LHCb Upgrade 2

Heavy flavor in the HL-LHC era

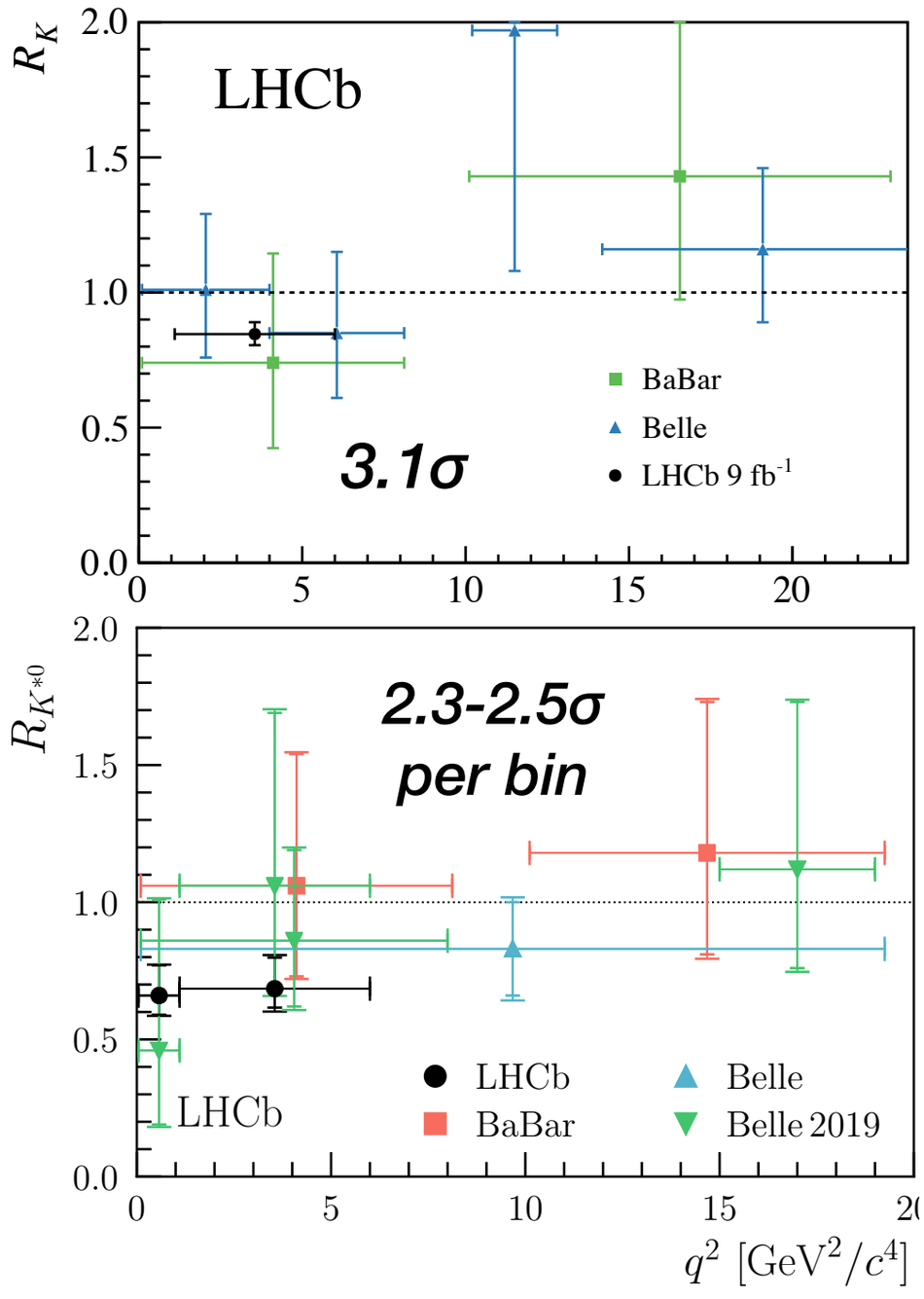
Angelo Di Canto

Why heavy flavor?

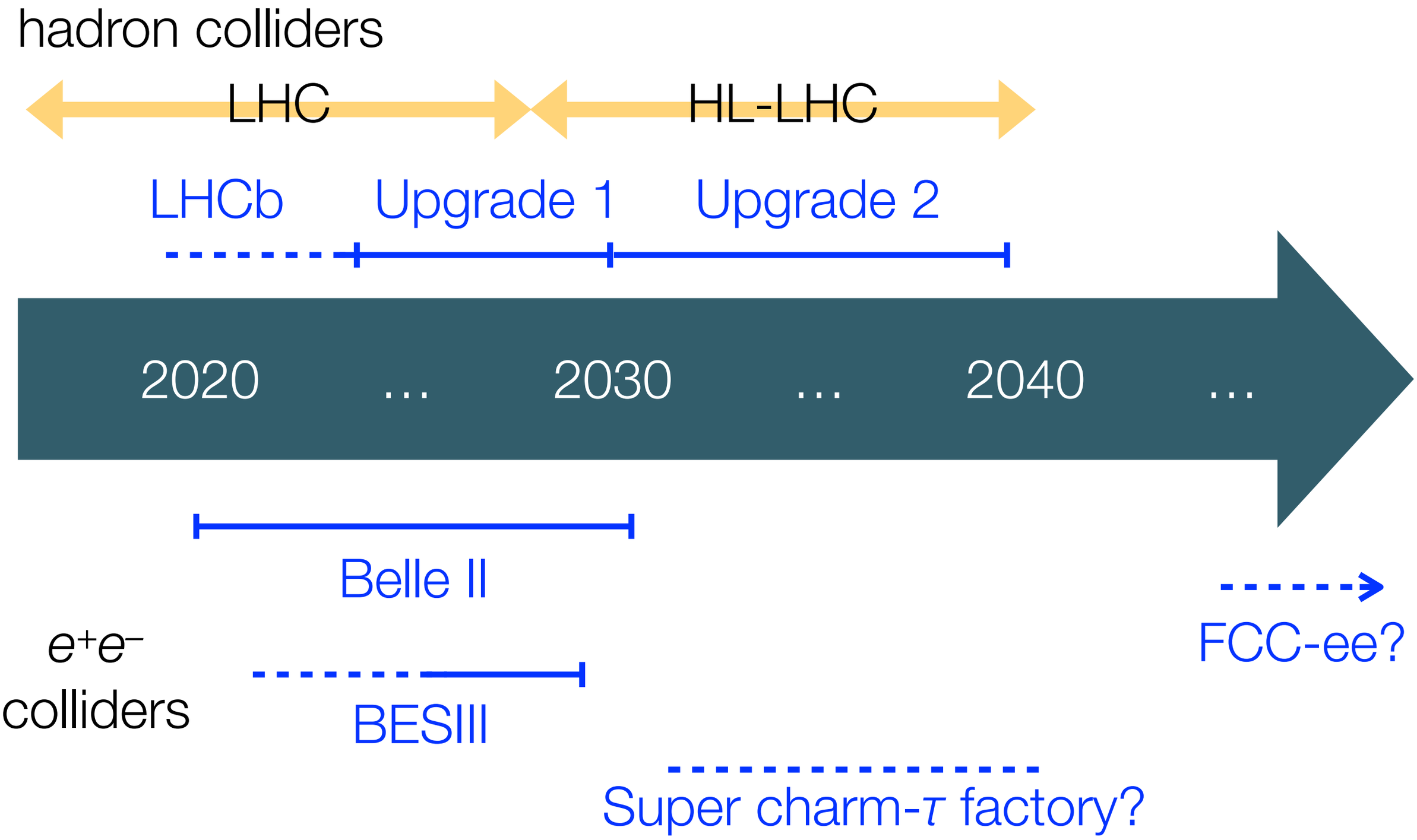
- Tool for NP searches at energy scales far beyond what directly accessible
- Rich, diverse and model-independent: NP has often revealed itself in very unexpected ways
- The only promising hints of NP from the LHC seem to be emerging from flavor

Evidence for LFU violation

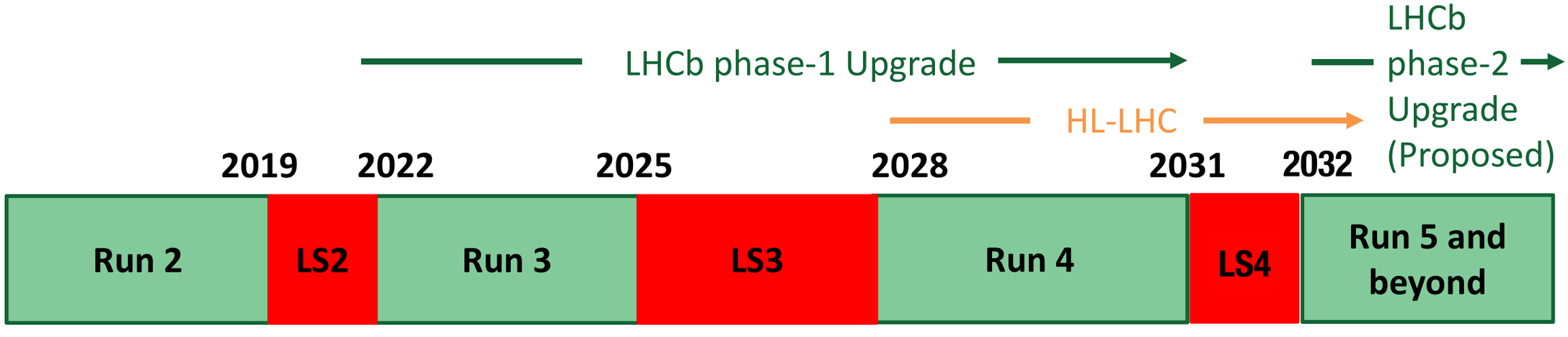
$(B \to K^{(*)}\mu^+\mu^-)/(B \to K^{(*)}e^+e^-)$



Heavy-flavor experiments in the next two decades



LHCb schedule



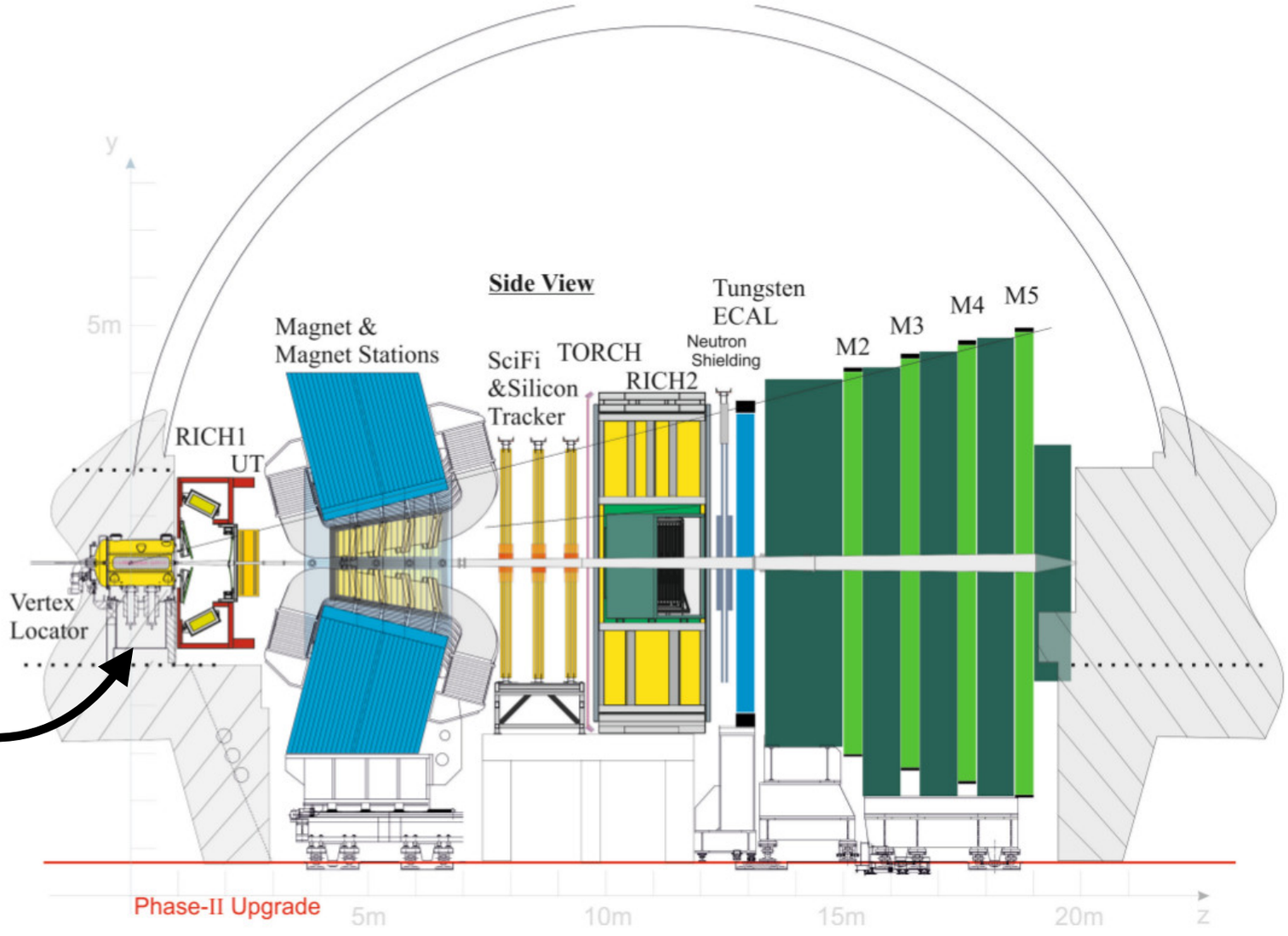
- LHCb Upgrade 1: new tracking/vertexing, new electronics, software-only trigger
- $L = 2\times10^{33}$ (5x Run 2)
- Target int. $L = 50$ fb^{-1} by Run 4

- Atlas/CMS phase-2 upgrades
- LHCb minor incremental/ consolidation upgrade (phase-1b)

- LHCb Upgrade 2: all new detector
- $L = 2\times10^{34}$
- Target int. $L = 300$ fb^{-1} by Run 6
- Framework TDR submitted to LHCC in Sep 2021
- Sub-detectors TDRs expected in 2-3 years

Detector concept

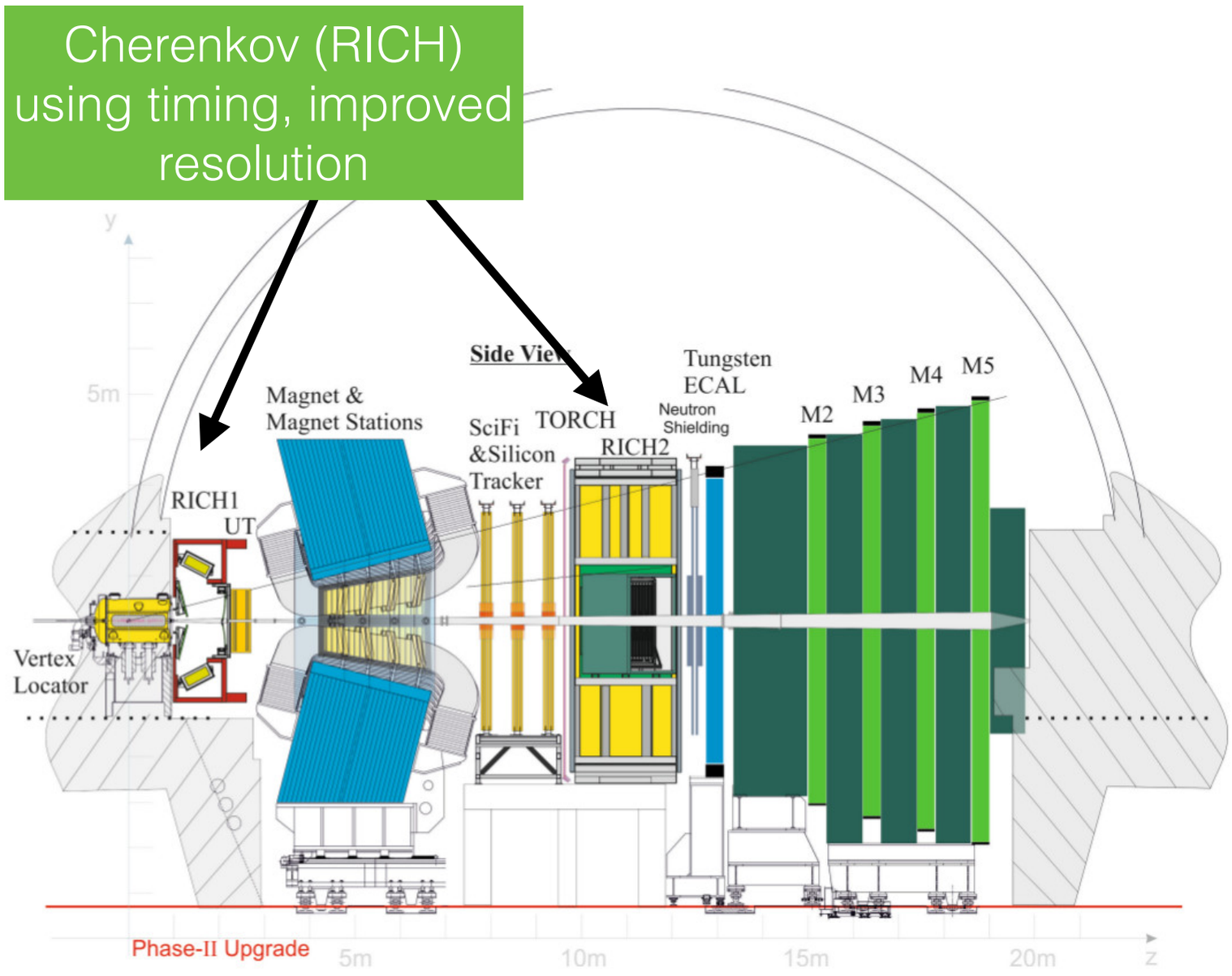
Pixel detector with timing



Detector concept

Cherenkov (RICH) using timing, improved resolution

Pixel detector with timing

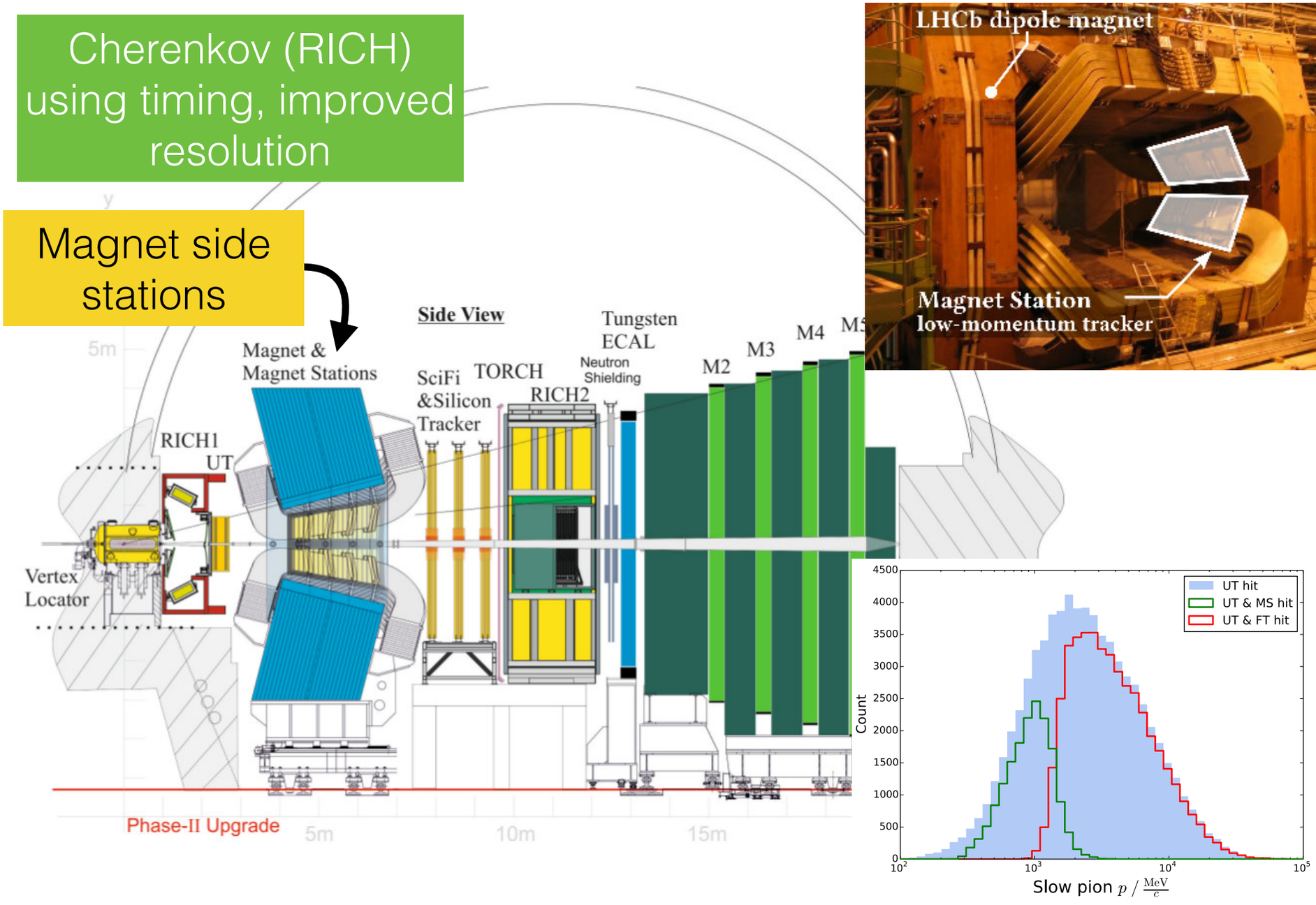


Detector concept

Cherenkov (RICH) using timing, improved resolution

Magnet side stations

Pixel detector with timing



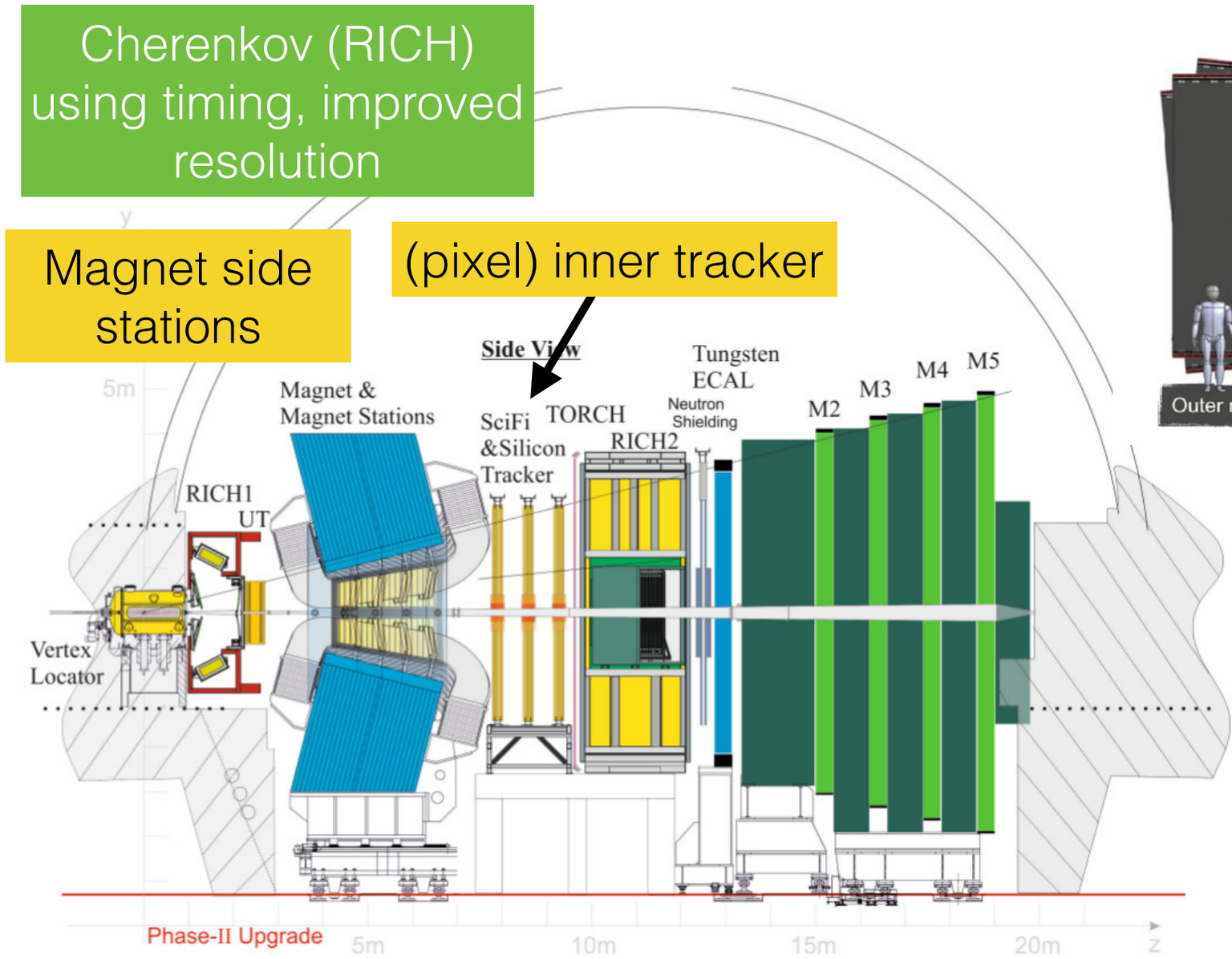
Detector concept

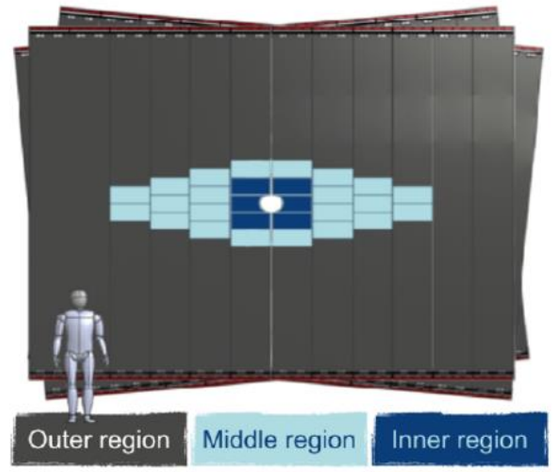
Cherenkov (RICH) using timing, improved resolution

Magnet side stations

(pixel) inner tracker

Pixel detector with timing





Detector concept

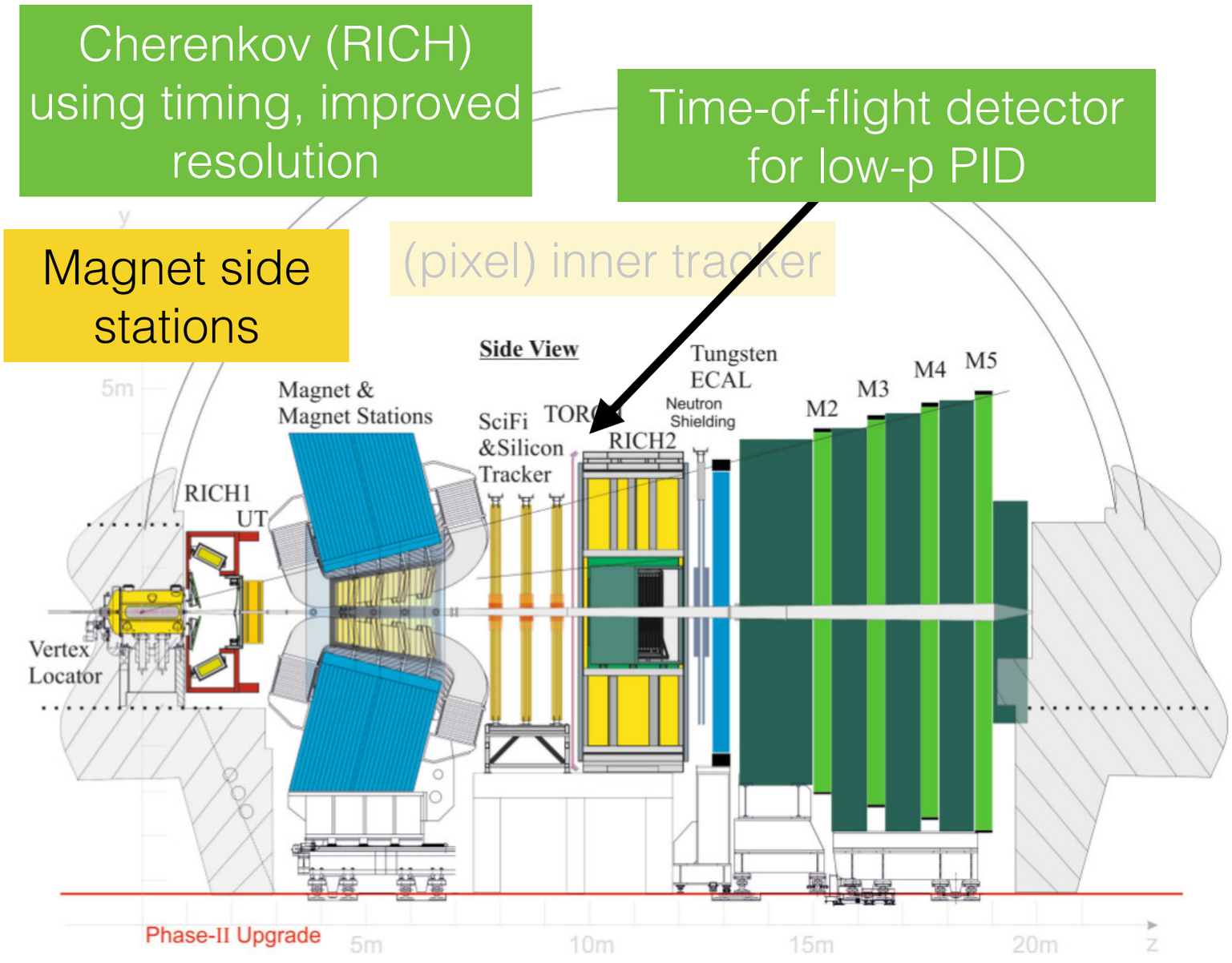
Cherenkov (RICH) using timing, improved resolution

Time-of-flight detector for low-p PID

Magnet side stations

(pixel) inner tracker

Pixel detector with timing



Detector concept

Cherenkov (RICH) using timing, improved resolution

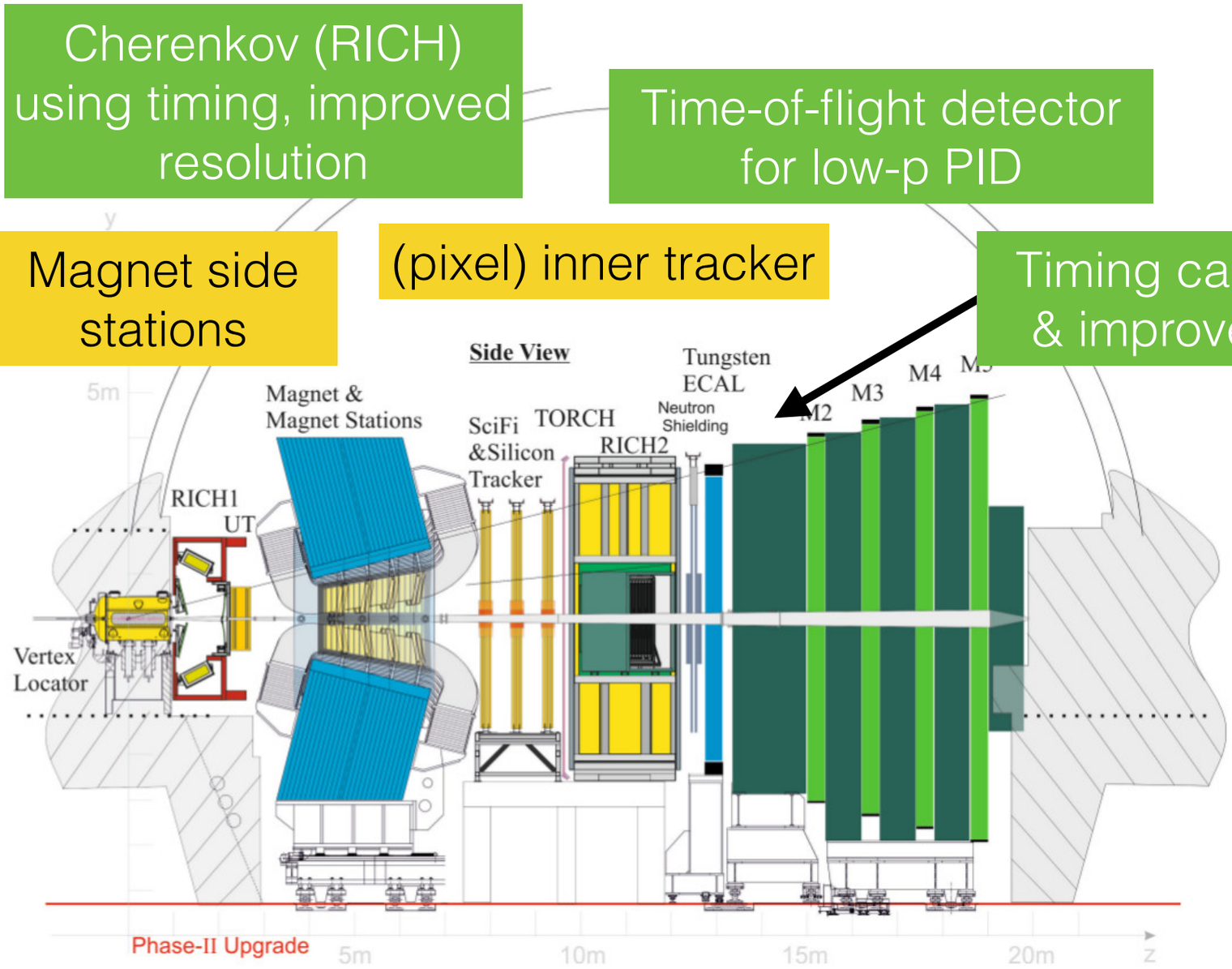
Time-of-flight detector for low-p PID

Magnet side stations

(pixel) inner tracker

Timing calorimeter & improved reso.

Pixel detector with timing



Detector concept

Cherenkov (RICH) using timing, improved resolution

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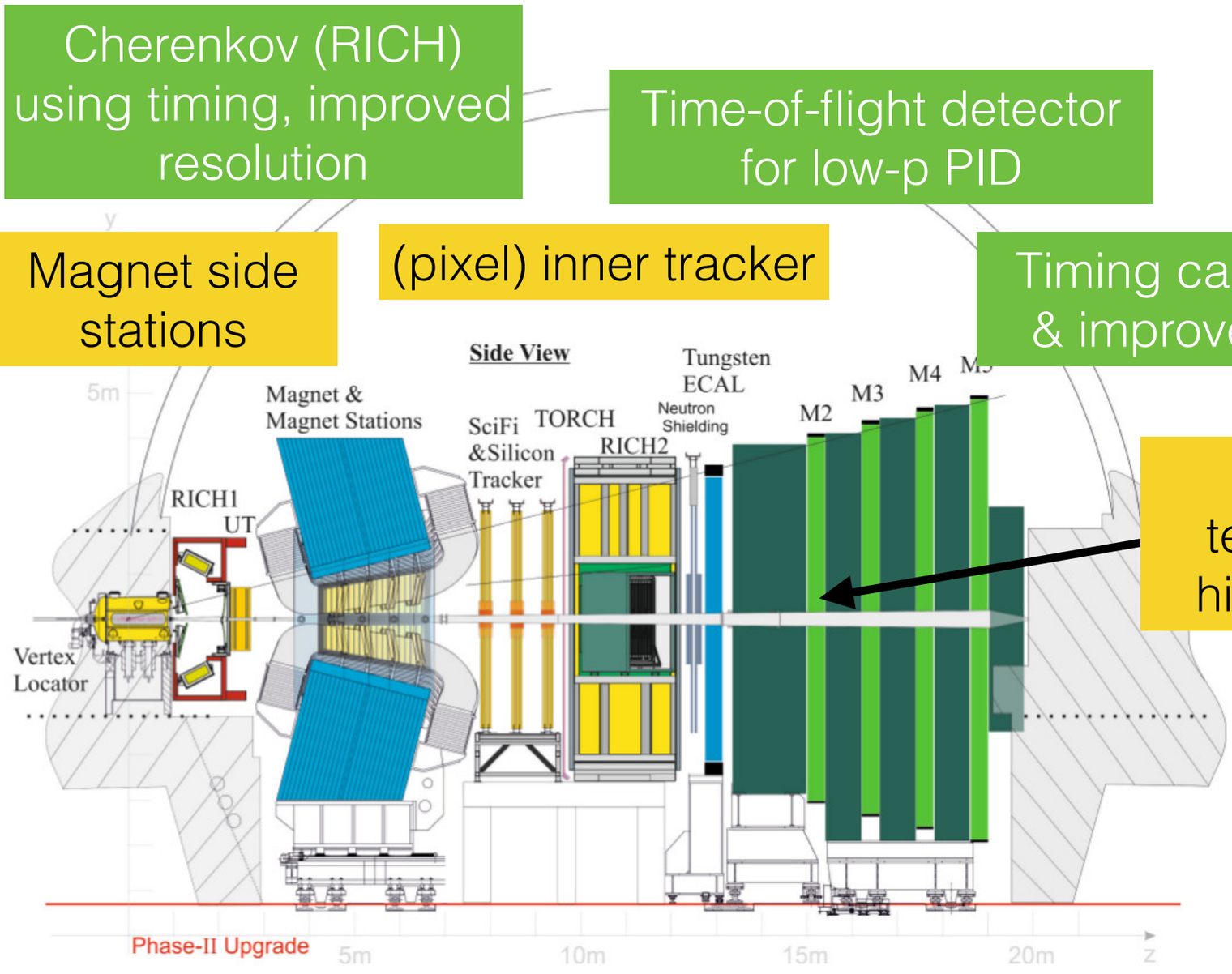
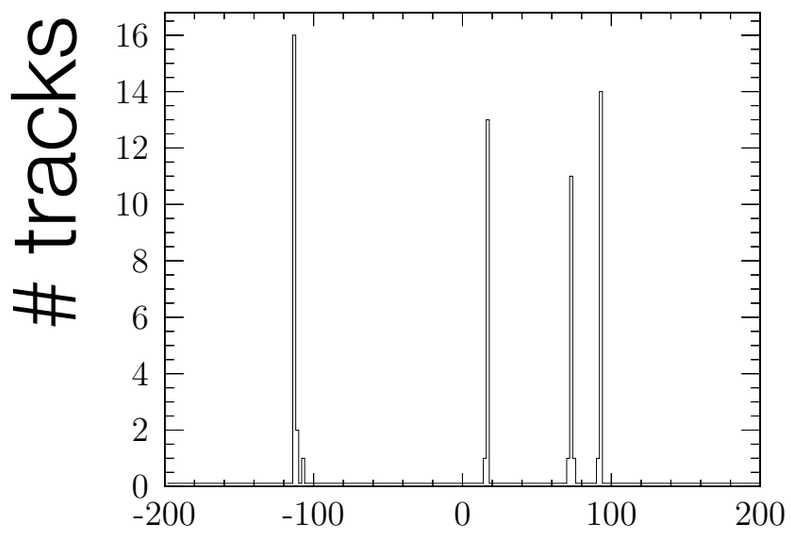


Alternative technologies for high-rate regions

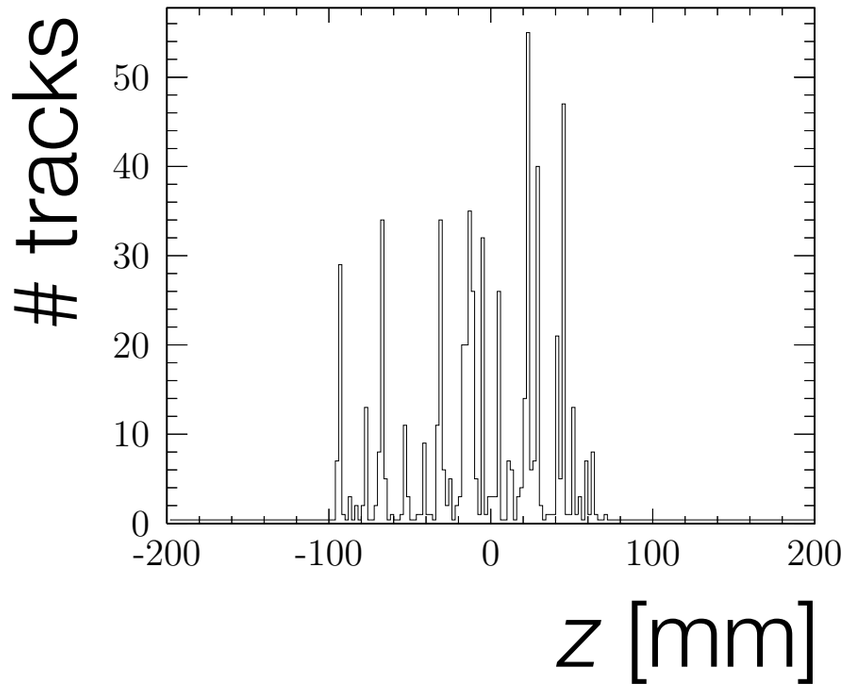
Pixel detector with timing

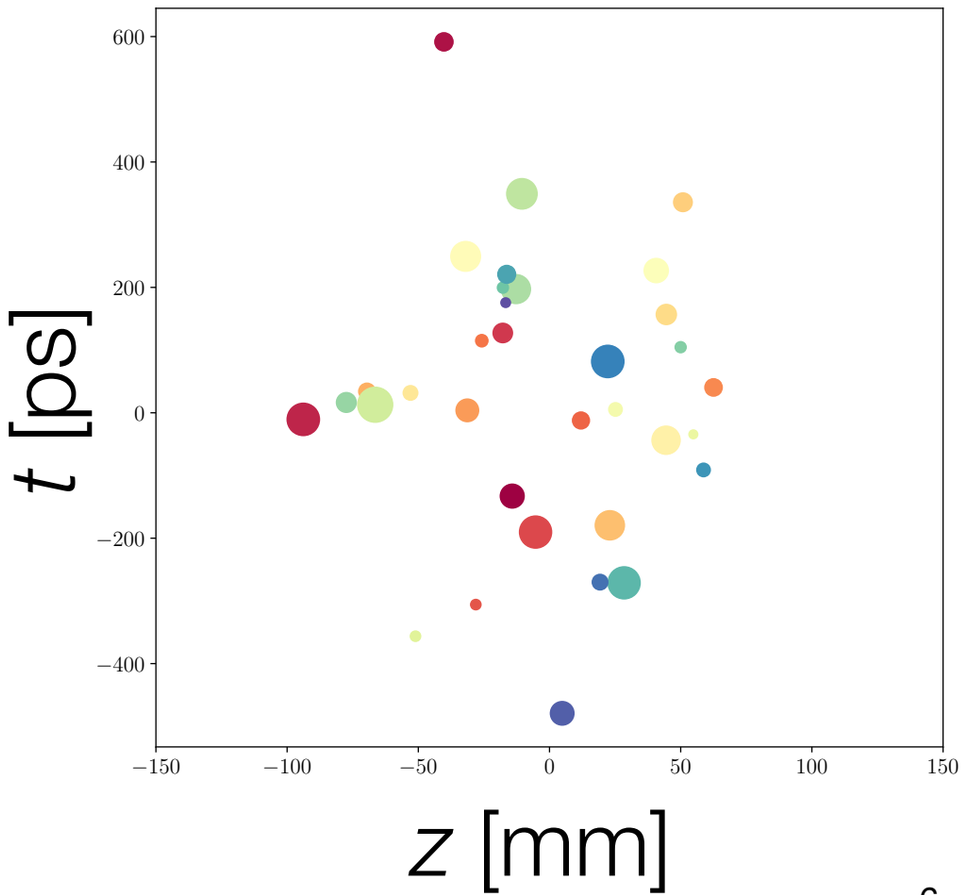
Why timing?

Upgrade 1



Upgrade 2



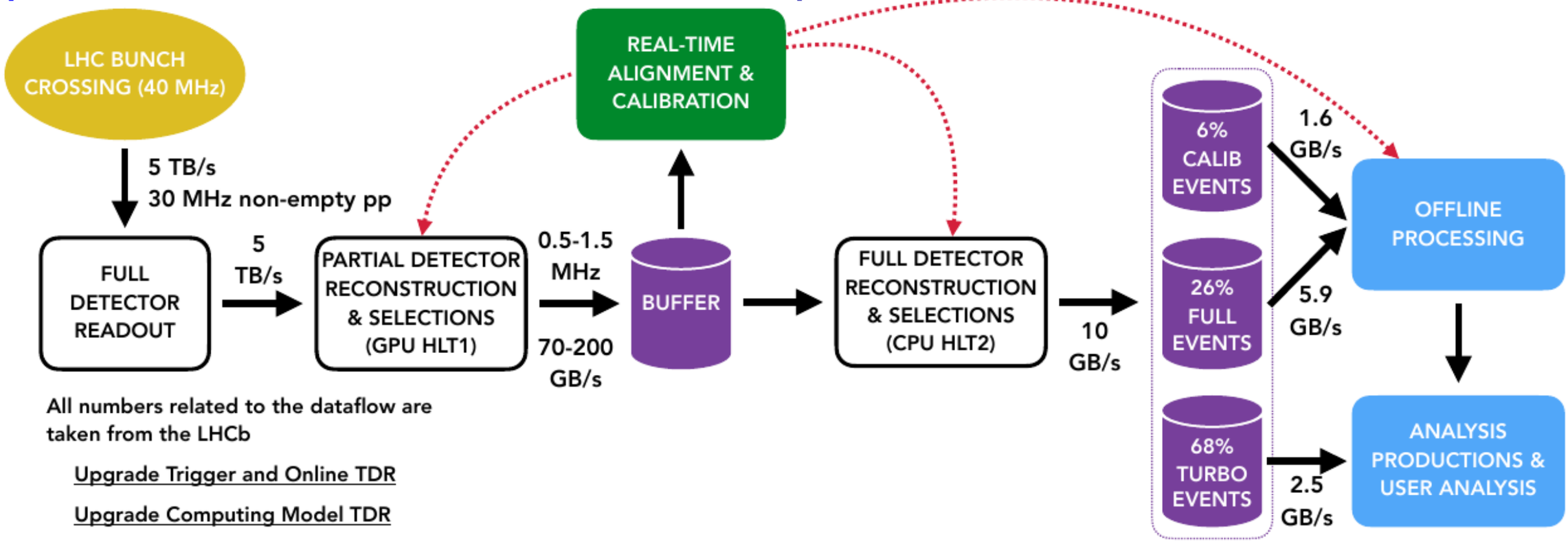


- During Upgrade 1 spacial resolution in *z* is sufficient to separate all primary vertices
- In Upgrade 2 pile-up is 10x larger: need 10-20 ps time resolution to separate primary vertices in (*t*, *z*)
- Could leverage on BNL expertise with LGADs

Trigger and data processing

Upgrade 1 model (*a.k.a.* Real Time Analysis)

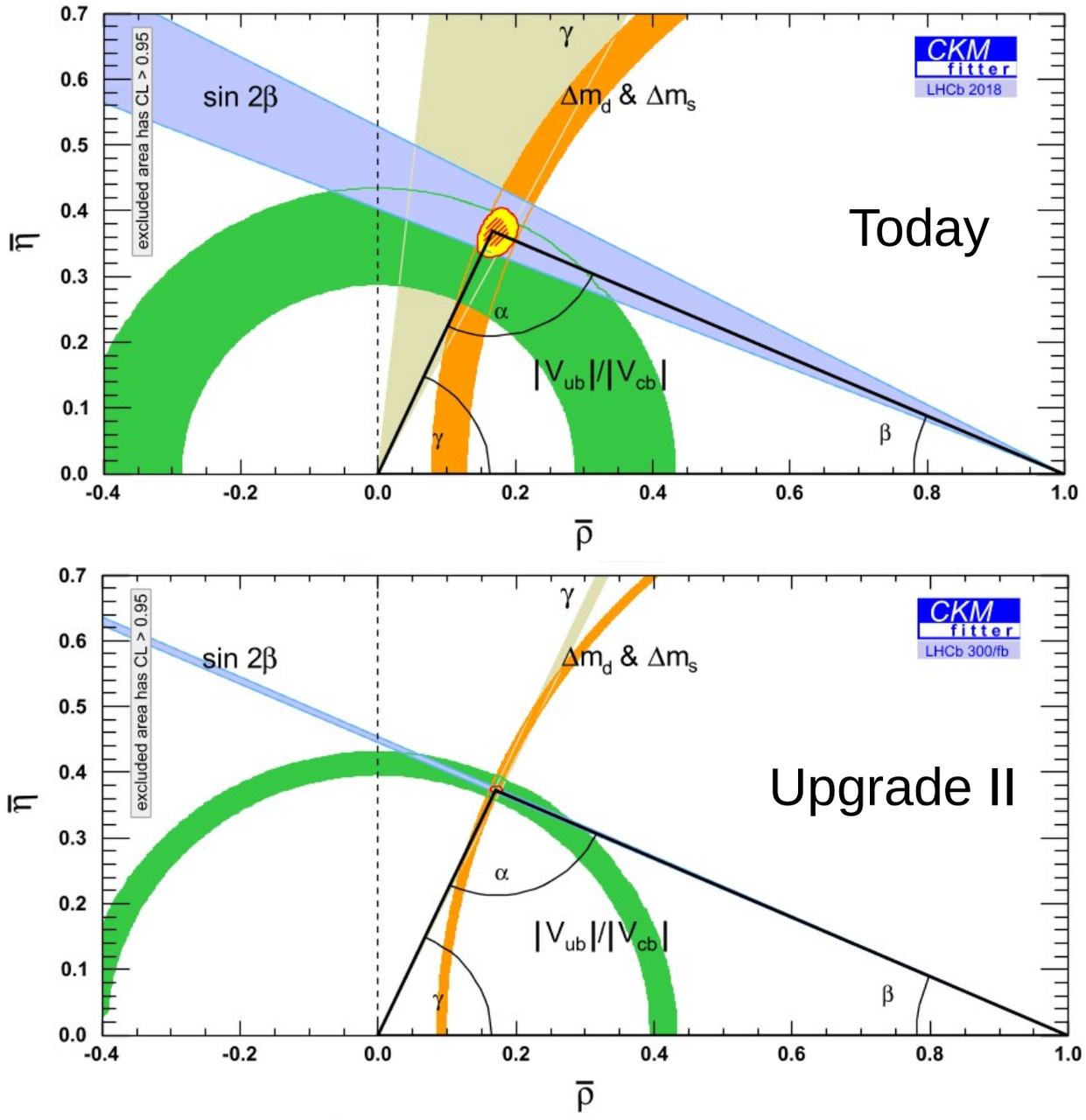
[LHCb-TDR-016; LHCb-TDR-017;LHCb-TDR-021]



Possible synergies at BNL: online reconstruction/trigger at Atlas and EIC, ML/AI in CSI

Physics potential

- Just a few examples:
  - Approach SM uncertainty on clean NP probes: *e.g.*, $B_s^0 \to \mu^+\mu^-$, CKM angle γ, …
  - Sub-1% precision on LFU tests in $b \to s\ell^+\ell^-$, with unique access to $b \to d\ell^+\ell^-$ and $c \to d\ell^+\ell^-$
  - Discovery potential for *CP* violation in charm mixing
- Physics program not limited to flavor: forward high-p_T physics, dark sector, exotic hadrons, heavy-ions and fixed-target physics



Support

September 2019, CERN research board

A recommendation was made to prepare a **framework Technical Design Report**, with the remark that LHCb is expected to run throughout the HL-LHC. Document expected to consolidate on design options based on physics studies.

European Strategy Update 2020

"The flavour physics programme made possible with the proton collisions delivered by the LHC is very rich, and will be enhanced with the ongoing and proposed future upgrade of the LHCb detector."

"The full potential of the LHC and the HL-LHC, including the study of flavour physics ... should be exploited"

Opportunities

- Applications from new groups actively encouraged
  - Technical Associate membership: continue to do physics on other experiments while pursuing R&D on LHCb
- Major project after construction timescale of ATLAS/CMS, on a similar timescale as EIC detectors
  - Many synergetic R&D prospects w/ already existing BNL activities: precise timing, software trigger, computing, …
- Joining “now” means having the chance to influence the R&D decisions and impact the physics reach of the experiment

Summary

- LHCb Upgrade 2 is the only proposed heavy-flavor experiment past 2030
  - Potential to increase the explored NP mass scale by close to a factor two wrt LHCb Upgrade 1 + Belle II, reaching standard model precision for many key observables
- BNL should join to continue its research effort in heavy-flavor physics past Belle II
  - Continue to do physics on Belle II while pursuing R&D on LHCb

Want to know more?

- Supporting documents:
  - Expression of interest [LHCC-2017-003], Physics case [arXiv:1808.08865], Accelerator Study [CERN-ACC-2018-038], Luminosity Scenarios [LHCb-PUB-2019-001], Framework TDR to become public soon

- Attend next week's Particle Physics Seminar


Particle Physics Seminars at BNL

Promise and challenges of the future LHCb upgrade

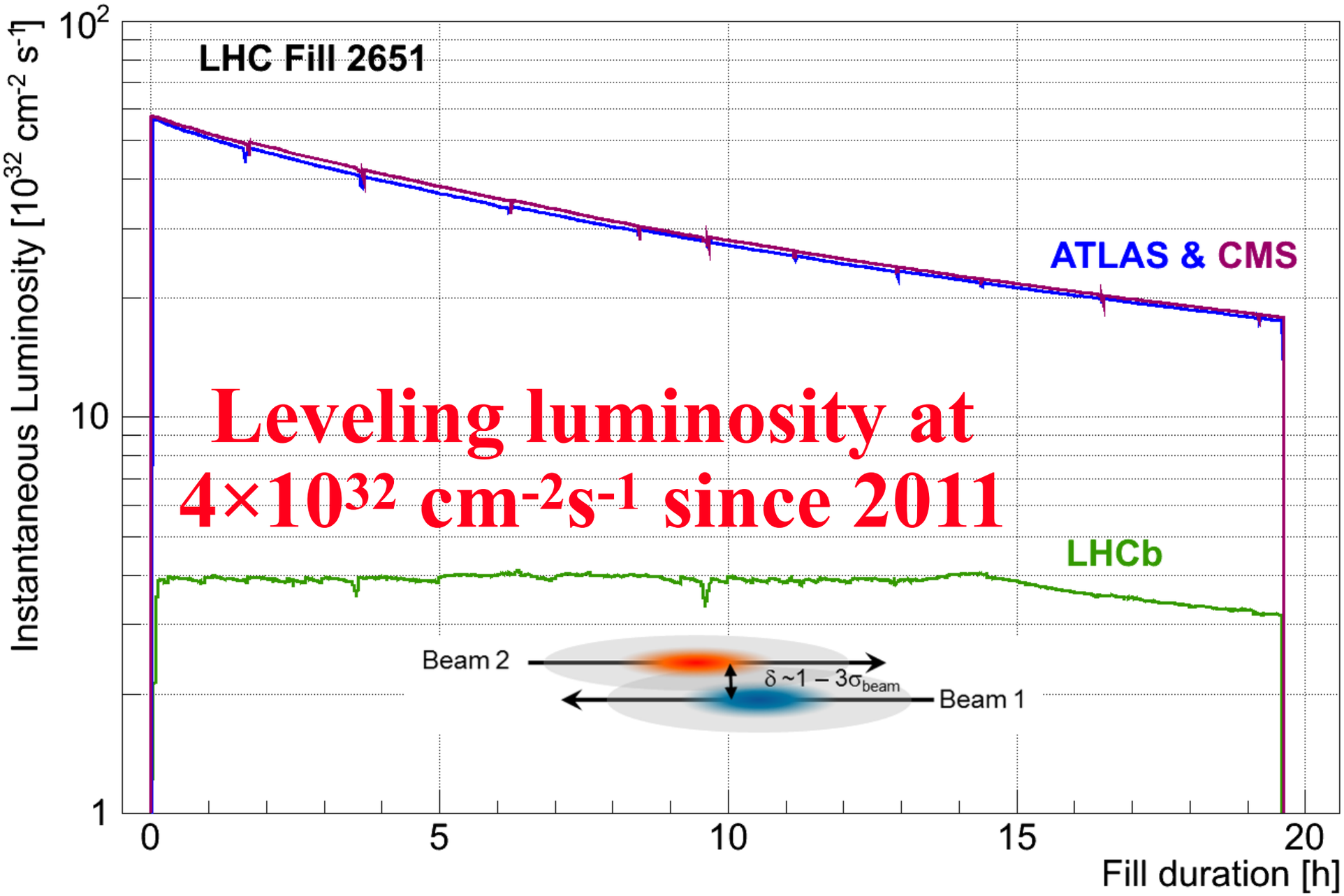
by Matthew Rudolph (Syracuse University)

Thursday 27 Jan 2022, 15:00 → 16:00 US/Eastern

Description The physics program of LHCb has been a resounding success in Runs 1 and 2 of the LHC. World-best measurements of the CKM matrix, discoveries of exotic hadrons, and some of the best hints for physics beyond the Standard Model in lepton flavor universality measurements are pieces of an extremely broad program. Exciting new results will come from the first upgrade installing now, but a future Upgrade II will further cement LHCb as a premiere flavor physics experiment. Operation at even higher luminosity brings a host of new challenges, and requires the utilization of technologies like picosecond timing. In this seminar, I will discuss the future promise of the LHCb physics program through the HL-LHC era, and discuss the detector developments needed to meet the challenge.

Backup

Luminosity leveling



Physics prospects

Observable	LHCb 2018	LHCb 2025	Belle II 2030	End of HL-LHC (2039) LHCb	End of HL-LHC (2039) 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 $B^0 \to J/\psi K^0_S$	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^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B^0_s \to \mu^+\mu^-}$	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}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Not only beauty and charm

- LHCb has already a strong program beyond heavy flavors:
  - Rare kaons and light-flavor decays
  - Exotic hadrons and QCD in the forward region
  - Electroweak, top, Higgs physics in the forward region
  - Dark sector
  - Heavy ions and fixed-target

Most-cited LHCb papers:

The LHCb Detector at the LHC #1

LHCb Collaboration • A.Augusto Alves, Jr. (Rio de Janeiro, CBPF) et al. (Aug 14, 2008)

Published in: *JINST* 3 (2008) S08005

DOI cite 3,435 citations

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays #2

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

pdf links DOI cite 1,109 citations

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays #3

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)

Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]

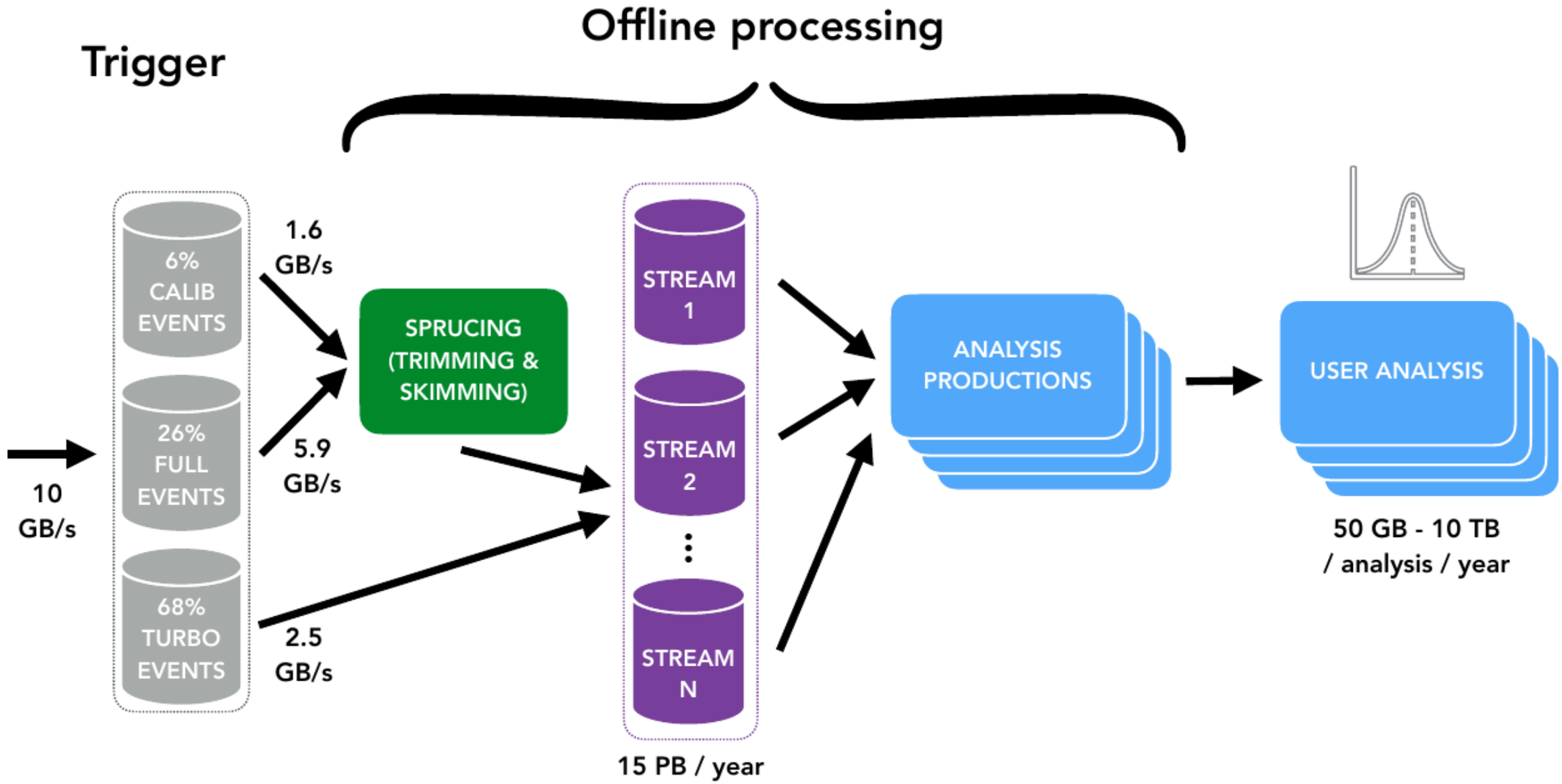
pdf DOI cite 1,045 citations

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ #4

LHCb Collaboration • Roel Aaij (CERN) et al. (Jun 29, 2015)

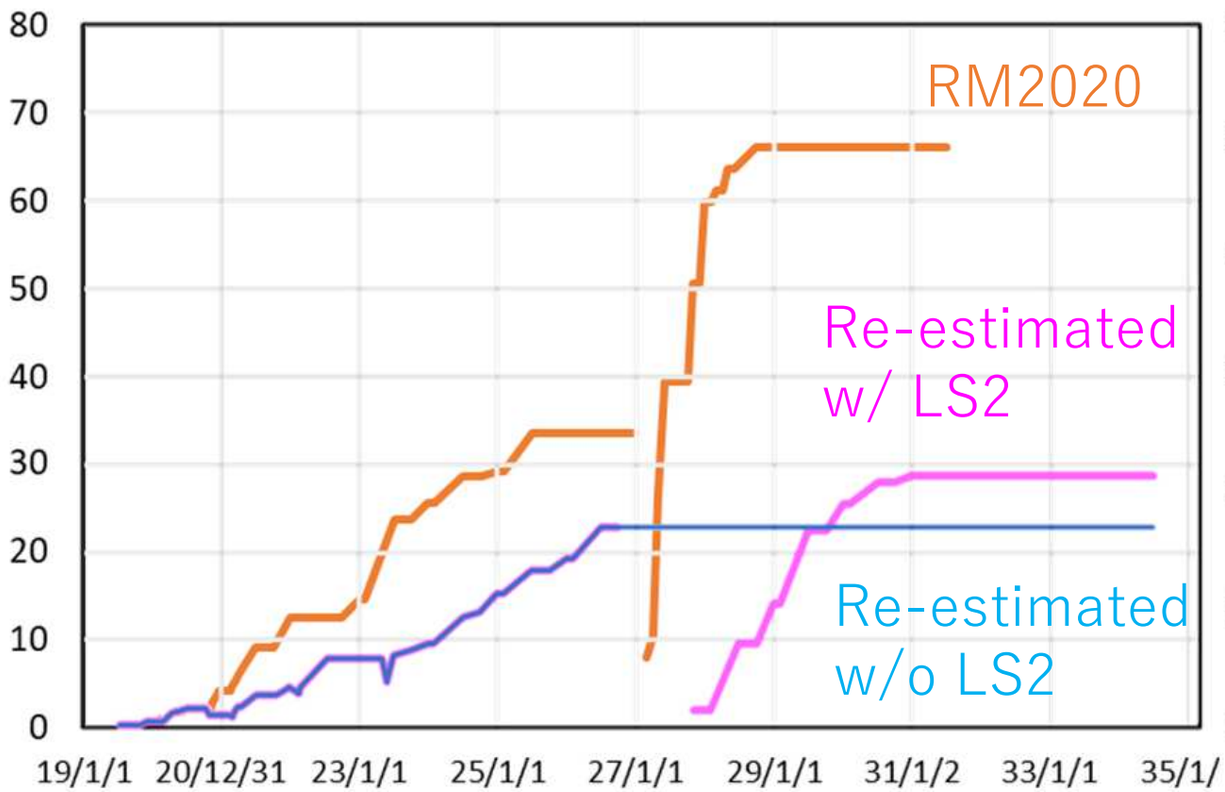
- Flexible trigger was key in making LHCb a general-purpose detector in the forward region. Upgrade II should preserve enough head room for innovative/unplanned techniques/developments

Upgrade I model for offline data processing

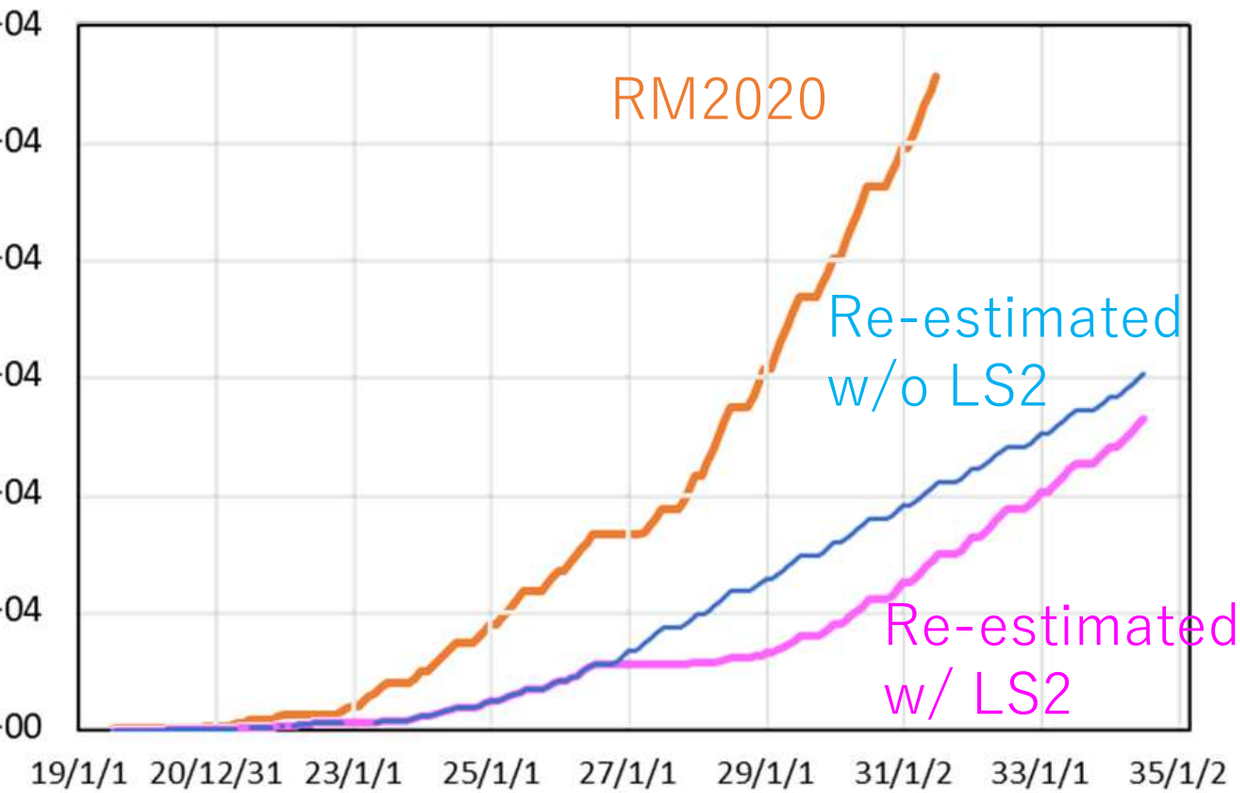


Belle II prospects

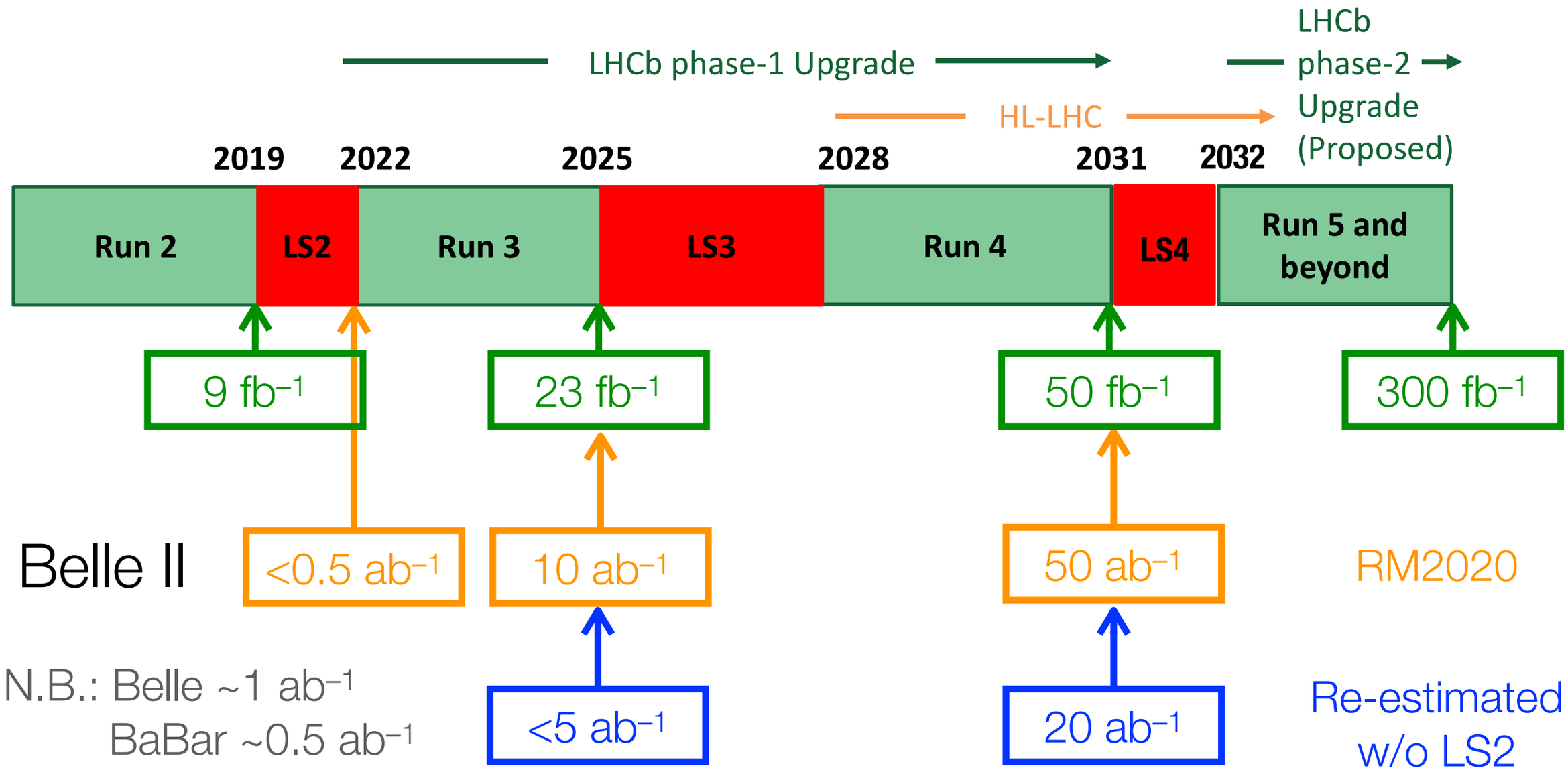
L_p [x10^{34} cm^{-2}s^{-1}]



Int. L [fb^{-1}] (Delivered)



LHCb schedule (in comparison w/ Belle II)



Rule of thumb for *B* production: 1 fb^{-1} @ LHCb ≈ 1 ab^{-1} @ Belle II

(invalid for prompt charm production)