Kruger 2018

Workshop on Discovery Physics at the LHC

Hazyview, South Africa, December 3 - 7, 2018

LHCb Upgrades

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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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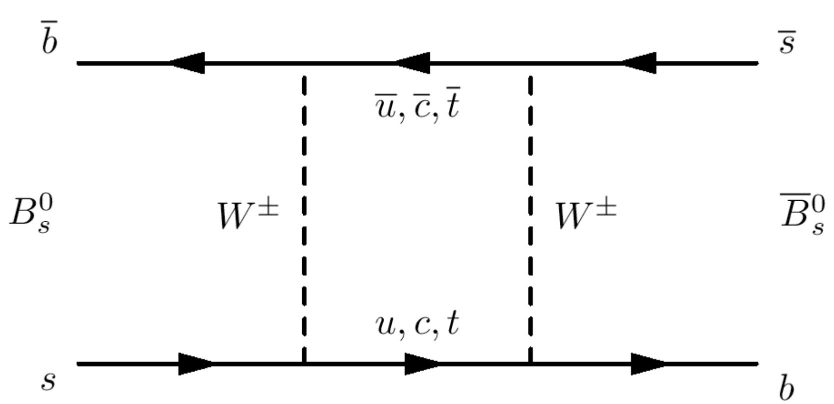
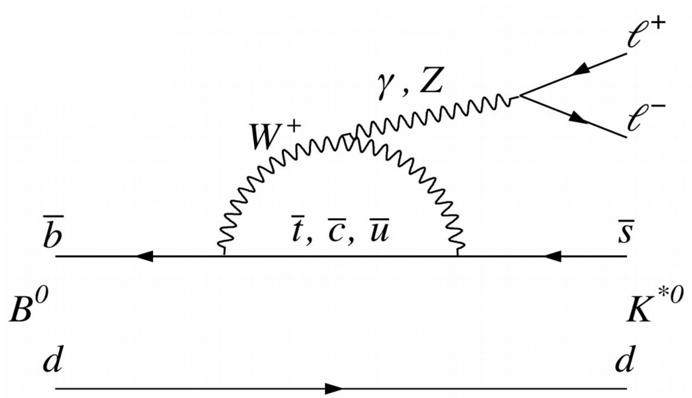
→ most BSM physics models predict additional heavy particles

→ can cause additional amplitudes in processes with internal loops





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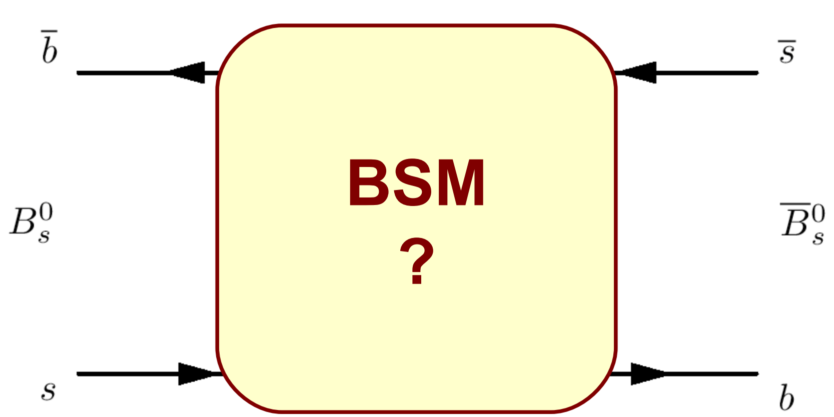
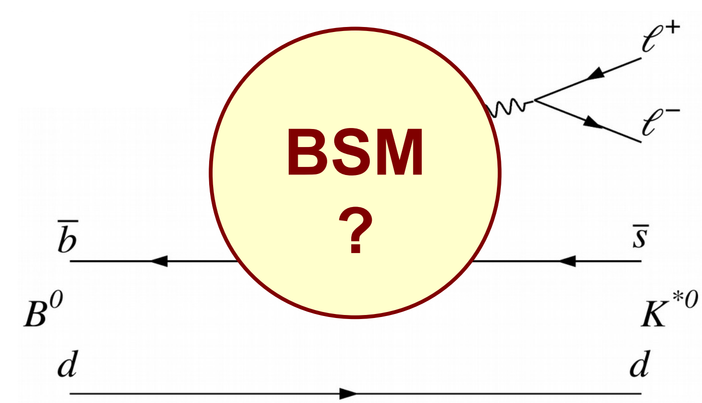
→ can lead to sizeable modifications of observables
(rates, angular distributions, *CP* violating phases)





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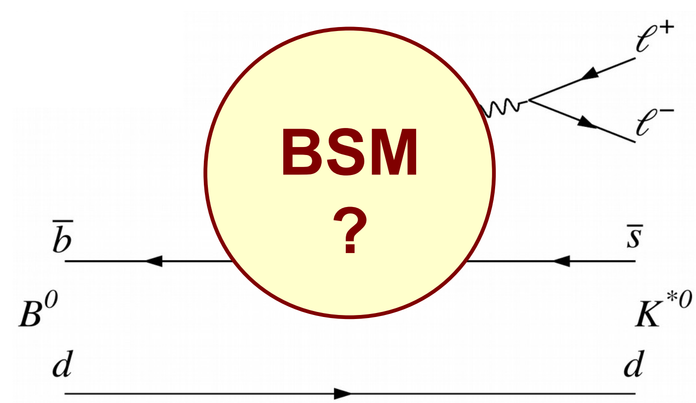
→ most BSM physics models predict additional heavy particles

→ can cause additional amplitudes in processes with internal loops

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

Uncover deviations from Standard Model expectations
by comparing its predictions with <u>precision measurements</u>



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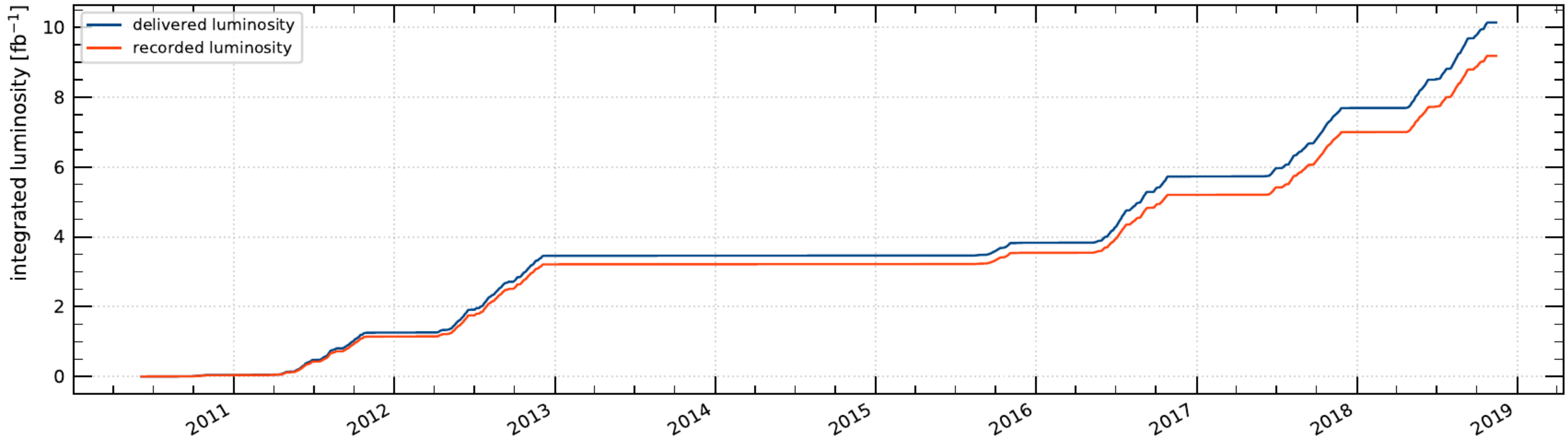
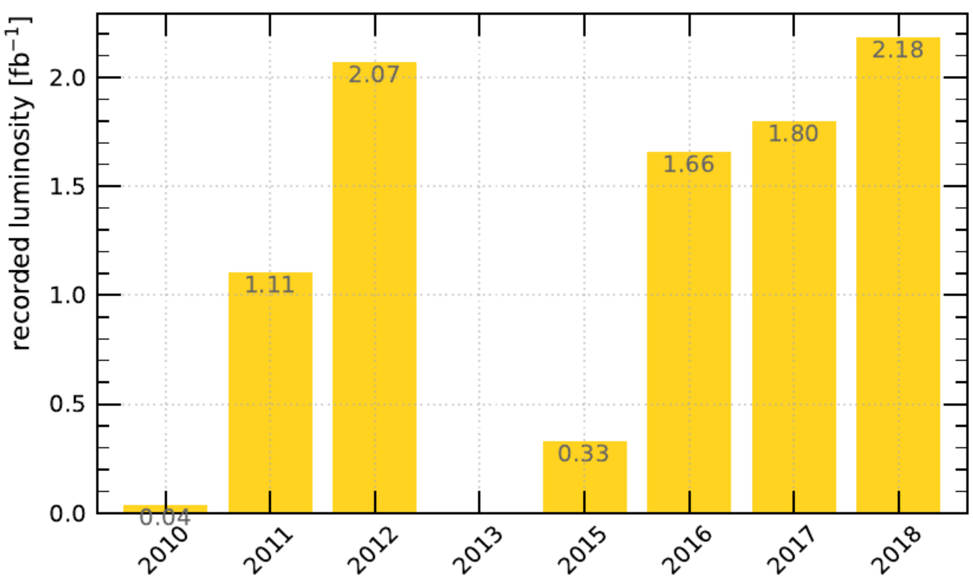
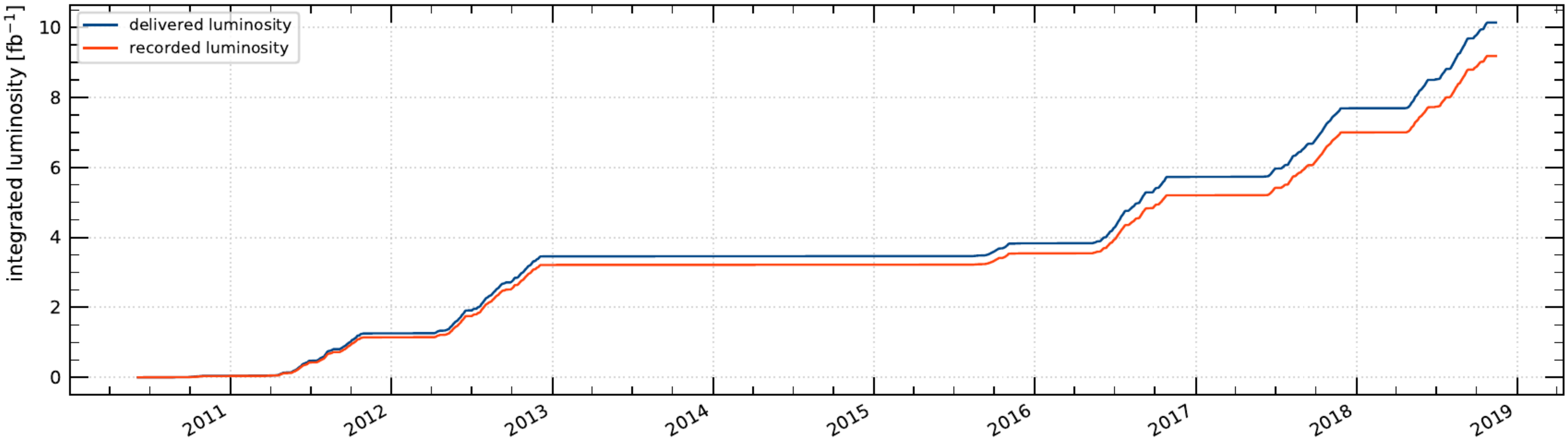
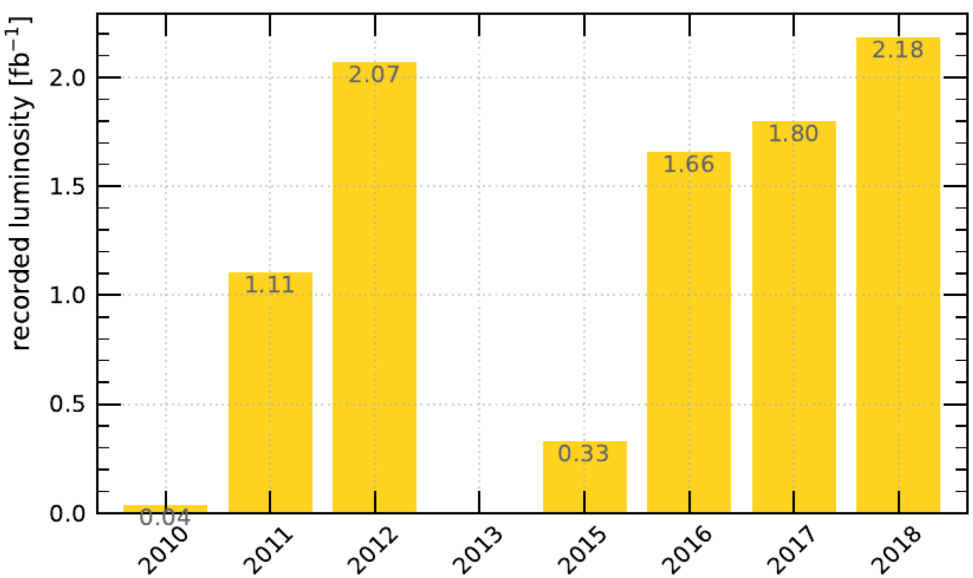




9.18 fb^{-1} recorded in *pp* collisions

Motivation



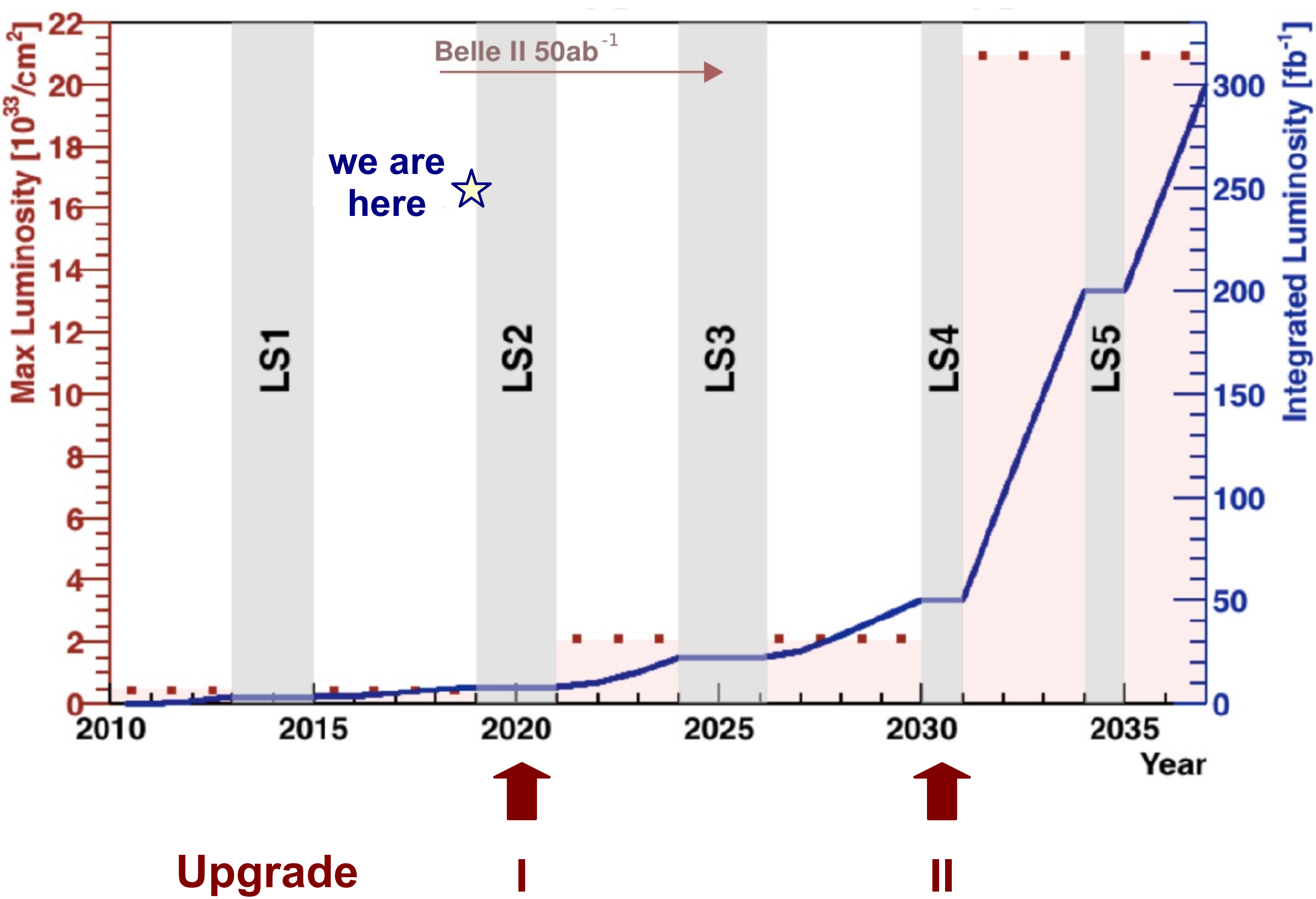


Most results limited by statistical uncertainty

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

→ 15 years of data taking at current conditions

Scenario


Belle II 50ab^{-1}
we are here
LS1
LS2
LS3
LS4
LS5
Max Luminosity [10^{33}/cm^2]
Integrated Luminosity [fb^{-1}]
22
20
18
16
14
12
10
8
6
4
2
0
300
250
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150
100
50
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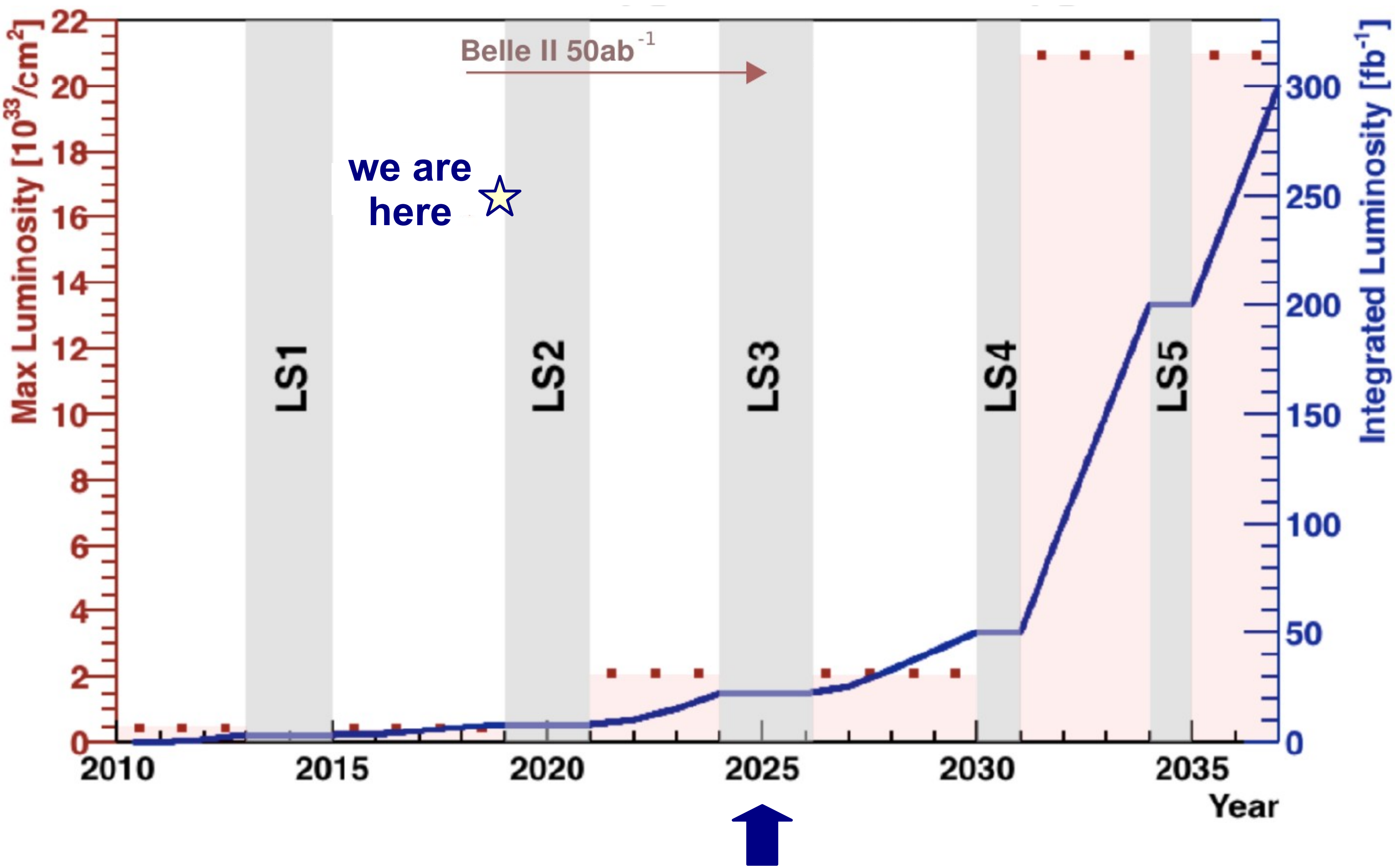
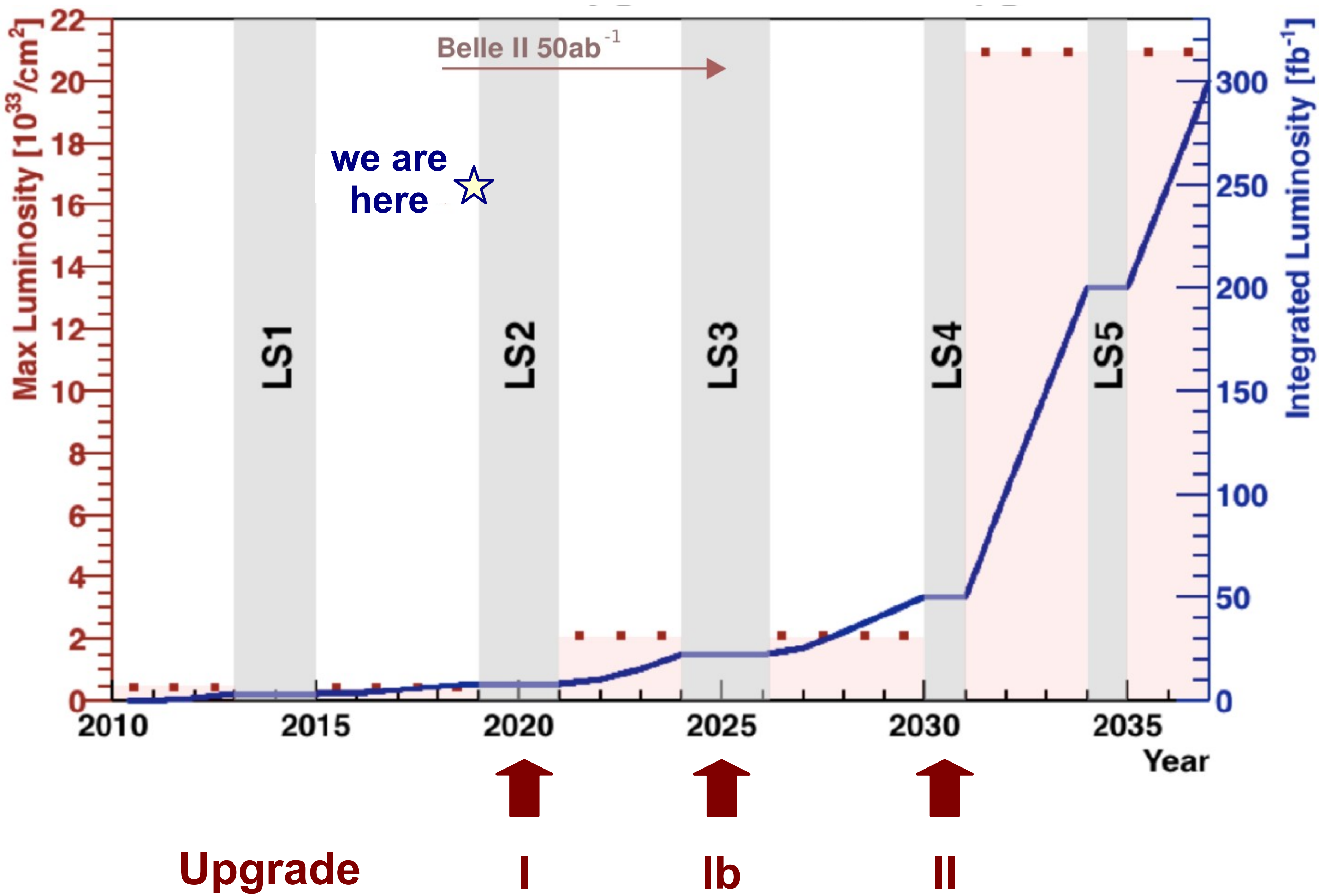
2010
2015
2020
2025
2030
2035
Year
Upgrade
I
II

Scenario



HL-LHC, ATLAS / CMS upgrades

Scenario



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Status

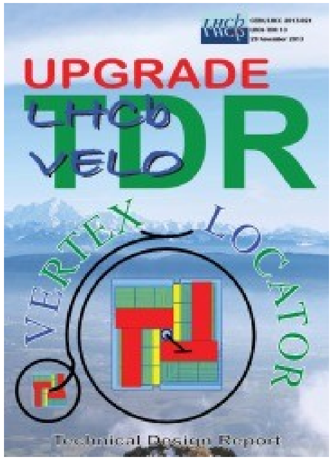
Upgrade I: 2019/2020

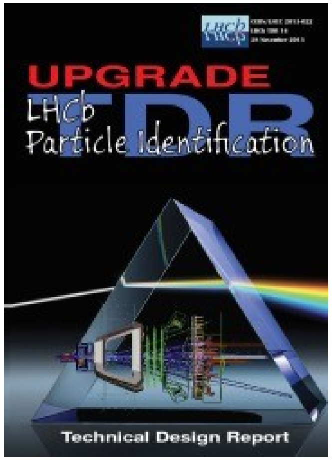
→ Technical Design Reports
→ construction underway

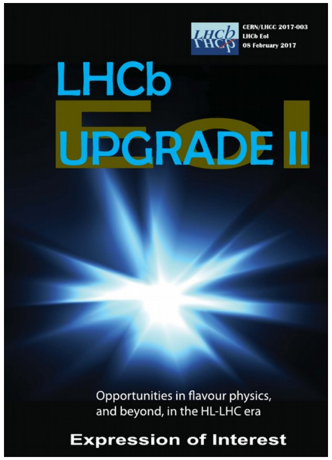
Upgrade II: 2030

→ EoI, Physics Case
→ feasibility studies underway

[CERN-LHCC 2013-021] [CERN-LHCC 2013-022]

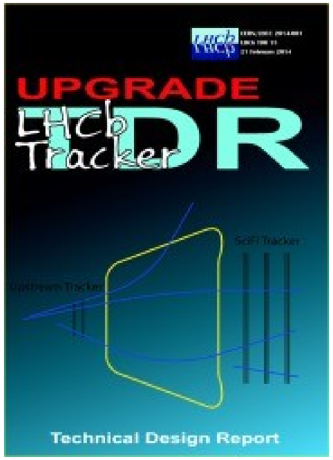


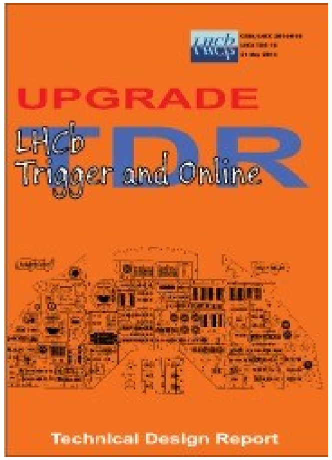


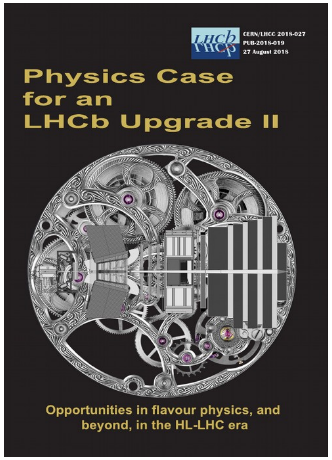


[CERN-LHCC-2017-003]

[CERN-LHCC 2014-001] [CERN-LHCC 2014-016]



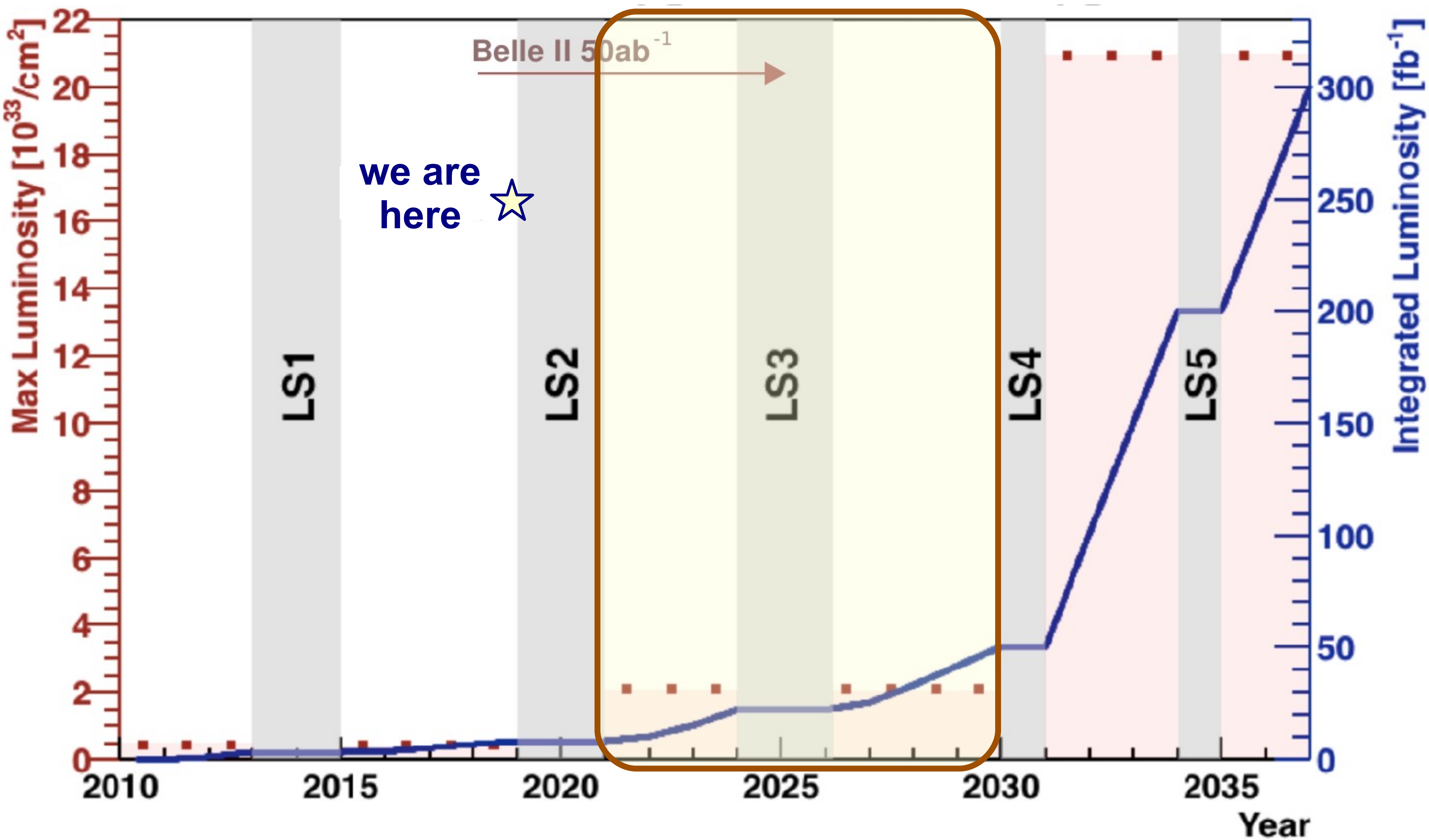




[CERN-LHCC-2018-027]


Upgrade I

Upgrade I



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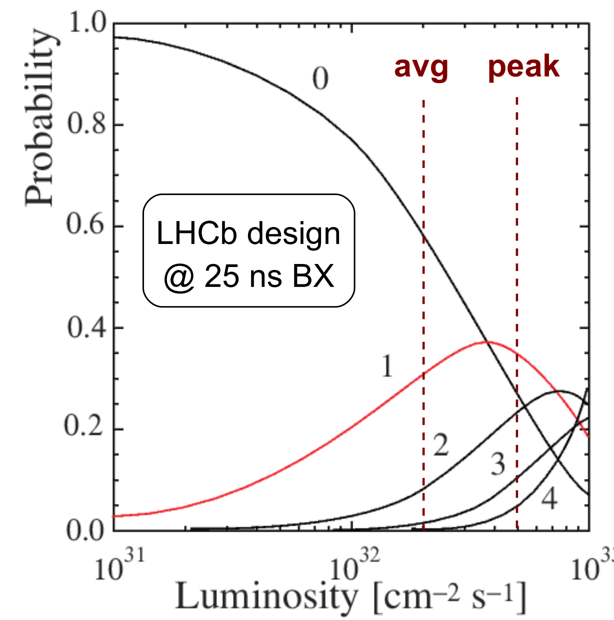
Upgrade I

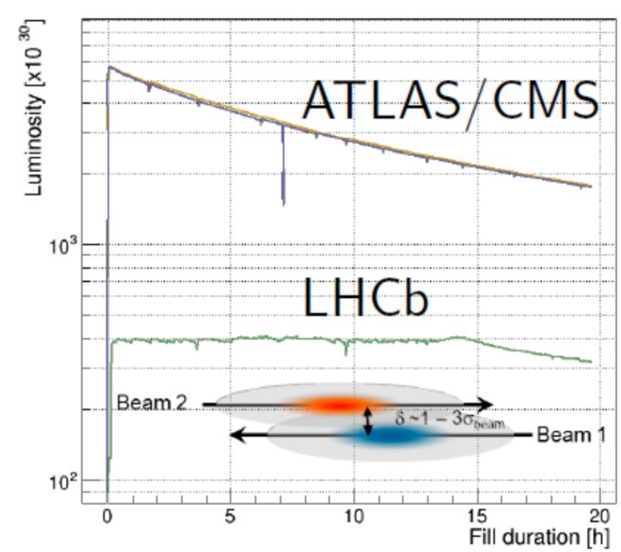
Increase instantaneous luminosity
$4 \times 10^{32} \rightarrow 2 \times 10^{33}\ cm^{-2} s^{-1}$

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 any LHC upgrade





(very old plot, but illustrates the point)

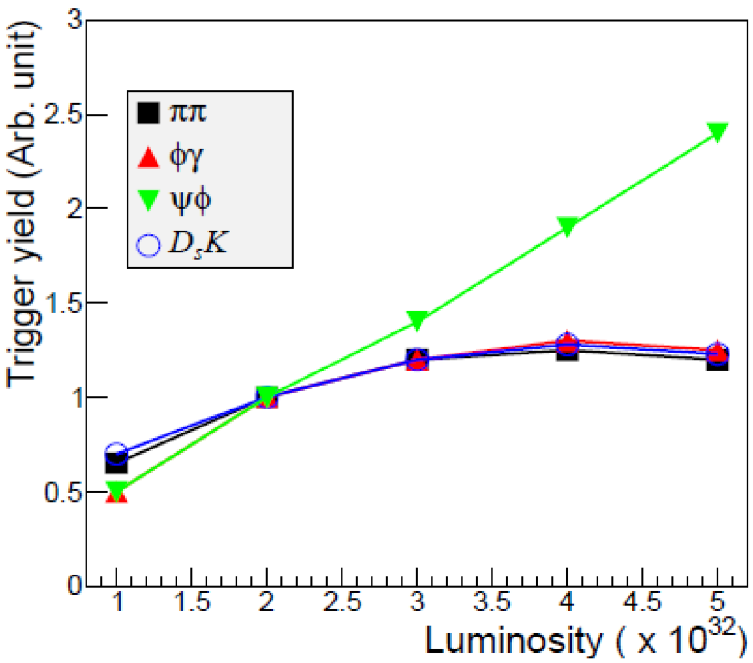
Upgrade I

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

Abolish hardware trigger stage to fully exploit higher collision rate

→ read out full detector at 40 MHz

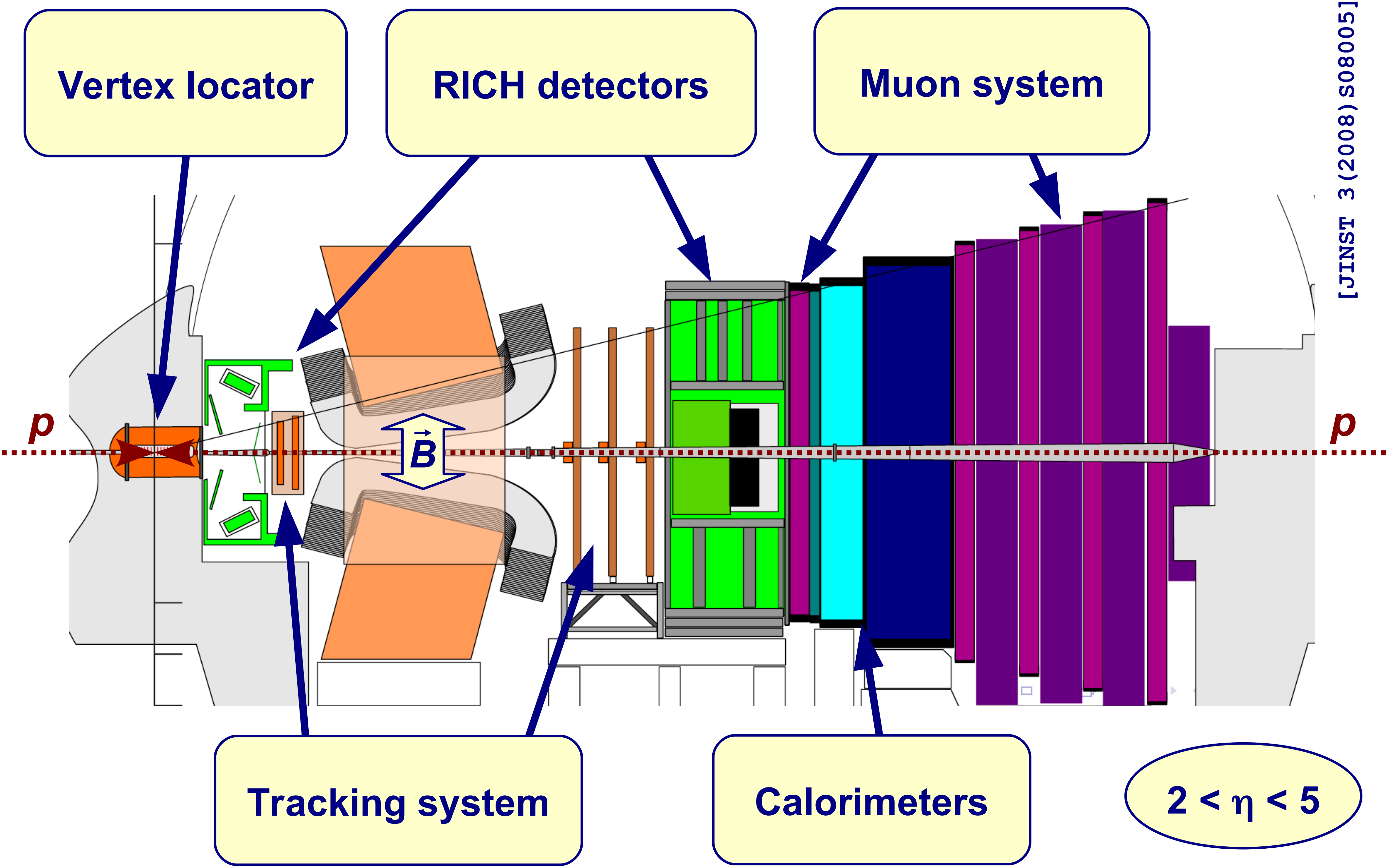
→ operate software trigger at 40 MHz input rate !



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

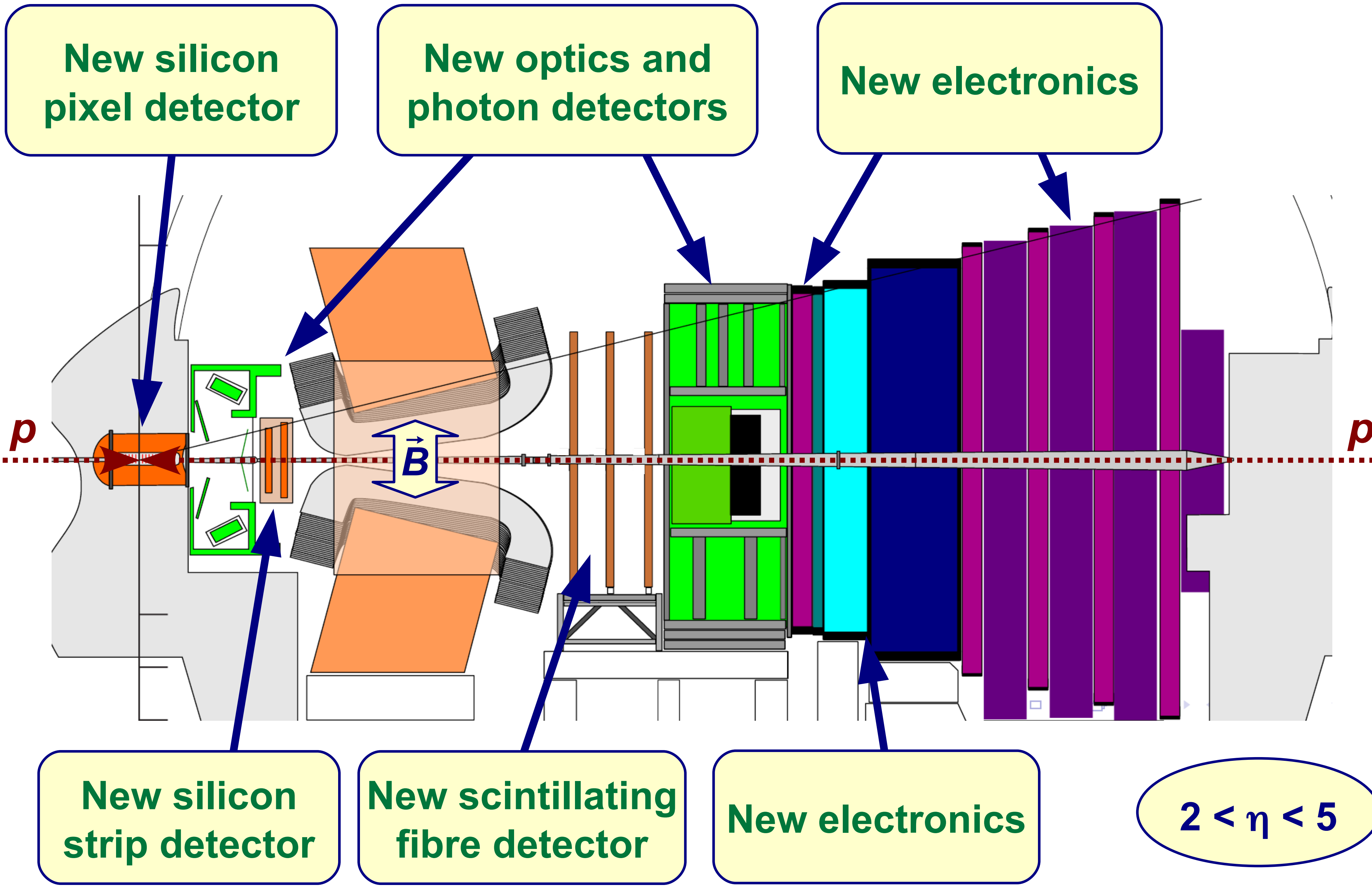
Complete overhaul of readout for all detectors

LHCb Detector



2 < η < 5

LHCb Upgrade I



VELO

Current VELO:

21 layers of silicon micro-strips

→ 170 k readout channels

Inside LHC vacuum chamber

→ active area at 8.2 mm from beam

→ separated from beam only by a 300 μm thin aluminium foil

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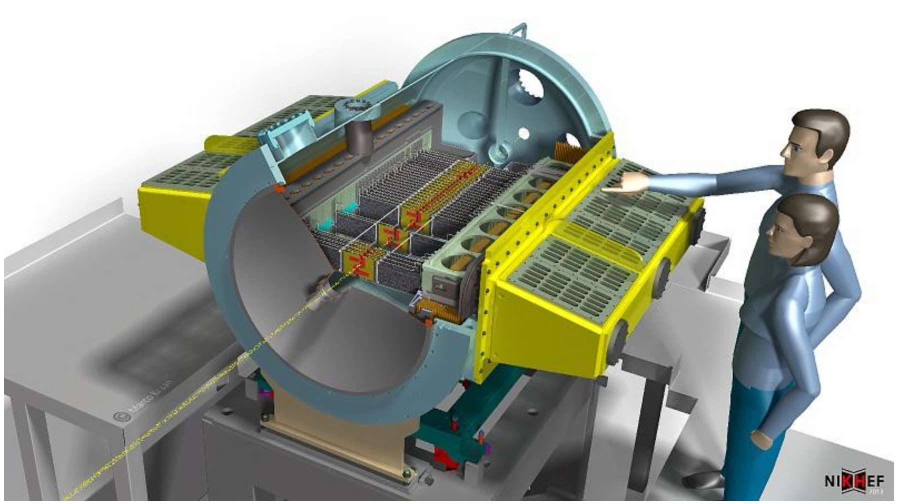
VELO Upgrade:
26 layers of silicon pixel detectors
→ 41 million readout channels
Even closer to beam
→ active area 8.2 → 5.1 mm
Even less material
→ thinner sensors (300 → 200 µm)
→ thinner aluminum foil (300 → 250 µm)



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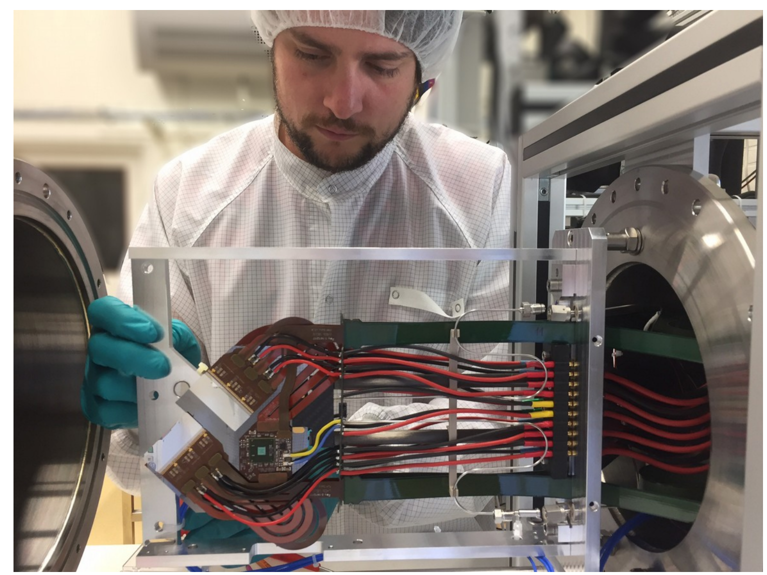

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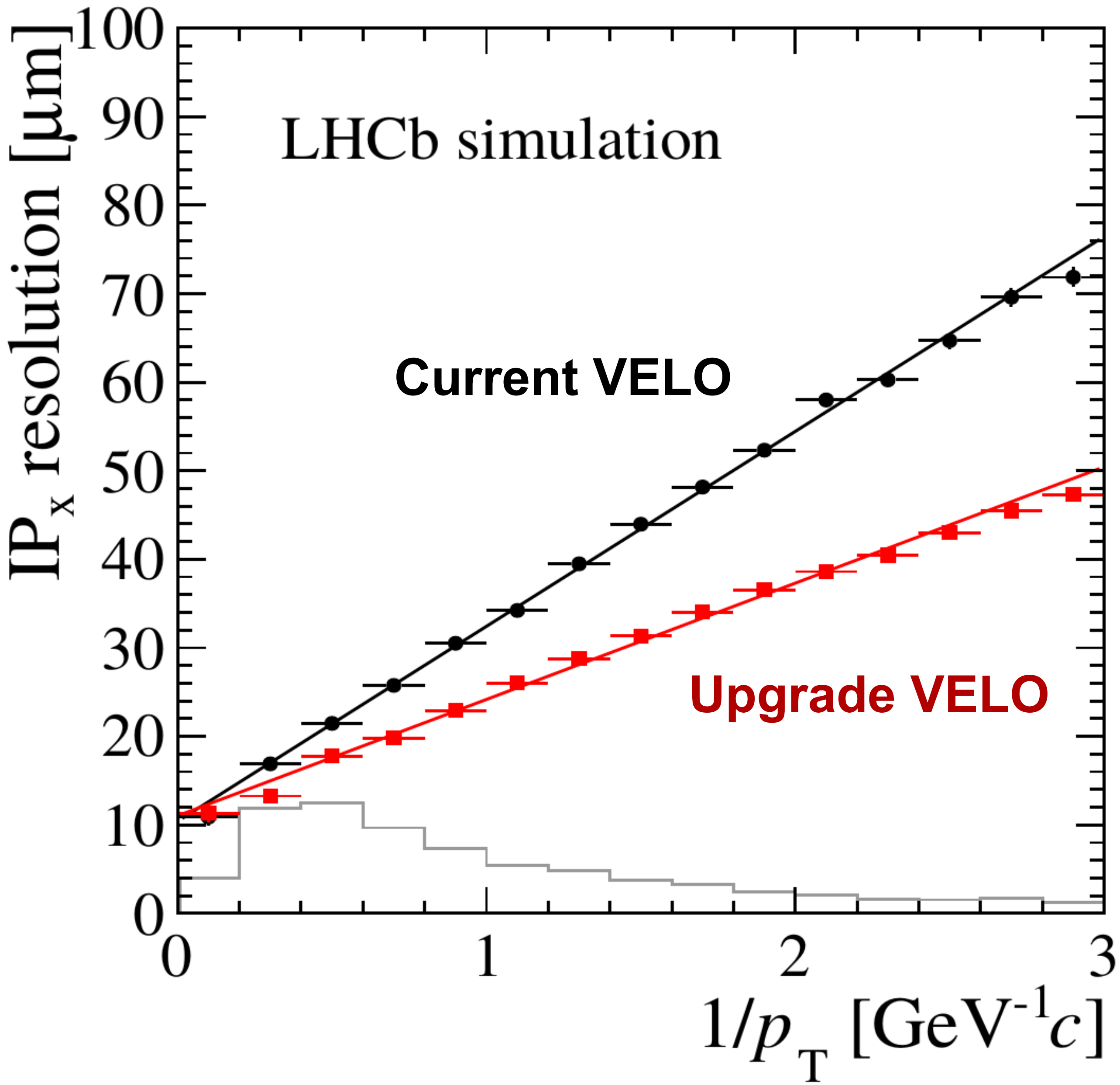


[CERN/LHCC 2014-001, LHCb TDR 15]

Upstream Tracker

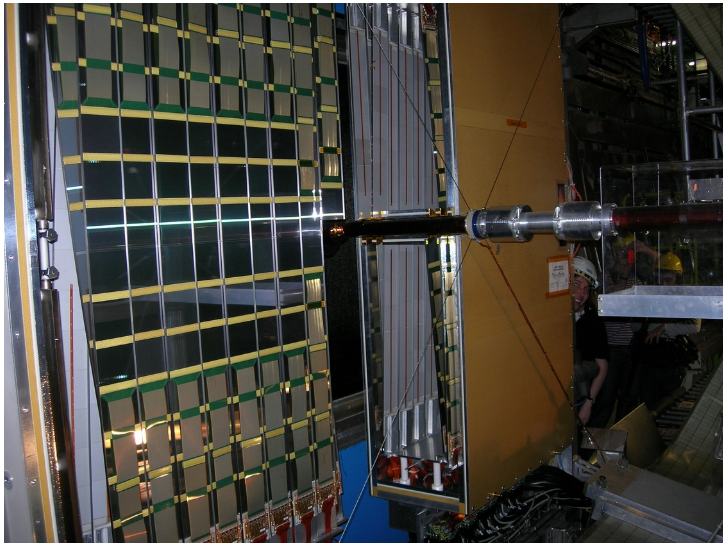
Current: TT

4 layers of silicon micro-strips

→ 183 μm pitch

→ 40, 30, 20, 10 cm in length

→ 143 k readout channels



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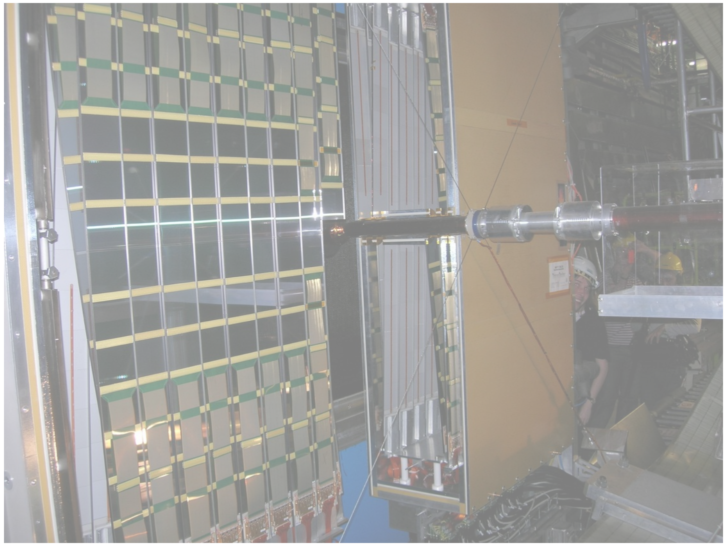


Upgrade: UT

4 layers of silicon micro-strips, but finer granularity

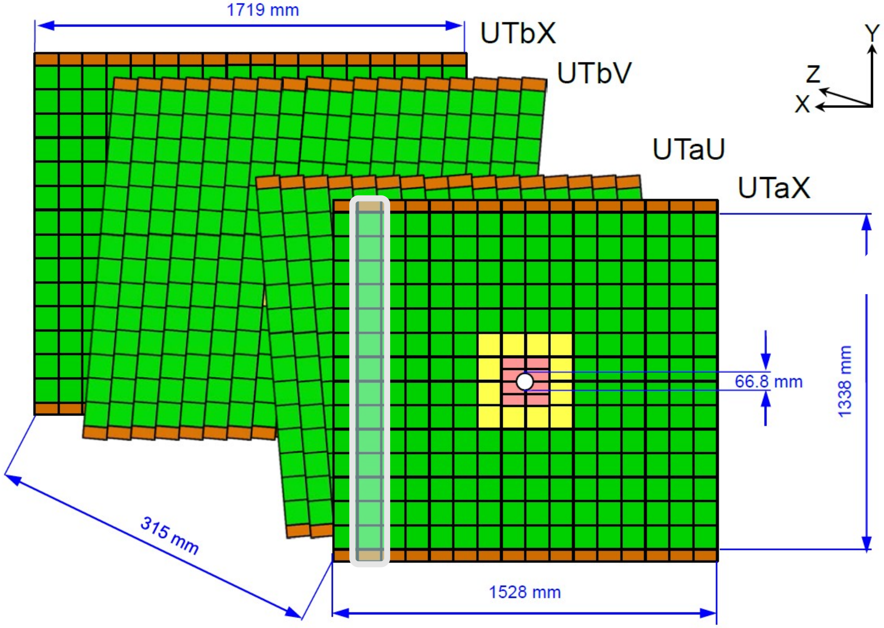
→ 190 and 95 μm pitch

→ 10 and 5 cm in length

→ 537 k readout channels

and better radiation hardness

New readout chip, compatible with 40 MHz readout scheme



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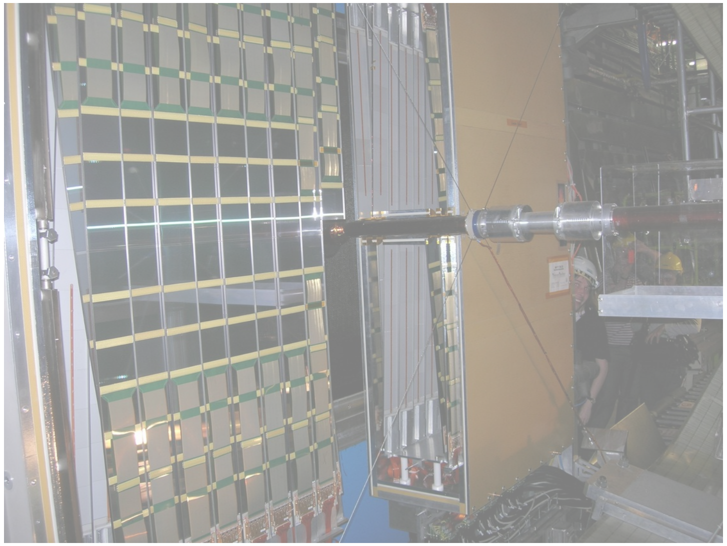

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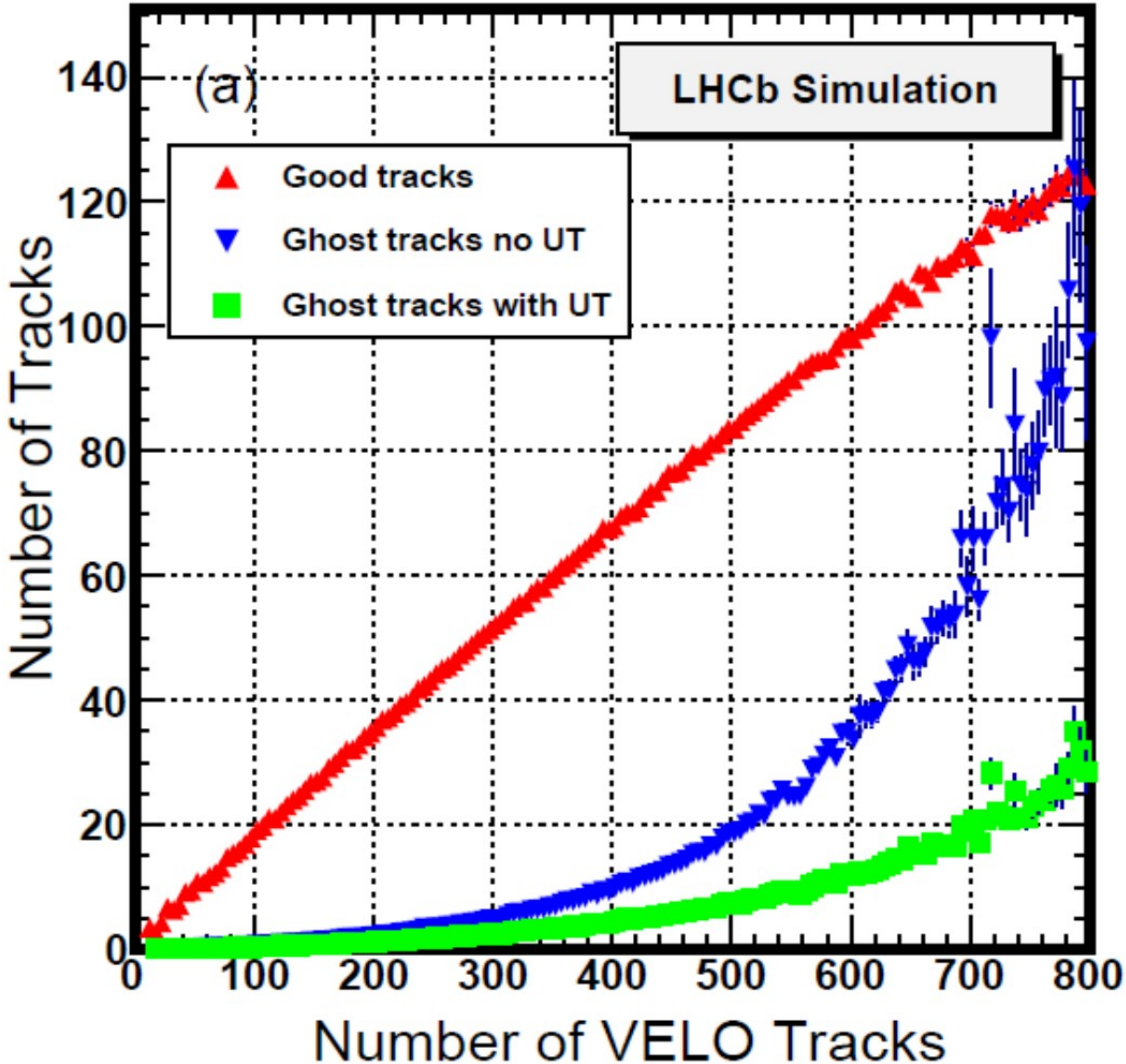

[CERN-LHCC-2014-001]

Downstream Tracker

Current: IT & OT

3 stations with 4 layers each

→ silicon micro-strips in innermost region

→ straw drift tubes in outer region

→ 130 k + 54 k readout channels

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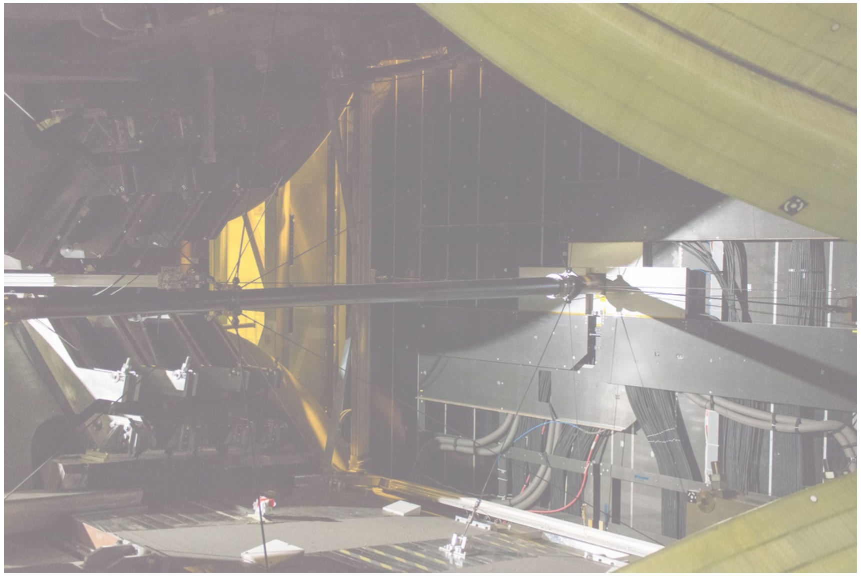


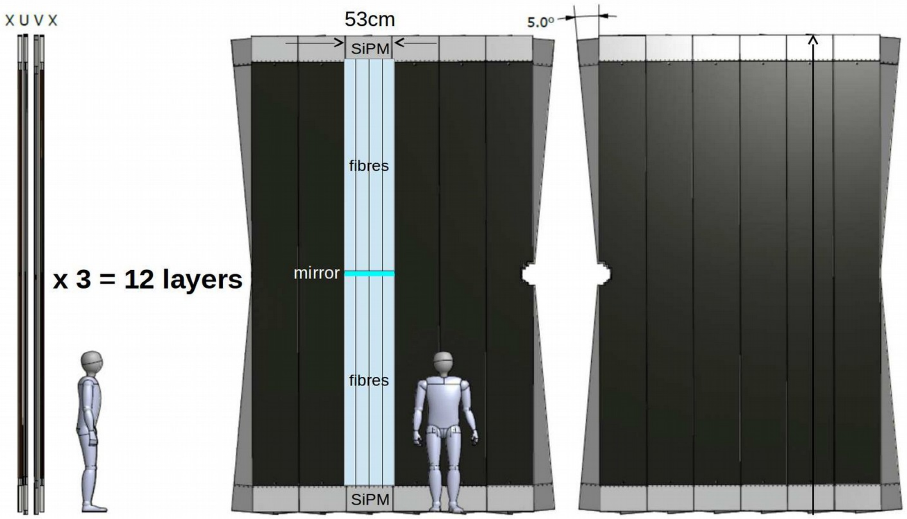
Upgrade: SciFi

3 stations of scintillating fibres

→ 2.5 m long, 250 μm diameter

→ read out with silicon photomultipliers

→ 590 k readout channels



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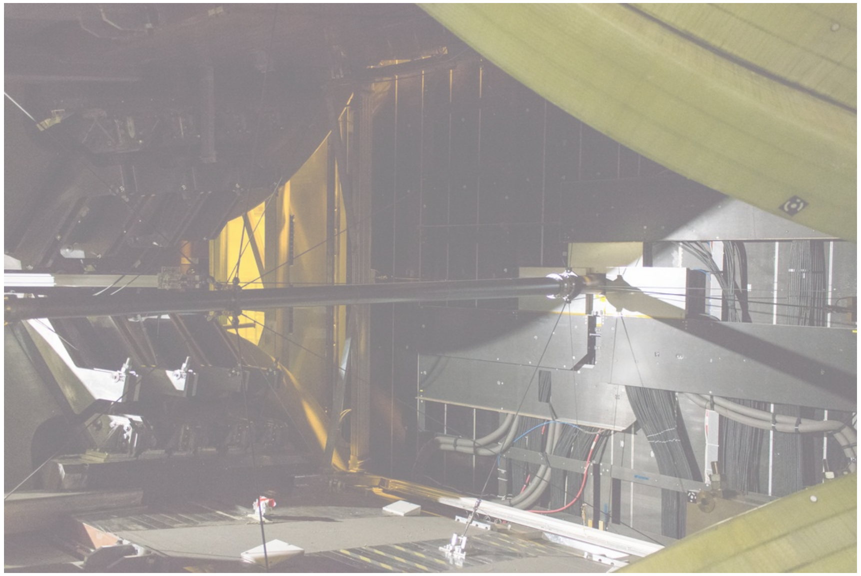

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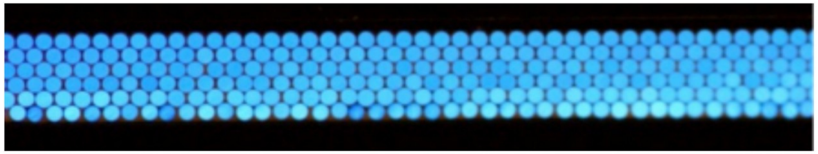

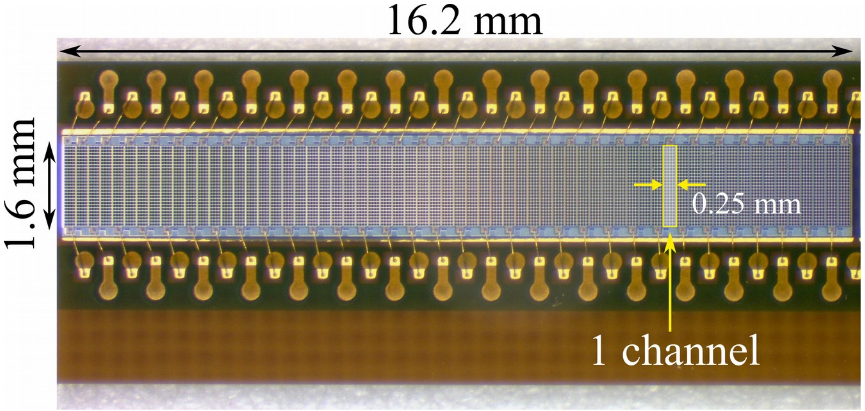

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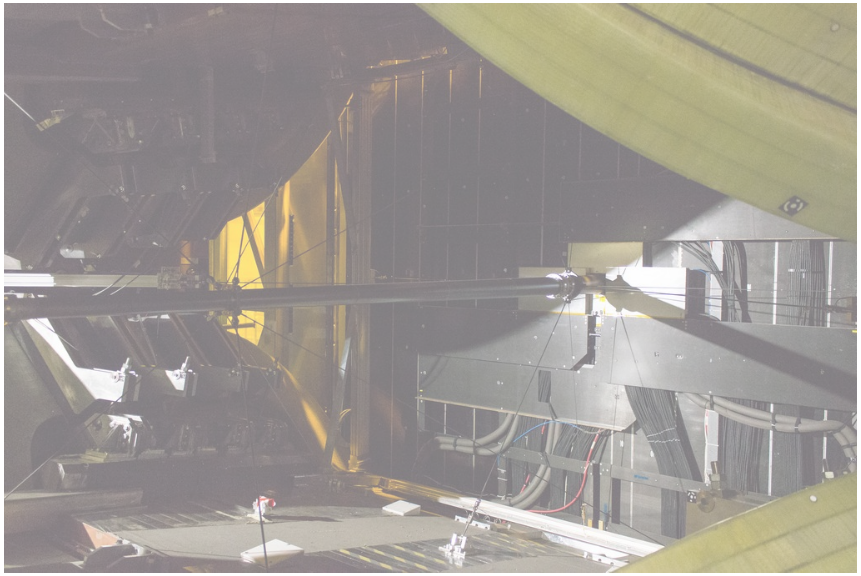

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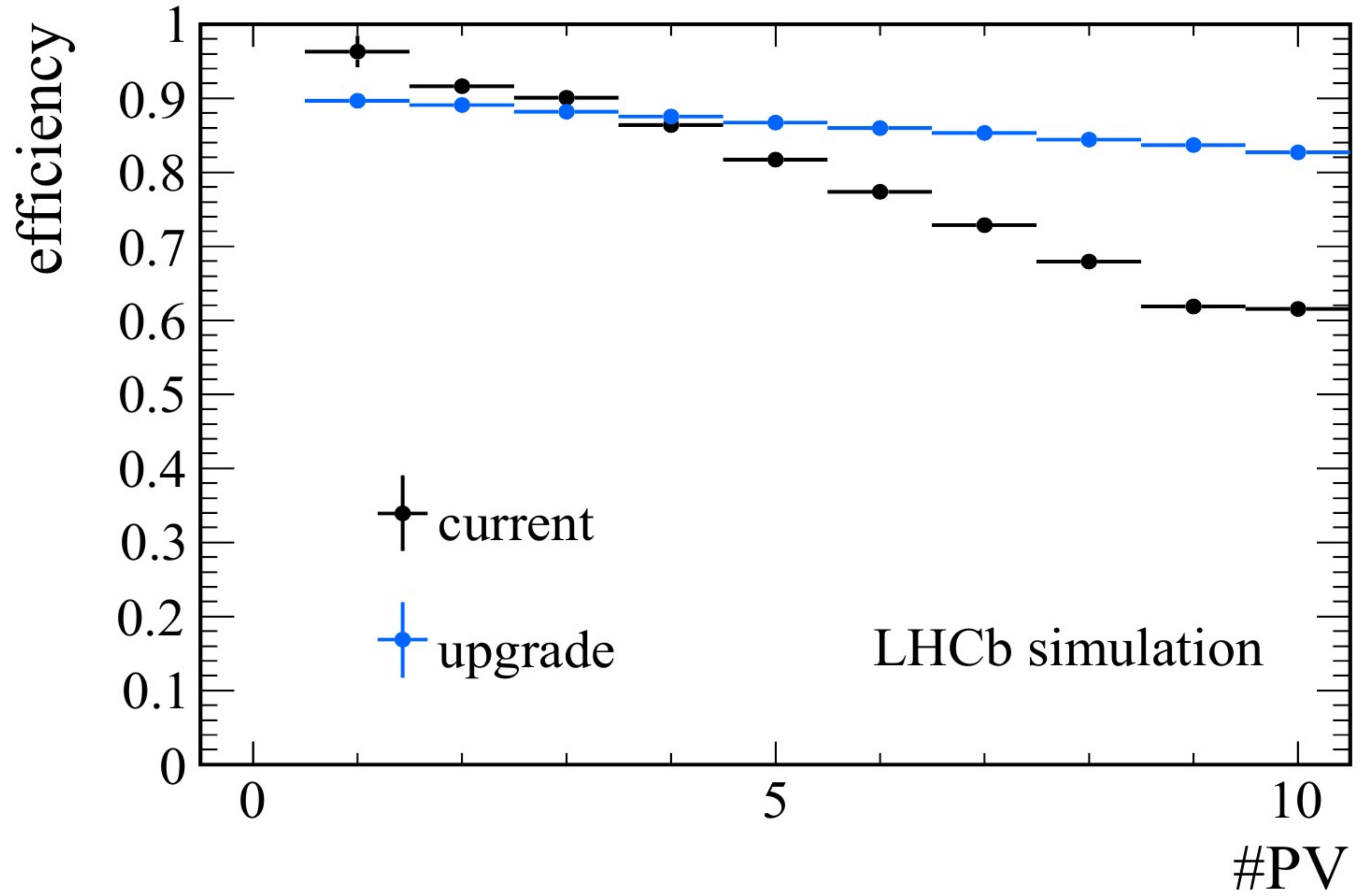

[CERN/LHCC 2014-001, LHCb TDR 15]

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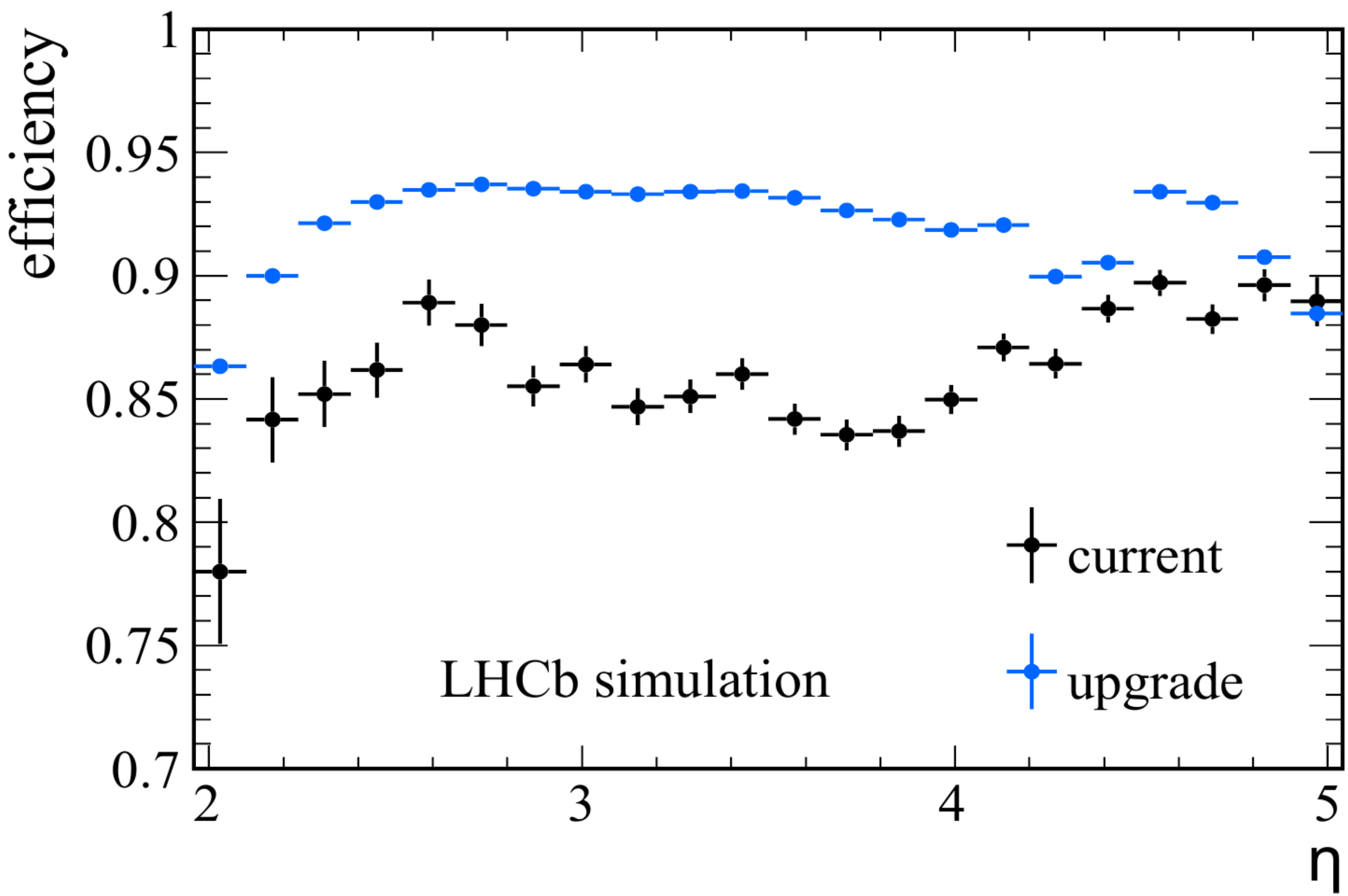

[CERN/LHCC 2014-001, LHCb TDR 15]

Physics Reach

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

[CERN-LHCC-2018-027]

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$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	–
$S_{\mu\mu}$	–	–	–	–
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[CERN-LHCC-2018-027]

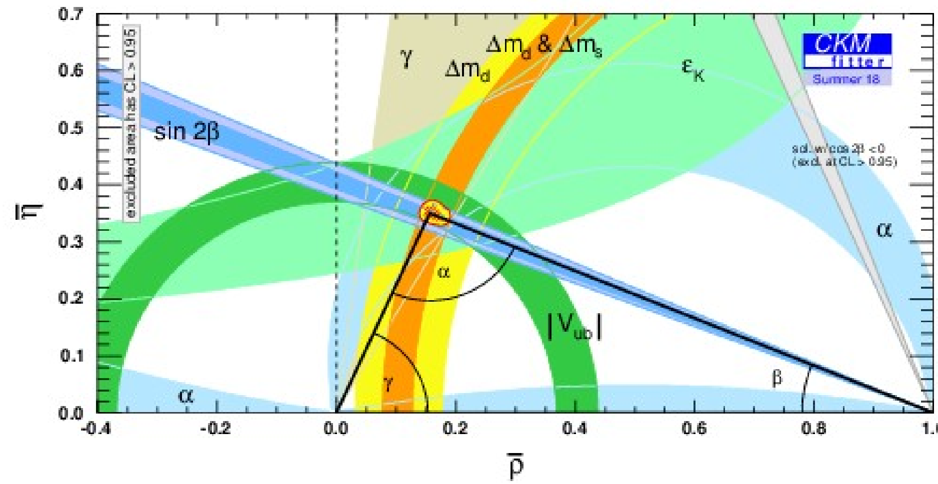
Physics Reach: Example

"Unitarity Triangle":

from unitarity condition of CKM matrix

→ all angles and sides related to observables

→ over-constrained fits test Standard Model



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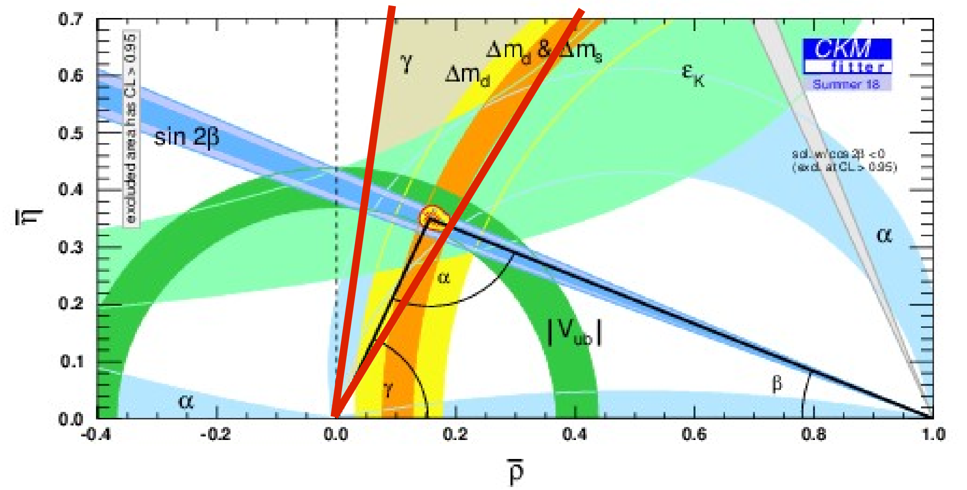

$$\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

→ theory uncertainty negligible

→ measurement uncertainty still significant and limited by available statistics

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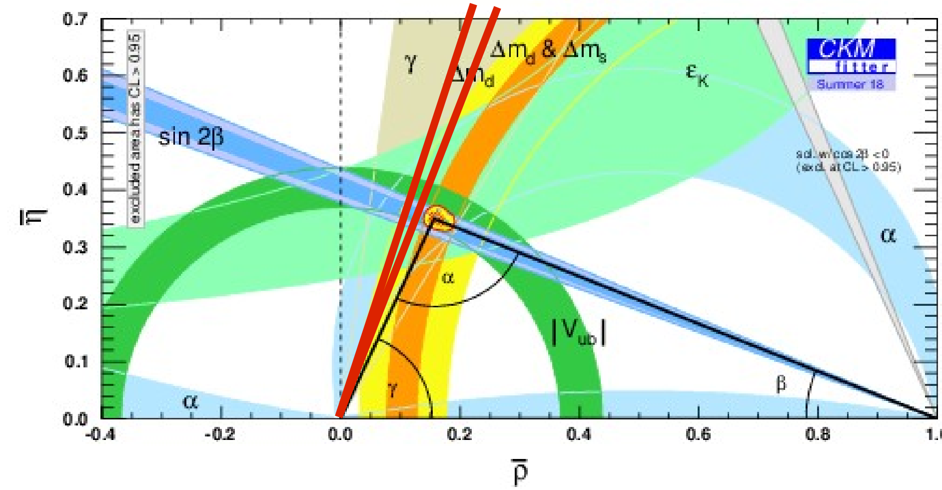
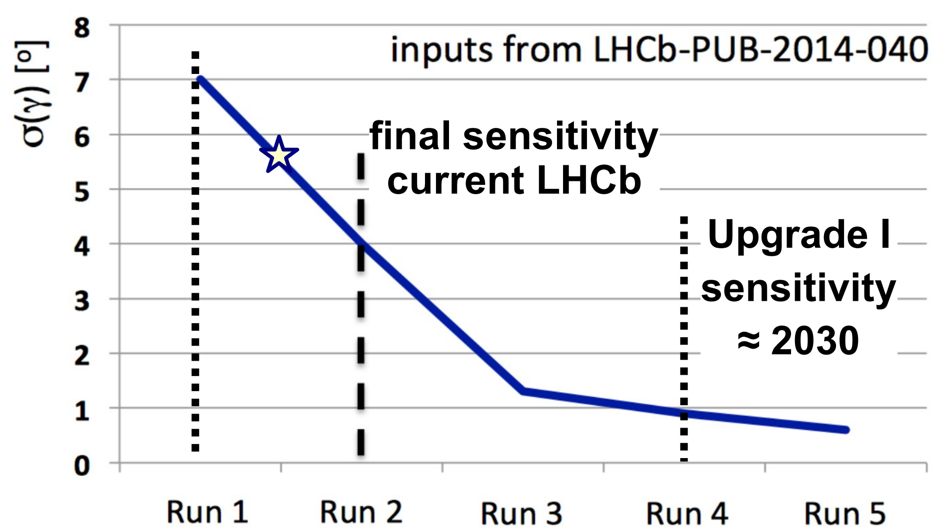




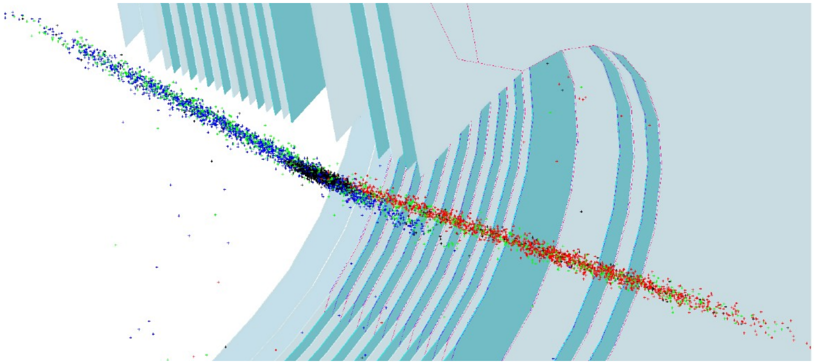
[LHCb-PUB-2014-040]

SMOG

"System for Measuring Overlap with Gas"

→ inject small amounts of noble gas
into the LHC vacuum
(increase pressure from 10^{-9} to 10^{-7} mbar)

→ main purpose: measure beam profiles
for determination of instantaneous luminosity



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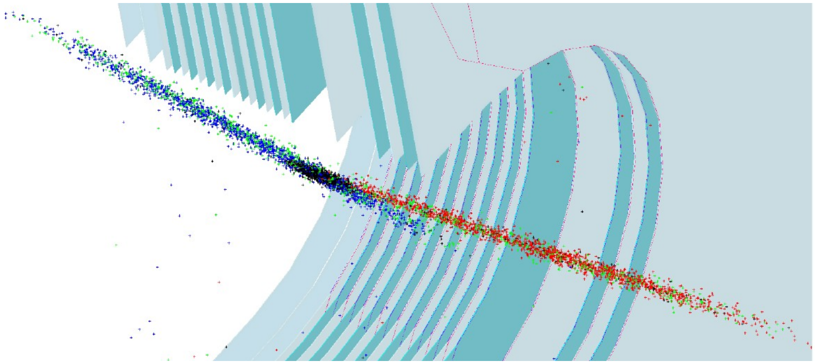

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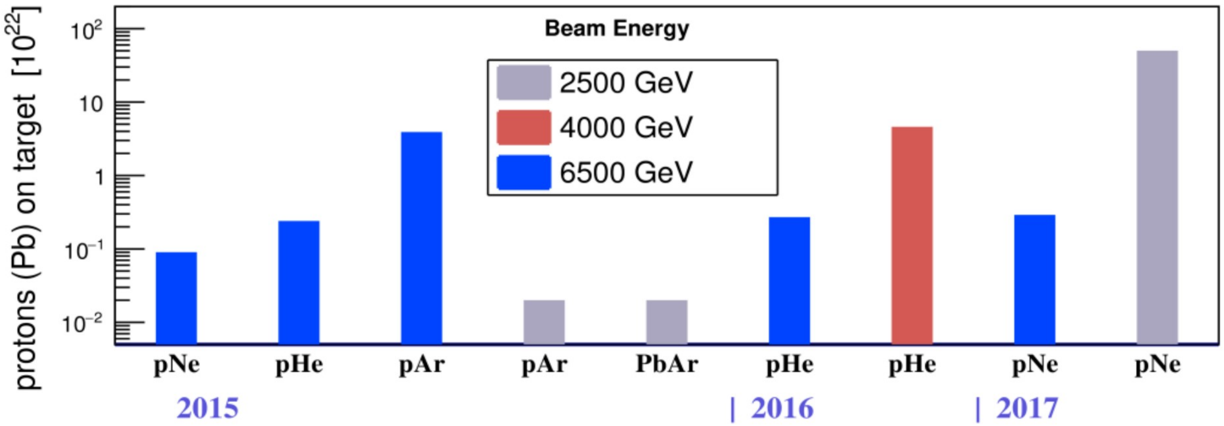
**Allows to study fixed-target collisions
of proton or ion beam on gas atoms**



$\sqrt{s_{NN}}$ = 69 – 110 GeV

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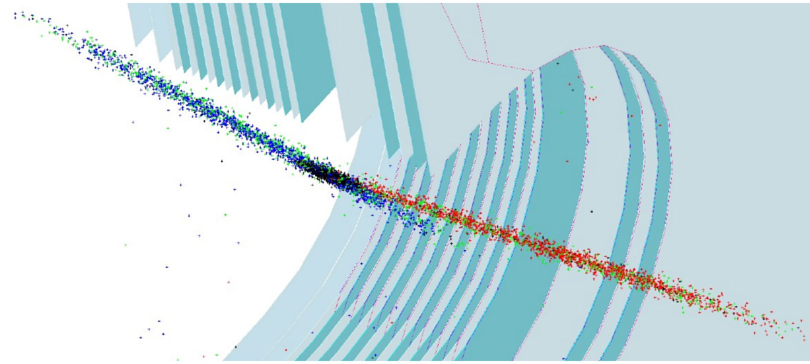

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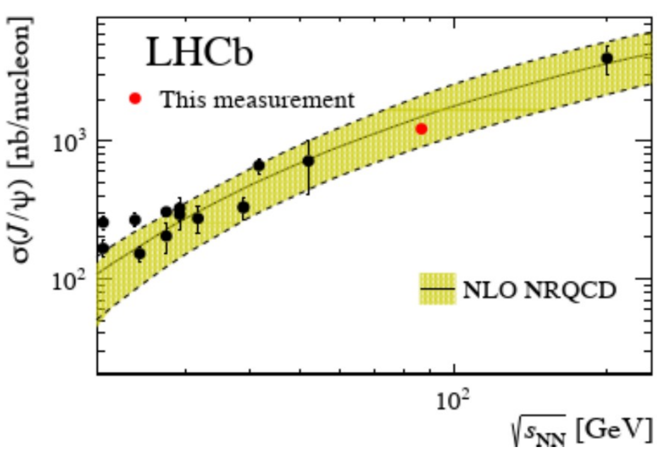

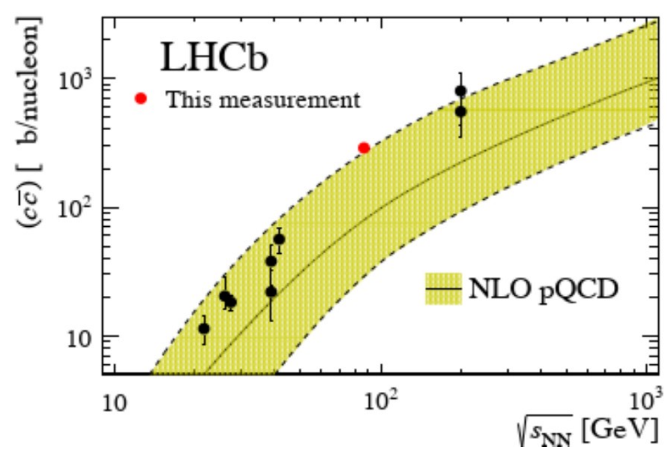

[arXiv:1810.07907]

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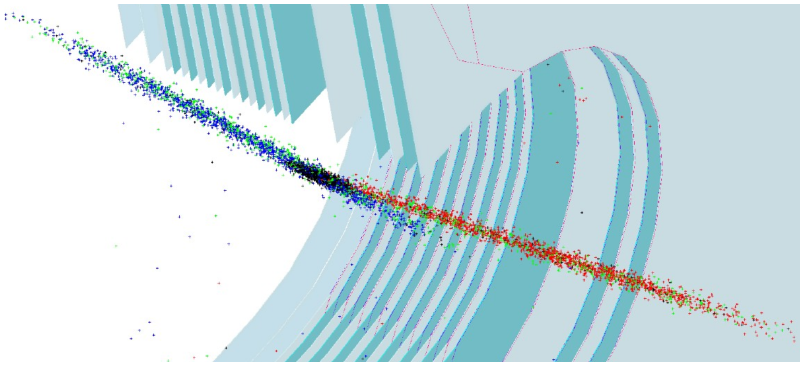


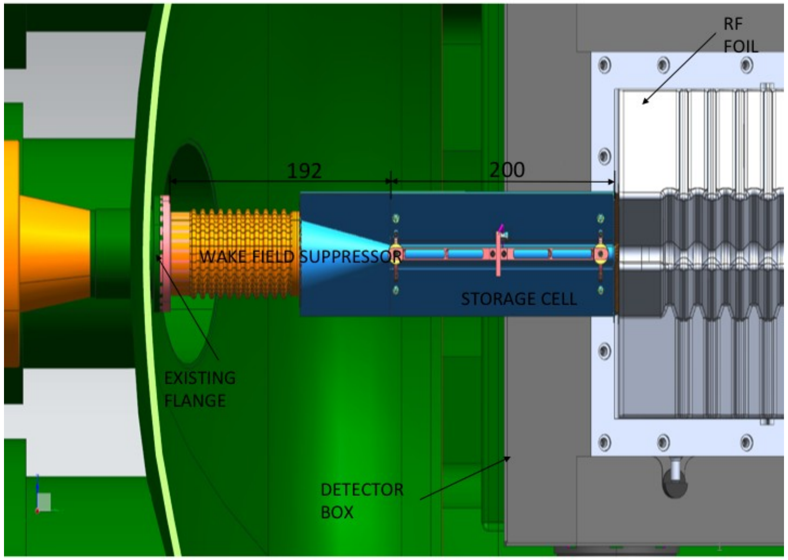
→ main purpose: measure beam profiles for determination of instantaneous luminosity

Currently under approval:
Insert storage cell upstream of VELO

→ 10 – 100 times higher instantaneous luminosity per unit length

→ also injection of H_2, D_2 as reference

(see also Giacomo's talk on Monday)



SMOG Physics Reach

	Current SMOG result pHe@86 GeV	SMOG largest sample pNe@68 GeV	SMOG2 example pAr@115 GeV
Int. Lumi.	7.6/nb	$\sim$ 100/nb	$\sim$ 10/pb
syst. error on J/ψ x-sec.	7%	6 - 7%	3 - 4 %
J/ψ yield	400	15k	3.5M
D^0 yield	2000	100k	35M
Λ_c yield	20	1k	350k
ψ' yield	negl.	150	35k
$\Upsilon(1S)$ yield	negl.	10	3k
DY $\mu^+\mu^-$ yield $(5 < M < 9$ GeV)	negl.	10	3k

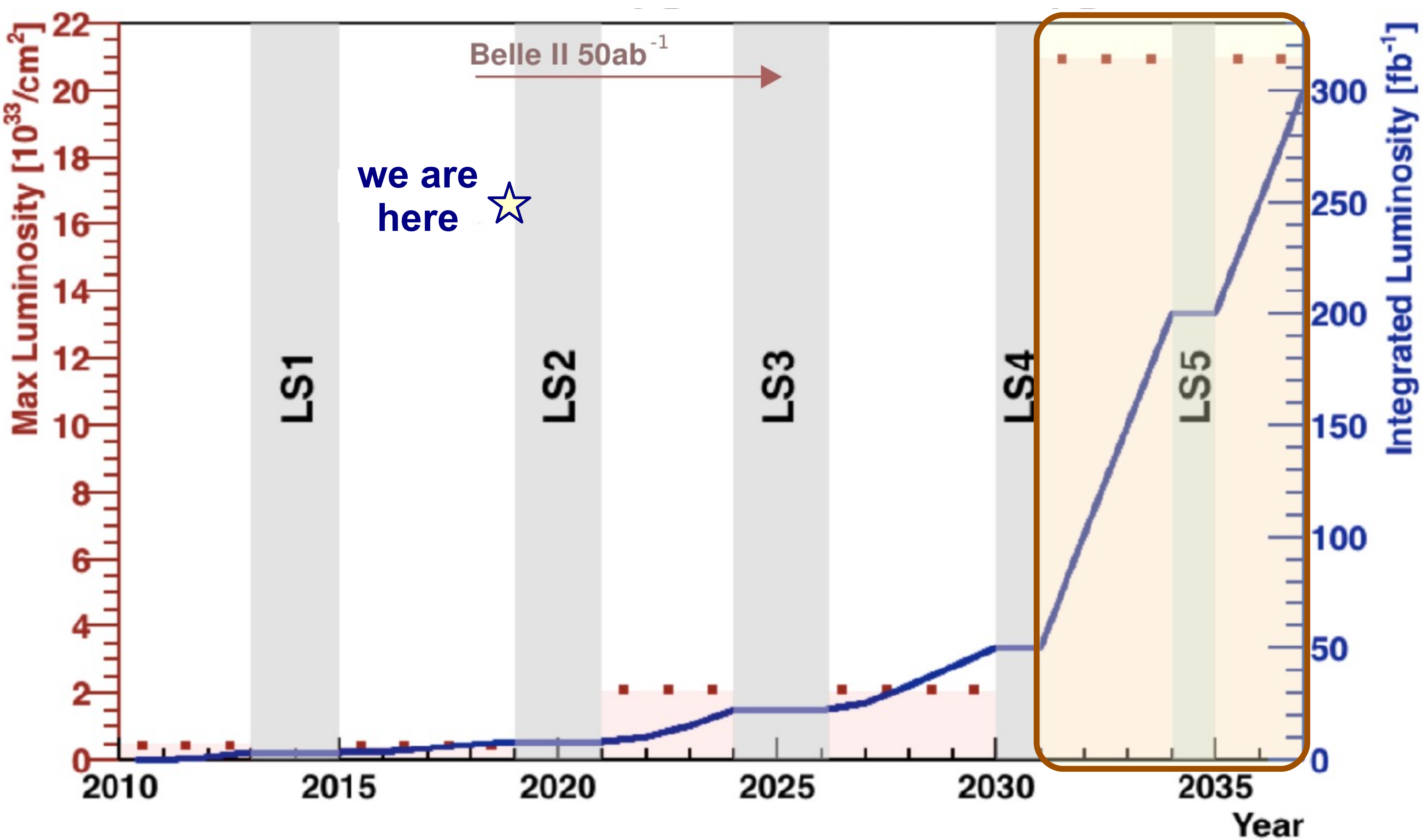
→ **list of topics far from exhaustive**

→ **extrapolations based on crude estimates**

→ **expect significant reduction in systematics from better luminosity determination**


Upgrade II

Upgrade II



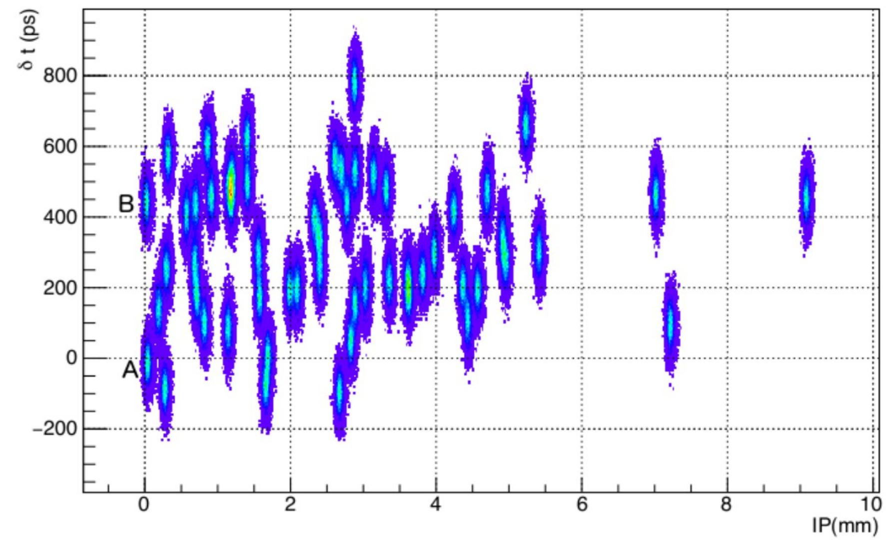
Max Luminosity [10^33/cm^2]
Integrated Luminosity [fb^-1]
Belle II 50ab^-1
we are here
LS1
LS2
LS3
LS4
LS5
22
20
18
16
14
12
10
8
6
4
2
0
300
250
200
150
100
50
0
2010
2015
2020
2025
2030
2035
Year

Upgrade II

Increase instantaneous luminosity from 2×10^{33} to $1.5 - 2 \times 10^{34}$ $cm^{-2} s^{-1}$

→ 55 *pp* interactions /crossing

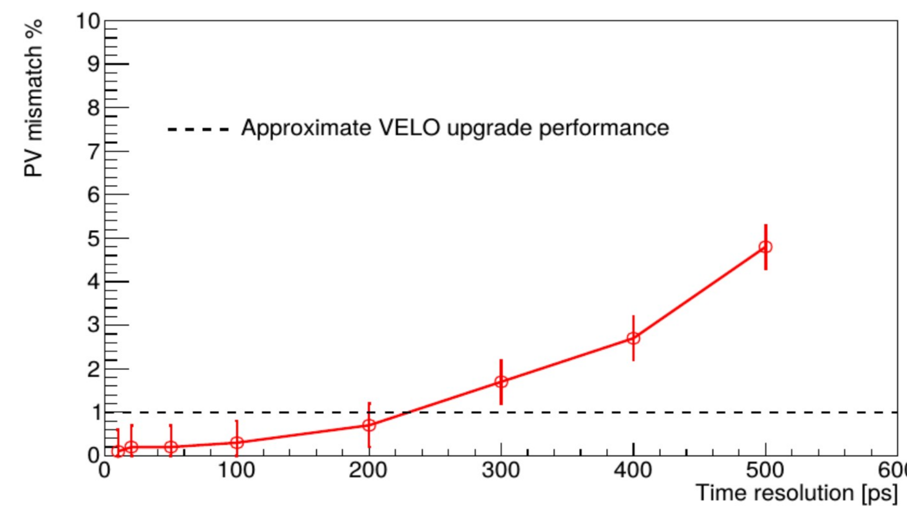
→ 1500 – 3000 charged particles



Detectors with even finer granularity and with excellent timing resolution

→ assign objects to the correct *pp* collision

→ in particular, assign *b* decay vertex to its correct production vertex



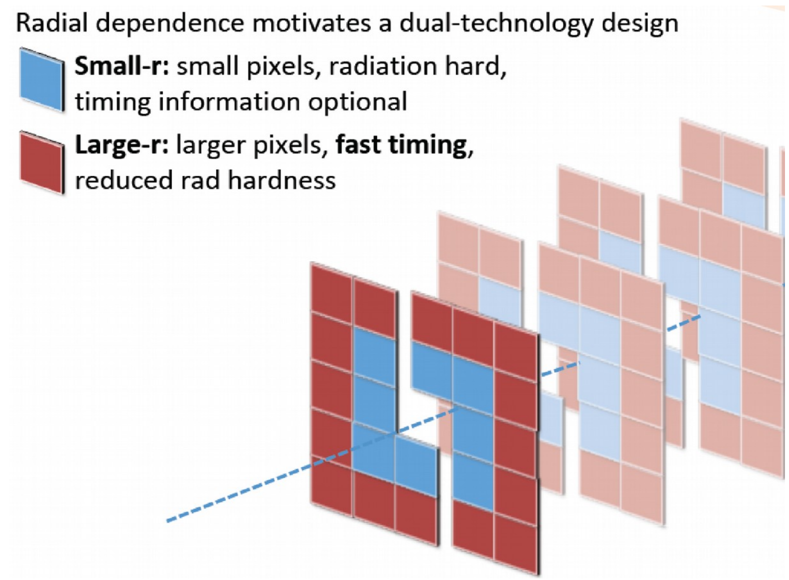
Radiation hardness !

Upgrade II

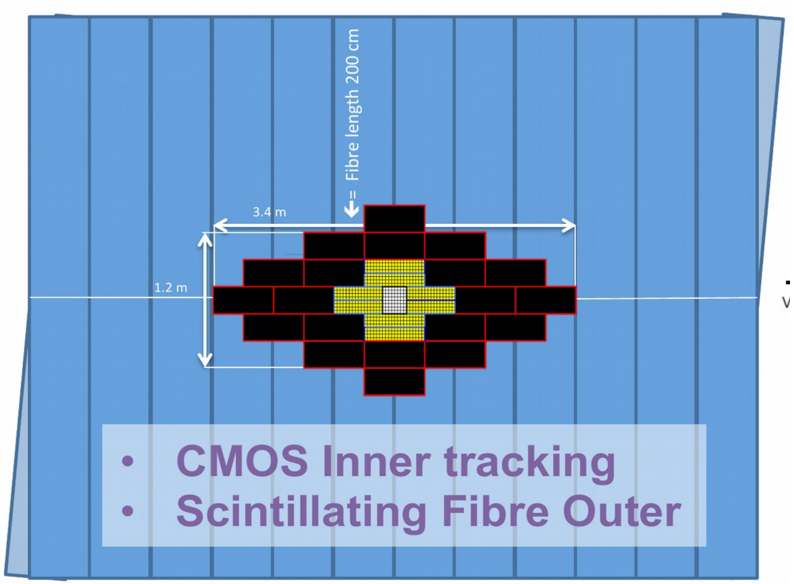
Examples of detector developments

VELO: silicon pixels with timing resolution

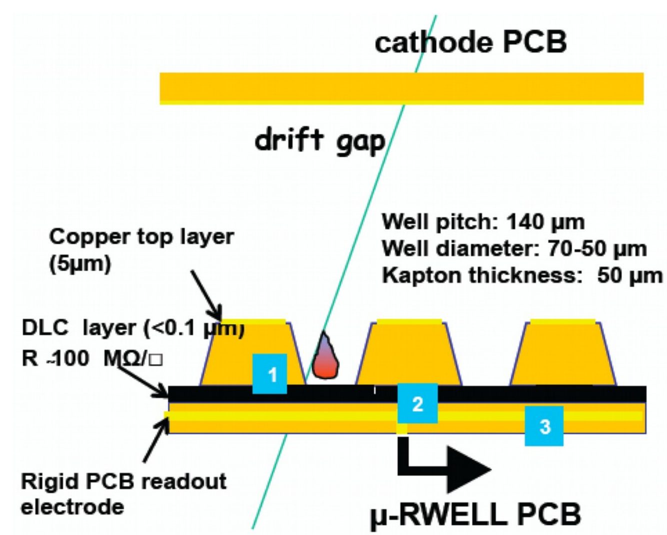
→ LGAD (Limited Gain Avalanche Detectors)



Tracking: central region with silicon
→ HV-MAPS (Monolithic Pixels)



Muon detectors: finer granularity
→ μ-RWELL



Upgrade II

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
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
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
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%
$B_s^0, B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ 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}

[CERN-LHCC-2018-027]

Summary

LHCb tests Standard Model by performing precision measurements of observables with good sensitivity to BSM physics

→ sensitivity to higher mass scales than direct searches

Interesting hints (see Katharina's talk on Monday) **but need more statistics to consolidate**

→ **UPGRADES:**

Upgrade 1 in LS3 (starting now):

→ factor 5 in luminosity
→ full software trigger
→ detectors with finer granularity
→ electronics with 40 MHz readout

Upgrade 2 in LS5 (around 2030):

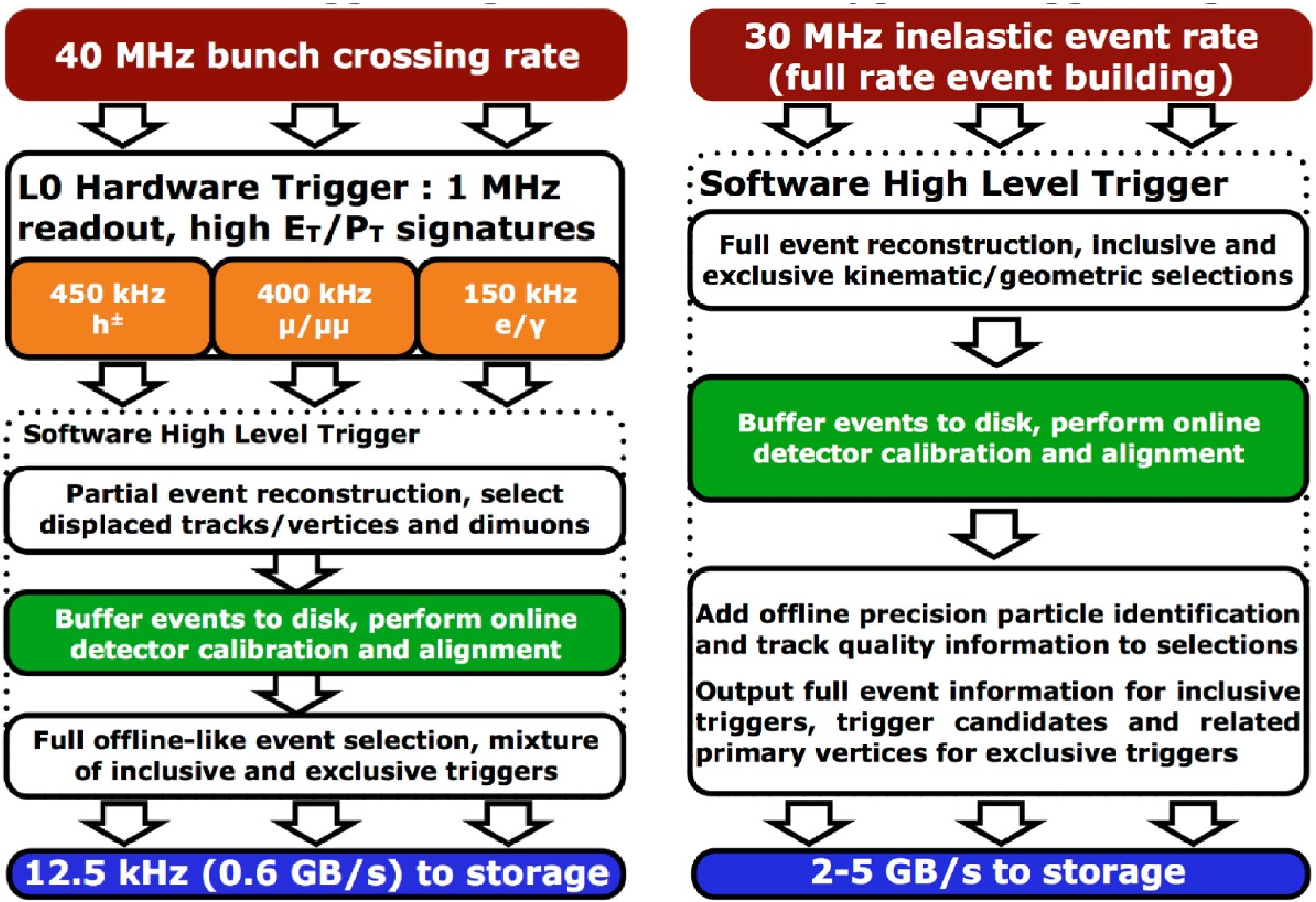
→ another factor 10 in luminosity
→ detectors with 4D resolution (space and timing)
→ radiation hardness


This is the end …

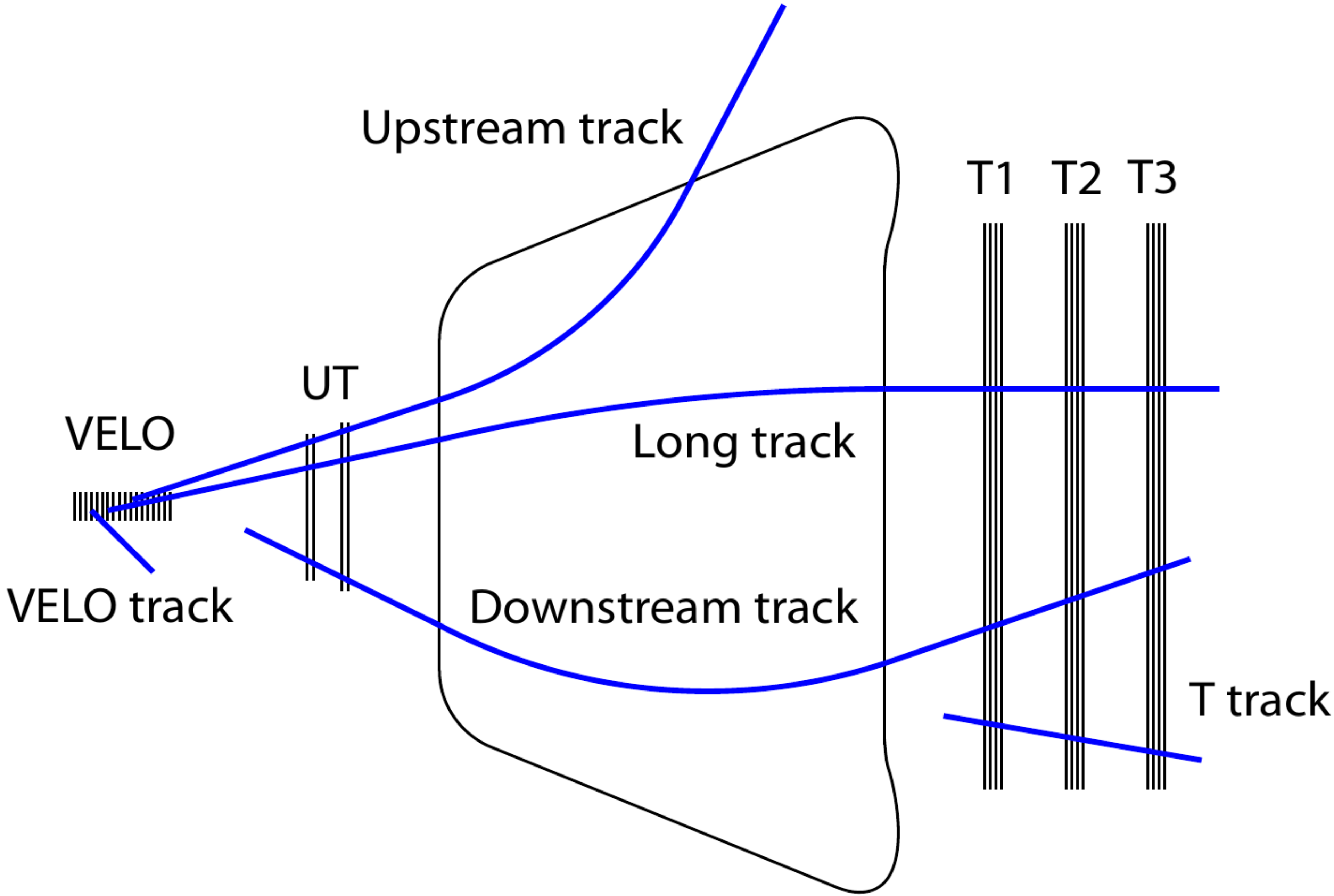

But we'll be back
(even) stronger

Upgrade Trigger

LHC Run II (2015) | **Upgrade**



Upgrade Ib: Magnet Tracking



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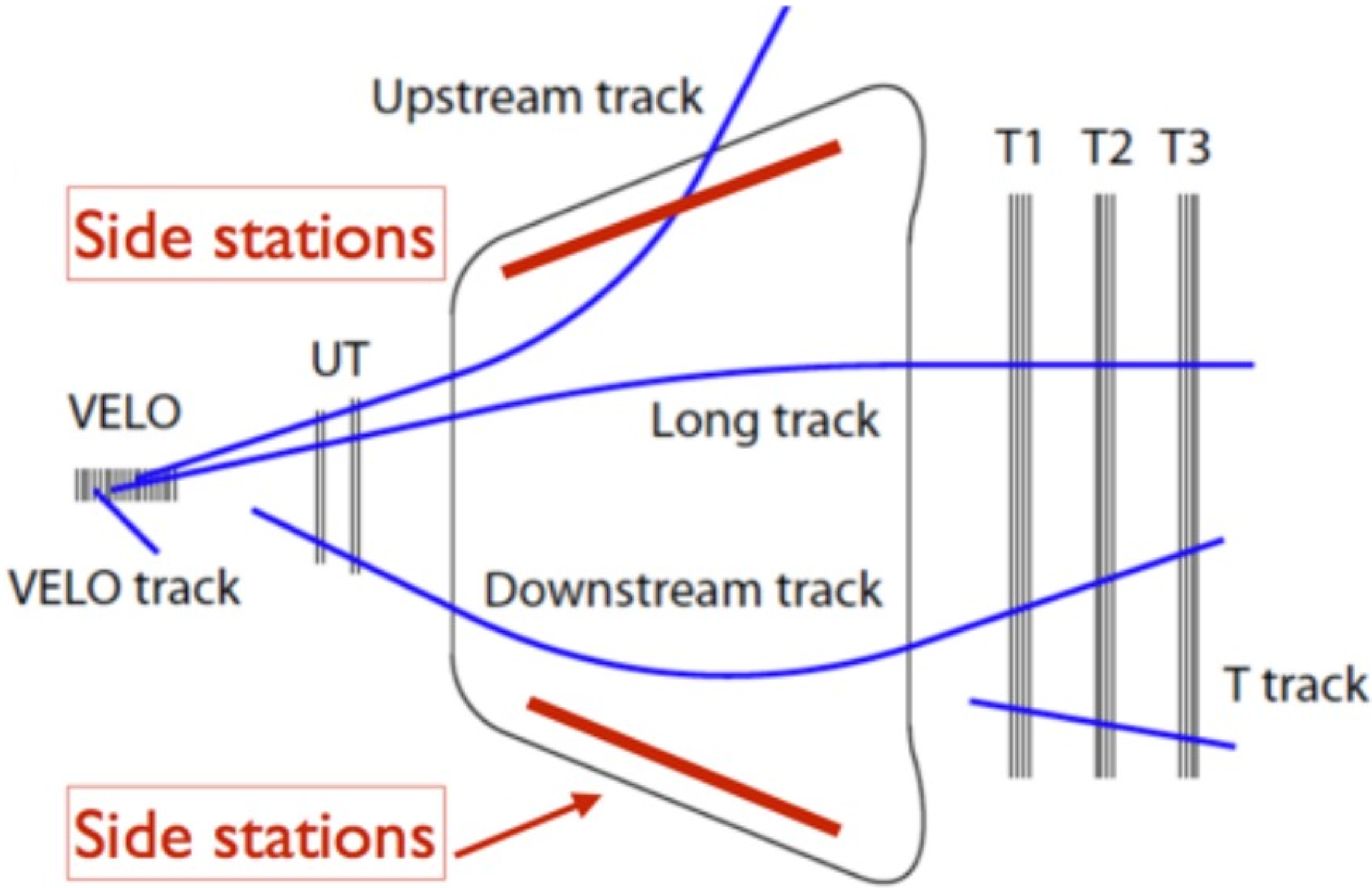
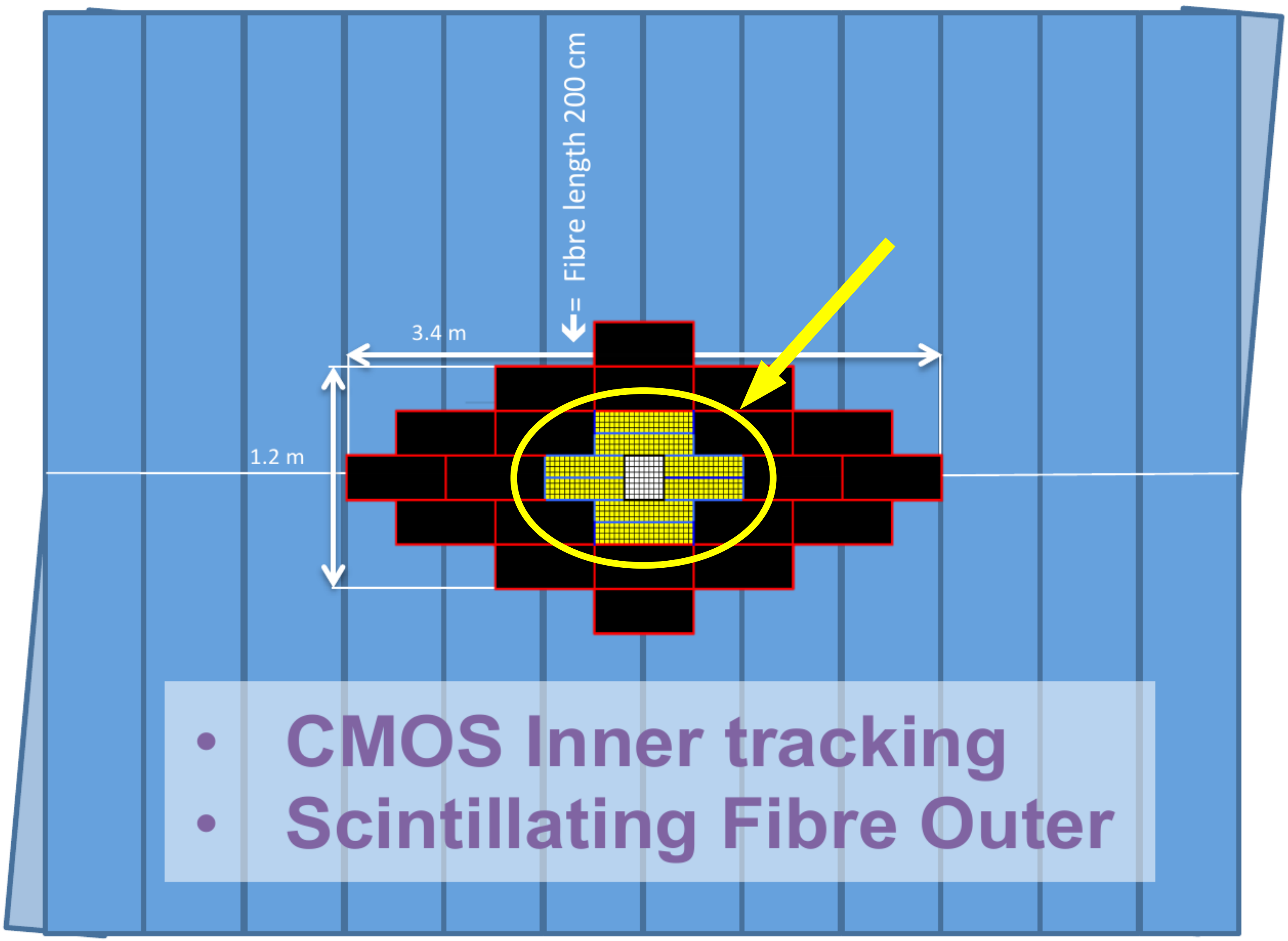


Upgrade Ib: Downstream Tracking



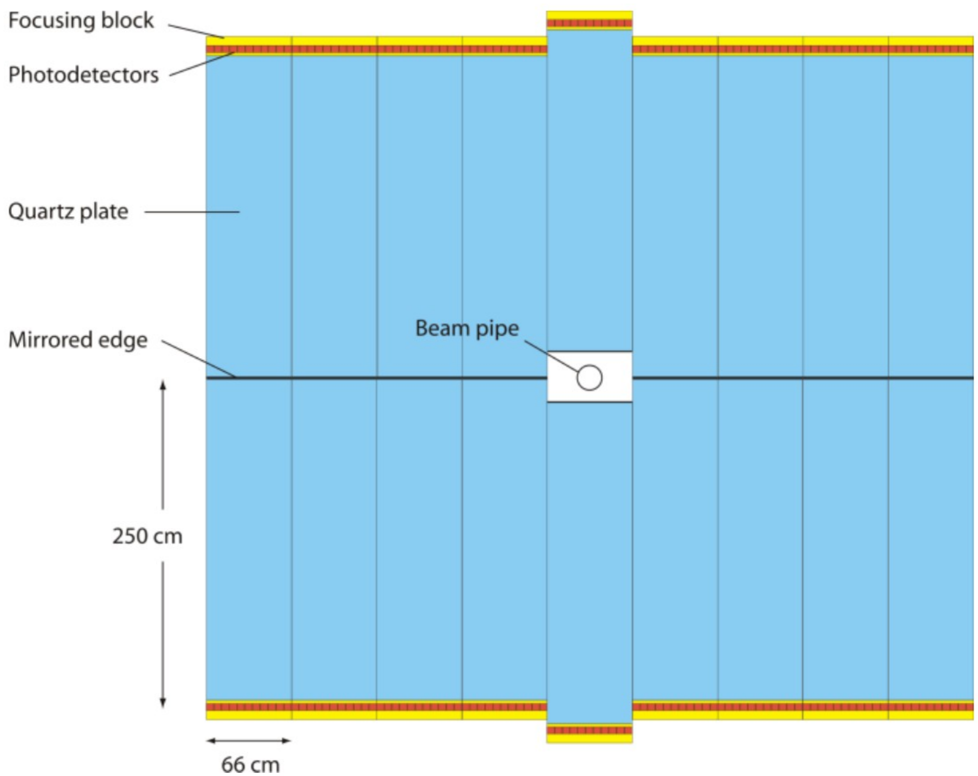
Upgrade Ib: TORCH

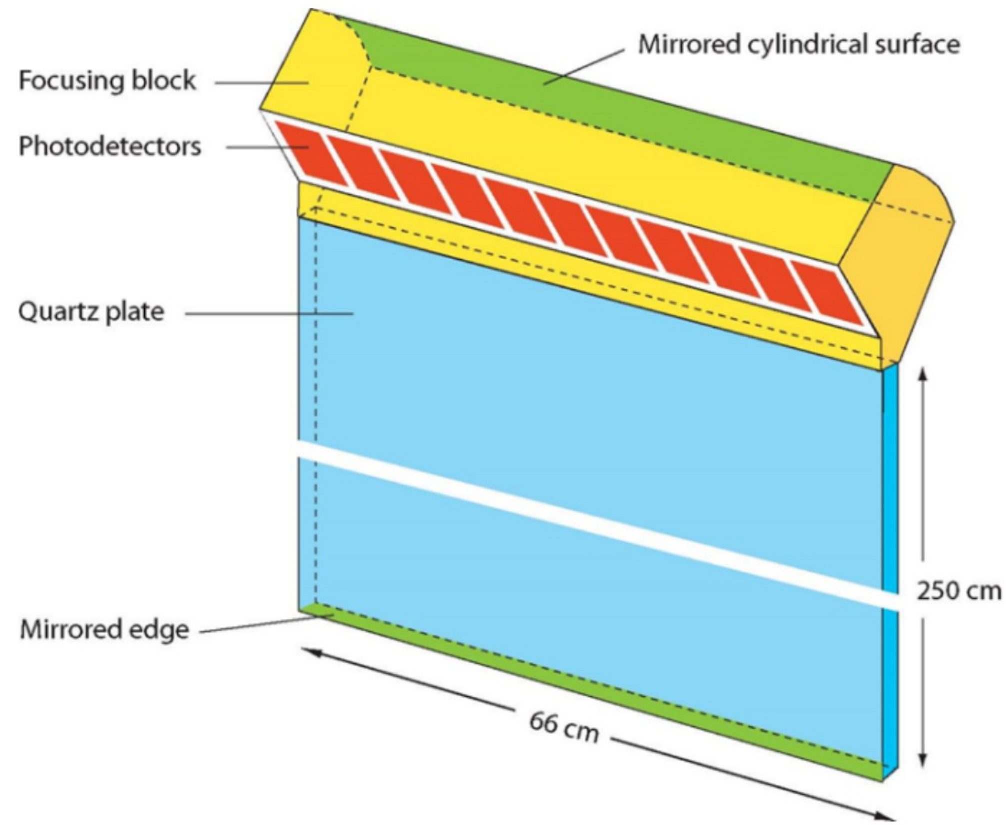
"Time Of interally Reflected CHerenkov light"

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

→ PID below 10 GeV/c

→ time resolution of ≈ 15 ns per track



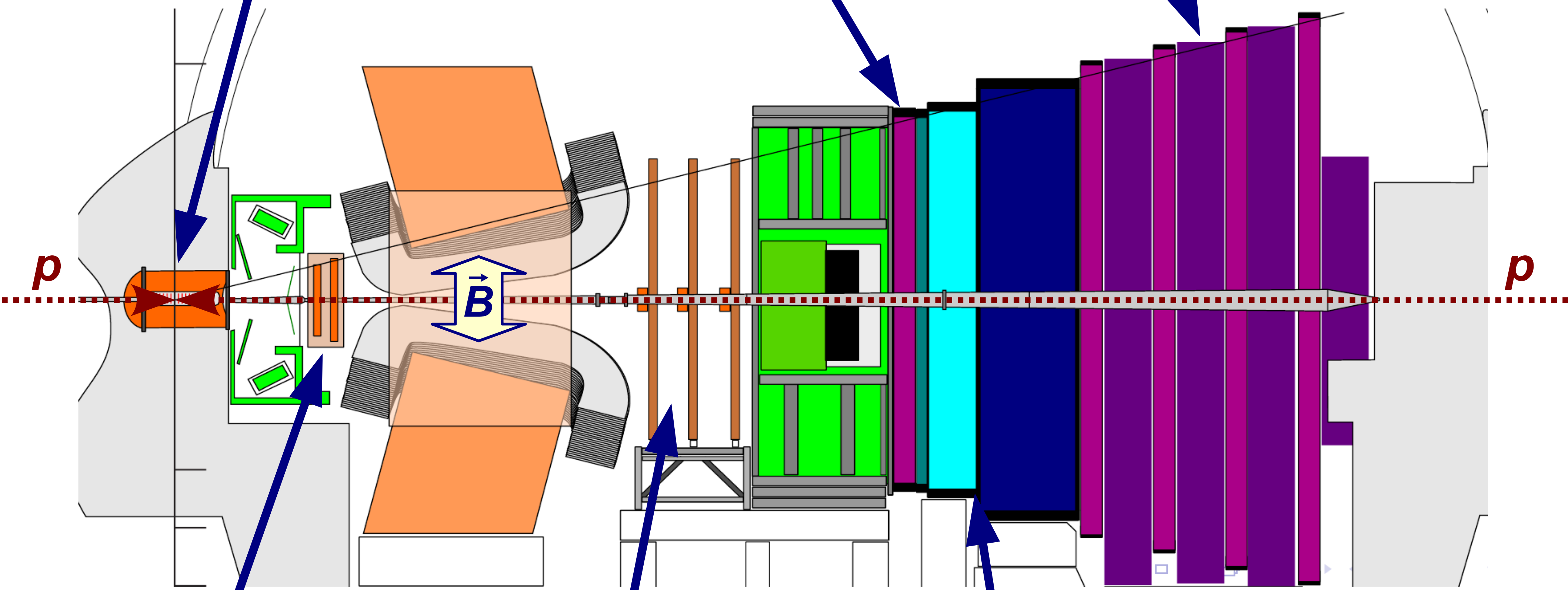


Upgrade II

Silicon pixels with timing resolution (e.g. LGAD)

"TORCH"
PID for $p < 10$ GeV
$\sigma_t \approx 15$ ps

Finer segmentation (Inner region: μ-RWELL)



Finer segmentation in inner region Timing resolution ?

Silicon pixels/strips in inner region (e.g. HV-MAPS)

ECAL with finer segmentation, $\sigma_t \approx 20 - 50$ ps

$2 < \eta < 5$