LHCb upgrades

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Future Flavours

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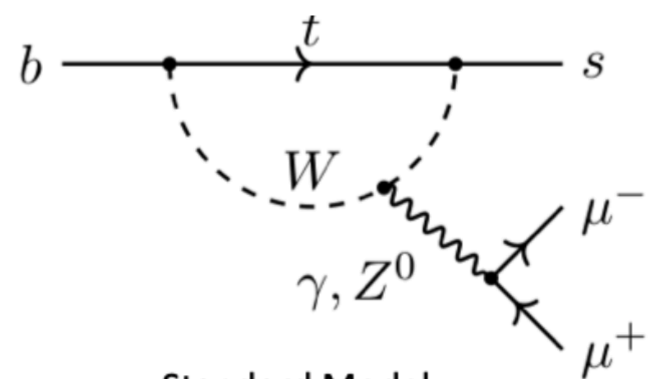
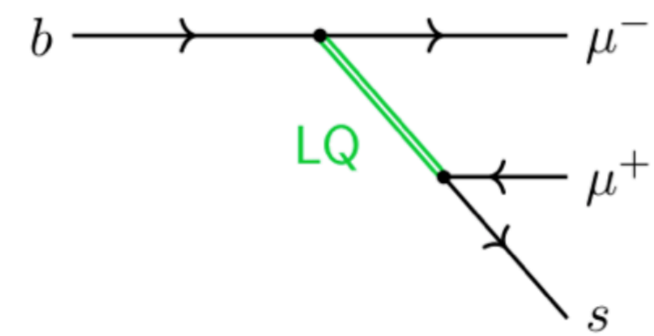
International Centre for Theoretical Sciences
Tata Institute of Fundamental Research

New Physics searches with flavour

Instead of searching for new particles directly produced, look for their indirect effects to low energy processes, e.g. in rare b-hadron decays



Standard Model



Leptoquarks

Enhanced NP sensitivity due to smallness of c_{SM} (loop + CKM suppression)

$$A = A_0 \left[c_{SM} \frac{1}{M_W{}^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

Increase of precision in flavour physics will allow to probe mass scales not accessible directly at LHC

Need huge statistics: energy scale scales as $\sim L_{int}^{1/4}$

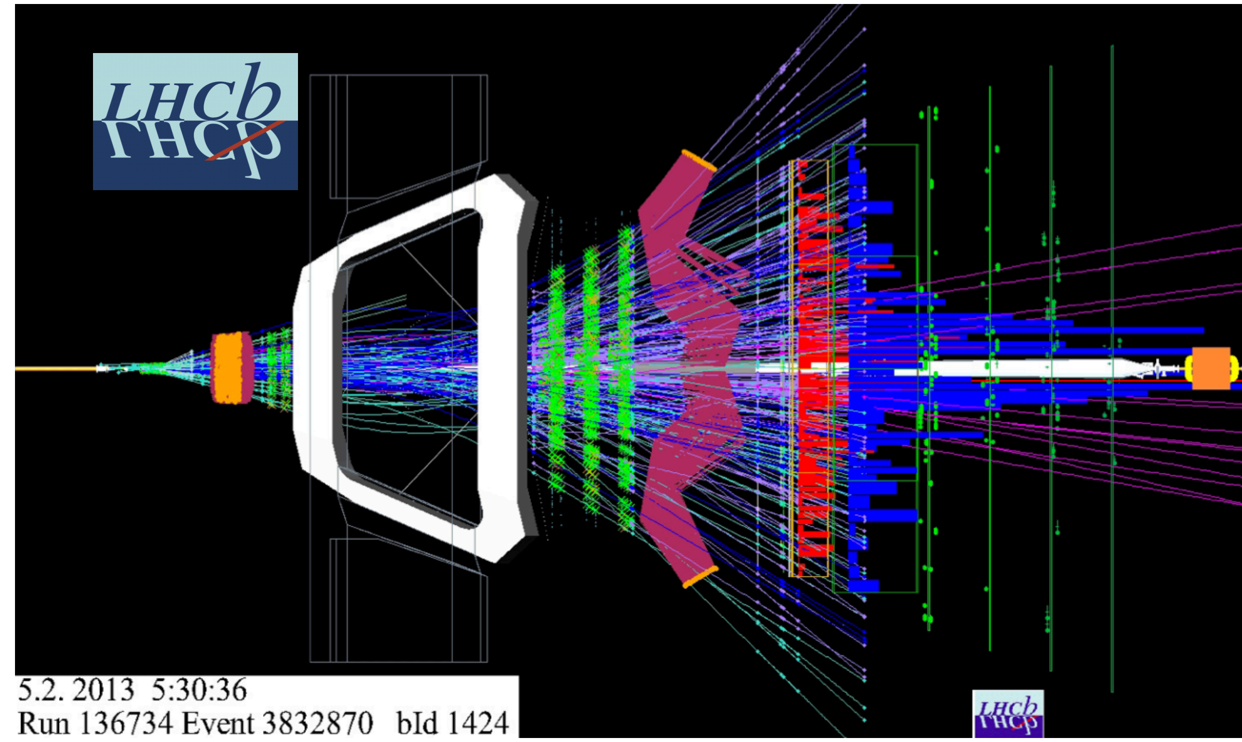
Need low syst uncertainties: excellent detector, clever design

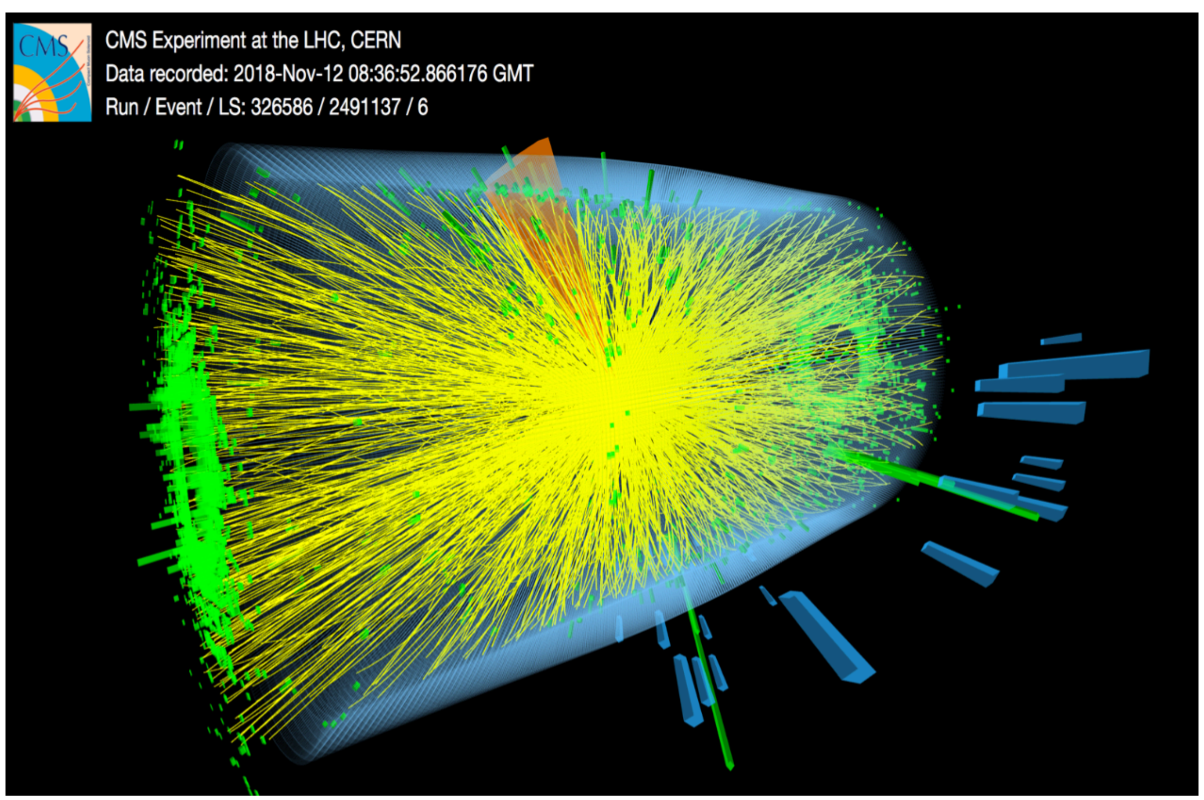
Need precise SM predictions: clean observables (LFU ratios,…), calculable hadronic contributions at sub-percent level (lattice QCD,…), null tests (LFV,…)

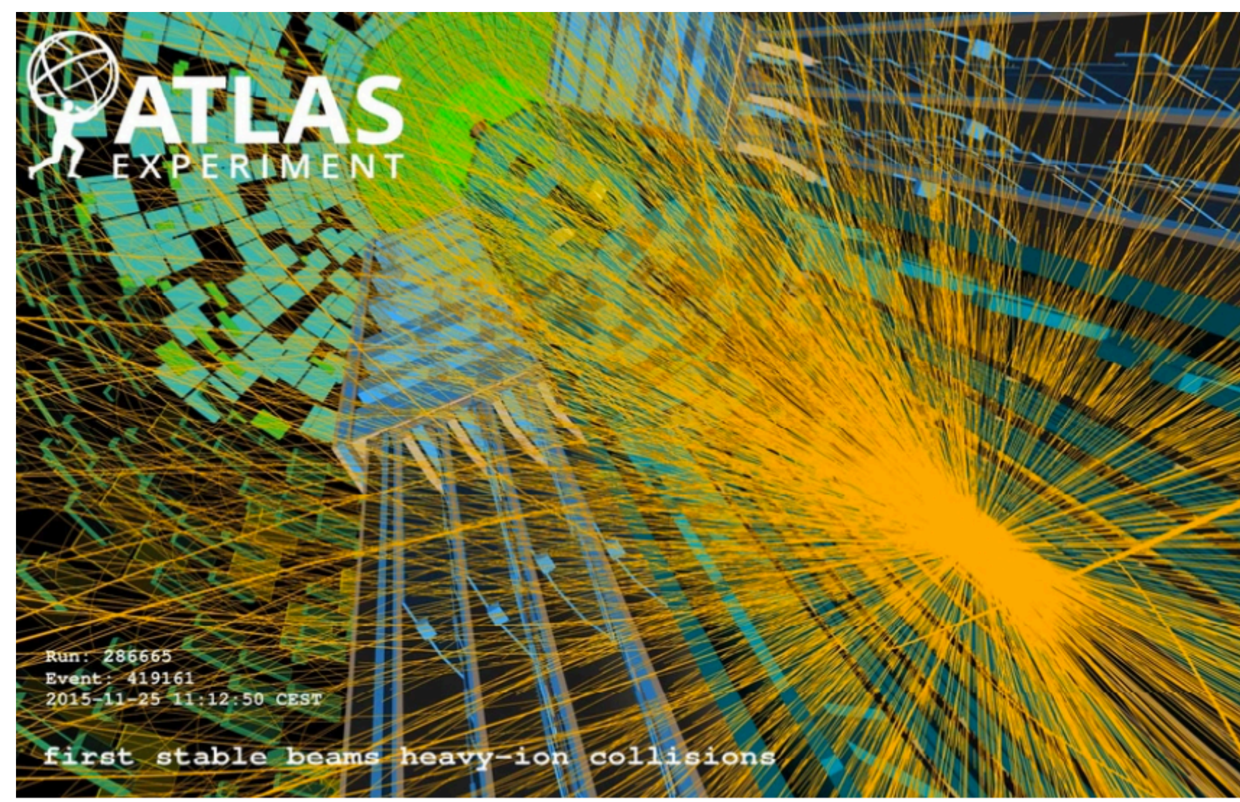
Flavour physics at the LHC

High gain: unprecedented statistics
+ access to all c- and b-hadrons

High risk: extremely difficult event topology







Need excellent tracking and PID, and capability to trigger with low p_T → this is LHCb!!

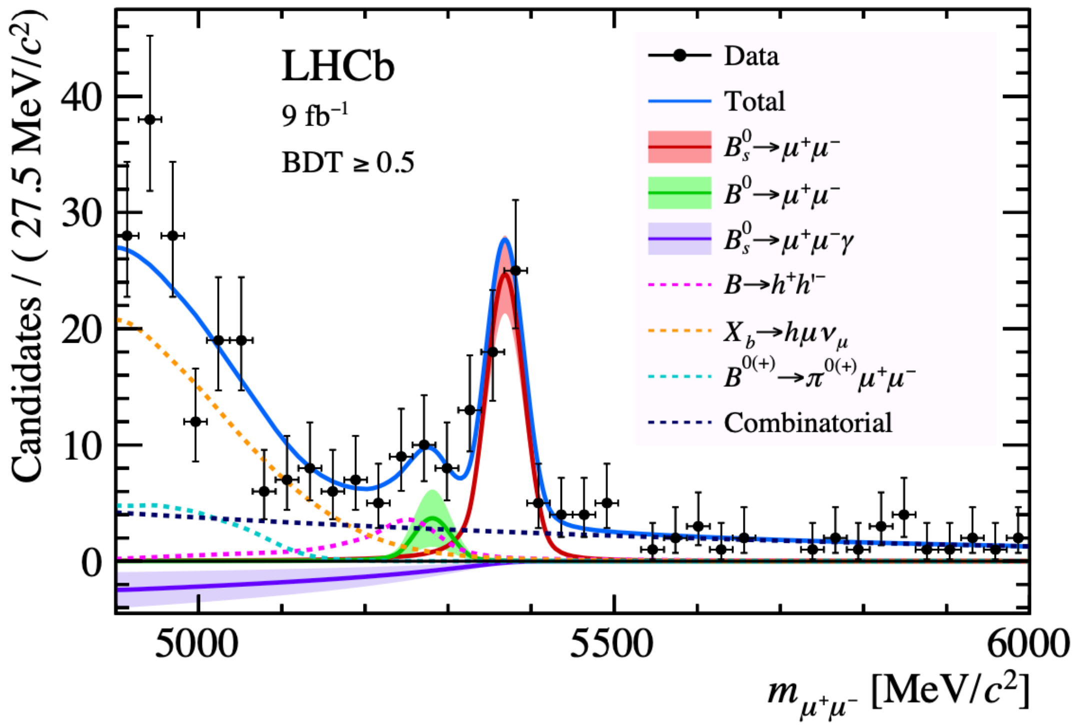
LHCb highlights

Future plans build on the success of the experiment during Run 1 and Run 2

for the expected...

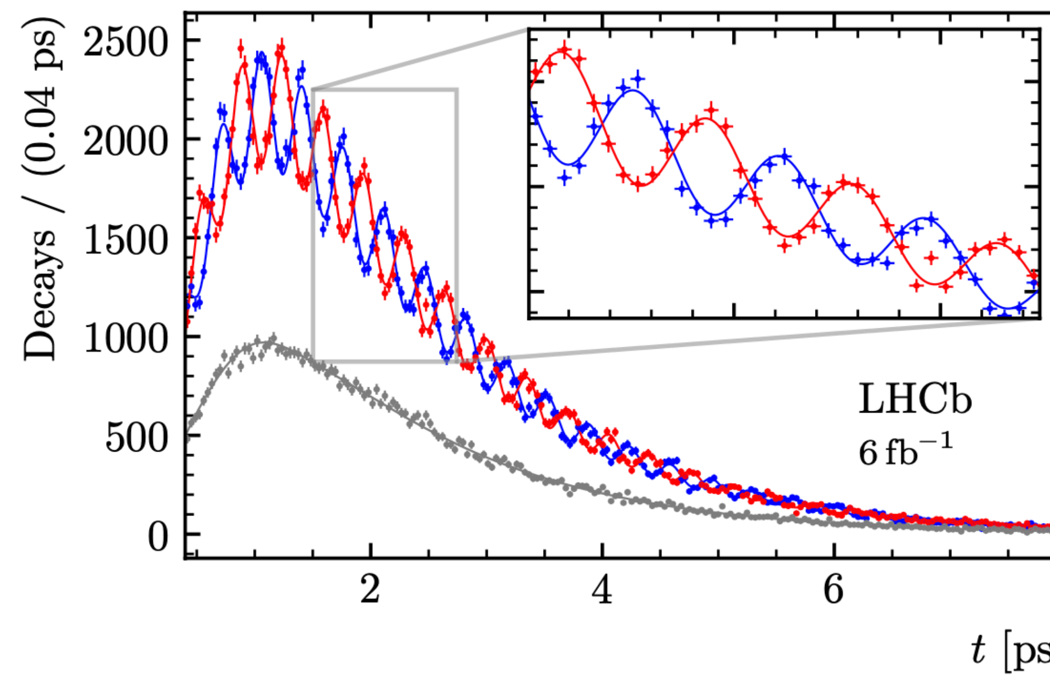
PRL 128 (2022) 041801

$B_s^0 \to \mu\mu$



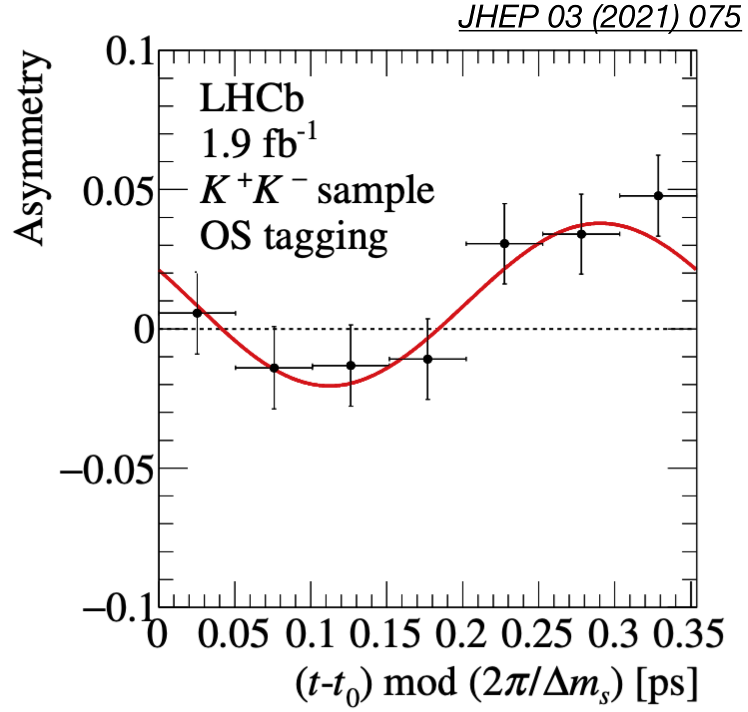
Nat. Phys. 18 (2022) 1

Δm_s



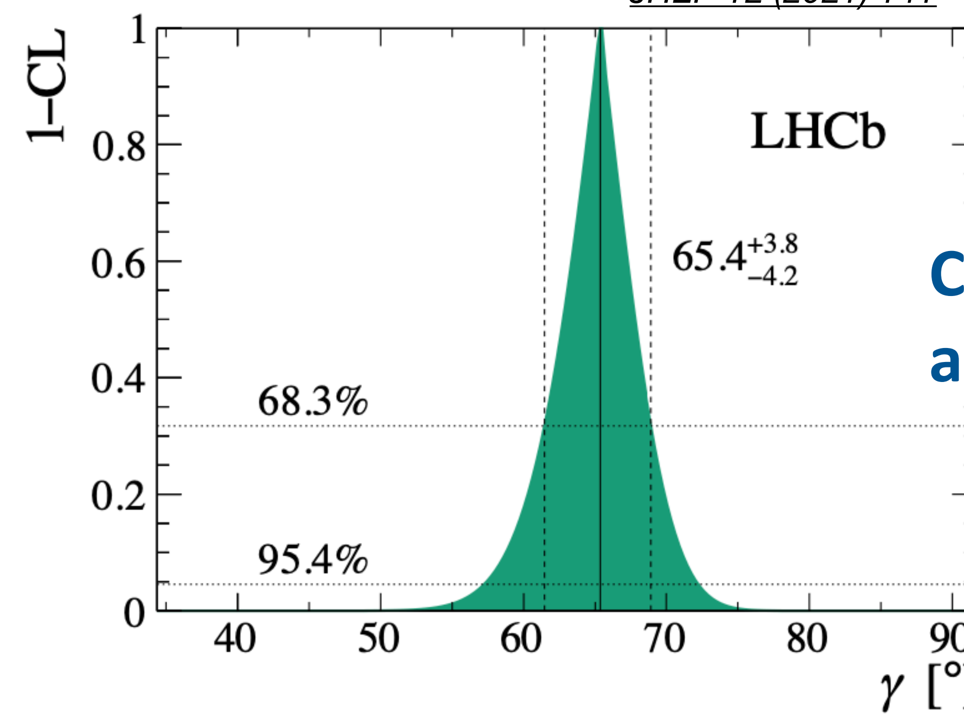
JHEP 03 (2021) 075

Time-dependent CPV in B_s



JHEP 12 (2021) 141

CKM angle γ



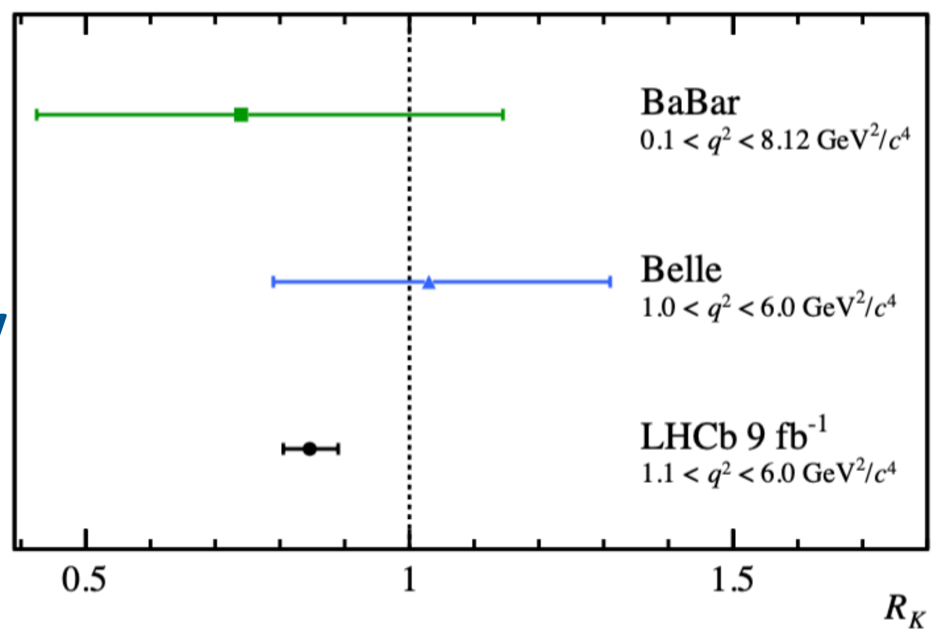
LHCb highlights

Future plans build on the success of the experiment during Run 1 and Run 2

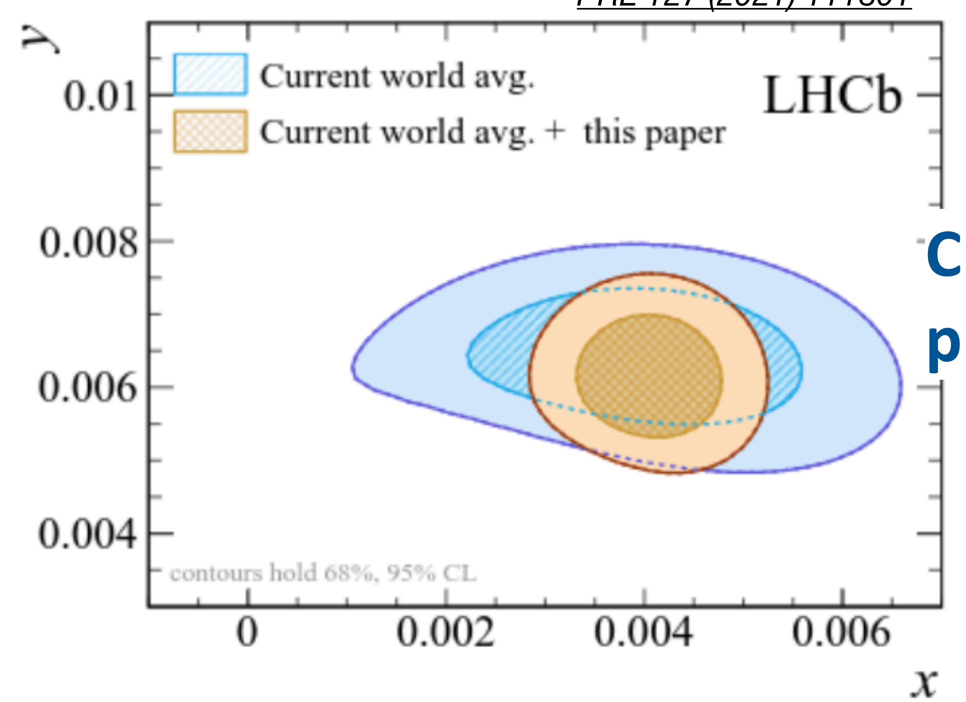
...and for the unexpected!

Lepton flavour universality

arXiv:2103.11769



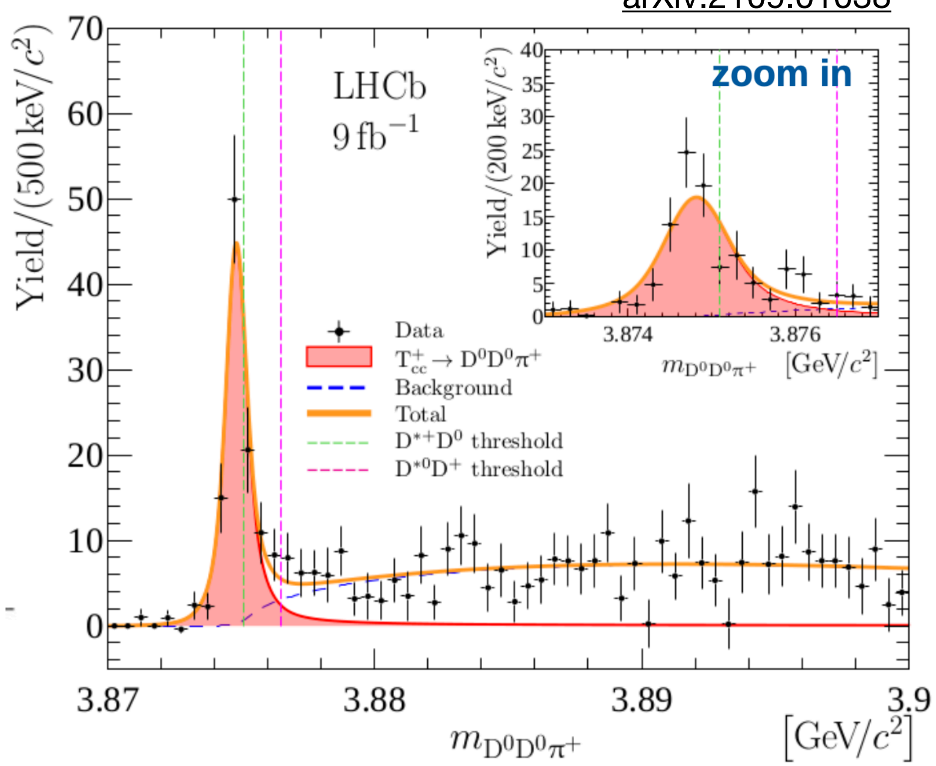
PRL 127 (2021) 111801



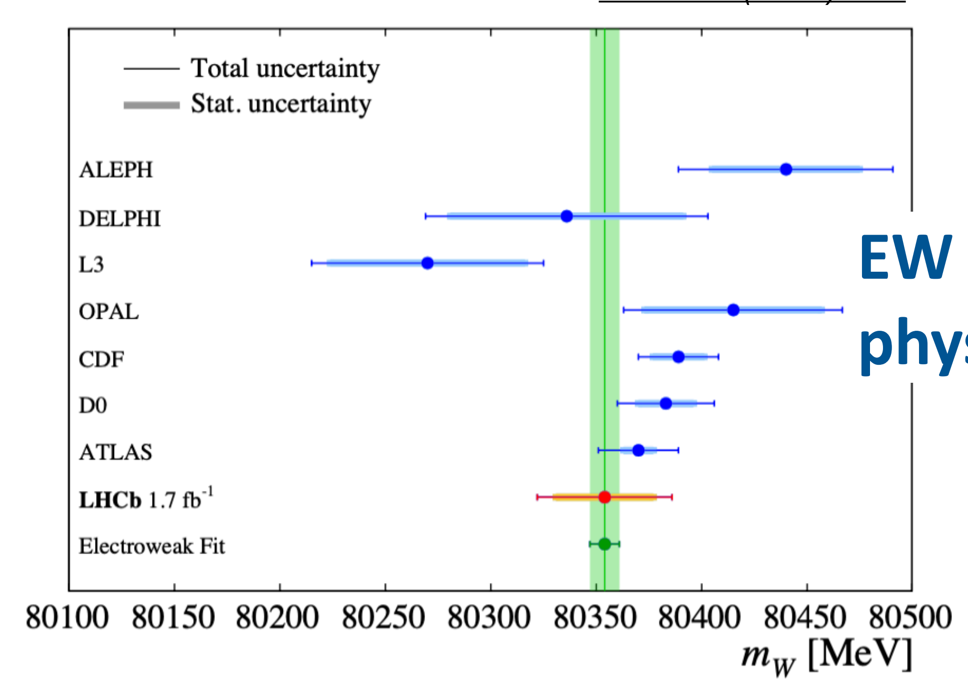
Charm physics

Exotic hadrons

arXiv:2109.01038



JHEP 01 (2022) 036



EW physics

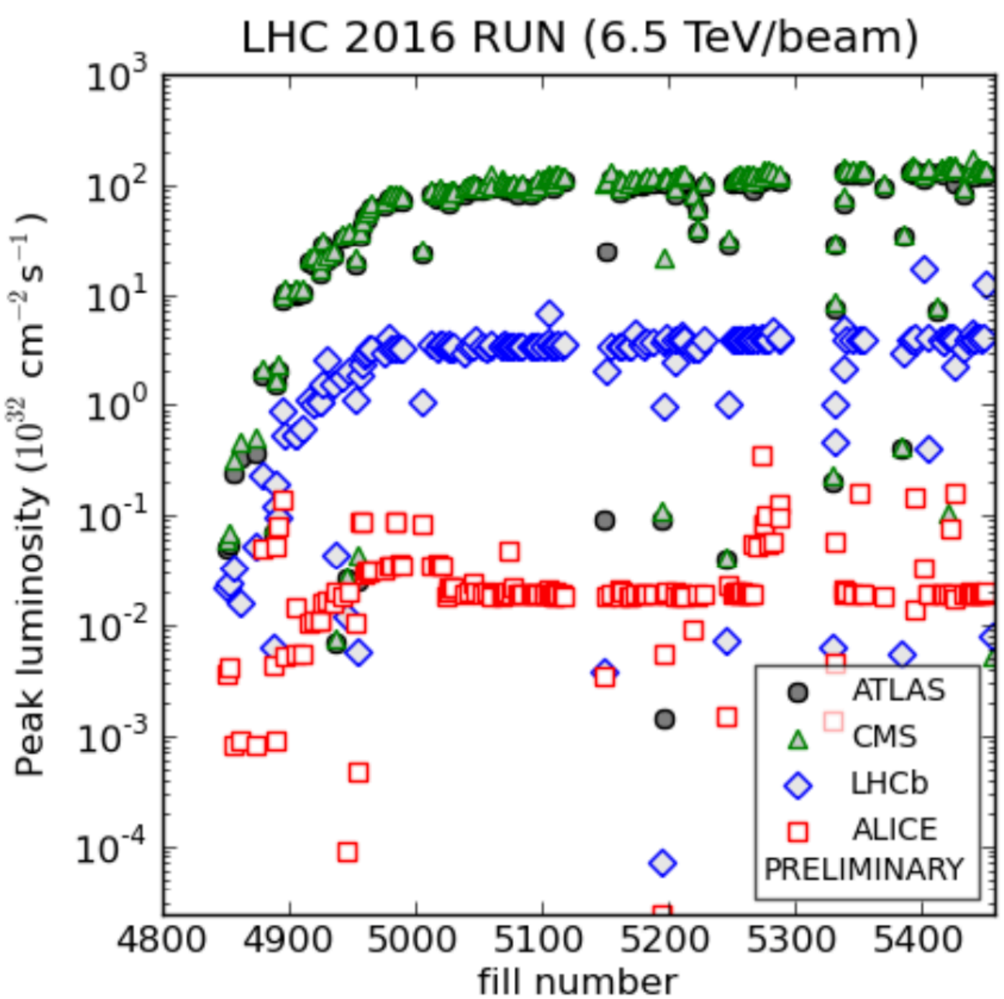
LHCb highlights

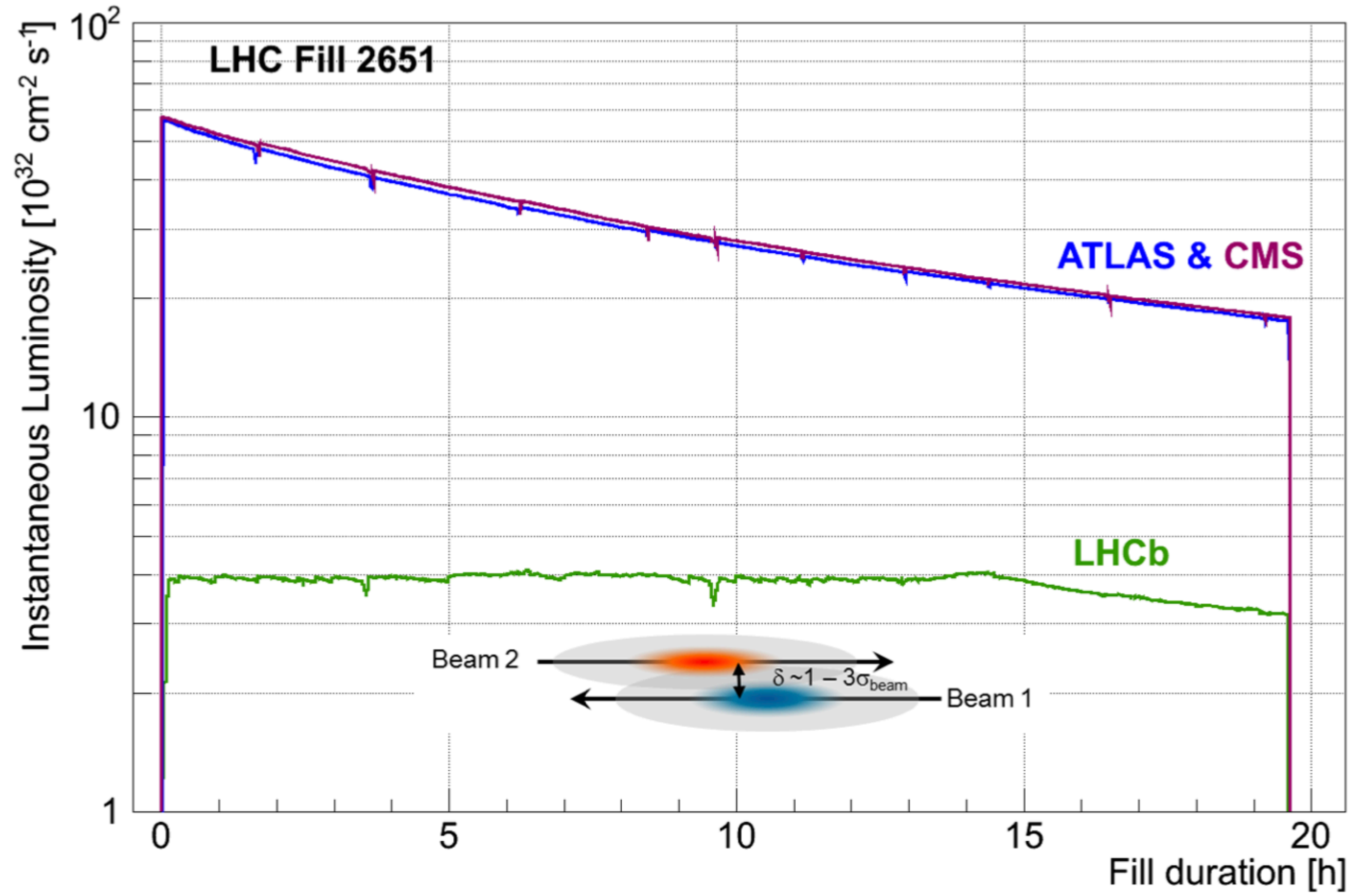
Future plans build on the success of the experiment during Run 1 and Run 2

to the LHC for the excellent performance during Run 1 and Run 2 !!!

LHCb running conditions Run 2

Physics programme so far limited by detector, and NOT by the LHC





For LHCb $L_{peak} \sim 4\times10^{32}$ cm^{-2} s^{-1} levelled, ~1 visible interaction/crossing

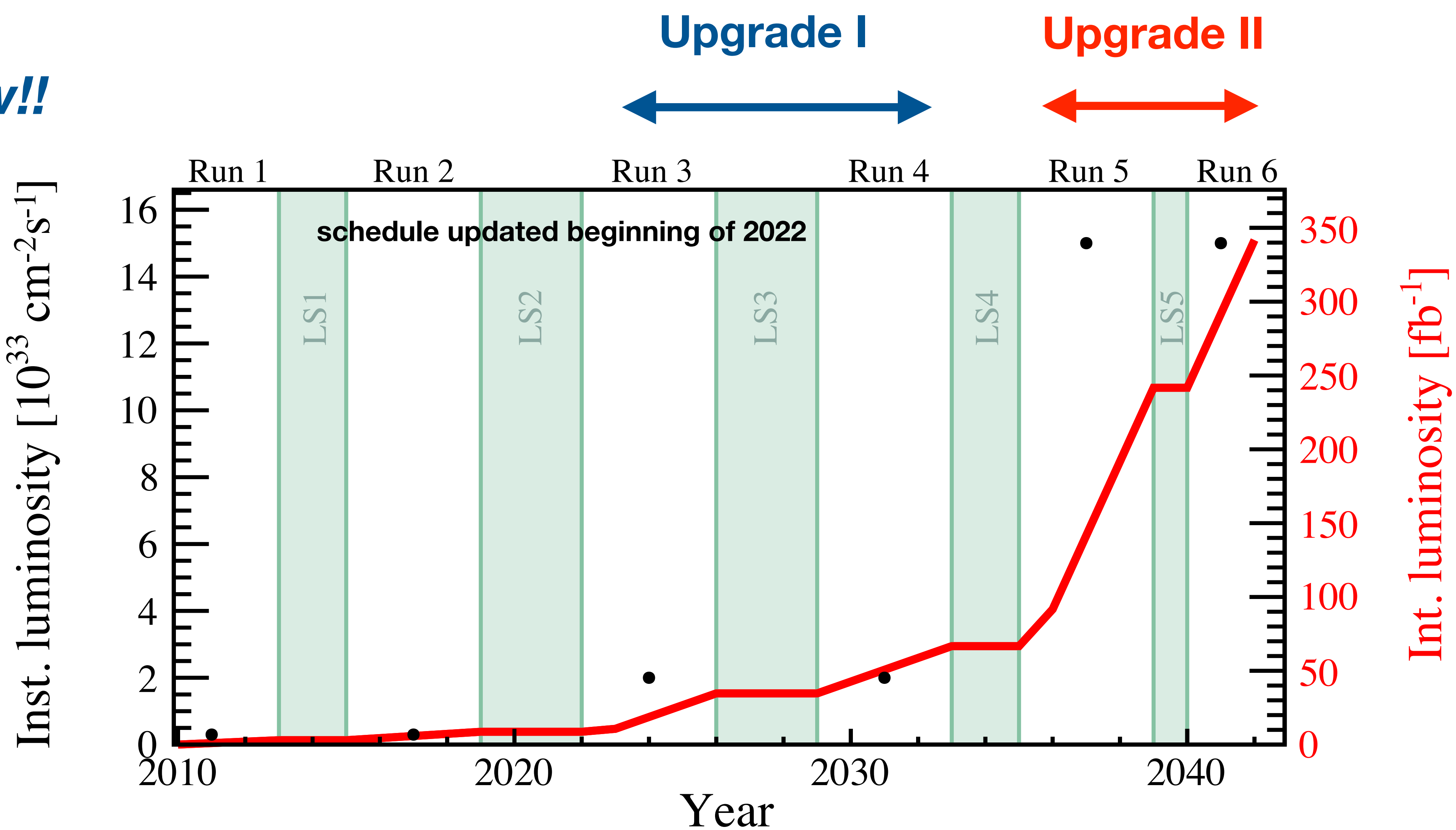
To be compared with ATLAS/CMS $L_{peak} \sim 2\times10^{34}$ cm^{-2}s^{-1}, pile-up ~40

LHCb upgrades

Physics programme limited by detector, and NOT by the LHC, so there's a clear case for an ambitious plan of upgrades

Upgrade I starting now!!

- L_{peak} = 2x10^{33} cm^{-2} s^{-1}
- L_{int} = 50 fb^{-1} during Run 3 & 4
- *Healthy competition with Belle II at 50 ab^{-1}*

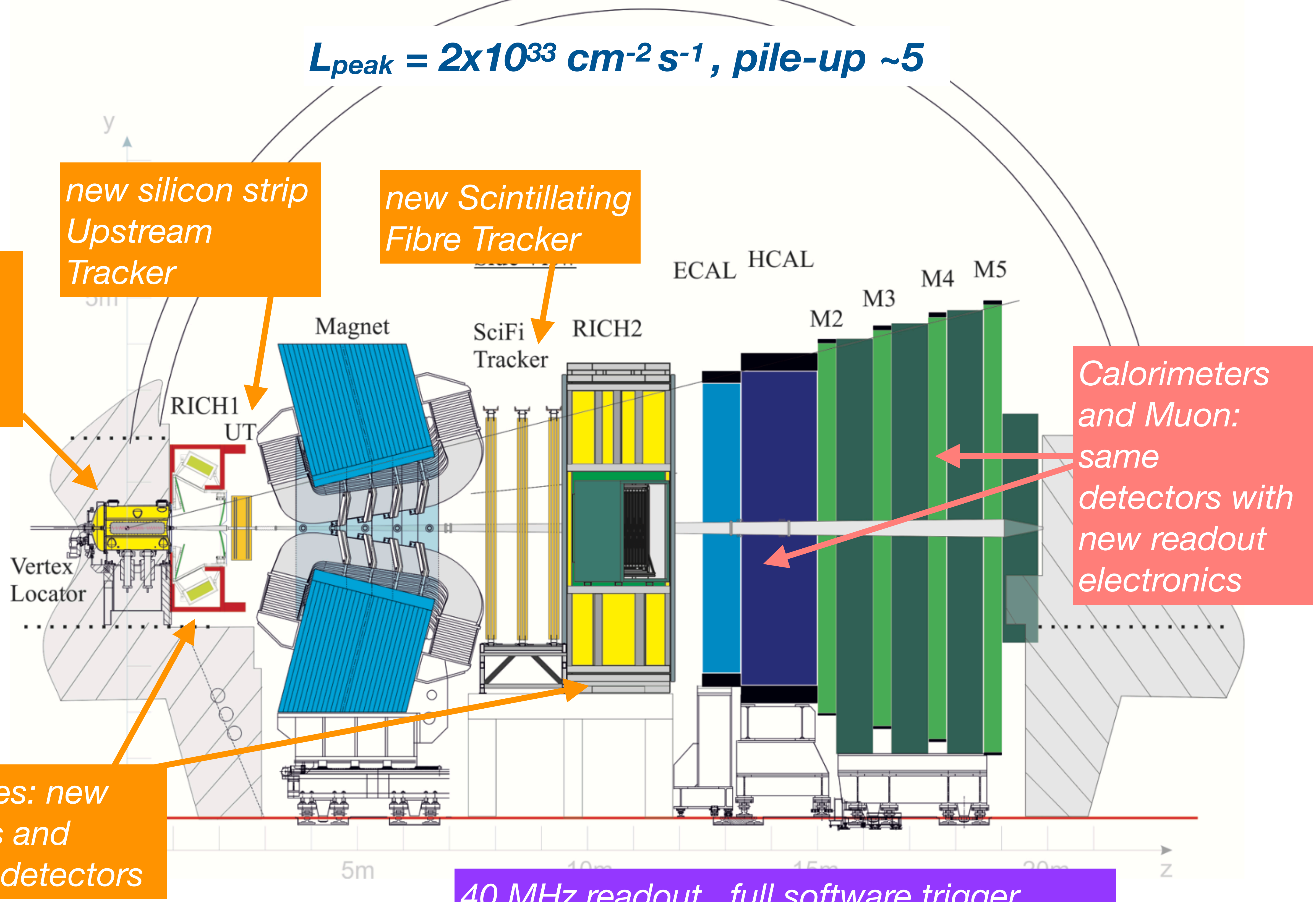


Upgrade II

- L_{peak} = 1.5x10^{34} cm^{-2} s^{-1}
- L_{int} = ~300 fb^{-1} during Run 5 & 6
- *Potentially the only general purpose flavour physics facility in the world on this timescale*

LHCb Upgrade I at the starting line!

Major upgrade of all subdetectors, less than 10% of channels kept (calorimeters and muon)



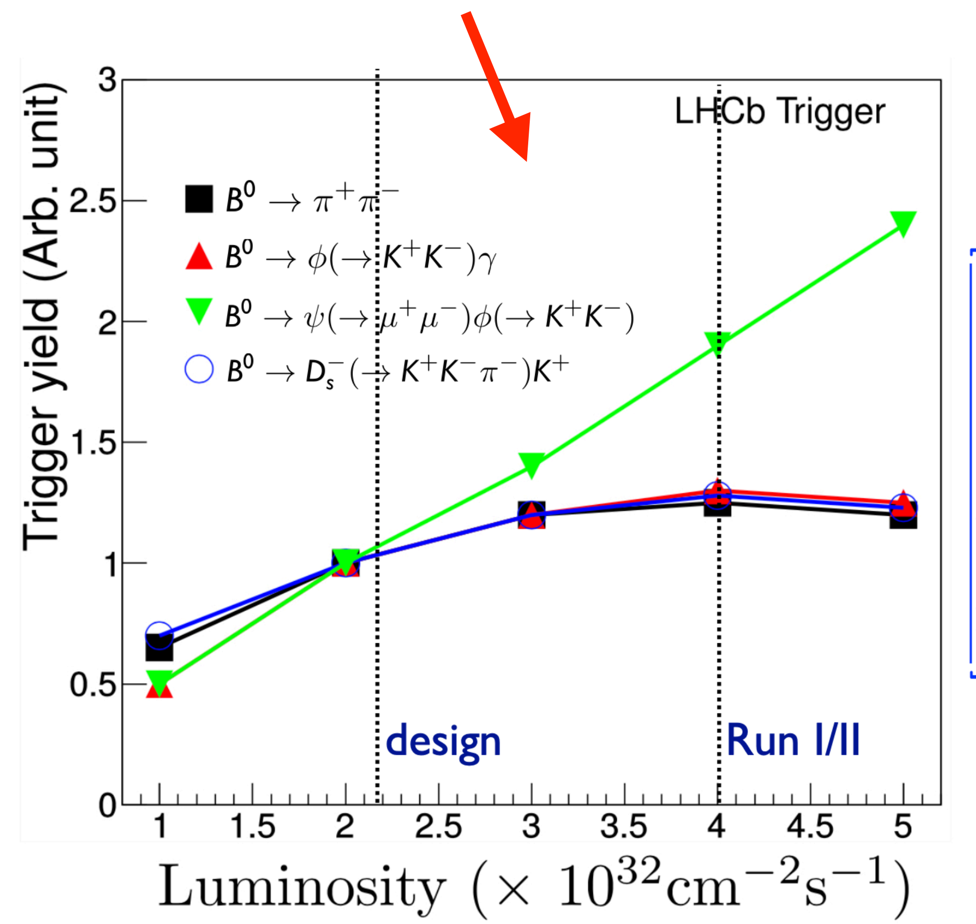
40 MHz readout, full software trigger

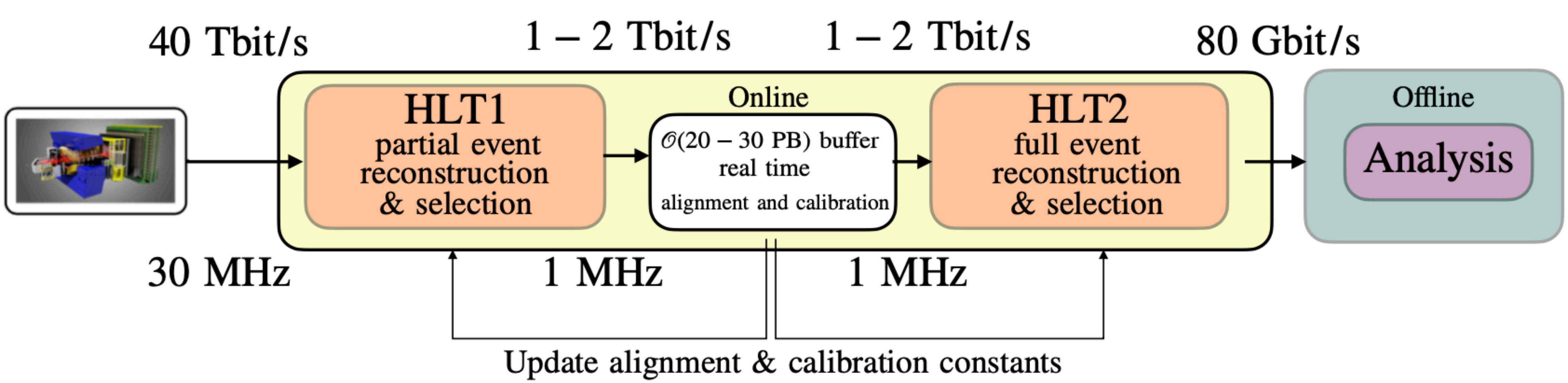
Run 3 trigger revolution

LHCC-2011-001

L0 hardware trigger will be removed, since its max bandwidth of 1 MHz would force to increase too much the CALO E_T thresholds, thus saturating the hadronic yields

- *full detector readout at 40 MHz*
- *full software trigger based on track and vertex reconstruction (1st level based on GPUs)*
- *for hadronic final states ~x2 gain in efficiency → x10 gain in yields wrt Run 2*
- *for muonic final states → x5 gain in yields*



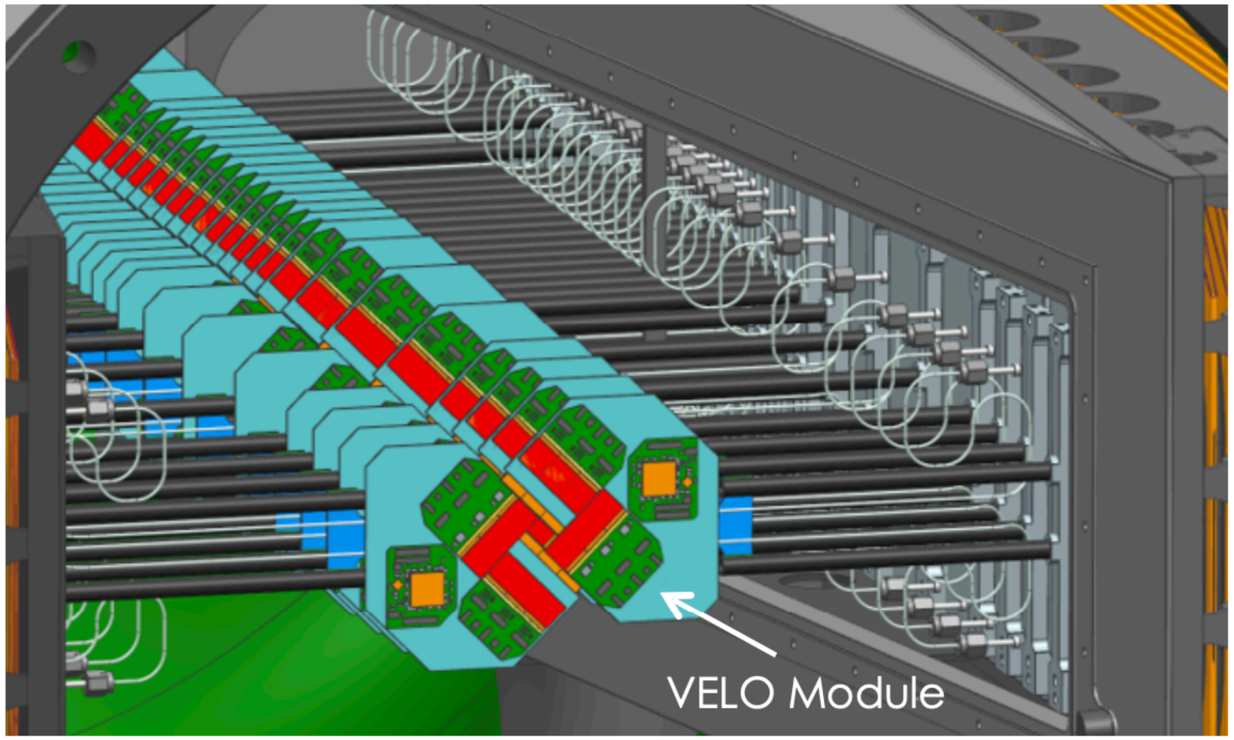


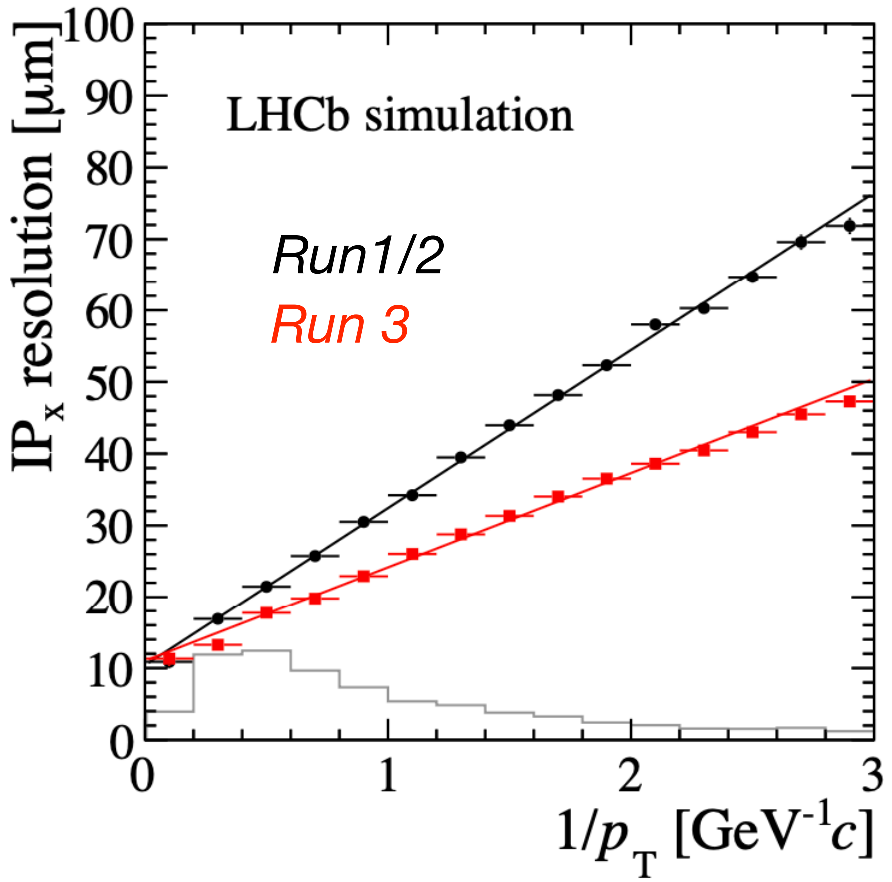
The new VErtex LOcator

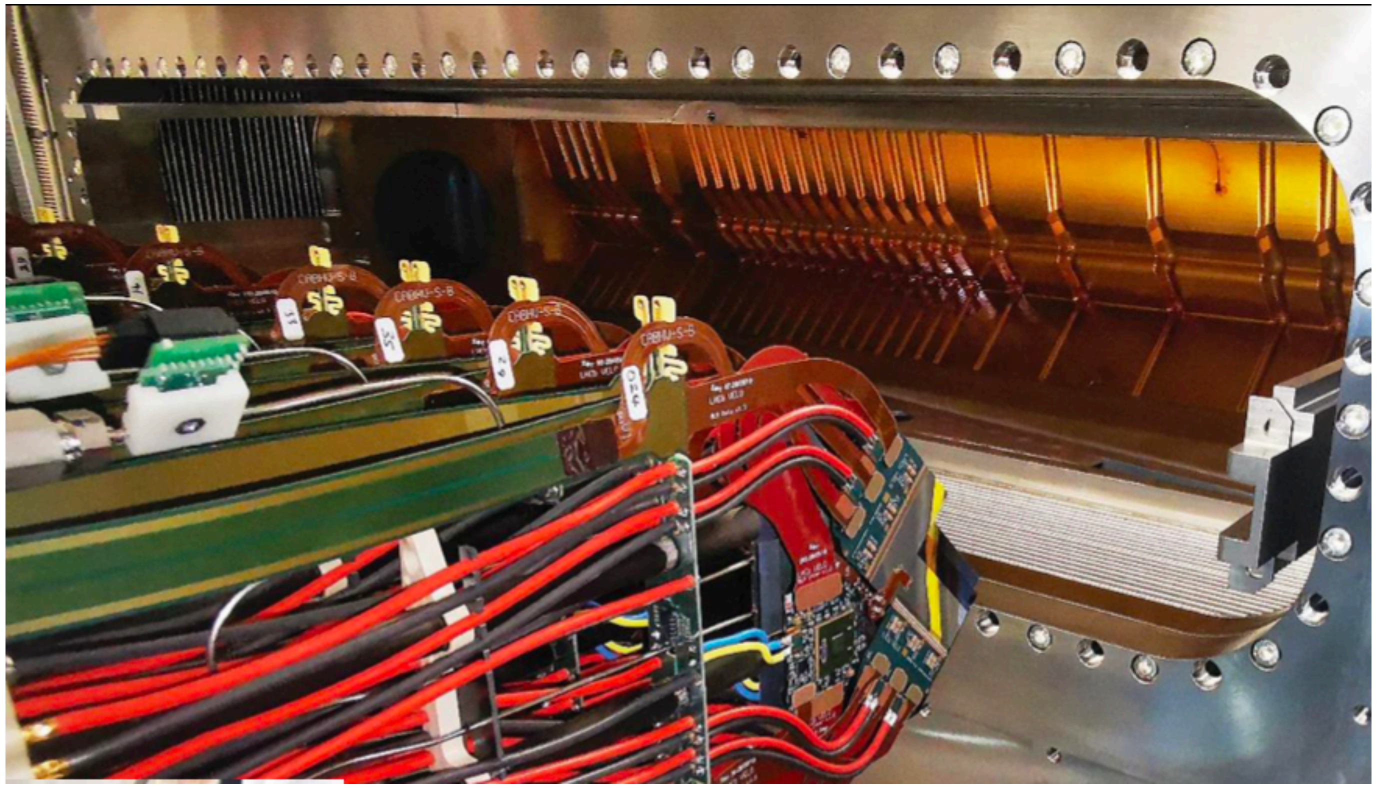
LHCC-2013-021

- *L-shaped modules with silicon pixels $55 \times 55 \mu m^2$*
- *Sensors get closer to the beam line: 8.2mm → 5.1 mm*
- *Reduced material before 1st measured point: 4.6% → 1.7% X_0*

Improved impact parameter and decay time resolution







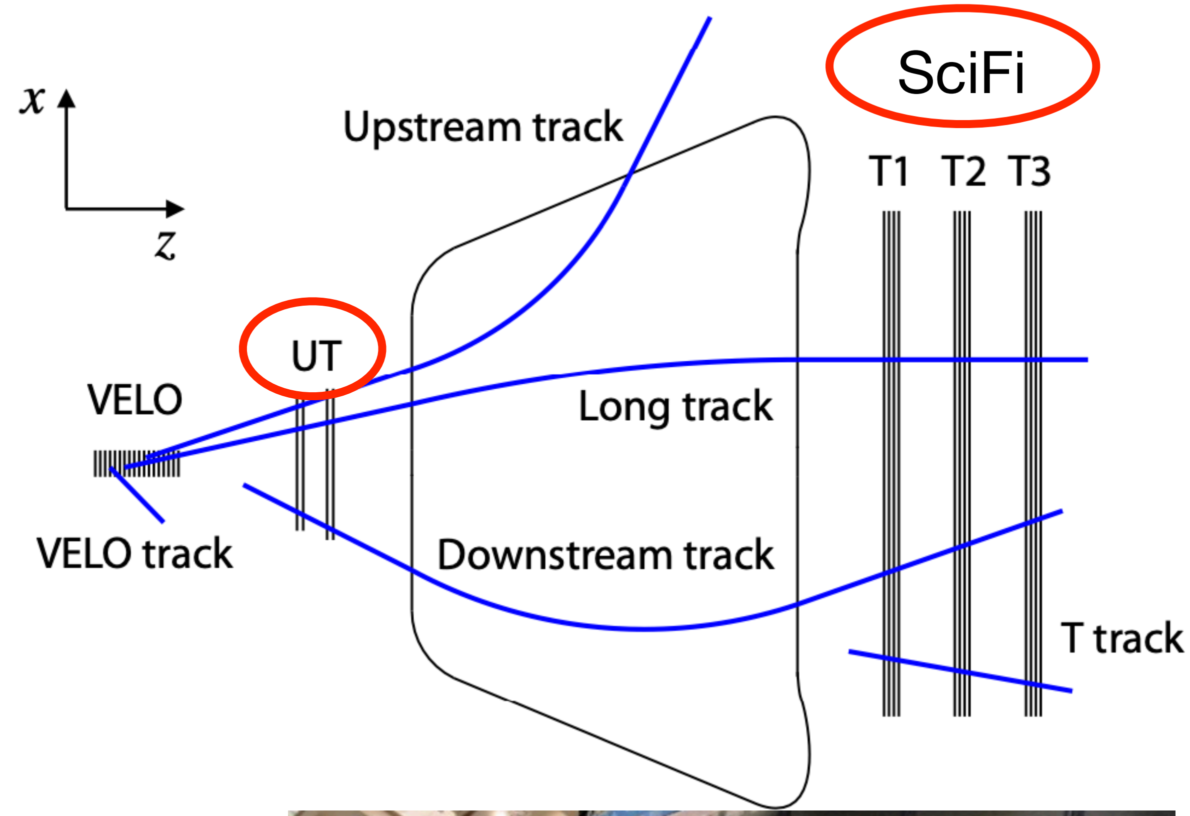
VELO half being installed

Tracking detectors

LHCC-2014-001

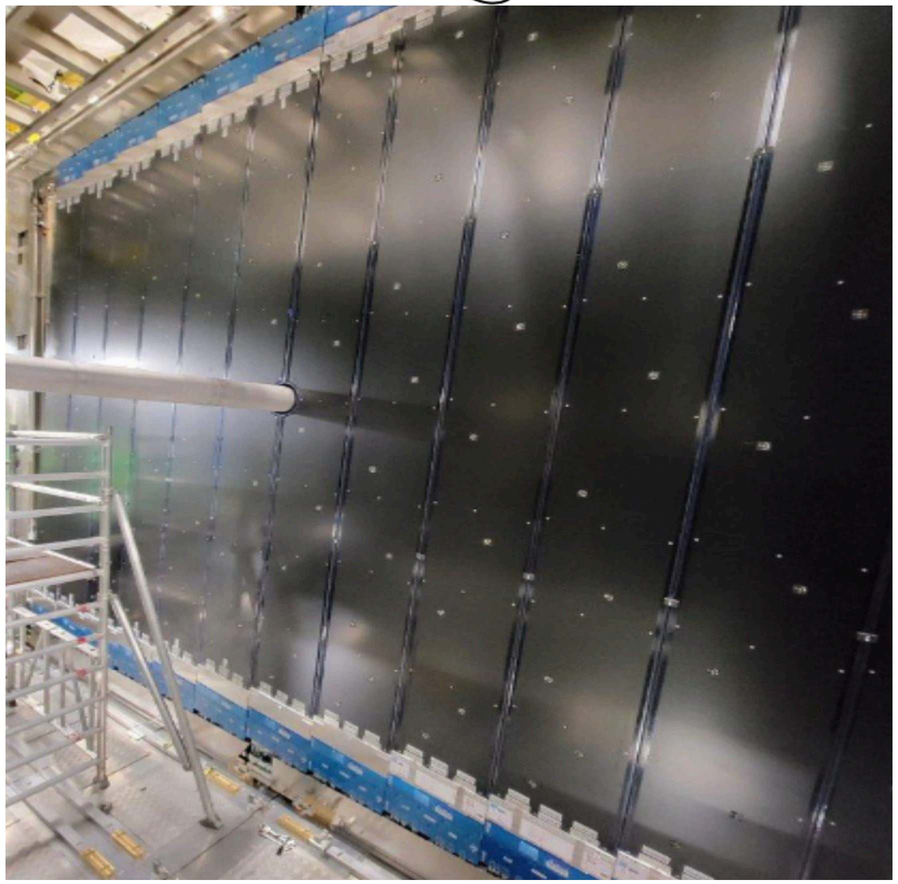
Upstream Tracker: 4 planes made of silicon strips, with finer segmentation and improved acceptance

- *fast p_T determination for track extrapolation → reduce ghost track, and improve trigger bandwidth*
- *long-lived particles decaying after VELO (K_S, Λ)*



SciFi: downstream tracker made of 12 planes scintillating fibres readout by SiPMs, to cope with increased occupancy

- *each plane, with dimensions 6x5 m^2, is made of 6 layers of scintillating fibres with 2.5 m length and 250 μm diameter*



SciFi plane fully installed and aligned

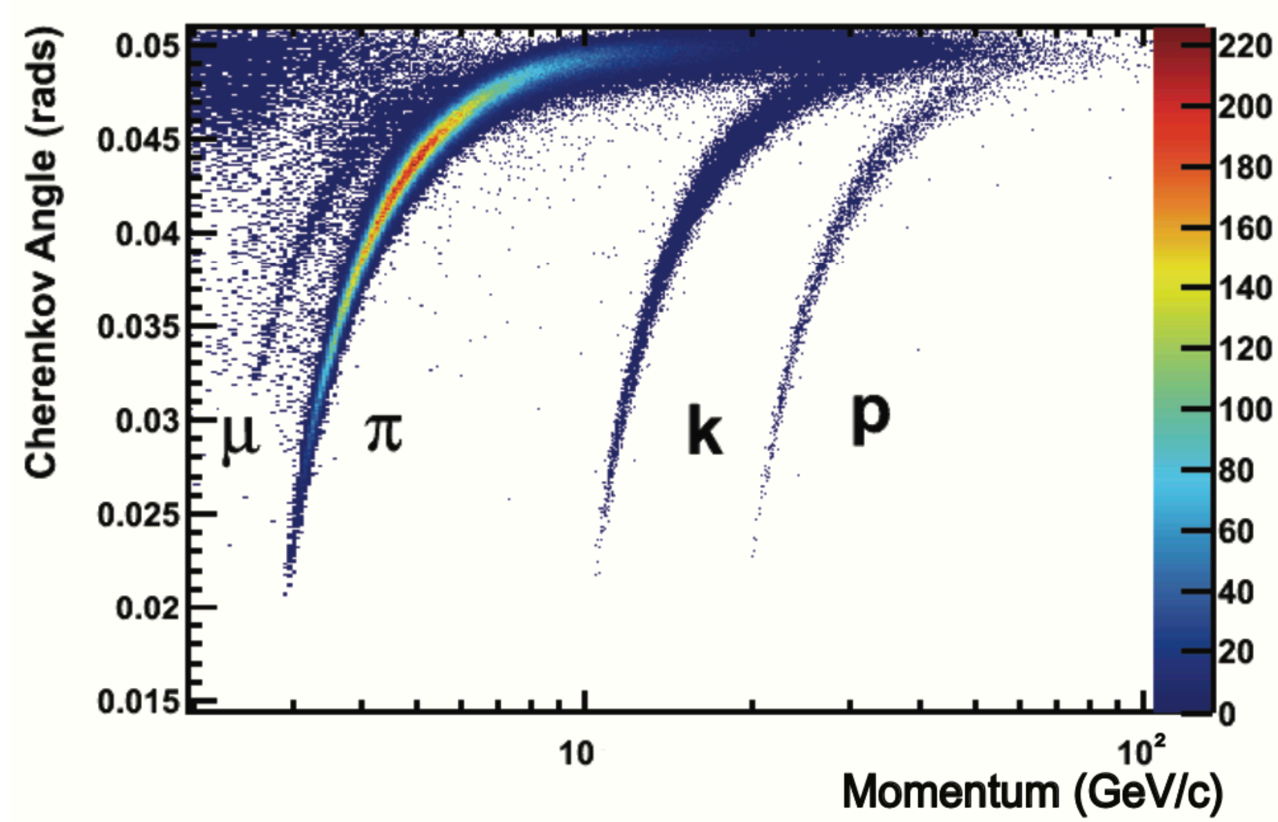
PID detectors: RICH

LHCC-2013-022

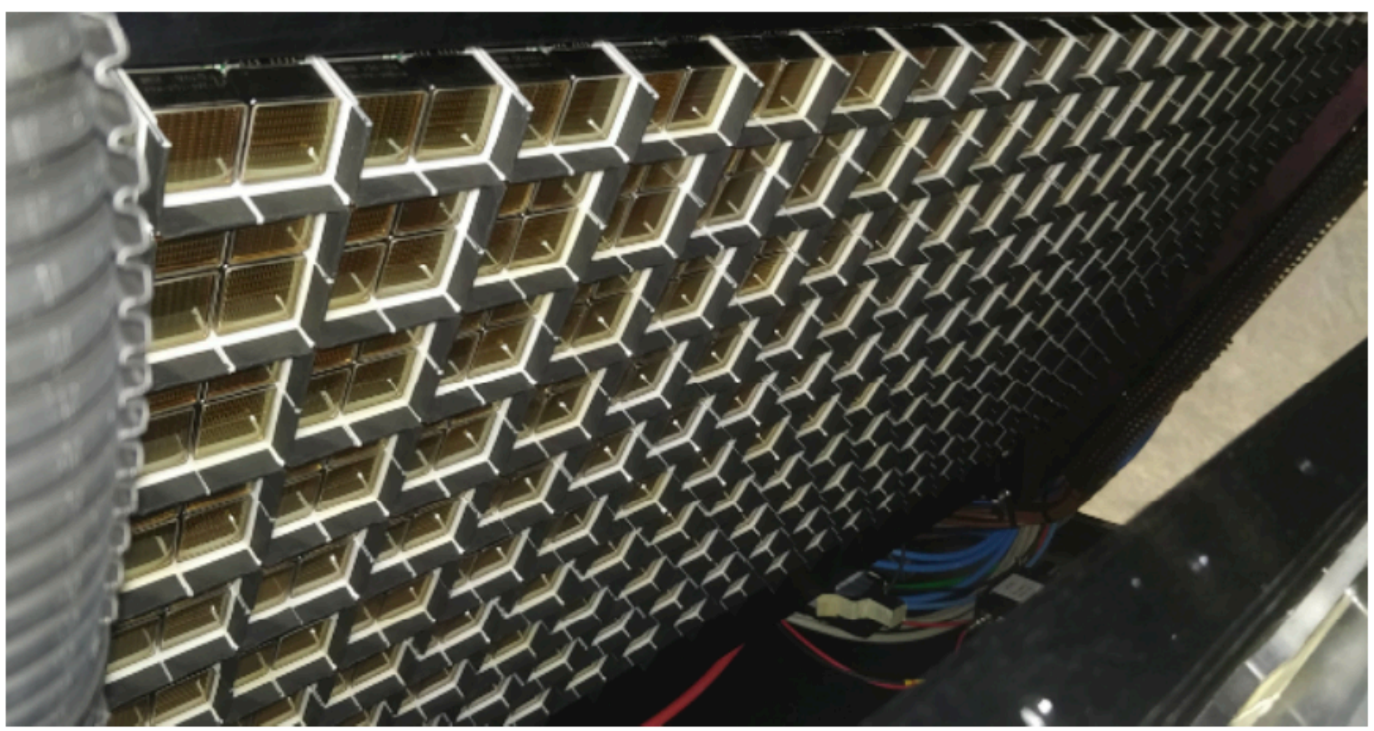
Goal is to maintain the excellent Run 1/2 performance with the increased occupancy foreseen at Run 3

- *RICH1 (closer to the IP): new mirrors with $\times\sqrt{2}$ focal length, to halve the occupancy*
- *RICH1/2: new photodetectors MaPMTs with increased granularity and 40 MHz readout*

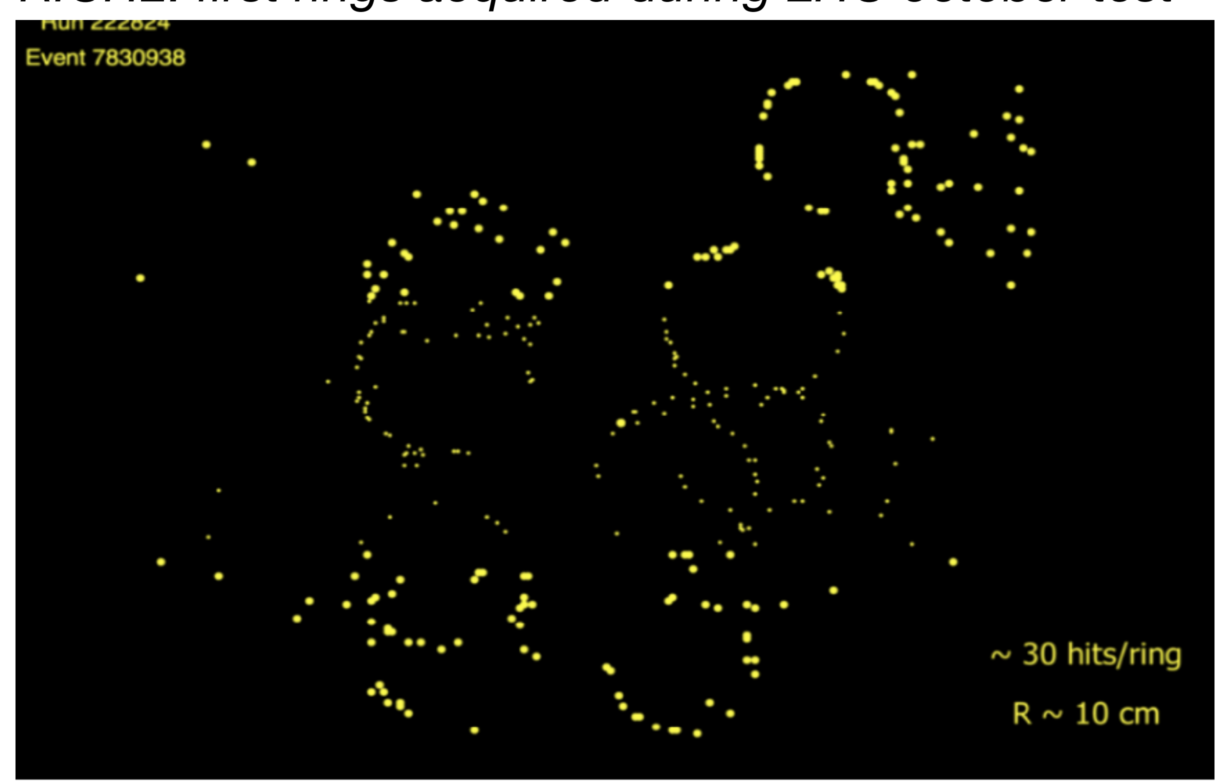
Run 1/2 performance of the RICH system



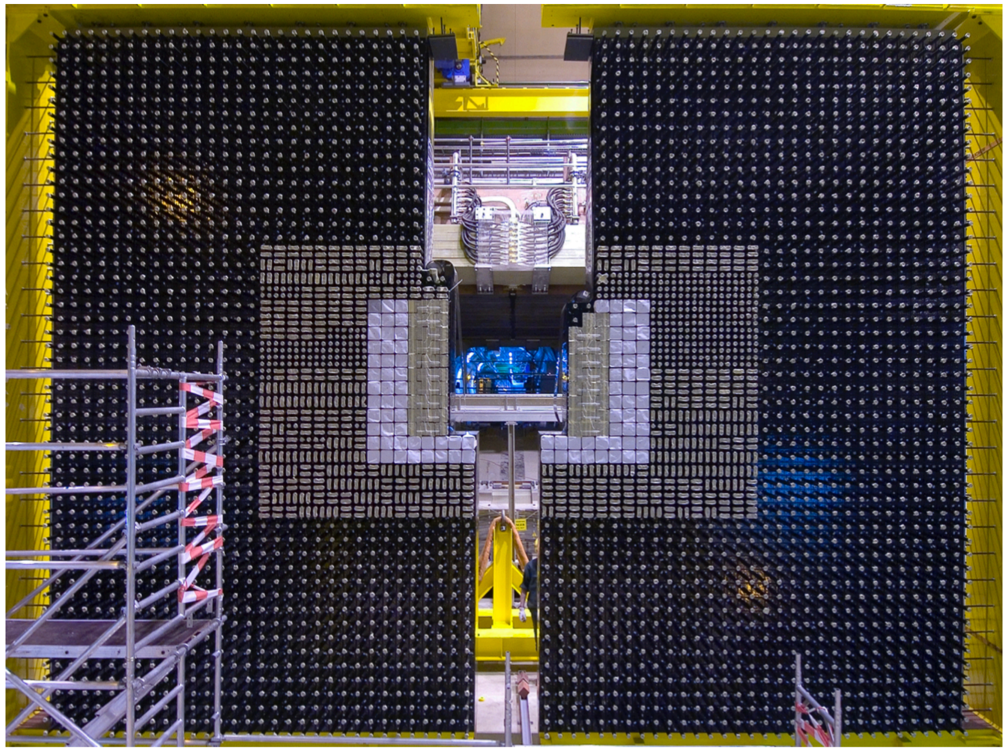
RICH1: MaPMTs installed upper side



RICH2: first rings acquired during LHC october test



PID detectors: CALO and MUON



Present detectors are capable to stand the increased luminosity of Run3/4

Shashlik calorimeters

- *ECAL = Pb+Sci ~25X_0, HCAL = Fe+Sci* $\sim 5\lambda_I$
- *PMT gain reduced to stand the higher occupancy*
- *new front-end electronics with improved S/N and 40 MHz readout*

Muon stations

- *4 walls equipped with MWPCs, and interleaved with iron filters*
- *front-end electronics upgraded for 40 MHz readout, granularity increased on first station to reduce occupancy*

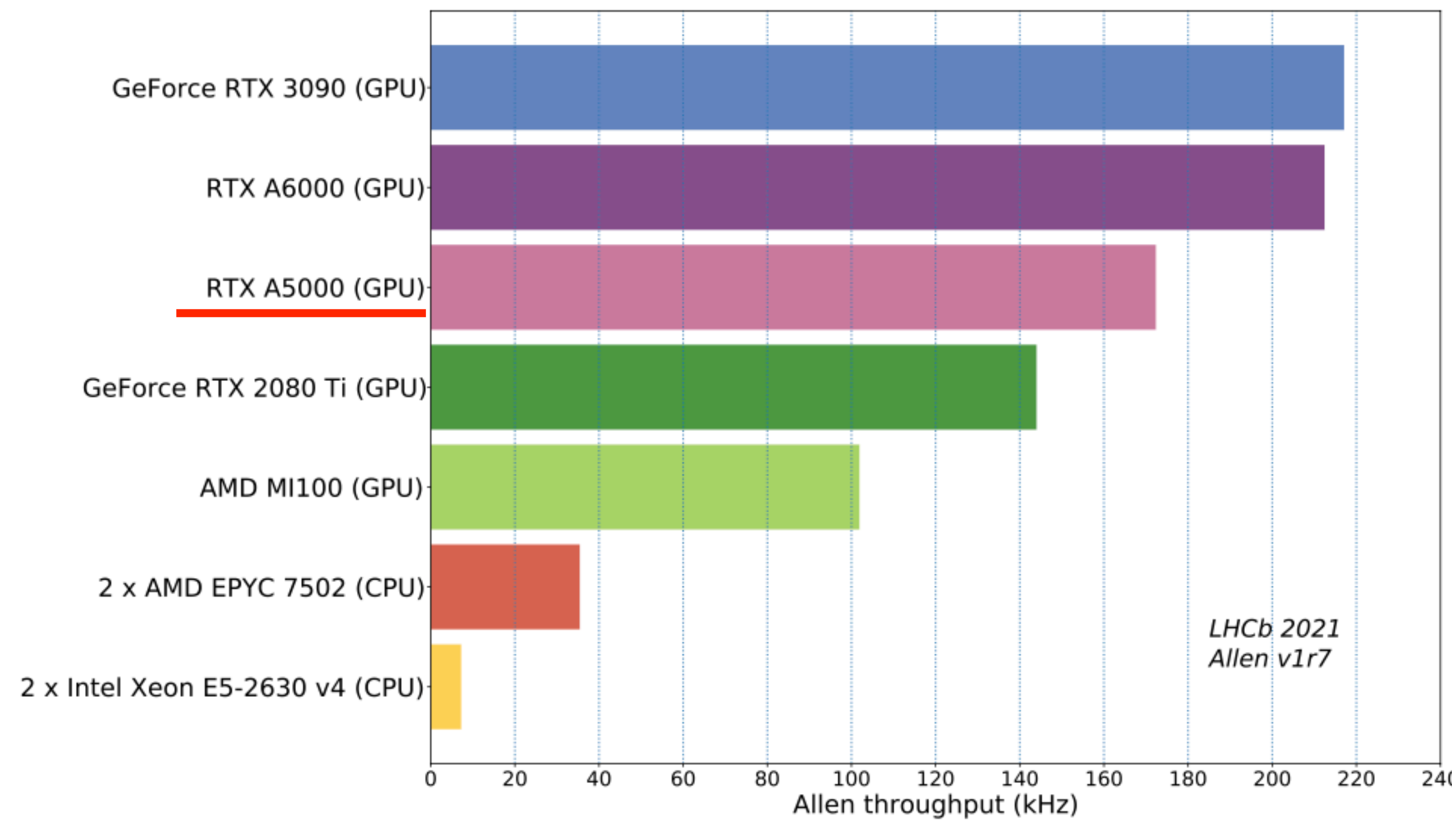
Large improvements expected from software trigger

- *reduced p_T threshold on electrons after removal of hardware L0*
- *improved muon software selection will allow to reject a factor of ~2 more bkg at trigger level*
- *more improvements in high-level electron and muon PID selections will allow to compensate the occupancy increase*

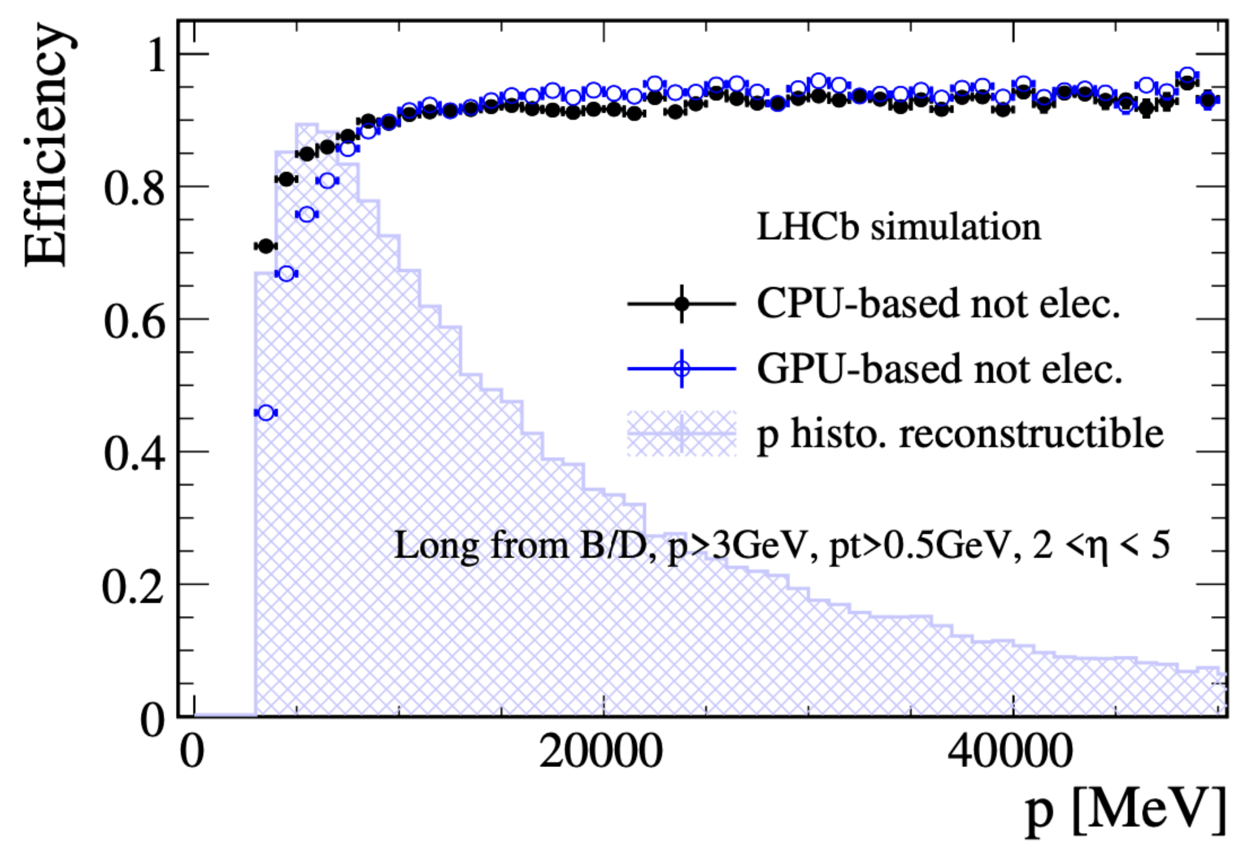
Getting ready to take data

30 MHz of inelastic collisions will be reduced to ~1MHz by the HLT1 (tracking/vertexing and muon ID) running on GPUs

- *achieved with ~200 cards*
- *room to expand to ~500 cards when porting more reco/selection functionalities into HLT1*



Track/vertex reconstruction on GPU essentially ready, performance very similar to CPU

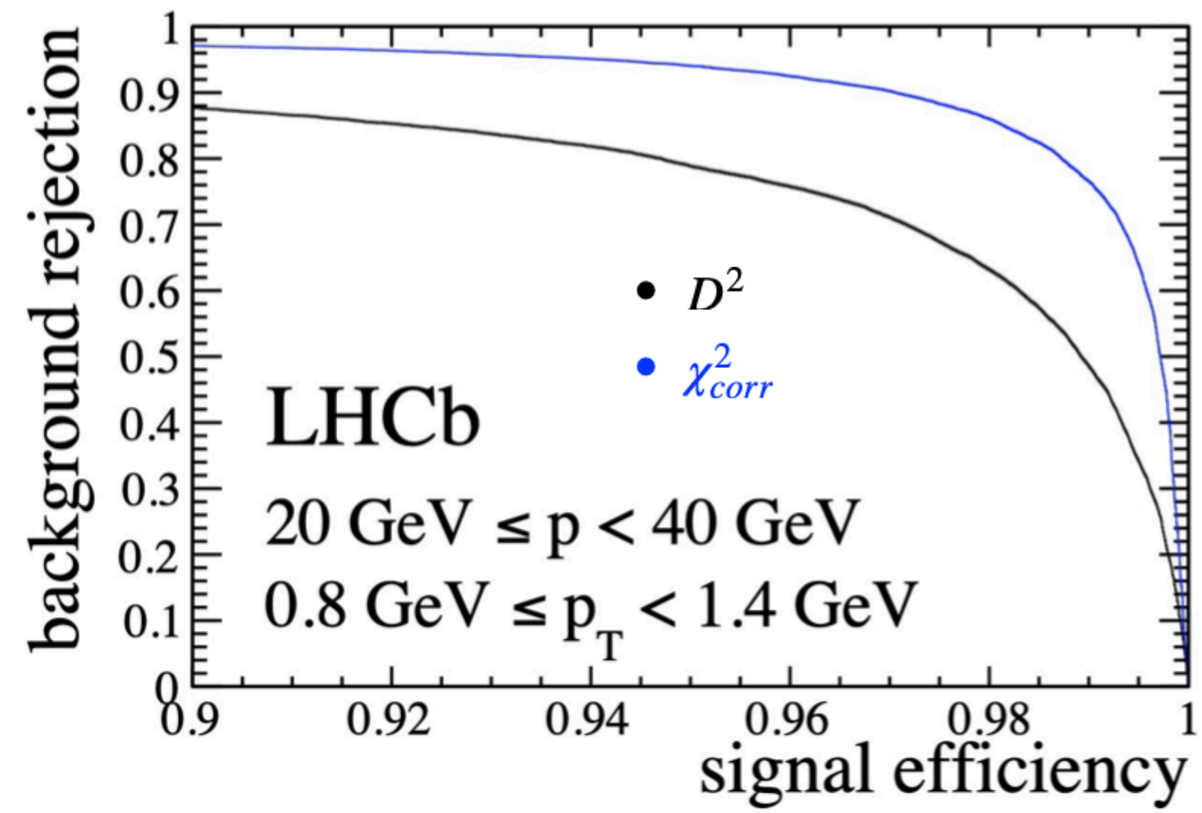


2105.04031

HLT2 will process the HLT1 output rate of 1MHz on few thousands CPU nodes and will select in output 10 GB/s of data as FULL/Turbo/Calib = 5.9/2.5/1.6 GB/s

A comment on muons and electrons

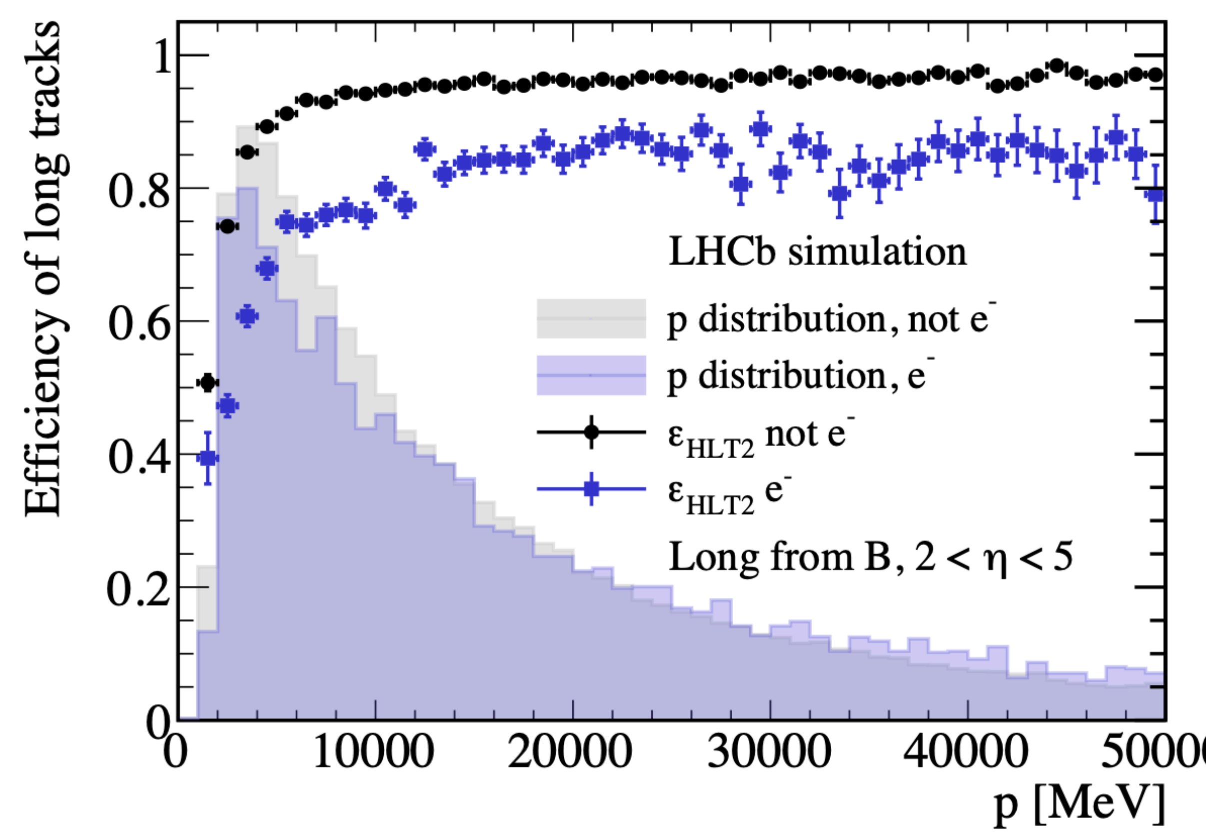
To face the increased bkg rates foreseen at Run 3, we improved the muon ID rejection power on pions



JINST 15 (2020) T12005

Electron reconstruction is more difficult due to bremsstrahlung

- *moderate track efficiency loss shown at HLT2*
- *removal of hardware trigger p_T thresholds will help to equalise muons and electrons, e.g. in 2018: $E_T > 2.5$ GeV for e vs $p_T > 1.75$ GeV for μ*
- *increasing performance of PID algorithms and bremsstrahlung momentum recovery*



LHCB-FIGURE-2021-003

Physics case: the full table

LHCC-2018-027

LHCC-2021-012

Upgrade I will not saturate precision in many key observables ⇒ Upgrade II will fully realise the flavour-physics potential of the HL-LHC

Key observables in flavour physics

— Run 3 — Run 4 — Run 6 →

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

In the next slides will discuss briefly a few examples

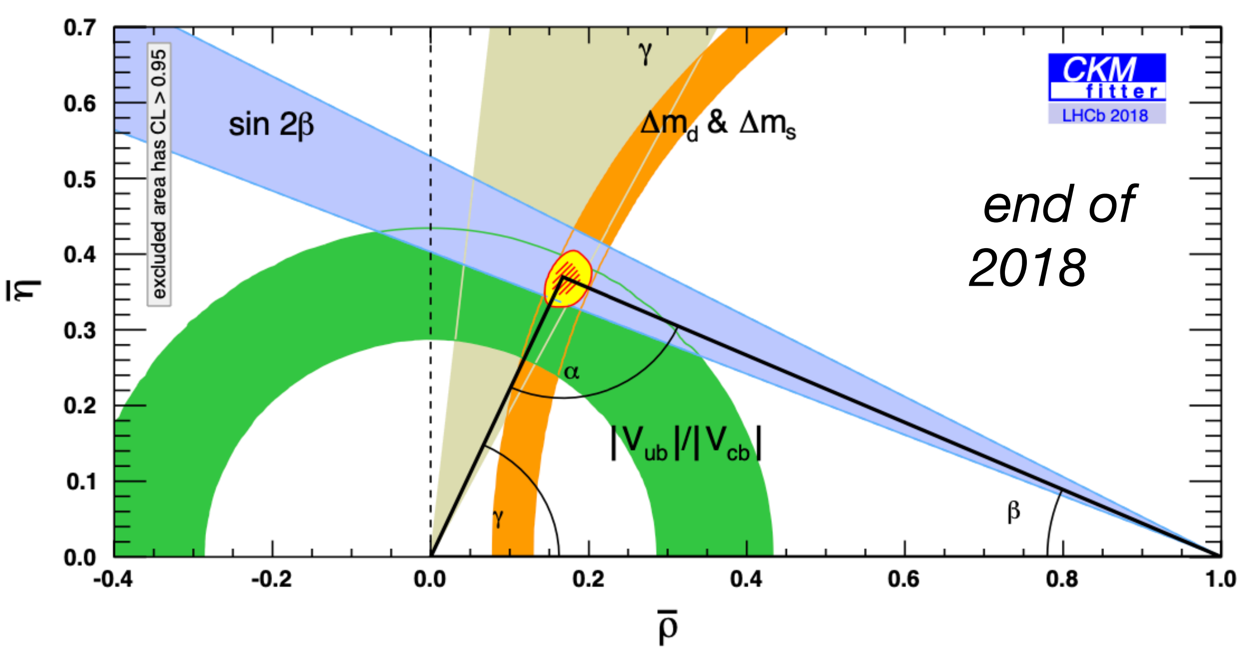
NOT ONLY: *LHCb, as a general purpose detector in forward region, will keep pursuing an ambitious programme in spectroscopy, EW precision and Higgs physics, dark sector, heavy ions and fixed target physics ...*

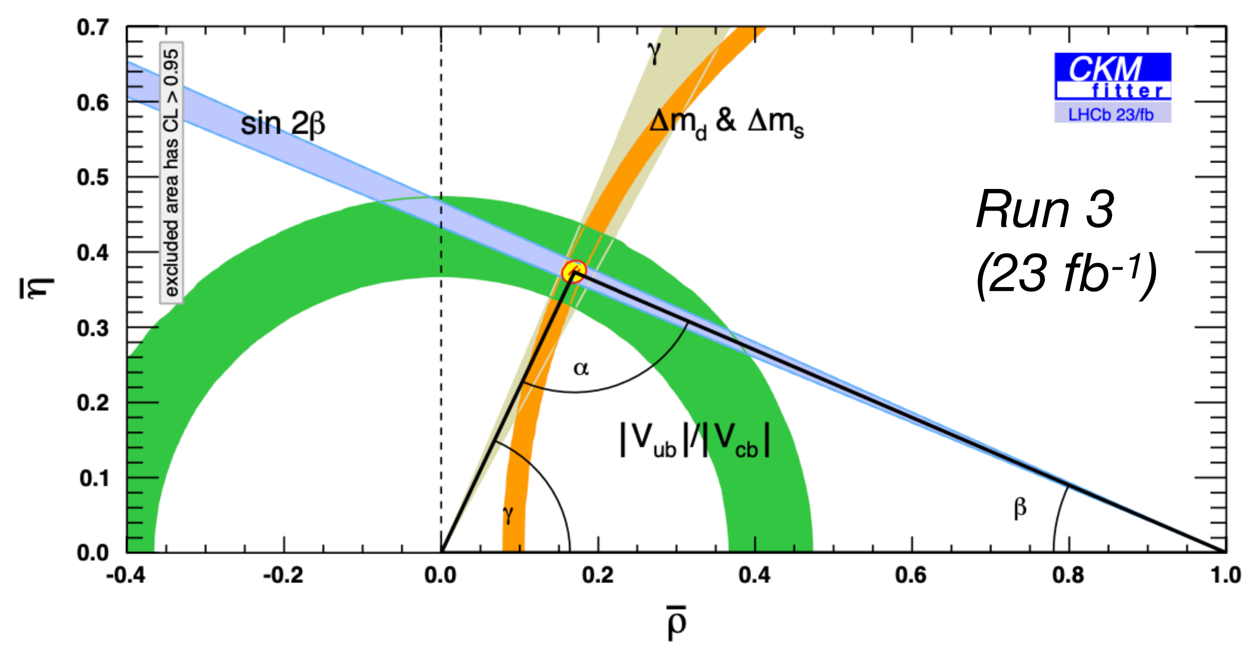
Constraining the unitarity triangle

Current data show no significant deviations from the SM on ΔF=2 observables and many other flavour-changing processes: either NP is very heavy of it has a highly non trivial structure

LHCb will test the CKM paradigm with unprecedented accuracy

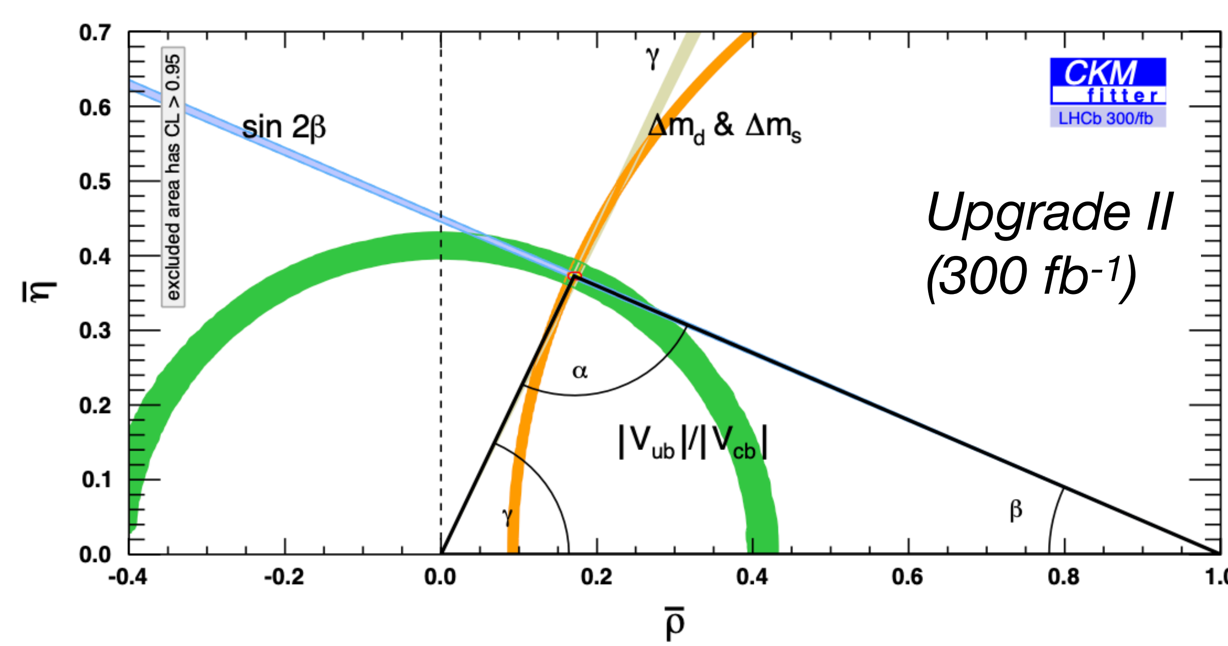
LHCb-only inputs, prepared for LHCC-2018-027





- *Two independent measurements of triangle apex: $(\Delta m_d/\Delta m_s, \sin 2\beta)_{loop}$ and $(V_{ub}, \gamma)_{tree}$*
- *Both pairs require Upgrade 2 for statistics ($\sin 2\beta$ and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})*

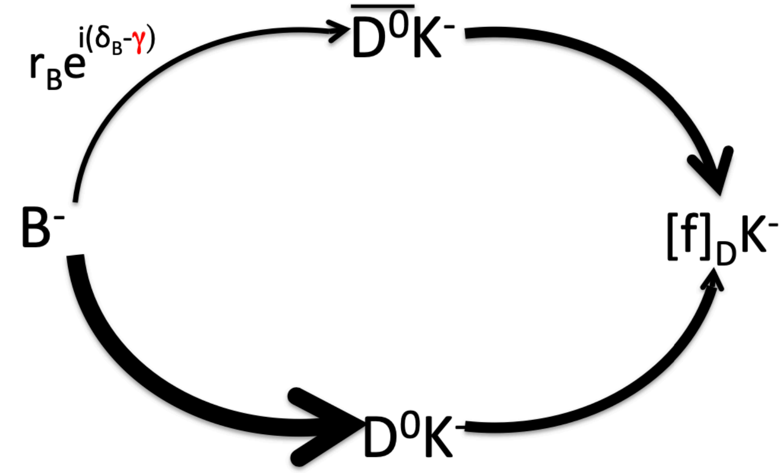
~order of magnitude improvement in LQCD is assumed for Upgrade II



Flagship measurement of γ

Current result with 9 fb^{-1}: $\gamma(LHCb) = (65.4^{+3.8}_{-4.2})^{\circ}$

- *Will slightly exceed Run 2 target of 4° when adding all modes*



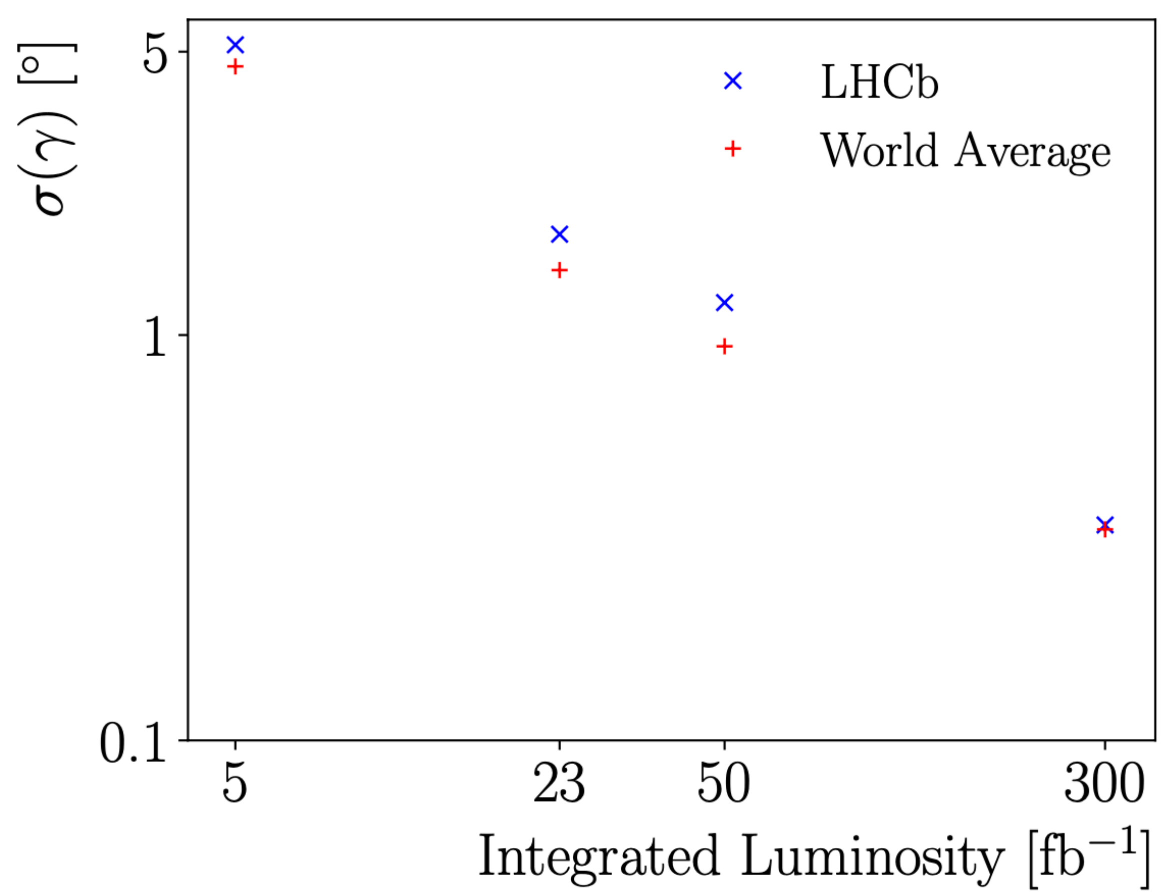
Excellent agreement with indirect determination

$\gamma(CKMfitter) = (65.55^{+0.90}_{-2.65})^{\circ}$

- *Many different decay modes used, uncertainty will scale with luminosity*

$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$
$B^0_s \to D^{\mp}_s K^{\pm}\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$

- *Combined uncertainty will reach 1.5° after Run 3, and will target ~0.4° with Upgrade II*



LHCC-2018-027

LHCb: JHEP02(2021)169
BESIII: PRD 101 (2020) 112002

Best single result on γ

Current best result from single channel from $B^\pm \to DK^\pm$ with $D \to K_S\pi^+\pi^-$

- Strong phases of D decay over the Dalitz plane from CLEO-c/BESIII

Full Run 1 + Run 2 (9 fb[-1]):

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$

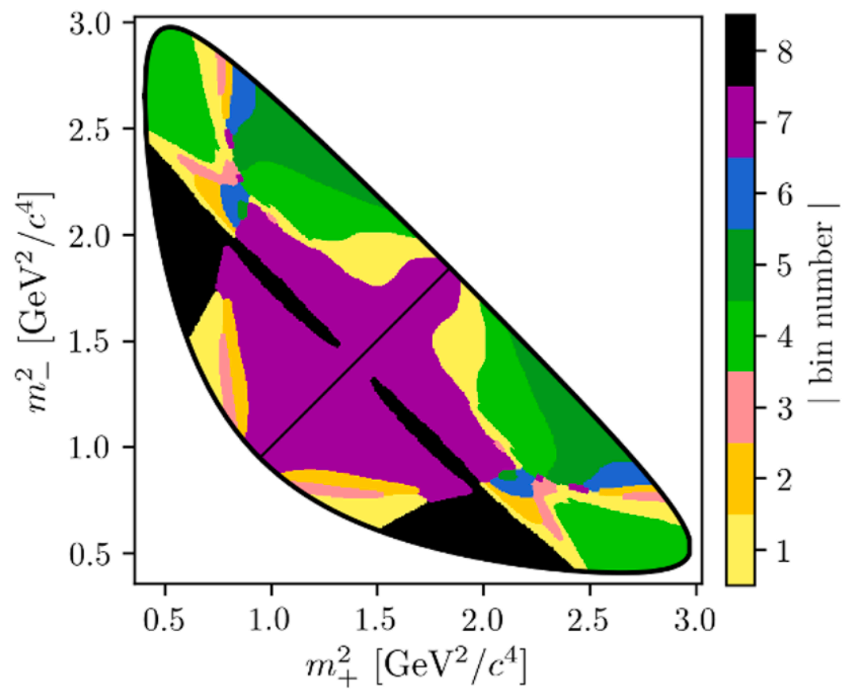
LHCb: stat~5°, syst~1°

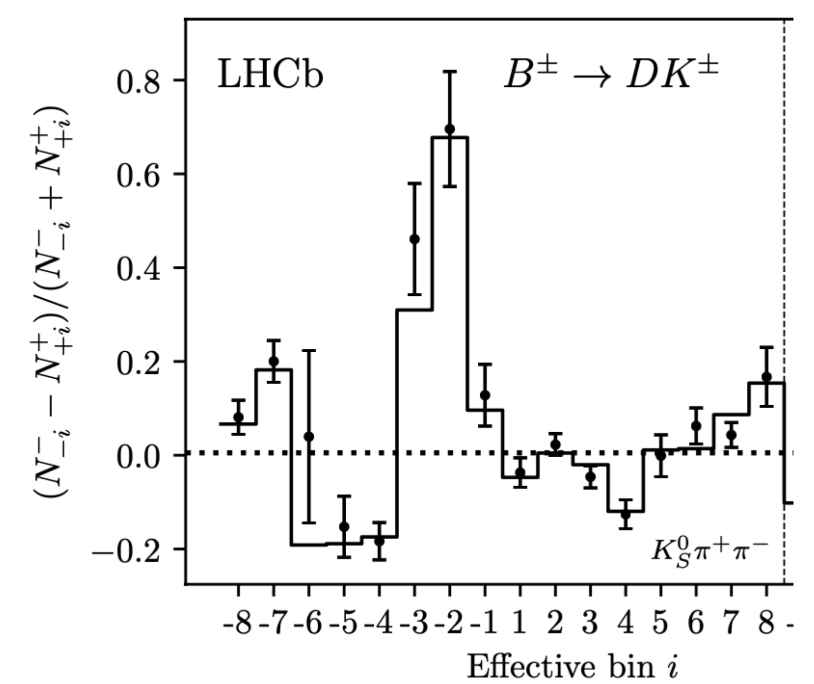
BESIII: D strong phases~1°

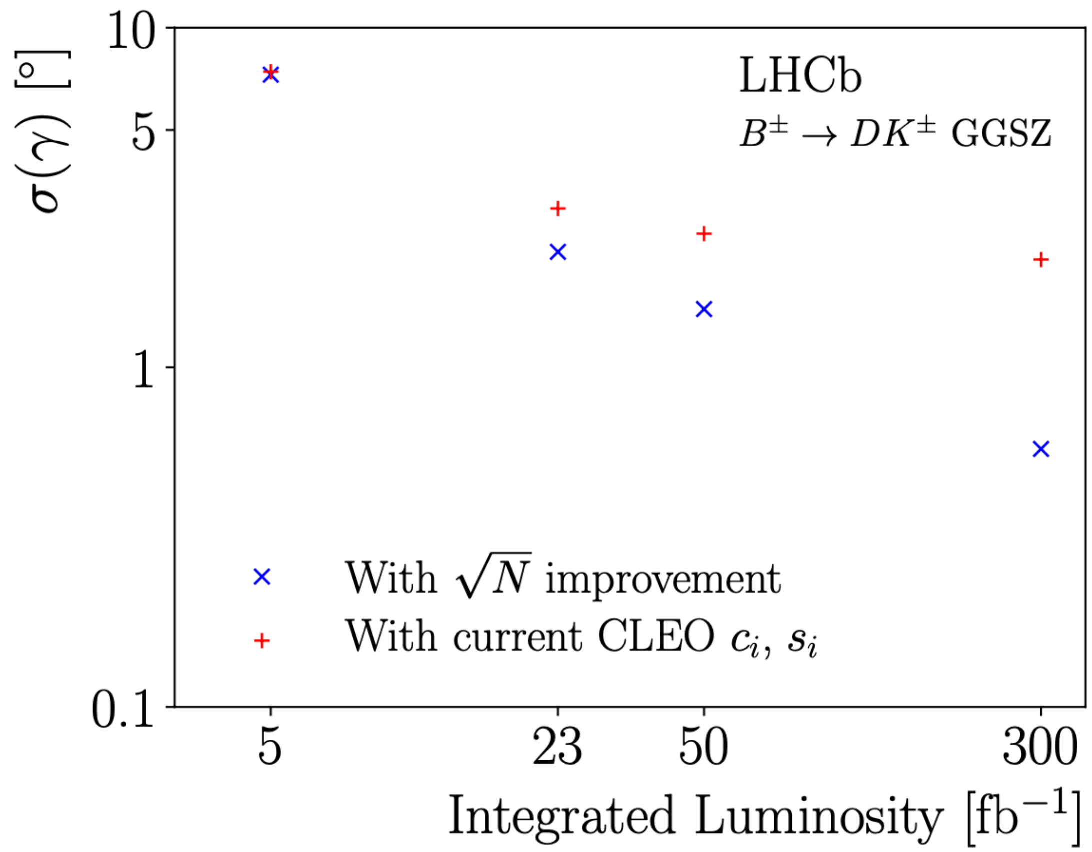
Large improvement is expected from this channel in the future

- further improvement on strong phase determination will become important in view of Upgrade II

CP asymmetry in bins of D phase space (model indep.)





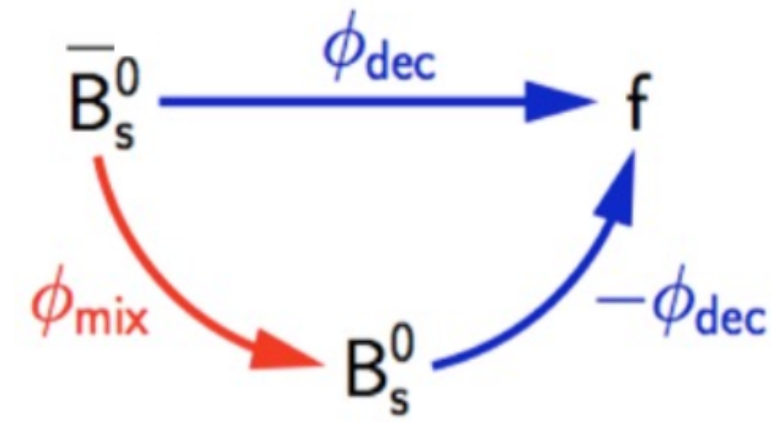


LHCC-2018-027

B_s time-dependent CPV: ϕ_s

Golden mode $B_s \to J/\psi\phi$ is the B_s analogue to $B^0 \to J/\psi K_S$

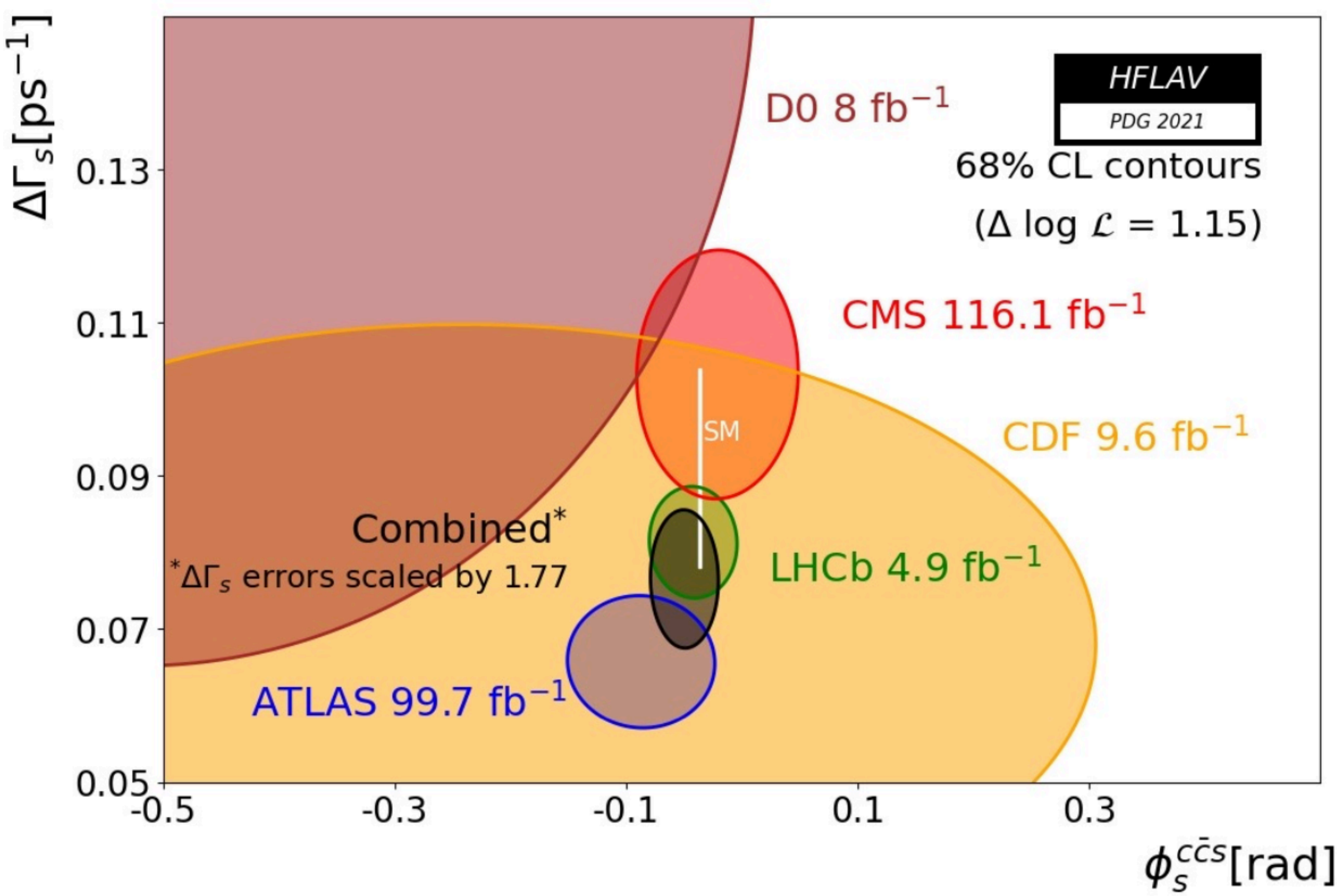
- interference btw mixing and decay graphs, predicted in the SM to be $\phi_s = -2\lambda^2\eta \simeq -37$ mrad → very small, can receive contribution from new physics



HFLAV average (LHCb+ATLAS+CMS)

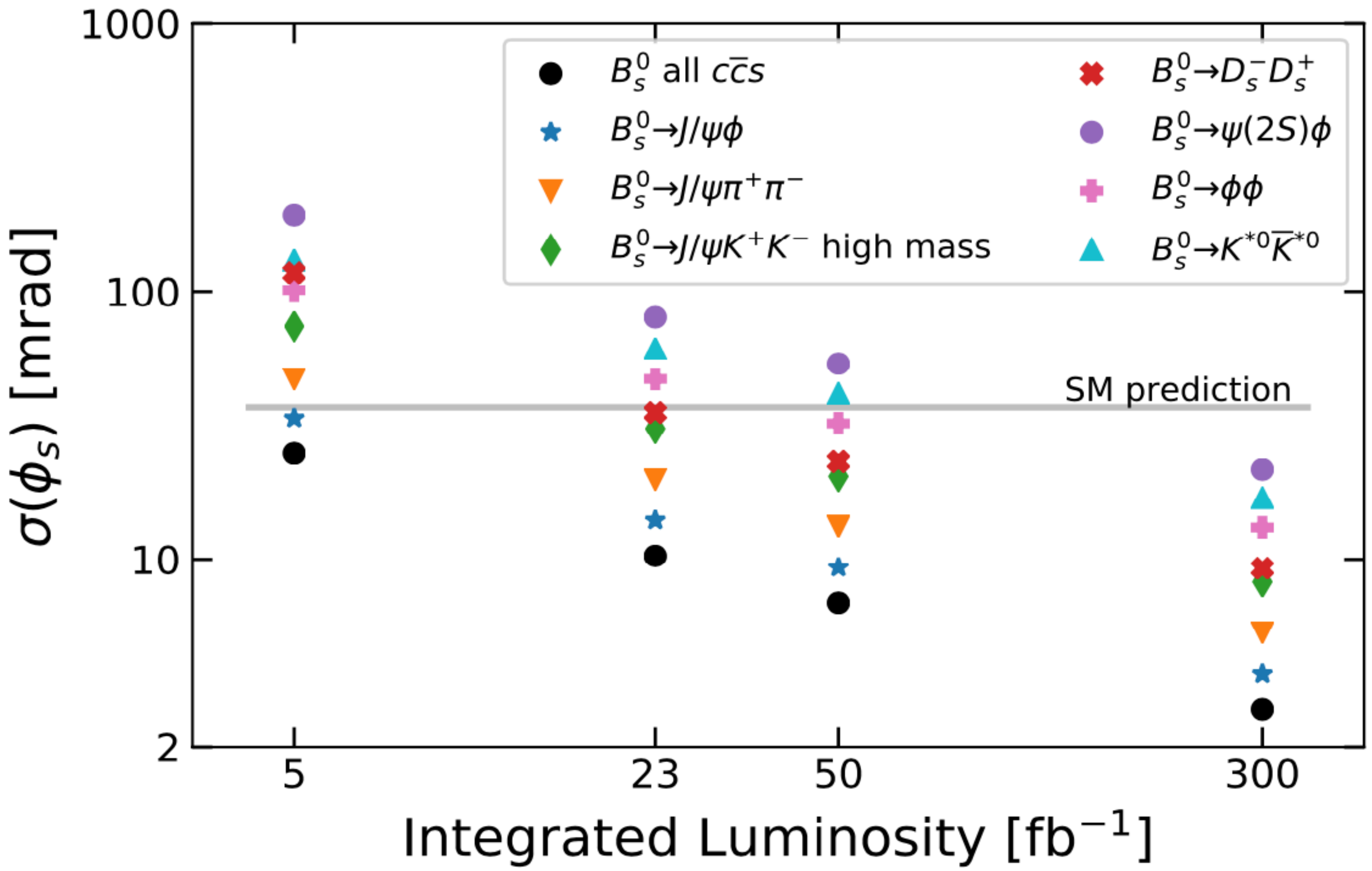
$$\phi_s = -50 \pm 19 \text{ mrad}$$

- well compatible with SM
- approaching sensitivity to observe a non-zero SM value
- tension btw the various measurements of Γ_s and $\Delta\Gamma_s$ calls for a clarification of the experimental picture

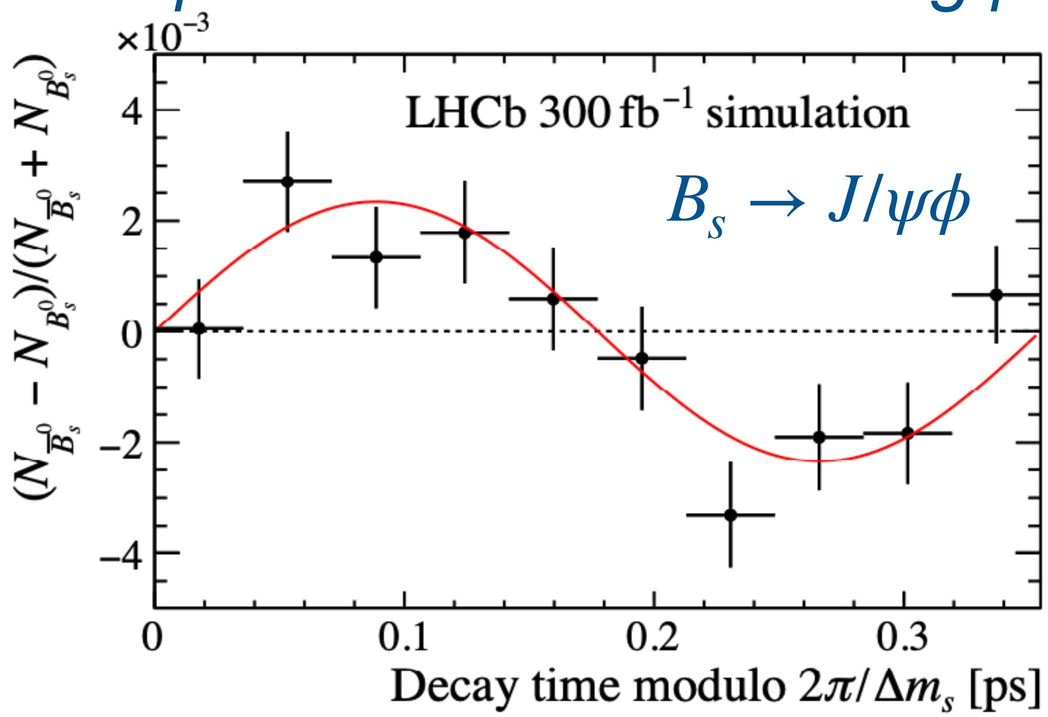


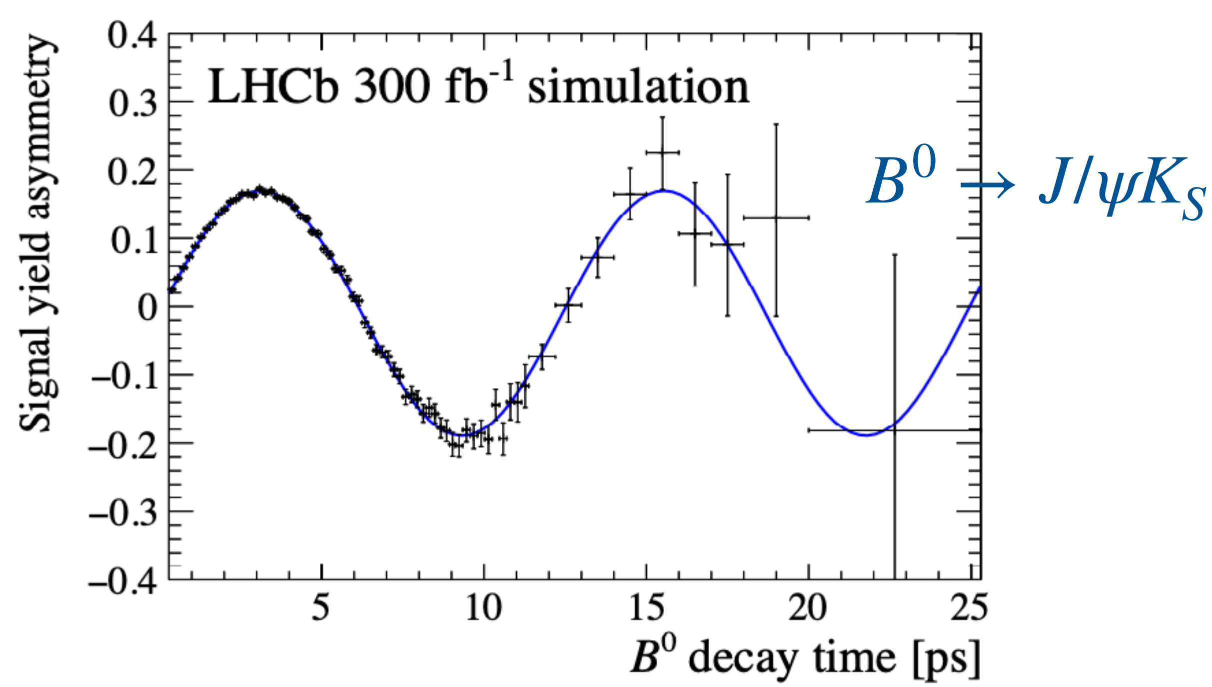
B_s time-dependent CPV: ϕ_s

- *Combined sensitivity on ϕ_s from $b \to ccs$ will reach ~10 mrad after Run 3 and will approach the SM uncertainty with Upgrade II*
- *Pure loop modes ($B_s \to \phi\phi$, $B_s \to K^{*0}K^{*0}$) will be crucial in constraining new physics*



Impressive precision on CP violating phases will be reached at Upgrade II





CP violation in charm

CP violation in charm mixing serves as an excellent null test for the SM: mixing amplitudes are approximately real ad are GIM or CKM suppressed

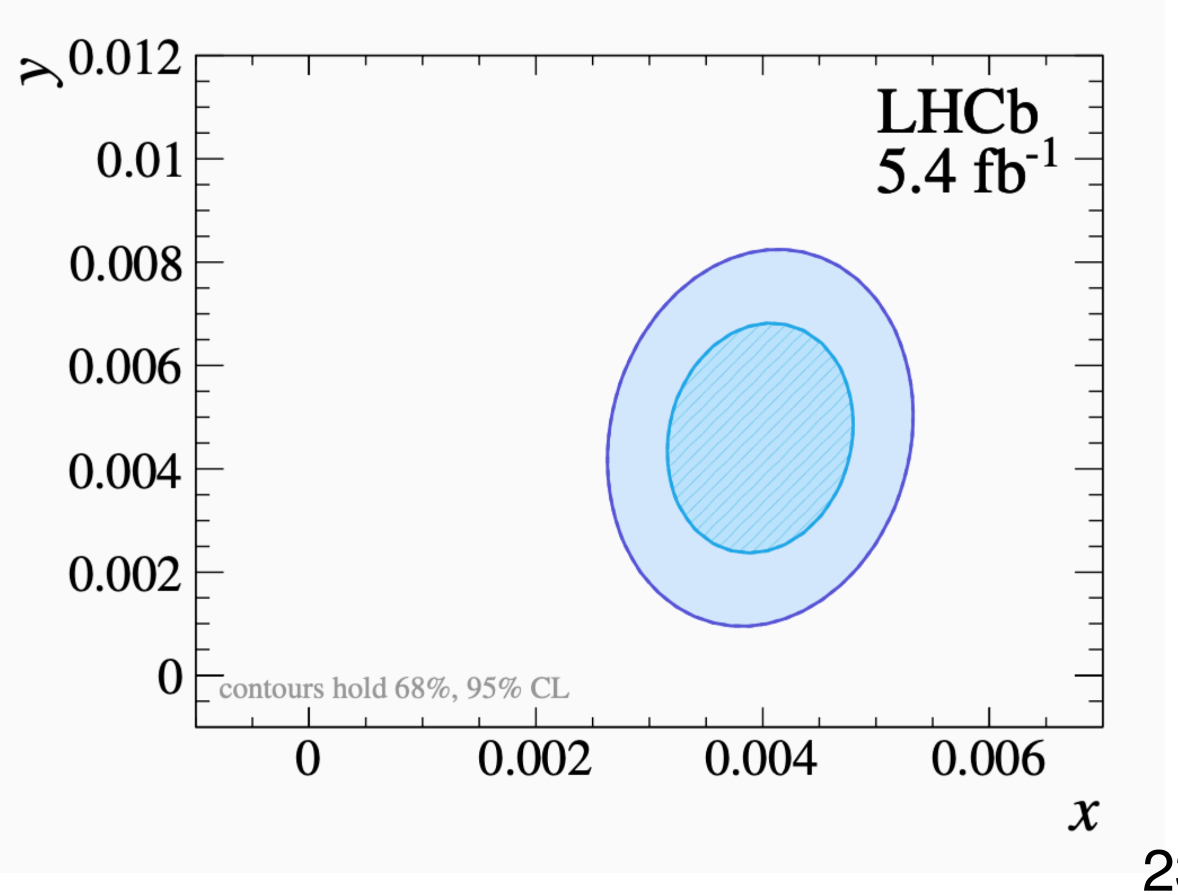
Neutral meson mixing: $|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle, \qquad |D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle.$

with mixing parameters $y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$ *and* $x = \dfrac{m_2 - m_1}{\Gamma}$ *and CP parameters* $\left|\dfrac{q}{p}\right|$ *and* ϕ_D

First step: measurement of charm mixing

Using a sample of 31M $D^0 \to K_S\pi^+\pi^-$ *LHCb has recently observed for the first time the mass difference (**x**) btw D mass eigenstates with significance of* $> 5\sigma$ PRL127(2021)111801

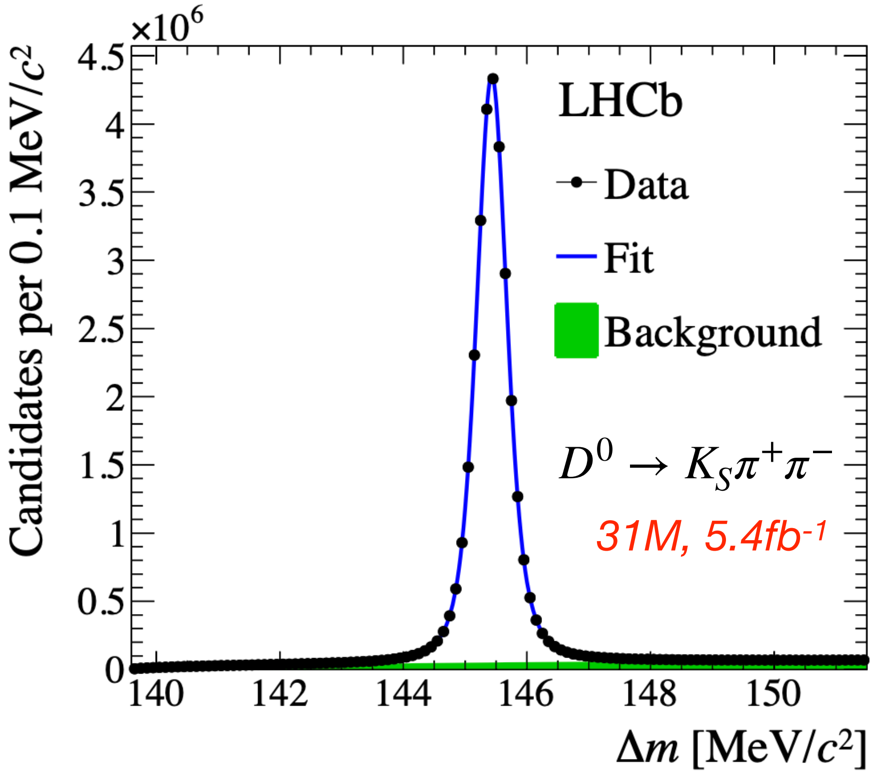
Using a sample of 94M $D^0 \to K^-\pi^+, K^-K^+, \pi^-\pi^+$ *LHCb has recently obtained the best measurement of the lifetime difference (**y**) btw D mass eigenstates with precision ~4%* LHCb-PAPER-2021-041



CP violation in charm

Unprecedented statistics

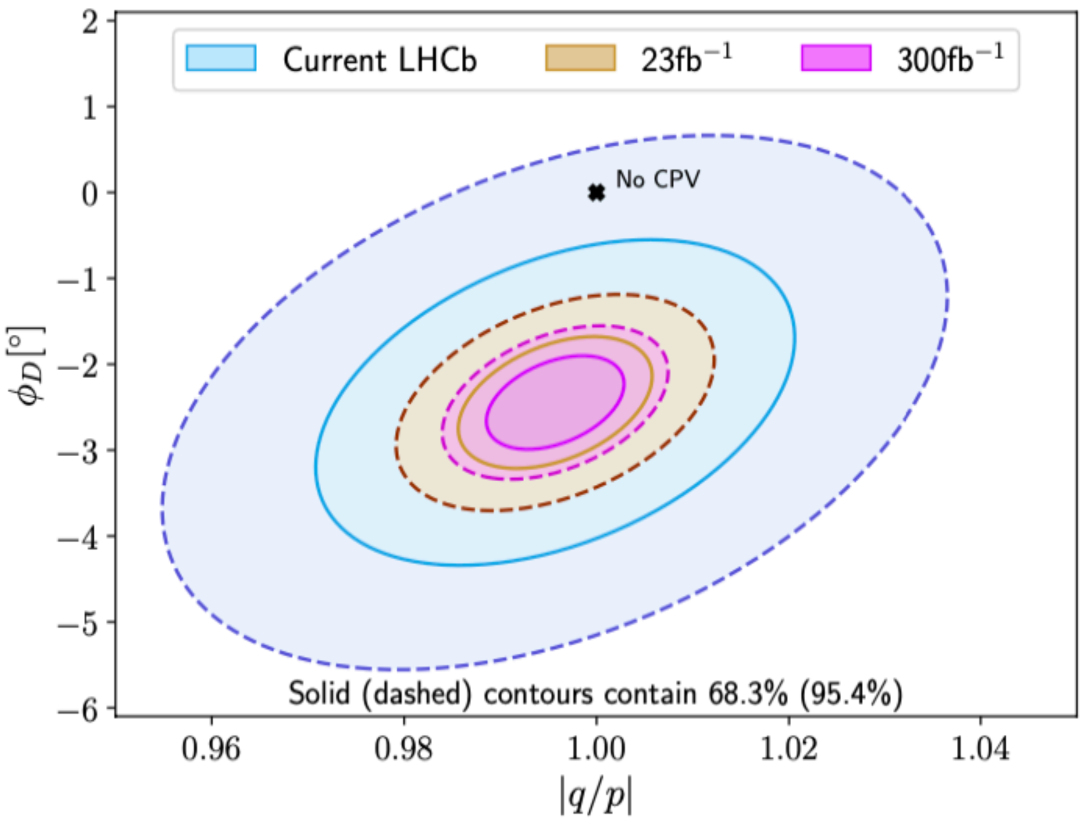
- *Huge cross section 2.5 mb → ~5 MHz of $c\bar{c}$ pairs in LHCb acceptance at Run 3*
- *Real-Time analysis: offline quality reconstruction in trigger, persist only trigger candidate to save storage bandwidth*
- *Detachment cuts to reduce background → very clean selections*



PRL127(2021)111801

LHCb Upgrade II is the only planned facility with a realistic possibility to observe CPV in charm mixing (at >5σ if present central values are assumed)

LHCb sensitivity is extrapolated to future data taking: with 300 fb^{-1} is approaching 0.002 and 0.15° on $\left|\frac{q}{p}\right|$ and ϕ_D, respectively



LHCC-2018-027

Flagship measurement of $B_{(s)} \to \mu^+\mu^-$

FCNC- and helicity-suppressed → precise SM prediction

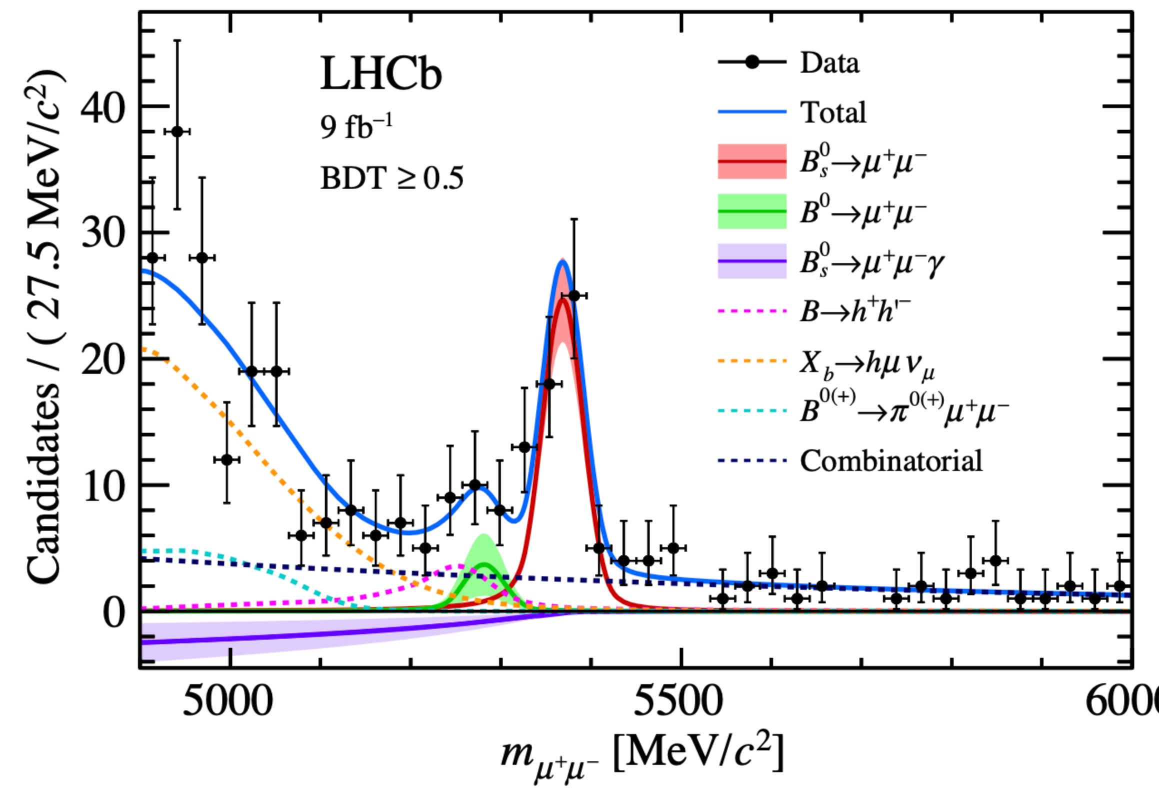
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

LHCb result with full Run 2 data

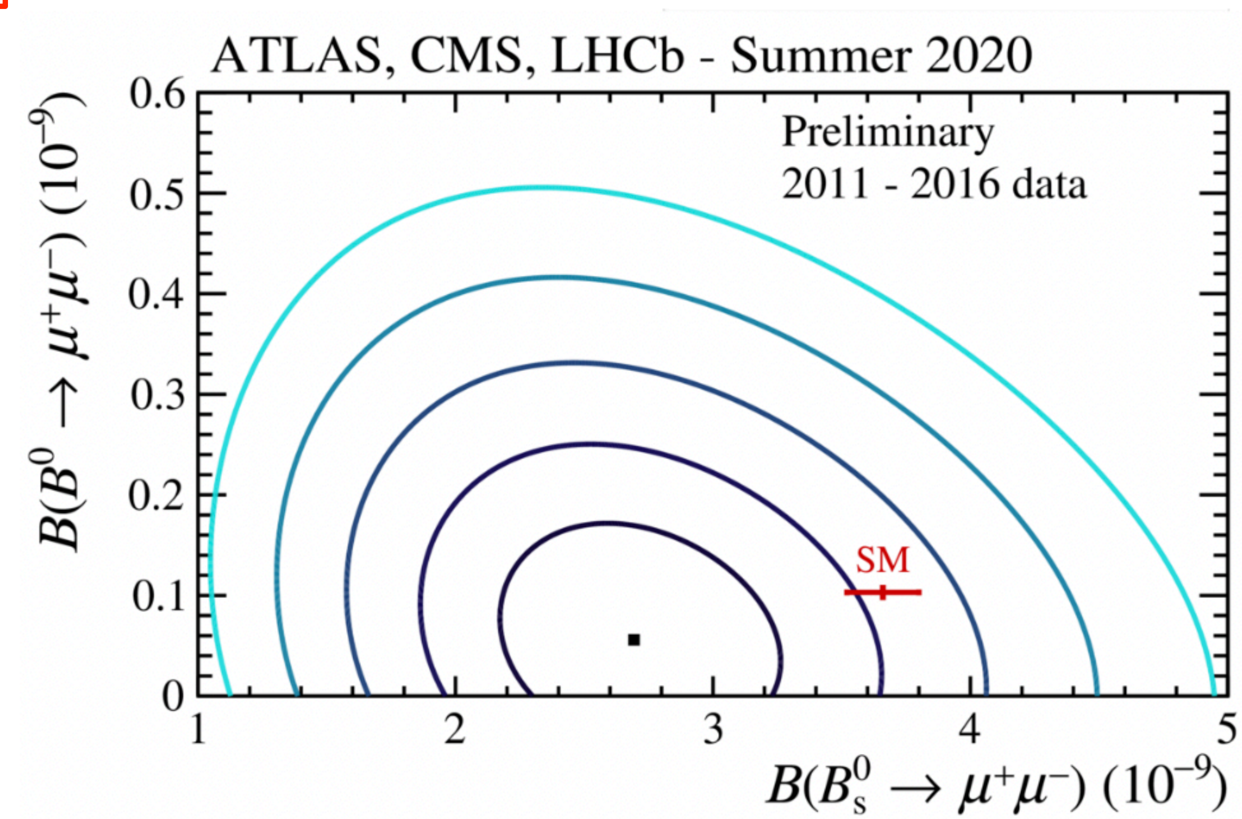
$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ @\ 95\,\%\ \mathrm{CL}$$

15% accuracy on B_s, compatible with SM

PRL 128 (2022) 041801



Present LHC combination, based on partial Run 2 data from all experiments, is 2.1σ below SM



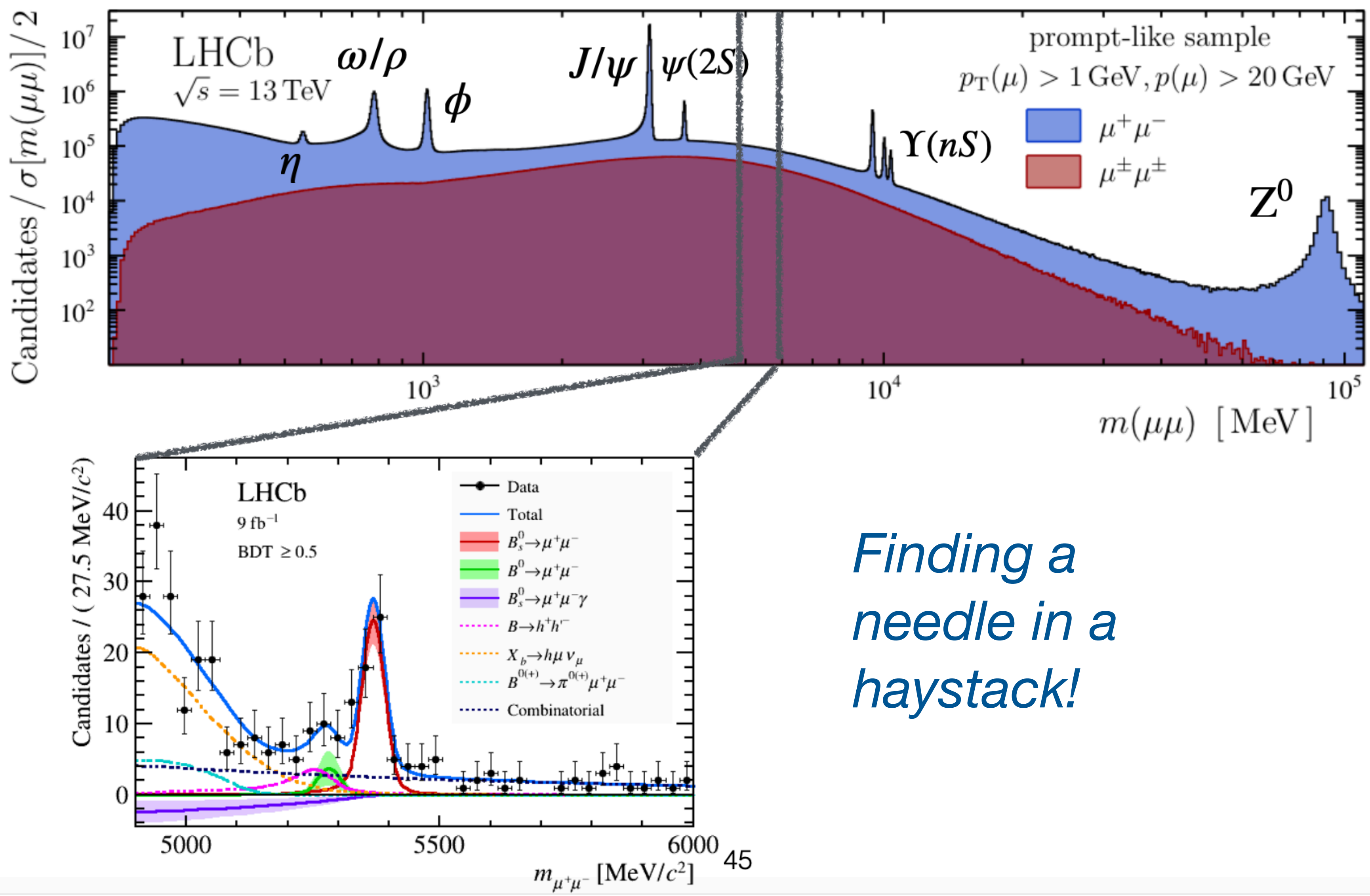
Final uncertainty with full Run 2 data from all LHC experiments is expected ≲10%: era of precision measurements started!

Flagship measurement of $B_{(s)} \to \mu^+\mu^-$

PRL 120 (2018) 061801

Key ingredients for success

- *Large cross section*
- *Efficient muon trigger*
- *Large boost (~1 cm) and excellent vertex and IP resolutions to separate out from primary interactions and from combinations of muons from different secondary vertices (combinatorial bkg)*
- *Excellent PID against $h \to \mu$ misID*

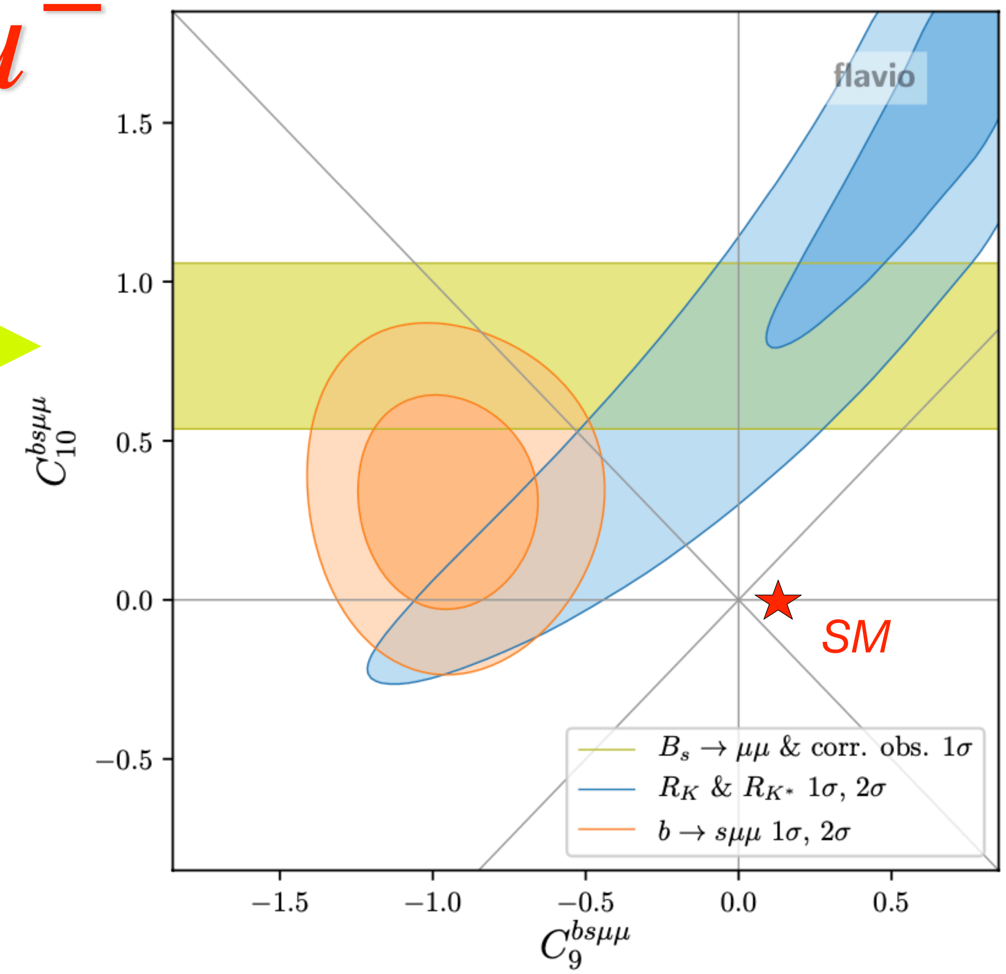


Finding a needle in a haystack!

All of the above characteristics will be kept at Run 3 and beyond

- ***Statistical precision on** $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ will be ~7% after Run 3 and ~2% at Upgrade II, systematics will be dominated by f_s/f_d, now ~3%*
- *Effective lifetime $\tau_{\mu\mu}$ will be measured at ~10% at Run 3 and ~3% at Upgrade II*
- *With Upgrade II we can also target a and a ~10% measurement of $B^0 \to \mu^+\mu^-$*

The role of $B_s \to \mu^+\mu^-$



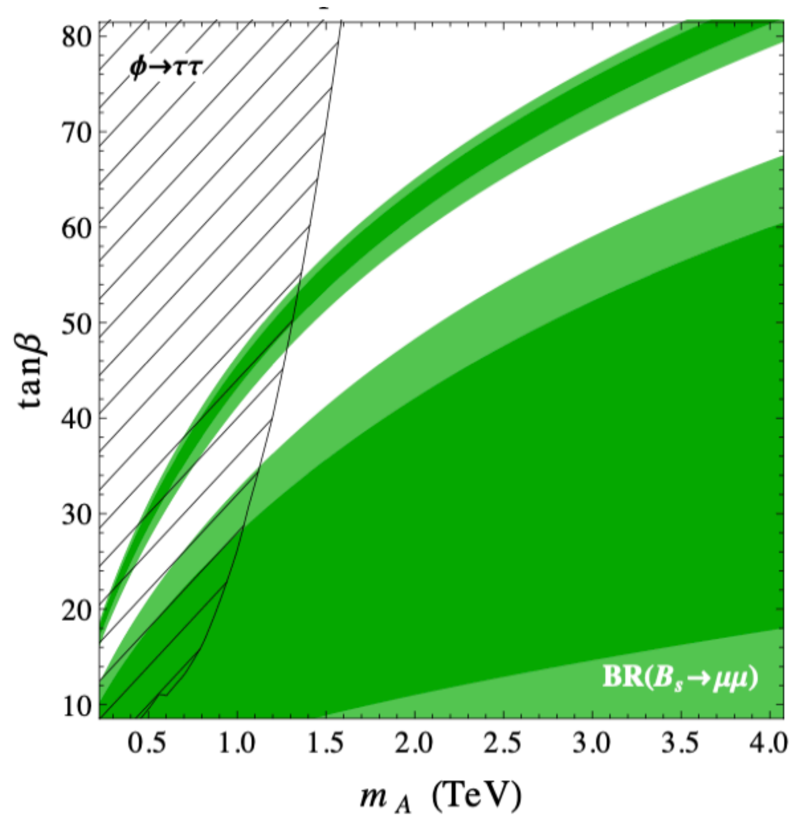
Stangl, La Thuile 2021

$B_s \to \mu^+\mu^-$ is fundamental to constrain Wilson coefficient C_{10} in global fits with the other $b \to sl^+l^-$ rare processes

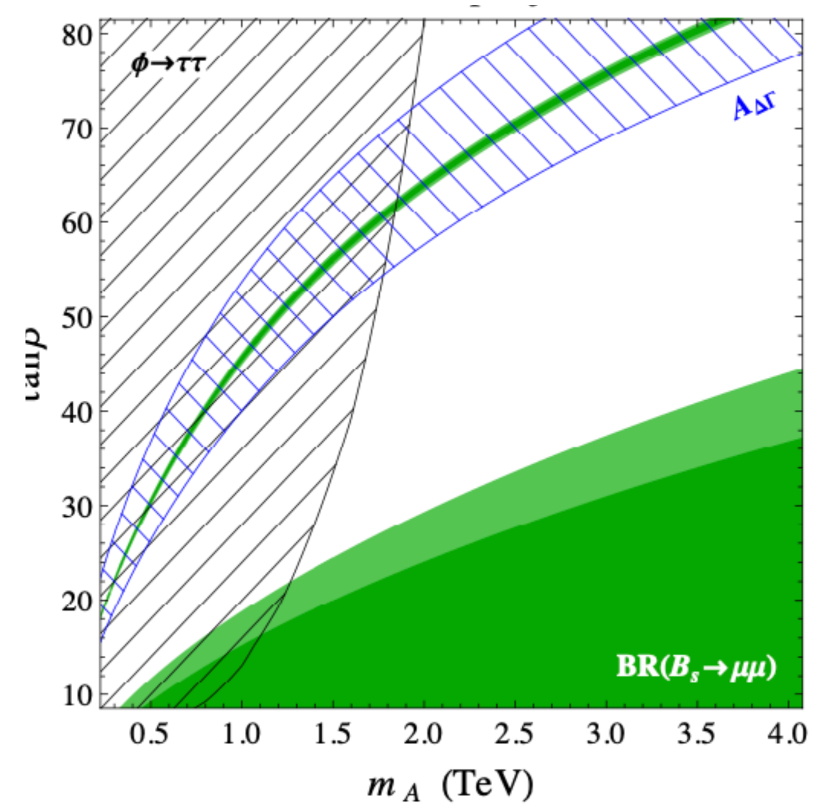
Constraining power on MSSM scenarios will also increase with precision on BR and effective lifetime, which gives access to $A_{\Delta\Gamma}$

$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^{\rm H} \to \mu^+\mu^-) - \Gamma(B_s^{\rm L} \to \mu^+\mu^-)}{\Gamma(B_s^{\rm H} \to \mu^+\mu^-) + \Gamma(B_s^{\rm L} \to \mu^+\mu^-)}.$$

LHCb ~now



LHCb ~end of Run 4



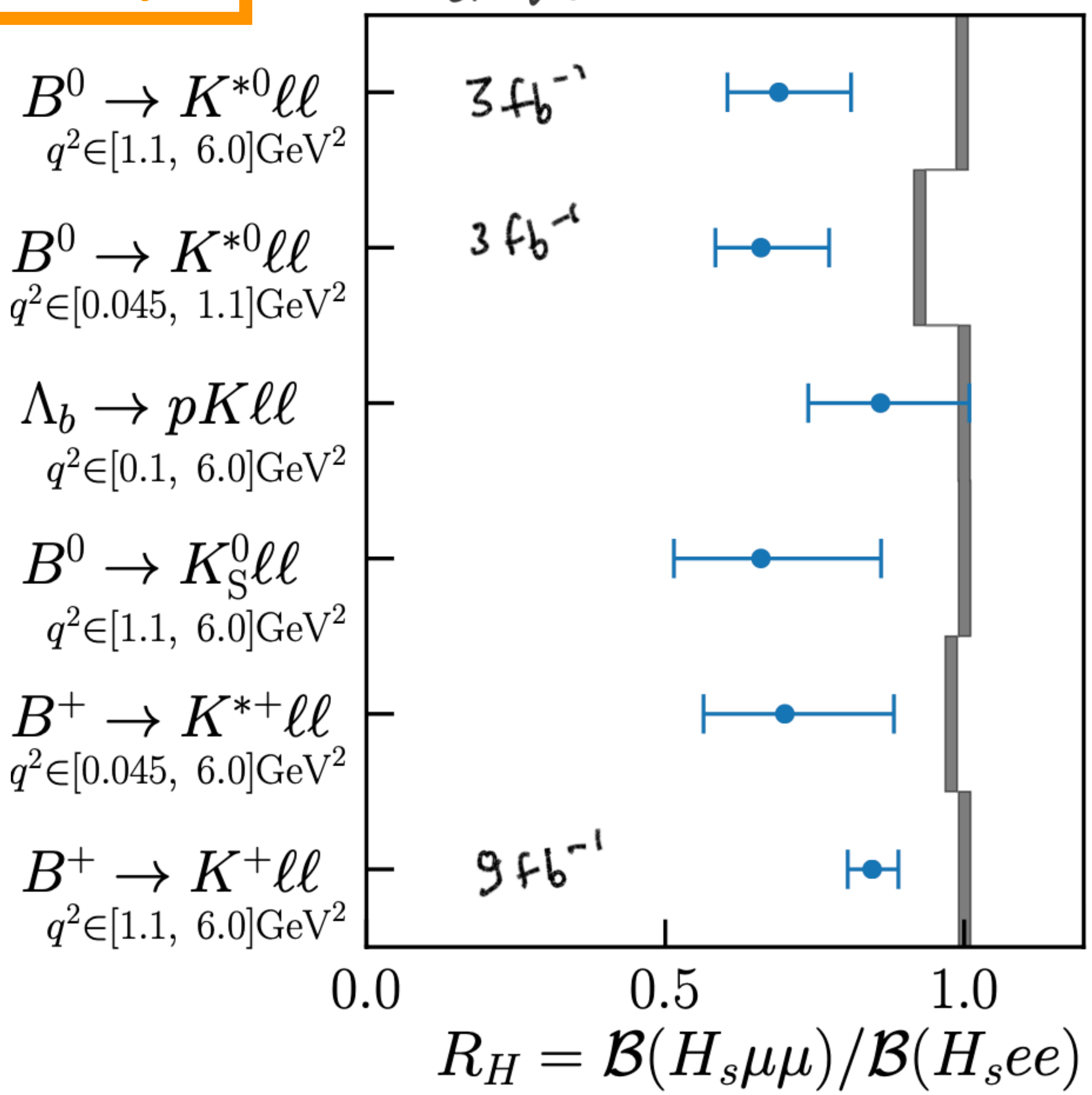
JHEP05 (2017) 076

A summary of $b \to s l^+ l^-$ results

no limitations from theory

- *LFU ratios*

credit Martino Borsato



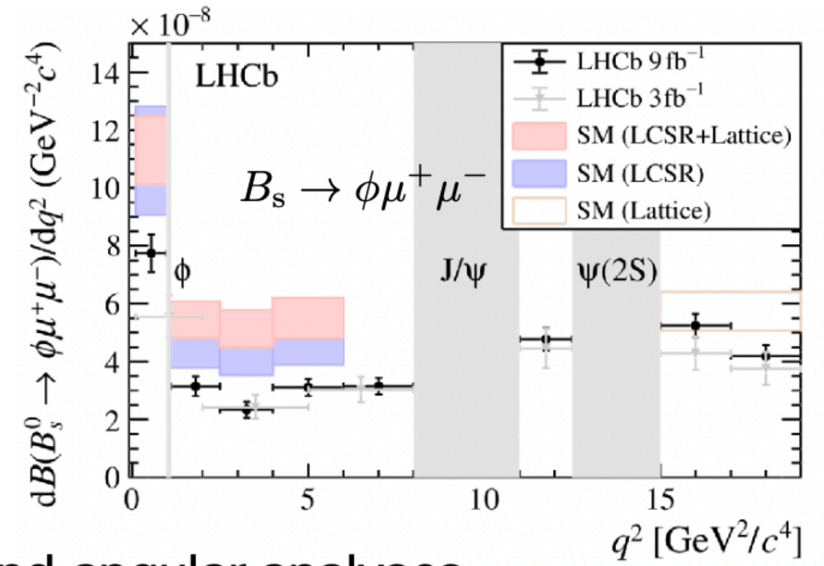
Th. calculated with flavio

31

Flavour Workshop 2021

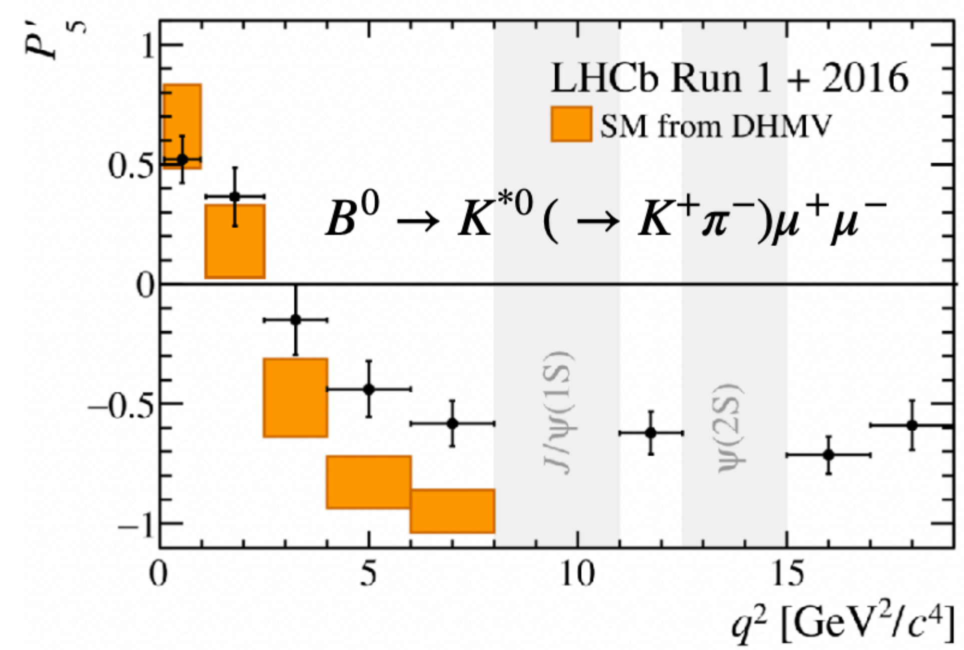
- Coherent set of $b \to s\ell\ell$ tensions in BFs

$B^+ \to K^+\mu^+\mu^-, B^0 \to K^{(*)0}\mu^+\mu^-, B_s \to \phi\mu^+\mu^-$



PRL 127 (2021) 151801

- and angular analyses



PRL 125 (2020) 011802

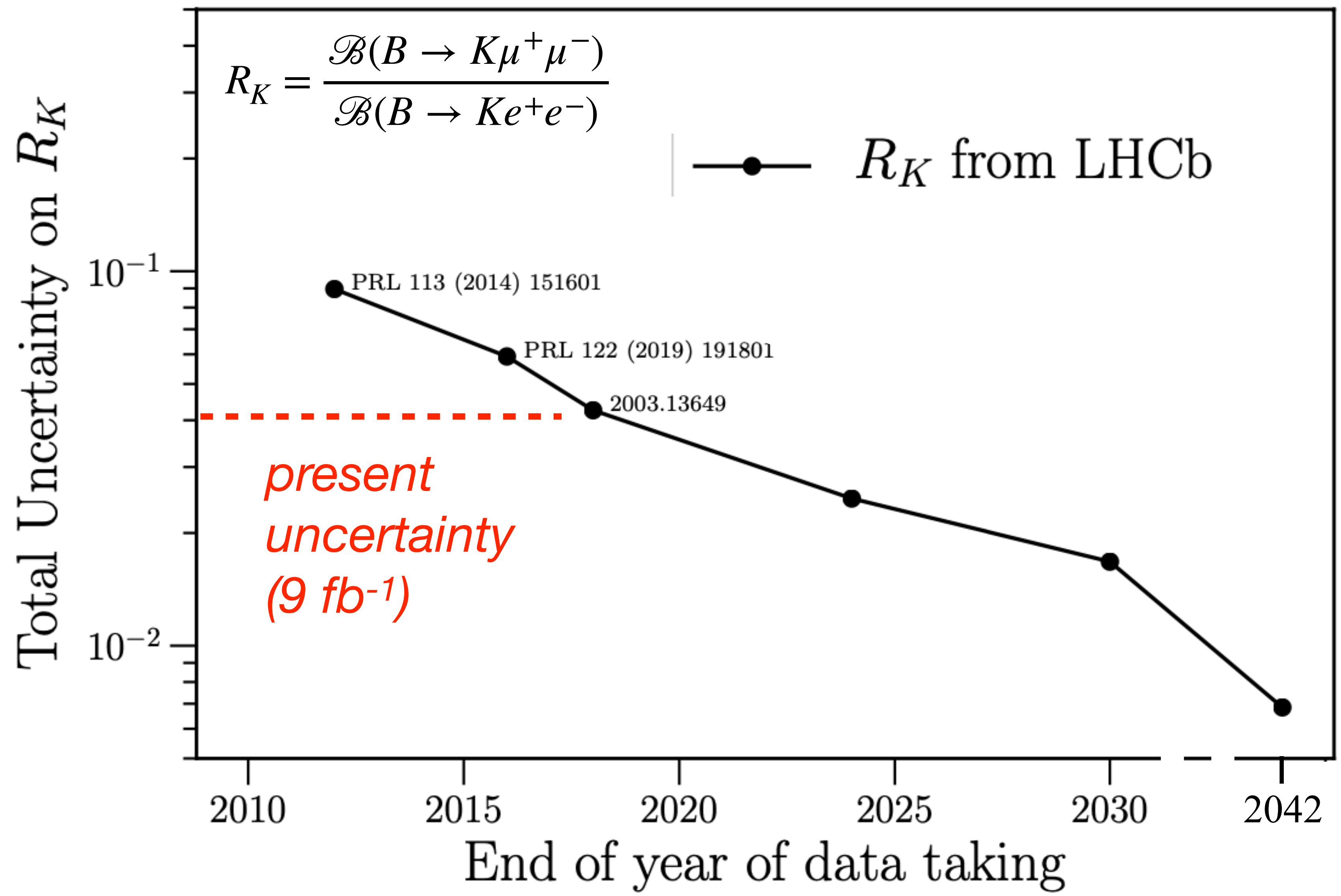
Overall picture is intriguing, more data are needed

Prospects for LFU in $b \to s l^+ l^-$

Absolute error on R_K is shown, will reach ~2.5% after Run 3 and <1% at Upgrade II

Larger stat will also be beneficial on systematics

e.g. in present R_K analysis (9 fb^{-1}) 1640 Kee signal evts are divided in 4 periods x 3 trigger bins, each with its eff. corrections → from Run 3 same stat. will be from 1 year only, trigger will be also simplified due to removal of hardware trigger



All other channels will follow with large statistics, too: $B^0 \to K^{*0}\ell\ell$, $B^0 \to K^0_S\ell\ell$, $B^+ \to K^{*+}\ell\ell$, $B_s \to \phi\ell\ell$, $\Lambda_b \to pK\ell\ell$ and multiple q^2 bins

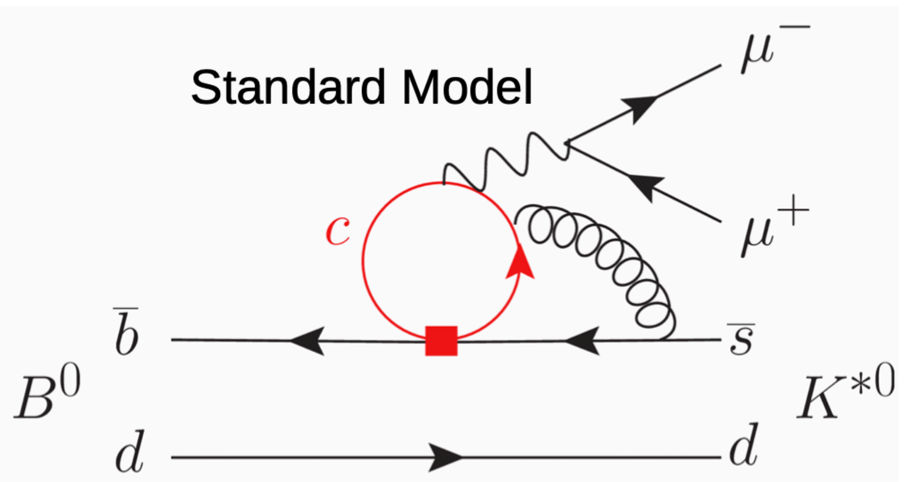
Input from other experiments (Belle II !) is fundamental

Prospects in angular analysis

$B^0 \to K^{*0}\mu^+\mu^-$: *optimised angular observable with reduced hadronic uncertainty* P_5'

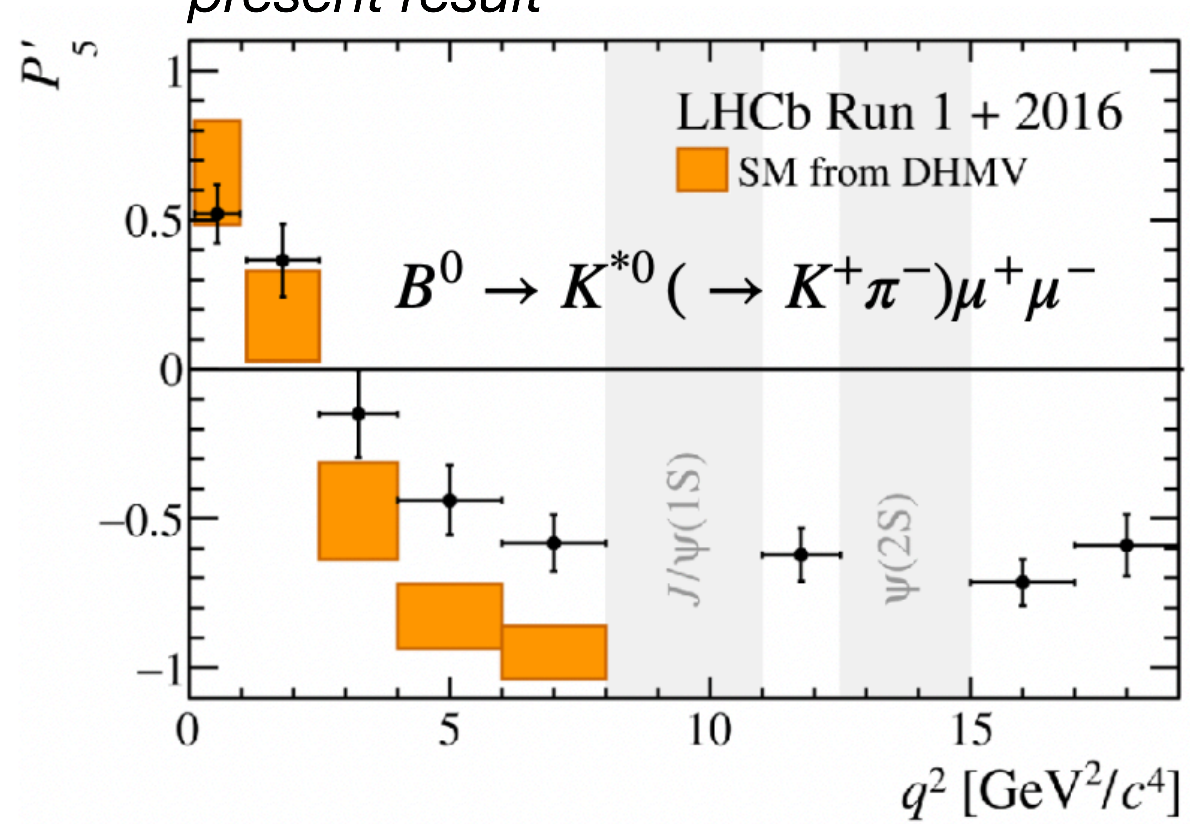
- *present result with Run 1 + 2016 data* $\sim 3\sigma$ *above the SM*
- *non-trivial contribution from charm-loop close to the resonant regions, fit to data will reduce syst*

EPJC 77 (2017) 161



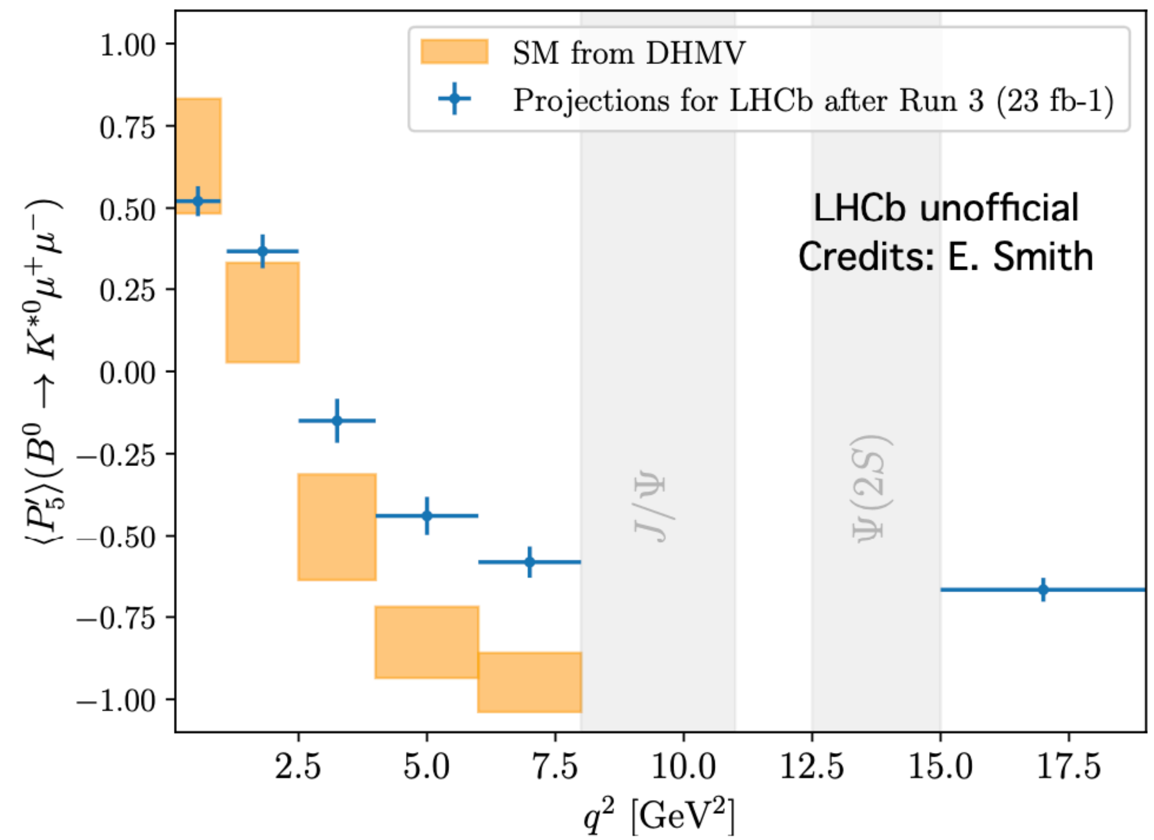
- *with large dataset it will possible to fit the Wilson coefficient in bins of* $q^2 \to$ *a genuine NP contribution will need to be flat*

present result



PRL 125 (2020) 011802

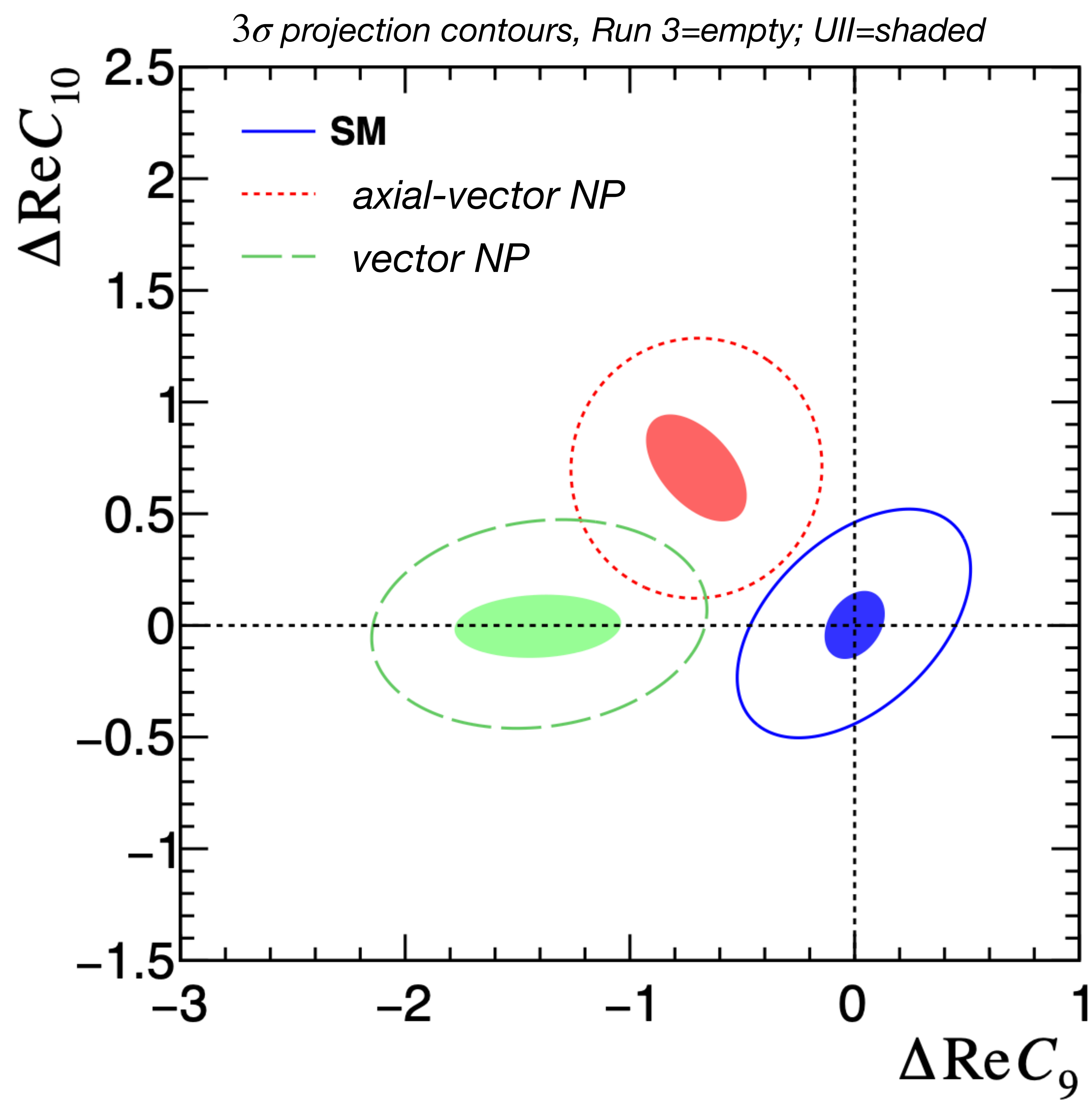
projection with 23 fb^{-1}



Global sensitivity from $b \to s l^+ l^-$

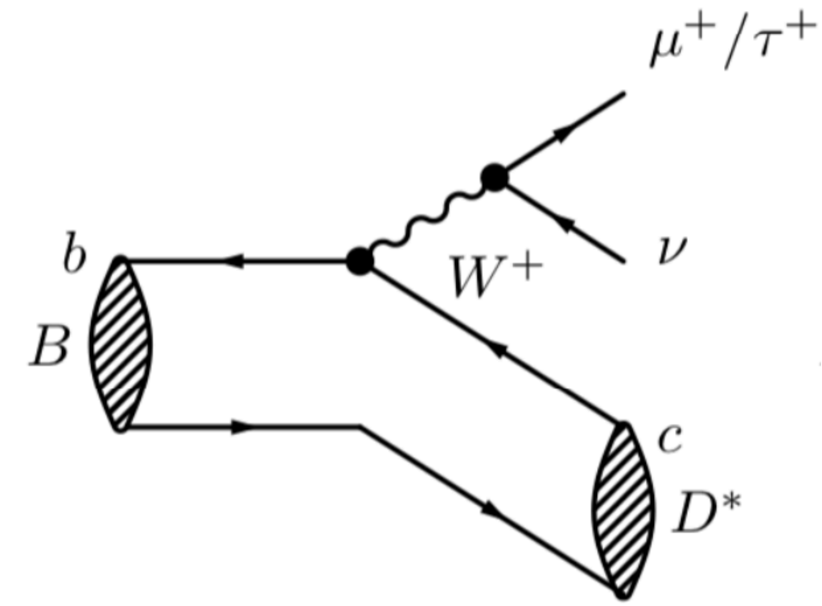
Upgrade II sensitivity (300 fb^{-1}) to the difference between μ and e mode contributions to the vector, C_9, and axial-vector, C_{10}, Wilson coeff.

Contribution from both LFU ratios and from angular observables in $b \to s\mu^+\mu^-$ and $b \to s e^+ e^-$ final states



Future data will allow to to discriminate between different NP scenarios

LFU in $b \to c\tau\nu$ decays



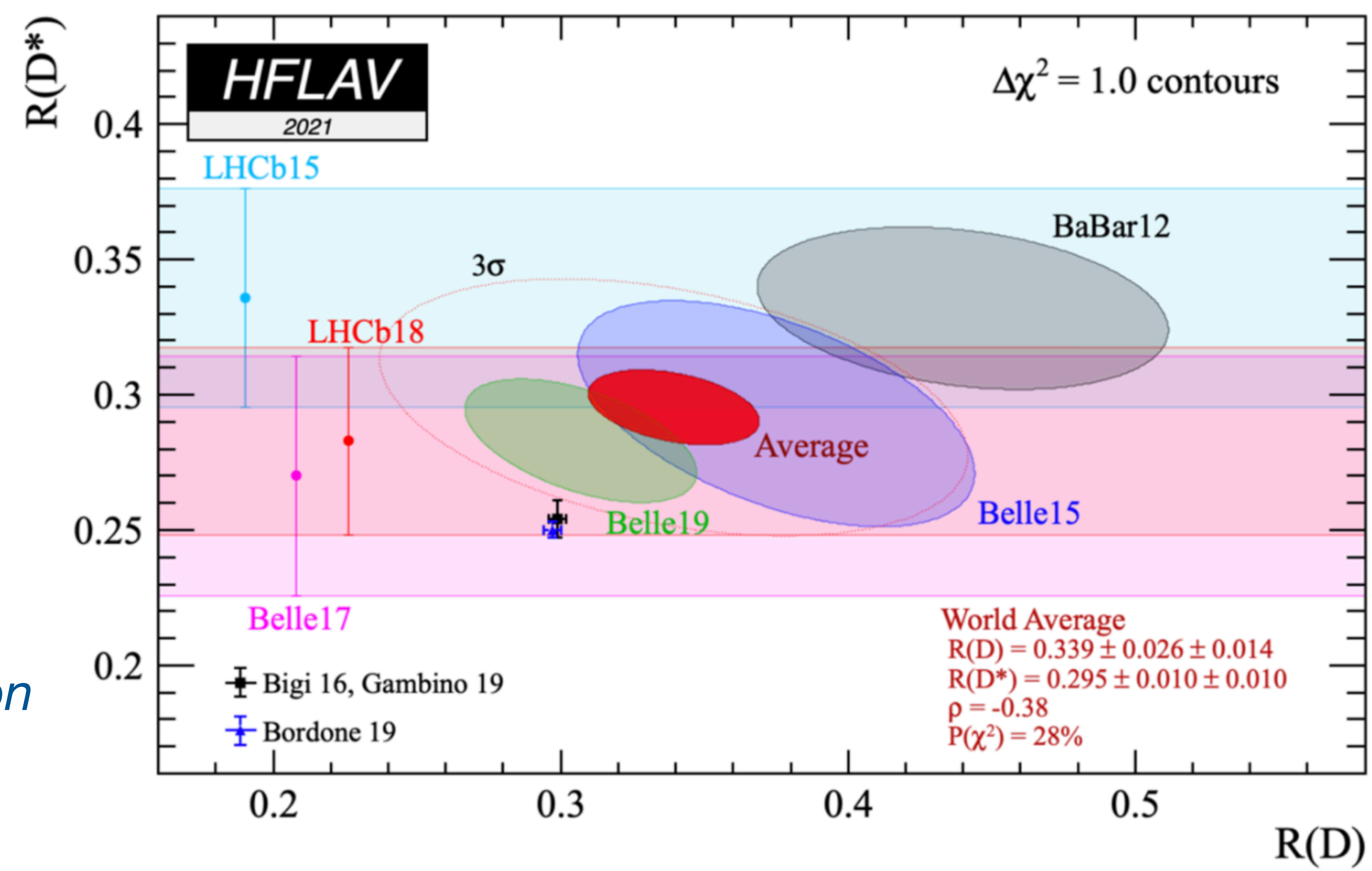
Measure $R(D^*) = \dfrac{\mathscr{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathscr{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$

Tree-level process, sensitive to NP coupling preferentially to 3rd generation

Predicted in SM at ~1%

Experiments see an excess wrt SM $\sim 3.4\sigma$

- *there could be a connection with* $b \to sl^+l^-$ *anomalies*



LFU in $b \to c\tau\nu$ decays

LHCb measured R(D) on Run 1 data (3 fb-1) using both* $\tau \to \mu\nu\nu$ *and* $\tau \to 3\pi\nu$

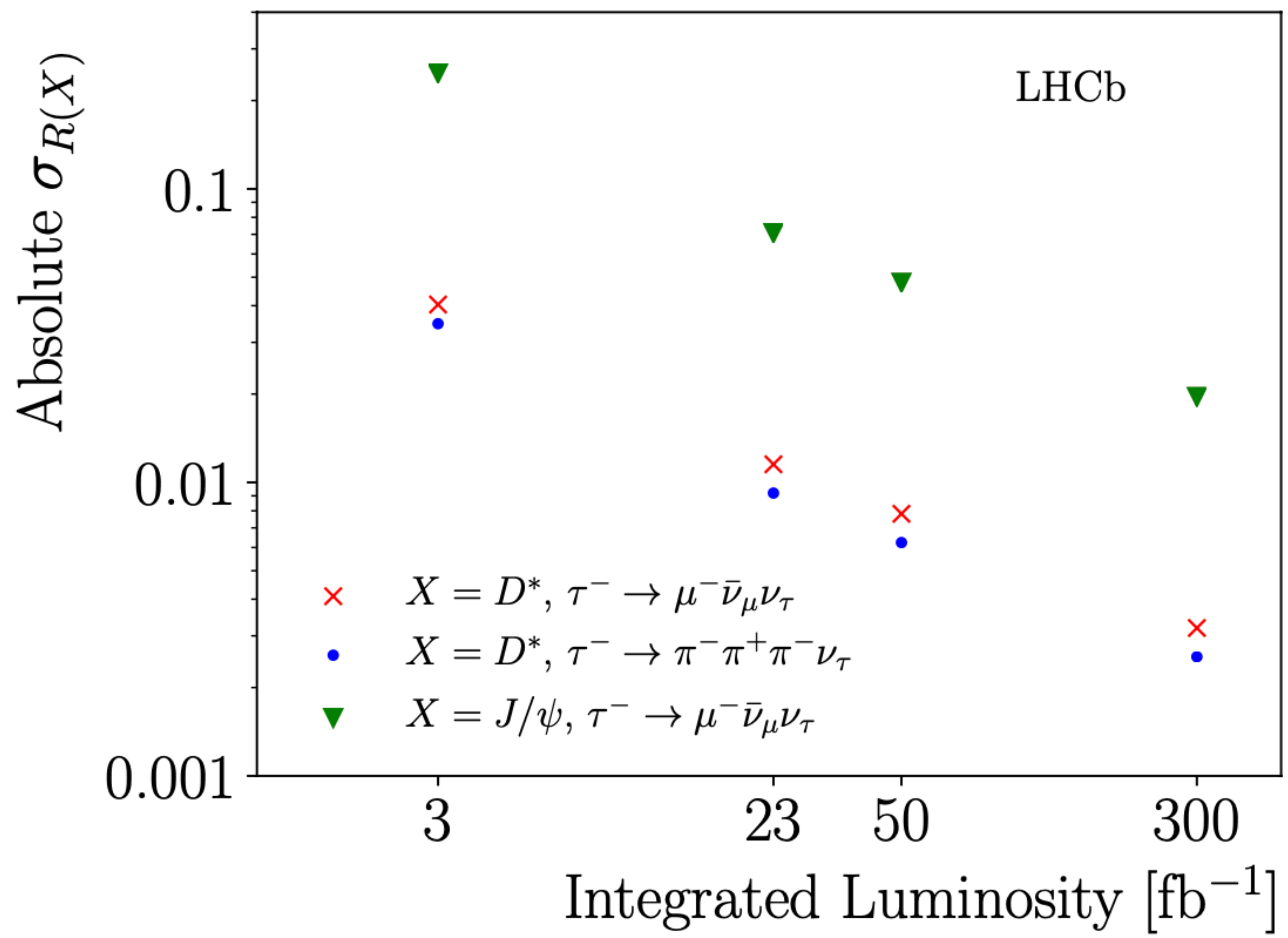
Difficult analyses at LHC: poor kinematic constraints, large backgrounds

- *profit from large boost and excellent vertexing capability*
- *also measured for the first time on 3 fb-1* $R(\Lambda_c) = \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) / \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)$ *and* $R(J/\psi) = \mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau) / \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)$ *with ~35% accuracy*

Only Run 1 measurements produced so far, there's large room for improvement

Excellent prospects to develop all these analyses during Run 3 and Upgrade II with multiple modes, targeting good precision

Strong competition from Belle II expected in the short period



Approaching conclusions…

- **There's a lot still to do using the LHCb present dataset**

  - many analyses may benefit from additional person-power

- **This year is crucial to commission the new detector and to start a successful Run 3 data taking**

  - signal event rates will increase by a factor of ~5 for muon final states and a factor of ~10 for hadronic final states

  - new data are expected to clarify the picture on $b \to s l^+ l^-$ *decays and LFU observables; very important contribution from other experiments also expected (Belle II, ATLAS, CMS)*

- **Upgrade II will fully realise the flavour-physics potential of the HL-LHC**

  - to successfully exploit the physics case, we will need to design and build a new detector able to run at $\sim \times 10$ *pile-up while keeping similar performances as the present one*

LHCb Upgrade II Framework TDR

CDS link https://cds.cern.ch/record/2776420/

165 pages, 10 chapters

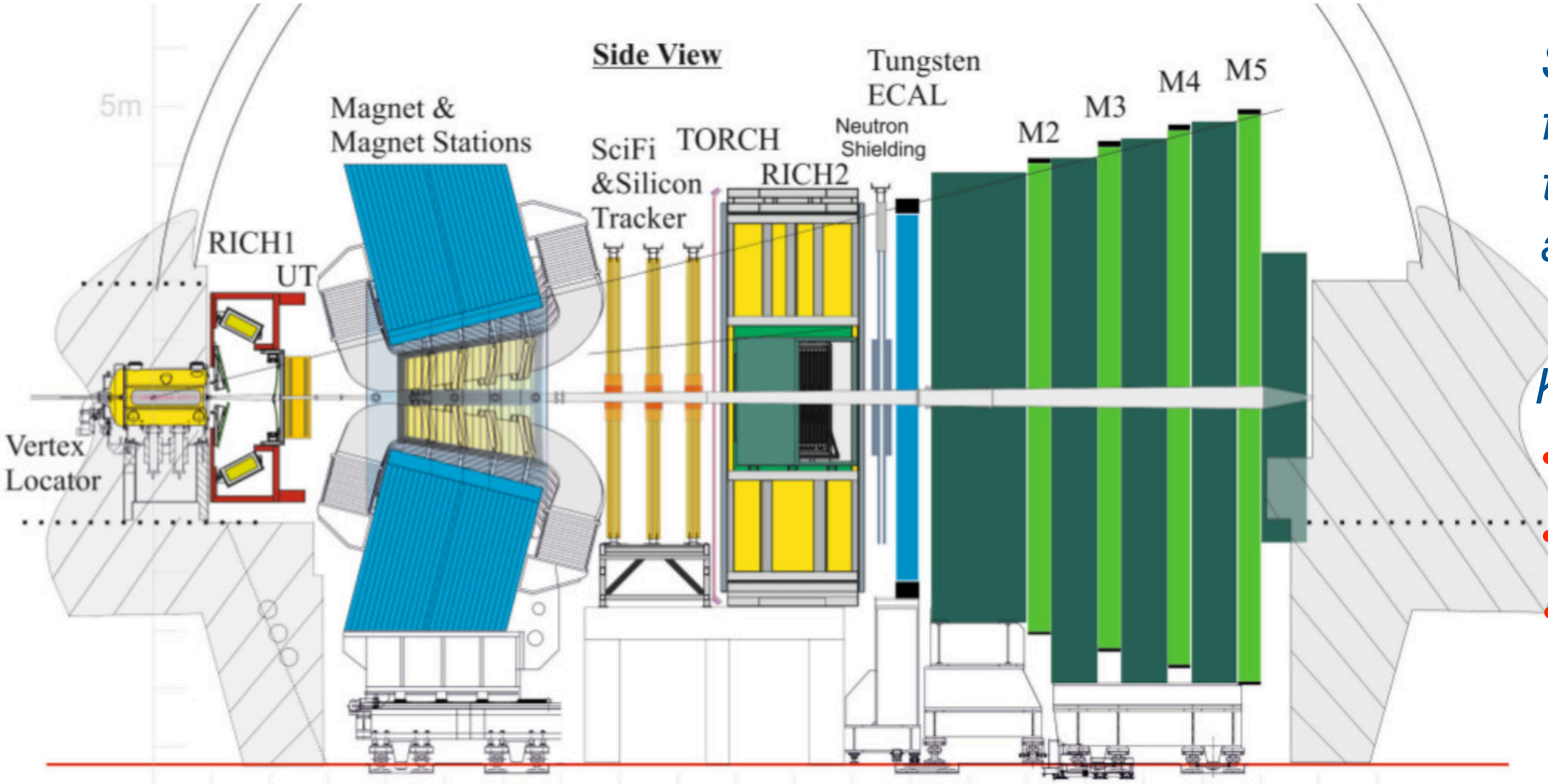
1. *Executive summary*
2. *Introduction*
3. *Tracking detectors*
4. *Particle identification detectors*
5. *Data acquisition and online processing*
6. *Simulation and offline computing*
7. *Infrastructure*
8. *Environmental protection and safety*
9. *Project timeline*
10. *Detector scenarios and costs*

1113 authors from 91 institutes

LHCC review concluded in March

The detector challenge

Targeting same performance as in Run 3, but with pile-up ~40!



Same spectrometer footprint, innovative technology for detector and data processing

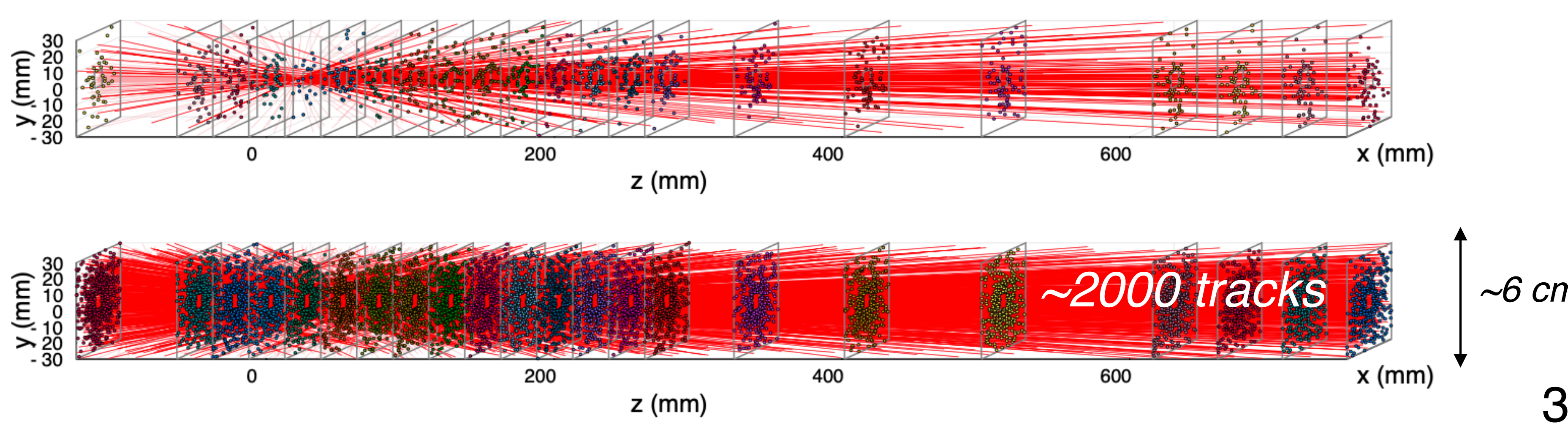
Key ingredients:

- *granularity*
- *fast timing (few tens of ps)*
- *radiation hardness (up to few $10^{16} n_{eq}/cm^2$)*

VErtex LOcator (VELO)

Run 3: pile-up ~5

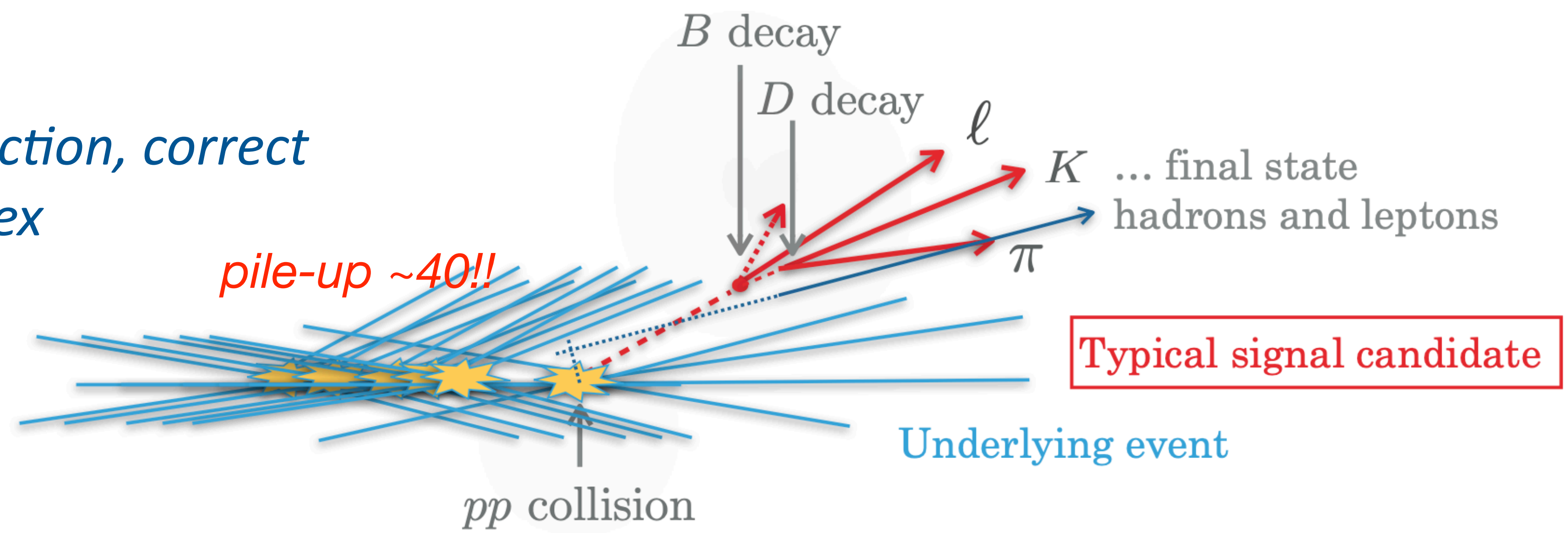
Upgrade II: pile-up ~40



4D tracking and vertex reconstruction

Essential for flavour physics

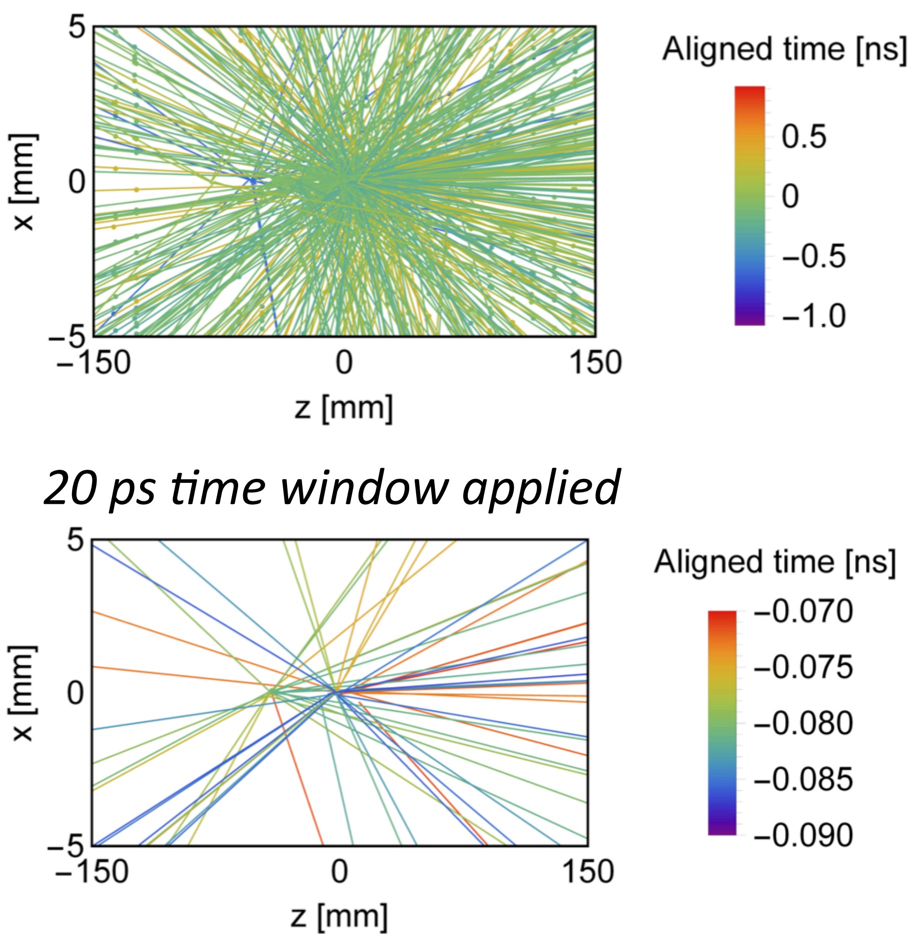
- *primary vertex (PV) reconstruction, correct association with B decay vertex*
- *decay time and impact parameter resolutions*



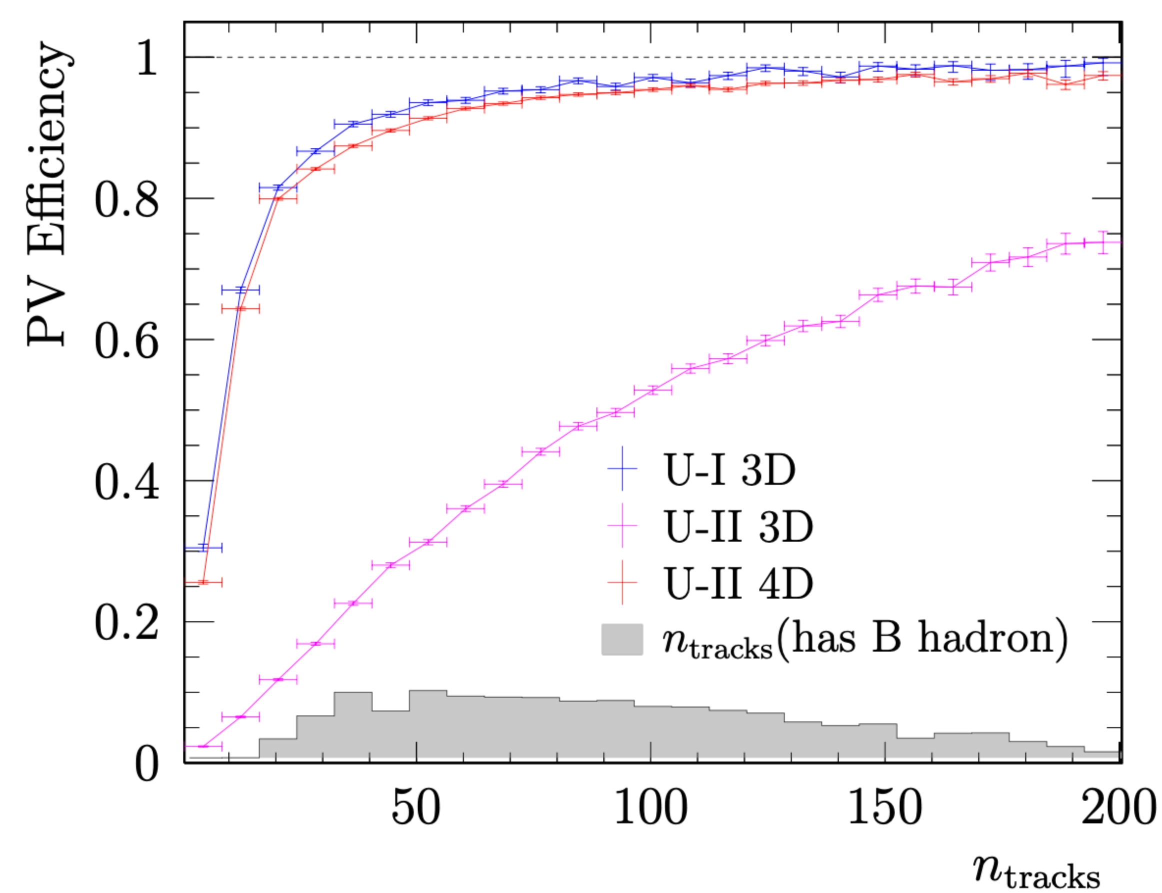
Timing to the rescue: each hit in VELO time-stamped with 50 ps resolution → 20 ps per track

track density with ~40 interactions

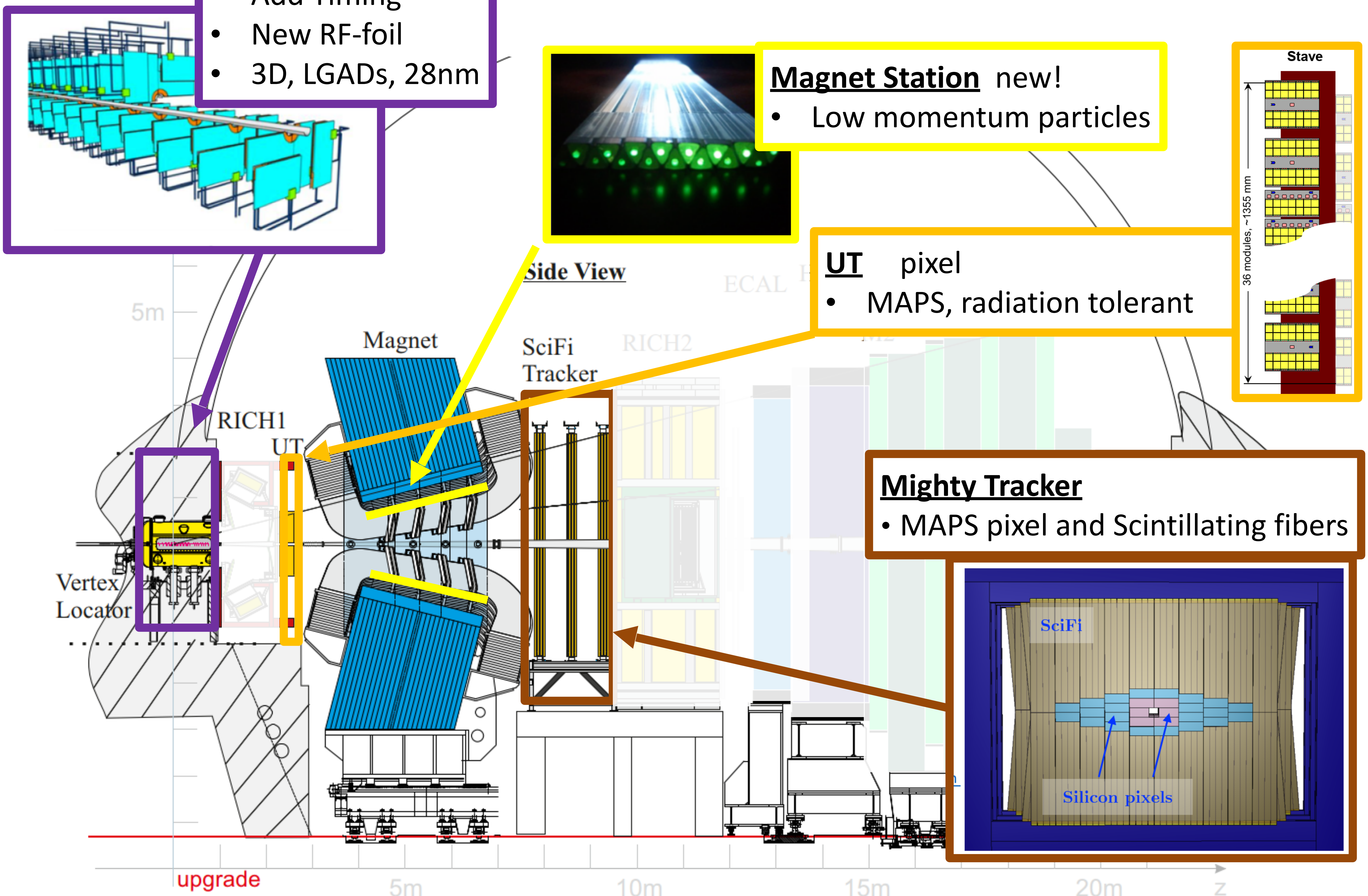
20 ps time window applied



PV reco efficiency for: UI 3D, UII 3D and UII 4D



The full tracking system

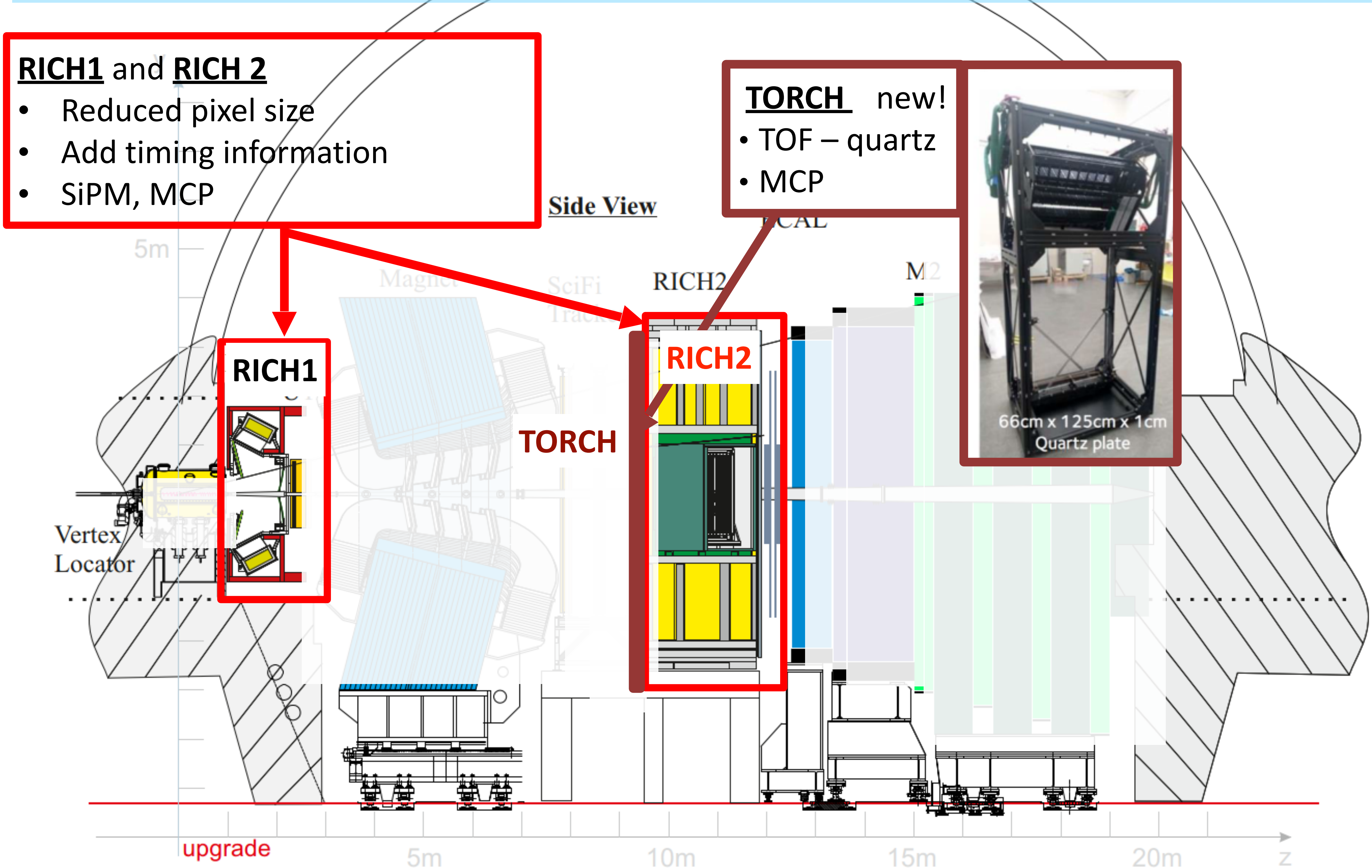


PID detectors 1

Need to maintain the present PID performance at increased pile-up: crucial ingredients granularity and fast timing at few tens of ps

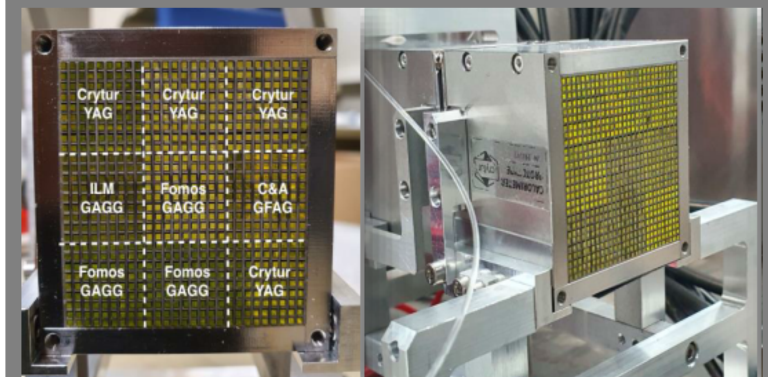
RICH1 and **RICH 2**
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new!
- TOF – quartz
- MCP

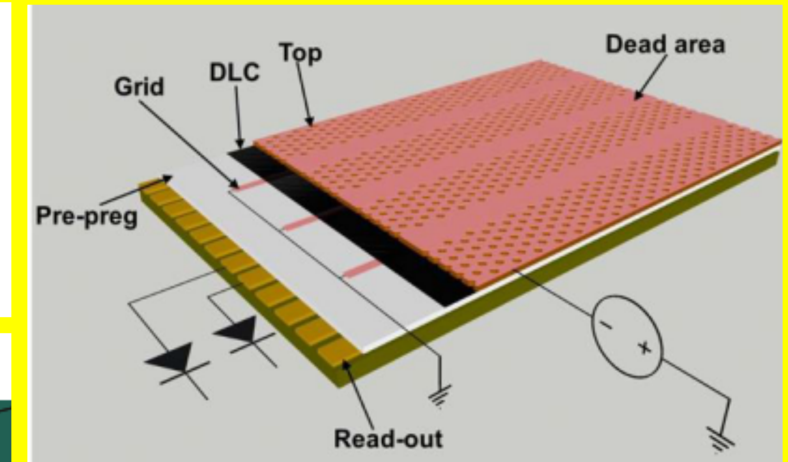


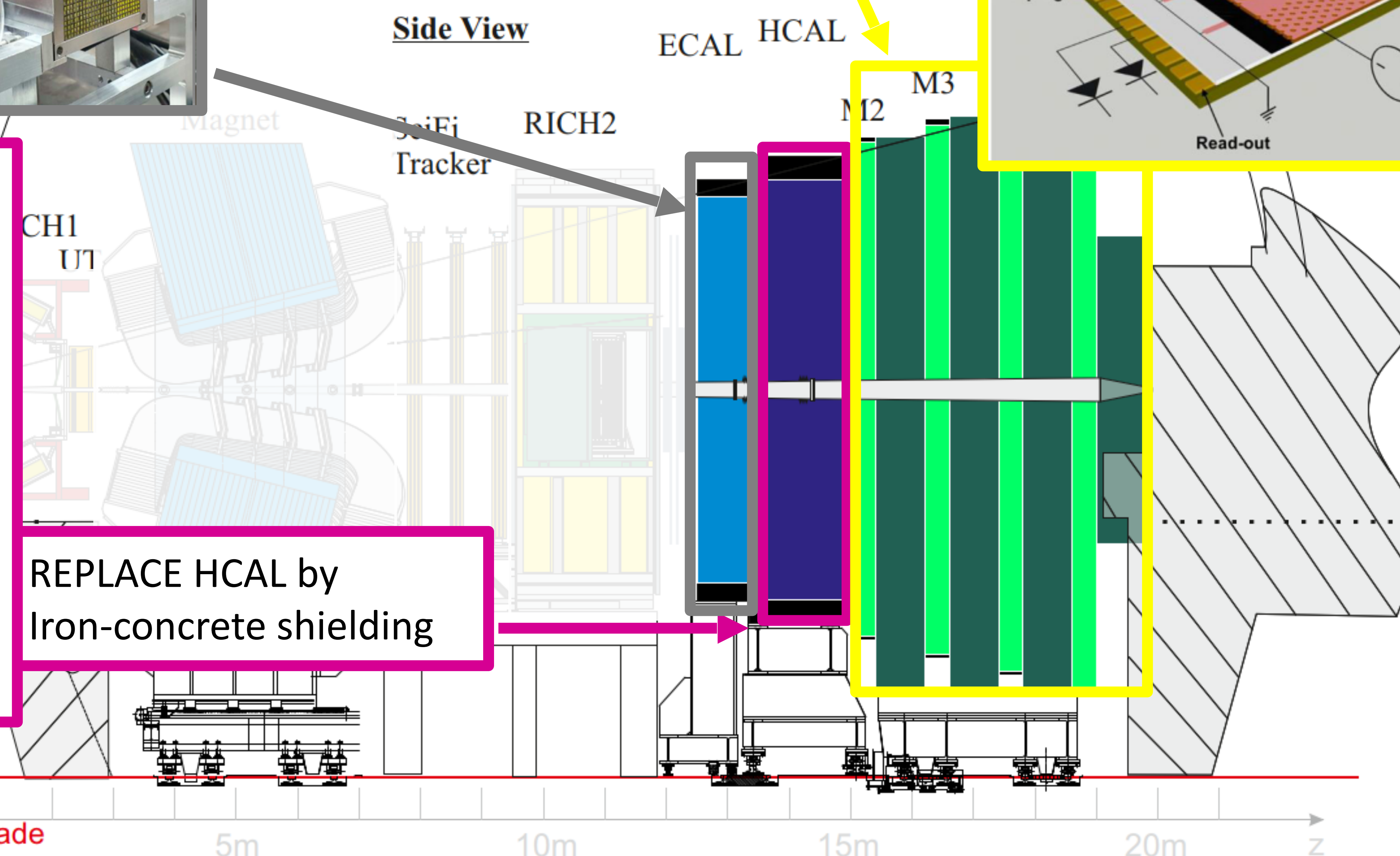
PID detectors 2

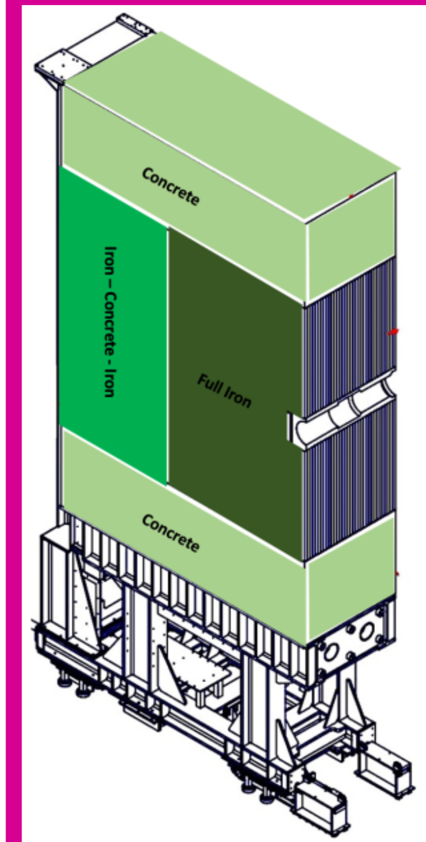
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals



Muon
- µRWELL for inner regions
- MWPC for outer regions (recycles)







REPLACE HCAL by
Iron-concrete shielding

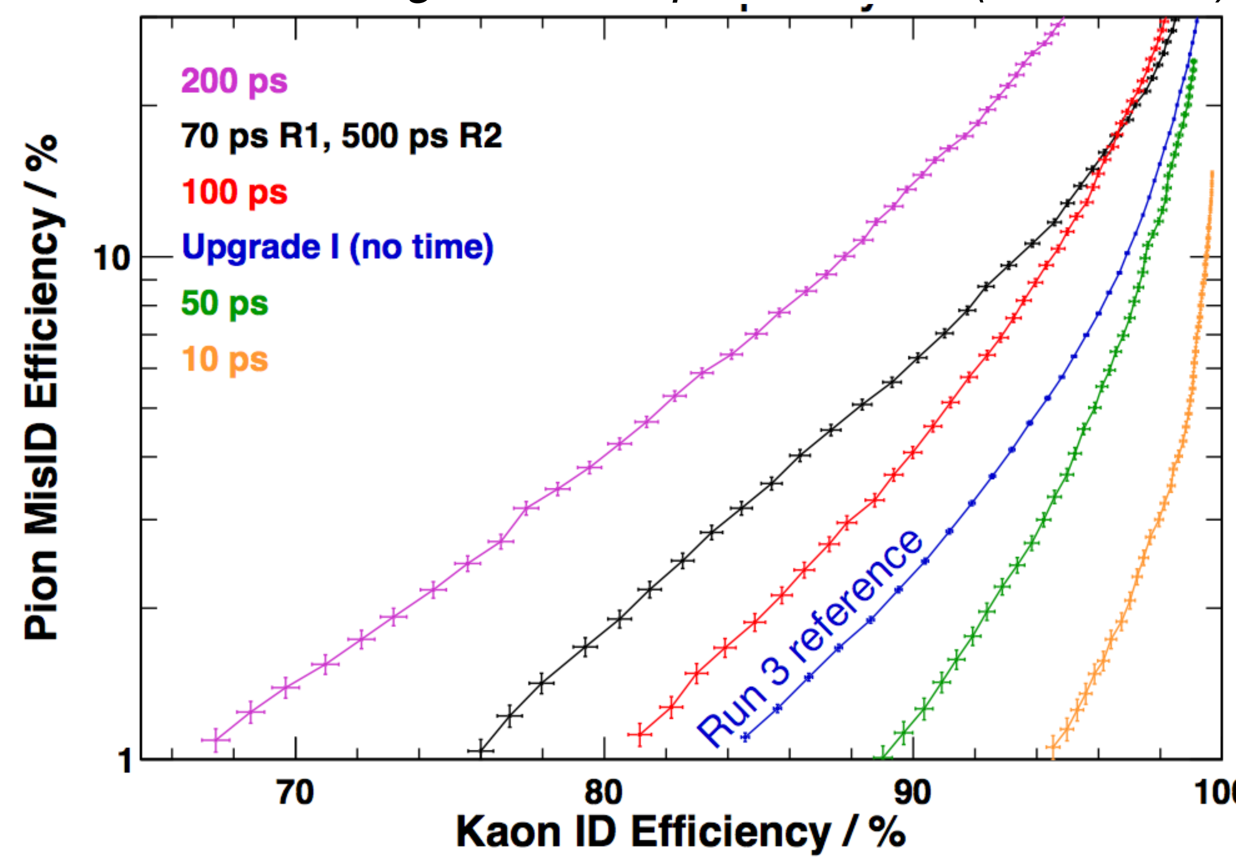
Timing for PID detectors

RICH

- New design with improved Cherenkov angle resolution (0.1-0.2 mrad) and timing capability (tens of ps) expected to recover Run 3 performance

- SiPM good candidate for high-granularity and time resolution; front-end with 65 nm CMOS (FASTIC + TDC)

Effect of timing on RICH performance (simulation)

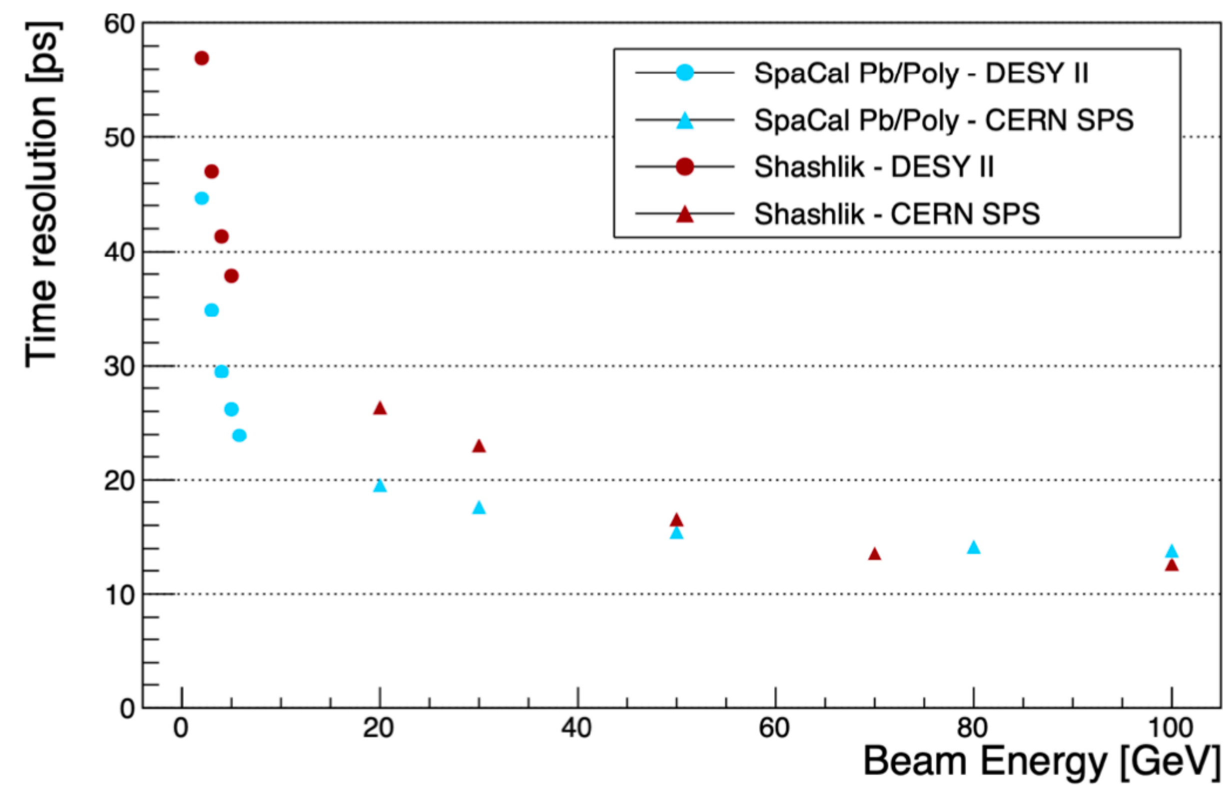


ECAL

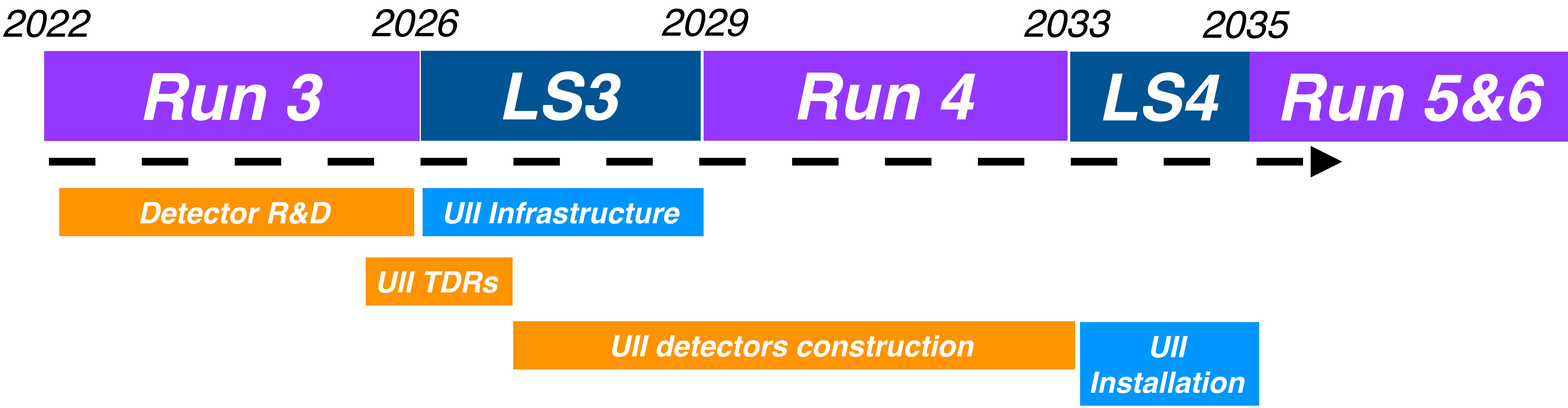
- Key features: radiation hardness (up to 1 MGy), timing capability (tens of ps) and granularity

- Very good timing resolution obtained in test-beams with SPACAL and Shashlik modules

SPACAL/Shashlik measured time resolution



Timeline for Upgrade II

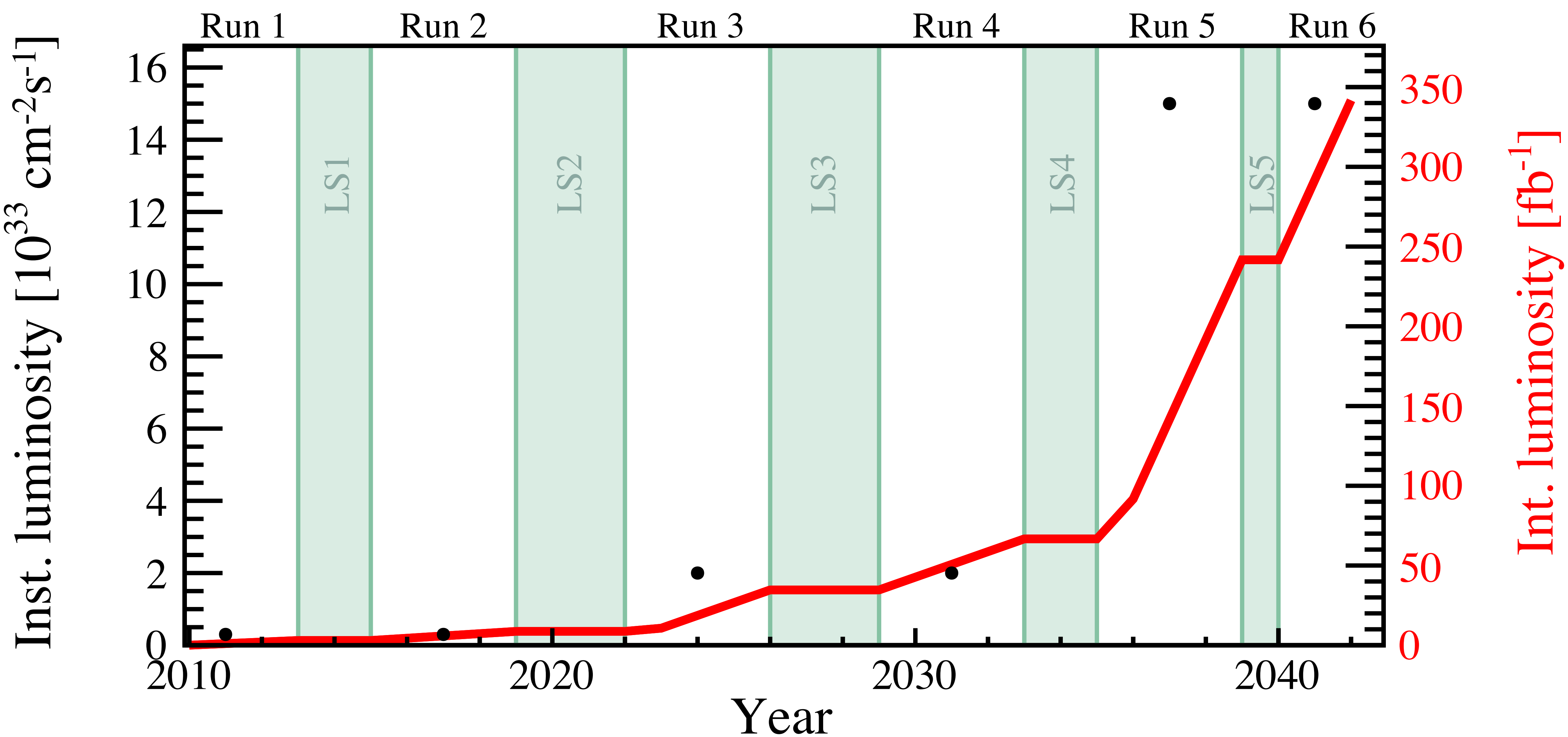


- *~4 year period for detector R&D, make technology choices and optimise the detector design*
- *TDRs expected at beginning of LS3, then ~6 year period for detector construction → being ready for LS4 installation is of primary importance*
- *Significant infrastructure preparation during LS3, to optimise LS4 duration*
- *Limited size detector consolidations also proposed for LS3 as anticipation of Upgrade II*

Upgrade II needs a significant expansion of the collaboration

Conclusions

Physics results!	Ready to start!	It's taking shape!
Original	Upgrade I	Upgrade II
2009-2018	2022-2032	2033-



Lots of data to analyse NOW, new technologies to develop for the FUTURE!

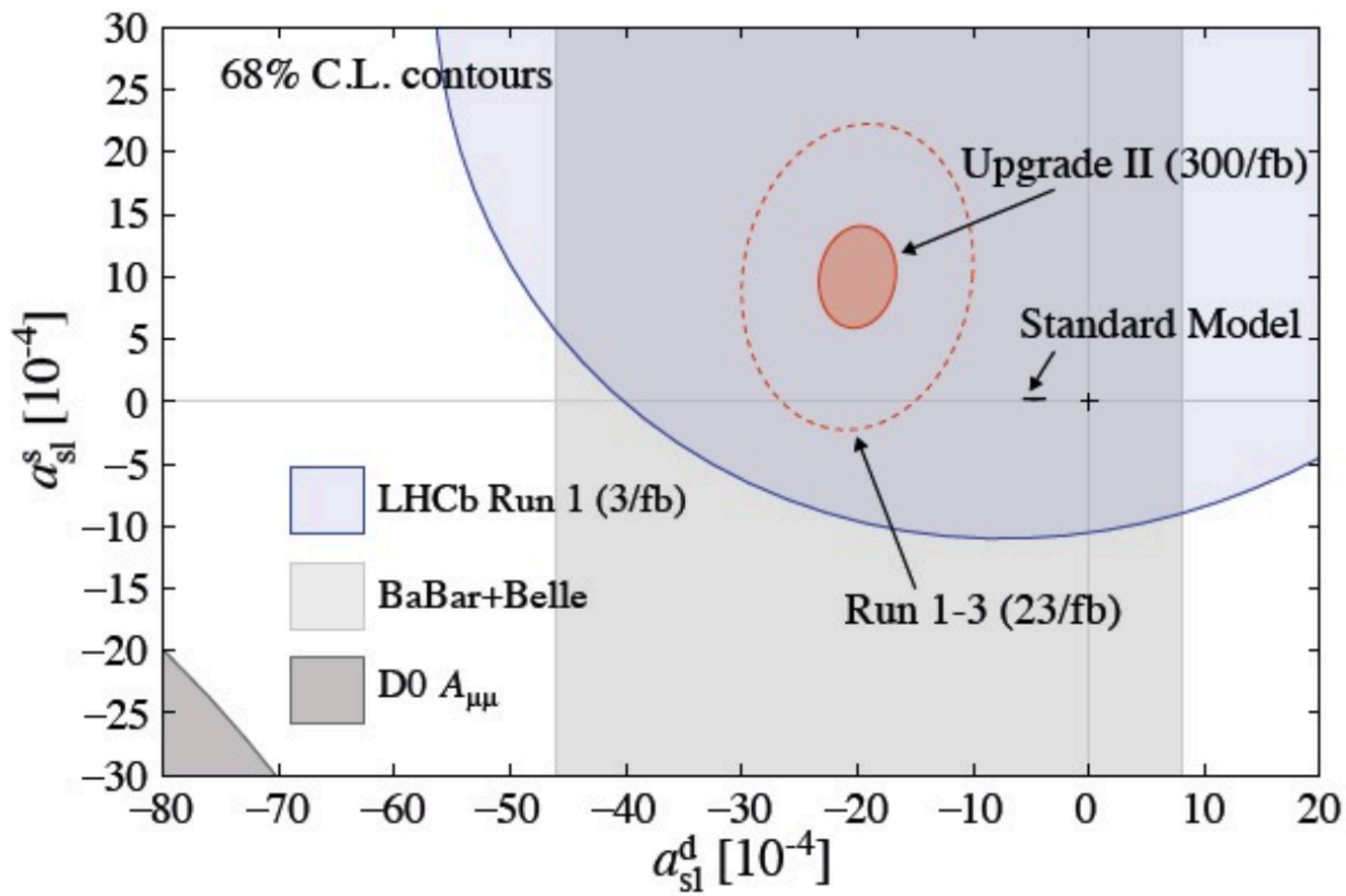
SPARES

Semileptonic asymmetries

B semileptonic asymmetries are sensitive to CPV in mixing

$$A_{\rm sl}^{q}(t) \equiv \frac{\Gamma(\bar{B}_{\rm q}^{0} \to f) - \Gamma(B_{\rm q}^{0} \to \bar{f})}{\Gamma(\bar{B}_{\rm q}^{0} \to f) + \Gamma(B_{\rm q}^{0} \to \bar{f})}$$

$$q = d, s \qquad f = D_q^- \mu^+ \nu_\mu X$$



Predicted to be very small by SM, could b enhanced by NP

LHCb measured with Run 1 data so far

Sample ($\mathcal{L}$)	$\delta a_{\rm sl}^{s} [10^{-4}]$	$\delta a_{\rm sl}^{d} [10^{-4}]$
Run 1 (3 fb^{-1}) [210, 211]	33	36
Run 1-3 (23 fb^{-1})	10	8
Run 1-3 (50 fb^{-1})	7	5
Run 1-5 (300 fb^{-1})	3	2
Current theory [34, 200]	0.03	0.6

Huge improvement expected in Run 3 and Run 4, and even more with Upgrade II

A word on $B^0_{(s)} \to e^+e^-$ and $B^0_{(s)} \to \tau^+\tau^-$

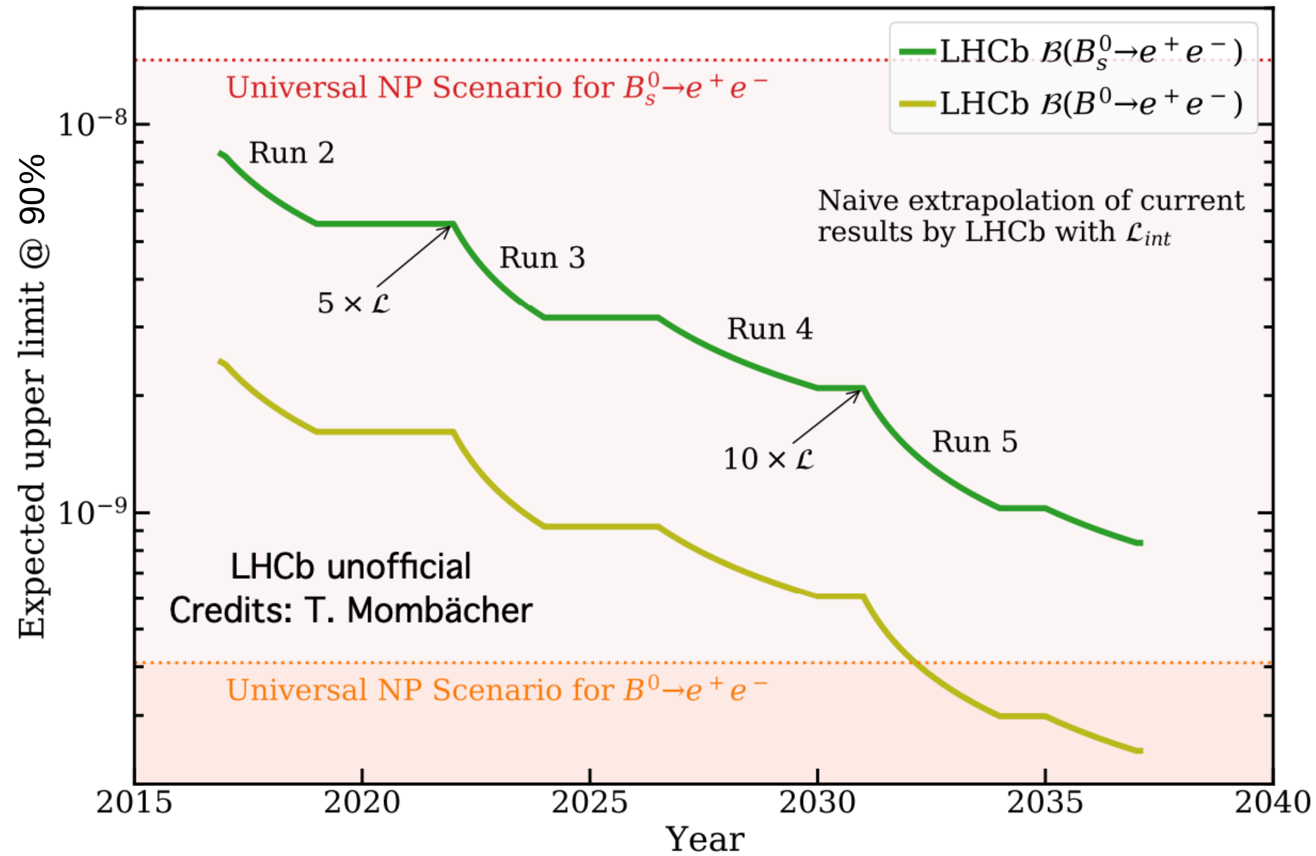
$B^0_s \to e^+e^-$ *in SM:* JHEP 10 (2019) 232

$$(8.60 \pm 0.36) \times 10^{-14}$$

Present best limit with Run 1 + 2016 data:
$\mathcal{B}(B^0_s \to e^+e^-) < 11.2 \times 10^{-9}$ *at 95% CL*

PRL 124 (2020) 211802

Improvement expected from additional stat and more efficient electron trigger at Run 3



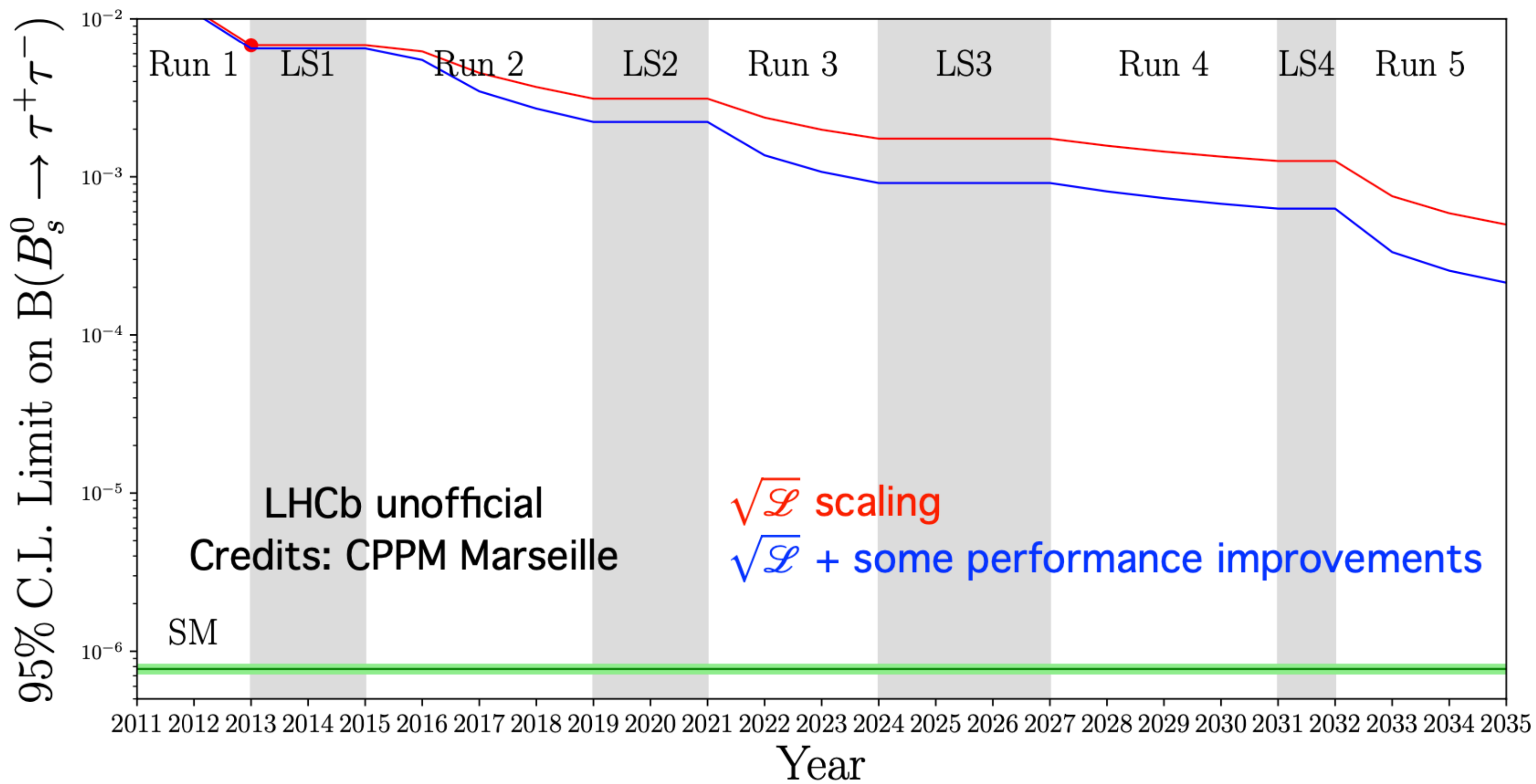
$B^0_s \to \tau^+\tau^-$ *in SM:* PRL 112 (2014) 101801

$$(7.73 \pm 0.49) \times 10^{-7}$$

Present best limit with Run 1:
$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ *at 95% CL*

PRL 118 (2017) 251802

Less helicity suppression but experimentally difficult for LHCb



Prospects in angular analysis

Increased Upgrade statistics it will possible to disentangle between different NP scenarios

I. *pure vector,* $b \to s l^+ l^-$ *data*

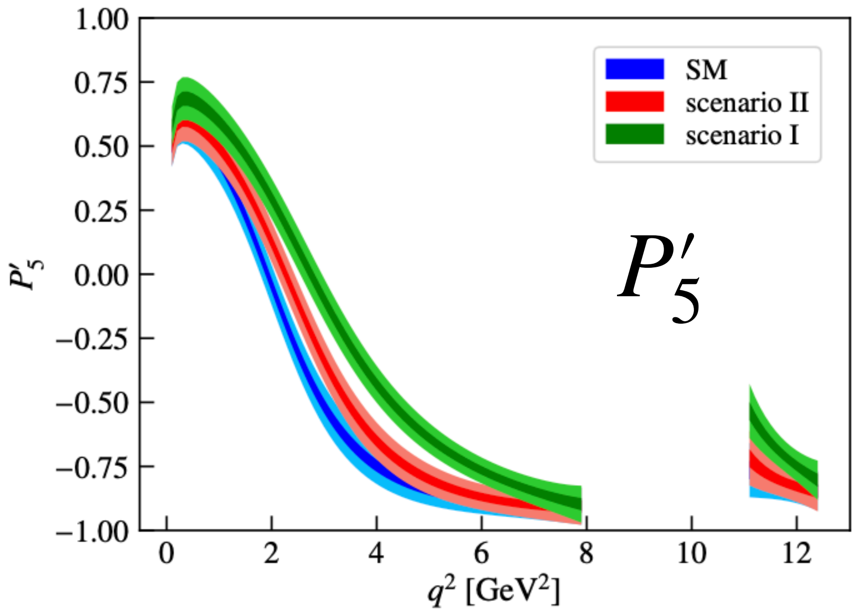
II. *axial-vector,* $b \to s l^+ l^-$ *and* $b \to c l \nu$ *data*

III. *and* IV. *small right-handed currents*

scenario	C_9^{NP}	C_{10}^{NP}	C_9'	C_{10}'
I	-1.4	0	0	0
II	-0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	-0.3

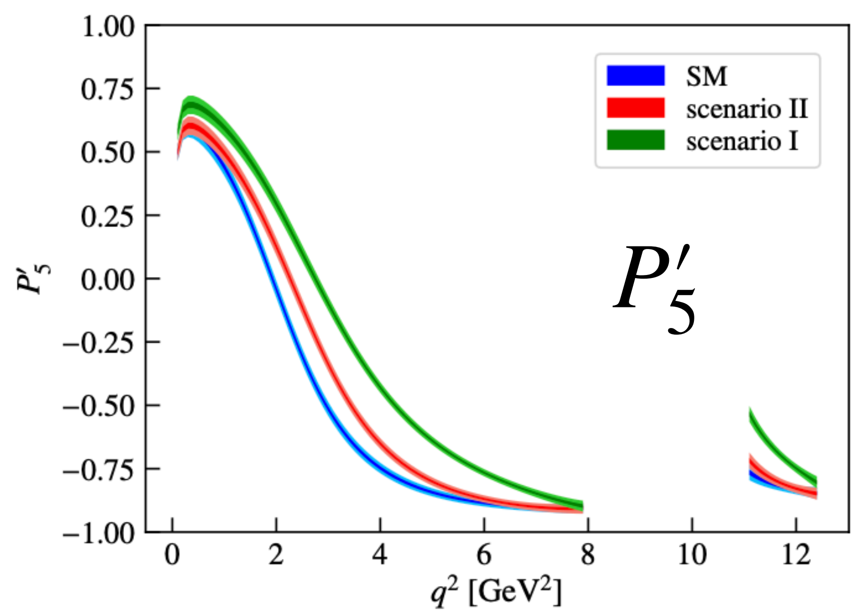
Run 3, 23 fb^{-1}

~35k $B^0 \to K^{*0}\mu^+\mu^-$

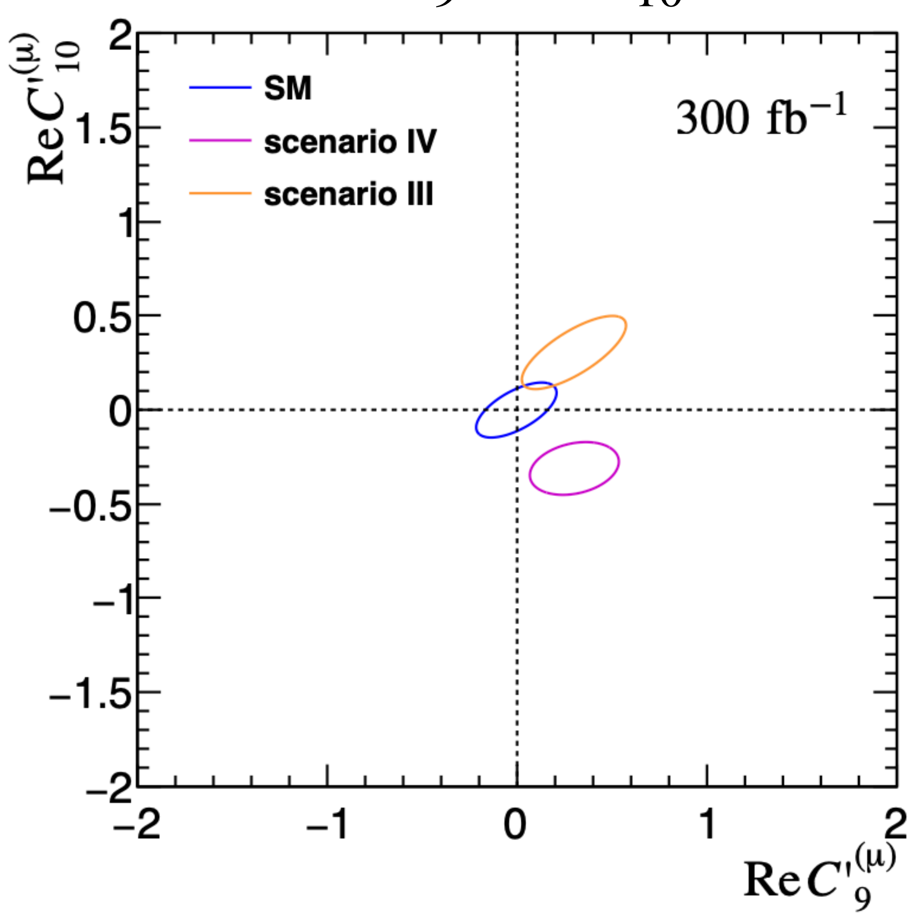


Upgrade II, 300 fb^{-1}

~440k $B^0 \to K^{*0}\mu^+\mu^-$



C_9' *and* C_{10}'



Lepton flavour universality

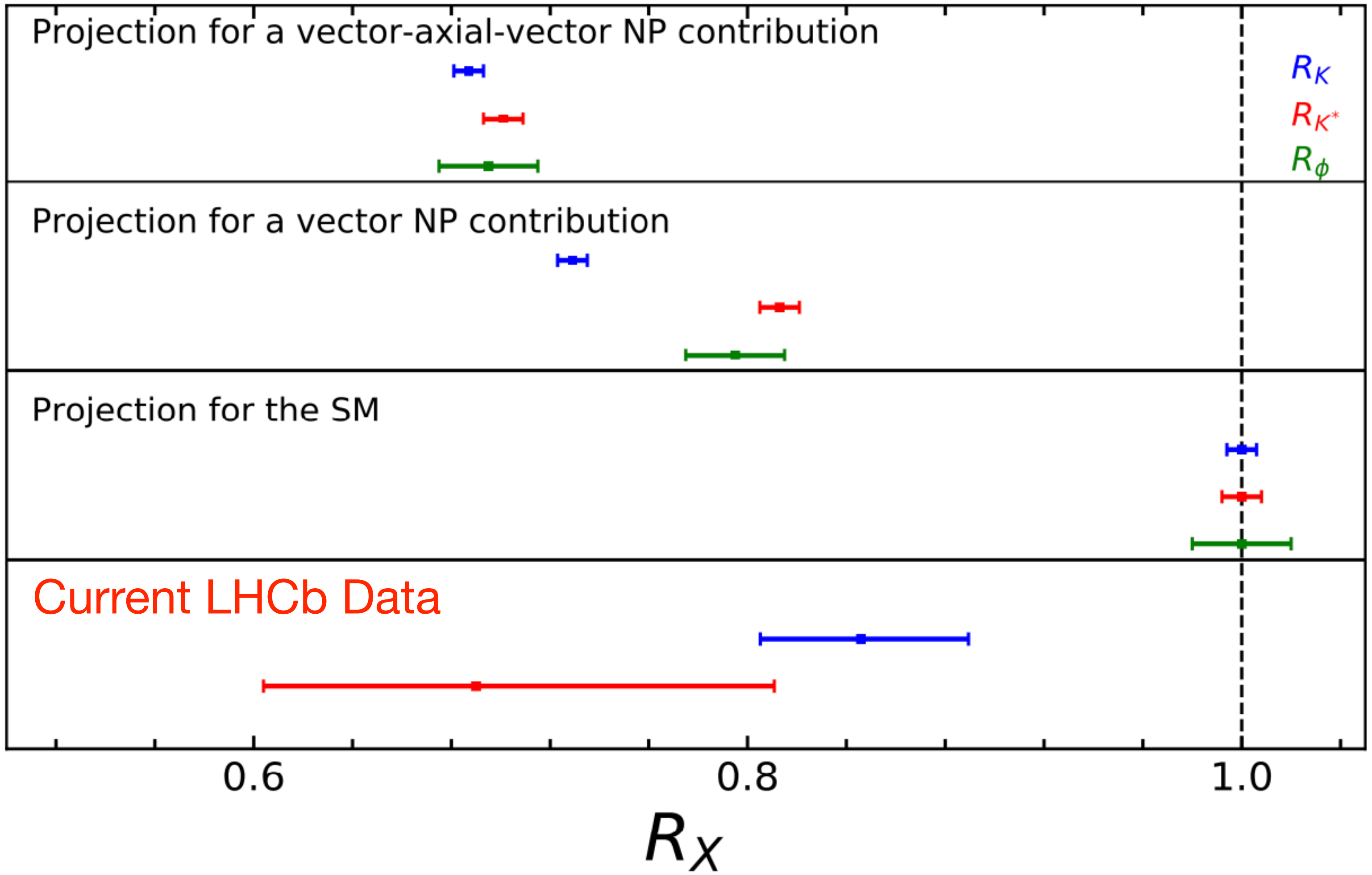
Looking for NP by comparing B rare decays with muons and electrons, a huge challenge

$$R_X = \frac{BR(B \to X\mu^+\mu^-)}{BR(B \to Xe^+e^-)} = 1 \text{ in SM}$$

with $X = K, K^*, \phi$

Benefit is in terms of observables with almost no theoretical uncertainty

Projected sensitivities for R_X meas. in different NP scenarios



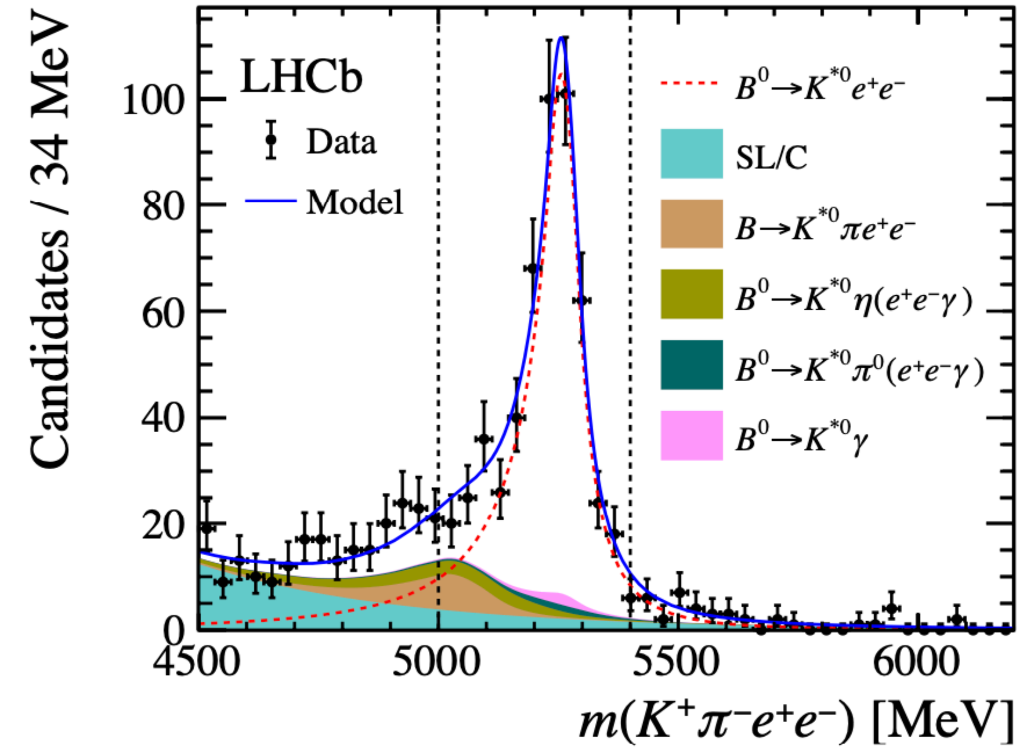
Additional informations from differences in angular observables between $B \to X\mu^+\mu^-$ and $B \to Xe^+e^-$

With Upgrade 2 statistics we will be able to discriminate between different NP scenarios

C_7' from $b \to s\gamma$ decays

We probe C_7' with time-dependent analysis of $B_s^0 \to \phi\gamma$ or via angular analysis of $B^0 \to K^{*0}e^+e^-$ rate at very low q^2

- *very stringent limits already set with Run1+Run2 data (9 fb^{-1})*

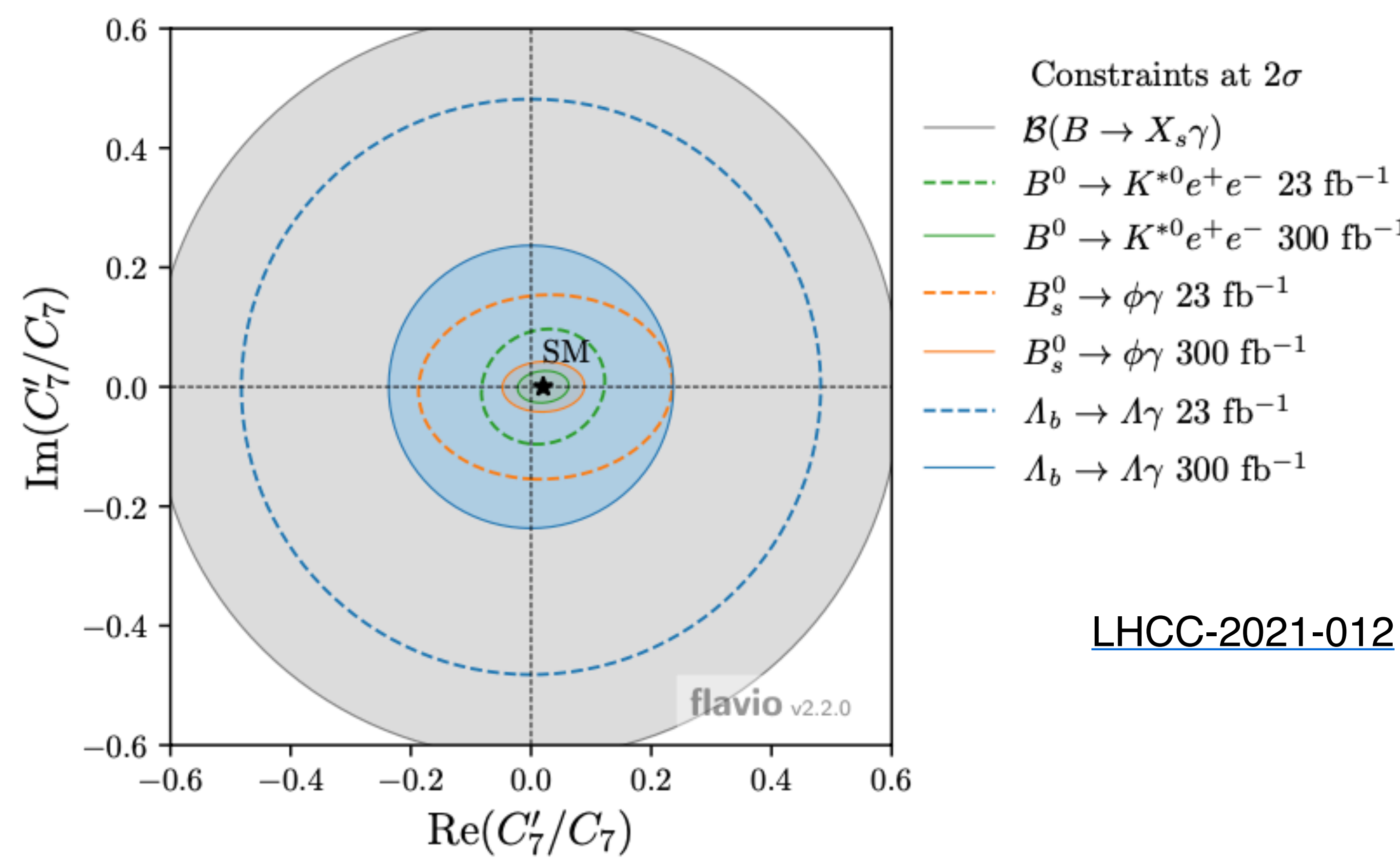


JHEP 12 (2020) 081

Excellent sensitivity also in Run 3, with improved trigger, and adding constraints from photon polarisation in $\Lambda_b \to \Lambda\gamma$

Measurements with three completely different physics processes give competitive constraints on C₇' !

Rely on calorimeter performances, to be maintained also at Upgrade II, and on material budget



LHCC-2021-012

LFV searches

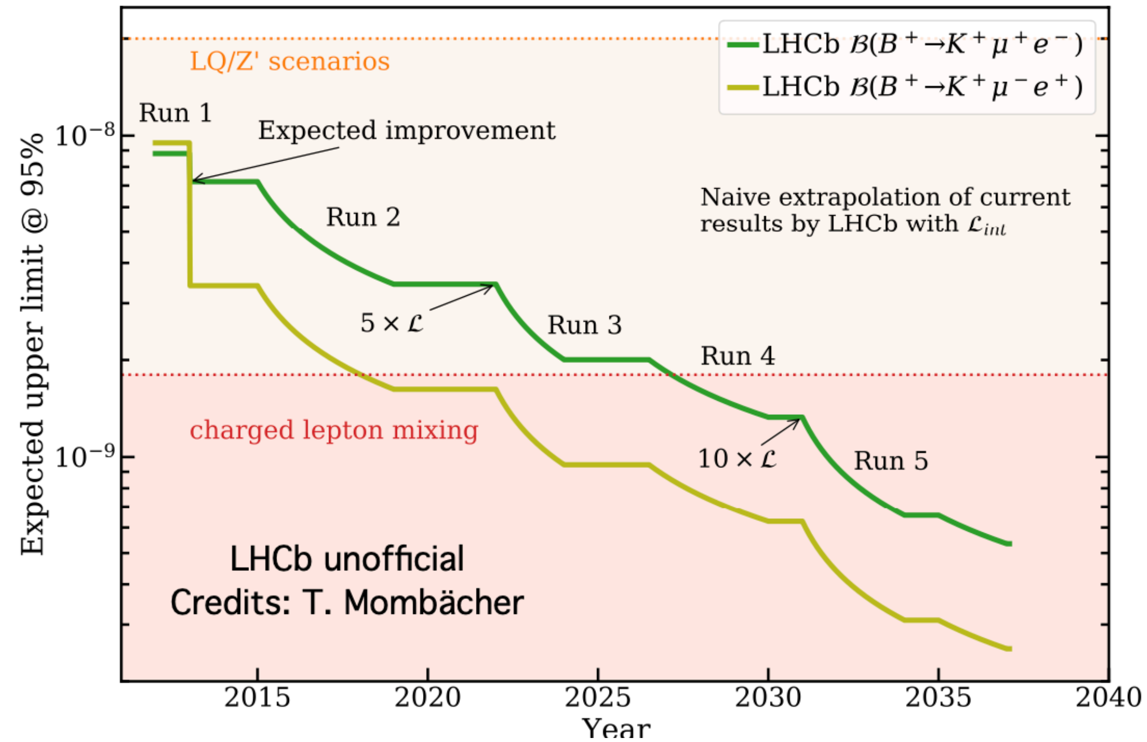
$B \to e^\pm\mu^\mp X$ simple final state

Upper limits from Run 1 data (at 95% CL):

$\mathscr{B}(B_s^0 \to e^\pm\mu^\mp) < 6.3 \times 10^{-9}$ JHEP 03 (2018) 078

$\mathscr{B}(B^+ \to K^+\mu^-e^+) < 9.5 \times 10^{-9}$ PRL 123 (2019) 241802

$\mathscr{B}(B^+ \to K^+\mu^+e^-) < 8.8 \times 10^{-9}$



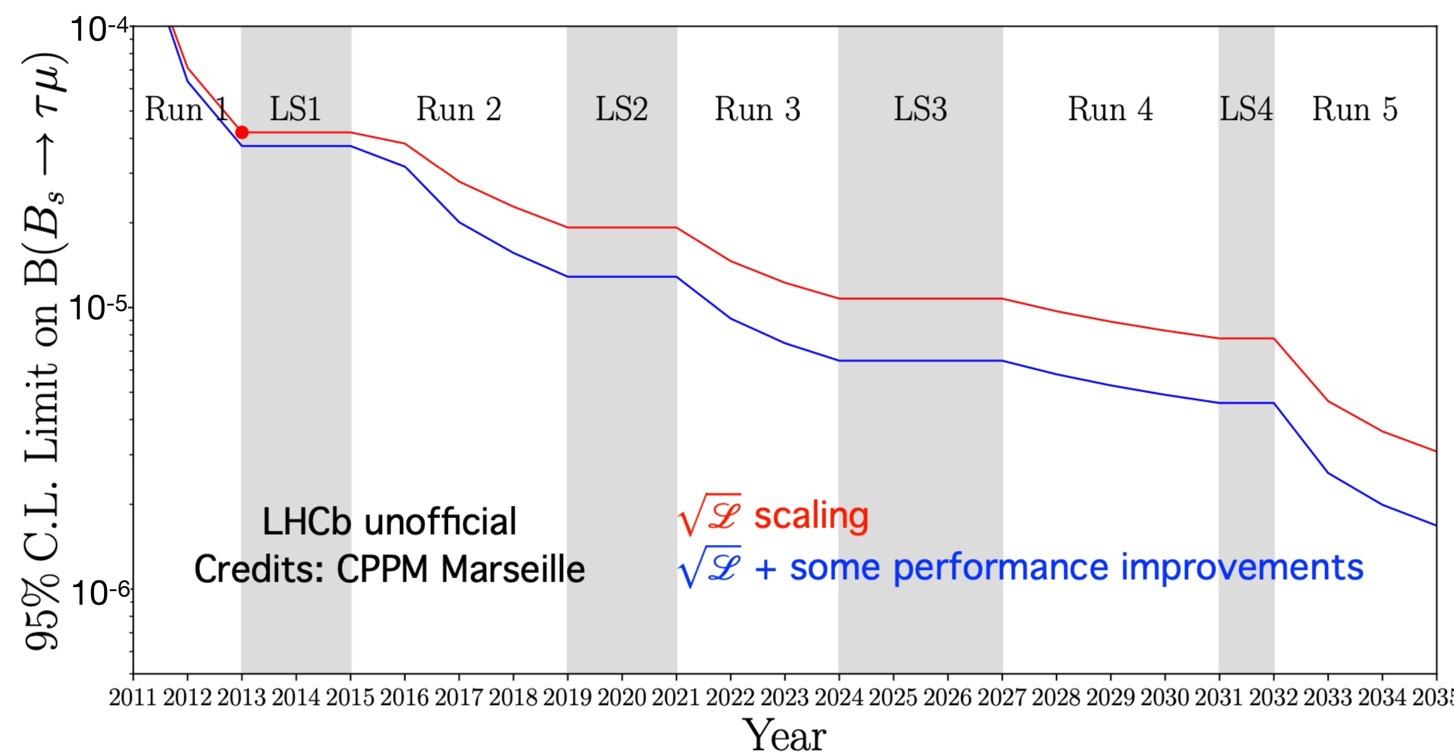
$B \to \tau^\pm\mu^\mp X$ to probe NP coupling to 3rd generation

Escaping ν: exploit $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$ vertex to reconstruct the mass

Upper limits (at 95% CL)

$\mathscr{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$ PRL 123 (2019) 211801

$\mathscr{B}(B^+ \to K^+\mu^-\tau^+ < 4.5 \times 10^{-5}$ JHEP 06 (2020) 129

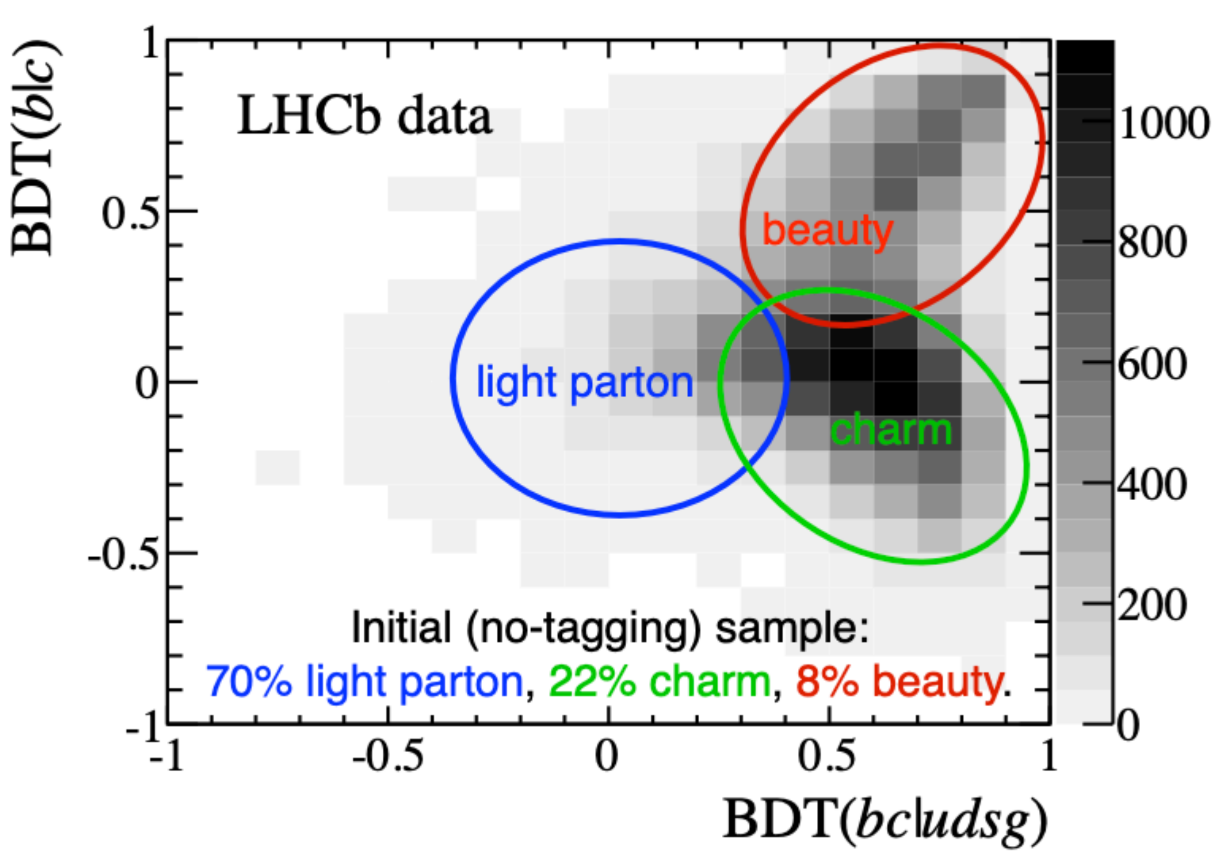


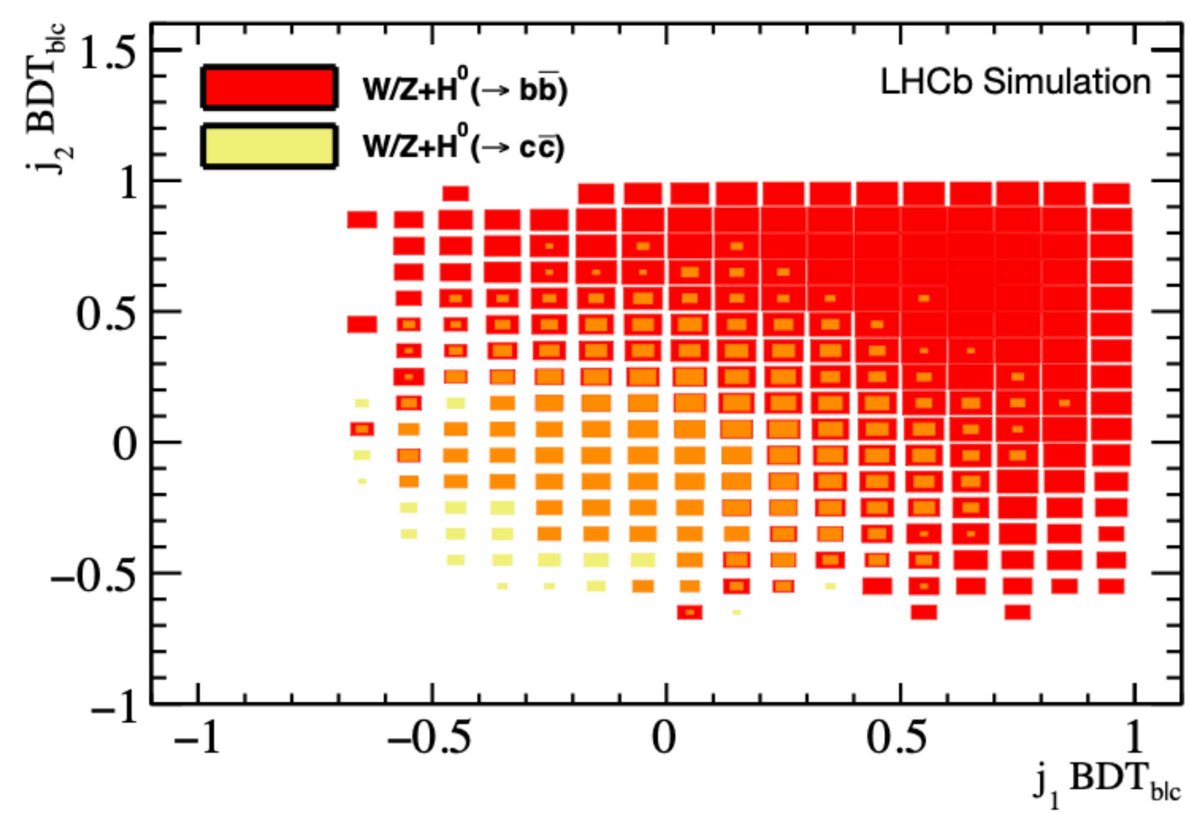
Full Run 2 statistics to be exploited in most cases, more modes ($\tau^+ \to \mu^+\mu^-\mu^+$, …)

QCD and Electroweak physics

LHCb geometry and momentum coverage provides access to a kinematic region complementary to other LHC expts for: Z and W production, parton distribution functions, W mass measurement down to few MeV (μ and e final states), effective weak mixing angle ($Z \to \ell^+\ell^-$ FB asymmetry at higher rapidities).

LHCb vertexing capability provides excellent discrimination btw different flavour jets for: $t\bar{t}$ production cross-section in the FW region down to ~4%, stringent limits on charm Yukawa coupling down to $\sim 2y_{\rm SM}$



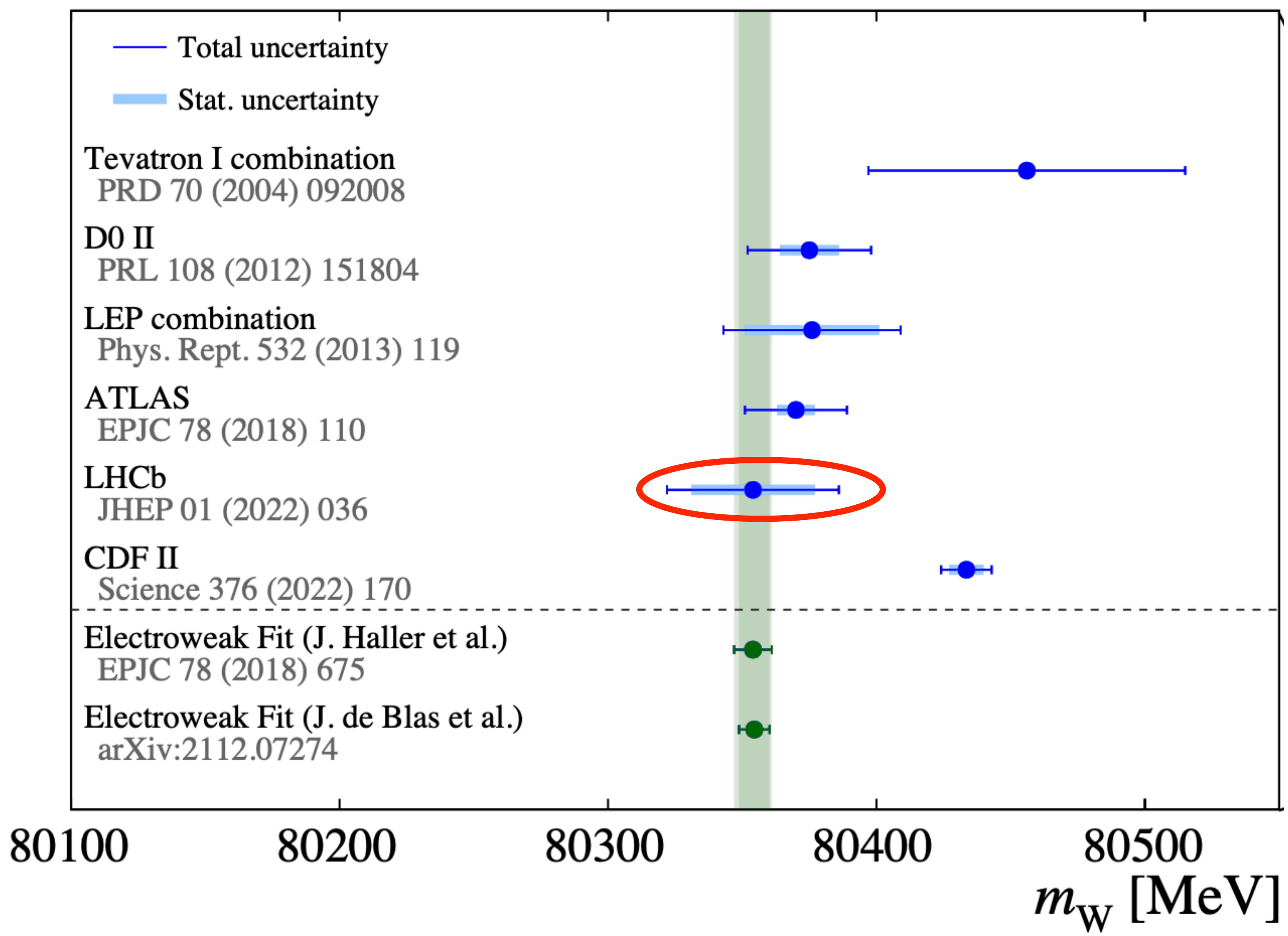


Measurement of m_W

Proof of principle measurement made on 2016 data

$$m_W = 80354 \pm 23_{stat} \pm 10_{exp} \pm 17_{theo} \pm 9_{PDF} \text{ MeV}$$

- *Stat error with full Run 2 will be better than ~10 MeV*
- *Will work with theory to improve the error on p_T and angular spectrum*
- *Excellent prospects for an LHC average, since PDF uncertainty is partially anti-correlated btw LHCb and ATLAS/CMS*



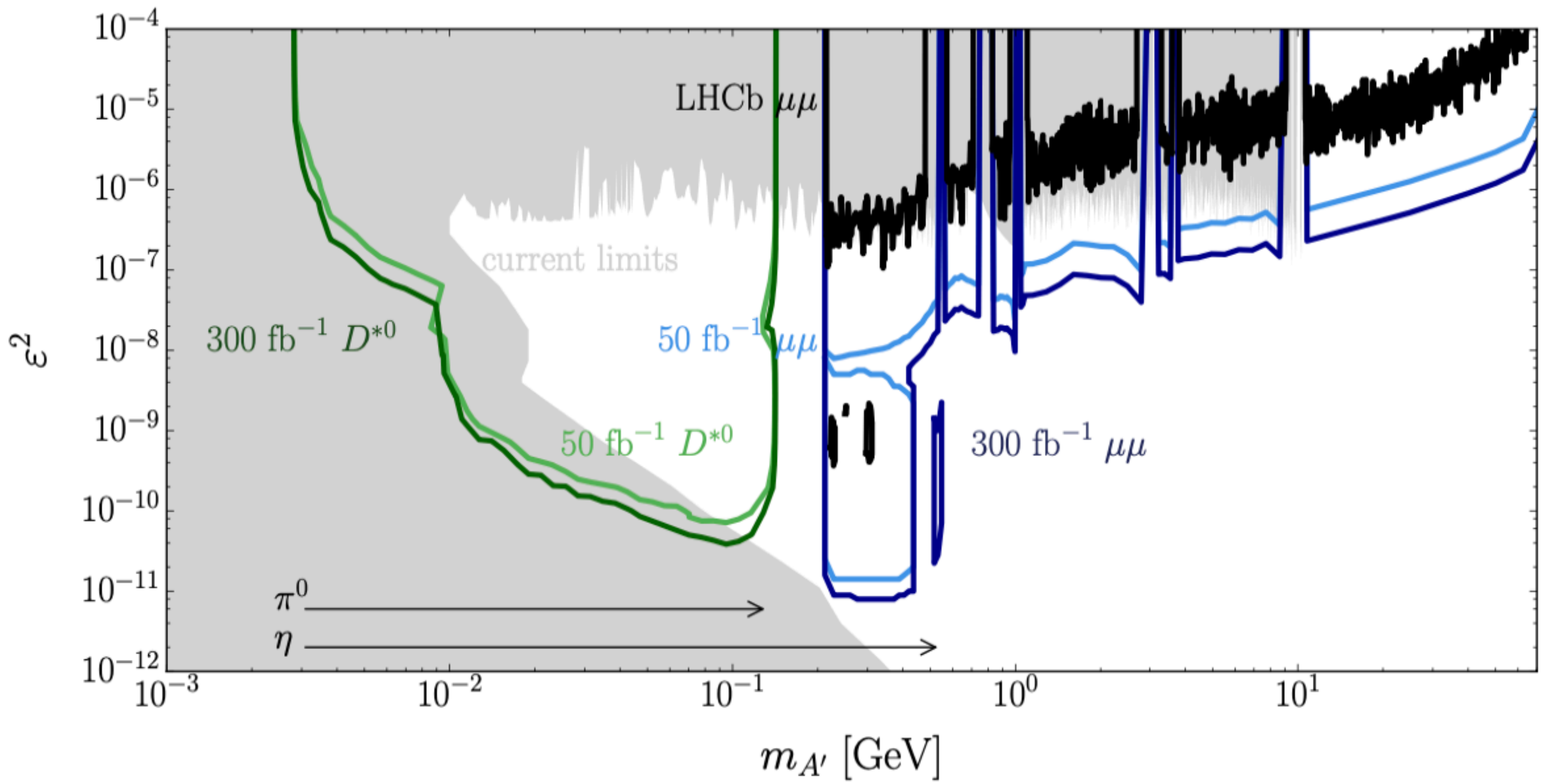
YES, LHCb is a general-purpose detector in the forward region!

Dark Sector

LHCC-2018-027

LHCb can explore significant portions of unconstrained A' parameter space. These searches are based on two strategies: prompt and displaced resonance searches using $D^{*0} \to D^0 e^+ e^-$ decays (green), and inclusive dimuon production (blue).

Presence of VELO enhances sensitivity to long-lived particles and hence probes complementary parts of the parameter space of NP models to ATLAS and CMS.



Heavy Ions

LHCC-2018-027

Unique forward coverage, in combination with particle identification and precision vertexing, gives access to many observables of interest:

Quarkonium and open heavy flavour

- *Ψ(2S), Υ*
- *open charm and beauty mesons down to $p_T \sim 0$*
- *P wave charmonium states, also for fixed target*

Dileptons and photons

- *dilepton spectrum in di-muon channel in the rho mass region*
- *real photons through conversions*

Nuclear PDFs and saturation

- *low-x regime of QCD*

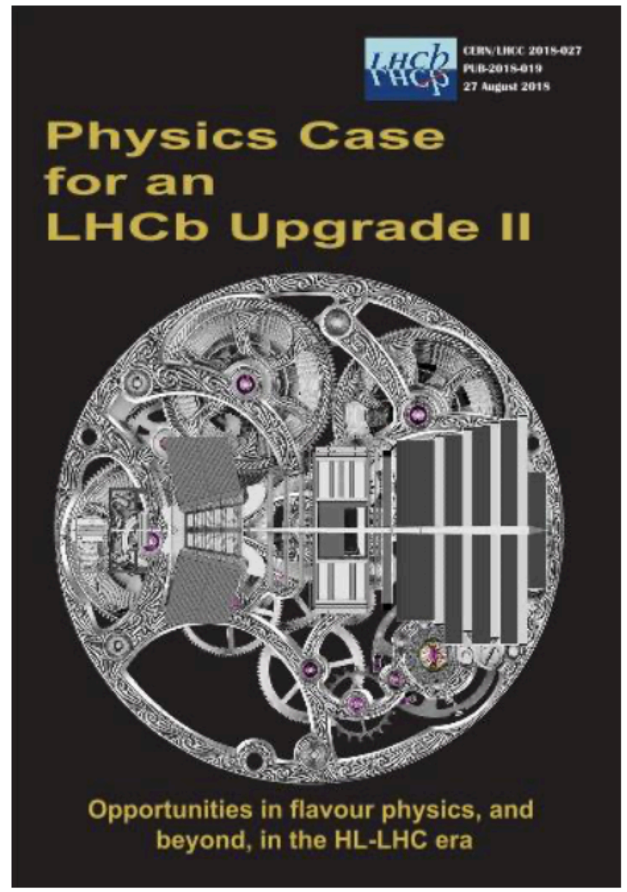
Reconstructing all the charged tracks produced in these collisions requires tracking detectors with high granularity. The use of pixel detectors in the inner region of the Mighty Tracker provides the potential to cover the full centrality range, while the addition of magnet stations will improve the efficiency for low momentum tracks.

LHCb upgrade II: previous steps

Expression of Interest

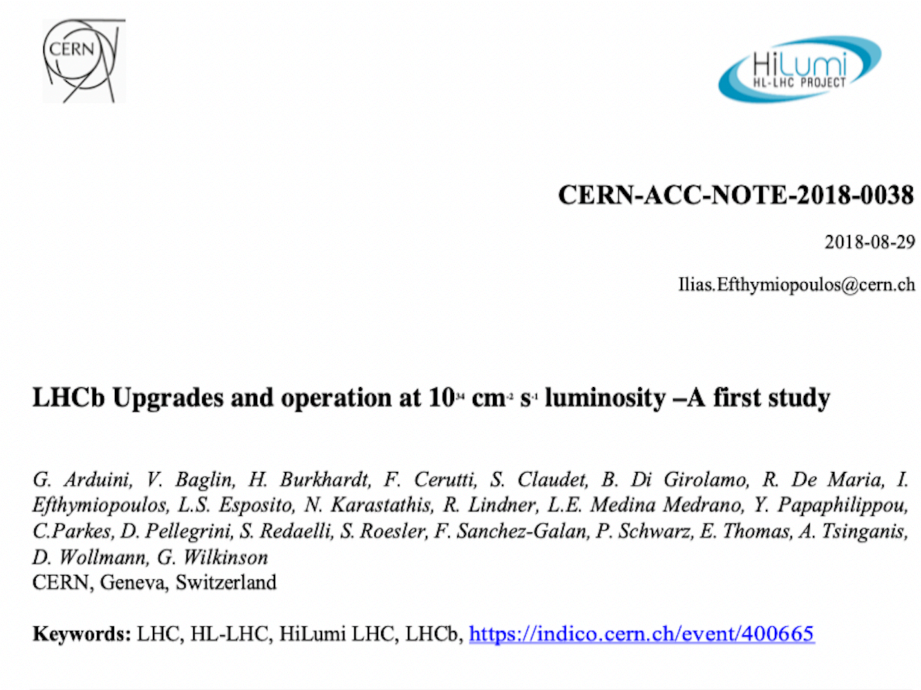
[LHCC-2017-003]()

Physics case



[LHCC-2018-027]()

Accelerator study



CERN-ACC-NOTE-2018-0038

2018-08-29

Ilias.Efthymiopoulos@cern.ch

LHCb Upgrades and operation at 10^{34} cm^{-2} s^{-1} luminosity –A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Keywords: LHC, HL-LHC, HiLumi LHC, LHCb, https://indico.cern.ch/event/400665

[CERN-ACC-2018-038]()

CERN Research Board
September 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."

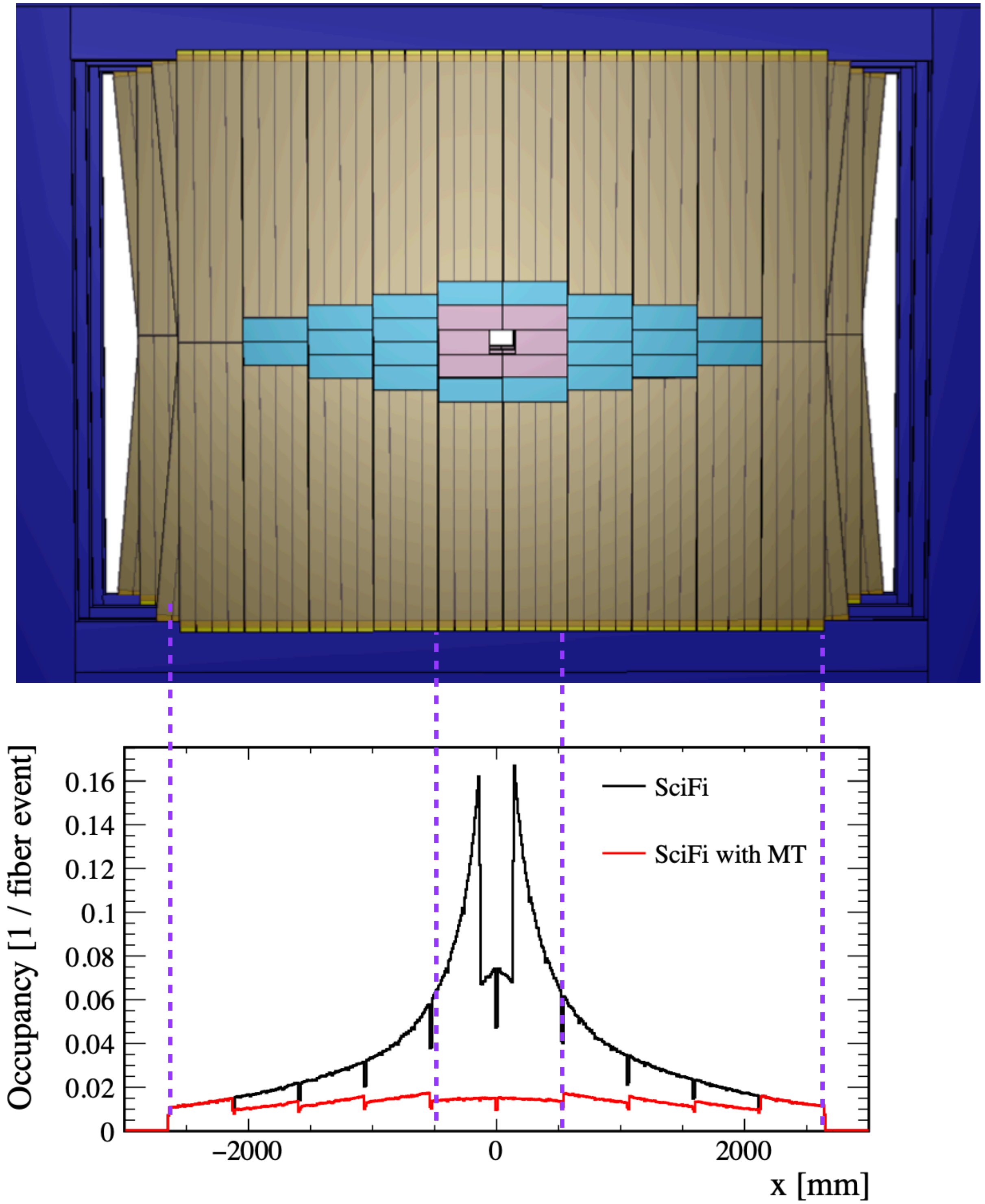
European Strategy Update 2020 *"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"*

Downstream tracking: Mighty Tracker

- *Monolithic Active Pixel Sensors in the inner region ($50 \times 150 \mu m^2$): low-cost commercial process, low material budget*

- *Scintillating fibres in the outer region*

- *Full fibre tracker not sufficient for track reconstruction (~50% efficiency, ~100% fake rate); the proposed design ensures long track efficiency ≥90%, similar to UI*



Detector R&D

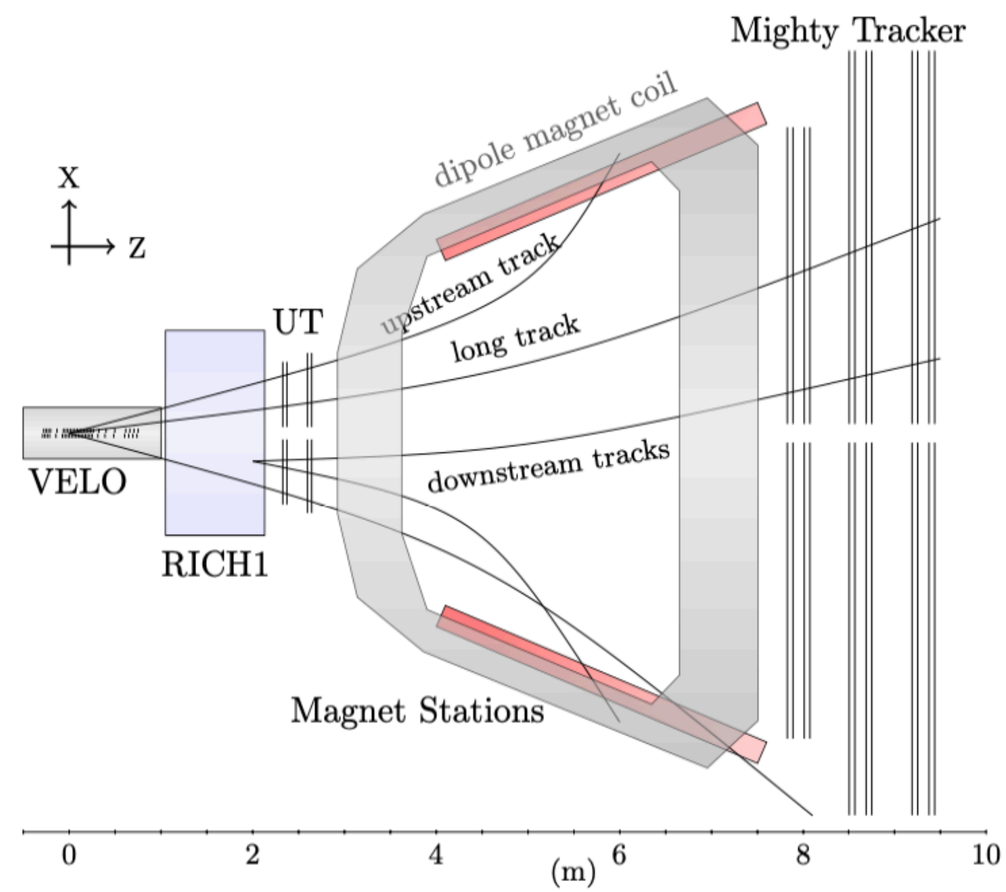
- *MAPS: multiple options (e.g. HV-CMOS), need to improve time resolution*
- *SciFi: radiation-hard fibres, cryogenic cooling, micro-lens enhanced SiPMs*

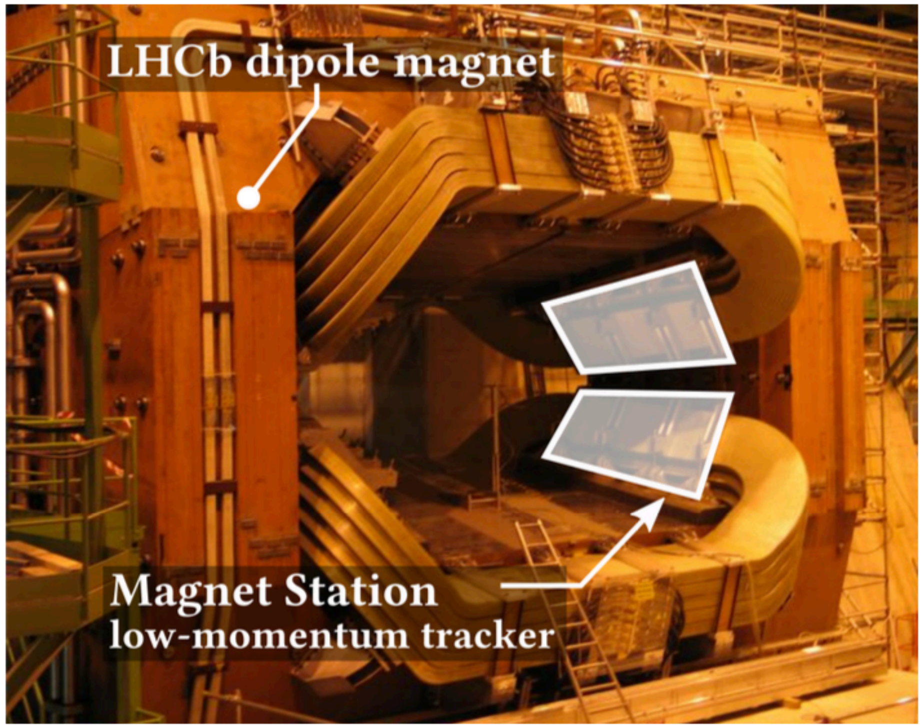
  → depending on the results, possible reduction of the area covered by MAPS

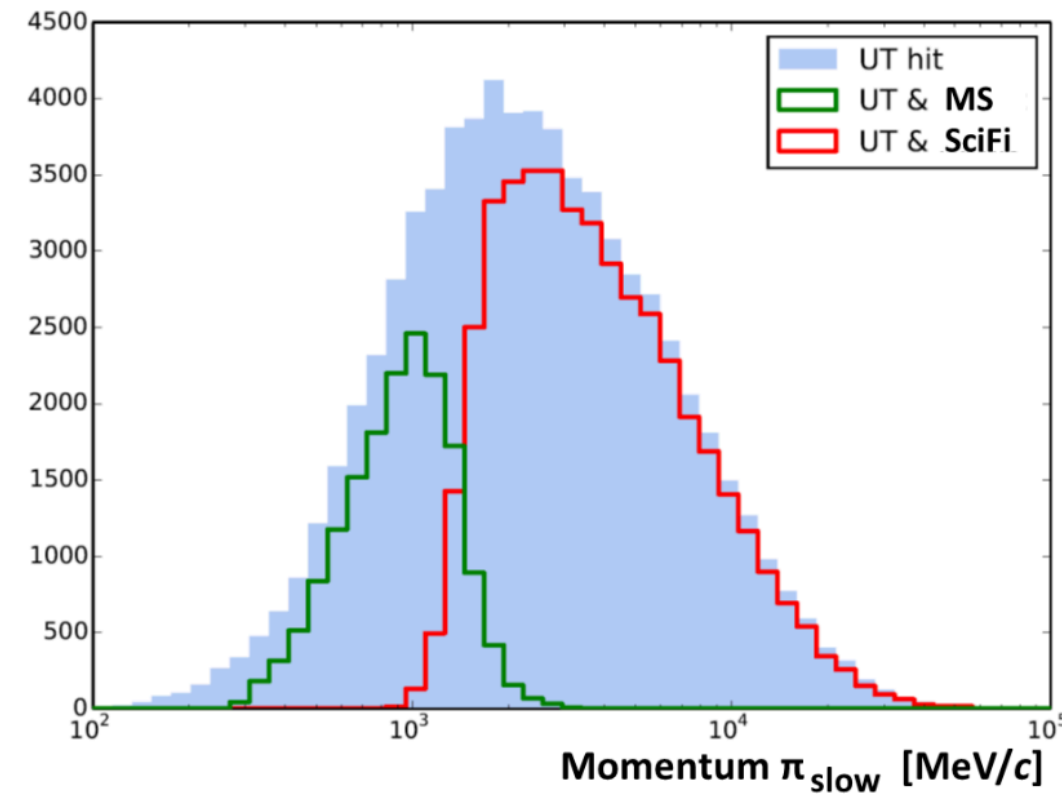
MAPS technology also being considered for UT

Magnet Stations

- *Scintillating-based tracking subsystem inside the magnet to measure the position and direction of particles hitting the magnet side walls. This improves the momentum resolution of **upstream** tracks to a sub-percent level, with significant benefit for the physics program*
- *Significant increase of acceptance for low momentum tracks, e.g. factor of ~2 gain in prompt D^{*+} with slow π*



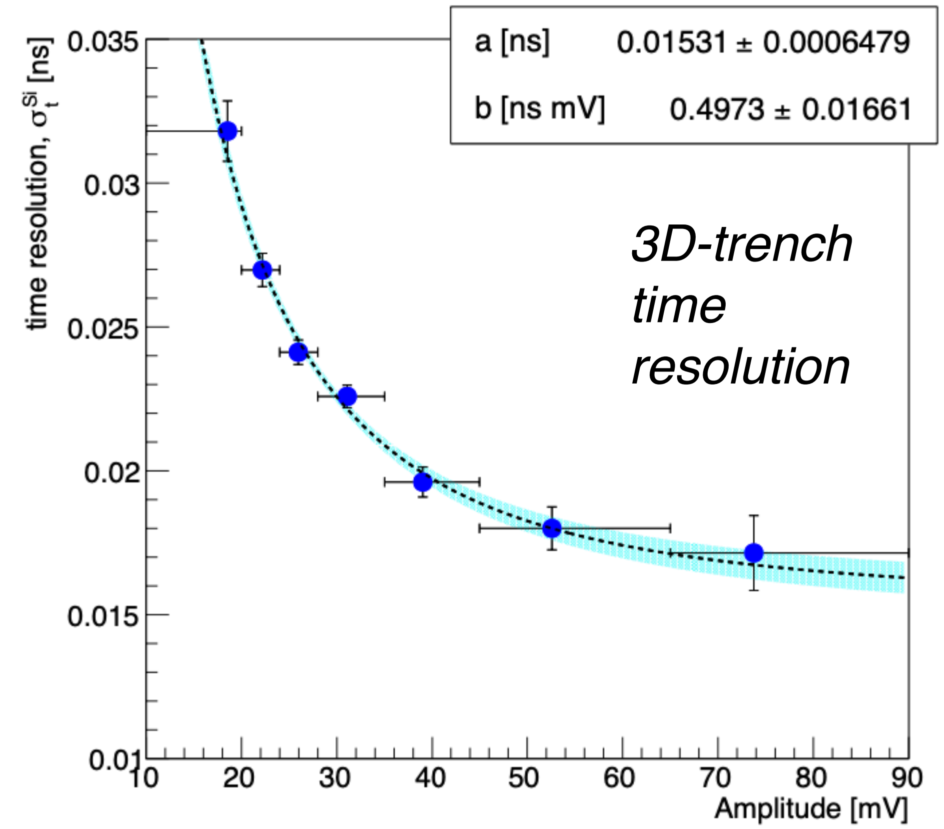




R&D on tracking

VELO

- Sensor technologies emerging: LGAD, 3D
- Very promising test-beam results on 3D with excellent timing resolution demonstrated
- Future ASIC (28 nm): Velopix2 (Timepix4), TimeSpot

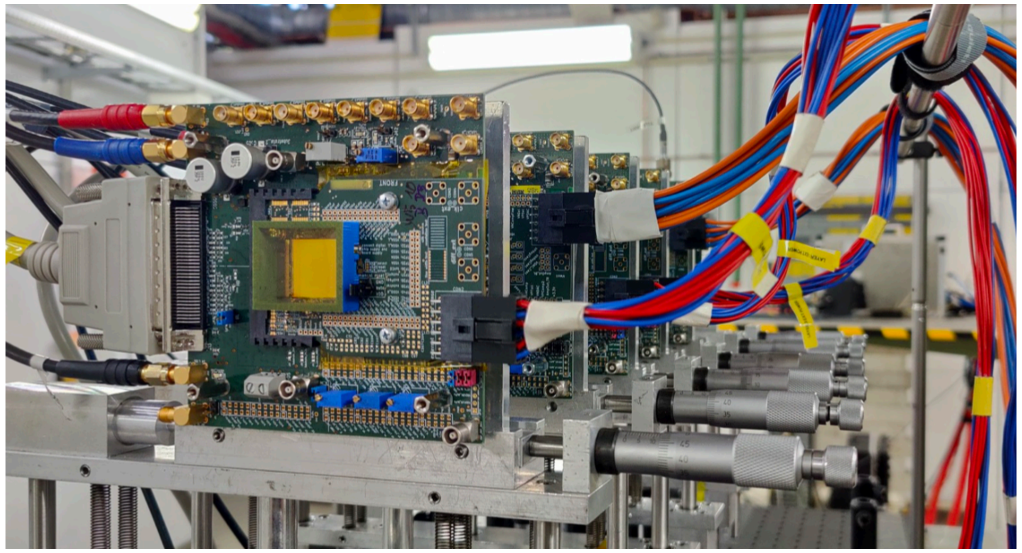


JINST 15 (2020) P09029

UT (upstream) and Mighty Tracker (downstream)

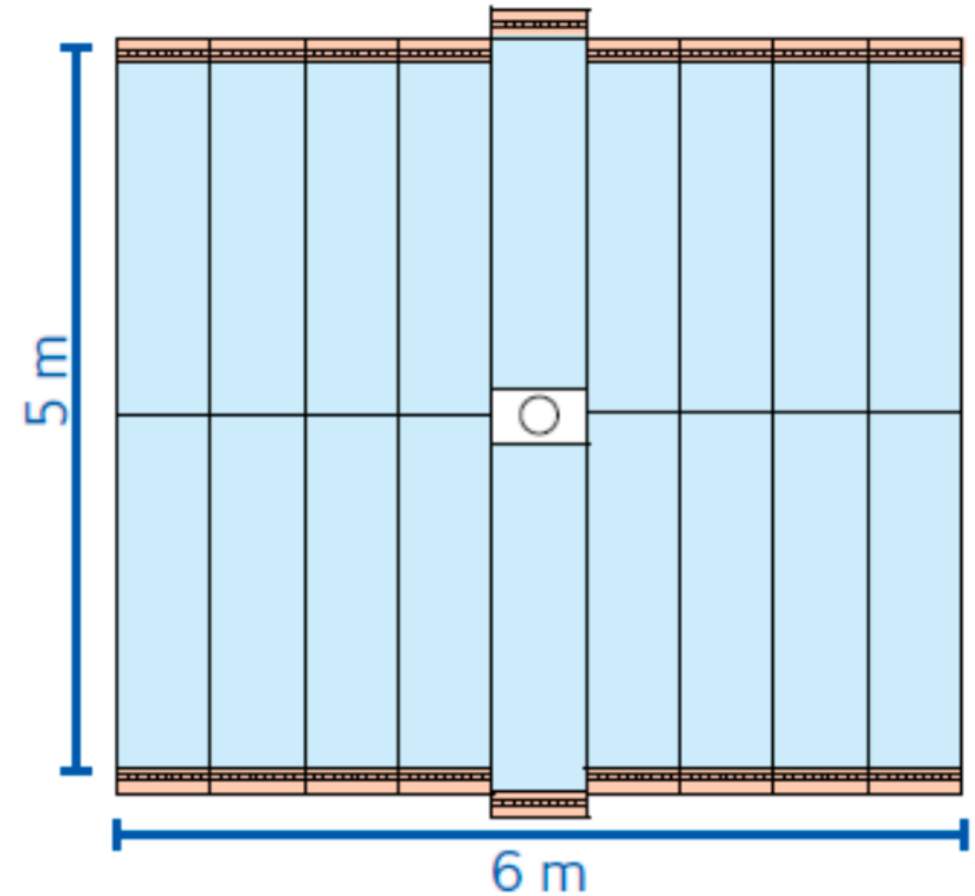
- Depleted Monolithic Active Pixel Sensors very promising and cost effective technology for large area pixel detectors
- Integrated pixel sensor and chip on single piece of silicon: low-cost commercial process, low material budget
- Multiple options (e.g. HV-CMOS) being tested

MightyPix1 MAPS under test at DESY



Adding TORCH time-of-flight

- *30 m² ToF detector with quartz plane readout by MCP-PMTs placed in front of RICH2*
- *will provide p/K separation <10 GeV/c and improve π/K separation <5 GeV/c, through 10-15 ps time resolution per track*



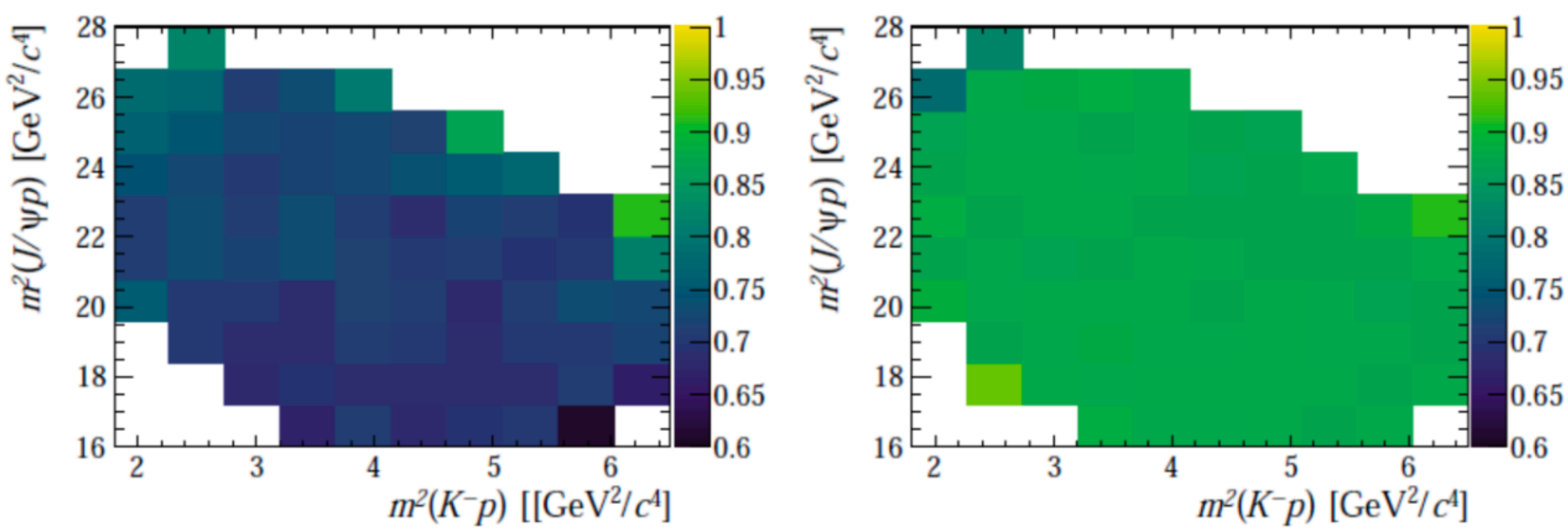
Detector R&D

- *Photon yields observed that are close to simulation, and time resolution that approach the 70 ps goal per photon*

Physics benefits from low momentum PID

- *Increased efficiency and background suppression for many channels*
- *Improvements to flavour tagging with soft kaons by 25-50%*
- *Improved uniformity in PID acceptance*

Dalitz plot efficiency for $\Lambda_b \to J/\psi p K^-$ *w/o and with TORCH*

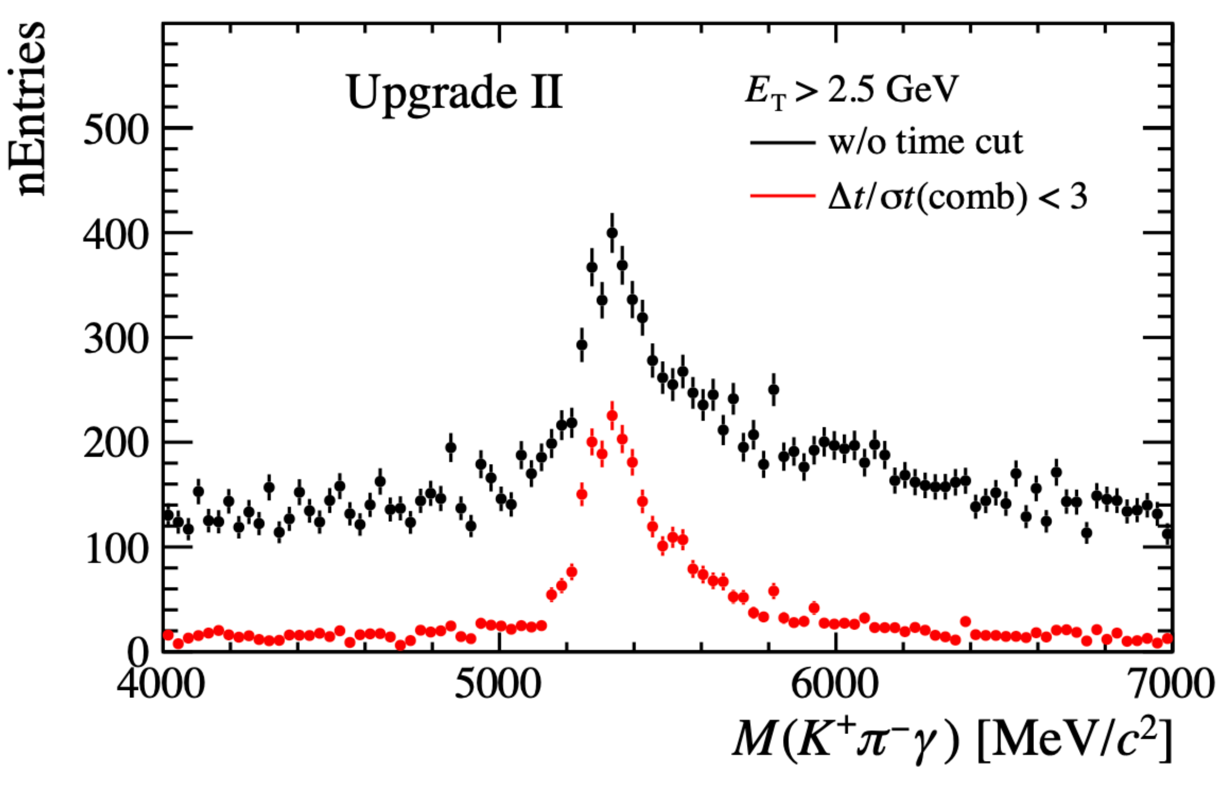


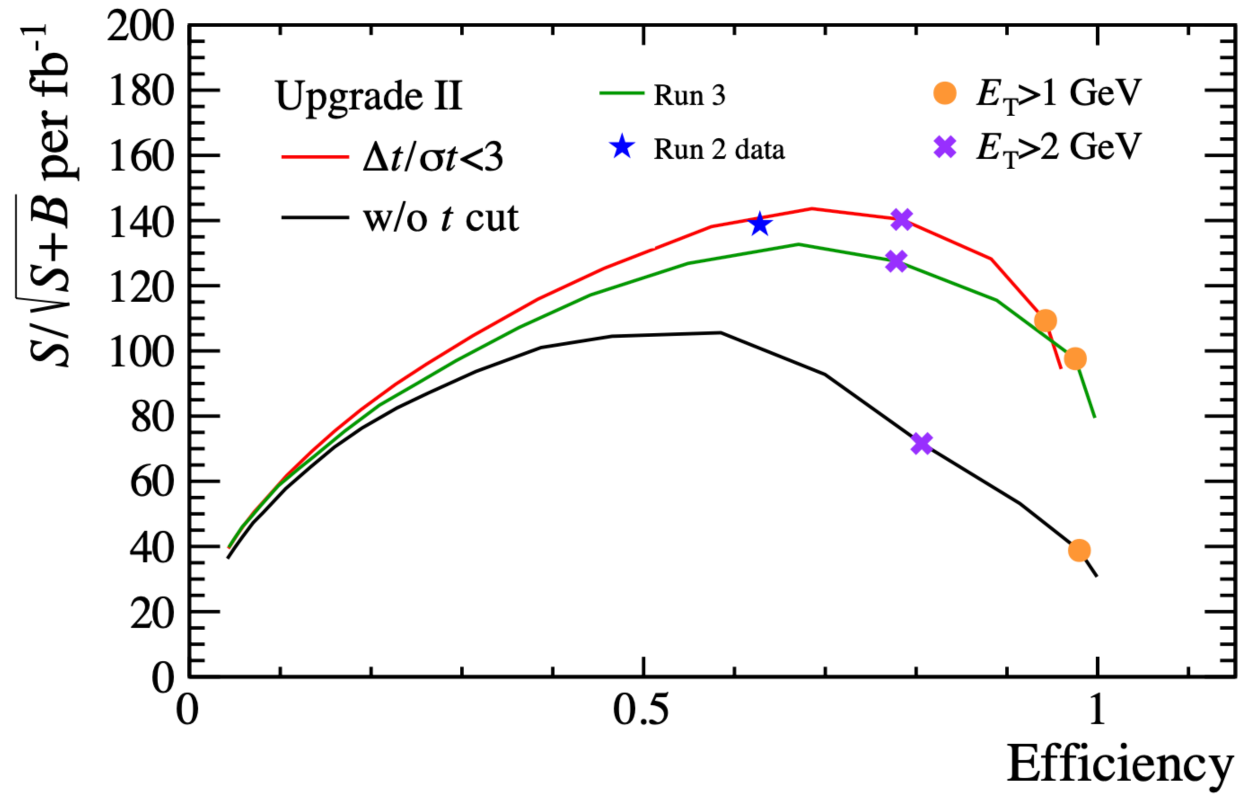
ECAL with timing

Goal: to achieve an energy resolution and reconstruction efficiency similar to Run 1/2, despite the much higher pile-up and radiation levels (up to 1 MGy)

Key ingredients: granularity increase, longitudinal segmentation, precise timing information

Effect of timing information (few tens of ps resolution) on $B^0 \to K^{*0}\gamma$

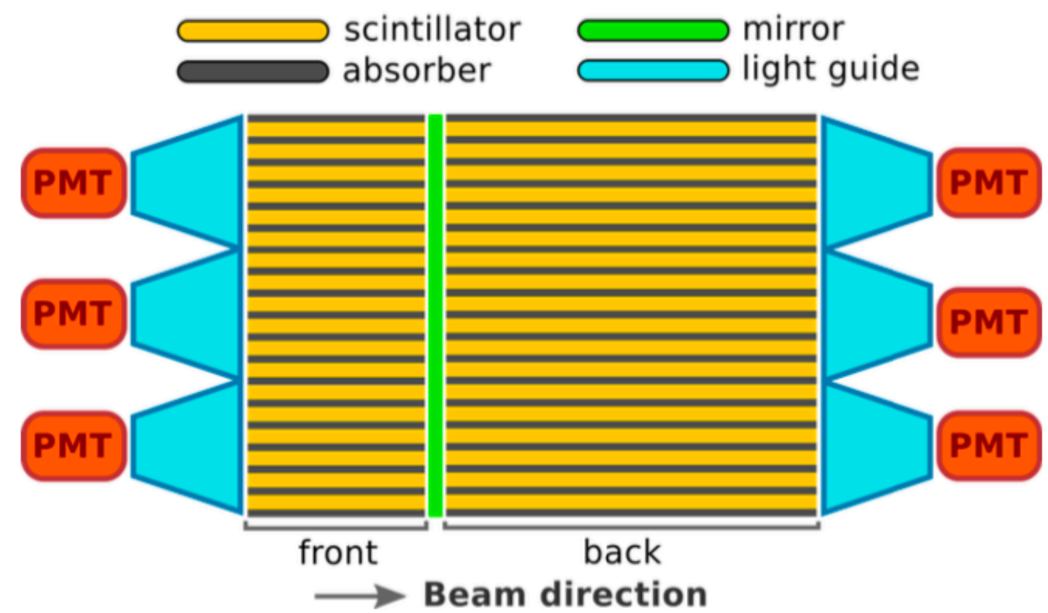




(Full simulation results on SpaCal/Shashlik ECAL)

ECAL technology: SpaCal/Shashlik

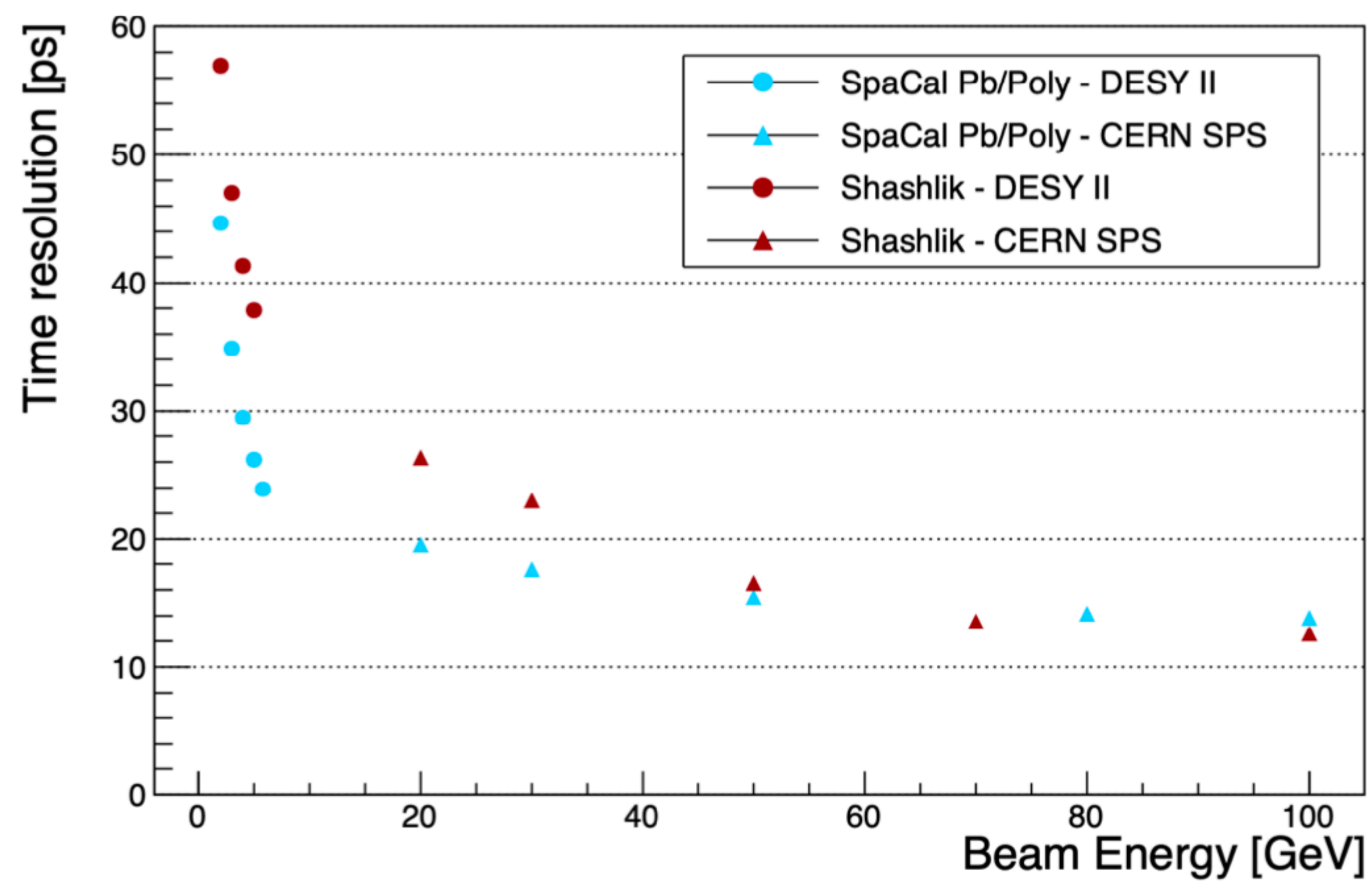
- > 200 kGy region: *SpaCal Tungsten + GAGG crystal fibres*
- > 40 kGy region: *SpaCal Lead + Polystyrene*
- *outer regions: Shashlik modules similar to present detector*



Detector R&D

- *Resolution of* $\sim 10\,\%/\sqrt{E}$ *achieved in test beam*
- *Time resolution of 15 ps obtained in test beams for both SpaCal and Shashlik modules*

→ future studies will focus on the rate dependence, PMPT ageing, S/N



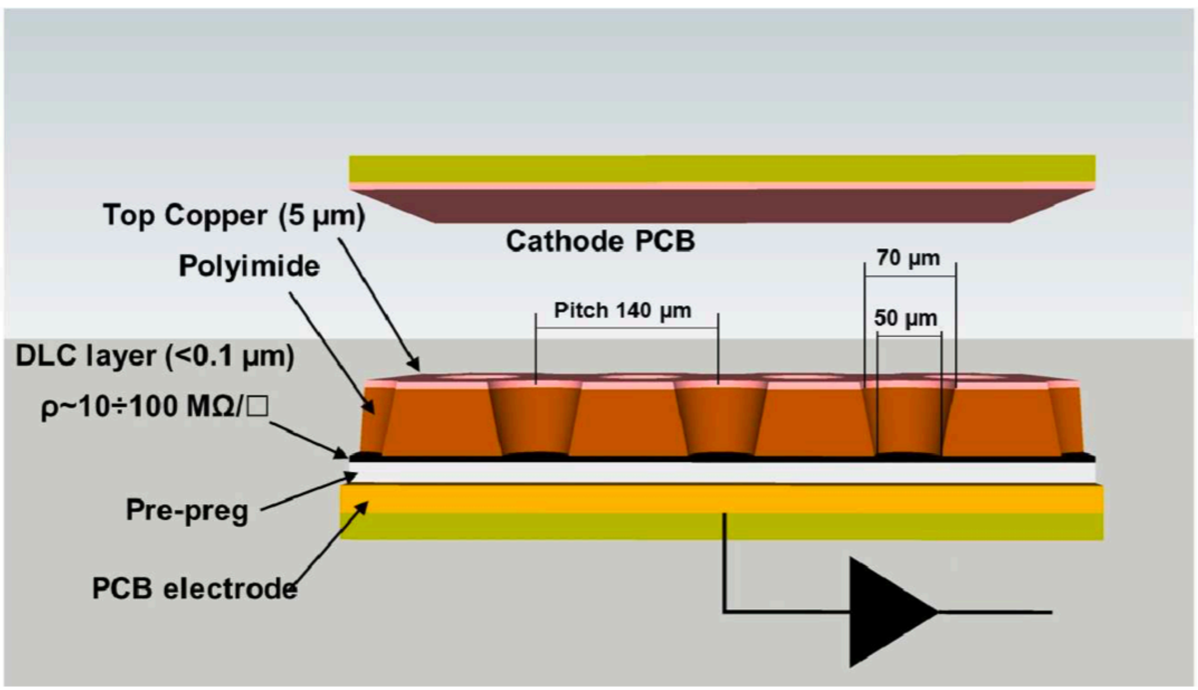
At the moment, this is considered as the baseline solution

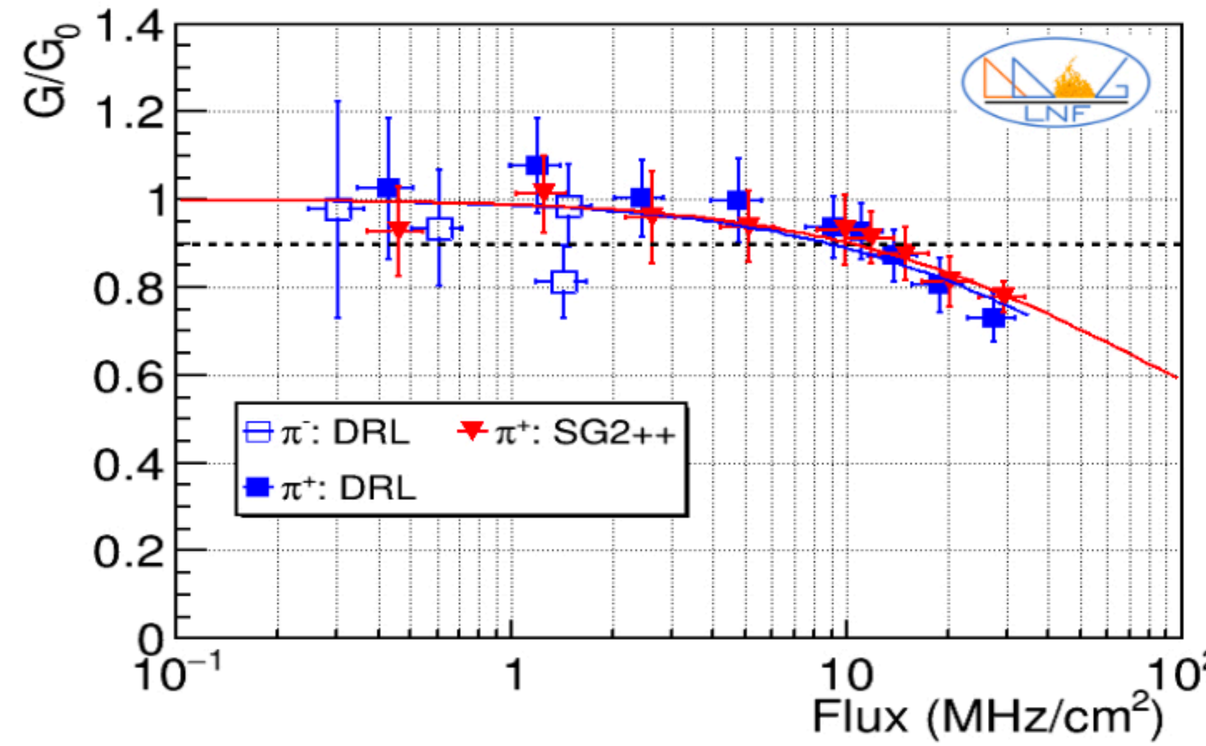
MUON

JINST 14 (2019) P05014

Novel MPGD μ-RWELL detectors proposed for innermost regions, capable to stand up to several MHz/cm² → 144 chambers to be built

Detector R&D *Ageing studies ongoing at PSI and GIF++, front-end electronics under development*





For external regions, baseline option is to keep most of the present MWPCs chambers → 880 MWPC reused, 80 to be rebuilt with higher granularity

Detector Studies *Ageing studies at GIF++, new options for front-end electronics under study*

Additional shielding ($6\lambda_I \rightarrow 10\lambda_I$) will be installed in front of Muon detector in place of HCAL, which will bring down the rate by a factor of ~2