Flavour Physics: current status from the experiment side

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Outline

- Introduction to flavour physics
- Current experimental status of main topics in flavour physics
  - For each topic a selection of relevant and recent results
- A look to the future
- Conclusions

What is flavour physics

WIKIPEDIA
L'enciclopedia libera

Flavour (particle physics)

Article Talk

In particle physics, **flavour** or **flavor** refers to the *species* of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles. They can also be described by some of the family symmetries proposed for the quark-lepton generations.

- Flavour physics is tightly connected with some of the most fundamental questions in particle physics
  - Why are there 3 families of fermions?
  - Where does the hierarchy of fermion masses comes from?
  - Why do we live in a matter-dominated universe?

Flavour in particle physics

Flavour quantum numbers

- Isospin: **I** or I_3
- Charm: C
- Strangeness: S
- Topness: T
- Bottomness: B'

Related quantum numbers

- Baryon number: B
- Lepton number: L
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity

V · T · E

A story full of successes

1950's Discovery of parity violation

1960's CP violation in K decays

1970's Discovery of J/ψ and charm quark

1980's Inference on top quark mass from B mixing

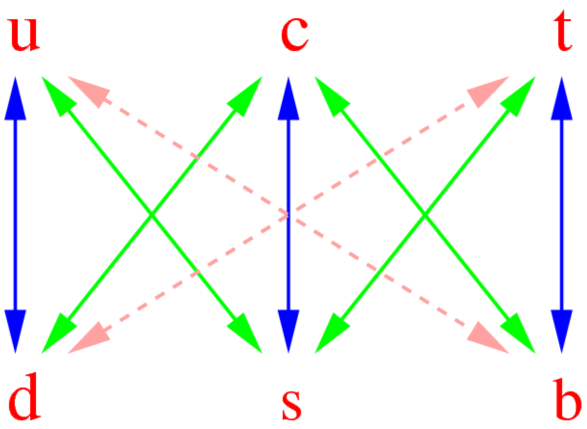
2000's CP violation in B decays

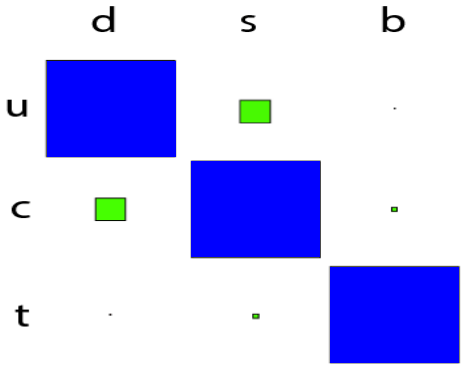
2010's Penta- and tetra-quarks

2020's CP violation in D decays

Cartoon presented by N. Cabibbo at the Berkeley conference in 1966

The CKM matrix



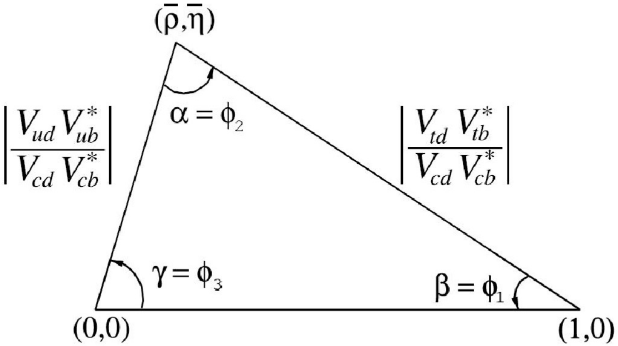


- The CKM matrix accommodates the mixing between mass and flavour eigenstates of quarks that arises from the electroweak symmetry breaking (Higgs mechanism)
- Encodes the strength of quark flavour-changing transitions
- Governs the breaking of CP symmetry in the SM

The CKM matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

3x3 complex unitary



Unitary conditions

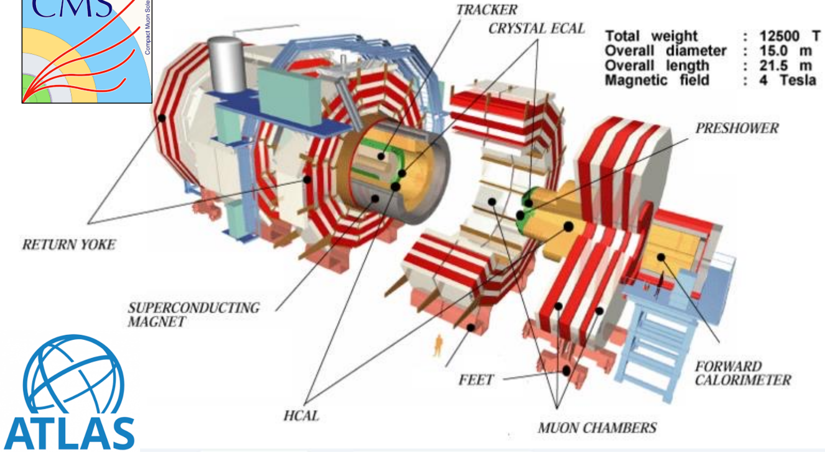
- The CKM matrix accommodates the mixing between mass and flavour eigenstates of quarks that arises from the electroweak symmetry breaking (Higgs mechanism)
- Encodes the strength of quark flavour-changing transitions
- Governs the breaking of CP symmetry in the SM

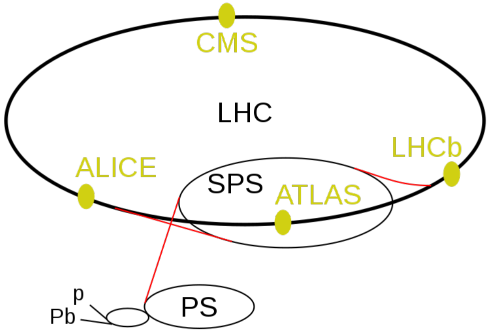
(I will not touch the PMNS matrix)

Many tools for discovery

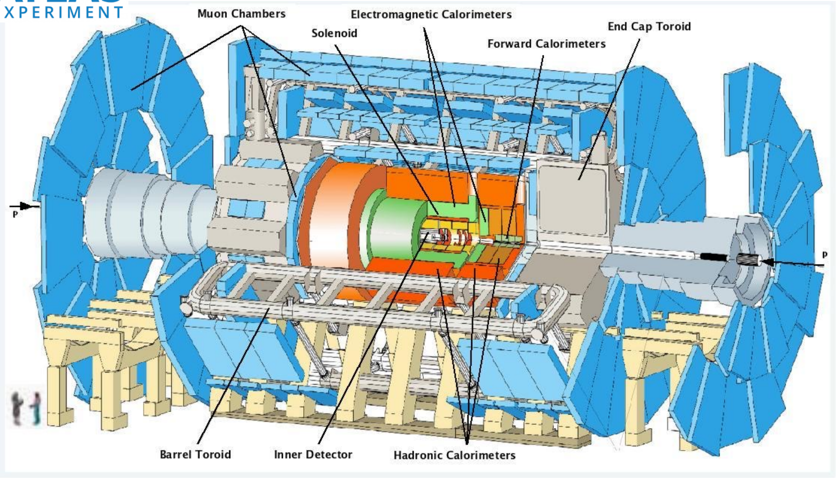
- Flavour physics provide a wide range of Standard Model tests
  - CKM metrology and constraining the UT apex
  - Spectroscopy
  - Search for rare and forbidden decays
  - Test of lepton-flavour universality and conservation
- By comparing precise measurements with theoretical predictions the nature of new physics can be inferred
  - **Complementary to direct searches** of new particles
  - **Not limited by the energy of collisions**
  - Requires inputs from theory

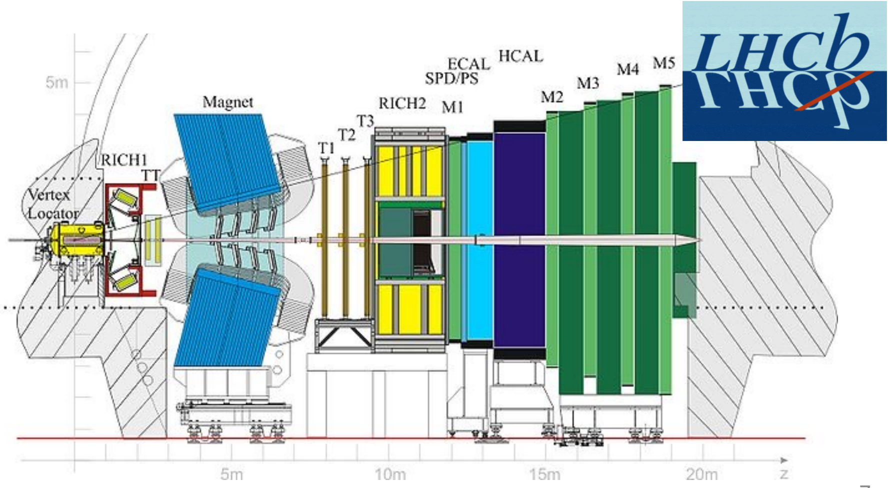
Main characters (I)



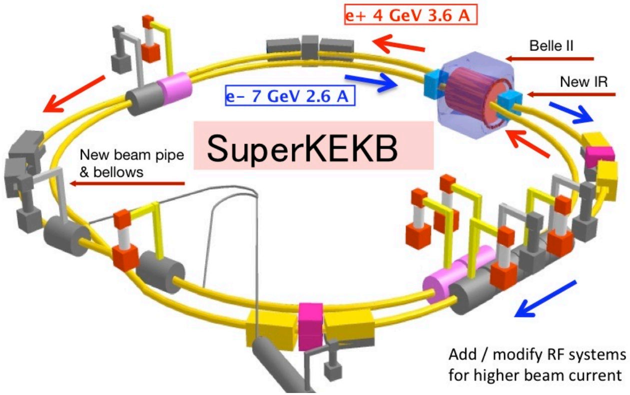


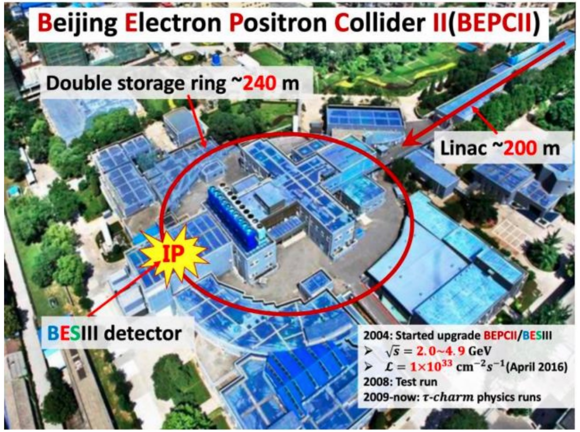
- Very large production cross-section of all heavy-flavoured hadrons (including baryons and B_c^+)
- Harsh environment



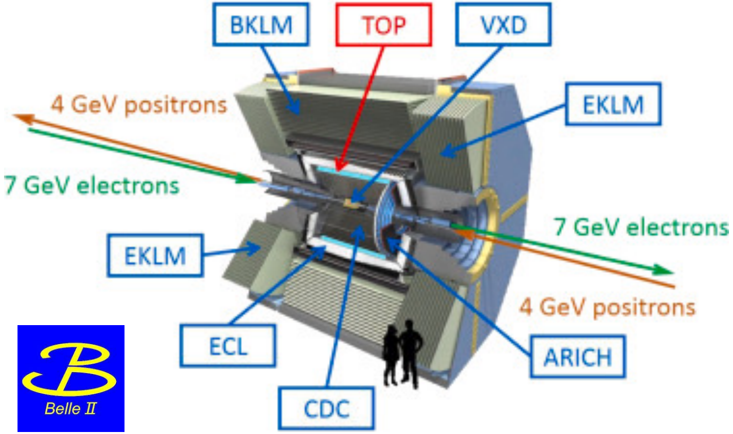


Main characters (II)

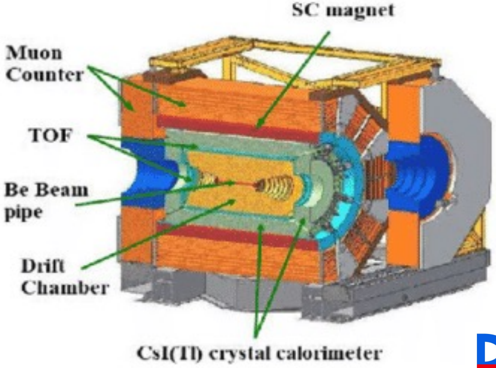




- Asymmetric e^+-e^- colliders
- Much cleaner environment
- Quantum-entangled final-state particles



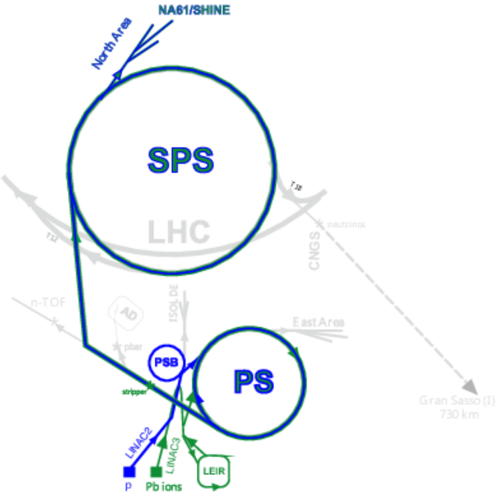
Belle II

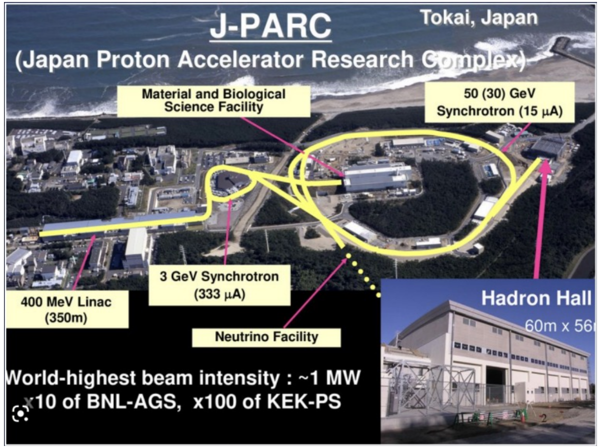


(a) Schematic view of the BESIII detector

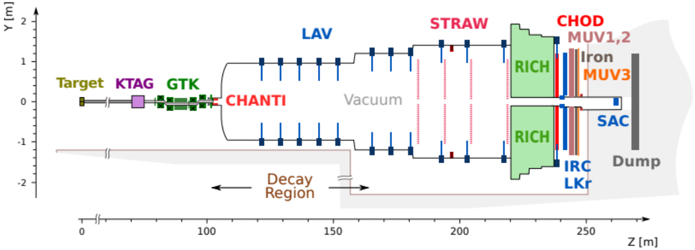
BESIII

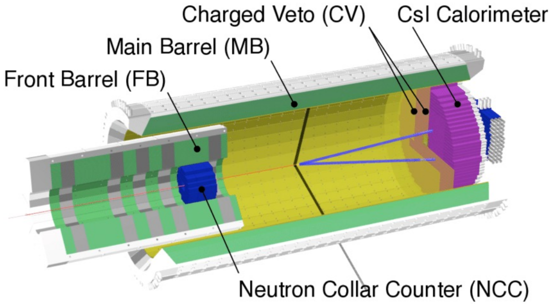
Main characters (III)





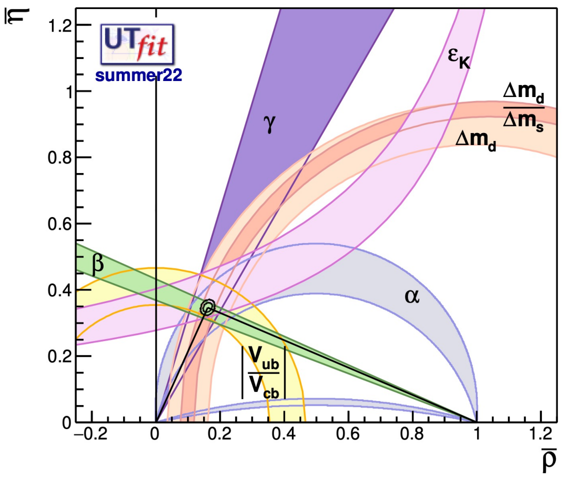
- Beam-dump experiments
- Dedicated to kaon physics
- Potentially able to search for light BSM particles

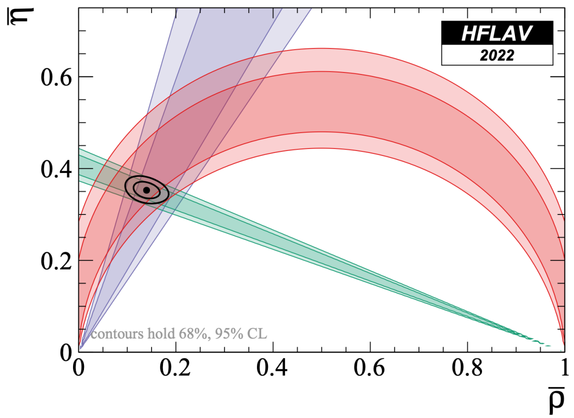


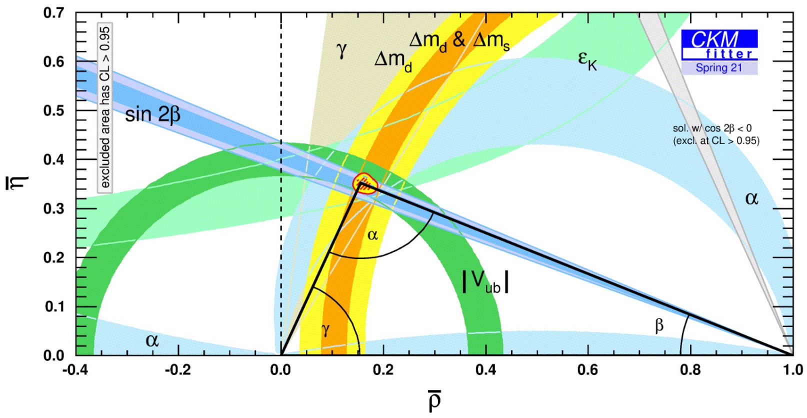


CKM metrology

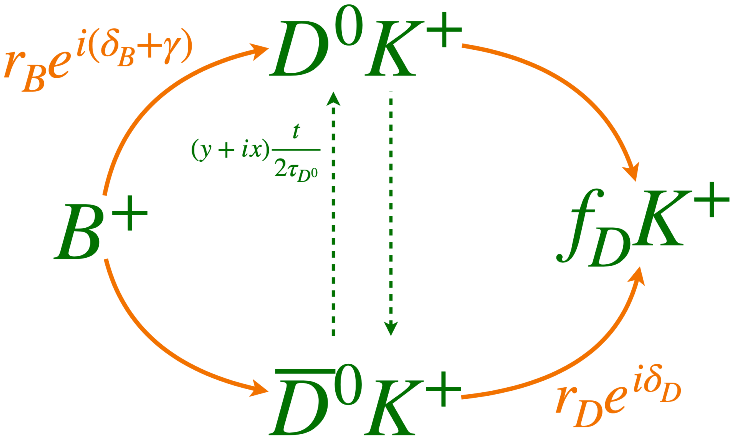
- One of the most powerful tools to test the Standard Model
- The CKM matrix has only 4 parameters
  - The Unitary Triangle is highly overconstrained from many measurements
  - Unique consistency check

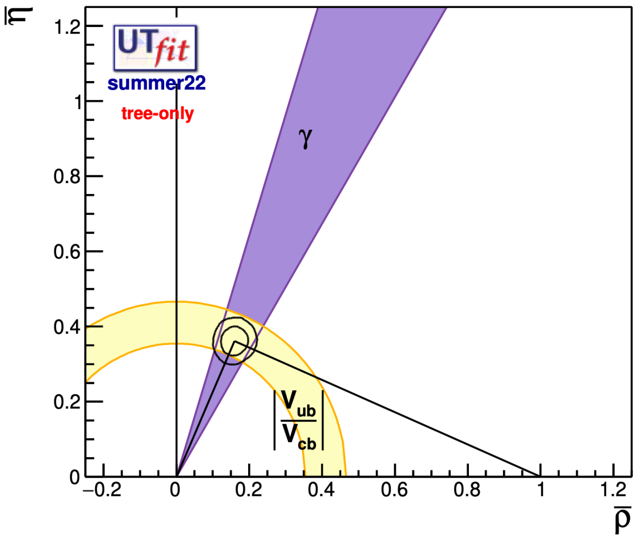






The angle γ



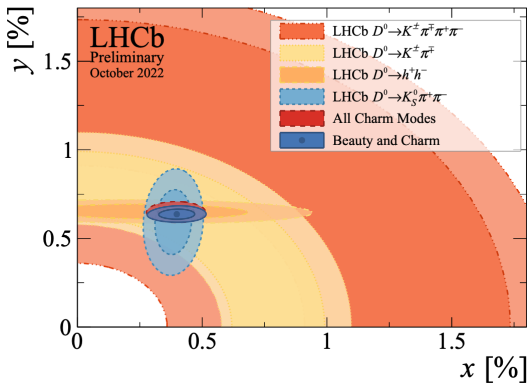


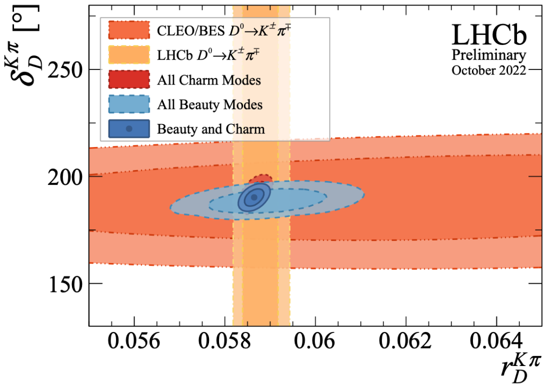
- Very clean quantity to test the SM
  - Theoretical uncertainty on the interpretation of γ measurements is ~10^{-7} [Zupan & Brod 1308.5663]
- Current experimental uncertainty is < 4°
  - Given the extreme precision also **CPV and mixing effects in charm decays** must be taken into account
  - Knowledge of **hadronic D decay parameters** fundamental to improve sensitivity to γ

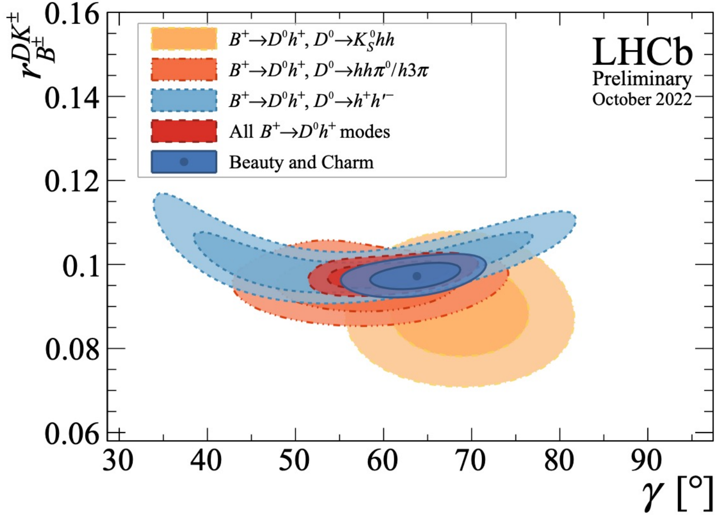
The angle γ

LHCb-CONF-2022-003

- Latest LHCb combination includes latest
  - $B^{\pm} \to Dh^{\pm}$ analyses
    [arXiv:2112.10617, arXiv2209.03692]
  - Direct and indirect CPV in charm
    [PRD105(2022)092013, arXiv:2208.06512, arXiv:2209.03179]
- Compatible with indirect determinations
  - $\gamma = (65.7^{+0.9}_{-2.7})^{\circ}$ CKMFitter
  - $\gamma = (65.8 \pm 2.2)^{\circ}$ UTFit
- LHCb largely dominates the WA







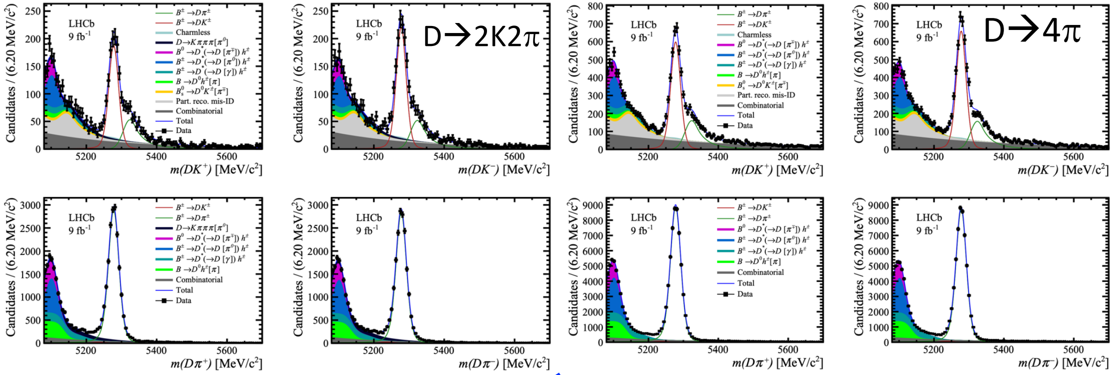
$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$$

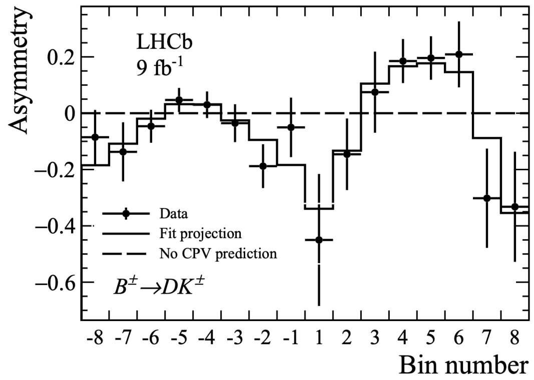
Frequentist approach
173 observables
52 parameters

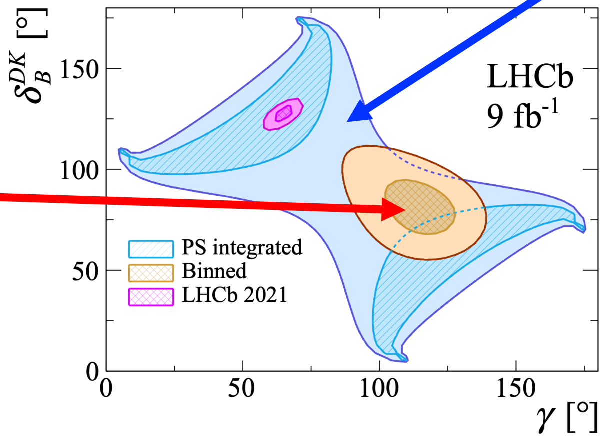
The angle γ

- Latest γ-related measurement from LHCb with $B^{\pm} \to [2K2\pi]_D h^{\pm}$ and $B^{\pm} \to [4\pi] h^{\pm}$
- Integrated over the phase space of the 4-body D decay
- Also binned in D phase space for the D→4K2π mode
  - Hadronic D decay parameters from LHCb amplitude analysis JHEP02(2019)126

Phase-space integrated







arXiv2301.10328

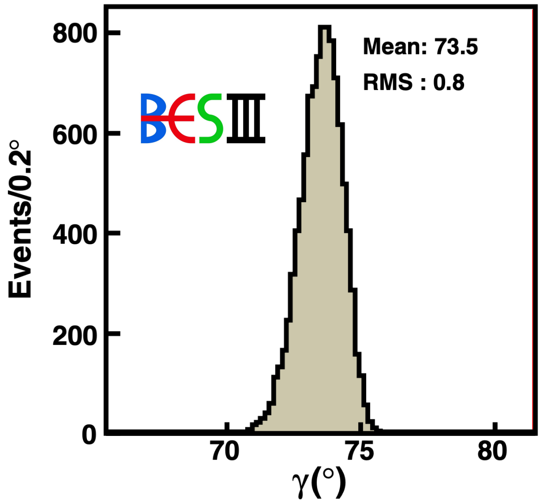
$$\gamma = \left(116^{+12}_{-14}\right)^{\circ}$$

Great improvement expected from better knowledge of D hadronic parameters

The angle γ

- **Team effort** will be required to measure γ to the ultimate precision
  - **Fundamental to exploit the full BESIII sample** of ψ(3770) (20 fb^{-1})
  - Sensitivity to γ from $B^{\pm} \to \left[K_S^0\pi^+\pi^-\right]_D h^{\pm}$ will be limited to $\sim 1°$ by current BESIII measurements of hadronic D parameters (~3 fb^{-1})
  - Sensitivity to γ from $B^{\pm} \to [4h]_D h^{\pm}$ modes can rival that of the $[K_S^0 h^+ h^-]_D$ thanks to inputs for hadronic D parametrs [arXiv:2103.05988]

PRD101(2020)112002



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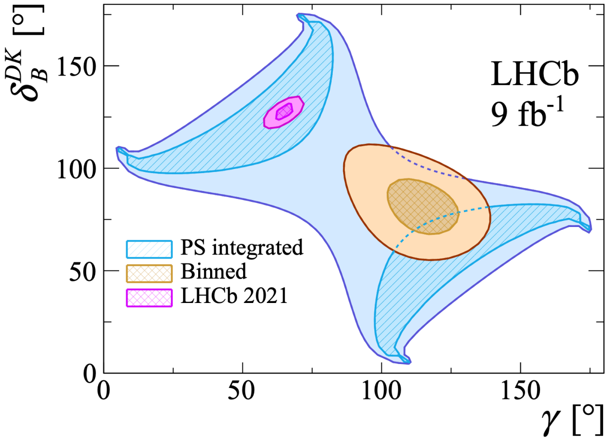
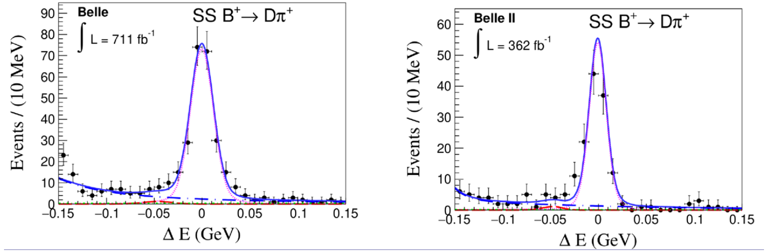


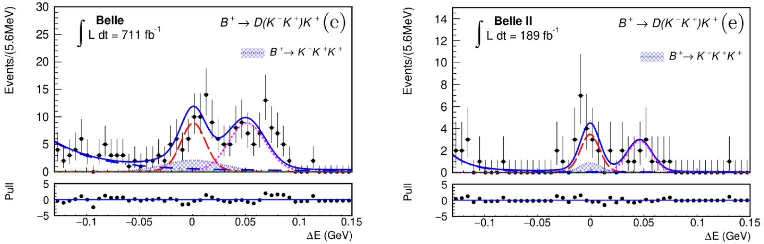
The angle γ

- Belle II is joining the effort
  - First γ determinations from joint Belle and Belle II samples are coming
- New measurements from other $B^{\pm} \to Dh^{\pm}$ modes are coming as well
  - **Not yet competitive, but sensitivity greatly improved over Belle**

$D \to K_S^0 K^{\pm} \pi^{\mp}$

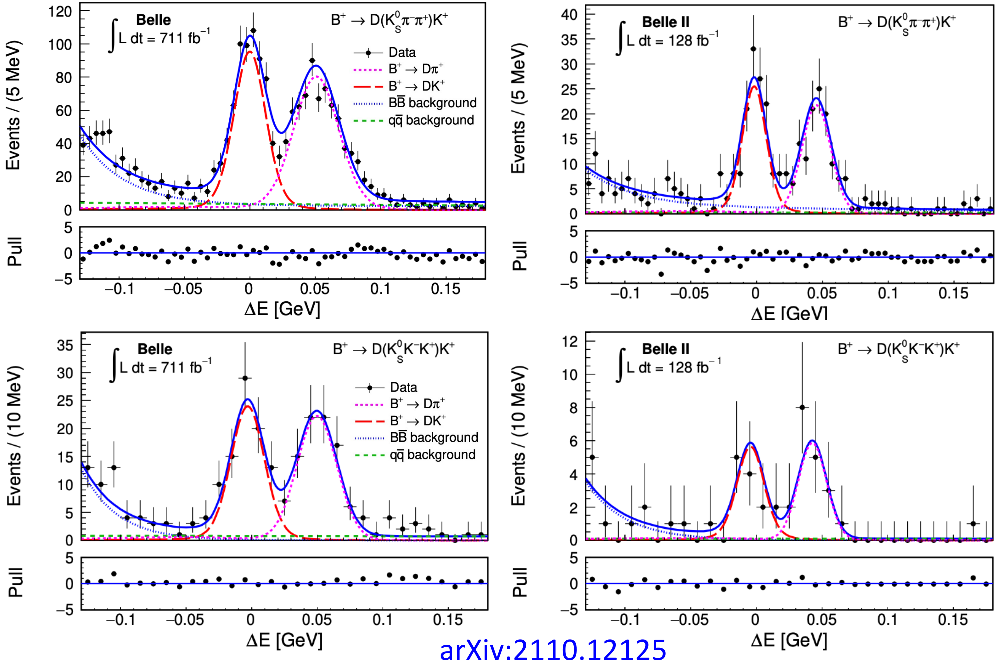


$D \to K^+ K^-$



[New at MoriondEW]()

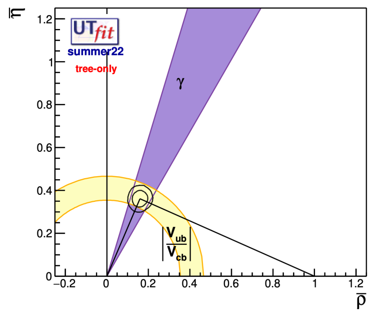
$D \to K_S^0 \pi^+ \pi^-$ and $D \to K_S^0 K^+ K^-$



[arXiv:2110.12125]()

$$\gamma = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^{\circ}$$

V_{ub} and V_{cb}

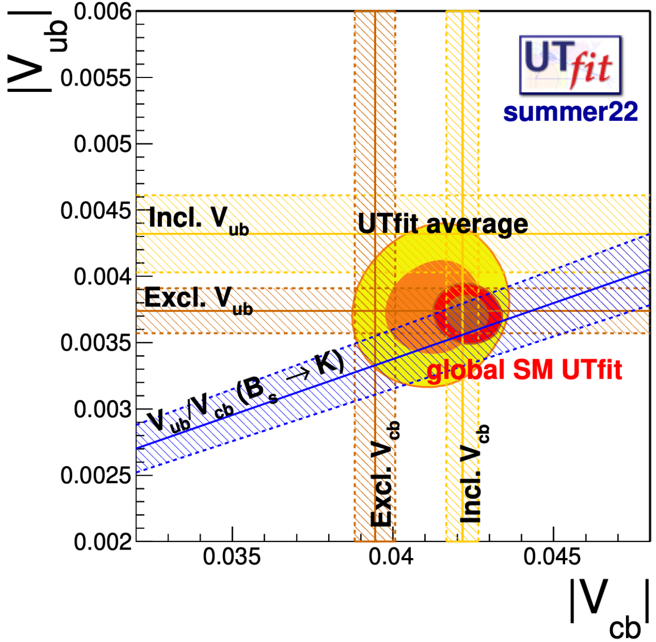


- Important tree-level constraint of the UT apex
  - **Currently limiting factor in the global constraining power**
- Determined from decay rates of semileptonic decays
  - Plus fundamental contribution from lattice QCD

$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$$

Experiment ($d\Gamma$) — **Lattice QCD** ($\left| L_\mu \langle X | \bar{q}\gamma_\mu P_L b | B \rangle \right|^2$)

[arXiv2212.03894](https://arxiv.org/abs/2212.03894)

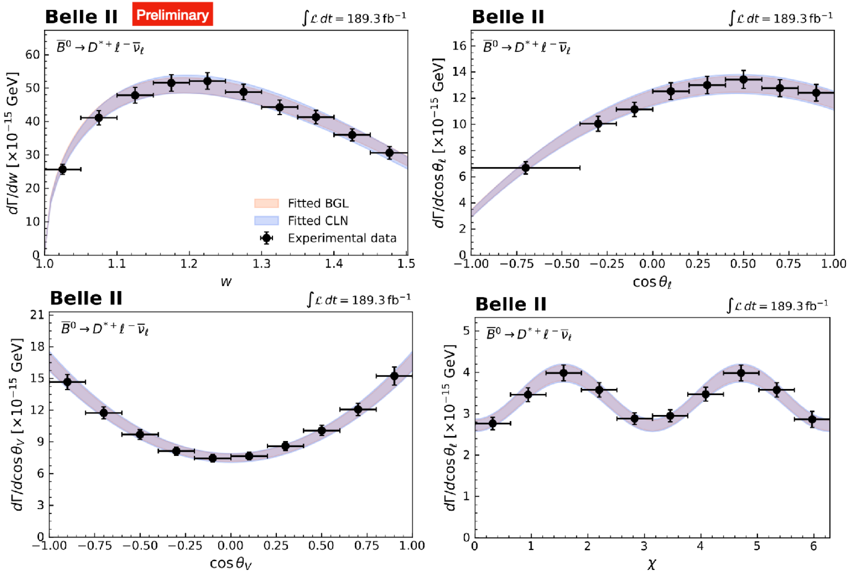


- Belle II will have the leading role thanks to energy-constraint and hermetic detector
- Long standing discrepancy between exclusive and inclusive determinations
- **More precise measurements must be matched with corresponding theory/lattice improvements**

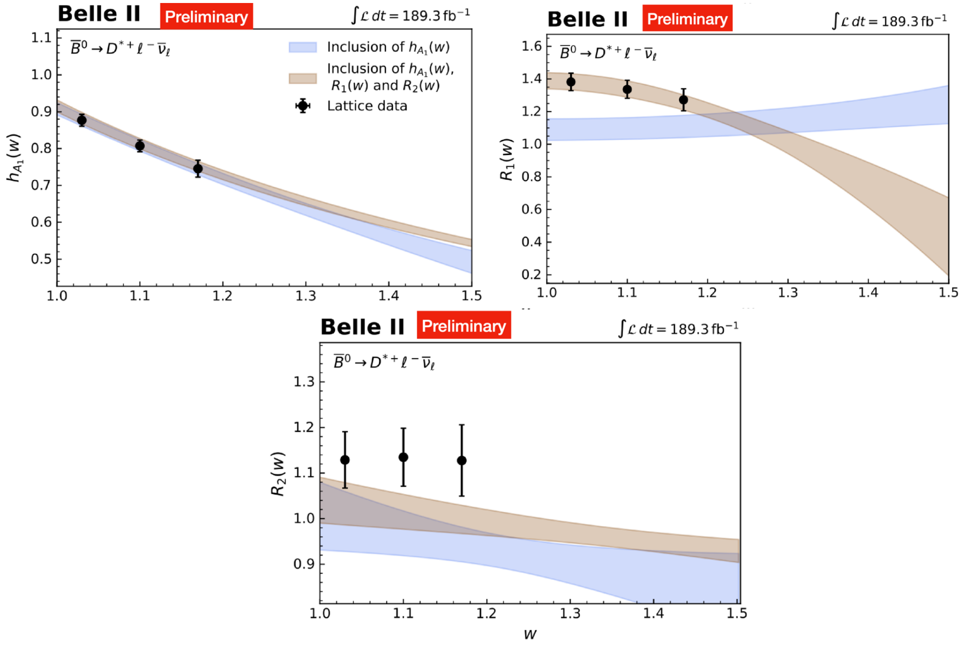
V_{cb} from $B \to D^* l \nu_l$

- Neutrino reconstructed inclusively thanks to energy-constrained environment
- Yields determined in bins of q^2 and pol. angles to properly determine form factors

New at MoriondEW



Latest LQCD results included to further constraints form factors EPJC82(2022)1141



$$|V_{cb}|_{BGL} = (40.9 \pm 0.3_{stat} \pm 1.0_{syst.} \pm 0.6_{theo.}) \times 10^{-3}$$

$$|V_{cb}|_{CLN} = (40.4 \pm 0.3_{stat} \pm 1.0_{syst.} \pm 0.6_{theo.}) \times 10^{-3}$$

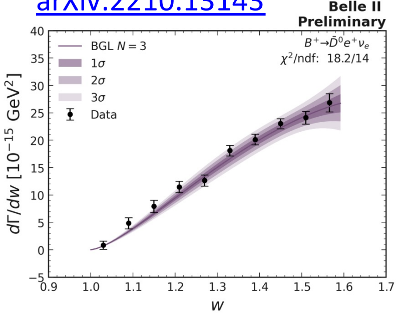
V_{ub} and V_{cb}

WA values [HFLAV 2021]

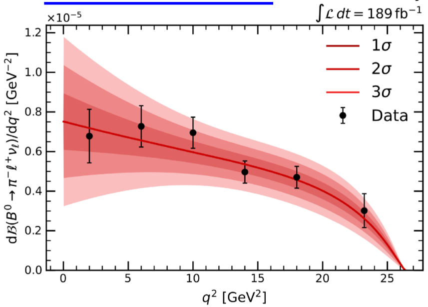
$$|V_{cb}|_{\text{excl}} = (39.10 \pm 0.50) \times 10^{-3}$$

$$|V_{ub}|_{\text{excl}} = (4.19 \pm 0.17) \times 10^{-3}$$

arXiv:2210.13143



arXiv:2210.04224

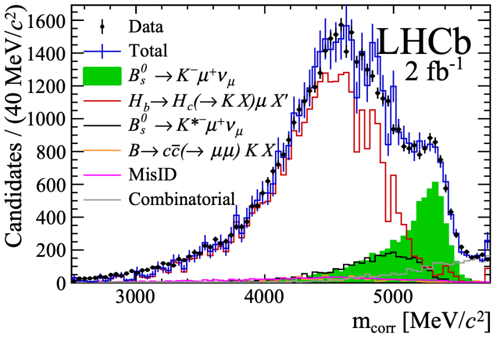


Exclusive V_{xb} from Belle II with only 189 fb^{-1} using latest LQCD inputs

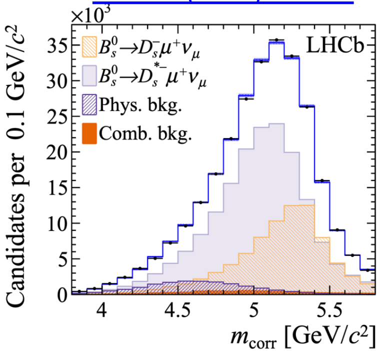
	$\|V_{cb}\|$ x 10^3	Reference
Belle II $B^0 \to D^{*-} l^+ \nu_l$ untagged	40.9 ± 1.2 (BGL)	To be submitted to PRD
Belle II $B^0 \to D^{*-} l^+ \nu_l$ tagged	37.9 ± 2.7 (CLN)	[arXiv.2301.04716]
Belle II $B^0 \to D l \nu_l$ untagged	38.28 ± 1.16 (BGL)	[arXiv:2210.13143]

	$\|V_{ub}\|$ x 10^3	Reference
Belle II $B^0 \to \pi e \nu_e$ tagged	3.88 ± 0.45	[arXiv:2206.08102]
Belle II $B^0 \to \pi e \nu_e$ untagged	3.55 ± 0.25	[arXiv.2210.04224]

PRL126(2021)081804



PRD101(2020)072004



Also LHCb in the game with B_s and Λ_b modes

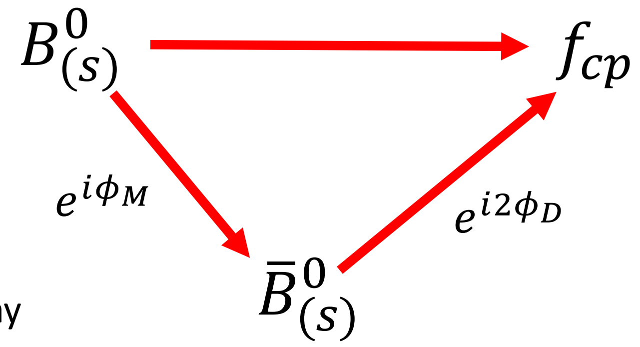
	$\|V_{cb}\|$ x 10^3	Reference
LHCb $B_s^0 \to D_s^{(*)} \mu \nu_\mu$	$41.4 \pm 0.6 \pm 0.9 \pm 1.2$ (BGL)	PRD101(2020)072004
LHCb $B_s^0 \to D_s^{(*)} \mu \nu_\mu$	$42.3 \pm 0.8 \pm 0.9 \pm 1.2$ (CLN)	PRD101(2020)072004

From the LHCb measurement of $|V_{ub}|/|V_{cb}|$ and using WA of exlusive $|V_{cb}| = (39.5 \pm 0.9) \times 10^{-3}$

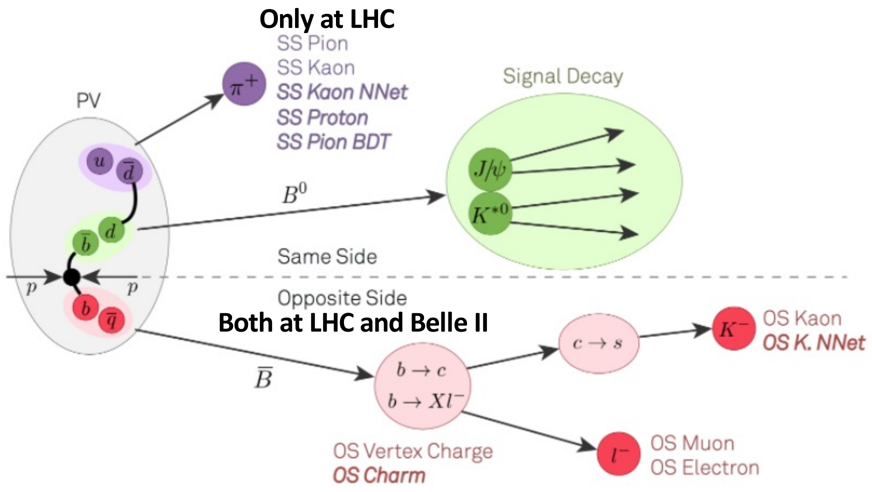
	$\|V_{ub}\|$ x 10^3	Reference
LHCb $B_s^0 \to K^- \mu^+ \nu_\mu$	2.40 ± 0.16 ($q^2 < 7$ GeV^2/c^4)	PRL126(2021)081804
LHCb $B_s^0 \to K^- \mu^+ \nu_\mu$	3.74 ± 0.32 ($q^2 > 7$ GeV^2/c^4)	PRL126(2021)081804
LHCb $\Lambda_b^0 \to p \mu^+ \nu_\mu$	3.27 ± 0.23	NaturePhysics11(2015)743

$B^0_{(s)}$ mixing phases

- Time-dependent CPV allows constraints to the UT apex to be derived from B^0 (sin2β) and B^0_s (ϕ_s) mixing phases
  - **Measure CP phase in the interference between B-mixing and decay**
  - Golden modes are $B^0_s \to J/\psi h^+ h'^-$ and $B^0 \to J/\psi K^0_S$ as decay dominated by tree-level $b \to c\bar{c}q$ transitions (No CPV in decay)

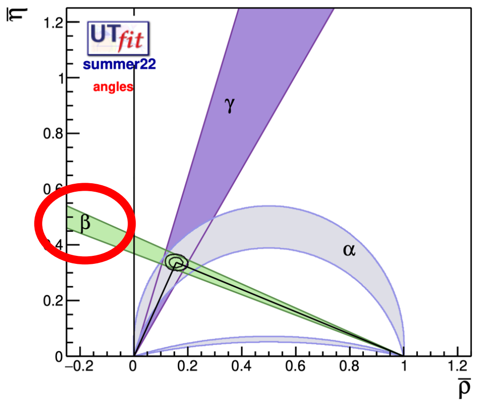


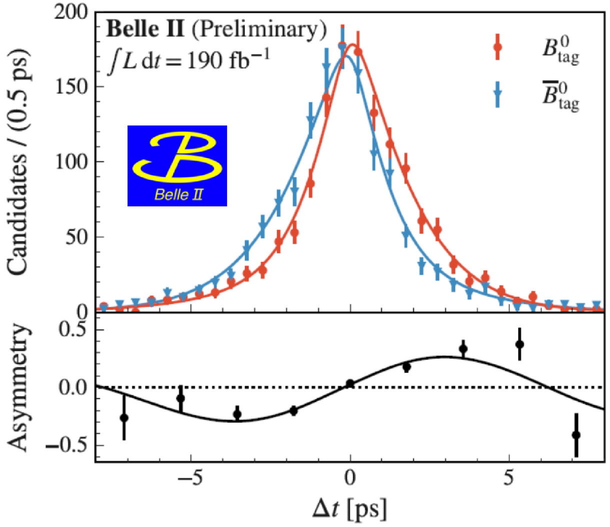
- Fundamental to identify the flavour of the B at the production → flavour tagging
  - $\sigma^{-2} \propto \varepsilon_{eff}$ effective tagging power
  - $\boldsymbol{\varepsilon^{LHC}_{eff} \approx 5-8\%, \varepsilon^{BelleII}_{eff} \approx 30\%}$
    Belle II profits from the much cleaner environment



$B^0_{(s)}$ mixing phase

- Measurement of sin2β is already **very precise**, but
  - LHCb still has x3 more statistics to add from Run2 alone and is working hard to update the measurement
  - Belle II is already investigating its potential arXiv:2302.12898

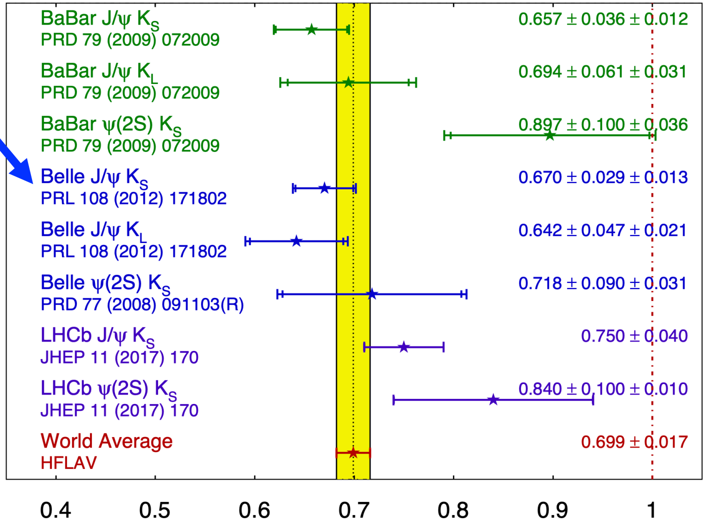




$$\sin(2\beta) = 0.720 \pm 0.062 \pm 0.016$$
$$C = 0.094 \pm 0.044^{+0.047}_{-0.017}$$

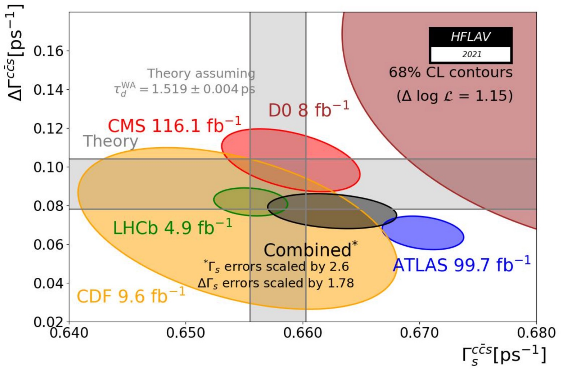
Not yet competitive but proof that everything is working

$\sin(2\beta) \equiv \sin(2\phi_1)$ HFLAV 2021

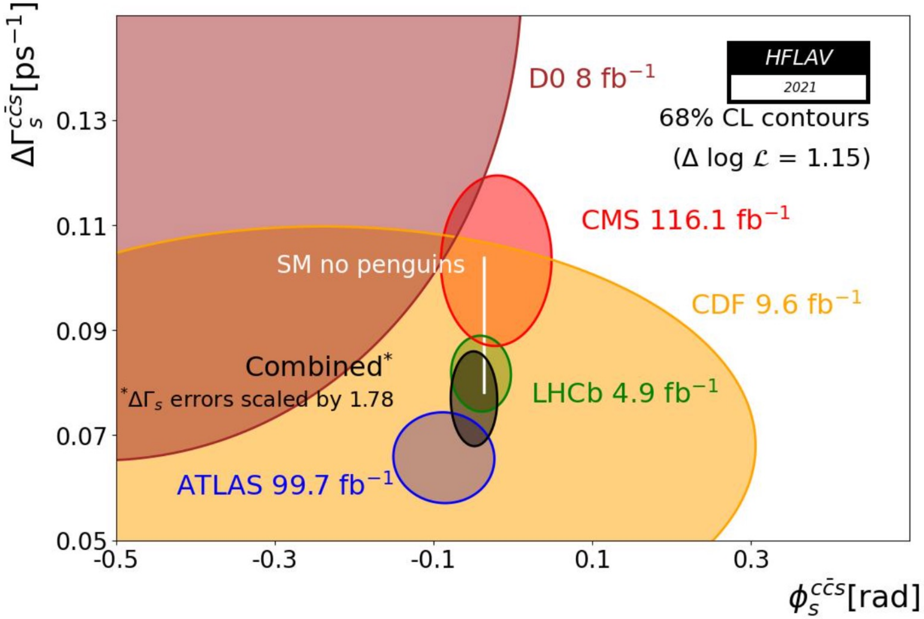


B_s^0 mixing phase

- In the SM the B_s^0 mixing phase is very small and very precisely determined from UT constraints
  - $\phi_s = -0.0368^{+0.0006}_{-0.0009}$ CKMFitter, $\phi_s = -0.0368 \pm 0.0010$ UTFit
- **Unique to LHC experiments** thanks to the large Lorentz boost in p-p collisions → $\Delta t = \Delta L/\gamma\beta c$
- Very good agreement of all LHC experiments with competitive measurements
  - In the long term will be **important to understand how good is the approximation $\phi_s \approx \phi_s^{ccs}$**
  - LHCb is updating the measurement for the golden mode $B_s^0 \to J/\psi K^+K^-$ to the full Run2 sample → ~4 more fb^{-1}

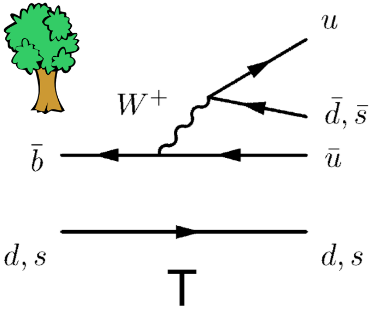


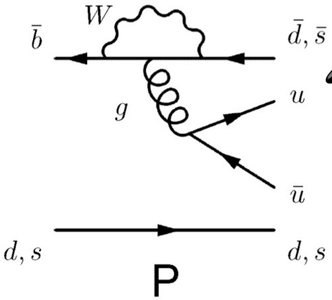
Tension between experiments for the B_s^0 lifetime measurement

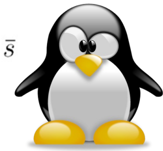


$B^0_{(s)}$ mixing with penguins

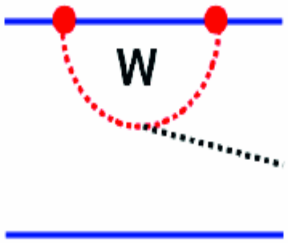
- Charmless B-hadron decays receive relevant contributions from b→s(d) penguin transitions
  - **Physics BSM** may appear in the loops

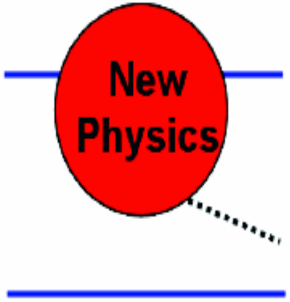






- Unique opportunity to compare the same quantity from pure SM processes and processes sensible to NP
  - **Interpretation in terms of CKM parameters is not trivial** and requires combination of several measurements (and inputs from theory)

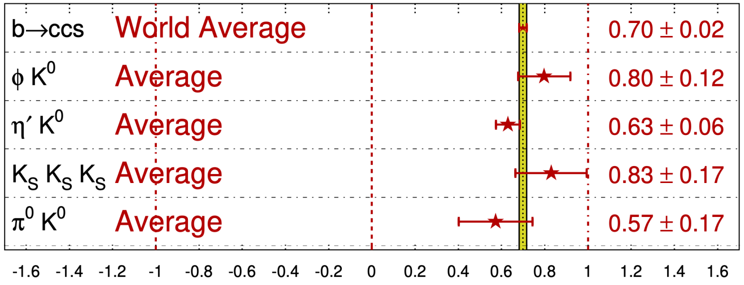




$B^0_{(s)}$ mixing with penguins

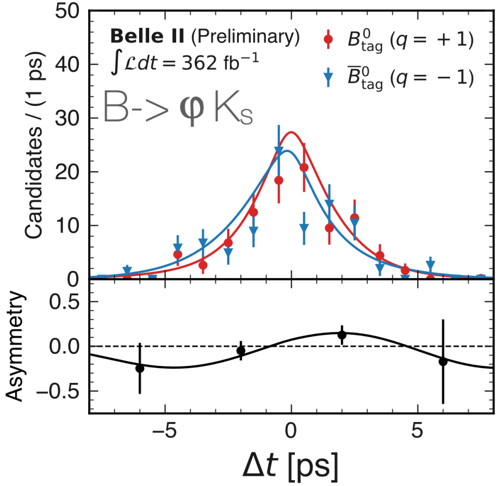
New Belle II measurements of $\sin(2\beta^{eff})$ at MoriondEW (362 fb^{-1})

$\sin(2\beta^{\mathrm{eff}}) \equiv \sin(2\phi_1^{\mathrm{eff}})$ HFLAV 2021



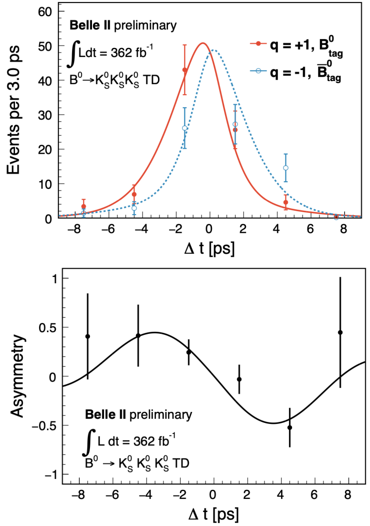
New at MoriondEW

$B^0 \to \phi K_S^0$



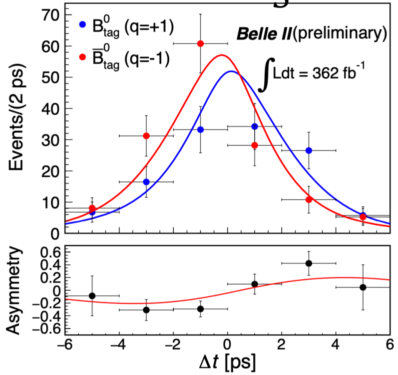
$$A_{CP} = 0.31 \pm 0.20^{+0.05}_{-0.06}$$
$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08}$$

$B^0 \to 3K_S^0$



$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

$B^0 \to K_S^0\pi^0$



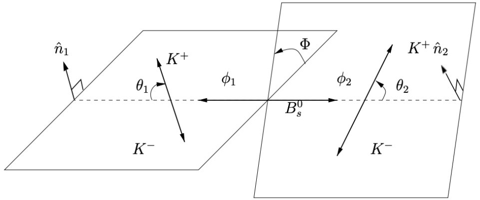
$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

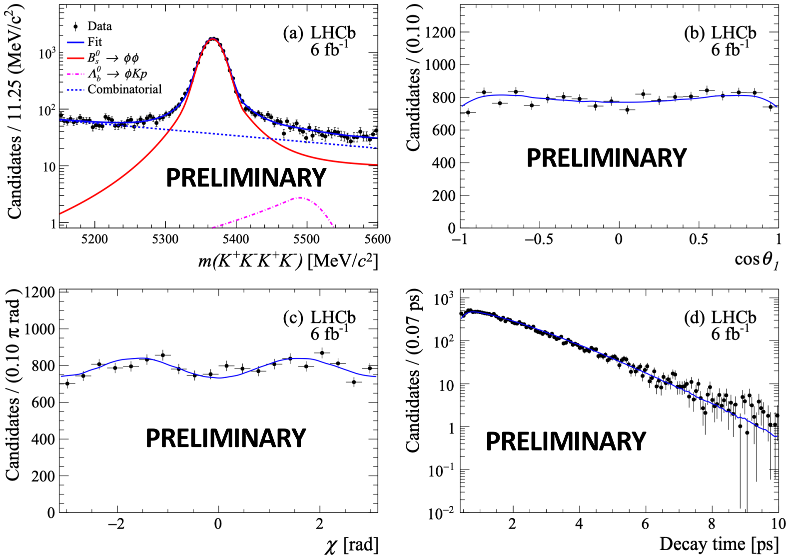
Already competitive with WA for some channels!

$B^0_{(s)}$ mixing with penguins

LHCb-PAPER-2023-001 (in preparation)

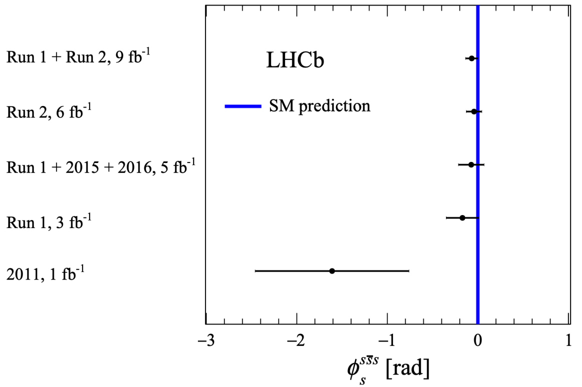
- Brand new angular TD CPV measurement with $B^0_s \to \phi(K^+K^-)\phi(K^+K^-)$ with full Run2 sample
- **Pure penguin decay → $\phi_s^{s\bar{s}s} \approx 0$**





Polarisation independent

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$
$$|\lambda| = 1.004 \pm 0.030 \pm 0.009,$$



Polarisation dependent (no evidence of polarisation dependence)

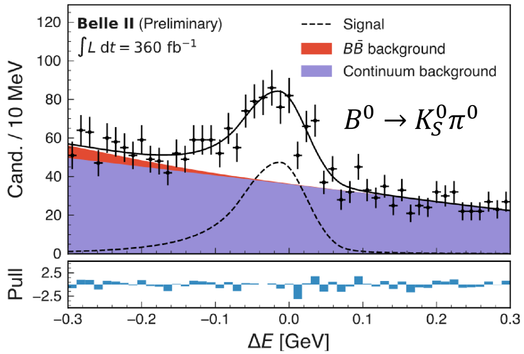
$$\phi_{s,0} = -0.18 \pm 0.09 \text{ rad}, \qquad |\lambda_0| = 1.02 \pm 0.17,$$
$$\phi_{s,\parallel} - \phi_{s,0} = 0.12 \pm 0.09 \text{ rad}, \qquad |\lambda_\perp/\lambda_0| = 0.97 \pm 0.22,$$
$$\phi_{s,\perp} - \phi_{s,0} = 0.17 \pm 0.09 \text{ rad}, \qquad |\lambda_\parallel/\lambda_0| = 0.78 \pm 0.21,$$

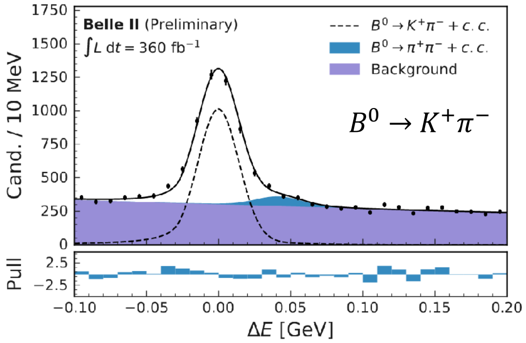
More penguins

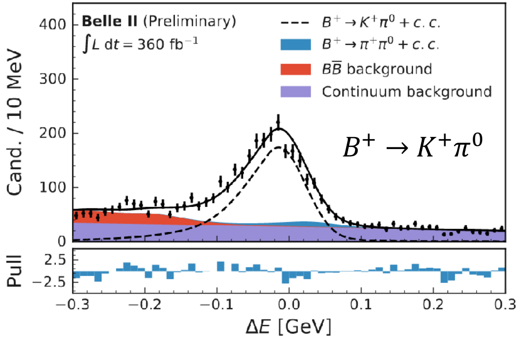
New at MoriondEW

- Isosping sum rule in B→Kπ system provides a stringent SM test [Gronau PLB627(2005)82]
  - **Predicted to be 0 with 1% theoretical uncertainty**
  - Uncertainty dominated by $A_{CP}^{K^0\pi^0}$

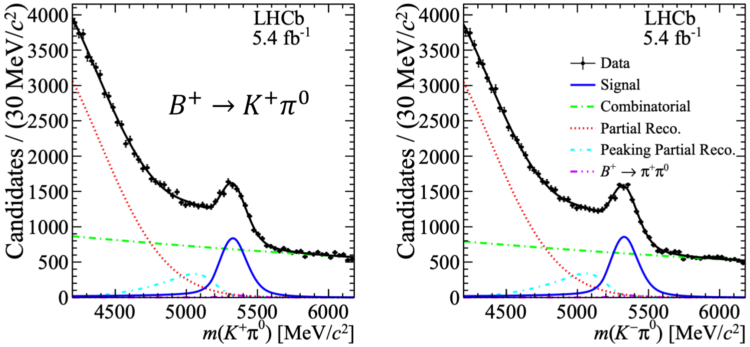
$$I_{K\pi} = \mathcal{A}_{CP}^{K^+\pi^-} + \mathcal{A}_{CP}^{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}}$$







PRL126(2021)091802



Belle II determination competitive with WA

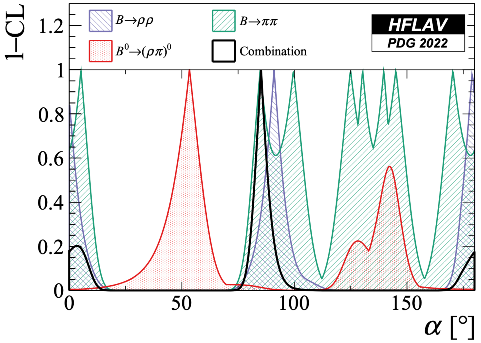
$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$

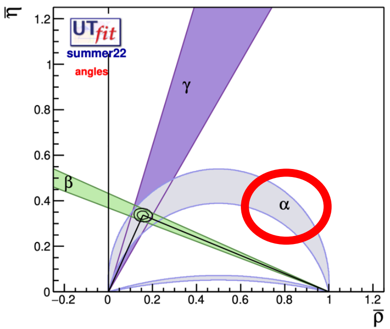
Consistent with SM expectation

Receiving contributions also from LHCb

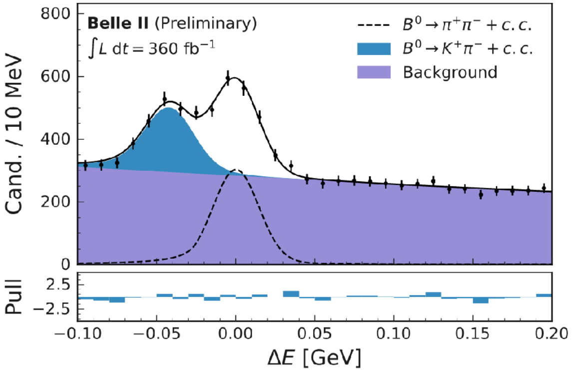
The angle α

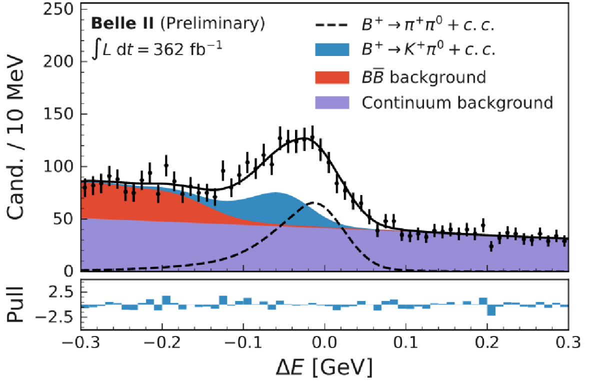
- Least well-known angle of the UT $\sigma_\alpha \sim 4-5^\circ$
  - Determination based on isospin analysis of B→ππ,ρρ,ρπ decays
  - **Intrinsic theoretical uncertainty of $\sim 1^\circ$**: from isospin breaking and EW penguin
- Precisions dominated by the B→ρρ system from B-factories
  - **Belle II has full access to all final states and in particular those with neutrals π^0 and $\rho^+ \to \pi^+\pi^0$**
  - LHCb can contribute in fully-charged final states (world's best TDCPV in $B^0 \to \pi^+\pi^-$)





New at MoriondEW





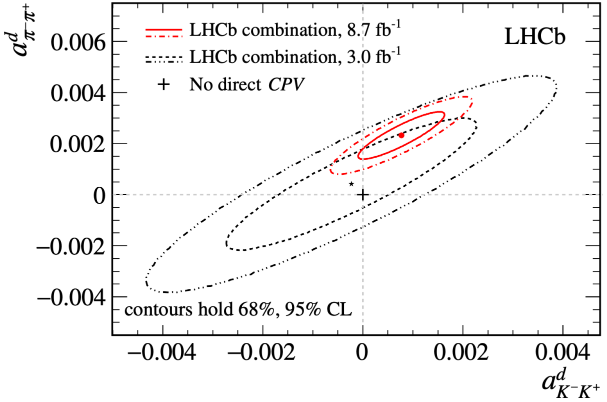
Belle II precision is the same as WA!

$$BR(B^+ \to \pi^+\pi^0) = (5.02 \pm 0.28 \pm 0.32)\times 10^{-6}$$

$$A_{CP}(B^+ \to \pi^+\pi^0) = -0.08 \pm 0.05 \pm 0.01$$

CPV in the charm sector

- **Unique laboratory to study CPV in up-type quark decays**
- Small CPV effects expected: $A_{CP} \sim 10^{-4} - 10^{-3}$
- **Theory predictions complicated by long distance contributions**
- Huge charm data sample from LHCb lead to **first observation of CPV in $D^0 \to h^+h^-$ decays in 2019**
  - Great improvement in efficiency in Run2 thanks to software trigger and even greater improvement expected in Run3
  - New measurements in more channels needed to unravel the mystery

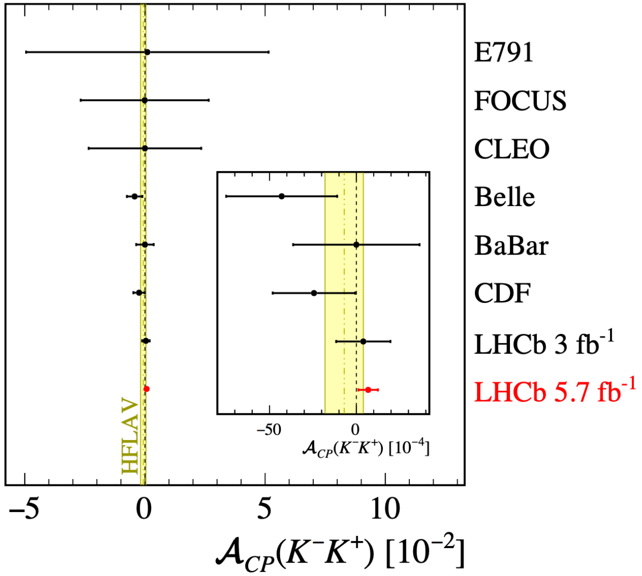


LHCb-PAPER-2022-024

$$a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d_{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

$$\rho(a^d_{KK}, a^d_{\pi\pi}) = 0.88$$



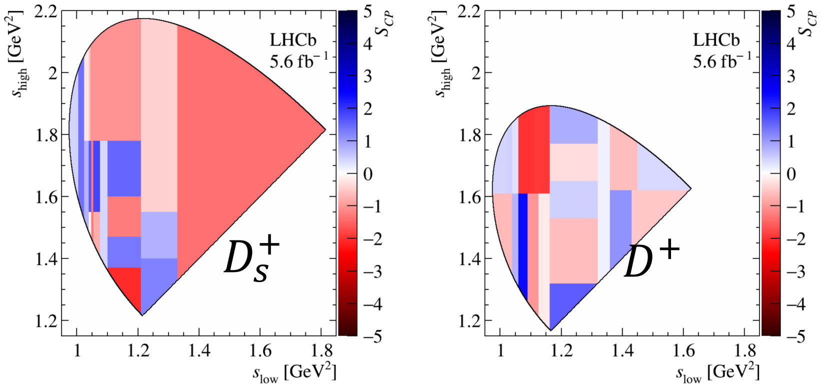
- **Evidence of direct CPV in $D^0 \to \pi^+\pi^-$ at 3.8σ**
- Exceeds at 2σ level U-spin breaking expectations

Systematic uncertainties controlled to 10^{-4}!!
May become necessary to scale to 10^{-5}!!

CPV in the charm sector

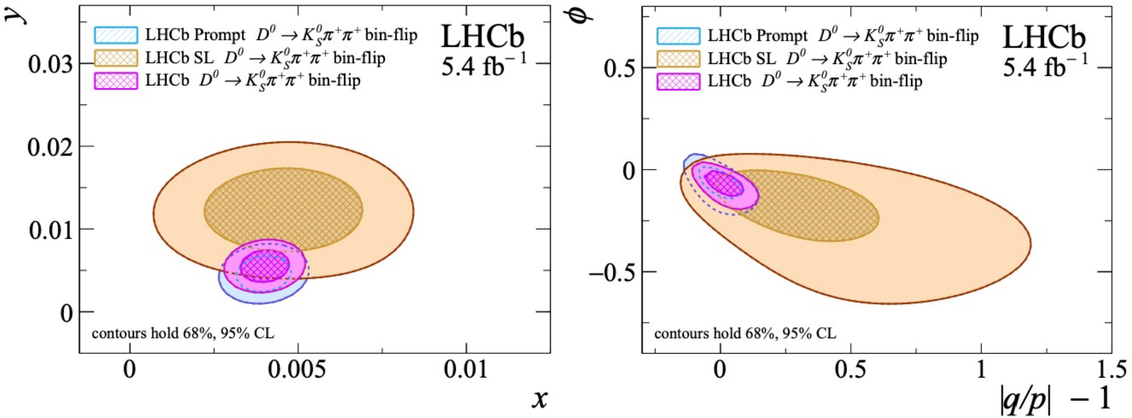
- New measurements in more channels needed to understand if CPV in charm is QCD effects or New Physics
  - Search for local CPV in $D^+_{(s)} \to 3K$ phase space
  - No evidence of local CPV has been found

arXiv:2303.04062



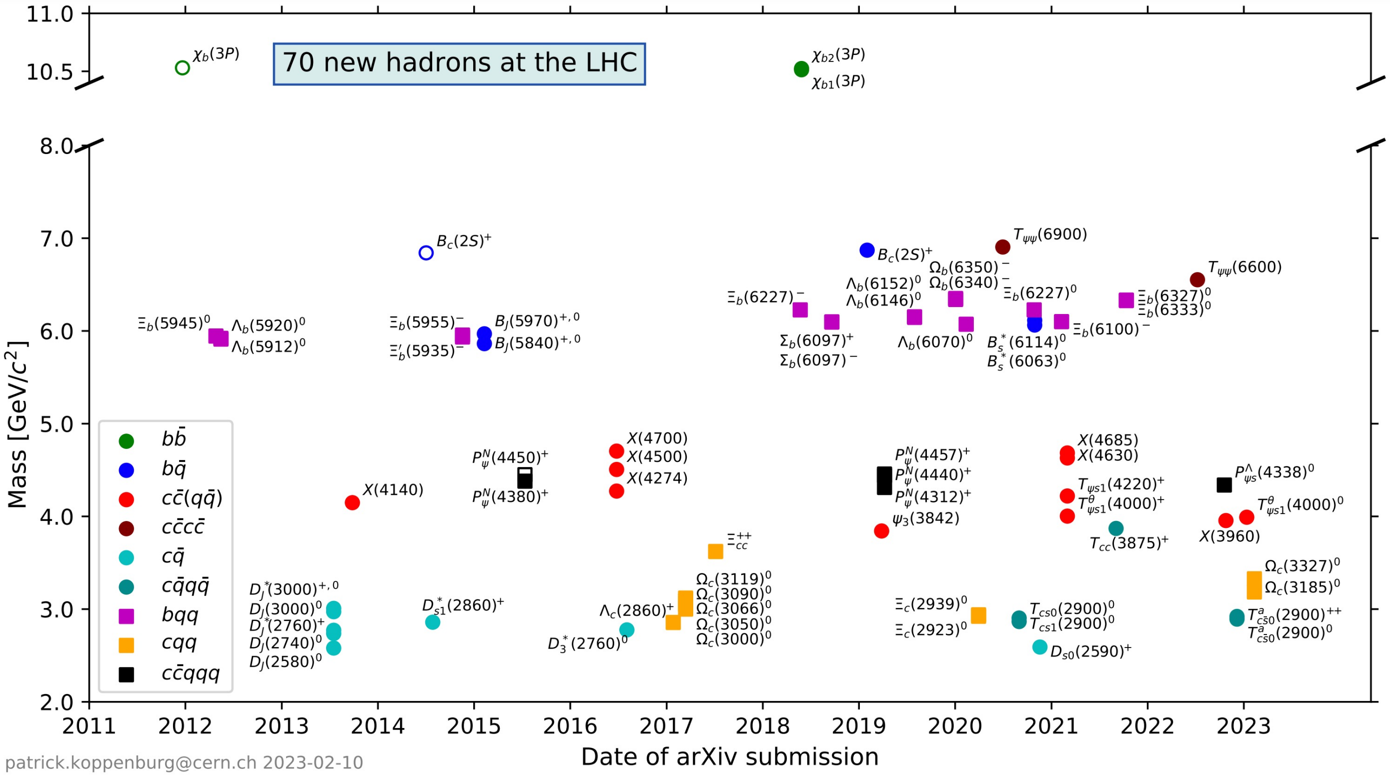
- Indirect CPV in charm mixing
  - Mixing well established since over a decade but still a long path ahead to see CPV
  - **Contribution from BESIII crucial for long-term sensitivity**
  - LHCb largely dominates WA

arXiv:2208.06512



Spectroscopy

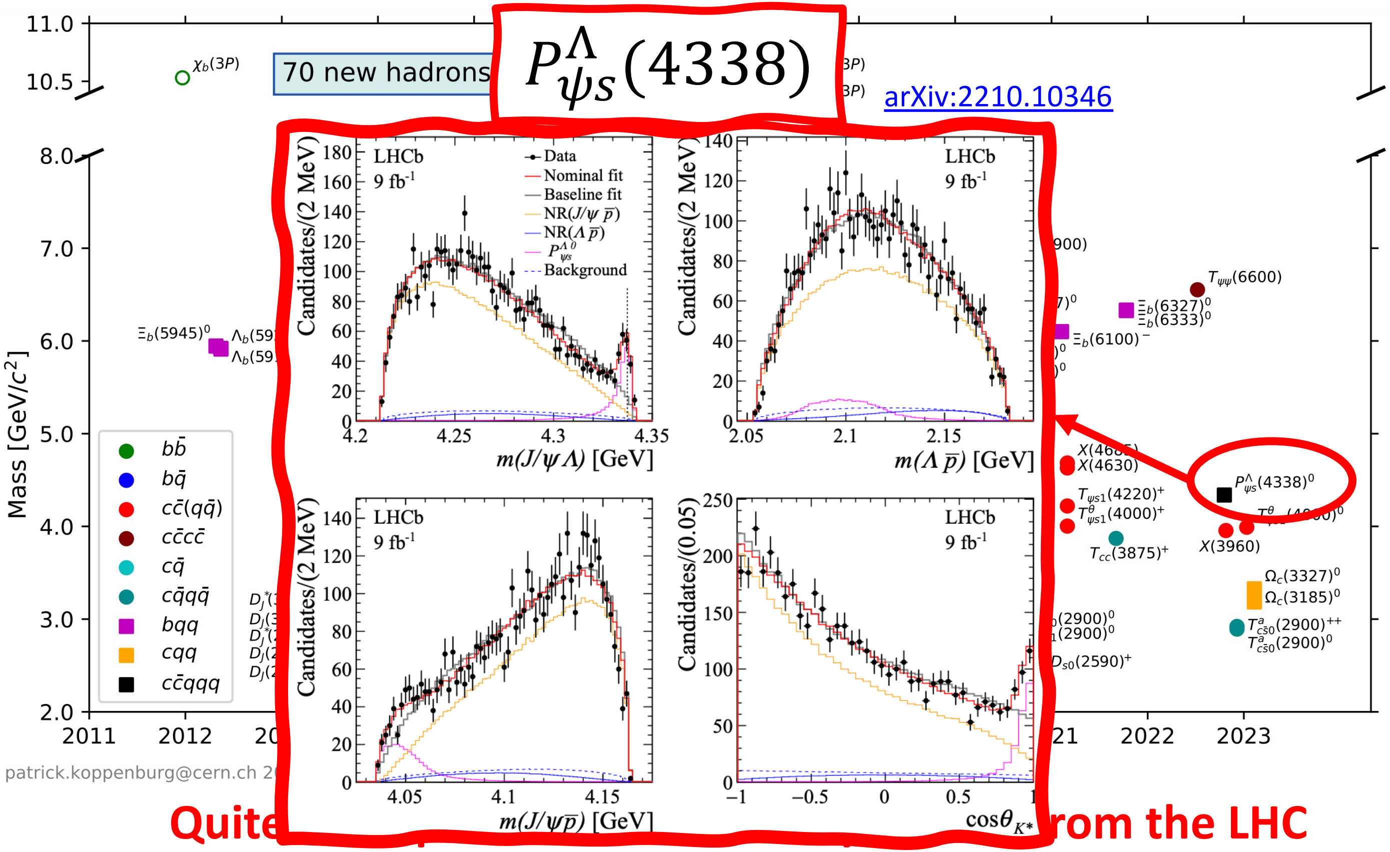
Thanks to Patrick Koppenburg



Quite an impressive zoo of new particles from the LHC

Including penta- and tetra-quarks

Spectroscopy

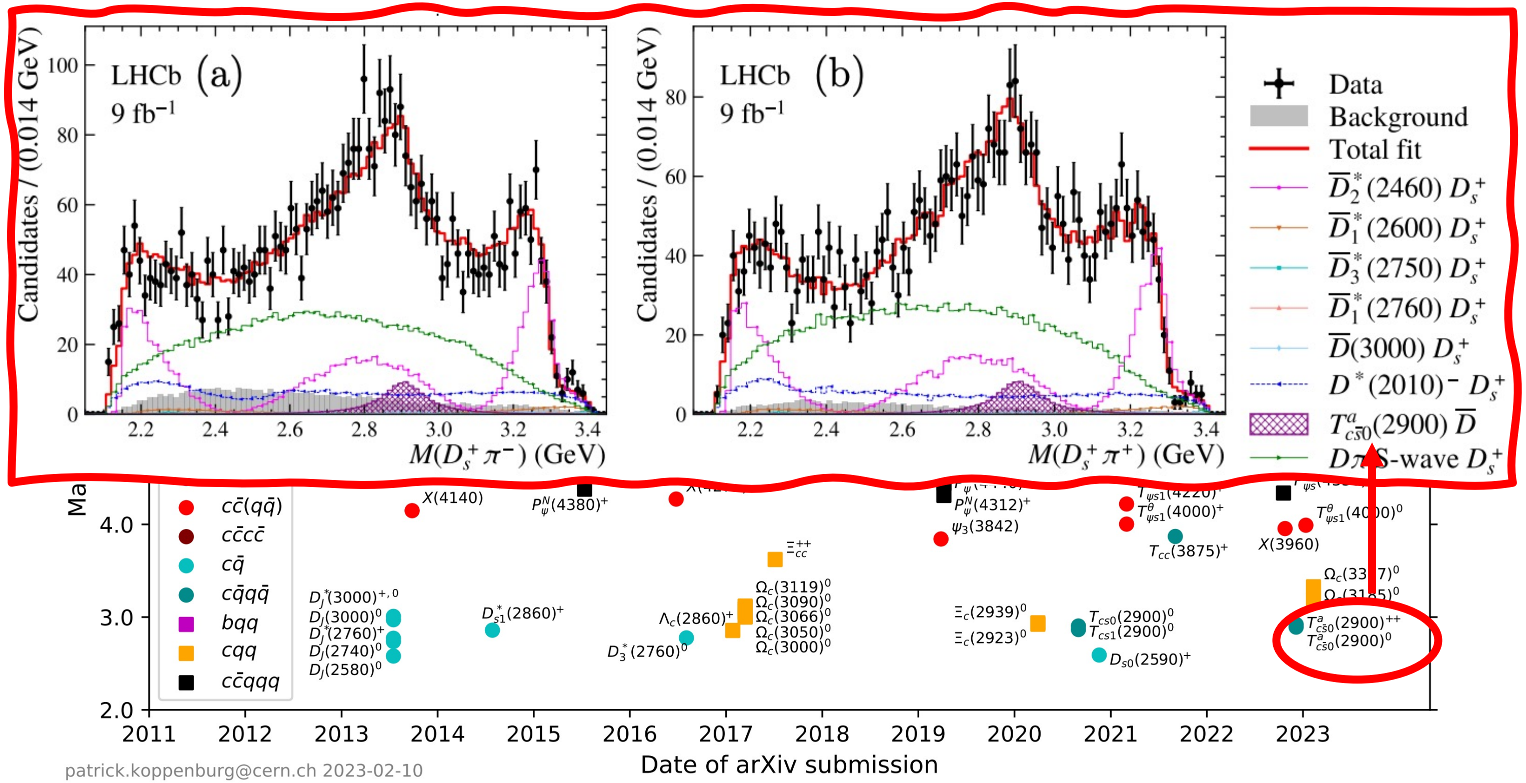


Quite … **rom the LHC**

Including penta- and tetra-quarks

Spectroscopy

arXiv:2212.02716

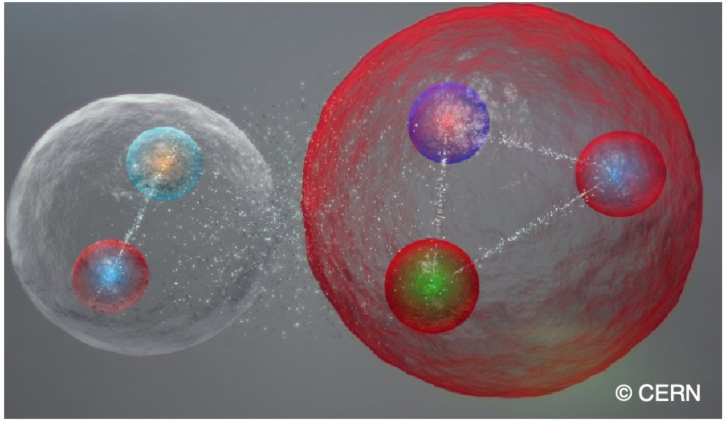


Quite an impressive zoo of new particles from the LHC

Including penta- and tetra-quarks

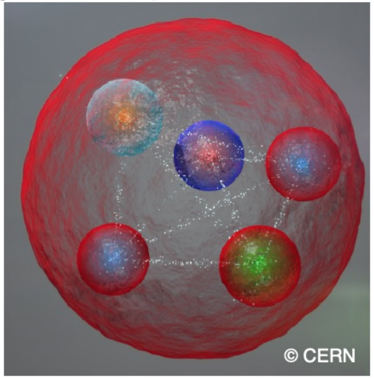
What is the nature of these penta- and tetra-quark?

Molecule model - nuclear forces



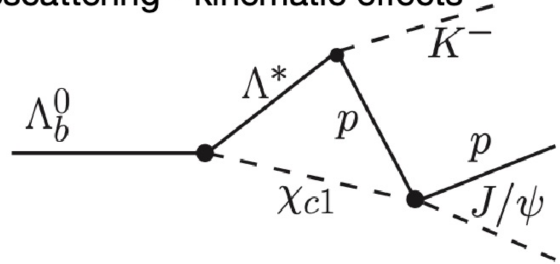
F.-K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004

Tightly bound quarks - color forces



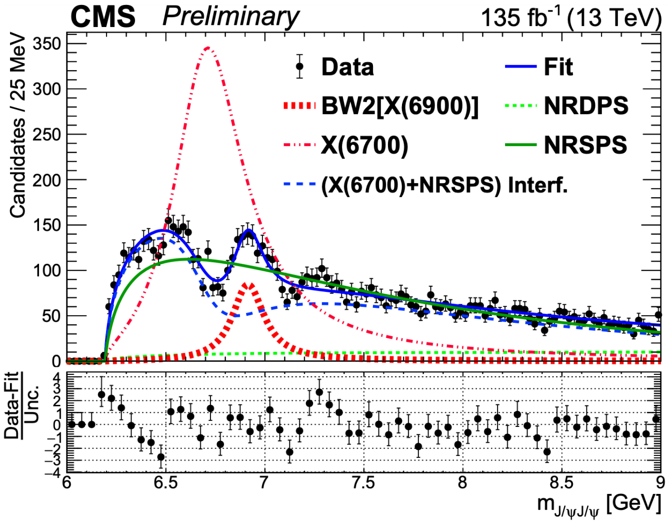
A. Esposito, A Pilloni, A. D. Polosa, Phys. Rept. 668 (2017) 1
J.-M. Richard, Few Body Syst. 57 (2016) 1185

Rescattering - kinematic effects

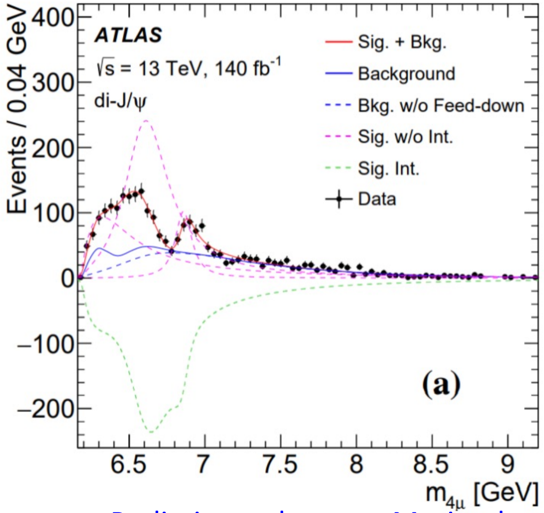


F. Guo et al., Phys. Rev. D 92, 071502 (2015)

Di-J/ψ spectrum



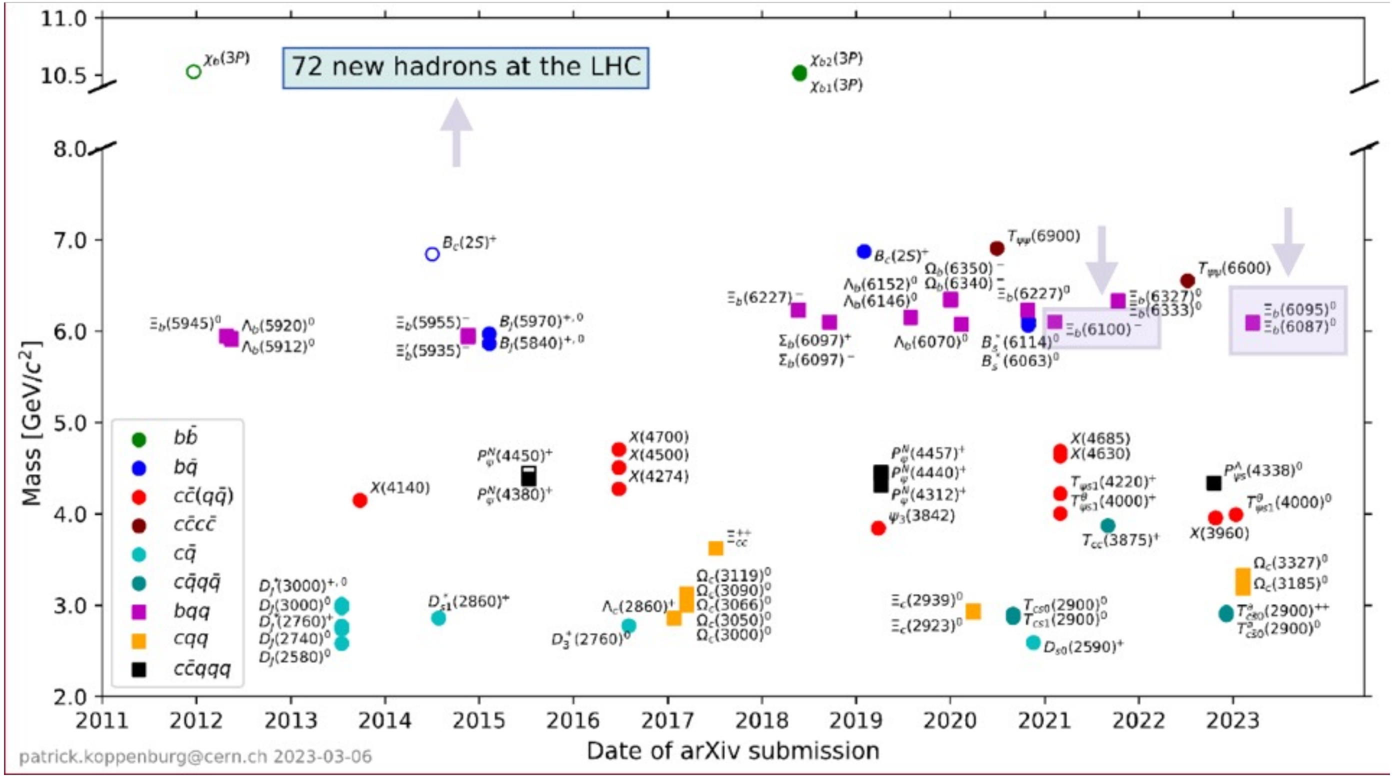
[CMS-PAS-BPH-21-003]



[Preliminary shown at Moriond]

- Observation of new structures in the di-J/ψ spectrum from CMS and ATLAS
- **More refined analysis is needed to establish the nature of these structures**
- The resonance at 6.9 GeV previously observed by LHCb is confirmed [Sci.Bull.66(2021(1278]

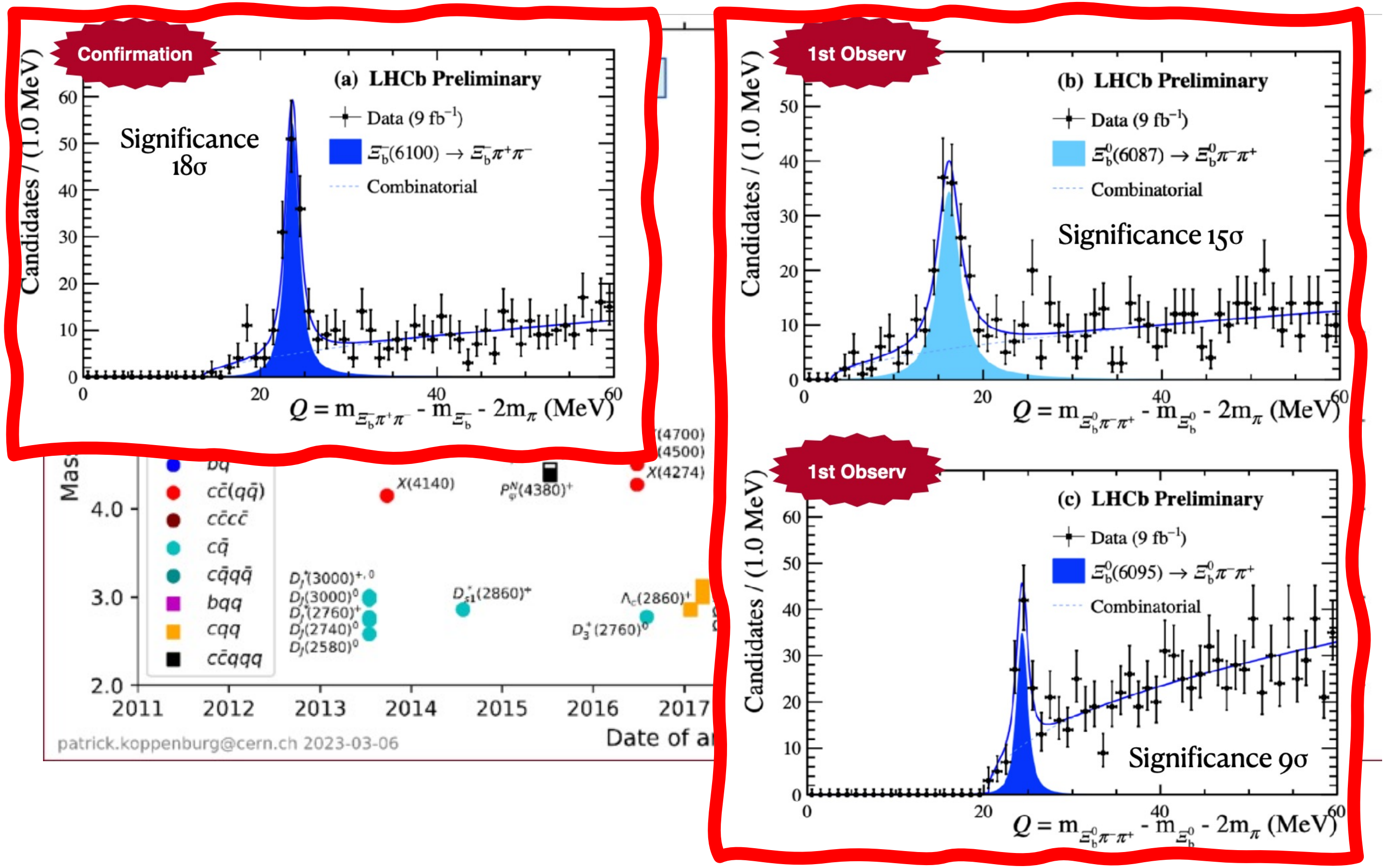
Spectroscopy



Continuous addition of new particles

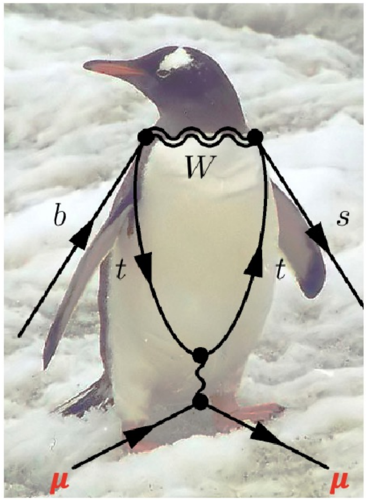
Spectroscopy

LHCb-PAPER-2023-008
(in preparation)

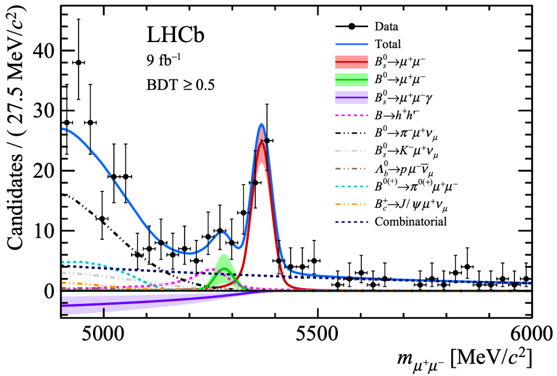


Search for new physics with rare decays

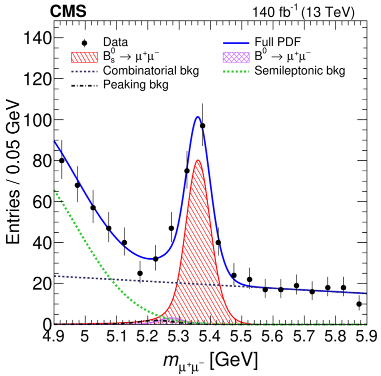
- $B^0_{(s)} \to \mu^+\mu^-$ decays are golden modes to search for New Physics
  - Pure penguin decays, highly suppressed in the SM
  - Very precise theoretical predictions



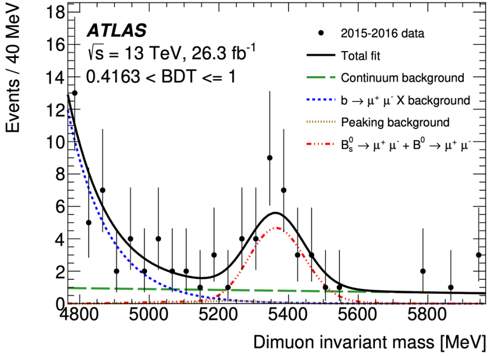
LHCb-PAPER-2021-008

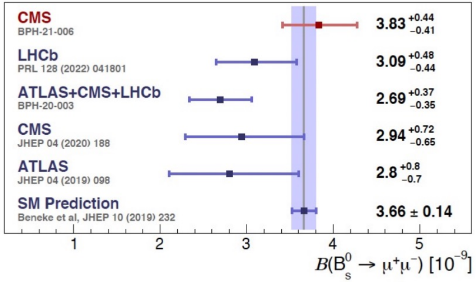


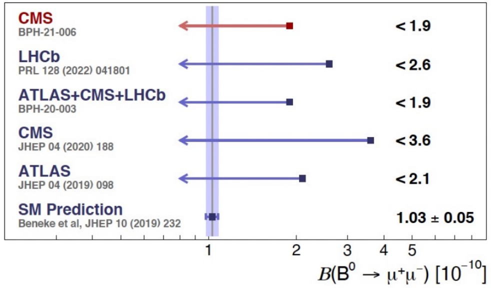
CMS-PAS-BPH-21-006

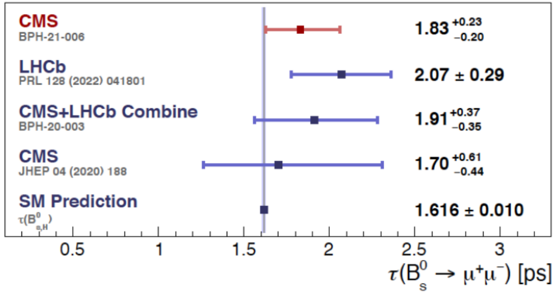


JHEP04(2019)098





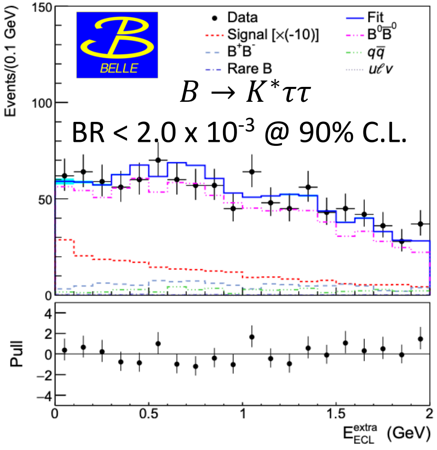




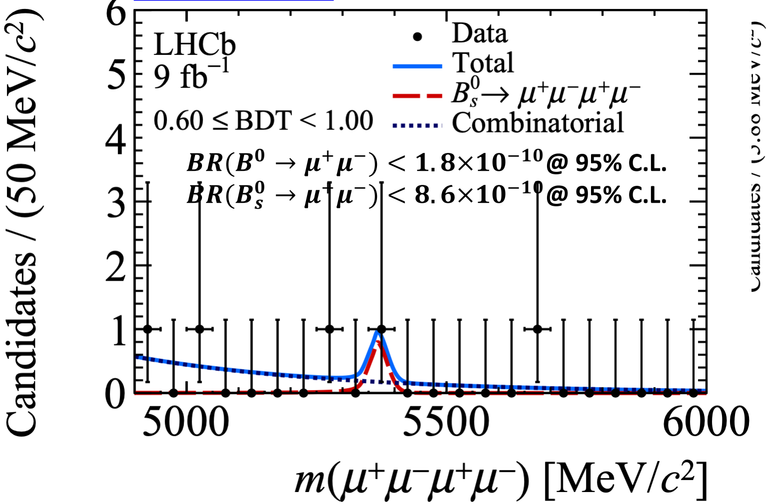
A lot has been done, but still a long way to observe B⁰ mode and eventually $B^0_{(s)} \to \mu^+\mu^-\gamma$

Search for new physics with rare decays

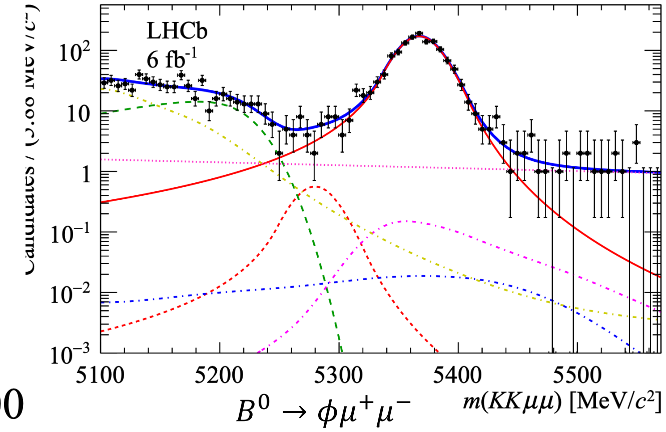
arXiv:2110.03871



JHEP03(2022)109



arXiv:2201.10167

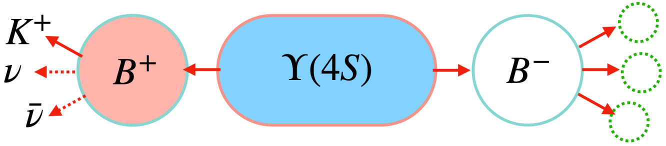


BR < 3.2 x 10^{-9} @ 90% C.L.

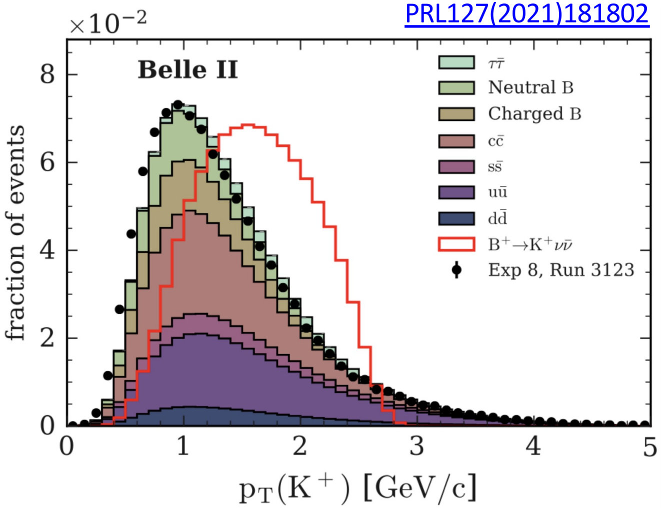
Many other modes worth to search for, but much more challenging from the experimental point of view

Search for new physics with rare decays

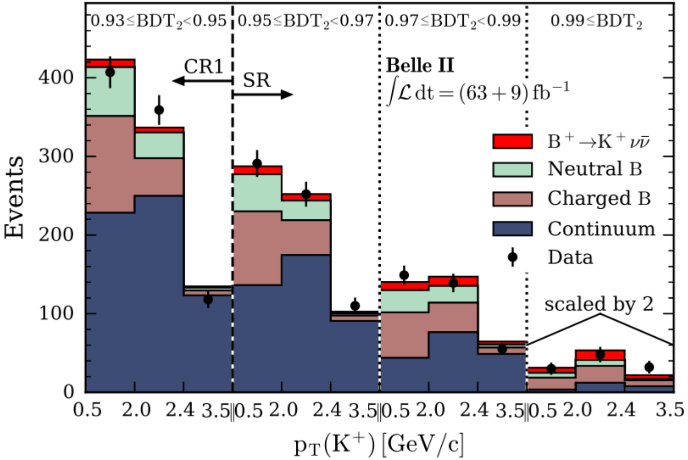
- $B \rightarrow X_s \nu \bar{\nu}$ unique to Belle II thanks to fixed-energy environment
- Inclusive approach
  - Signal = high-pT isolated kaon
  - All the rest of the event is the other B

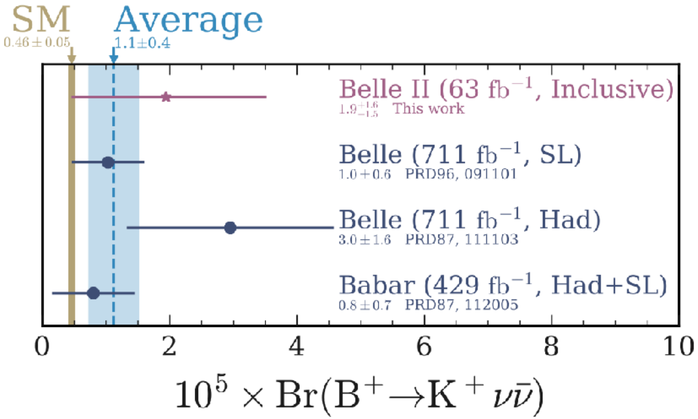


PRL127(2021)181802



PRL127(2021)181802

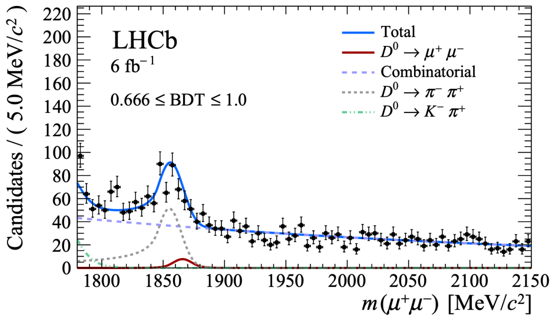


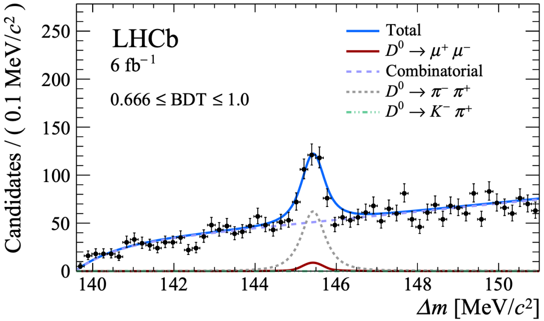


Competitive using only 63 fb^{-1}

Not only rare B, but also charm…

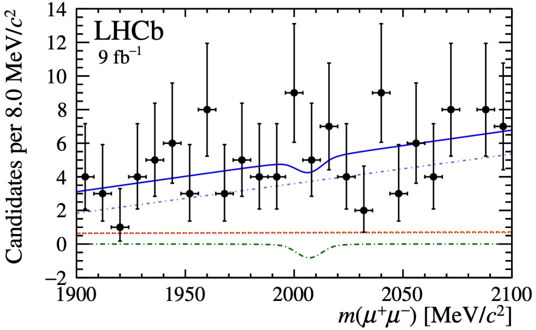
arXiv:2212.11203

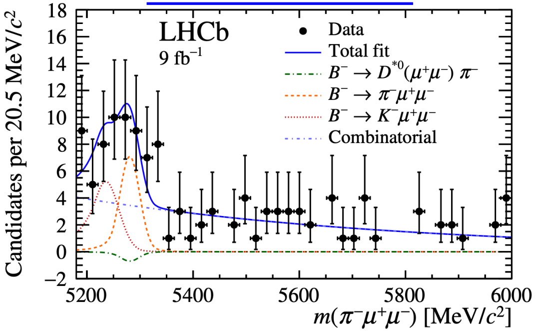


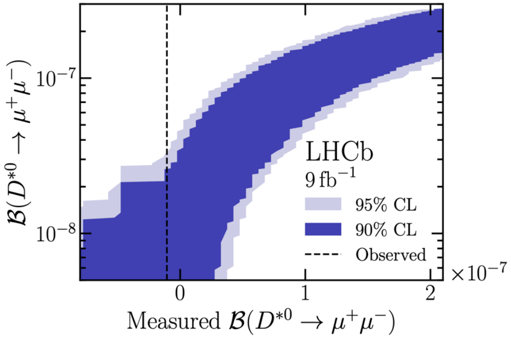


$$B(D^0 \to \mu^+\mu^-) < 2.94(3.25)\times10^{-9} @90(95)\% \text{ C.L.}$$

arXiv:2304.01981

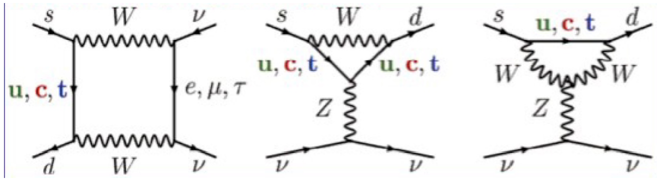






$$B(D^{*0} \to \mu^+\mu^-) < 2.6(3.4)\times10^{-8} @90(95)\% \text{ C.L.}$$

… and also strange

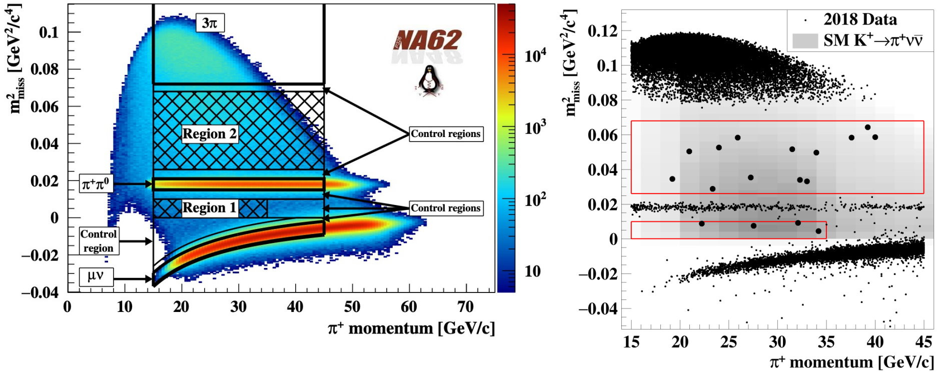


Theoretical predictions [PRD83(2011)034030]

$$\mathrm{Br}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.81^{+0.80}_{-0.71} \pm 0.29) \times 10^{-11}$$

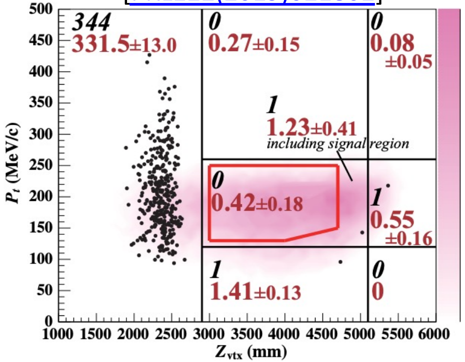
$$\mathrm{Br}(K_L \to \pi^0 \nu \bar{\nu}) = (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$$

JHEP06(2021)093



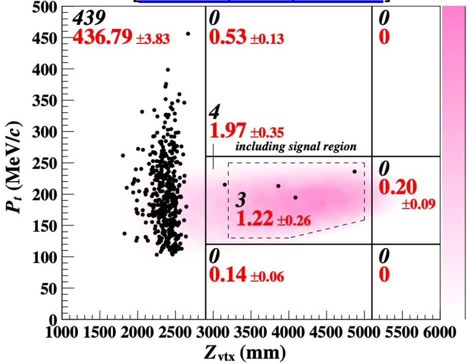
2015 Data

[PRL122(2019)021802]



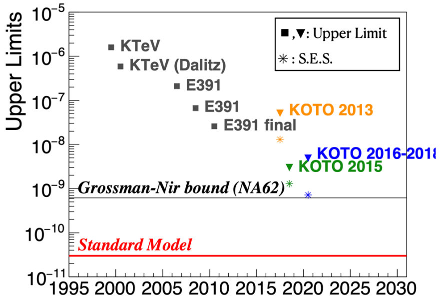
2016-18 Data

[PRL126(2021)121801]



$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$$

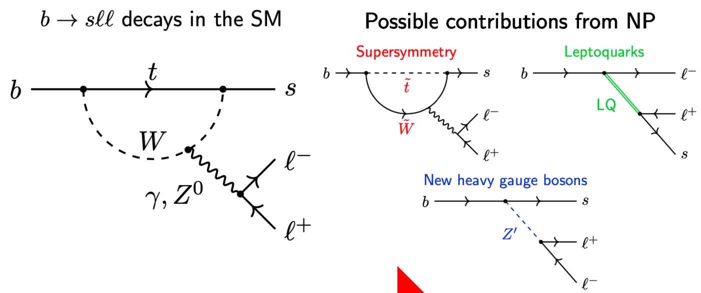
$$BR(K_L^0 \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9} \text{ @ 90\% C.L.}$$



Great effort from NA62 (@SPS) and KOTO (@J-PARC) to observe these two extremely rare and elusive decays

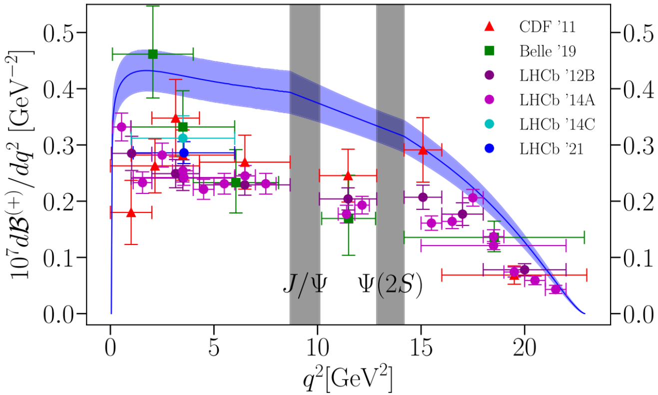
Anomalies in $b \to sl\bar{l}$ EW penguins

- Rich set of observables with different degrees of theoretical “cleanliness”
- Long standing set of deviations from the SM expectations
- Several NP scenarios could explain the situation



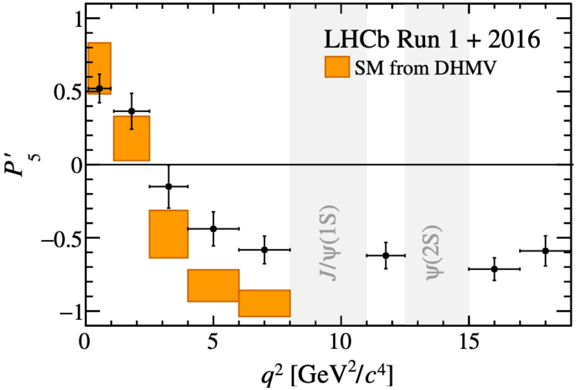
Increasing precision of SM predictions

PRD107(2023)014511



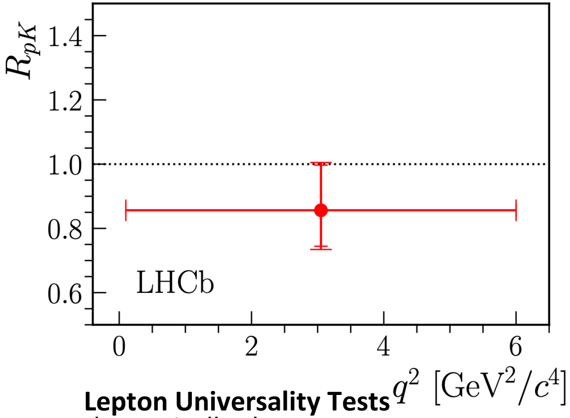
Branching fractions
affected by form factors and cc-loop

PRL125(2020)011802



Angular observables
affected by cc-loop

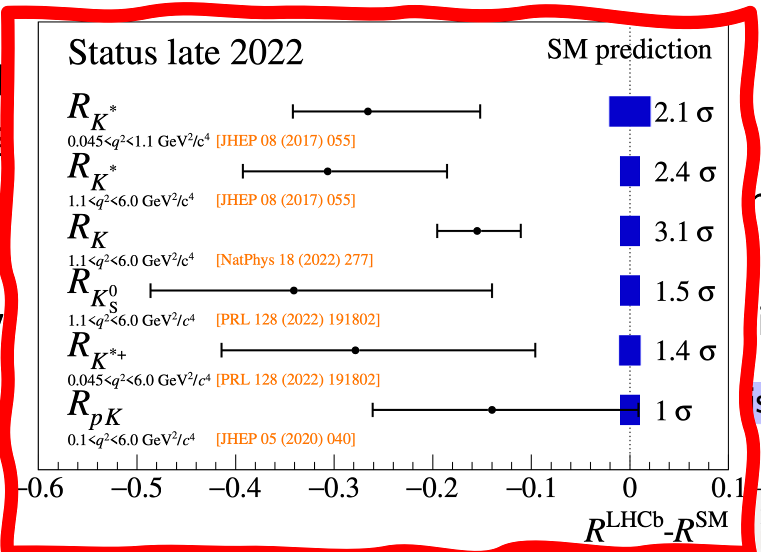
JHEP05(2020)040

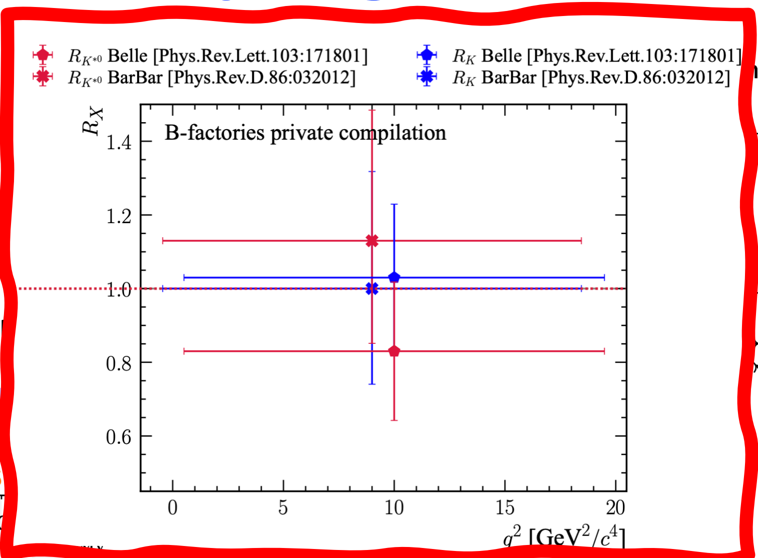


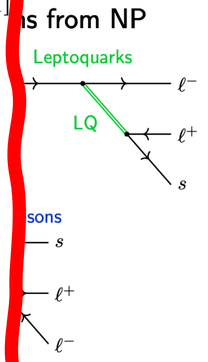
Lepton Universality Tests
theoretically clean

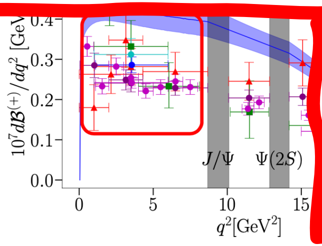
More on $b \to s l \bar{l}$ EW penguins

- Ricl… deg…
- An… fro…
- Sev…

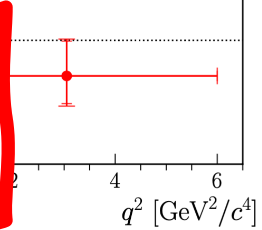








$$R_X = \frac{BR(X_b \to X_s \mu^+\mu^-)}{BR(X_b \to X_s e^+e^-)}$$



Branching fractions
affected by form-factors and $c\bar{c}$-loop

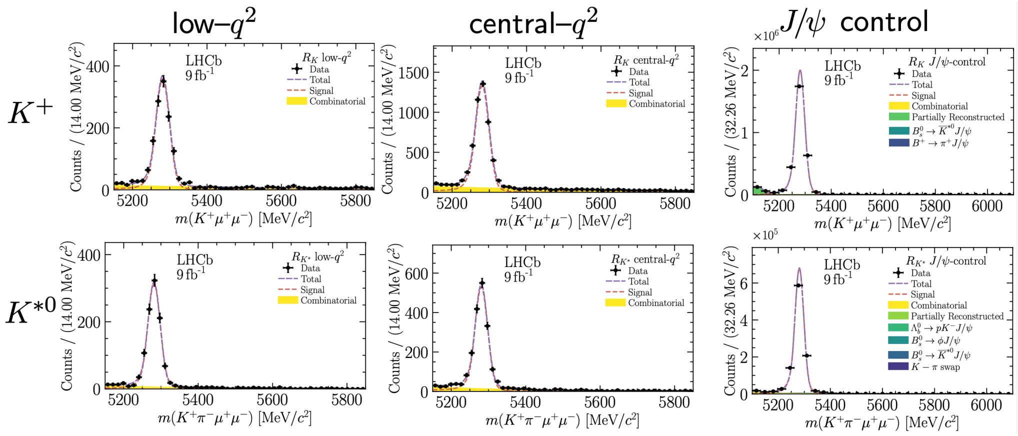
Angular observables
affected by $c\bar{c}$-loop

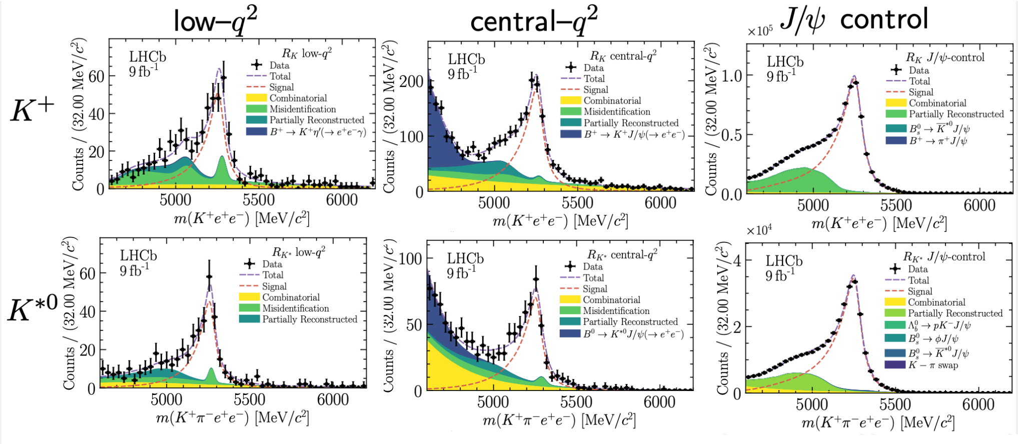
Lepton Universality Tests
clean

arXiv:2212.09152

arXiv:2212.09153

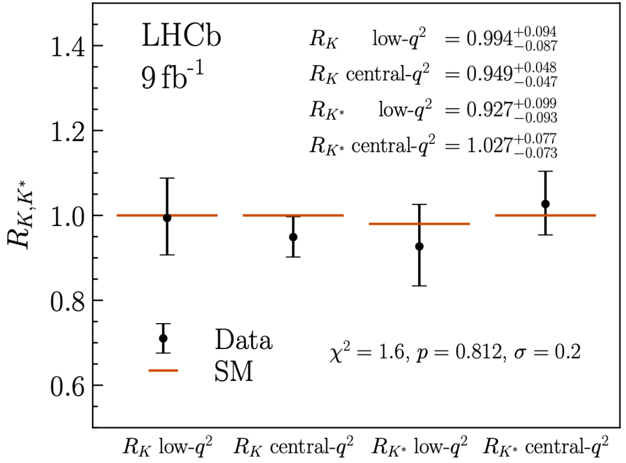
New LFU test from LHCb





Experimentally the double ratio with control modes is measured

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \times \overbrace{\frac{BR(B^+ \to K^+J/\psi(e^+e^-))}{BR(B^+ \to K^+J/\psi(\mu^+\mu^-))}}^{=\,1\ \text{[PRD88(2013)3]}}$$



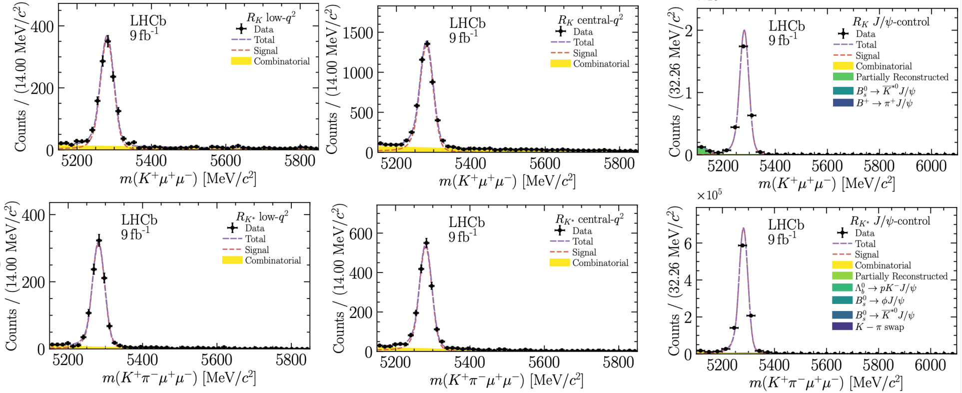
Updated measurement in good agreement with SM expectations

New LFU test from LHCb

low–q^2 central–q^2 J/ψ control

K^+

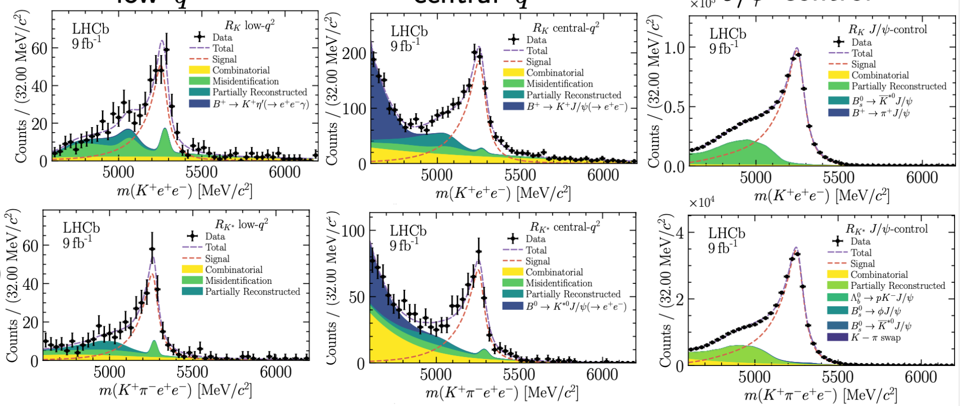
K^{*0}



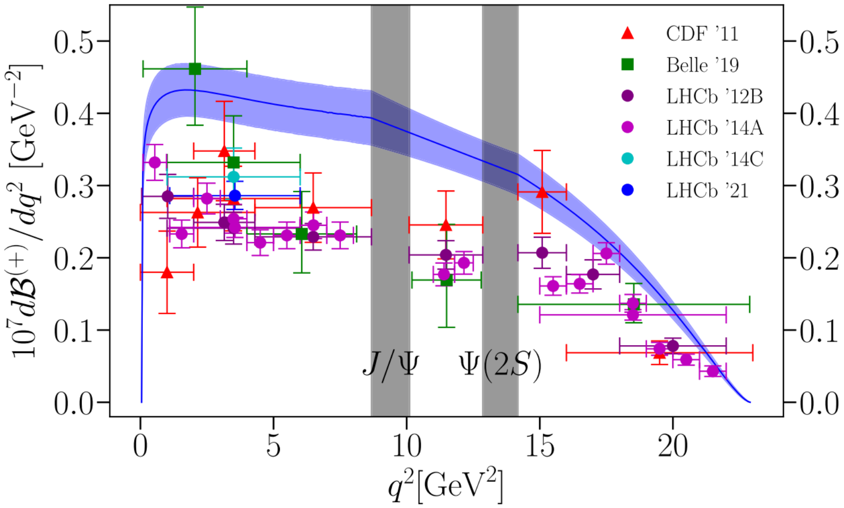
low–q^2 central–q^2 J/ψ control

K^+

K^{*0}



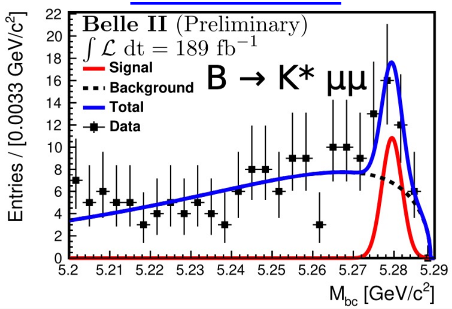
PRD107(2023)014511

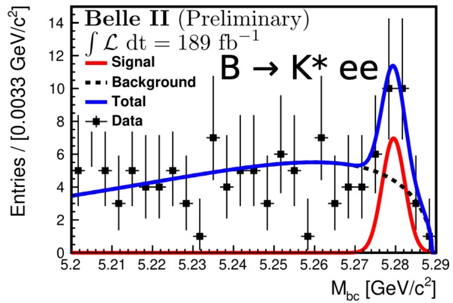


But tension remains in muonic BR and angular variables

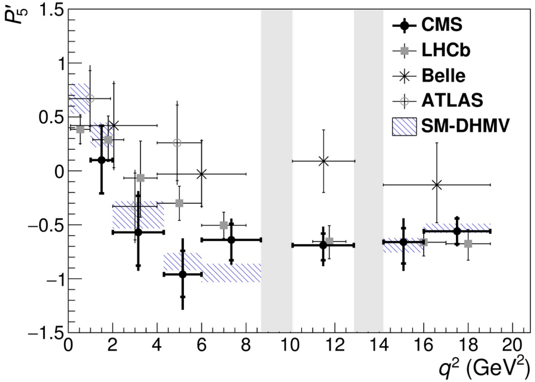
Contributions also from other experiments

arXiv:2206.05946

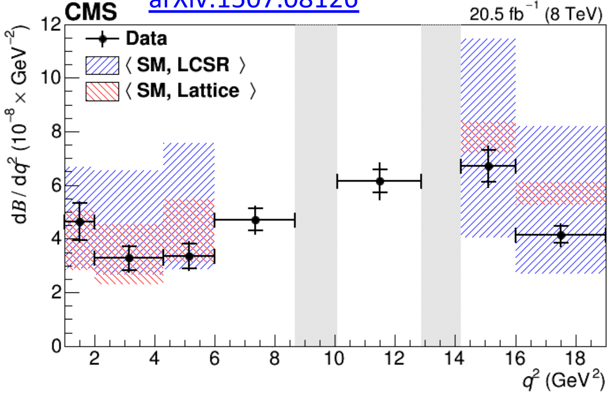




arXiv:1710.02846



arXiv:1507.08126



Observable	Signal Yield	Measured value $[10^{-6}]$	PDG $[10^{-6}]$
$\mathcal{B}(B \to K^*\mu^+\mu^-)$	22 ± 6	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09
$\mathcal{B}(B \to K^*e^+e^-)$	18 ± 6	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20

CMS does not observe discrepancies in BR and angular quantities with respect to SM

Waiting for analyses with more data

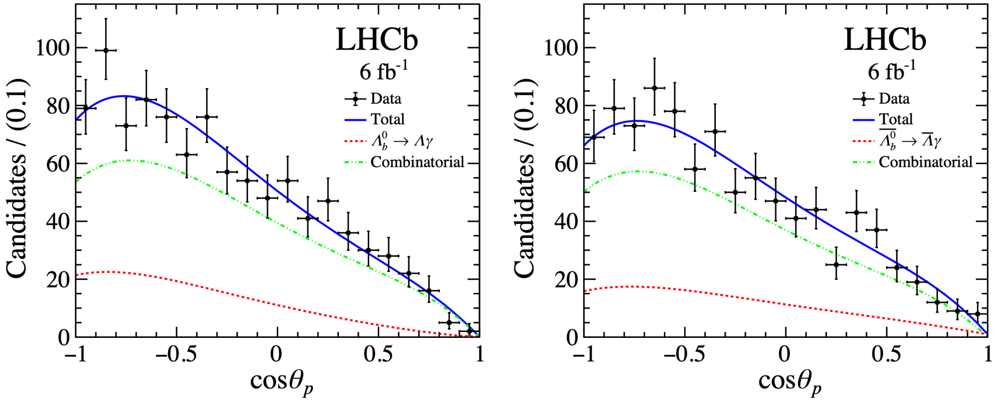
First look at these modes from Belle II

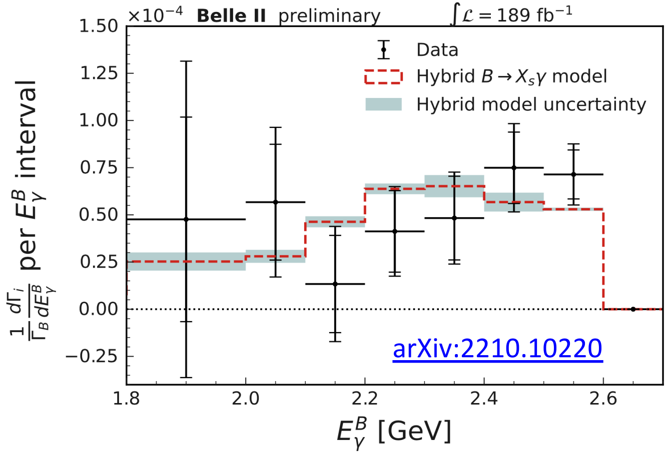
Similar sensitivity for $\mu^+\mu^-$ and e^+e^- modes

Radiative decays

- Decays governed by **$b \to s\gamma$ transitions are complementary to $b \to s l \bar{l}$** and allow a different set of operators to be investigated
- **Nice complementarity between LHCb** (large statistics and access also to b baryons) **and Belle II** (cleaner environment and access to inclusive measurements)

PRD105(2022)L051104





Photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$

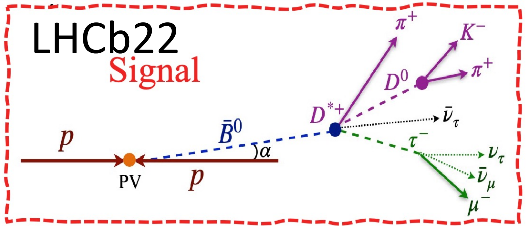
$$\alpha_\gamma^- > 0.56\,(0.44) \text{ at } 90\%\,(95\%) \text{ C.L.},$$

$$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}\,(\text{stat.})^{+0.16}_{-0.09}\,(\text{syst.}),$$

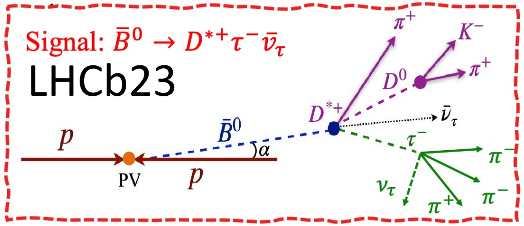
E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ [10^{-4}]	Experiment	L [fb^{-1}]	Signal Yield	Reference
1.8	**$3.54 \pm 0.78 \pm 0.83$**	Belle II	189	**343 ± 122**	[2210.10220]
2.0	**$3.06 \pm 0.56 \pm 0.47$**	Belle II	189	**285 ± 68**	[2210.10220]
1.9	$3.66 \pm 0.85 \pm 0.60$	BaBar	210		PRD 77 (2008) 051103
1.6	3.49 ± 0.19	World average			PDG 2022

Test LFU with semileptonic decays

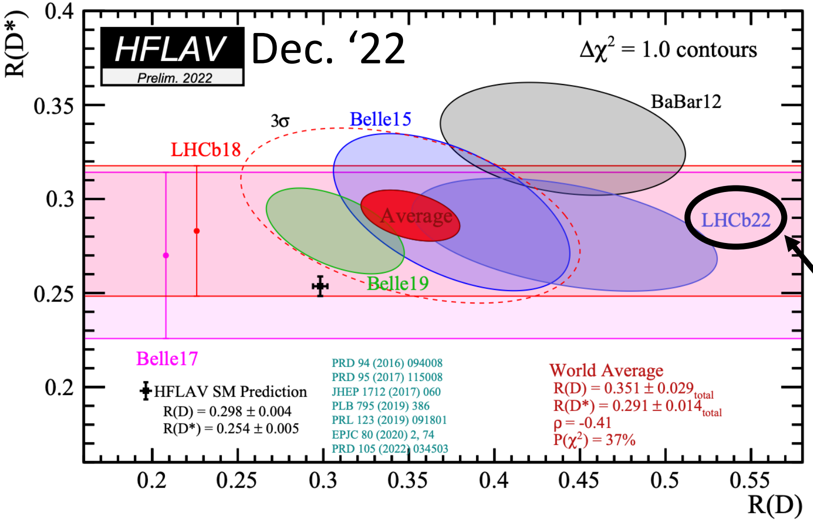
Long-standing tension between measurements and SM expectation for LFU tests



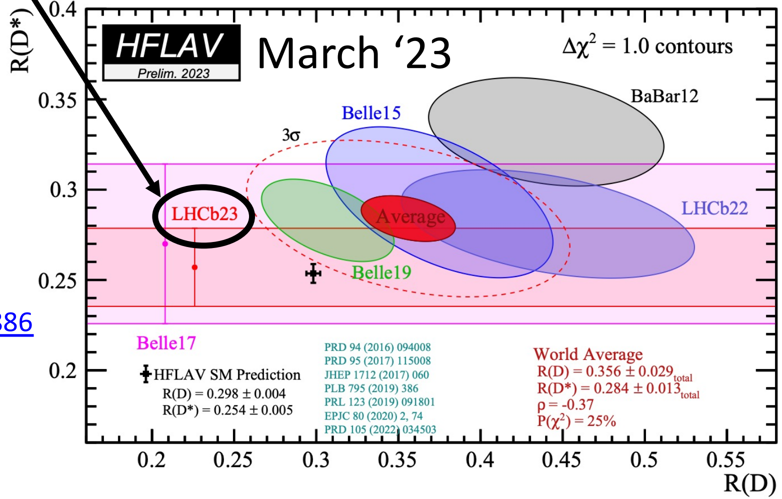
$$R(X_c) = \frac{BR(X_b \to X_c \tau \nu_\tau)}{BR(X_b \to X_c \mu \nu_\mu)}$$



LHCb-PAPER-2022-052
(in preparation)



arXiv:2302.02886



World Average remains at about 3σ from the SM

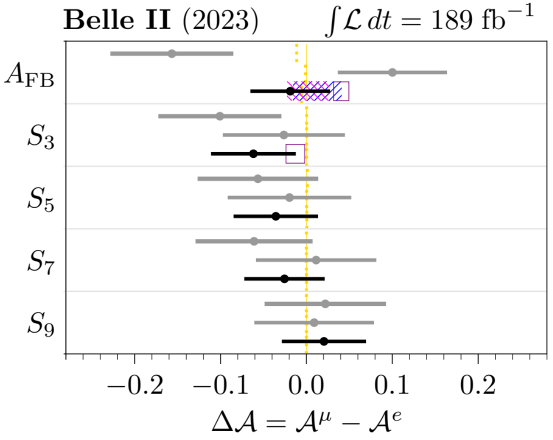
Test LFU with semileptonic decays

Belle II has the unique access to inclusive LFU tests

arXiv:2301.08266

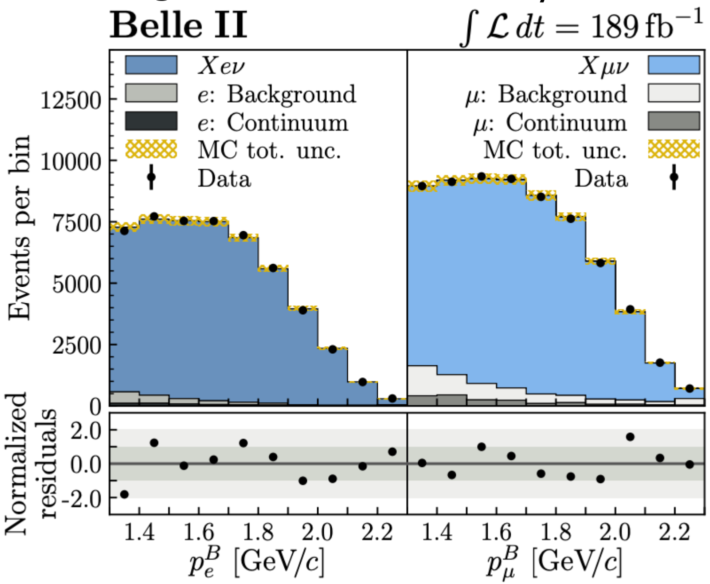
$$R(X_e) = \frac{B(B \to X e \nu_e)}{B(B \to X \mu \nu_\mu)} = 1.033 \pm 0.010(stat.) \pm 0.019(syst.)$$

Consistency test of angular asymmetries in $B \to D^* l \nu_l$



Consistent with SM

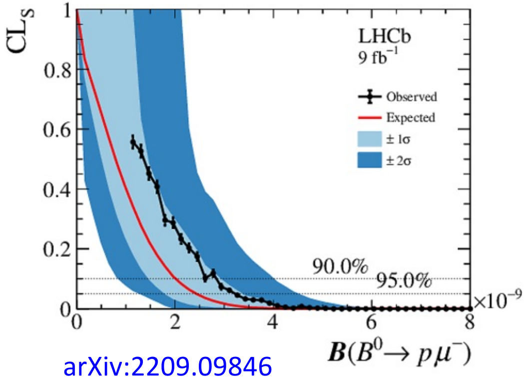
Signal channels $B^0\bar{B}^0/B^+B^-$



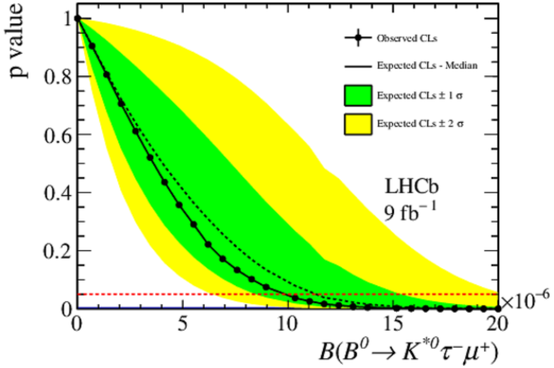
World leading measurements!!

Looking for LFV/LNV/BNV in B, D, K decays

arXiv:2210.10412

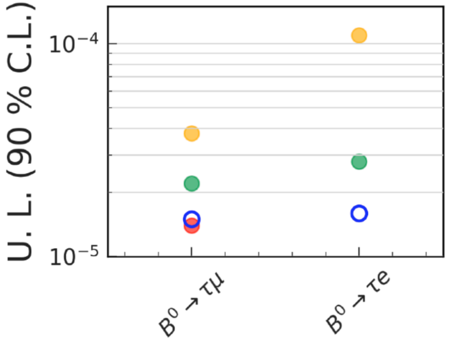


arXiv:2209.09846



PRD105(2022)032006 PRD99(2019)072006
PRD101(2020)031102

Decay mode	BES III UL on BR (90% CL)	Decay mode	BES III UL on BR (90% CL)
$D^0 \to \bar{p}e^+$	1.2×10^{-6}	$D^+ \to \Sigma^0 e^+$	1.7×10^{-6}
$D^0 \to pe^-$	2.2×10^{-6}	$D^+ \to \Sigma^0 e^+$	1.3×10^{-6}
$D^+ \to \Lambda e^+$	1.1×10^{-6}	$J/\Psi \to \Lambda_c e^-$	6.9×10^{-8}
$D^+ \to \bar{\Lambda} e^+$	6.5×10^{-7}	$J/\Psi \to pK^-\Lambda$ / $J/\Psi \to pK^-\bar{\Lambda}$	4.4×10^{-6} NEW @ ICHEP



PRD104(2021)L091105

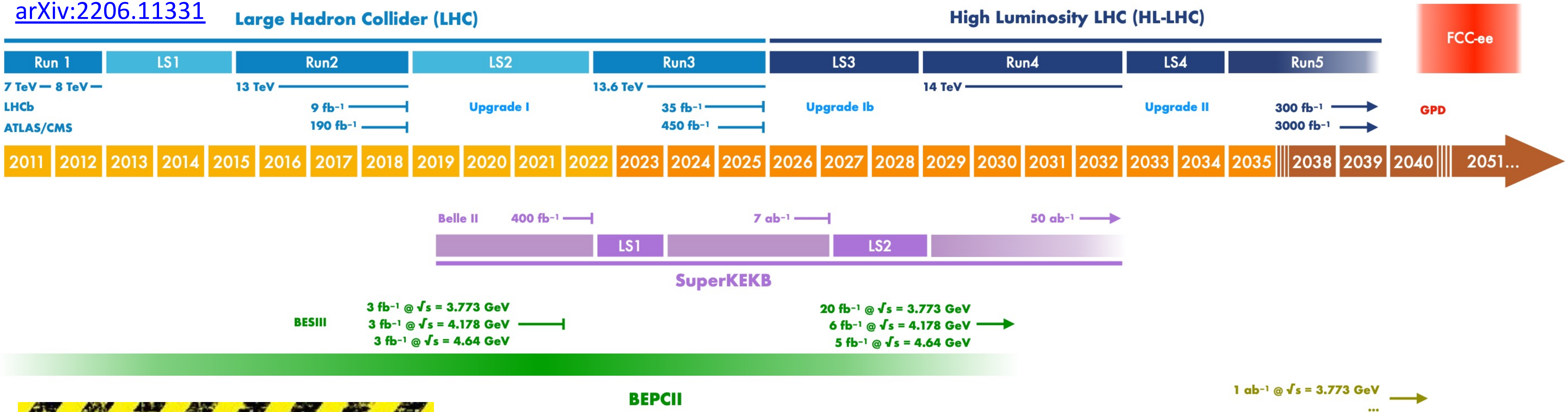
Shown at KAON2022

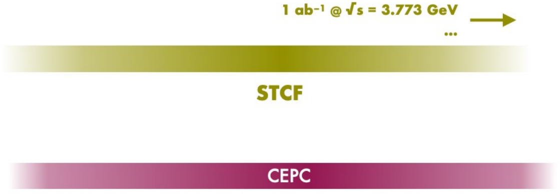
Decay channel	Previous $\mathcal{B}$ UL [8]	NA62 $\mathcal{B}$ UL	improvement
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11} [15]	4.2×10^{-11} [9]	~ factor 2
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10} [16]	5.3×10^{-11} [10]	~ factor 12
$K^+ \to \pi^-\pi^0e^+e^+$	–	8.5×10^{-11} [10]	first search
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10} [16]	4.2×10^{-11} [11]	~ factor 12
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10} [16]	6.6×10^{-11} [11]	~ factor 8
$\pi^0 \to \mu^-e^+$	3.4×10^{-9} [16]	3.2×10^{-10} [11]	~ factor 10
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8} [17]	8.1×10^{-11} [12]	~ factor 250

Experimental reach improve with increasing statistics (and control of backgrounds)

A look to the future

Thanks to F. Archilli and W. Altmannshofer
arXiv:2206.11331





Numbers are indicative

Physics reach for LHCb and Belle II

Belle II Upgrade snowmass white paper

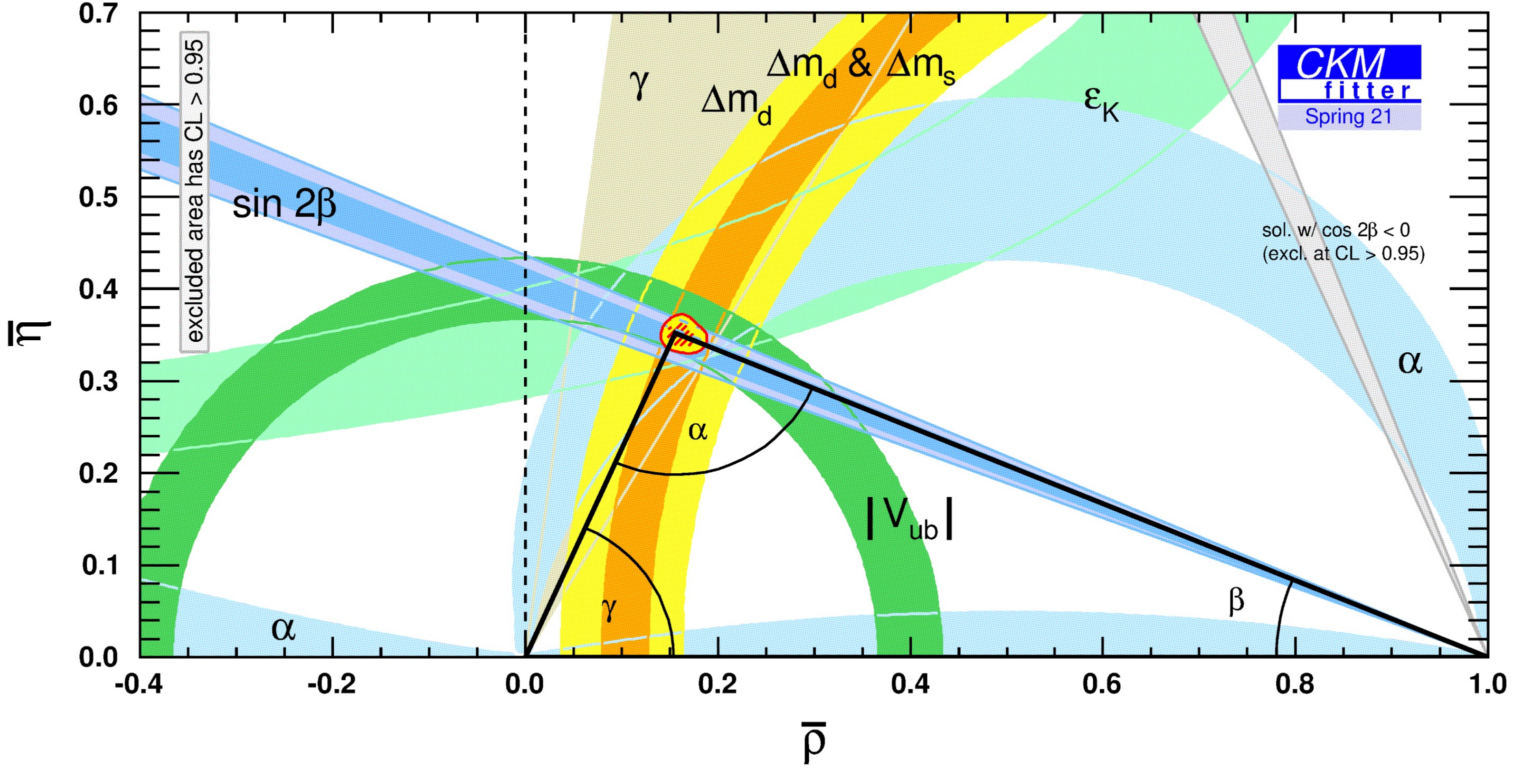
Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°
α/ϕ_2 (WA)	4°	2°	0.6°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.09	0.03
$R(B \to D^*\tau\nu)$	0.018	0.009	0.0045
$R(B \to D\tau\nu)$	0.034	0.016	0.008
$\mathcal{B}(B \to \tau\nu)$	24%	9%	4%
$B(B \to K^*\nu\bar{\nu})$	–	25%	9%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}

LHCb Upgrade II FTDR (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 ($B^0_s \to J/\psi\phi$)	32 mrad [8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6% [29, 30]	3%	2%	1%
$a^d_{\rm sl}$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a^s_{\rm sl}$ ($B^0_s \to D^-_s\mu^+\nu_\mu$)	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 ($D^0 \to K^0_S\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69% [40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—	—	—	0.2
$A^{(2)}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$A^{\rm Im}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$ [51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32 [51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [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

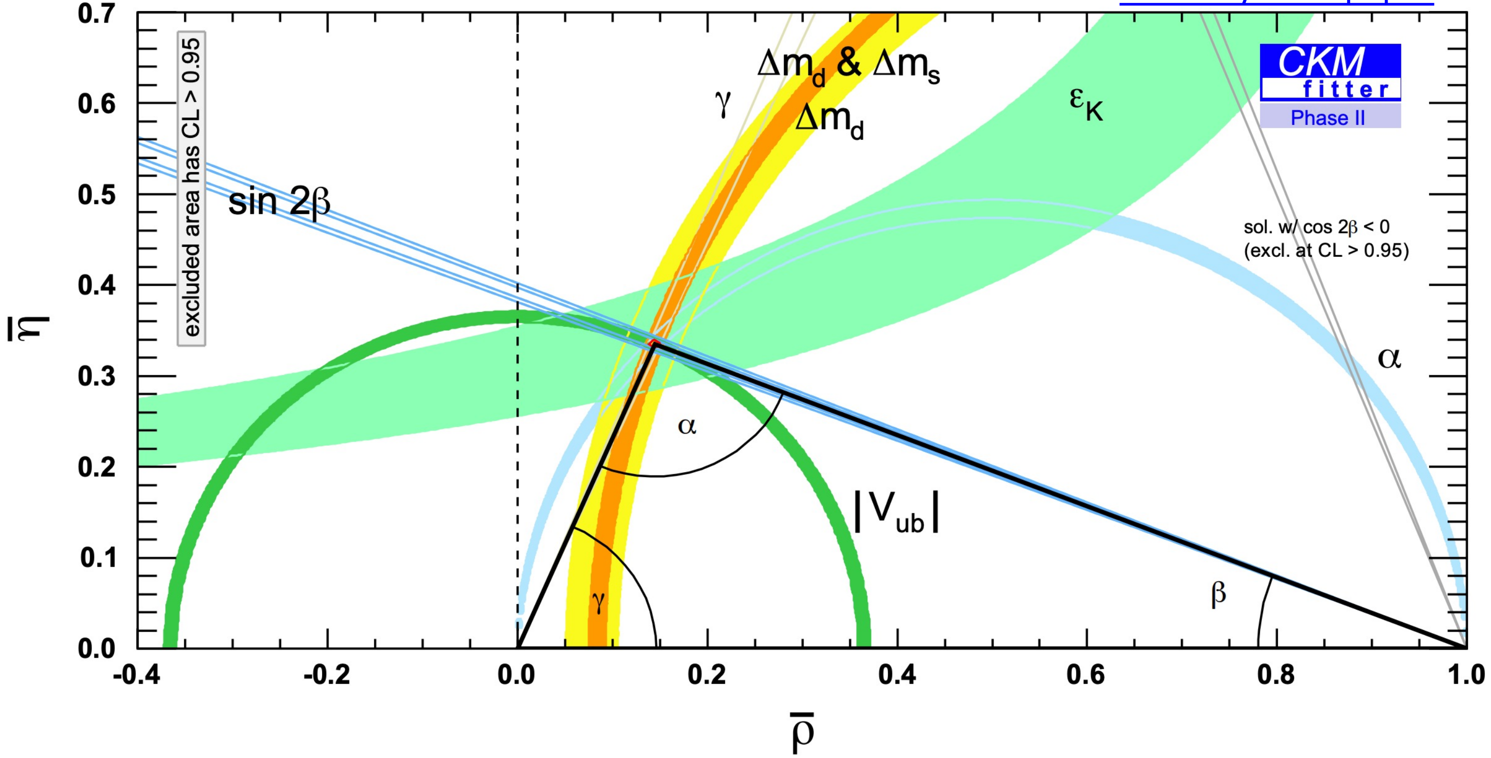
- It is fundamental to stress that LHCb and Belle II physics programmes complement each other exploiting the different environments provided by the LHC and KEK-II accelerators
- Nevertheless a large part of the programmes overlap allowing for mutual cross-check of key measurements

Constraining the UT to the per-mille level



Constraining the UT to the per-mille level

HL-LHC yellow paper

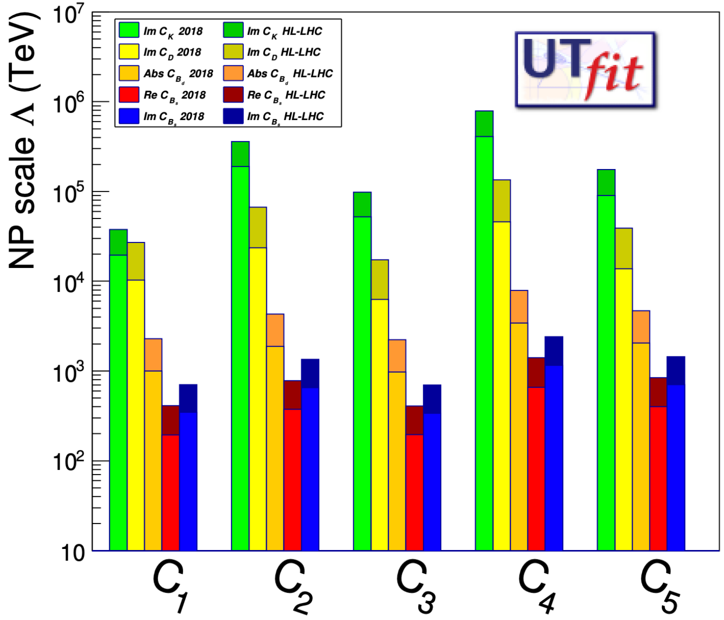


Improvements in lattice QCD inputs expected in the next 10 years are included in these predictions and are fundamental to achieve them

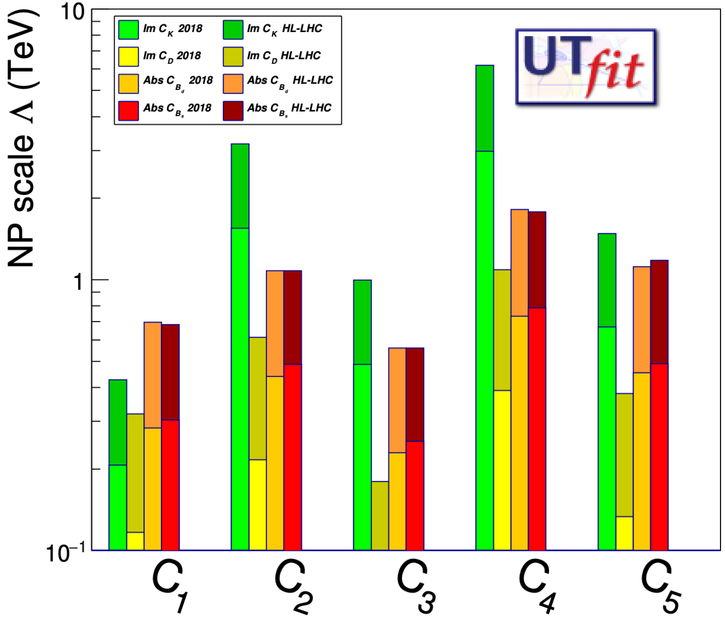
Constraining the UT to the per-mille level

HL-LHC yellow paper

New Physics with generic flavour couplings



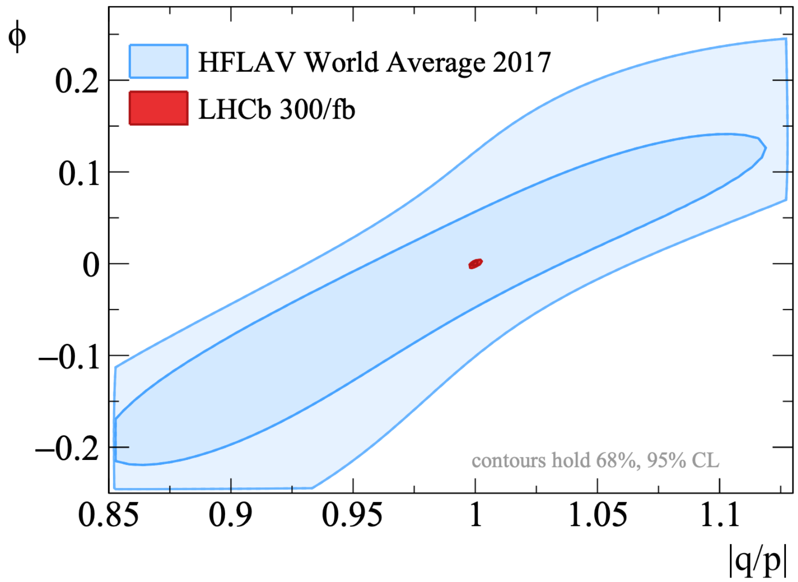
Minimal Flavour Violation scenario



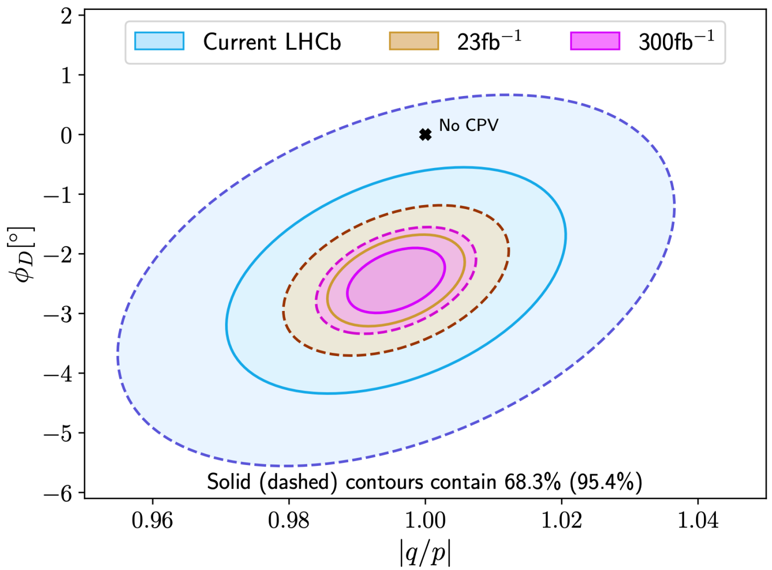
In the HL-LHC era the constraint on the UT apex will be able to test the presence BSM particles with masses 3 times higher than now a nd well above those reachable with direct searches

Test CPV in charm to unprecedented levels

arXiv:1808.08865



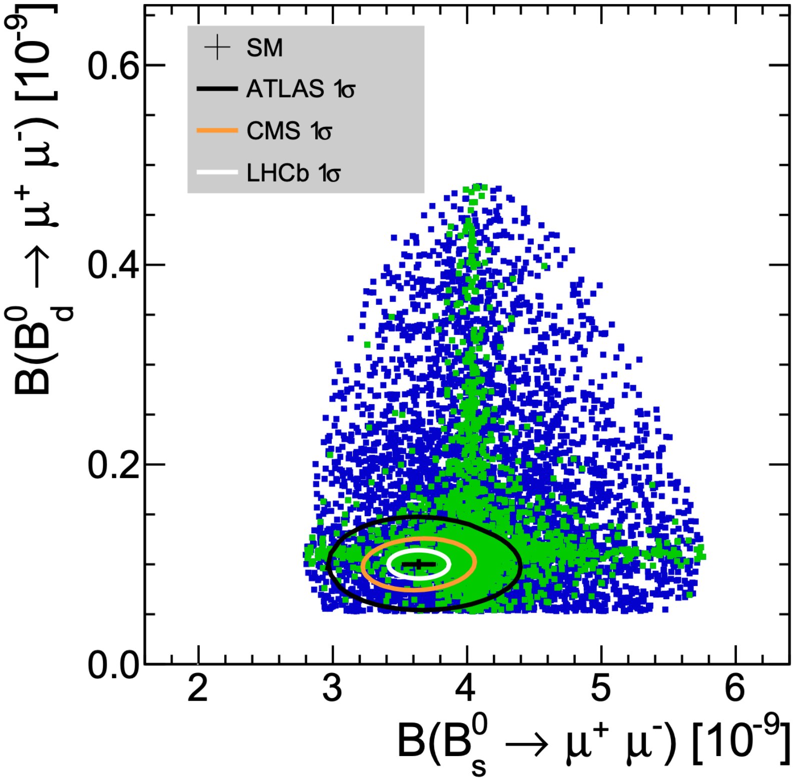
LHCb-TDR-023



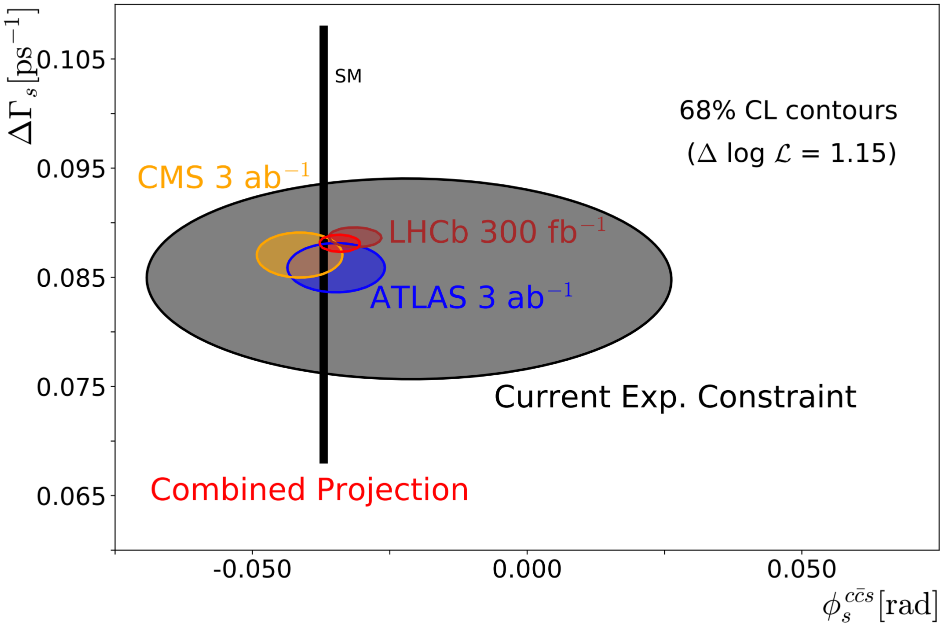
LHCb (and its upgrades) will be the biggest charm factory ever
It is essential to exploit it,
but that will require extreme control of experimental and theoretical systematics

Contribution from GPD at LHC

HL-LHC yellow paper



HL-LHC yellow paper



Conclusions

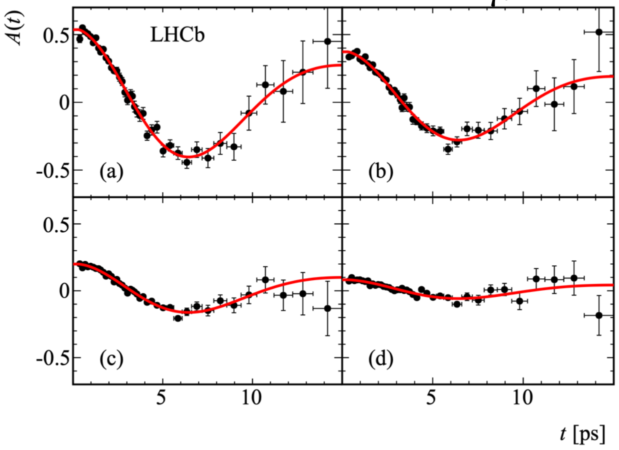
- Flavour physics has an **history rich of successes and discoveries**
- Its present demonstrates the **importance to invest in its future**
  - Constraining the apex of the UT will remain one of the **best long-term method to test the consistency of the SM**
  - Precise flavour physics measurements allow **NP scales beyond those accessible by direct searches to be investigated**
- **Advancements in both experiments and theory** are fundamental to exploit the full potential of flavour physics
- **Sinergy and complementarity** between different experiments will be crucial
  - LHCb and Belle II will have a leading role, but will soon be limited without the contribution from BESIII
  - General-purpose Detectors (ATALS and CMS) will also bring their relevant contribution as well as dedicated experiments like NA62 and KOTO
  - Had not time to discuss all the contributions from other experiments like Muon g-2, COMET, Mu2e, MEGII, Mu3E, PIONEER…

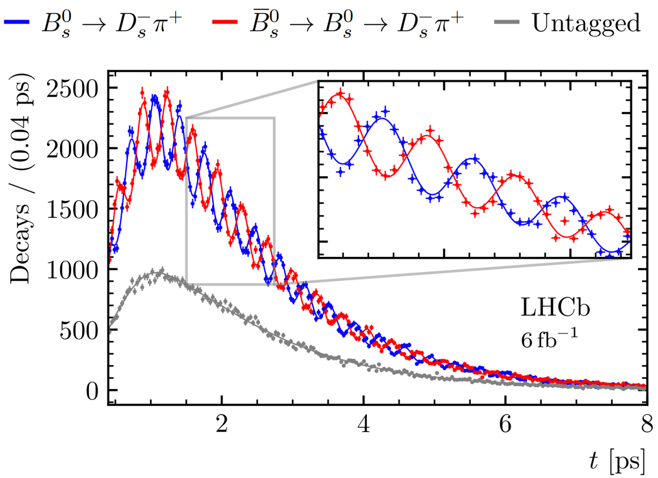
BACKUP

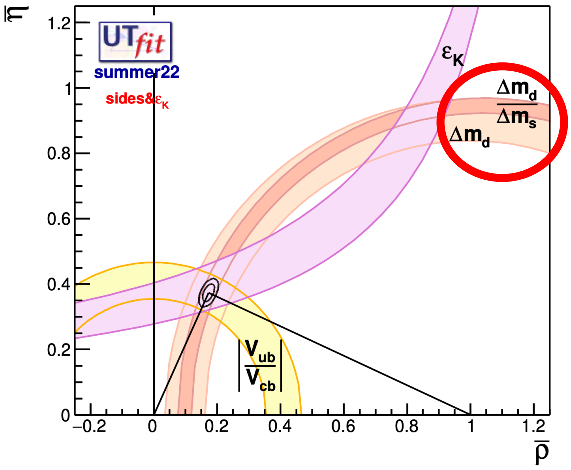
$B^0_{(s)}$ mixing

- From the study of $B^0_{(s)}$ mixing come also other constraints to the UT apex thanks to Δm_d and Δm_s
  - Experimental precision dominated by LHCb
  - Interpretation in terms of CKM strongly limited by lattice QCD

$B^0 \to D^{(*)}\mu\nu_\mu$





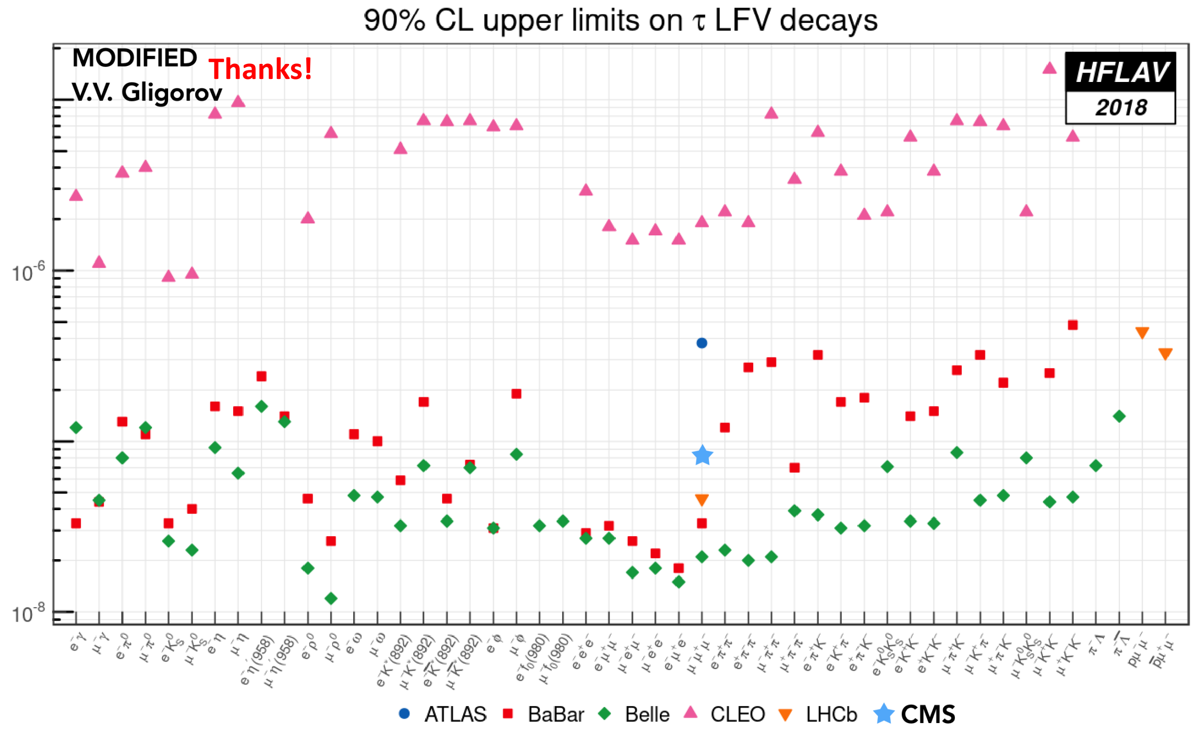


EPJC76(2016)76

NaturePhysics18(2022)1

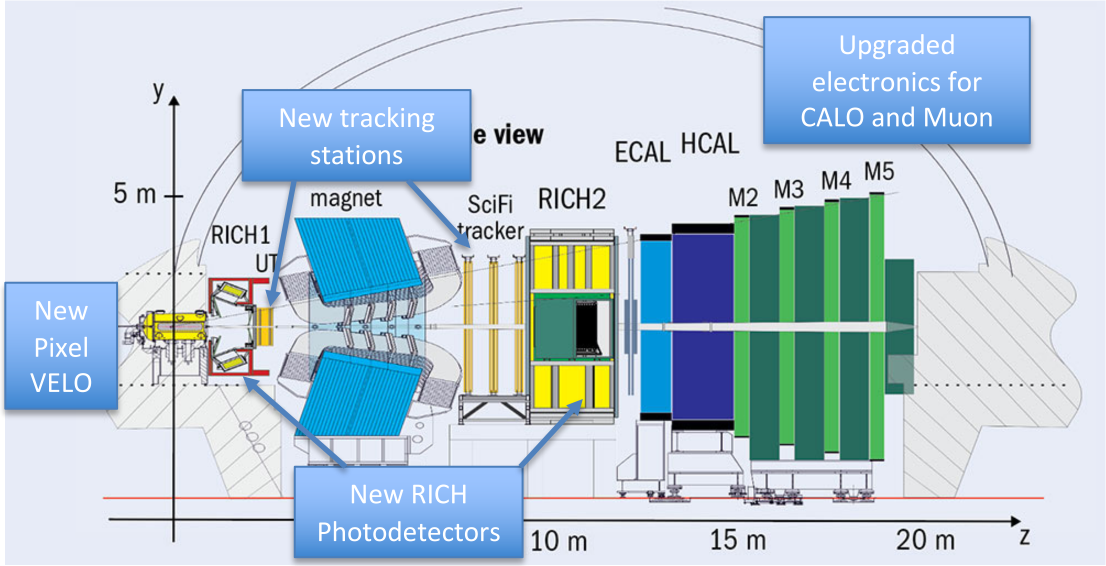
$\Delta m_d = 0.5050 \pm 0.0021 \pm 0.0010$ ps^{-1} $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032$ ps^{-1}

Looking for LFV/LNV/BNV



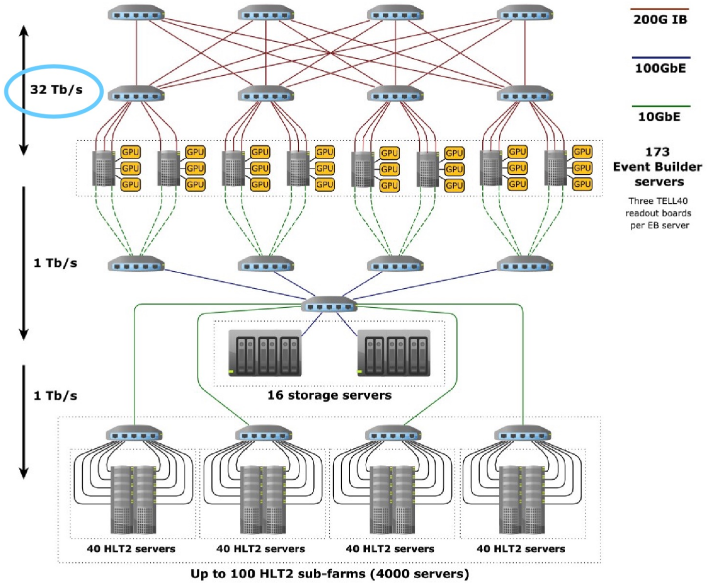
The violation of LFU is usually explained by models that also predict LFV and LNV close to current experimental reach

The LHCb Upgrade I



New fully-software trigger

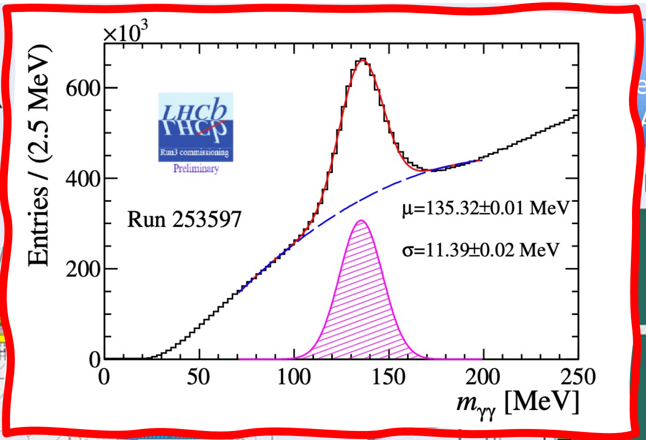
Comput.Softw.Big Sci. 6 (2022) 1



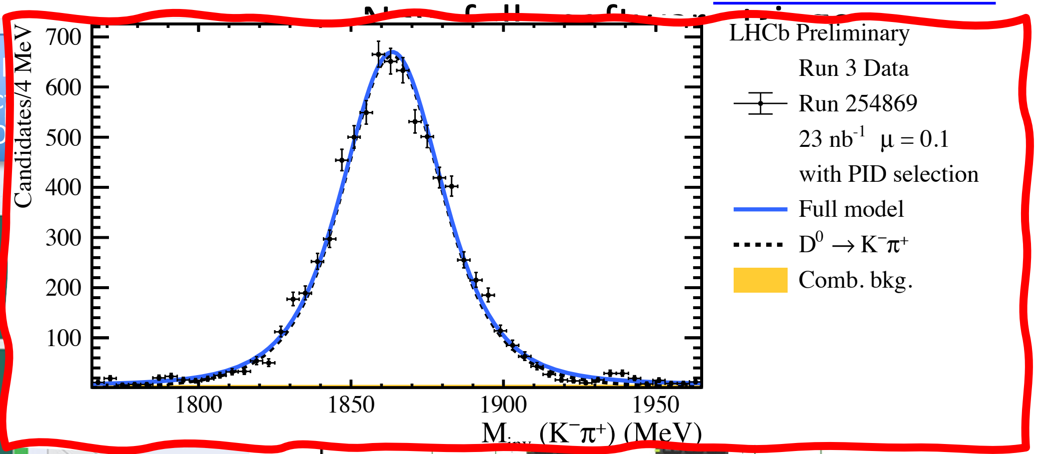
- Almost completely new detector is being commissioned this year
  - Many detectors have been improved and the DAQ adapted to acquire data at 30 MHz with fully software trigger
  - Great improvement in trigger efficiency for kaon, charm and hadronic B decays

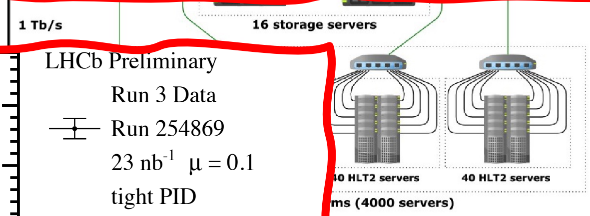
The LHCb Upgrade I

LHCb-FIGURE-2022-019

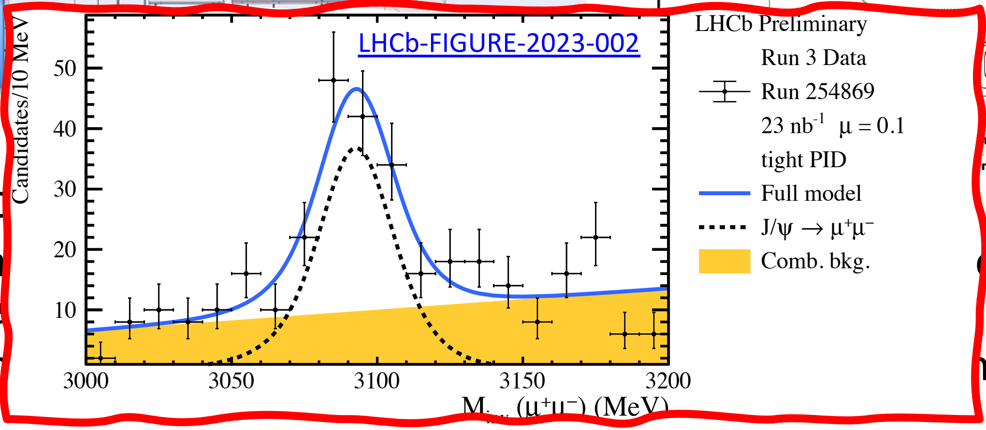


LHCb-FIGURE-2023-002





LHCb-FIGURE-2023-002



- Almost new detecto
  - Many detectors ha … e data at 30 MHz with fully software
  - Great improvemen … nic B decays

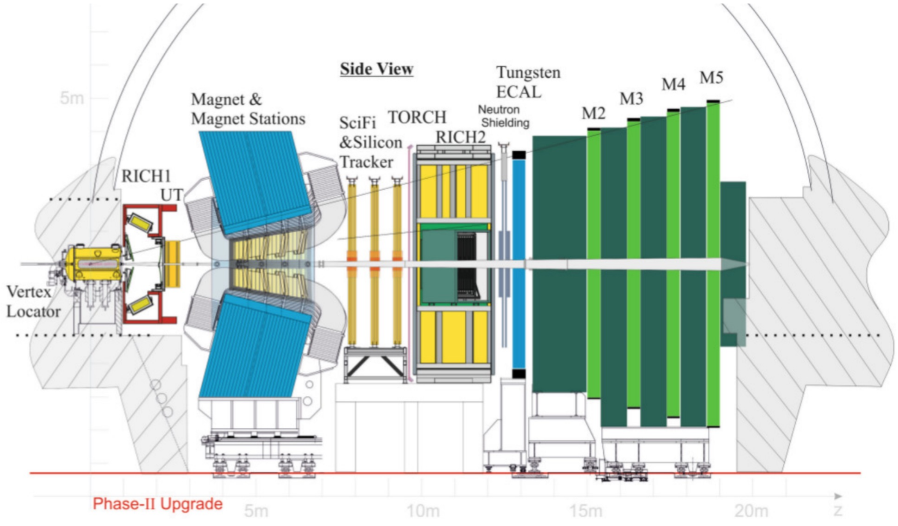
The LHCb Upgrade II

Goal: 50 fb^{-1} ⟷ | Goal: 300 fb^{-1} ⟷

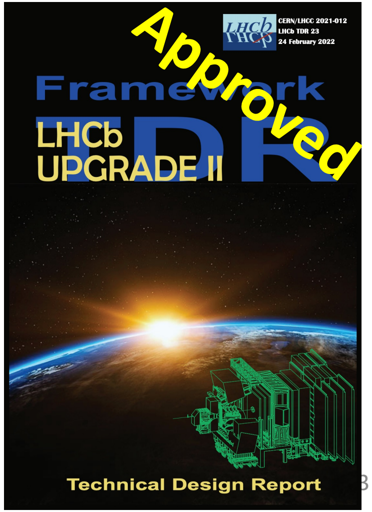
LHCb Consolidation | Upgrade II

Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2023 2024 2025	2026 2027 2028	2029 2030 2031 2032	2033 2034	2035 2036 2037 2039	2040	2041 2042

Another new detector with **extreme granularities**, **radiation hardness** and **picosecond timing** capabilities

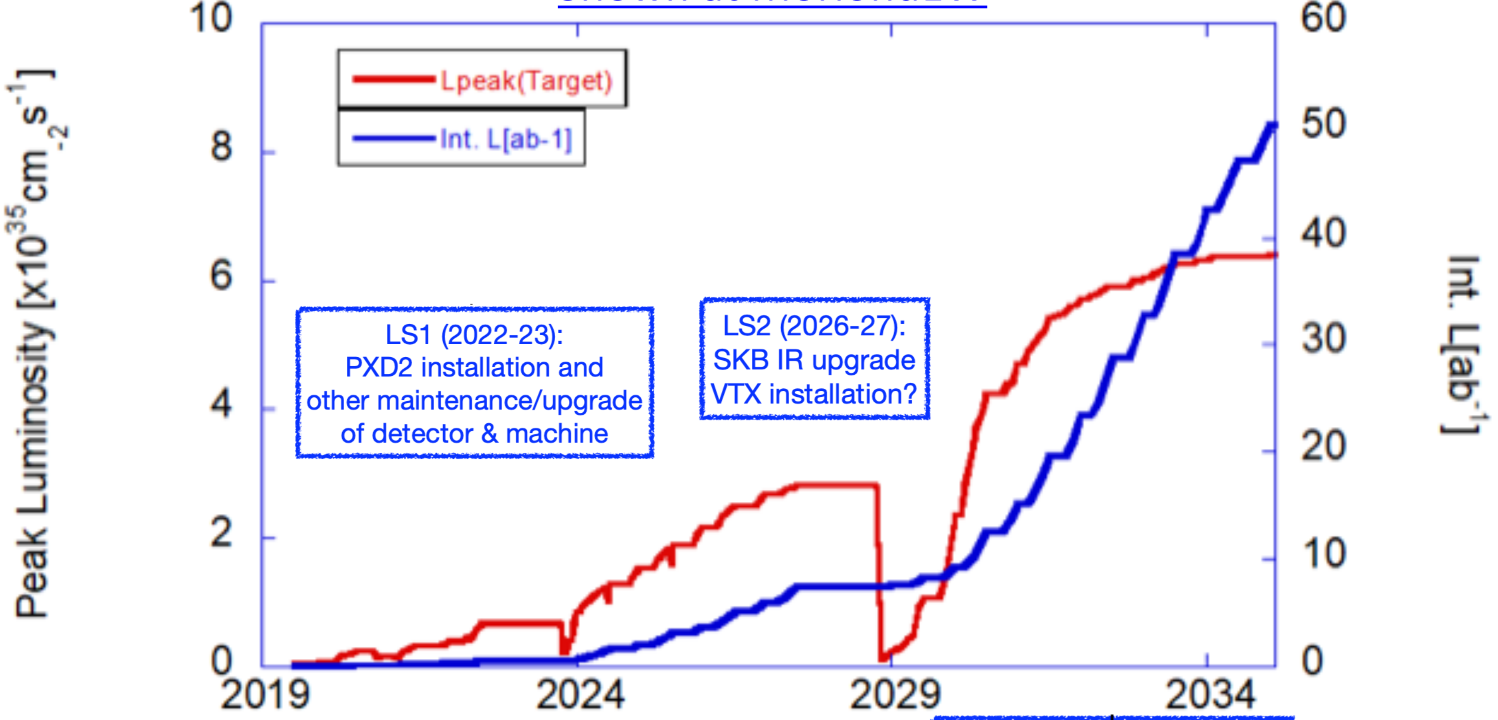


LHCb-TDR-023



Belle II plans

Shown at MoriondEW



Goal in the mid 2030ies:
$\mathscr{L}_{\text{recorded}} \approx 50/\text{ab}$