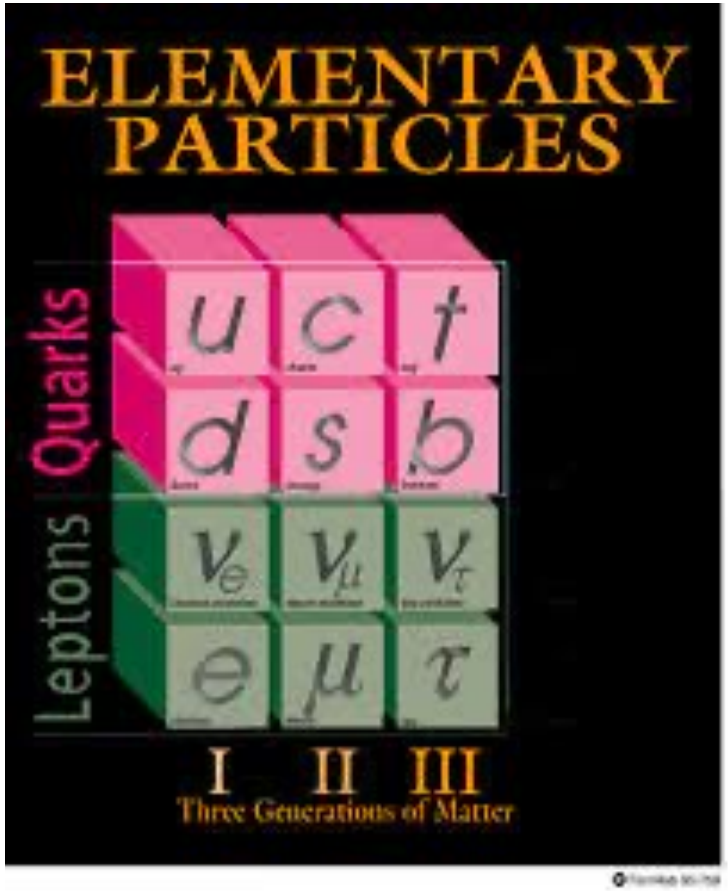
Flavor physics: current status and future goals

Marina Artuso

An experimentalist perspective

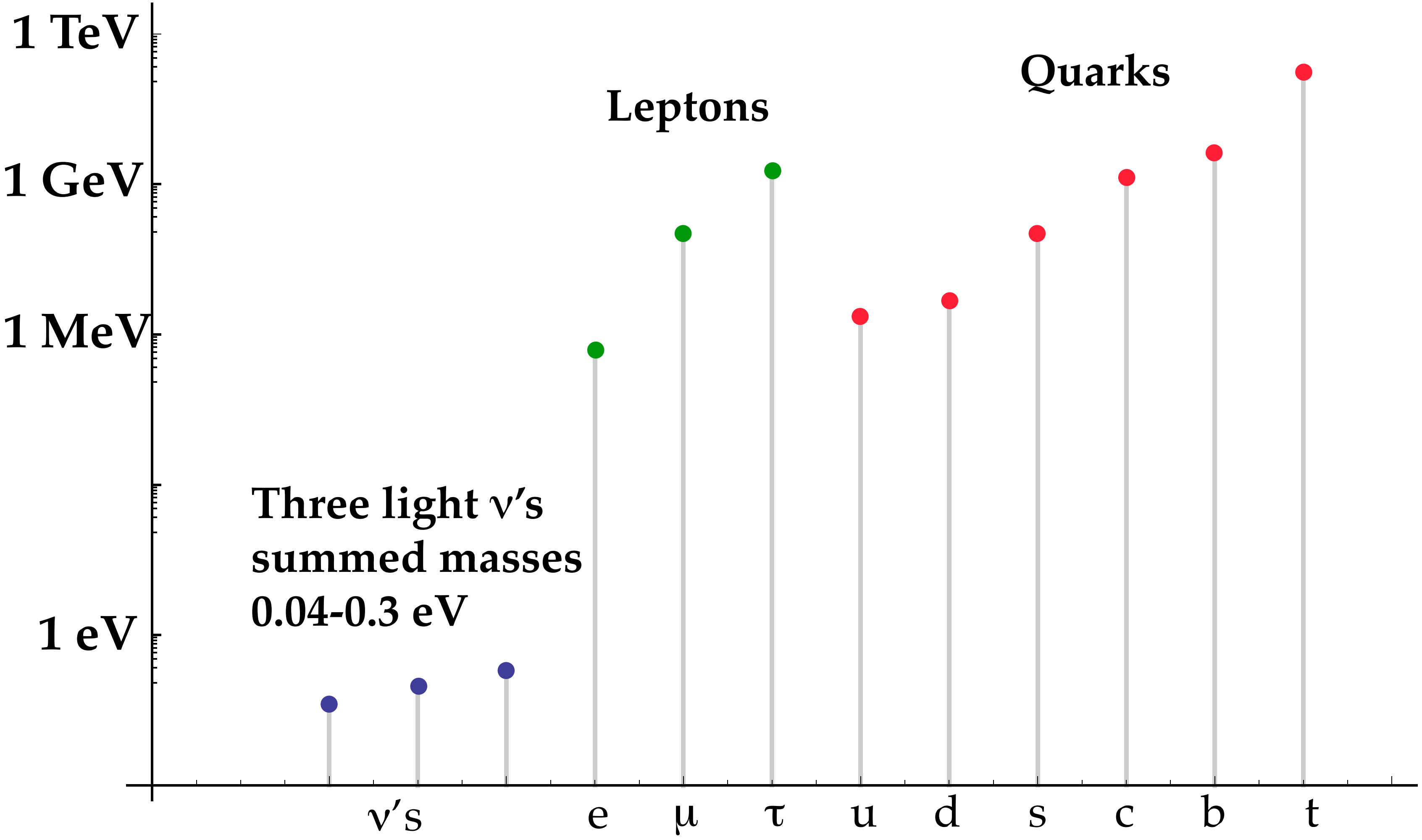
What about flavor physics?



Who ordered them?

Flavor physics is the physics that distinguishes the 3 generations: in the Standard Model described by the Yukawa Lagrangian (fermion masses and couplings)

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

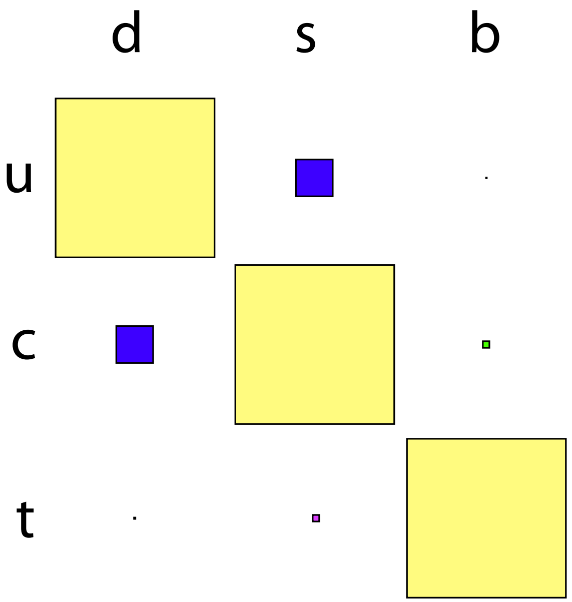
Quark sector: **C**abibbo **K**obayashi **M**askawa matrix

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

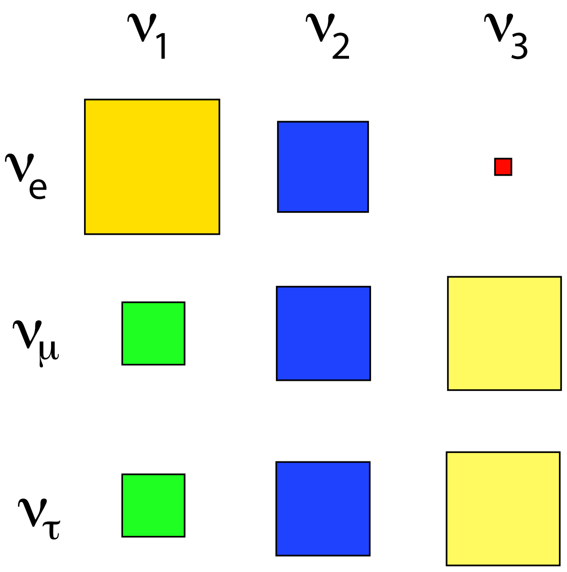
Lepton sector: **P**ontercorvo-**M**aki-**N**akagawa-**S**akata matrix

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

CKM



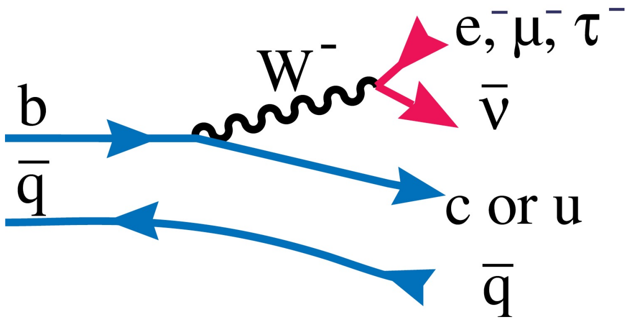
PMNS



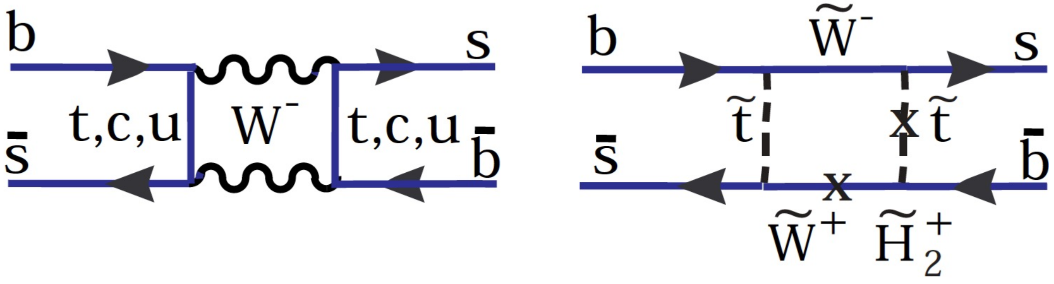
Flavor physics as a tool for discovery

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

Tree diagram example



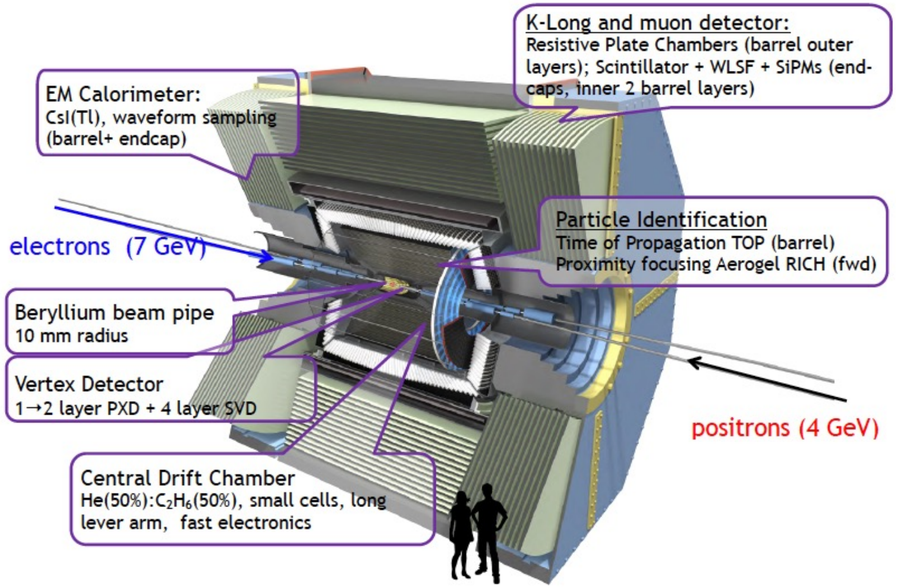
Loop diagram example: $B - \bar{B}$ mixing



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

Experimental techniques

e^+e^- colliders



K-Long and muon detector:
Resistive Plate Chambers (barrel outer layers); Scintillator + WLSF + SiPMs (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel+ endcap)

Particle Identification
Time of Propagation TOP (barrel)
Proximity focusing Aerogel RICH (fwd)

electrons (7 GeV)

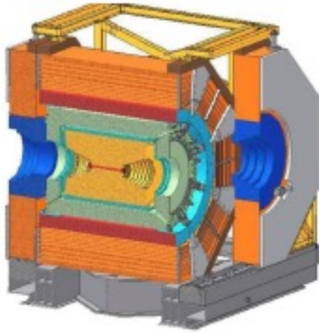
Beryllium beam pipe
10 mm radius

Vertex Detector
1→2 layer PXD + 4 layer SVD

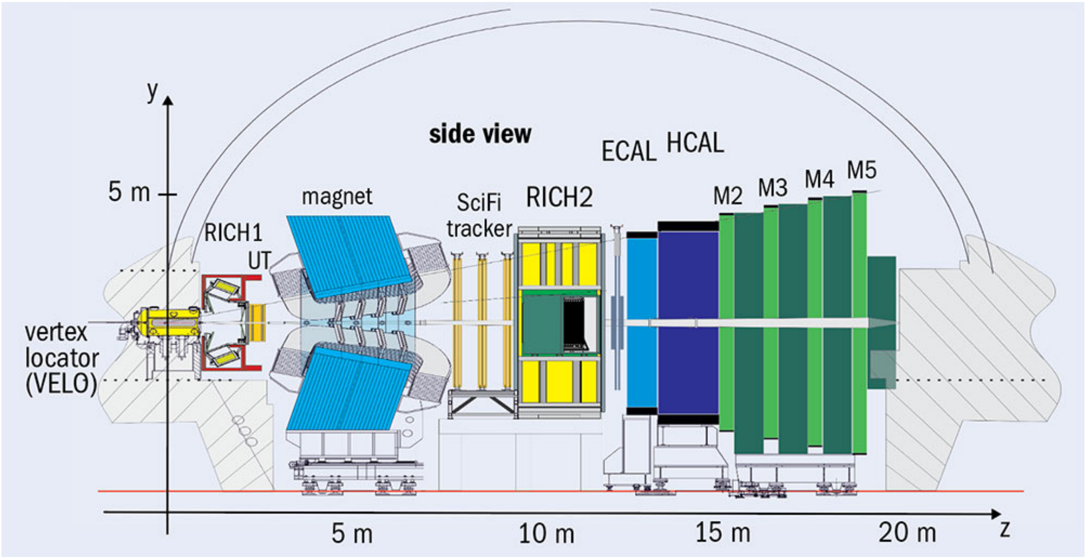
positrons (4 GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

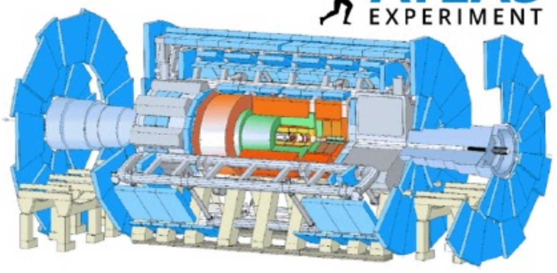
BESIII



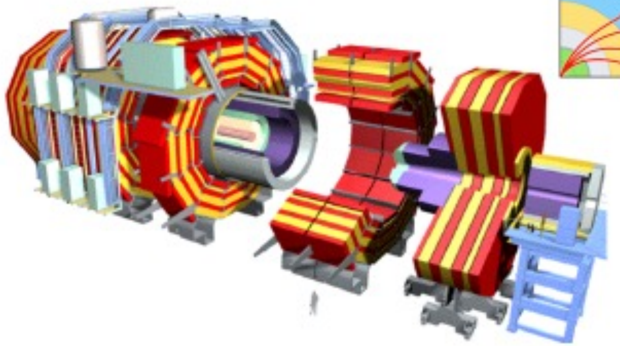
Hadron machines



ATLAS EXPERIMENT



CMS



Advantages of e+e- machines:

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

On the other hand:

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

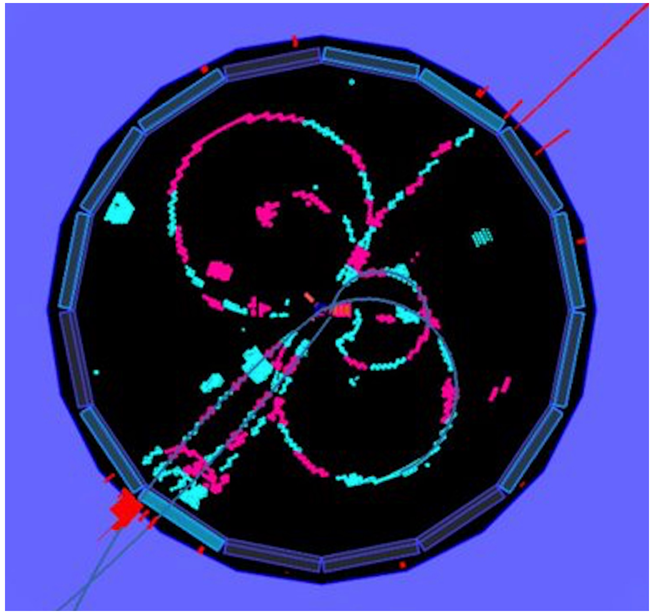
Advantages of experiments at LHC:

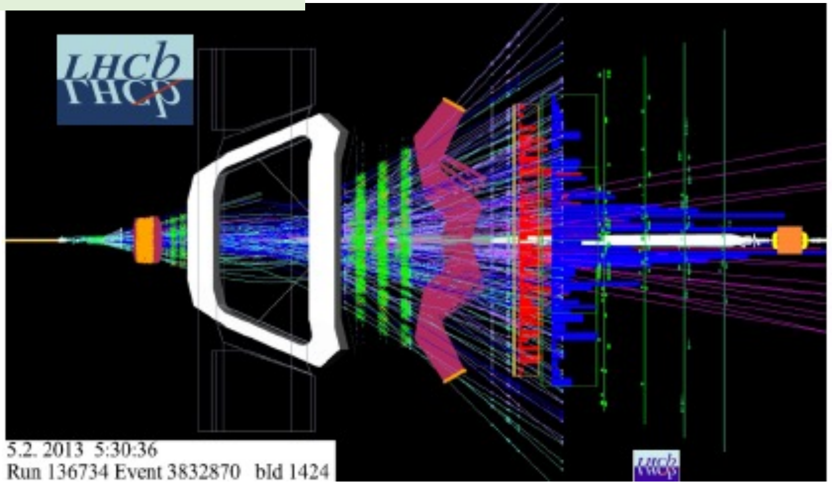
- High statistics, lots of flavored hadron species.
- Boost of the beauty and charmed hadrons and excellent vertex detectors allow precision measurement of the vertex topology information.

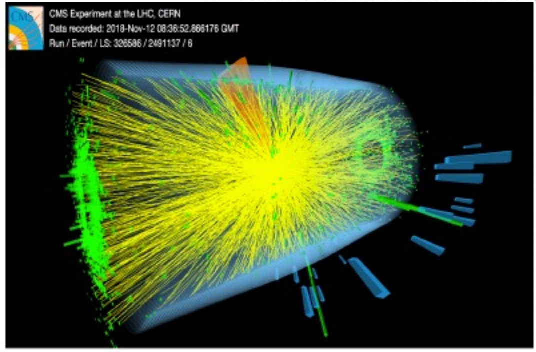
Dedicated flavor experiments feature excellent hadron identification

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

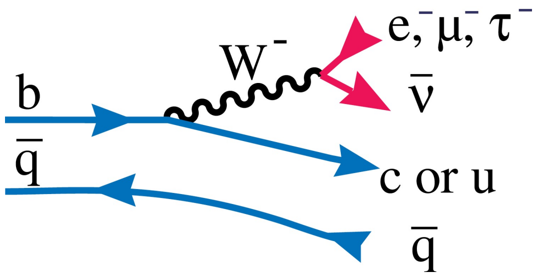




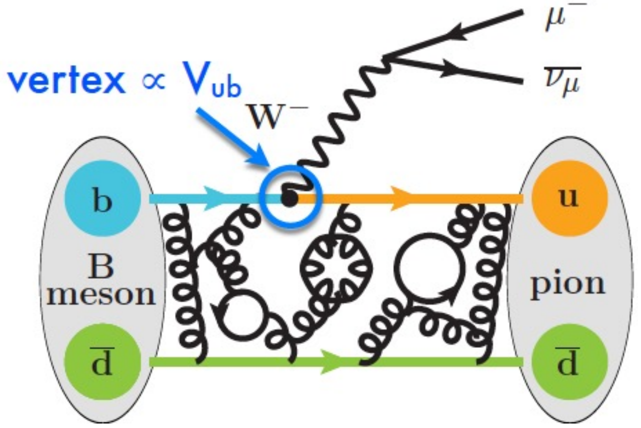


Interplay between theory and experiment

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



In reality



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

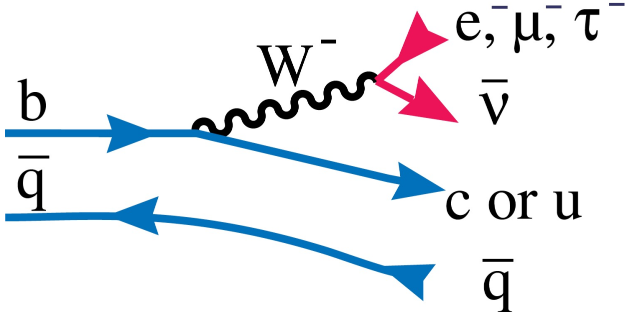
Inclusive processes

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

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

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*

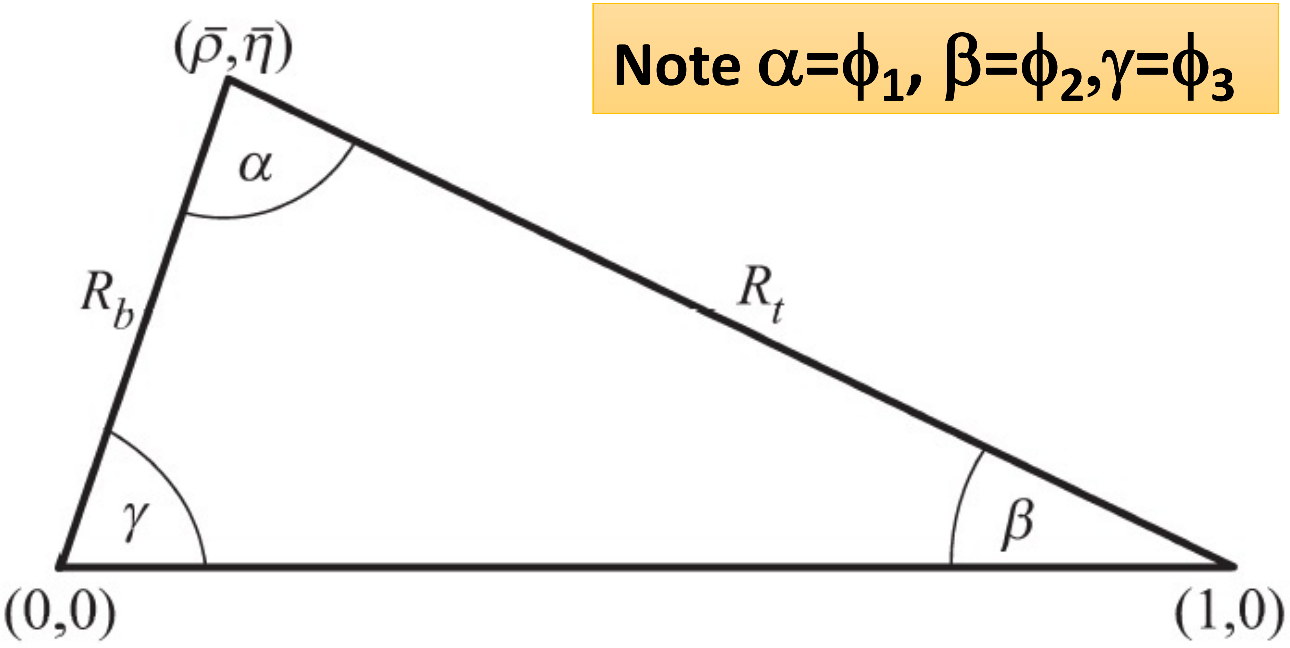
The reference unitarity triangle

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

Triangles depict unitarity constraints

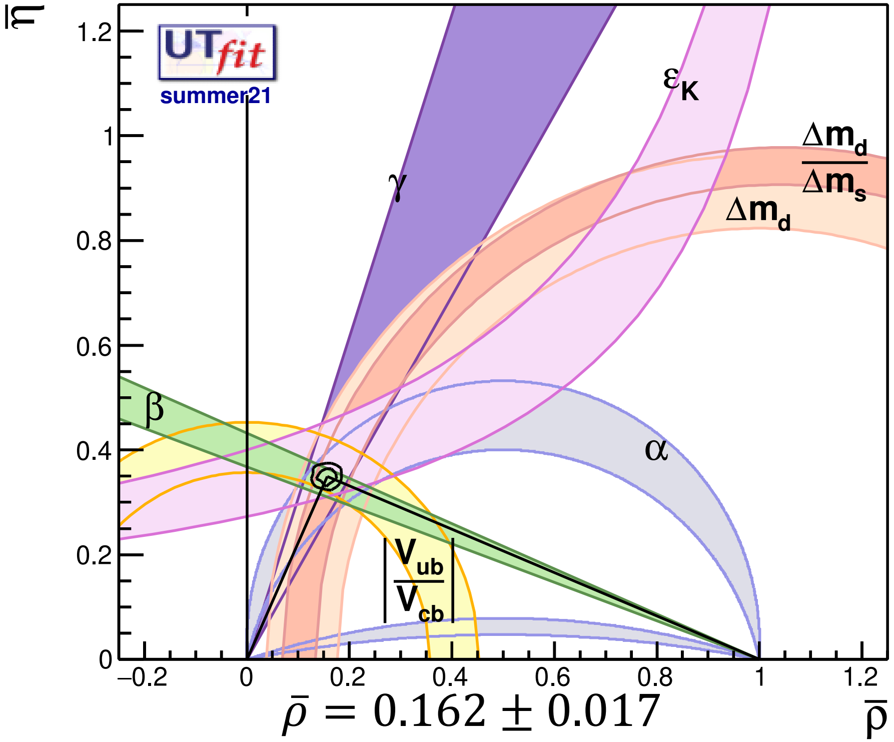
R_b, γ should establish the SM foundation (tree level processes)

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



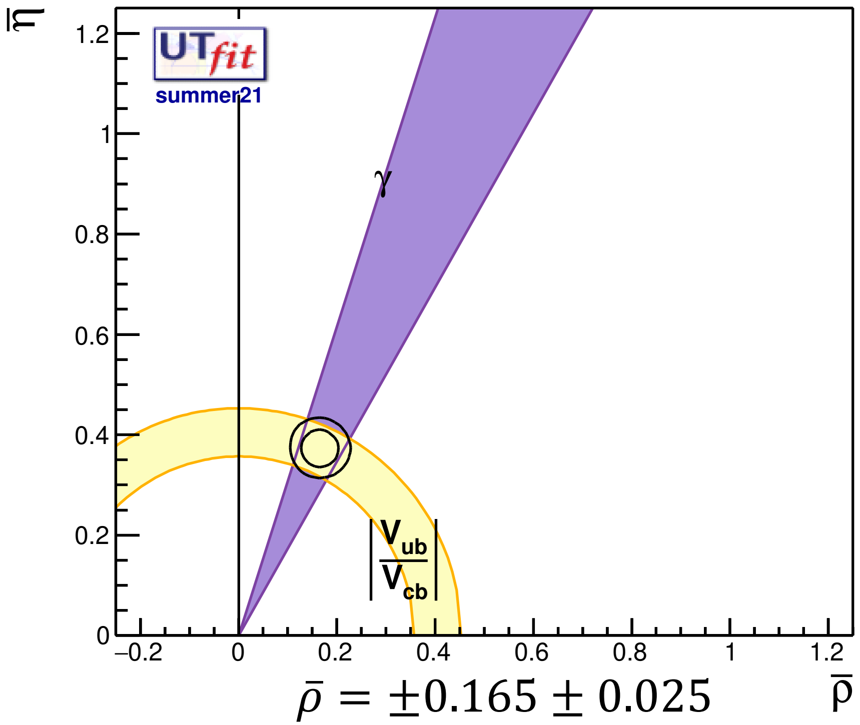
The reference unitarity triangle now

5-10% resolution on individual measurements, lots of room for improvement



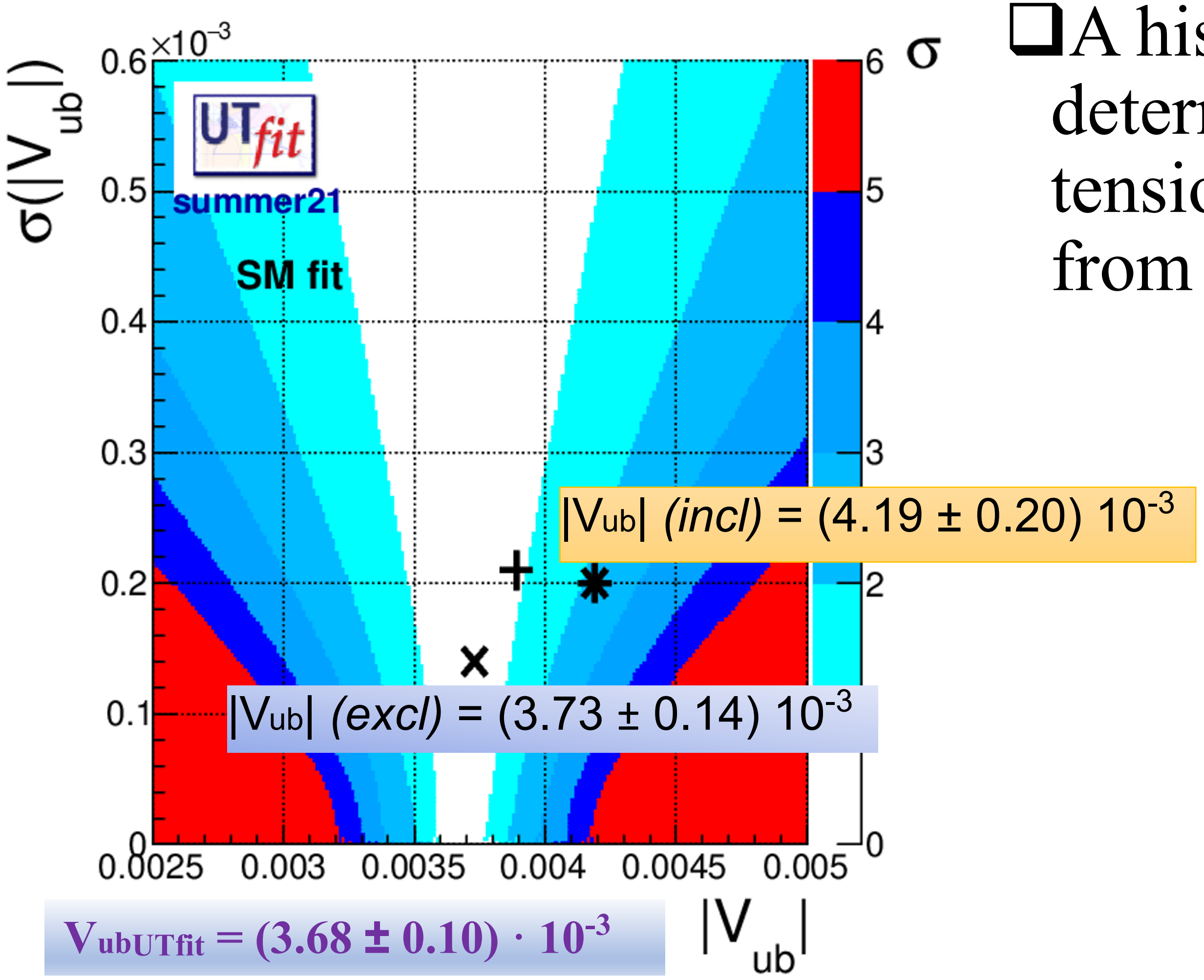
$$\bar{\rho} = 0.162 \pm 0.017$$
$$\bar{\eta} = 0.341 \pm 0.011$$

Information from "tree" quantities



$$\bar{\rho} = \pm 0.165 \pm 0.025$$
$$\bar{\eta} = \pm 0.373 \pm 0.025$$

A historic tension to be resolved

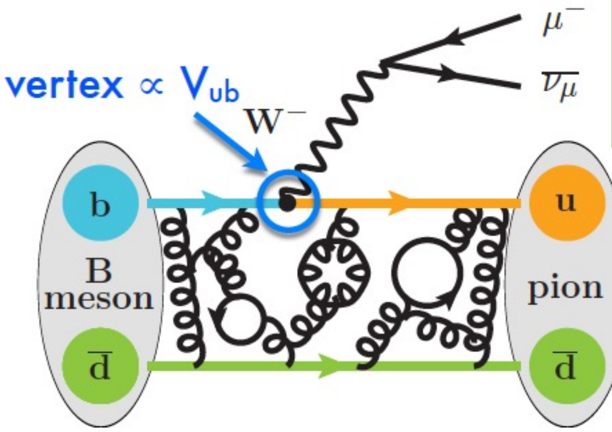


$|V_{ub}|$ *(incl)* = $(4.19 \pm 0.20)\ 10^{-3}$

$|V_{ub}|$ *(excl)* = $(3.73 \pm 0.14)\ 10^{-3}$

$V_{ubUTfit} = (3.68 \pm 0.10) \cdot 10^{-3}$

- ❑A historic tension: both |Vub| and |Vcb| determination encompass a persisting tension between the values extracted from **inclusive** or **exclusive** final state



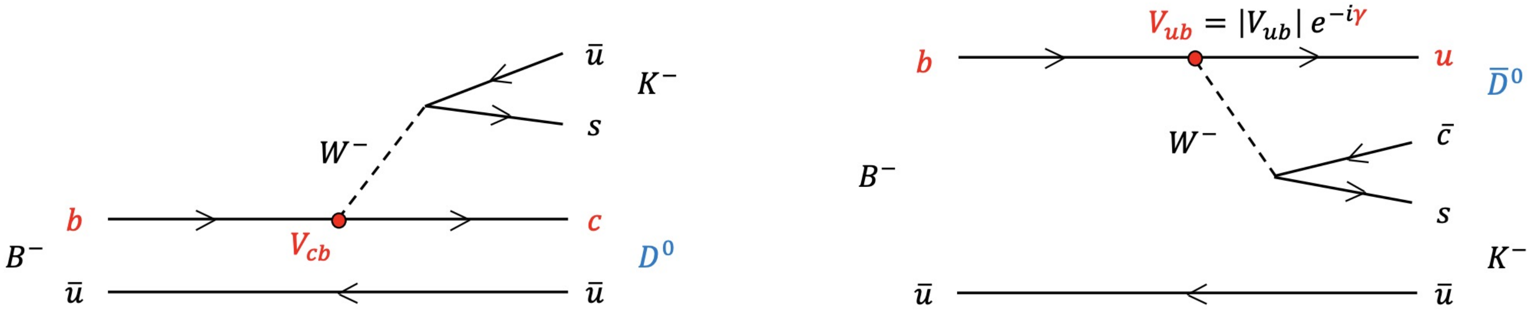
Inclusive: reconstruct a physical property such as lepton momentum spectrum integrated over final state

Exclusive: reconstruct the hadron in the final state

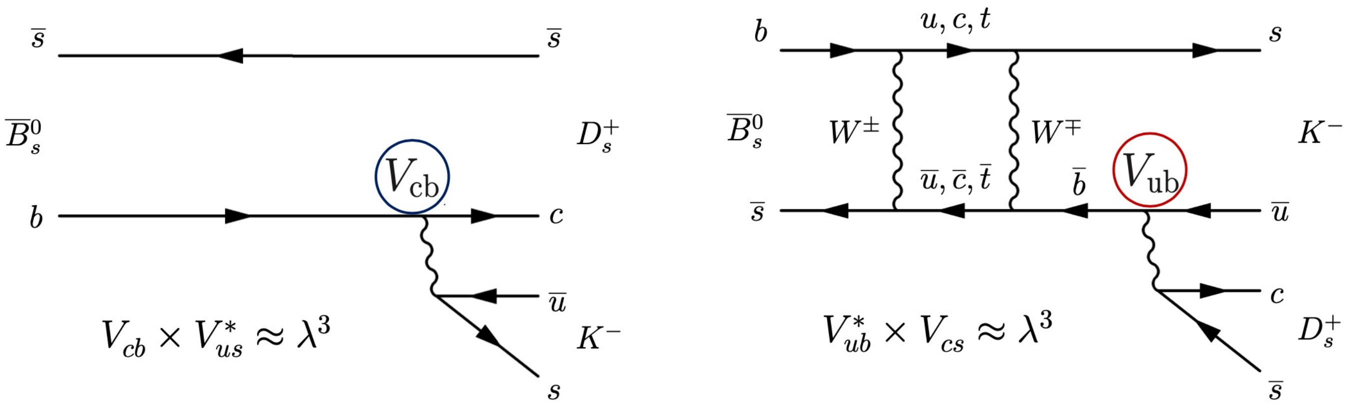
A pillar in our Standard Model challenge: the angle γ

- ☐ 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

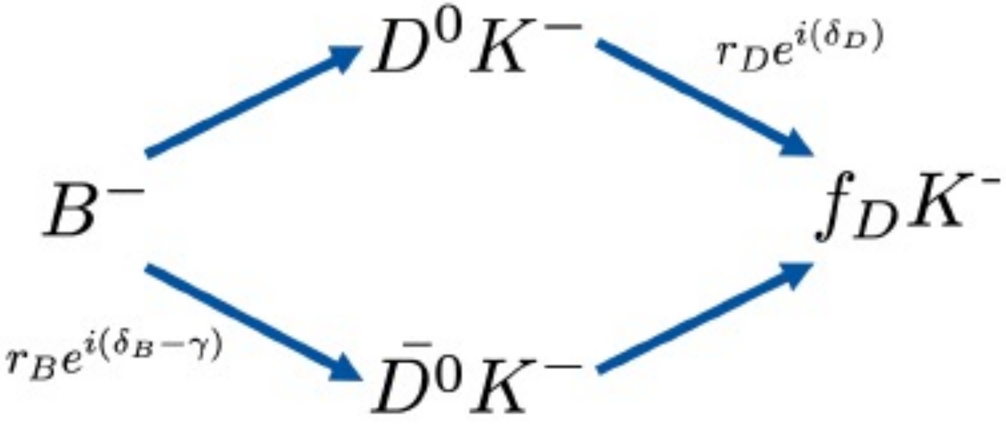


$V_{cb} \times V^*_{us} \approx \lambda^3$

$V^*_{ub} \times V_{cs} \approx \lambda^3$

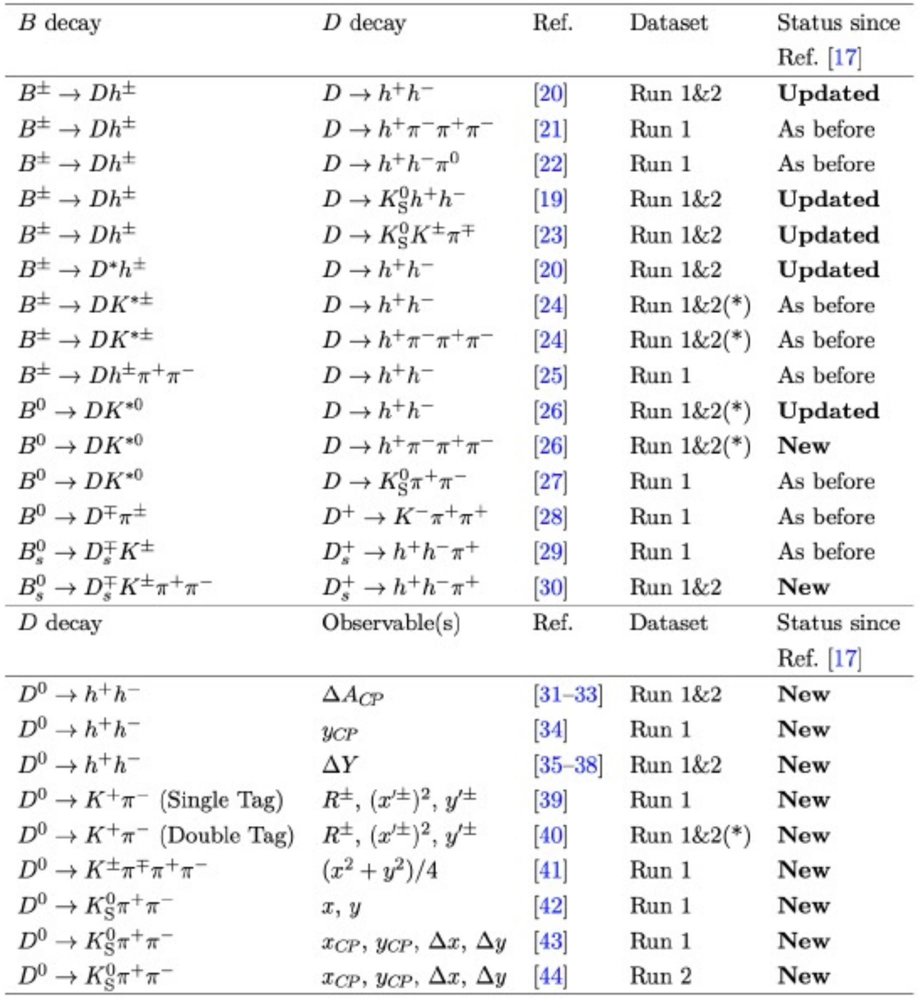
Most recent LHCb combination

- 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 $\Longrightarrow$ New combination of γ and charm mixing parameters arXiV:2110.023350

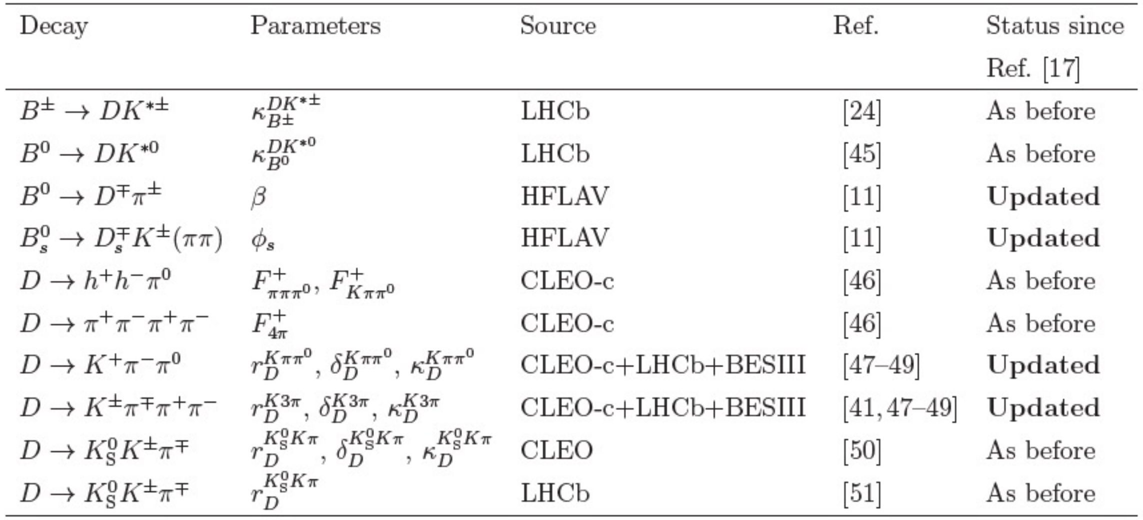


Measurements used in the combination

- ❑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

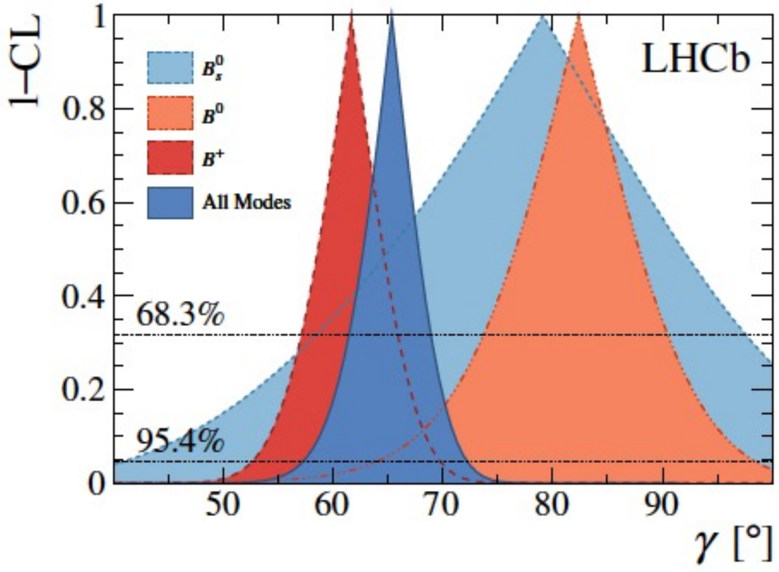


B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	[19]	Run 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

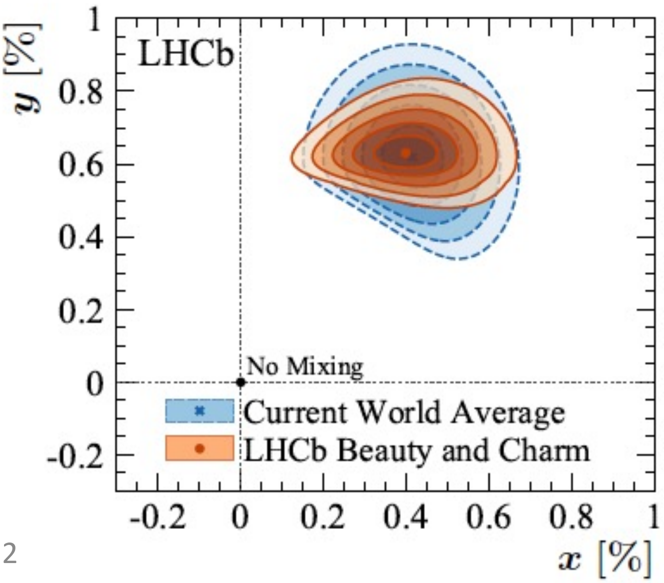
Results:

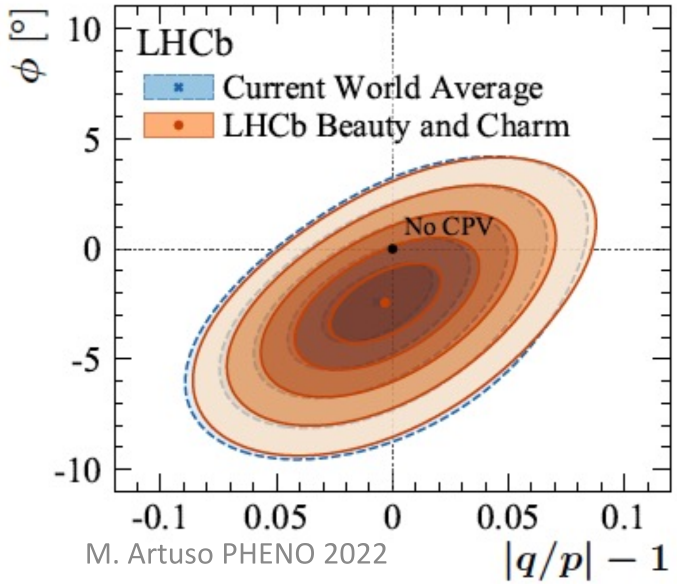


Species	Value [°]	68.3% CL Uncertainty	68.3% CL Interval	95.4% CL Uncertainty	95.4% CL Interval
B^+	61.7	$^{+4.4}_{-4.8}$	[56.9, 66.1]	$^{+8.6}_{-9.5}$	[52.2, 70.3]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B_s^0	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

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

Average of all the measurements



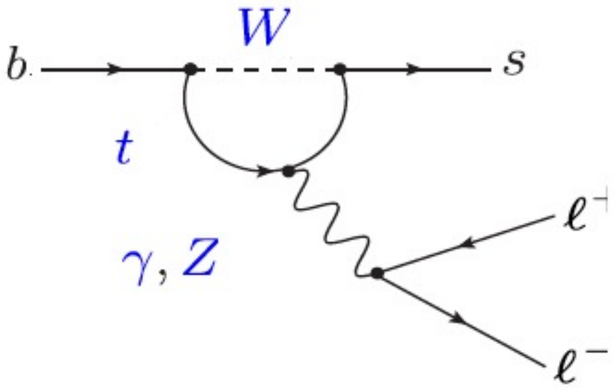


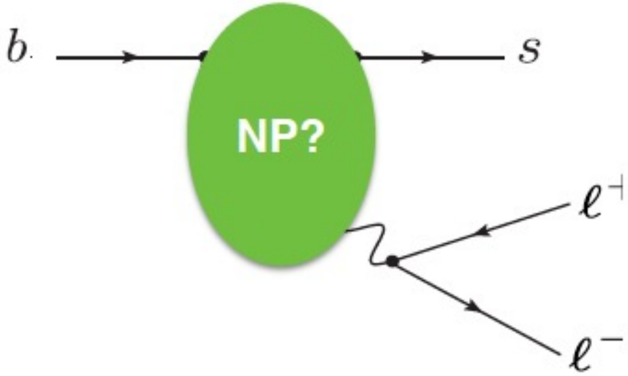
$$x \equiv \frac{\Delta M}{\Gamma} = 0.400^{+0.052}_{-0.053}$$

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

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

Rare decays and generic searches for new physics





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

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

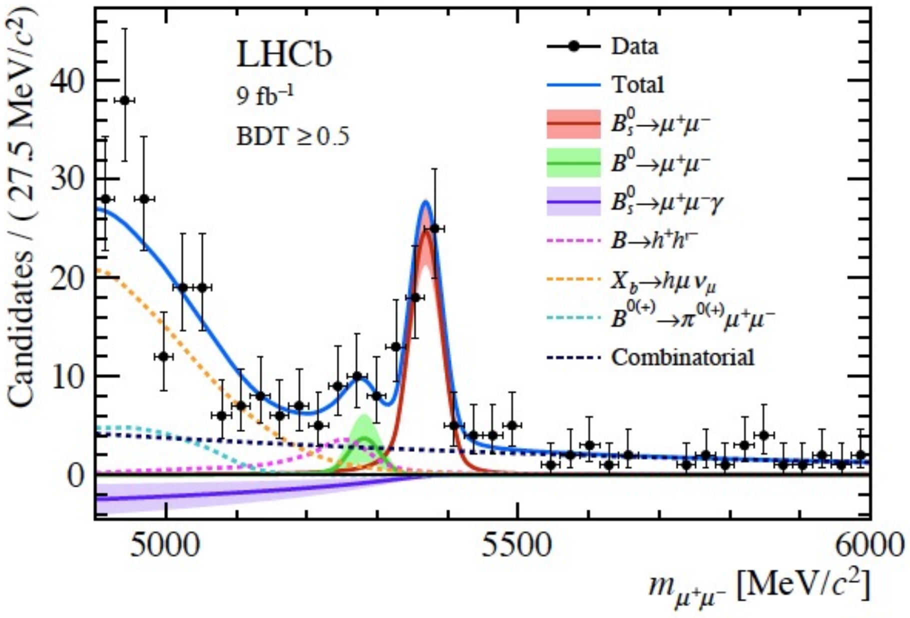
i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

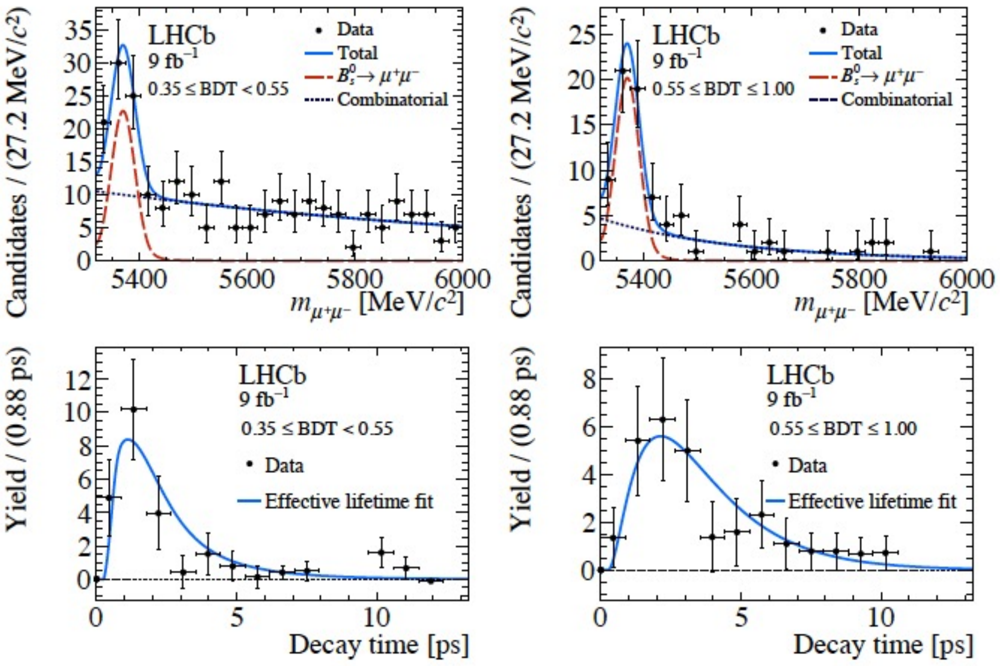
How can we pin down new physics contributions?

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

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

arXiV 2108.09284





$$\tau\,(B_s^0 \to \mu^+\mu^-) = (2.07 \pm 0.29 \pm 0.03)\mathrm{ps}$$

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

$$\left[\tau\,(B_s^0 \to \mu^+\mu^-) = \frac{\tau_{B_s^0}\left(1 + 2A^{\mu\mu}_{\Delta\Gamma_s} y_s + y_s^2\right)}{\left(1 - y_s^2\right)\left(1 + A^{\mu\mu}_{\Delta\Gamma_s} y_s\right)}\right]$$

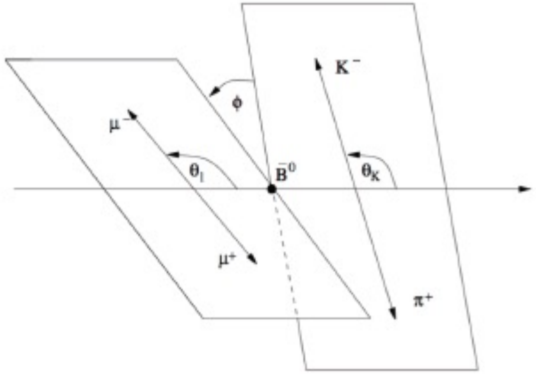
SM predictions:

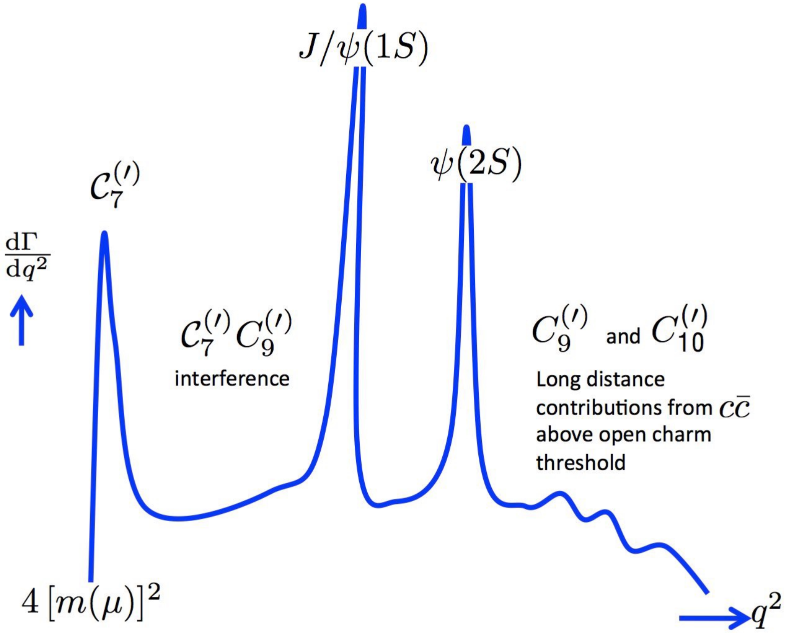
$$\overline{\mathrm{Br}}^{(0)}_{s\mu} = \begin{pmatrix}3.599\\ 3.660\end{pmatrix}\left[1 + \begin{pmatrix}0.032\\ 0.011\end{pmatrix}_{f_{B_s}} + 0.031|_{\mathrm{CKM}} + 0.011|_{m_t} + 0.006|_{\mathrm{pmr}} + 0.012|_{\text{non-pmr}}\ {}^{+0.003}_{-0.005}|_{\mathrm{LCDA}}\right]\cdot 10^{-9},$$

arXiV:1908.07011
Note: they use $|V_{cb}|$ inclusive

$B \to K^* \ell^+ \ell^-$ observables

- ❑Need to select regions in q^2 not dominated by resonances
- ❑When a vector is involved in the final state many observables



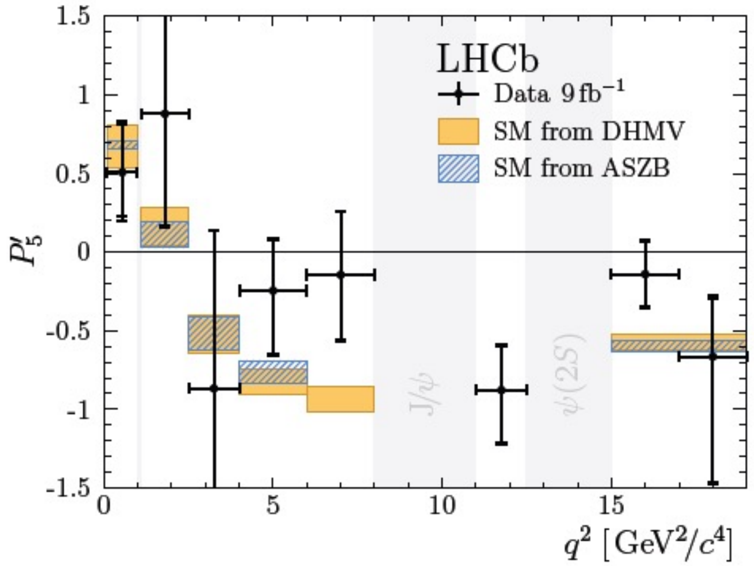


$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[& \frac{3}{4}(1-F_{\rm L})\sin^2\theta_K + F_{\rm L}\cos^2\theta_K + \frac{1}{4}(1-F_{\rm L})\sin^2\theta_K\cos 2\theta_\ell \\
& - F_{\rm L}\cos^2\theta_K\cos 2\theta_\ell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

Angular analysis of $B \to K^{*}\mu^{+}\,\mu^{-}$

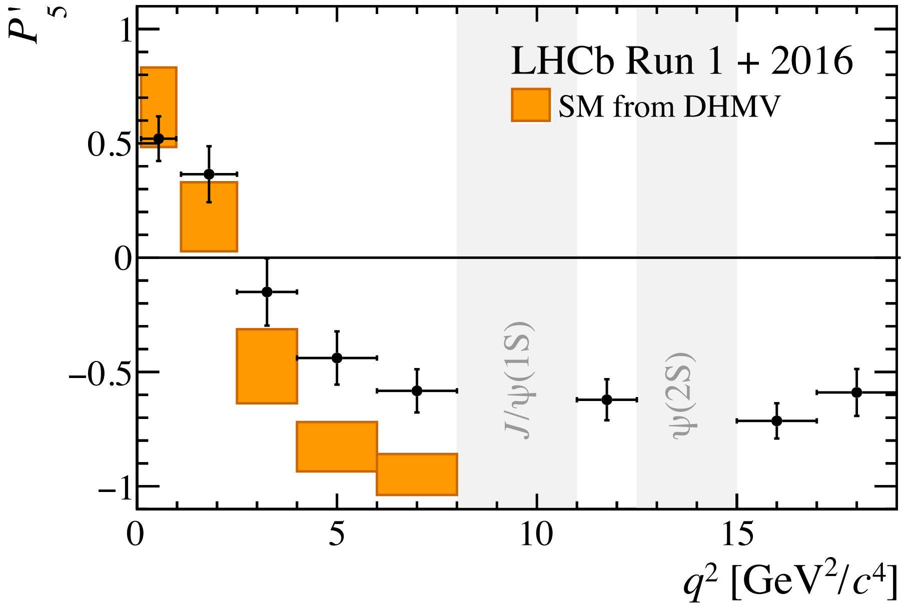
arXiV 2012.13241

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



arXiV 2003.04831

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



Local deviations from Standard Model predictions are observed, similar to those reported originally in $B^0 \to K^{*0}\mu^+\,\mu^-$, global tension depends upon which effective couplings are considered and on the choice of the theory nuisance parameters.

Lepton flavor universality in $B \to K^{(*)}\ell^+\ell^-$

- ❑In the Standard Model, couplings of the gauge bosons to leptons are independent of lepton flavor
- ❑Ratios of the form

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \cong 1 \ \text{[SM]}$$

are free from QCD uncertainties that affect other observables

- ○ Hadronic effect cancel [O(10^{-4}), JHEP 07(2007) 040]
- ○ QED corrections can be O(10^{-2}), EPJC 76 (2016) 440]

- ❑**Theory consensus: LFU violation an unambiguous sign of New Physics!**

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

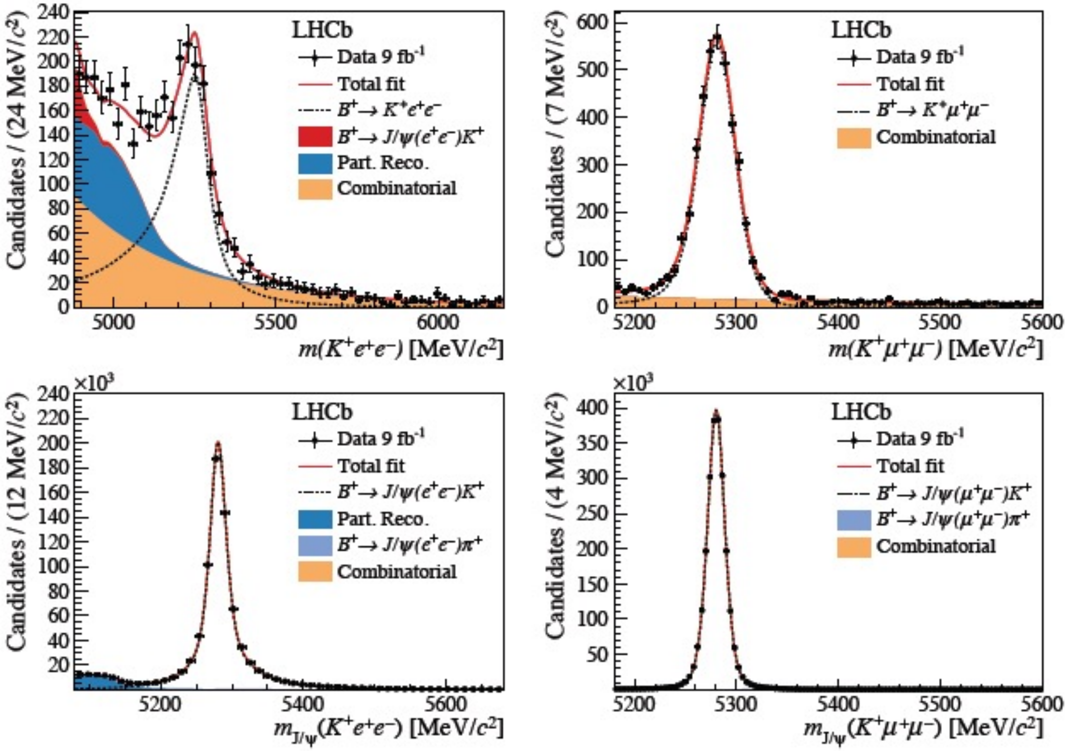
$$R_K = \frac{B^- \to K^-\mu^+\mu^- / B^- \to J/\psi(\to \mu^+\mu^-)K^-}{B^- \to K^-e^+e^- / B^- \to J/\psi(\to e^+e^-)K^-}$$

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

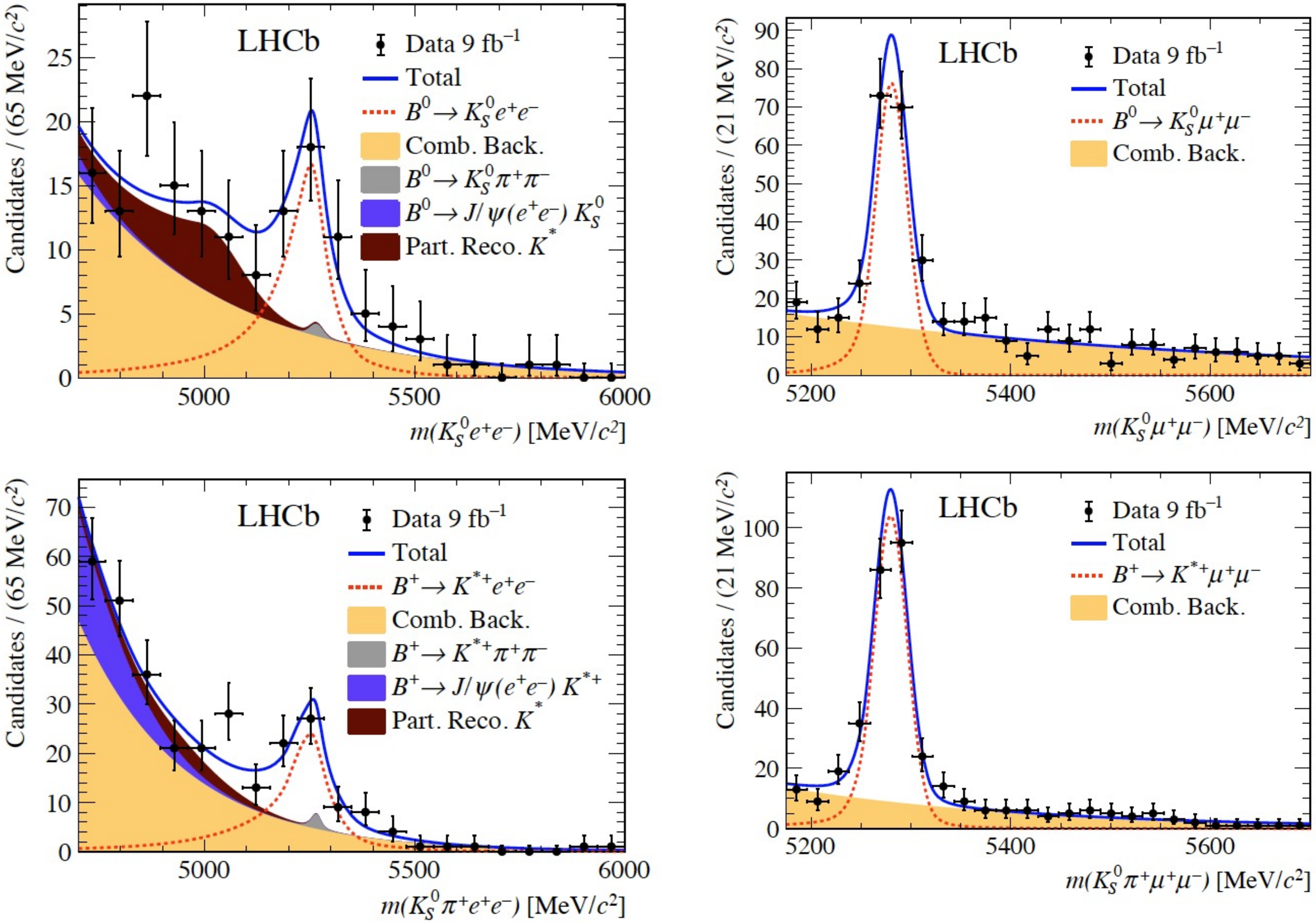
LFU in the isospin partners $\boldsymbol{B^0 \to K_s^0 \ell^+ \ell^-}$, $\boldsymbol{B^+ \to K^{*+} \ell^+ \ell^-}$

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

Consistent with SM at 1.5 σ

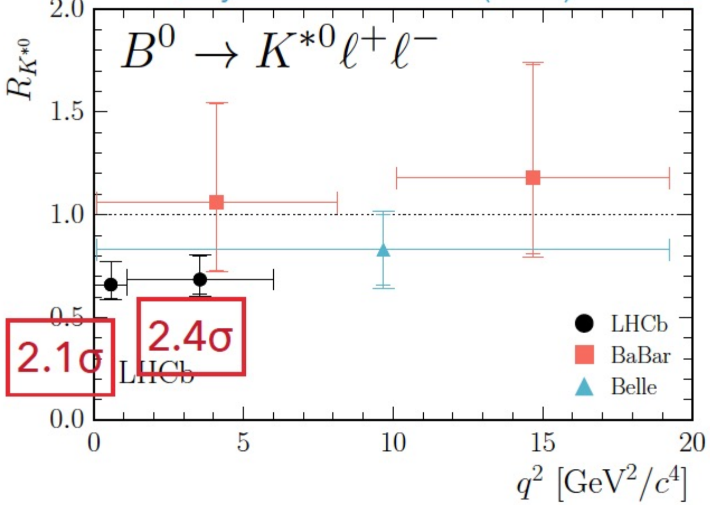
$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

Consistent with SM at 1.4 σ

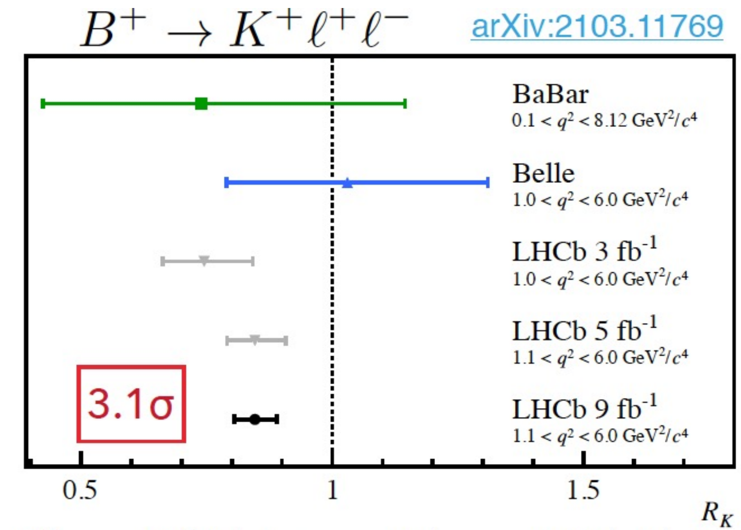


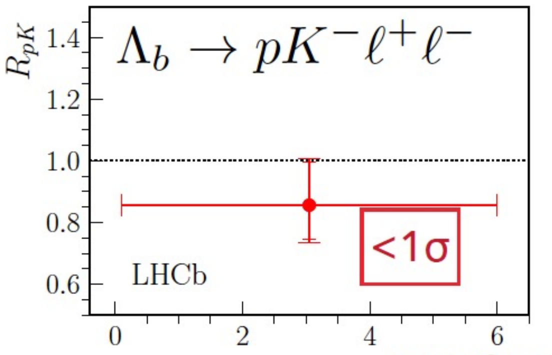
LFU ratio current status

Phys. Rev. Lett. 125 (2020) 011802

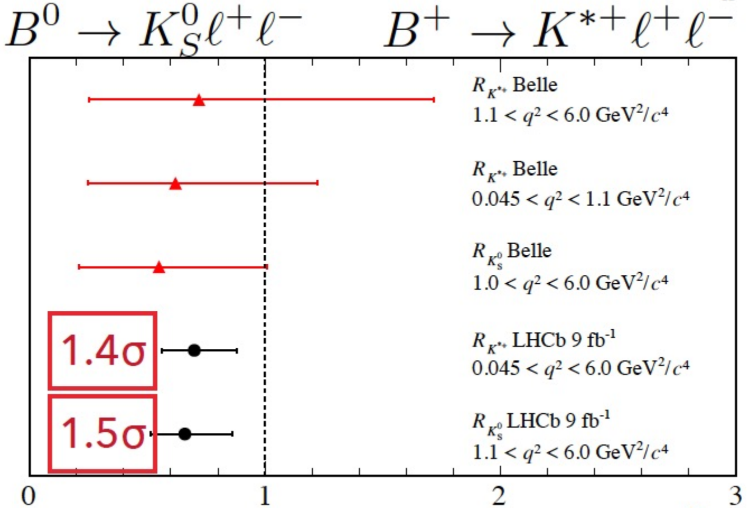


arXiv:2103.11769





JHEP 05 (2020) 040

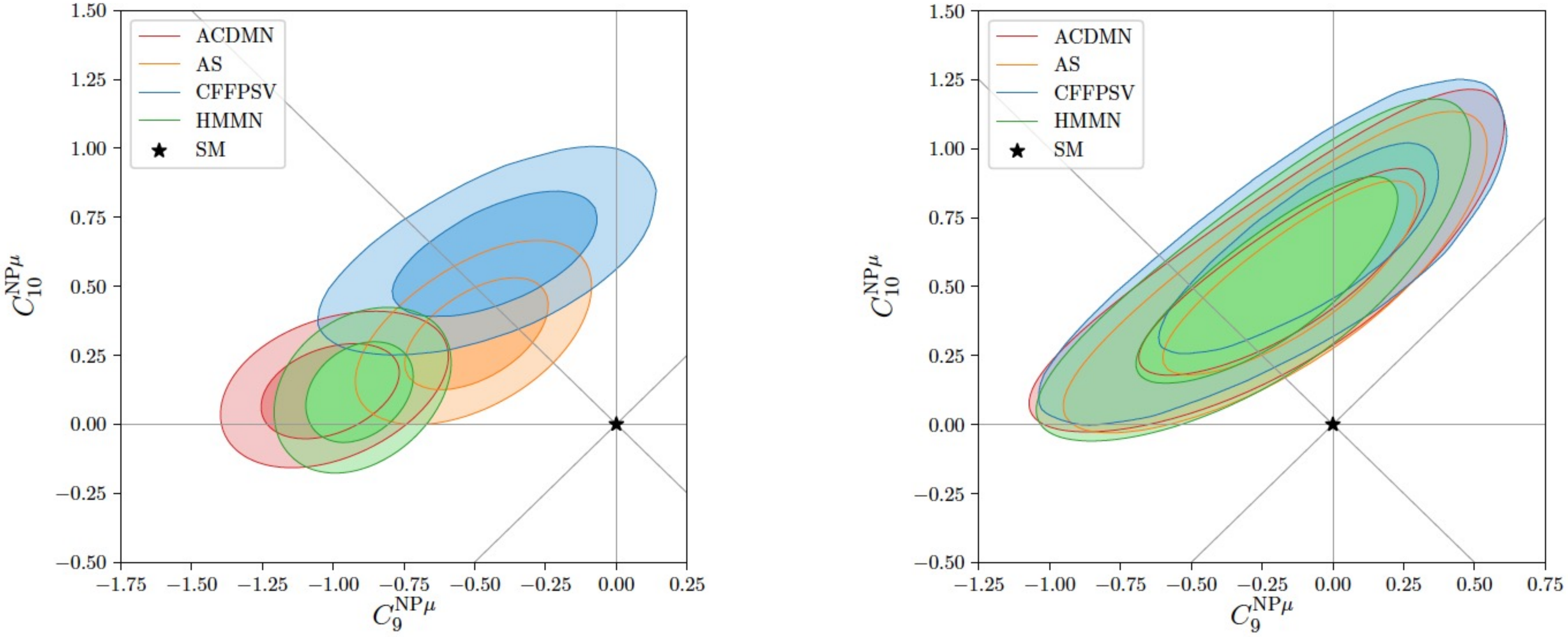


arXiv:2110.09501

Theoretical interpretation

B. Capdevila et al Flavor Anomaly Workshop '21

2-dimensional fits



global fit

fit to LFU observables + $B_s \to \mu\mu$

B. Capdevila, M. Fedele, S. Neshatpour, P. Stangl

Flavour Anomaly Workshop, 20 Oct. 2021

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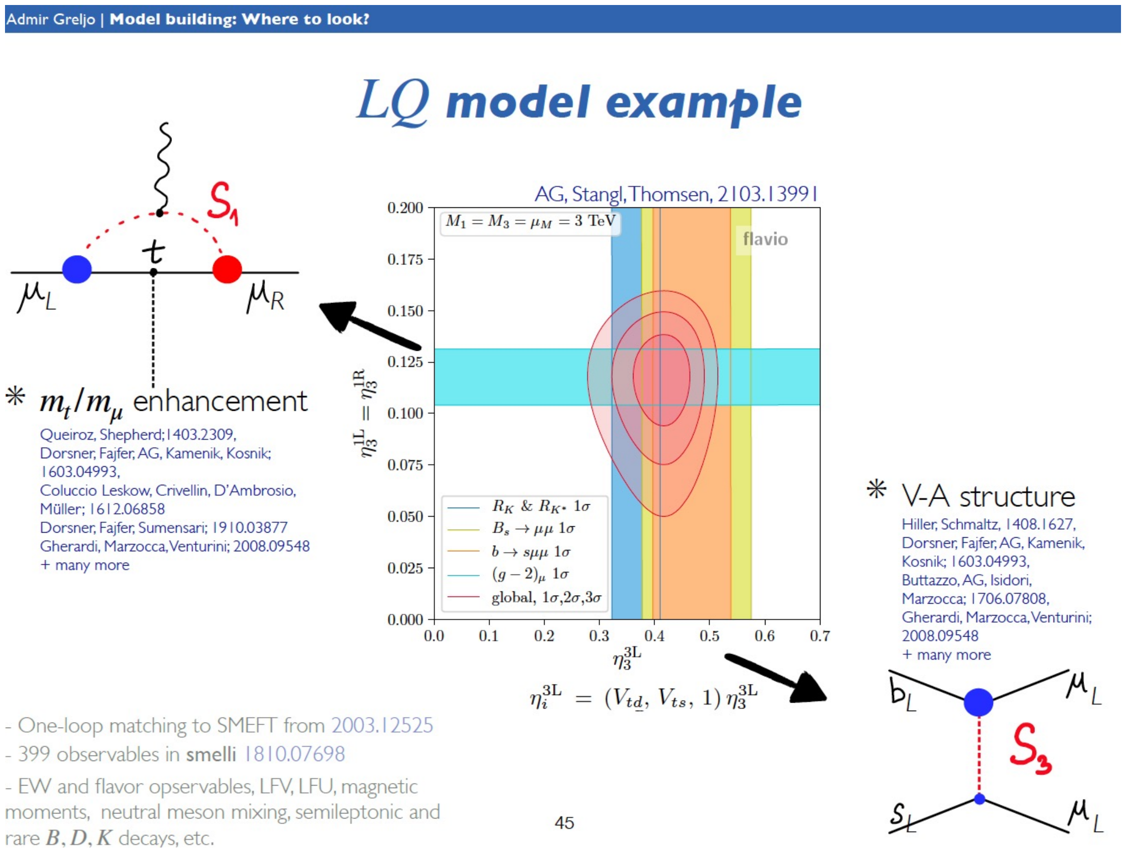
Theoretical interpretation top-down

An example from A. Greljo's presentation at the Anomaly workshop 2021



Admir Greljo | **Model building: Where to look?**

LQ model example

AG, Stangl, Thomsen, 2103.13991

* m_t/m_μ enhancement

Queiroz, Shepherd; 1403.2309,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Coluccio Leskow, Crivellin, D'Ambrosio, Müller; 1612.06858
Dorsner, Fajfer, Sumensari; 1910.03877
Gherardi, Marzocca, Venturini; 2008.09548
\+ many more

$\eta_i^{3L} = (V_{td}, V_{ts}, 1)\, \eta_3^{3L}$

* V-A structure

Hiller, Schmaltz, 1408.1627,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Buttazzo, AG, Isidori, Marzocca; 1706.07808,
Gherardi, Marzocca, Venturini; 2008.09548
\+ many more

- One-loop matching to SMEFT from 2003.12525
- 399 observables in **smelli** 1810.07698
- EW and flavor opservables, LFV, LFU, magnetic moments, neutral meson mixing, semileptonic and rare B, D, K decays, etc.

45

JHEP06 (2021) 044

Search for $D^+_{(s)} \to h^\pm\mu^+\mu^-$

- Analysed 25 decays $D^+_{(s)} \to h\ell\ell$
  - h is a charged kaon or pion
  - ℓ is an electron or muon
  - Includes LFV and LNV decays

$D^+ \to \pi^+\mu^+\mu^-$
$D^+ \to \pi^-\mu^+\mu^+$
$D^+ \to \pi^+\mu^+e^-$
$D^+ \to \pi^-\mu^+e^+$
$D^+ \to \pi^+e^+\mu^-$

$D^+ \to \pi^+e^+e^-$
$D^+ \to \pi^-e^+e^+$
$D^+ \to K^+\mu^+\mu^-$
$D^+ \to K^+\mu^+e^-$
$D^+ \to K^+e^+\mu^-$

$D^+ \to K^+e^+e^-$
$D^+_s \to \pi^+\mu^+\mu^-$
$D^+_s \to \pi^-\mu^+\mu^+$
$D^+_s \to \pi^+\mu^+e^-$
$D^+_s \to \pi^-\mu^+e^+$

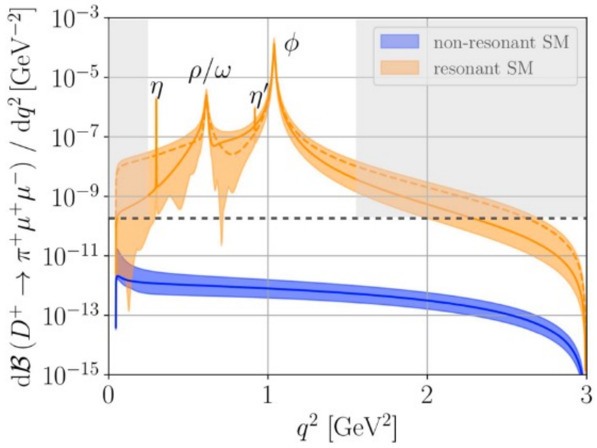
$D^+_s \to \pi^+e^+\mu^-$
$D^+_s \to \pi^+e^+e^-$
$D^+_s \to \pi^-e^+e^+$
$D^+_s \to K^+\mu^+\mu^-$
$D^+_s \to K^-\mu^+\mu^+$

$D^+_s \to K^+\mu^+e^-$
$D^+_s \to K^-\mu^+e^+$
$D^+_s \to K^+e^+\mu^-$
$D^+_s \to K^+e^+e^-$
$D^+_s \to K^-e^+e^+$

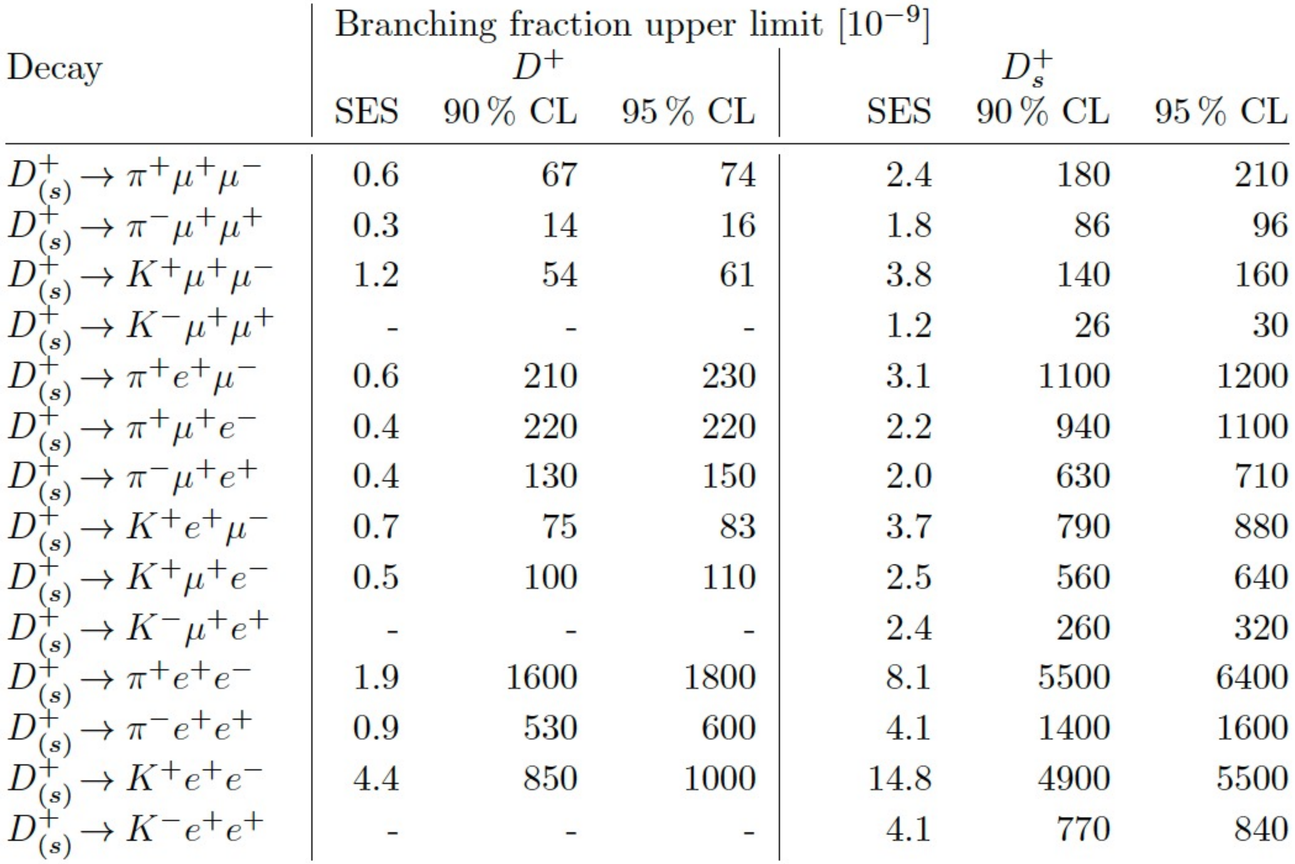
Allowed in the SM, Forbidden in the SM

- Analysis performed with 2016 dataset (1.7 fb^{-1})
- Normalisation with $D^+_{(s)} \to \phi(\ell\ell)\pi^+$
- Regions dominated by resonances in dilepton mass are vetoed when fitting for the signal

Mod. Phys. Lett. A 36 (2021) 2130002



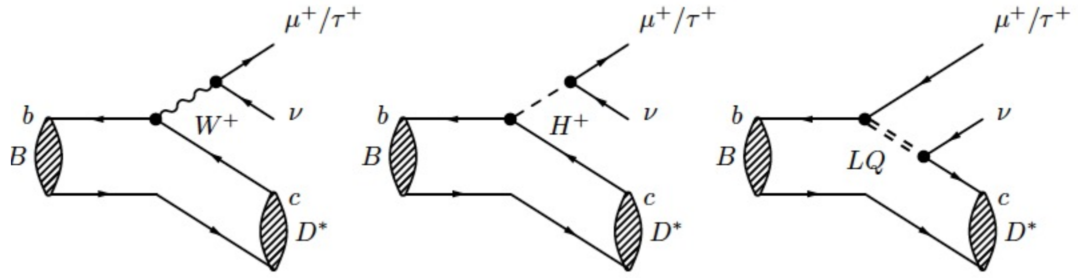
- Results consistent with background only hypothesis
- Limits set between 1.4×10^{-8} and 6.4×10^{-6}
- Results improve upon the prior world's best constraints by up to a factor of 500

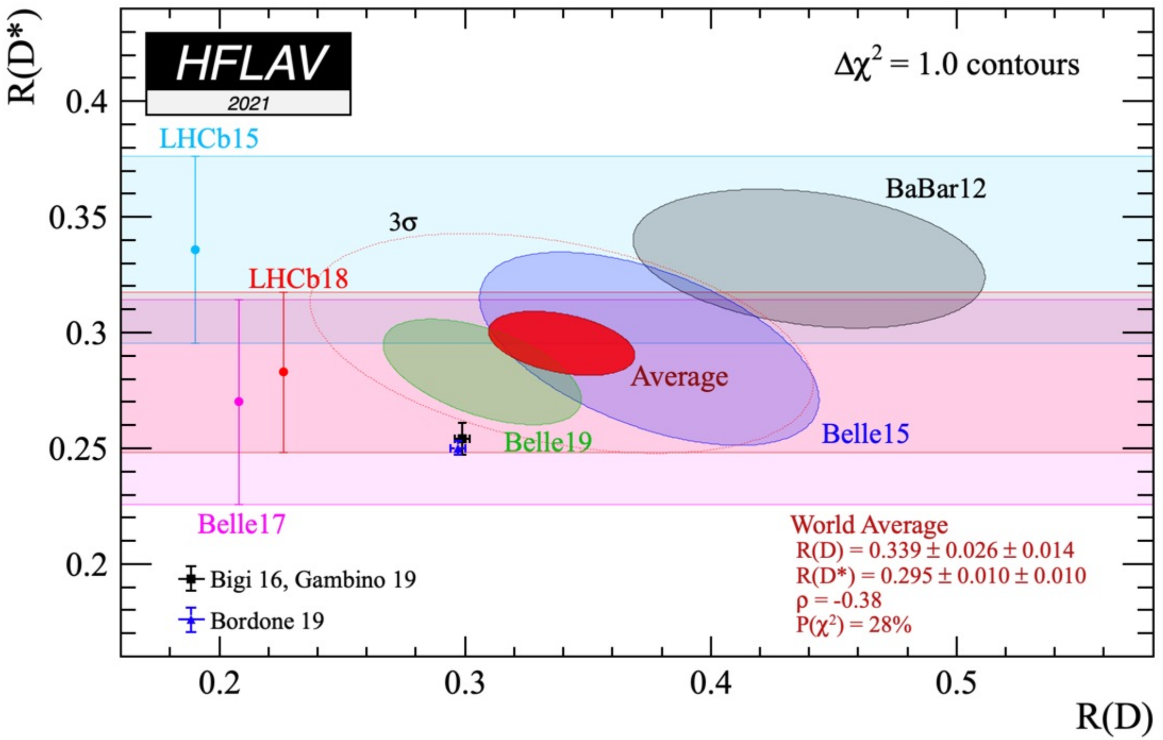


Decay	Branching fraction upper limit $[10^{-9}]$					
	D^+			D_s^+		
	SES	90 % CL	95 % CL	SES	90 % CL	95 % CL
$D^+_{(s)} \to \pi^+\mu^+\mu^-$	0.6	67	74	2.4	180	210
$D^+_{(s)} \to \pi^-\mu^+\mu^+$	0.3	14	16	1.8	86	96
$D^+_{(s)} \to K^+\mu^+\mu^-$	1.2	54	61	3.8	140	160
$D^+_{(s)} \to K^-\mu^+\mu^+$	-	-	-	1.2	26	30
$D^+_{(s)} \to \pi^+e^+\mu^-$	0.6	210	230	3.1	1100	1200
$D^+_{(s)} \to \pi^+\mu^+e^-$	0.4	220	220	2.2	940	1100
$D^+_{(s)} \to \pi^-\mu^+e^+$	0.4	130	150	2.0	630	710
$D^+_{(s)} \to K^+e^+\mu^-$	0.7	75	83	3.7	790	880
$D^+_{(s)} \to K^+\mu^+e^-$	0.5	100	110	2.5	560	640
$D^+_{(s)} \to K^-\mu^+e^+$	-	-	-	2.4	260	320
$D^+_{(s)} \to \pi^+e^+e^-$	1.9	1600	1800	8.1	5500	6400
$D^+_{(s)} \to \pi^-e^+e^+$	0.9	530	600	4.1	1400	1600
$D^+_{(s)} \to K^+e^+e^-$	4.4	850	1000	14.8	4900	5500
$D^+_{(s)} \to K^-e^+e^+$	-	-	-	4.1	770	840

SES = single event sensitivities, i.e. the BF corresponding to a single observed signal event

Lepton flavor violation in $B \to D^{(*)}\tau\nu$



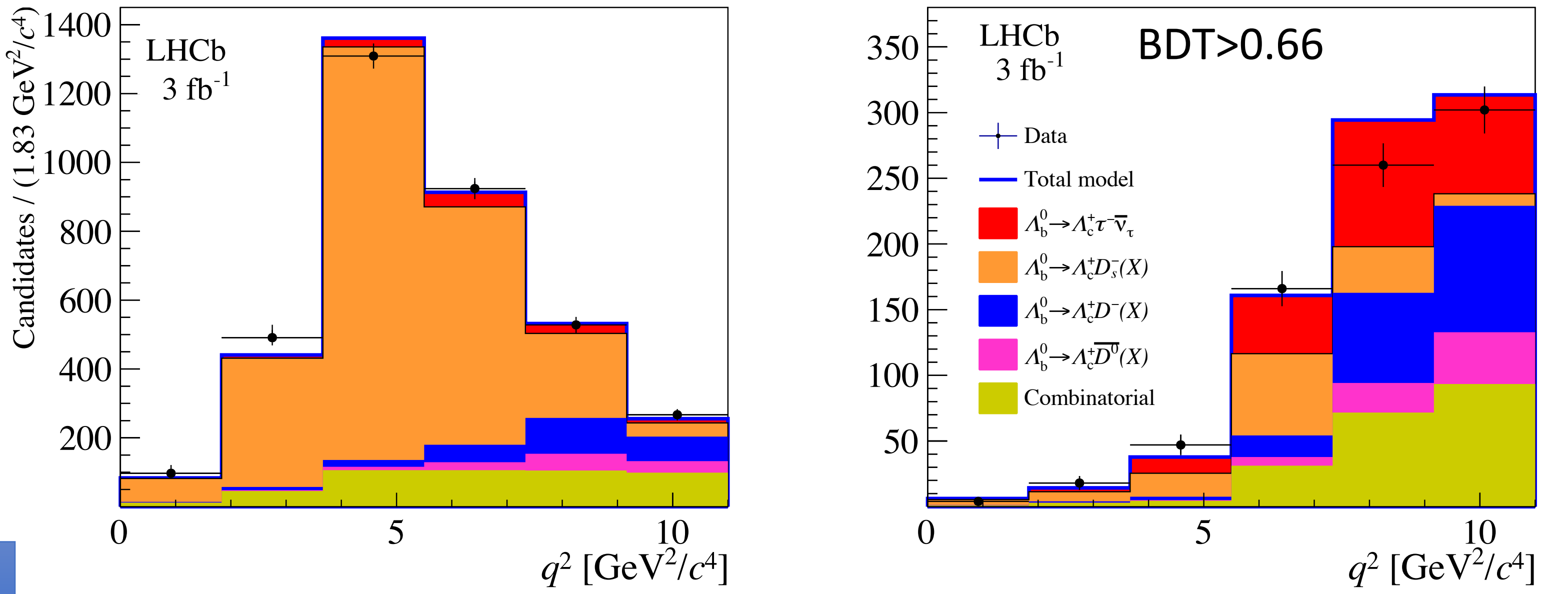


- ❑ Measured quantity: ratio $R_{D^{(*)}} \equiv \dfrac{B \to D^{(*)}\tau\nu}{B \to D^{(*)}\mu\nu}$
- ❑ Deviation from SM expectation would imply new physics at tree level
- ❑First reported by BaBar [PRL109, 101802 (2012)], 4 more measurements by BaBar, Belle & LHCb
- ❑Combined RD and RD* fit about 3.4σ from SM predictions [persistent but diminishing tension]

arXiV:2201.03497

Observation of the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$

- Key analysis features:
  - Run I data set (3fb^{-1})
  - $\tau^- \rightarrow 3\pi(\pi^0)\nu_\tau$
  - BDT to distinguish $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau$ from $\Lambda_b^0 \rightarrow \Lambda_c^+ DX$ background modeled by $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-$
  - Binned ML fit to t_τ, q^2 and BDT
  - Normalization mode $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$



Input from PDG:
$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi) = [6.14 \pm 0.94] \times 10^{-3}$
$\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \bar{\nu}_\mu) = [6.2 \pm 1.4] \times 10^{-2}$

Based on an old DELPHI result & PDG fit including some 2 body decays Λ_b^0 decays, needs to be updated

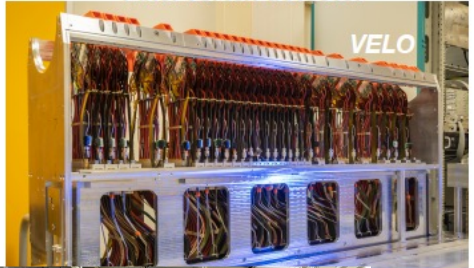
With these assumptions $R(\Lambda_c^+) = 0.242 \pm 0.026\,(stat) \pm 0.040(sys) \pm 0.059(ext.\mathcal{B})$

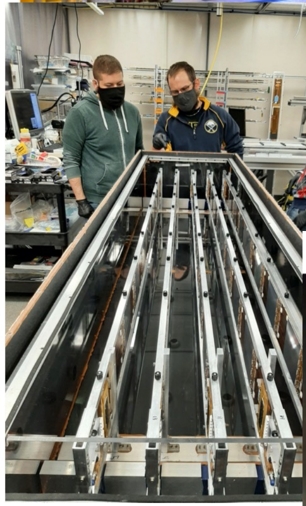
$R(\Lambda_c^+) = 0.324 \pm 0.004$

arXiV:1812.07593

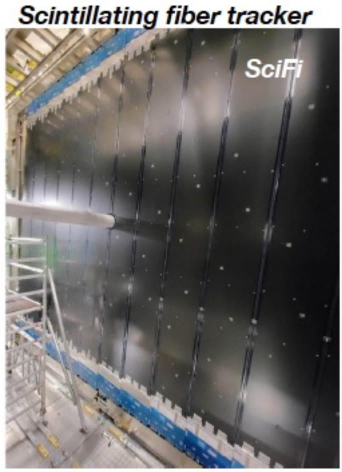
LHCb Upgrade I starting operation with beams now

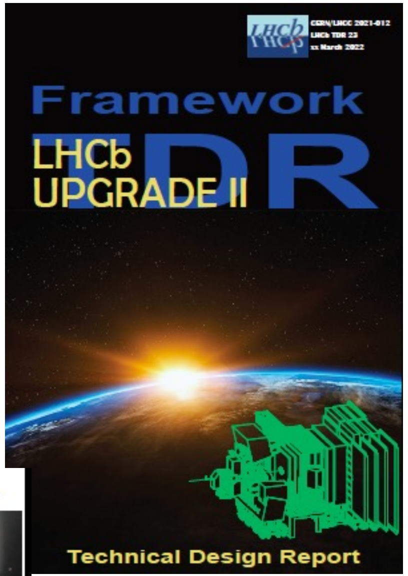
LHCb future plans





Upstream tracker

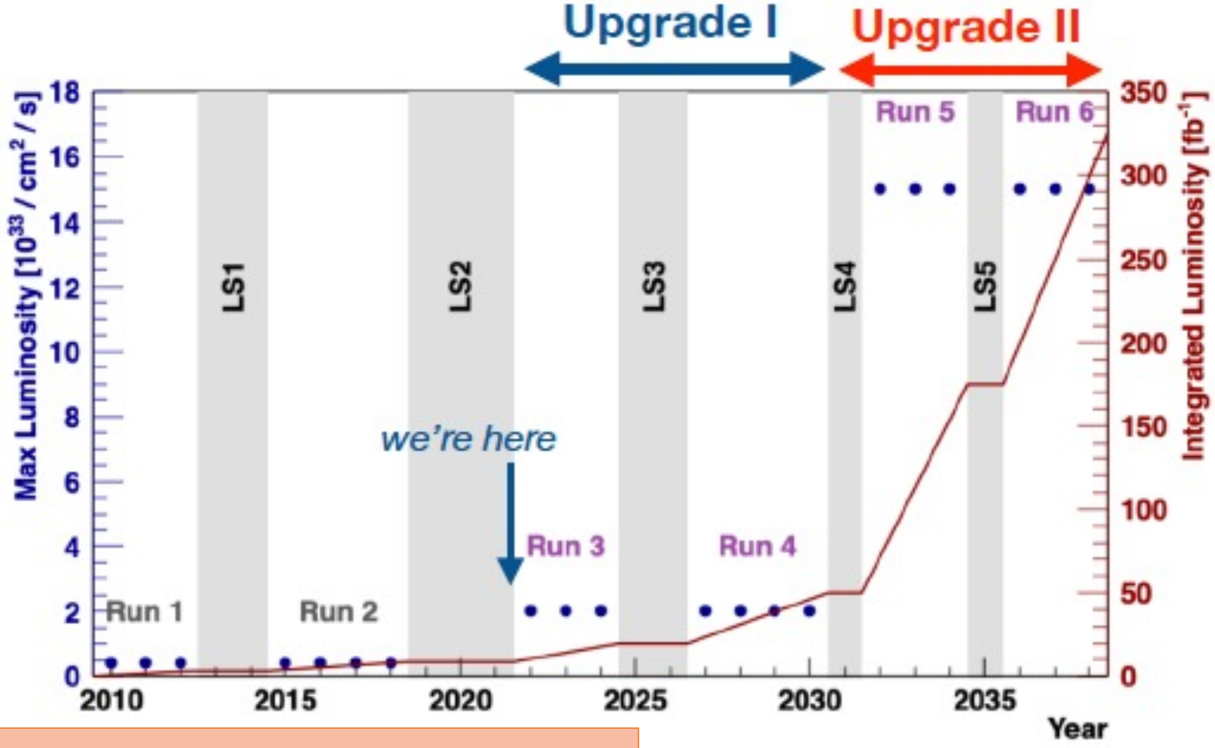




CERN/LHCC 2021-012
LHCb TDR 23
xx March 2022

Framework
LHCb UPGRADE II
TDR

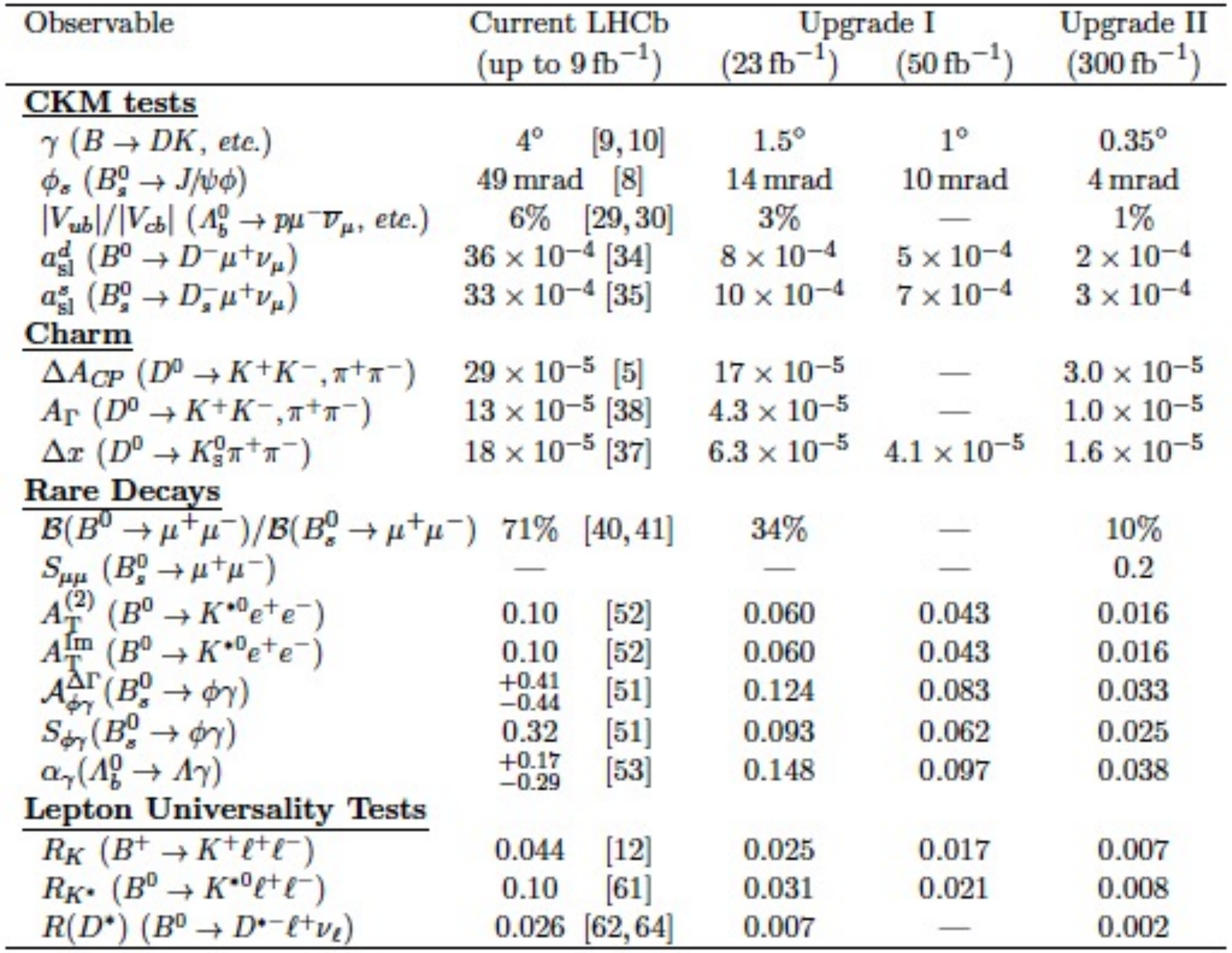
Technical Design Report



Upgrade I:
$\mathcal{L}_{peak} = 2\times10^{33} cm^{-2}s^{-1}$
$\mathcal{L}_{int} = 50\ fb^{-1}$ during Run 3+Run 4
Healthy competition with Belle II at 50 ab^{-1}

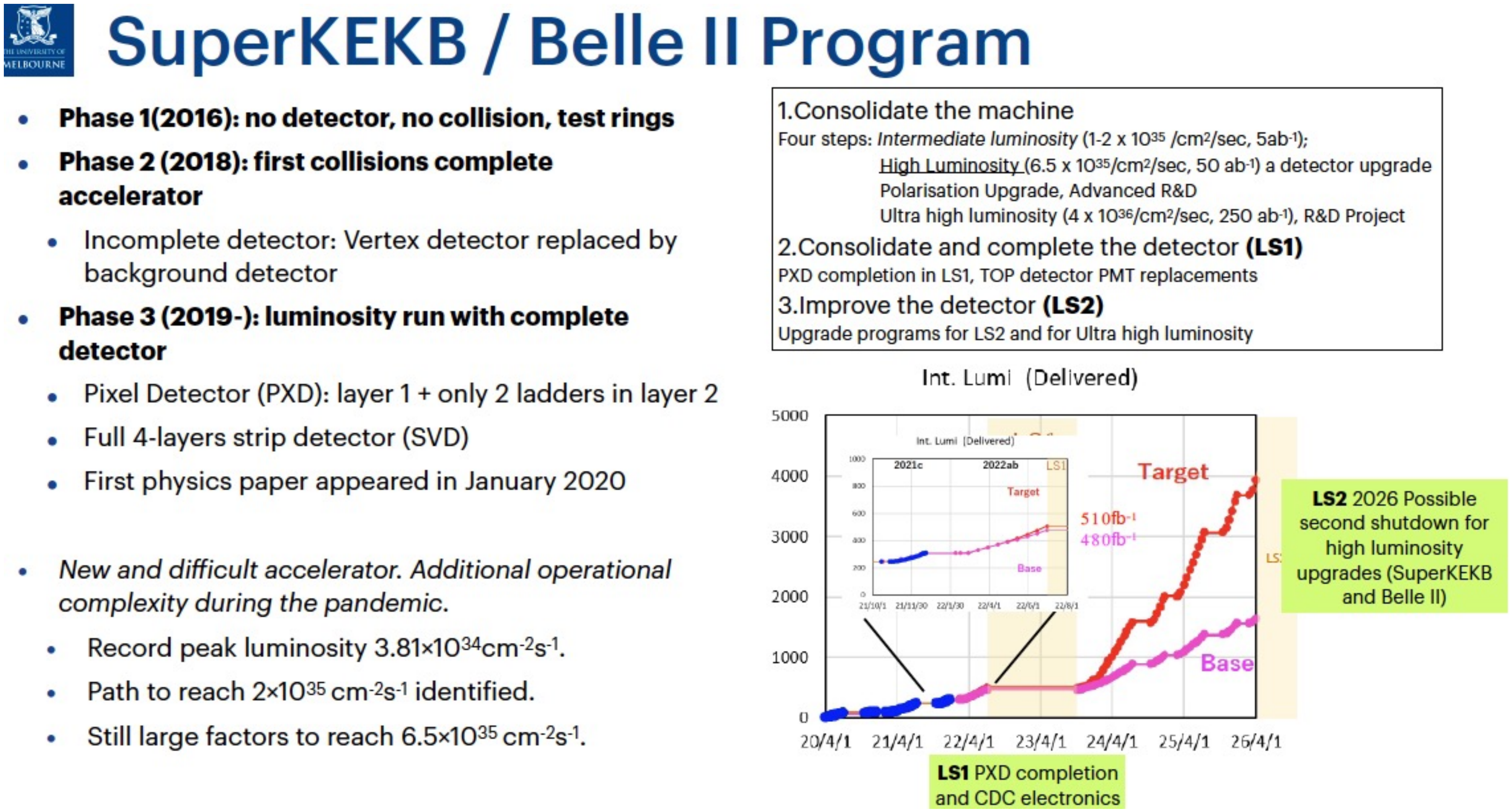
Upgrade II
$\mathcal{L}_{peak} = 1.5\times10^{34} cm^{-2}s^{-1}$
$\mathcal{L}_{int} = 300\ fb^{-1}$ during Run 5 +Run 6

Projection of LHCb sensitivities to key physics quantities



Observable	Current LHCb	Upgrade I		Upgrade II
	(up to $9\,\mathrm{fb}^{-1}$)	($23\,\mathrm{fb}^{-1}$)	($50\,\mathrm{fb}^{-1}$)	($300\,\mathrm{fb}^{-1}$)
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
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [53]	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10 [61]	0.031	0.021	0.008
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026 [62,64]	0.007	—	0.002

P.Urquijo May 2022, Flavor physics school, Tata institute of Fundamental research



SuperKEKB / Belle II Program

- **Phase 1(2016): no detector, no collision, test rings**
- **Phase 2 (2018): first collisions complete accelerator**
  - Incomplete detector: Vertex detector replaced by background detector
- **Phase 3 (2019-): luminosity run with complete detector**
  - Pixel Detector (PXD): layer 1 + only 2 ladders in layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper appeared in January 2020

- *New and difficult accelerator. Additional operational complexity during the pandemic.*
  - Record peak luminosity $3.81\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
  - Path to reach $2\times10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ identified.
  - Still large factors to reach $6.5\times10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

1.Consolidate the machine

Four steps: *Intermediate luminosity* (1-2 x 10^{35} /cm²/sec, 5ab^{-1});

High Luminosity (6.5 x 10^{35}/cm²/sec, 50 ab^{-1}) a detector upgrade

Polarisation Upgrade, Advanced R&D

Ultra high luminosity (4 x 10^{36}/cm²/sec, 250 ab^{-1}), R&D Project

2.Consolidate and complete the detector **(LS1)**

PXD completion in LS1, TOP detector PMT replacements

3.Improve the detector **(LS2)**

Upgrade programs for LS2 and for Ultra high luminosity

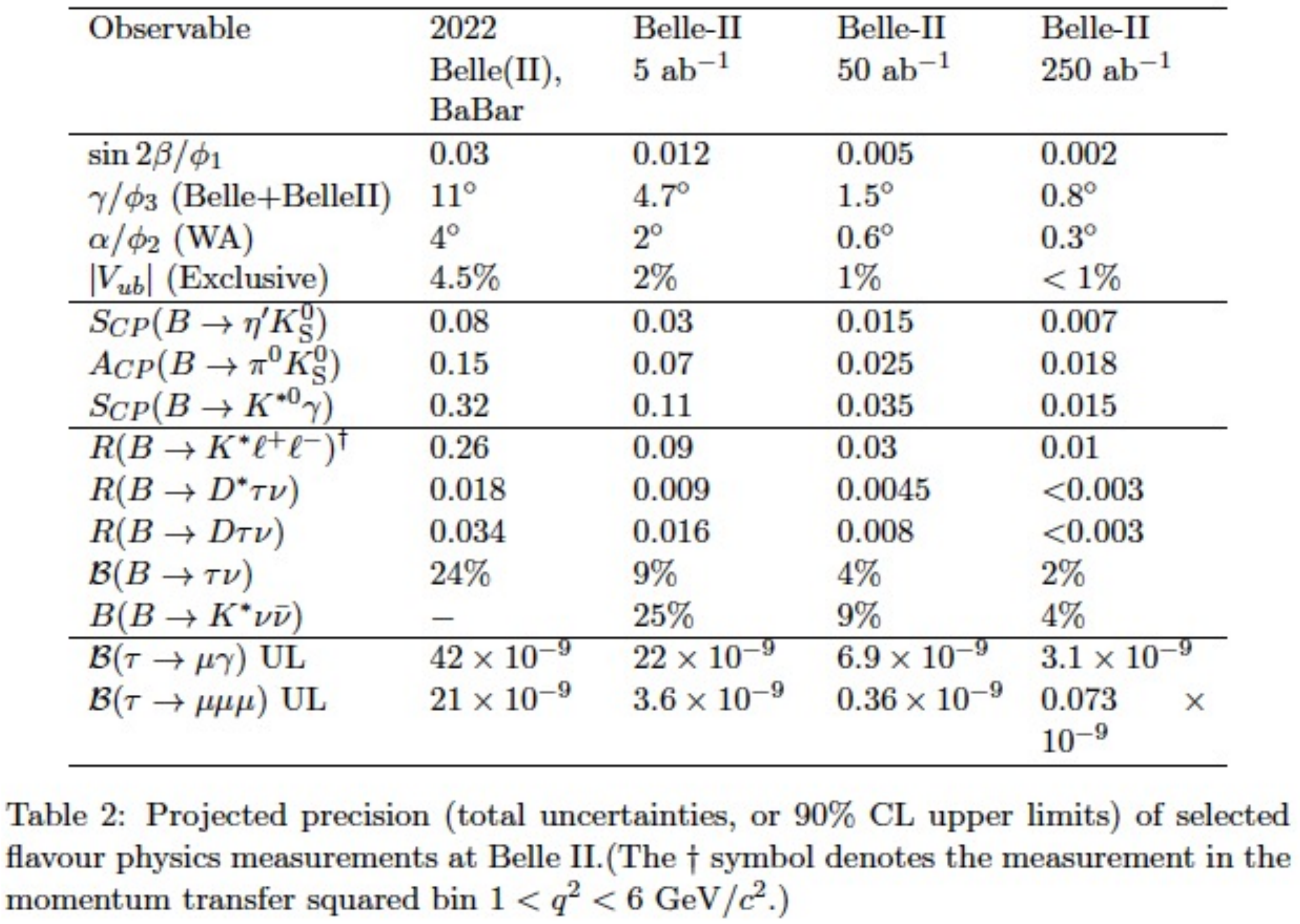
Int. Lumi (Delivered)

LS2 2026 Possible second shutdown for high luminosity upgrades (SuperKEKB and Belle II)

LS1 PXD completion and CDC electronics

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.)

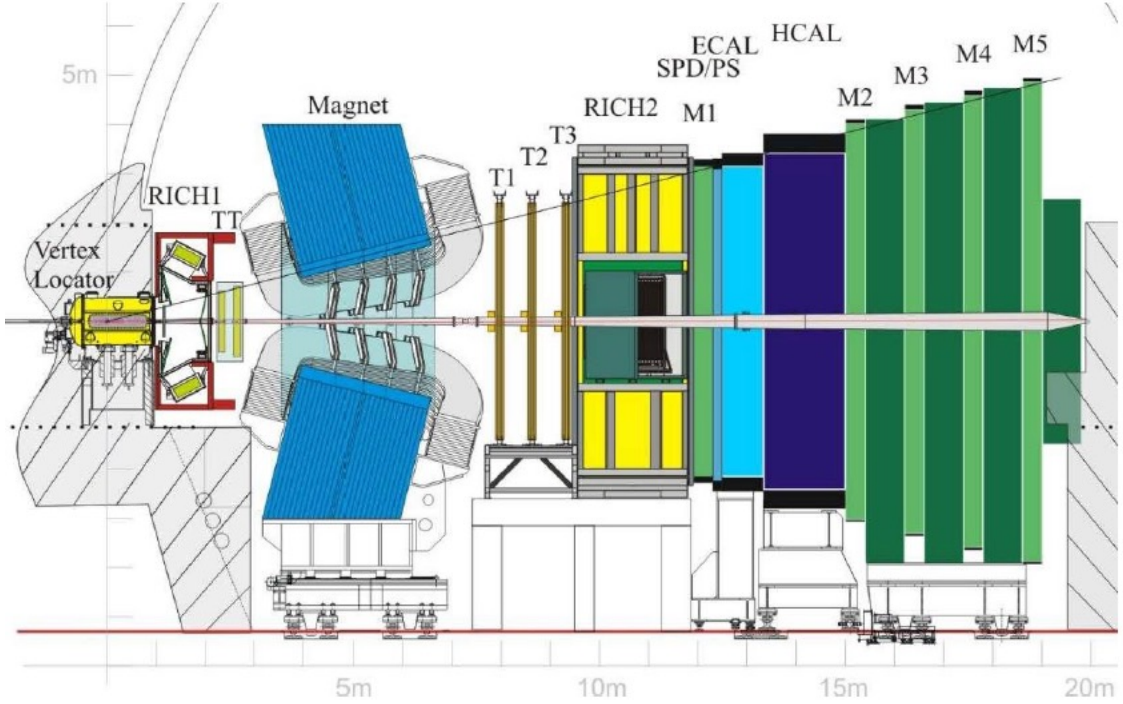
Conclusions

- ☐ Precision SM tests in flavor observables still key: deviations may be subtle!
- ☐ Intriguing tensions in EW penguin decays have surfaced:
  - ☐ lepton flavor universality violation is the anomaly with more direct connection to new physics interpretation
  - ☐ Angular variables selected to be less vulnerable to hadronic uncertainties show consistent tensions
- ☐ Precise calculations of the hadronic matrix element are necessary to broaden the scope of unambiguous statements about physics beyond the Standard Model
- ☐ Flavor physics has a long journey ahead!

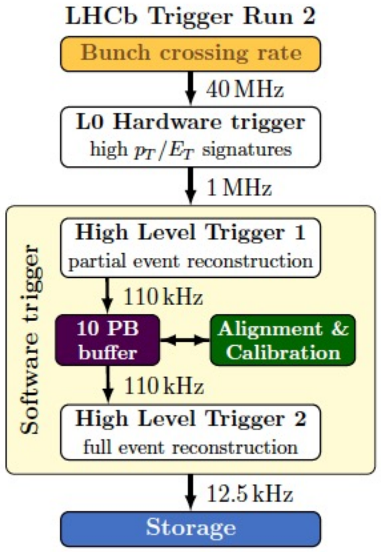
The end

Some back-up slide will follow

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 Trigger Run 2

Bunch crossing rate

40 MHz

L0 Hardware trigger
high p_T/E_T signatures

1 MHz

Software trigger

High Level Trigger 1
partial event reconstruction

110 kHz

10 PB buffer

Alignment & Calibration

110 kHz

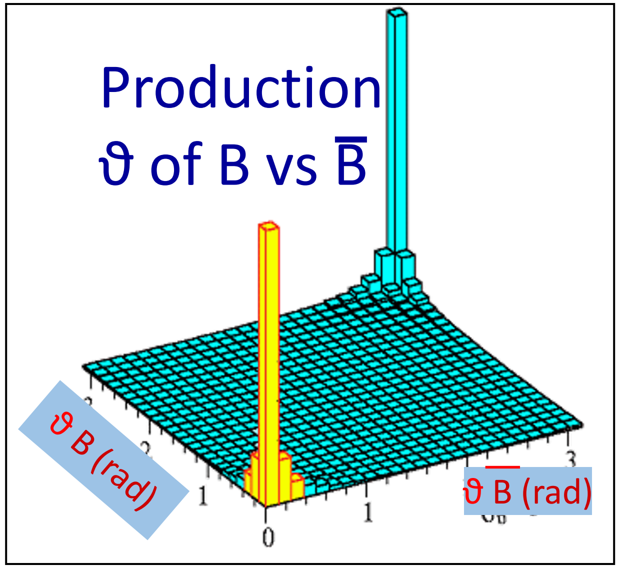
High Level Trigger 2
full event reconstruction

12.5 kHz

Storage

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

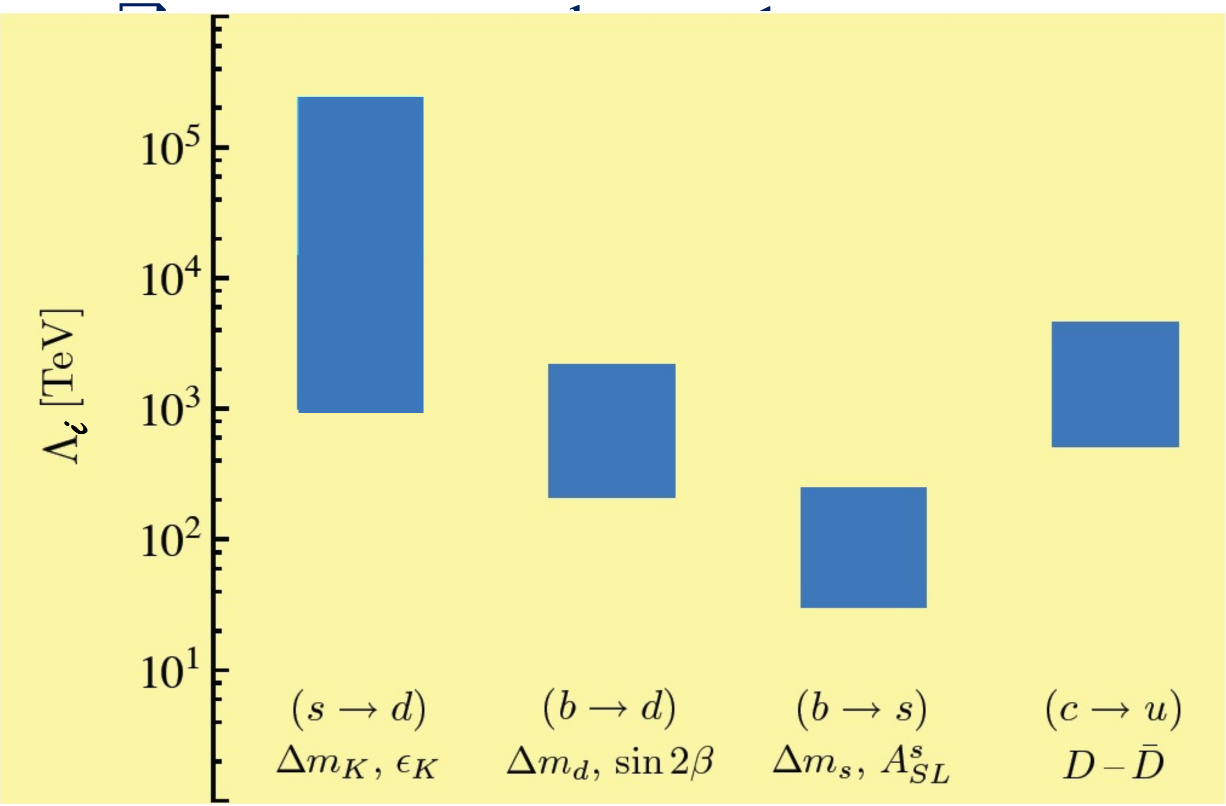
- In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b & b quarks are both likely to be in the acceptance. Essential for “flavor tagging”
- LHCb uses the forward direction where the B’s are moving with considerable momentum ~100 GeV, thus minimizing multiple 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

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

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

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

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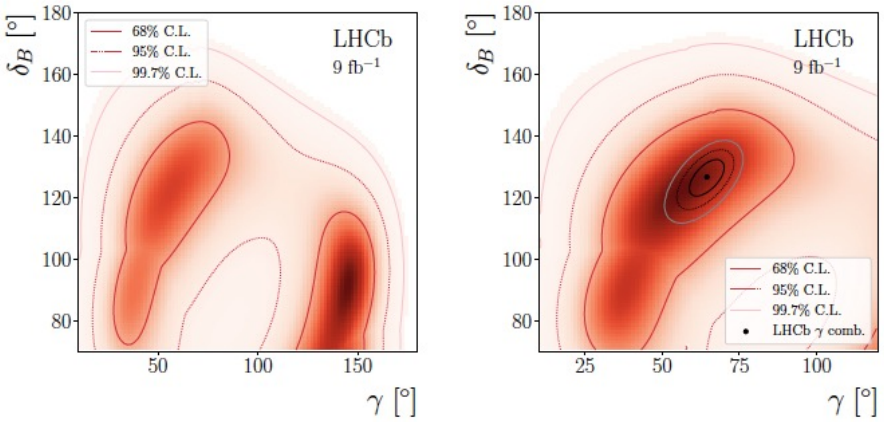
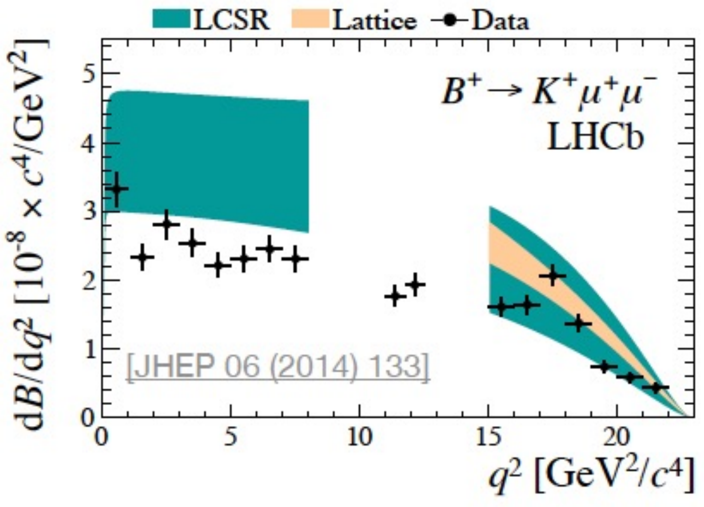


Global maximum $\gamma = (145^{+9}_{-39})^{\circ}$

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

Other branching fractions



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