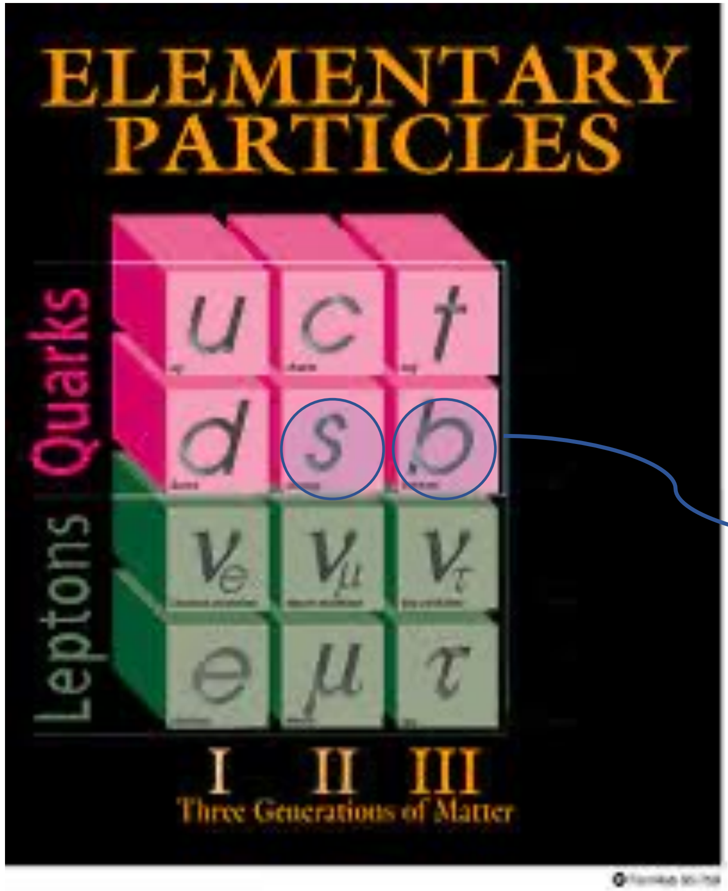
Experimental studies on heavy flavor physics: what is next?

An experimental sketchbook, not a comprehensive review!

Marina Artuso

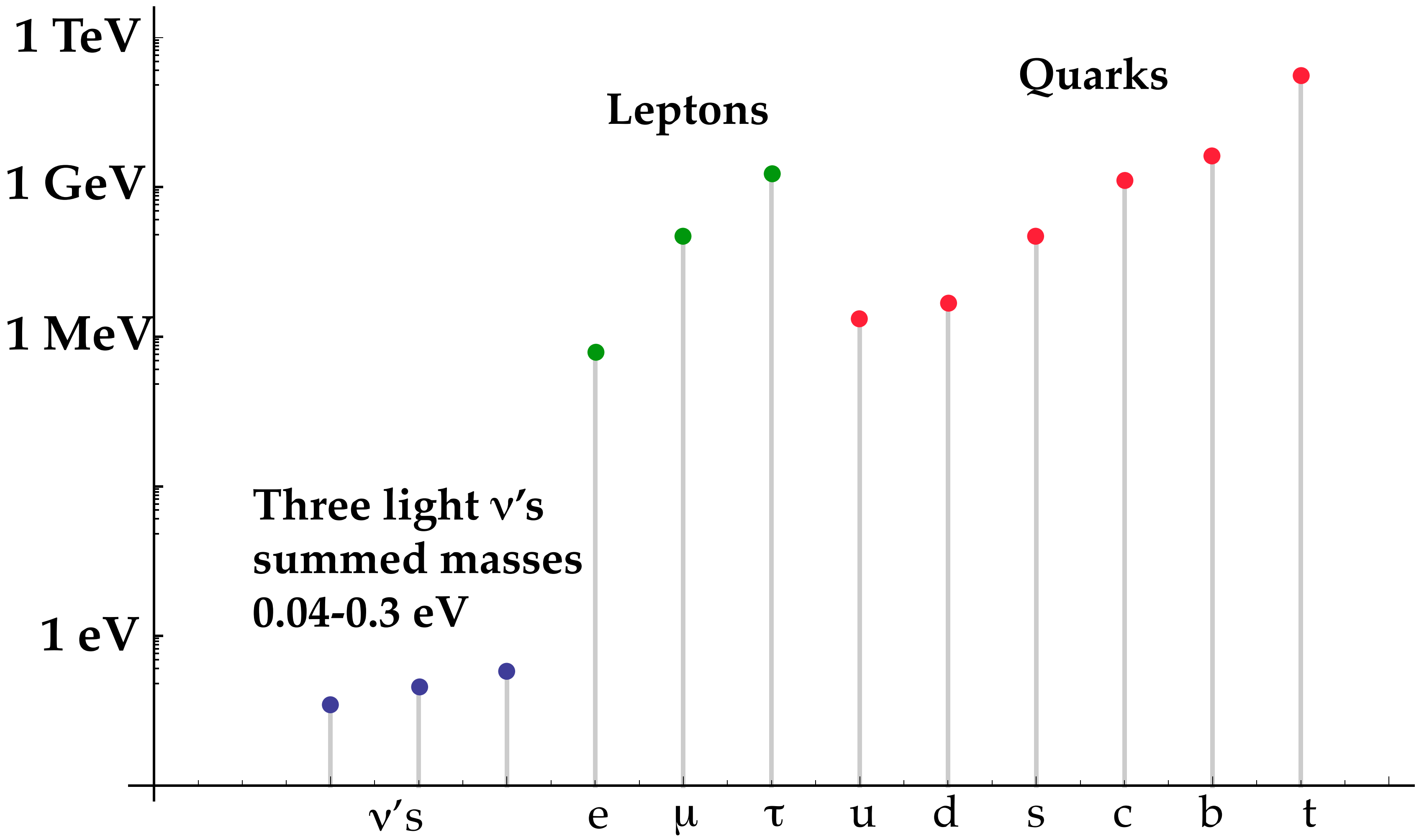
What is flavor physics?

- Flavor physics is the physics that distinguishes the 3 generations: in the Standard Model described by the ***Yukawa Lagrangian (fermion masses and couplings***)
- Definition of heavy flavor is a bit fuzzy [t-quark is the heaviest and generally in its own category]



- Emphasis of this talk – and time span is LHC era
- FCC-ee covered by R. Novotny
- Super tau-charm covered by H.P. Peng

Fermion masses



12 orders of magnitude differences not explained; t quark as heavy as Tungsten (so heavy that I do not have the strength to pursue it further here!)

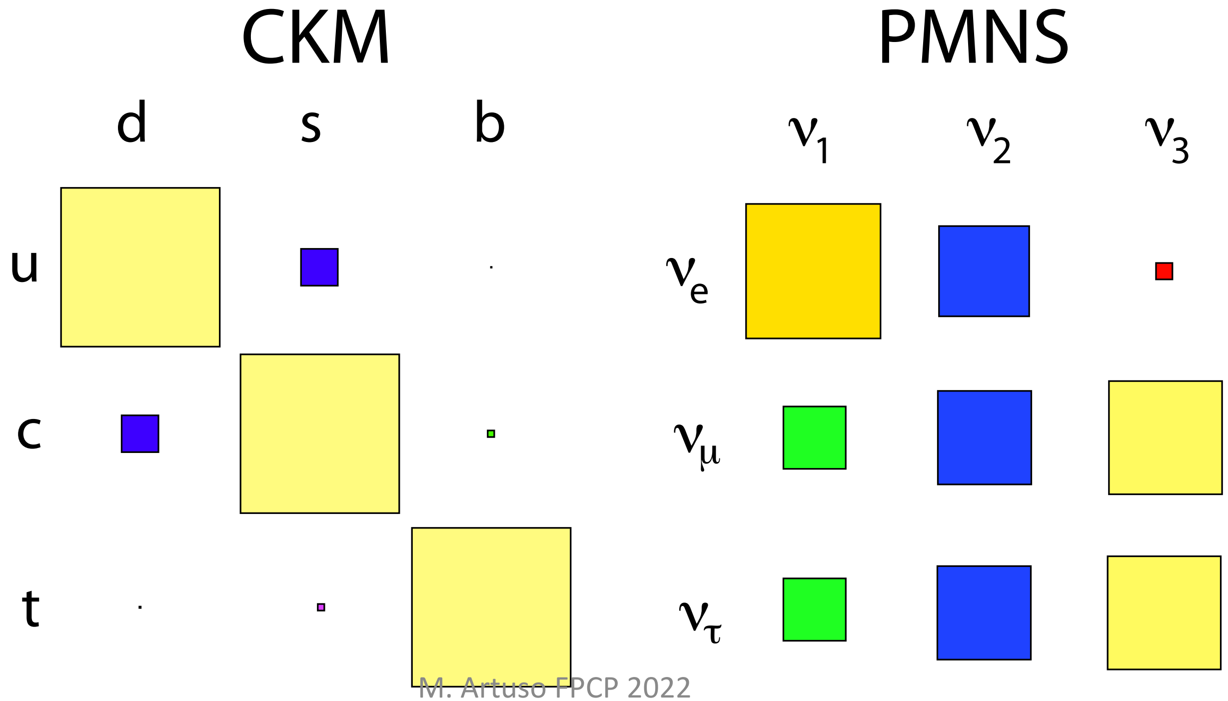
Mixing matrices

Quark sector: **C**abibbo **K**obayashi **M**askawa matrix

$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Lepton sector: **P**ontercorvo-**M**aki-**N**akagawa-**S**akata matrix

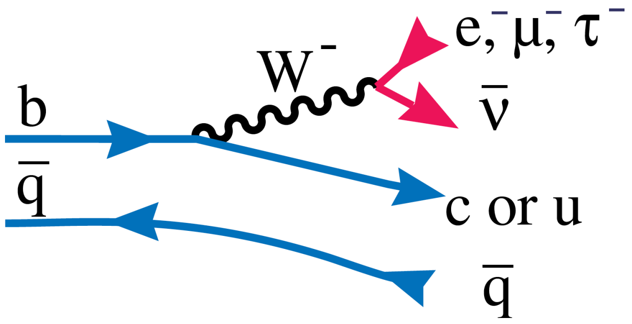
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



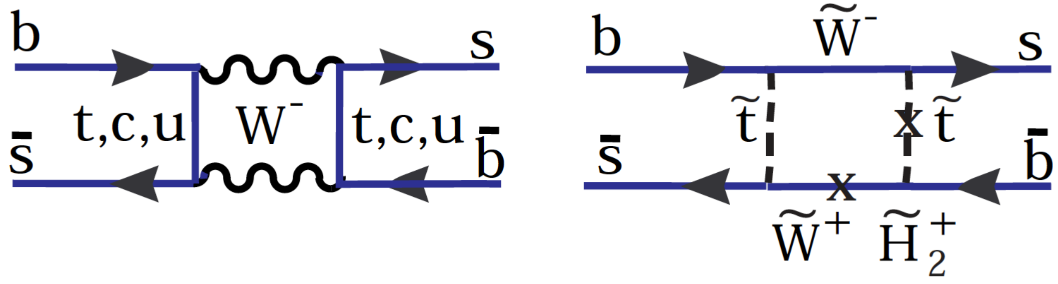
Flavor physics as a tool for discovery

- New physics manifestations in flavor physics = new couplings or new forces

Tree diagram example



Loop diagram example: $B-\bar{B}$ mixing

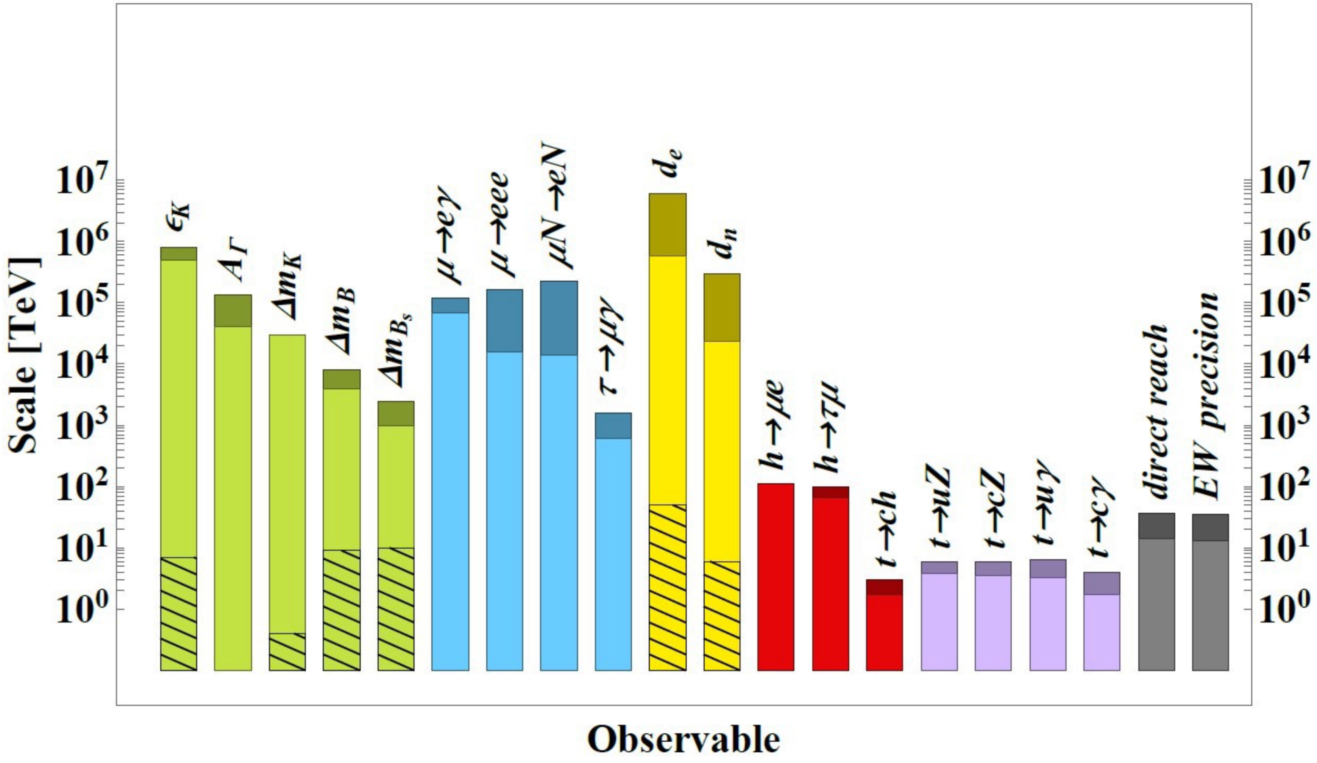


While all flavors are interesting, the following discussion will focus on b-flavored hadrons, with a very brief excursion into charm

A tale of many scales

Model independent tool of effective Lagrangian

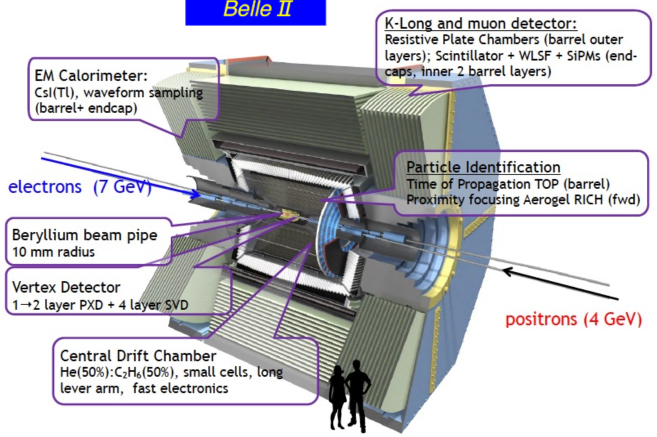
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{C_5}{\Lambda_M}\mathscr{O}^{(5)} + \sum_a \frac{C_6^a}{\Lambda^2}\mathscr{O}_a^{(6)} + \cdots .$$

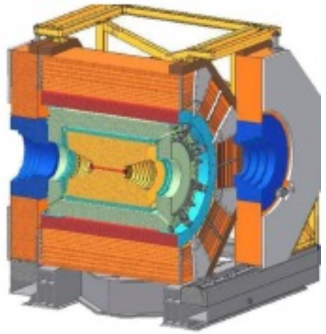


Experimental methods

e^+e^- colliders

b and c hadrons, τ decays

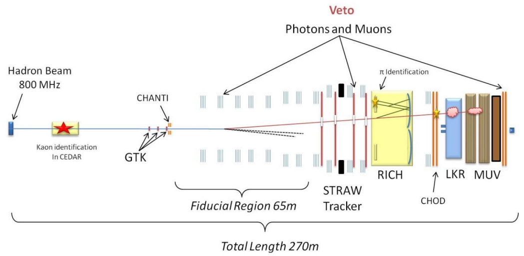


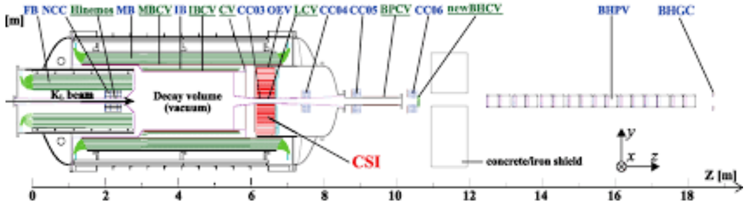


Charmed hadrons τ decays

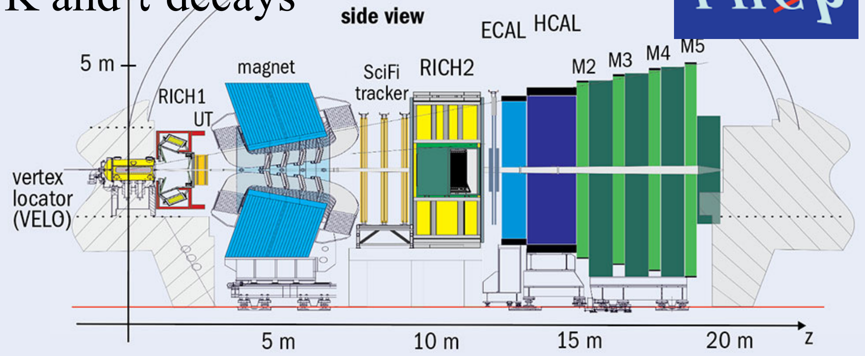
Hadron machines

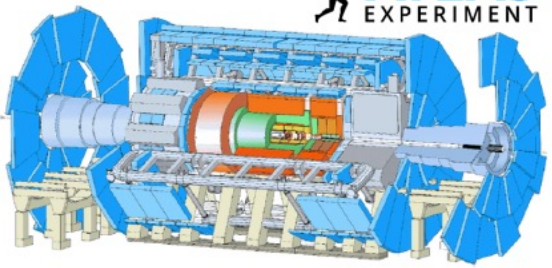
Rare K decays

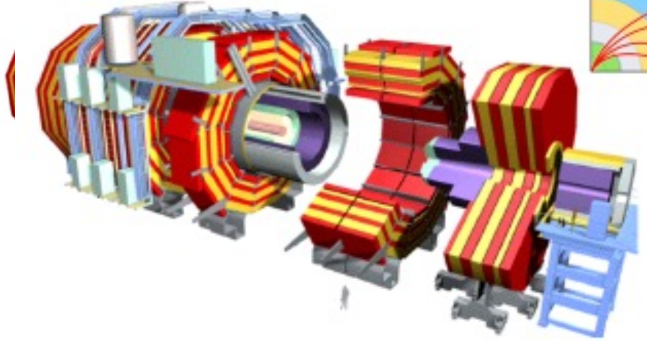




b and c hadrons, some rare K and τ decays







The future of K physics

Rare K decays well known theoretically, their experimental study key for SM checks, possibly NP opportunities

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.62 \pm 0.42) \times 10^{-11}$
$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$

Buras et al., 2109.11032

CERN

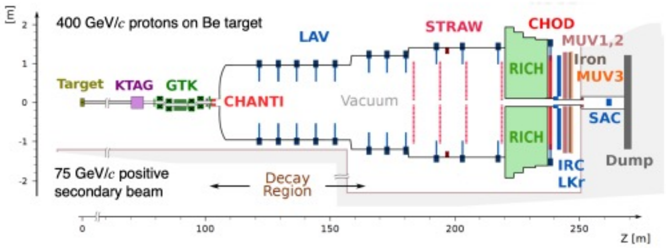
Integrated programme with high-intensity K^+ and K_L beams proposed to run until ~2039

support from European Strategy (CERN-ESU-014)

NA62

$K^+ \to \pi^+ \nu\bar{\nu}$ at ~5% in 5 years

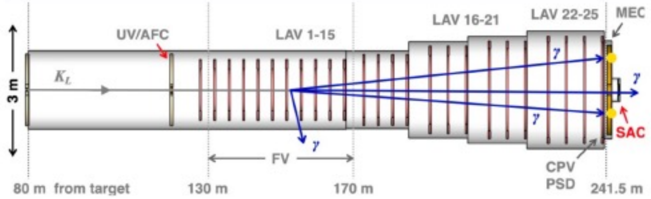
- *$\times$ 4 intensity ~7×10^{18} pot/year*
- *Maintain key performance at high rate: space-time reco., low material, photon effi.*
- *Much improved time resolution to keep random veto rate under control*



KLEVER

$K_L \to \pi^0 \nu\bar{\nu}$ with ~60 SM events in 5 years

- *$\times$ 6 intensity ~10^{19} pot/year*
- *2γ with unbalanced p_T + nothing else*
- *Optimise beam line to suppress $\Lambda \to n\pi^0$*



R&D
- *GigaTracker <50 ps (LGAD, 3D, 28 nm), KTAG <20 ps (MCP PMTs), new Straw Chambers*
- *New calorimeter: Shashlik with longitudinal information*
- *Small-angle photon veto: compact Cherenkov calorimeter with oriented crystals*

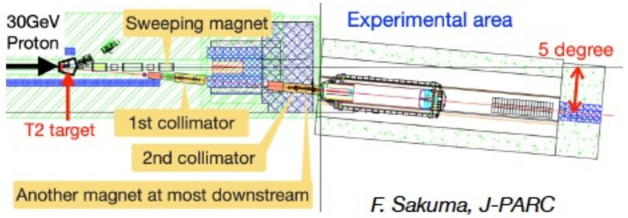
J-PARC

Extension of hadron experimental facility in discussion, with increased beam power

KOTO Step-2

$K_L \to \pi^0 \nu\bar{\nu}$ with ~35 SM events in ~3 years

- *$\times$ 2.4 beam intensity*
- *Expand fiducial volume*
- *Profit of KOTO experience to reduce bkg*



F. Sakuma, J-PARC review, Aug.'21

Advantages of e+e- machines:

- Simplicity of initial state
- Good photon-π^0 reconstruction
- High flavor tagging efficiency

Advantages of experiments at LHC:

- High statistics, lots of flavored hadron species.
- Boost of the beauty and charmed hadrons and excellent vertex detectors allow precision measurement of the vertex topology information.

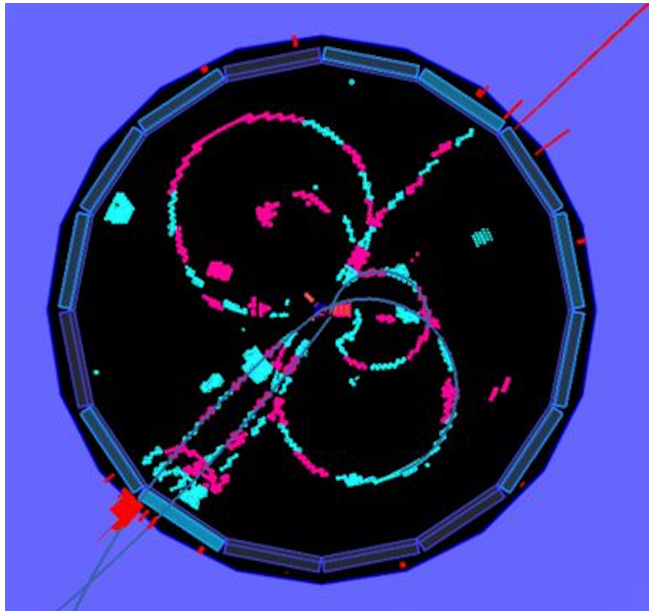
On the other hand:

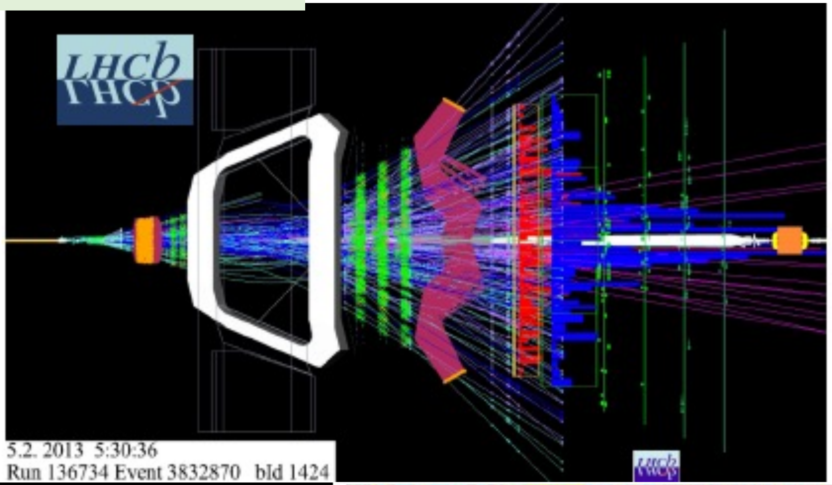
Dedicated flavor experiments feature excellent hadron identification

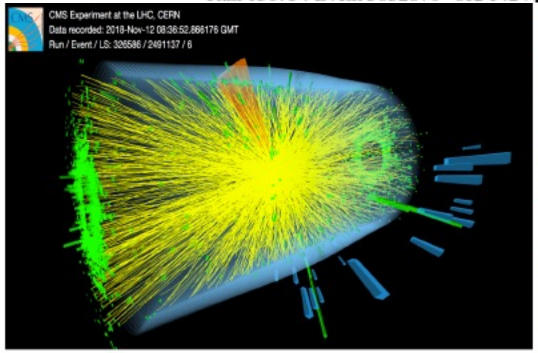
- Lower cross-section
- At the $\Upsilon(4S)$ only B^0 and B^+
- High luminosity challenging

On the other hand:

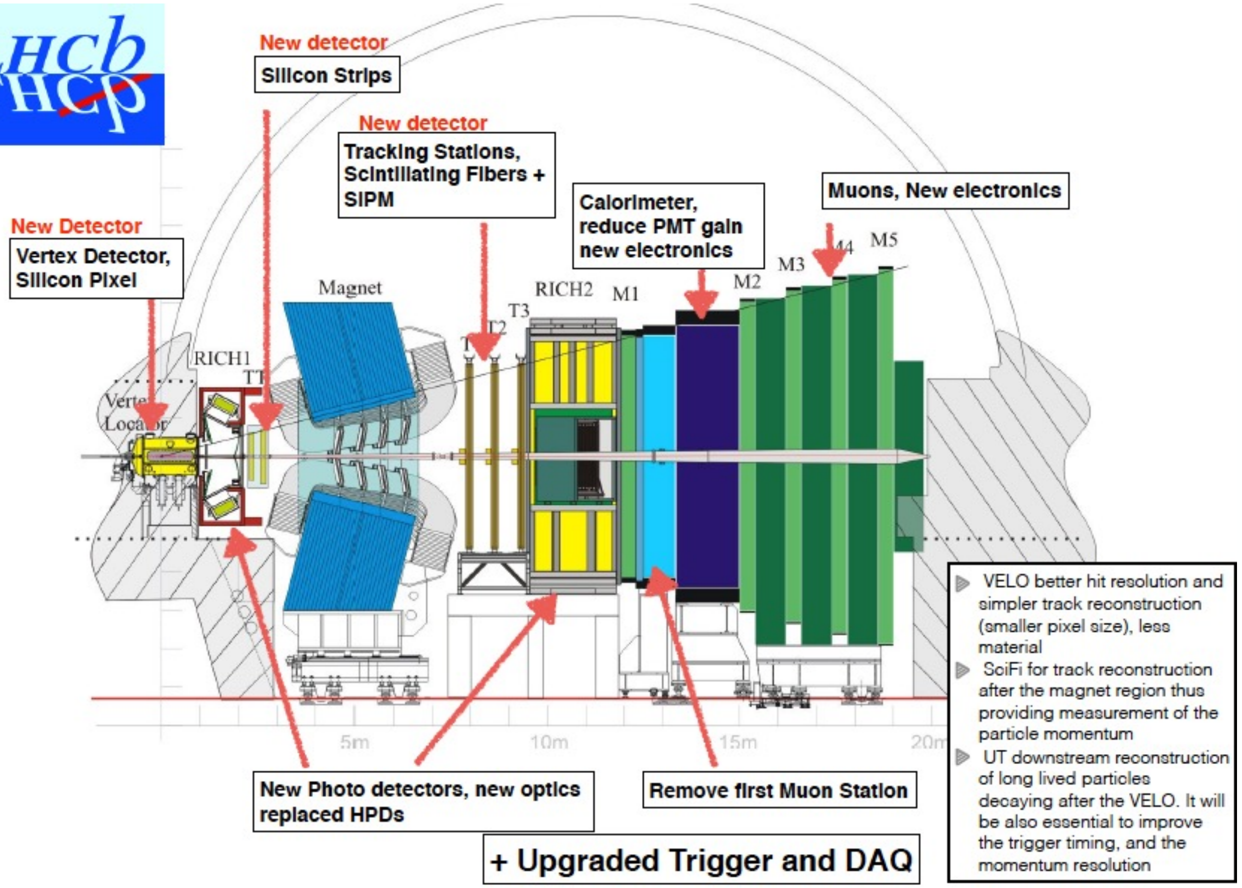
- Development of clever trigger strategy needed (now LHCb is poised to implement a purely software trigger!) needed
- Lots of particles, pile-ip

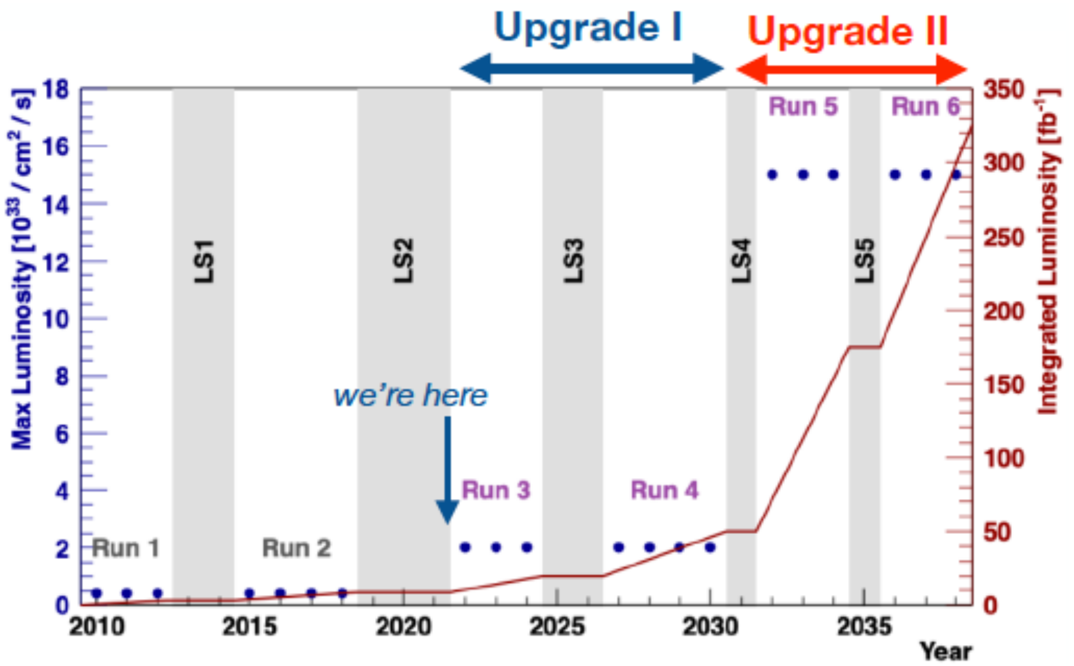






LHCb Upgrades





Upgrade II

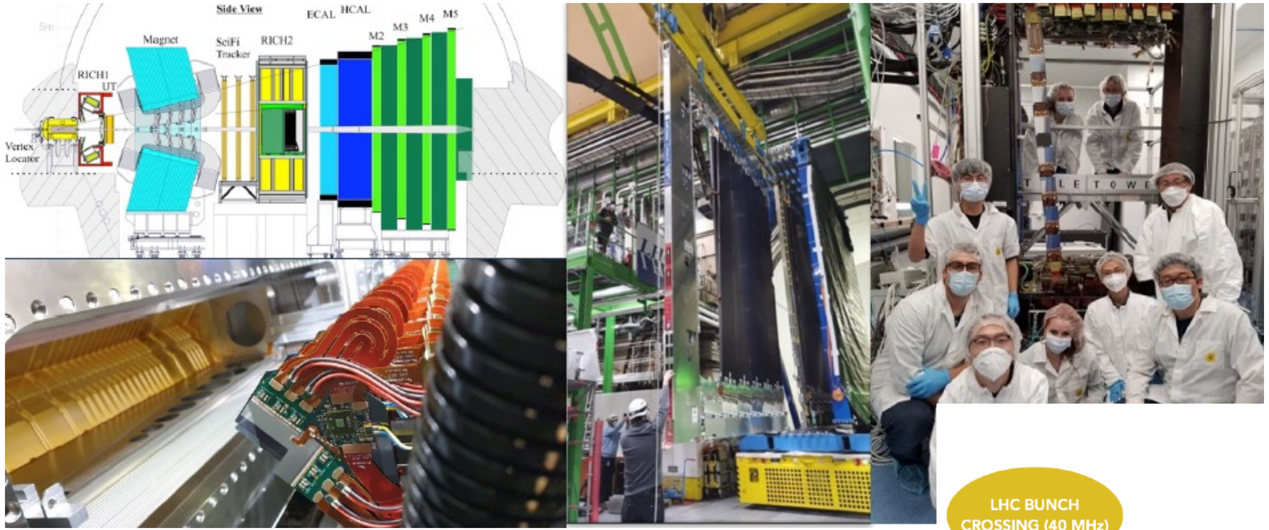
$\mathcal{L}_{peak} = 1.5 \times 10^{34} cm^{-2} s^{-1}$

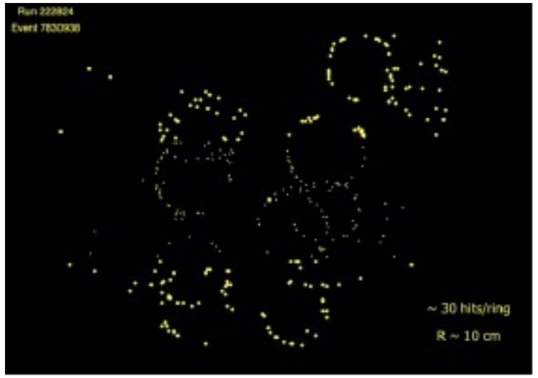
$\mathcal{L}_{int} = 300 fb^{-1}$

Upgrade I

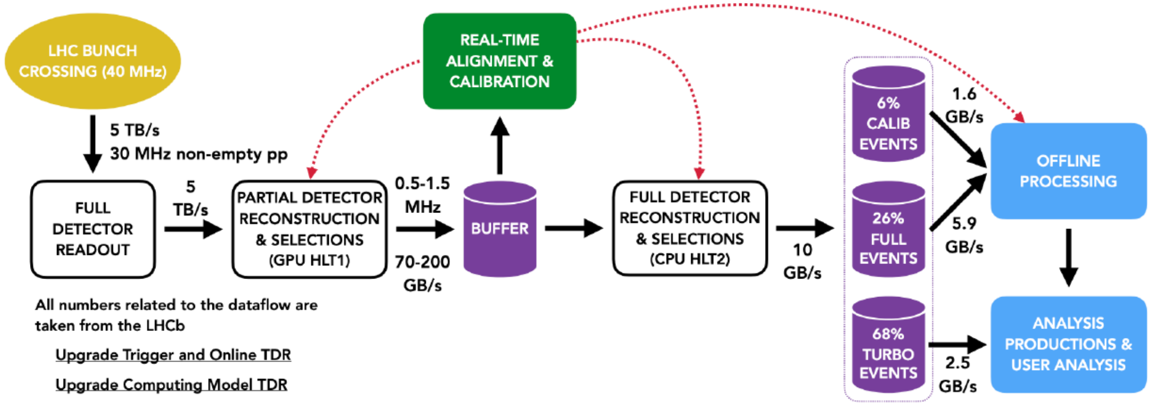
- $L_{peak} = 2x10^{33}\ cm^{-2}\ s^{-1}$
- $L_{int} = 50\ fb^{-1}$ during Run 3 + Run 4
- LHCb 50 fb^{-1}: healthy competition with Belle II at 50 ab^{-1}

LHCb Upgrade I





No longer using hardwarer trigger!

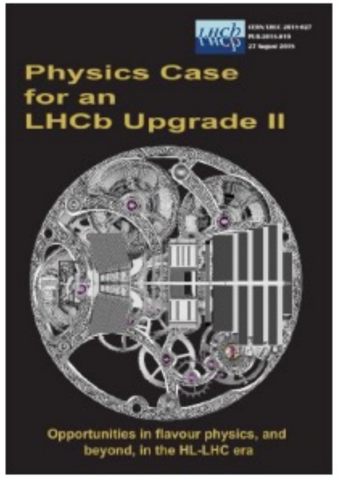


LHCb Upgrade II: steps so far

Expression of Interest

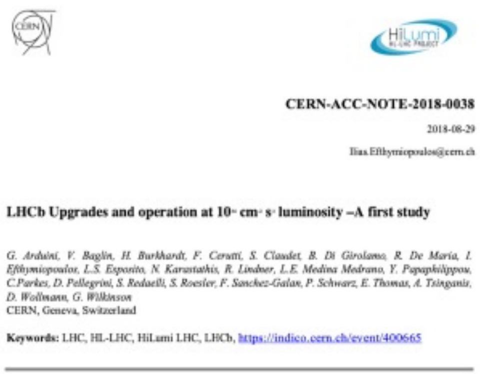
LHCC-2017-003

Physics case

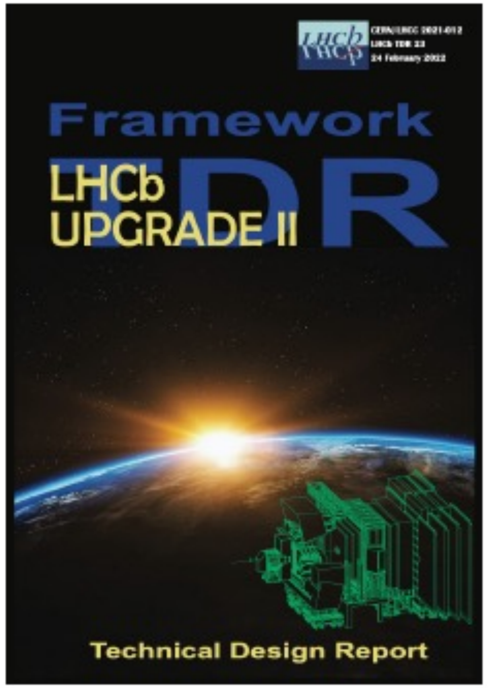


LHCC-2018-027

Accelerator study



CERN-ACC-2018-038



LHCC-2021-012

CERN Research Board September 2019 *"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."*

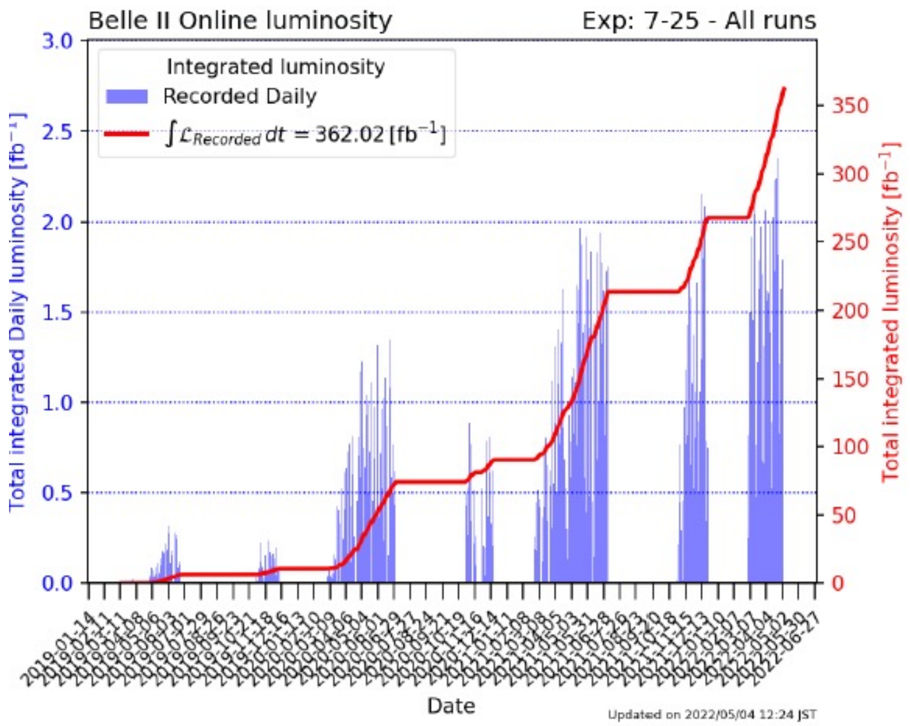
European Strategy Update 2020 ***"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"***

Approved March 2022
R&D programme followed by sub-system TDRs

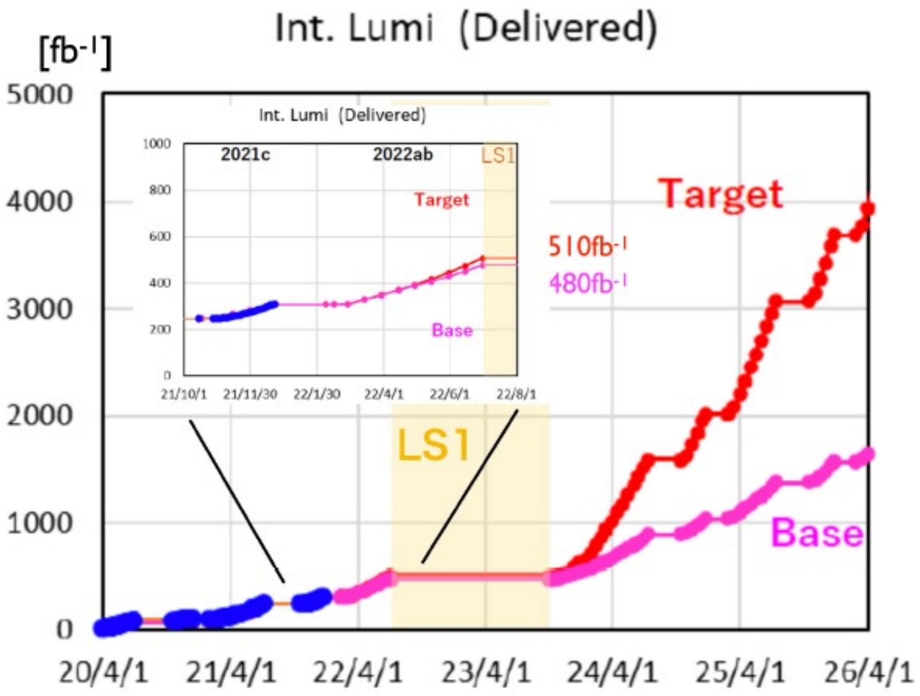
Belle II Upgrade(s)

Medium term plans

Starting to achieve Super B-factory performance levels.
Int(L dt)/day =2.4 fb^{-1}/day (May 18, 2020)
Int(L dt)/week = 15 fb^{-1}/week

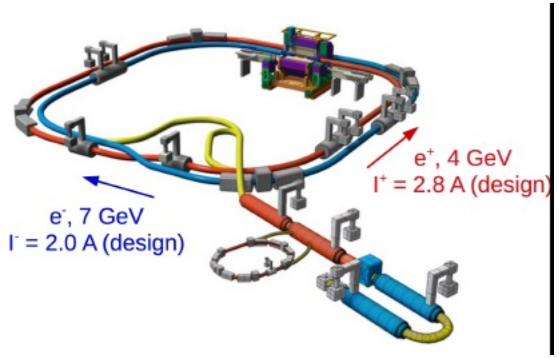


B factory reference values:
KEKB (1.48 fb^{-1}/day); PEP-II (0.911 fb^{-1}/day);
KEKB (8 fb^{-1} /week); PEP-II (5 fb^{-1}/week);



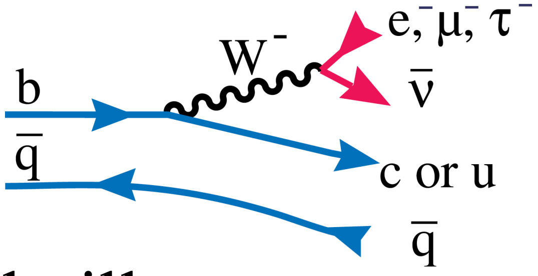
SuperKEK-b / Belle II program

- Machine consolidation in 4 steps:
  - Intermediate luminosity ($1.2\times10^{35} cm^{-2}s^{-1}$, 5ab^{-1}
  - High luminosity ($6.5\times10^{35} cm^{-2}s^{-1}$)+ detector upgrade
  - Polarization upgrade (advanced R&D)
  - Ultra-high luminosity ($4.0\times10^{36} cm^{-2}s^{-1}$,250 ab^{-1}) R&D project
- Now on ”Phase 3”: luminosity run with complete detector:
  - Pixel detector layer 1+ only 2 ladders in layer 2; full 4-layer strip detector
  - New and difficult accelerator, peak luminosity $\sim4\times\mathbf{10^{34} cm^{-2}s^{-1}}$
  - Path to $2\times\mathbf{10^{35} cm^{-2}s^{-1}}$ identified
  - Still large factors to reach $6.5\times\mathbf{10^{35} cm^{-2}s^{-1}}$

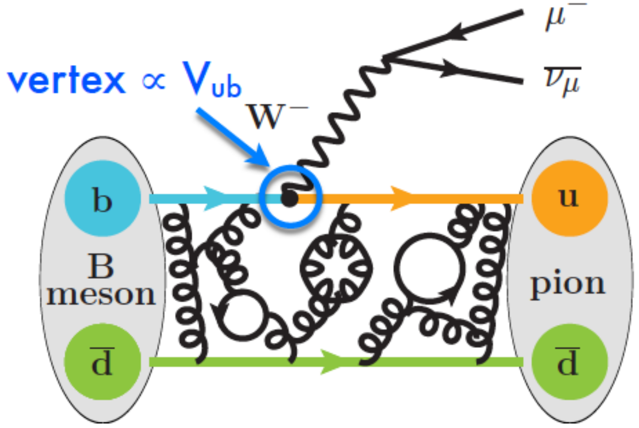


Interplay between theory and experiment

- ❑The importance of the hadronic matrix element, example: semileptonic decays.



In reality



- ❑theoretical pillars:
  - ❑Insight provided by effective theories [HQET]
  - ❑Heavy quark expansion [HQE]:

Inclusive processes

$$\Gamma_{\rm sl}(B)=\frac{G_F^2}{192\pi^3}|V_{cb}|^2 m_b^5 z_0\left(\frac{m_c^2}{m_b^2}\right)\left[1+c_\pi\frac{1}{2m_b^2}\frac{\langle B|\bar{b}(i\vec{D})^2 b|B\rangle}{2M_B}+c_G\frac{1}{2m_b^2}\frac{\langle B|\bar{b}(\frac{i}{2}\sigma_{\mu\nu}G^{\mu\nu}b|B\rangle}{2M_B}+ c_D\frac{1}{m_b^3}\frac{\langle B|\bar{b}(-\frac{1}{2}\vec{D}\vec{E})b|B\rangle}{2M_B}+\frac{32\pi^2}{z_0 m_b^3}\frac{\langle B|\bar{b}\vec{\gamma}(1-\gamma_5)c\,\bar{c}\vec{\gamma}(1-\gamma_5)b|B\rangle_{\rm IC}}{2M_B}+\ldots\right], \quad (1)$$

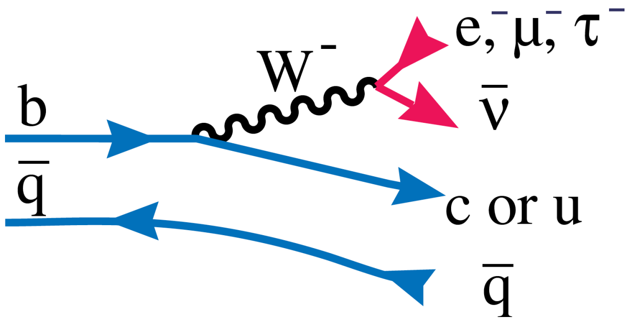
  - ❑Progress in lattice QCD calculations [and having the resources to exploit the new computational techniques developed]

How far can the Standard Model go?

CKM sector with tree level processes

Quark Mixing & CKM Matrix

The charged current couples the "up-type quarks" with a linear combination of "down-type" quarks



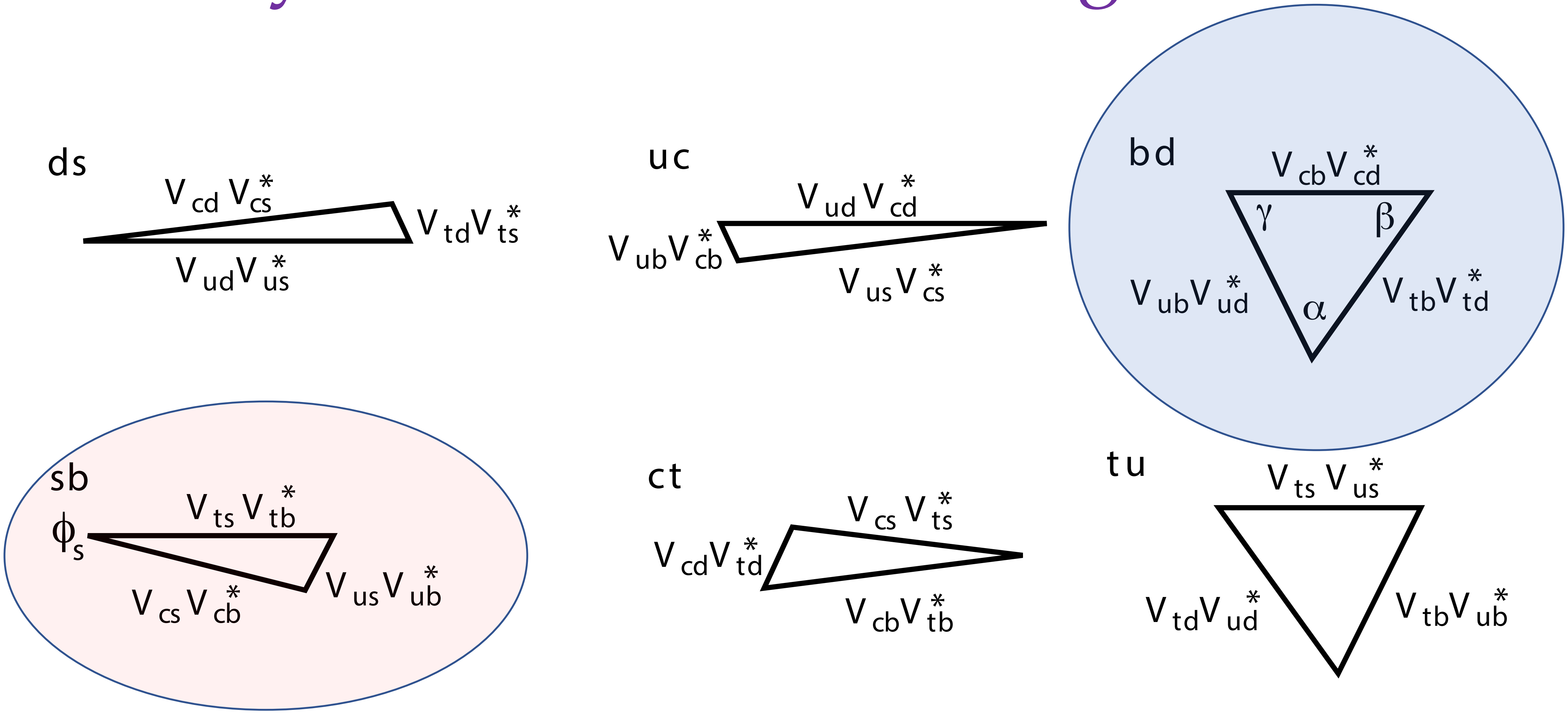
Tree level diagram – SM dominated (with some possible caveats)

- Described by CKM matrix [**unitary** matrix]

$$V_{\left(\frac{2}{3},-\frac{1}{3}\right)} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

λ=0.225, A=0.8, constraints on ρ & η *will be discussed*

Unitarity constraints: the triangles



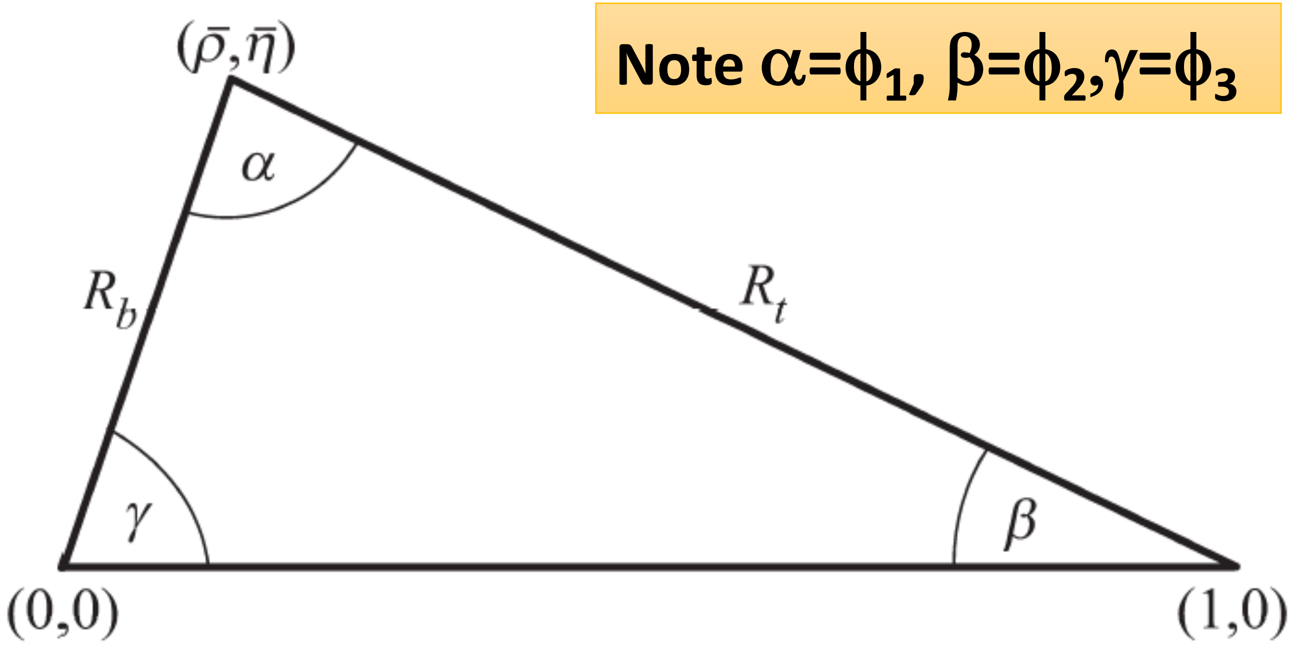
The reference unitarity triangle

$$R_b = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\frac{|V_{ub}|}{|V_{cb}|}$$

Triangles depict unitarity constraints

R_b, γ should establish the SM foundation (tree level processes)

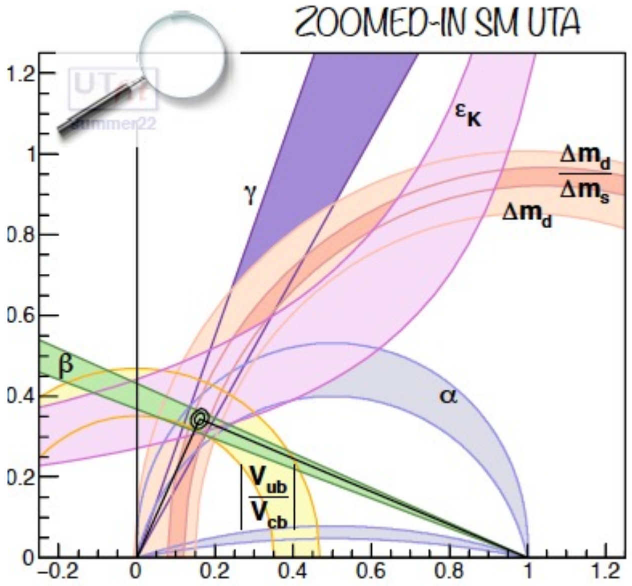
Note $\alpha=\phi_1$, $\beta=\phi_2$, $\gamma=\phi_3$



The reference unitarity triangle now

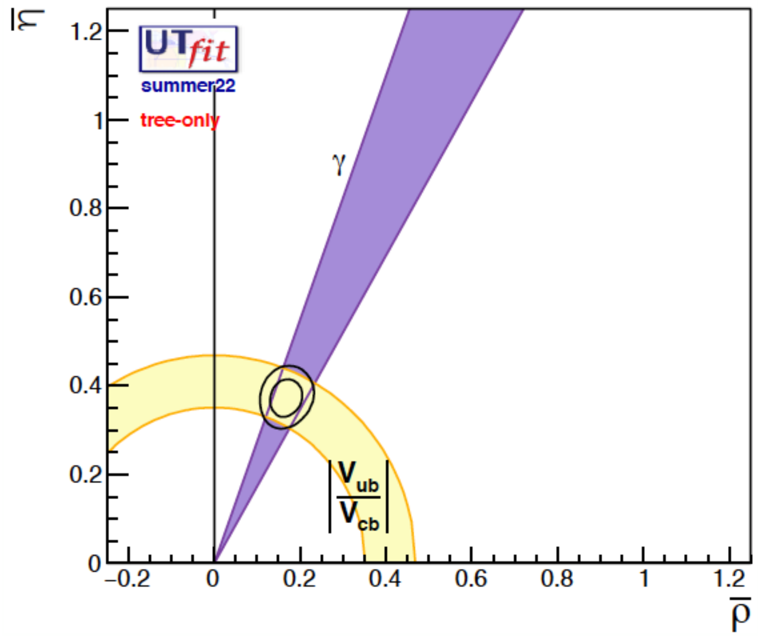
~few % uncertainty in individual determinations: lots of room for improvement

$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$



M. Valli

*** i.e., using constraints from tree-level processes only ***
b → c



tree-only UTA

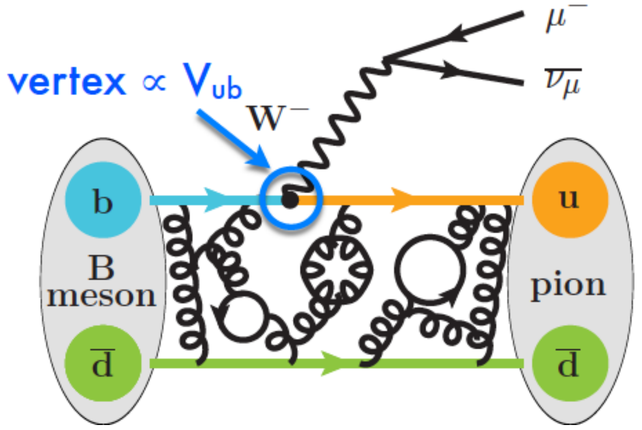
$$\bar{\rho} = 0.168 \pm 0.025 \sim 15\%$$
$$\bar{\eta} = 0.374 \pm 0.029 \sim 8\%$$

$$\bar{\rho} = 0.161 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.344 \pm 0.010 \sim 3\%$$

SM UTA

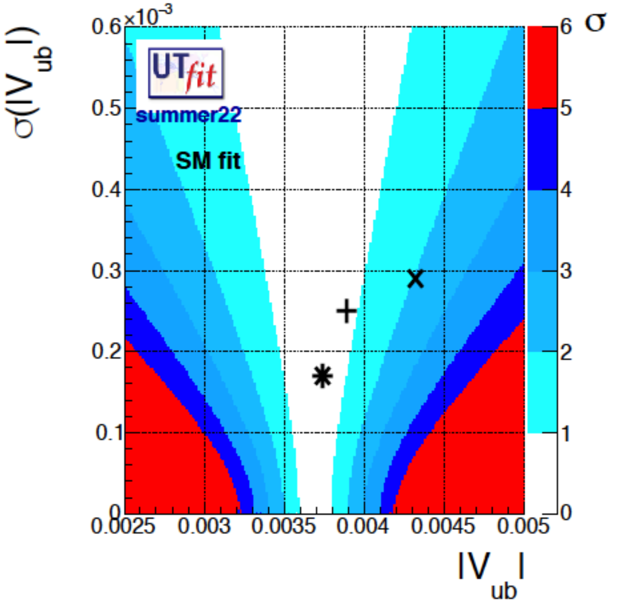
Old tensions to be resolved

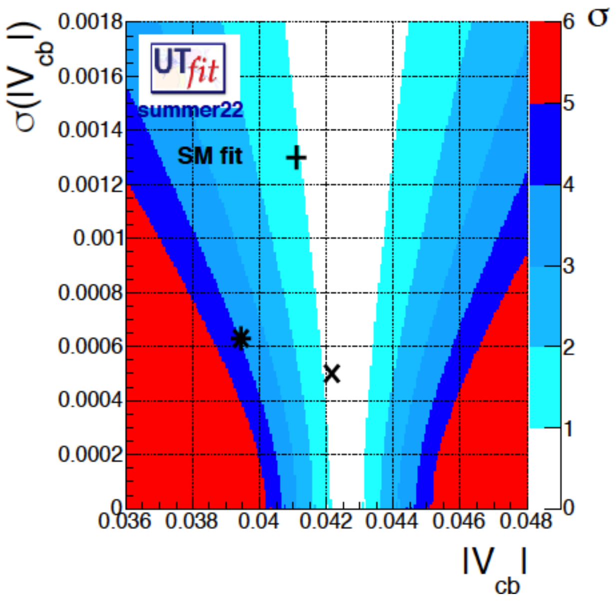
See M. Valli, F. Bernlochner presentations



Inclusive: reconstruct a physical property integrated over hadronic final states

Exclusive: reconstruct the hadron in the final state

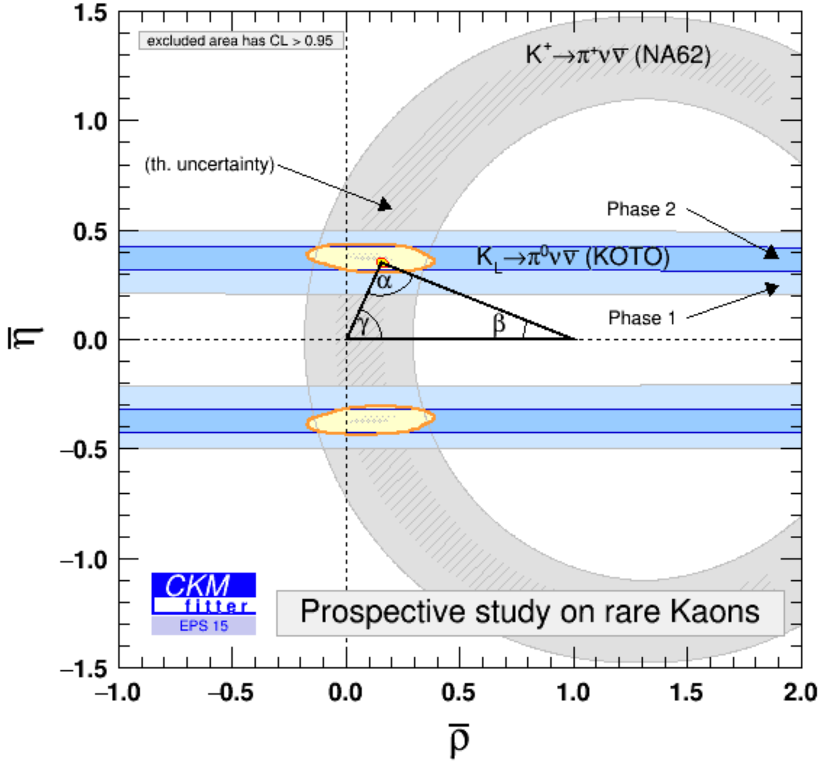




- A multidecade puzzle: both $|V_{ub}|$ and $|V_{cb}|$ determination encompass a persisting tension between the values extracted from **inclusive** or **exclusive** final state

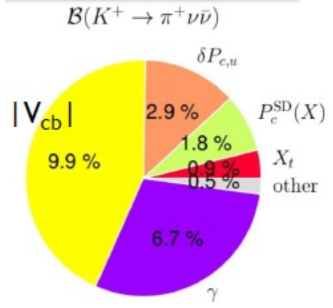
$$x = |V_{ub}|_{incl} \times 10^3 = 4.32 \pm 0.29$$
$$* = |V_{ub}|_{excl} \times 10^3 = 3.74 \pm 0.19$$
$$+ = |V_{ub}|_{ave} \times 10^3 = 3.89 \pm 0.25$$

$$x = |V_{cb}|_{incl} \times 10^3 = 42.16 \pm 0.50$$
$$* = |V_{cb}|_{excl} \times 10^3 = 39.44 \pm 0.63$$
$$+ = |V_{cb}|_{ave} \times 10^3 = 41.1. \pm 1.3$$

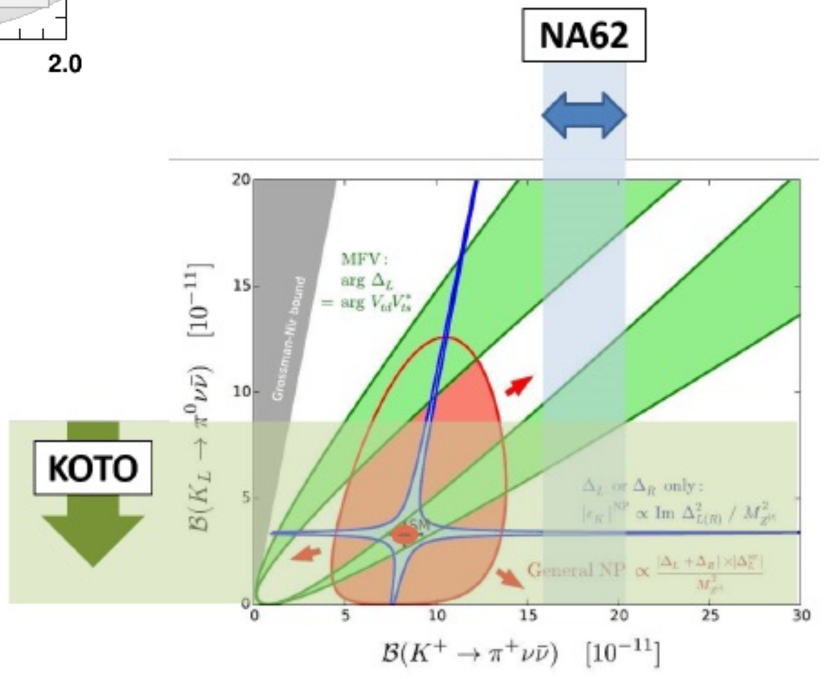


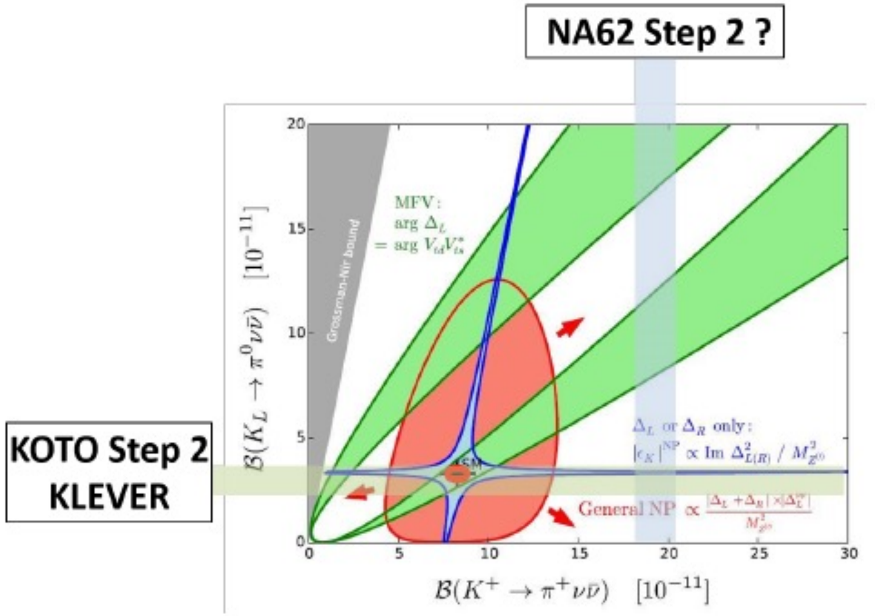
The K input to the reference unitarity triangle

$$BR(K^+\to\pi^+\nu\bar\nu) = (8.39\pm0.30)\times10^{-11}\cdot\left[\frac{|V_{cb}|}{0.0407}\right]^{2.8}\cdot\left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$



$$BR(K_L\to\pi^0\nu\bar\nu) = (3.36\pm0.05)\times10^{-11}\cdot\left[\frac{|V_{ub}|}{3.88\times10^{-3}}\right]^2\cdot\left[\frac{|V_{cb}|}{0.0407}\right]^2\cdot\left[\frac{\sin\gamma}{\sin73.2^\circ}\right]^2$$

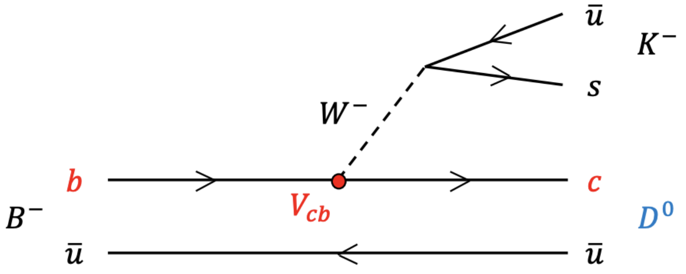


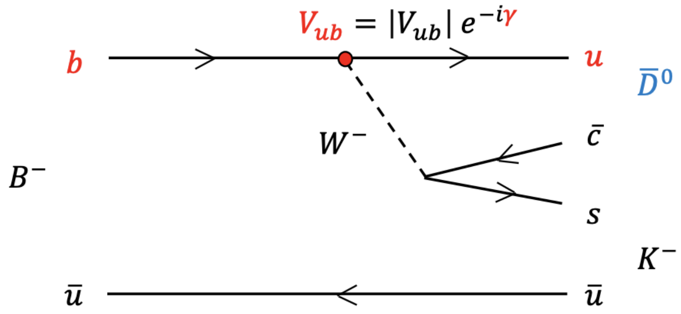


The angle γ

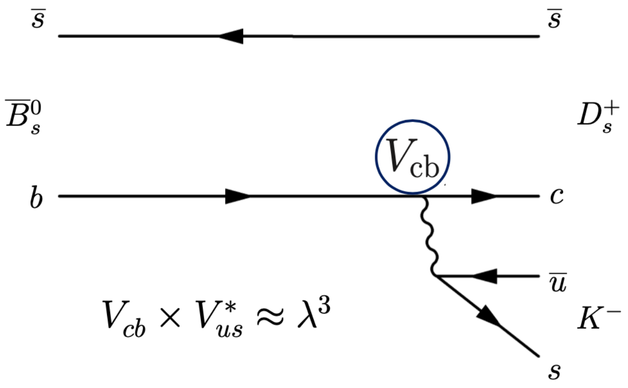
- Accessible from tree level processes (good Standard Model probe)
- Negligible theoretical uncertainty [Brod-Zupan,arXiV:1308.5663]

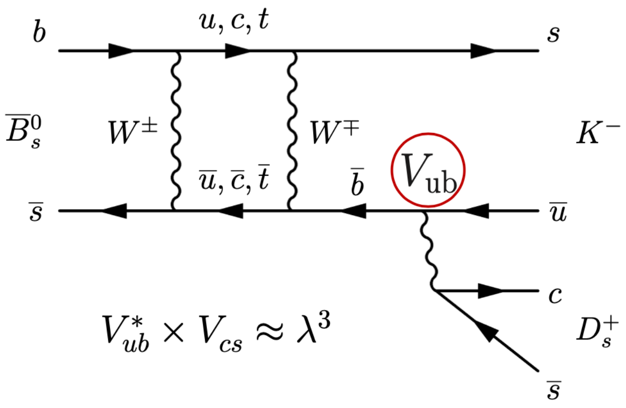
Key processes in charged B decays





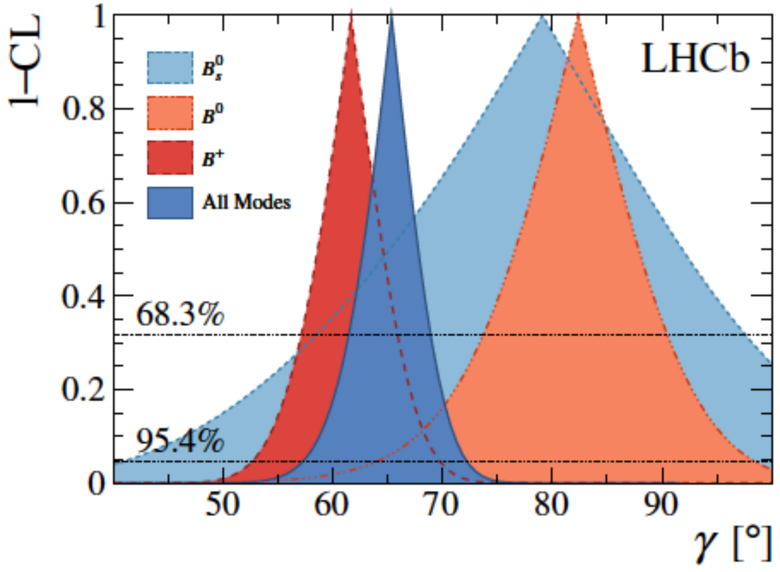
Key processes in B^0 decays





More details in D. Manuzzi's talk

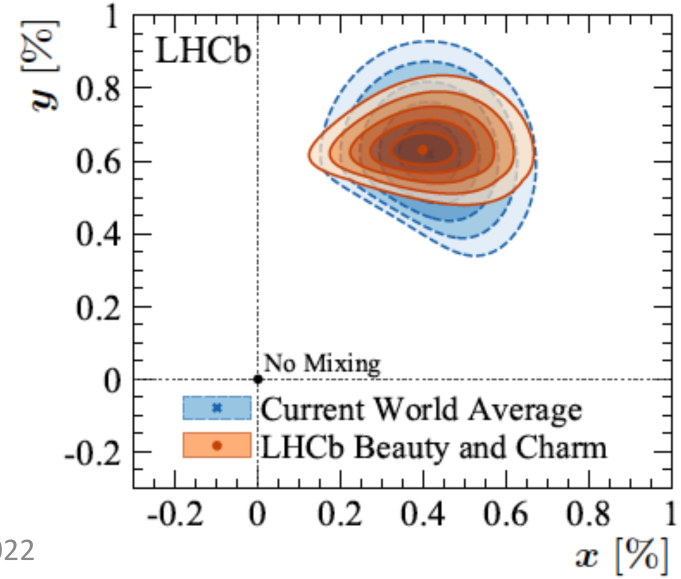
LHCb average:

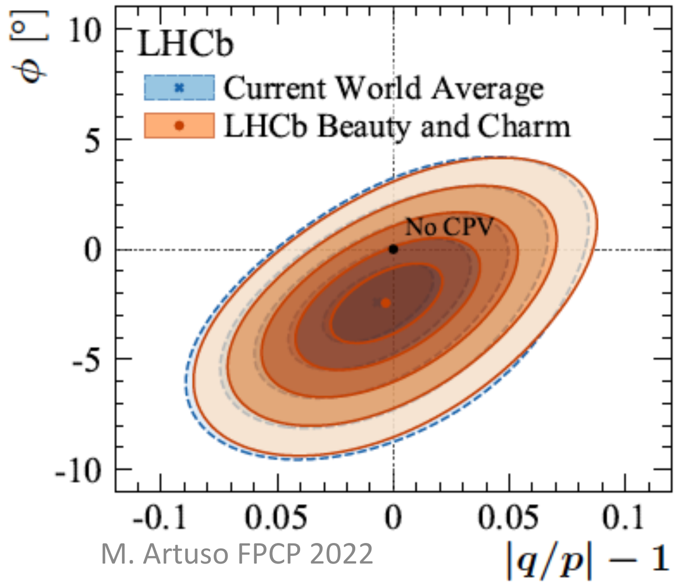


Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	61.7	$^{+4.4}_{-4.8}$	[56.9, 66.1]	$^{+8.6}_{-9.5}$	[52.2, 70.3]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B_s^0	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

$$\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$$

Average of all the measurements





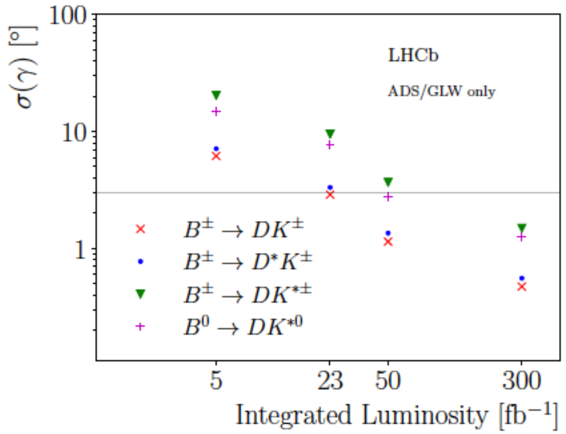
$$x \equiv \frac{\Delta M}{\Gamma} = 0.400^{+0.052}_{-0.053}$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma} = (0.630^{+0.033}_{-0.030})\%$$

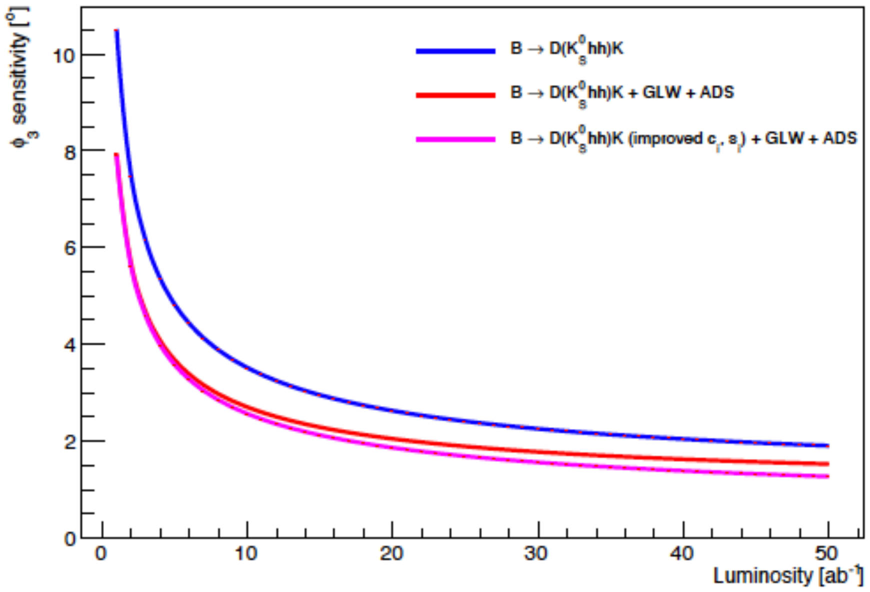
$$\left|\frac{q}{p}\right| = 0.997 \pm 0.016$$

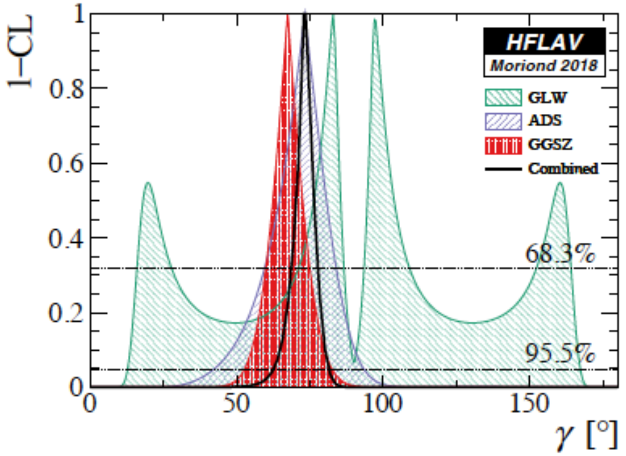
Future prospects

arXiV:1808.08865



Belle II Snowmass white paper





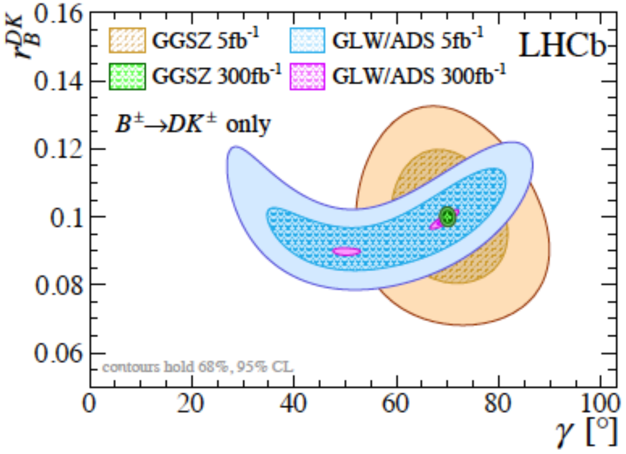
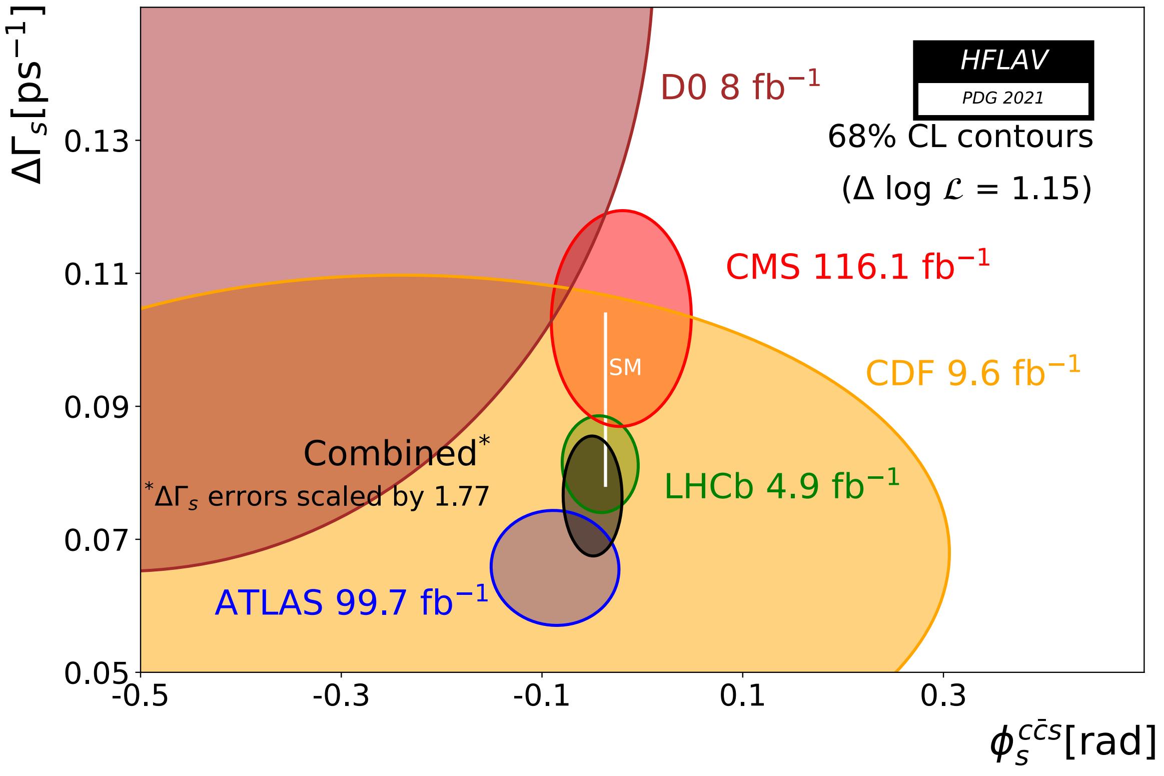


Illustration using selected decay modes, the neutral modes are really interesting too!

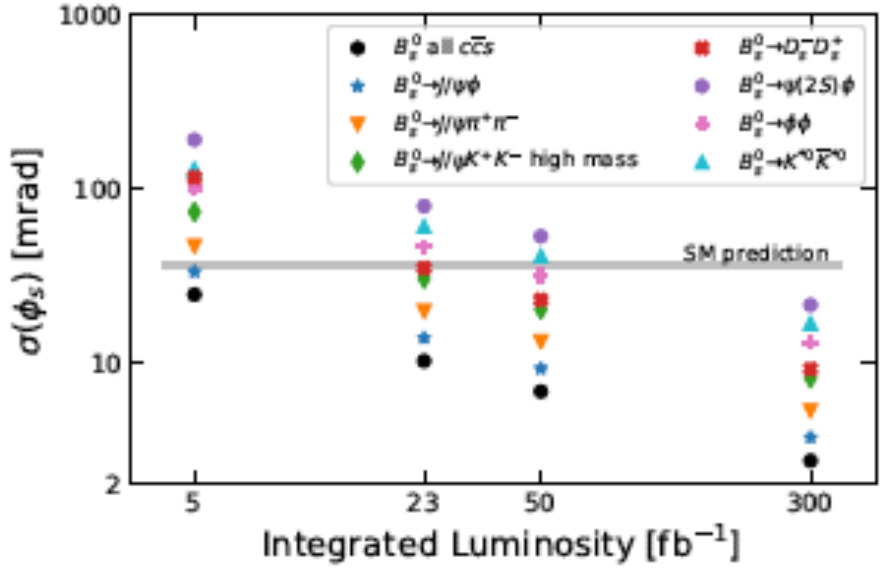
The B_s^0 triangle

CPV in B_s^0 $b \to [c\bar{c}s]$ decays

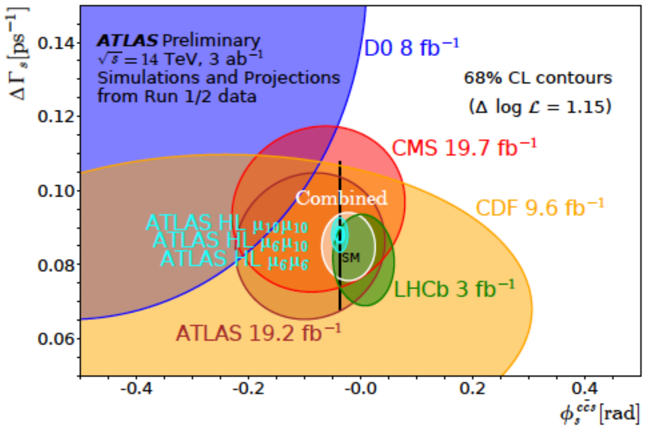
Current status



LHCb-TDR-023



ATL-PHYS-PUB-2018-041



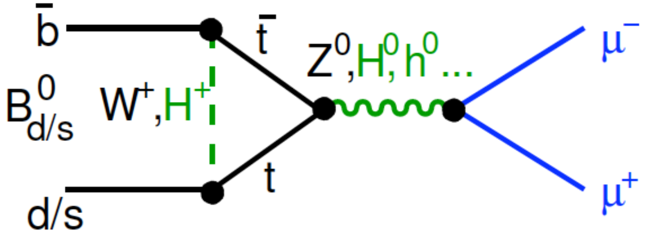
Searching for signatures of new physics in (mostly) rare decays

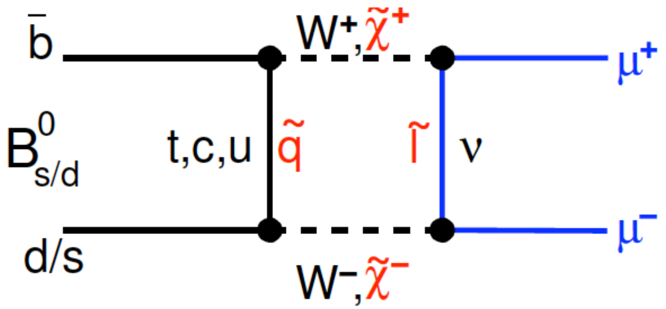
Mostly interference between loop diagrams with one exception

Rare decays and generic searches for new physics

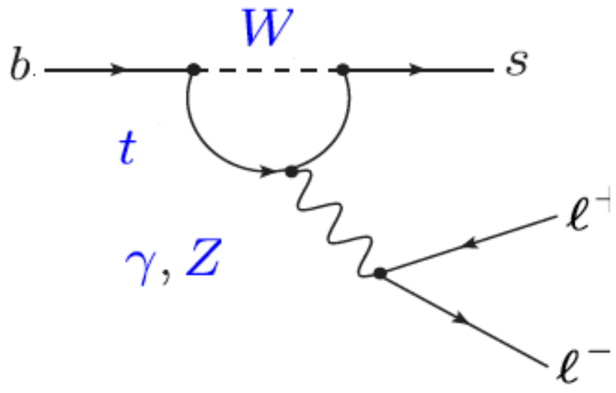
Model independent parameterization of the new physics that can appear in interference with SM loop diagrams

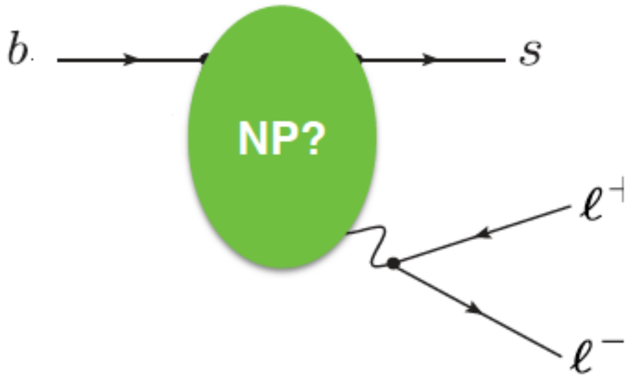
$B_s^0 \to \mu^+\mu^-$





$b \to s\ell^+\ell^-$





Rare decays are described by an effective Hamiltonian expressed in terms of an operator product expansion:

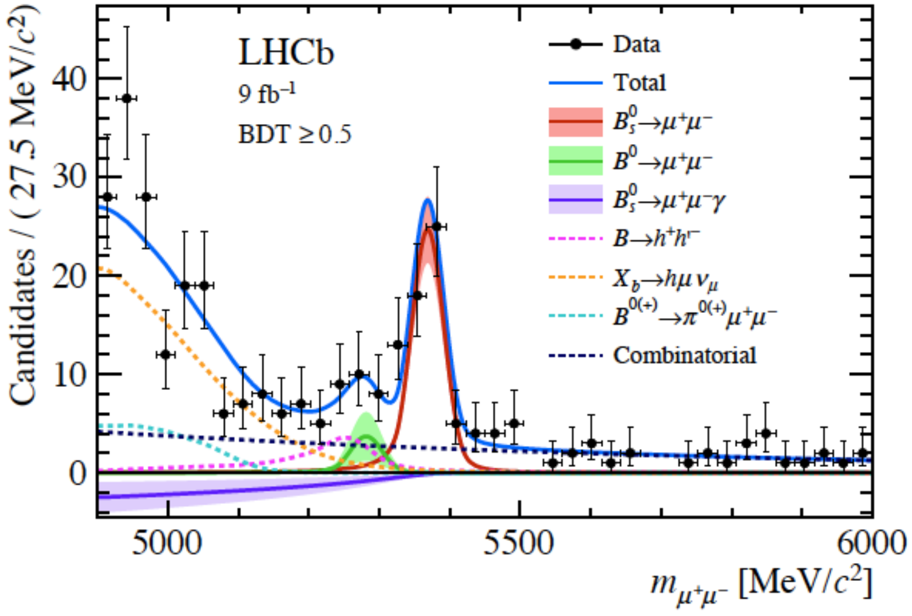
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

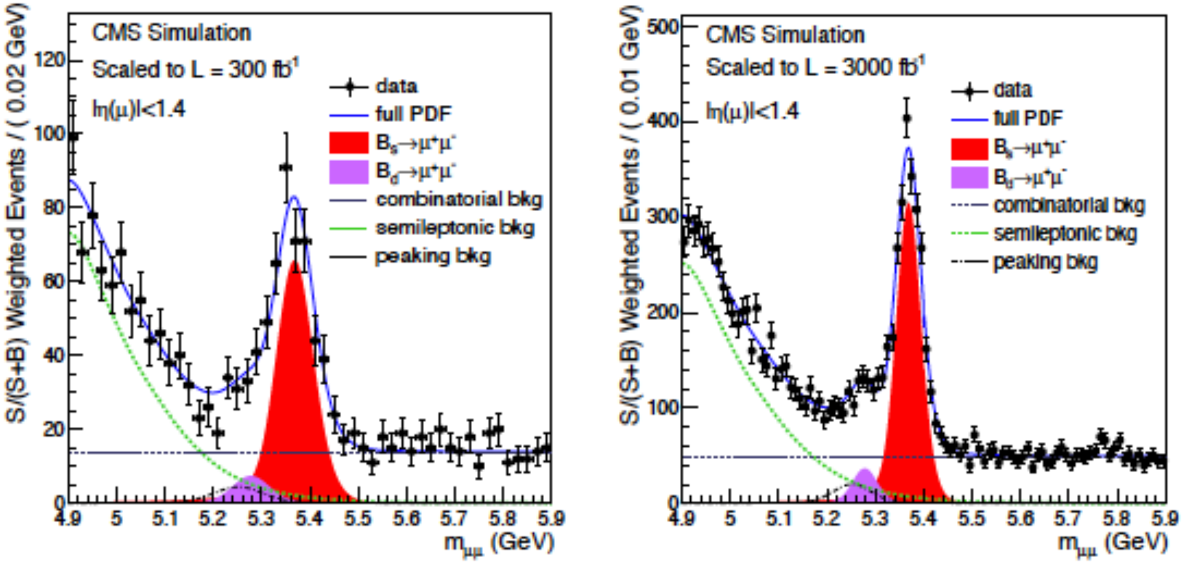
Operator	$B_{d,s} \to X_{s,d}\,\mu\mu$	$B_{s,d} \to \mu\mu$	$B \to X_{s,d}\,\gamma$
O_7	√		√
O_9	√		
O_{10}	√	√	
$O_{S,P}$		√	

$B_s^0 \to \mu^+\mu^-$

now [arXiV 2108.09284](https://arxiv.org/abs/2108.09284)



CMS-PAS-FTR-14-015



- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09^{+0.46+0.15}_{-0.43-0.11}\right)\times 10^{-9}$

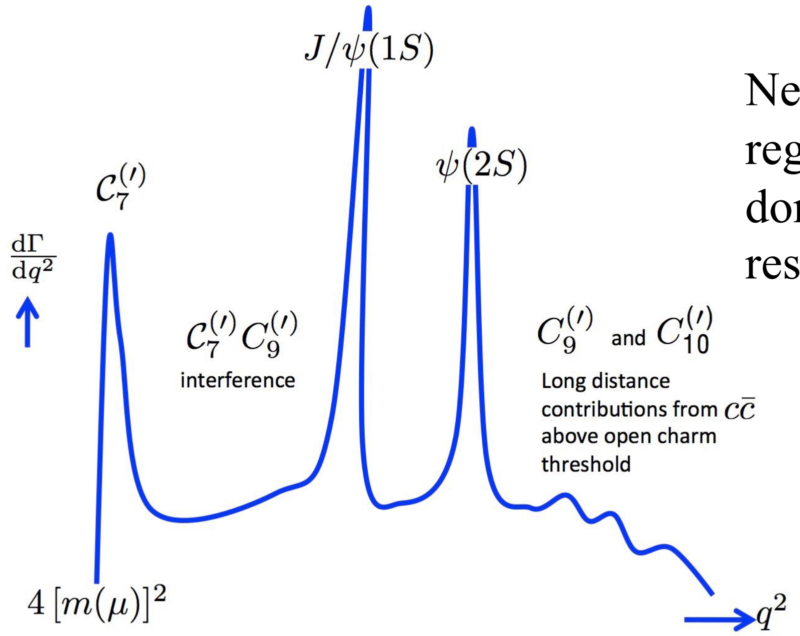
SM predictions:

$$\overline{\mathrm{Br}}^{(0)}_{s\mu} = \begin{pmatrix} 3.599 \\ 3.660 \end{pmatrix} \Big[1 + \begin{pmatrix} 0.032 \\ 0.011 \end{pmatrix}_{f_{B_s}} + 0.031\big|_{\mathrm{CKM}} + 0.011\big|_{m_t} + 0.006\big|_{\mathrm{pmr}} + 0.012\big|_{\text{non-pmr}} \, {}^{+0.003}_{-0.005}\big|_{\mathrm{LCDA}} \Big] \cdot 10^{-9},$$

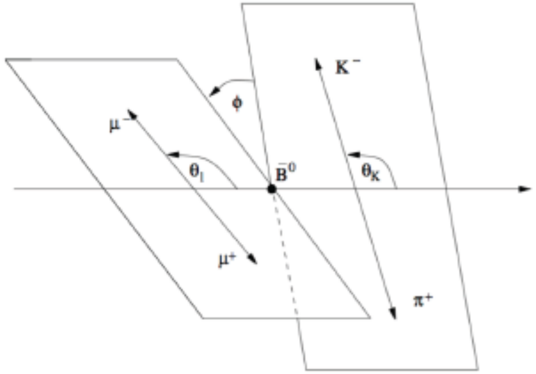
[arXiV:1908.07011](https://arxiv.org/abs/1908.07011)
Note: they use $|V_{cb}|$ inclusive

$B \to K^{(*)}\ell^+\ell^-$ and $b \to s\ell^+\ell^-$

- Different lepton pairs accessible in the final states, precise SM prediction of ratios⇒ lepton flavor universality tests
- When a vector is involved in the final state many observables



Need to select regions in q^2 not dominated by resonances



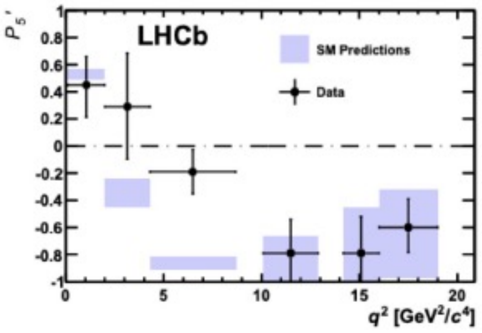
$$\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Several tensions currently reported in $B \to K^{(*)}\mu^+ \mu^-$

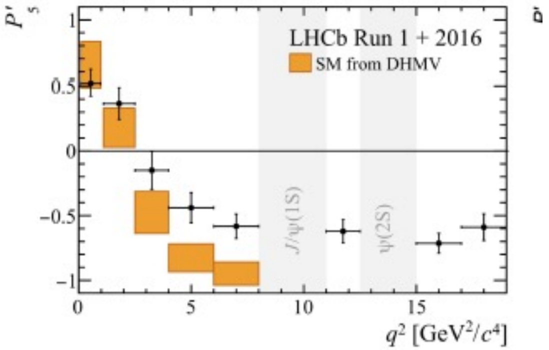
Nicola Serra's talk

Angular distribution $B^0 \to K^{*0}\mu^+\mu^-$

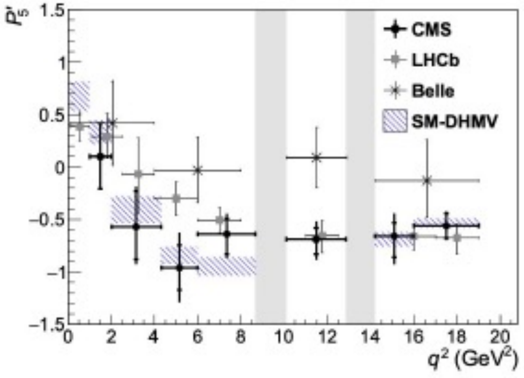
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$



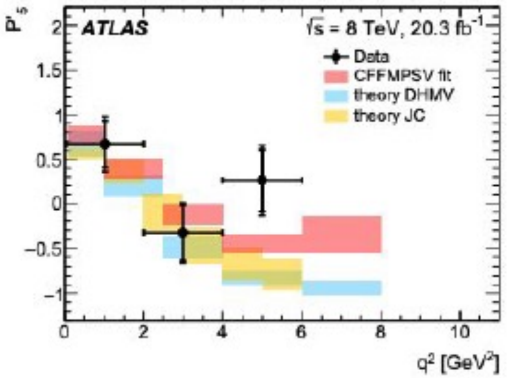
Phys.Rev.Lett. 111 (2013) 191801



Phys.Rev.Lett. 125 (2020) 1, 011802

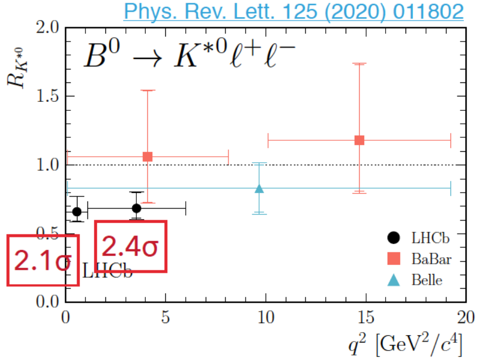


Phys.Lett.B 781 (2018) 517-541

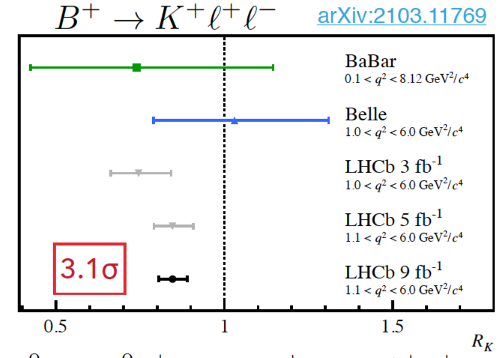


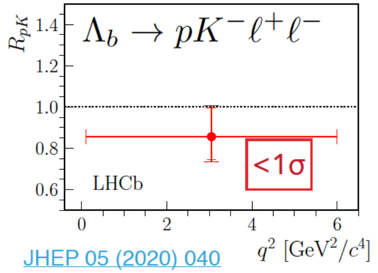
JHEP 10 (2018) 047

Phys. Rev. Lett. 125 (2020) 011802

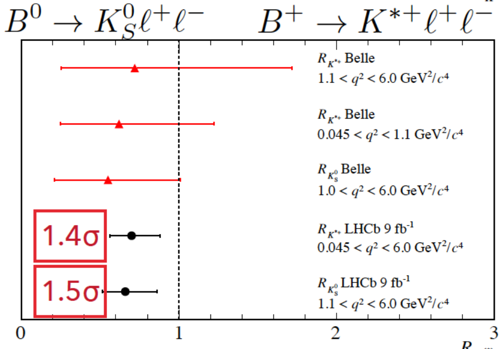


arXiv:2103.11769





JHEP 05 (2020) 040



arXiv:2110.09501

Future prospects: two snashots

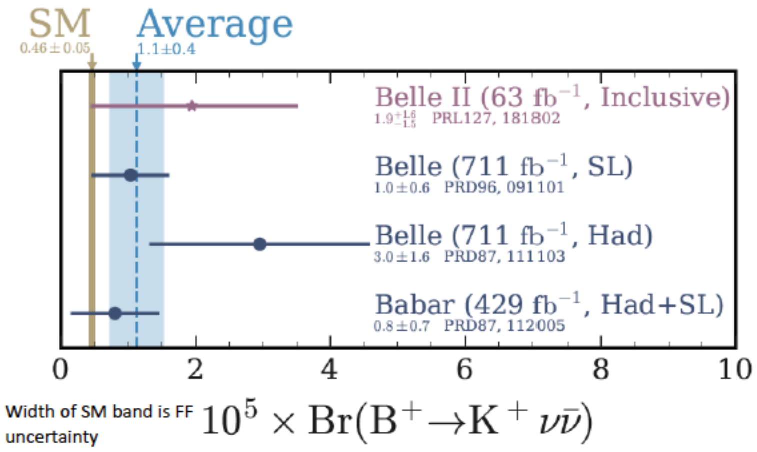
Belle II

$B \to K\nu\bar{\nu}$

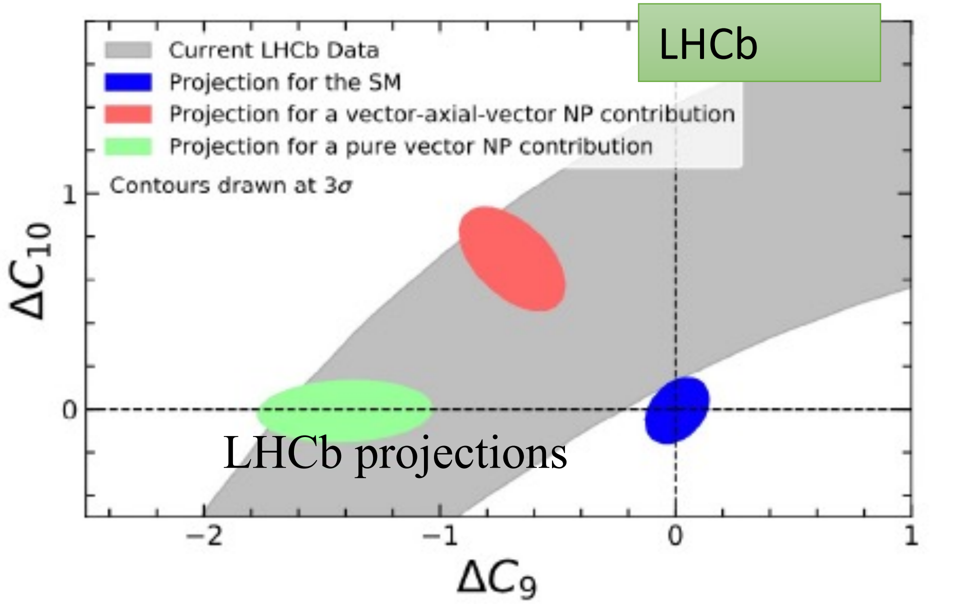
New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.

Phys. Rev. Lett. 127, 181802, (2021)

An emerging anomaly ???



4% experimental error on $B \to K^{*}\nu\bar{\nu}$ with 250ab^{-1}



Integrated Luminosity	3 fb^{-1}	23 fb^{-1}	300 fb^{-1}
R_K and R_{K^*} measurements			
$\sigma(C_9)$	0.44	0.12	0.03
$\Lambda^{\text{tree generic}}$ [TeV]	40	80	155
$\Lambda^{\text{tree MFV}}$ [TeV]	8	16	31
$\Lambda^{\text{loop generic}}$ [TeV]	3	6	12
$\Lambda^{\text{loop MFV}}$ [TeV]	0.7	1.3	2.5
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis			
$\sigma^{\text{stat}}(S_i)$	0.034–0.058	0.009–0.016	0.003–0.004
$\sigma(C'_{10})$	0.31	0.15	0.06
$\Lambda^{\text{tree generic}}$ [TeV]	50	75	115
$\Lambda^{\text{tree MFV}}$ [TeV]	10	15	23
$\Lambda^{\text{loop generic}}$ [TeV]	4	6	9
$\Lambda^{\text{loop MFV}}$ [TeV]	0.8	1.2	1.9

Projection of LHCb sensitivities to key physics quantities

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 ($B_s^0 \to J/\psi\phi$)	49 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%	—	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{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]	17×10^{-5}	—	3.0×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	13×10^{-5} [38]	4.3×10^{-5}	—	1.0×10^{-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				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	71% [40, 41]	34%	—	10%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	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
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$ [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^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10 [61]	0.031	0.021	0.008
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026 [62, 64]	0.007	—	0.002

arXiV:2203.11349

Belle II projection, long term plans in early phase of discussion/study

Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	$< 1\%$
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015	0.007
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025	0.018
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \to K^* \ell^+ \ell^-)^\dagger$	0.26	0.09	0.03	0.01
$R(B \to D^* \tau\nu)$	0.018	0.009	0.0045	<0.003
$R(B \to D \tau\nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \to \tau\nu)$	24%	9%	4%	2%
$B(B \to K^* \nu\bar{\nu})$	–	25%	9%	4%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

Table 2: Projected precision (total uncertainties, or 90% CL upper limits) of selected flavour physics measurements at Belle II.(The † symbol denotes the measurement in the momentum transfer squared bin $1 < q^2 < 6$ GeV/c^2.)

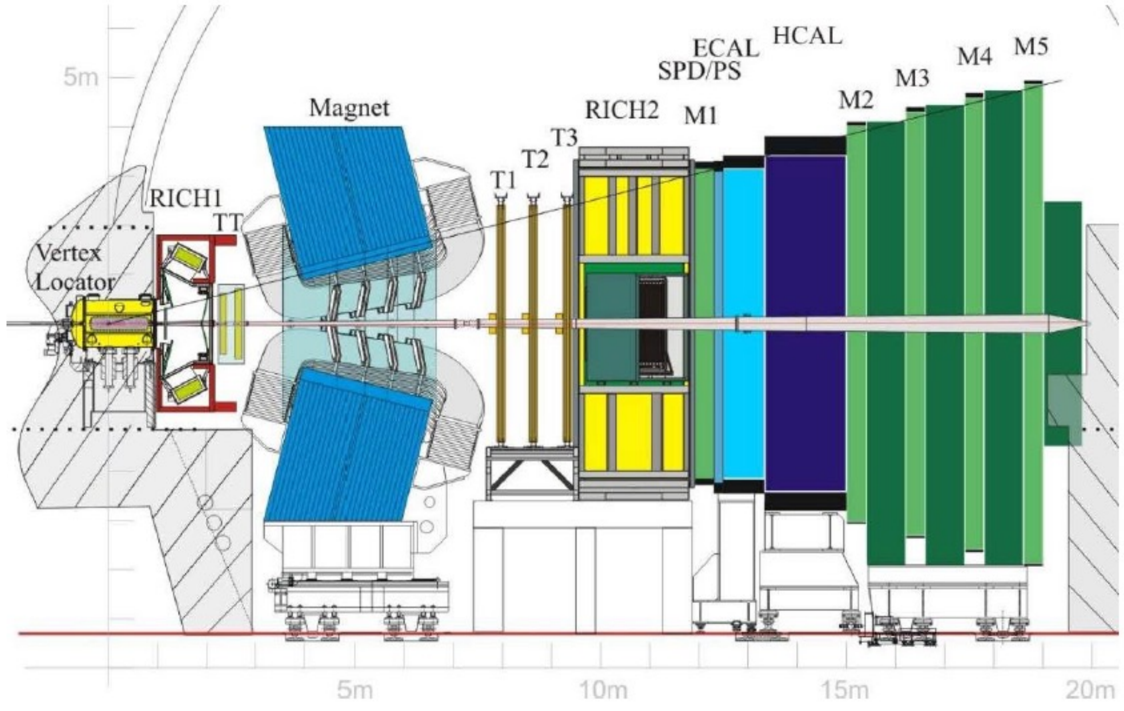
Conclusions

- Precision SM tests in flavor observables still key: deviations may be subtle!
- Intriguing tensions in flavor physics observables have emerged: increase in precision of upgraded experiments is needed to gain a complete picture
- A rich and diverse experimental program is under way:
  - Rare K decays offer unique probes of SM and beyond with the prospect of measuring few 10^2 events of ultra rare $K \to \pi\nu\bar{\nu}$
  - Super tau-charm factories proposed to continue the program of BESII
  - Belle II and LHCb will provide complementary information on the full SM reach and a variety of new physics prospects
  - Atlas and CMS will continue b-physics program with muons in the final state
- Precise calculations of the hadronic matrix element are necessary to complete this exciting physics program

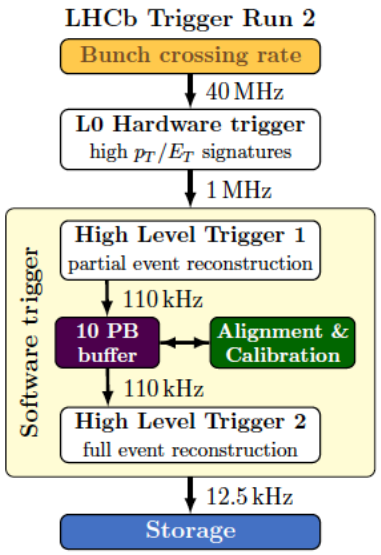
The end

With many thanks to the organizers for a lovely conference and for honoring the memory of Sheldon!

The LHCb detector 2010-2018

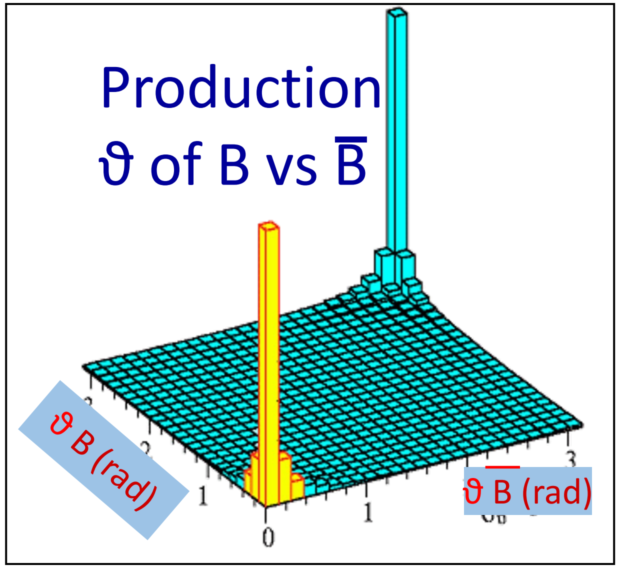


- Key performance parameters:
  - Vertex resolution: PV with 25 tracks has 13μm resolution in xy and 71μm in z & asymptotic IP 13μm
  - Decay time resolution 50fs
  - Mass resolution $\frac{\sigma_m}{m}$=0.5%, $(m < \sim 20\ GeV)$
  - Excellent hadron ID
  - Fast software trigger



LHCb Methodology: study b and c in the forward direction at the LHC

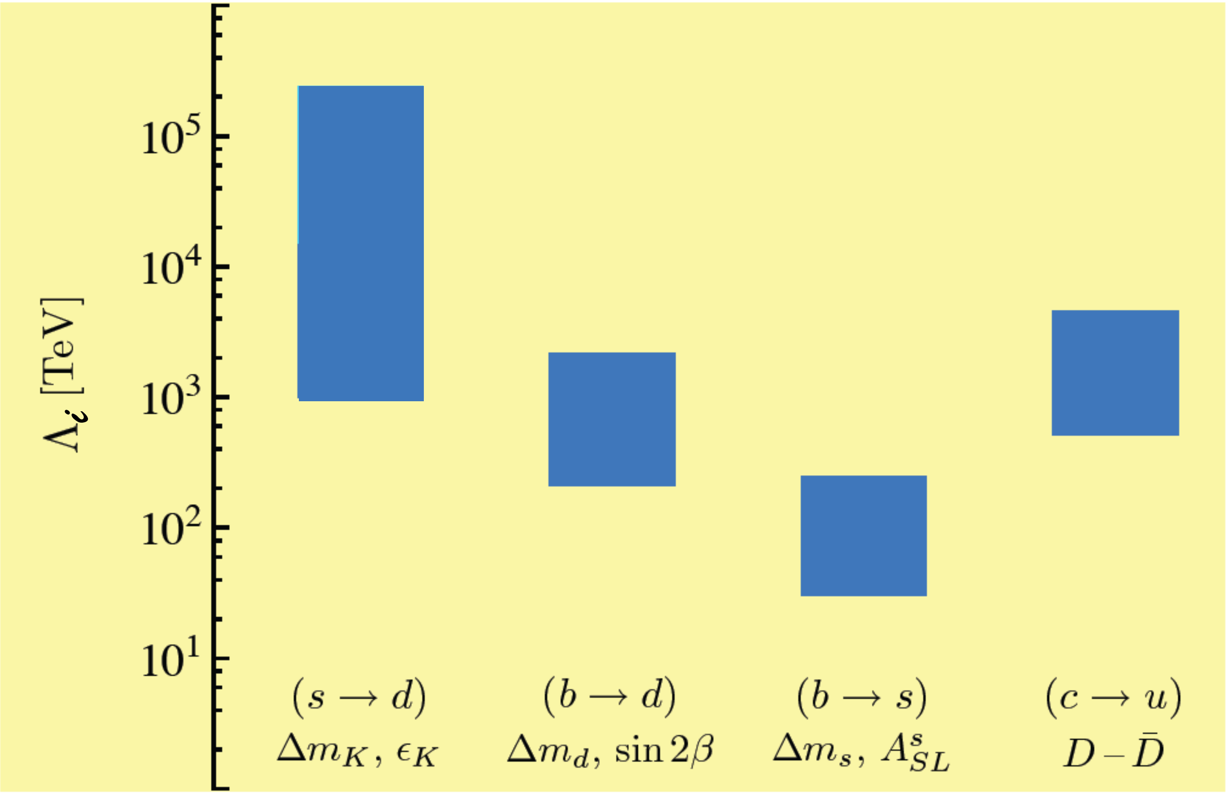
- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & b quarks are both likely to be in the acceptance. Essential for "flavor tagging"
- LHCb uses the forward direction where the B's are moving with considerable momentum ~100 GeV, thus minimizing multiple scattering
- At $\mathcal{L}=2\text{x}10^{32}/\text{cm}^2/\text{s}$, we get 10^{12} B hadrons in 10^7 sec



Flavor as a High Mass Probe

$$L_{\text{eff}} = L_{\text{SM}} + \frac{c_i}{\Lambda_i^2} O_i$$

❑ Already excluded ranges



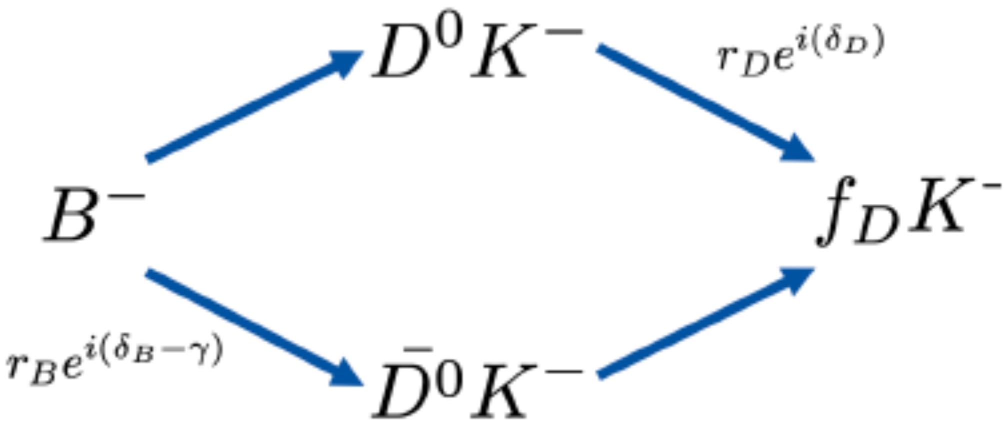
Interpretations:

1. New particles have large masses >>1 TeV
2. Mixing angles in new sector are small, same as in SM (MFV)
3. The above already implies strong constrains on NP

See: Isidori, Nir & Perez arXiv:1002.0900; Neubert EPS 2011 talk

Most recent LHCb combination

- Simultaneous determination of γ and charm mixing parameters
- Many measurements of γ with this approach, they differ on the D^0 decay modes considered
- LHCb has a rich array of data, internal combination of different measurements reported previously
- LHCb has also precise measurements of D^0 mixing parameters $\Rightarrow$ New combination of γ and charm mixing parameters [arXiV:2110.023350]



Measurements used in the combination

- ❑First combination where the LHCb charm inputs are included
- ❑"updated" with respect to LHCb-CONF-2018-002
- ❑Frequentist approach with 151 observables to determine 52 parameters

B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[23]	Run 1&2	**Updated**
$B^\pm \to D^* h^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[27]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[29]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[30]	Run 1&2	**New**
D decay	**Observable(s)**	**Ref.**	**Dataset**	**Status since Ref. [17]**
$D^0 \to h^+h^-$	ΔA_{CP}	[31–33]	Run 1&2	**New**
$D^0 \to h^+h^-$	y_{CP}	[34]	Run 1	**New**
$D^0 \to h^+h^-$	ΔY	[35–38]	Run 1&2	**New**
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[39]	Run 1	**New**
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[40]	Run 1&2(*)	**New**
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[41]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[42]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[43]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[44]	Run 2	**New**

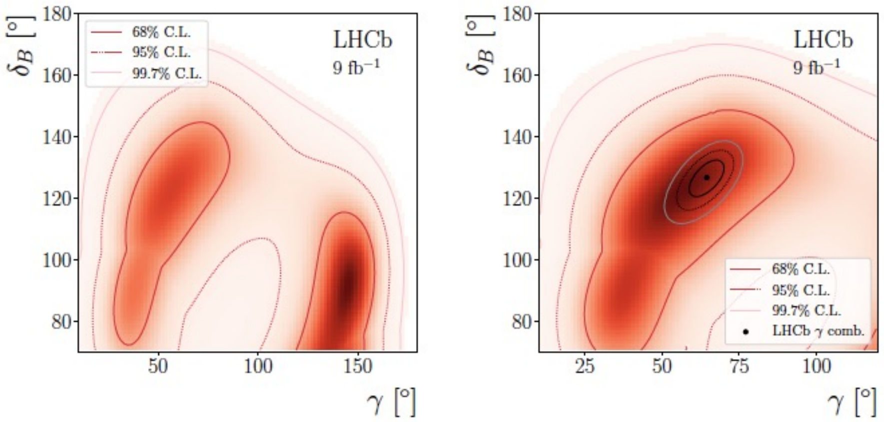
Decay	Parameters	Source	Ref.	Status since Ref. [17]
$B^\pm \to DK^{*\pm}$	$\kappa^{DK^{*\pm}}_{B^\pm}$	LHCb	[24]	As before
$B^0 \to DK^{*0}$	$\kappa^{DK^{*0}}_{B^0}$	LHCb	[45]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[11]	**Updated**
$B^0_s \to D^\mp_s K^\pm(\pi\pi)$	ϕ_s	HFLAV	[11]	**Updated**
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{K\pi\pi^0}$	CLEO-c	[46]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c	[46]	As before
$D \to K^+\pi^-\pi^0$	$r^{K\pi\pi^0}_D$, $\delta^{K\pi\pi^0}_D$, $\kappa^{K\pi\pi^0}_D$	CLEO-c+LHCb+BESIII	[47–49]	**Updated**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r^{K3\pi}_D$, $\delta^{K3\pi}_D$, $\kappa^{K3\pi}_D$	CLEO-c+LHCb+BESIII	[41, 47–49]	**Updated**
$D \to K^0_S K^\pm\pi^\mp$	$r^{K^0_S K\pi}_D$, $\delta^{K^0_S K\pi}_D$, $\kappa^{K^0_S K\pi}_D$	CLEO	[50]	As before
$D \to K^0_S K^\pm\pi^\mp$	$r^{K^0_S K\pi}_D$	LHCb	[51]	As before

Measurement of γ with $B^{\pm} \to Dh^{\pm}\pi^{0}$

- Final states $D \to \pi^{-}\pi^{+}\pi^{0}$ and $D \to K^{-}K^{+}\pi^{0}$ are mixture of CP odd and CP even eigenstates [$\Rightarrow$ dilution factor of the overall CP asymmetry]
- 11 CP observables measured

arXiV 2112.10617

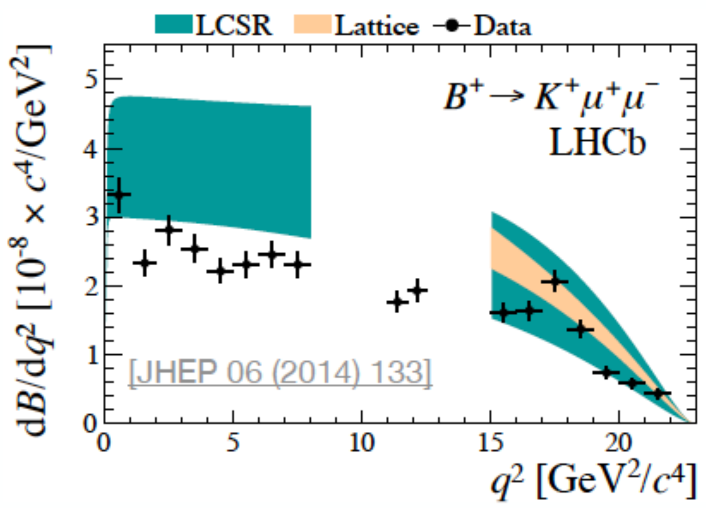
$R^{KK\pi^0}$	$=$	1.021	$\pm$	0.079	$\pm$	0.005
$R^{\pi\pi\pi^0}$	$=$	0.902	$\pm$	0.041	$\pm$	0.004
$A_K^{K\pi\pi^0}$	$=$	-0.024	$\pm$	0.013	$\pm$	0.002
$A_K^{KK\pi^0}$	$=$	0.067	$\pm$	0.073	$\pm$	0.003
$A_K^{\pi\pi\pi^0}$	$=$	0.109	$\pm$	0.043	$\pm$	0.003
$A_\pi^{KK\pi^0}$	$=$	-0.001	$\pm$	0.019	$\pm$	0.002
$A_\pi^{\pi\pi\pi^0}$	$=$	0.001	$\pm$	0.010	$\pm$	0.002
R_K^+	$=$	0.0179	$\pm$	0.0024	$\pm$	0.0003
R_K^-	$=$	0.0085	$\pm$	0.0020	$\pm$	0.0004
R_π^+	$=$	0.00188	$\pm$	0.00027	$\pm$	0.00005
R_π^-	$=$	0.00227	$\pm$	0.00028	$\pm$	$0.00004,$



Global maximum $\gamma = (145^{+9}_{-39})^{\circ}$

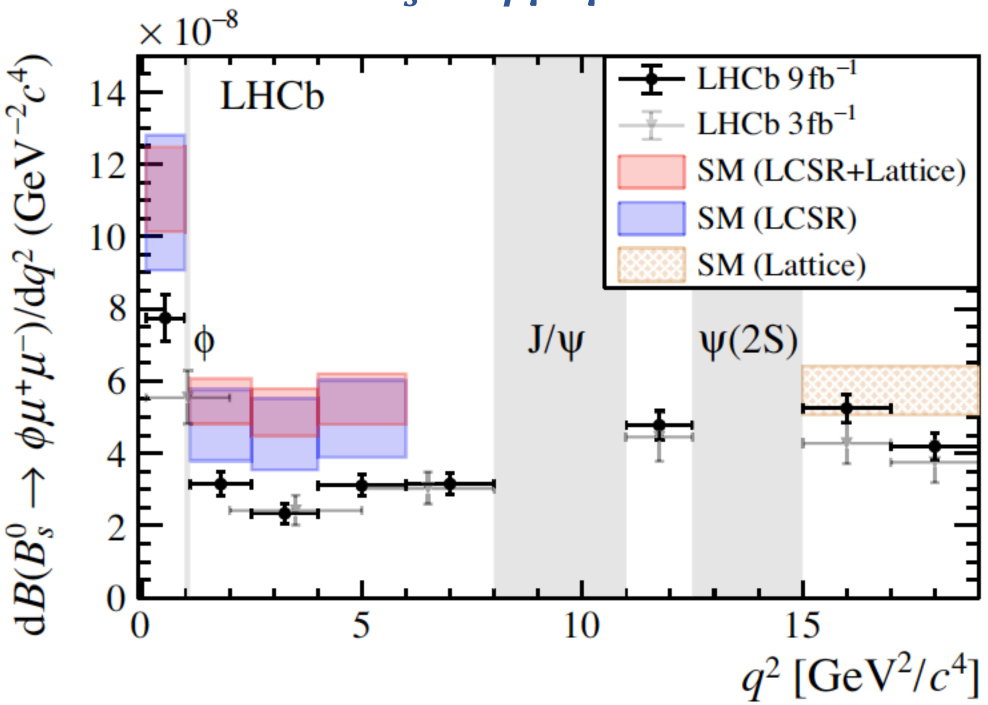
$$\begin{aligned} \gamma &= (56^{+24}_{-19})^{\circ}, \\ \delta_B &= (122^{+19}_{-23})^{\circ}, \\ r_B &= (9.3^{+1.0}_{-0.9}) \times 10^{-2}, \end{aligned}$$

Other branching fractions



2105.14007

$B_s^0 \to \phi\mu^+\mu^-$



https://arxiv.org/pdf/2103.11769

LFU violation in $B^+ \to K^+ \ell^+ \ell^-$

$$R_K = \frac{Br(B \to K\mu^+\mu^-)}{Br(B \to Ke^+e^-)}$$

The quantity of interest

$$R_K = \frac{B^- \to K^-\mu^+\mu^- / B^- \to J/\psi(\to \mu^+\mu^-)K^-}{B^- \to K^-e^+e^- / B^- \to J/\psi(\to e^+e^-)K^-}$$

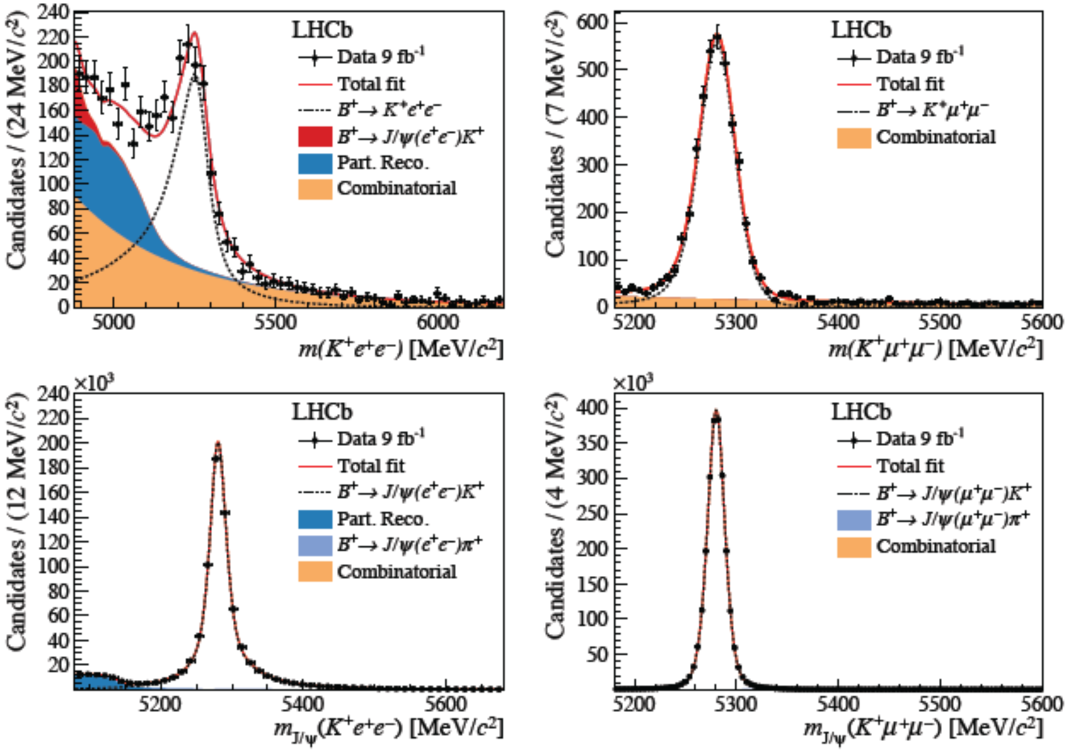
The quantity measured: double ratio of corrected yields, only relative efficiency needed

$$R_{J/\psi} = \frac{B^- \to J/\psi(\to \mu^+\mu^-)K^-}{B^- \to J/\psi(\to e^+e^-)K^-} = 0.981 \pm 0.020$$

$$\frac{d\mathcal{B}(B^- \to K^-e^+e^-)}{dq^2} = (28.6^{+1.5}_{-1.4} \pm 1.3)\times 10^{-9}/GeV^2$$

In $1.1<q^2<6.0$ GeV^2, consistent with SM expectations

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012},$$



arXiv:2110.09501

LFU in the isospin partners $B^0 \to K_s^0 \ell^+ \ell^-$, $B^+ \to K^{*+} \ell^+ \ell^-$

$$R_{K_S^0} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$$

Consistent with SM at 1.5 σ

$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

Consistent with SM at 1.4 σ