The LHCb Upgrade II project

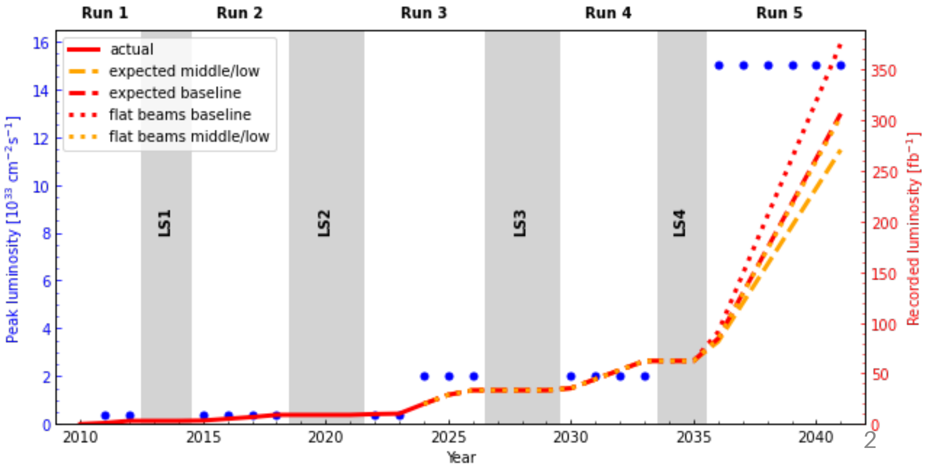
Patrick Robbe, IJCLab Orsay & CERN, 2 June 2025

LHCb Upgrade II

Run 1-2

$L=4 \times 10^{32}\ cm^{-2}.s^{-1}$
~1.1 interaction per bunch crossing
~9 fb^{-1} (Run 1+2)

- Most of the observables in heavy flavour dominated by ***statistical uncertainties*** at the end of Run 4
- New detector proposed for LHCb during Run 5 of the LHC to integrate ***300 fb^{-1}*** of data at the end of the LHC and exploit the full potential of HL-LHC for heavy flavor physics

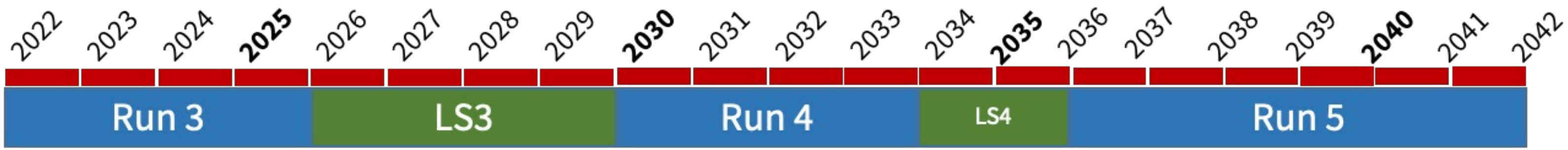


Physics Program

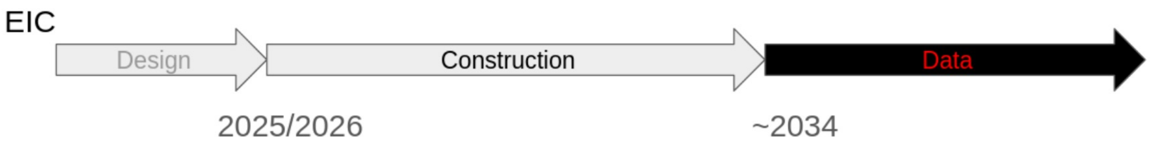
- Unique and broad program with Beyond Standard Model discovery potential for full exploitation of High Luminosity LHC:
  - Unique ***forward acceptance*** at the LHC
  - Unprecedented sensitivity for ***flavour physics in B and D decays***
  - ***Spectroscopy***, ***electroweak*** precision measurements, ***heavy ion*** physics, …
  - Beyond luminosity scaling, thanks to ***new detectors and techniques***
- Flavour physics linked to several important open questions in high energy physics: ***matter/antimatter imbalance***, ***mass hierarchy of fermions***, ***strong CP problem***, ***dark matter, color confinement***
- Strategy: increase statistics to probe new physics with indirect searches:
  - Look for ***deviations from theory*** predictions in precise measurements of Standard Model processes
  - Search for ***rare decays***, highly suppressed or forbidden in the Standard Model
- Precision measurements in flavour physics will lead to sensitivity to new physics scale ***above 10 TeV***

Other facilities

ATLAS/ALICE/CMS/LHCb



LHCb Upgrade 2 / ALICE 3



Belle II [arXiv:2406.19421]

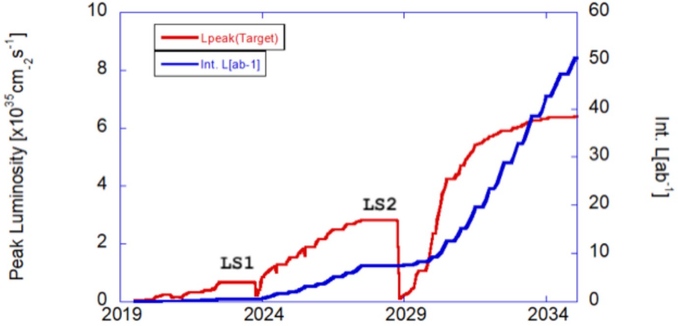


Figure 1.3: Projected luminosity for SuperKEKB.

LS2: Detector and accelerator upgrades (time of LS2 not yet certain)

+ flavour physics programs at future accelerators

Ingredients for high precision in heavy flavour

High production rate	Large data sample	Selection efficiency	Ability to resolve signal
b/*c* cross-section enormous at LHC	Collect maximum possible by end of HL-LHC	Go beyond precision gain with statistics with enhanced detector capabilities	In flavour physics: momentum and vertex resolution, hadron PID (π,K,p)

Matched only by ATLAS and CMS

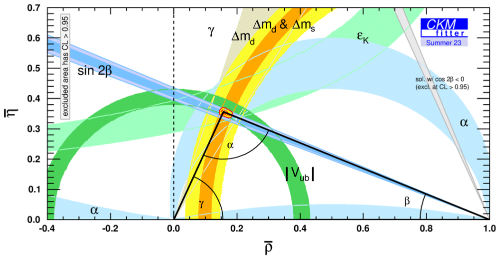
Channel dependent

- (e,μ,p,π,K): LHCb unique and superior to any other experiment for final states with only charged stable particles. ATLAS & CMS competitive with decays with μ.
- One or more γ, π^0 or ν: Belle II competitive or superior.

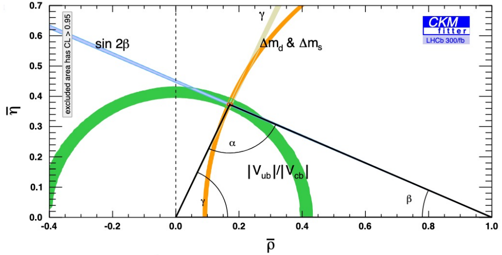
Standard Model Benchmarks

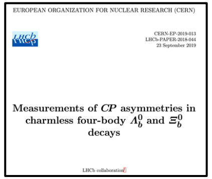
- In Standard Model (SM), *CP* violation described by CKM mechanism:
  - Matter-antimatter asymmetry from SM sources is not enough: need additional sources of *CP* violation
  - Many New Physics (NP) models predict new CP-violation processes
- Need precision measurement of the CKM parameters from complementary methods:
  - Tree level processes: γ, V_{ub}, V_{cb}
  - Involving flavour-changing neutral current (FCNC) processes, in SM only through loop diagrams: β, oscillation frequencies: Δm_d, Δm_s
  - Tensions between the two can reveal NP processes
- Golden benchmark is γ: measured at tree level with decays of the type $B \to D^{(*)}K^{(*)}$, possibly with a $\pi^0 \to \gamma\gamma$ in the *D* final state:
  - Direct measurements: precision of 3° [LHCb-CONF-2024-004]; constraints from indirect measurements: precision of 1°
  - With upgrade II: precision of 0.3°
  - Charmless decays such as $B \to K_S^0\, hh'$ are also sensitive to γ
- Precision measurements of $|V_{ub}|$ and $|V_{cb}|$ with new modes: B_c^+ decays, $B_s^0 \to K^- \mu\, \nu_\mu$, …

Global CKM fit 2023



With LHCb Upgrade II

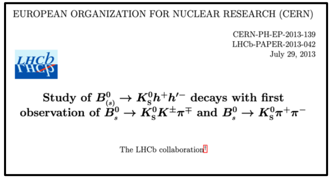



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-013
LHCb-PAPER-2018-044
23 September 2019

Measurements of *CP* asymmetries in charmless four-body Λ_b^0 and Ξ_b^0 decays

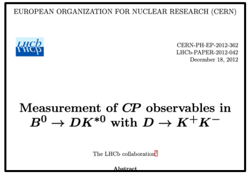
LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2013-139
LHCb-PAPER-2013-042
July 29, 2013

Study of $B^0_{(s)} \to K^0_S h^+ h'^-$ decays with first observation of $B^0_s \to K^0_S K^\pm\pi^\mp$ and $B^0_s \to K^0_S\pi^+\pi^-$

The LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-362
LHCb-PAPER-2012-042
December 18, 2012

Measurement of *CP* observables in $B^0 \to DK^{*0}$ with $D \to K^+K^-$

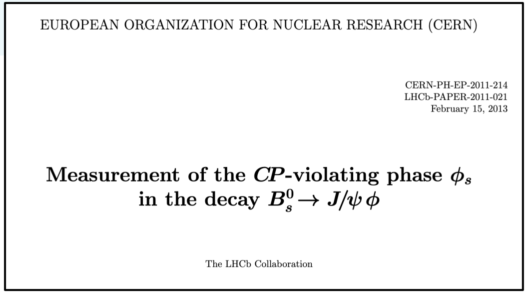
The LHCb collaboration

Abstract

Observable precision	Current LHCb (9fb^{-1})	Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})	Belle II (50 ab^{-1})
$\gamma(B\to DK$, etc.)	2.8°	1.3°	0.8°	0.3°	1.0°
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu\nu$, etc.)	6%	3%	2%	1%	1%
	[LHCb Upgrade II Scoping Document]				[arXiv:2207.06307]

New Physics in *CP* violation

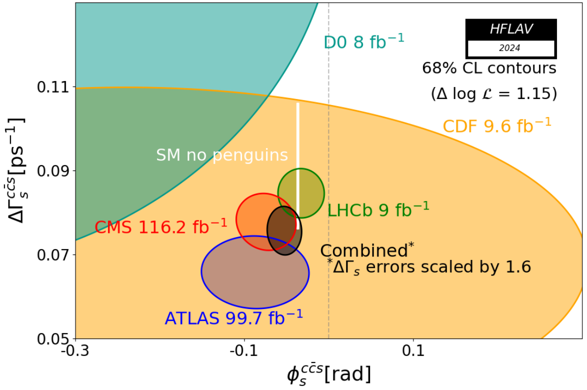
- Weak phase ϕ_s in interferences between B_s^0 oscillations and $b \to c\bar{c}s$ decay is sensitive to NP:
  - small value in SM: ϕ_s= 37±1 mrad
- Current measured value of ϕ_s compatible with 0, observation of non-zero value can be reached at the end of Run 4.
  - Upgrade II will improve the precision of the measurement to 1 mrad
    - Reached with $B^0_s \to J/\psi\phi$ and $B^0/B^0_s \to J/\psi\pi^+\pi^-$
  - ϕ_s can also be measured with charmless $B^0_s \to \phi\phi$ and $B^0_s \to K^{*0}\bar{K}^{*0}$ and input from $B^0 \to K^{*0}\bar{K}^{*0}$
- *CP* violation in B^0 and B^0_s mixing is expected small in the Standard Model: measured with semi-leptonic decays, a_{sl}^d and a_{sl}^s.


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2011-214
LHCb-PAPER-2011-021
February 15, 2013

Measurement of the *CP*-violating phase ϕ_s in the decay $B^0_s \to J/\psi\,\phi$

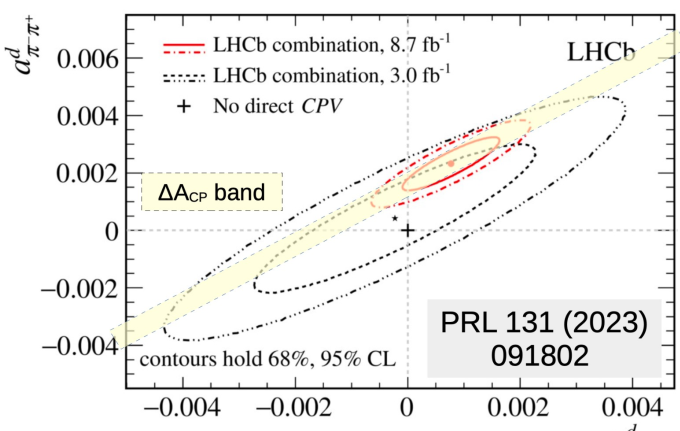
The LHCb Collaboration



Observable precision	**Current LHCb** (9fb^{-1})	**Upgrade I** (23 fb^{-1})	(50 fb^{-1})	**Upgrade II** (300 fb^{-1})	**ATLAS/CMS** (3000 fb^{-1})
$\phi_s(B_s^0 \to J/\psi\phi)$	20 mrad	12 mrad	8 mrad	3 mrad	4-9 mrad/3 mrad
a_{sl}^d	3.6%	0.8%	0.5%	0.2%	
a_{sl}^s	3.3%	1.0%	0.7%	0.3%	
[LHCb Upgrade II Scoping Document], [arxiv:1808.08865]					[ATL-PHYS-PUB-2018-041][CMS FTR-18-041]

New Physics in Charm

- *CP* violation probes NP in a fundamentally different way in *D* than in *B* and *K* decays:
  - Expected very small in the SM
  - First observation made at LHCb measuring $\Delta A_{CP} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$
  - Measurement with new decays (some with π^0) are required to understand if this *CP* violation is explained in the SM
- *CP* violation in D^0 mixing is an important observable, expected at the 10^{-5} level (A_{Γ}, Δx)
- Due to huge charm production cross-section, LHCb upgrade II is the only experiment that will reach the necessary precision to understand *CP* violation in charm.

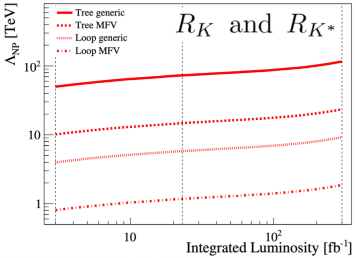


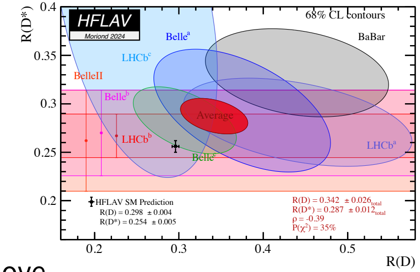
[PRL 122 (2019) 211803]

Observable precision	Current LHCb (9fb^{-1})	Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})	Belle II (50 ab^{-1})
$\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$	29×10^{-5}	13×10^{-5}	8×10^{-5}	3.3×10^{-5}	6.0×10^{-4}
$A_{\Gamma}(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5}	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}	
$\Delta x(D^0 \to K_S^0 \pi^+\pi^-)$	18×10^{-5}	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}	4.0×10^{-4}
		[LHCb Upgrade II Scoping Document]			[hep-ex:arXiv:1808-10567]

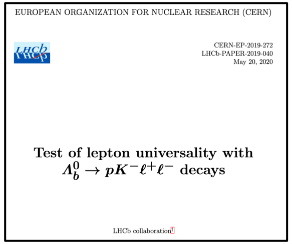
New Physics with Lepton Flavours

- Lepton universality given by the SM can be tested with $b \to s\ell^+\ell^-$ comparing ℓ=e and ℓ=μ
  - Measurements of R(X) = BR($B \to X\mu\mu$) / BR($B \to Xee$) with unparalleled precision at Upgrade II with several B species
  - Rarer modes with $b \to d\ \ell^+\ell^-$ will then be also possible.
- Lepton universality tests with semi-leptonic B decays, comparing ℓ=τ and ℓ=μ, e.g. R(D^*)=BR($B \to D^*\tau\nu$)/BR($B \to D^*\mu\nu$):
  - All b hadron species are accessible at LHCb Upgrade II, including the B_c^+ decays





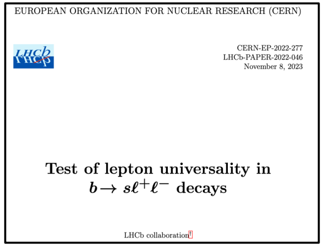
Generic NP scales probed above 100 TeV with Upgrade II statistics


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-272
LHCb-PAPER-2019-040
May 20, 2020

Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays

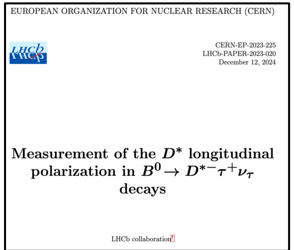
LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2022-277
LHCb-PAPER-2022-046
November 8, 2023

Test of lepton universality in $b \to s\ell^+\ell^-$ decays

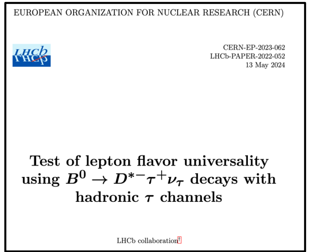
LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-225
LHCb-PAPER-2023-020
December 12, 2024

Measurement of the D^* longitudinal polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-062
LHCb-PAPER-2022-052
13 May 2024

Test of lepton flavor universality using $B^0 \to D^{*-}\tau^+\nu_\tau$ decays with hadronic τ channels

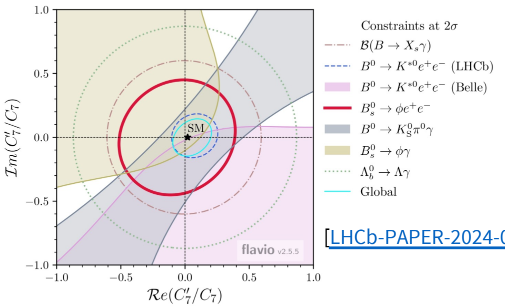
LHCb collaboration

Observable	**Current LHCb**	**Upgrade I**		**Upgrade II**	**Belle II**
precision	(9fb^{-1})	(23 fb^{-1})	(50 fb^{-1})	(300 fb^{-1})	(50 ab^{-1})
R_K (1.1<q^2<6 GeV^2/c^4)	0.05	0.025	0.018	0.007	0.036
R_{K^*} (1.1<q^2<6 GeV^2/c^4)	0.08	0.031	0.022	0.008	0.032
R(D^*)	0.06	0.032	0.03	0.03	0.01
		[arxiv:1808.08865]			[hep-ex:arXiv:1808-10567]/[arXiv:2207.06307]

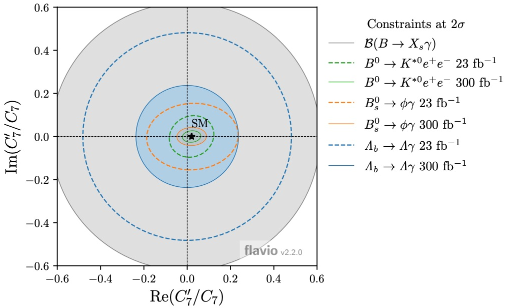
New Physics with Rare Decays

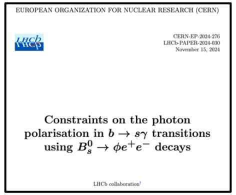
- Right-handed currents can appear in NP processes and show in the polarisation of the photon in $b \rightarrow s\gamma$ transition, only accessible at LHCb with Upgrade II for the necessary precision:
  - $B^0 \rightarrow K^{*0} e^+ e^-$ or similar decays at low e^+e^- mass
  - $B_s^0 \rightarrow \phi\gamma$ or $\Lambda_b \rightarrow \Lambda\gamma$,
- Decays proceeding only through FCNC are highly sensitives to NP:
  - Golden modes are $B_s^0 \rightarrow \mu^+\mu^-$ with $BR_{PDG}=(3.34\pm0.27) \times 10^{-9}$ [SM: $(3.34\pm0.17) \times 10^{-9}$]
  - And the not yet observed $B^0 \rightarrow \mu^+\mu^-$ [SM: $(1.06\pm0.09) \times 10^{-10}$] or $B_s^0 \rightarrow \mu^+\mu^-\gamma$.
  - With Upgrade II data sample, measurements of the decay-time distributions ($\tau(B_s^0 \rightarrow \mu^+\mu^-)$) different from SM predictions would provide unambiguous observation of NP.

Observable precision	Current LHCb (9fb^{-1})	(23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})	ATLAS/CMS (3000 fb^{-1})	Belle II
BR($B^0 \rightarrow \mu^+\mu^-$)	0.79 x 10^{-10}		0.30 x 10^{-10}	0.12 x 10^{-10}	(0.32-0.48) x 10^{-10} / 0.12 x 10^{-10}	
BR($B_s^0 \rightarrow \mu^+\mu^-$)	0.48 x 10^{-9}		0.23 x 10^{-9}	0.16 x 10^{-9}	(0.33-0.40) x 10^{-9} / 0.22 x 10^{-9}	
$\tau(B_s^0 \rightarrow \mu^+\mu^-)$	0.29 ps		0.11 ps	0.05 ps	(0.07-0.11) ps / 0.05 ps	
$A_T^{(2)}(B^0 \rightarrow K^{*0} e^+e^-)$	0.1	0.060	0.043	0.016		0.08
$S_{\phi\gamma}(B_s^0 \rightarrow \phi\gamma)$	0.32	0.093	0.062	0.025		
$\alpha_\gamma(\Lambda_b^0 \rightarrow \Lambda\gamma)$	0.26	0.148	0.097	0.038		
			[LHCb Upgrade II Scoping Document]		[ATL-PHYS-PUB-2018-005][CMS FTR-18-041]	[hep-ex:arXiv:1808-10567]



[LHCb-PAPER-2024-030]

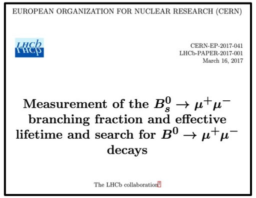



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-276
LHCb-PAPER-2024-030
November 15, 2024

Constraints on the photon polarisation in $b \rightarrow s\gamma$ transitions using $B_s^0 \rightarrow \phi e^+e^-$ decays

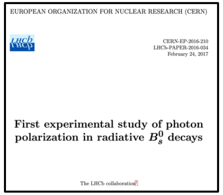
LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2017-041
LHCb-PAPER-2017-001
March 16, 2017

Measurement of the $B_s^0 \rightarrow \mu^+\mu^-$ branching fraction and effective lifetime and search for $B^0 \rightarrow \mu^+\mu^-$ decays

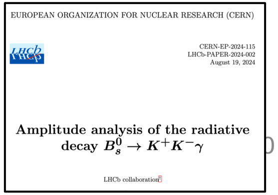
The LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2016-210
LHCb-PAPER-2016-034
February 24, 2017

First experimental study of photon polarization in radiative B_s^0 decays

The LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

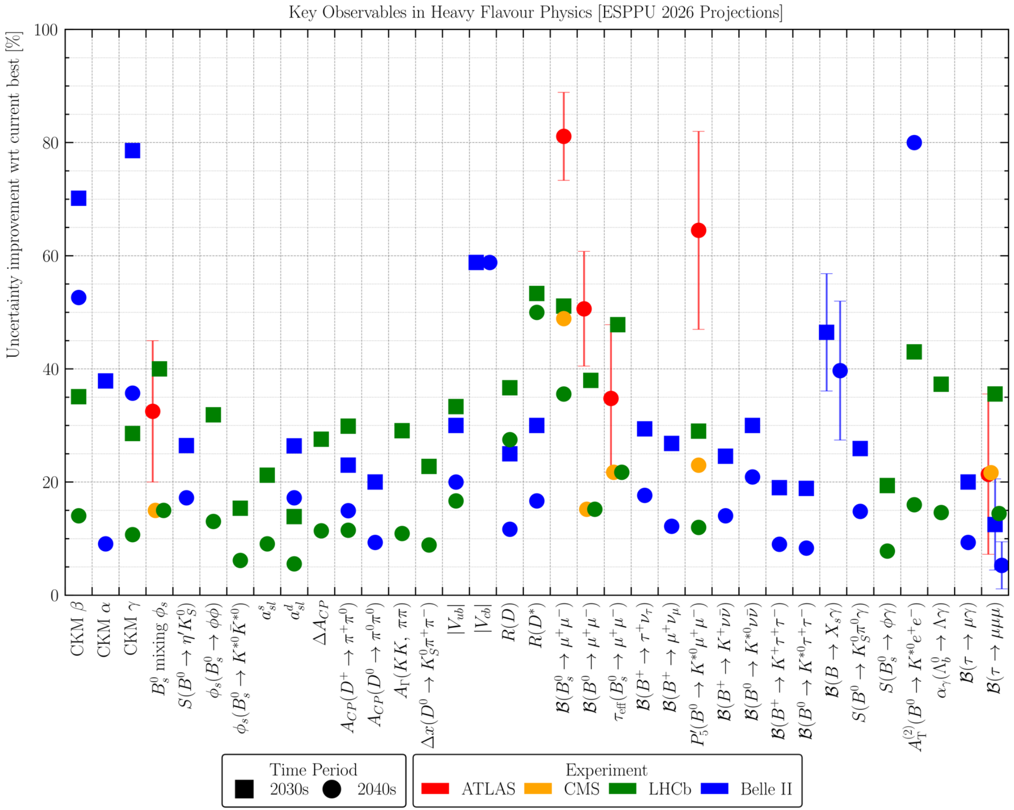
CERN-EP-2024-115
LHCb-PAPER-2024-002
August 19, 2024

Amplitude analysis of the radiative decay $B_s^0 \rightarrow K^+K^-\gamma$

LHCb collaboration

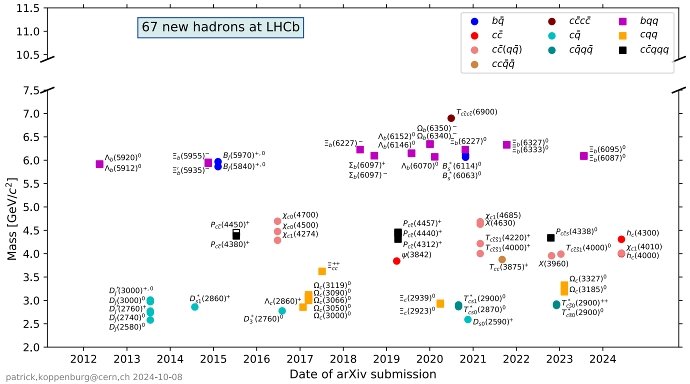
Comparison plots

- Projections for key measurements in Heavy Flavour Physics [arXiv:2503.24346]

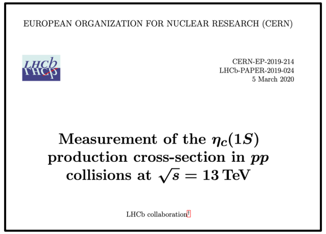


Hadron Spectroscopy

- Huge production cross-sections of *b* and *c* quarks allows searching for new hadrons, either in prompt production or from *B* decays if mass allows: 67 new hadrons discovered at LHCb since Run 1.
- Traditional hadrons:
  - Many expected states with multiple heavy quarks have not been observed because of their small production rates, but will be accessible with much larger statistics: Ω_{ccc}, Ξ_{bc}, Ξ_{bb}, Ω_{bb}, …
  - Production cross-section measurements of non-1^{--} quarkonium (h_c, η_c, h_b, η_b, …) can be decisive in understanding their production mechanisms in *pp* collisions and in the interpretation of Heavy Ion measurements
- Exotic states (i.e. tetra/pentaquarks):
  - Since the first discovery of the $\chi_{c1}(3872)$ in *B* decays at Belle and BaBar, several other exotic states with open or hidden heavy flavours have been discovered, many of them in LHCb, pentaquarks ($P_{c\bar{c}}$) or the most recent one T_{cc}^{+} ($cc\bar{u}\bar{d}$) [LHCb-PAPER-2021-031]
  - New ones are expected, e.g. in B_c^+ decays, that will be of reach only with the Upgrade II dataset.
  - Precise measurements of their properties will help understanding their nature (tightly bound tetra/penta-quarks or hadron molecules).



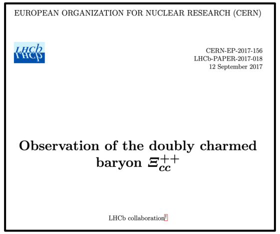
[https://koppenburg.ch/particles.html]


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-214
LHCb-PAPER-2019-024
5 March 2020

Measurement of the $\eta_c(1S)$ production cross-section in *pp* collisions at $\sqrt{s} = 13$ TeV

LHCb collaboration


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

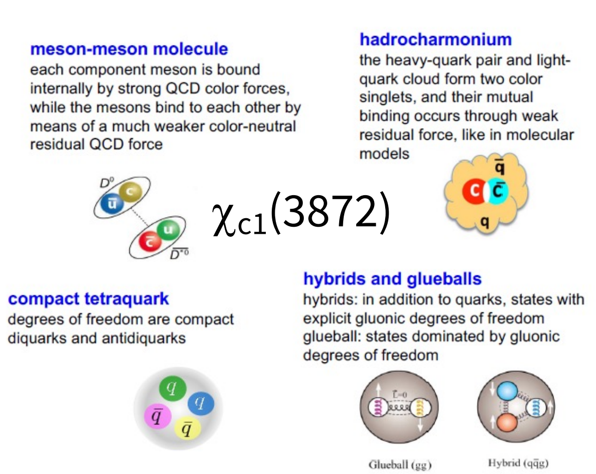
CERN-EP-2017-156
LHCb-PAPER-2017-018
12 September 2017

Observation of the doubly charmed baryon Ξ_{cc}^{++}

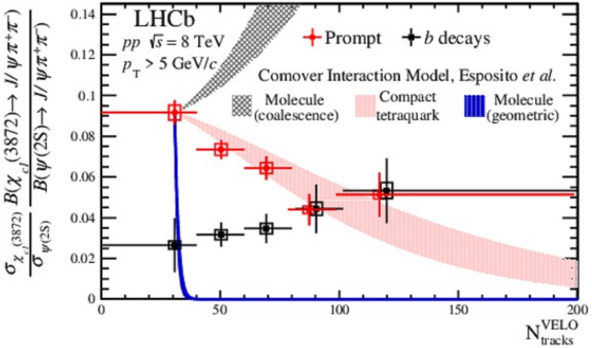
LHCb collaboration

LHCb Heavy Flavour Spectroscopy with Heavy Ions

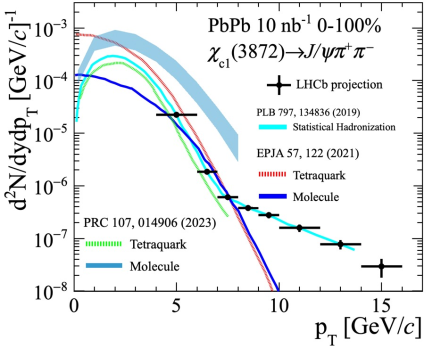
- Measurements in Heavy Ion or in large multiplicity *pp* collisions can be decisive in understanding the nature of the new exotic states
- Example of interplay between flavor physics and heavy ion physics: new states discovered in decays of *B* hadrons are interpreted from Heavy Ion measurements



$\chi_{c1}(3872)$ production as a function of multiplicity [LHCb-PAPER-2020-023]



$\chi_{c1}(3872)$ production as a function of p_T in PbPb collisions: projection for Upgrade II

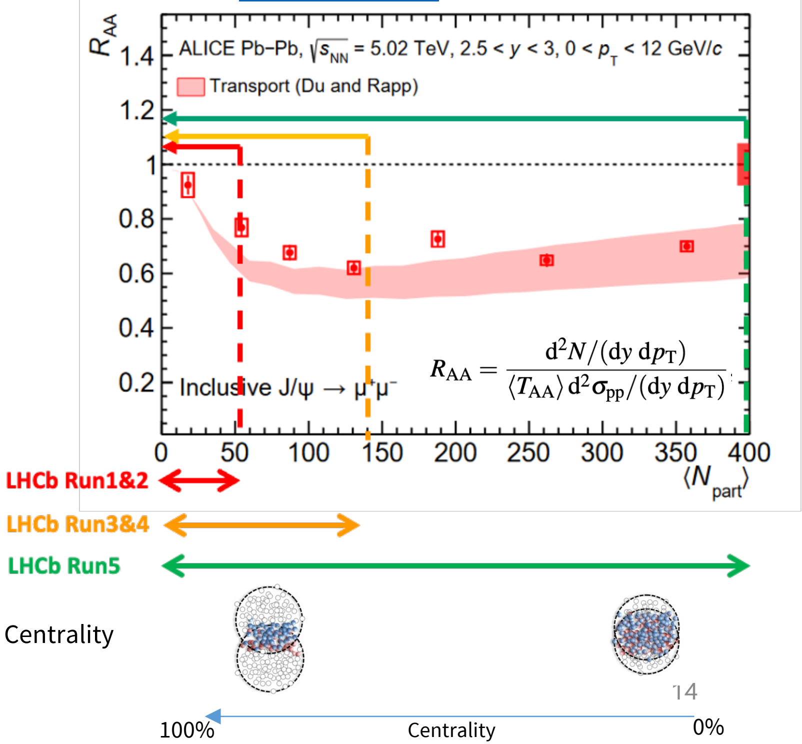


LHCb and Heavy Ions

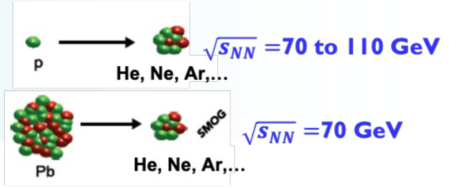
- Physics questions:
  - ***High-temperature matter*** in the early universe (Quark Gluon Plasma, QGP)
  - ***Ordinary matter*** in the current universe (Cosmic rays, …)
- How:
  - ***Mass spectrum*** of hadrons, ***confinement*** and ***hadronization*** mechanisms
  - Strongly interacting matter ***properties***
  - ***Gluon saturation*** at high energy
  - ***Thermalisation*** of strong interacting matter
- Heavy flavour hadrons are important probes of the QGP. LHCb performances are ideal to study them:
  - Full detector covering the ***forward region***: only LHCb during Run 5
  - Reconstruction of *b* and *c* hadrons down to ***very low p_T***
  - Both ***muonic and hadronic decays*** are accessible
  - Precise vertexing to ***separate prompt production*** from *B* decays
- Reach in centrality is currently limited to 30% centrality in PbPb collisions but the tracking system of Upgrade II will be able to reach the full centrality range.
- Consequences for the Heavy Ion program
  - Tracking limitation (due to occupancy) in **Run1&2: PbPb 60<centrality<100%**
  - Better tracking performances in **Run3&4: PbPb 30<centrality<100%**
  - **Full tracking performances for Run5: PbPb 0<centrality<100%**

  ➔ **Full tracking performances for lighter systems (SMOG, pPb, OO)**

Modification of J/ψ production in PbPb compared to *pp* as a function of the number of participants in the collision [JHEP02 (2020) 041]

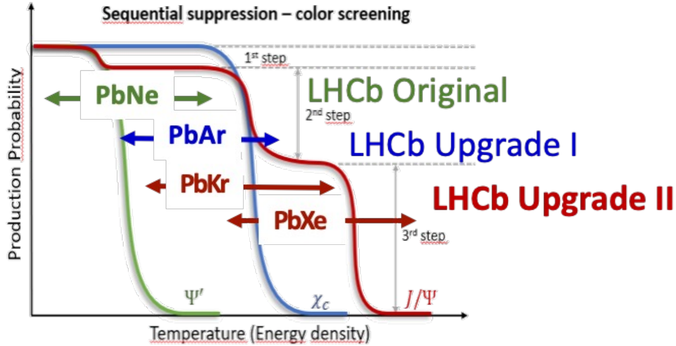


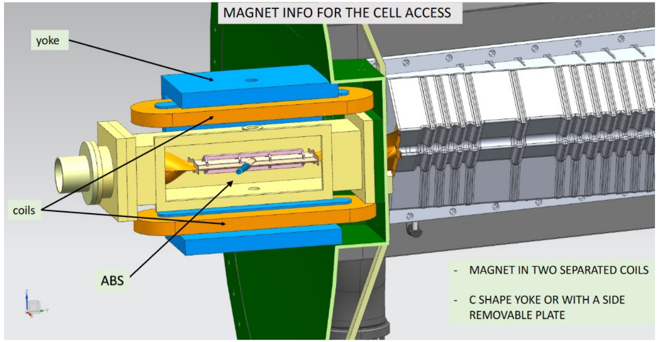
LHCb Fixed Target in Upgrade II



At $\sqrt{s_{NN}} = 110$ GeV, $y_{centre\text{-}of\text{-}mass} = y_{lab} - 4.77$

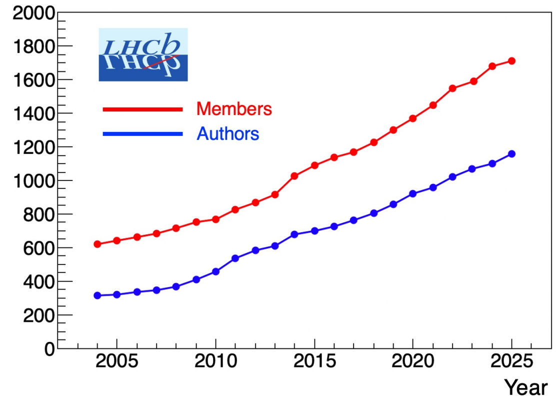
- Unique feature in the world: center-of-mass energy of around 100 GeV and mid-rapidity
- From SMOG to SMOG2
  - ***SMOG: During Run 2*** injecting gas directly in the VELO tank
    - Limited statistics
  - ***SMOG2: Starting Run 3*** injecting gas in a storage cell 30 cm upstream of the VELO
    - ***More gas species***: He, Ne, Ar, H_2, D_2, O_2
    - Up to ***100 times more stat*** than SMOG (10^5 to 10^6 J/ψ in *p*A)
    - SMOG2 IP displaced wrt to collider IP: ***operation in parallel*** with *pp* or PbPb collider mode
    - In Run 3 and 4: limited to PbAr (because of occupancy limitations)
  - ***In Run 5***:
    - ***no limitation*** from detector, heavier gases can be considered (Kr, Xe)
    - Explore ***QGP at different temperatures***, with sequential quarkonium suppression for example
- New ***polarized*** gas target for Run 5:
  - A compact dipole magnet (300 mT) provides the polarisation
  - Continue to inject unpolarised gases
  - Alternative setup with gas jet investigated in parallel





LHCb in France

- Since the beginning of the collaboration, involved in the *pp* heavy flavour physics program
  - **LAPP Annecy**
  - **LPCA Clermont-Ferrand**
  - **CPPM Marseille**
  - **IJCLab Orsay**
  - A bit later **LPNHE Paris**
- Groups joined later for the heavy-ion physics program initiated at IJCLab Orsay and LLR Palaiseau:
  - **LLR Palaiseau**
  - **IRFU Saclay**
  - **Subatech Nantes**, currently Technical Associate, full member in a few years
- Technical Associate for PicoCal: **LPC Caen**
- In 2025: **37 researchers** (CNRS or Universities), **17 post-docs** and **31 PhD students**
- Strong links with the theory groups hosted in our institutes for heavy flavour and heavy ion physics (Annecy, Clermont-Ferrand, Marseille, Nantes, Orsay, Palaiseau)



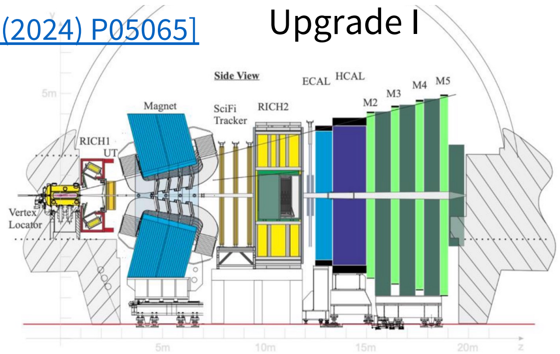
1200 authors in 125 institutes from 21 countries, growing constantly

Detector for Upgrade II

- Same performances as Run 3, with a pile-up of 40 instead of 5

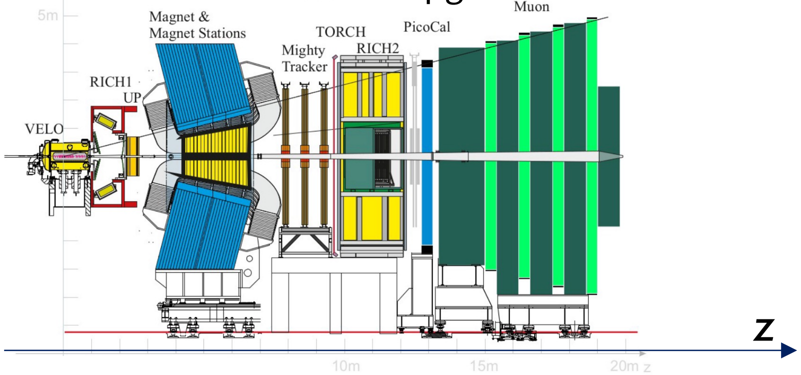
[JINST19 (2024) P05065]

Upgrade I



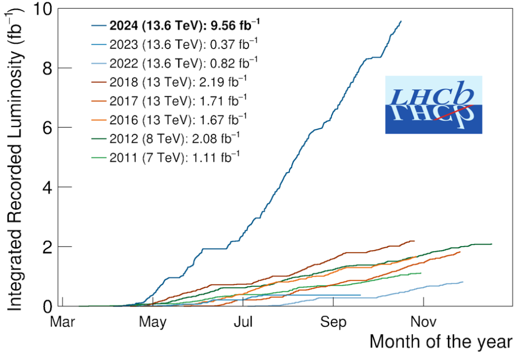
Run 3

Upgrade II

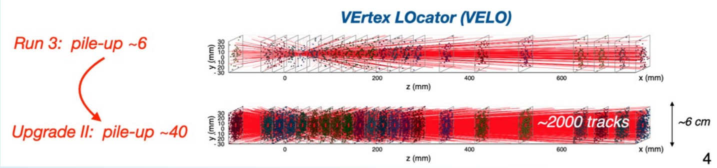


Run 5

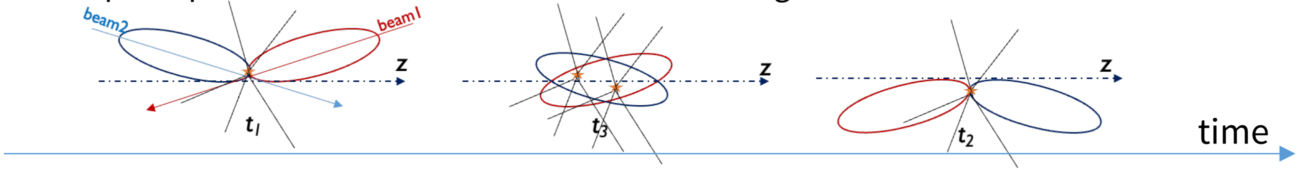
Status of data taking:



Upgrade 2 Challenges



- Same geometry for the detector with innovative technologies for sub-detectors and data processing
- Main elements:
  - Increase ***granularity***
  - Add ***timing*** measurement (resolutions up to 10-50 ps, in VELO, RICH/TORCH, ECAL)
  - ***Radiation hardness*** (up to 10^{16} n_{eq}/cm^2)
  - ***Data rate***: 200 Tbit/s
- Time spread of *pp* interaction region ~200 ps (t_2-t_1): measurement of time of particles with ***~10ps precision*** to distinguish different pile-up interactions in the same bunch crossing.



- For Heavy Ion collisions:
  - ***No or very small pile-up***: time measurement does not help
  - Contrary to *pp*, one interaction can have a ***wide range of multiplicity*** depending on the system (proton-Helium vs PbPb) and on the centrality (overlap of the two colliding ions):
    - From less than 1 *pp* interaction to up to 360 *pp* interactions for the most central PbPb collisions. A pile-up of 40 *pp* interactions corresponds to 40% centrality in PbPb.

Run 3					LS3			Run 4				LS4		Run 5					
2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
		TDR phase			Construction phase							Installation		Exploitation					

Scenarios

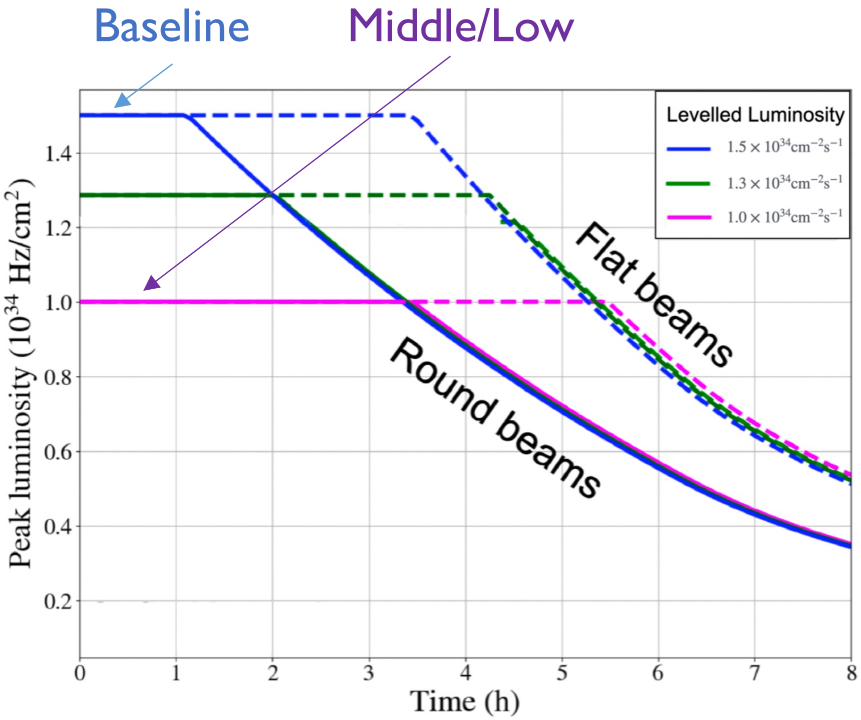
	Baseline	Middle	Low
$\mathcal{L}_{\text{peak}}$ $(10^{34}\,\text{cm}^{-2}\,\text{s}^{-1})$	1.5	1.0	1.0
	(kCHF)	(kCHF)	(kCHF)
VELO	16672	15906	13753
UP	8077	7719	6887
Magnet Stations	2592	2234	0
Mighty-SciFi	21767	21273	17388
Mighty-Pixel	15994	11641	11061
RICH	21450	18415	14794
TORCH	12508	8756	0
PicoCal	27607	27607	21584
Muon	9785	8266	8266
RTA	18800	11700	9500
Online	11800	9467	8993
Infrastructure	14463	13284	12430
Total	181515	156268	124656

- Integrated luminosities for 2 LHC configurations:
  - Round optics (baseline)
    - 49 fb^{-1}/year for L_{peak}=1.5x$10^{34}$$cm^{-2}$.$s^{-1}$
    - 42 fb^{-1}/year for L_{peak}=1.0x$10^{34}$$cm^{-2}$.$s^{-1}$
  - Flat optics (needs R&D from accelerator)
    - 63 fb^{-1}/year for L_{peak}=1.5x$10^{34}$$cm^{-2}$.$s^{-1}$
    - 49 fb^{-1}/year for L_{peak}=1.0x$10^{34}$$cm^{-2}$.$s^{-1}$
- Recorded luminosities assuming 45% data taking efficiency for 2036 and 90% for 2037-2041 (conservative):

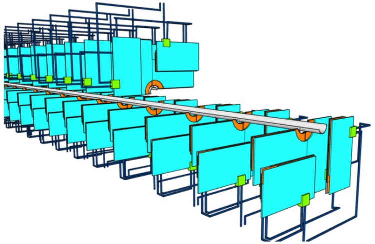
	Round optics		Flat optics	
Scenario	Middle/Low	Baseline	Middle/Low	Baseline
Run 1-5 (fb^{-1})	270	306	303	375

LHC Optics

- Main difference between Baseline and Middle scenarios is the peak luminosity:
  - 12% reduction in integrated luminosity for round optics, 20% for flat optics
  - 6% reduction in sensitivity for round optics, 10% for flat optics
- Detector is adapted for lower instantaneous luminosities in the Middle and Low scenarios:
  - reduced margin in case one needs to run at higher instantaneous luminosity (to compensate for incidents in the LHC, …)
  - to a less extent with the possibility to run in very central PbPb collisions with good efficiency.
- On the other hand, running at lower luminosity has other benefits:
  - Better performances in some areas (calorimeter in particular)
  - Levelling time is longer: data taken in more stable and homogenous conditions

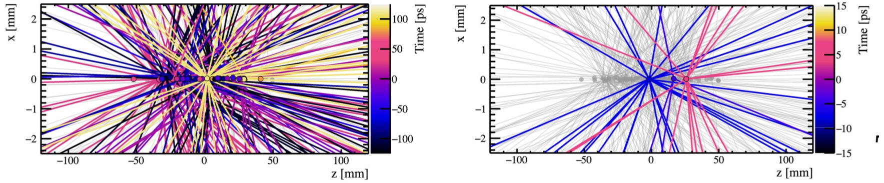


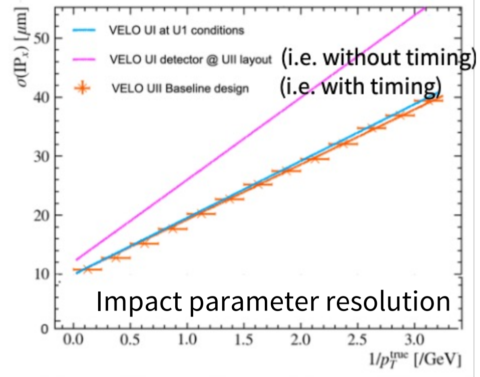
VELO

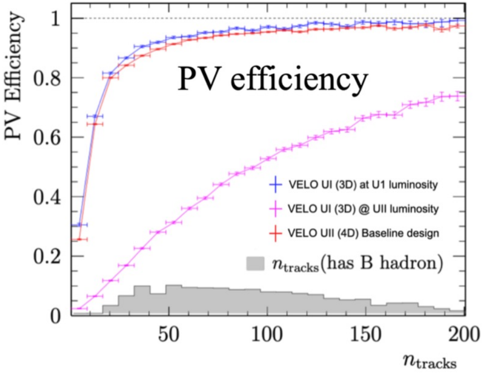


- Pixel 3D silicon sensors in 28nm technology with a dedicated ASIC:
  - 2 candidates: TimePix/PicoPix and TimeSpot/ IGNITE
  - 50ps hit resolution (20ps/track)
  - 90-95% hit efficiency
  - Low material budget
- Middle scenario: reduction of DAQ infrastructure cost due to lower peak luminosity
- Low scenario: less stations, thicker RF foil: reduced acceptance and worse impact parameter resolution

Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
	VELO	
32 stations, $\eta < 4.8$	32 stations, $\eta < 4.8$	28 stations, $\eta < 4.7$
module 0.8% X_0	module 0.8% X_0	module 1.6% X_0
RF foil 75 µm	RF foil 75 µm	RF foil 150 µm

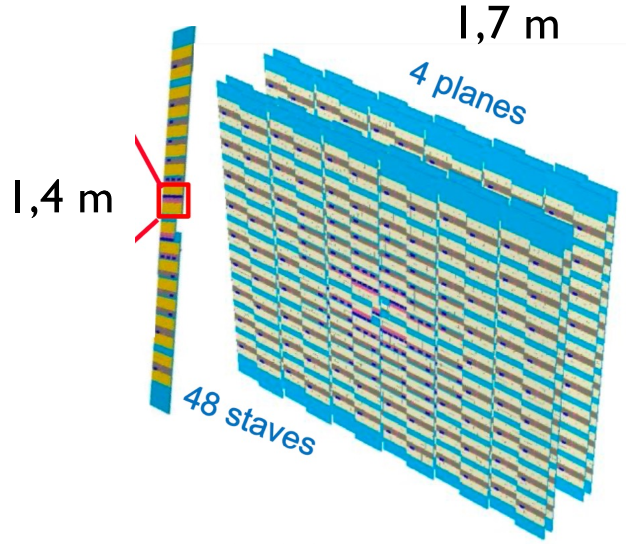




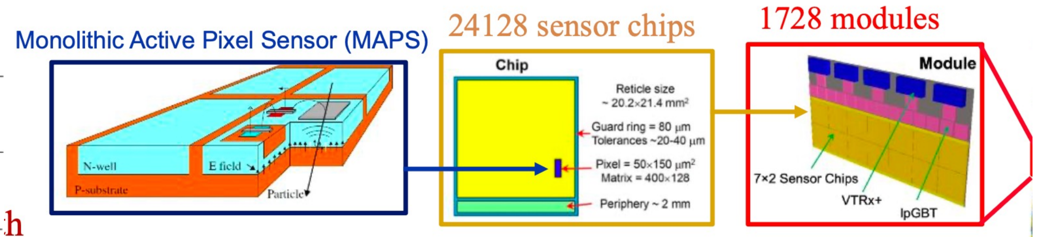


UP: Upstream Pixel detector

- Important for downstream track (without VELO) reconstruction and ghost removal.
- Hit density (5.9 hits/cm^2/crossing) in *pp* collisions and radiation levels (fluence up to $3\text{x}10^{15}$ neq/cm^2, 2.4MGy) are out of reach of the current technologies.
- R&D on DMAPS (Depleted Monolithic Active Pixel Sensors) with 3 main candidates: MightyPix (HV-CMOS 180nm), RadPix (HV-CMOS LF 150nm), COFFEE (TPSCo 55nm)
- Middle scenario: reduction of DAQ infrastructure because of lower peak luminosity
- Low scenario: reduce acceptance

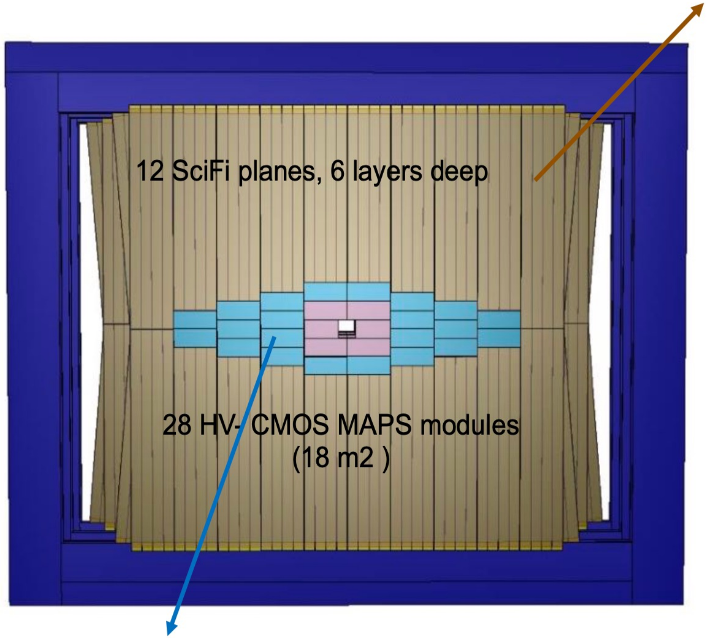


Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
	UP	
4 planes pixel $\times 1.7\,\mathrm{m}^2$	as baseline	remove corners



Mighty Tracker

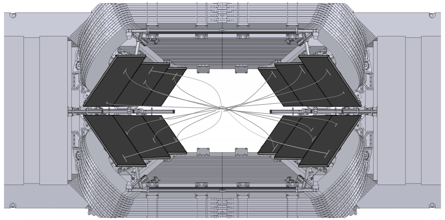
- DMAPS Pixel for inner region (HV CMOS candidates MightyPix/RadPix) to cope with higher occupancy: synergy with UP
- Scintillating fibers for the outer region with modified SiPM readout
- Middle scenario: shorter SciFi modules, reduction by 37% of pixel coverage
- Low scenario: remove the 2 outermost SciFi modules (out of 12) in each station

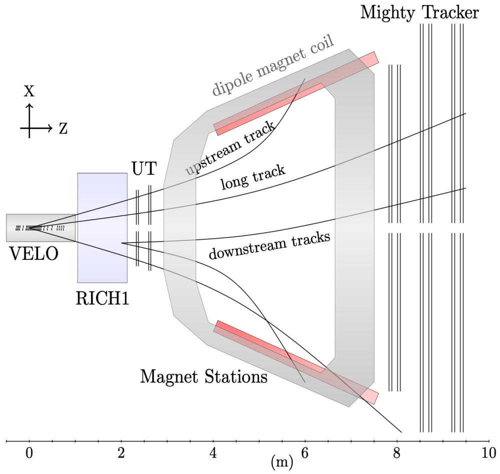


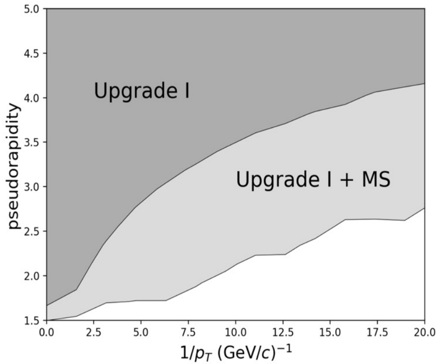
	Mighty-Pixel	
6 planes pixel $\times 2.1\,\mathrm{m}^2$	6 planes pixel $\times 1.3\,\mathrm{m}^2$	6 planes pixel $\times 1.3\,\mathrm{m}^2$
	Mighty-SciFi	
12 planes fibres	12 planes fibres	12 planes fibres
$25.9\,\mathrm{m}^2$/plane	shorter, $23.7\,\mathrm{m}^2$/plane	narrower, $18.9\,\mathrm{m}^2$/plane

Magnet Stations

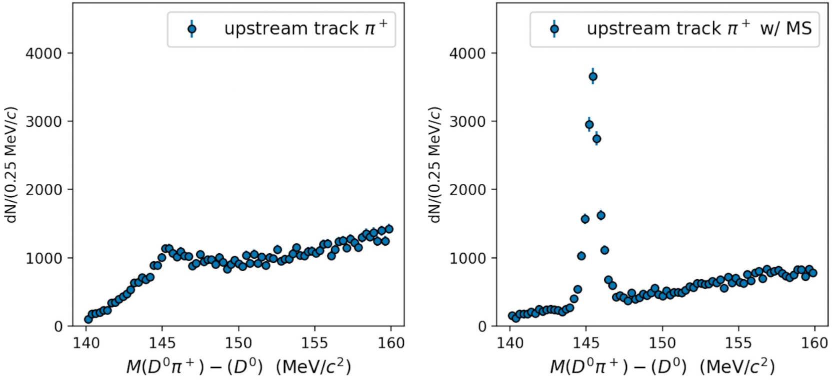
- New system, scintillating slabs covering the side walls inside the magnet to reconstruct low p_T charged particles (upstream tracks that do not reach the Mighty Tracker).
- For example:
    - ~10% gain in precision for CP violation parameters in charm mesons
    - Factor 2 more signal for exotic $\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$ reconstruction
- Middle scenario: as baseline
- Low scenario: remove completely





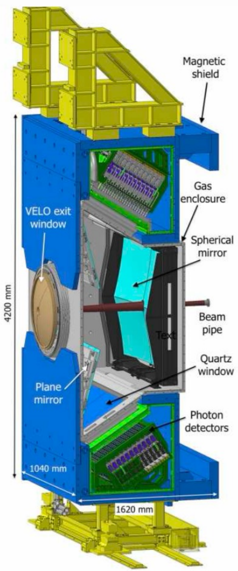


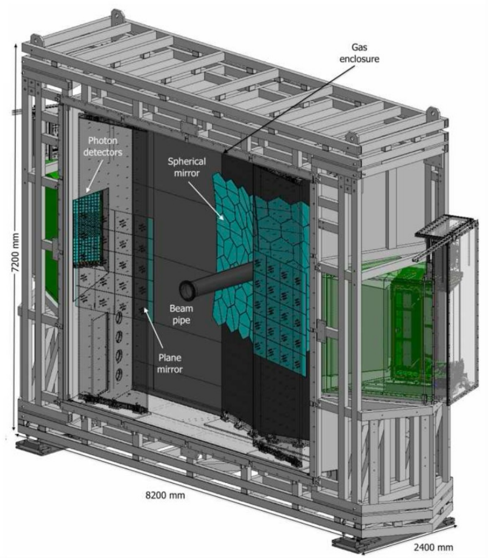
$D^{*+} \rightarrow D^0\,\pi^+$ reconstruction without and with Magnet Stations



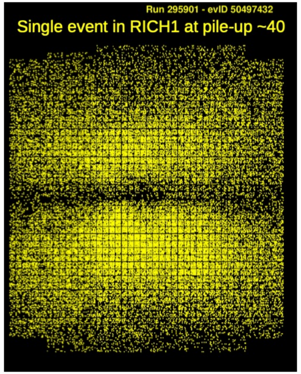
RICH 1&2

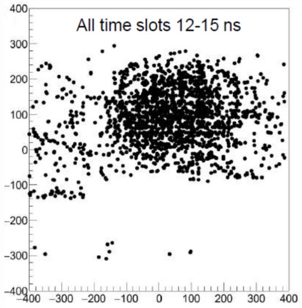
- Smaller pixels with timing information:
  - fast photon detector (SiPM or MCP)
  - fast electronics
- Middle scenario: reduced granularity due to reduced instantaneous luminosity
- Low scenario: reuse current MaPMTs for RICH2 and further reduction of granularity

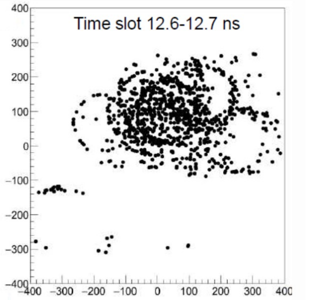




Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
	RICH1/2	
inner:outer $\frac{1}{3}$:$\frac{2}{3}$	inner:outer $\frac{1}{4}$:$\frac{3}{4}$	inner:outer $\frac{1}{4}$:$\frac{3}{4}$
inner 1.4 mm SiPM	inner 2.0 mm SiPM	inner 2.0 mm SiPM
outer 2.8 mm SiPM	outer 2.8 mm SiPM	outer 2.8 mm MaPMT
new optics	new optics	new optics (RICH1 only)
750,000 channels	469,000 channels	445,000 channels



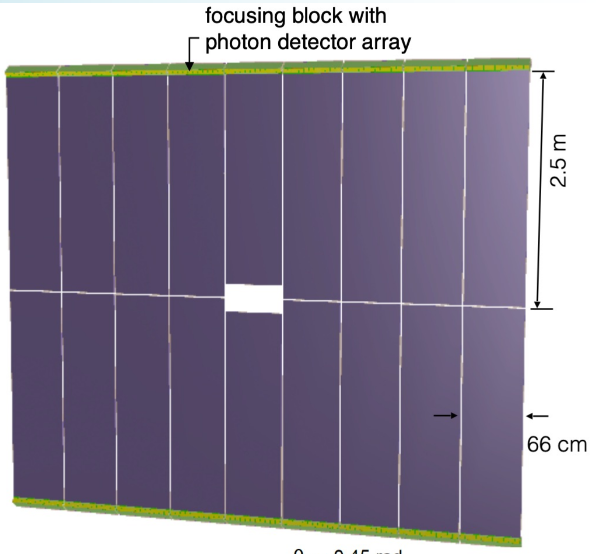


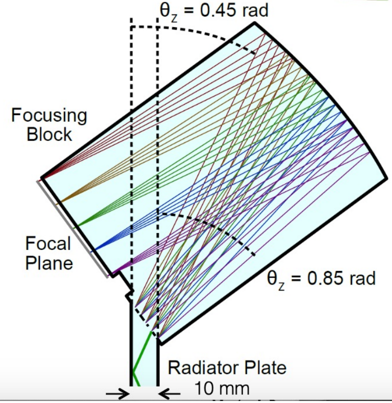


TORCH

- New system:
  - Time-of-flight with quartz and SiPM/MCP
  - Add PID for low momentum particles.
- 70ps per photon time resolution (15ps per track)
- Middle scenario: 30% reduction of detector coverage
- Low scenario: removed completely

Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
	TORCH	
18 quartz bars	12 quartz bars	removed
225,000 channels	158,000 channels	—

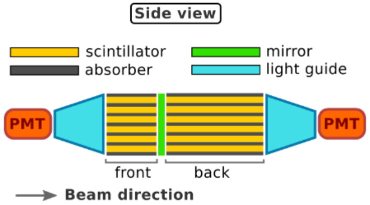




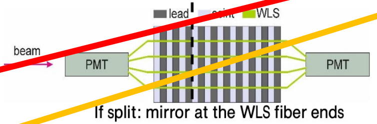
Modules ECAL (PicoCal)

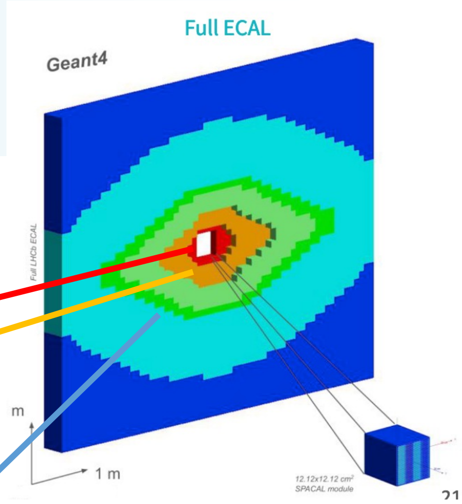
- Ongoing R&D to produce modules that allow precise time measurement and an energy resolution of 10%/sqrt(E)

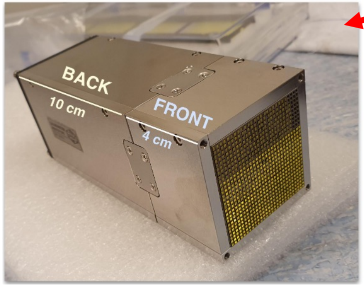
SPACAL:



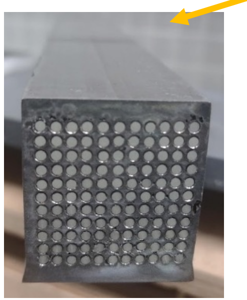
SHASHLIK:



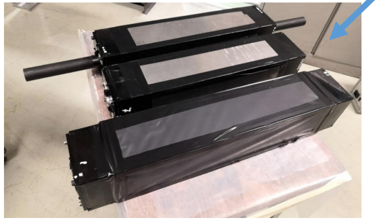




W absorber, cristal fibers (GAGG, gadolinium aluminium gallium garnet):
Large tolerance to radiations and small Molière radius



Pb absorber, polystyrene fibres



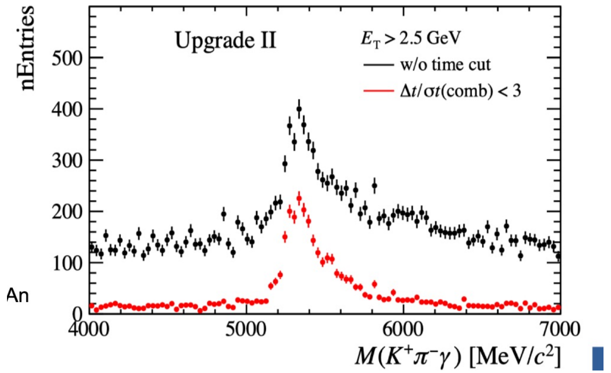
Current modules: outer region

- Reorganize the ECAL zones in rhombic shapes to follow better radiation and cell occupancies
- Add longitudinal segmentation at shower maximum to improve time resolution (useful also for particle identification: separation electron/hadron)

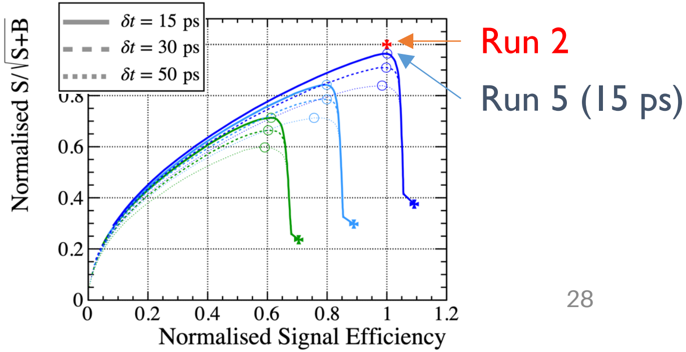
PicoCal: Precise time measurement

- To fight against the important background due to pile-up: add time measurement in ECAL with a precision of 15 ps RMS = PicoCal
- Reach with pile-up 40 performances of Run 2 (~no pile-up)
- Select cell wher $|t_{ECAL}-t_{PV}|/\sigma(t)<3$
  - t_{PV} : time of the collision measured in the VELO
  - t_{ECAL} : time measured in the ECAL, corrected from the time of flight
  - $\sigma(t)$: ECAL time resolution

Effect of timing cut on invariant mass for B→ K*γ

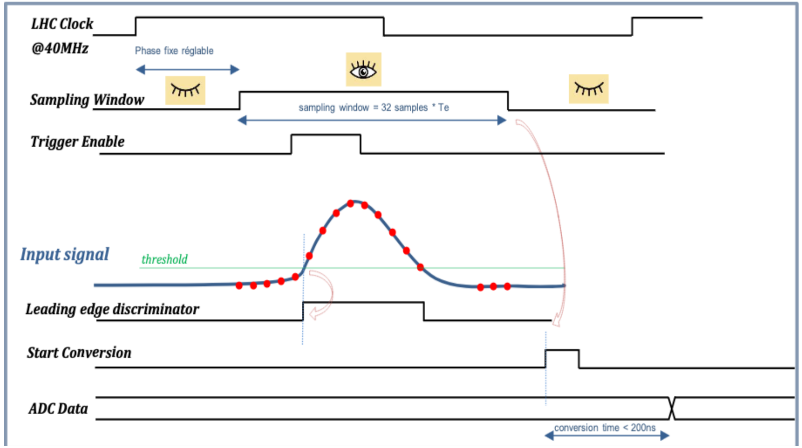


Full simulation of signal $B^0 \rightarrow K^{*0}\gamma$ with pile-up

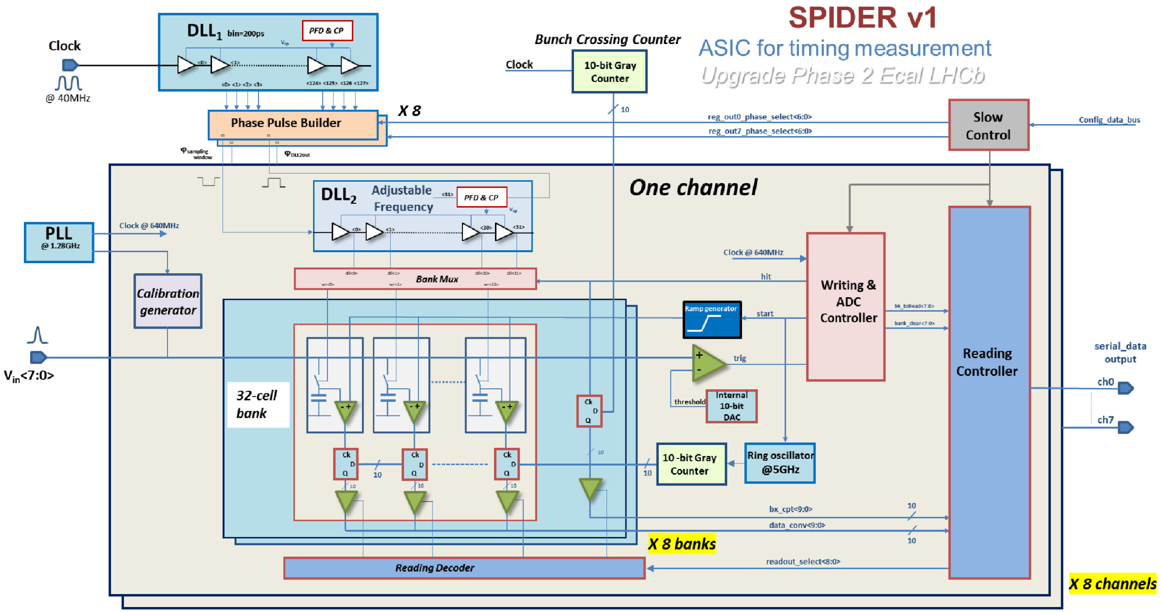


Time measurement: Waveform Digitizing

- Time measurement can be done by sampling the shape of the signal, using analog memories associated to a FPGA: development of a dedicated ASIC, SPIDER
- Time is measured from :
  - A DLL to define the region of interest (200 ps step)
  - Samples on the signal shape (adjustable period: 50ps, 100ps, 200ps, 400ps, 600ps)
- The interpolation in an associated FPGA allows to measure the time with digital Constant Fraction Discriminator (CFD): precision of a few ps RMS with a precise calibration even for signals with low amplitude.
- The main challenges that SPIDER must address are:
  - Large deadtime (~ 100 μs) limiting the usage for high rates (goal = 40 MHz) => **massively parallel** analog-digital conversion, which can reach at least 50% occupancy
  - Need for a trigger: every channel is **self-triggered**



SPIDER



Technology: TSMC CMOS 65nm

- 10-bit Wilkinson ADC at 5 GHz
- Memory cells (switches/capacitors) with ~0.8V dynamic range and noise level ~0.5mV RMS
- DLL between 40 and 640 MHz

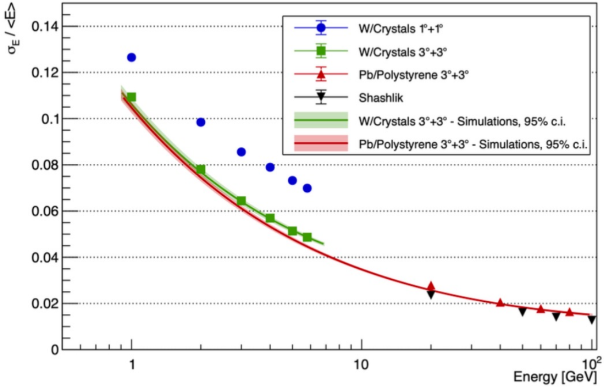
First prototype submitted in December 2024, to be tested after Summer 2025. Production in ~2030

PicoCal

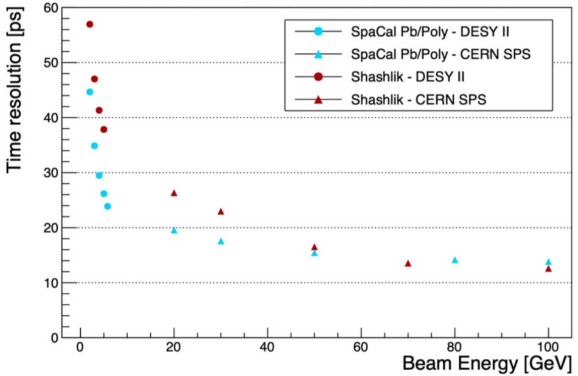
- SPACAL and Shashlik modules tested in test beam with similar methods that SPIDER (WaveCatcher), giving good performances
- Baseline scenario: 20976 channels instead of 6016 now.
- Middle scenario: as baseline
- Low scenario: reduction by 35% of number of channels removing longitudinal segmentation in outer regions

Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
	PicoCal	
40 SpaCal-W	40 SpaCal-W	40 SpaCal-W
408 SpaCal-Pb	408 SpaCal-Pb	408 SpaCal-Pb
2864 Shashlik	2864 Shashlik	2864 Shashlik
double R/O	double R/O	single R/O except 176 inner
30,976 channels	30,976 channels	20,224 channels

Energy resolution of SpaCal & Shashlik modules

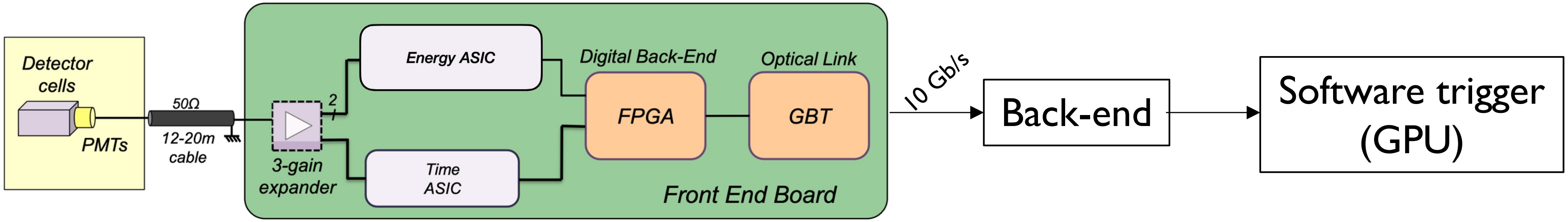


Time resolution of SpaCal & Shashlik modules



PicoCal data processing

- New Front-End board to develop:

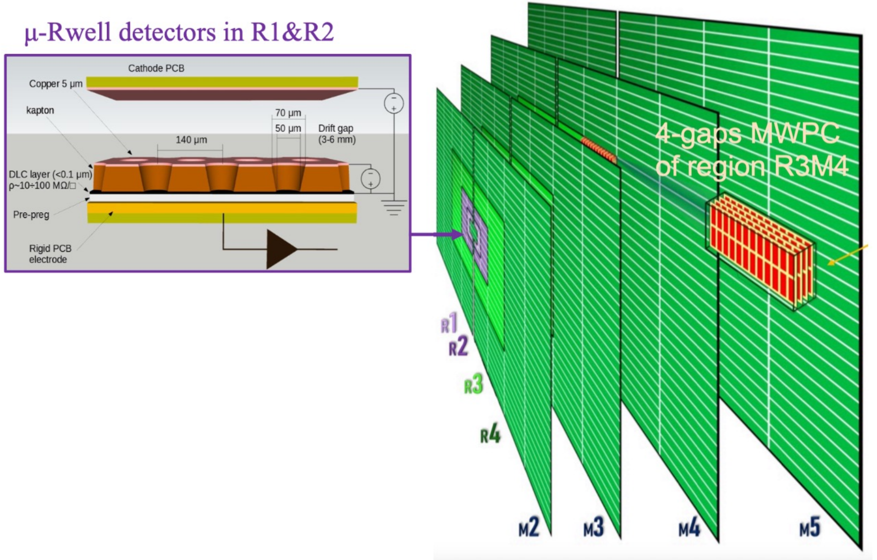


- Readout and real time reconstruction will be challenging:
  - Explore pre-processing solutions, such as compression algorithms in the FPGAs of the Front-End board (auto-encoders)
  - Pre-clustering in back-end boards: exploit FPGAs of the back-end board, to be compared with performances of the GPUs available in the online farm.

Muon

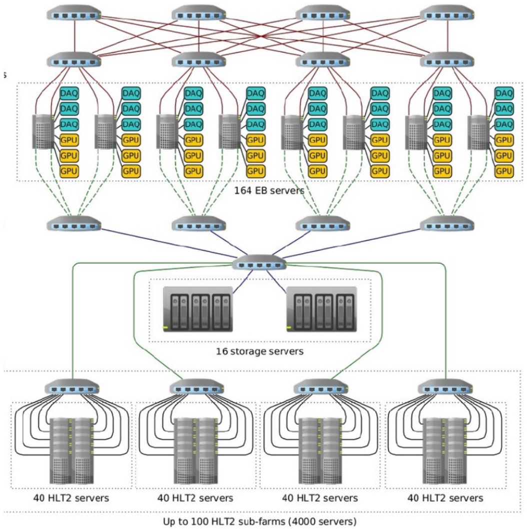
- muRWELL technology in the inner region (R1, R2): micro pattern gas detector technology for the high-rate region
- Keep most of the current MultiWire Proportional Chambers (MWPC) with increased granularity, and add a few new ones in the outer region (R3, R4)
- Middle/Low scenarios: do not add new MWPC

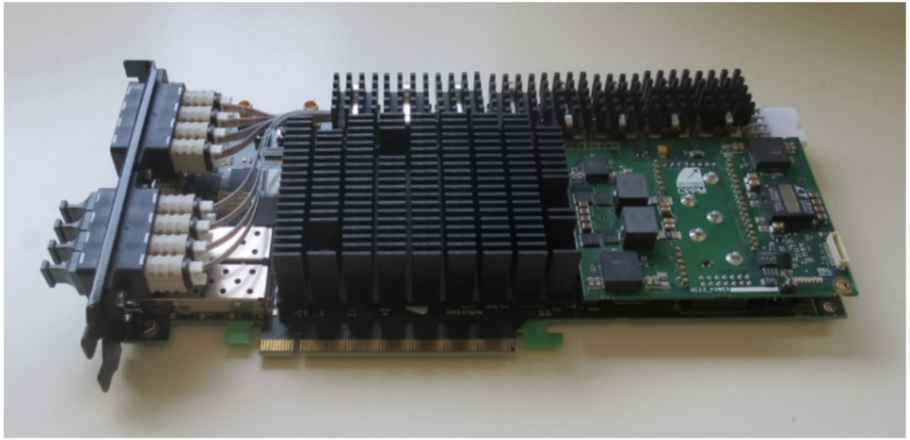
Baseline $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	Middle $1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	Low $1.0 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
	Muon	
μ-RWELL in R1/R2	μ-RWELL in R1/R2	μ-RWELL in R1/R2
96/192 new MWPC in R3	keep old MWPC in R3	keep old MWPC in R3
keep old MWPC in R4	keep old MWPC in R4	keep old MWPC in R4
additional shielding	keep HCAL	keep HCAL
718,848 channels	608,256 channels	608,256 channels



Online: Run 3

- Read-out in Run 3 is based on a custom board and with standard protocols (PCIexpress, infiniband network)
  - Trigger-free architecture with 40 Tb/s total bandwidth
- PCIe40 board:
  - used by LHCb, ALICE, Belle II and Mu3e experiments (with different firmwares)
  - Installed in servers (PCIe) together with software trigger GPUs





PCIe40	
FPGA	
Family:	Arria 10
Logic Elements:	1 150 kLE
Max frequency:	644 MHz
RAM:	53 Mb
Optical I/O	
bidirectional links 10 Gbps:	up to 48
TFC PON:	2
CPU I/O	
PCIe GEN3:	16
Output bandwidth:	100 Gbps
Form Factor	
PCIe:	241 x 111 mm

Online: Upgrade 2

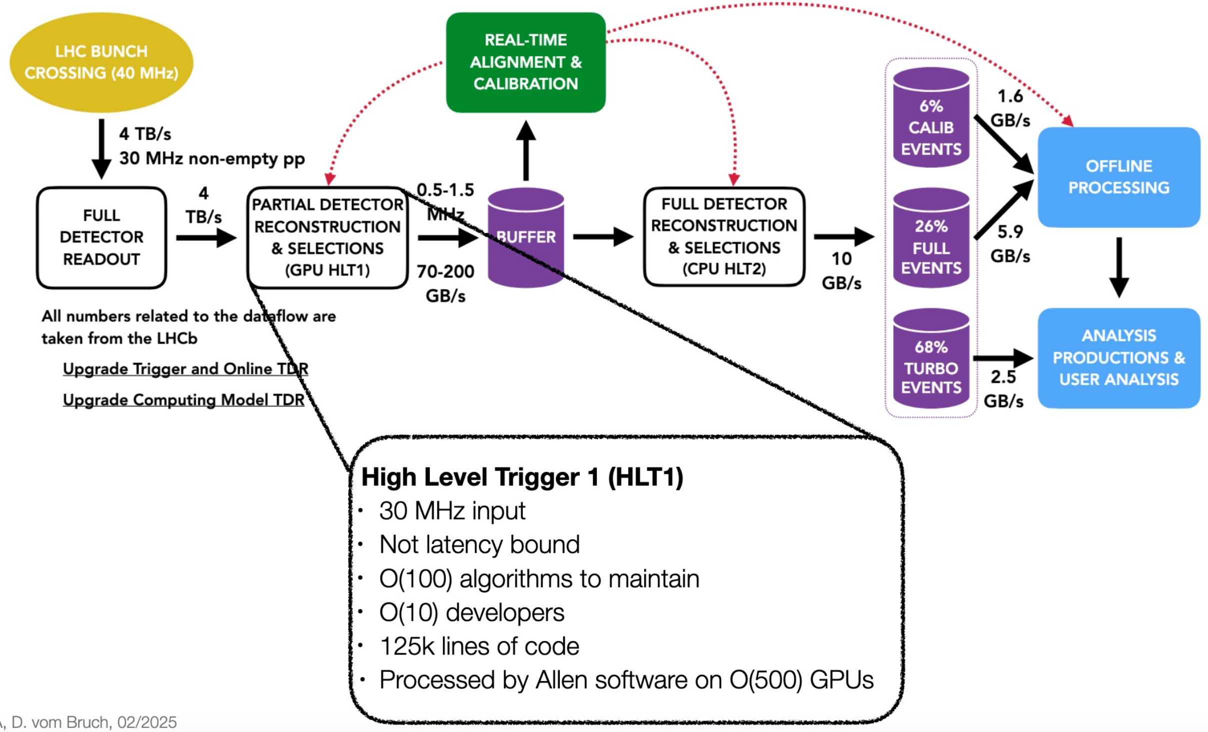
- Trigger-free architecture with 200 Tb/s bandwidth, close to Run 3 architecture: PCIe40 board must be replaced to follow the rate and granularity increase
- Still many unknowns to decide the back-end solution:
  - Evolutions of the computers market: form factors of GPU, PC servers, …
  - Roadmap for the future generations of FPGAs
  - Processing power needed by sub-detectors for their pre-processing
- Need for a precise clock distribution:
  - jitter and phase reproducibility < 10ps
- Aim at developing a generic and multi-purpose board, collection of requirements ongoing

Online

- Middle/Low scenarios: reduction of cost due to lower peak luminosity, i.e. lower throughput

	Baseline	Middle
$\mathcal{L}_{\text{peak}}$ ($10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$)	1.5	1.0
Available GPU slots	840	560
	(kCHF)	(kCHF)
Fixed cost	4800	4800
Variable cost	7000	4667
Total Online	11800	9467

Trigger (RTA = Real Time Analysis) in Run 3



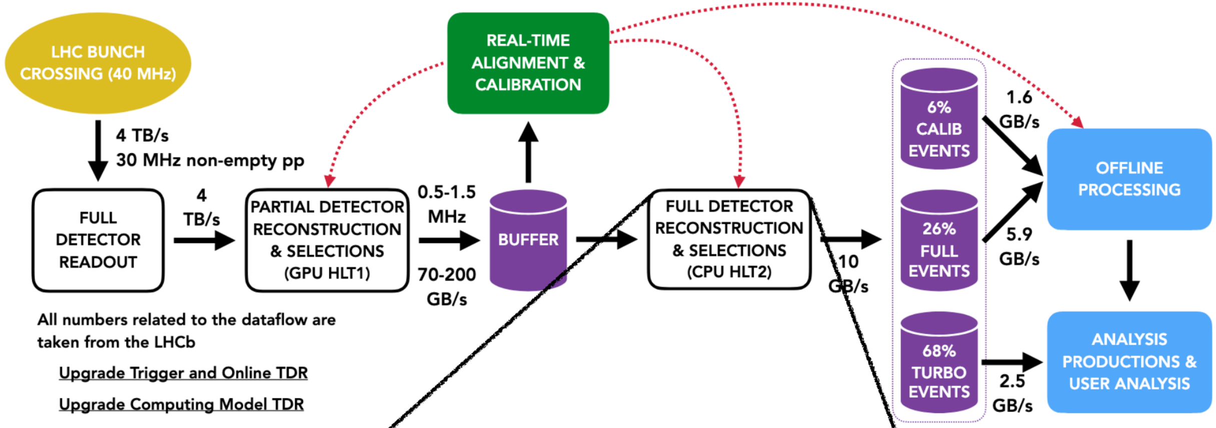
Allen software:

- Single source code running both on CPU and GPU
- Standalone build or integrated with LHCb software stack
- Include memory manager and multi-event scheduler
- Configuration via Python

Design of Allen:

- Do all the work on GPU (minimise copies to/from GPU)
- Parallelise on multiple levels
- Maximise performance of algorithms on GPU:
  - Optimise algorithm throughput performance
  - Interleave Machine Learning/Artificial Intelligence and classical algorithms

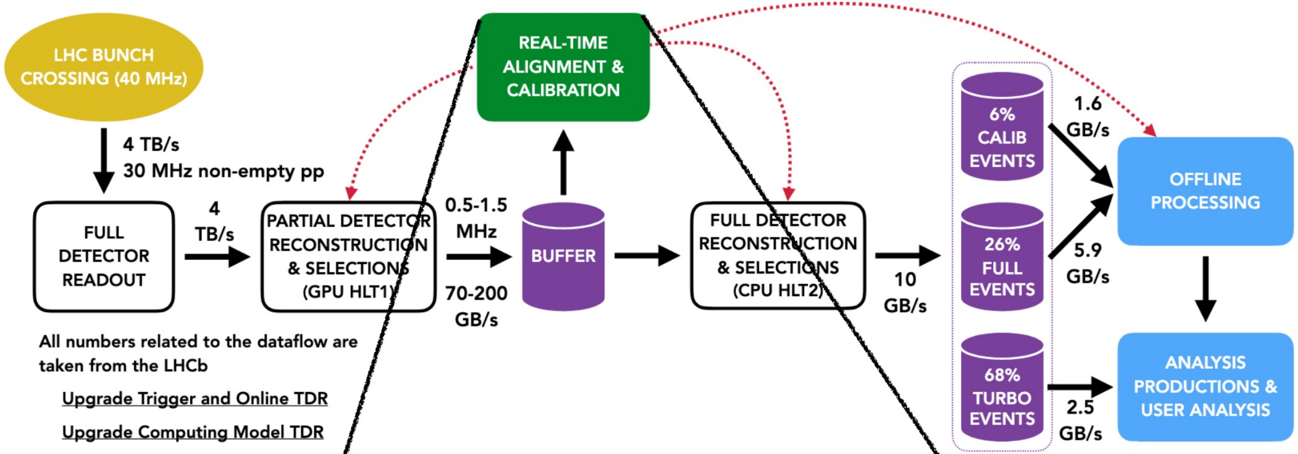
Trigger in Run 3



High Level Trigger 2 (HLT2)

- 1 MHz input
- Not latency bound
- O(2000) algorithms to maintain
- O(100) developers
- 2M lines of code
- Processed by Moore software on CPUs

Trigger in Run 3

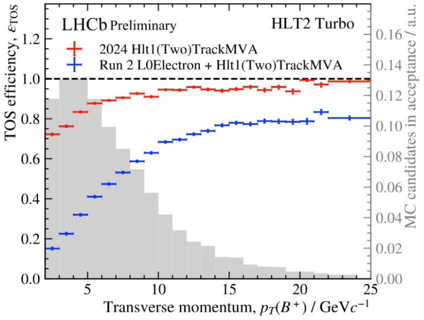


Alignment & Calibration

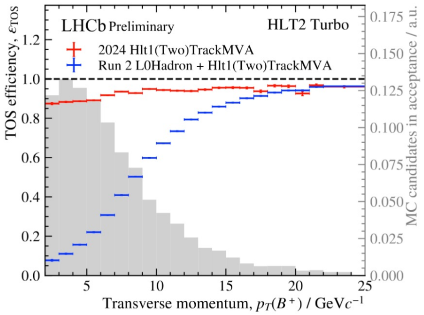
- Determine detector position based on reconstructed quantities
- RICH mirror alignment & refractive index calibration
- Calibrate calorimeter

Allen: HLT1 performances in Run 3

- Many algorithms added in addition to what was initially foreseen in HLT1:
  - Additional long track reconstruction method: gain of 20% efficiency at p_T=500 MeV
  - Downstream track reconstruction
  - ECAL reconstruction
  - Jet reconstruction
  - Additional PID methods for electrons and muons



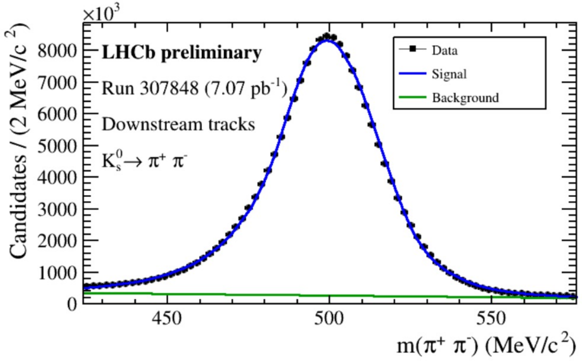
(a) TOS efficiencies in $B^+ \to J/\psi\,(e^+e^-)\,K^+$.



(a) TOS efficiencies in $B^+ \to \overline{D}^0\,(K^+\pi^-)\,\pi^+$.

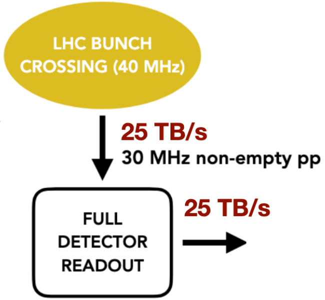
LHCB-FIGURE-2024-030

Reconstruction with downstream tracks

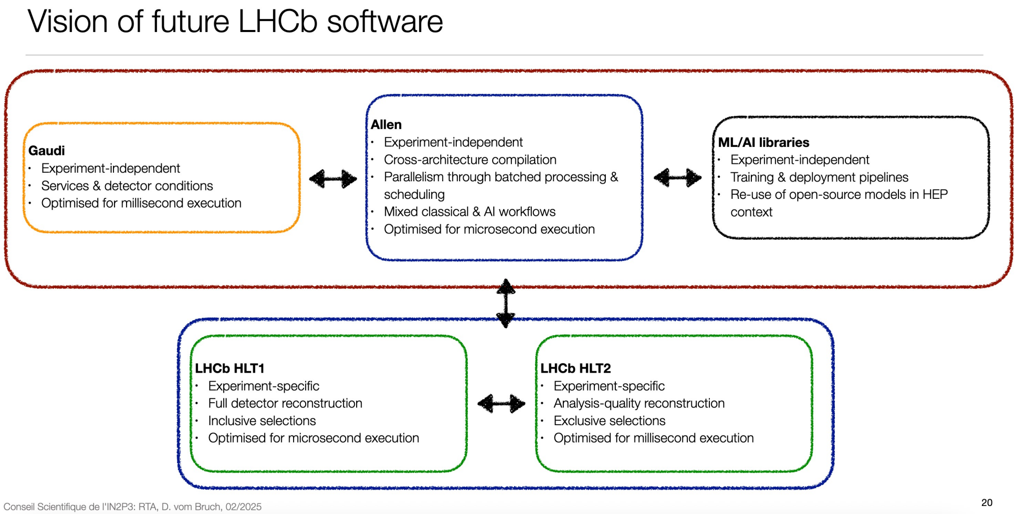


LHCb-FIGURE-2024-035

Trigger in Upgrade 2



- Potentially interesting decay in most of the events:
  - follow Run 3 strategy with two software trigger levels, HLT1 (GPU in Run 3) and HLT2 (CPU in Run 3)
  - extend to other architectures and hardware: at the moment, doing HLT2 on GPUs is the only viable solution



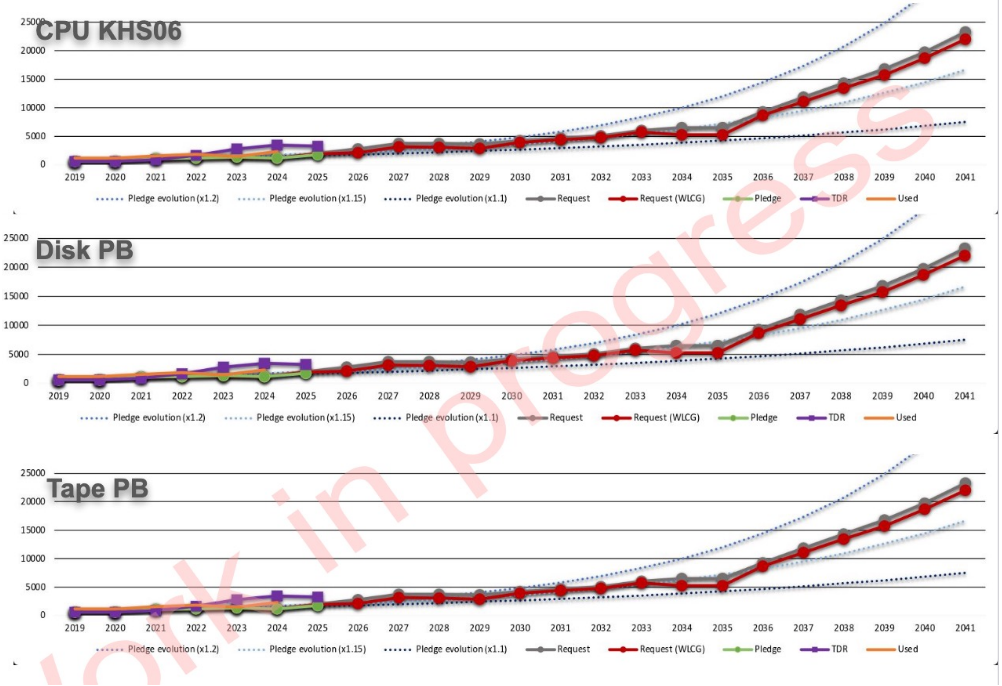
RTA

- Middle scenario: software trigger complexity remains the same, cost of the farm scales with the peak luminosity, HLT2 cost scales as the square of the peak luminosity
- Low scenario: further downscoping assuming a more aggressive annual performance-price ratio improvement: risk to the physics program for high-rate modes (charm)

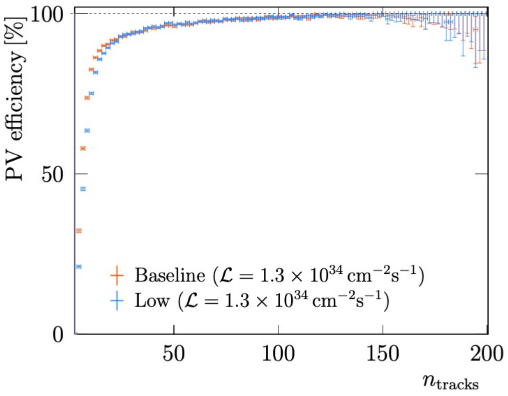
	Baseline	Middle	Low
$\mathcal{L}_{\text{peak}}$ ($10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$)	1.5	1.0	1.0
$\mathcal{L}_{\text{int}}$/year [fb^{-1}]	55.7	43.0	43.0
	(kCHF)	(kCHF)	(kCHF)
HLT1	736	491	491
HLT2	15200	9070	7280
Disk buffer	2800	2160	1760
Total RTA	18800	11700	9500

Computing

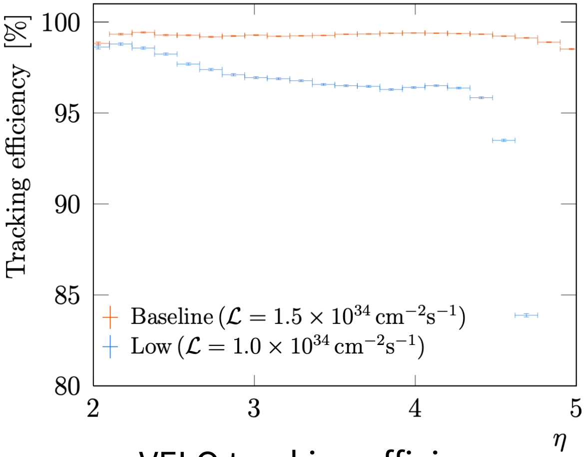
- Naive extrapolation gives a factor 5 more resources for offline computing
- R&D required to deal with these offline computing challenges:
  - Review of current computing model
  - Adapt to changing computing landscape
  - Ongoing R&D in Dirac to implement more flexible worflows for the various data and simulation streams
  - Efforts to start these developments in LS3 to integrate improvements already in Run 4



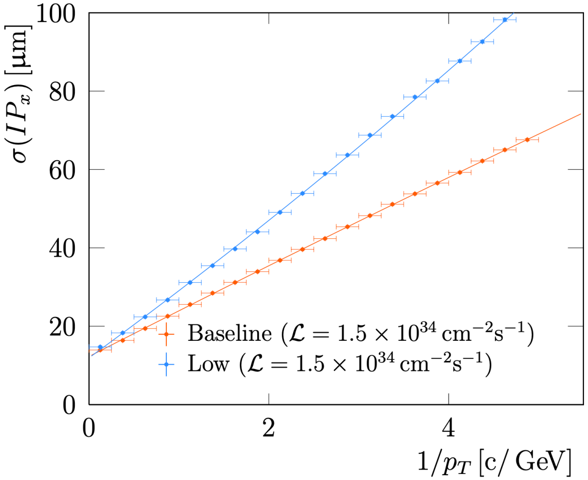
Performances: vertexing



Primary vertex efficiency



VELO tracking efficiency



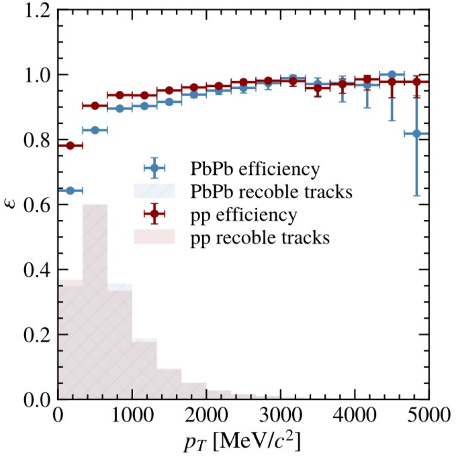
Impact Parameter Resolution

- Primary vertex efficiency is high in all scenarios, due to good timing precision in the VELO
- VELO tracking efficiency affected by reduction of acceptance in Low scenario
- Impact parameter resolution affected by more materiel in VELO (sensors and thicker RF foil) in the Low scenario

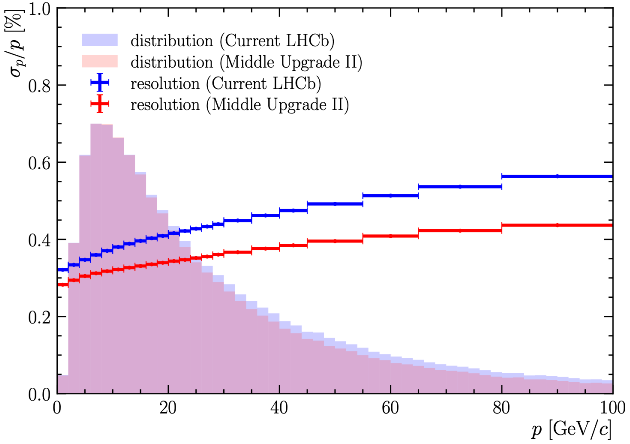
[LHCb Upgrade II Scoping Document]

Performances: tracking

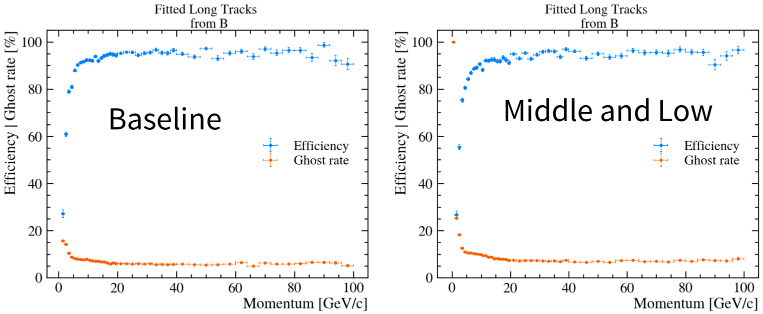
(long) track reconstruction efficiency



(long) track momentum resolution



(long) track reconstruction efficiency and ghost rates

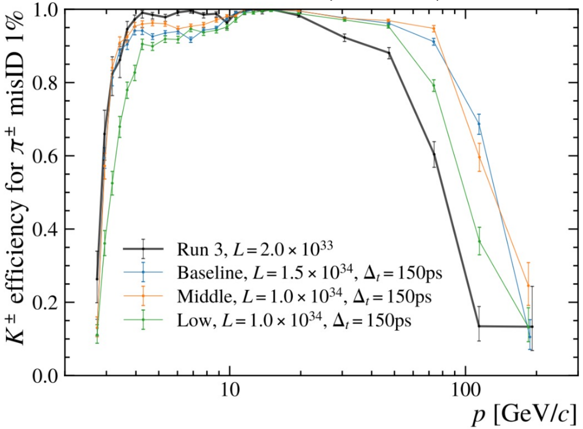


- High long tracking efficiency, also in central PbPb collisions for all scenarios, in the acceptance. This is also true for downstream and upstream tracks.
- Momentum resolution better than Run 3, in baseline/middle scenarios, affected by higher amount of material in Low scenario
- Visible loss of efficiency due to reduced acceptance in the Low scenario

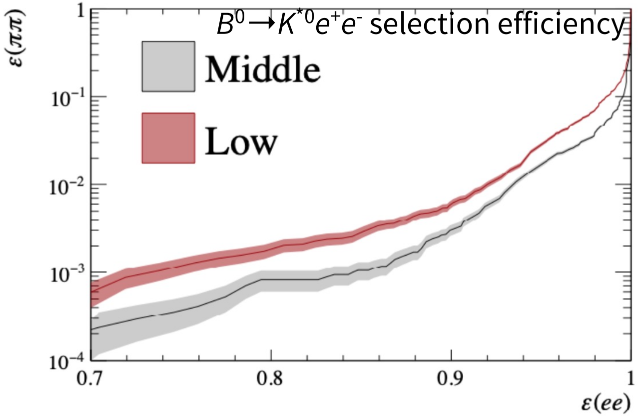
Channel	Relative acceptance %	
	Middle	Low
$B_s^0 \to \mu^+\mu^-$	99.3 ± 0.1	95.3 ± 0.1
$B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$	99.4 ± 0.1	90.6 ± 0.2
$D^0 \to K_S^0(\to \pi^+\pi^-)\pi^+\pi^-$	99.7 ± 0.1	84.8 ± 0.8

Performances: PID

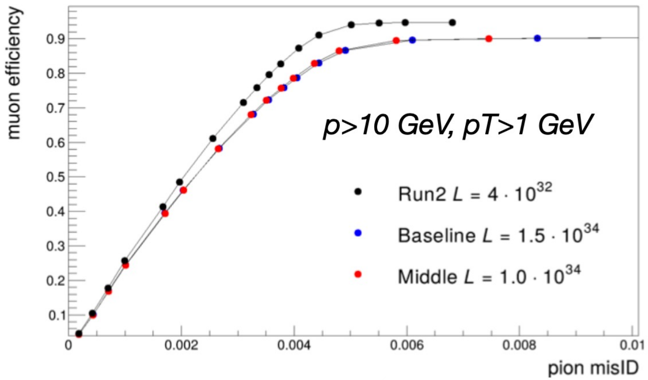
Kaon ID (RICH)



Electron ID (PicoCal): mis-id rate of $B^0 \to K^{*0}\pi^+\pi^-$ as a function of $B^0 \to K^{*0}e^+e^-$ selection efficiency



Muon ID (Muon)



- RICH PID close to Run 3 efficiencies, low momentum region affected in Low scenario
- Electron ID is affected by removal of PicoCal longitudinal segmentation in Low scenario
- Muon ID not yet at Run 2 performances: optimization of shielding in front of detector will improve performances
- For $B^0 \to K^{*0}e^+e^-$:
  - Medium scenario is affected mainly by reduction of luminosity: -12% yields, -6% for sensitivity
  - Low scenario: roughly -12% (lumi) / -10% (electron id) / -10% (acceptance) / -10% (kaon id) / -10% (worse resolutions) → ~-50% yields, -25% sensitivity

Impact on sensitivity

Compared to Run 3

Baseline	Middle	Low
$B^0_{(s)} \to \mu^+\mu^-$		
Improved background rejection from VELO with timing	Improved background rejection from VELO with timing	Worse background rejection
Improved mass resolution to separate B^0 and B^0_s peaks	Improved mass resolution to separate B^0 and B^0_s peaks	Improved mass resolution to separate B^0 and B^0_s peaks
Loss of muon identification	Loss of muon identification	Loss of muon identification
Acceptance comparable to current detector	Acceptance comparable to current detector	Reduced acceptance
γ from $B^+ \to DK^+, D \to K^0_S\pi^+\pi^-$		
Improved high momentum kaon/pion separation	Improved high momentum kaon/pion separation	Less or no improvement
Background rejection for downstream tracks with RICH2 & TORCH timing	Reduced TORCH acceptance	RICH2 timing only
Acceptance comparable to current detector	Acceptance comparable to current detector	Reduced acceptance also for downstream tracks
$D^{*+} \to D\pi^+, D \to K^+K^-$		
Acceptance for long tracks comparable to current detector	Acceptance for long tracks comparable to current detector	Reduced acceptance
Improved slow pion acceptance from Magnet Stations	Improved slow pion acceptance from Magnet Stations	No improvement
Trigger throughput comparable to current detector	Trigger throughput comparable to current detector	Reduced online farm capacity
ϕ_s from $B^0_s \to J/\psi\phi$		
Loss of muon identification	Loss of muon identification	Loss of muon identification
Improved high momentum kaon/pion separation	Improved high momentum kaon/pion separation	Less or no improvement
Improved decay time resolution	Improved decay time resolution	Worse performance
Improved flavour tagging	Improved flavour tagging	No improvement

Baseline →Middle	***Middle →Low***	
-6%	- Long track acceptance - Worse IP resolution - Worse decay-time resolution and flavour tagging	-10%
	- Track acceptance - 10% yield reduction due to worse K/π PID - Worse IP resolution - Higher background (x3) due to lack of TORCH timing	-20%
	- Long track acceptance - Less low p_T p (no Magnet Stations) - Worse IP resolution and K PID - Saturation of online farm capacity	-20%
	- Long track acceptance - Worse IP resolution and K PID - Worse decay-time resolution - >4% worse flavour tagging (no TORCH)	-20%

- Middle vs. baseline: 12% luminosity loss but comparable detector performance and better data taking stability
- Low vs. middle: significant degradation of detector performance and reduced range of physics programme

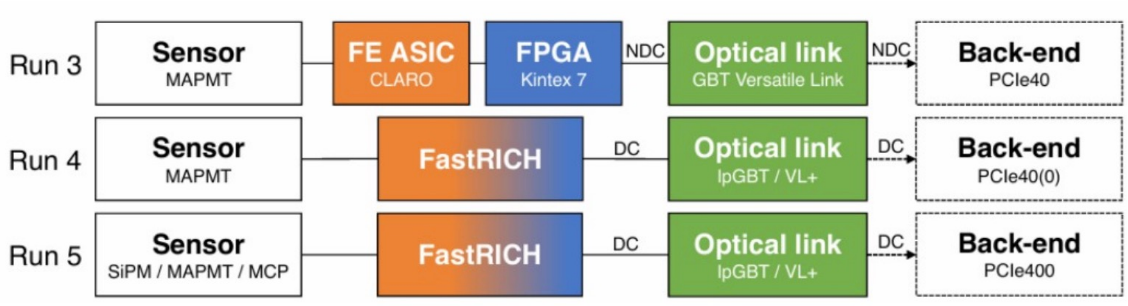
LS3 enhancements

- During LS3:
  - Advance some infrastructure work from LS4 since LS4 will be short
  - Improvements of the ECAL granularity:
    - Most of the ECAL mechanical modifications will be done
    - Gain experience on the SPACAL calibration
  - Add timing measurement to RICH:
    - Gain experience with timing during Run 4
    - Will benefit Upgrade II and readout board development.
  - Improve DAQ with PCIe400 boards
- Corresponding TDRs have been approved in 2023 and 2024

[LHCC-2023-005] Approved 03/2024

[LHCC-2024-001] Approved 12/2024

Online: Run 4



Phase Determinisme

200 ps

50 ps

10 ps

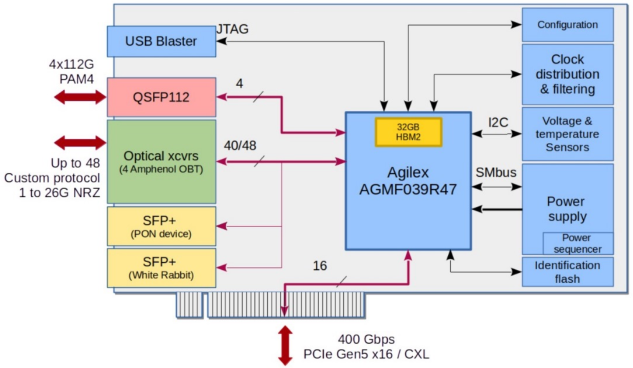
- During LS3, LHCb will deploy:
  - New RICH Front-End ASIC, with timing precision of 25 ps: need phase determinism in clock distribution of 50 ps (RICH photodetector precision of 150 ps)
  - New optical link protocol: lpGBT for the RICH
  - Custom Downstream Tracker processor, to reconstruct track segments in a network of powerful FPGAs

PCIe400

Generic and multi-purpose card developed for Run 4:

PCIe400	
FPGA	
Family:	Agilex 7M
Logic Elements:	3 851 kLE
Max frequency:	1 GHz
RAM:	311 Mb
HBM:	32 GB
ARM Cortex processor:	4 core
Optical I/O	
bidirectional links 25 Gbps:	up to 48
bidirectional links 112 Gbps:	up to 4
TFC PON or White Rabbit:	2
CPU I/O	
PCIe GEN5:	16
Output bandwidth:	400 Gbps
Timing	
	high precision PLL with jitter < 100 fs
	White Rabbit node
Form Factor	
PCIe:	268 x 111 mm

exploratory features

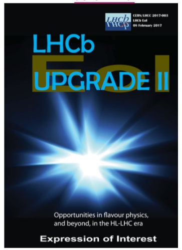


First prototype – January 2025

Project Timeline

‣ 2017

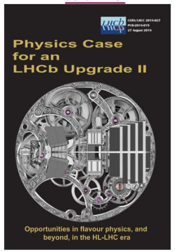
Expression of Interest



[LHCC-2017-003]

‣ 2018

Physics Case



[LHCC-2018-023]

‣ 2021

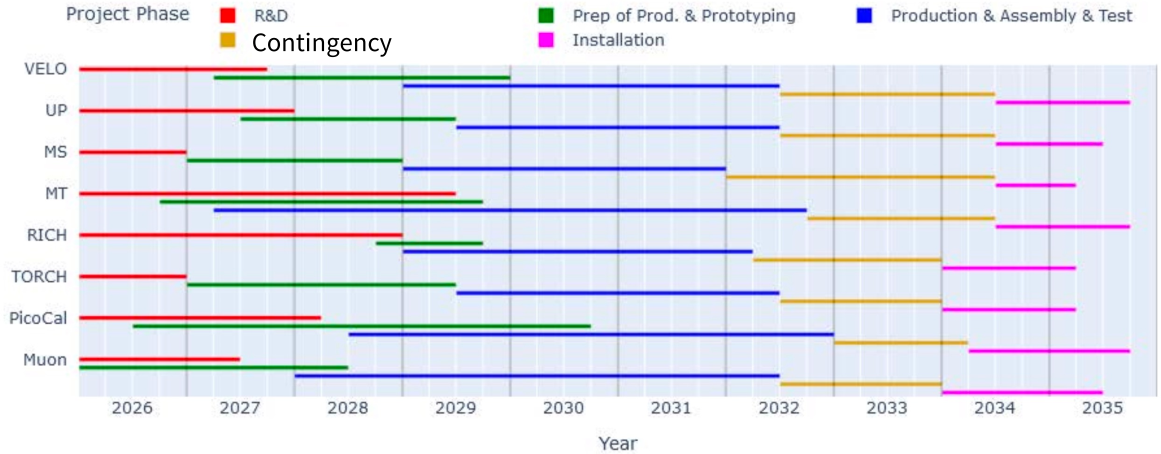
Upgrade II FTDR

[LHCC-2021-012]

Accelerator studies: [CERN-ACC-NOTE-2018-0038]

Approved 03/2022

- Endorsement of scoping document by LHCC: March 2025, recommendation by CERN Research Board to focus on Middle scenario in April 2025
- Money matrix definition: End 2025
- TDRs: 2026



Subsystem(s)	Date of TDR
VELO	Q4 /2026
Tracker (UP, MT, Magnet Stations)	Q3/2026
PID (RICH, TORCH, PicoCal, Muon)	Q2/2026

Conclusions

- LHCb Upgrade 2 will make by far the most precise measurements of a large range of key flavour physics observables: test of CKM mechanism, *CP* violation, flavour changing neutral currents, charm decays, …
- Huge discovery potential in hadron spectroscopy, in particular for the understanding of exotic hadrons.
- Unique geometry and performances for heavy flavour measurements in heavy ion physics, with a completely original fixed target system (SMOG).
- Important technology challenges that will benefit to other experiments and also outside of high energy physics: high granularity detectors, precise timing measurement, sensors with extreme radiation resistance.
- Experiments at future accelerators (FCC-ee, …) will include a flavour physics program that will benefit from the strong competencies acquired with LHCb Upgrade II.

Backup

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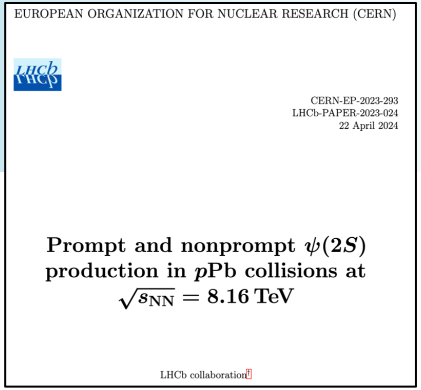
LHCb Heavy Flavours

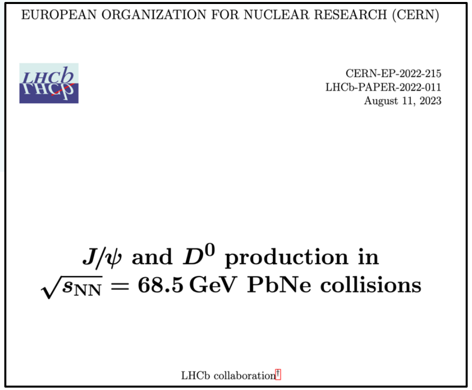
- Important probes for many of the questions that we want to address
- More detailed measurements are now needed to understand better these questions:
  - ***Open heavy flavour*** production down to low p_T (absolute normalisation, nPDFs)
  - ***Quarkonium*** feed-downs and non-vector production (deconfinement)
  - Hadrons with ***multi-heavy quarks*** (hadronization)
  - Hadron ***correlations*** (thermalisation)
- Good complementarity with measurements in flavor physics done by IN2P3 teams:
  - Expertise gained in measurement of rare or new hadrons (Ξ_{cc}, η_c, B_c, …) in *pp* collisions is transferred to the heavy ion measurements


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2023-293
LHCb-PAPER-2023-024
22 April 2024

Prompt and nonprompt $\psi(2S)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

LHCb collaboration

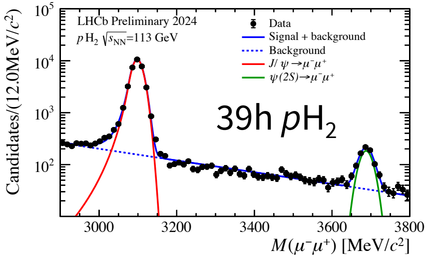

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2022-215
LHCb-PAPER-2022-011
August 11, 2023

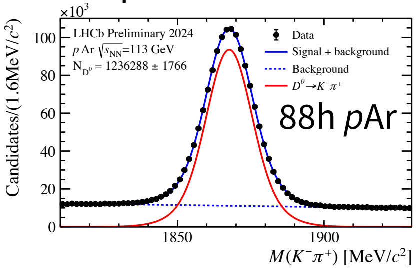
J/ψ and D^0 production in $\sqrt{s_{NN}} = 68.5$ GeV PbNe collisions

LHCb collaboration

Charmonium [LHCb-FIGURE-2024-023]

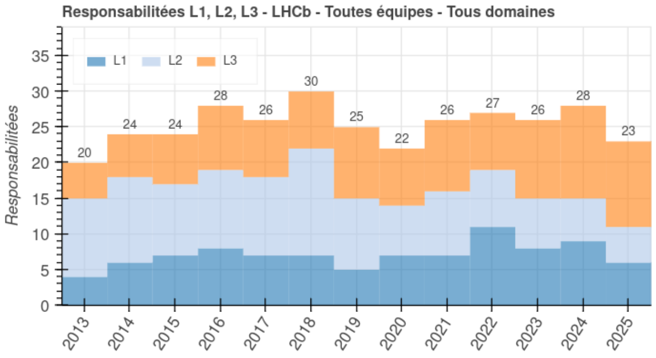


Open charm hadron



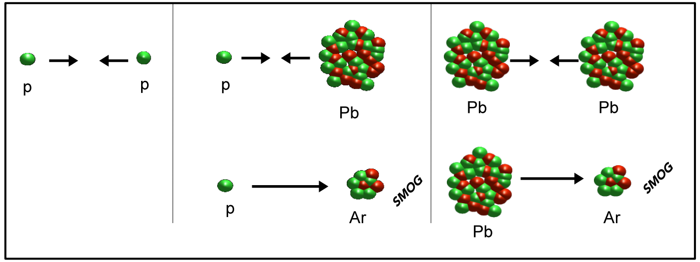
LHCb at IN2P3

- About 15 researchers currently members of ALICE in LPCA Clermont-Ferrand, IJCLab Orsay and Subatech Nantes express interest in joining LHCb before LS4.
- Interests for Upgrade II:
  - **PicoCal**: LAPP Annecy, LPC Caen, LPCA Clermont-Ferrand, Subatech Nantes, IJCLab Orsay, (IP2I Lyon)
  - **Generic Readout Card**: LAPP Annecy, CPPM Marseille, Subatech Nantes, IJCLab Orsay, LPNHE Paris
  - **RTA**: LAPP Annecy, LPCA Clermont-Ferrand, CPPM Marseille, Subatech Nantes, IJCLab Orsay, LLR Palaiseau, LPNHE Paris,
  - **Tracker**: Subatech Nantes, LLR Palaiseau, (C4PI Strasbourg)
- Current Level 1 responsibilities:
  - Andrei Tsaregorodtsev (CPPM, **Coordinator Dirac and Computing LHCb France**)
  - Frédéric Machefert (IJCLab, **Calorimeter Project Leader**)
  - Pascal Perret (LPCA Clermont-Ferrand, **SciFi Project Leader**)
  - Patrick Robbe (IJCLab, **Deputy Spokesperson**)
  - Renaud Le Gac (CPPM, **project leader PCIe40 and Online Deputy Project Leader**)
- Renaud Le Gac (data processing) and Patrick Robbe: members of the Upgrade II LHCb Planning Group

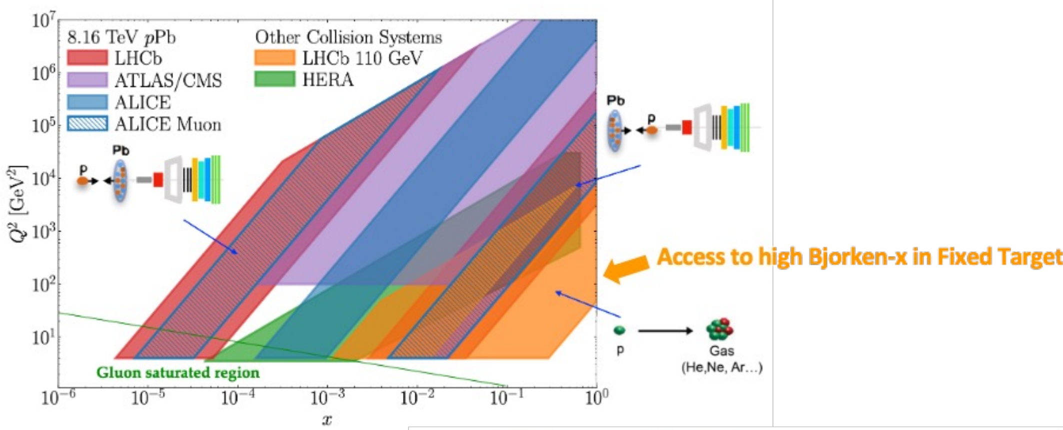


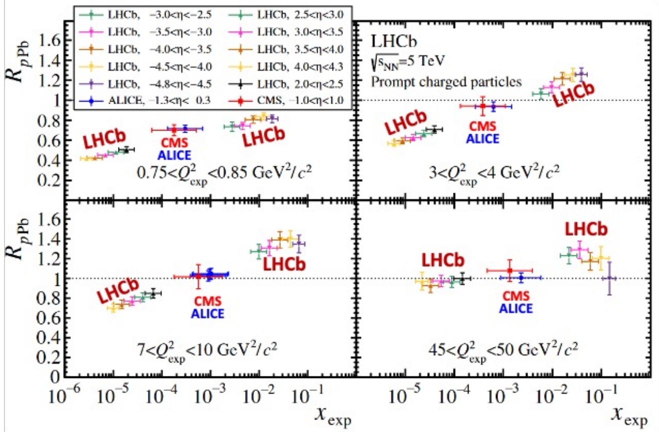
LHCb acceptance

Unique acceptance, several experiments in one:



- Pseudo-rapidity coverage
  - LHCb acceptance: $2 < \eta < 5$
  - Well placed to access the high parton density regime (***gluon saturation***)
- Bjorken-*x* coverage
  - $x_{1,2} \sim \frac{Q}{\sqrt{s_{NN}}} e^{\pm\eta}$ *with* $Q^2 \sim m^2 + p_T^2$
  - LHCb in *collider mode:*
    - *p*Pb: $10^{-6} < x < 10^{-4}$
    - Pb*p*: $10^{-3} < x < 10^{-1}$
  - LHCb in Fixed-Target mode (*p*A):
    - $10^{-3} < x < 0.5$



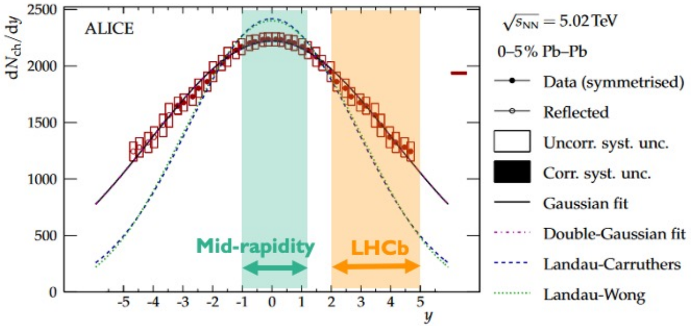


Prompt charged particle production in *p*Pb as a function of *x*
[PRL 128 (2022) 142004]

LHCb forward acceptance

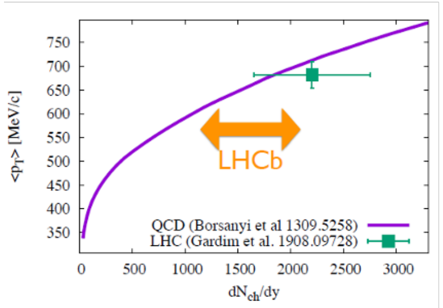
[J.-Y. Ollitrault, LHCb IFT Workhop Santiago de Compostela, 1-3 July 2024]

- Bulk (π, K, p) properties of the QGP: Multiplicity smaller at large rapidity (within the same transverse area): initial temperature smaller at large rapidity



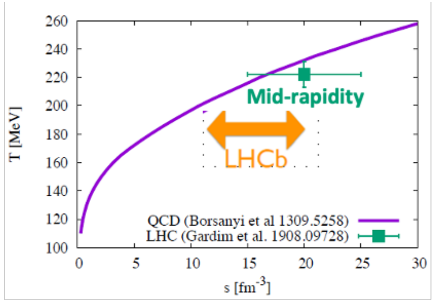
[PLB772 (2017) 567]

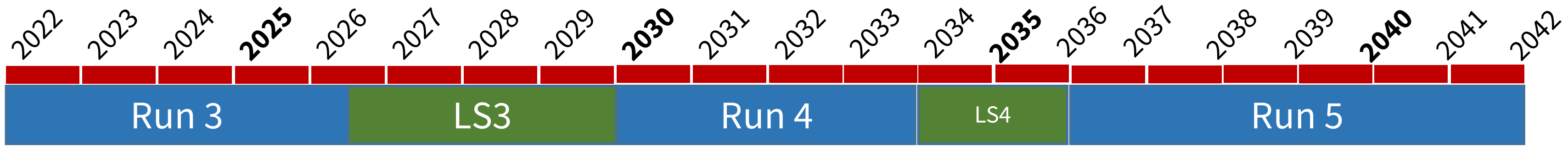
- With PID and tracking capabilities in its acceptance, LHCb allows a precise scan of the equation of state of the medium in the range 190 < T < 220 MeV



$$s(T_{eff}) \propto \frac{dN_{ch}}{dy}$$

$$T_{eff} \propto \langle p_T \rangle$$





$L = 2x10^{33}\ cm^{-2}.s^{-1}$
~6 interactions per bunch crossing
~50 fb^{-1} (Run 1 to Run 4)

$L = 2x10^{34}\ cm^{-2}.s^{-1}$
~40 interactions per bunch crossing
~300 fb^{-1} (Run 1 to Run 5)

Resources

- Estimated person-power requirements for 2025 – 2035 :
  - 90 FTE for PicoCal, 54 FTE for the readout card, 52 FTE for RTA
  - 34 researchers in 2025 → about 50 researchers in 2035
- Estimated cost, using a fraction of 6.85% (fraction for 2025) to compute the common fund contribution

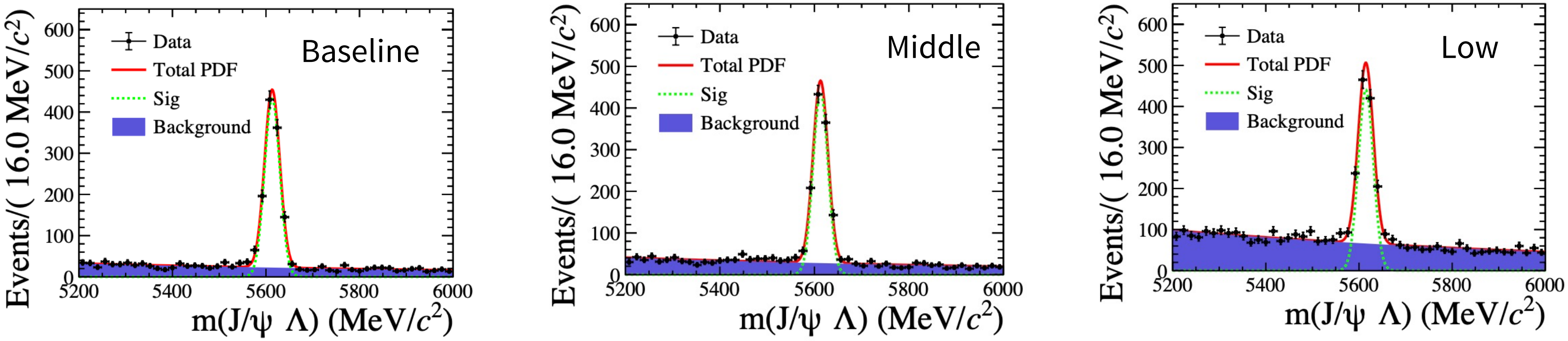
	Baseline	Middle	Low
Common Fund	3.3	2.5	2.3
PicoCal LS3	0.4	0.4	0.4
PicoCal LS4	2.7	2.7	2.1
DAQ LS3 (PCIe400)	0.2	0.2	0.2
DAQ LS4	0.6	0.6	0.6
CDD construction	1.4	1.3	1.1
Safety	1.3	1.2	1.0
Total [MEuros]	9.9	8.9	7.7

Comparison Υ(4S), pp and Z^0 [arXiv:2106.01259]

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Performances (background): tracking + PID

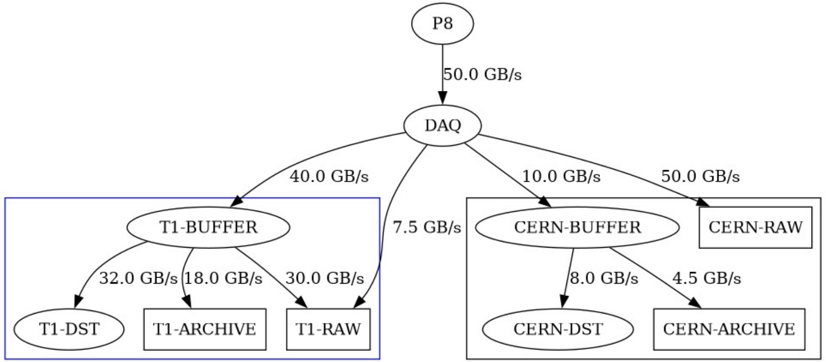
$\Lambda_b \to J/\psi\, \Lambda$ signal Monte Carlo simulation



- Reconstruction of a large fraction of the K_s^0 and Λ relies on downstream tracks (without VELO information)
- Using track timing measured with RICH and TORCH is a powerful handle to reduce ***backgrounds***, which is much less effective in the Middle scenario (reduced TORCH acceptance) or in the Low scenario (no TORCH)

Computing

Model assumptions		
	Upgrade I	Upgrade II
Peak L ($cm^{-2}s^{-1}$)	2×10^{33}	1.5×10^{34}
Yearly integrated luminosity (fb^{-1})	10	50
Logical bandwidth to tape (GB/s)	10	50
Logical bandwidth to disk (GB/s)	3.5	17.5
Running time (s)	5×10^6	
Trigger rate fraction (%)	26 / 68 / 6 Full / Turbo / TurCal	
Ratio Turbo/Full event size	16.7%	
Ratio full/fast/param. MC	40:40:20	
CPU work per event full/fast/param. MC (HS06.s)	1200 / 400 / 20	
Number of simulated events	4.8×10^9/ fb^{-1}/year	
Data replicas on tape	2 (1 for derived data)	
Data replicas on disk	2 (Turbo); 3 (Full, TurCal)	
MC replicas on tape	1 (MDST)	
MC replicas on disk	0.3 (MDST, 30% of the total dataset)	

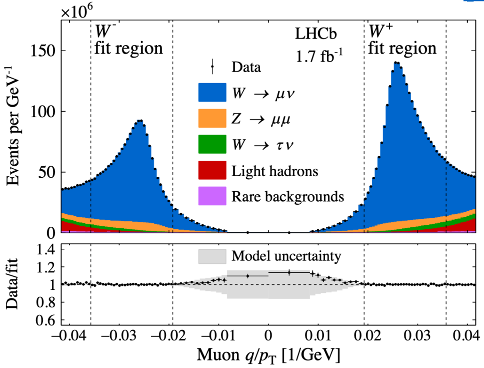


Storage needs dominated by data
CPU needs dominated by MC production

QCD and Electroweak Physics

- LHCb forward acceptance is unique amongst the LHC experiment: extension of the original LHCb program with the study of *Z* and *W* production and properties.
- Big impact on the knowledge of proton (and nuclear) gluon PDFs, important inputs to ATLAS and CMS for Higgs measurements and New Physics searches.
- Measurement of the *W* mass, with improved precision of a few MeV with Upgrade II.

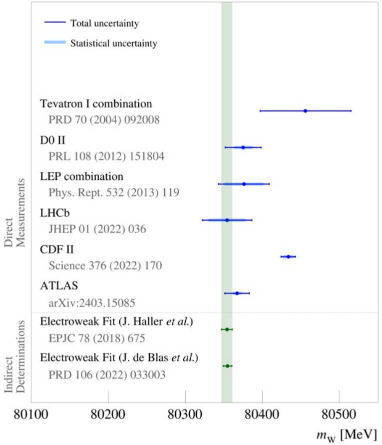
[JHEP01 (2022) 036]



- no access to p_T^{miss}: perform template fits to q/p_T for $W \to \mu\nu$ candidates
- Result:

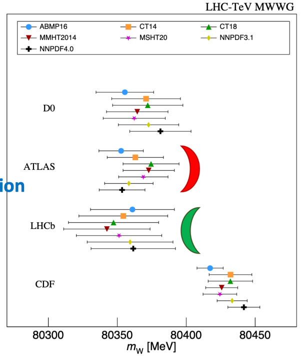
  $m_W = 80354 \pm 23_{stat.} \pm 10_{exp.} \pm 17_{th.} \pm 9_{PDF}$ MeV
- stat. unc.: ×2 more data are analyzed
- exp. unc.: momentum scale and resolution – the largest contributor

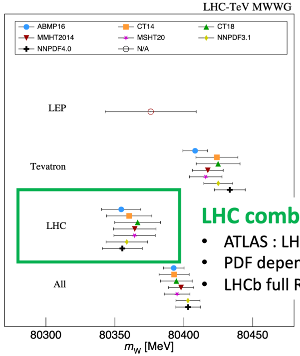
Experimental total (MeV)	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2



[arXiv:2308.09417]

ATLAS & LHCb:
PDF anticorrelation





LHC combination:
- ATLAS : LHCb – 70% : 30%
- PDF dependence already reduced
- LHCb full Run 2 result is crucial!

Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	2.8°	[18, 19]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[22]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[55, 56]	3%	2%	1%
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[25]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[29]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[57]	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%	[30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[60]	0.148	0.097	0.038

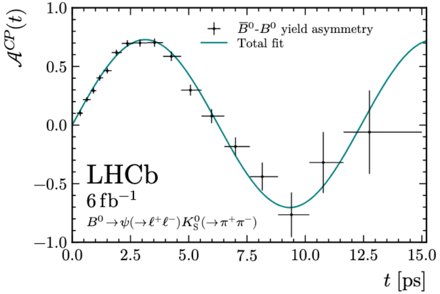
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°
γ, all modes	3° [167]	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.013 [609]	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	20 mrad [44]	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%
$B_s^0, B^0 \to \mu^+\mu^-$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$b \to c\ell^-\bar{\nu}_l$ LUV studies				
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002
$R(J/\psi)$	0.24 [220]	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.9×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

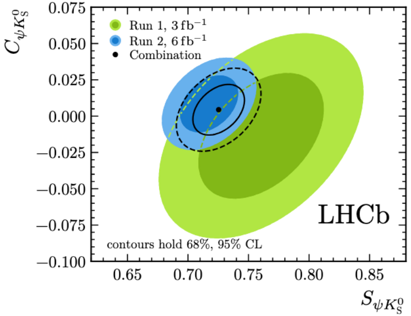
From CERN-LHCC-2018-027
With some edits for current LHCb

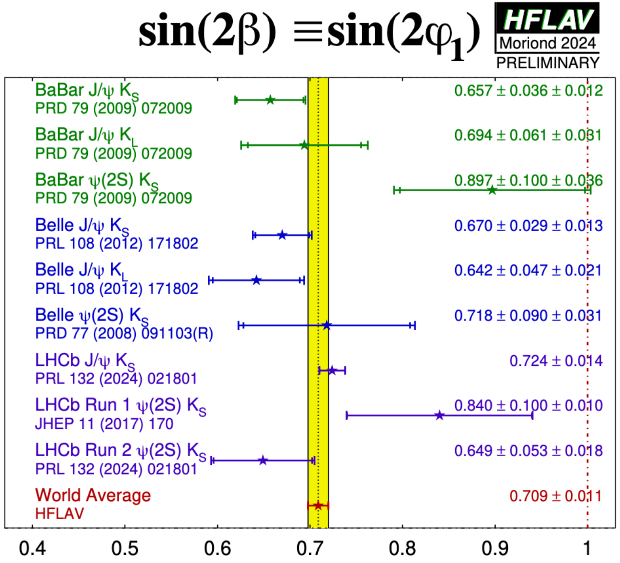
sin(2β)

PRL132 (2024) 021801

$$\text{Run 2:}\quad S_{\psi K^0_S} = 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012(\text{stat}) \pm 0.003(\text{syst})$$







https://arxiv.org/pdf/1808.08865

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

Current precisions (https://arxiv.org/pdf/2503.24346)

Experiment Assumed data sample	**ATLAS** 20.3-99.7 fb^{-1}	**CMS** 116-140 fb^{-1}	**LHCb** 2-9 fb^{-1}	**Belle II** 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.087 [17]
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	69 [22]	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	130 [23]	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**				
a^s_{sl} $[10^{-4}]$	—	—	33 [24]	—
a^d_{sl} $[10^{-4}]$	—	—	36 [25]	40 [26]
***CP* violation in the charm sector**				
ΔA_{CP} $[10^{-5}]$	—	—	29 [27]	630 [16]
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ $[10^{-5}]$	—	—	900 [28], —	870, 750
$A_\Gamma(KK, \pi\pi)$ $[10^{-5}]$	—	—	11 [29]	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-5}]$	—	—	18 [30]	140 [31]
Semileptonic B decays				
$\lvert V_{ub}\rvert$	—	—	6% [32]	6.3% [33]
$\lvert V_{cb}\rvert$	—	—	—	1.7% [34]
$R(D)$, $R(D^*)$	—	—	14% [35], 6% [36]	12%, 7% [17]
Leptonic B decays				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ $[10^{-9}]$	$^{+0.8}_{-0.7}$ [37]	0.45 [38]	0.48 [39]	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ $[10^{-10}]$	$< 2.1^*$ [37]	< 1.5 [38]	0.79 [39]	—
$\tau_{\text{eff}}(B^0_s \to \mu^+\mu^-)$ [ps]	$^{+0.45}_{-0.18}$ [40]	0.23 [38]	0.29 [39]	—
$S(B^0_s \to \mu^+\mu^-)$	—	—	—	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	34% [17]
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	41% [17]
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ $[10^{-3}]$ †	390 [41]	100 [42]	111 [43]	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\overline{\nu})$	—	—	—	57%, 110% [17]
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ $[10^{-4}]$	—	—	—	< 10, < 18 [44]
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\text{GeV})$	—	—	—	$(16 - 18)\%$ [17]
$S(B^0 \to K^0_S\pi^0\gamma)$	—	—	—	0.27 [45]
$S(B^0_s \to \phi\gamma)$	—	—	0.32 [46]	—
$A^{(2)}_T(B^0 \to K^{*0}e^+e^-;\text{very low } q^2)$	—	—	0.10 [47]	0.76 [48]
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	—	—	0.26 [49]	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ $[10^{-8}]$	—	—	—	< 7.5 [16]
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ $[10^{-8}]$	< 37.6 [50]	< 2.9 [51]	< 4.6 [52]	< 1.8 [53]

† The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0]\,\text{GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0]\,\text{GeV}^2$ for CMS.

Precisions after Run 4 (https://arxiv.org/pdf/2503.24346)

Experiment	LHCb	Belle II
Assumed data sample	$50\,\mathrm{fb}^{-1}$	$10\,\mathrm{ab}^{-1}$
CKM angles		
β	0.20°	0.4°
α	—	2.5°
γ	0.8°	2.2°
ϕ_s [mrad]	8	—
***CP* violation in loop-dominated decays**		
$S(B^0 \to \eta' K^0_S)$	—	0.023
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	22	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	20	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**		
a^s_{sl}	7	—
a^d_{sl}	5	9.5
***CP* violation in the charm sector**		
ΔA_{CP} $[10^{-5}]$	8	130
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ $[10^{-5}]$	260, —	200, 150
$A_\Gamma(KK,\pi\pi)$ $[10^{-5}]$	3.2	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-5}]$	4.1	60
Semileptonic B decays		
$\lvert V_{ub}\rvert$	2%	1.8%
$\lvert V_{cb}\rvert$	—	1.0%
$R(D)$, $R(D^*)$	4.4%, 3.2%	3.0%, 1.8%
Leptonic B decays		
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ $[10^{-9}]$	0.23	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ $[10^{-10}]$	0.30	—
$\tau_{\mathrm{eff}}(B^0_s \to \mu^+\mu^-)$ [ps]	0.11	—
$S(B^0_s \to \mu^+\mu^-)$	—	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	10%
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	11%
Flavour-changing neutral current $b \to s\ell\ell$ decays		
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ $[10^{-3}]$	29	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\overline{\nu})$	—	14%, 33%
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ $[10^{-4}]$	—	< 1.9, < 3.4
Flavour-changing neutral current $b \to s\gamma$ decays		
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\mathrm{GeV})$	—	$(6.2 - 9.6)\%$
$S(B^0 \to K^0_S\pi^0\gamma)$	—	0.07
$S(B^0_s \to \phi\gamma)$	0.062	—
$A^{(2)}_{\mathrm{T}}(B^0 \to K^{*0}e^+e^-;$ very low $q^2)$	0.043	0.15
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	0.097	—
Lepton flavour violation in τ decays		
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ $[10^{-8}]$	—	< 1.5
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ $[10^{-8}]$	< 0.64	$< (0.08 - 0.37)$

† The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0]\,\mathrm{GeV}^2$.

Precisions at the end of LHC (https://arxiv.org/pdf/2503.24346)

Experiment Assumed data sample	**ATLAS** 3000 fb^{-1}	**CMS** 3000 fb^{-1}	**LHCb** 300 fb^{-1}	**Belle II** 50 ab^{-1}
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_s [mrad]	(4 – 9)	3	3	—
***CP* violation in loop-dominated decays**				
$S(B^0 \to \eta' K^0_S)$	—	—	—	0.015
$\phi_s(B^0_s \to \phi\phi)$ [mrad]	—	—	9	—
$\phi_s(B^0_s \to K^{*0}\overline{K}^{*0})$ [mrad]	—	—	8	—
***CP* violation in $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mixing**				
$a^s_{\rm sl}$	—	—	3	—
$a^d_{\rm sl}$	—	—	2	6.2
***CP* violation in the charm sector**				
ΔA_{CP} [10^{-5}]	—	—	3.3	60
$A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$ [10^{-5}]	—	—	100, —	130, 70
$A_\Gamma(KK, \pi\pi)$ [10^{-5}]	—	—	1.2	—
$\Delta x(D^0 \to K^0_S\pi^+\pi^-)$ [10^{-5}]	—	—	1.6	40
Semileptonic *B* decays				
$\lvert V_{ub}\rvert$	—	—	1%	1.2%
$\lvert V_{cb}\rvert$	—	—	—	1.0%
$R(D)$, $R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%
Leptonic *B* decays				
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$ [10^{-9}]	(0.33 – 0.40)	0.22	0.16	—
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ [10^{-10}]	(0.32 – 0.48)	0.12	0.12	—
$\tau_{\rm eff}(B^0_s \to \mu^+\mu^-)$ [ps]	$^{+(0.07-0.11)}_{-(0.05-0.08)}$	0.05	0.05	—
$S(B^0_s \to \mu^+\mu^-)$	—	—	0.2	—
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	—	—	—	6%
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	—	—	—	5%
Flavour-changing neutral current $b \to s\ell\ell$ decays				
$P'_5(B^0 \to K^{*0}\mu^+\mu^-)$ [10^{-3}] †	(47 – 82)	23	12	—
$\mathcal{B}(B^{+,0} \to K^{+,*0}\nu\bar{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \to K^{+,*0}\tau^+\tau^-)$ [10^{-4}]	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current $b \to s\gamma$ decays				
$\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,\text{GeV})$	—	—	—	(4.7 – 8.8)%
$S(B^0 \to K^0_S\pi^0\gamma)$	—	—	—	0.04
$S(B^0_s \to \phi\gamma)$	—	—	0.025	—
$A^{(2)}_{\rm T}(B^0 \to K^{*0}e^+e^-;\text{very low } q^2)$	—	—	0.016	0.08
$\alpha_\gamma(\Lambda^0_b \to \Lambda^0\gamma)$	—	—	0.038	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \to \mu^+\gamma)$ [10^{-8}]	—	—	—	< 0.7
$\mathcal{B}(\tau^+ \to \mu^+\mu^+\mu^-)$ [10^{-8}]	$<$ (0.13 – 0.64)	< 0.39	< 0.26	$<$ (0.02 – 0.17)

† The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0]$ GeV^2 for ATLAS and LHCb and $q^2 \in [4.3, 6.0]$ GeV^2 for CMS.

Tables with links

Observable precision	Current LHCb ($9 fb^{-1}$)	Upgrade I ($23 fb^{-1}$)	($50 fb^{-1}$)	Upgrade II ($300 fb^{-1}$)	Belle II ($50 ab^{-1}$)
$\gamma(B \to DK$, etc.)	2.8°	1.3°	0.8°	0.3°	1.0°
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu\nu$, etc.)	6%	3%	2%	1%	1%
[LHCb Upgrade II Scoping Document]					[arXiv:2207.06307]

Observable precision	Current LHCb ($9 fb^{-1}$)	Upgrade I ($23 fb^{-1}$)	($50 fb^{-1}$)	Upgrade II ($300 fb^{-1}$)	ATLAS/CMS ($3000 fb^{-1}$)
$\phi_s(B_s^0 \to J/\psi\phi)$	20 mrad	12 mrad	8 mrad	3 mrad	4-9 mrad/3 mrad
a_{sl}^d	3.6%	0.8%	0.5%	0.2%	
a_{sl}^s	3.3%	1.0%	0.7%	0.3%	
[LHCb Upgrade II Scoping Document], [arxiv:1808.08865]					[ATL-PHYS-PUB-2018-041][CMS FTR-18-041]

Tables with links

Observable precision	**Current LHCb** (9fb^{-1})	**Upgrade I** (23 fb^{-1})	(50 fb^{-1})	**Upgrade II** (300 fb^{-1})	**Belle II** (50 ab^{-1})
$\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$	29 x 10^{-5}	13 x 10^{-5}	8 x 10^{-5}	3.3 x 10^{-5}	6.0 x 10^{-4}
$A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$	11 x 10^{-5}	5 x 10^{-5}	3.2 x 10^{-5}	1.2 x 10^{-5}	
$\Delta x(D^0 \to K_S^0\pi^+\pi^-)$	18 x 10^{-5}	6.3 x 10^{-5}	4.1 x 10^{-5}	1.6 x 10^{-5}	4.0 x 10^{-4}
		[LHCb Upgrade II Scoping Document]			[hep-ex:arXiv:1808-10567]

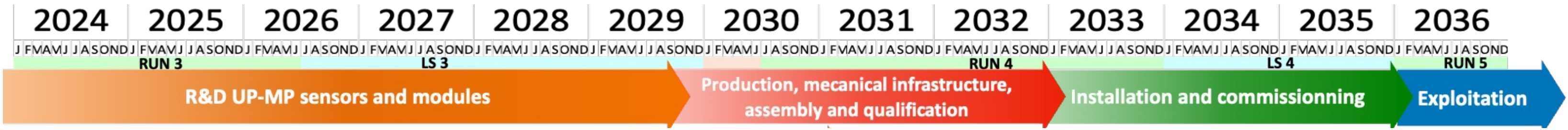
Observable precision	**Current LHCb** (9fb^{-1})	**Upgrade I** (23 fb^{-1})	(50 fb^{-1})	**Upgrade II** (300 fb^{-1})	**Belle II** (50 ab^{-1})
R_K (1.1<q^2<6 GeV^2/c^4)	0.05	0.025	0.018	0.007	0.036
R_{K^*} (1.1<q^2<6 GeV^2/c^4)	0.08	0.031	0.022	0.008	0.032
$R(D^*)$	0.06	0.032	0.03	0.03	0.01
		[arxiv:1808.08865]			[hep-ex:arXiv:1808-10567]/[arXiv:2207.06307]

Tables with links

Observable precision	Current LHCb (9fb^{-1})	(23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})	ATLAS/CMS (3000 fb^{-1})	Belle II
$BR(B^0 \to \mu^+\mu^-)$	0.79×10^{-10}		0.30×10^{-10}	0.12×10^{-10}	$(0.32\text{-}0.48) \times 10^{-10}$ / 0.12×10^{-10}	
$BR(B_s^0 \to \mu^+\mu^-)$	0.48×10^{-9}		0.23×10^{-9}	0.16×10^{-9}	$(0.33\text{-}0.40) \times 10^{-9}$ / 0.22×10^{-9}	
$\tau(B_s^0 \to \mu^+\mu^-)$	0.29 ps		0.11 ps	0.05 ps	(0.07-0.11) ps / 0.05 ps	
$A_T^{(2)}(B^0 \to K^{*0} e^+e^-)$	0.1	0.060	0.043	0.016		0.08
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	0.093	0.062	0.025		
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	0.26	0.148	0.097	0.038		
		[LHCb Upgrade II Scoping Document]			[ATL-PHYS-PUB-2018-005][CMS FTR-18-041]	[hep-ex:arXiv:1808-10567]

Tracking: proposal for R&D from IN2P3 labs (+IRFU)

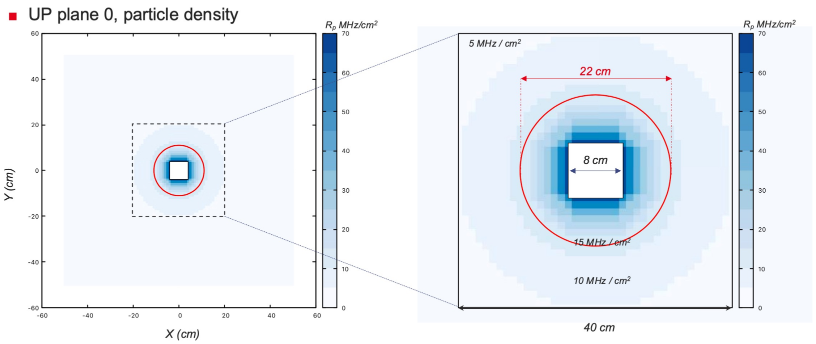
- LHCb is currently making concerted efforts and ***is converging since recently on the same DMAPS*** sensor for the ***Pixel Tracker*** (PT = Mighty Pixel + Upstream Pixel), using then same modules.
- Tracking is ***crucial for*** carrying out the ***proton-proton*** at high pileup ***and*** the ***heavy-ion*** Physics ***programs***.



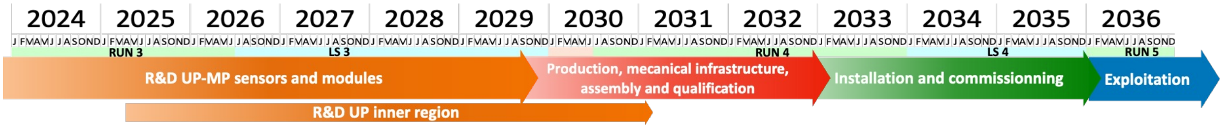
- *French R&D contribution* to the **Pixel Tracker** : sensor, module, system qualification
  - **IN2P3/Subatech : 2 (2025) → 7 (2033) FTE phys. + 3 FTE IT**
    - Contribution to the **R&D of the MAPS module conception for the Pixel Tracker** covering mechanical, thermal, electrical, electronics and readout design
    - Design and exploitation of **test bench for mechanical and readout** chain
    - Simulation and performance studies (phys.)
  - **IN2P3/LLR : 0.5 (2025) → 4 (2033) FTE Phys. + 0.5 FTE IT**
    - Implementation of a **functional testing platform** towards validation of the chip production
    - Simulation and performance studies (phys.)
  - ***Irfu:***
    - ***Sensor design (periphery)*** *and* ***characterisation***, ***module conception and prototyping***
    - *Simulation and performance studies (phys.)*
  - No overlap with the person power involved in the other projects (PicoCal, PCIe400, RTA)

Tracking: further possible R&D, UP Inner Region

- Current proposed technologies for Pixel Tracker ***still do not cope with UP inner region*** (R<11cm) requirements: the need for R&D in new technologies (65nm-55nm) + LF 150nm emerged very recently.



- Since area to equip is small, R&D and production can be delayed compared to the Pixel Tracker chips:



- **IN2P3/C4PI** is developing MAPS sensors in 65nm technology, common for various experiments (ALICE3, Belle II, FCC-ee) that could be used for the UP Inner Region:
  - Interest to adapt and test this common design for LHCb: **0.1 FTE Phys. + 3 FTE IT**
- **Subatech Nantes**, **LLR Palaiseau** and **IRFU Saclay** would extend their respective activities to cover also the UP Inner Region (module conception, tests and sensor periphery design)

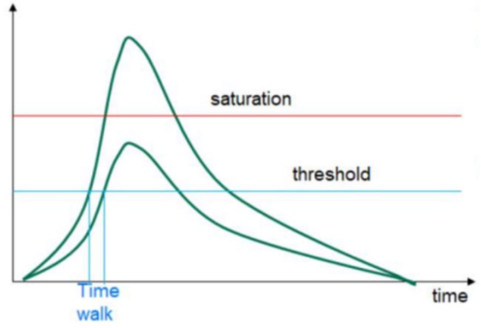
Timing measurement

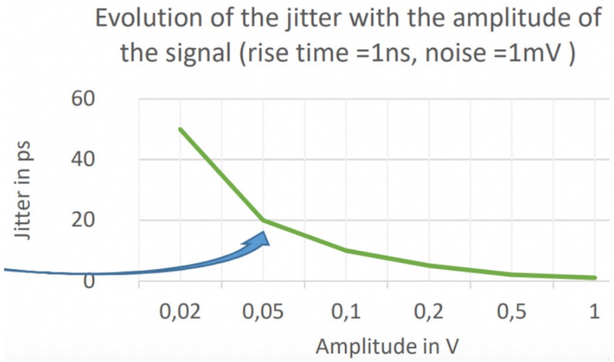
Requirements:

- Time resolution for entire chain: **15 ps** at high energy
- Dynamic range: **E_T = 50 MeV to 5 GeV**
- Up to an average cell occupancy of **50% (baseline 10%)**
- Possibility to process up to **8 consecutive events at 40 MHz**

- **Theoretical time resolution :** $\sigma_t = \dfrac{t_{rise}}{SNR}$
- Typical rise-times (as seen in test-beam): 1-5 ns, quite challenging to reach time resolution goal

Time measurement based on leading edge discriminator





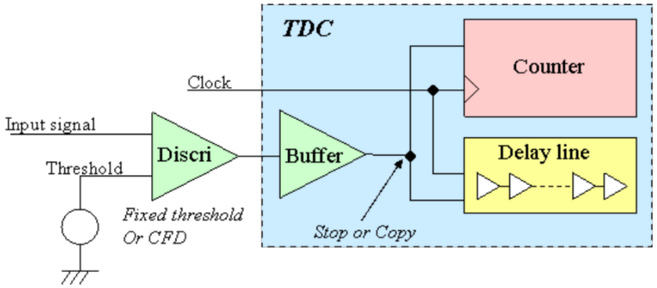
Timing extraction methods

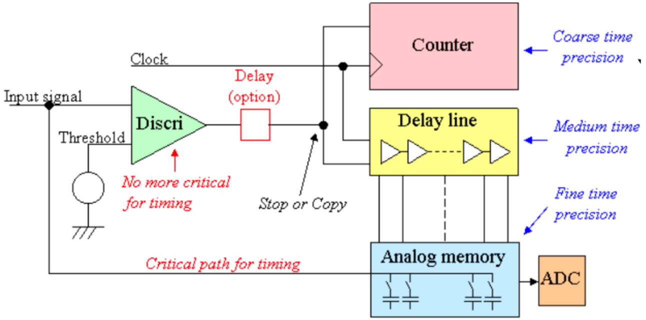
Leading-edge discriminator + Time-to-digital converter (TDC)

- High counting rate and low dead time
- Hard to achieve good resolution over large dynamic range because of the constant discriminator threshold
- Requires time walk compensation

Waveform TDC + digital Constant Fraction discriminator (CFD)

- Good resolution over large dynamic range thanks to waveform sampling (discriminator not on the critical path)
- Time walk strongly compensated by CFD
- Successful implementation in SAMPIC & WaveCatcher chips (CEA & LAL, D. Breton, E. Delagnes)
- Main limitation is rate and dead time



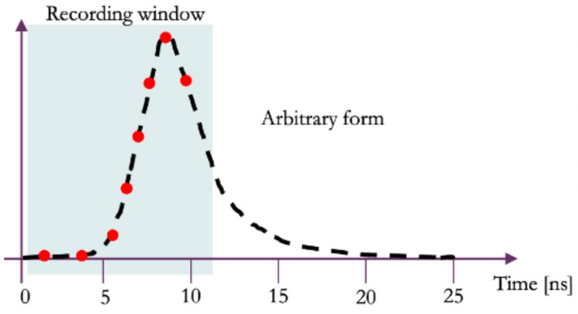


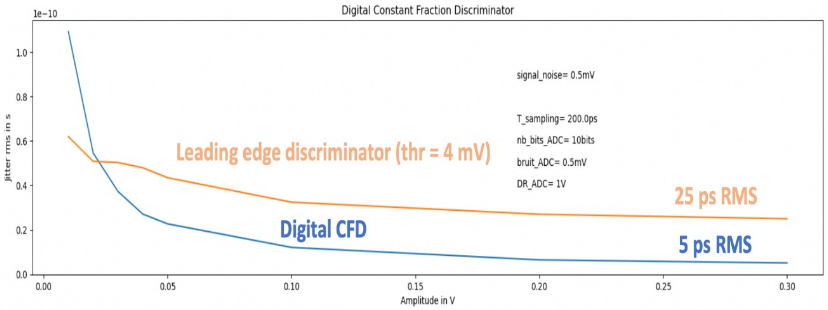
The SPIDER ASIC: a Swift Pipelined DigitizER

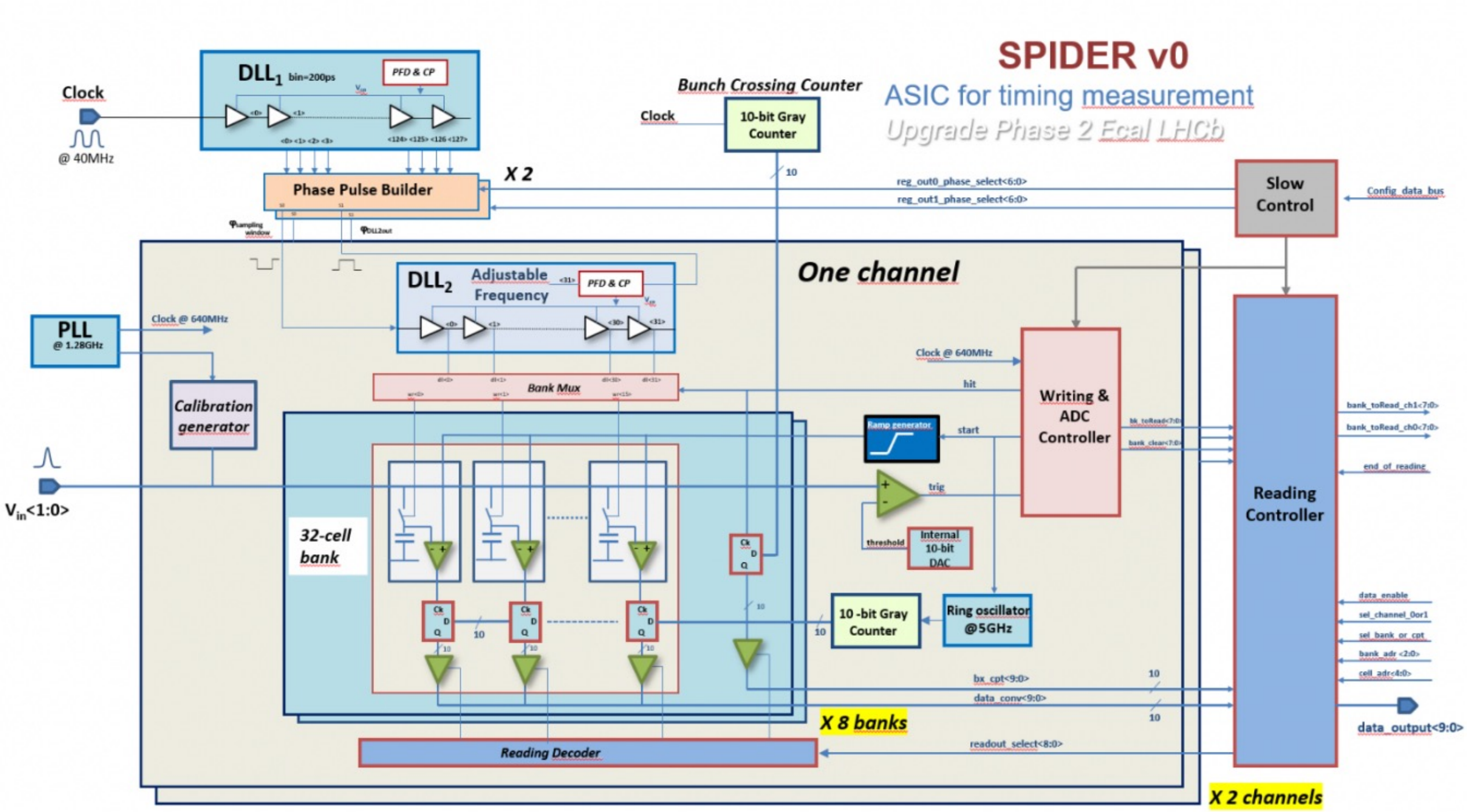
Waveform TDC + digital CFD

- Designed in 65nm TSMC - 8 channels / ASIC
- Counting rate limitation is mitigated by introducing a **pipeline of fast analog memories** recording discontinuous time segments linked to the LHC clock
- 8 32-cell banks per channel - adjustable sampling frequency : 2.5 to 20GS/s
- Adjustable sampling window around signal to reduce memory bank size - acquisition triggered by discriminator, so timing will only be available for particles with E_T>50 MeV
- Read-out rate minimised by sending only necessary samples - typically 8 samples
- CFD (or alternative time extraction / preprocessing methods) applied on FE FPGA

Based on years of experience with WaveCatcher and SAMPIC - IJCLab + LPCA among world leaders in this technology







SPIDER v0
ASIC for timing measurement
Upgrade Phase 2 Ecal LHCb
Clock
@ 40MHz
DLL1 bin=200ps
PFD & CP
Bunch Crossing Counter
Clock
10-bit Gray Counter
Phase Pulse Builder
X 2
reg_out0_phase_select<6:0>
reg_out1_phase_select<6:0>
Slow Control
Config_data_bus
One channel
DLL2 Adjustable Frequency
PFD & CP
PLL @ 1.28GHz
Clock @ 640MHz
Calibration generator
Bank Mux
Clock @ 640MHz
hit
Writing & ADC Controller
Ramp generator
start
trig
threshold
Internal 10-bit DAC
Reading Controller
bank_toRead_ch1<7:0>
bank_toRead_ch0<7:0>
end_of_reading
Vin<1:0>
32-cell bank
10 -bit Gray Counter
Ring oscillator @5GHz
data_enable
sel_channel_0or1
sel_bank_or_cpt
bank_adr <2:0>
cell_adr<4:0>
bx_cpt<9:0>
data_conv<9:0>
X 8 banks
data_output<9:0>
Reading Decoder
readout_select<8:0>
X 2 channels