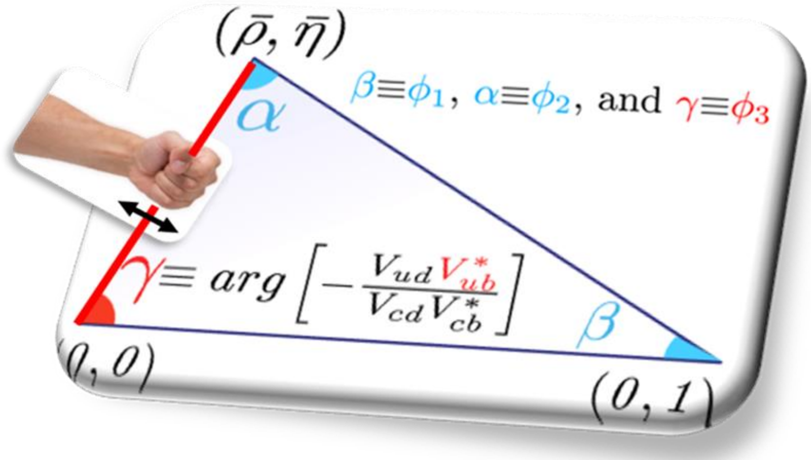
Opportunities in Heavy Flavour Physics at HL-LHC experiments

V. Tisserand*, LPCA-Clermont Ferrand, France

LHCP 2024, Northeastern U Boston, June 7th 2024



BSM may be **reached at**
Heavy Flavour INTENSITY frontier

GDR-InF

*On behalf of the 4 LHC collaborations
thanks for discussions while preparing:

- B. Hippolyte (ALICE)
- S. Turchikhin (ATLAS)
- C. Rovelli (CMS)
- Y. Amhis & T. Gershon (LHCb)

NUCLÉAIRE & PARTICULES

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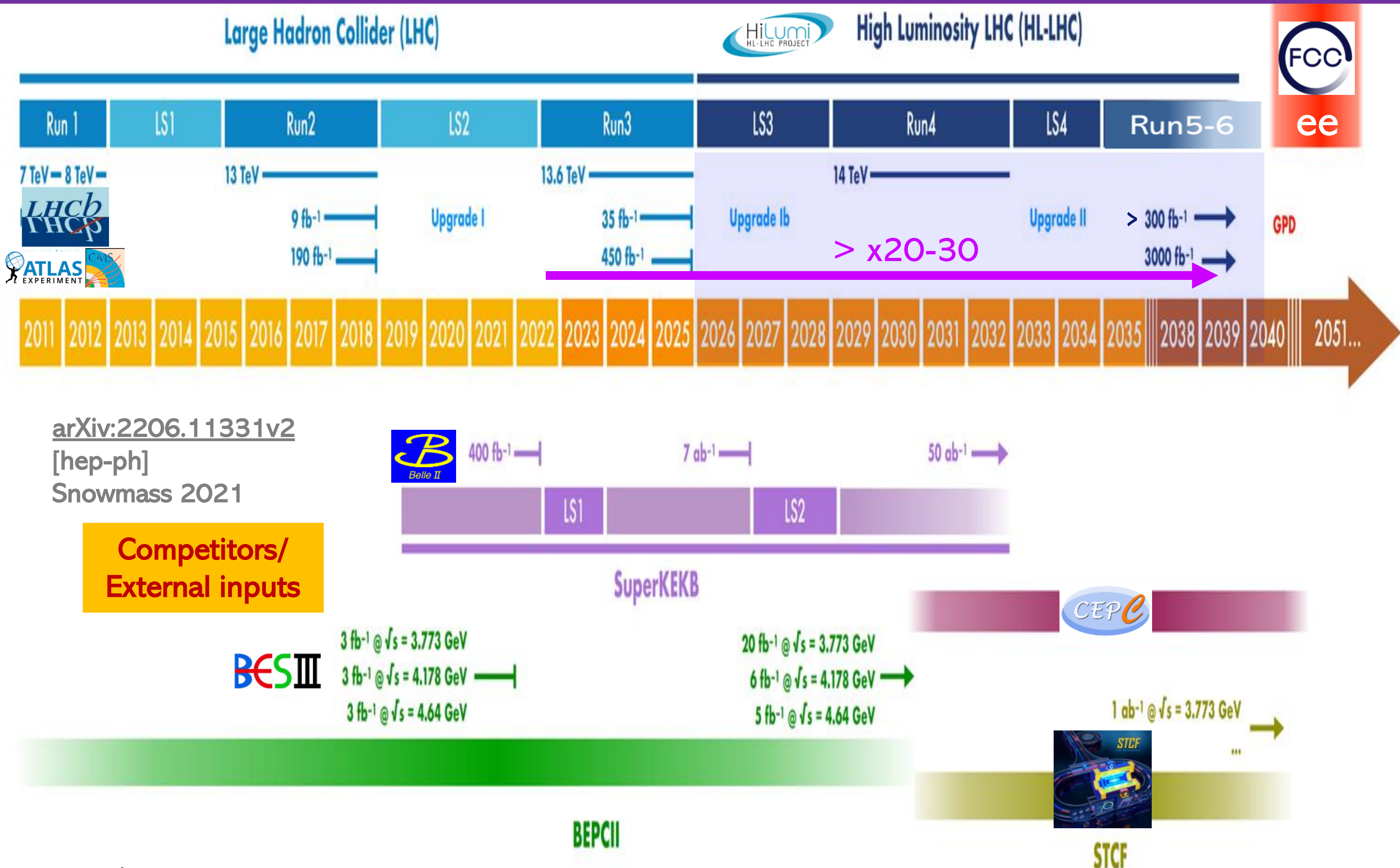
LHCP Boston 2024

Opportunities in Heavy Flavour Physics at (HL-)LHC experiments over more than 30 years!

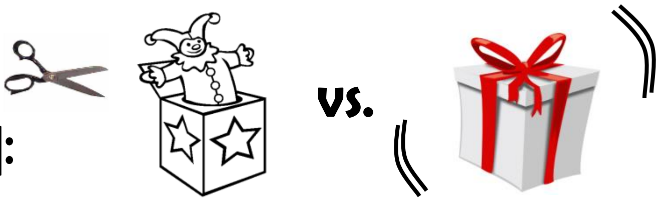


Flavour Physics: an open gate to Beyond the Standard Model ?

➔ New Physics (NP) BSM can be discovered in complementary approaches
"bottom-up" : from data how to unfold the NP Lagrangian

☑ **Direct Search** [ATLAS/CMS] : production/observation of new particles @ $\mathcal{O}$(few TeV)

Special relativity $E=mc^2 \Rightarrow \sqrt{s} + \int \mathcal{L}.dt$



☑ **Indirect Search** [LHCb/Belle II/ ATLAS/CMS]:

➔ K, D, $B_{d,u}$, B_c, Λ_B & B_s ...

- Quantum corrections due to virtual effects ⇒ deviations wrt SM predictions
- Open gates to yet inaccessible energy scales at accelerators : $\Lambda_{NP} > 0.5\text{-}2\times10^4$ TeV
- Unique source of CP violation (CKM matrix)
- NP@TeV: what Flavour physics « structure » explains the observed FCNC processes ?

Flavour Physics and 60 years of SM foundation :

•$\mathcal{B}(K_L\rightarrow\mu\mu)/\mathcal{B}(K^+\rightarrow\mu\nu)$: prediction of 4^{th} quark (GIM)
•Δm_K: prediction of charm quark mass ($m_c \sim 1.5$ GeV/c^2)
•Δm_d : prediction of top quark mass ($m_t > 50$ GeV/c^2)
\+ Kaon CPV ('64) + KM ('73) ⇒ '74 (c), & 3^{rd} family observed in '77 (b), '95 (t)
\+ neutral currents Gargamelle ('73) & UA1 au SppS ('83) …

Far before direct observations!

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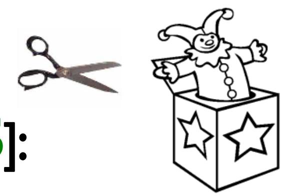

vs.

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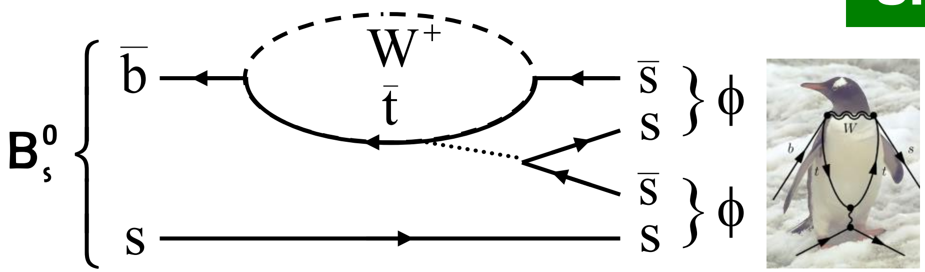
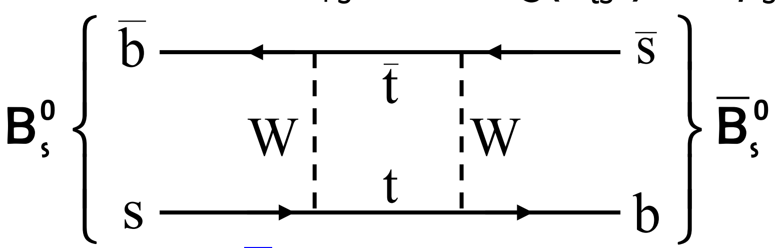
SM



$B_s \to \phi\phi$ rare decay: "Penguin"

$\Delta m_s^{SM} \propto |V_{ts}^2|$,
$\phi_s^{SM} = -\arg(V_{ts}^2) = 2\beta_s$



$B_s - \bar{B}_s$ oscillation: "Box"

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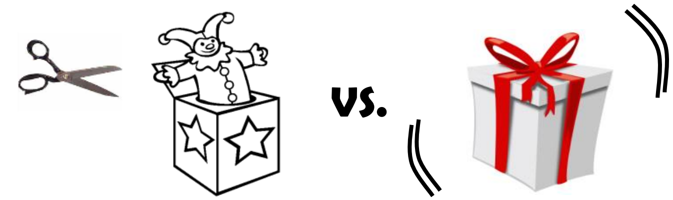

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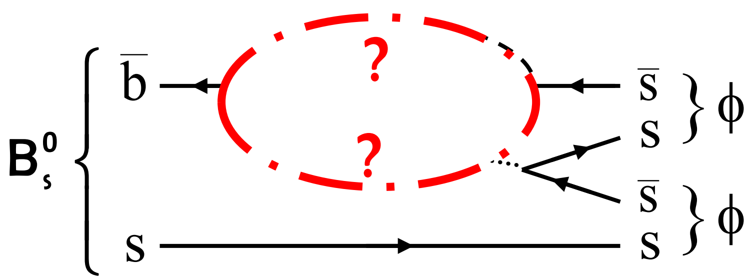
↪ Quantum mechanics $\Delta E.\Delta t \sim \hbar \Rightarrow \int\mathcal{L}.dt$ → accessing new couplings/phases in loops/boxes : CPV &/or rare decays

NP

$\Delta m_s \neq \Delta m_s^{SM} \propto |V_{ts}^2|,$
$\phi_s \neq \phi_s^{SM} = -\arg(V_{ts}^2) = 2\beta_s$



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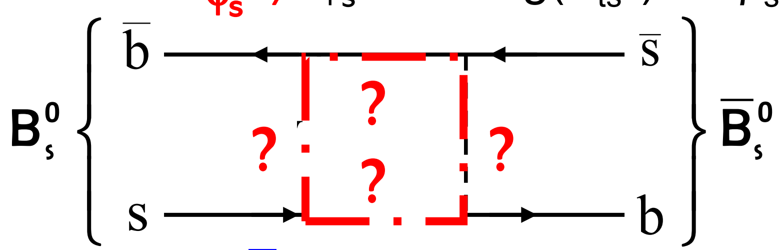


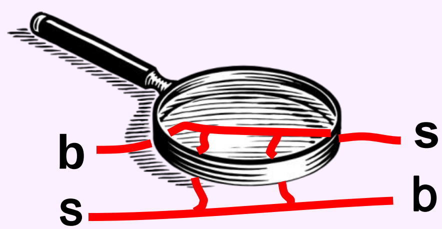
$B_s - \bar{B}_s$ oscillation: "Box"

LHC(b/c) Physics Programme: Precision / Intensity Frontiers

Dedicated experiment for precision measurements for NP quest in CPV/rare decays with all the b(c) hadrons produced: B_d(40%), B_u(40%), B_s (10%), B_c (0.1%), b-baryons (10%) (matter/anti-matter)

1) Precision CKM deviations/SM:
- UT coherence tests : angle γ many methods/modes+ trees/penguins
- Redundancy measurement of same parameters : NP sensitive or not [*e.g.*: sin(2β) tree/penguins $B_d \to (J/\Psi K_S \Leftrightarrow \varphi K_S)$].

2) NP through new CP phases:
- B_s mixing phase ($|\Delta F|=2$) $\varphi=-2\beta_s$ $B_s \to J/\Psi\varphi, J/\Psi\pi\pi, J/\Psi KK$ +($J/\Psi\eta^{(\prime)}$, $\eta_c\varphi$, D_sD_s…)
- penguin with small CPV: $B_s \to \varphi\varphi$



3) NP in rares decays ($|\Delta F|=1$ FCNC): asymmetries (A_{FB}, direct, time dep: C, S, …), angular/ampli. analysis transversity/helicity structure of currents (V-A), polarization (RH γ ?), differential BFs, BFs >SM pred ? $B \to K^*\gamma$, $B_s \to \varphi\gamma$, $B \to K^* l^+ l^-$, $B_{(s)}/D \to \mu^+\mu^-$…

4) LFU tests
+$R_{D(*)} = \mathcal{B}[B \to D(*)\tau\nu]/\mathcal{B}[B \to D(*)\mu\nu]$
+ $R_X = \mathcal{B}[H_{b,c} \to X\mu\mu]/\mathcal{B}[H_{b,c} \to Xee]$

See also Physics case for an LHCb Upgrade II and references therein for ATLAS/CMS

Ingredients for High Precision with Heavy Flavour

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

High production rate

Enormous beauty & charm production cross-sections at LHC energies

[Approx 3×10^{11} b hadrons & 5×10^{12} c hadrons per fb^{-1}]**

Largest possible dataset

Detector upgrade needed to collect maximum possible (>300 fb^{-1} LHCb)

by end of High Lumi-LHC operation

Matched by ATLAS EXPERIMENT & CMS: $\int\mathcal{L}.dt > 3000\ fb^{-1}$ (LHCb exceeded)

* Update in 2 years

** See for *e.g.*: Fabio Catalano @LHCP2023

Ingredients for High Precision with Heavy Flavour

Good selection efficiency

Go beyond 1/√N scaling with existing detector performances with improvements to acceptance and detection capability

Ability to resolve signal

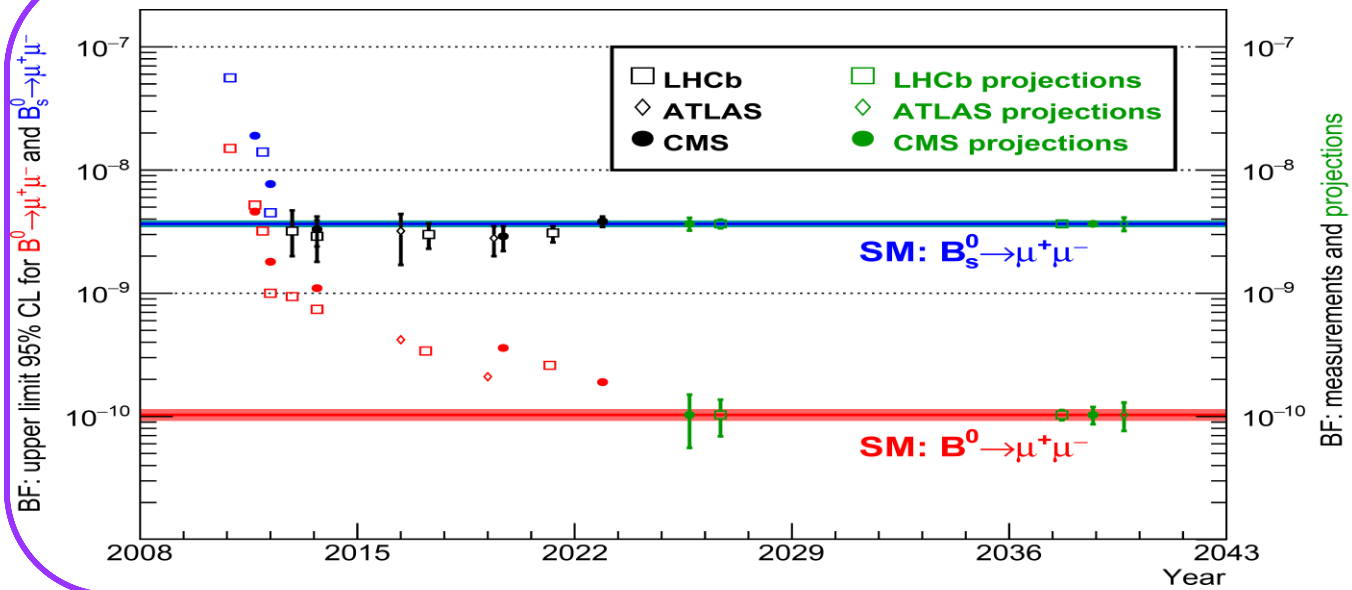
Requirements for flavour physics at high occupancy (momentum, vertexing, timing, and PID π/K/p separation, including γ/π^0) distinct to those for high p_T physics

Channel dependent- All charged tracks: LHCb is superior to any other experiment (*far* superior **except** for a **few final states including muons, where** ATLAS EXPERIMENT & CMS **are competitive)**
One (or more) neutral particles: Belle II is competitive (or better)

➔ **Heavy Flavour physics triggers at LHC are based on secondary vertices, it's crucial to trigger efficiently at high-pileup environment !**
➔ Here we only have 15 minutes, and the HF at HL-LHC ATLAS/CMS/LHCb physics case was already presented back in March 2019 by P. Owen at the HL/HE-LHC Physics Workshop: final jamboree

ATLAS EXPERIMENT ATLAS-PHYS-PUB-2018-005 CMS CMS-PAS-FTR-18-041

The power of muons/new tracking at ATLAS/CMS (& LHCb)



Rare (BSM SUSY)

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

ATLAS-PHYS-PUB-2018-005

CMS-PAS-FTR-18-013

Lepton Flavour Violation (LFV)

$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$ sensitivity around 10^{-9} (UL @90% CL)

ATLAS-PHYS-PUB-2018-032

CMS-TDR-016 (2017)

Rare penguins, angular analysis

(P_5' anomaly) $B \to K^{*0}\mu^+\mu^-$

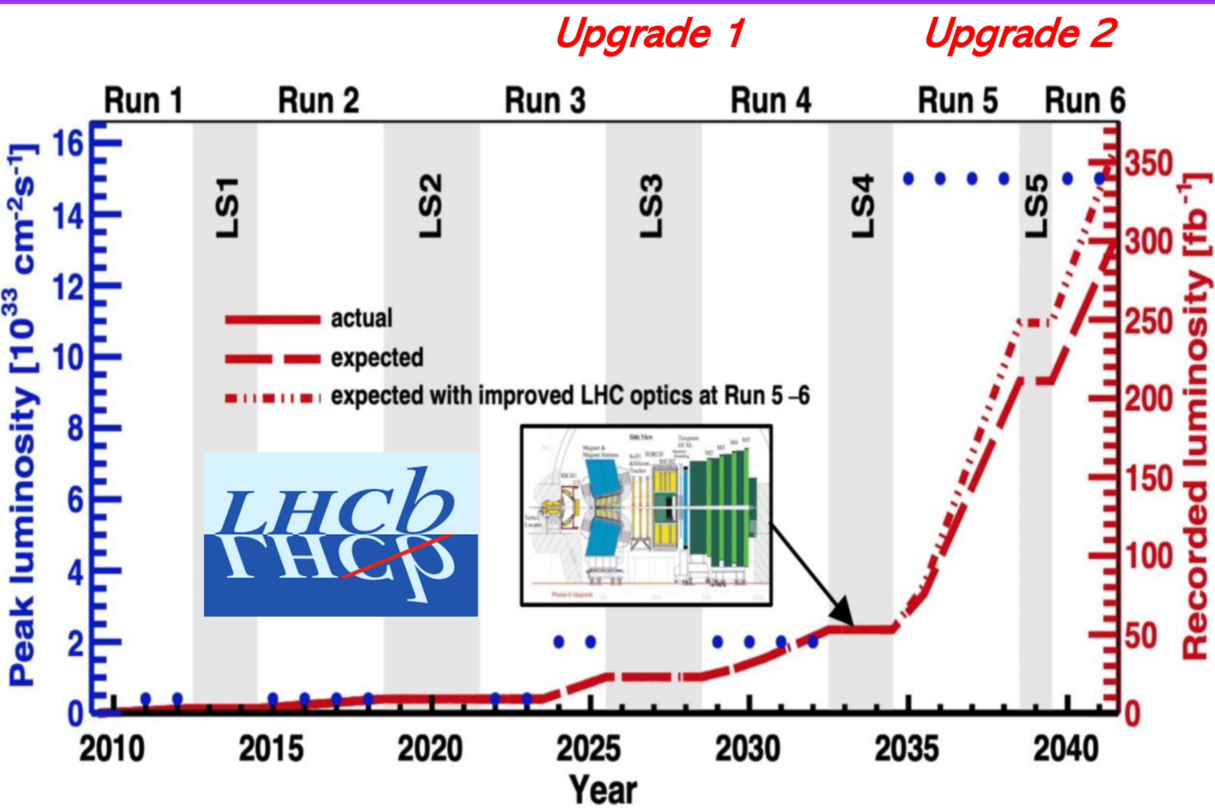
ATLAS-PHYS-PUB-2019-003

CMS-PAS-FTR-18033

- Those studies are quite known now (~5 years old)
- will discuss the $B_s \to J/\psi[\mu^+\mu^-]\phi(1020)[K^+K^-]$ CKM ϕ_s case again later,

HL-LHC refs are CMS-PAS-FTR-18-041 and ATL-PHYS-PUB-2018-041

The HL-LHC ATLAS & CMS upgrades are granted
LHCb Upgrade II (U2) approval steps so far



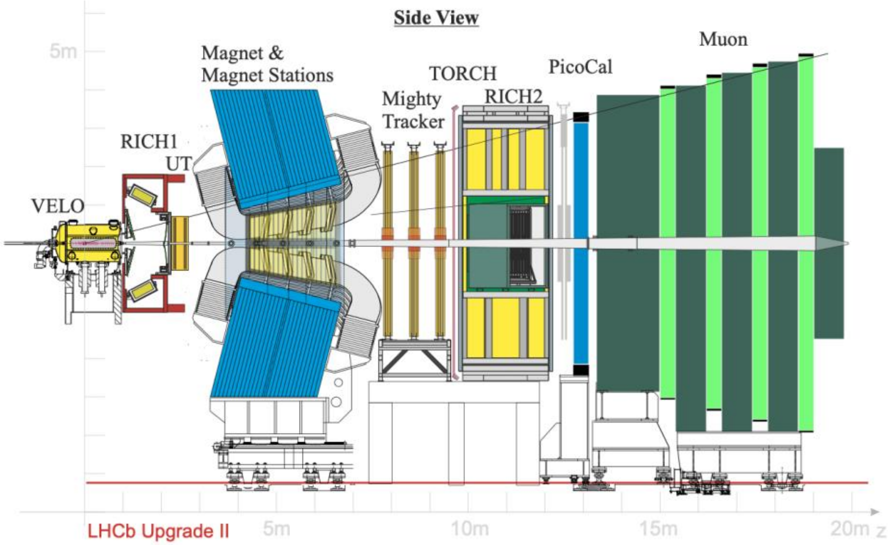
Besides the luminosity increase and the necessary detector modifications to allow for higher multiplicity and radiation damage, it is also proposed to add further sub-detectors to expand the original programme

LHCb-Pub-2018-009 (physics case) & LHCb-TDR-023 ('22 detector design) LHCb-TDR -24 ('23 FTDR enhancements PID at LS3), documents being updated (scoping document required by LHCC underway, due after this '24 summer)

➔ LHCb to operate at HL-LHC : accumulate maximum unprecedented samples and a compelling bright physics programme to search for BSM (not only Heavy Flavour !)

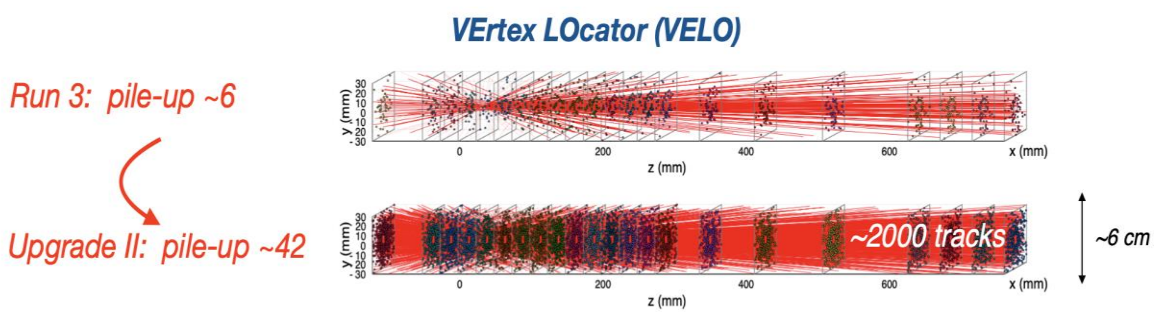
➔ LHC optics may be improved at LHCb & allow for 370/300 fb^{-1} @1.5x10^{34}cm^{-2}.s^{-1}

- Targeting **the same performance, or even better in certain areas**, as in Run 3, but **with an increased pile-up of a factor 7**
- Same footprint of the LHCb(U1) spectrometer, but with **innovative technology** for sub-detectors/data processing ("technology frontier")



- **Key ingredients to cope with HL:**

- High(er) granularity

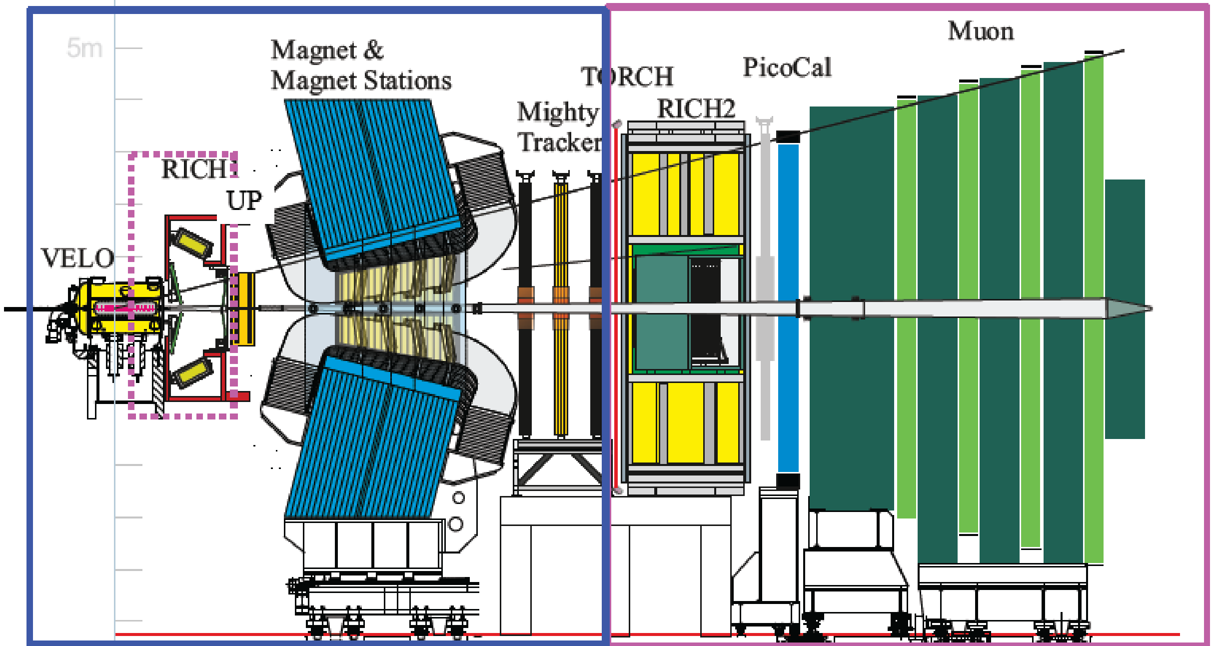


- Fast timing: few tens of pico-seconds

- New components radiation hard: up to few 10^{16} neq/cm^2

The features of the new LHCb (U2) detector

Baseline design: *targeting same (or better in certain domains) performance as in Run 3, but running at 1.5x10^{34}cm^{-2}s^{-1} with pile-up ×7 wrt Run 3!*



PID system

RICH: *reduced pixel with SiPM/MCP, timing info added*

TORCH: *new time-of-flight for low momentum, quartz and SiPM/MCP* *NEW SYSTEM*

PicoCal: *timing and longitudinal segmentation, SPACAL with radiation hard crystals inner region, old Shashlik outer region* *+time fit ~20ps*

Muon: *muRWELL technology inner region, keep old MWPCs outer region*

Tracking system

VELO: *pixel 3D silicon, hit time resolution 50ps, ASIC 28nm*

UP (upstream tracker) and Mighty Tracker (downstream): *MAPS pixel for UP and inner region of Mighty Tracker, scintillating fibres for outer region of Mighty Tracker*

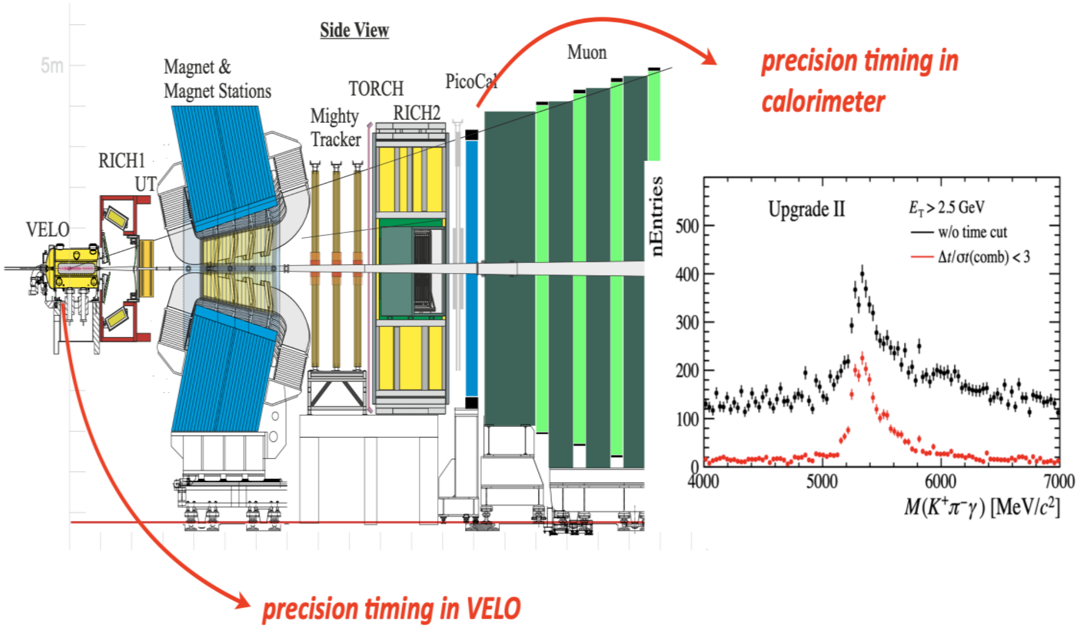
Magnet Stations: *scintillating slabs covering side walls of magnet, for low momentum* *NEW SYSTEM*

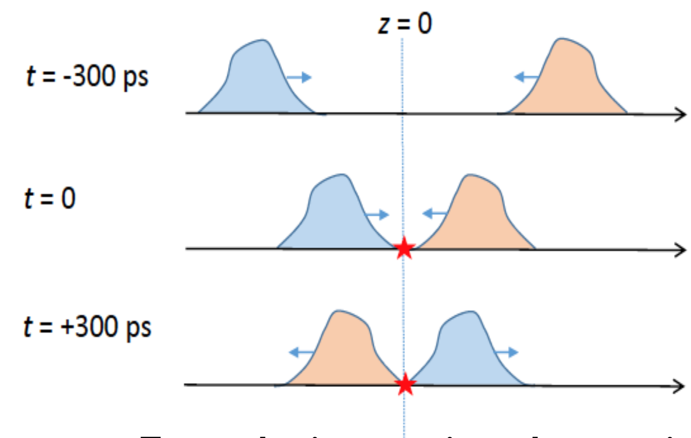
Exciting technology roadmap: the developments needed to face the harsh experimental conditions of HL-LHC in the forward direction will represent a bridge towards projects based at future accelerators

More details by E. Niel on LHCb upgrades plenary yesterday

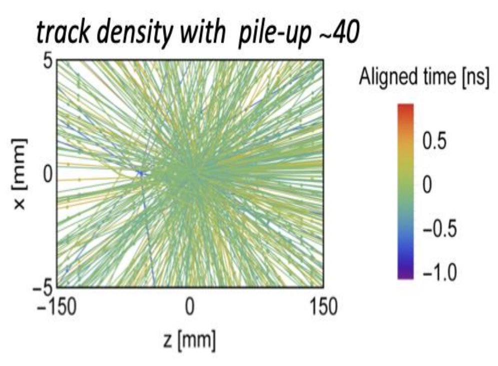
The importance of precision timing

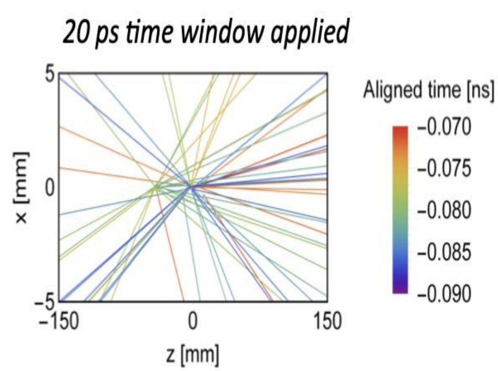
➔ Timing capability with a resolution of a few tens of picoseconds is a key to reduce background and associate signal decays to correct p-p primary vertices (LHC beam vertex diamond with ~ 6 cm [200 ps])





Example: interactions happening are at same *z* but separated by 300 ps in time





The programme requires strong R&D on sensors, already ongoing, and dedicated efforts for the design of new FEE (Tracking and PID (TORCH RICH and PicoCal))

The key observables of LHCb U2 HF physics programme relies on sub-detectors performance

LHCb-Pub-2018-009
LHCb-TDR-023

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

need efficient tracking (especially multi-body decays), and robust reconstruction of decay vertices

need best charged hadron PID

need light detector

need increased acceptance for low p_T tracks

need best muon ID and mass resolution

need best calorimetry and charged hadron PID

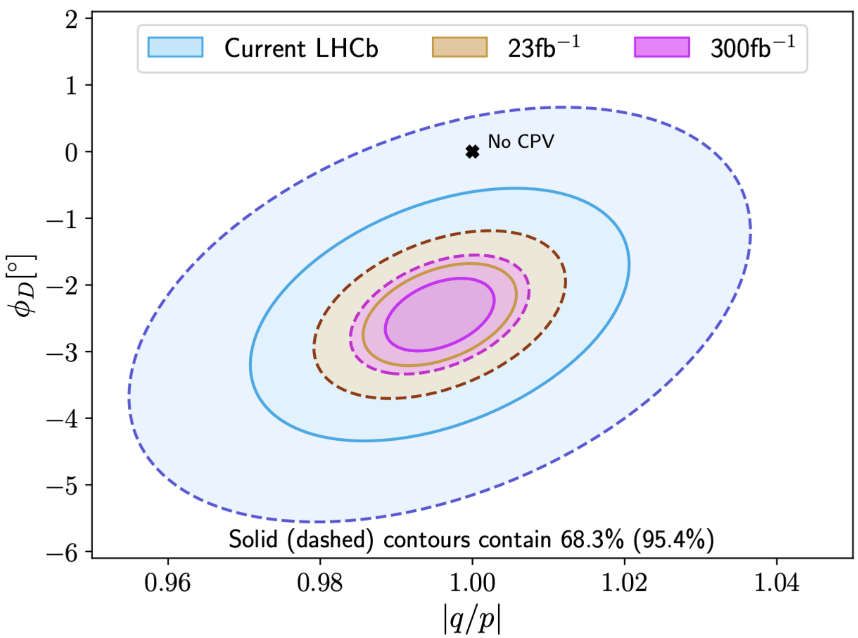
More details in 7[th] LHCb upgrade II Workshop (March 2024 at CERN) [public material]

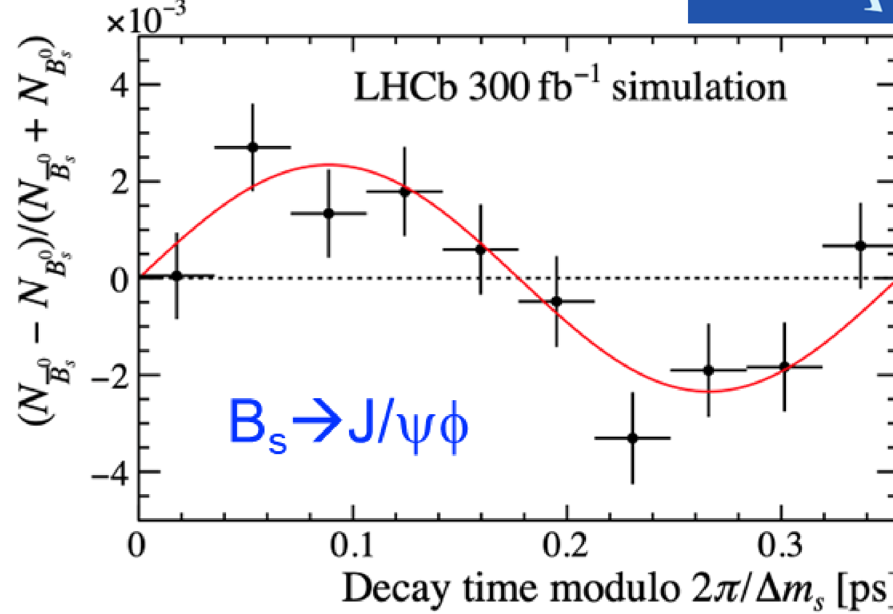
LHCC for Sept '24: studies ongoing with full MC simul. on various benchmark complementary channels and various LHC machine and LHCb U2 detector scoping scenarios

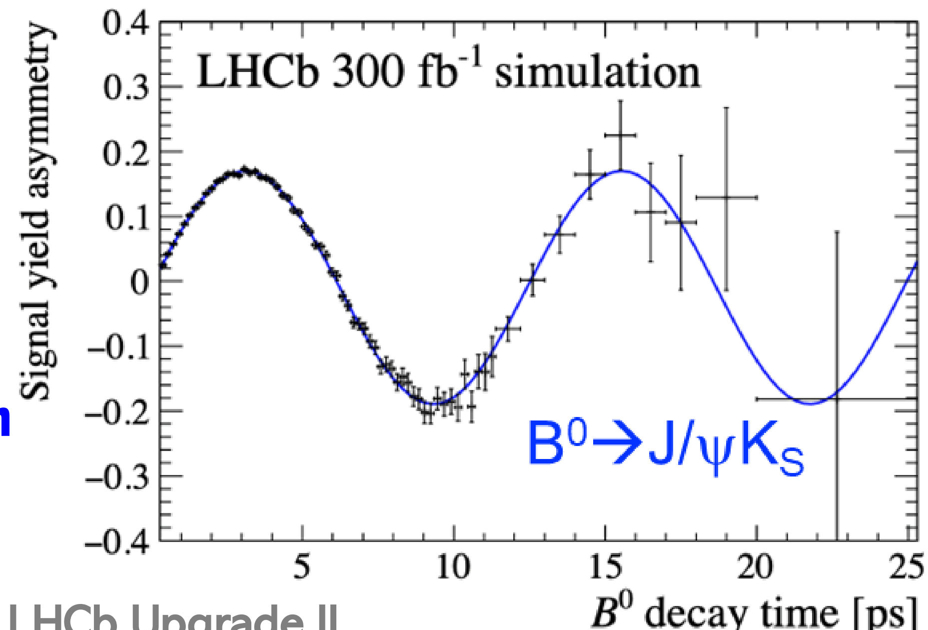
LHCb Upgrade II Physics Case: CP violation

- $\sigma(\gamma)$: 0.35°
- $\sigma(\phi_s)$: 4 mrad
- $\sigma(\sin 2\beta)$: 0.003
- σ(Charm CPV): $\mathcal{O}(10^{-5})$

Impressive precision on CP violation phases







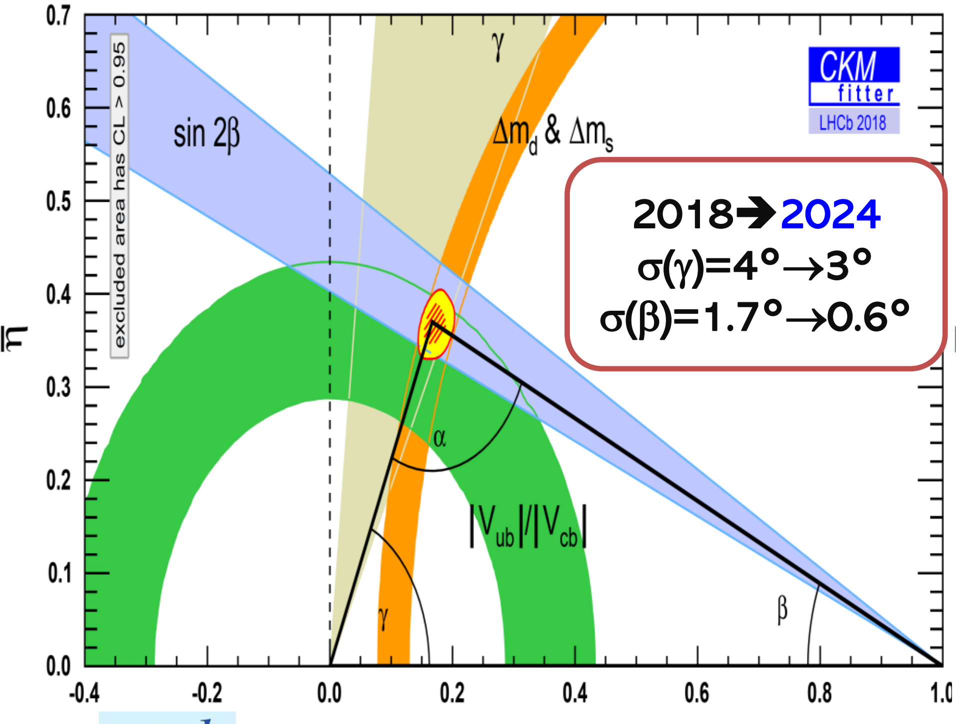
LHCb Upgrade II is the only planned facility with a realistic possibility to observe CP violation in charm mixing !

See Physics case for an LHCb Upgrade II

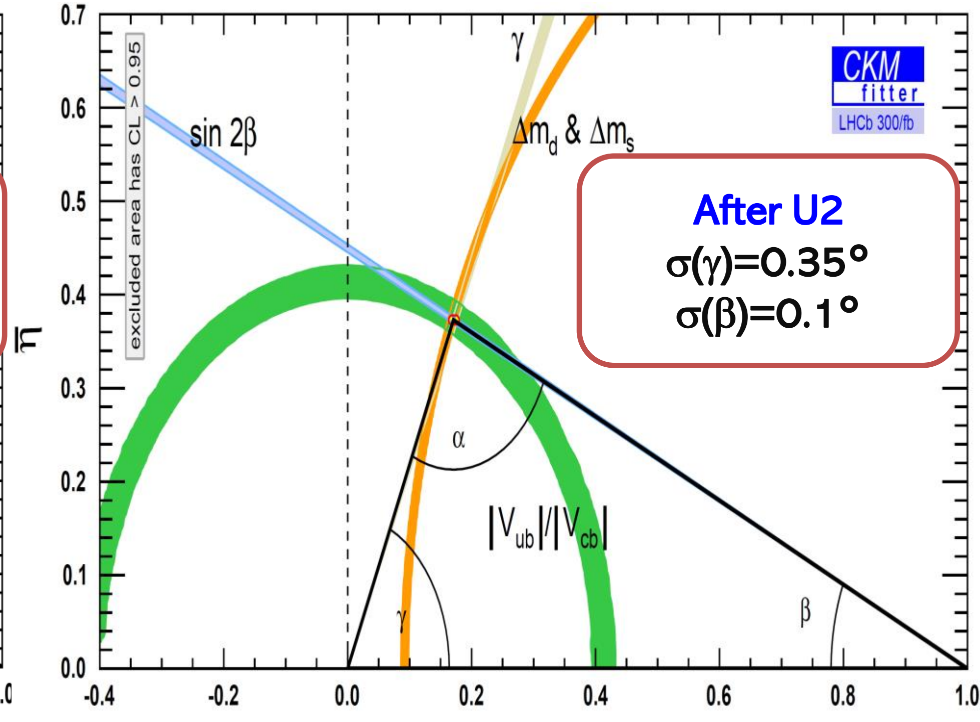
Unitarity Triangle expected improvements after Upgrade II

LHCb has outperformed expected 2018 sensitivities for both β and γ

Many other BSM searches rely on these benchmarks (global CKM test)



LHCb "alone now"



LHCb "alone" after HL-LHC

Upgrade 2 will make the most precise measurements of all of the 5 key CP violation parameters (β, γ, ϕ_s, A_{sl}^s, A_{sl}^d) in the $B_{(s)}$ system

[But not without competition, both contemporary and further into the future ATLAS/CMS & Belle II]

HL-LHC synergy LHCb vs ATLAS/CMS (and Belle II)

Observable	2018 Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

0.013 already achieved

First results from CMS parked data do not appear really competitive

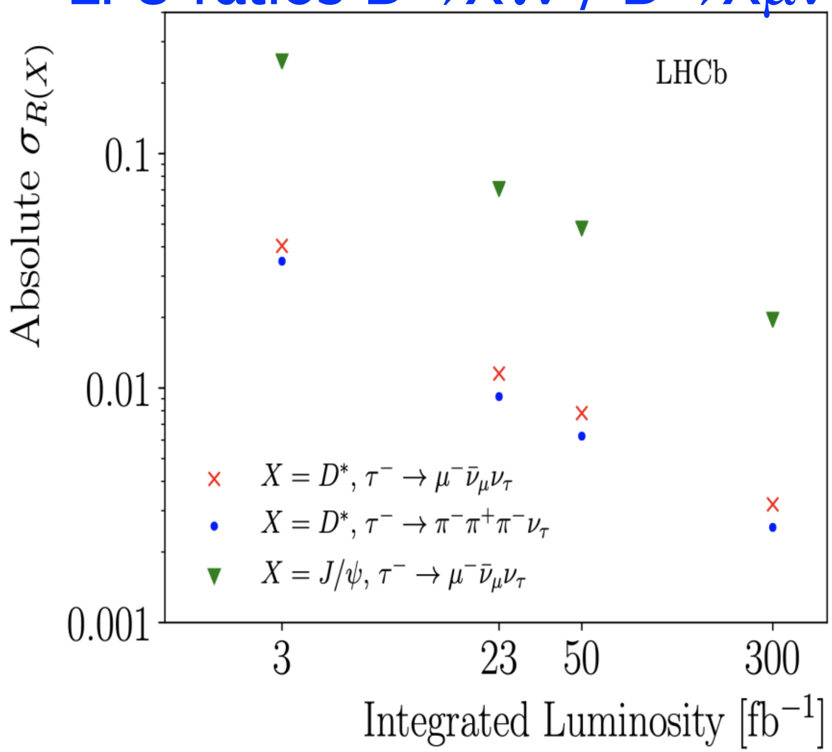
CMS showed 23 mrad with Run2 at MEW24!

See Physics case for an LHCb Upgrade II

LHCb U2 Physics Case: semi-leptonics

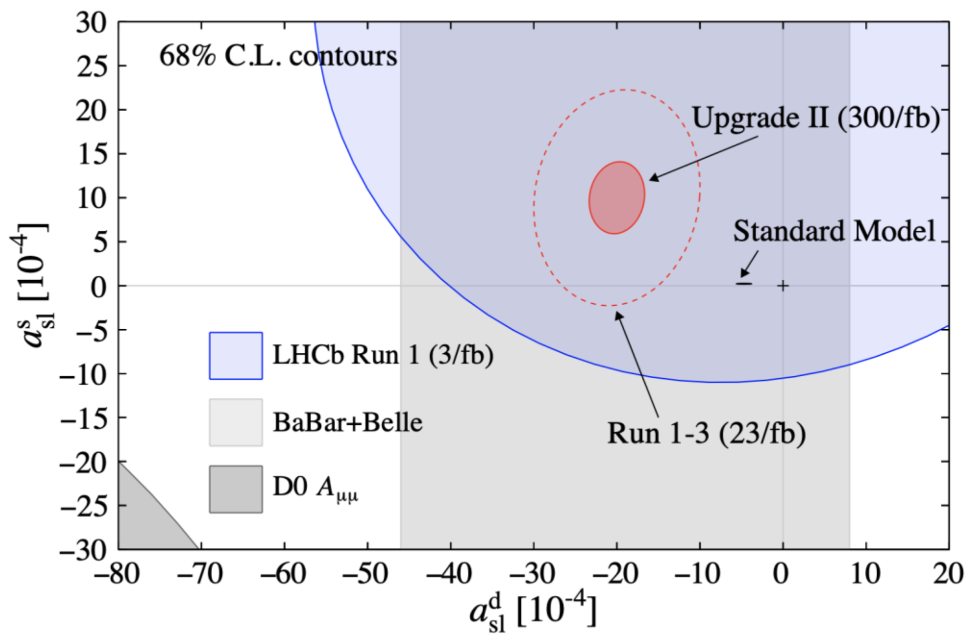
- Semileptonic sector is another key laboratory for new physics searches
- Very strong impact from Upgrade II

LFU ratios $B \to X\tau\nu$ / $B \to X\mu\nu$



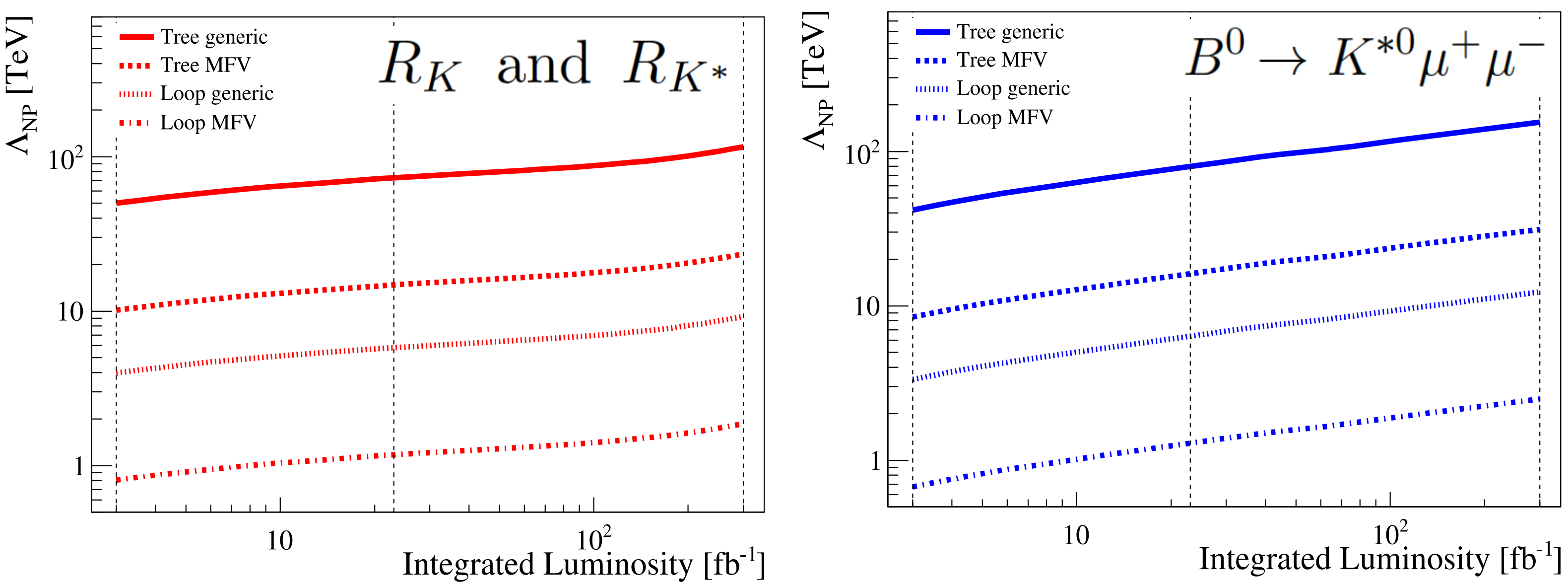
Semileptonic asymmetries a_{sl}^d and a_{sl}^s

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

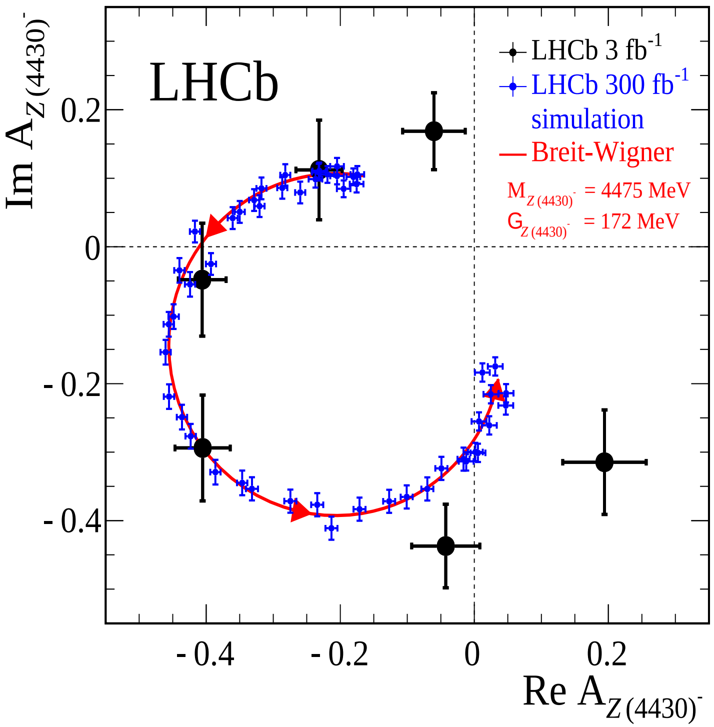


LHCb U2 Physics Case: rare penguin decays

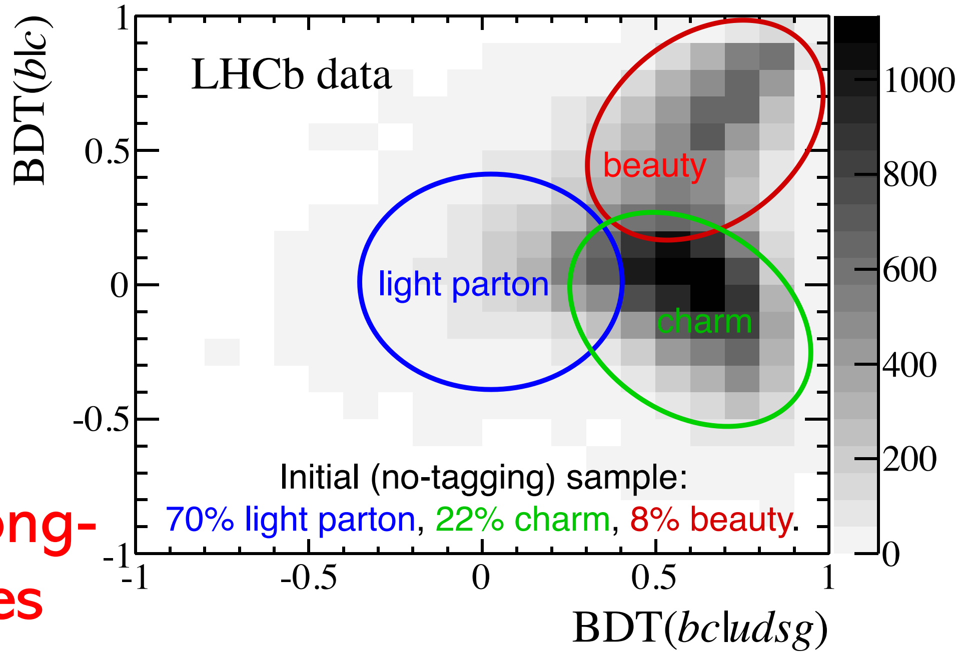
- Although hints for new physics in $b \to s l^+ l^-$ transitions have been largely reabsorbed (*i.e.* "$R_{K(*)}$ anomalies"), this is still interesting physics with strong discovery potential at Upgrade II statistics, also imposing relevant constraints on new physics models



- EFT approach ➔ generic new physics scale probed exceeds 100 TeV
- Concerning $B \to \mu\mu$ ➔ 11% precision on B^0 / B_s ratio of branching fractions looks feasible
- Besides $b \to s l^+ l^-$, LHCb U2 will have access also to rarer $b \to d l^+ l^-$ transitions



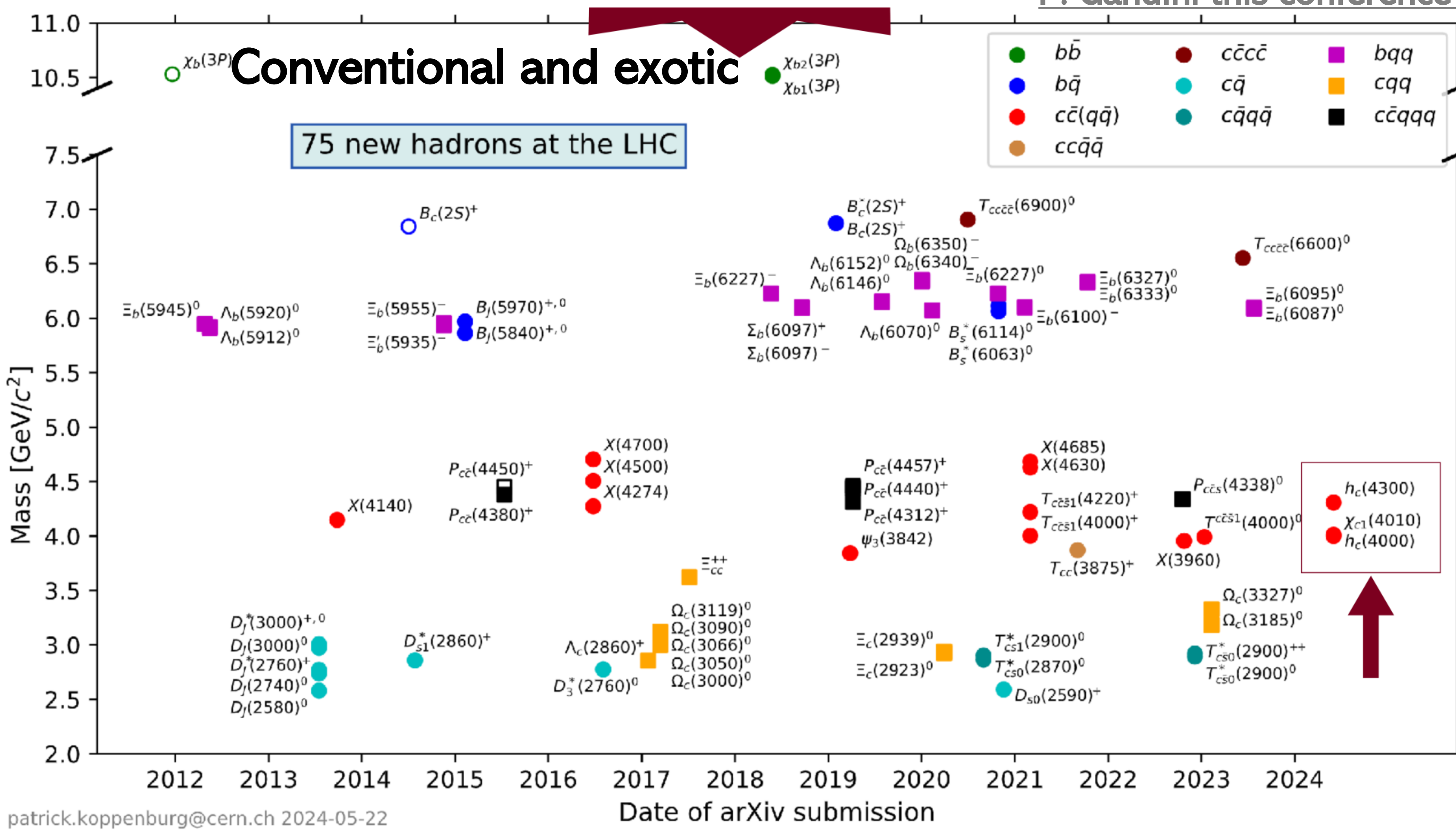
- General purpose facility
  - Unique forward acceptance
- LHCb has had transformative effect on spectroscopy
  - Many more discovery opportunities



- Potential for best Higgs to charm limits at LHC
- Unique sensitivity for BSM long-lived and dark sector particles

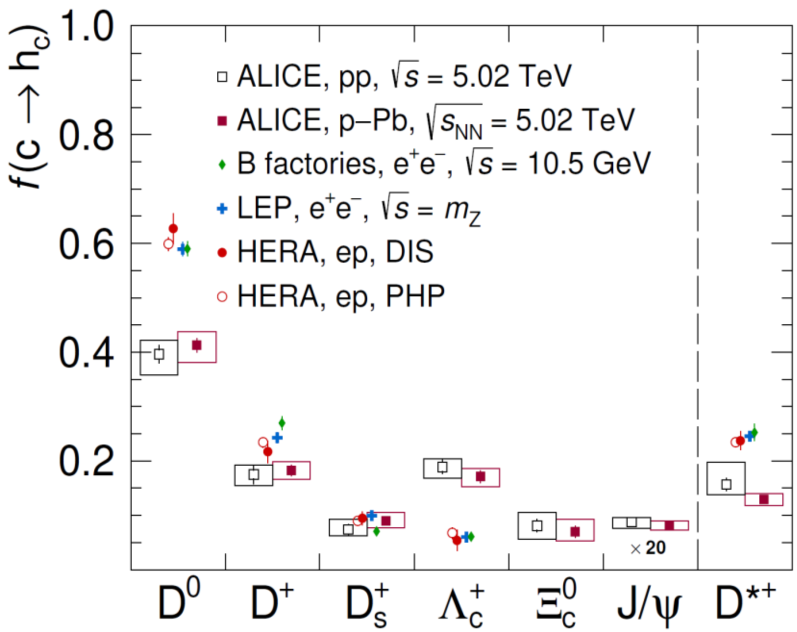
75 new hadrons already discovered at LHC and counting !

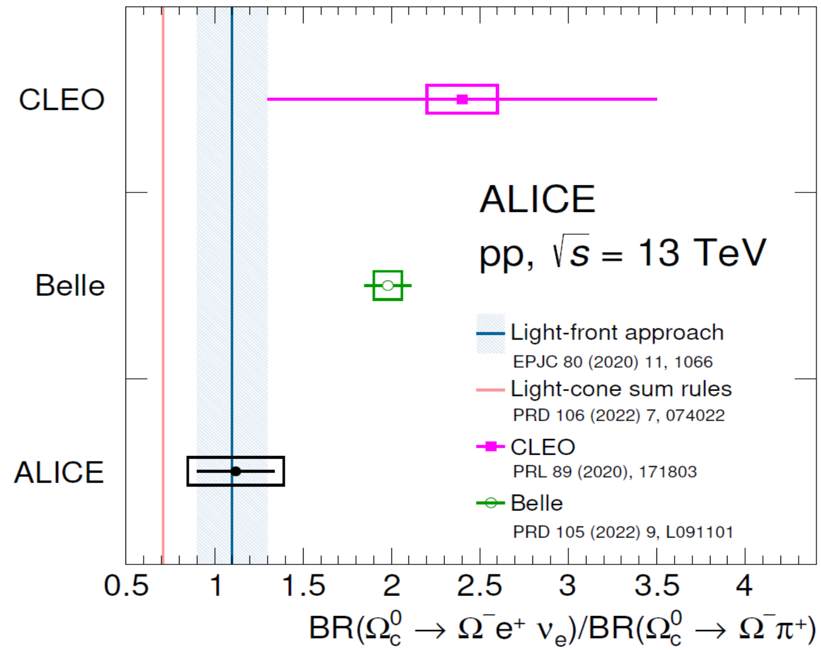
P. Gandini this conference



LHCb main player here (67/75 new hadrons discovered at LHCb), but ATLAS and CMS also in the game

Even HF opportunities with ALICE at Run4-6





See ALSO, some references on the ALICE (3) heavy flavour physics programme:

- Charm fragmentation fractions and cc cross section in p−Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV arXiv:2405.14571v1 [hep-ex]
- Measurement of Ω_c^0 baryon production and branching-fraction ratio BR($\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$) / BR($\Omega_c^0 \rightarrow \Omega^- \pi^+$) in pp collisions at $\sqrt{s}$ = 13 TeV arXiv:2404.17272v1 [hep-ex]
- In ALICE-TDR-021 2024 ALICE Inner Tracking System 3 - ITS3, p9-10
- **ALICE 3 LoI (2022):** see Physics Performances parts on Open Heavy Flavours, Quarkonia and Exotica

Uniqueness of LHCb Upgrade II Physics Case

We have a once-in-a-lifetime opportunity to optimise the design of what will be a remarkable experiment, with unique capabilities to achieve the best possible heavy flavour-physics results (and more) from the HL-LHC

- LHCb Upgrade 2 will make by far the most precise measurements of a huge range of key flavour physics observables

Unique tests of the SM predictions for CKM unitarity, CP violation, flavour changing neutral currents (FCNCs) in both mixing & decay, both beauty and charm

- Unrivalled discovery potential for understanding of exotic hadrons
- Completely unique access to fixed target hadron collisions (SMOG)
- Unique geometry, probing complementary regions of parameter space in heavy ion physics, long-lived particle searches, etc…

Most of this physics can only be done with LHCb U2 at the HL-LHC

We must not miss this opportunity

HL-LHC Heavy Flavour Physics Opportunities: key messages

- Host of theoretically clean (or clean-ish) observables that will not be limited by systematics (ϕ_s, γ, $\sin 2\beta$, $R_K(^*)$, $B \rightarrow \mu\mu$, $B \rightarrow K^*ll$, LFU tests …)
- New physics scale probed will increase by a factor ~2/… compared with pre-HL-LHC
- Widen the set of observables under study to search and characterise new physics ($b \rightarrow sll$, $b \rightarrow dll$, $b \rightarrow cl\nu$, …)
- Strong program beyond flavour exploiting unique acceptance
  - Of course, known at the GPDs ATLAS and CMS, relying on great muons power and new tracking system, but not only …
  - Even Higgs physics, spectroscopy, electroweak, dark sector, heavy ions, fixed target

➔ Great opportunities and bright future ahead of us at HL-LHC to challenge (B)SM with Heavy Flavour Physics with LHCb in complement to ATLAS EXPERIMENT and CMS