Opportunities of the LHCb upgrade(s)

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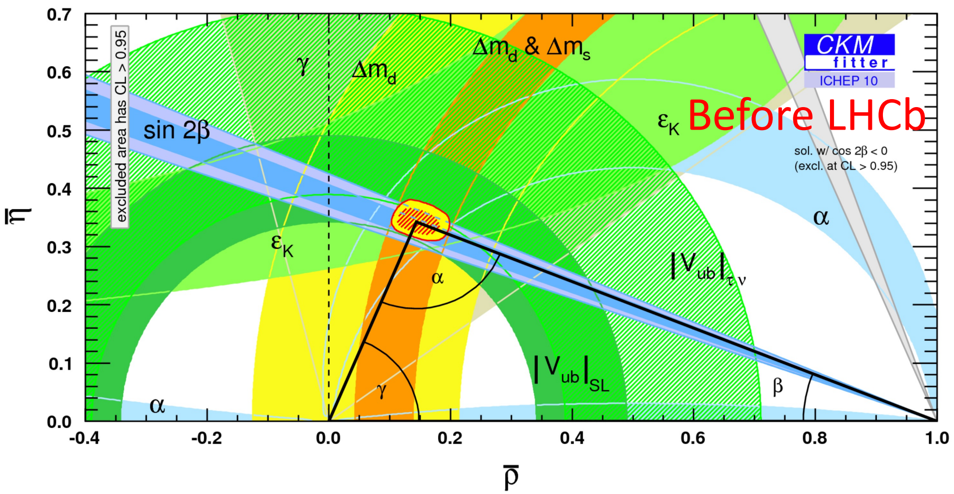
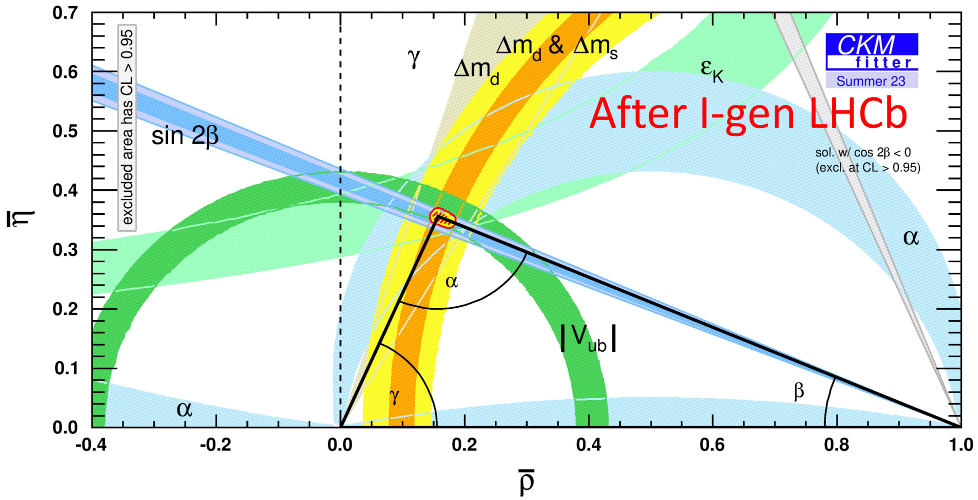
for the LHCb Ferrara group

Input to the European Strategy for Particle Physics

Introduction

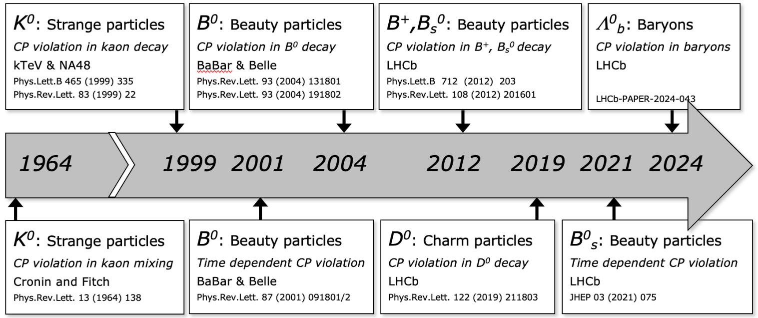
- **LHCb is a precision frontier experiment at the Large Hadron Collider designed to study the flavour puzzle in the quark and charged leptons sector**
- The second generation of the LHCb detector (LHCb Upgrade I) is functional and **collected during 2024 an integrated luminosity that surpasses the one of Run 1+Run 2**
- A further upgrade of the LHCb experiment, starting to be operational in 2036, is foreseen

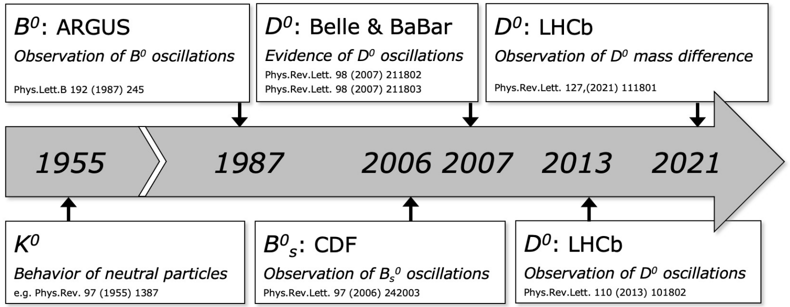


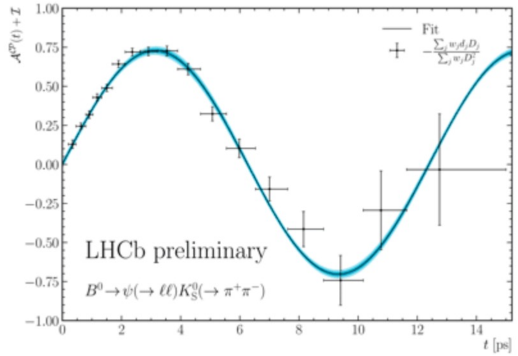


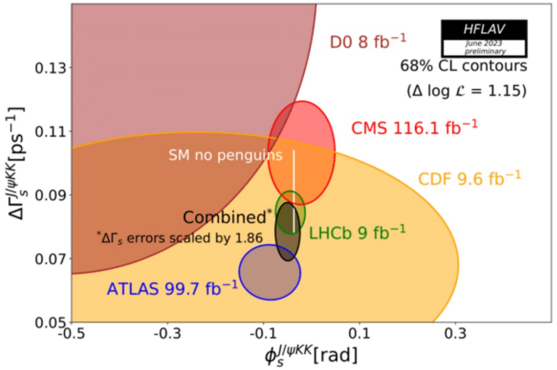
Nature hides the secrets of the fundamental physical laws in the tiniest nooks of space and time. By developing technologies to probe ever-higher energy and thus smaller distance scales, particle physics has made discoveries that have transformed the scientific understanding of the world. Nevertheless, many of the mysteries about the universe, such as the nature of dark matter, and the preponderance of matter over antimatter, are still to be explored.

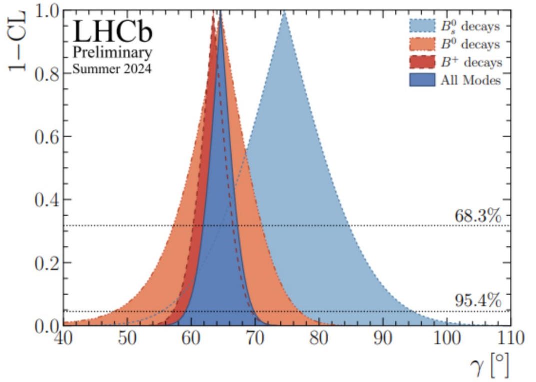
Inputs to the quark and charged lepton flavour sector ...

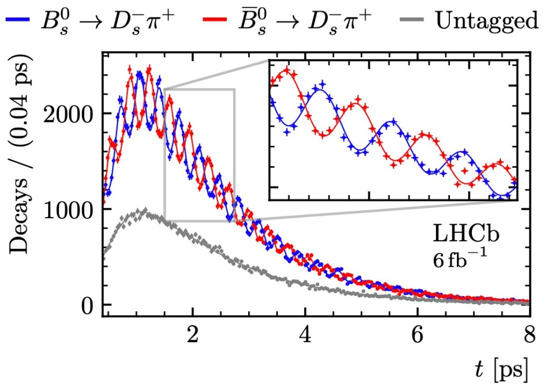


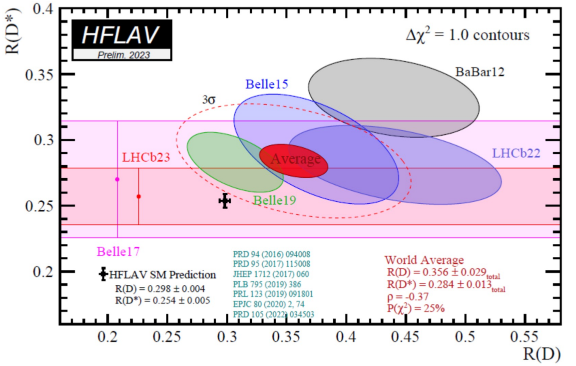


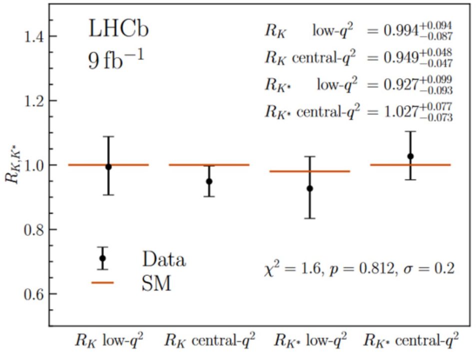


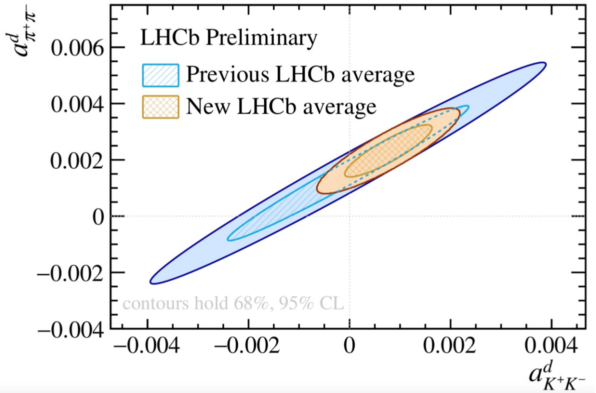


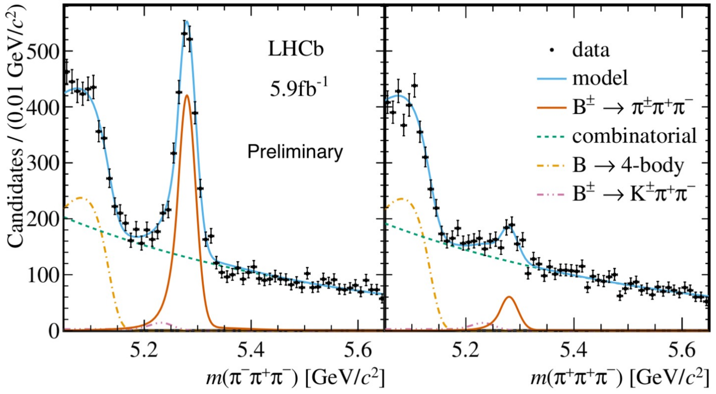


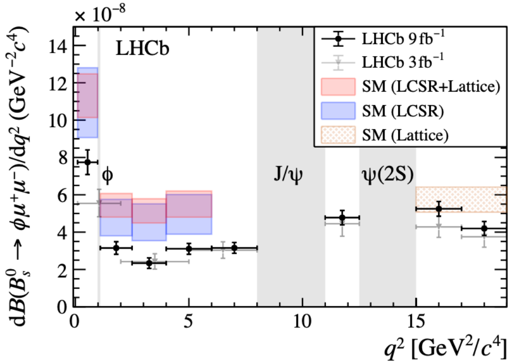


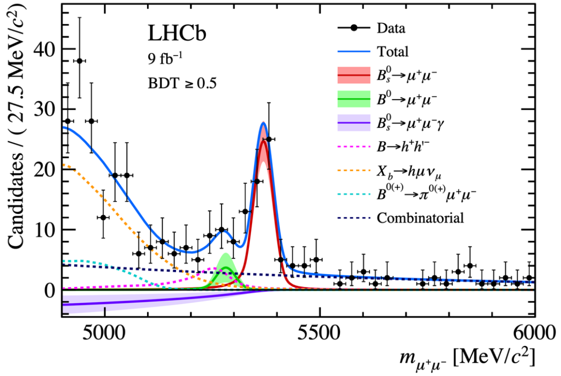








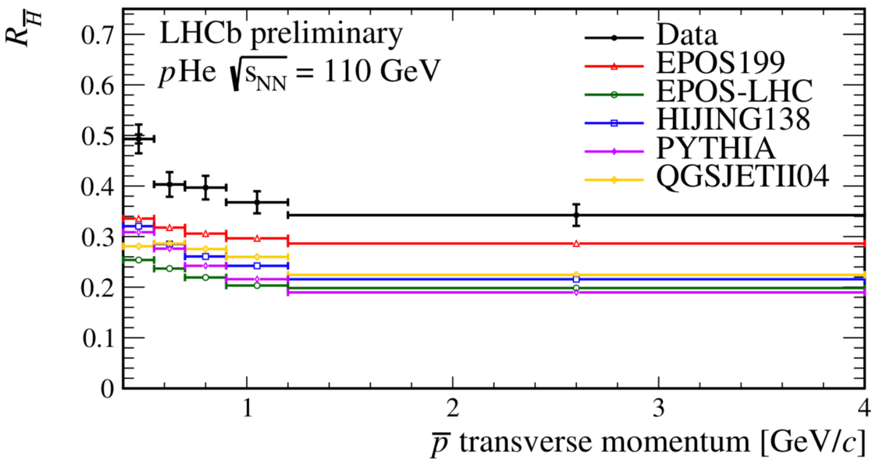


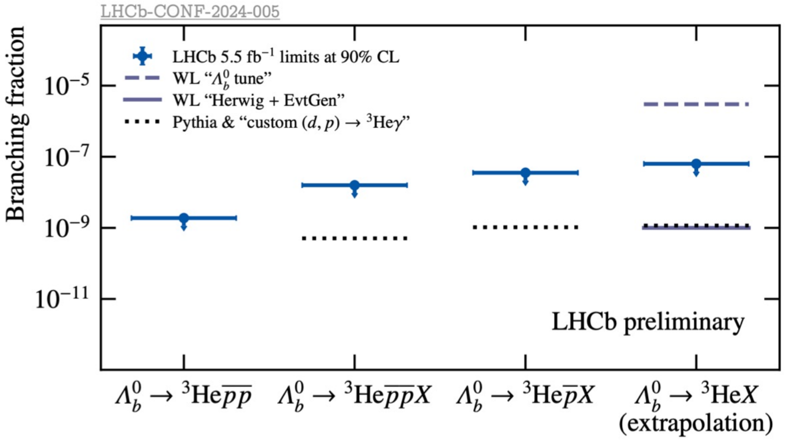


INFN

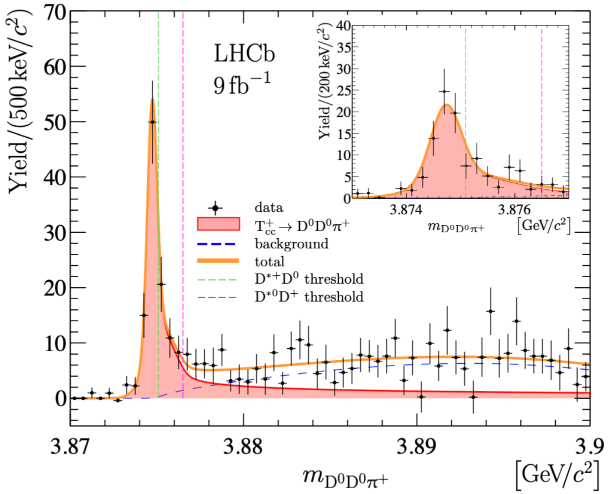
... and beyond

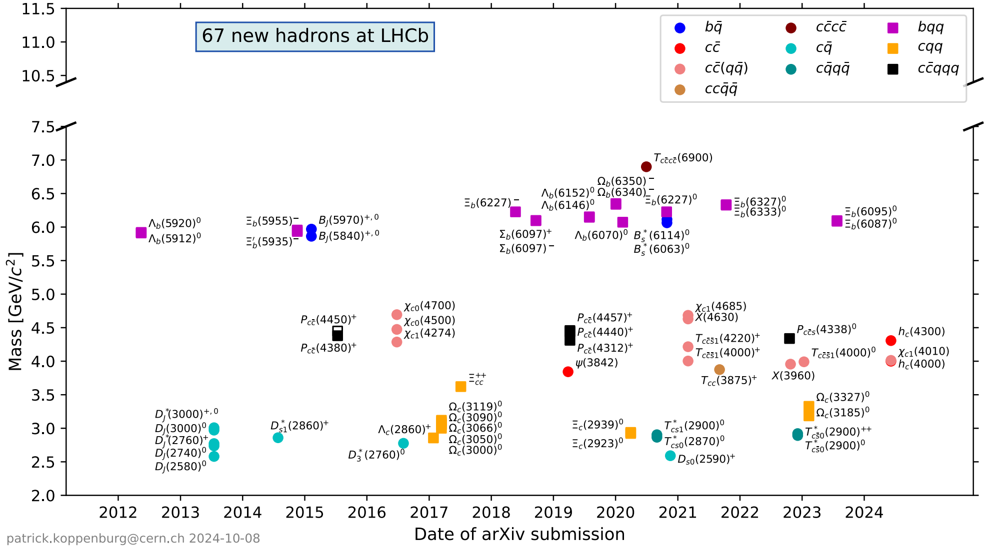
Constraints to anti-proton productions cross-section injecting gas in the beam pipe (SMOG) to study the excess seen in cosmic rays



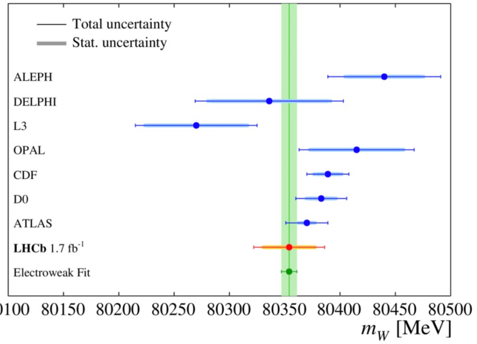


Spectroscopy





EW measurements



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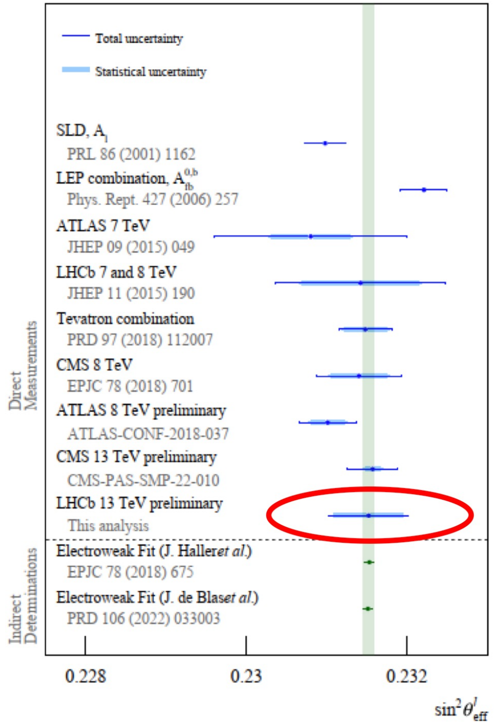
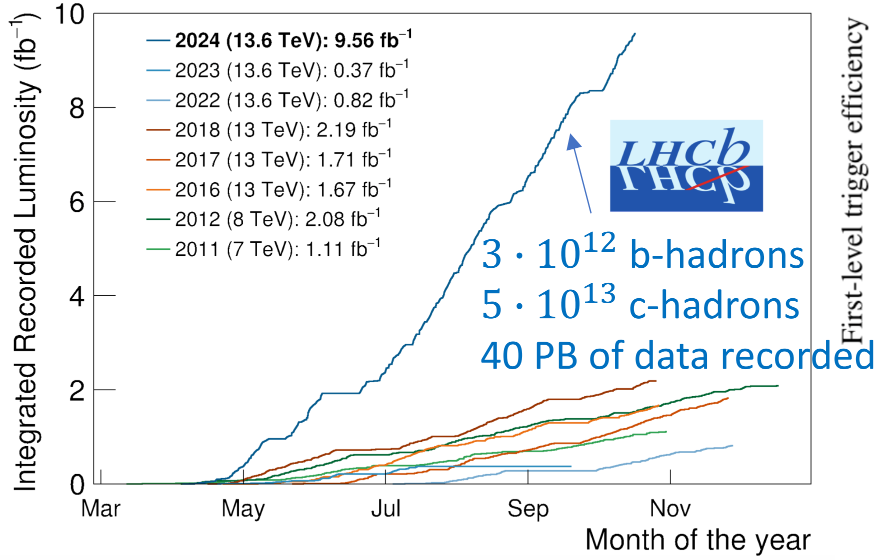
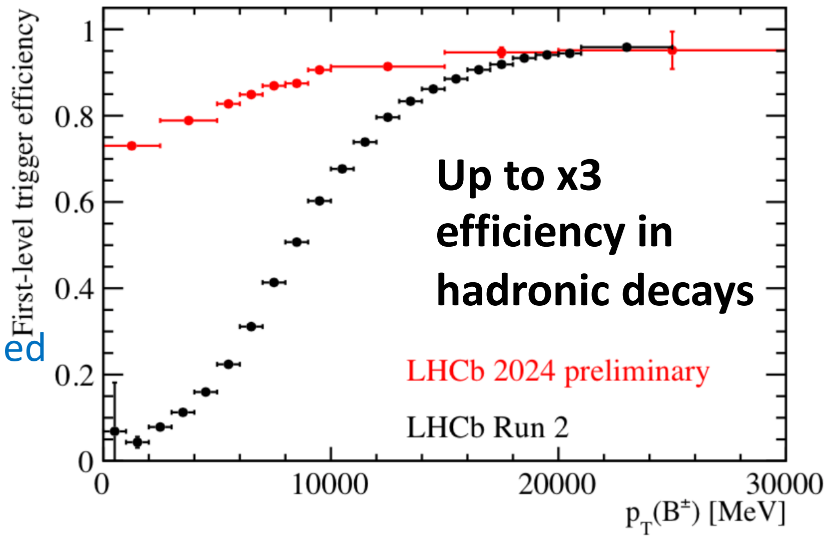


LHCb Upgrade I (2022 – 2033)

Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})
CKM tests			
γ ($B \to DK$, *etc.*)	2.8° [18, 19]	1.3°	0.8°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad [22]	12 mrad	8 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6% [55, 56]	3%	2%
Charm			
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5} [25]	13×10^{-5}	8×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5} [29]	5×10^{-5}	3.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5} [57]	6.3×10^{-5}	4.1×10^{-5}
Rare decays			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69% [30, 31]	41%	27%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [58]	0.060	0.043
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32 [59]	0.093	0.062
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [60]	0.148	0.097





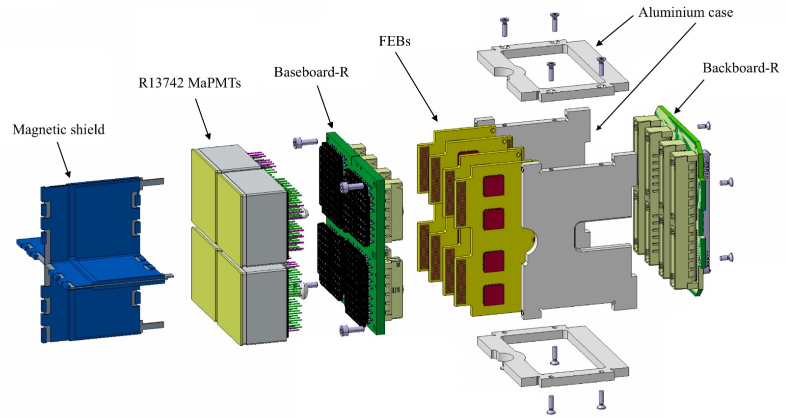
- $\mathcal{L} = 2 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, triggerless readout at 40 MHz for all subdetectors
- 40 Tb/s input bandwidth to a first software trigger stage in GPUs followed by a second level of software trigger writing at 10 GB/s to storage

A. An ambitious next-generation collider project will require global collaboration and a long-term commitment to construction and operations by all parties.

A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles.

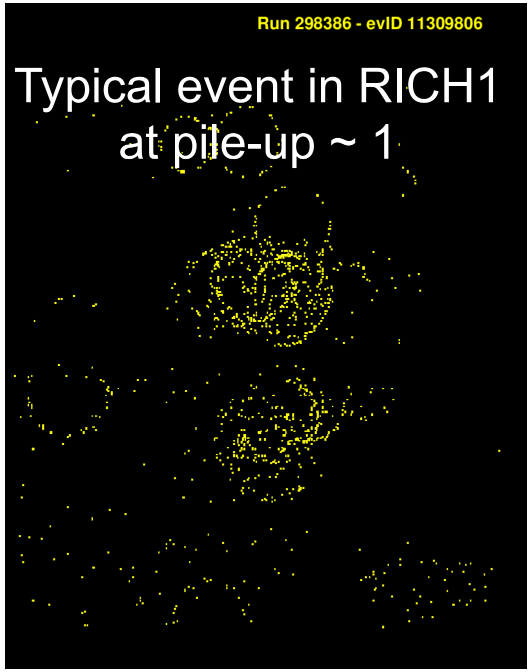
FE involved in the construction and operations of the upgraded experiment (RICH detectors, SMOG2 system, Run Coordination, Luminosity, Computing)

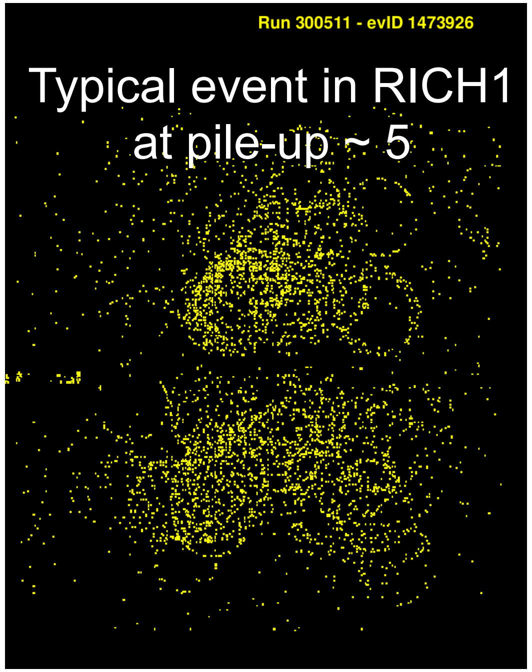
RICH detectors in LHCb Upgrade I

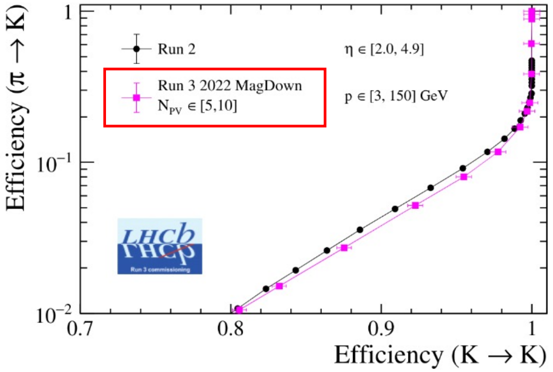


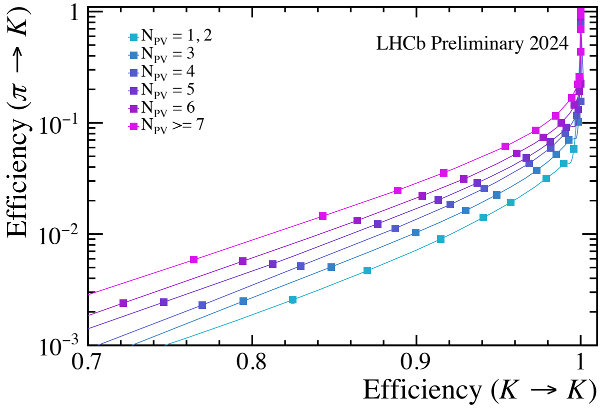
FE involved in the design of the CLARO ASIC, FEB, Backboard, EC-QA, construction and commissioning of RICH1 and RICH2 arrays ($\sim 4\ \mathrm{m}^2$ photon detection area, ~ 200k channels), operations and performance (by design since day 1 of Run 3)

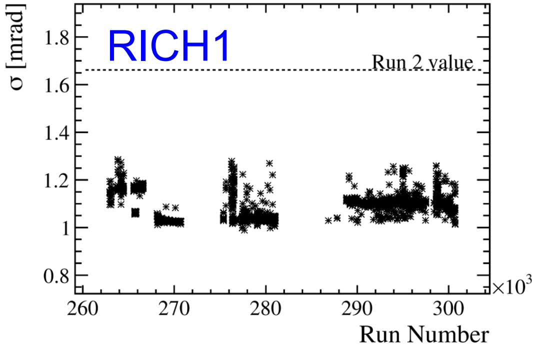
Up to $100\ \mathrm{MHz/cm}^2$ illumination rate and less than $1\ \mathrm{kHz/cm}^2$ dark count rate

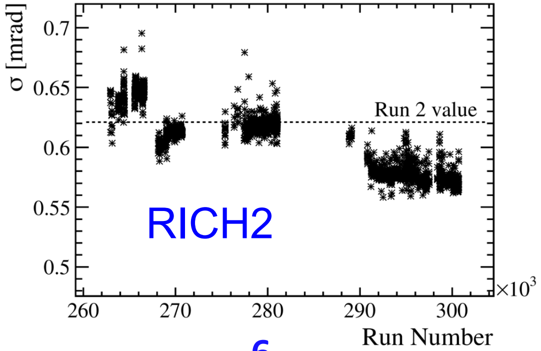








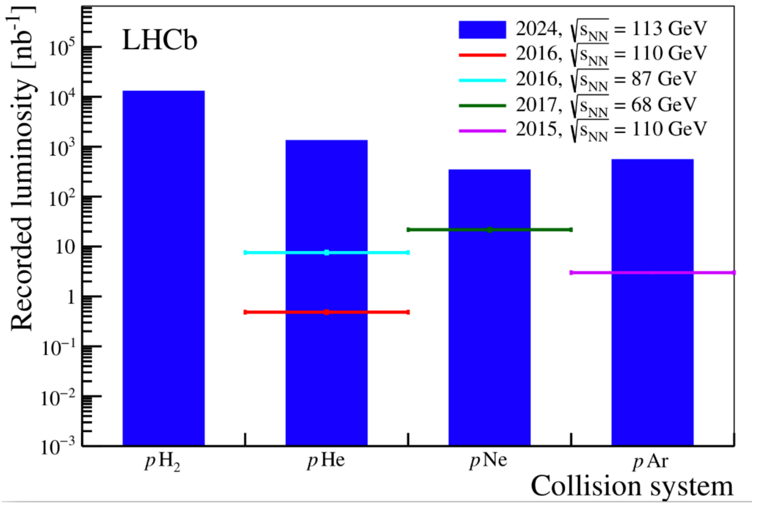


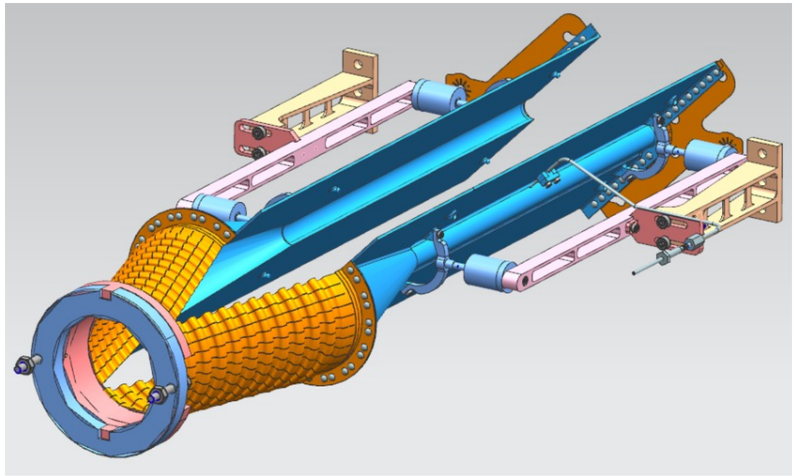


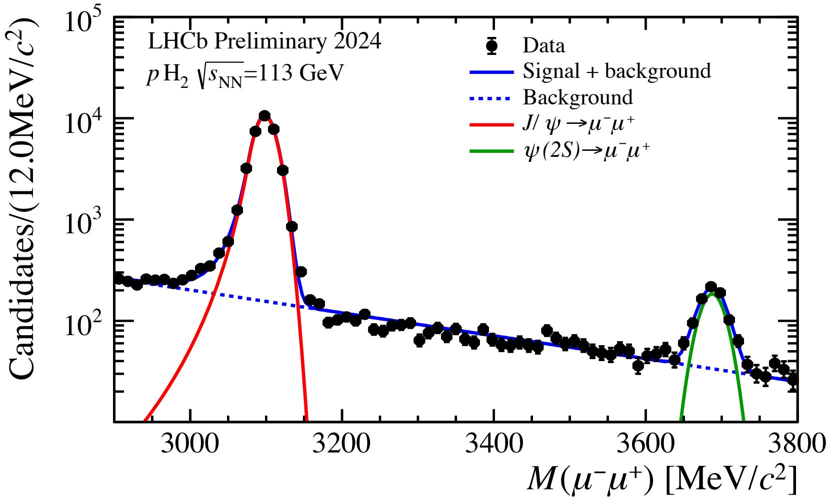
The SMOG2 system in LHCb Upgrade I

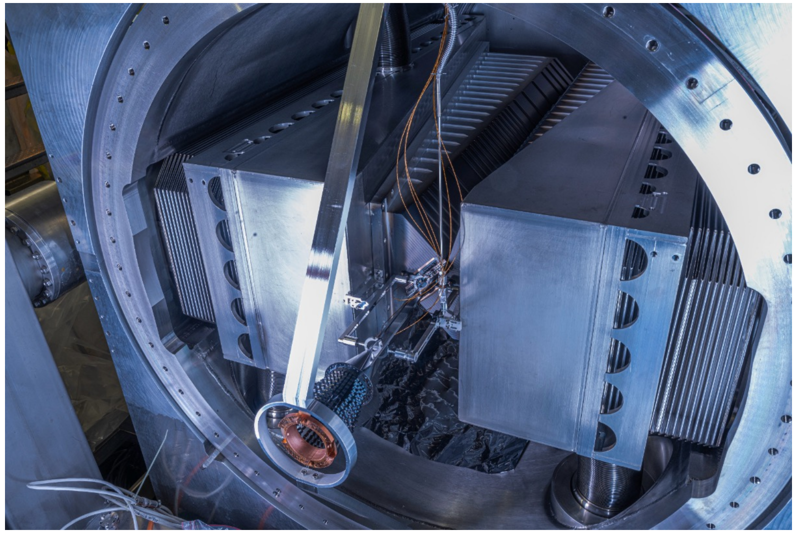
- Innovative SMOG2 cell, allowing to operate the LHCb experiment in fixed-target p-gas mode concurrently with pp (and PbPb) physics
- Probe high-x and moderate Q^2 regions

FE involved in the proposal and in the construction and installation of the cell









A. A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments and facilities. Europe has a vibrant nuclear physics programme at CERN, including the heavy-ion programme, and at other European facilities. In the global context, a new electron-ion collider, EIC, is foreseen in the United States to study the partonic structure of the proton and nuclei, in which there is interest among European researchers. ***Europe should maintain its capability to perform innovative experiments at the boundary between particle and nuclear physics, and CERN should continue to coordinate with NuPECC on topics of mutual interest.***

B. Astroparticle physics, coordinated by APPEC in Europe, also addresses questions about the fundamental physics of particles and their interactions. The ground-breaking discovery of gravitational waves has occurred since the last Strategy update, and this has contributed to burgeoning multi-messenger observations of the universe. ***Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.***

LHCb Upgrade II (2036 – 2041)

- **Emphasis in flavour puzzle in the last ESPP update**
- LHCb reaches full potential with Upgrade II thanks to the enormous heavy-flavour cross-sections at the LHC (**unbeatable at any future lepton collider**)
- Factor 2 in BSM mass scales with 300/fb of integrated luminosity reached with 6 years exploitation thanks to a seven-fold increase in the instantaneous luminosity with respect to Upgrade I

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.*)	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
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *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}
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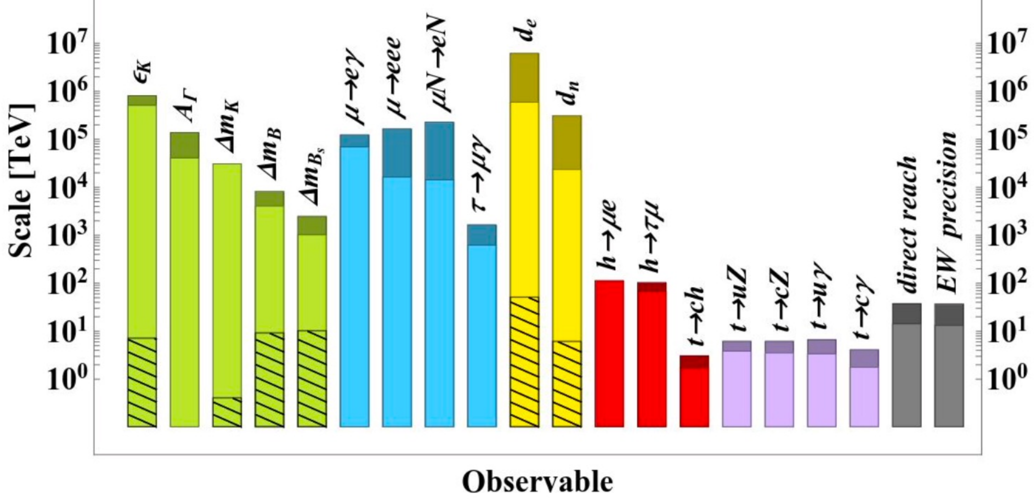
Rare decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69% [30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32 [59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [60]	0.148	0.097	0.038

ESPP '20 update

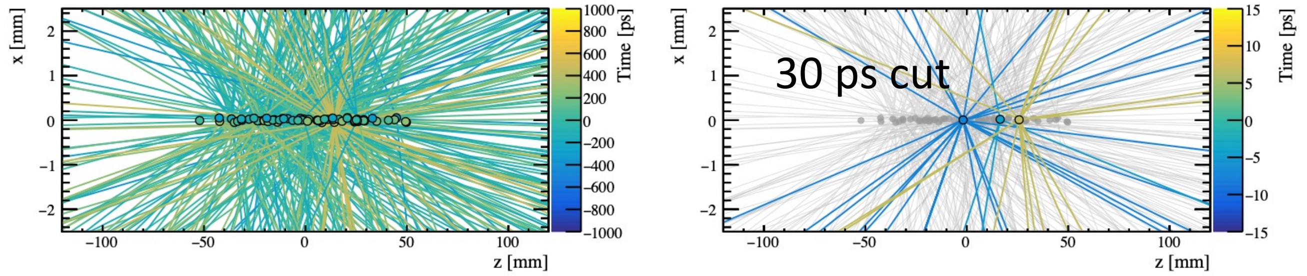


> ***The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.***

LHCb UII: challenges and technological innovations

- Technological developments required to perform precision flavour physics measurements with a pile-up of order 40 at $\mathcal{L} = 1 - 1.5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Higher granularity (=> full exploitation of heavy ions LHC programme), introduction of timing, extreme radiation hardness
- Other challenges related to software and computing: data throughput/bandwidth/data distribution
- **FE willing to contribute in various fields on-top of what is delivered for UI**

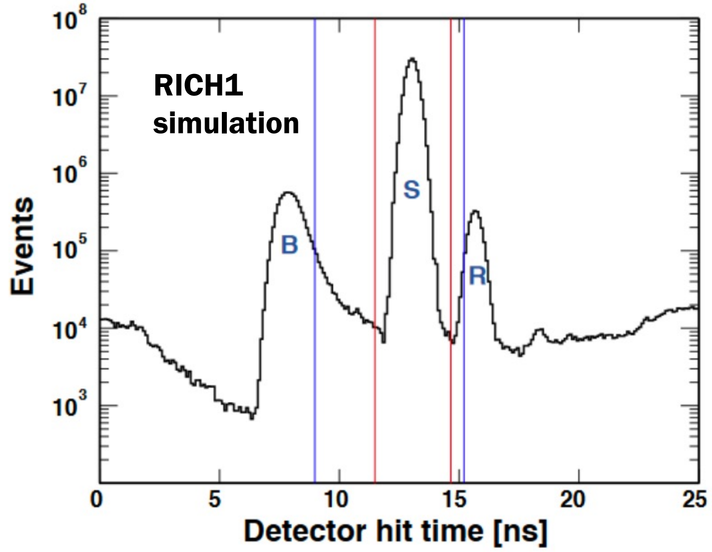
C. The success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures. To prepare and realise future experimental research programmes, the community must maintain a strong focus on instrumentation. ***Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.***

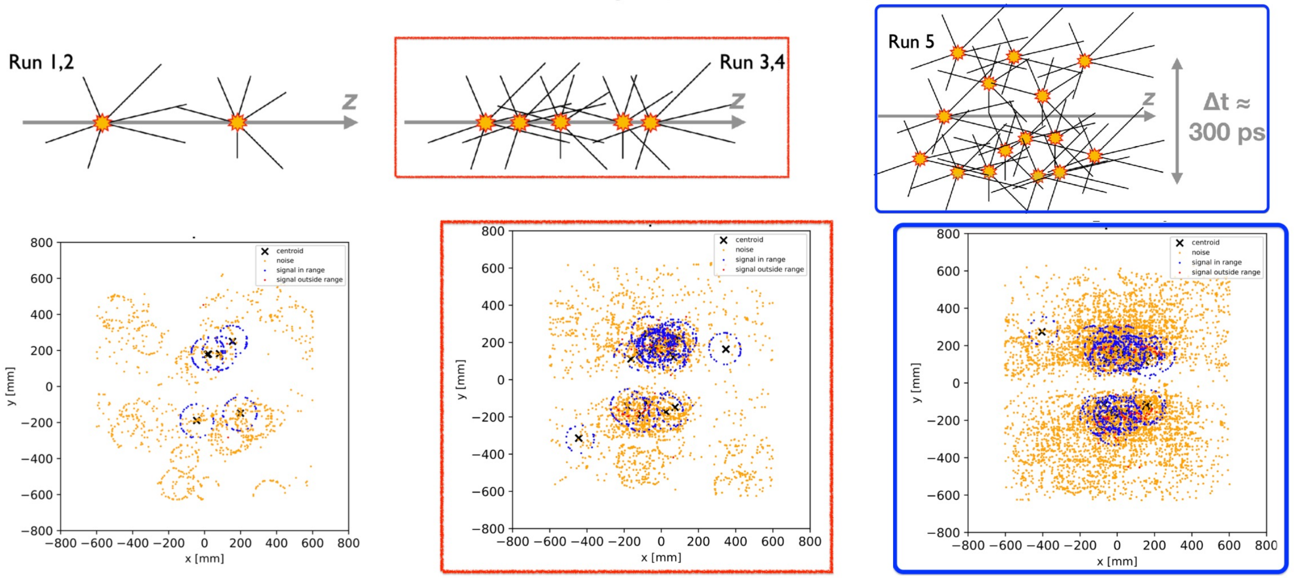


2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
Run 3		LS3				Run 4				LS4		Run 5					
TDR phase			Construction phase							Installation		Exploitation					

RICH detectors in LHCb Upgrade II

- Keep excellent performance in a harsher environment, with **illumination rates up to $10\ \mathrm{MHz/mm^2}$**
- Introduction of timing to associate single photons to tracks from individual PVs
- Concept of ns-level hardware gate to remove non-Cherenkov signals already operational with Upgrade I RICH detectors

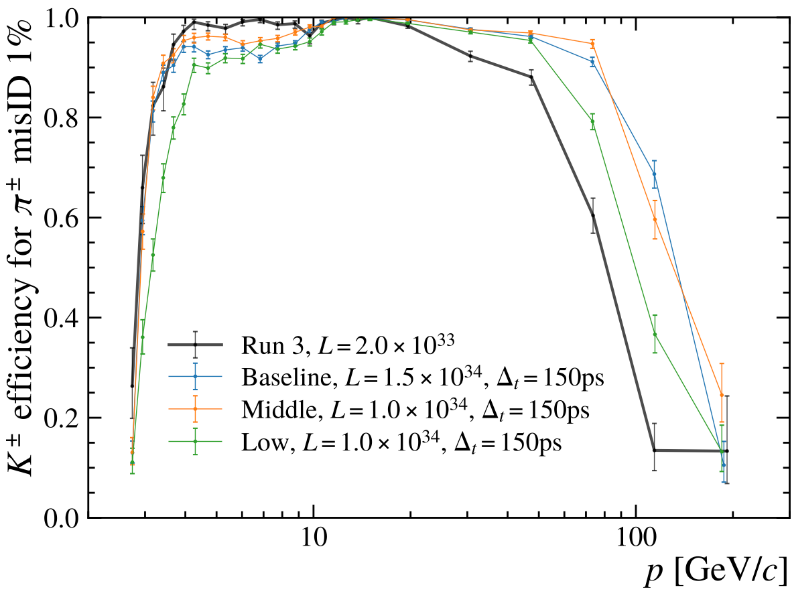




RICH1 rings with 1 PV

RICH1 rings with 5 PVs

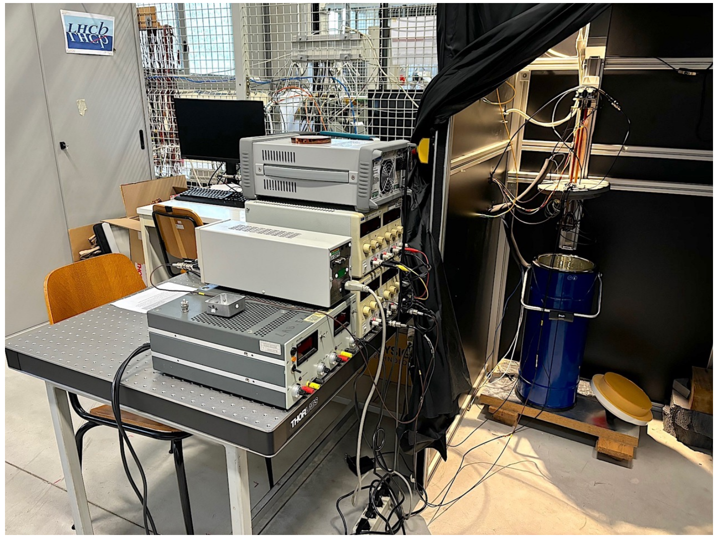
RICH1 rings with 10 PVs

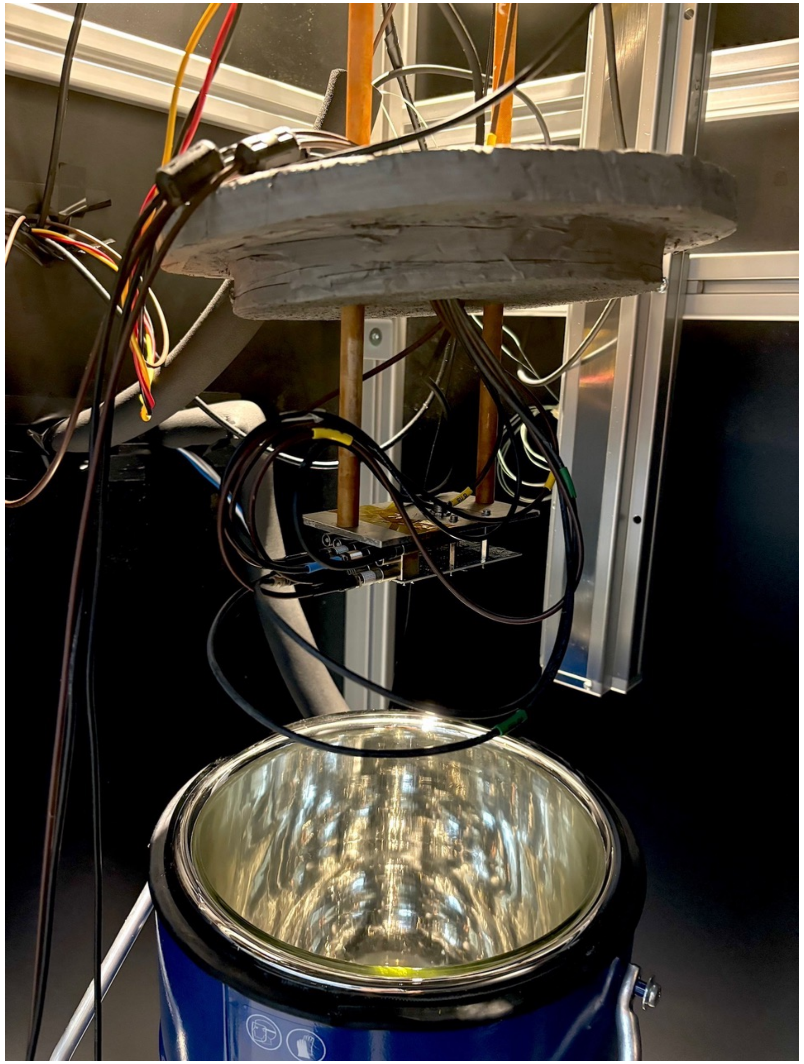


Development of RICH detectors for LHCb Upgrade II

- Sensors have to allow single-photon detection (=> PDE>40%) with time resolutions below 100 ps rms, high granularity (down to ~ $1 \times 1\ \mathrm{mm}^2$), less than $100\ \mathrm{kHz/mm}^2$ dark count rate, radiation hardness for 2 Mrad TID, $2 \cdot 10^{13}\ 1\ \mathrm{MeV}\ \mathrm{n_{eq}/cm}^2$
- **Started vigorous R&D phase to select the photon sensor (coordinated by FE)**
- **Next phase of R&D driven by FE is the design of new high-density Front-End Modules for fast-signal transmission with efficient heat dissipation and thermal decoupling of photon sensors, ASICs and digital components**
  - FE is also currently designing a new FEB that will host the new FastRICH ASIC, anticipating some of the features needed for UII (to be possibly installed during LS3)
- Both R&D programmes have a strong synergy with DRD4 activities

R&D on photon detectors for RICH Upgrade II

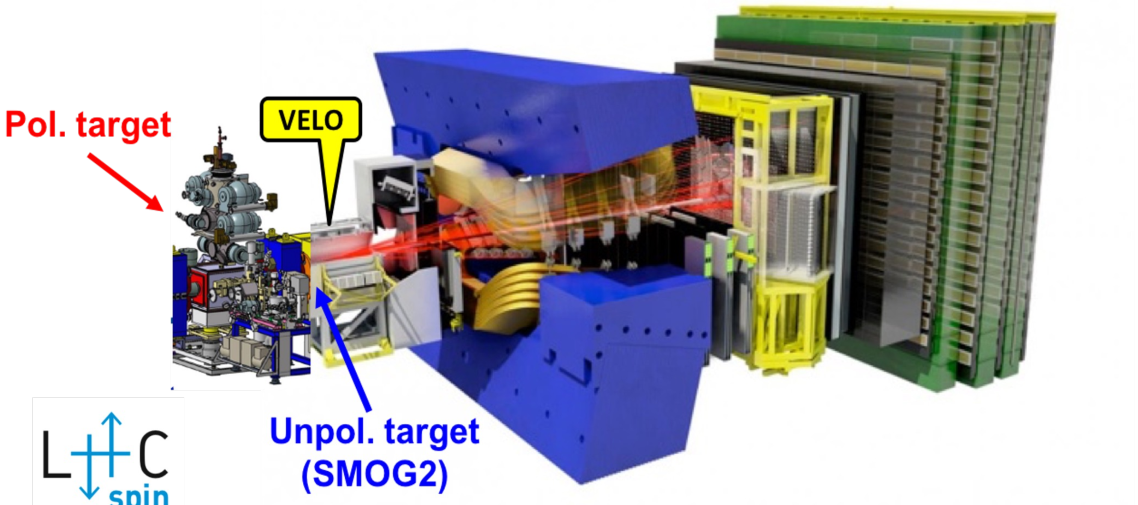




- Characterise commercially available and customised SiPMs at different temperatures before and after irradiation
- Setup including amplifier working at cold temperatures well advanced in FE
- **Steer developments with vendors to find a suitable photon sensor tailored to the LHCb RICH Upgrade II application**

The LHCspin project

The **LHCspin** project aims to perform spin physics measurements at the LHC through the implementation of a new-generation HERMES-like **polarized gaseous fixed target** in the **LHCb** spectrometer.



Motivations and points of strenght

- ✓ unique kinematic conditions
- ✓ polarized gas target technology well established
- ✓ marginal impact on LHC and LHCb performances
- ✓ can run in parallel with collider mode
- ✓ can benefit from both protons and heavy-ion beams
- ✓ allows also injection of non-polarized gases (a-la SMOG2)

The Ferrara group:

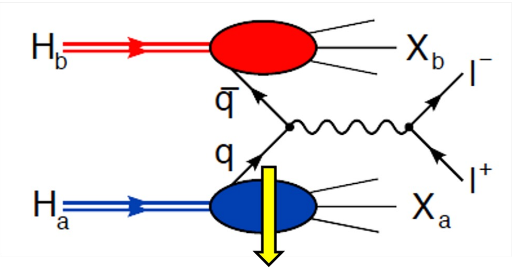
(V. Carassiti, G. Ciullo, P. Lenisa, L. Pappalardo, A. Piccoli, R. Shankar,…)

- ✓ World-recognized expertise in polarized gaseous targets
- ✓ Long-term experties in high-energy spin physics (HERMES, PAX, JLAB, COSY)
- ✓ Experties in cryogenics, SC magnets, vacuum tecnologies

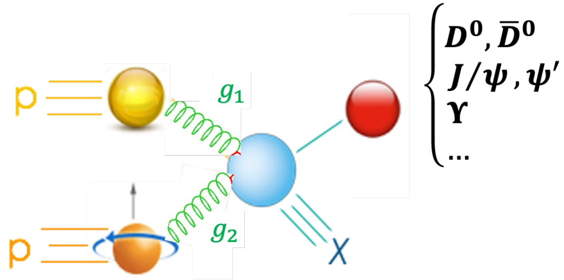
Broad and unique physics program

- **Study of multi-dimensional nucleon structure**
- Experimental observables sensitive to **quarks and gluons TMDs**
- Make use of new probes (charmed and beauty mesons)
- Complement present and future SIDIS results
- Polarized physics with heavy-ions

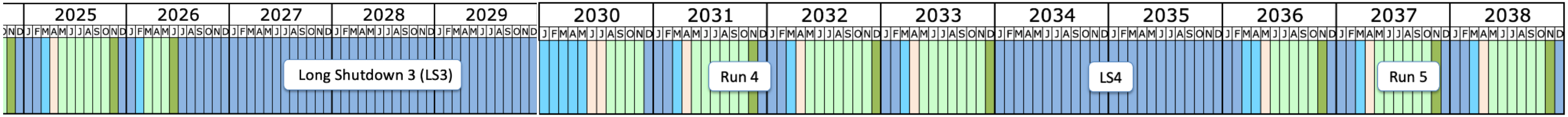
Transv. polarized Drell-Yan



Inclusive production of quarkonia



Timeline of the project

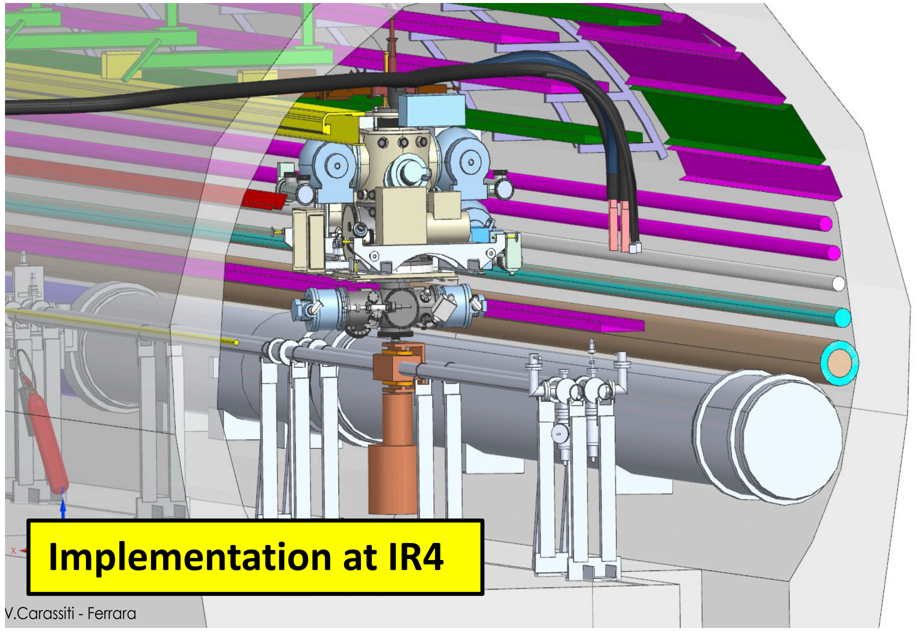


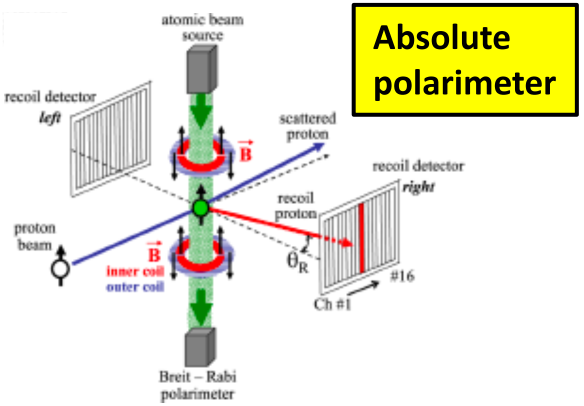
Installation at IR4 (LHC):
- ABS + Breit-Rabi polarimeter
- Absolute polarimeter
- minimal spectrometer

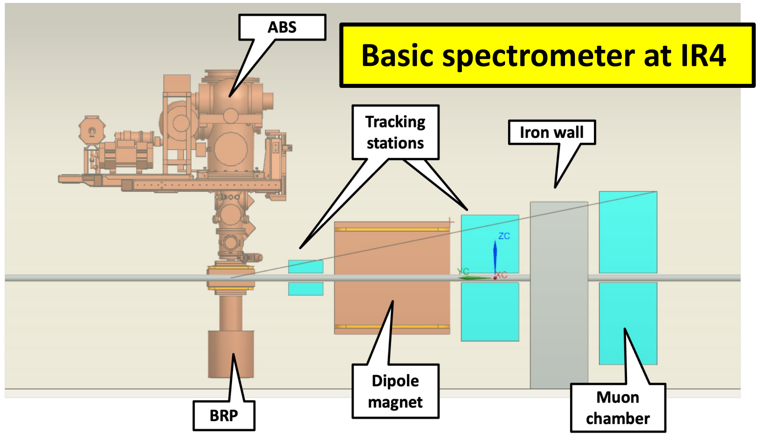
- Calibration of absolute polarimeter
- First physics measurements (SSAs)

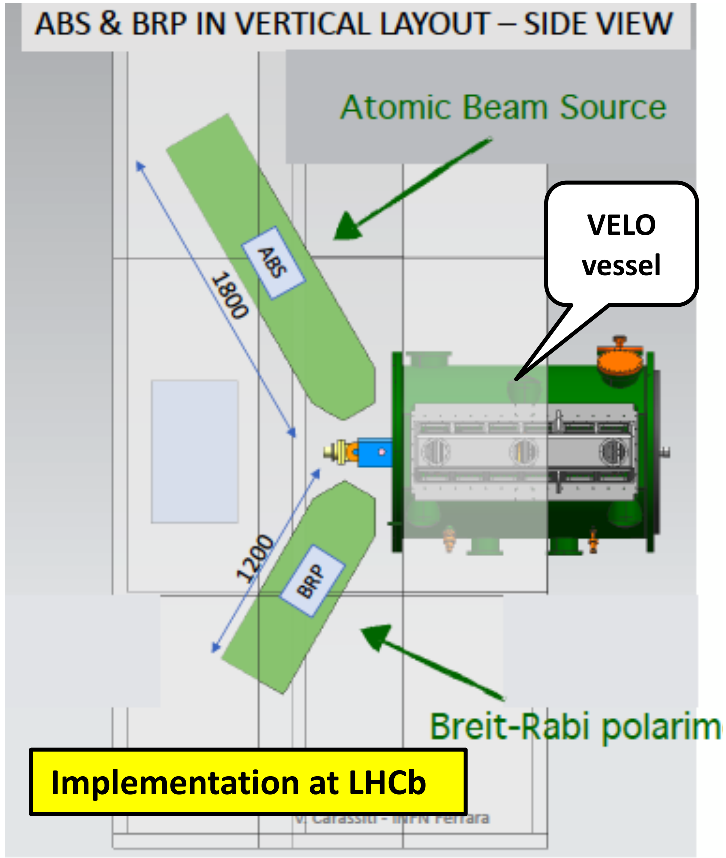
Move apparatus from IR4 to LHCb

Data taking with LHCb









Conclusions and inputs for the ESPP update

- **Mid-term**: **LHCb Upgrade II is the only way to achieve European Strategy of full HL-LHC exploitation**
- **Long-term:** for the best exploitation of a future lepton collider **a dedicated flavour physics experiment should be envisaged to enrich the physics motivations of the project**
  - Precision studies in b- and c-hadron decays involving **neutrals** and **τ-leptons** at the Z pole, **top** decays at higher centre-of-mass energies
  - improved **vertex resolution** and **hadron identification** with respect to the current CLD and IDEA concepts

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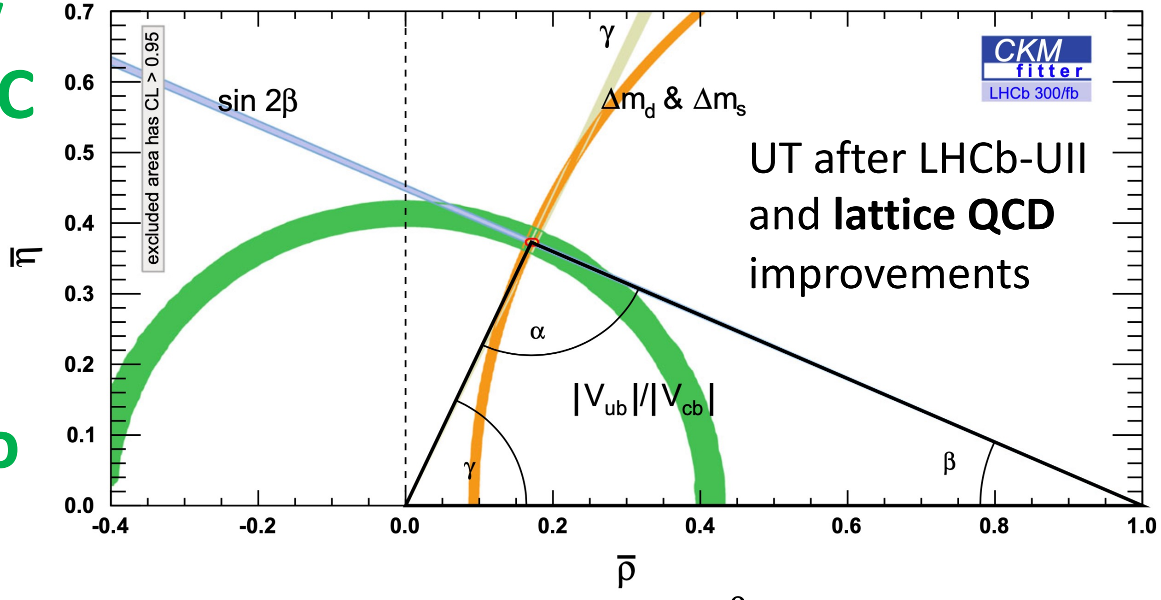

Sensitivity to NP in $B^0_{(s)}$ mixing