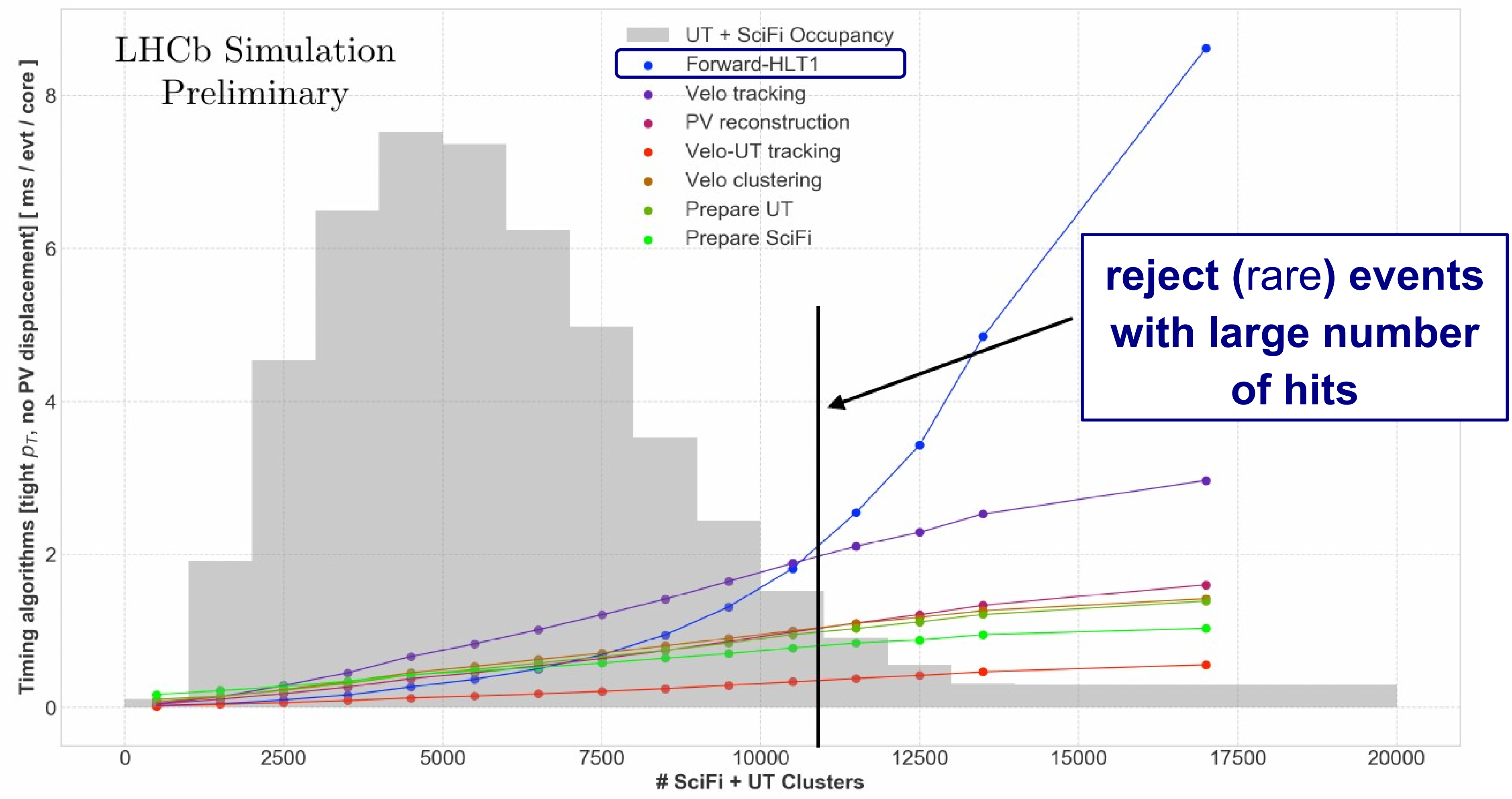

Upgrade II

Increase instantaneous luminosity
from 2×10^{33} to $1 - 2 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$

→ 28 – 55 ⟨ *pp* interactions / crossing ⟩

→ 1250 – 2500 ⟨ charged particles ⟩

→ 250 – 500 TB / s

Detectors / front-end electronics

→ finer granularity

→ timing resolution

→ radiation hardness

→ data preparation/processing

Pattern recognition algorithms

→ "ghost" rate

→ execution time

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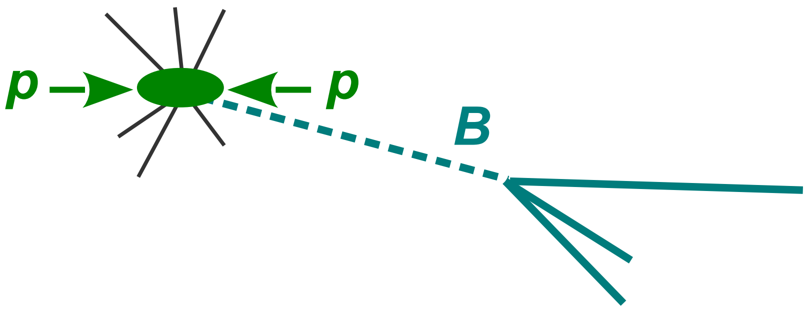

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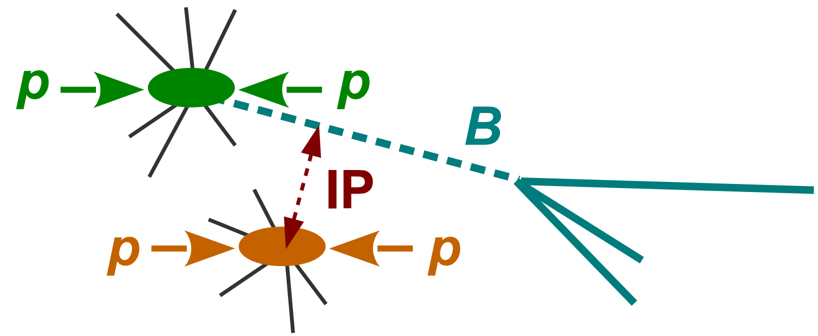

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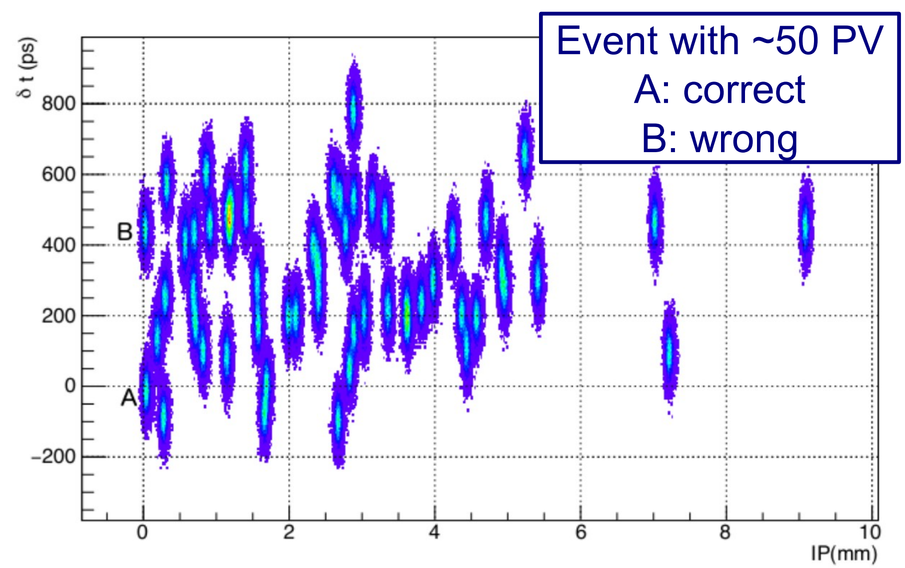

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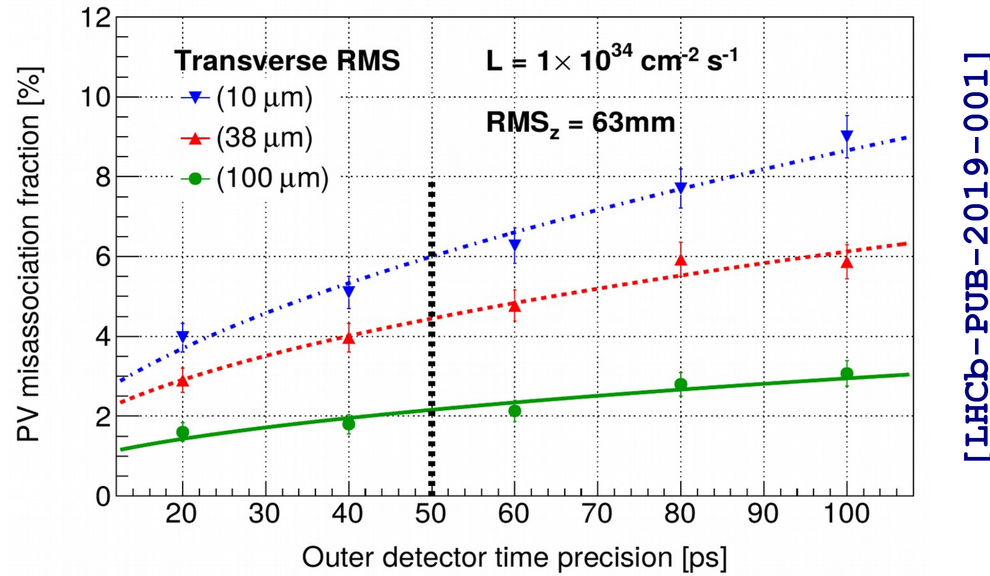

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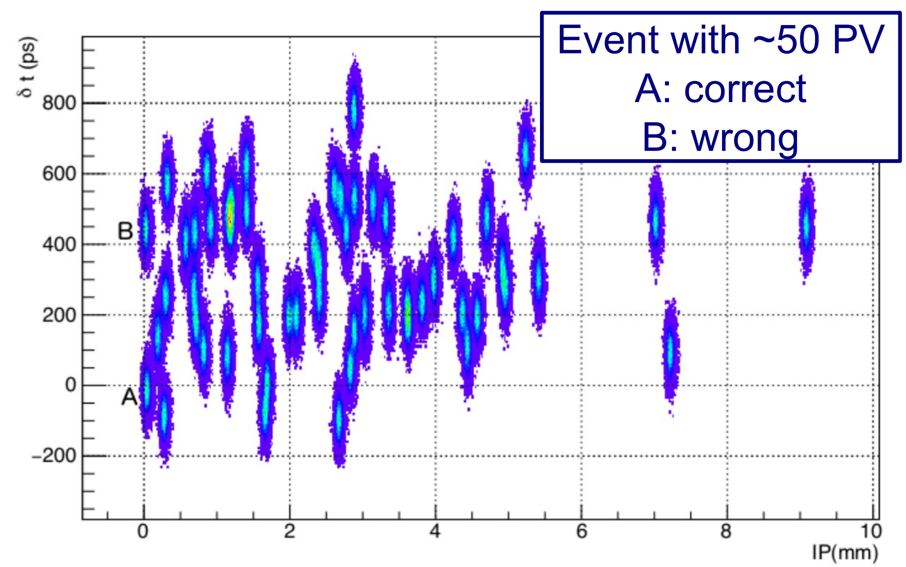
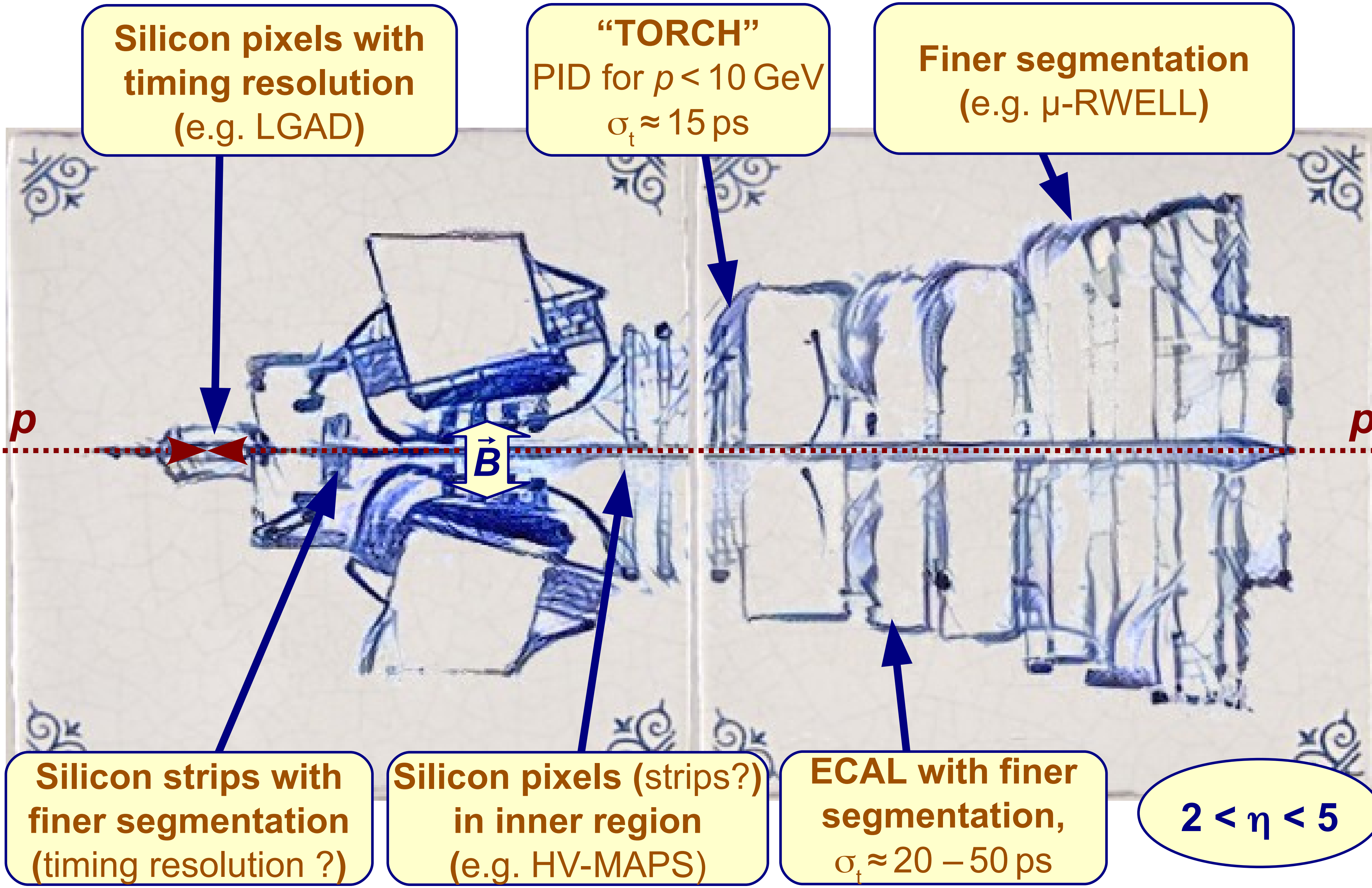
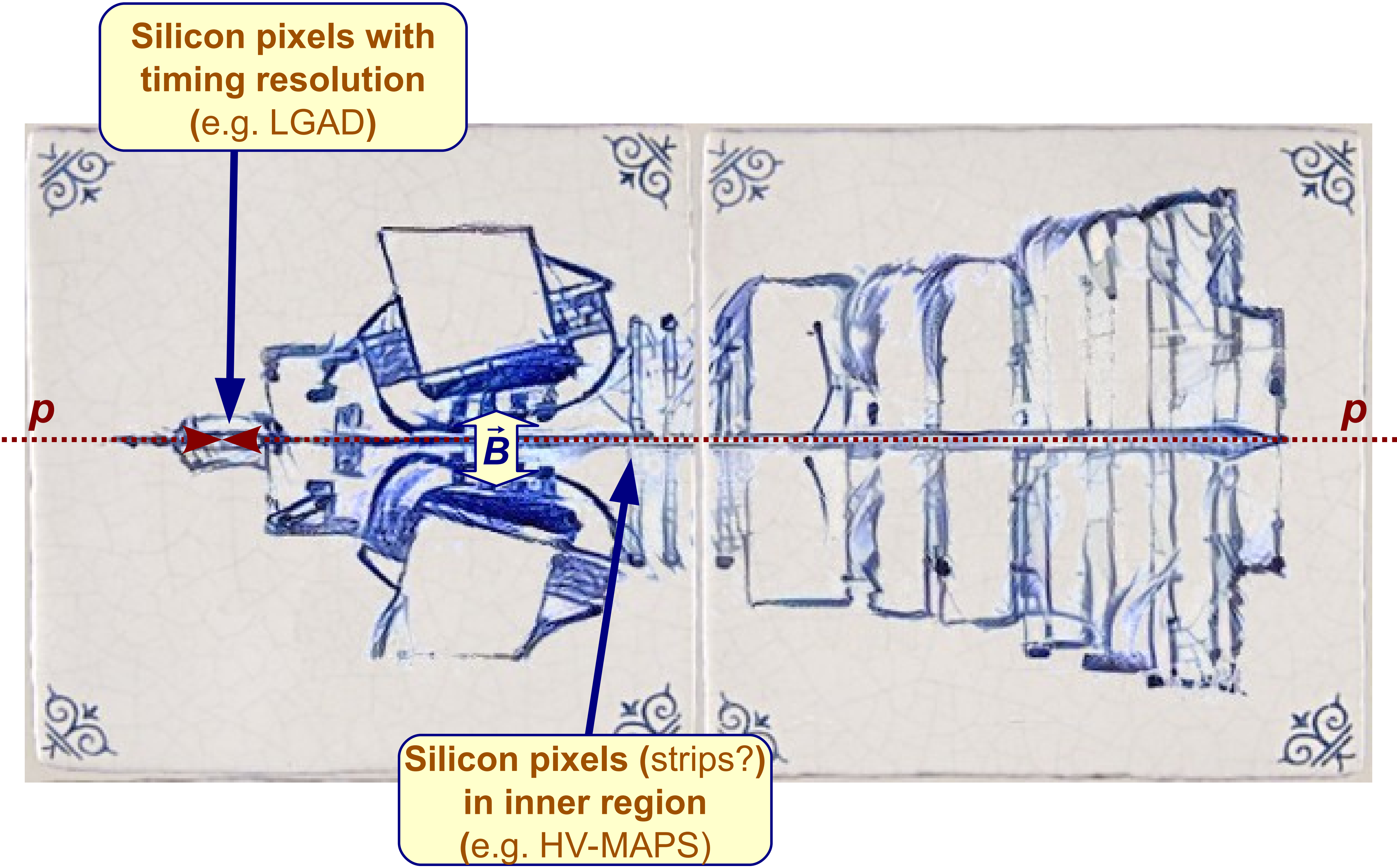


Upgrade II


Silicon pixels with timing resolution (e.g. LGAD)
"TORCH" PID for $p < 10$ GeV $\sigma_t \approx 15$ ps
Finer segmentation (e.g. µ-RWELL)
p
p
$\vec{B}$
Silicon strips with finer segmentation (timing resolution ?)
Silicon pixels (strips?) in inner region (e.g. HV-MAPS)
ECAL with finer segmentation, $\sigma_t \approx 20 - 50$ ps
$2 < \eta < 5$

Upgrade II



Silicon pixels with timing resolution (e.g. LGAD)
p
B
p
Silicon pixels (strips?) in inner region (e.g. HV-MAPS)

Upgrade II: VELO

Two-day retreat in Swiss Alps, two weeks ago

→ 44 participants from 18 institutes

→ mechanics and cooling

→ detector technologies

→ trigger, reconstruction, physics

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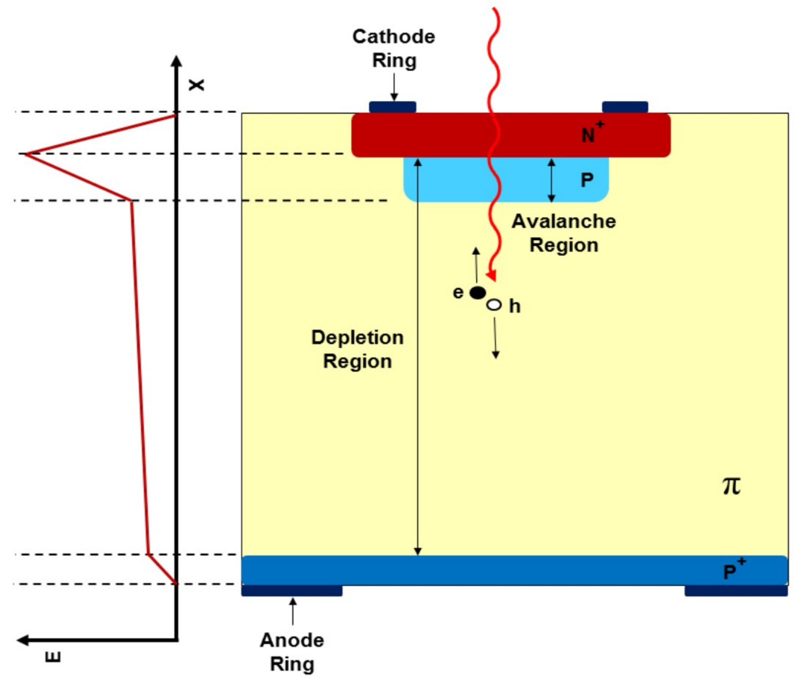
Low-Gain Avalanche Detectors

→ thin, highly doped gain layer

→ large signal despite thin sensor

→ time resolution of 30 ps feasible

→ pursued in ATLAS / CMS



[Giovanni Pellegrini @ 23rd RD50]

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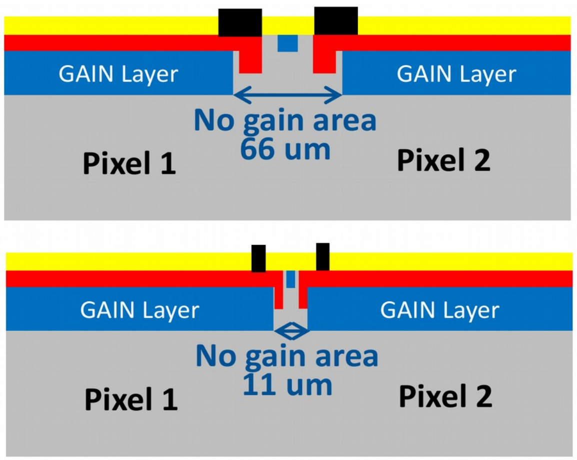
Performance for small pixels ?

→ low-gain area between pixels
→ non-uniform electric field

→ ATLAS/CMS investigate 1.3 × 1.3 mm²
→ VELO about 50 × 50 μm²



[Giovanni Paternoster @ TREDI 2019]

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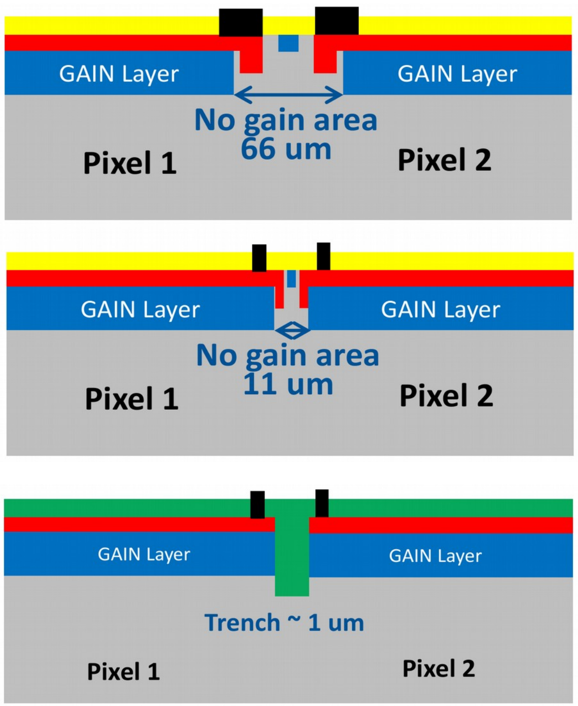

[Giovanni Paternoster @ TREDI 2019]

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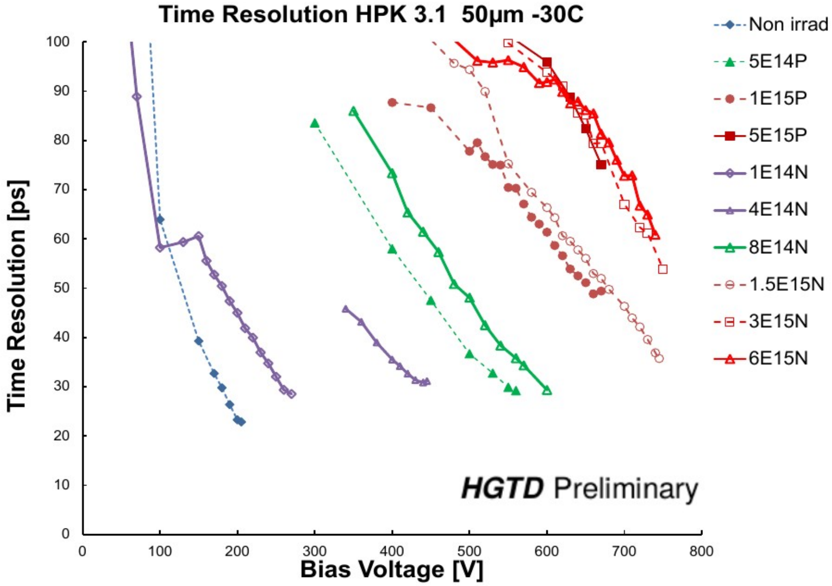
Low-Gain Avalanche Detectors

→ thin, highly doped gain layer
→ large signal despite thin sensor
→ time resolution of 30 ps feasible

Radiation hardness ?

→ donor removal in gain layer
→ higher bias voltage to maintain gain

→ few × 10^{15} 1-MeV n / cm^2 feasible
→ VELO expect up to 6 × 10^{16} 1-MeV n / cm^2



[Stefan Guindon @ TREDI 2019]

Upgrade II: VELO

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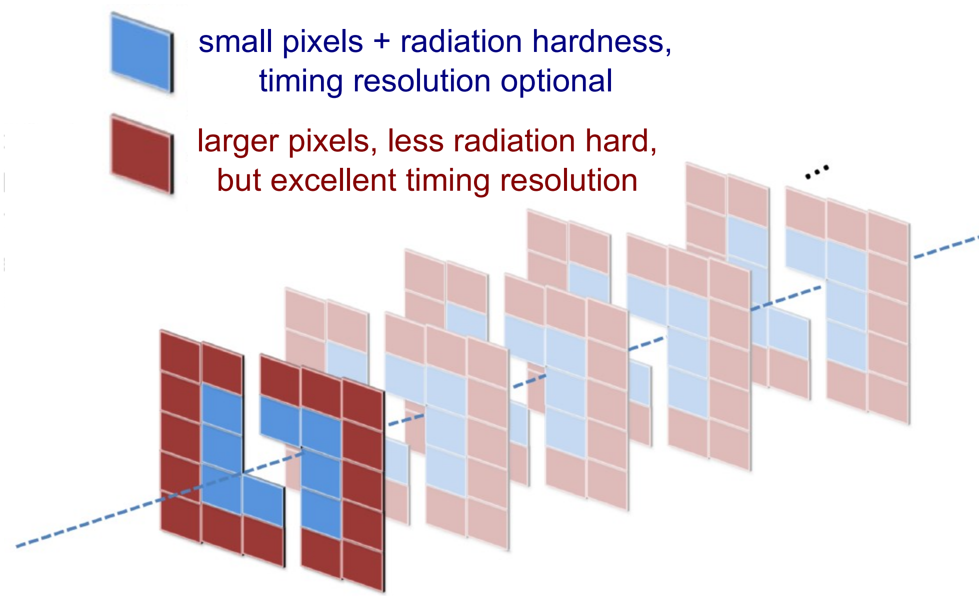
Possible hybrid approach:

→ emphasis on pixel size and extreme radiation hardness in inner region of each detection layer

→ emphasis on fast timing in outer region of each detection layer

→ but ... 2 detector technologies



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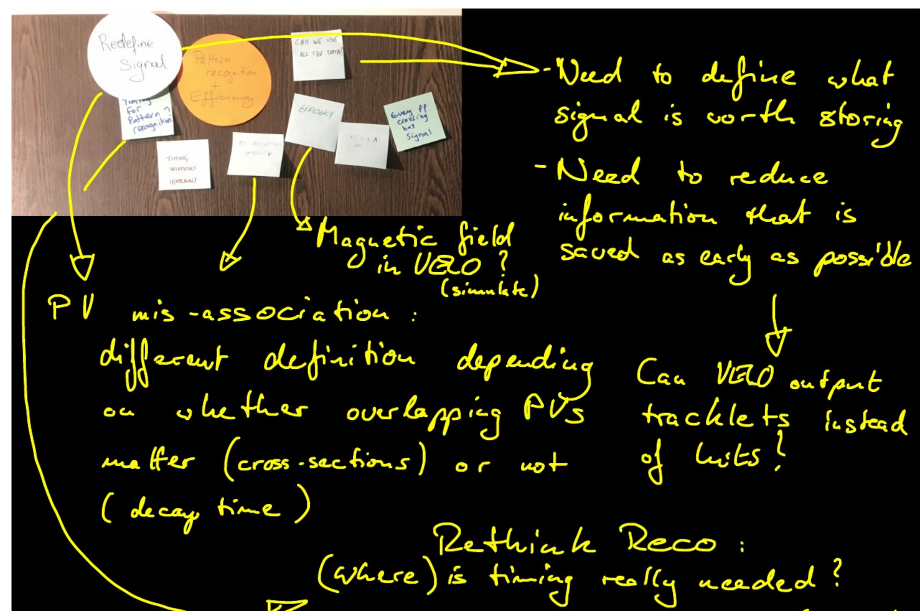
Track reconstruction at 3×10^7 events / s:

→ software (CPU/GPU) ?
→ firmware (FPGA) ?
→ hardware ???

VELO likely to play important role
→ low magnetic field, simple algorithms



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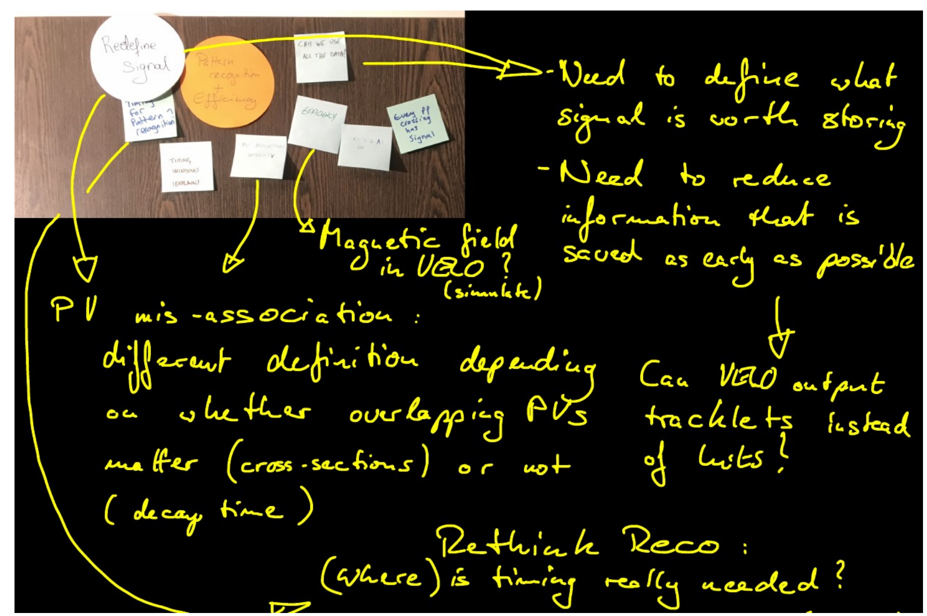
Track reconstruction at 3×10^7 events / s:
→ software (CPU/GPU) ?
→ firmware (FPGA) ?
→ hardware ???

VELO likely to play important role
→ low magnetic field, simple algorithms

Minimize time spent on data preparation
→ parallelize inside front-end electronics ?

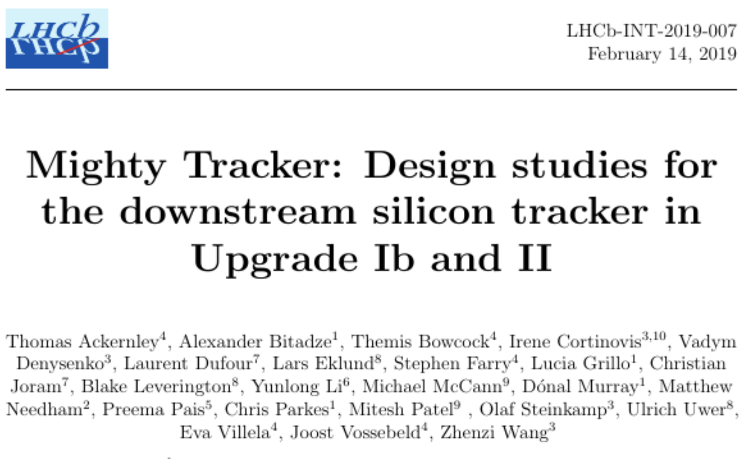


Upgrade II: “Mighty Tracker”

Design study for internal review

→ 23 authors from 9 institutes

→ size and layout
→ detector technology
→ mechanics, cooling
→ readout, pattern recognition


LHCb-INT-2019-007
February 14, 2019

Mighty Tracker: Design studies for the downstream silicon tracker in Upgrade Ib and II

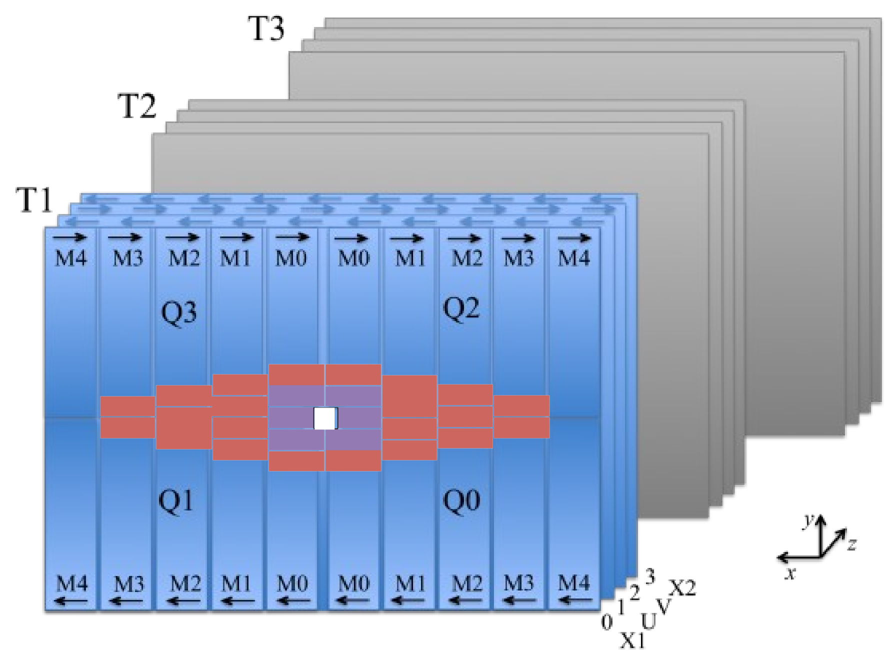
Thomas Ackernley[4], Alexander Bitadze[1], Themis Bowcock[4], Irene Cortinovis[3,10], Vadym Denysenko[3], Laurent Dufour[7], Lars Eklund[8], Stephen Farry[4], Lucia Grillo[1], Christian Joram[7], Blake Leverington[8], Yunlong Li[6], Michael McCann[9], Dónal Murray[1], Matthew Needham[2], Preema Pais[5], Chris Parkes[1], Mitesh Patel[9], Olaf Steinkamp[3], Ulrich Uwer[8], Eva Villela[4], Joost Vossebeld[4], Zhenzi Wang[3]

Silicon detector for inner part of downstream tracking stations

Staged approach:

→ ”small” Inner Tracker
for LS 3 (Upgrade Ib)

→ full-size Middle Tracker
for LS4 (Upgrade II)



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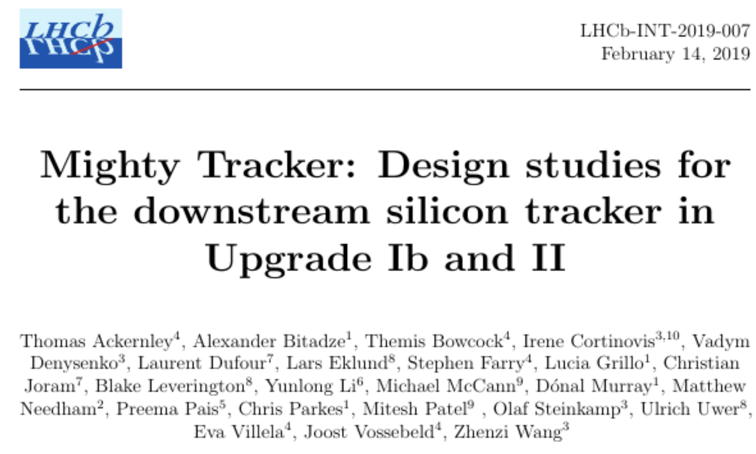
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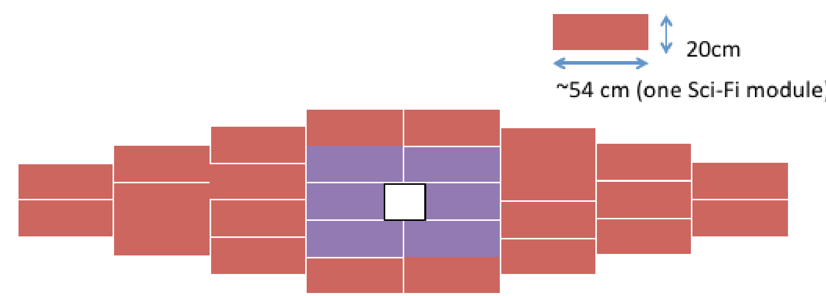
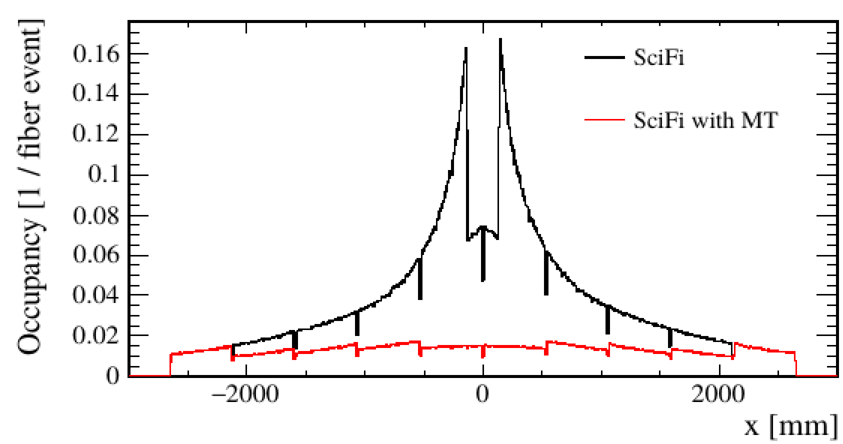
Size and layout determined by occupancies and radiation damage in surrounding SciFi Tracker



→ 3 m^2 per detection layer

→ 18 m^2 for six detection layers



→ largest silicon detector built for LHCb so far

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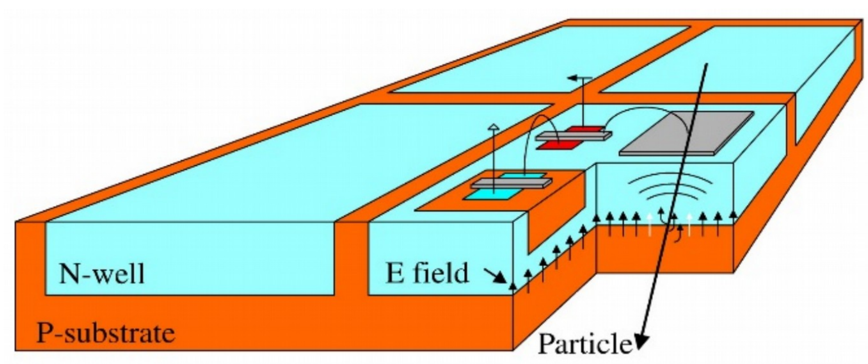
Promising technology: HV-CMOS pixel detectors

→ pioneered by mu3e at PSI, (ATLAS phase II upgrade)

→ time resolution ≤ 10 ns achieved in mu3e

→ sufficiently radiation hard

→ low power consumption (0.3 W/cm²)



[I.Peric, NIM A582(2007)876]

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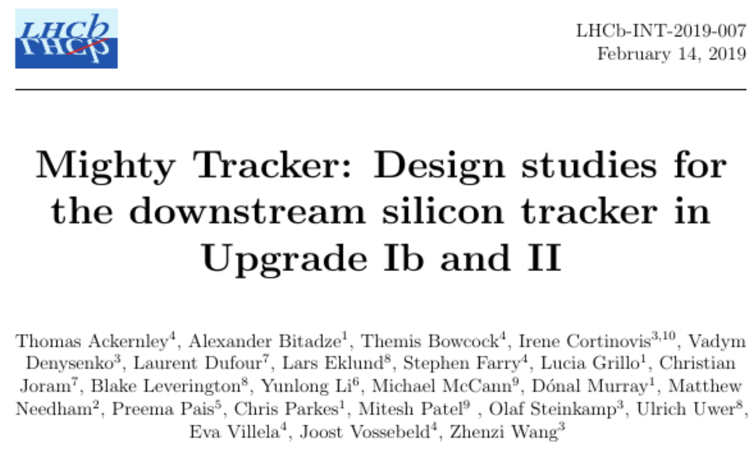
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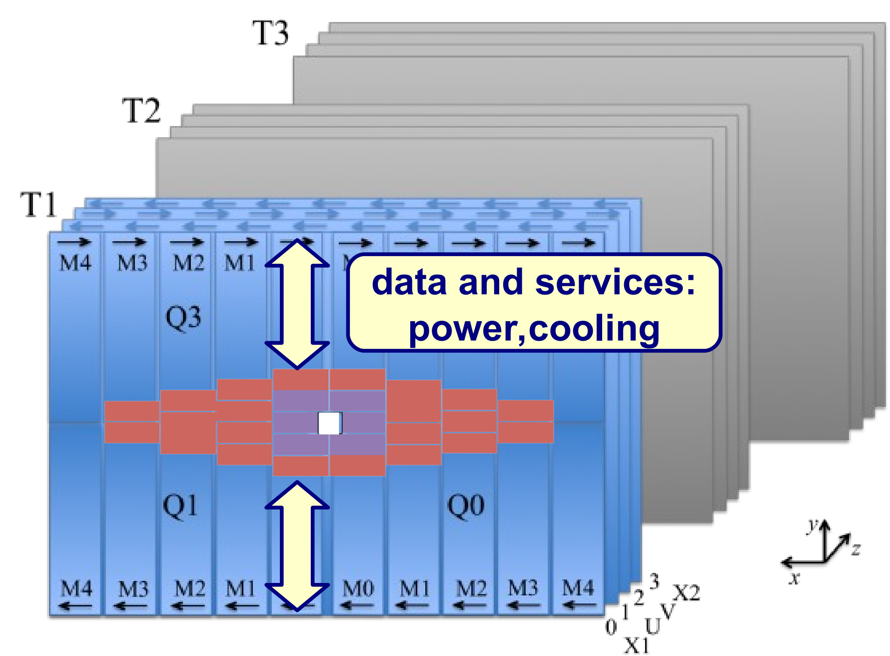

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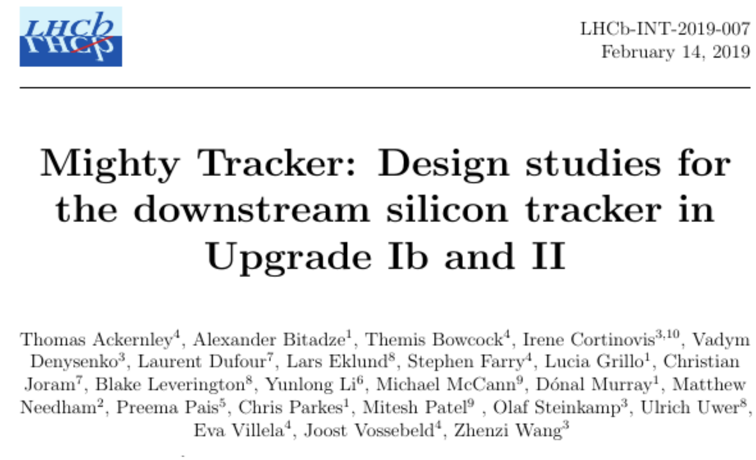
→ readout, **pattern recognition**

Occupancy < 1 % for pixel size of 100 × 500 µm²

→ c.f. 80 × 80 µm² for mu3e, 50 × 150 µm² for ATLAS phase II

Expect biggest challenge to be matching between upstream and downstream

→ combinatorics depend on track density, not occupancy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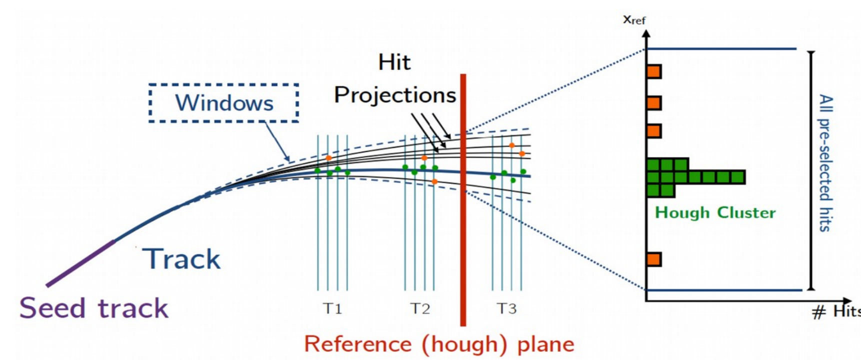

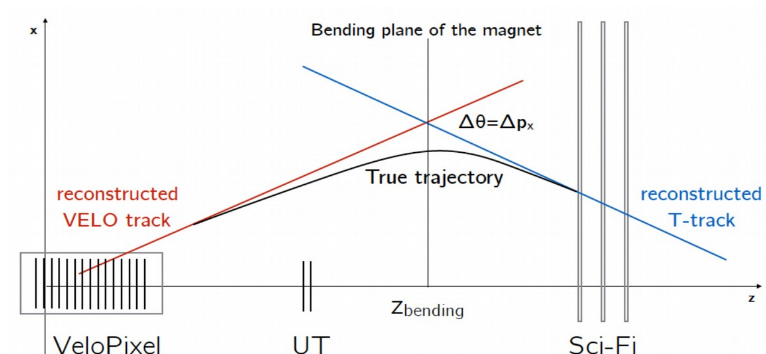

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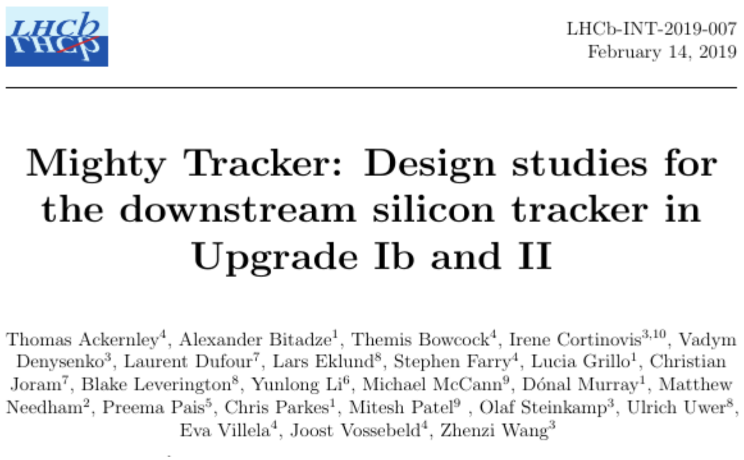
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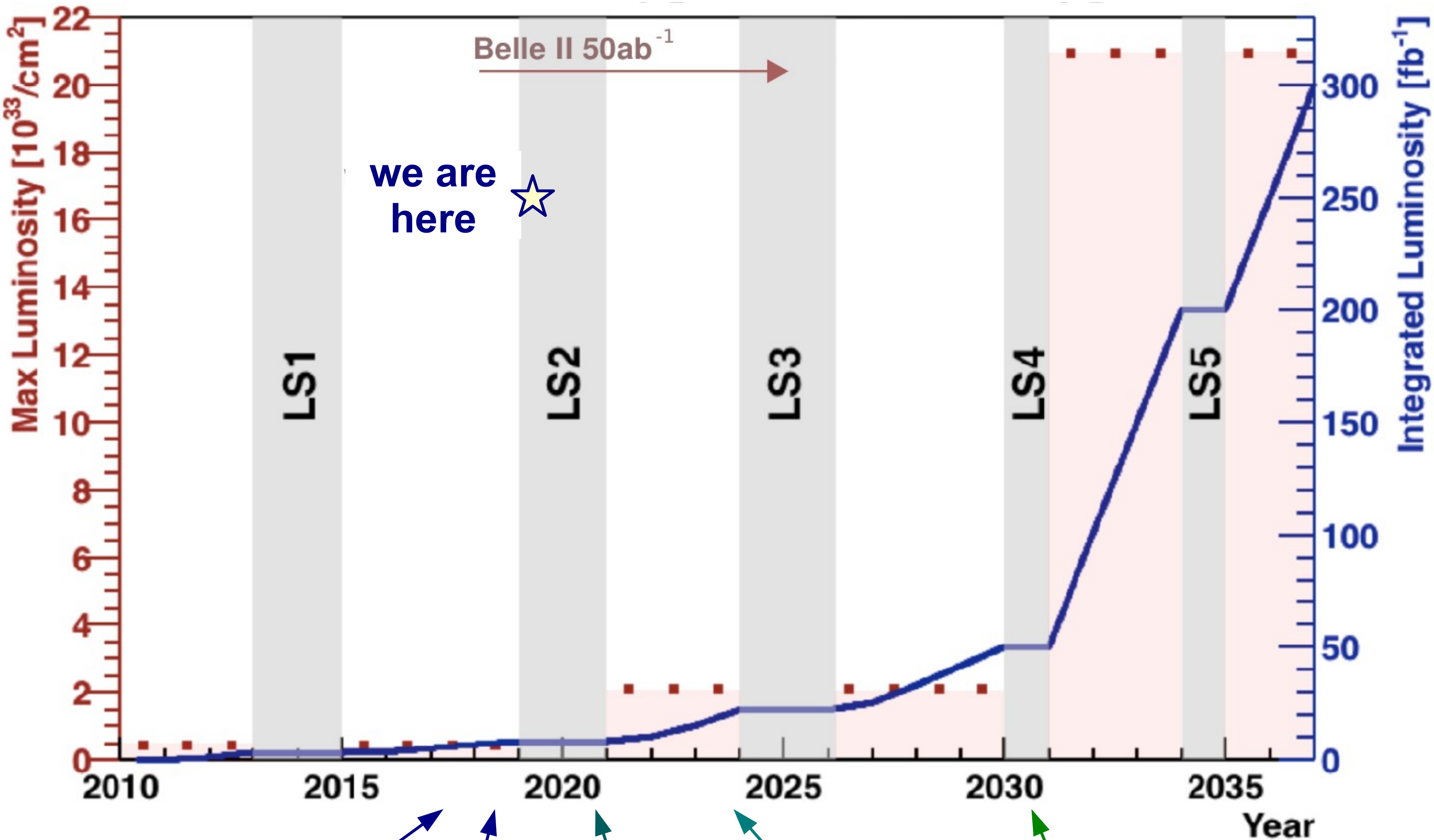
→ c.f. 80 × 80 μm² for mu3e,
50 × 150 μm² for ATLAS phase II

Expect biggest challenge to be matching between upstream and downstream

→ combinatorics depend on track density, not occupancy

Explore and investigate novel algorithms

Upgrade II: Timeline



Expression of Interest | Physics case | Framework TDR | Subdetector TDRs | Installation

Summary

Upgrade I in LS2 (now):

→ factor 5 in luminosity
→ full software trigger at 30 million events / s

→ detectors with finer granularity and 40 MHz readout

Upgrade Ib in LS3 (around 2025):

→ overall consolidation
→ e.g. silicon Inner Tracker

Upgrade II in LS4 (around 2030):

→ another factor 5-10 in luminosity

→ detectors with 4D resolution (space and timing)
→ radiation hardness

→ pattern recognition algorithms

Summary

Upgrade I in LS2 (now)

Tough, interesting challenges
→ detector technologies
→ reconstruction algorithms

Good initial ideas,
lots more work needed

New collaborators
welcome !

→ pattern recognition algorithms

Summary

Upgrade I in LS2 (now):

→ factor 5 in luminosity

→ full software trigger at 30 milli

... factor 5-10 in luminosity

→ detectors with 4D resolution (space and timing)

→ radiation hardness

→ pattern recognition algorithms

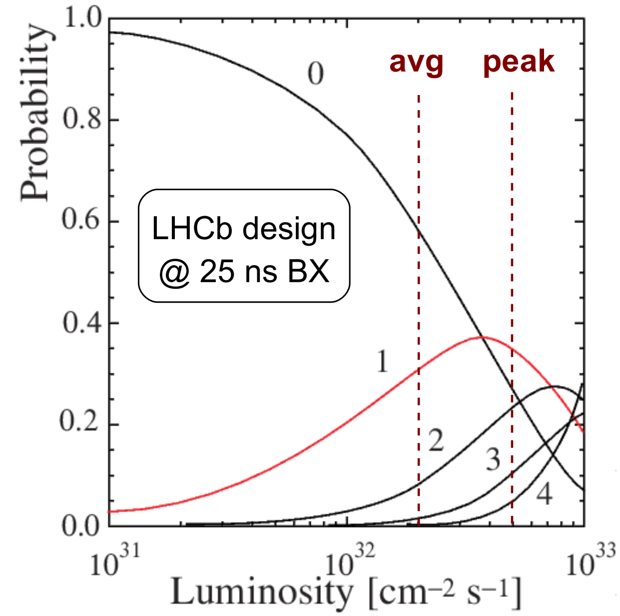
Extra

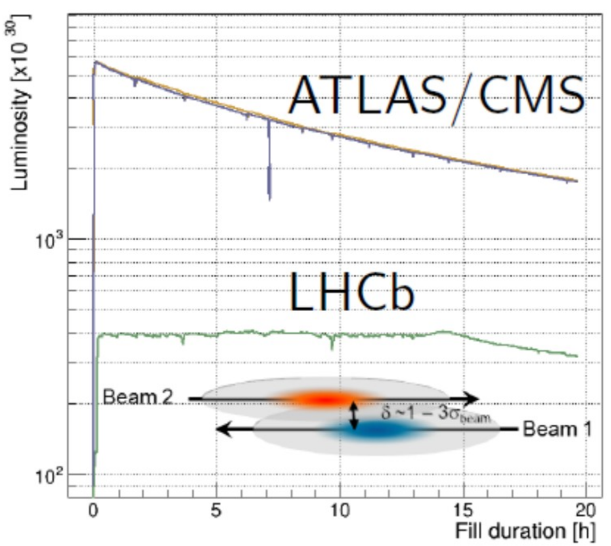
Increase instantaneous luminosity
$4 \times 10^{32} \rightarrow 2 \times 10^{33}\ cm^{-2}\ s^{-1}$

Remember:
LHCb operates at lower luminosity than ATLAS/CMS

→ achieved by colliding beams with small relative offset in LHCb interaction point

→ higher luminosity for LHCb does not require LHC upgrade

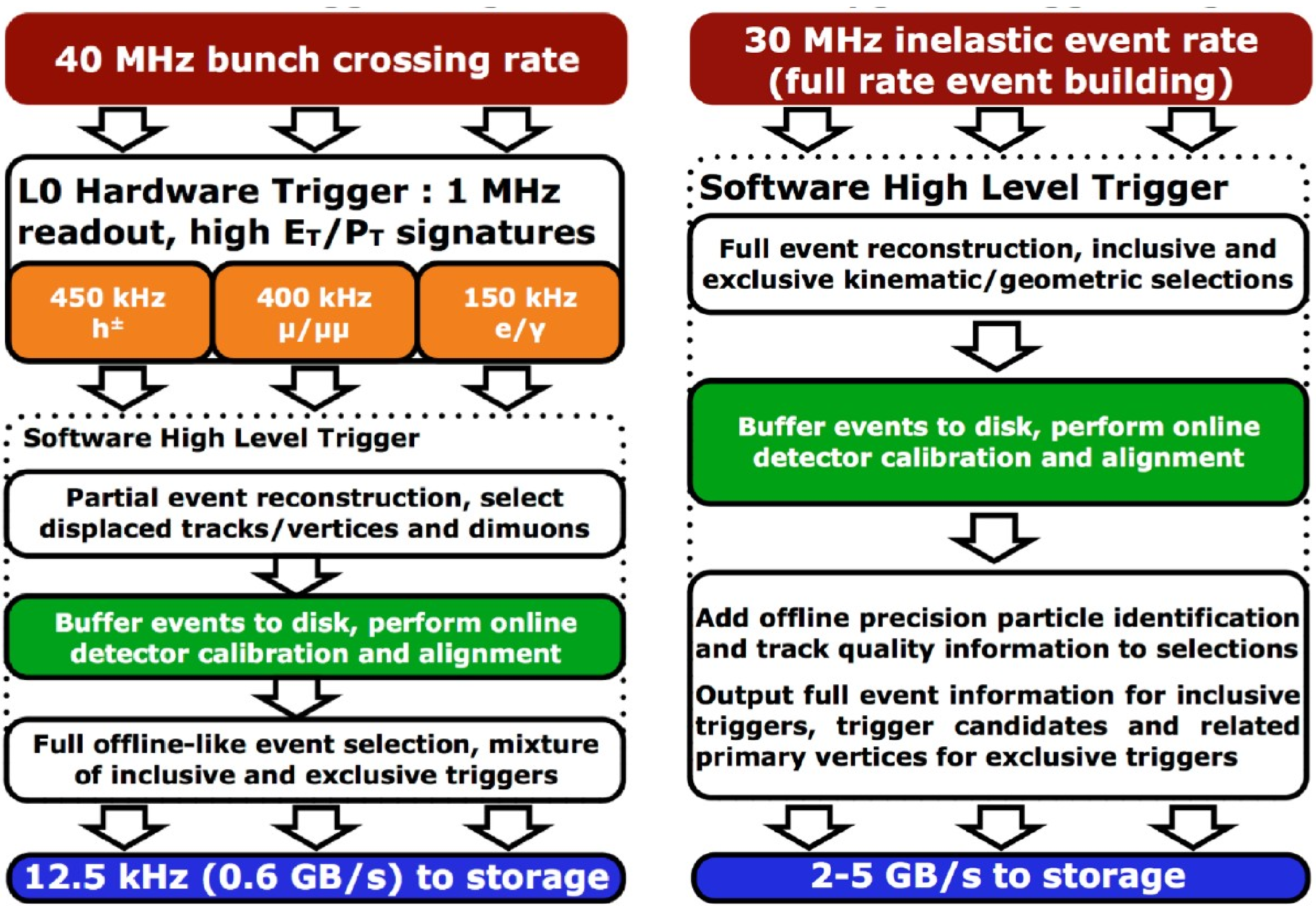




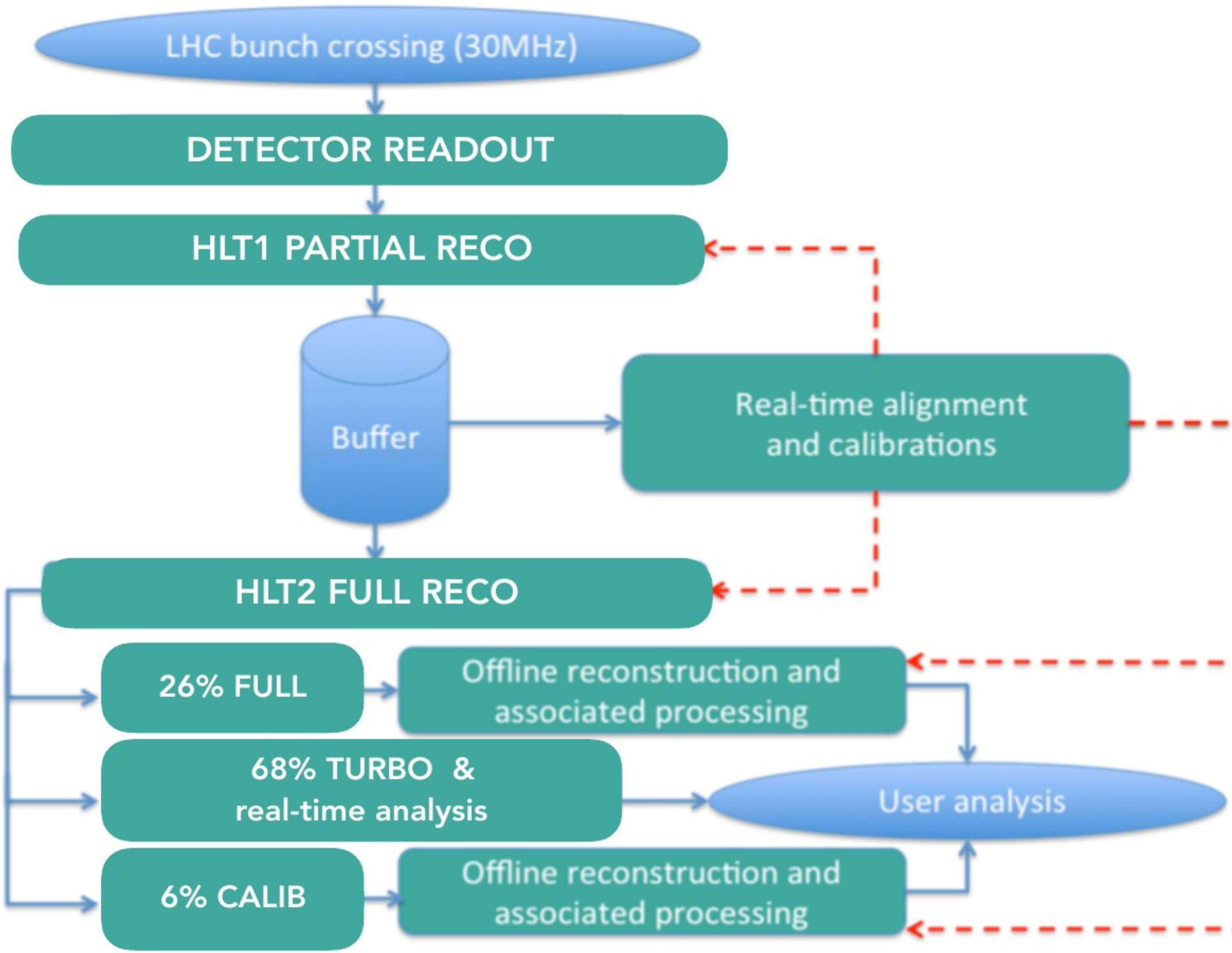
(very old plot, but illustrates the point)

Upgrade I: Trigger

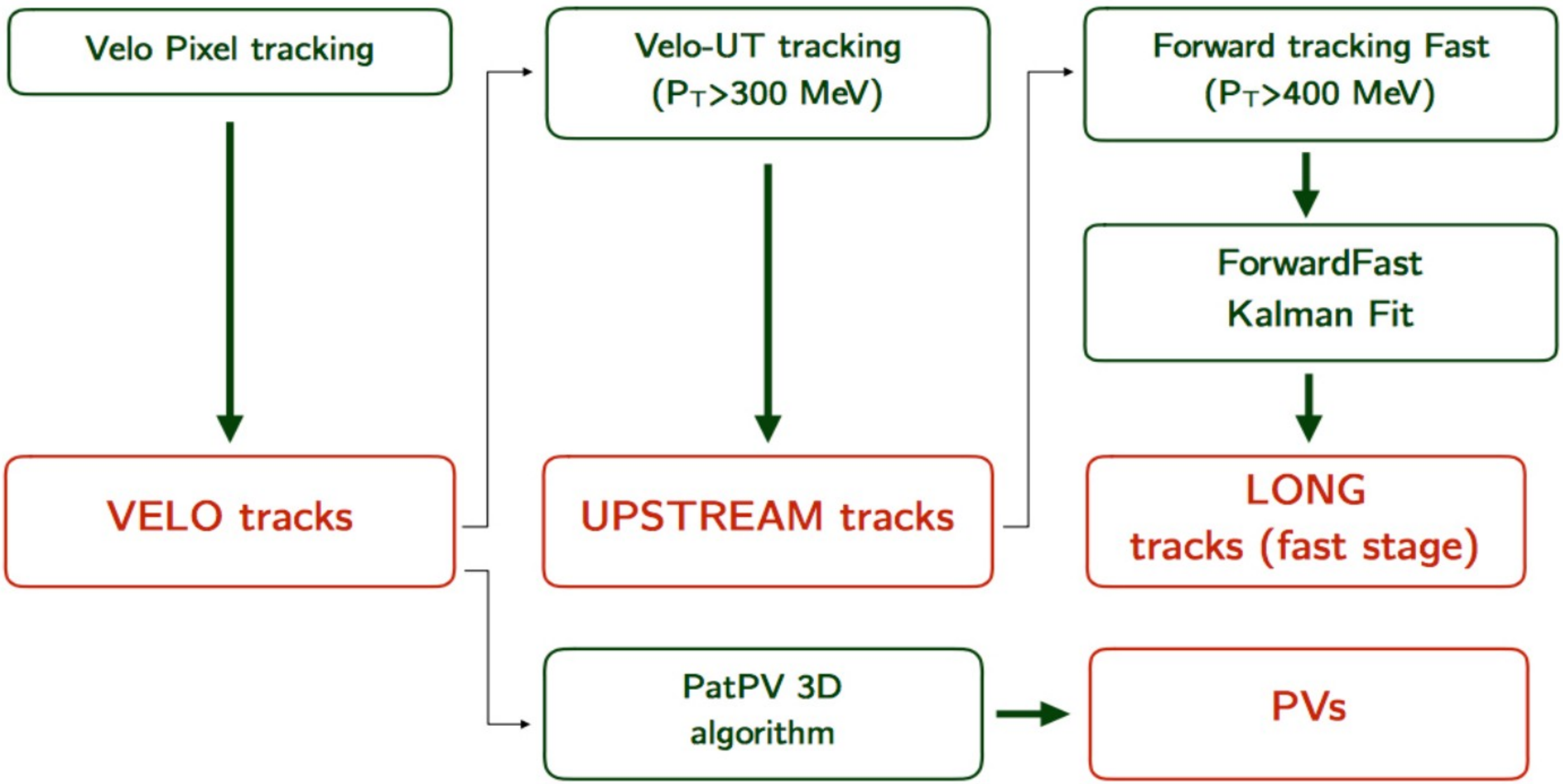
LHC Run II (2015) | Upgrade



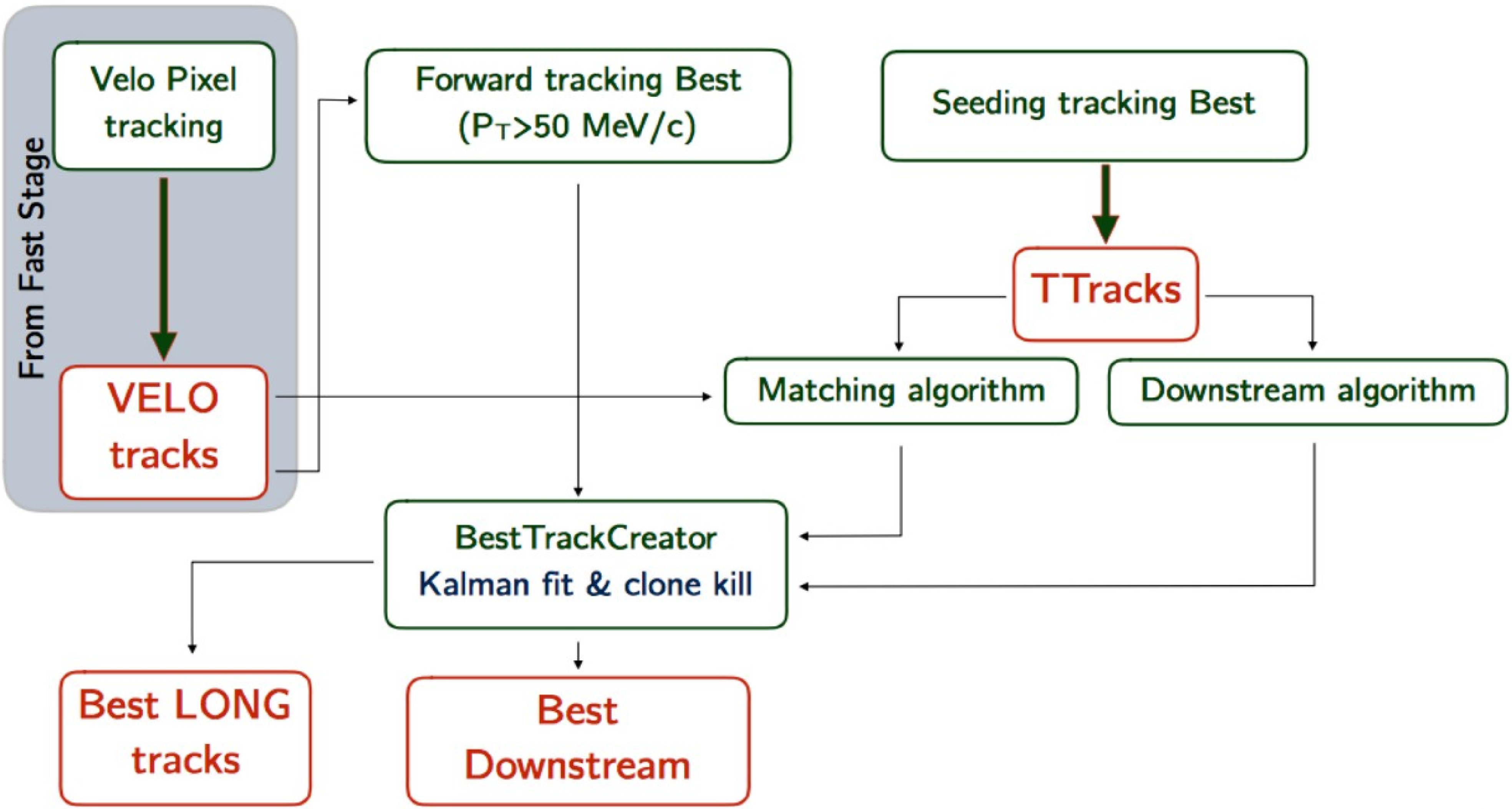
Upgrade I: Trigger/Reconstruction



Upgrade I: Track Reconstruction



Upgrade I: Track Reconstruction



Upgrade I: VELO

26 layers of silicon pixel detectors

→ VeloPix

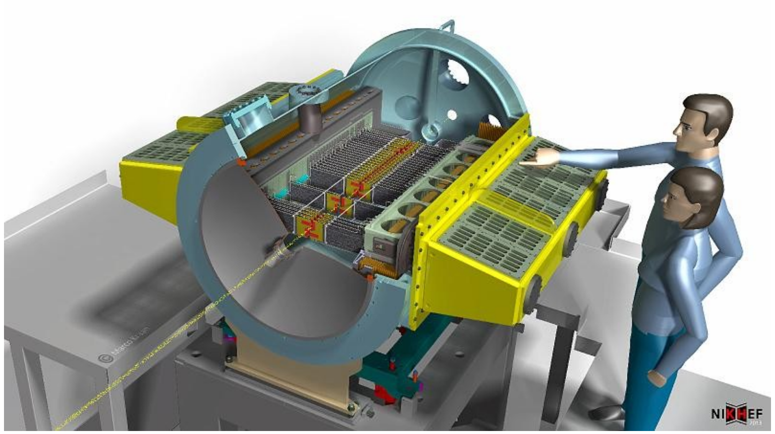
Closer to beam

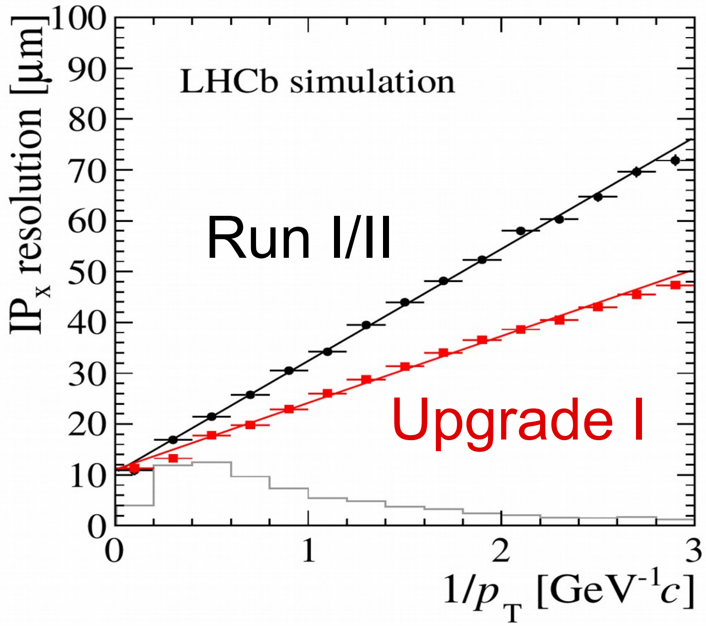
→ active area 8.2 → 5.1 mm

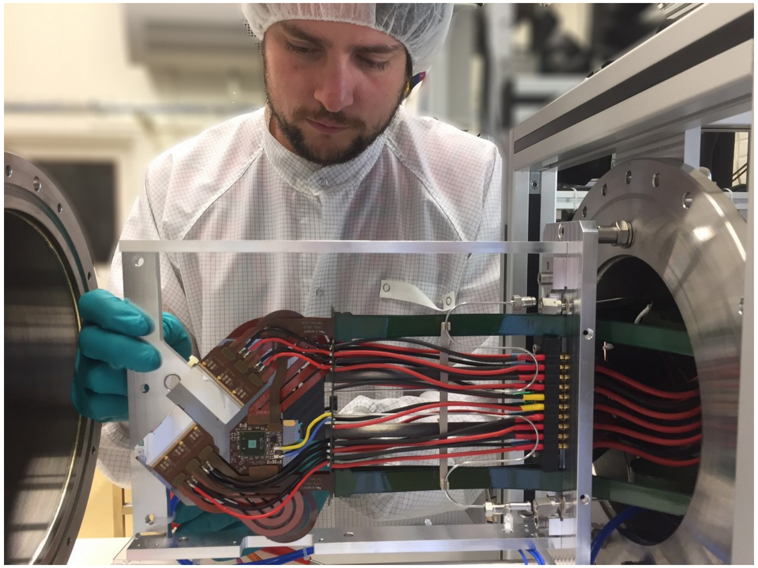
Less material

→ thinner sensors (300 → 200 μm)

→ thinner aluminium foil (300 → 150-250 μm)







[CERN/LHCC 2014-001, LHCb TDR 15]

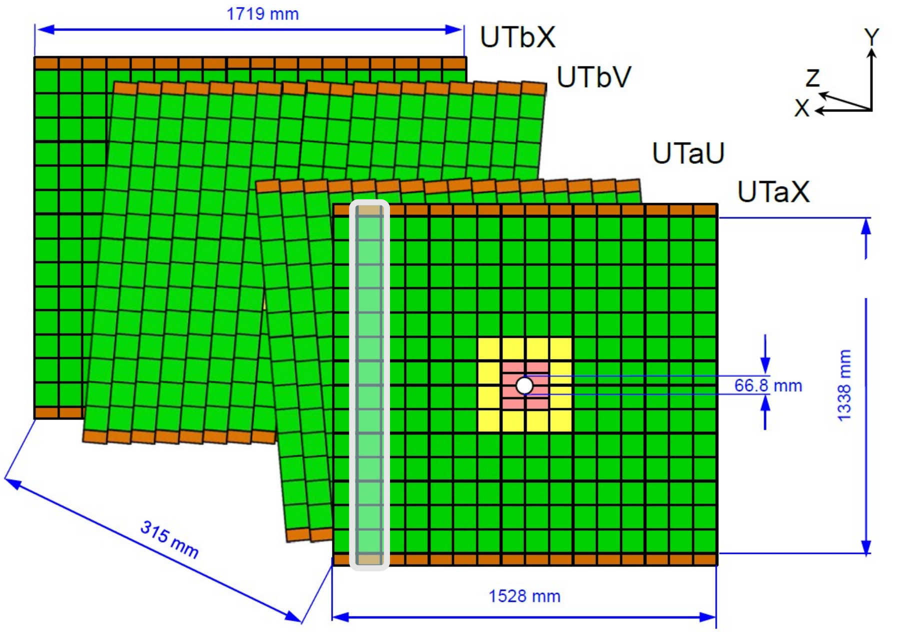
Upgrade I: Upstream Tracker

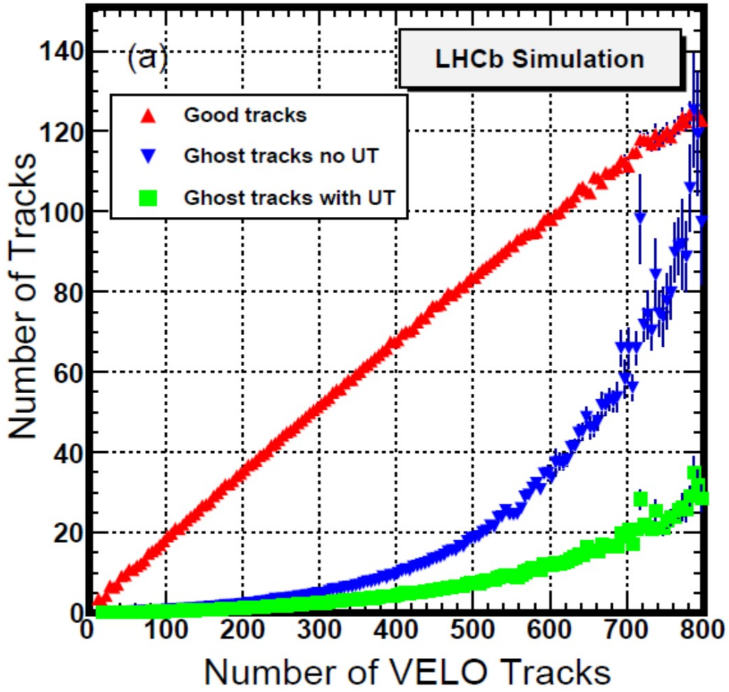
4 layers of silicon micro-strips

→ 190 and 95 µm pitch

→ 10 and 5 cm in length

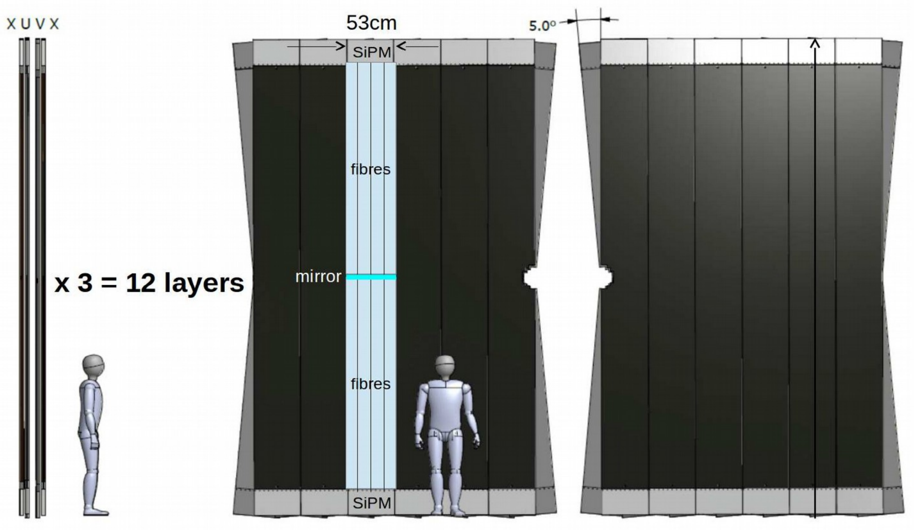
(finer granularity in inner region)

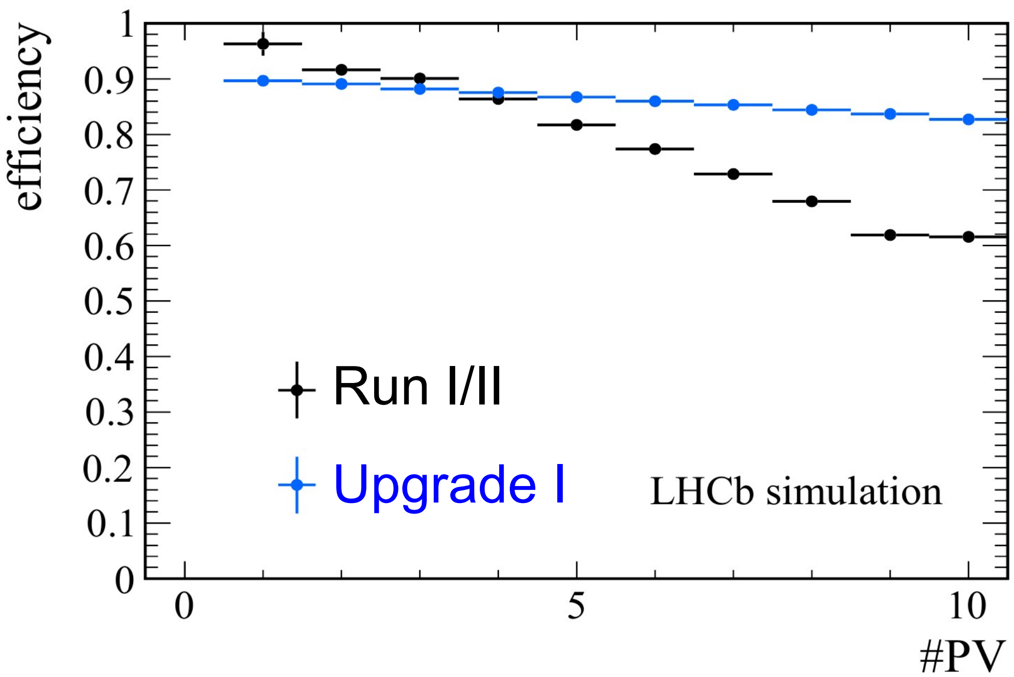




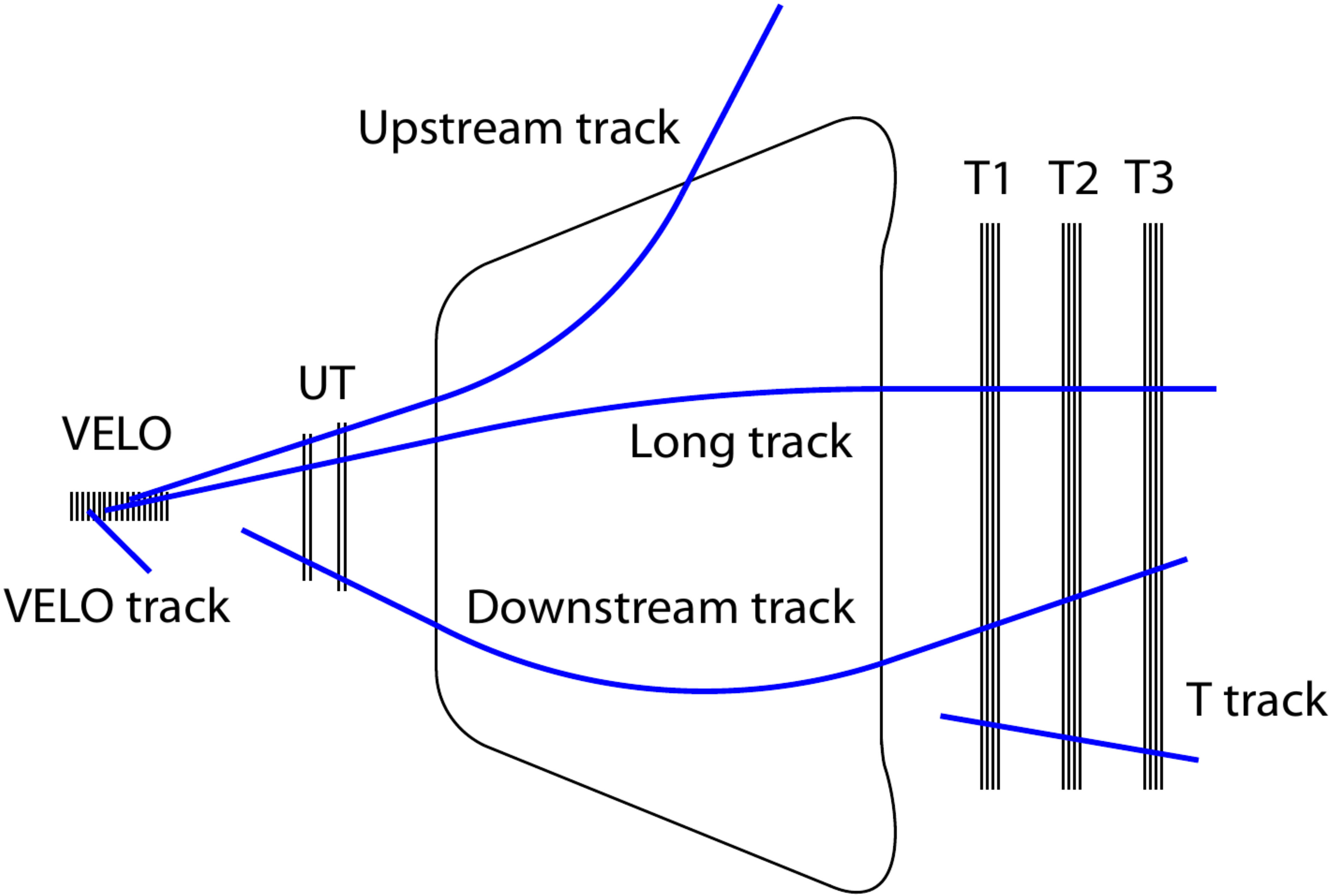
Upgrade I: Downstream Tracker

3 stations of scintillating fibres,
four detection layers each
→ 2.5 m long, 250 µm diameter
→ read out with silicon photomultipliers

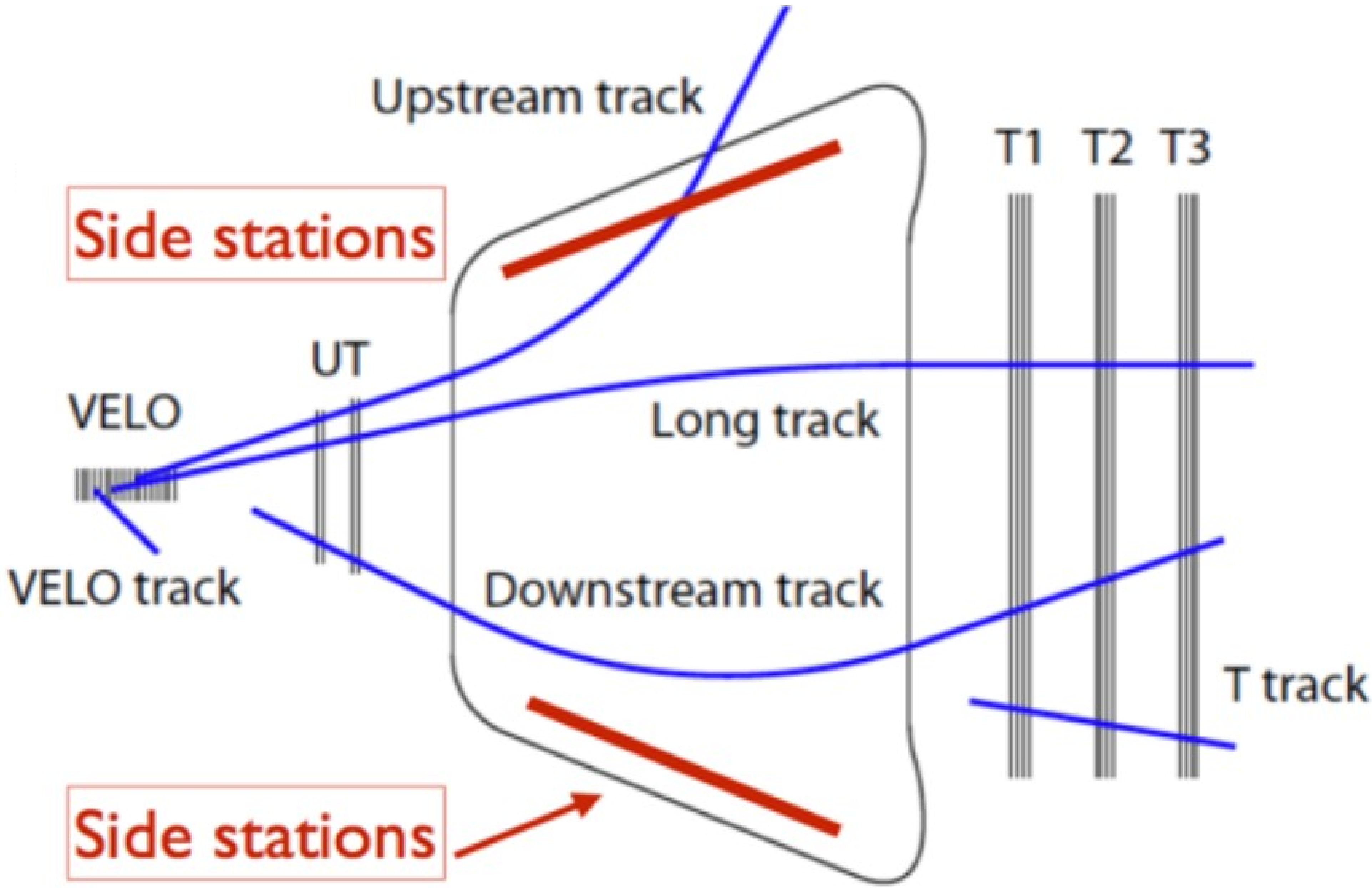




Upgrade Ib: Low-Momentum Tracking



Upgrade Ib: Low-Momentum Tracking



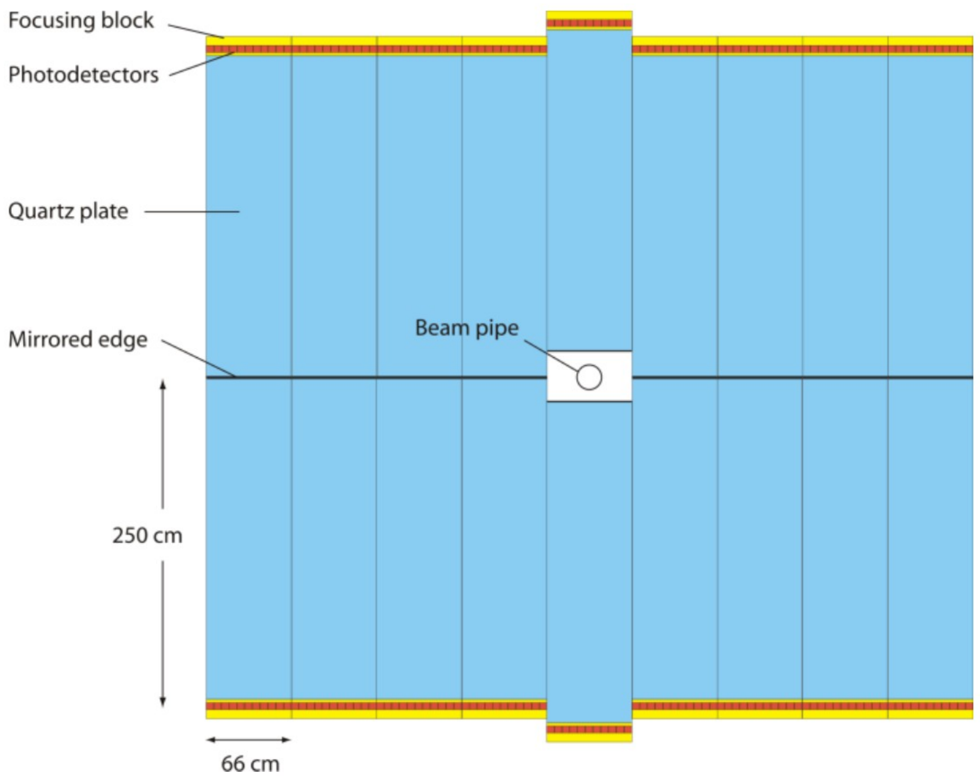
Upgrade Ib: TORCH

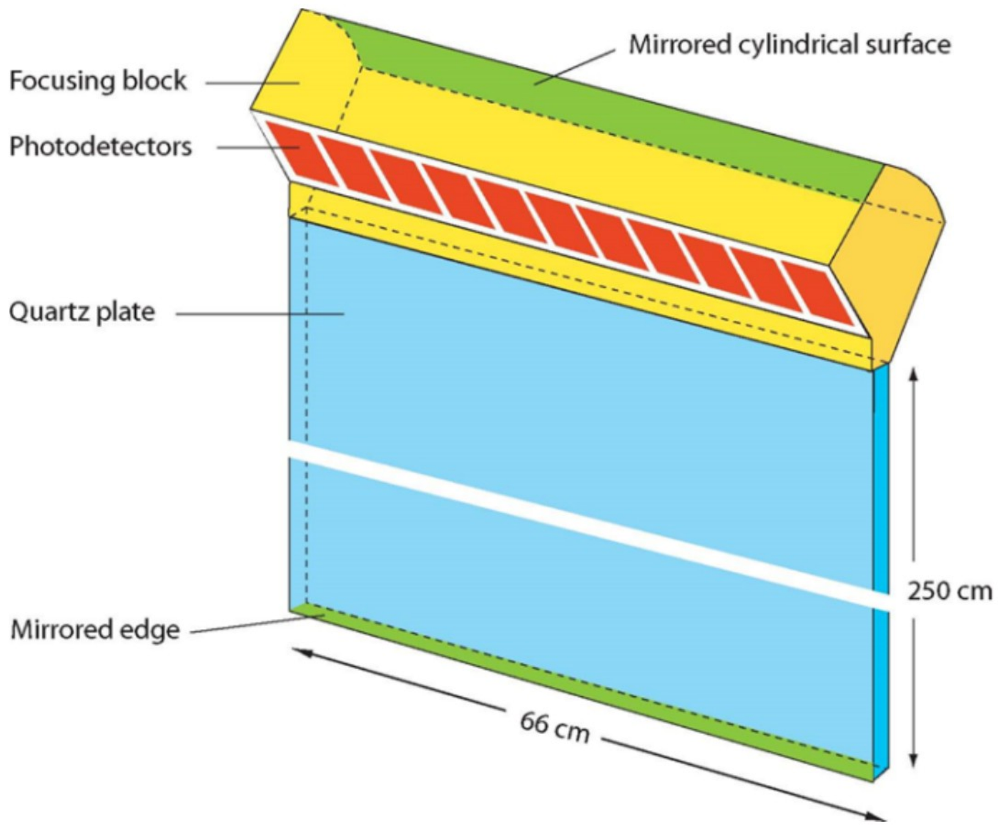
“Time Of interally Reflected CHerenkov light”

→ 250 cm long, 1 cm thin slabs of quartz glass

→ PID below 10 GeV/c

→ time resolution of ≈ 15 ns per track





Upgrade II: Luminosity Scenarios

LHC Run Year	Integrated Luminosity fb^{-1}		
	$1 \times 10^{34} cm^{-2} s^{-1}$	$1.5 \times 10^{34} cm^{-2} s^{-1}$	$2.0 \times 10^{34} cm^{-2} s^{-1}$
Run 1-4	50	50	50
LS4	-	-	-
Run 5 Year 1	21	25	26
Run 5 Year 2	43	50	51
Run 5 Year 3	43	50	51
LS5	-	-	-
Run 6 Year 1	43	50	51
Run 6 Year 2	43	50	51
Run 6 Year 3	43	50	51
Total	**284**	**325**	**331**
Run 6 Year 4	43	50	51
Total	**326**	**374**	**381**

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