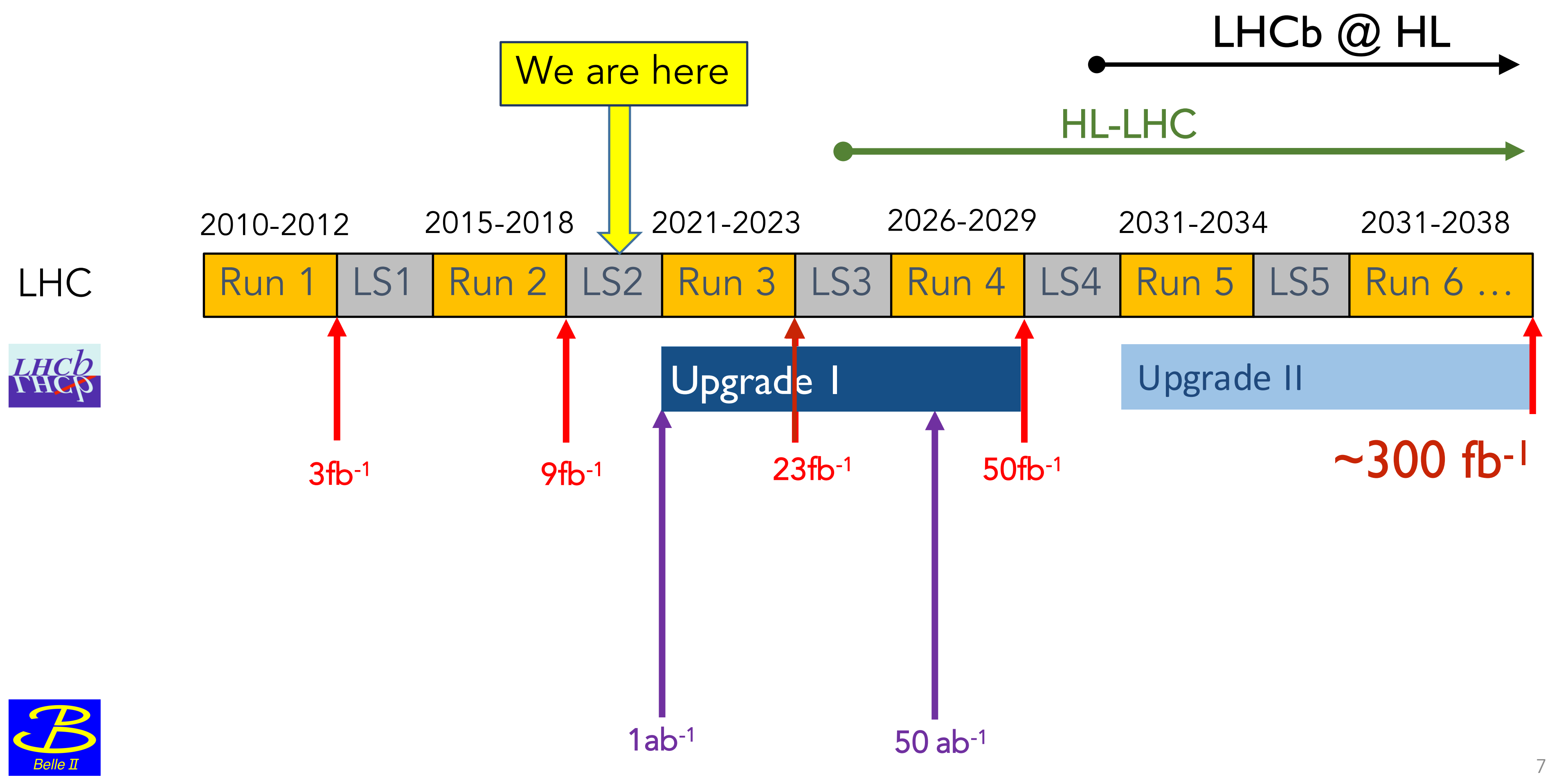
Phase-II upgrade for LHCb

BEAUTY September 24, 2020

Laurent Dufour, on behalf of the LHCb collaboration

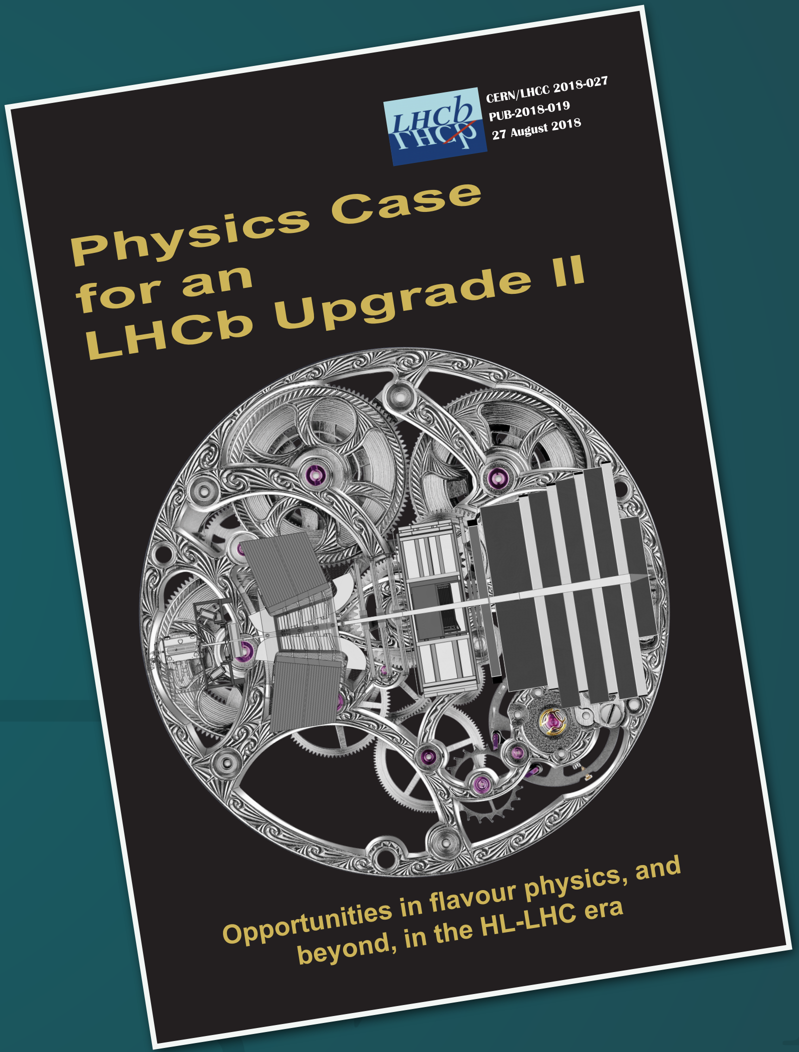
[Marie-Helene Schune '19]

LHCb's phase-2 upgrade



Goal > 30 times the current integrated luminosity,
pile-up ~40, from ~5 for Run 3/4 (today's challenge)

Physics

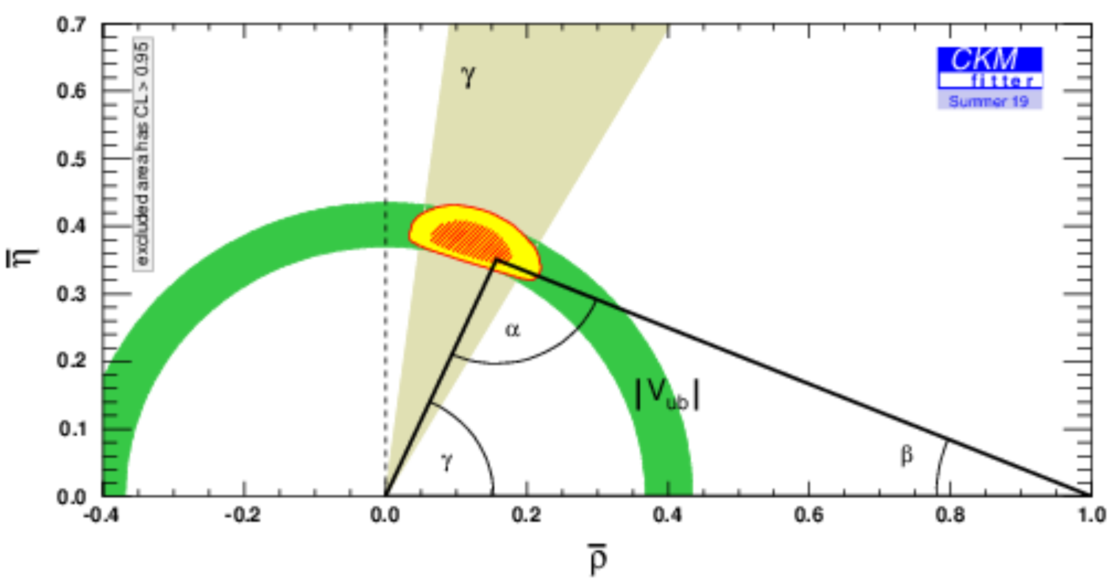

CERN/LHCC 2018-027
PUB-2018-019
27 August 2018
Physics Case for an LHCb Upgrade II
Opportunities in flavour physics, and beyond, in the HL-LHC era

CKM triangle: γ

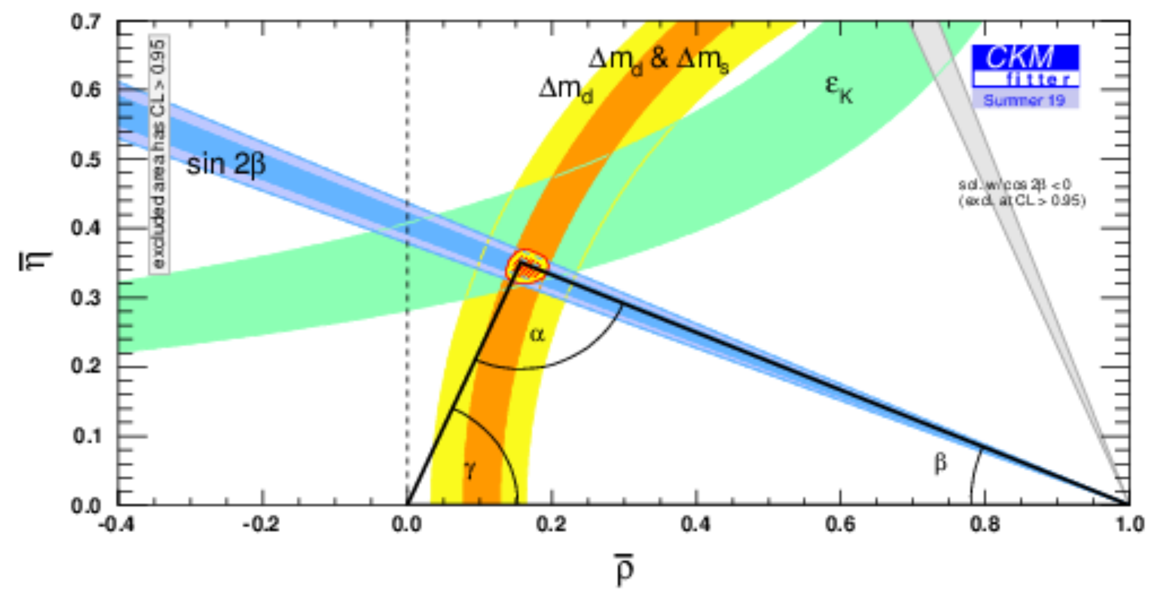
Testing the **consistency** of the **unitarity triangle** is one of the main goals of flavour physics today. Measurements of γ allow for a comparison between **tree** and **loop** dominated processes, forming a stringent test of the CKM paradigm.

(room for NP to affect <u>both</u>)

Direct

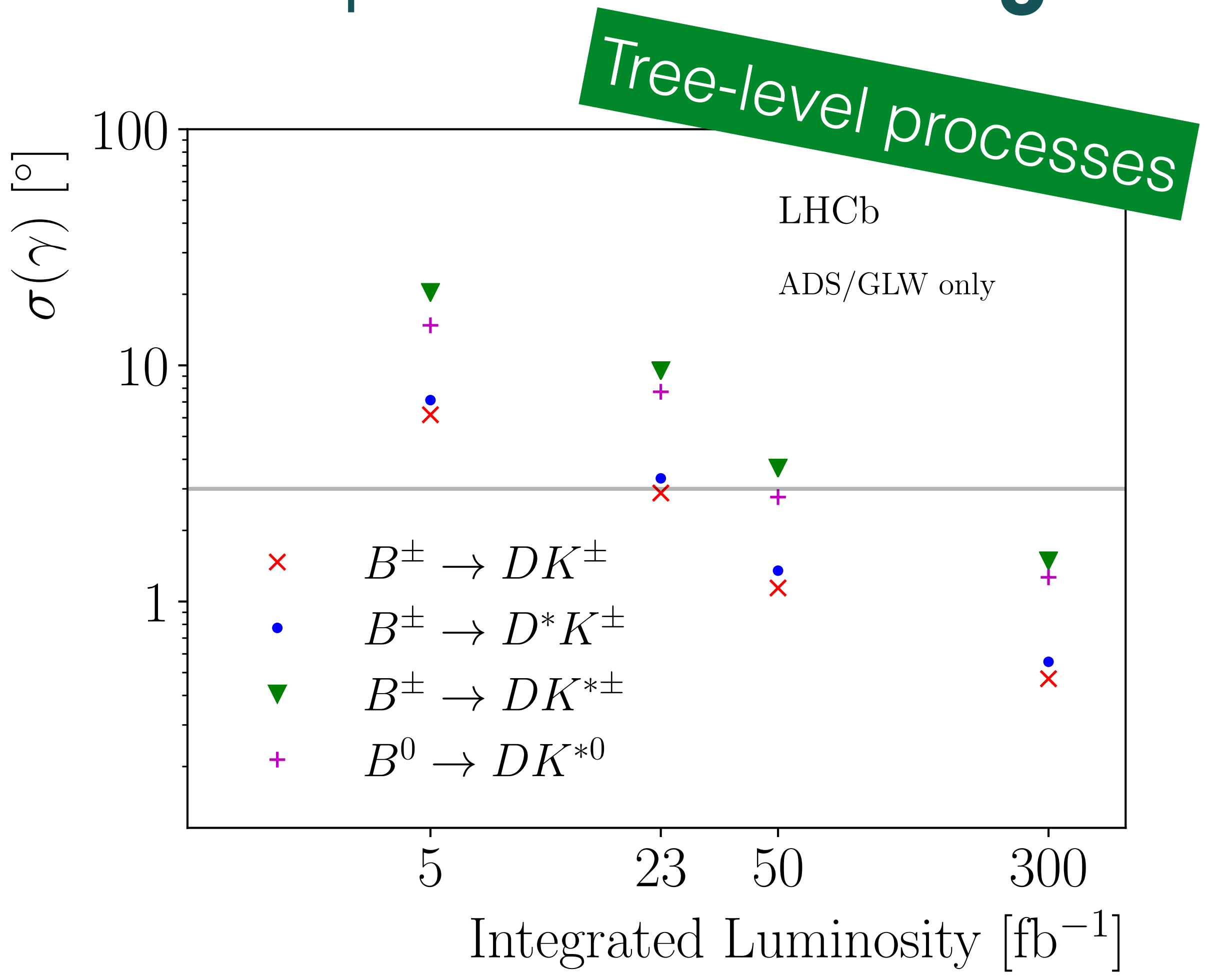


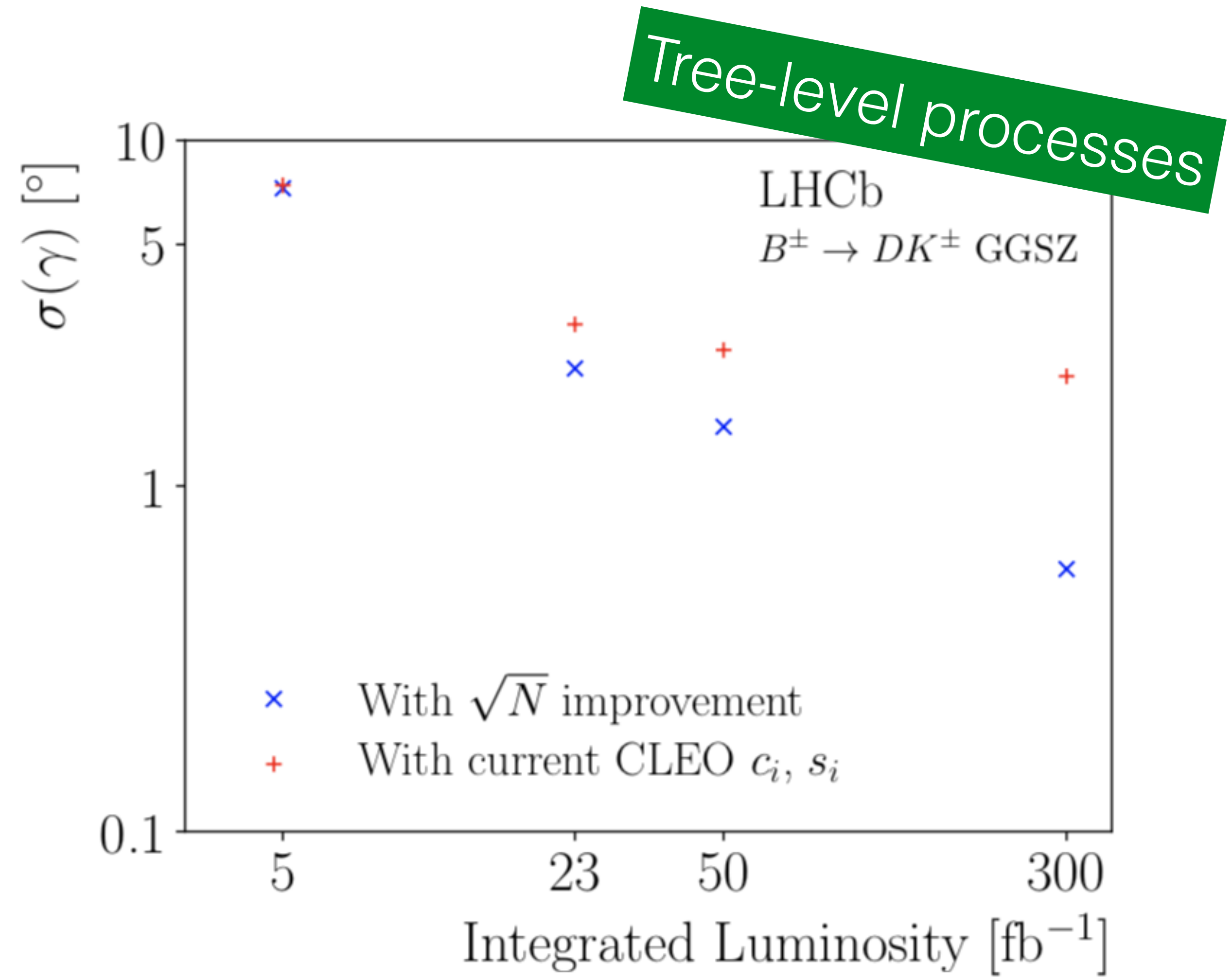
"Indirect"



Currently the *direct measurements* on gamma are limiting

Prospects for γ

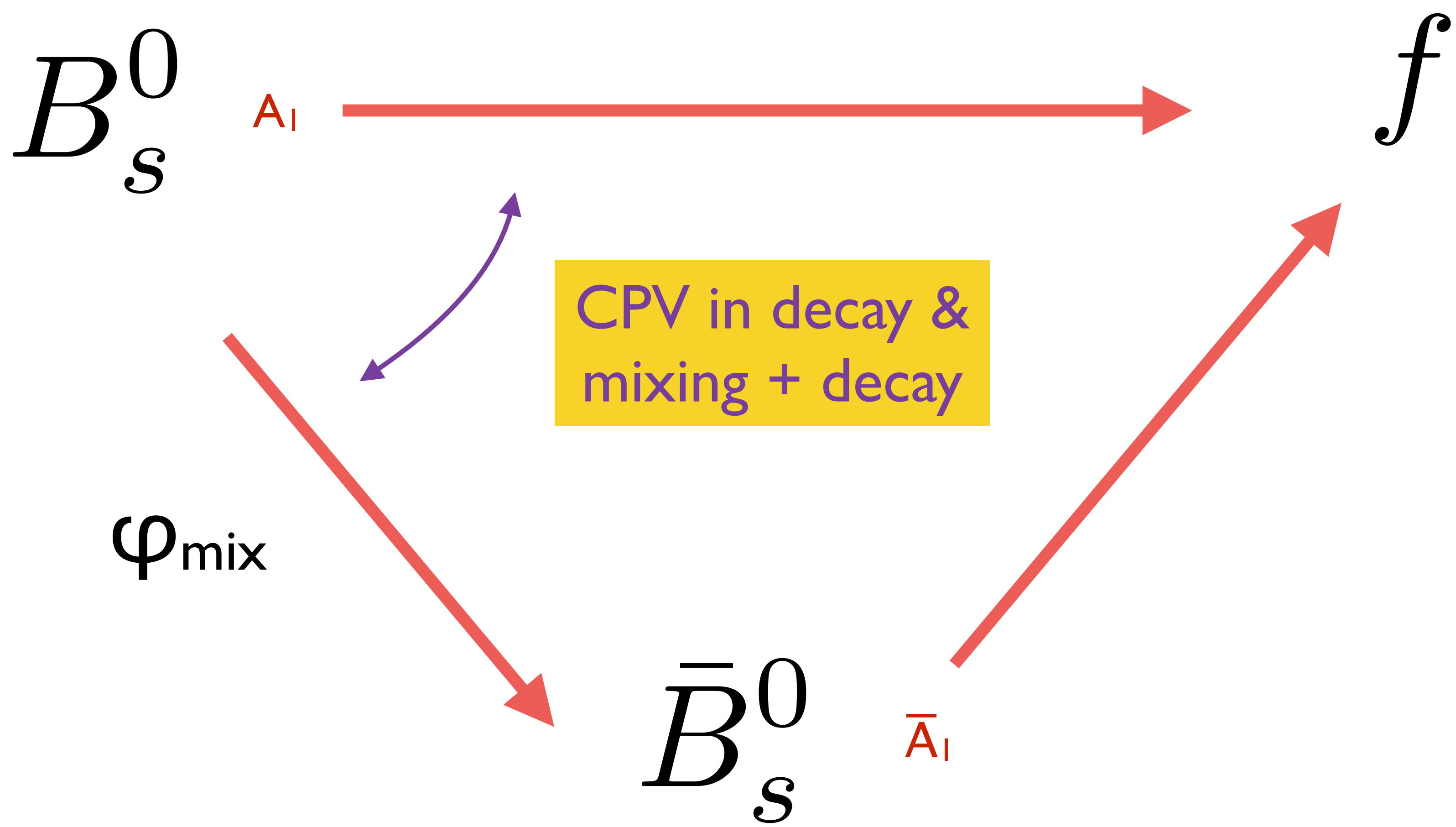




Expected **statistical** sensitivity for gamma down to the degree level for **individual channels** (already comparable to today's indirect limits), also allowing to compare with loop-level measurements of gamma.

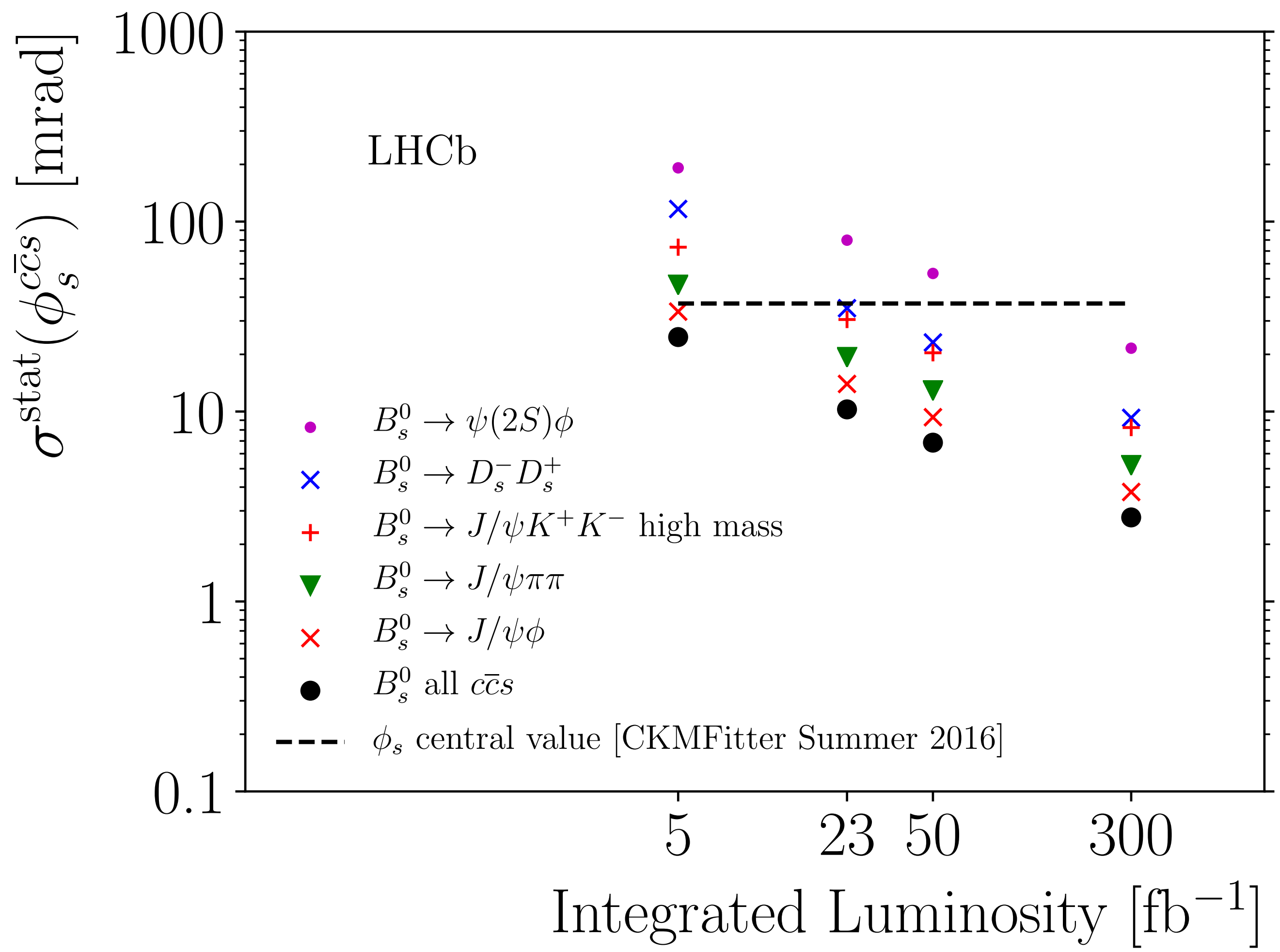
Expect a **0.35°** combined sensitivity. Possibility to include other channels, e.g. ones containing neutrals.

Mixing phase for B_s: ϕ_s



Sensitive probes to New Physics [Phys. Rev. D 89, 033016]
"Golden channels": $J/\psi\ \varphi$ for B_s ($J/\psi\ K_s$ for B_d)

ϕ_s in $b \to c\bar{c}s$



Assuming SM, the mixing phase will be **resolved** to a high precision, with consistency checks through various diagram topologies.

Requires control of **penguin pollution** through different modes, and keeping the **tagging power** as high as Run 2 (or better).

Mixing asymmetry: a_{sl}

$$B_q^0 \longrightarrow \overline{B}_q^0$$

Mixing asymmetry: $a_{\rm sl}$

M_{12}: off-shell contributions (driven by top quark loop)
Γ_{12}: on-shell contributions

Two amplitudes, which can **interfere**

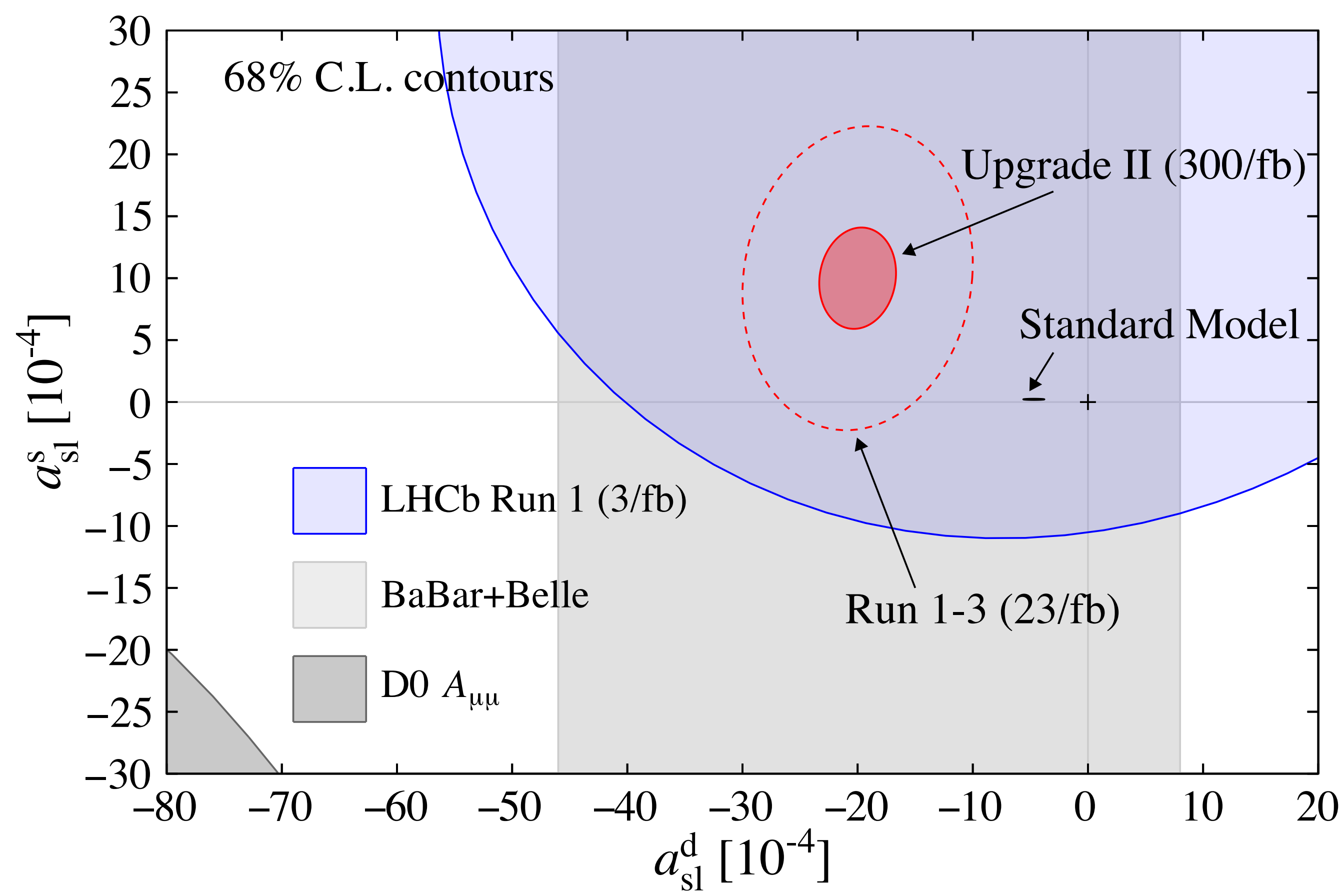
$$\mathcal{P}(B_q \to \bar{B}_q) \neq \mathcal{P}(\bar{B}_q \to B_q)$$

Mixing asymmetry: a_{sl}

The pure mixing asymmetry is measurable through **flavour-specific** decays, such as semileptonic decays, hence the name a_{fs} or a_{sl}. Typical measurement dominated by systematic uncertainties: perfect control of **instrumental asymmetries** required.

Current precision still an order-of-magnitude above SM prediction.

≥ Upgrade 2 luminosities **needed** to constrain O(1) signals of BSM physics directly in a_{sl}^{d}.

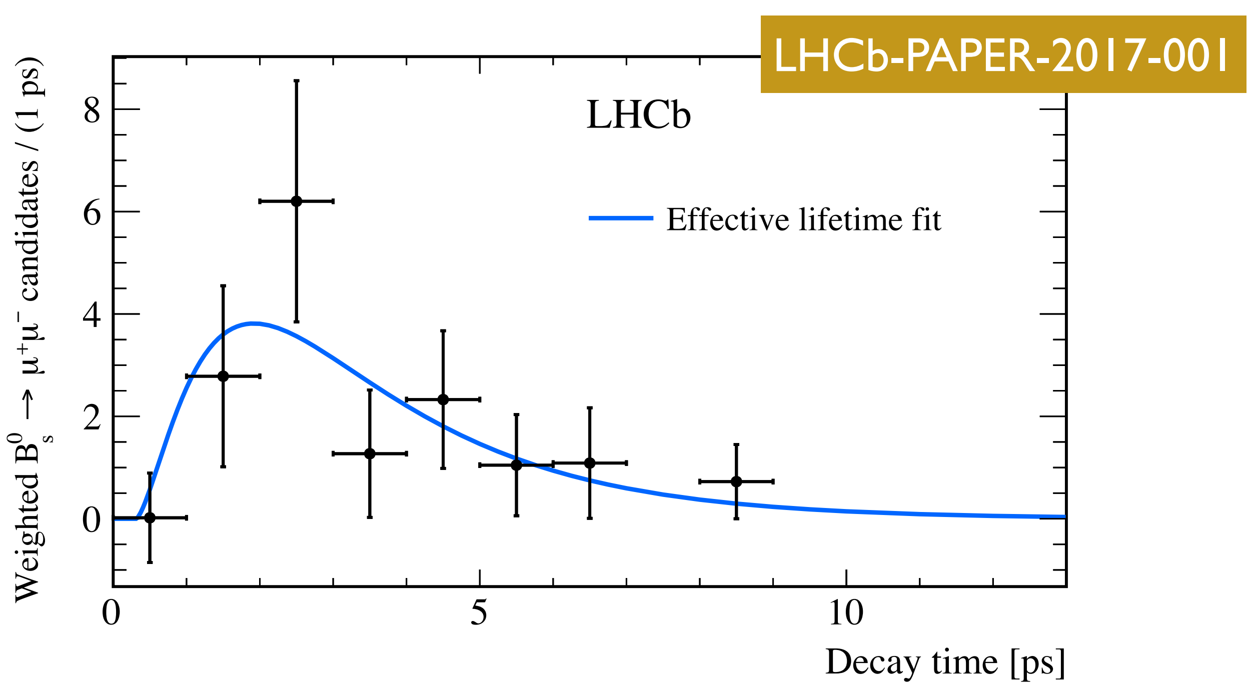


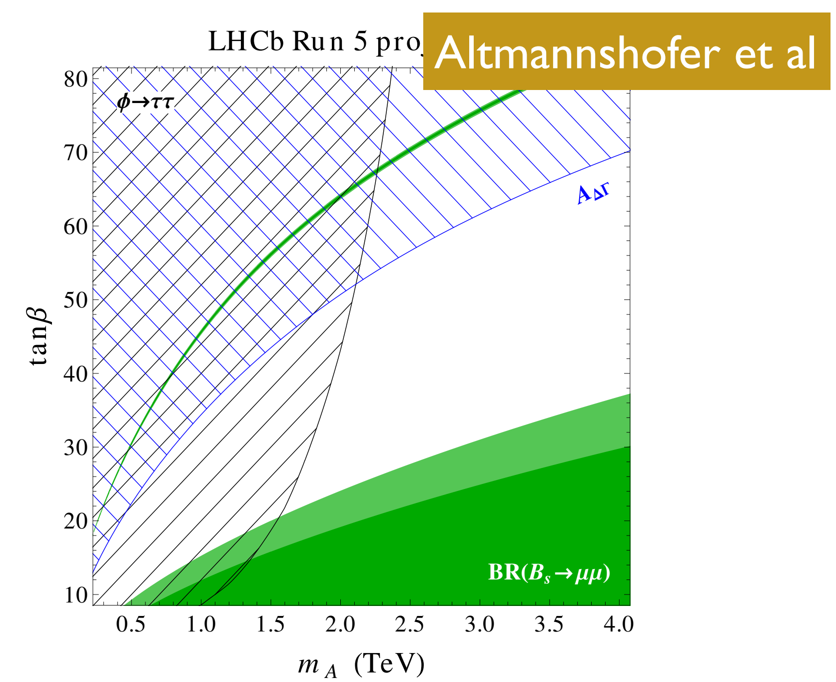
[Flavio Archilli '20]

Rare decays: $B_{(s)} \to \mu\,\mu$

The branching fraction (ratio) of rare decays $B_{(s)}$ -> $\mu\mu$ is a clean, strong <u>constraint to New Physics</u>, including supersymmetric extensions of the SM. Expect a **10%** uncertainty on the ratio with Upgrade-II, from **90%** today.

Both the effective lifetime and the time-dependent CP asymmetry can be a measured well with 300fb^{-1}, with a precision of **0.03ps** and **10-20%**, respectively.





Charm physics

PHYSICAL REVIEW LETTERS 122, 211803 (2019)

Editors' Suggestion | Featured in Physics

Observation of CP Violation in Charm Decays

R. Aaij *et al.**
(LHCb Collaboration)

(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

A search for charge-parity (CP) violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is reported, using pp collision data corresponding to an integrated luminosity of 5.9 fb^{-1} collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0\pi^+$ decays or from the charge of the muon in $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays. The difference between the CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4}$ for π-tagged and $\Delta A_{CP} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}$ for μ-tagged D^0 mesons. Combining these with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than 5 standard deviations. This is the first observation of CP violation in the decay of charm hadrons.

DOI: 10.1103/PhysRevLett.122.211803

The noninvariance of fundamental interactions under the combined action of charge conjugation (C) and parity (P) transformations, so-called CP violation, is a necessary condition for the dynamical generation of the baryon asymmetry of the universe [1]. The standard model (SM) of particle physics includes CP violation through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2,3]. The realization of CP violation in weak interactions has been established in the K- and B-meson systems by several experiments [4–12], and all results are well interpreted within the CKM formalism. However, the size of CP violation in the SM appears to be too small to account for the observed matter-antimatter asymmetry [13–15], suggesting the existence of sources of CP violation beyond the SM.

The observation of CP violation in the charm sector has not been achieved yet, despite decades of experimental searches. Charm hadrons provide a unique opportunity to measure CP violation with particles containing only up-type quarks. The size of CP violation in charm decays is expected to be tiny in the SM, with asymmetries typically of the order of $10^{-4} - 10^{-3}$, but due to the presence of low-energy strong-interaction effects, theoretical predictions are difficult to compute reliably [16–34]. Motivated by the fact that contributions of beyond-the-SM virtual particles may alter the size of CP violation with respect to the SM expectation, a number of theoretical analyses have been performed [19,27,32,35].

Unprecedented experimental precision can be reached at LHCb in the measurement of CP-violating asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays. The inclusion of charge-conjugate decay modes is implied throughout except in asymmetry definitions. Searches for CP violation in these decay modes have been performed by the BABAR [36], Belle [37], CDF [38,39], and LHCb [40–44] Collaborations. The corresponding CP asymmetries have been found to be consistent with zero within a precision of a few per mille.

This Letter presents a measurement of the difference of the time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, performed using pp collision data collected with the LHCb detector at a center-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 5.9 fb^{-1}.

The time-dependent CP asymmetry, $A_{CP}(f;t)$, between states produced as D^0 or $\bar{D}^0$ mesons decaying to a CP eigenstate f at time t is defined as

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}, \quad (1)$$

where Γ denotes the time-dependent rate of a given decay. For $f = K^-K^+$ or $f = \pi^-\pi^+$, $A_{CP}(f;t)$ can be expressed in terms of a direct component associated with CP violation in the decay amplitude and another component associated with CP violation in D^0-$\bar{D}^0$ mixing or in the interference between mixing and decay.

*Full author list given at the end of the article.

0031-9007/19/122(21)/211803(12)

The observation of CPV in charm decays is a milestone that marks the start of a next era for charm physics.

The interpretation of needs additional **measurements in complementary modes**. Can we relate SU(3) breaking in different processes?

With a magnitude of about one in a thousand, it is a beautiful example of LHCb as the intensity frontier.

Direct CPV in charm: $D^0 \to K_S K_S$

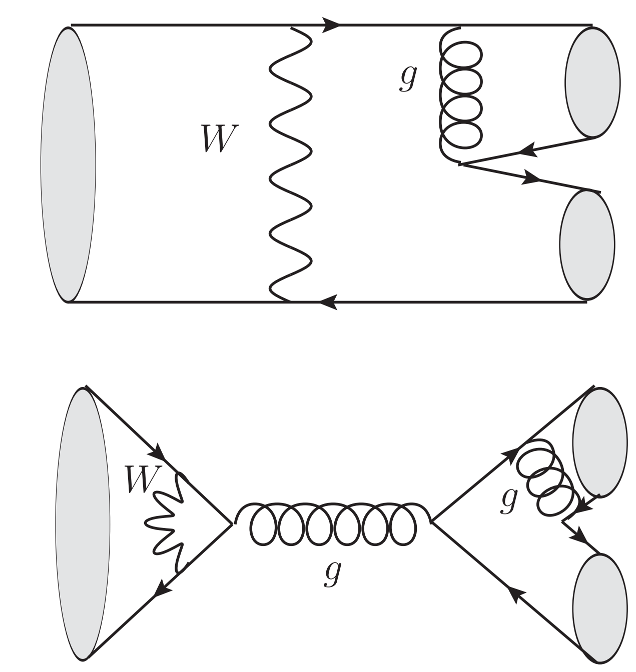
Significant theory interest in $A_{CP}(D^0 \to K_s K_s)$

Estimates vary from ~ 1% to $O(3/2\ \Delta A_{CP})$

(depending on SU(3) breaking)

	Uncertainty [%]
Belle I	± 1.53 ± 0.17
LHCb ’12-‘16	± 2.8 ± 0.9
LHCb Run 2	± 1.5
Belle II	± 0.23
LHCb Upgrade-II	± 0.12 - 0.23*

Upgrade-II essential, event trigger main challenge



[1]: Nierste, Schacht ’15
[2]: Hiller, Jung, Schacht ‘13
[2]: Cheng, Chaing ‘12

*: Tuci '19

Charm mixing

$$\begin{tikzcd} D^0 \arrow[r, bend left] & \bar{D}^0 \arrow[l, bend left] \end{tikzcd}$$

Like all other neutral mesons, also D⁰ mesons **mix**…
but rarely!

$$\langle D^0_{1,2}| = p\,\langle D^0| \mp q\,\langle \overline{D^0}|$$

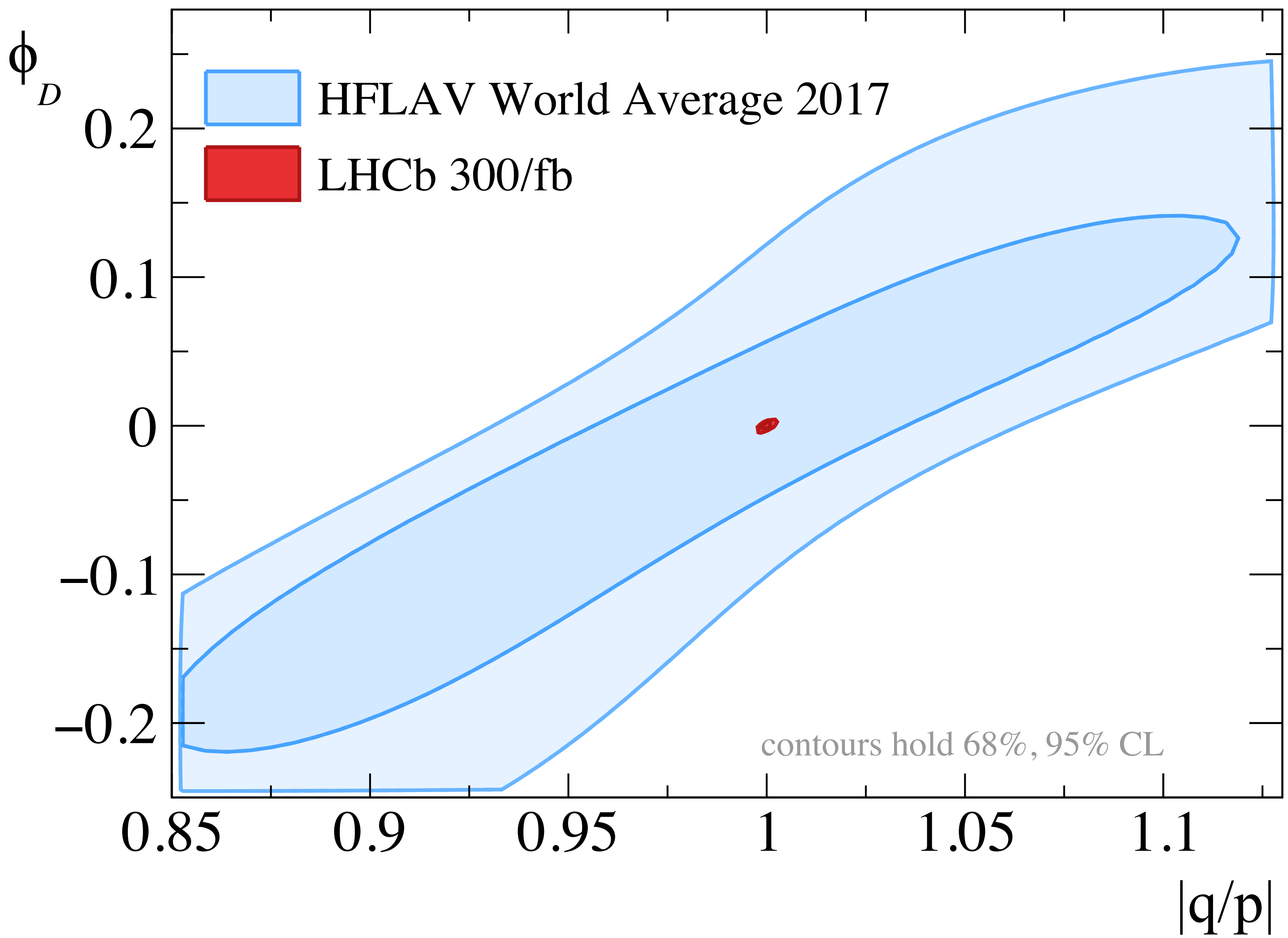
$$P(D^0 \to \overline{D^0}) \approx \left|\frac{p}{q}\right|^2 e^{-\Gamma t}\frac{x^2+y^2}{2}(\Gamma t)^2$$

Observables

CPV in mixing	$\lvert q/p \rvert$
Mixing phase	φ_D
#diffraction	x
#absorption	y

Indirect CPV: charm mixing

Mixing phase



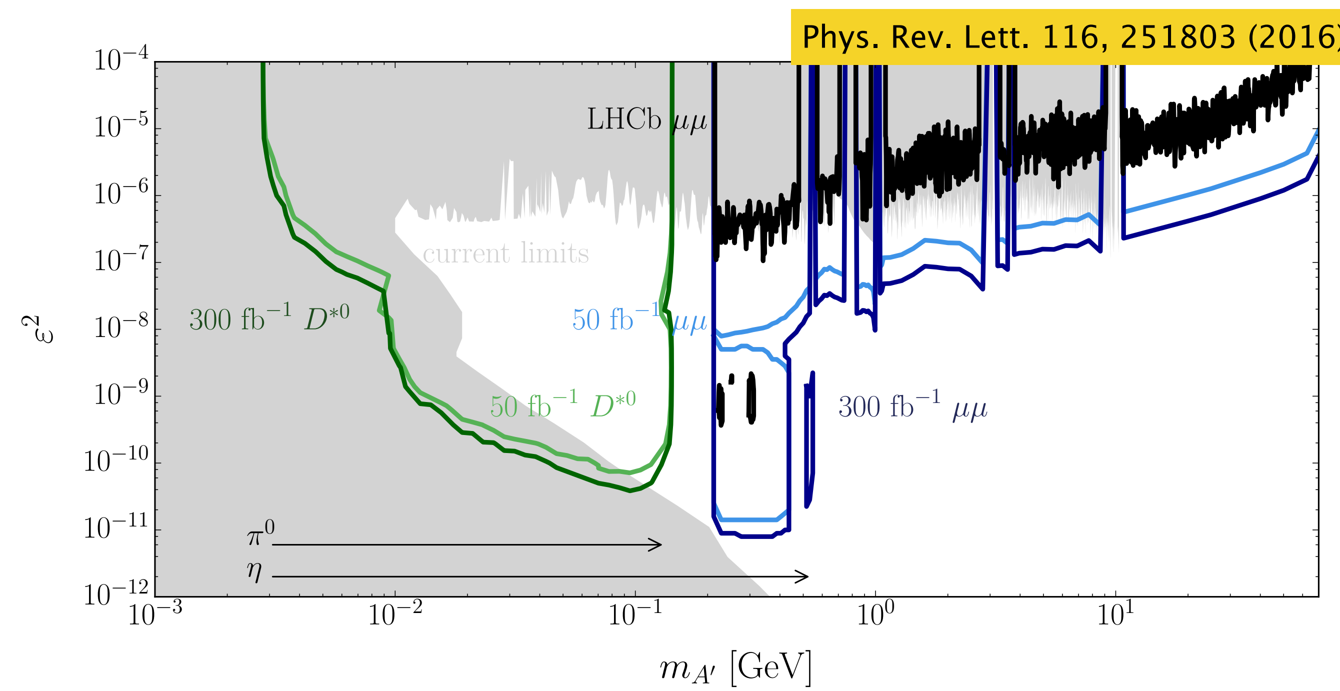
CPV in mixing (similar to a_{sl})

[LHCb LoI ’95]

Beyond the planned physics

Part of the success of the LHCb experiment was the **unplanned**:

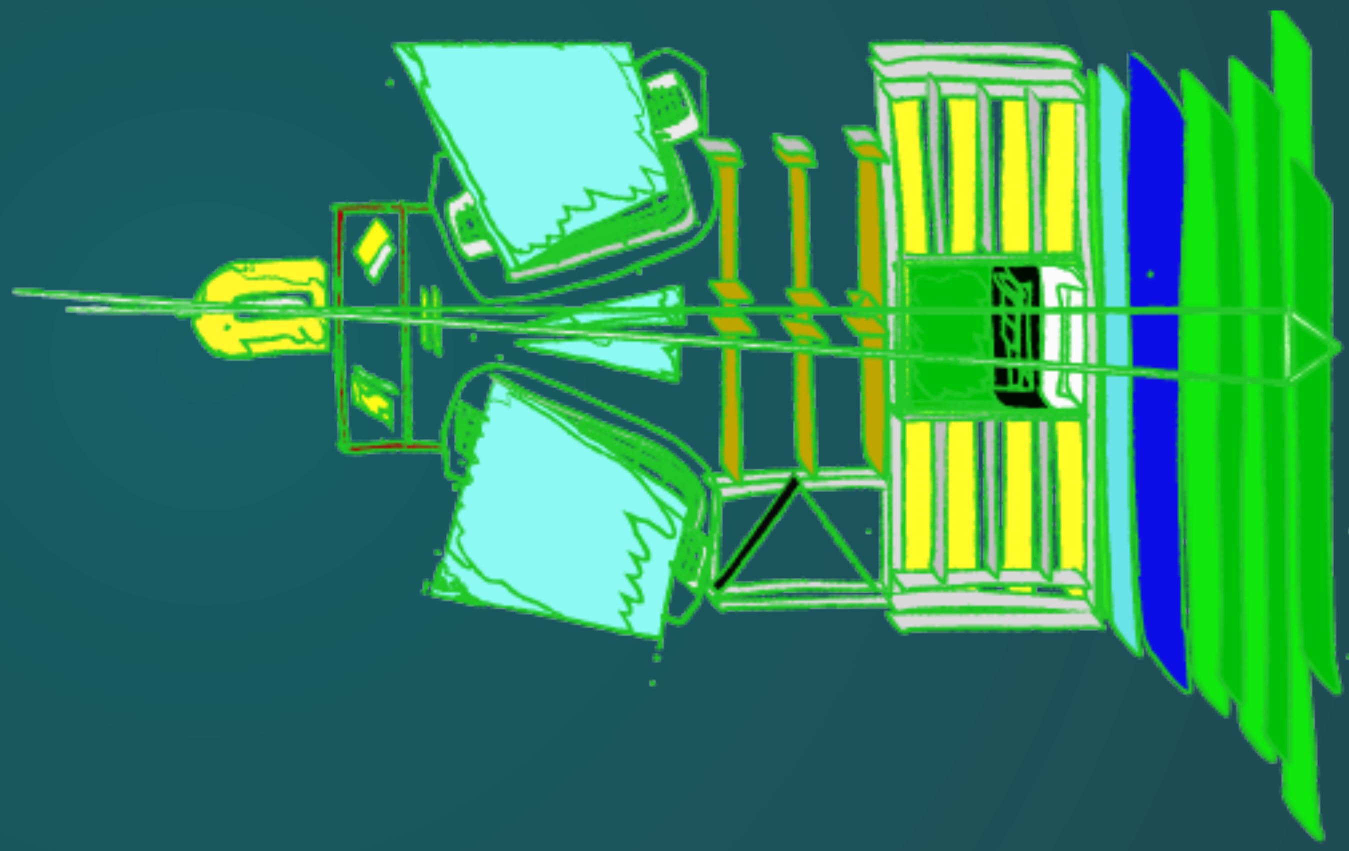
- Λb physics and baryon CPV;
- spectroscopy;
- top and electroweak physics;
- **searches for dark photons**;
- heavy ion physics;
- …



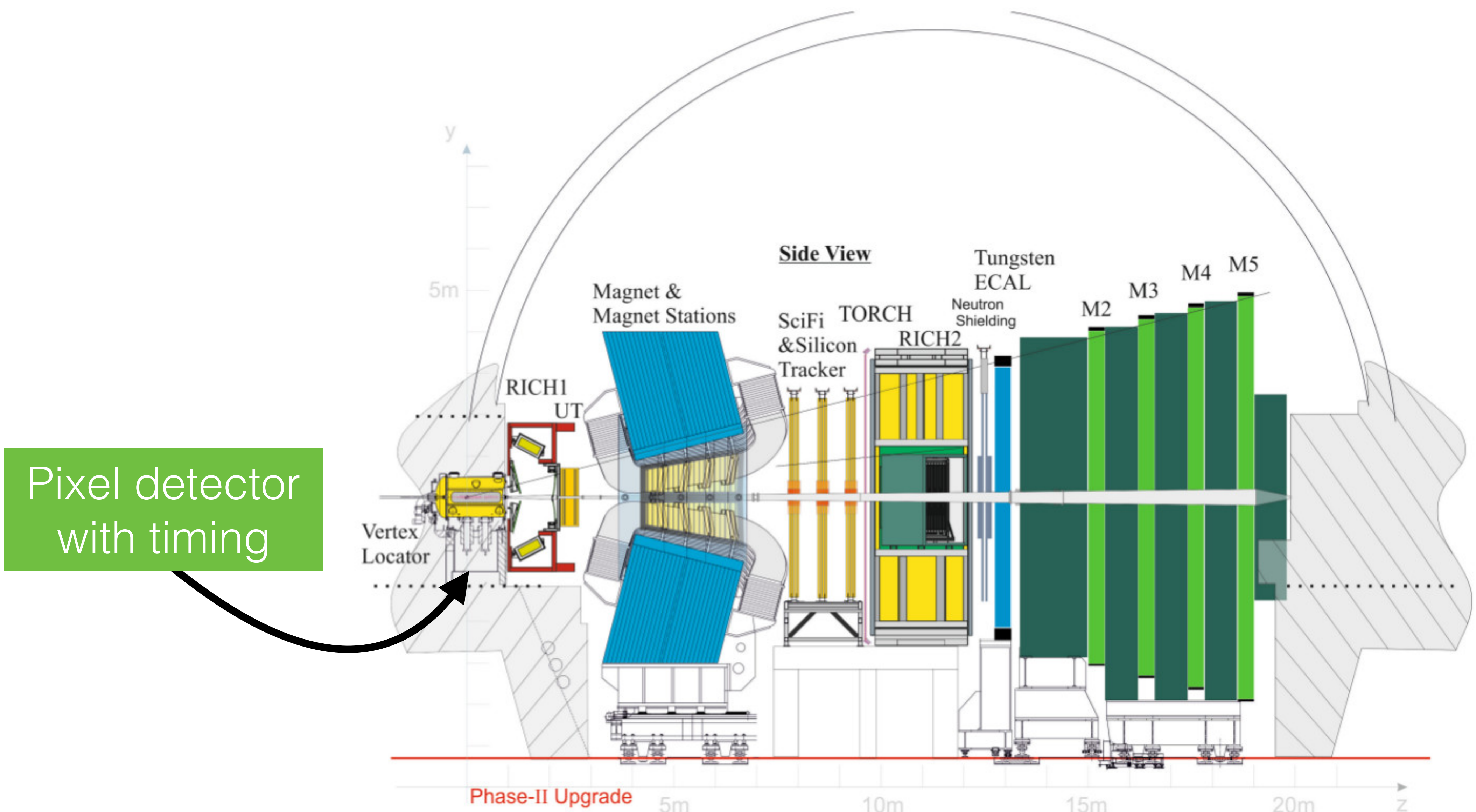
With its flexible trigger, LHCb has proven itself as a general purpose detector in the forward region. **Head room** for innovative techniques was key for these developments. The phase-2 upgrade detector should preserve this.

Detector

Preparing for the unexpected



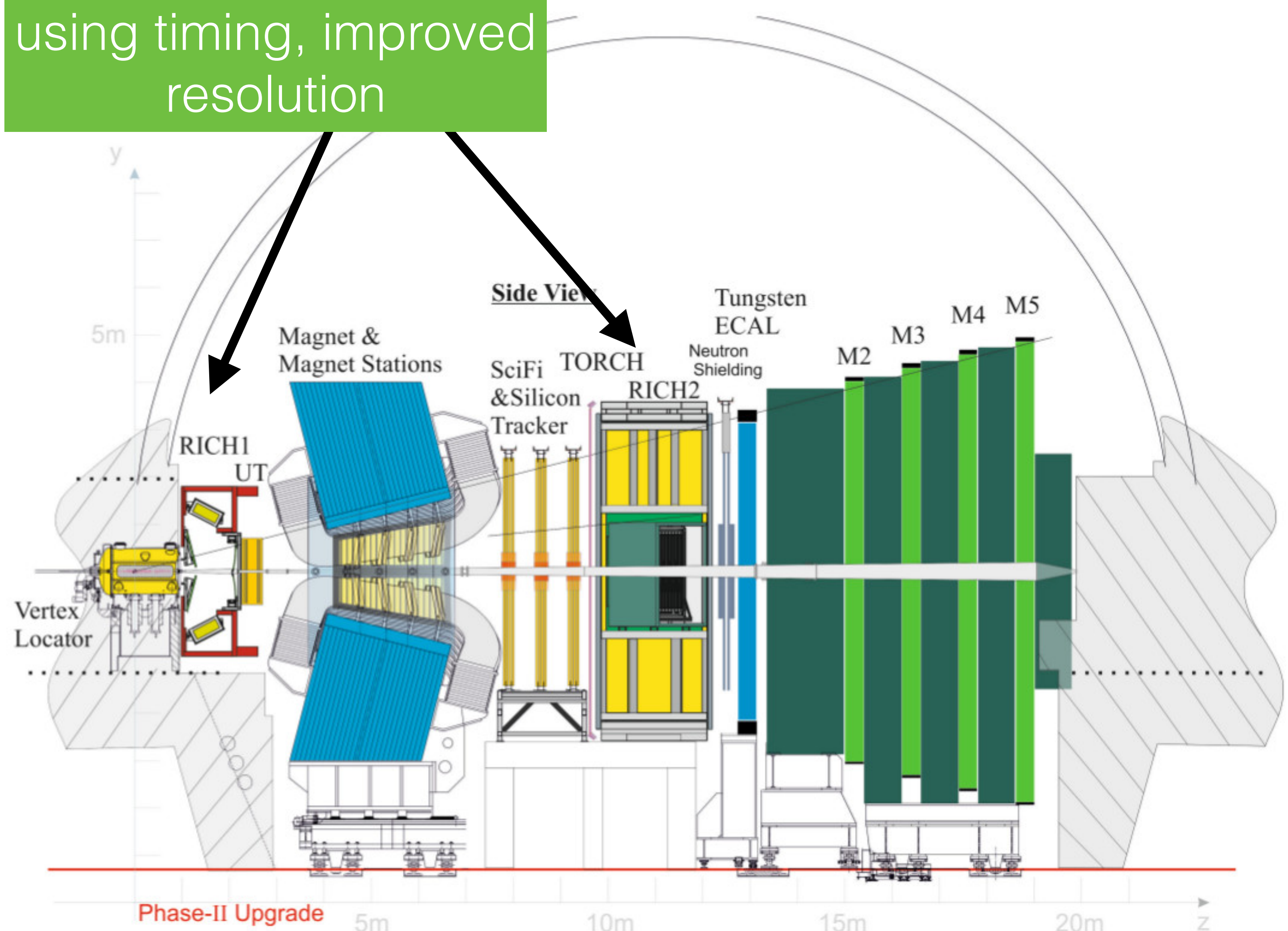
Detector concept overview



Detector concept overview

Cherenkov (RICH) using timing, improved resolution

Pixel detector with timing

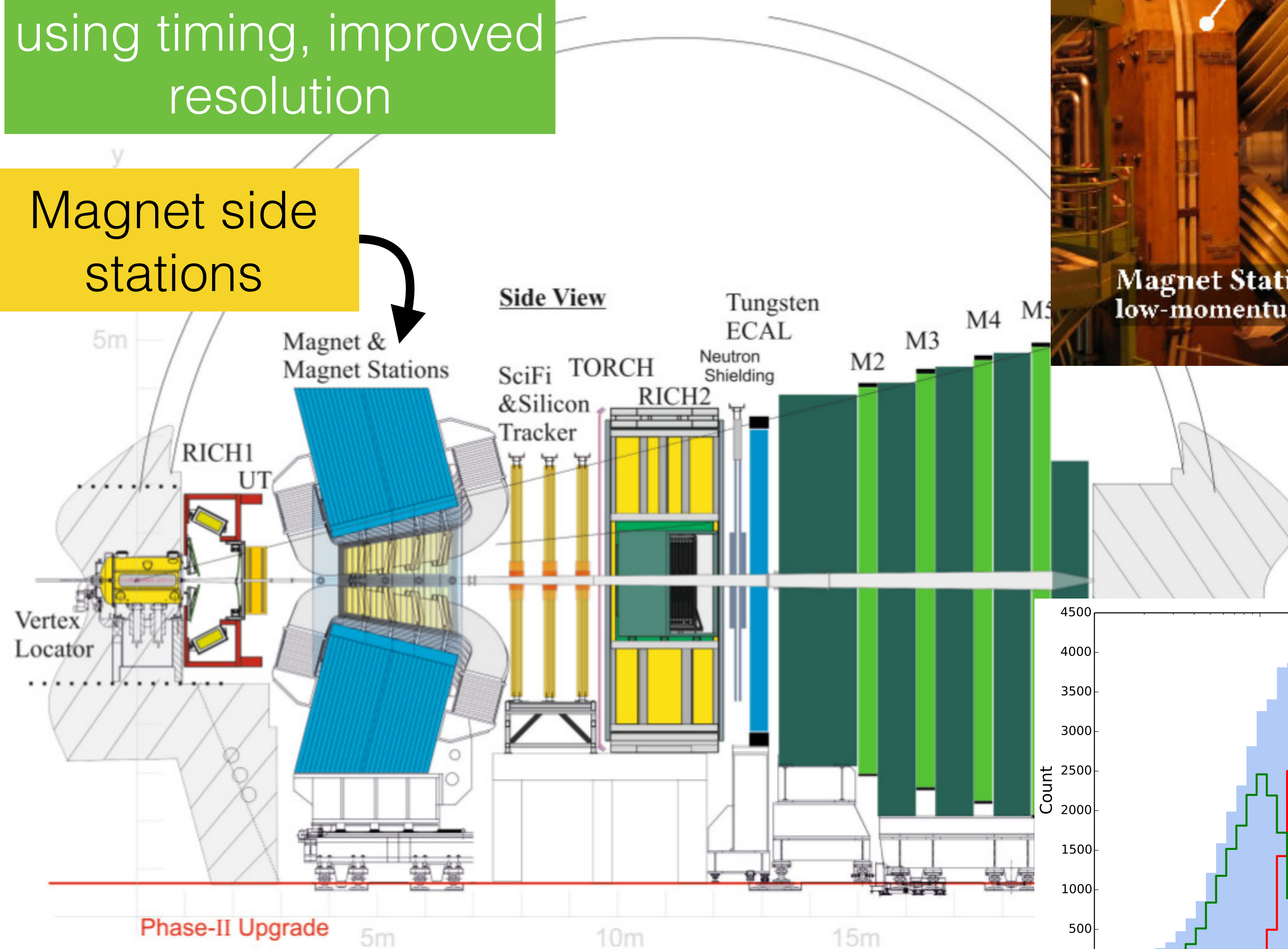


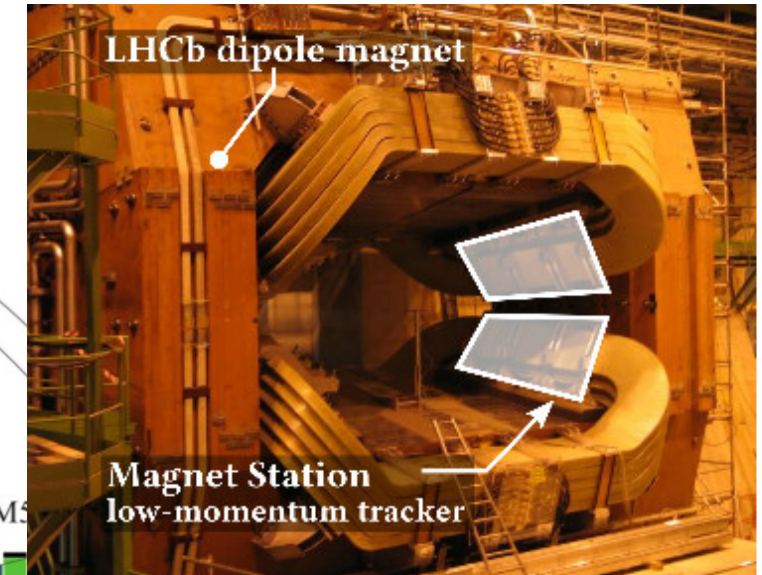
Detector concept overview

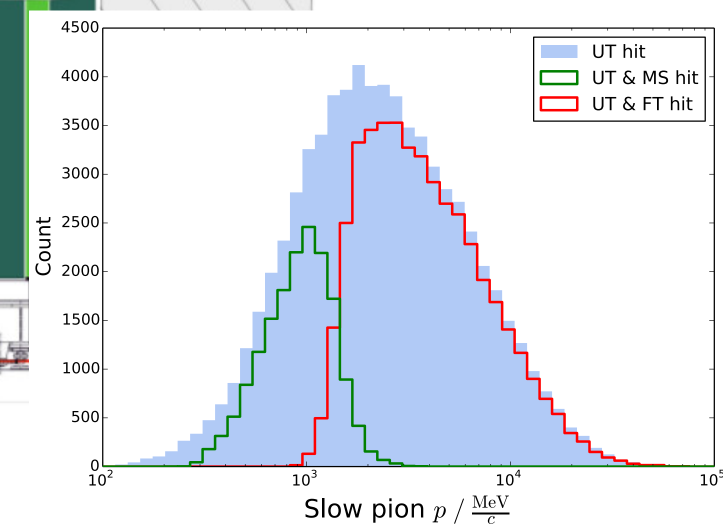
Cherenkov (RICH) using timing, improved resolution

Magnet side stations

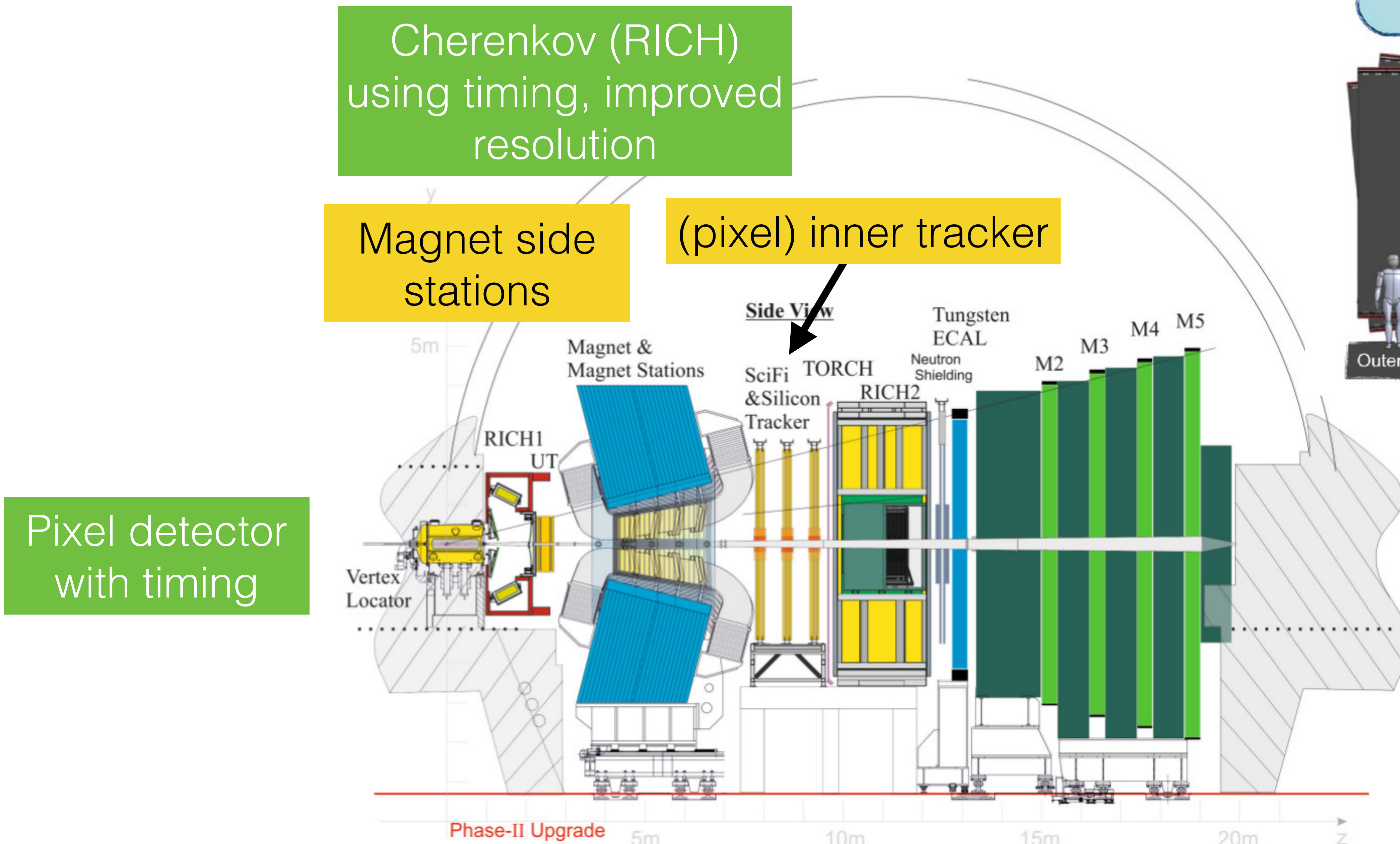
Pixel detector with timing



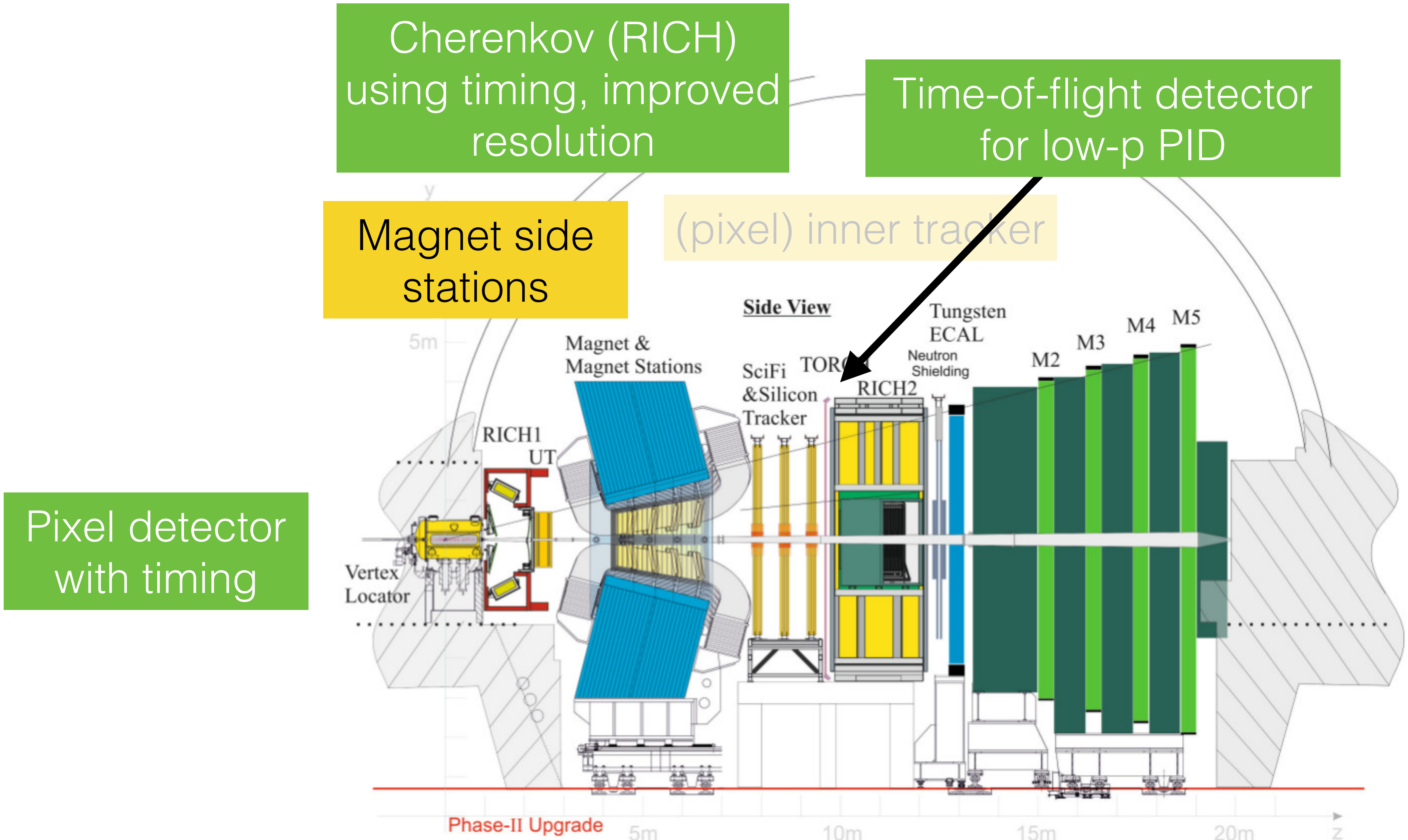




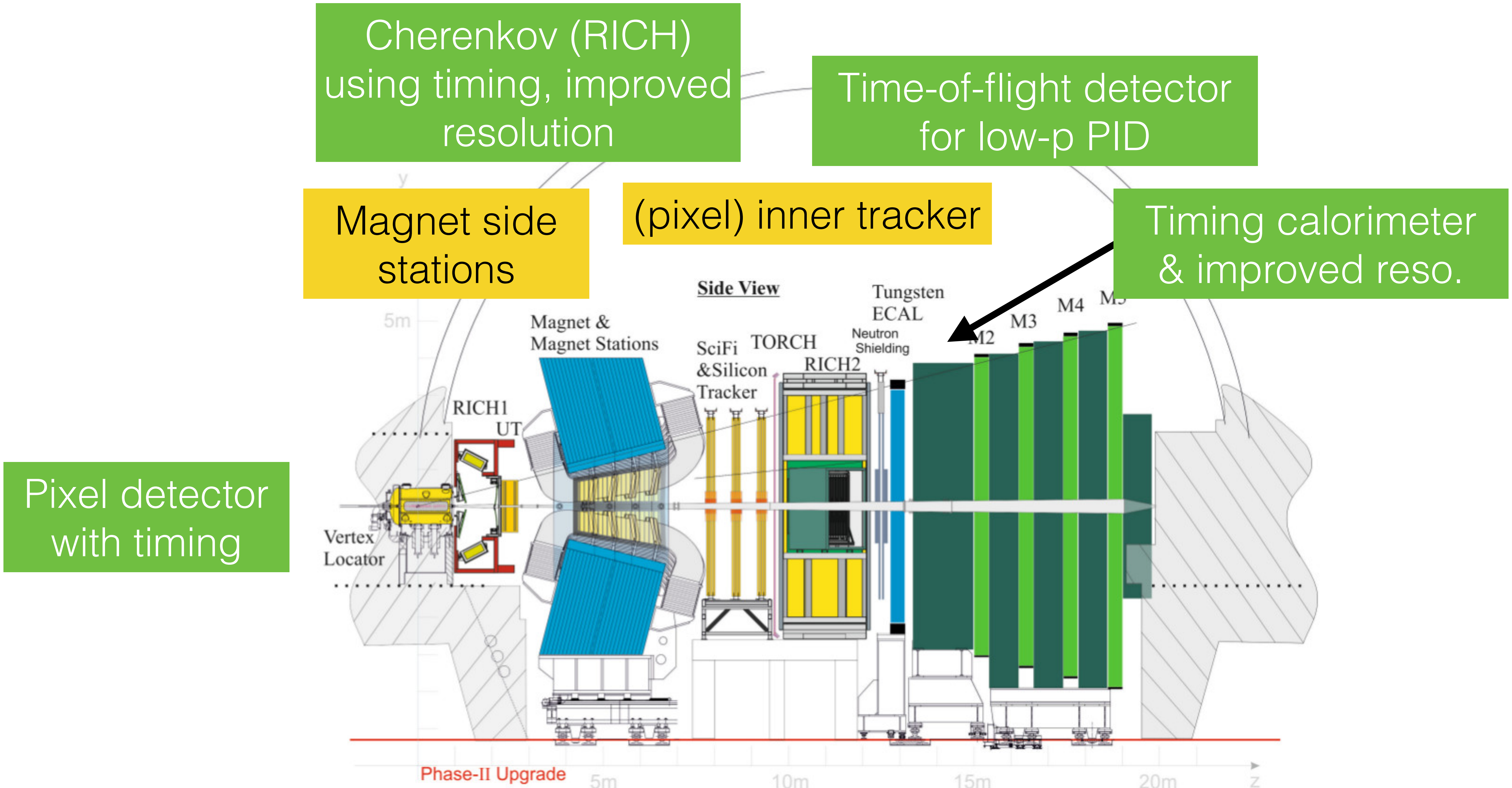
Detector concept overview



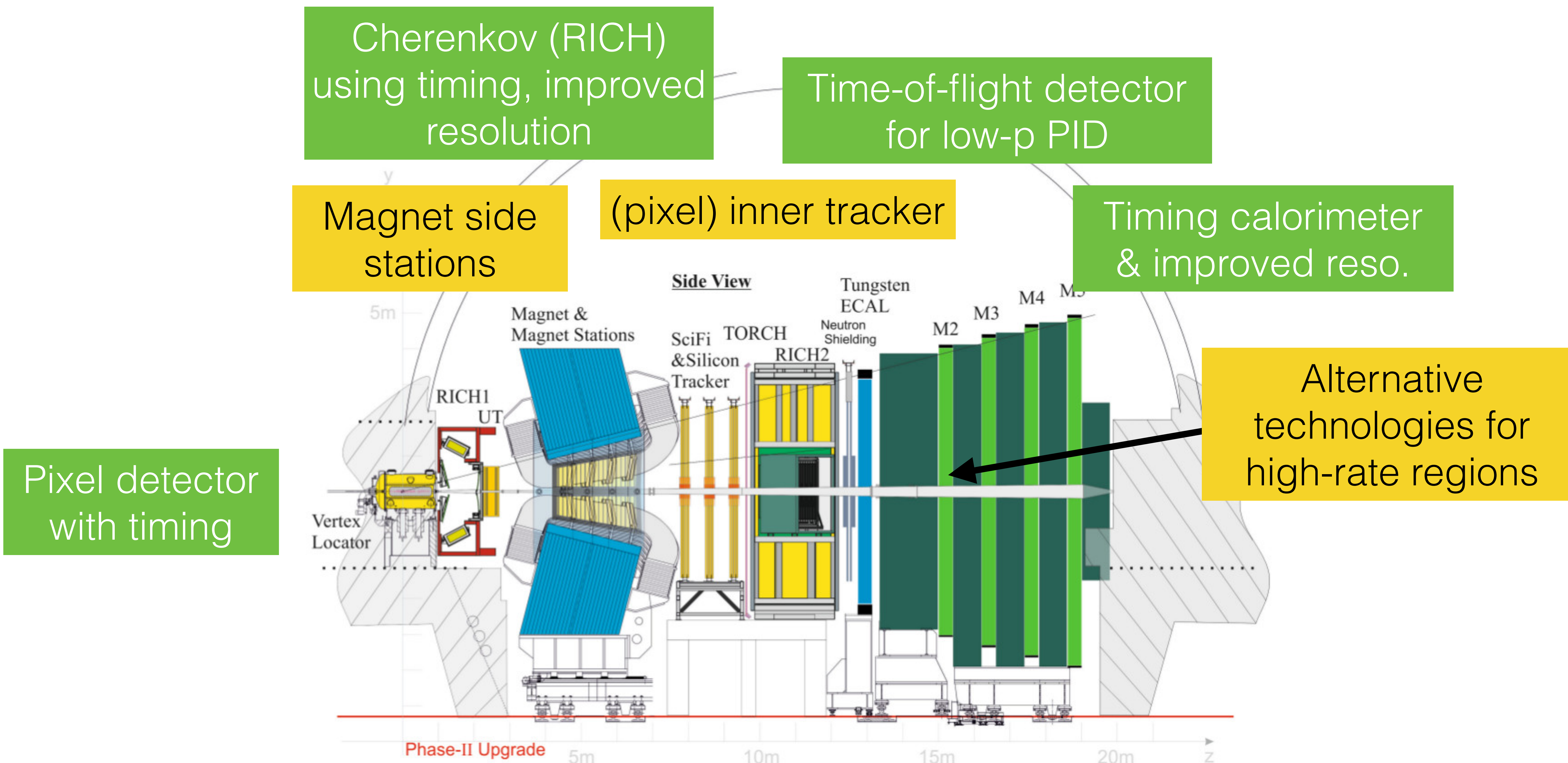
Detector concept overview



Detector concept overview

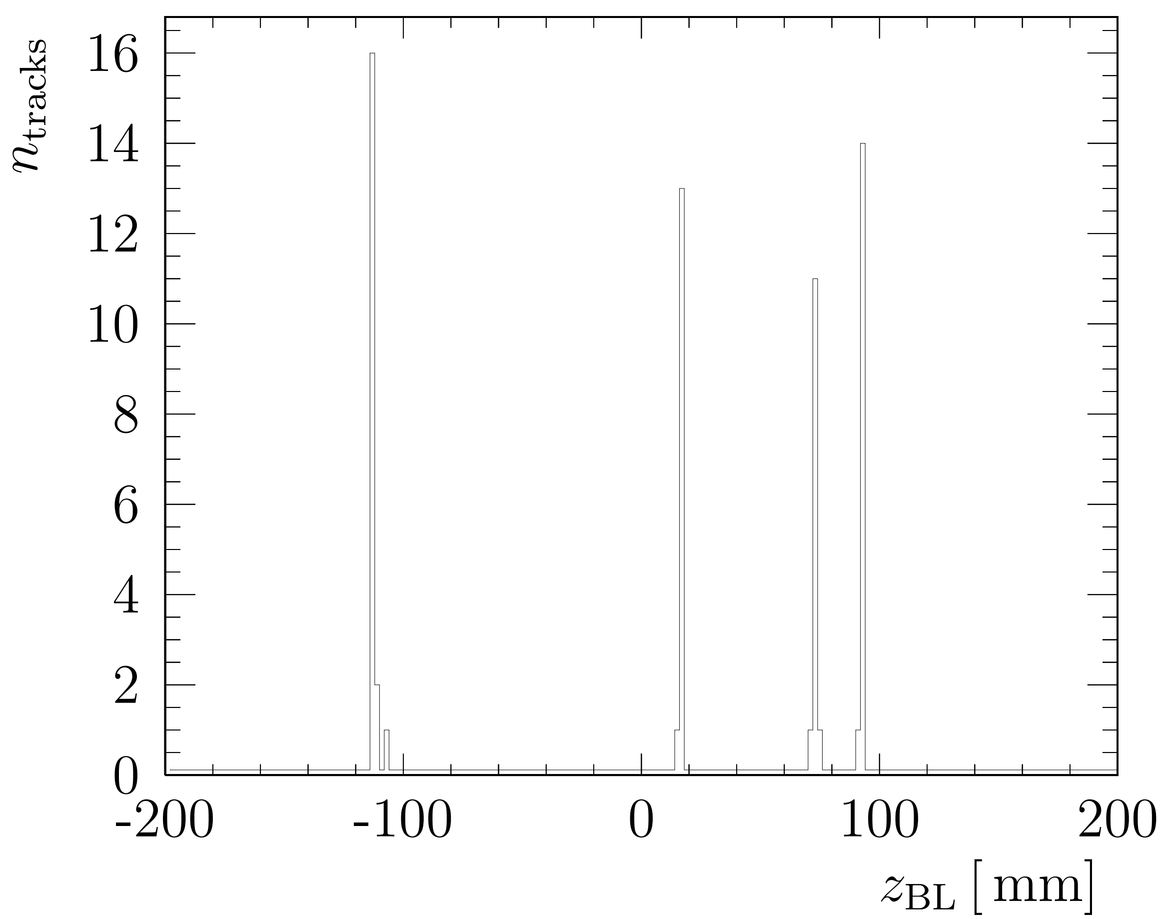


Detector concept overview



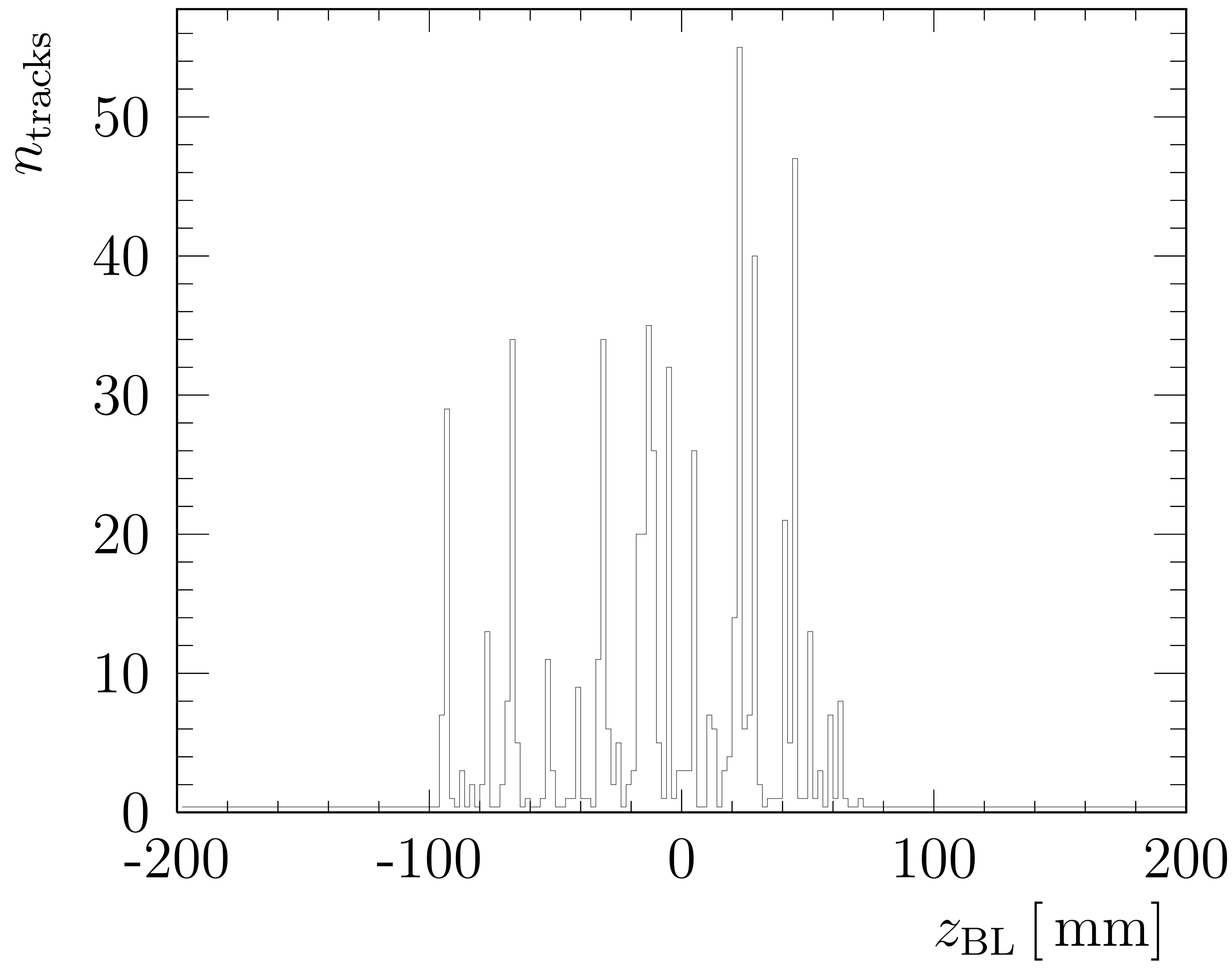
Why timing?

Primary vertex finding in Run 3

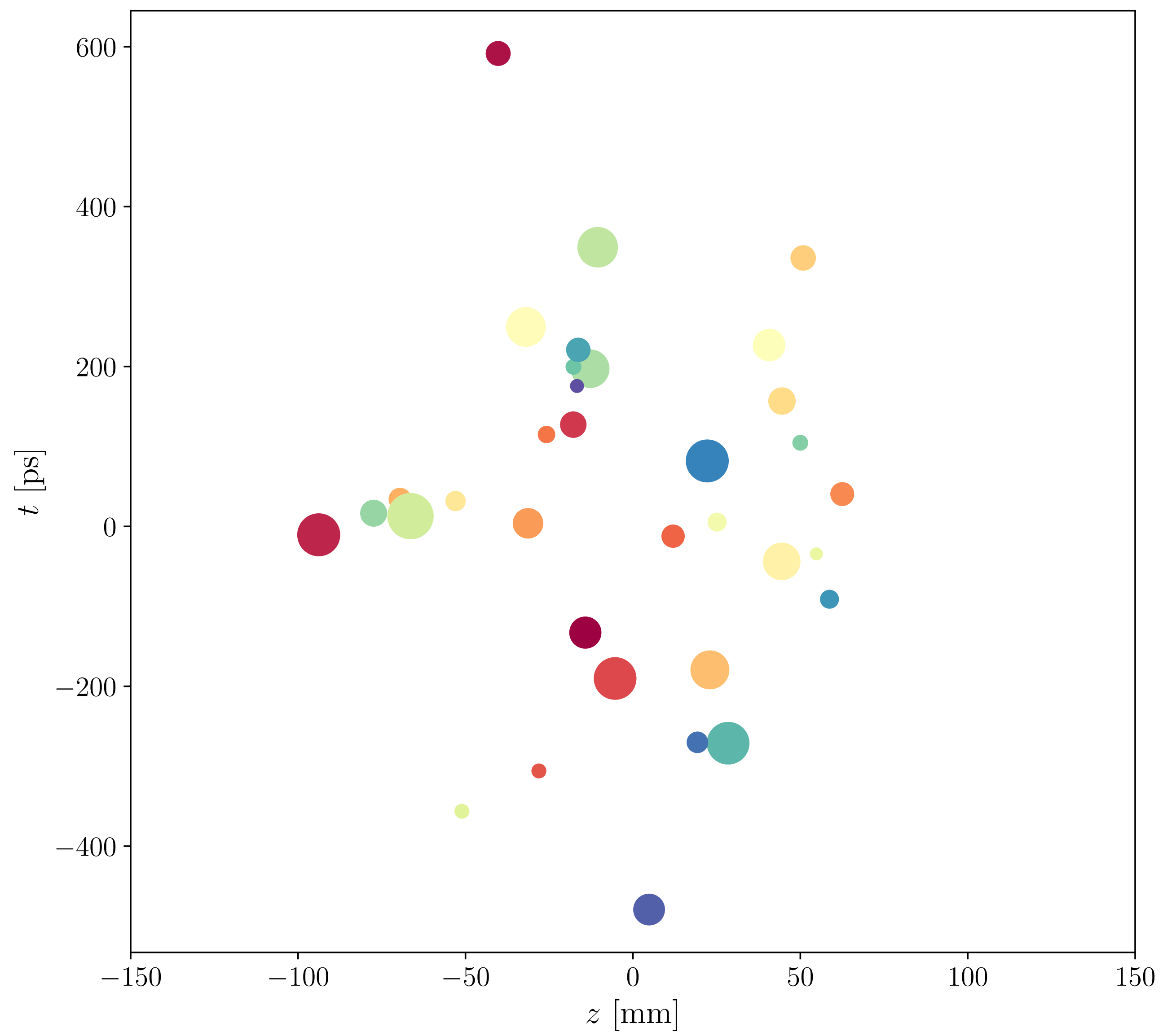


Why timing?

Upgrade 2: ~ 40 peaks



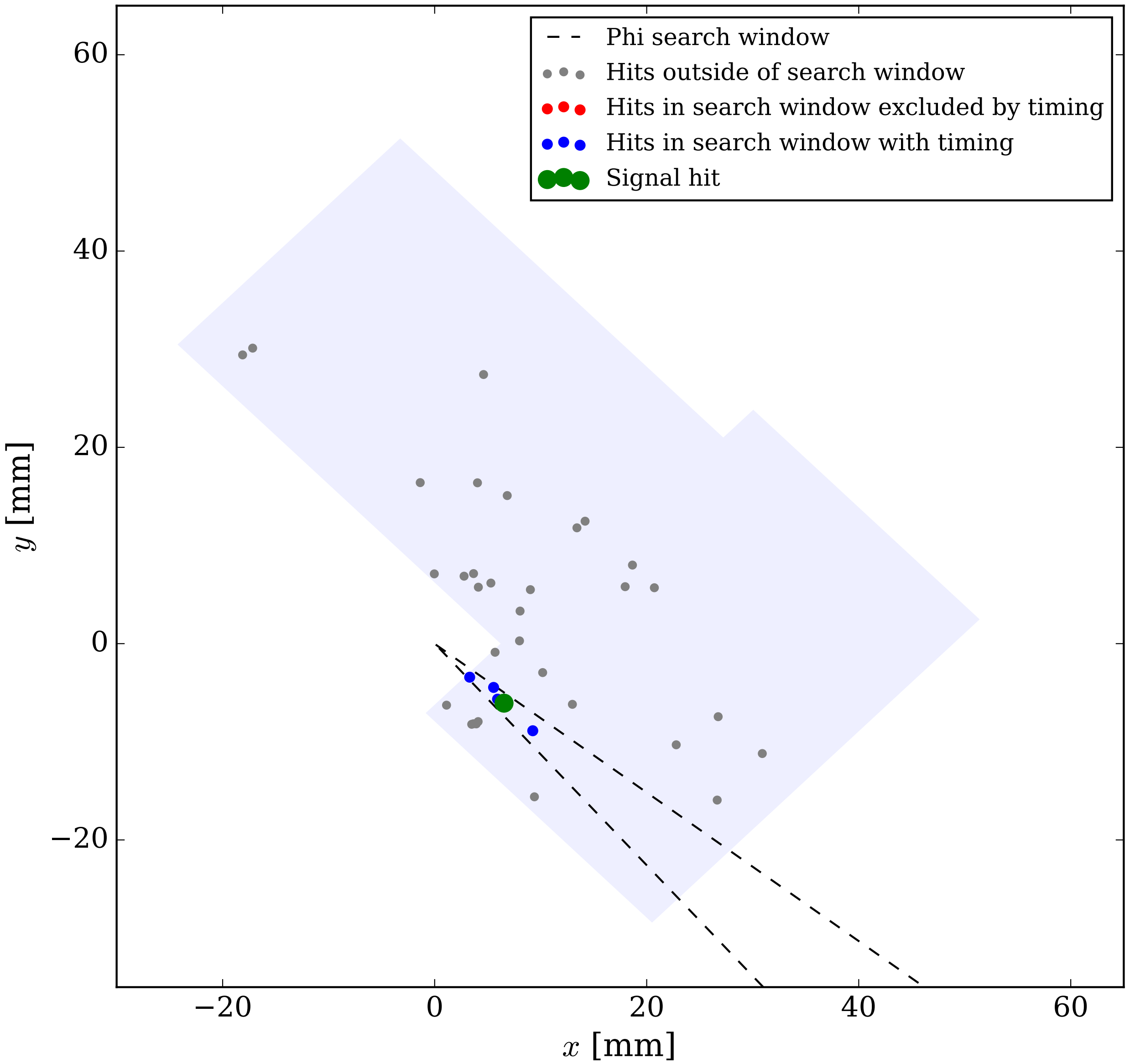
Why timing?



Primary vertices are also spread in time

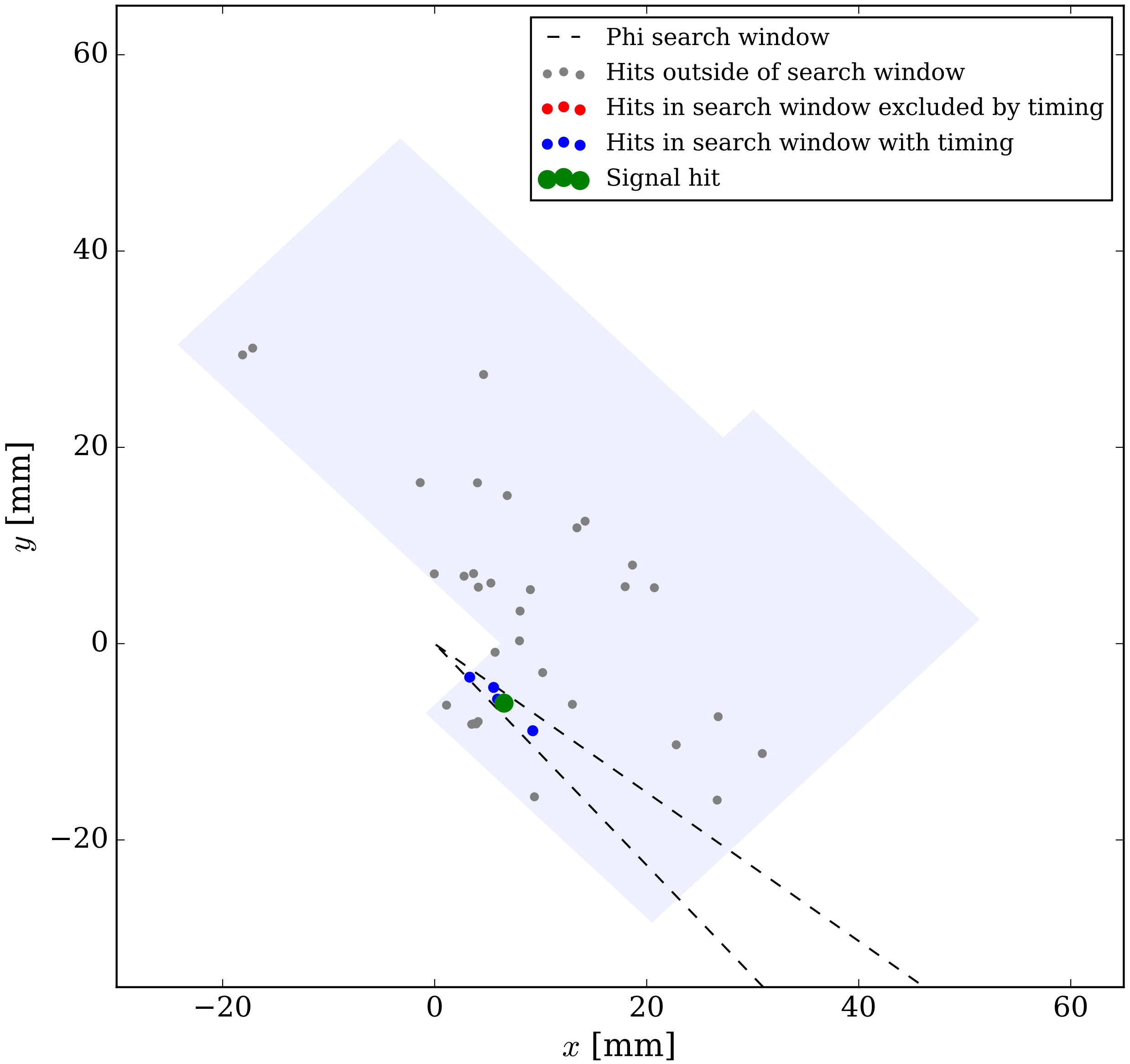
Using timing in tracking

Upgrade I

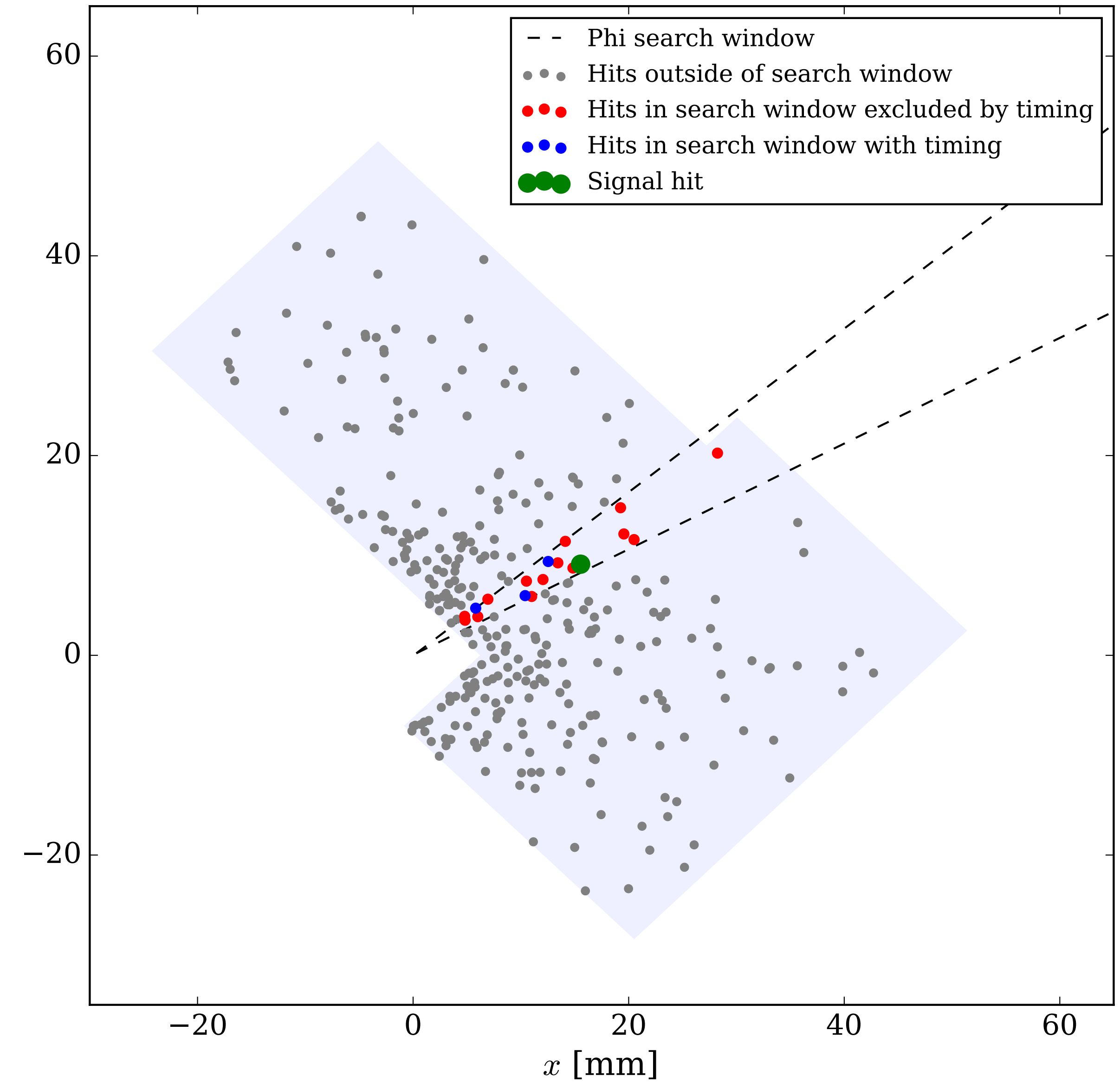


Using timing in tracking

Upgrade 1



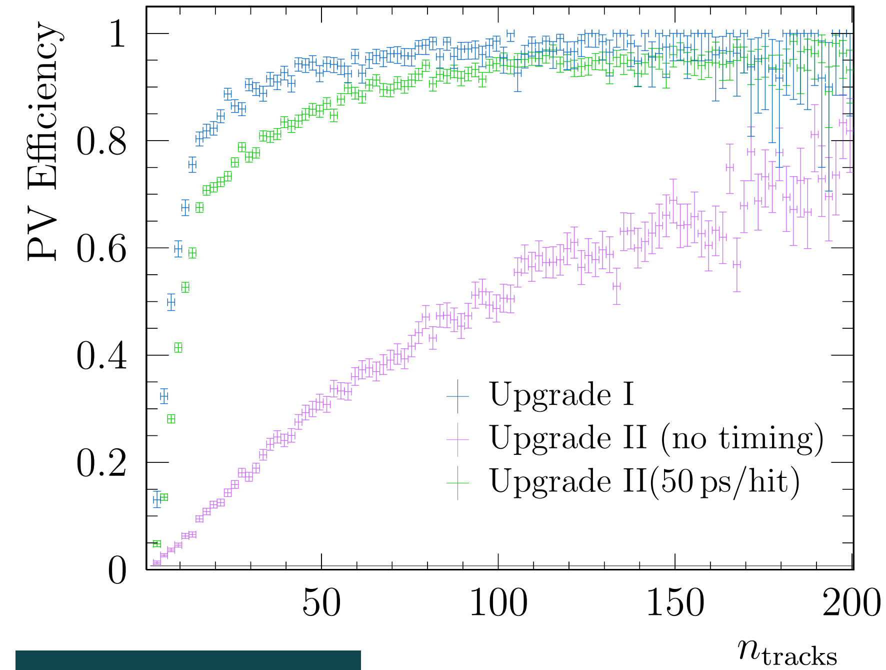
Upgrade 2 (50ps resolution)



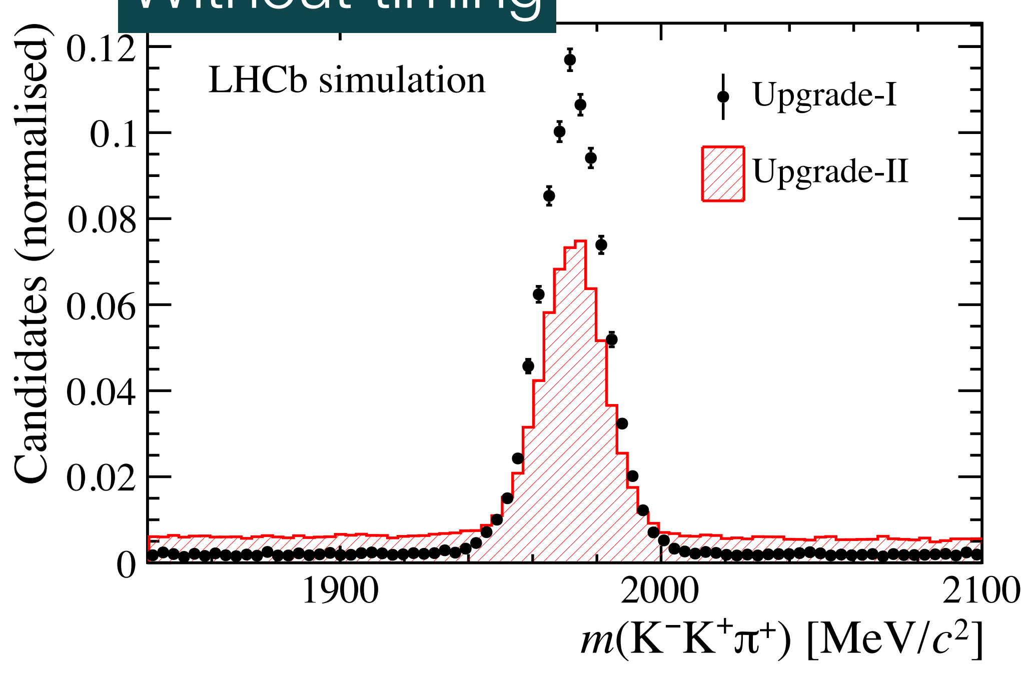
First implementation of 4D tracking at these intensities

Using timing in event reconstruction

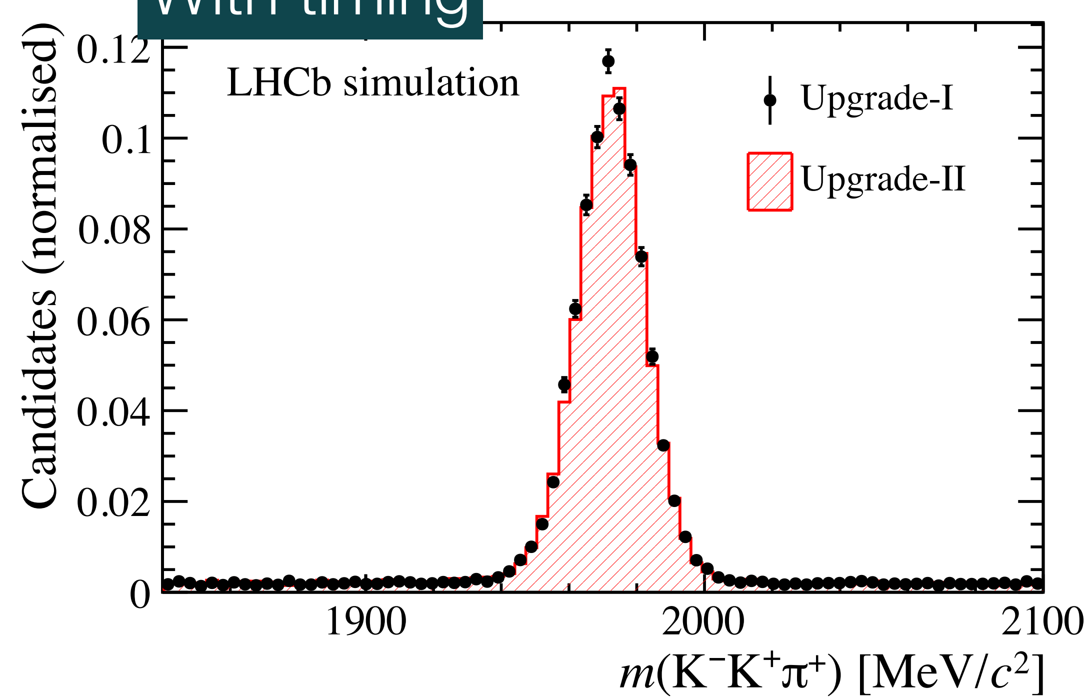
Having a timestamp for each of the **tracks** in turn helps drastically in reconstructing **vertices**, both primary and secondary. Essential already in the first level of the **event trigger**.



Without timing

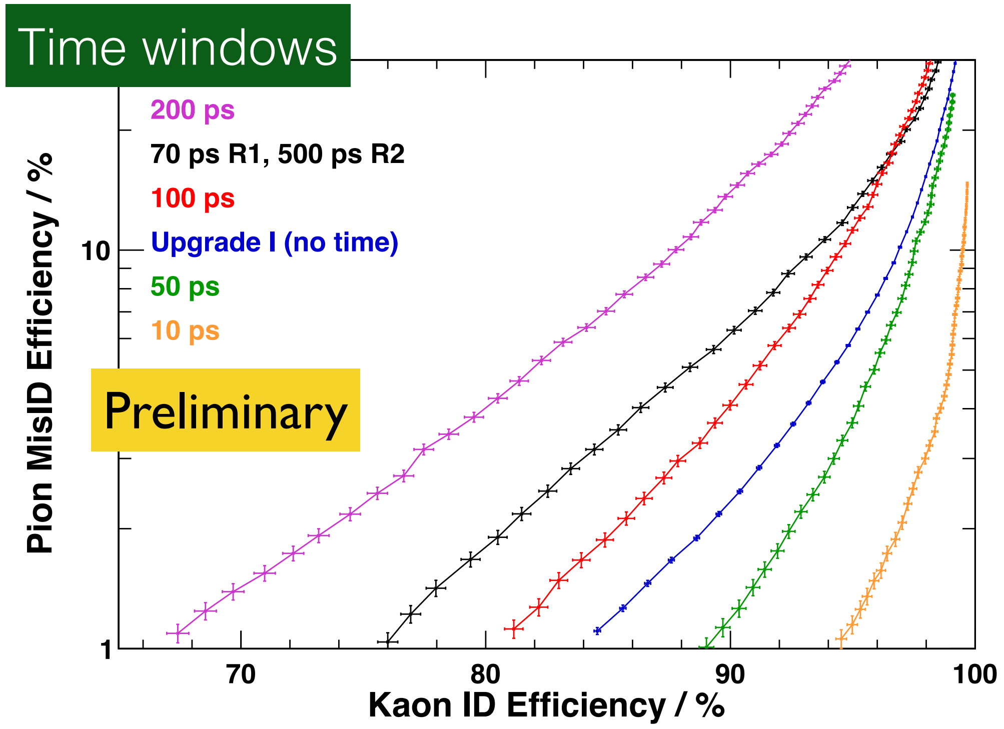


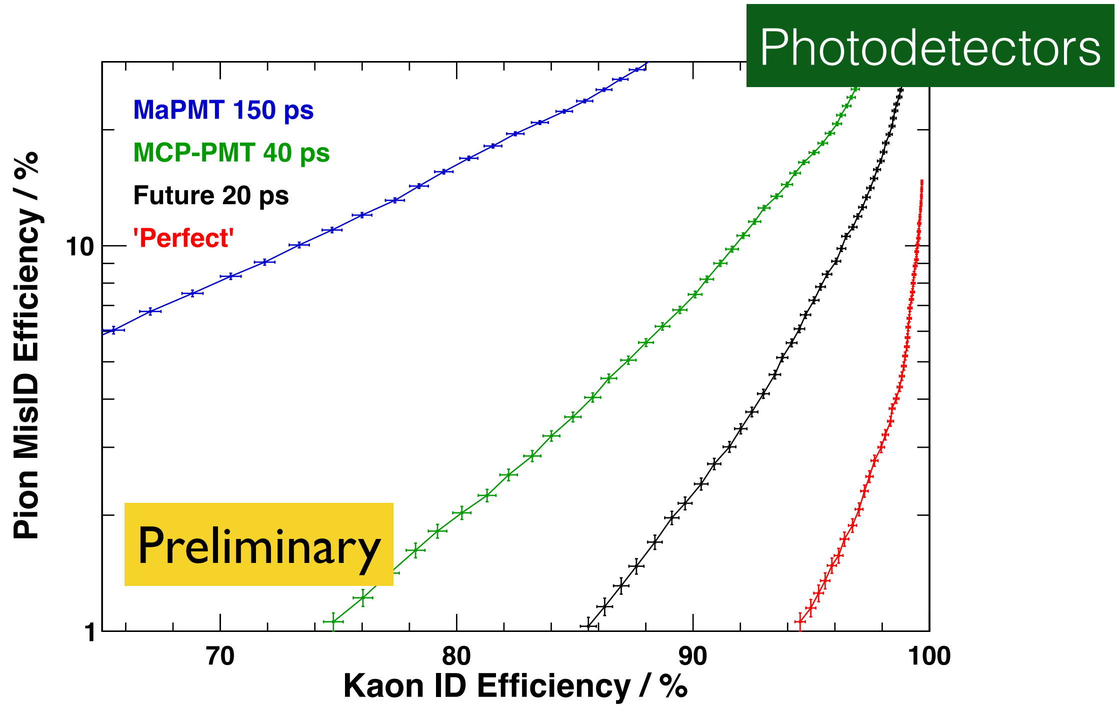
With timing



Timing in the RICH detectors

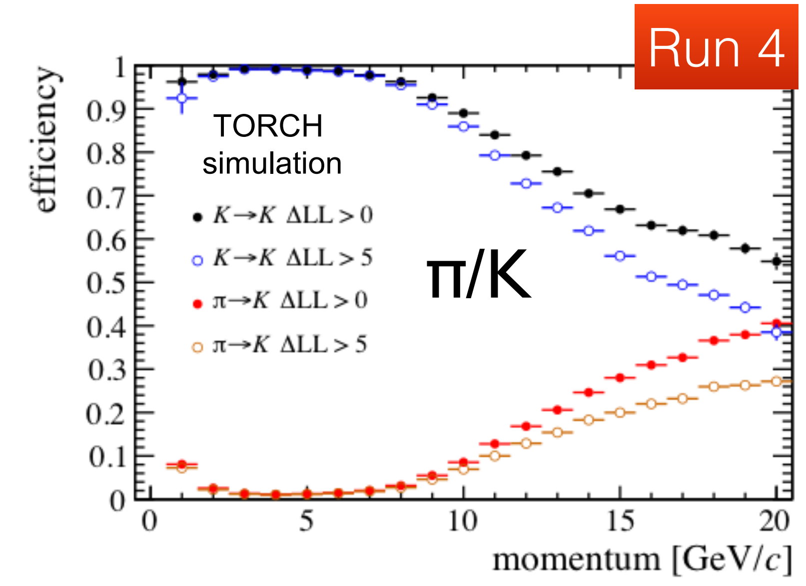
Similarly, one can consider photodetectors with fast timing information for the **RICH** detectors, the main input for **hadron PID**. Knowing which photons belong to which track is key here. Evaluated impact from timing alone, but plan to improve the spatial resolution as well. First implementation of timing in electronics to be made in **Run 4**.

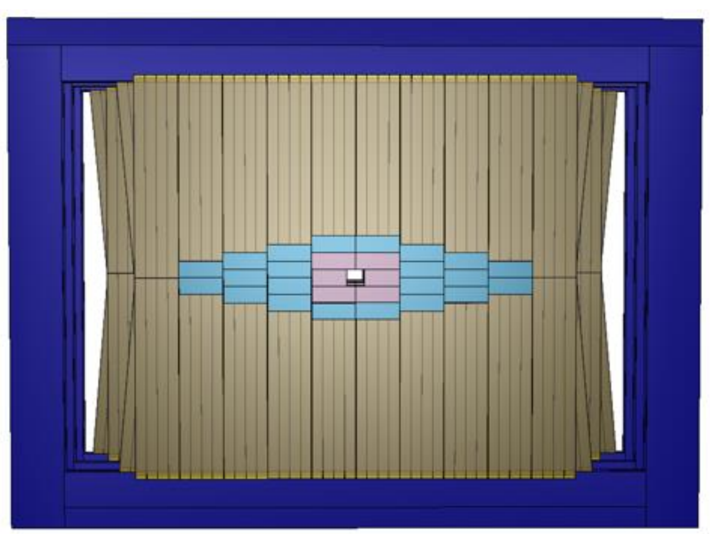




Broadening the horizon

TORCH A large-area ~10-15ps per-track TOF detector downstream of the dipole magnet will improve the kaon-pion separation at **low momentum** drastically. Planned already for **Run 4** ("Upgrade 1b")





Mighty Tracker A silicon **m**iddle and **i**nner **t**racker, combined with scintillating fibres (SciFi) for the outside, required for **radiation damage** to the SciFi with higher occupancy. Improve momentum resolution for high-p tracks and simplify the track reconstruction in the region of highest occupancy. **Inner** Tracker planned for **Run 4** already

Consolidation phase

Impact of several options on physics performance are now studied. Some very attractive for the physics programme, but do require **extensive R&D** for e.g. **radiation hardness** and **mechanics**.

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.

Support

Documentation

Expression of interest	LHCC-2017-003
Physics case	LHCC-2018-027
Accelerator Study	CERN-ACC-2018-038
Luminosity Scenarios	LHCb-PUB-2019-001
Framework TDR	**September ‘21**

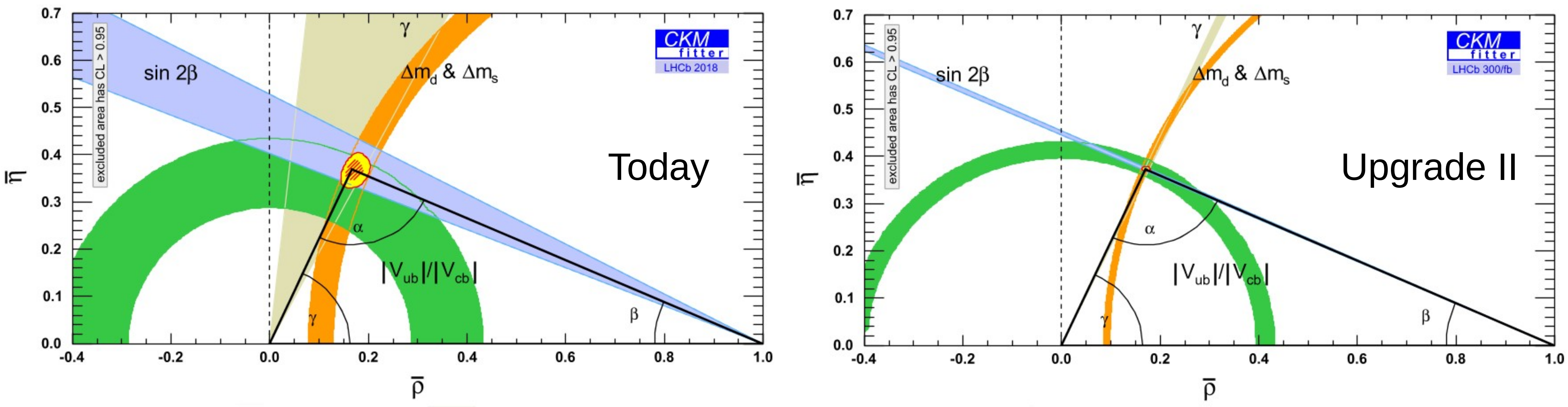
European Strategy Update 2020

“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”

Conclusion

The Phase-II upgrade of LHCb is a unique opportunity for a **general purpose** experiment in the forward region. It will be able to reach SM precision for both *CP* violation in B^0 mixing and the charm mixing parameters, underlining its role at the **frontier** for heavy **flavour physics**



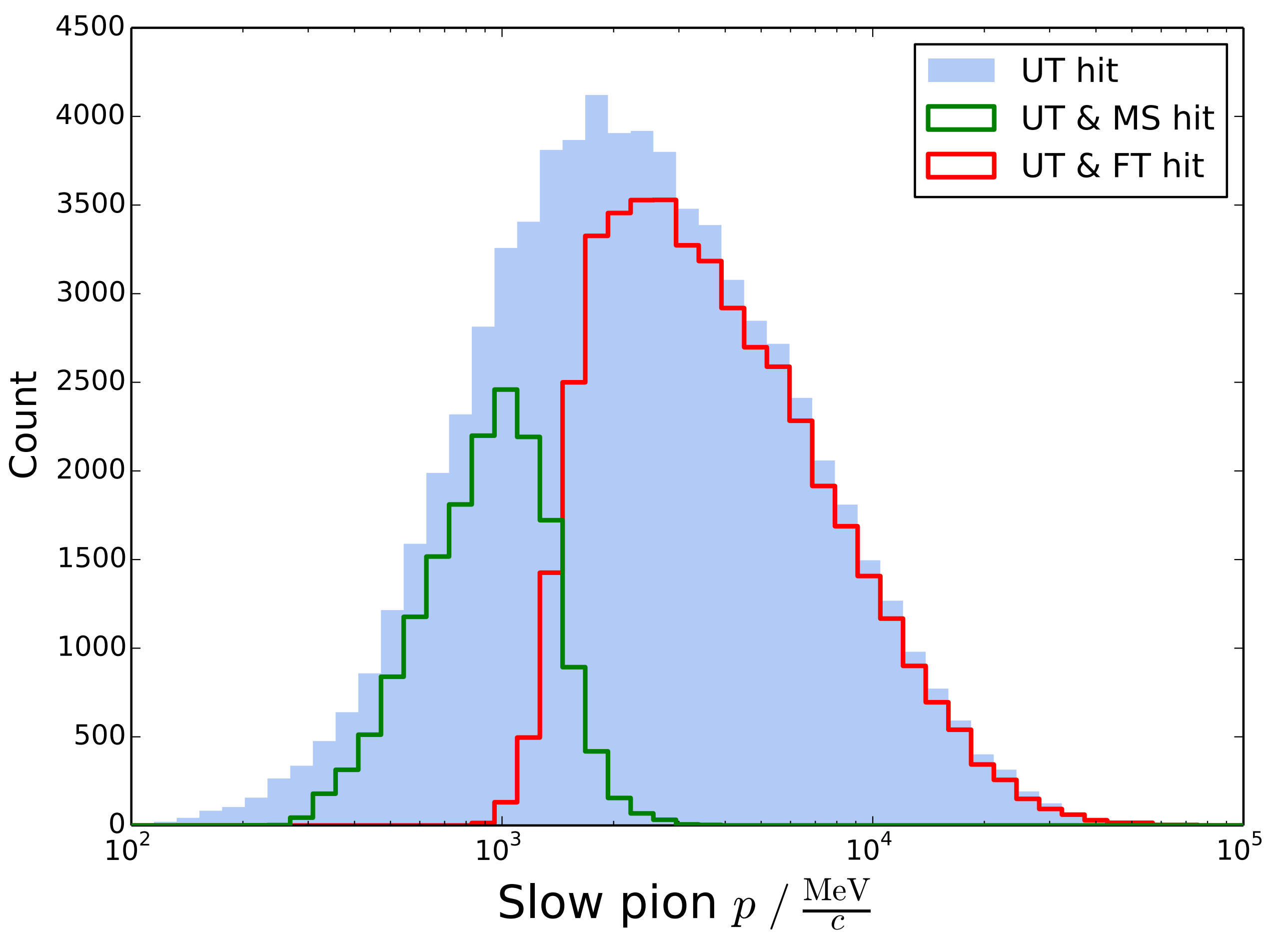
Aim for a **detector design** which provide sufficient **head room**. **Timing information** across many subdetectors likely to play a big role, and motivates further R&D. **Framework TDR** expected for September 2021.

Phase-II upgrade for LHCb

BEAUTY September 24, 2020

Laurent Dufour, on behalf of the LHCb collaboration

Magnet side-stations



Over 20% more D^{*+} decays reconstructed

Overview

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected 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 $B^0 \to J/\psi K_\mathrm{S}^0$	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}	$(K_\mathrm{S}^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

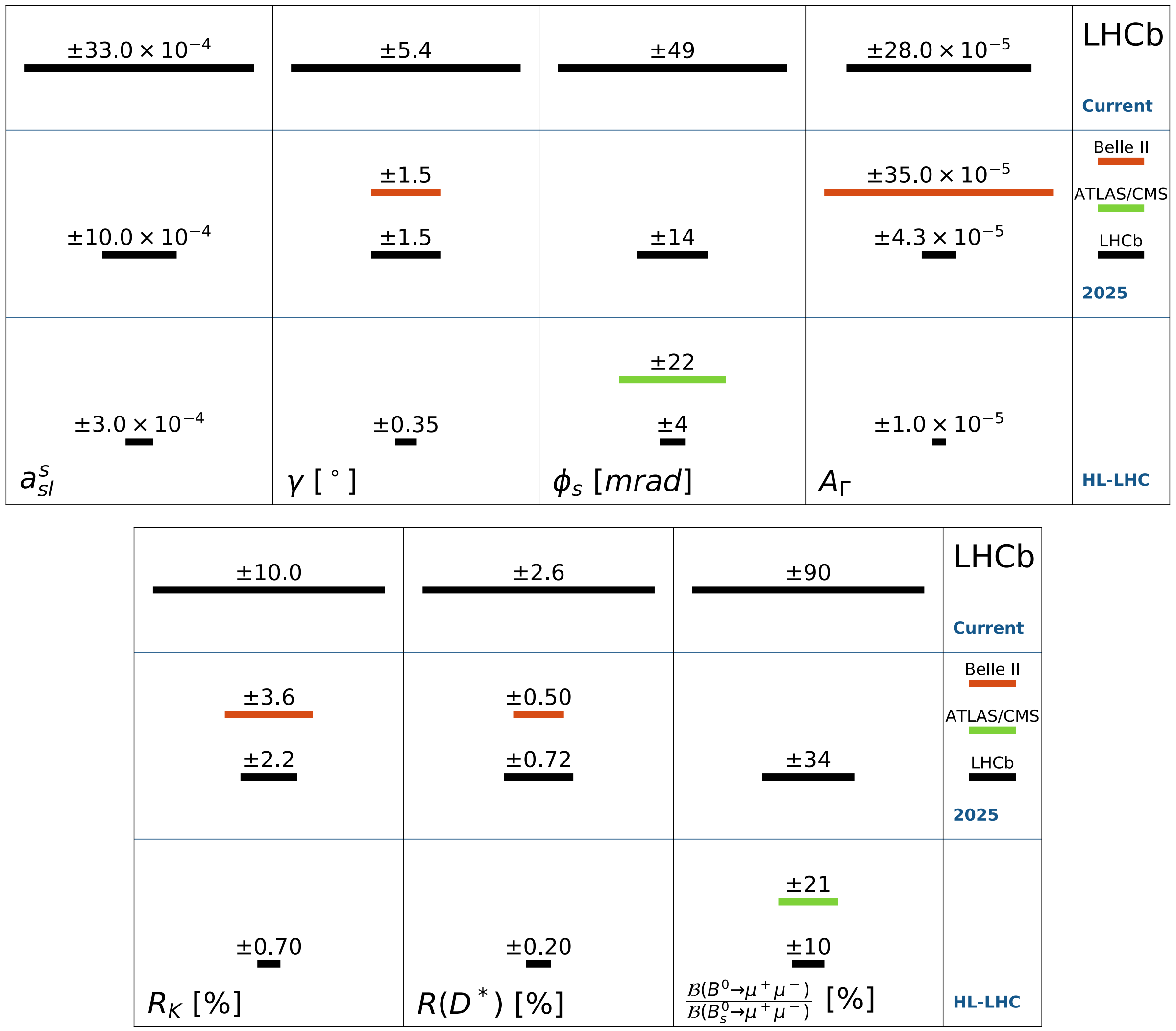
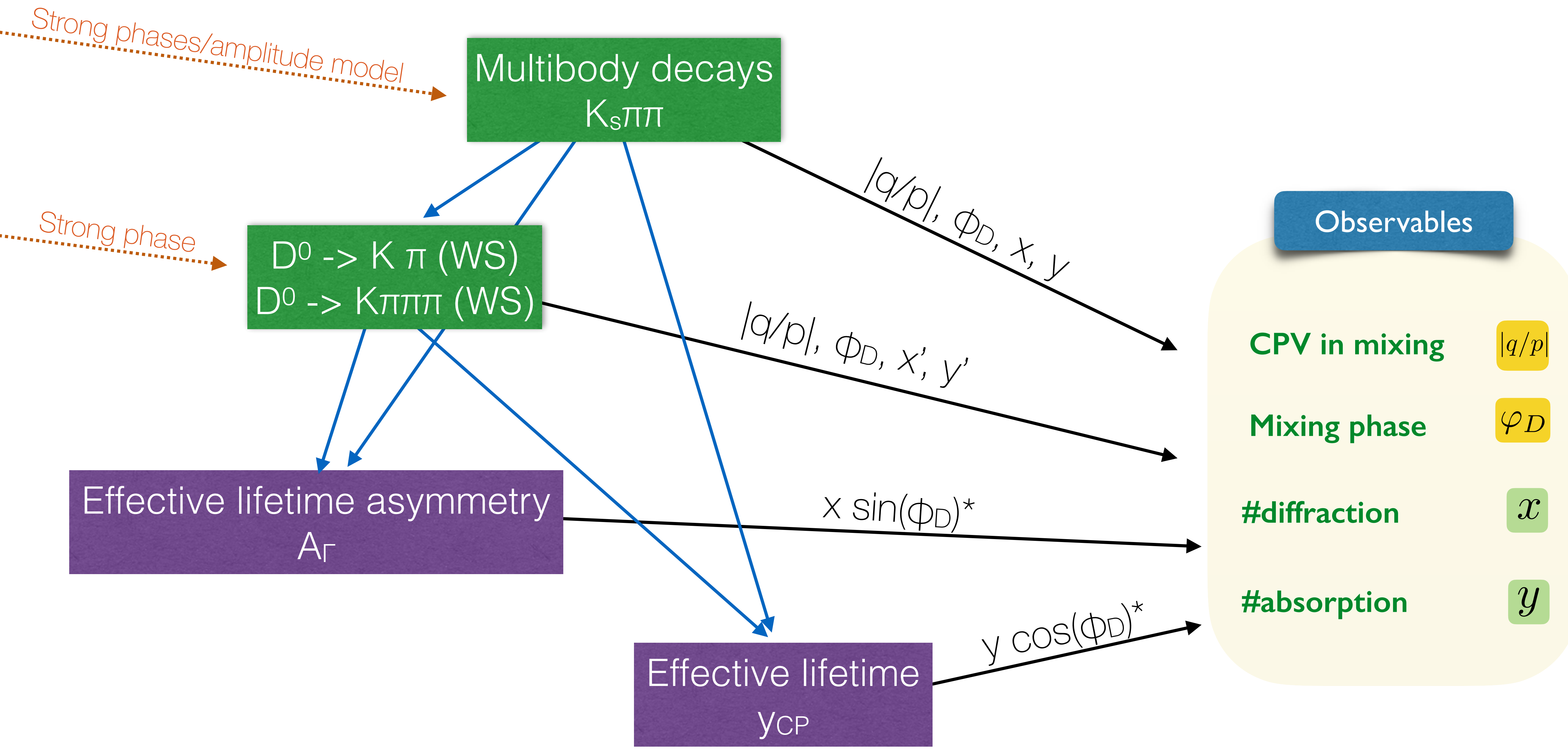


Figure 10.1: Projected improvement in sensitivities for selected *CP*-violating observables (upper) and for rare decays and lepton-universality tests (lower).

Charm mixing

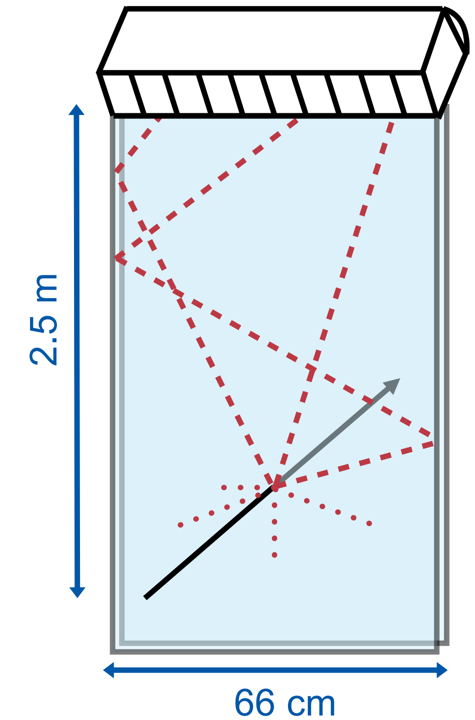
Complete programme



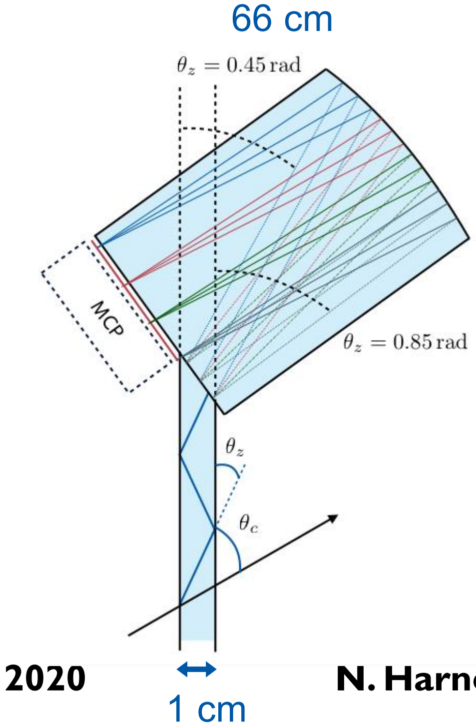
*: if $|q/p|\neq1$, then more complex

The TORCH detector

- A charged track produces Cherenkov light in a plane of 1 cm thick quartz
- Cherenkov photons travel to the periphery of the detector by total internal reflection and focused → their position and arrival time is measured by Micro-Channel Plate PMTs (MCPs)
- The Cherenkov angle θ_c and path length L in the quartz are measured. The time of arrival is used to correct for the chromatic dispersion in the quartz.
- From simulation, ~1 mrad precision is required on measurement of the angles in both planes to achieve the required intrinsic timing resolution



Non-focussing plane



Focussing plane