

Flavour physics delicacies

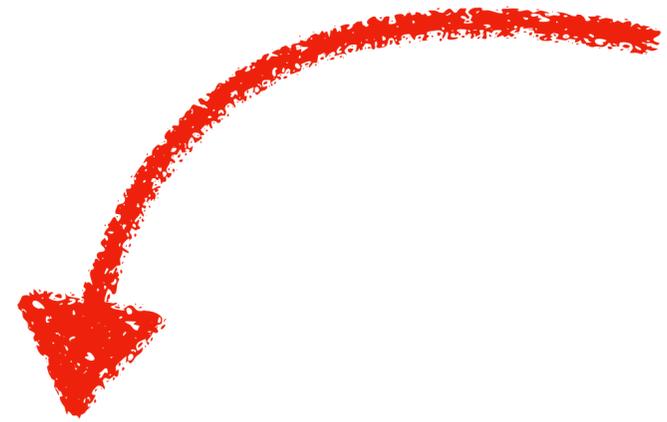
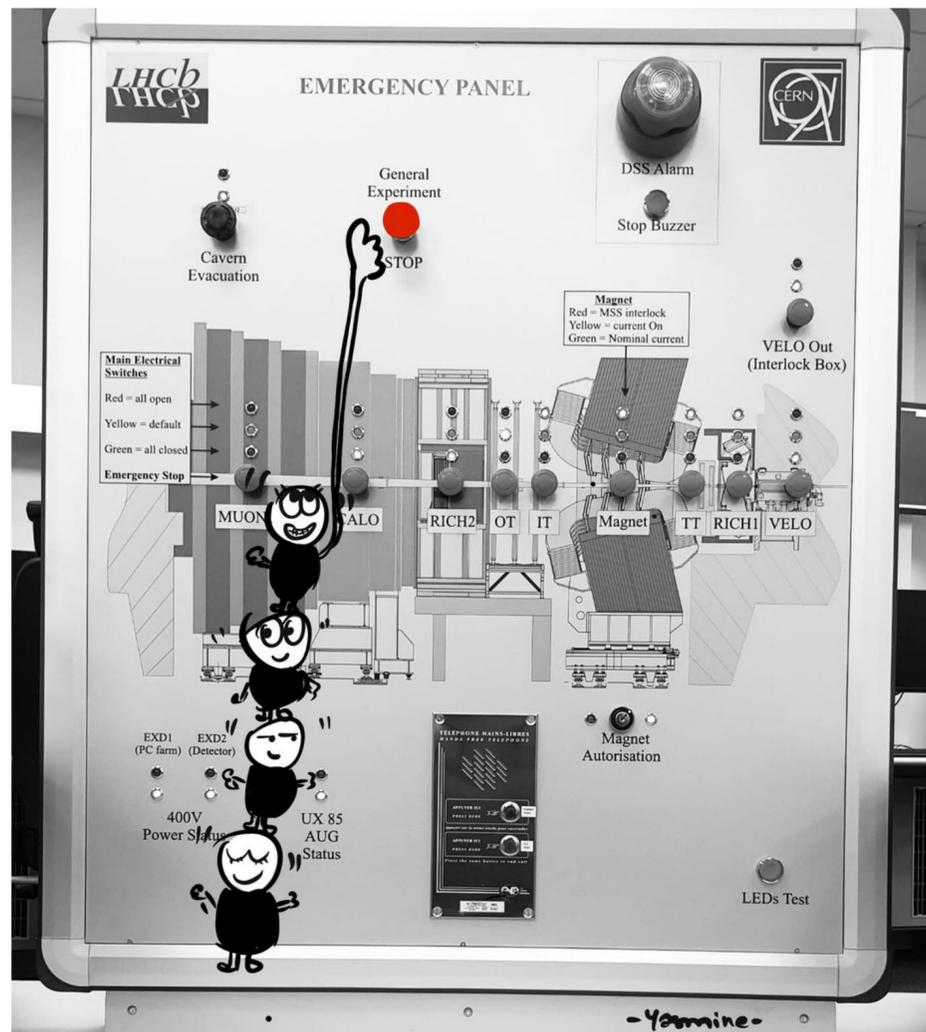


Yasmine Amhis

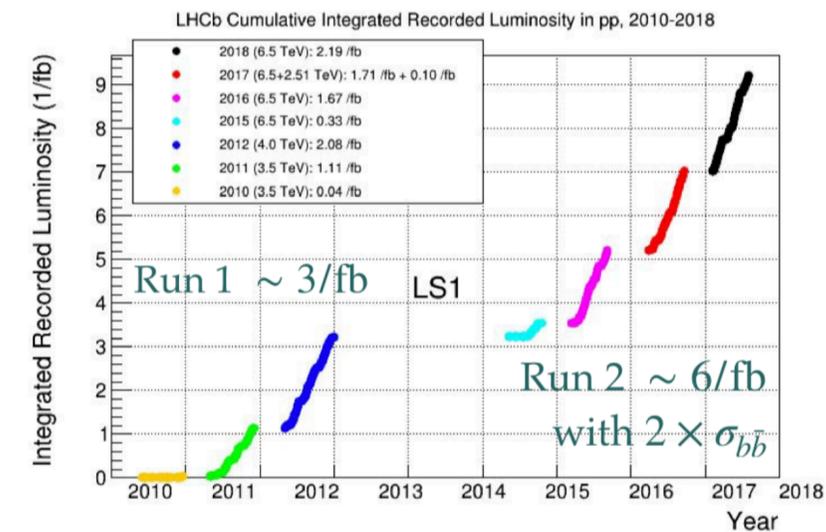
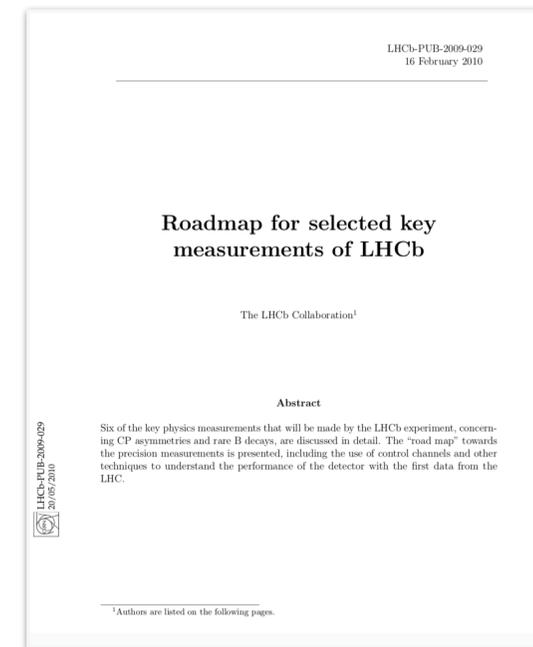
Journée P2I

02.12.2021

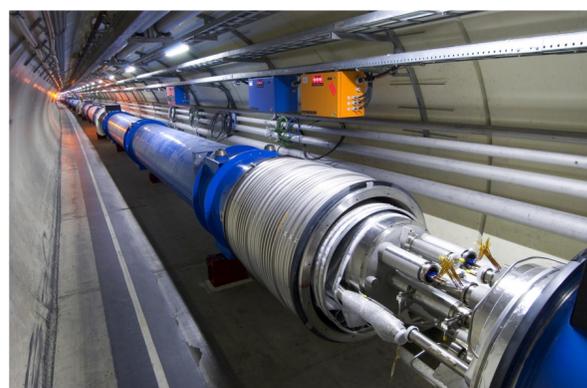
Préambule



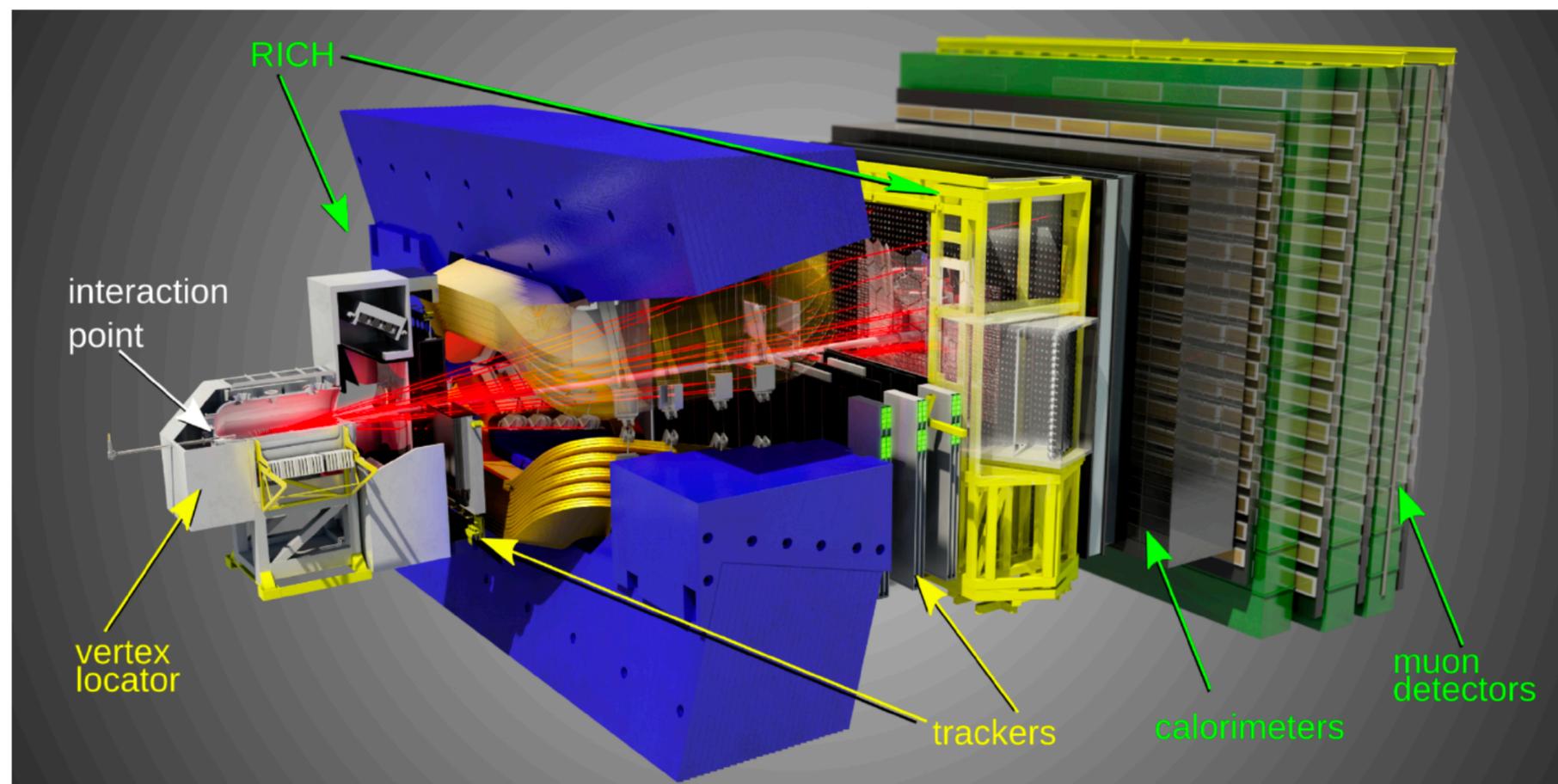
23-Nov-2009 18:03:46		Fill #: 883	Energy: 0.450 TeV	I(B1): 4.72e+09	I(B2): 4.72e+09
Experiment Status	ATLAS	ALICE	CMS	LHCb	
	STANDBY	STANDBY	STANDBY	COLLIDING!	
Instantaneous Luminosity	3.154e+00	0.000e+00	-1.068e-03	6.725e+01	
Integrated Luminosity	3.154e+00	0.000e+00	0.000e+00	0.000e+00	
BKGD 1	0.000	0.001	0.001	0.051	
BKGD 2	25002.000	0.000	0.000	0.141	
BKGD 3	0.000	0.012	0.000	0.050	
LHCf	STANDBY	Count(Hz): 0	LHCb VELO Position	OUT	TOTEM: NO RUN



Where are we today ?



The LHCb detector



- Good vertex and impact parameter resolution $\sigma(\text{IP}) = 15 + 29/p_T$ mm.
- Excellent momentum resolution $\sim 25 \text{ MeV}/c^2$ two-body decays.
- Excellent particle ID (μ -ID 97% for $(\pi \rightarrow \mu)$ misID of 1-3%).
- Versatile & efficient trigger.



Particle Identification

Magnet

Particle Identification

Muons

Velo

Tracking

Tracking

Calorimeters

LHCb

The case flavour physics and indirect searches

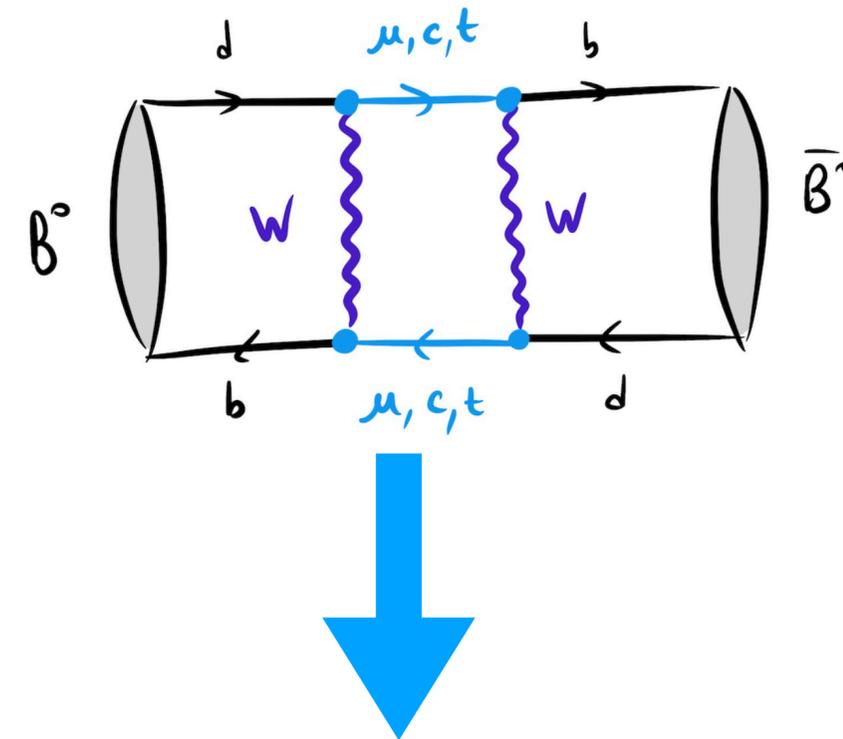
PLB 192 (1987)

OBSERVATION OF $B^0-\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that $B^0-\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson (\approx pion) decay constant
$m_b < 5$ GeV/ c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$ s	B meson lifetime
$ V_{td} < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{\text{QCD}} < 0.86$	QCD correction factor ^{a)}
$m_t > 50$ GeV/ c^2	t quark mass



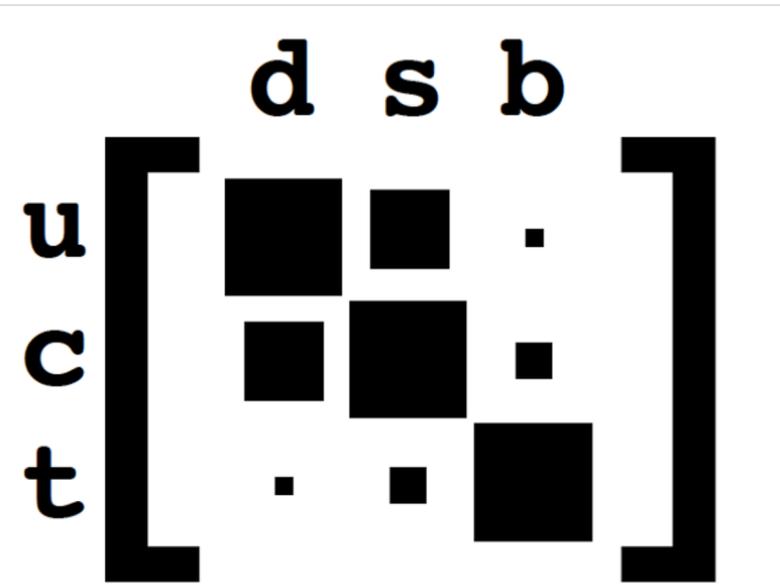
$$\omega(B^0 - \bar{B}^0) \propto \sum_{ij} (V_{ib} V_{id}^*) (V_{jb} V_{jd}^*) F(m_{u_i}^2, m_{u_j}^2)$$

“The SM is fantastic but it’s not the end of the story”

Today's menu

- ✿ CP violation, γ , ϕ_s , B_s -mixing.
- ✿ Very rare decays, $b \rightarrow s l^{+/-}$ angular analyses + LU.
- ✿ A touch of spectroscopy.

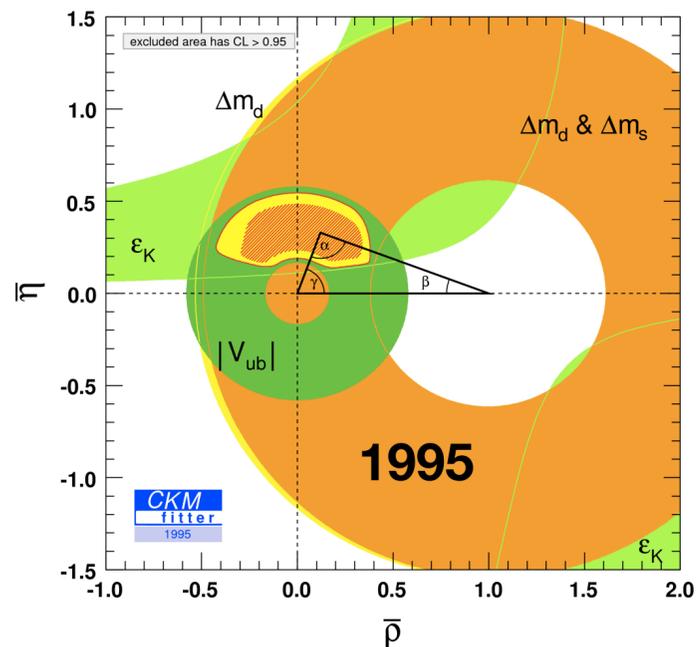
CP violation



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

Origin of CP violation in the SM

Build Unitarity triangle



Parametrisation

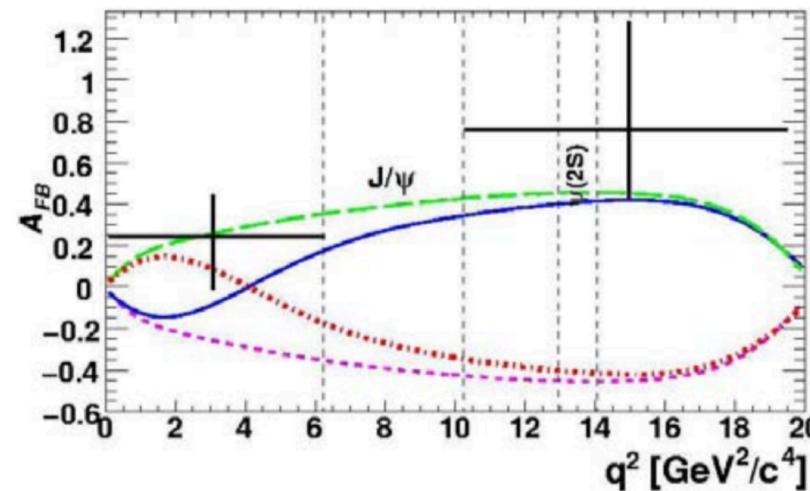
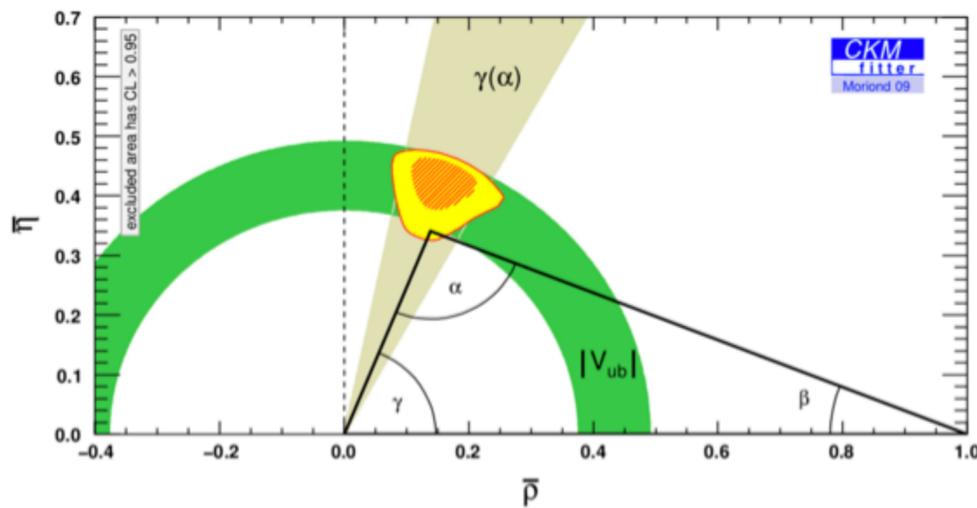
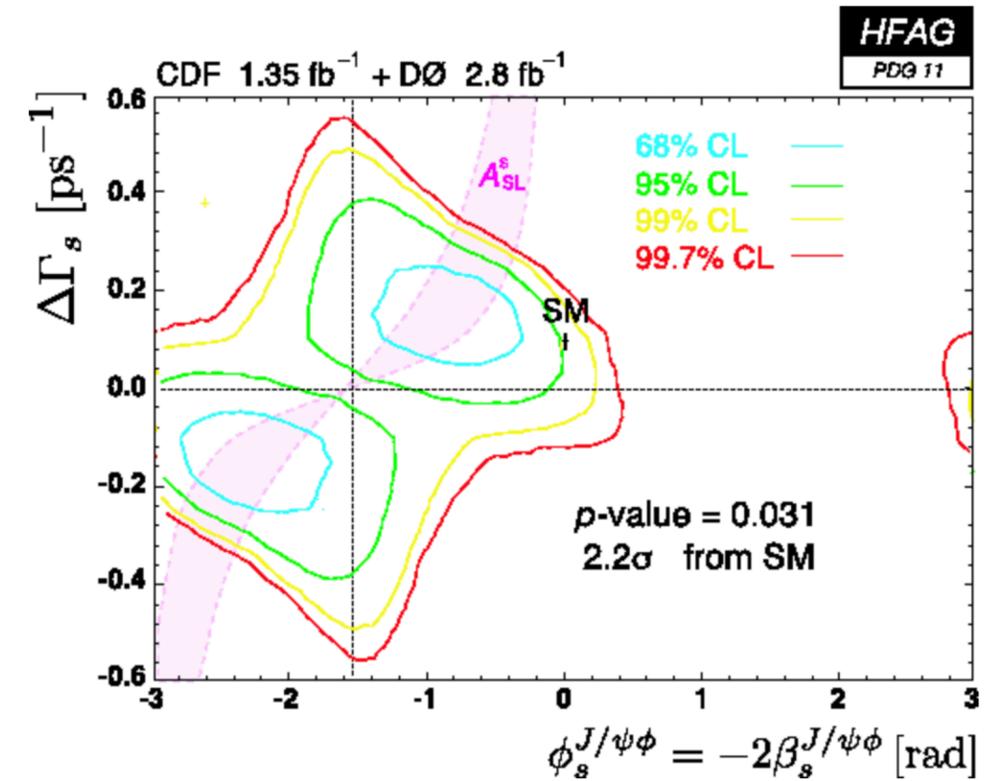
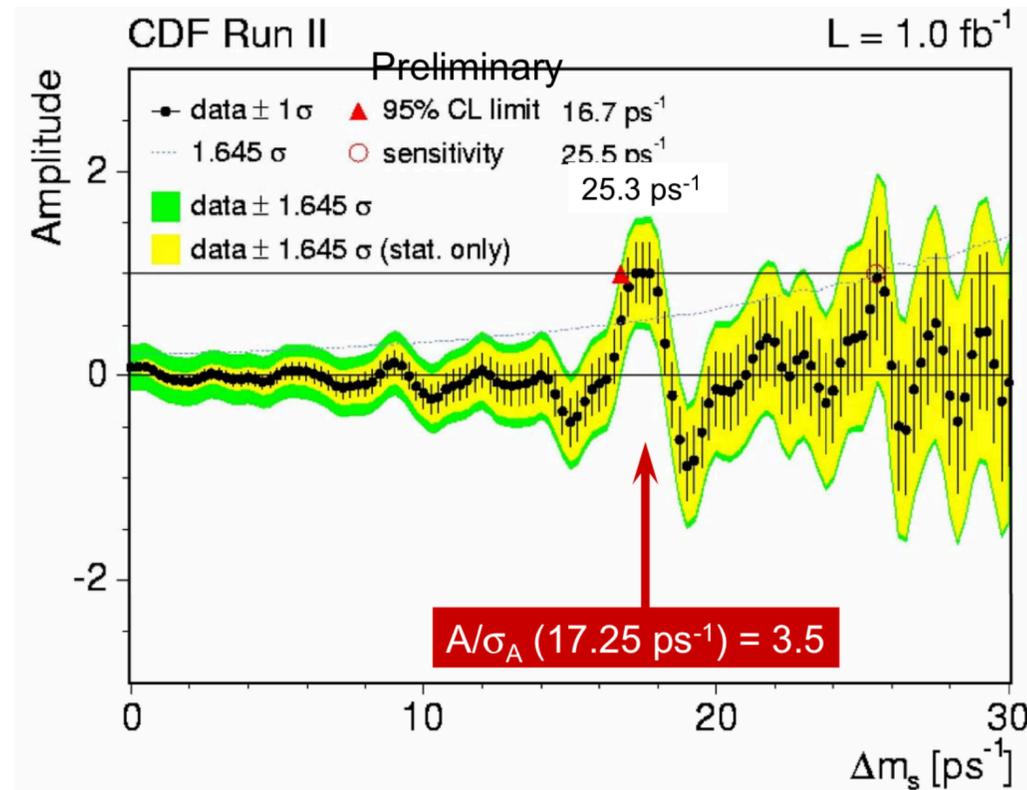
$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

Goal: constrain sides and angles.

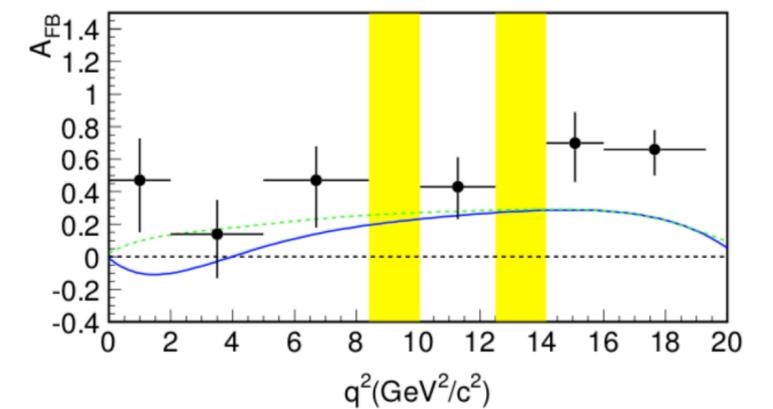


Landscape before the LHC(b)

We had the B-factories and the Tevatron.

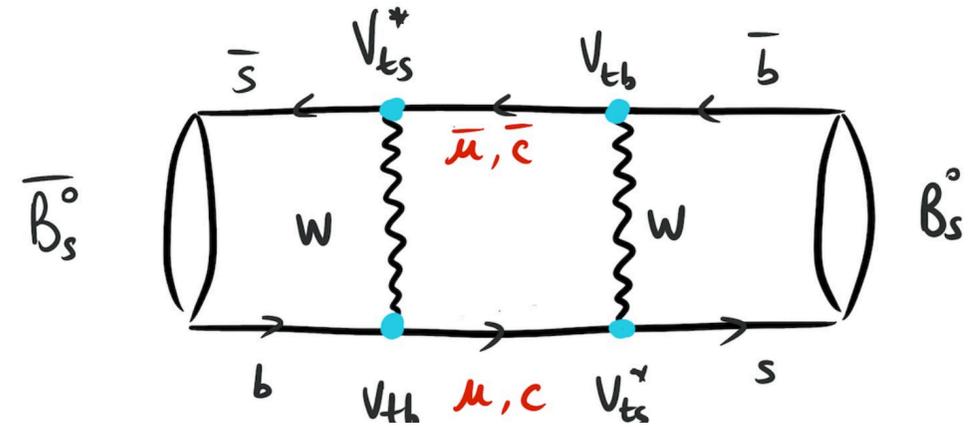
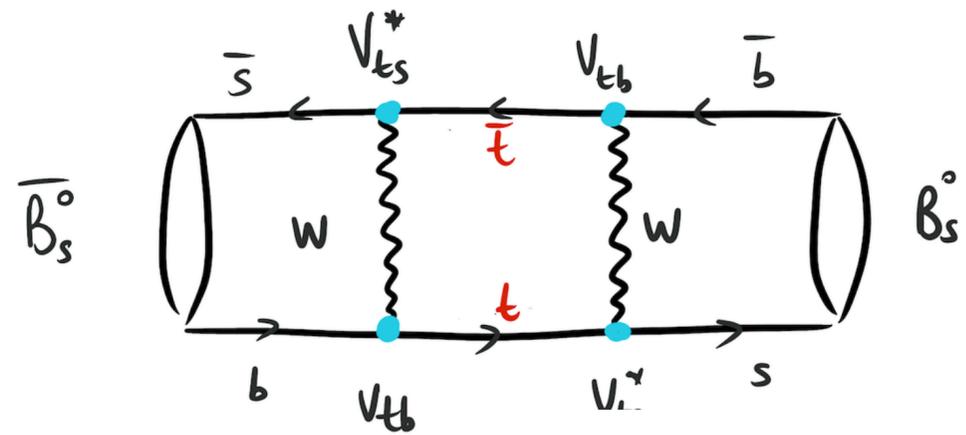
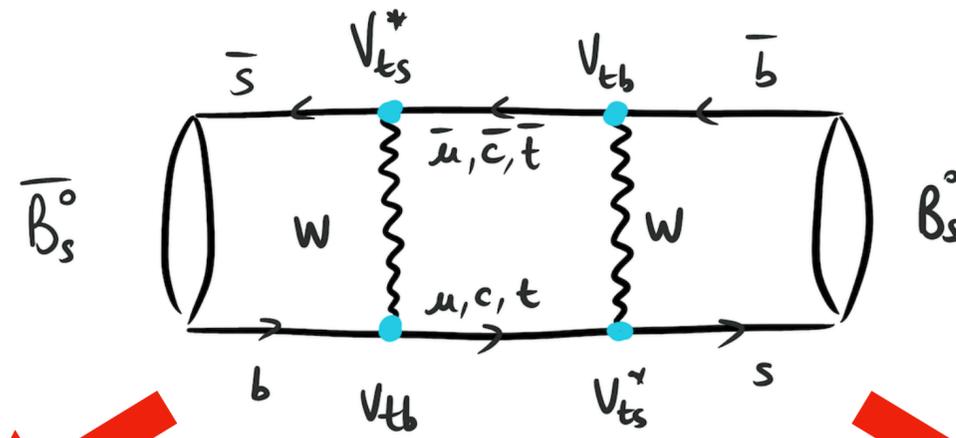


(a)



(b)

B_s mixing



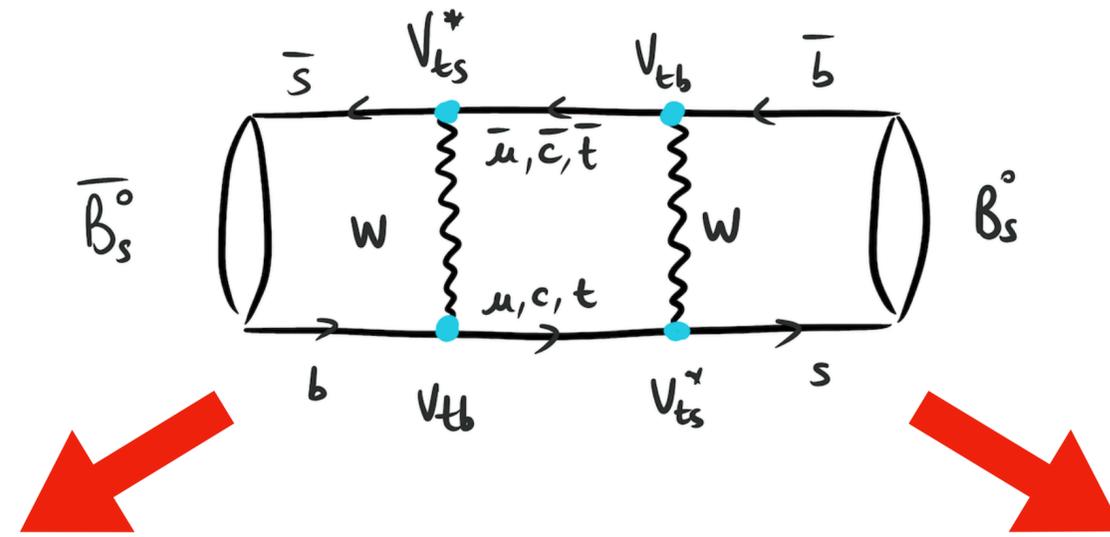
Time evolution :

$$i \frac{d}{dt} \begin{pmatrix} |B_s(t)\rangle \\ |\bar{B}_s(t)\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} M^s & \\ & -\frac{i}{2} \Gamma^s \end{pmatrix}} \begin{pmatrix} |B_s(t)\rangle \\ |\bar{B}_s(t)\rangle \end{pmatrix}$$

M^s = Mass Matrix
 Γ^s = Decay matrix

Diagonalize to obtain
 physical eigenstates
 $|B_H\rangle, |B_L\rangle$

B_s mixing

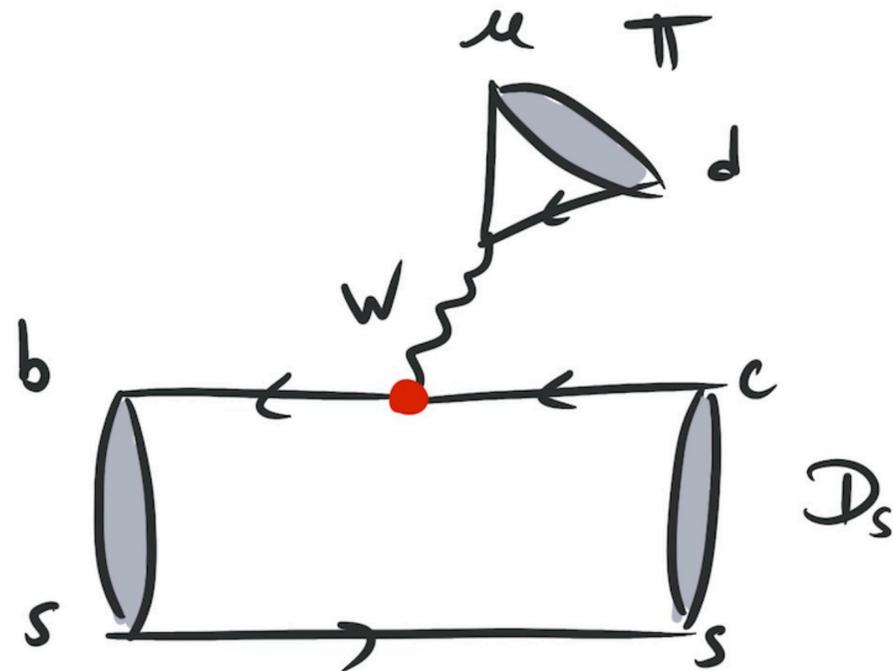


$$\Delta m_s = M_H^s - M_L^s \quad \Delta \Gamma_s = \Gamma_L^s - \Gamma_H^s$$

$$\phi_s = \arg \left(- \frac{M_{12}^s}{\Gamma_{12}^s} \right)$$

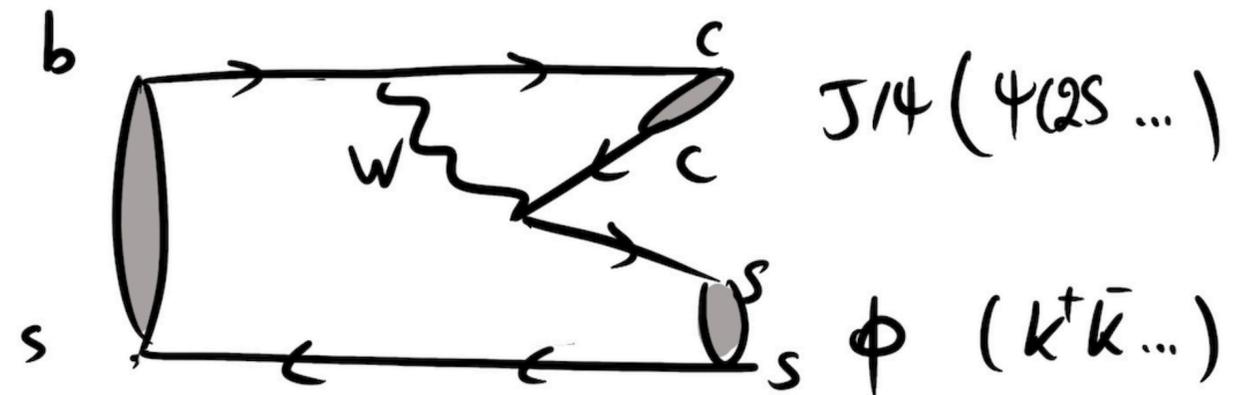
Which decays should we use?

Frequency



Flavour specific decay
Purely hadronic final state.

Phase



Mixture of CP odd and CP even
Dimuon in the final state.

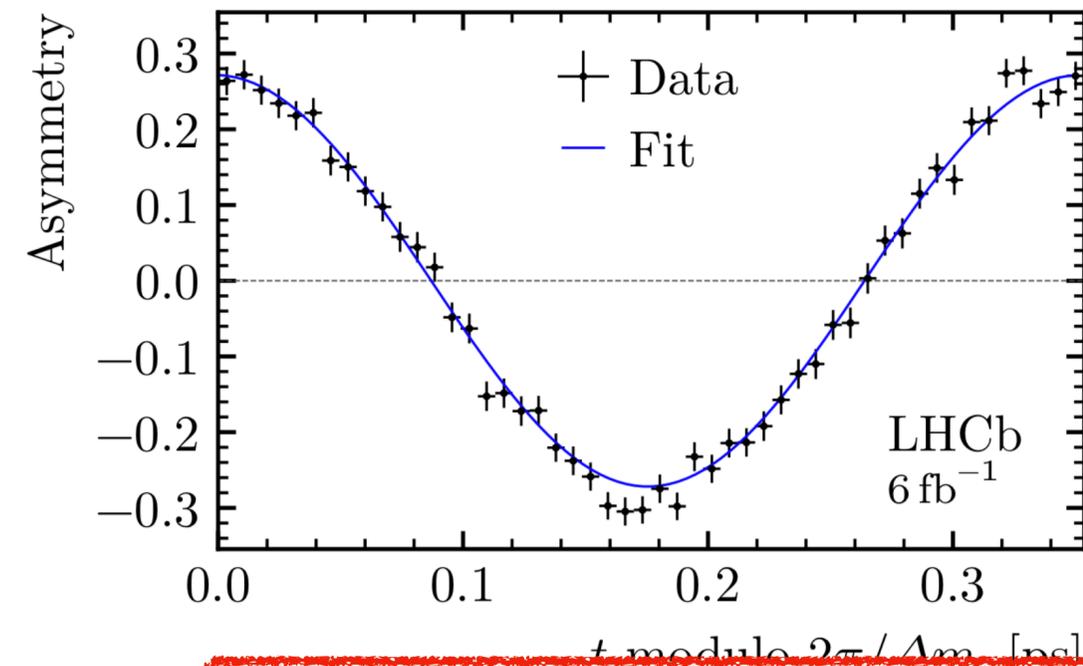
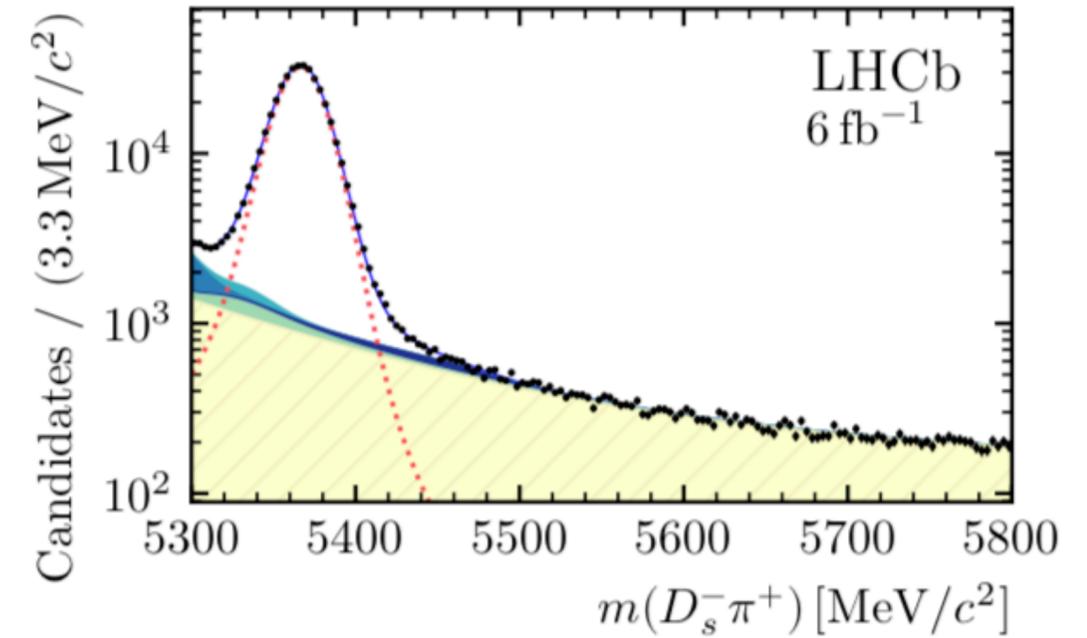
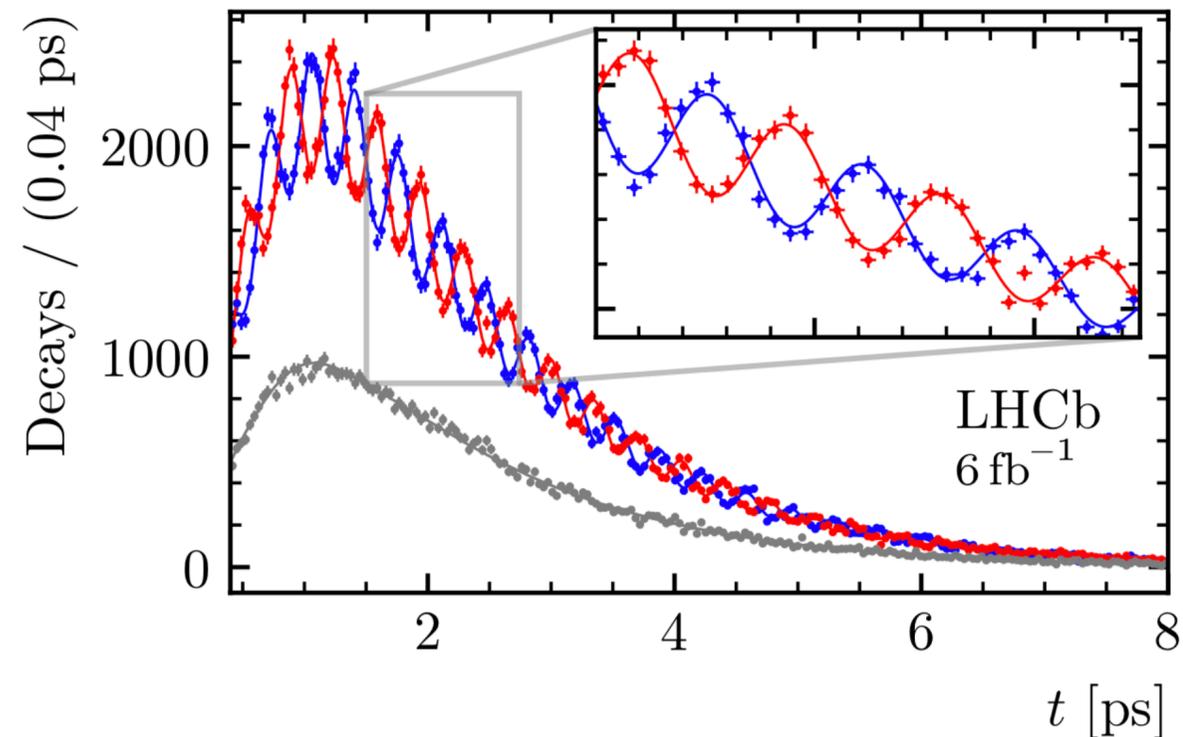
B_s mixing

$$P(t) \sim e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t) \right]$$

After reconstruction and selection

Perform a time dependent analyse with flavour tagging

— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow D_s^- \pi^+$ — Untagged

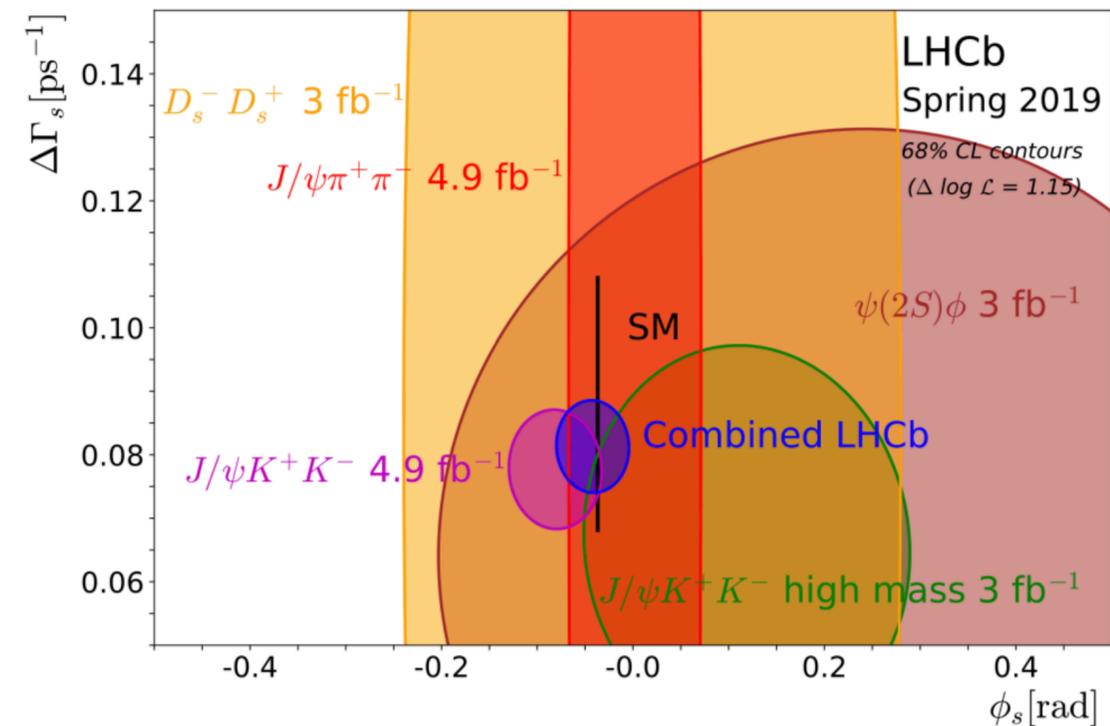
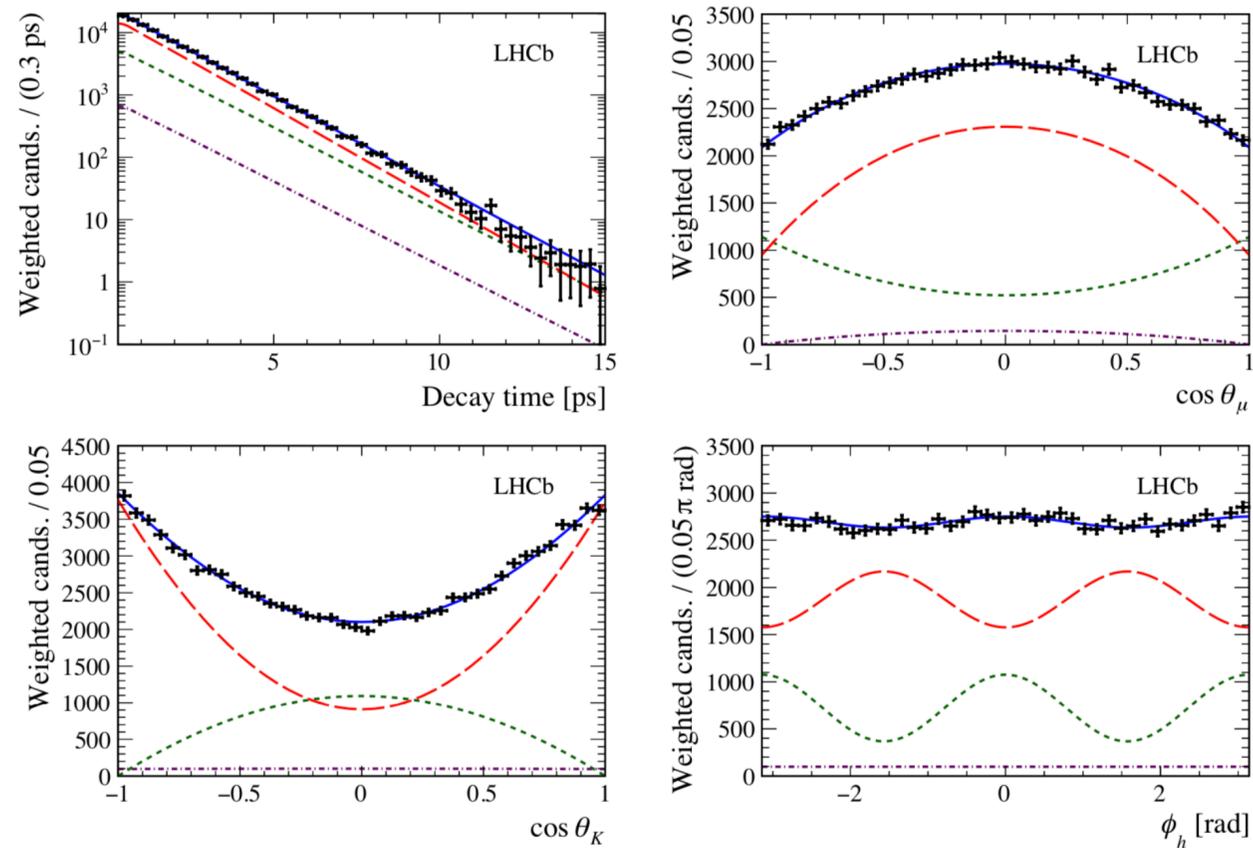
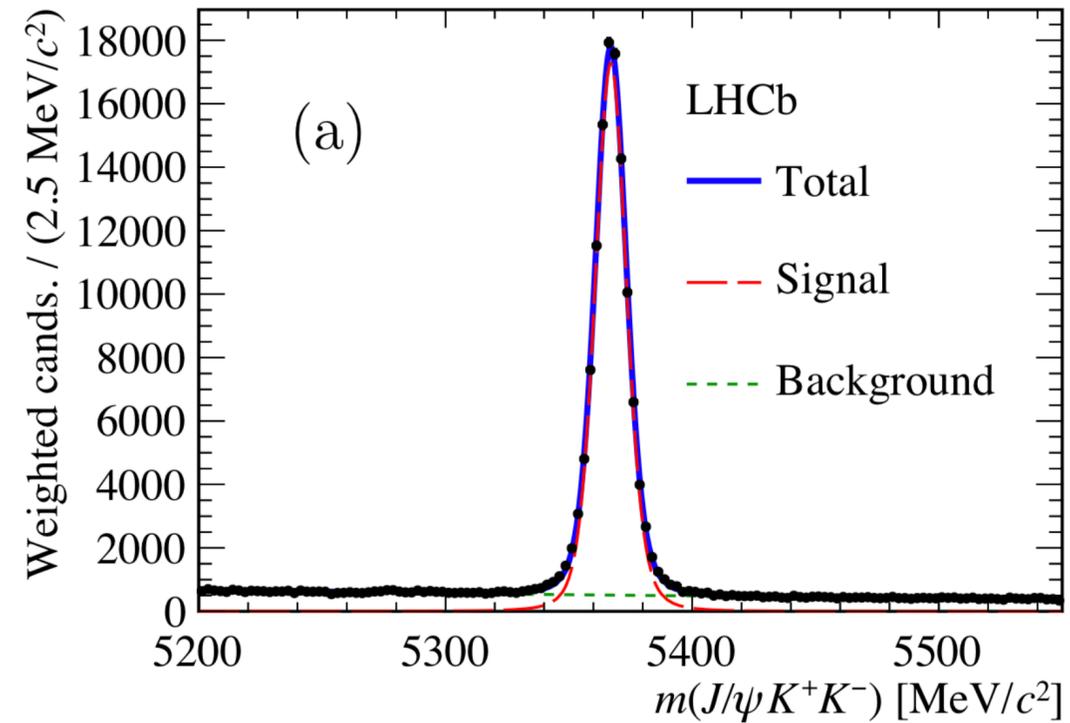


$$\Delta m_s = 17.7683 \pm 0.0051 \text{ (stat)} \pm 0.0032 \text{ (syst)} \text{ ps}^{-1}$$

B_s Phases

1906.08356

After reconstruction and selection
 Perform a time dependent analyse with flavour tagging
 And use angular information to spectate
 The CP odd and CP even components in the final state.

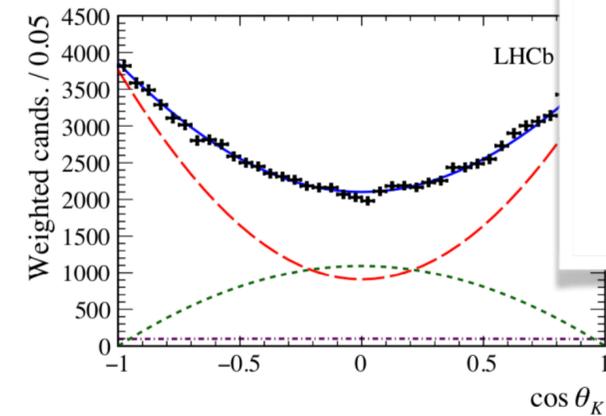
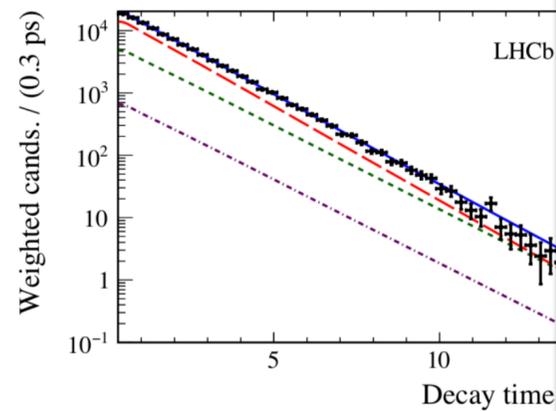
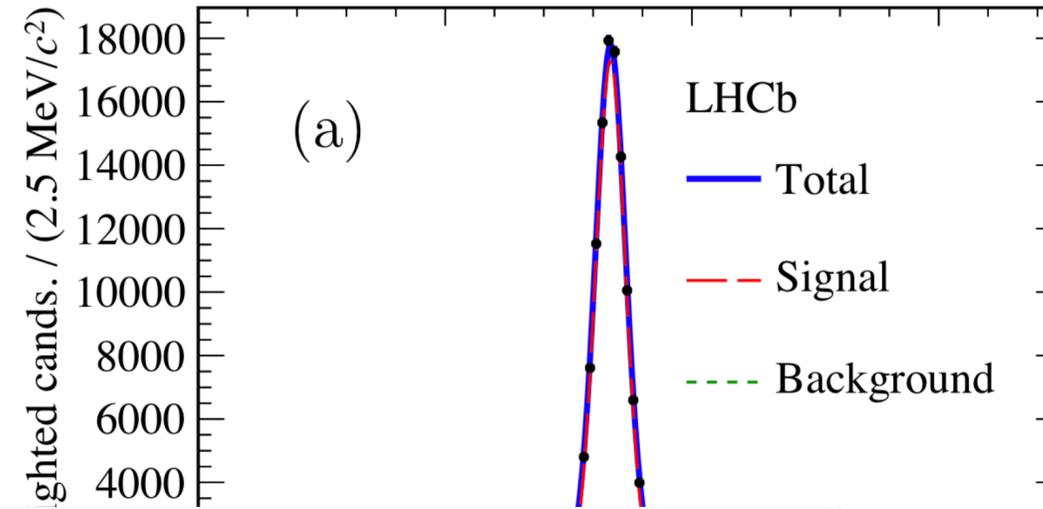


Everything nicely compatible with the Standard Model

B_s Phases

1906.08356

After reconstruction and selection
 Perform a time dependent analyse with flavour tagging
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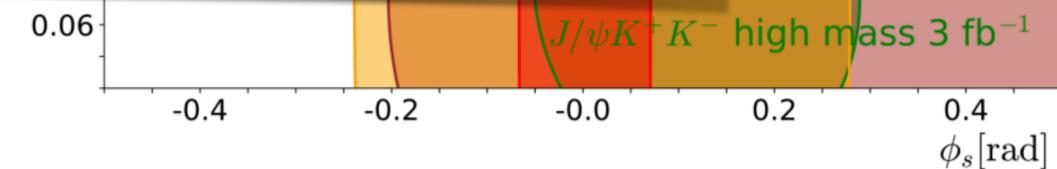
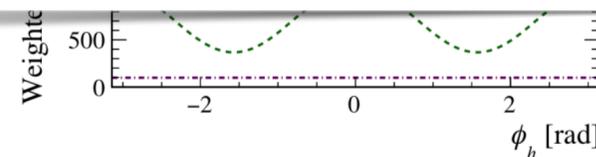


$$\phi_s = -0.042 \pm 0.025 \text{ rad} ,$$

$$|\lambda| = 0.993 \pm 0.010 ,$$

$$\Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1} ,$$

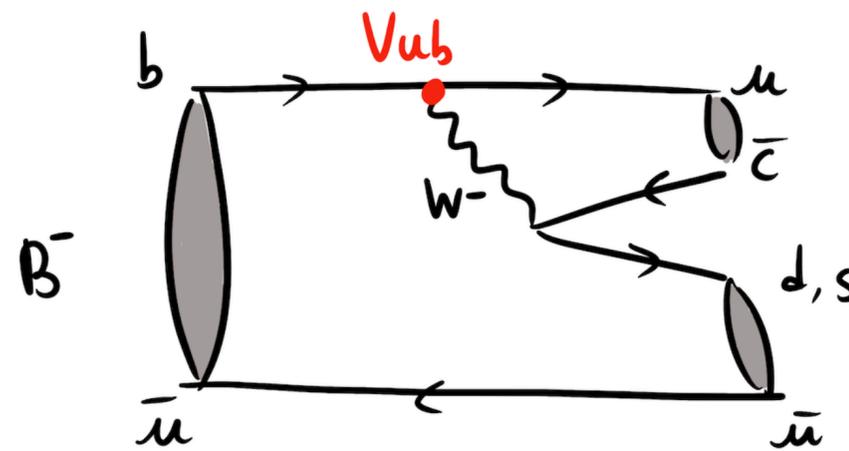
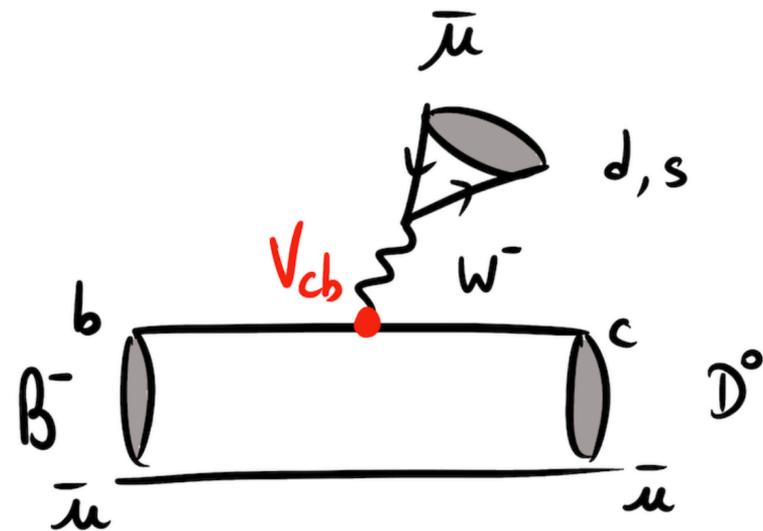
$$\Delta\Gamma_s = 0.0813 \pm 0.0048 \text{ ps}^{-1} .$$



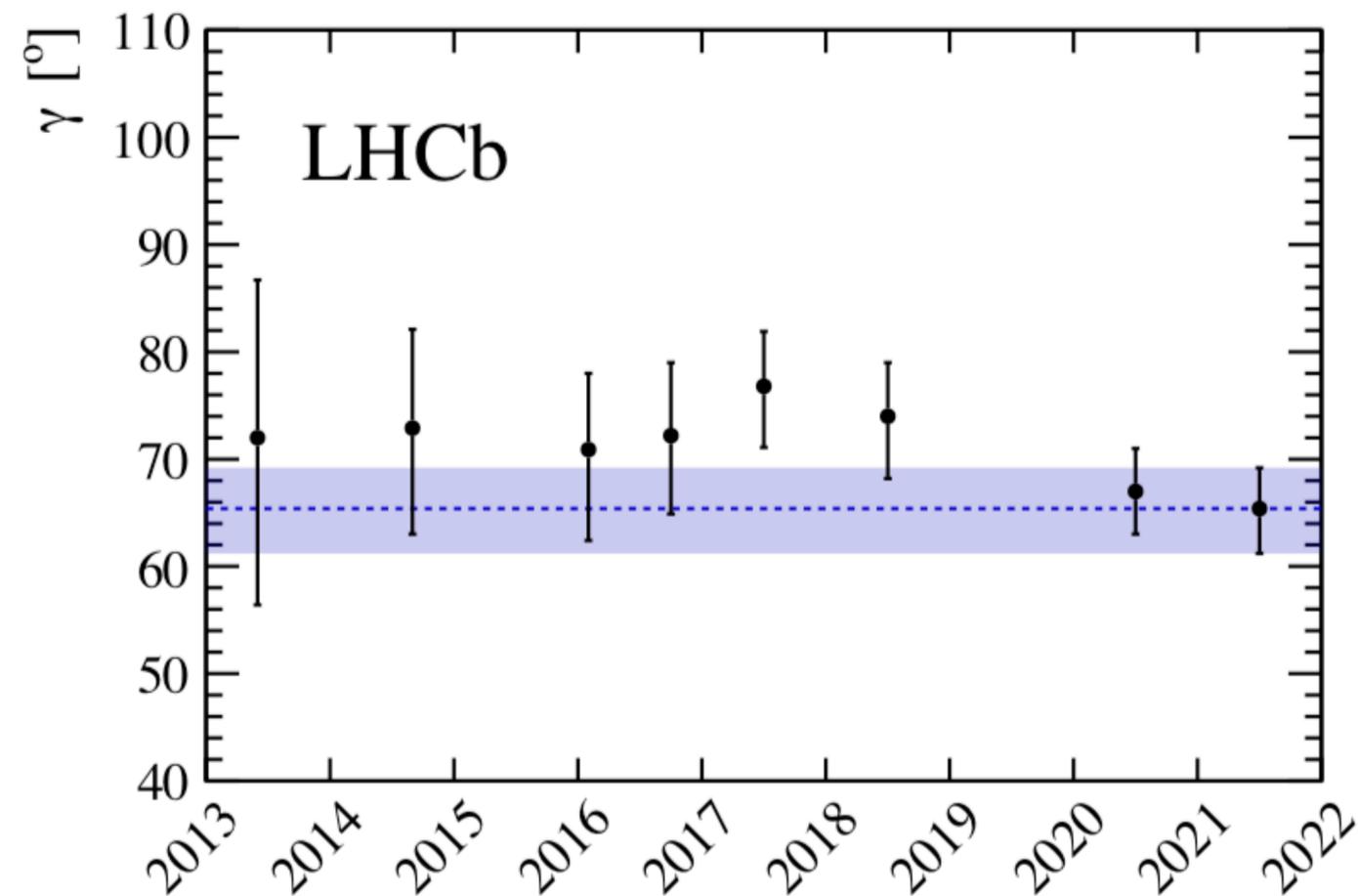
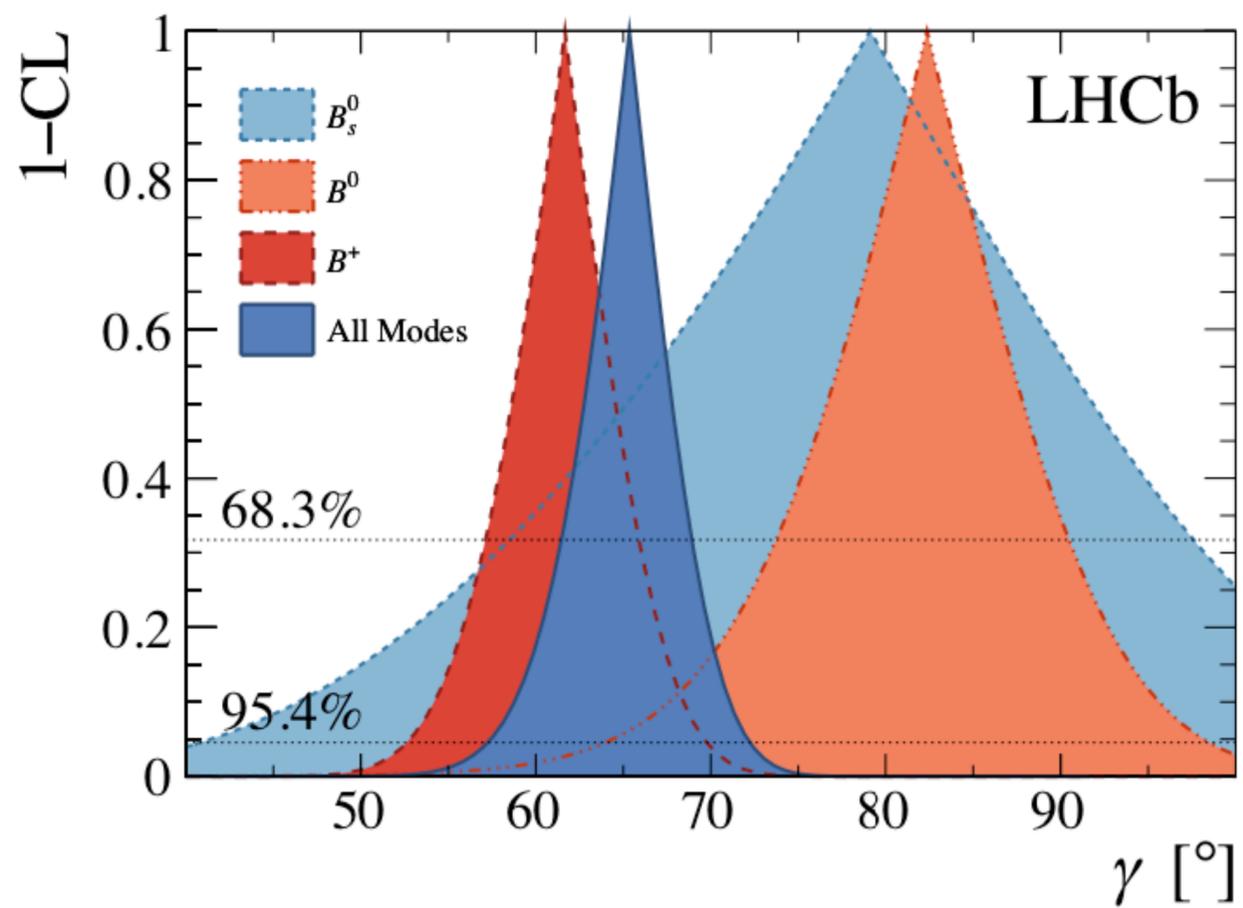
<https://hflav.web.cern.ch>

Democratic γ

- $\gamma \equiv \varphi_3$
 - from time-dependent CP asymmetries in $b \rightarrow c\bar{u}d/\bar{u}c\bar{d}$ decays, like $B_d^- \rightarrow D^{(*)-+}\pi^{+-}, \dots$
 - extraction of constraints on $|\sin(2\beta+\gamma)| \equiv |\sin(2\varphi_1+\varphi_3)|$ from the above
 - from time-dependent CP asymmetries in $b \rightarrow c\bar{u}s/\bar{u}c\bar{s}$ decays, like $B_s^- \rightarrow D_s^{*-+}K^{+-}, \dots$
 - extraction of constraints on $\gamma-2\beta_s$ from the above
 - from rates and asymmetries in $b \rightarrow c\bar{u}s/\bar{u}c\bar{s}$ decays, like $B^\pm \rightarrow D^{(*)}K^{*\pm}, \dots$
 - extraction of constraints on $\gamma \equiv \varphi_3$ from the above

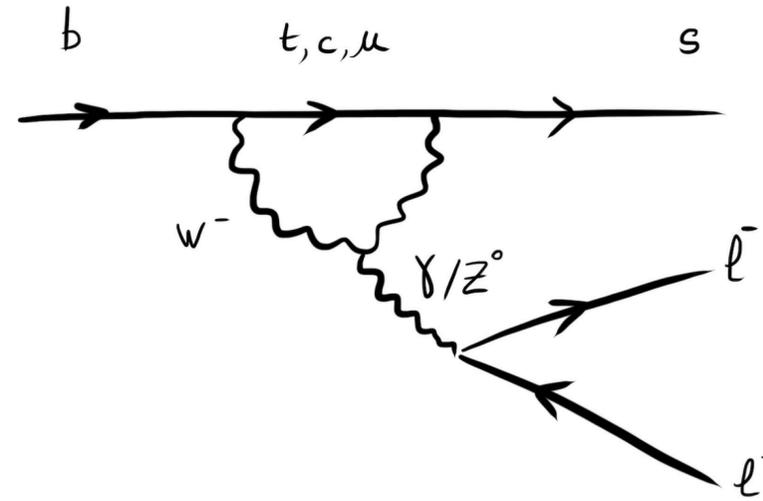


$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right],$$

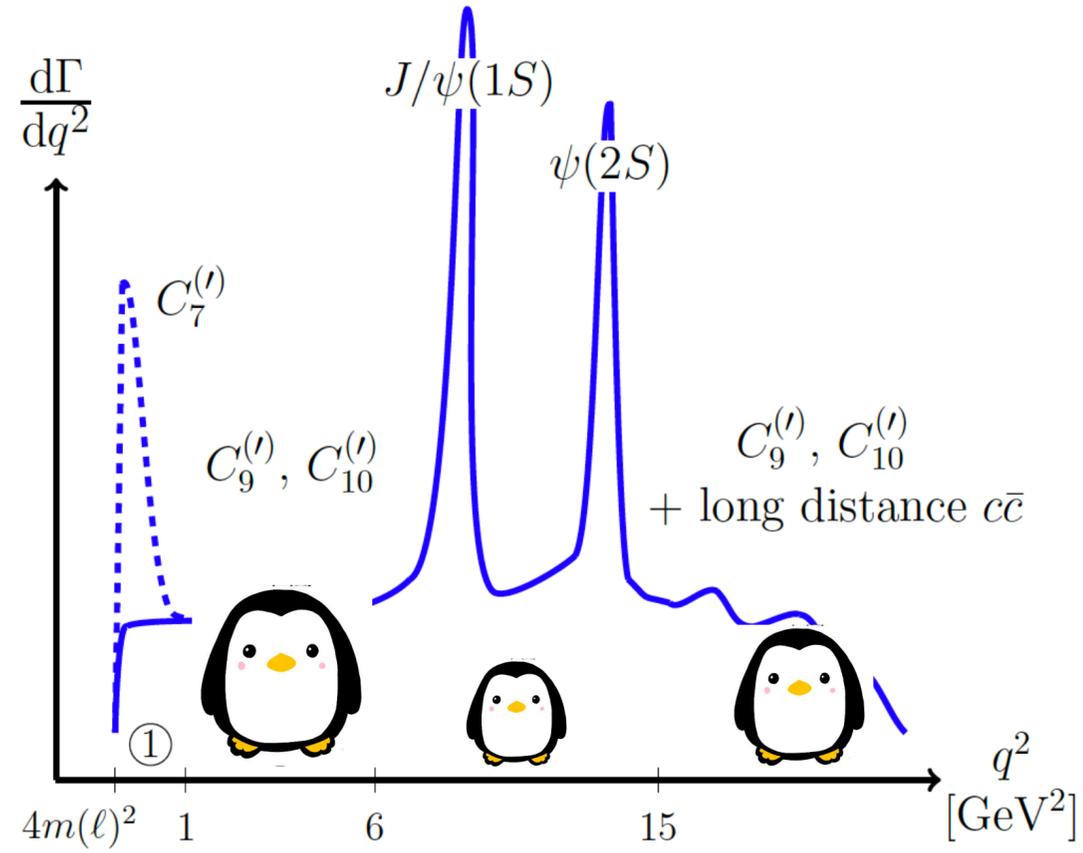
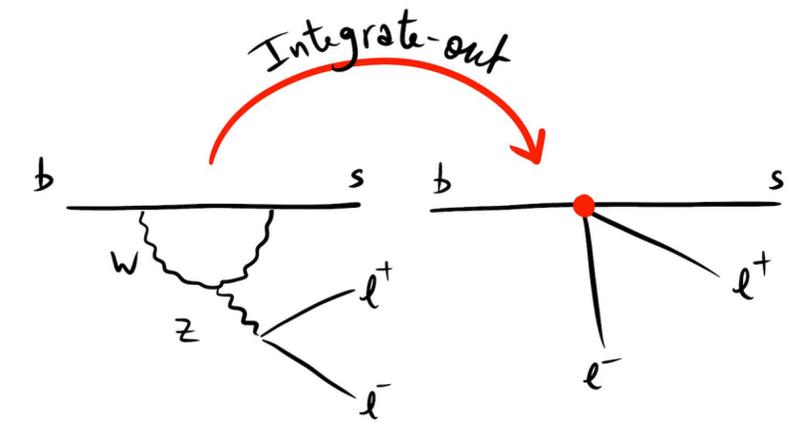
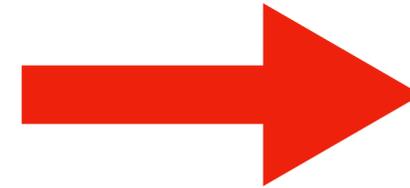


Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	61.7	+4.4 -4.8	[56.9, 66.1]	+8.6 -9.5	[52.2, 70.3]
B^0	82.0	+8.1 -8.8	[73.2, 90.1]	+17 -18	[64, 99]
B_s^0	79	+21 -24	[55, 100]	+51 -47	[32, 130]

Multiscale problem



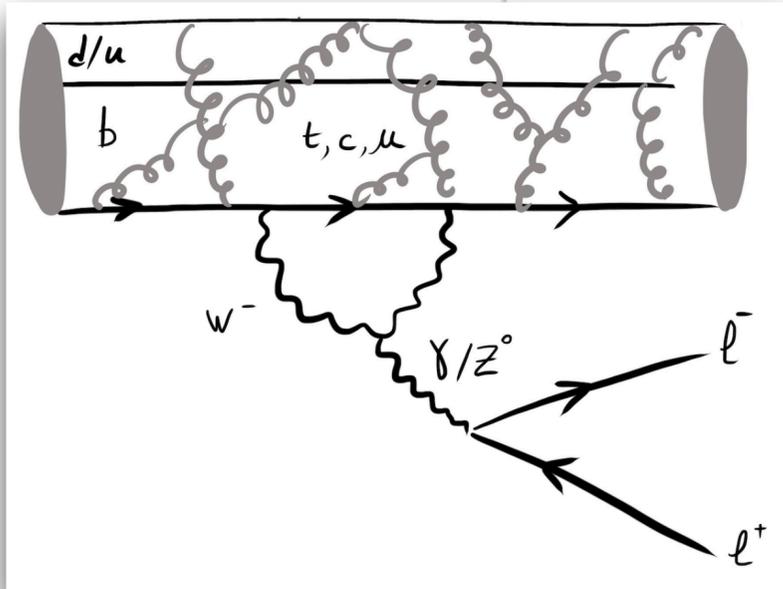
EFT



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c.,$$

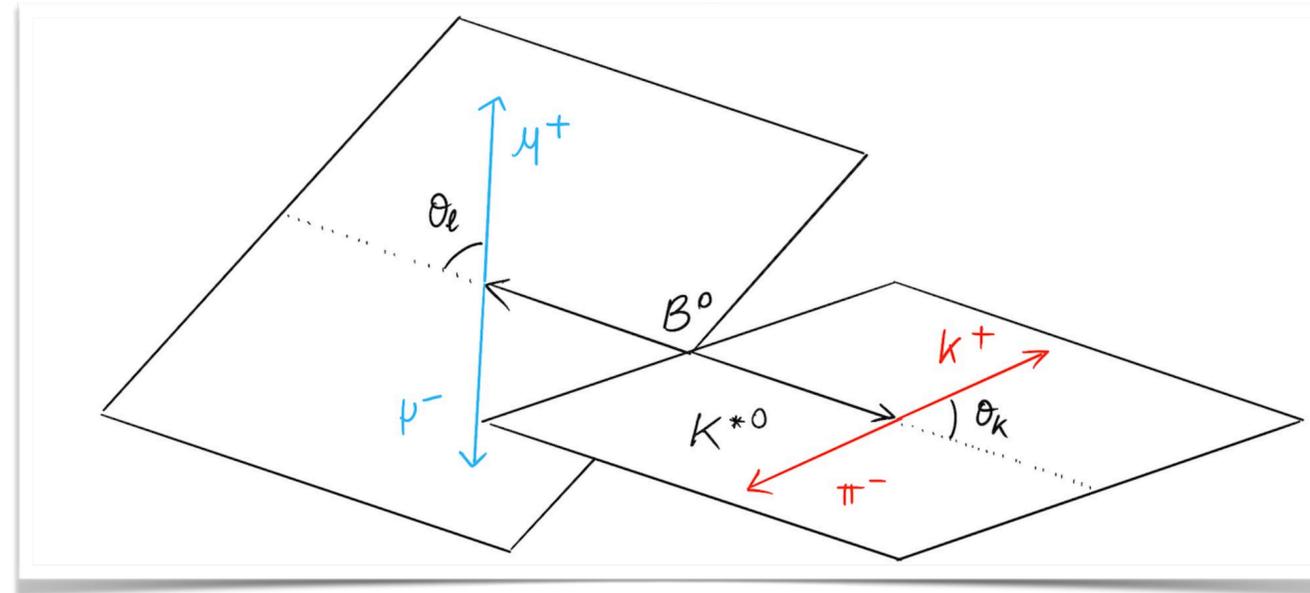
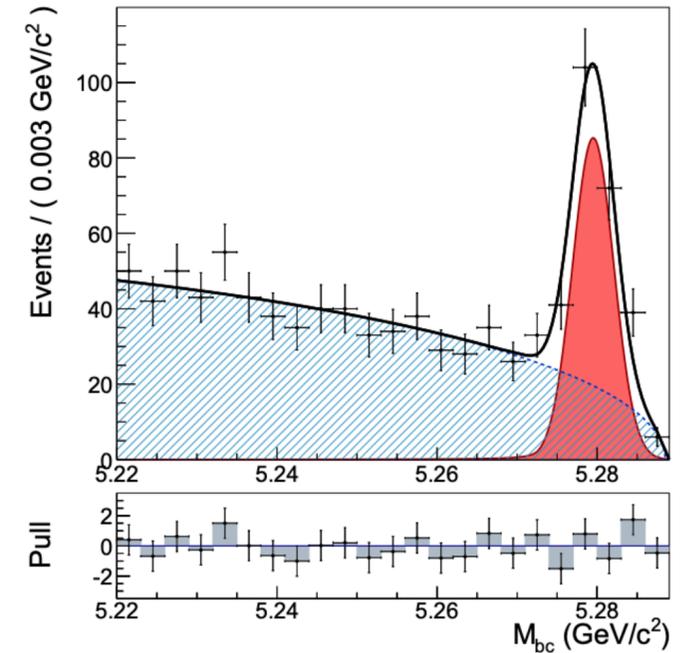
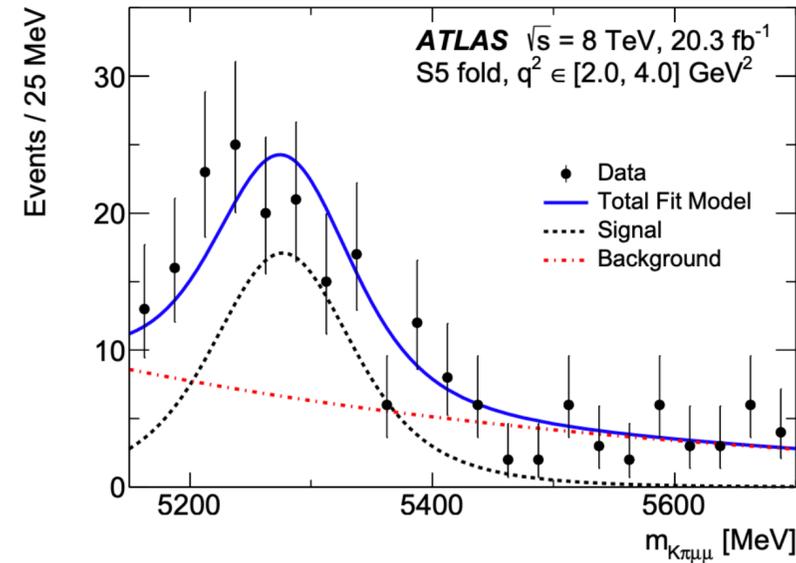
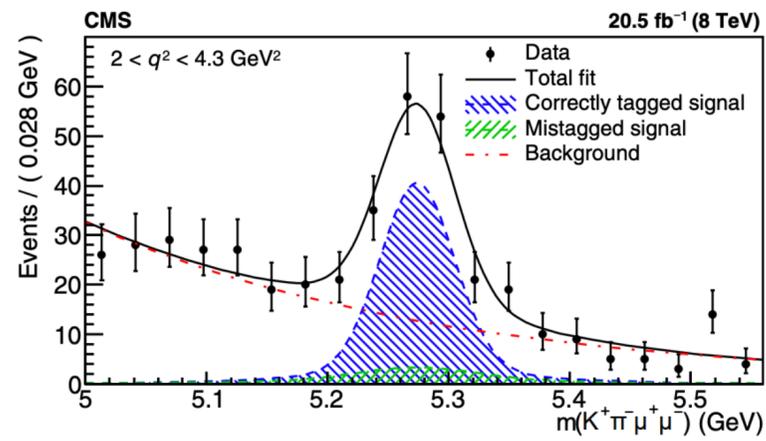
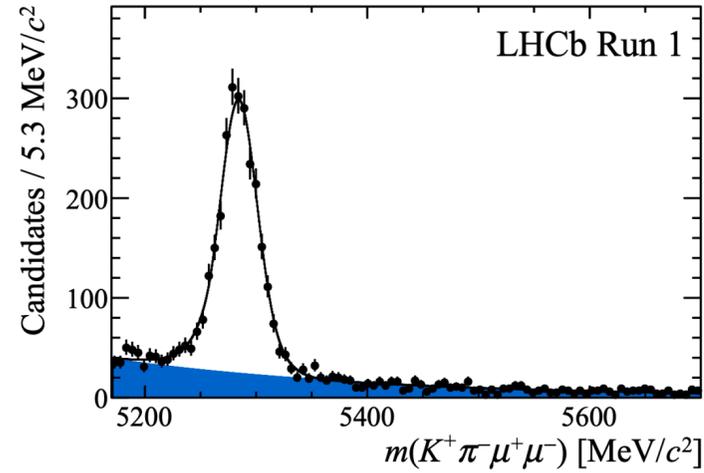
Theoretically clean (or not)

“cleanliness” of $b \rightarrow s$ observables in the SM



	parametric uncertainties	form factors	non-local matrix elements
$\mathcal{B}(B \rightarrow Mll)$	X	X	X
angular observables	✓	X	X
$\overline{\mathcal{B}}(B_s \rightarrow ll)$	X	✓	✓ (N/A)
LFU observables	✓	✓	✓

$b \rightarrow sl^+l^-$ angular analyses



LHCb PRL 125 (2020) 011802
CMS PRL B781 (2018) 517
ATLAS JHEP 10 (2018) 048
Belle PRL 118 (2017) 111801

Many observables:

- * Decay rates or ratio of lepton flavours.
- * Angular asymmetries.
- * decay rates as a function of angles of decay products give access to large range of obs. (with small theory uncertainties).
- * Helps to deduce nature of New Physics models.

$B^0 \rightarrow K^* \mu^+ \mu^-$ Angular expressions

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} \Big|_P = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.$$

$$+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l$$

$$- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$$

$$+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi$$

$$+ \frac{4}{3} A_{\text{FB}} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi$$

$$+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \Big]$$

S_i 8 CP-averaged observables are extracted from the fit



Optimise the observables which are expressed in an different basis P_i

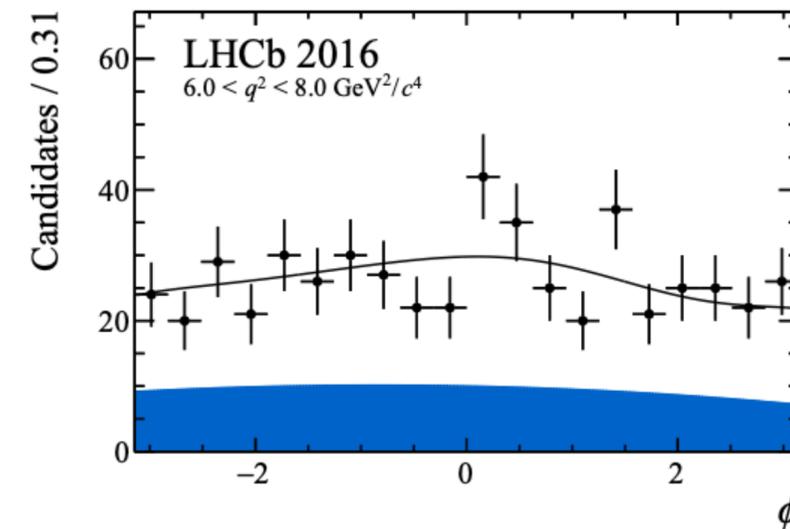
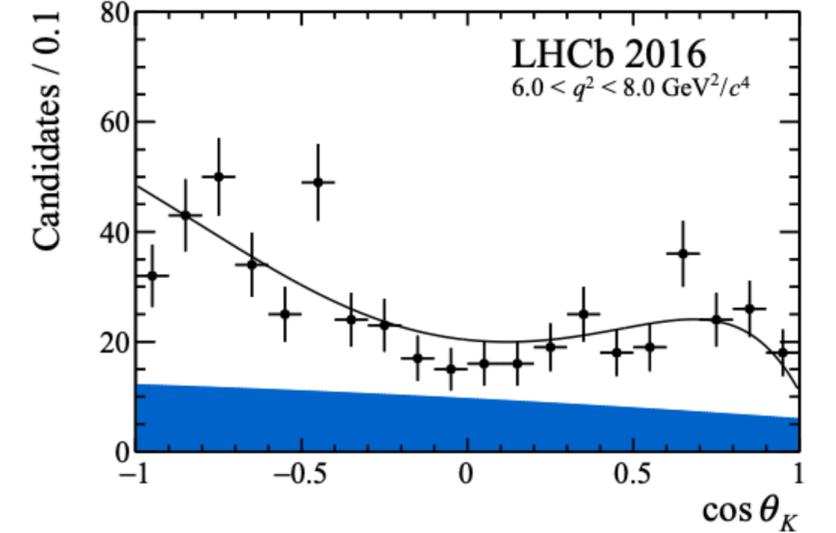
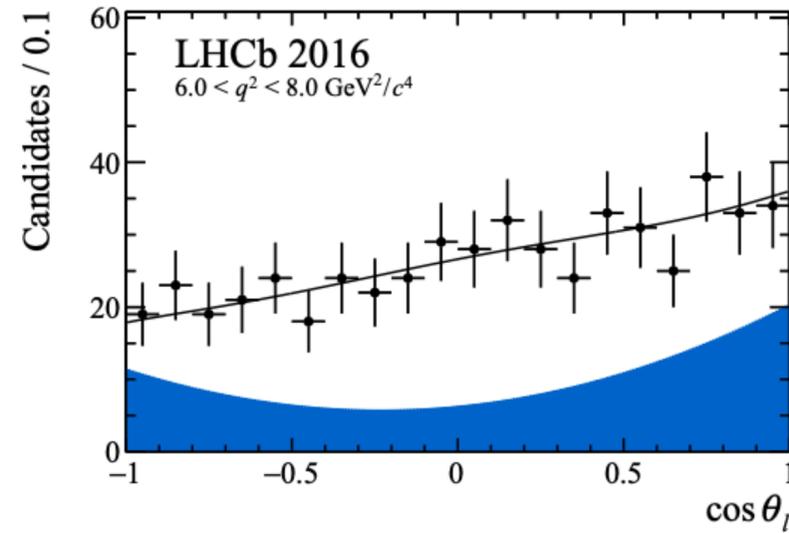
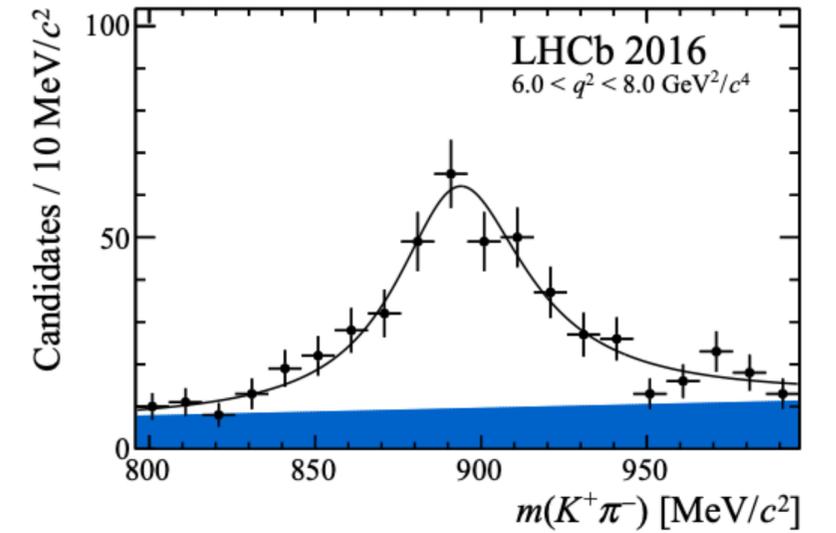
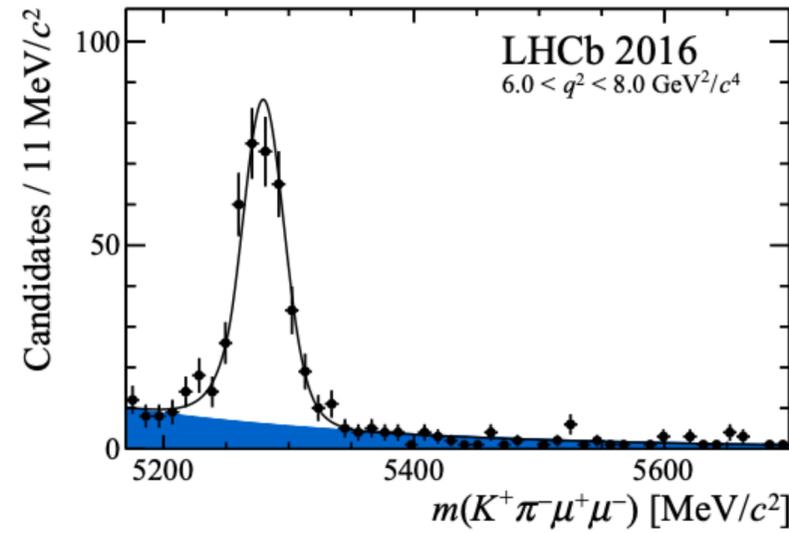
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}$$

$$P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}$$

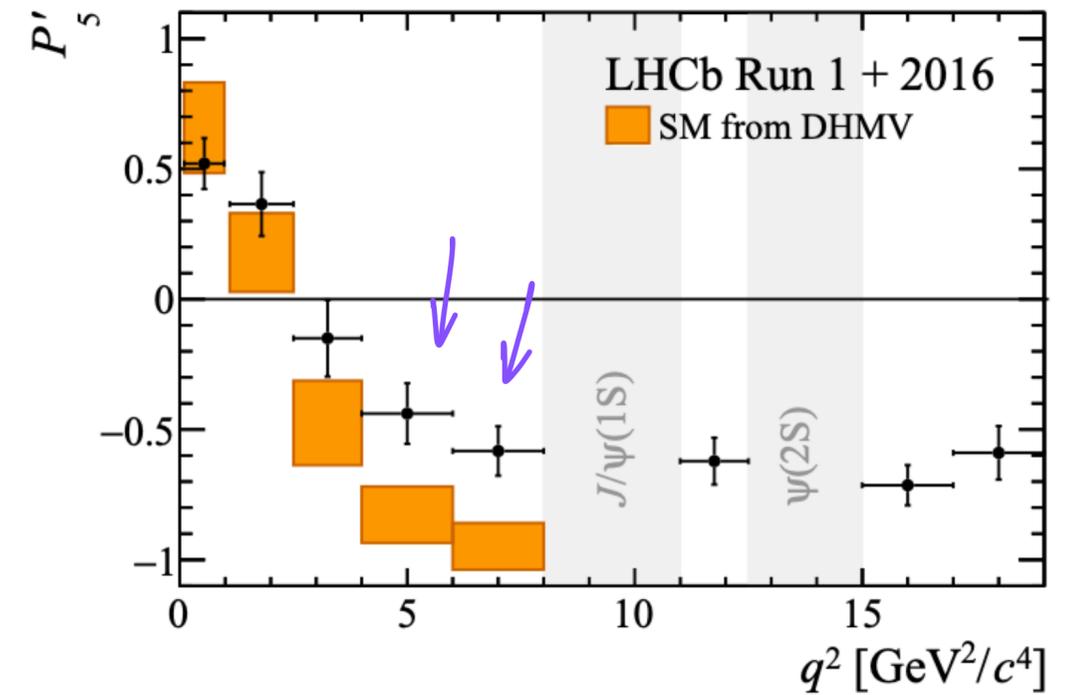
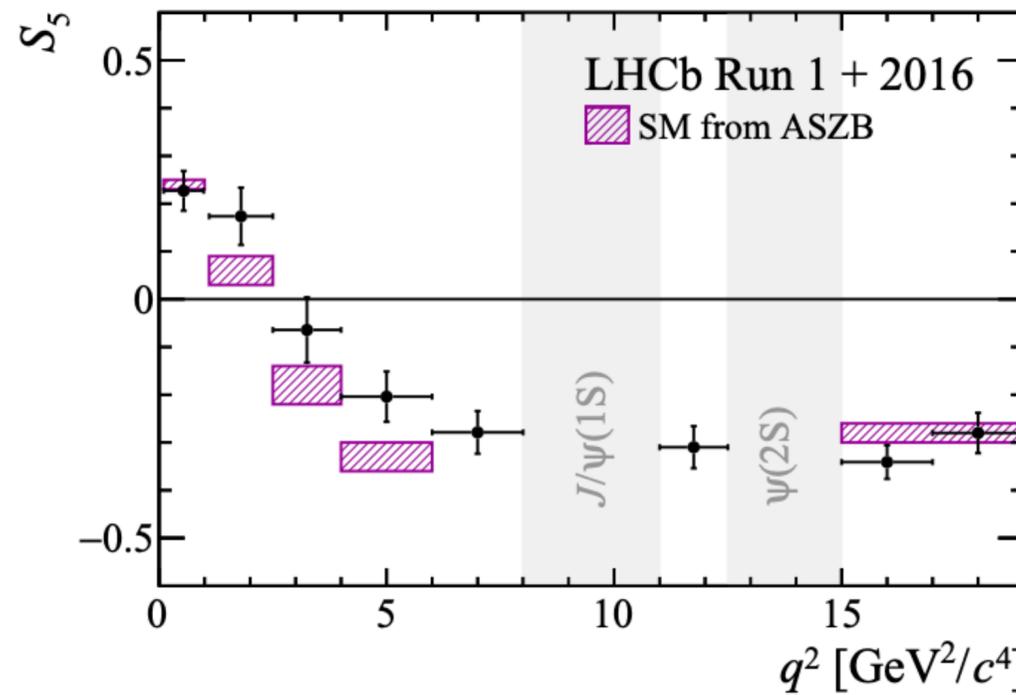
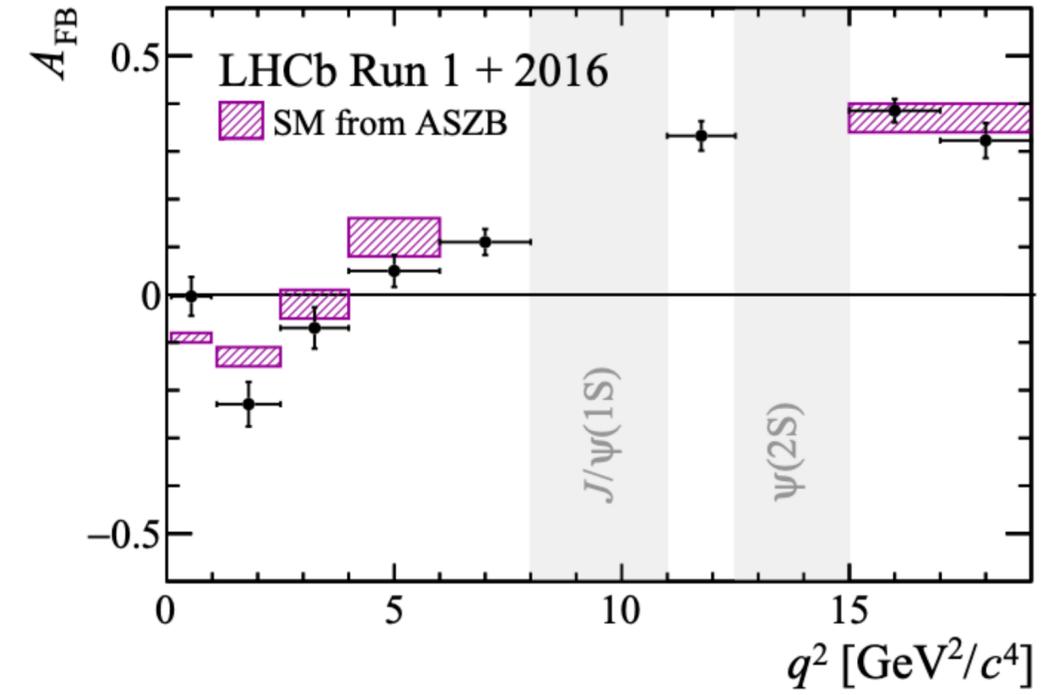
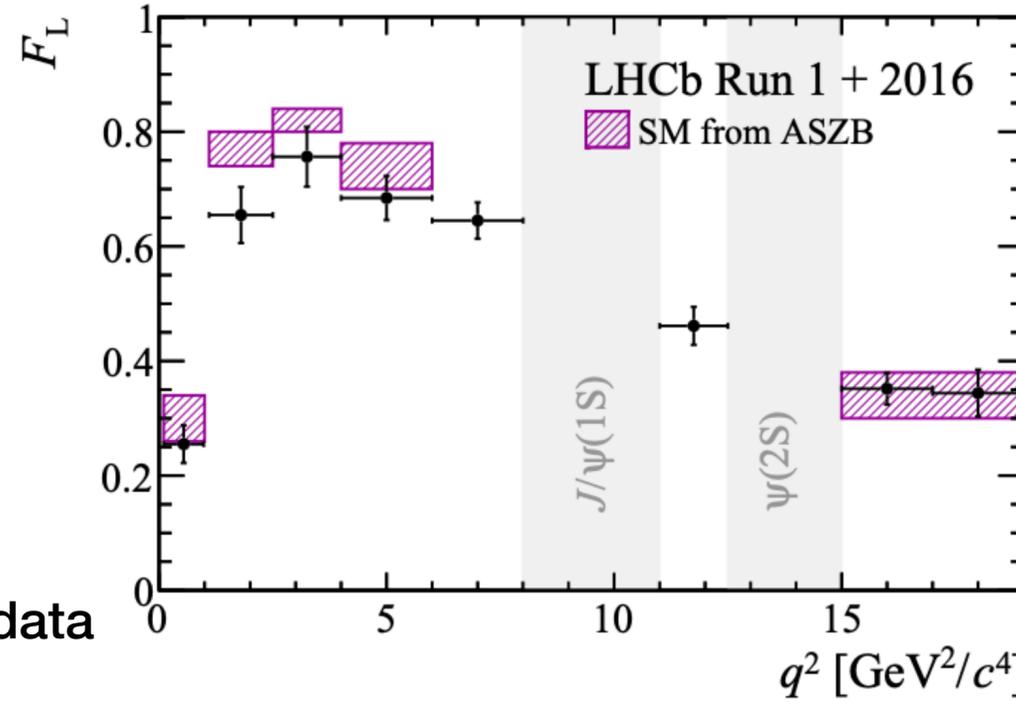
The fit is performed in both basis S_i and P_i !

$$B^0 \rightarrow K^* \mu^+ \mu^-$$

- 5D fit B and K^* mass + angles.
- Use 8 q^2 bins.
- 4D (q^2 and angles) acceptance correction is convoluted into the fit PDF
- simultaneous fit of Run 1 & 2016 data samples.



$$B^0 \rightarrow K^* \mu^+ \mu^-$$



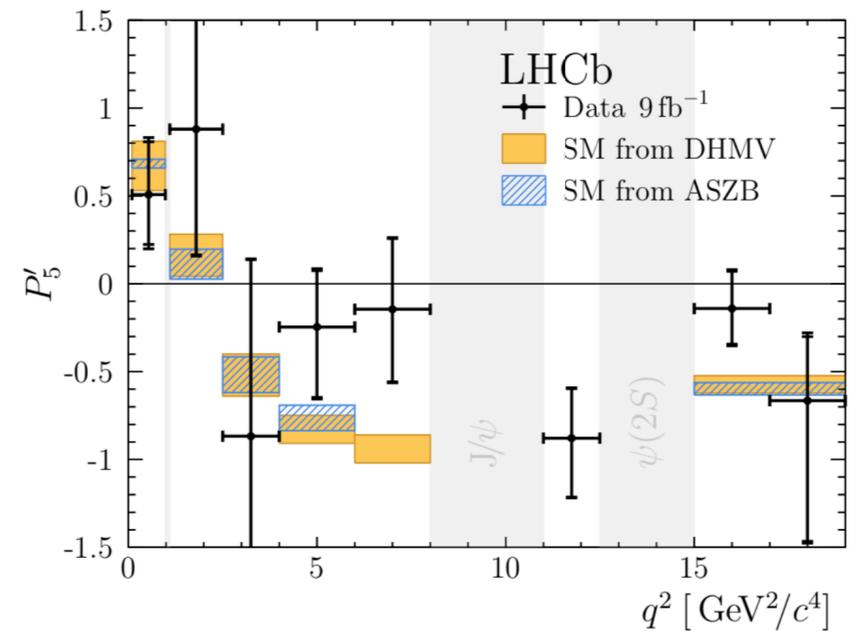
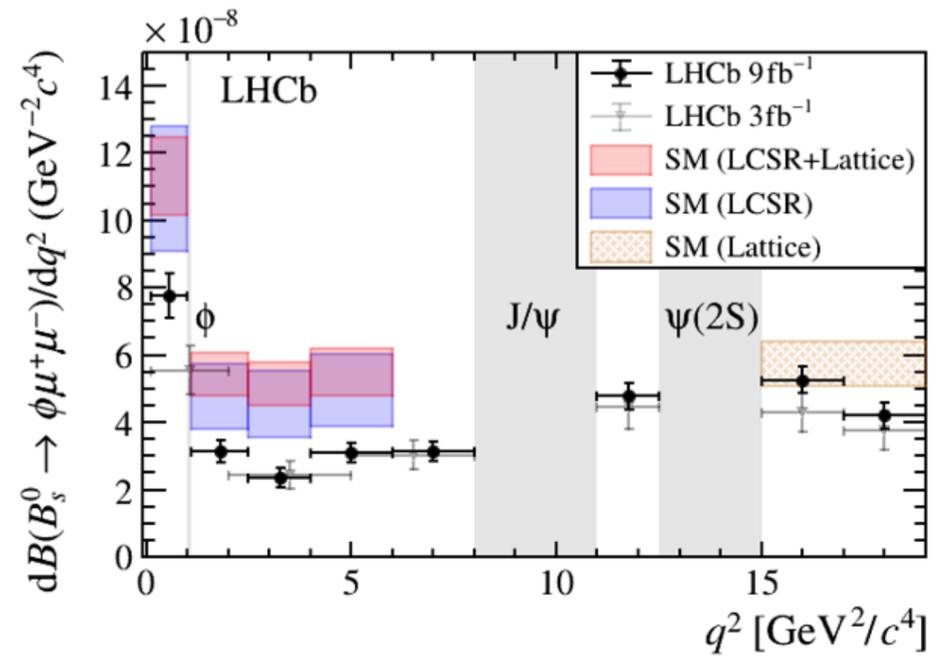
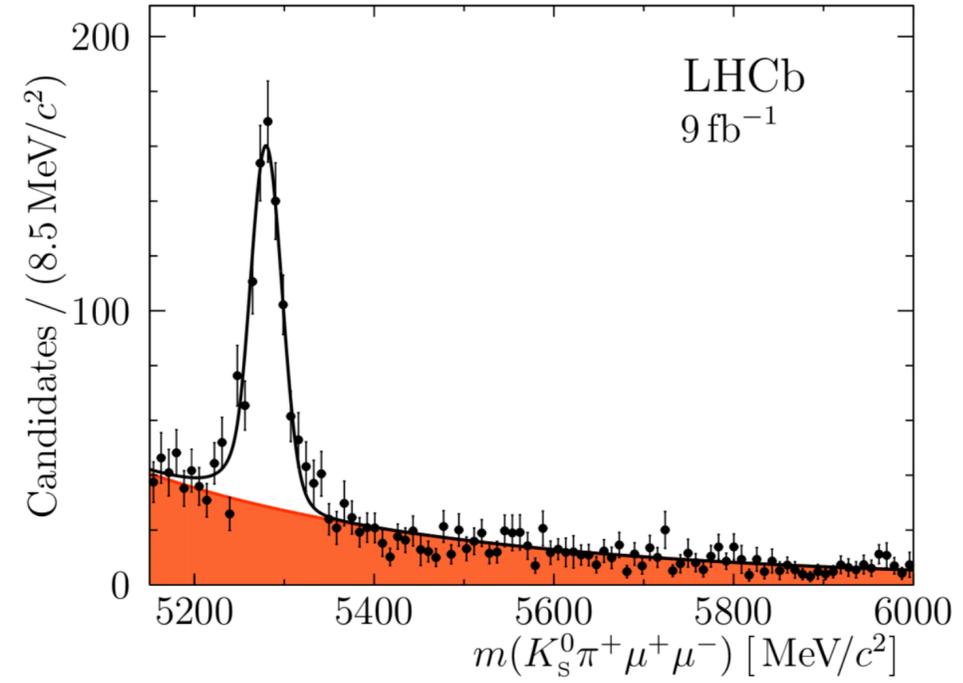
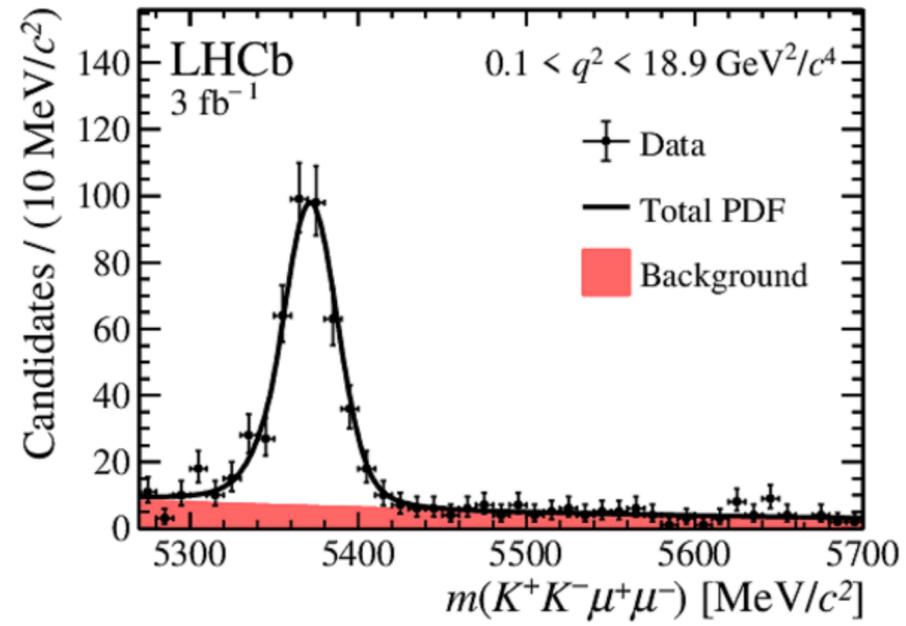
Very good agreement between Run1 & 2016 data

Local discrepancies between 2.5 and 2.9 for P'_5 in middle q^2 bins.

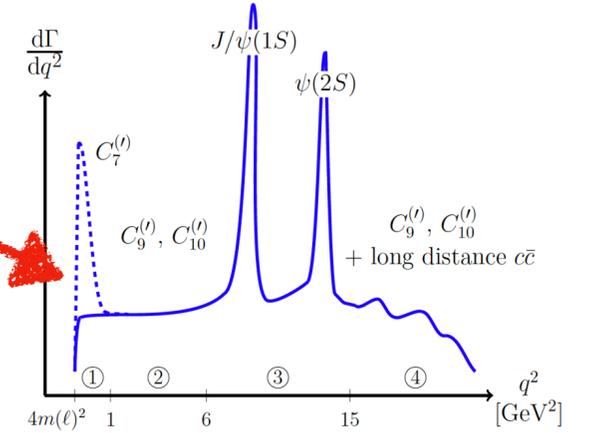
Global fits to the Wilson coefficients
 Indicate tension of 2.9 standard deviations !

Theory predictions from
 S. Descotes Genon et al. JHEP 12 (2014) 125,
 A. Khojamirian et al. JHEP 09 (2010) 089

But also...



$B^0 \rightarrow K^* e^+ e^-$ Angular analysis @ very low q^2



$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\cos\theta_\ell d\cos\theta_K d\tilde{\phi}} = \frac{9}{16\pi} \left[\frac{3}{4}(1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K \right. \\ \left. + \frac{1}{4}(1 - F_L) \sin^2\theta_K \cos 2\theta_\ell - F_L \cos^2\theta_K \cos 2\theta_\ell \right. \\ \left. + (1 - F_L) A_T^{\text{Re}} \sin^2\theta_K \cos\theta_\ell \right. \\ \left. + \frac{1}{2}(1 - F_L) A_T^{(2)} \sin^2\theta_K \sin^2\theta_\ell \cos 2\tilde{\phi} \right. \\ \left. + \frac{1}{2}(1 - F_L) A_T^{\text{Im}} \sin^2\theta_K \sin^2\theta_\ell \sin 2\tilde{\phi} \right]. \quad (1)$$

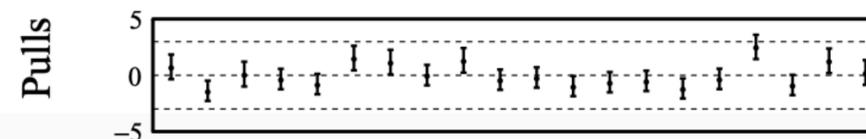
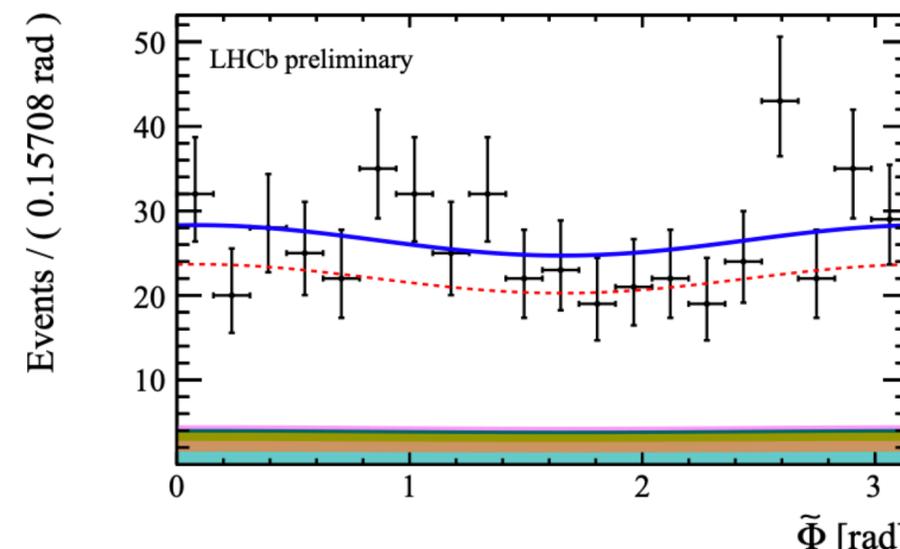
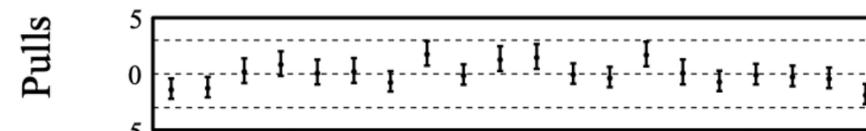
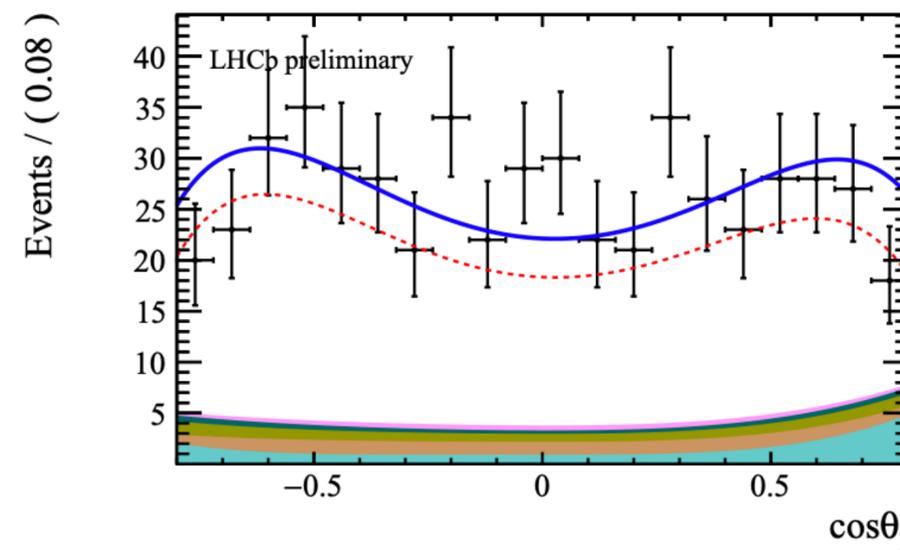
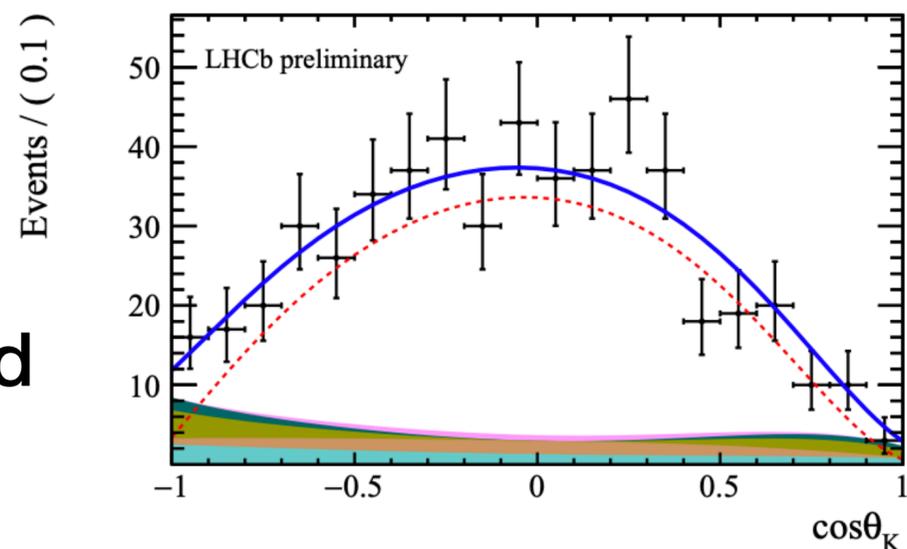
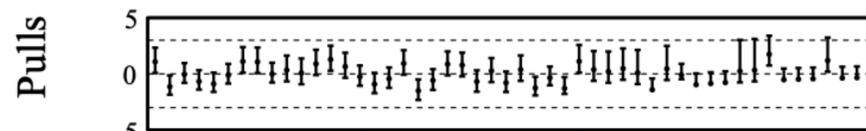
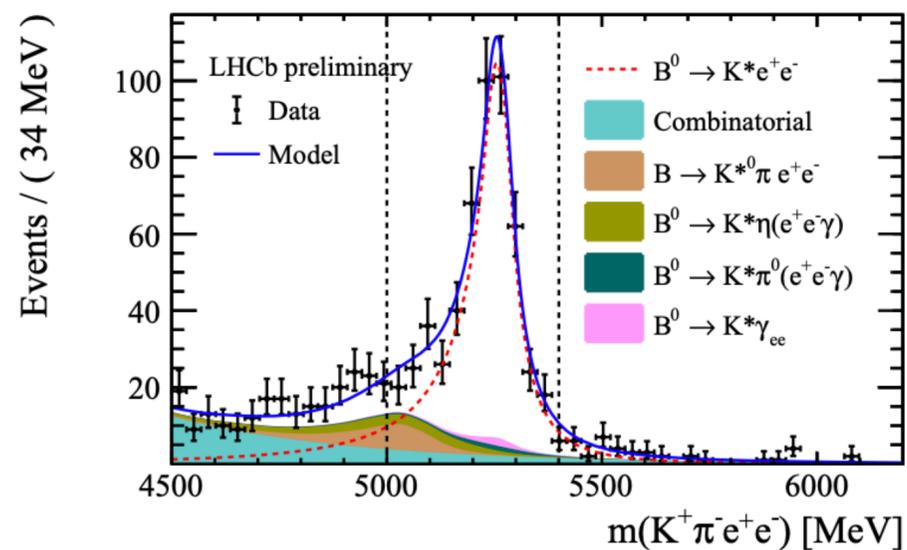
$$A_T^{(2)}(q^2 \rightarrow 0) = \frac{2\text{Re}(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

$$A_T^{\text{Im}}(q^2 \rightarrow 0) = \frac{2\text{Im}(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}$$

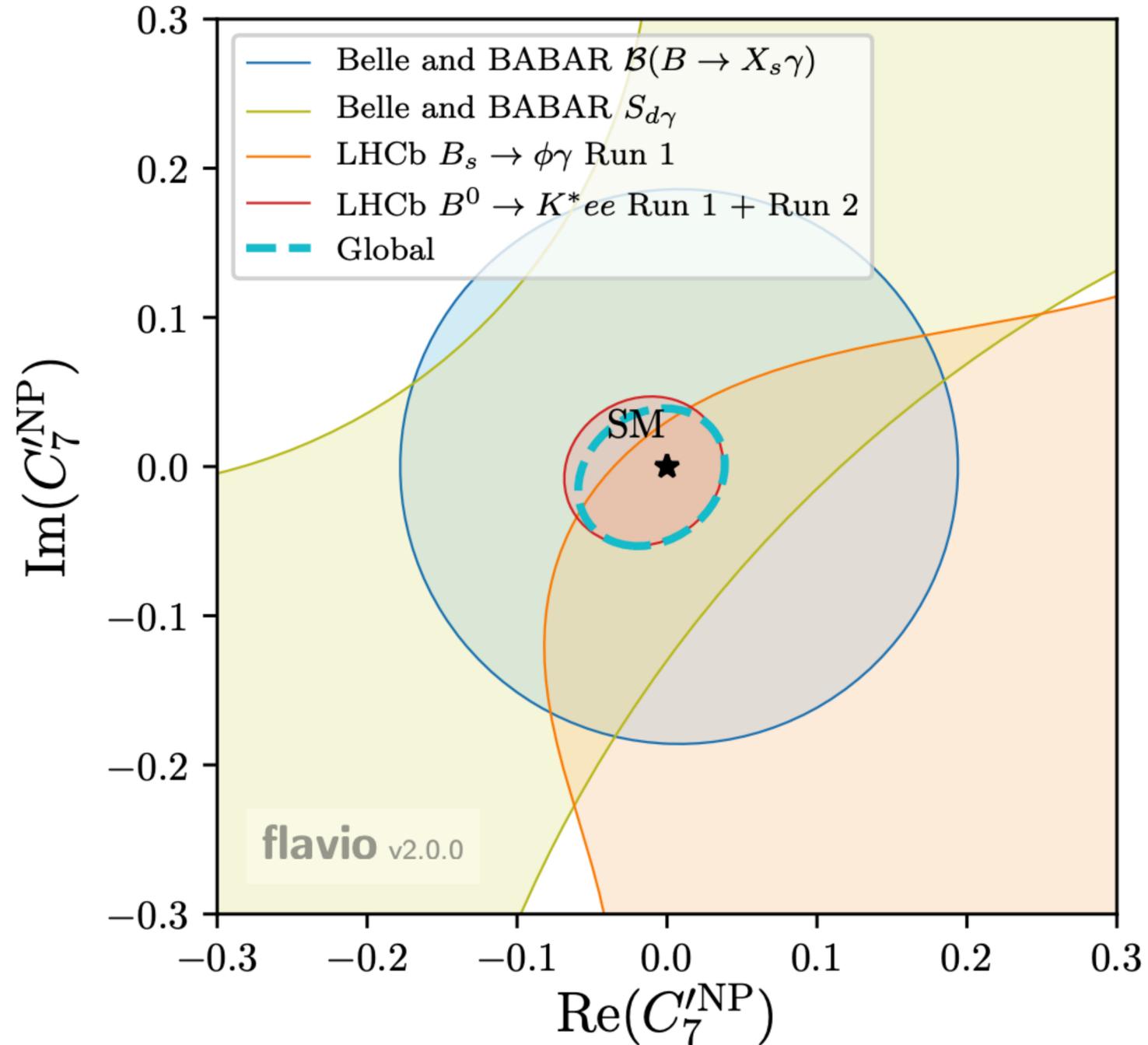
$$q^2 \in [0.0008, 0.257] \text{ GeV}/c^2$$

$$B^0 \rightarrow K^* e^+ e^-$$

- 4D-fit to B mass and angles.
- When possible backgrounds modelled using data.
- Main systematics from signal acceptance and angular background modelling.
- Fit procedure thoroughly tested with pseudo-experiments



$$B^0 \rightarrow K^* e^+ e^-$$



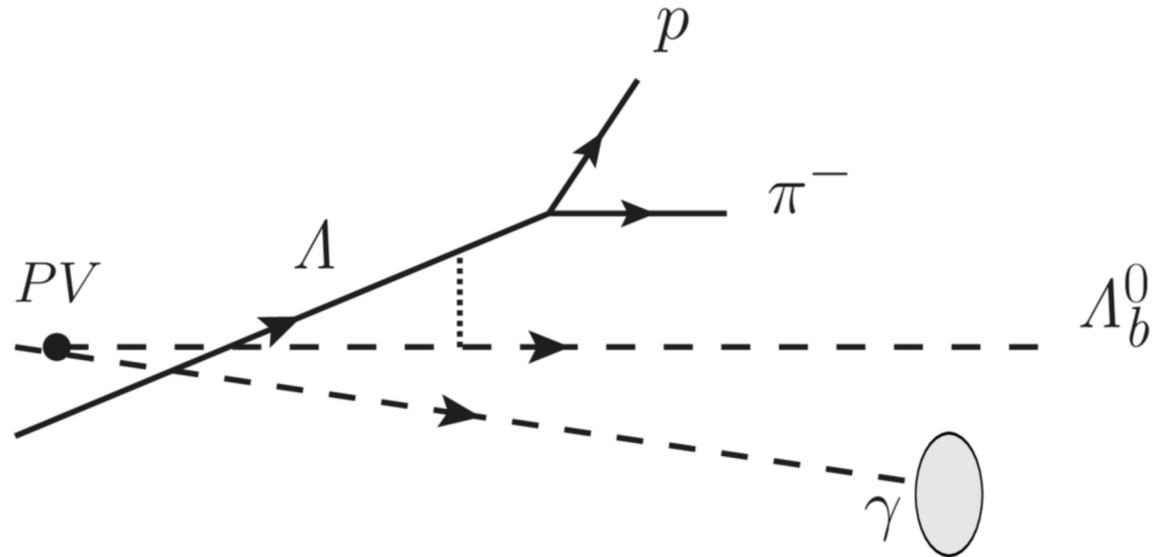
Results

$$\begin{aligned}
 F_L &= 0.044 \pm 0.026 \pm 0.014 \\
 A_T^{\text{Re}} &= -0.064 \pm 0.077 \pm 0.015 \\
 A_T^{(2)} &= +0.106 \pm 0.103_{-0.017}^{+0.016} \\
 A_T^{\text{Im}} &= +0.015 \pm 0.102 \pm 0.012,
 \end{aligned}$$

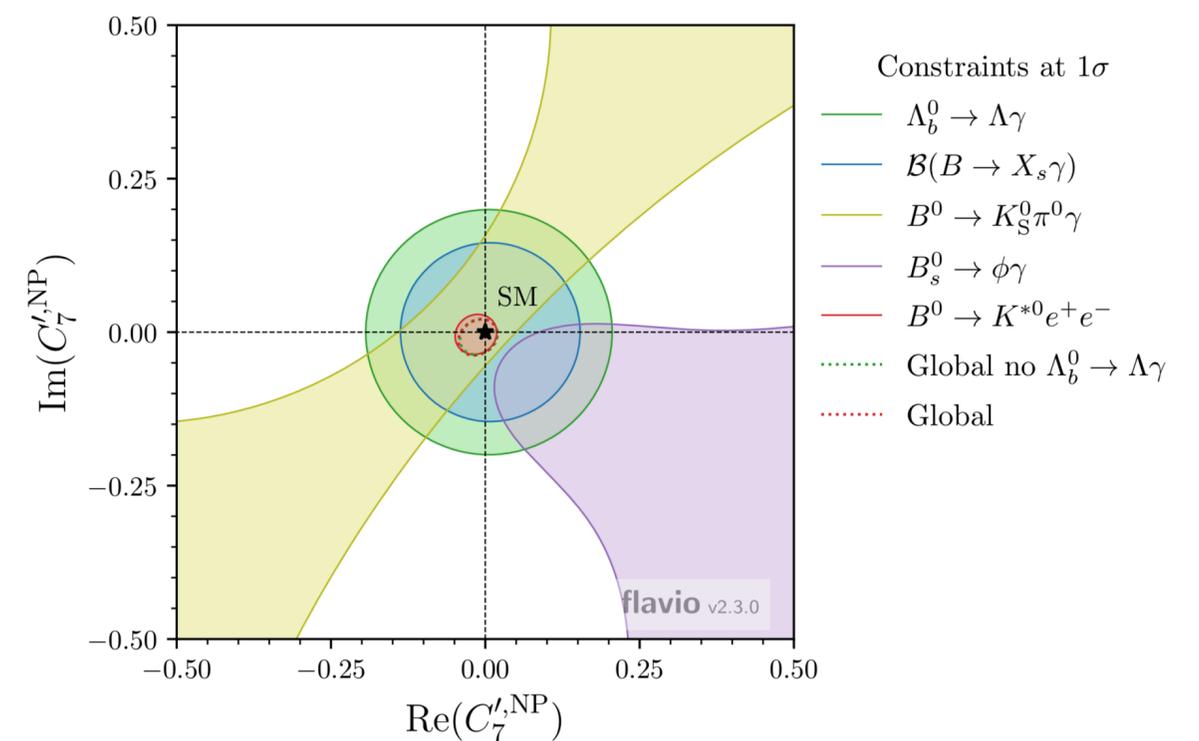
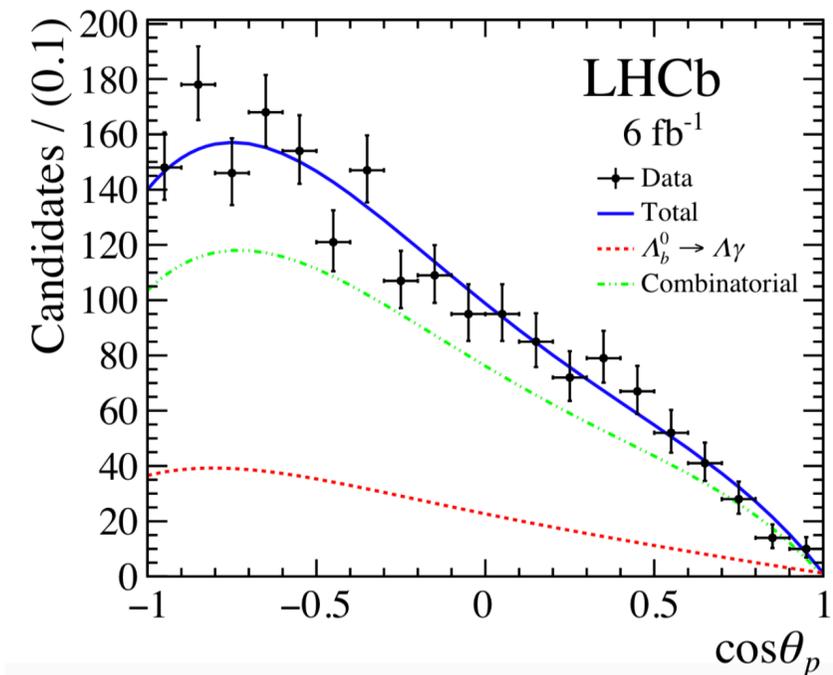
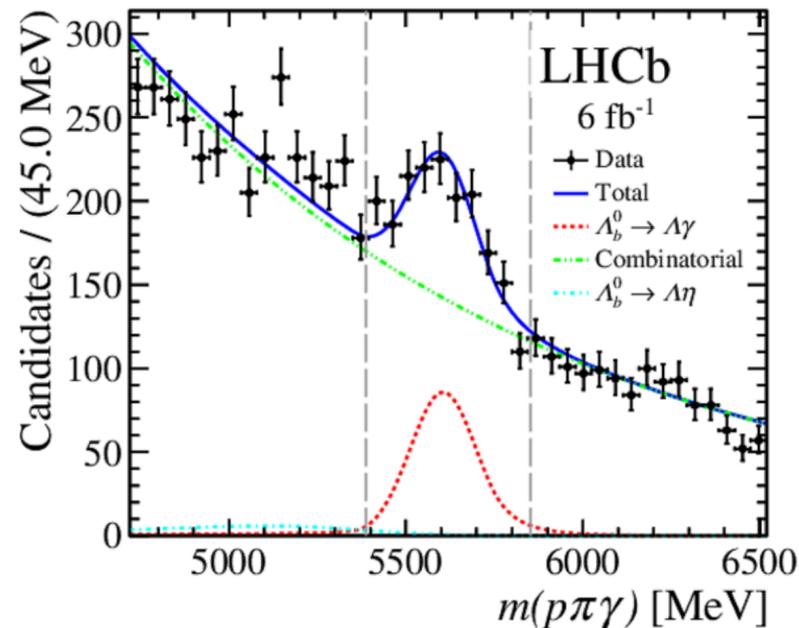
**Even if still statistically limited
best sensitivity to right-handed
quark coupling C_7'**

Adding a bit of complication

Benefit from the diversity of b-hadrons production @ the LHC



$$\frac{d\Gamma}{d(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p,$$



$$B_q^0 \rightarrow l^+ l^-$$

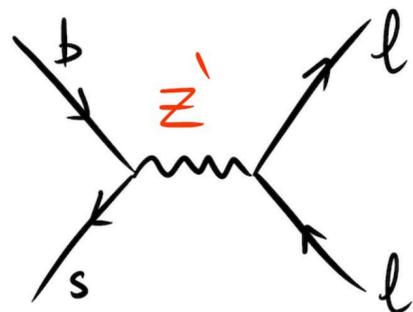
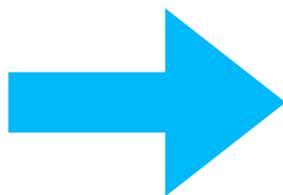
Branching fraction prediction in the SM:

$$\overline{B}_{ql} = \frac{|N|^2 M_{Bq}^3 f_{Bq}^2}{8\pi \Gamma_H} \beta_{ql} r_{ql}^2 |C_A(\mu_\mu)|^2 + \mathcal{O}(\alpha_{em})$$

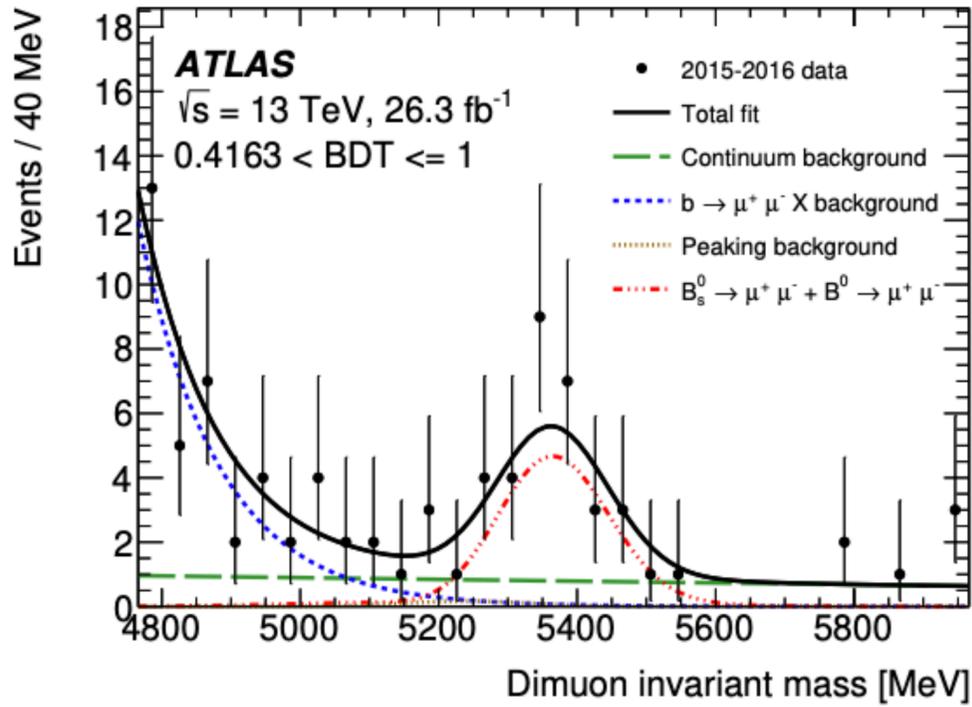
$$\frac{2m_e}{M_{Bq}}$$

$$\sqrt{1 - r_{ql}^2}$$

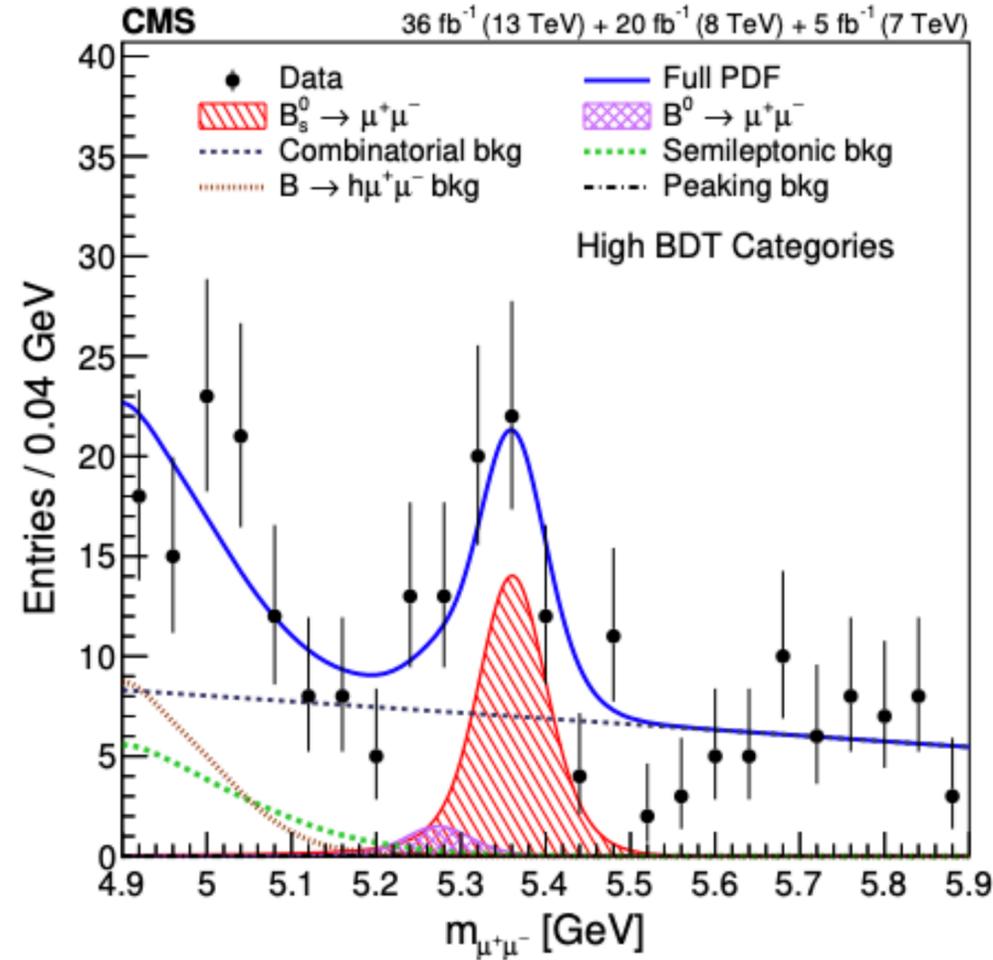
Theoretically clean observable



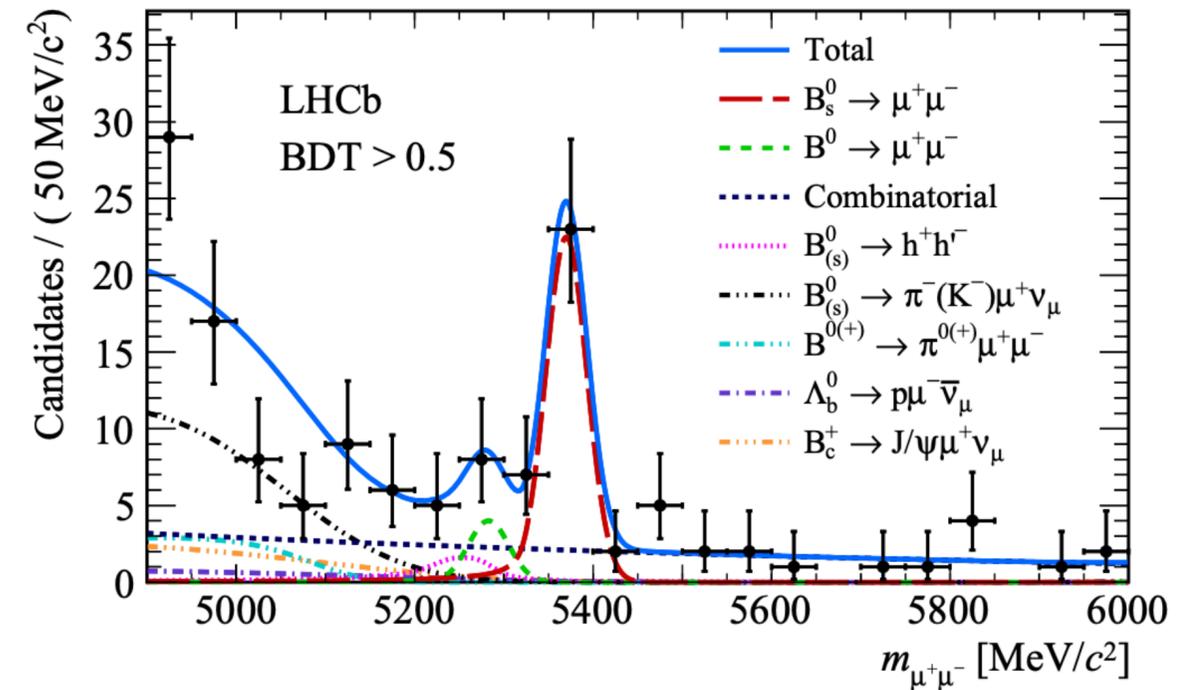
$B_s^0 \rightarrow \mu^+ \mu^-$ "seen" across the ring !



ATLAS JHEP04(2019)098

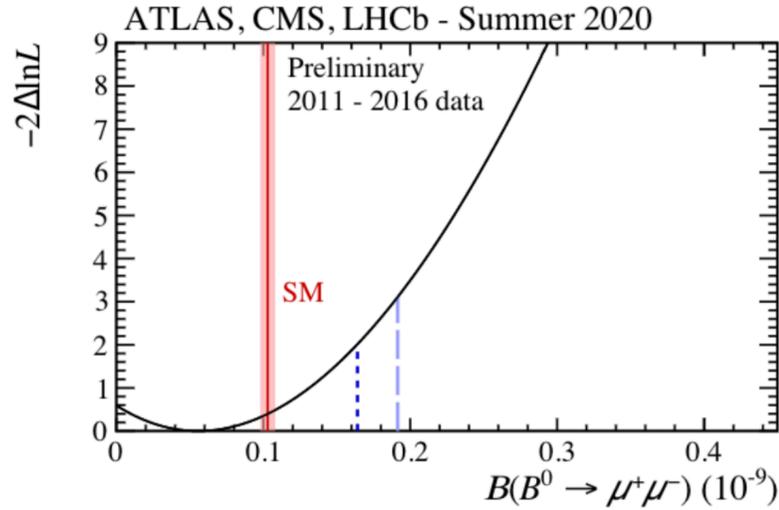
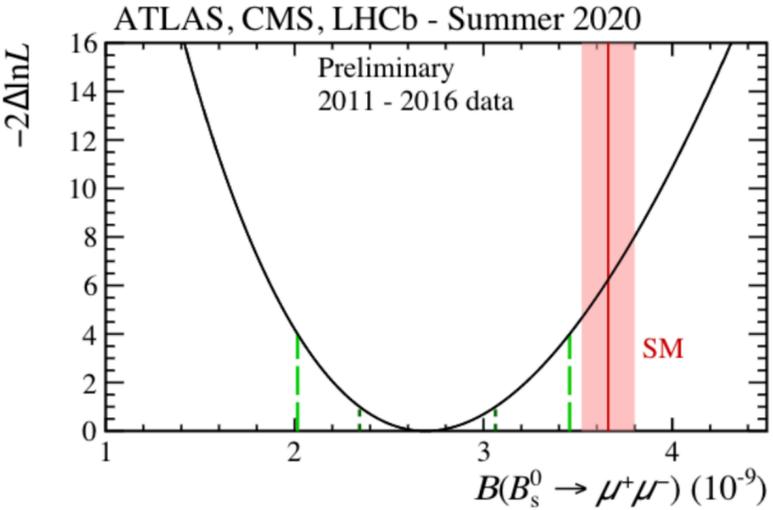
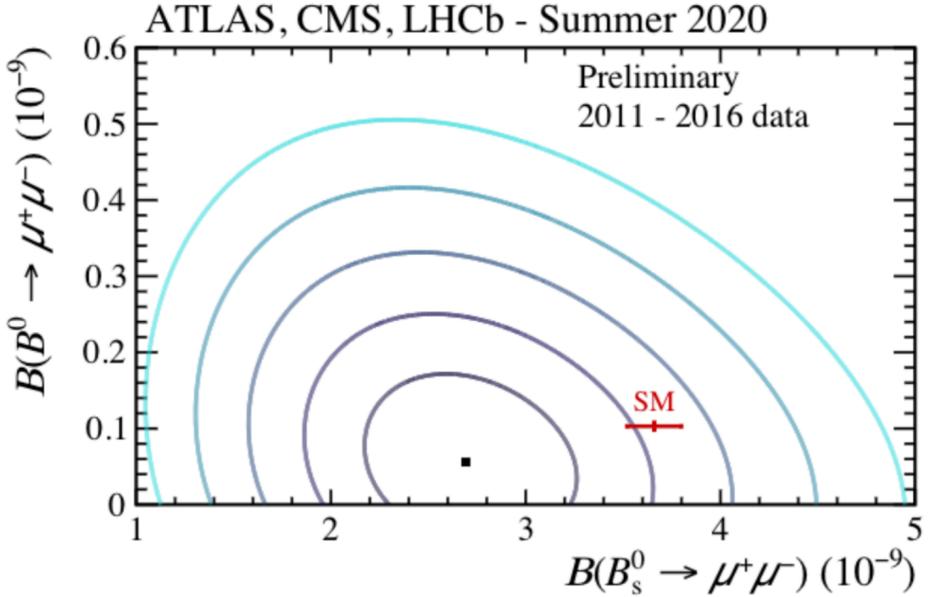
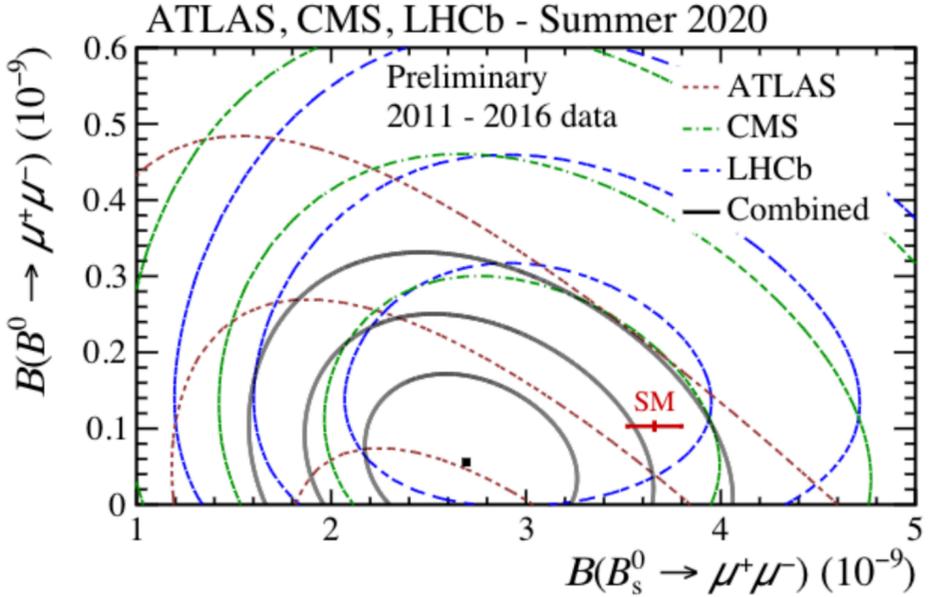


CMS JHEP04(2020)188



LHCb Phys. Rev. Lett. 118, 191801

ATLAS, CMS & LHCb combination

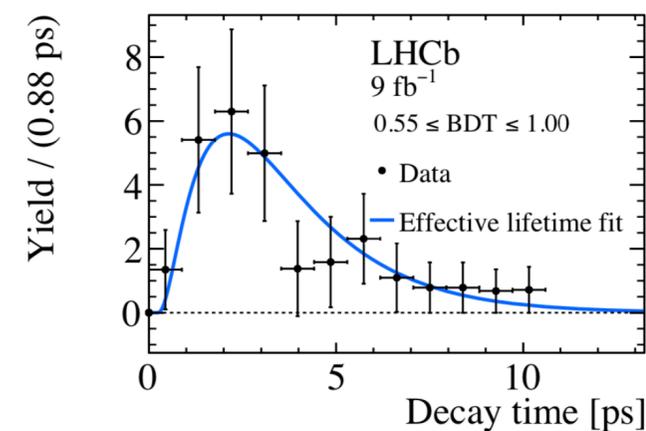
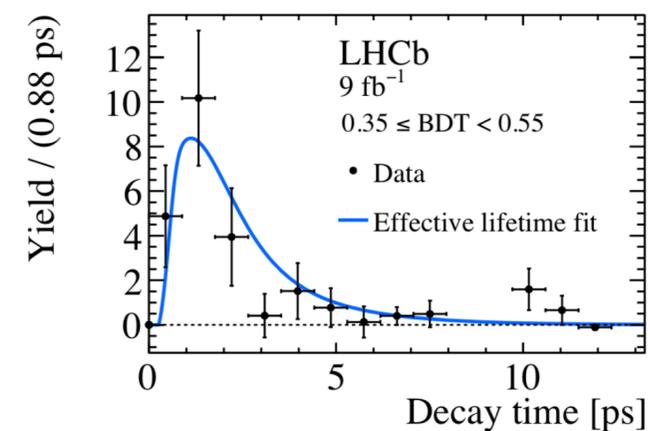
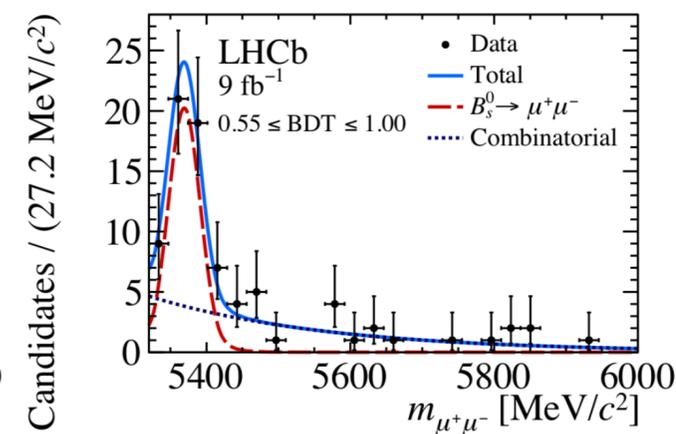
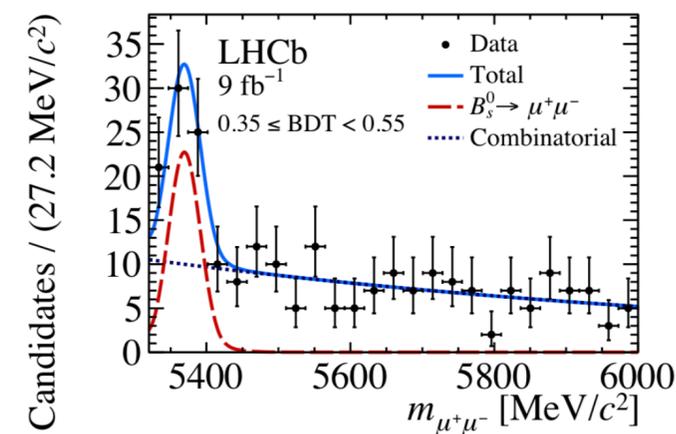
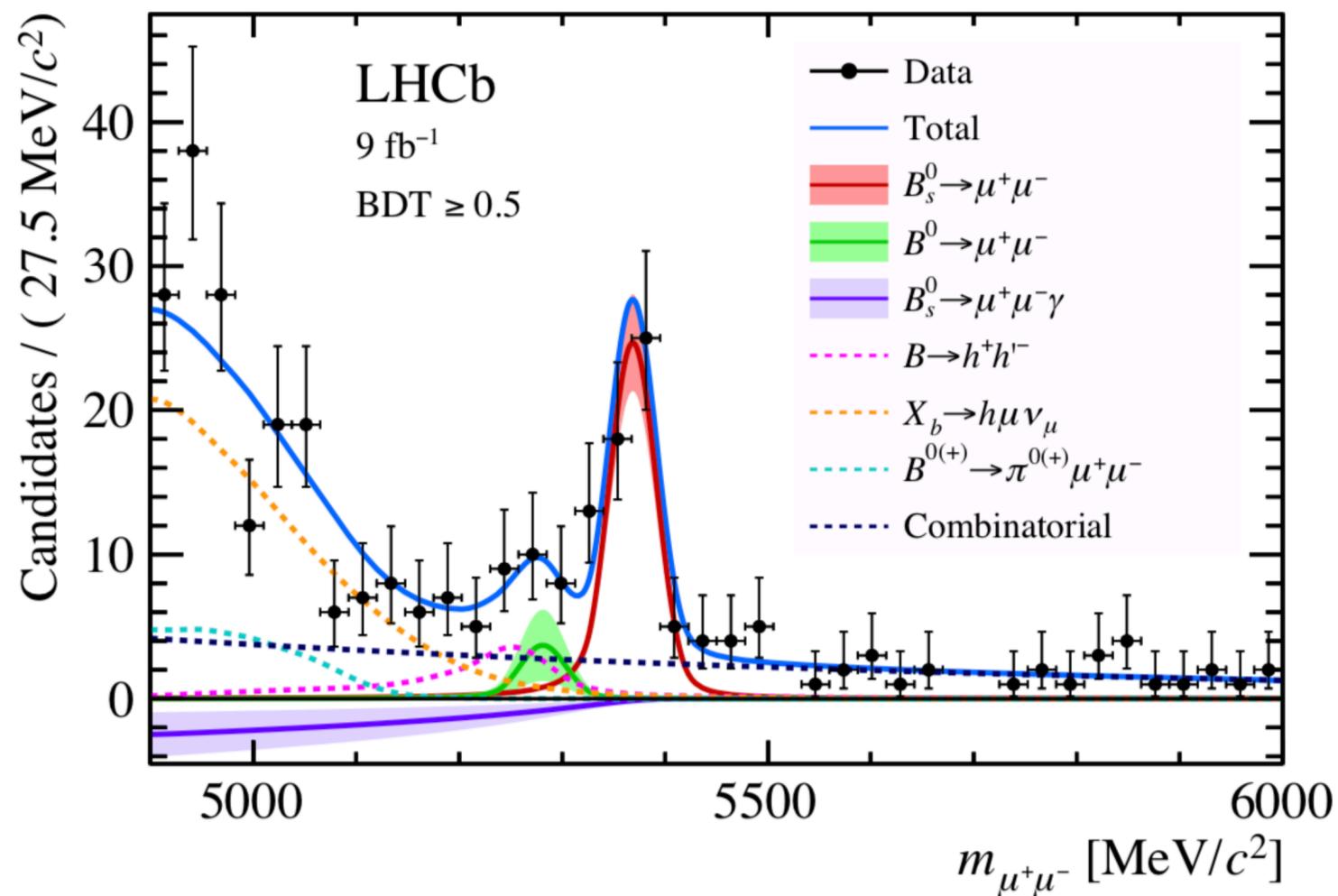


$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.6 (1.9) \times 10^{-10} @ 90 \% (95\%) \text{ CL}$$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

Results compatible with the SM within 2.1 standard deviations in 2D plane.

More recently...



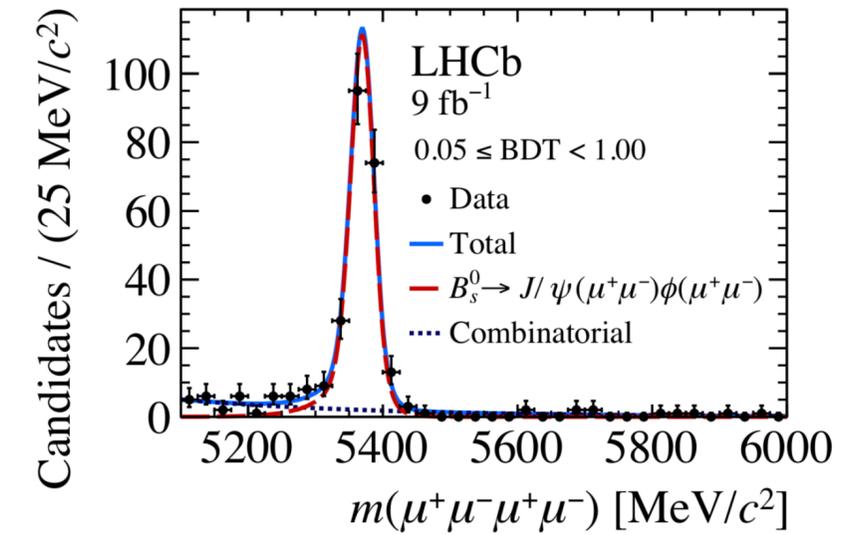
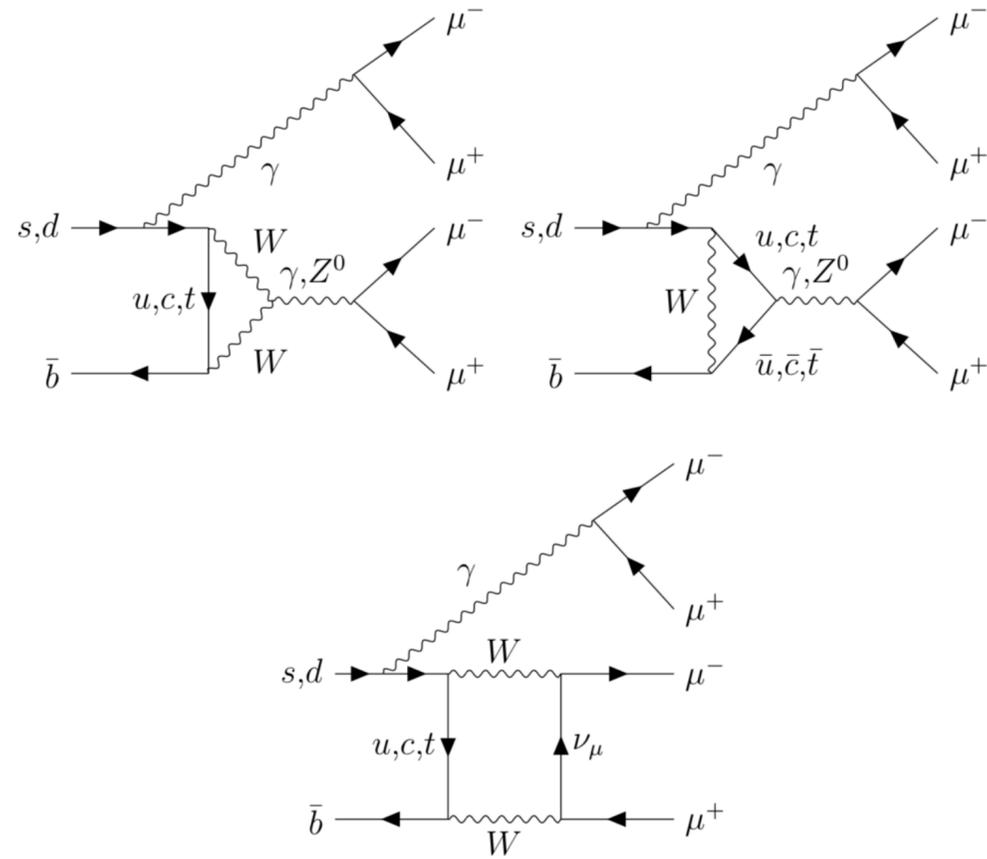
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9},$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10},$$

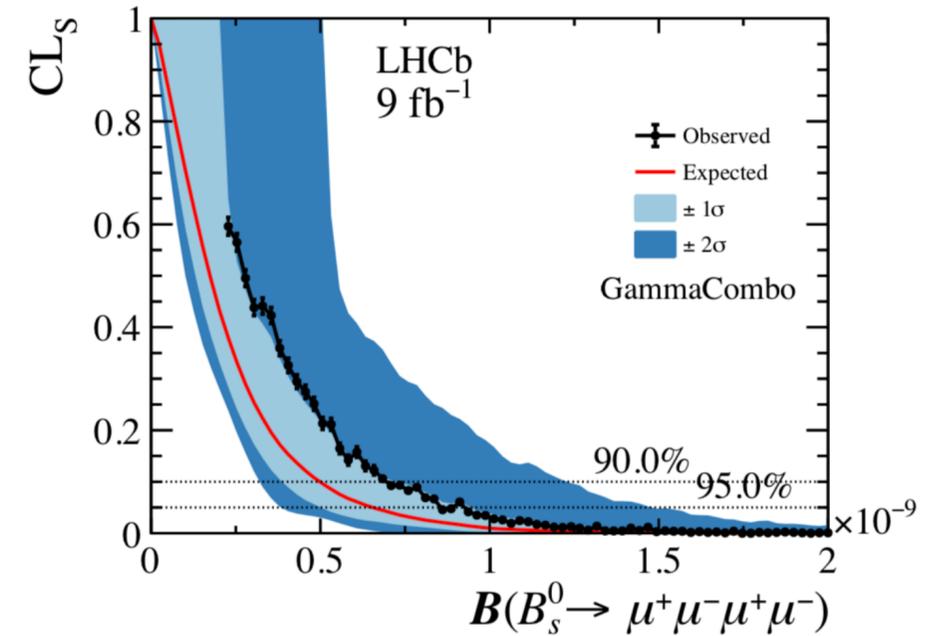
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-\gamma) = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} \text{ with } m_{\mu\mu} > 4.9 \text{ GeV}/c^2.$$

The $B_s^0 \rightarrow \mu^+\mu^-$ effective lifetime is $2.07 \pm 0.29 \pm 0.03$ ps.

Adding more complexity to the Feynman diagrams



$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-\mu^+\mu^-)$	$< 8.6 \times 10^{-10}$,
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-\mu^+\mu^-)$	$< 1.8 \times 10^{-10}$,
$\mathcal{B}(B_s^0 \rightarrow a(\mu^+\mu^-)a(\mu^+\mu^-))$	$< 5.8 \times 10^{-10}$,
$\mathcal{B}(B^0 \rightarrow a(\mu^+\mu^-)a(\mu^+\mu^-))$	$< 2.3 \times 10^{-10}$,
$\mathcal{B}(B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\mu^+\mu^-)$	$< 2.6 \times 10^{-9}$,
$\mathcal{B}(B^0 \rightarrow J/\psi(\mu^+\mu^-)\mu^+\mu^-)$	$< 1.0 \times 10^{-9}$.

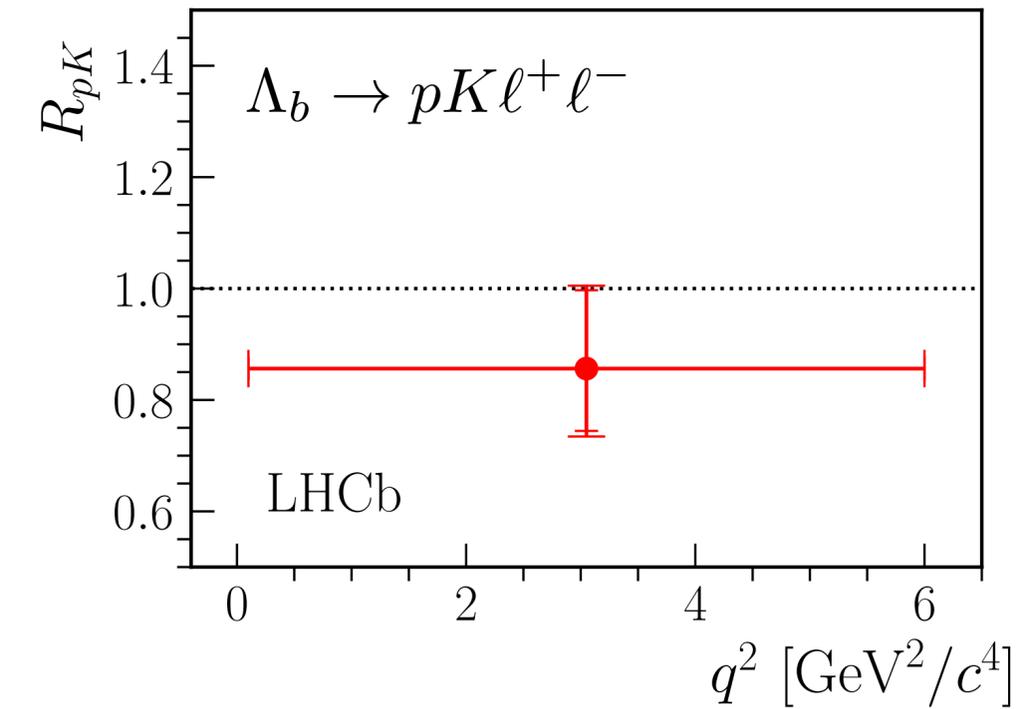


“The” observable

$$R_H \equiv \frac{\int \frac{d\Gamma(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \rightarrow H e^+ e^-)}{dq^2} dq^2},$$

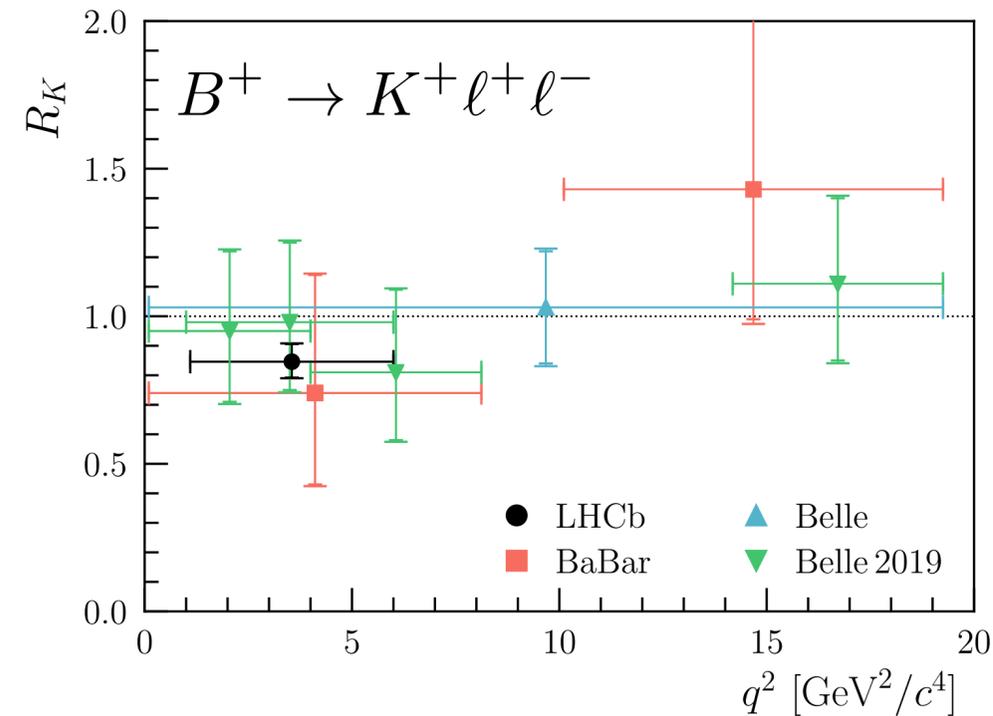
A powerful probe to look for NP in an indirect way.

Lepton Universality



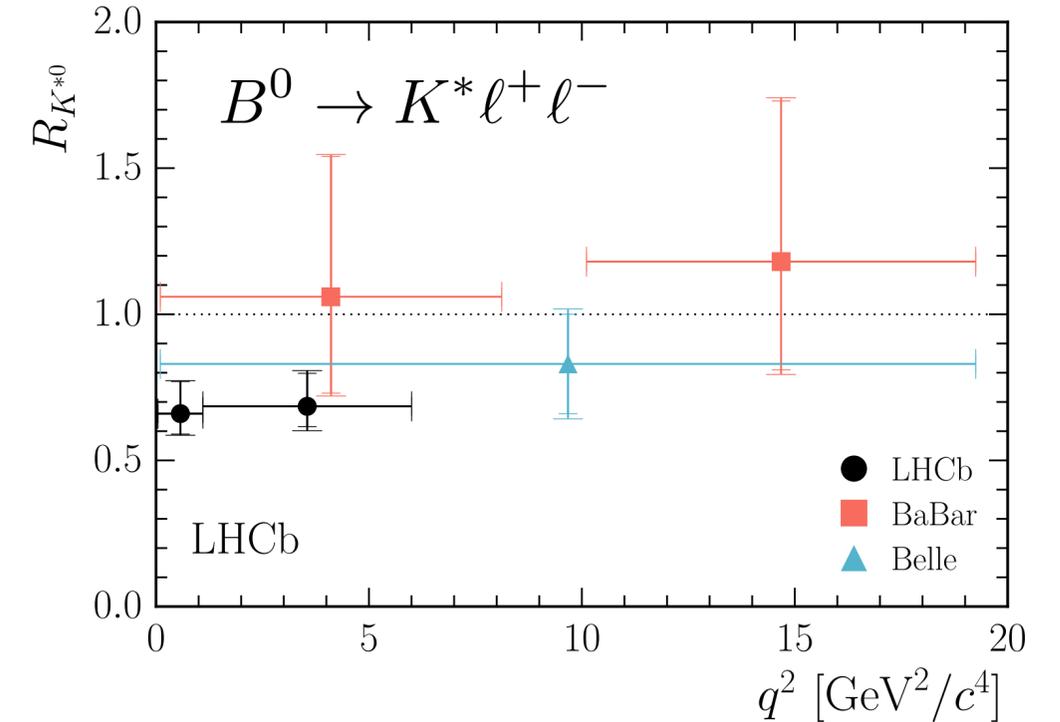
$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

$$0.1 < q^2 < 6 \text{ GeV}^2$$



$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

$$1.1 < q^2 < 6 \text{ GeV}^2$$

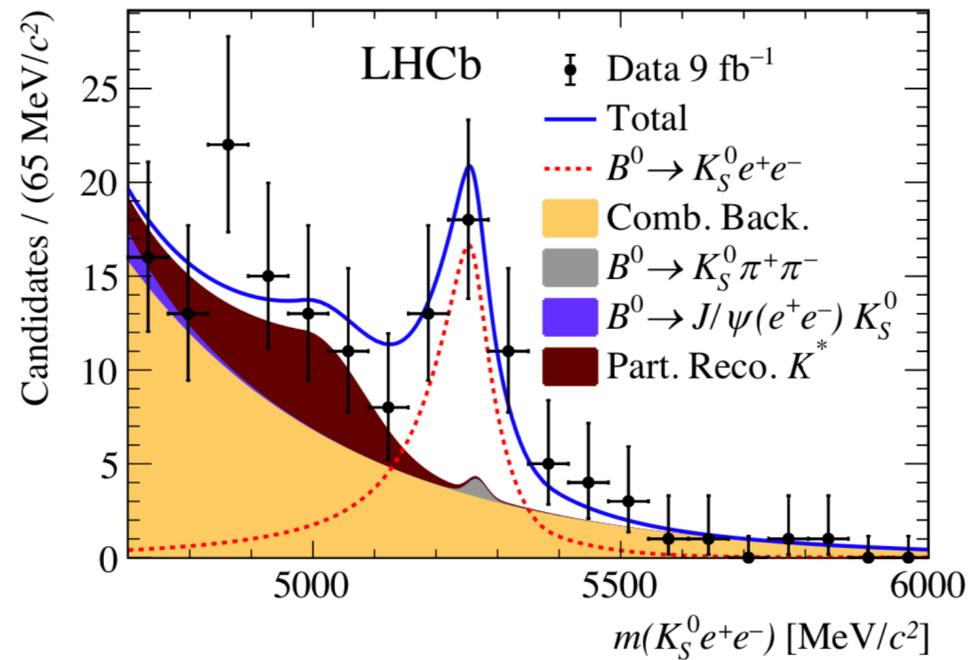


$$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

$$1.1 < q^2 < 6 \text{ GeV}^2$$

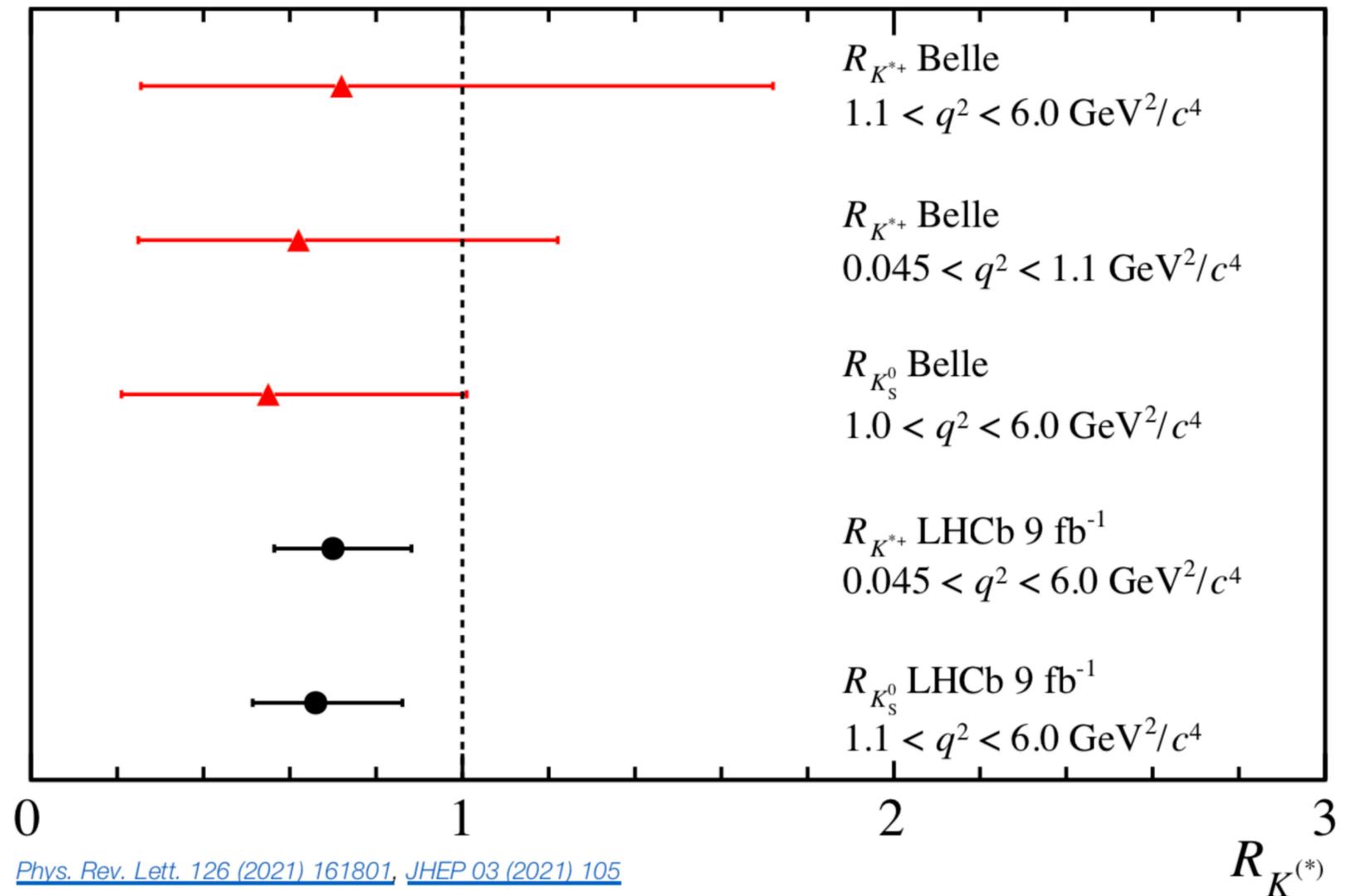
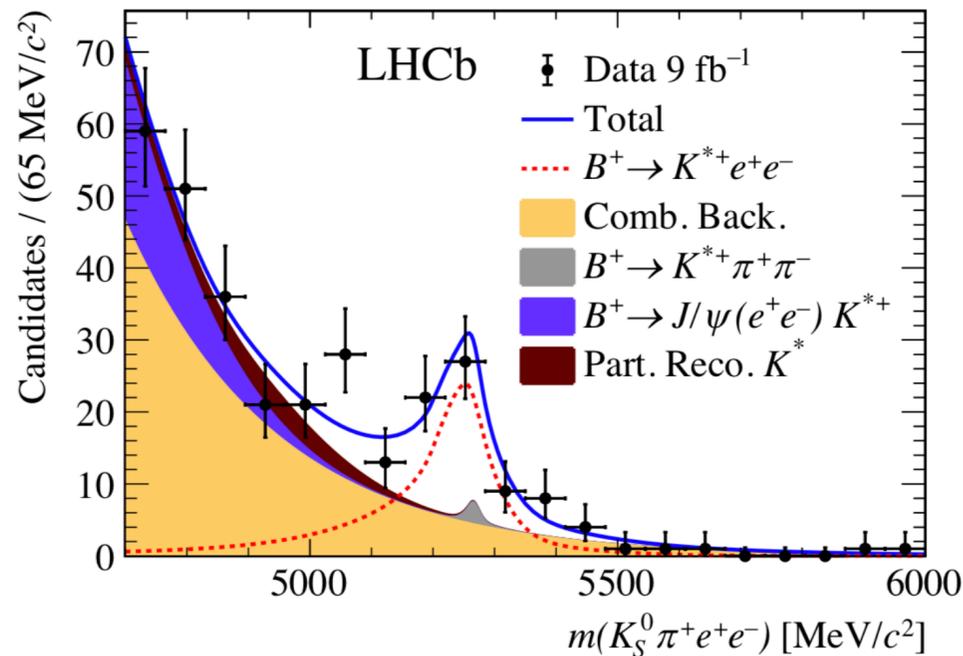
Are we seeing a coherent pattern in the data ?

And more recently, were added

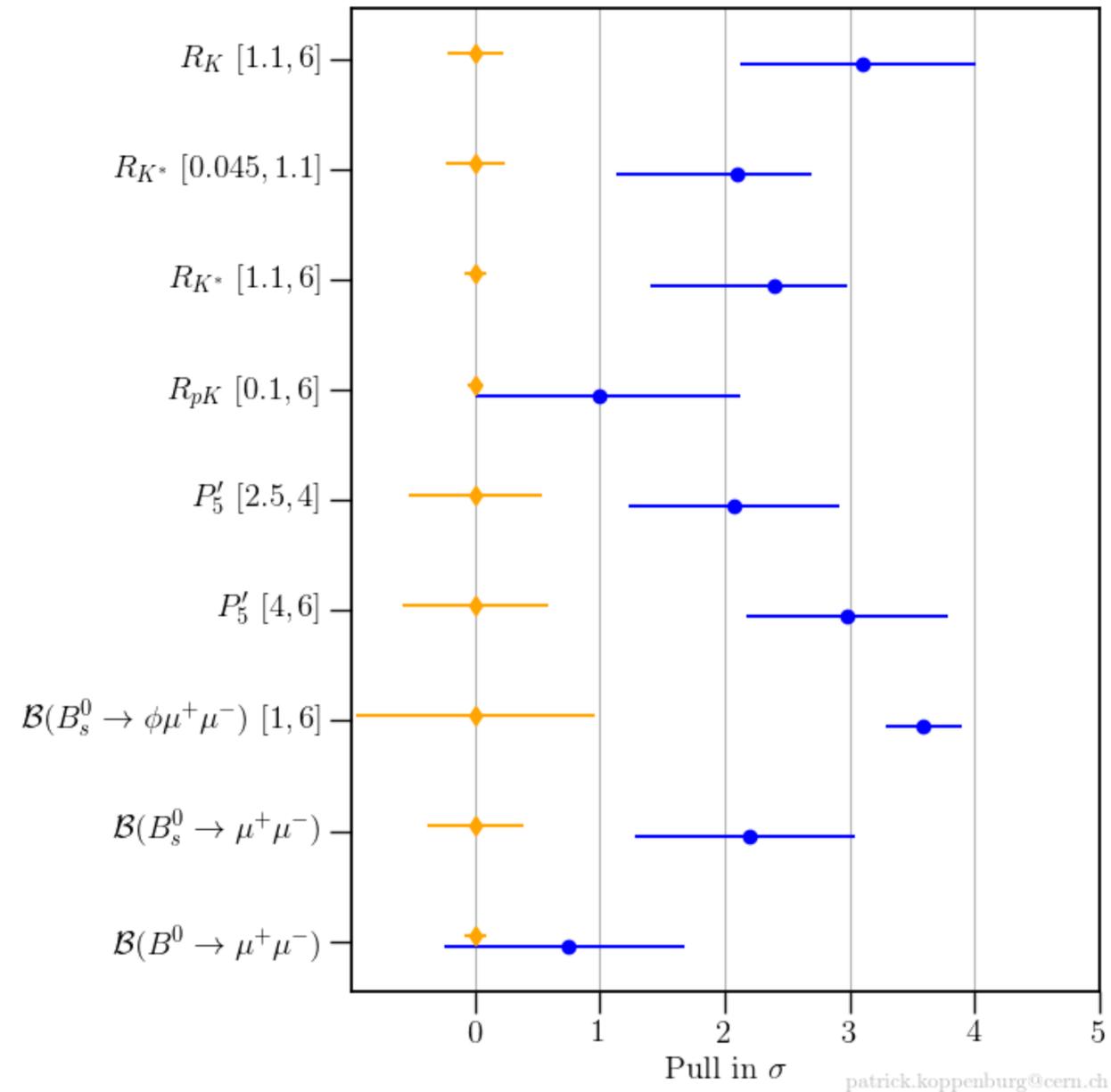


$$R_{K_S^0} = 0.66^{+0.20}_{-0.14} \text{ (stat.) }^{+0.02}_{-0.04} \text{ (syst.)},$$

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



Is there something “funny” happening with the muons ?



Only more data analysed and improvements in the theory will tell us.

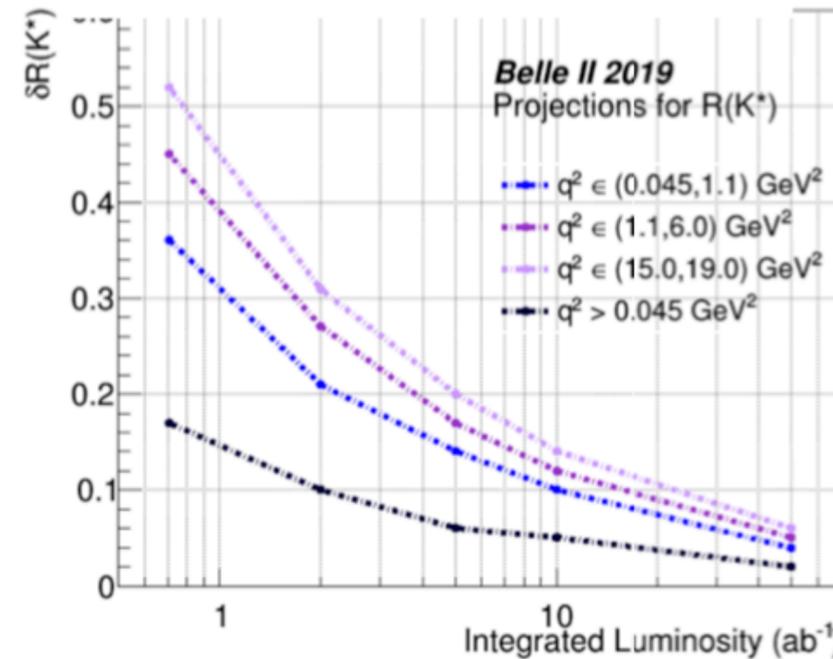
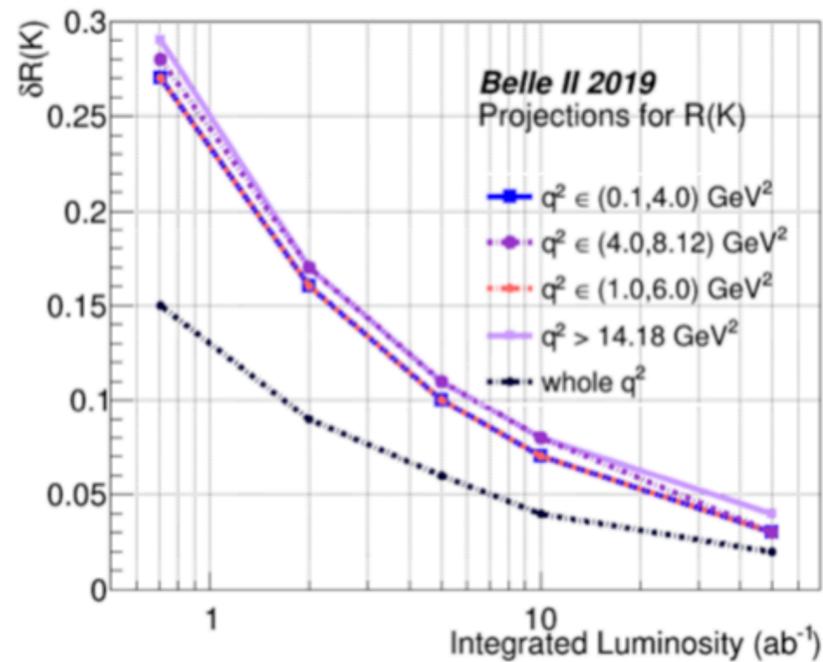
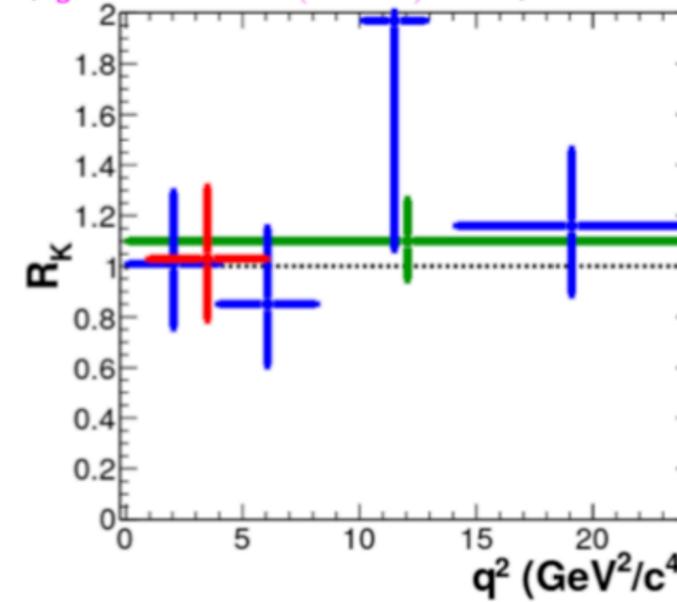
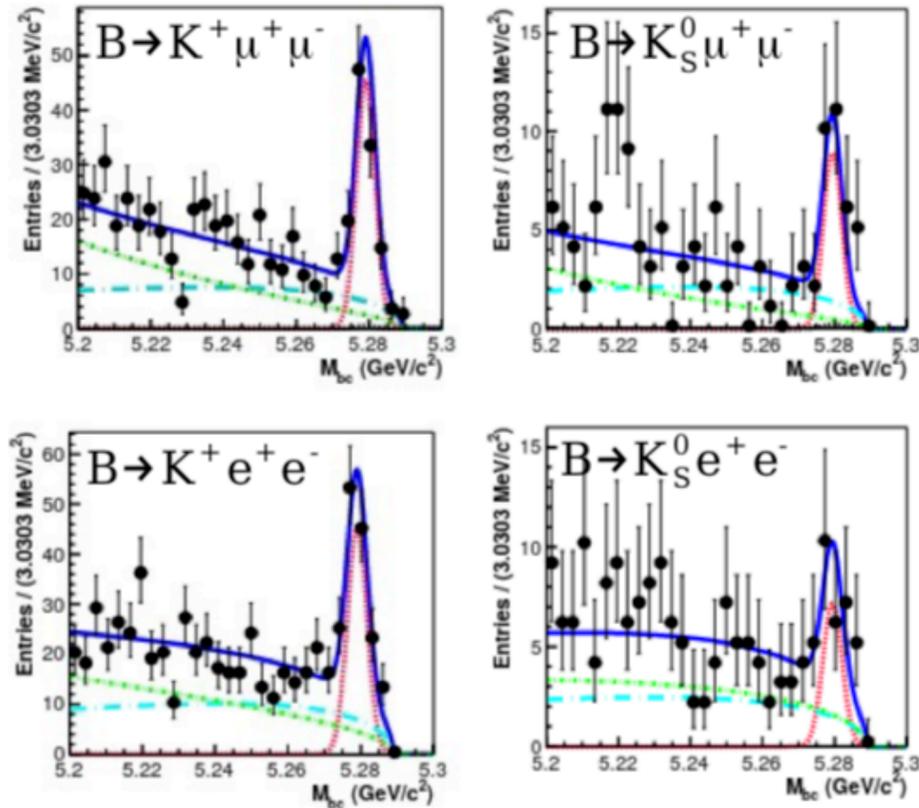
$R_{K^{(*)}}$ at Belle and Belle II

The "clean" Lepton Flavor Universality ratio

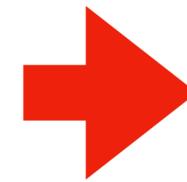
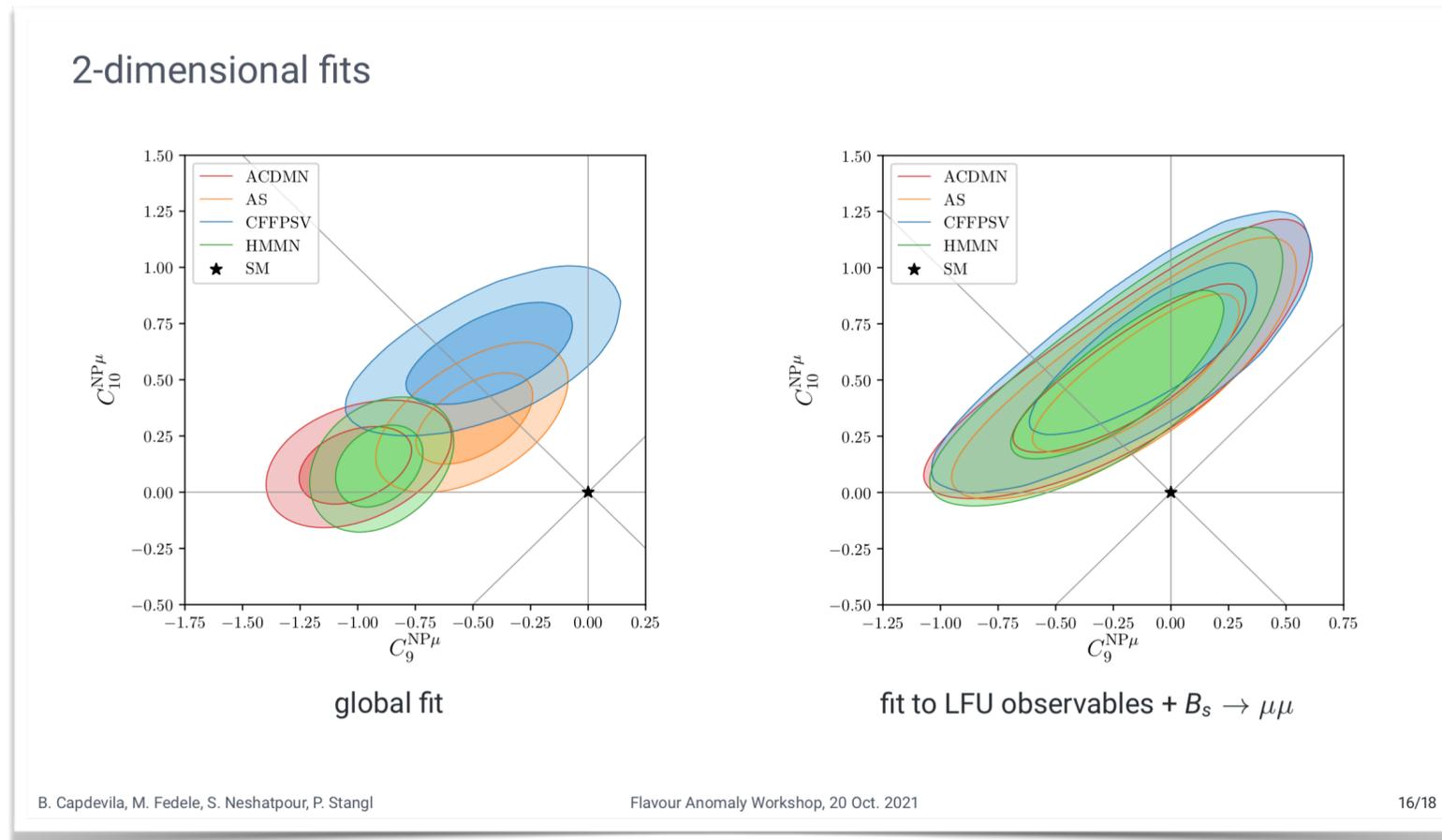
$$R_{K^{(*)}} = \frac{\text{Br}(B \rightarrow K^{(*)} \mu \mu)}{\text{Br}(B \rightarrow K^{(*)} e e)}$$

SM prediction very robust: $R_K(\text{SM}) = 1$
 [up tiny QED and lepton mass effects]

[Belle, JHEP 2013 (2021) 105, arXiv:1908.01848]



Where people debate, where people agree



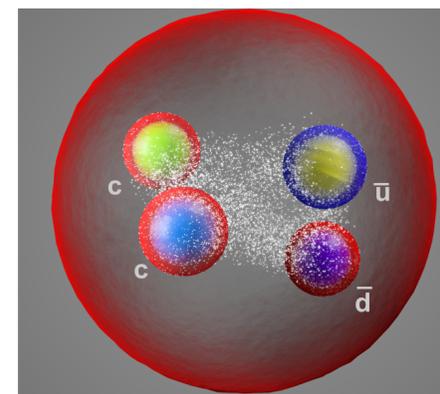
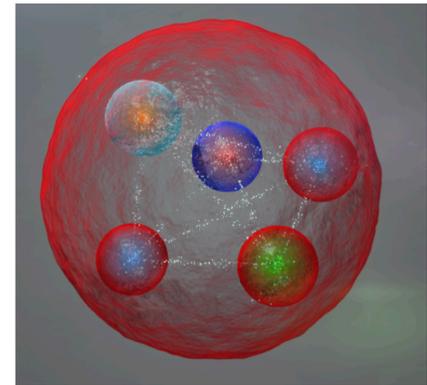
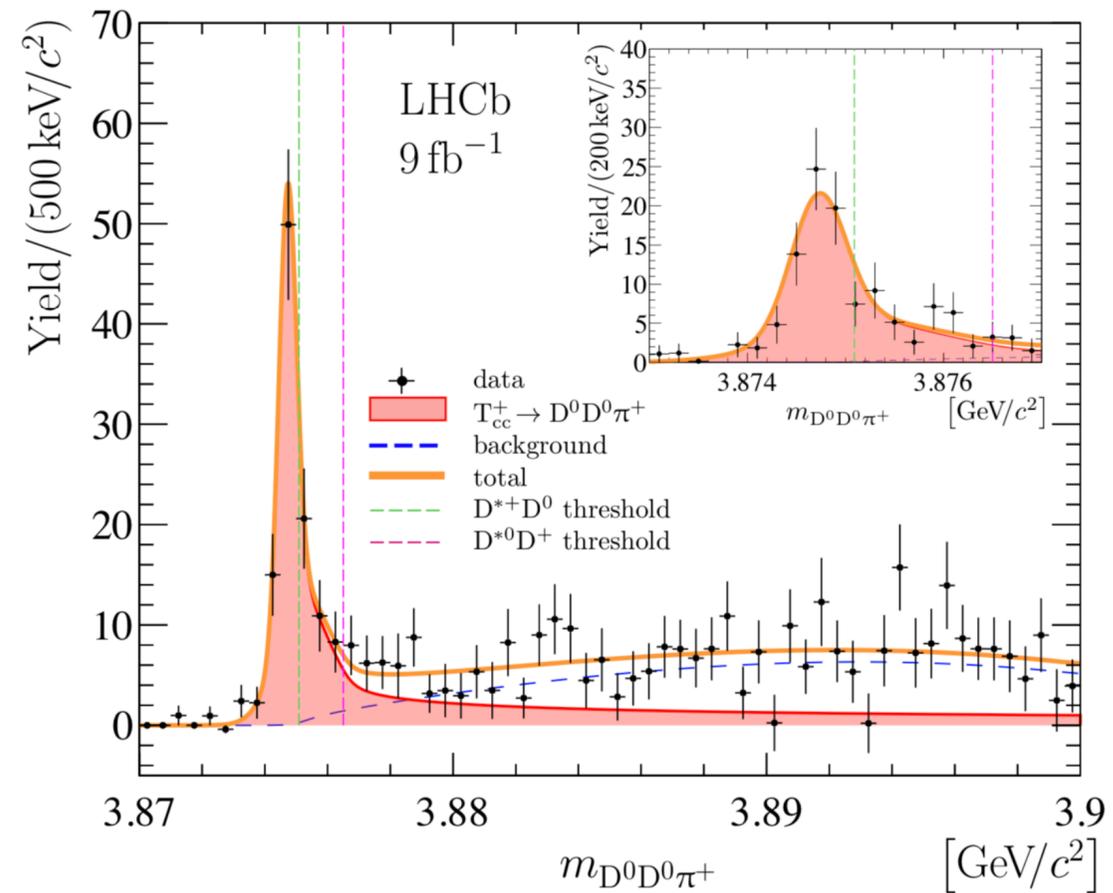
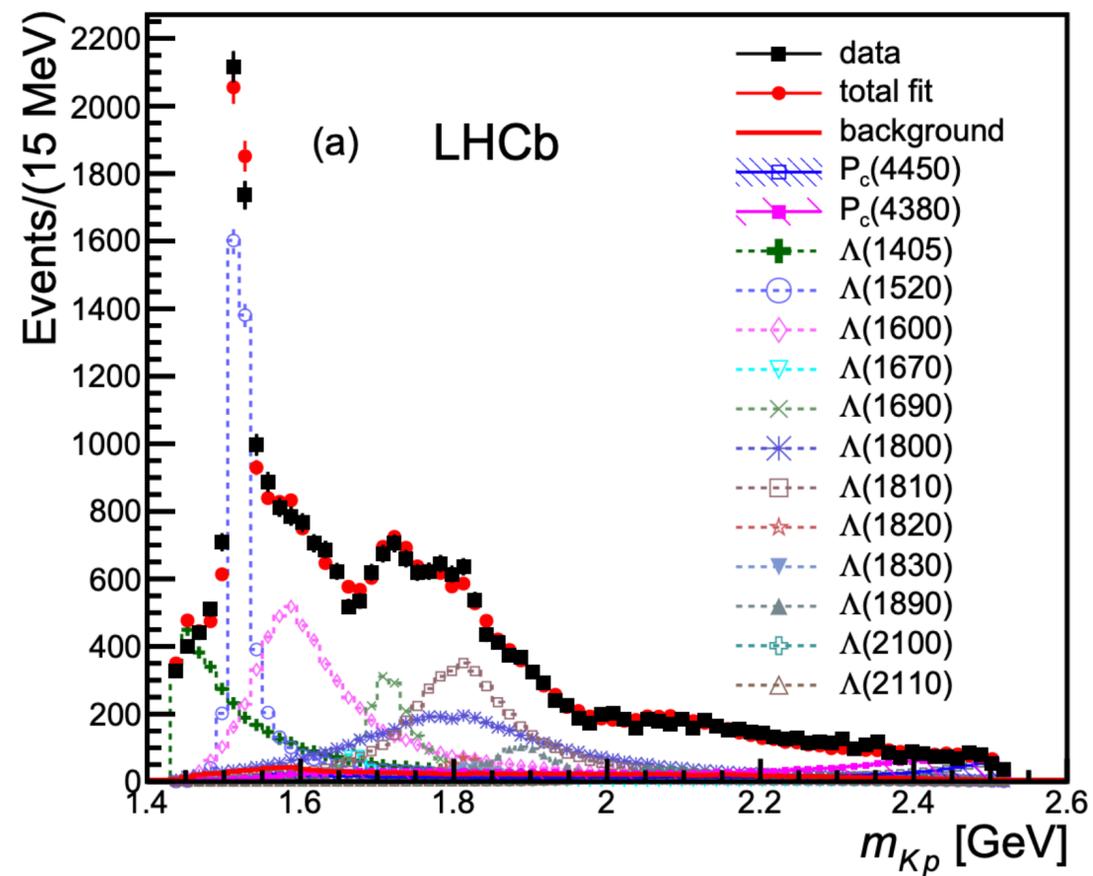
Model building...



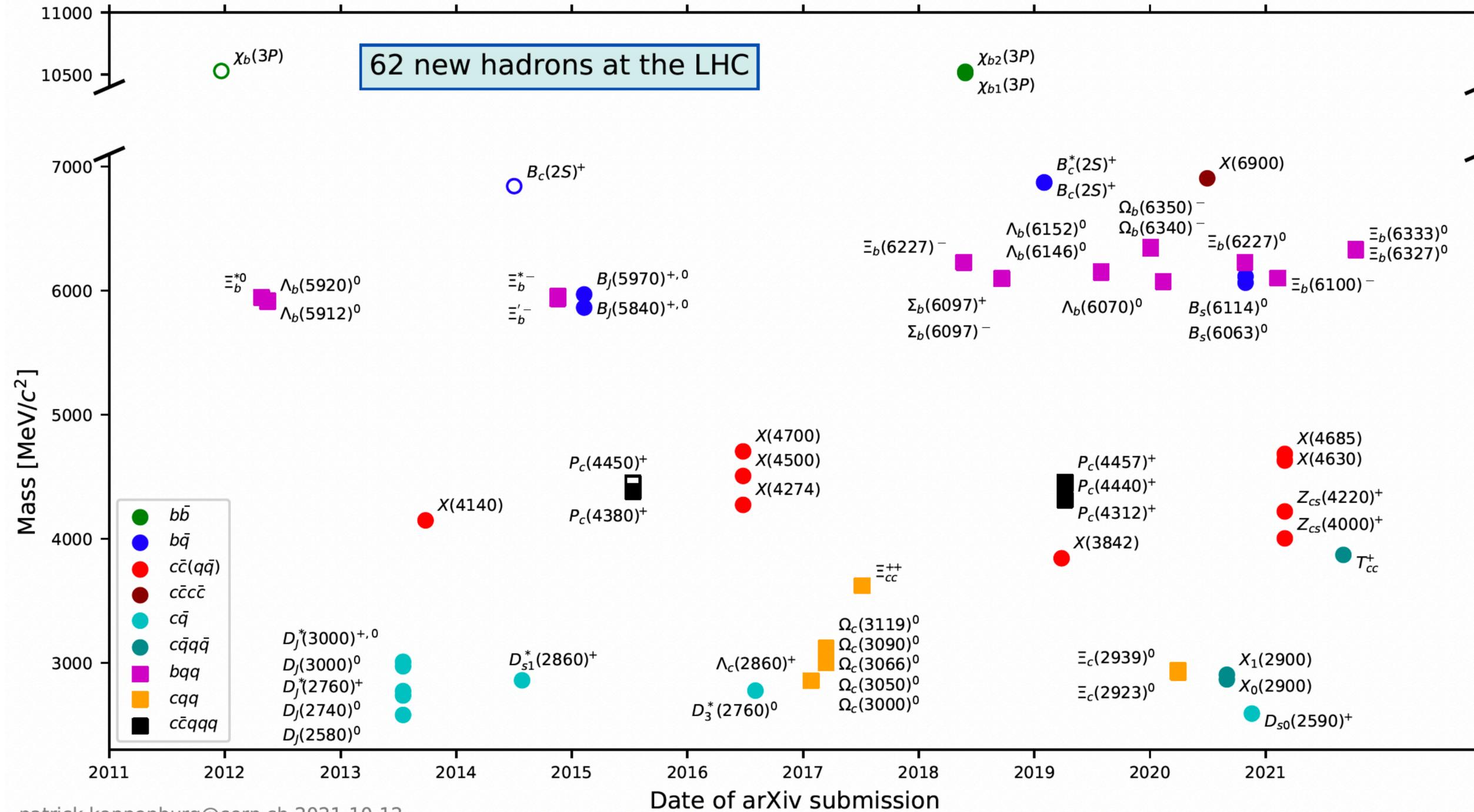
Flavour Anomalies Workshop @ CERN

Beyond mesons and baryons

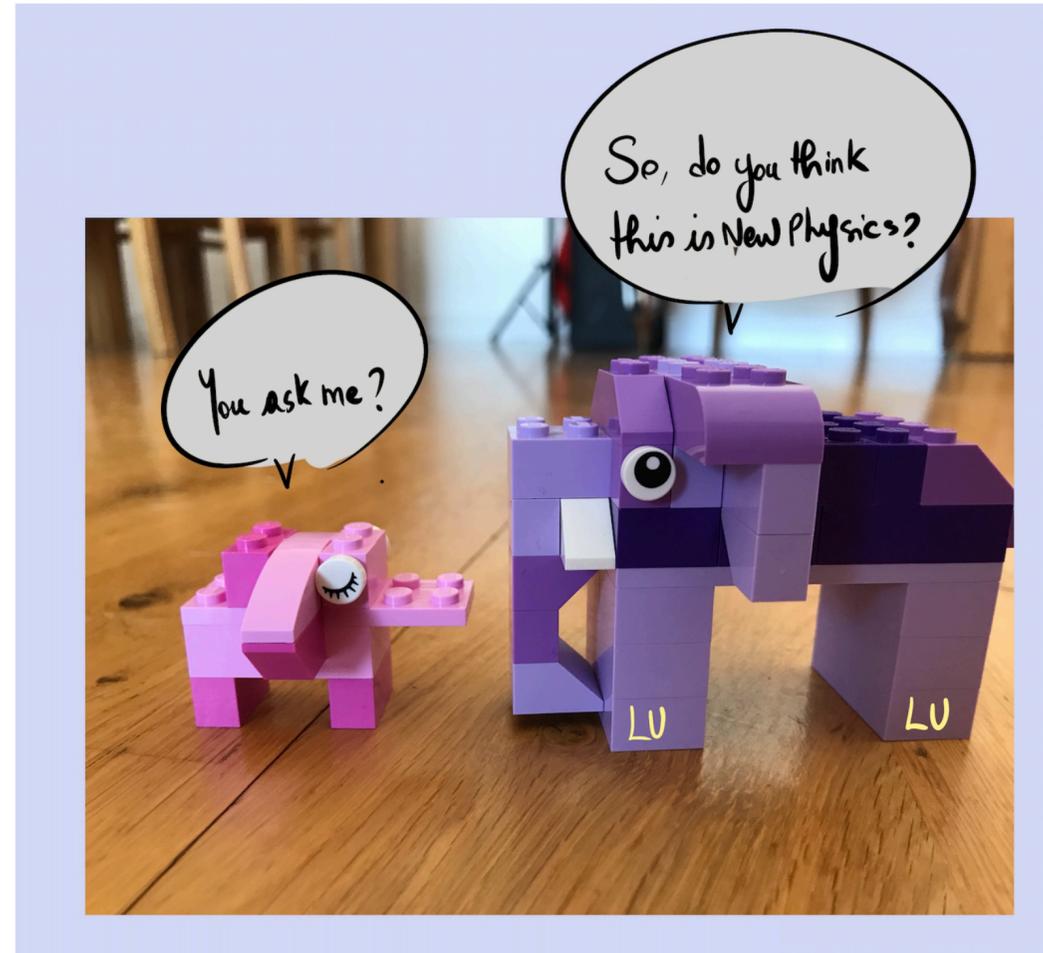
About 50 years after the predictions from Gell-Mann and Zweig



Overall...many new hadrons



Conclusion

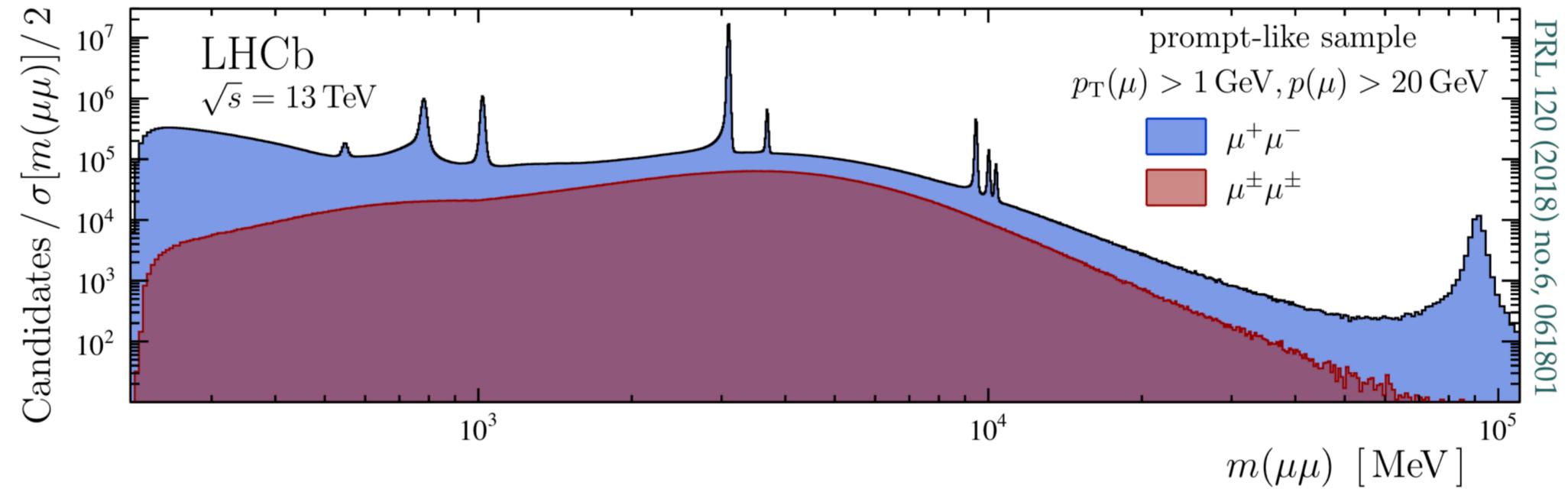


Did we discover NP ? Yes no maybe ?
We are looking forward to new results from LHCb (Run3),
Belle 2, ATLAS/CMS
and obviously theory work.

I'M
SIGNIFICANT!



Dimuon spectrum from **trigger output**



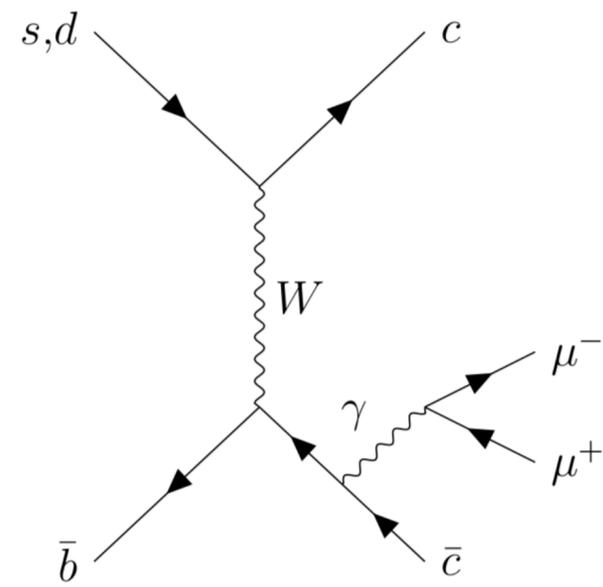
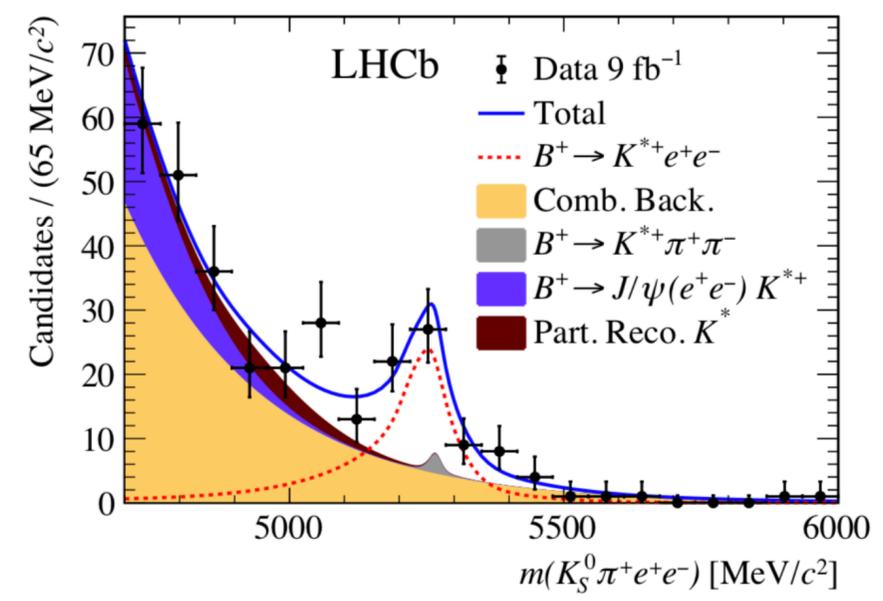
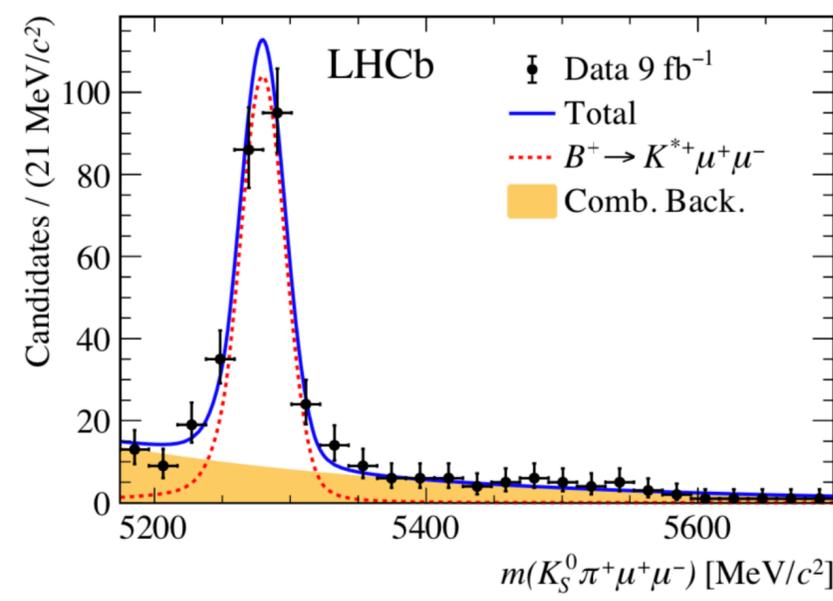
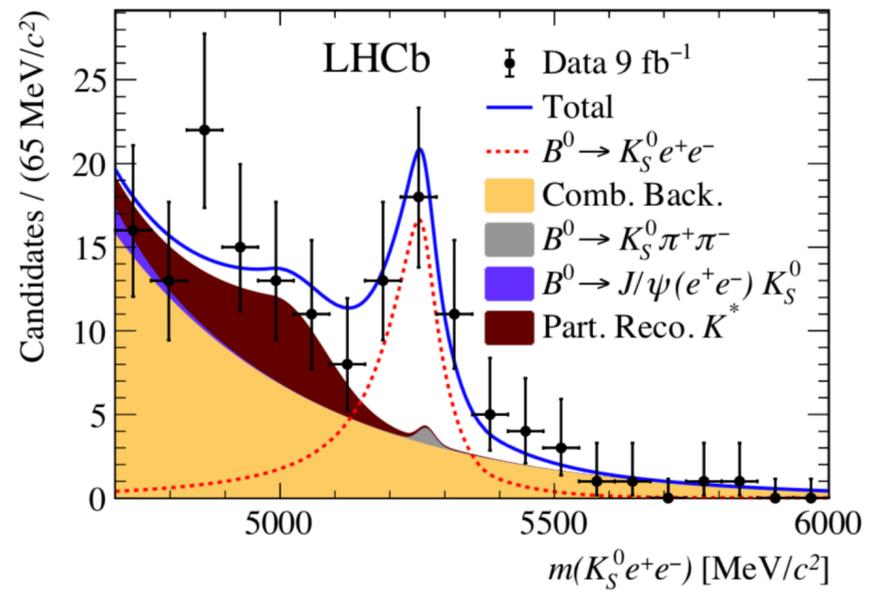
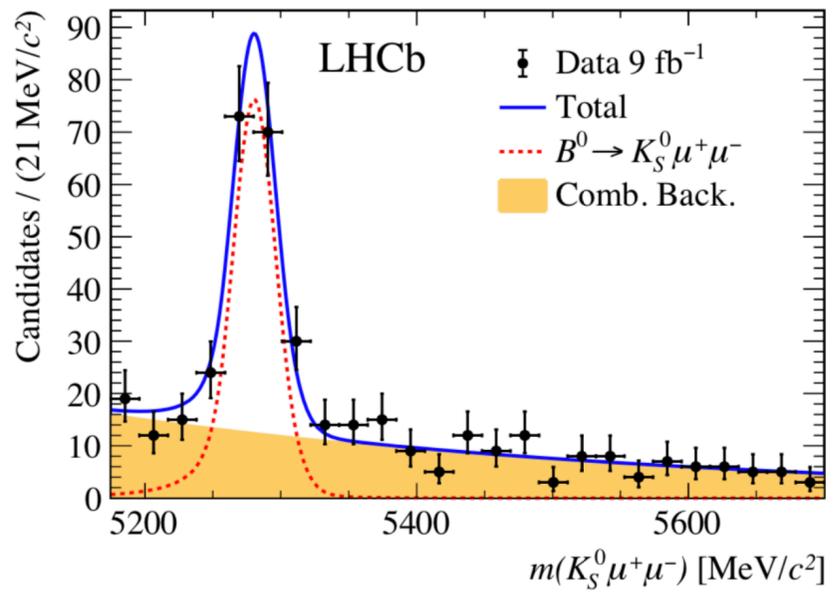
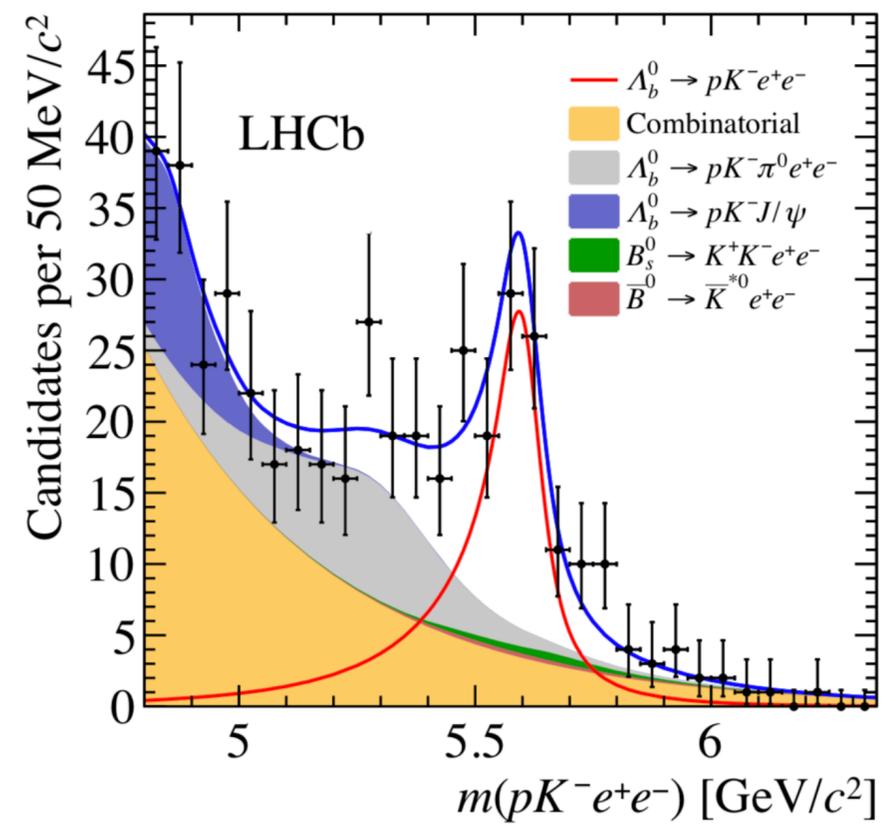
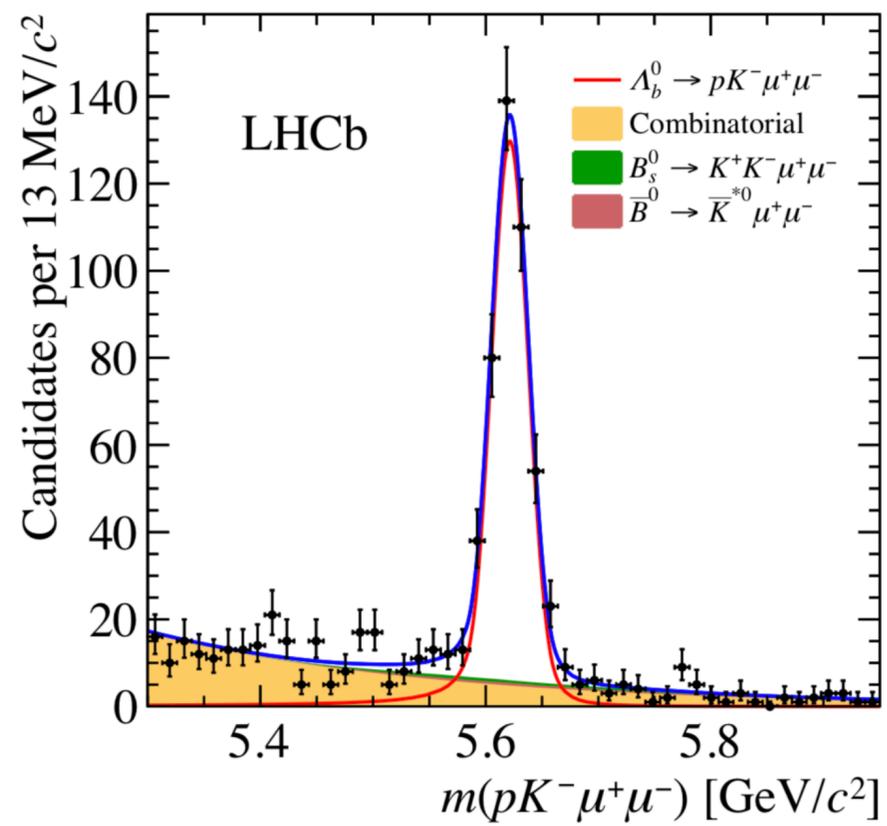


Figure 2: Feynman diagram for $B_s^0, B^0 \rightarrow J/\psi (\mu^+ \mu^-) \mu^+ \mu^-$ decays.

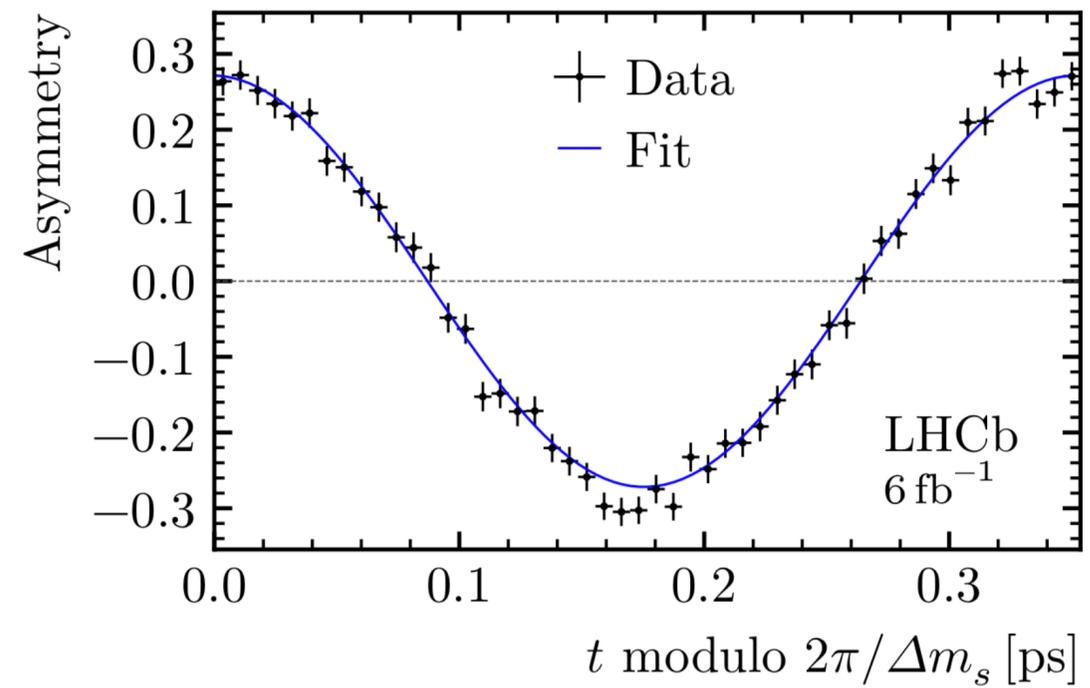
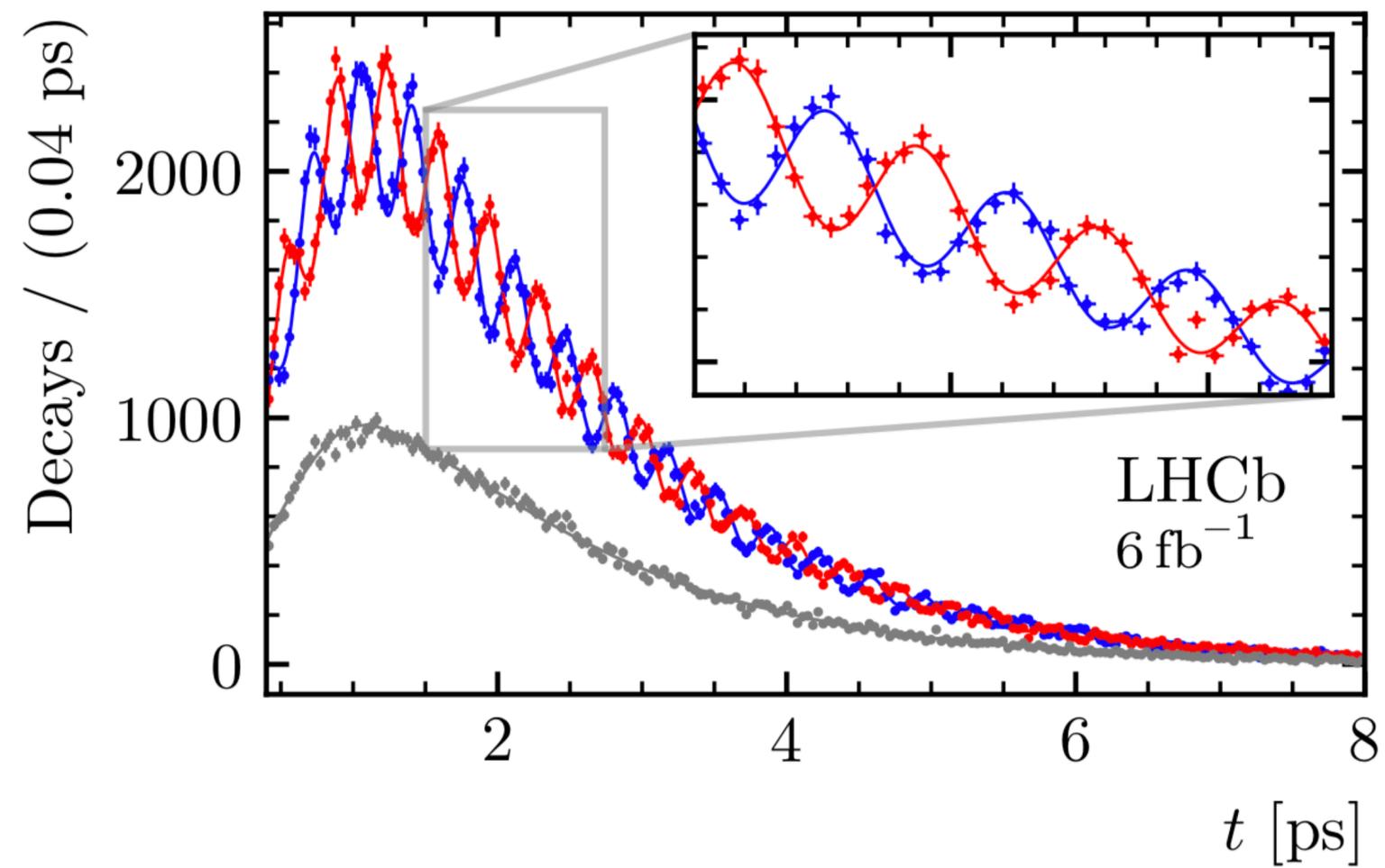


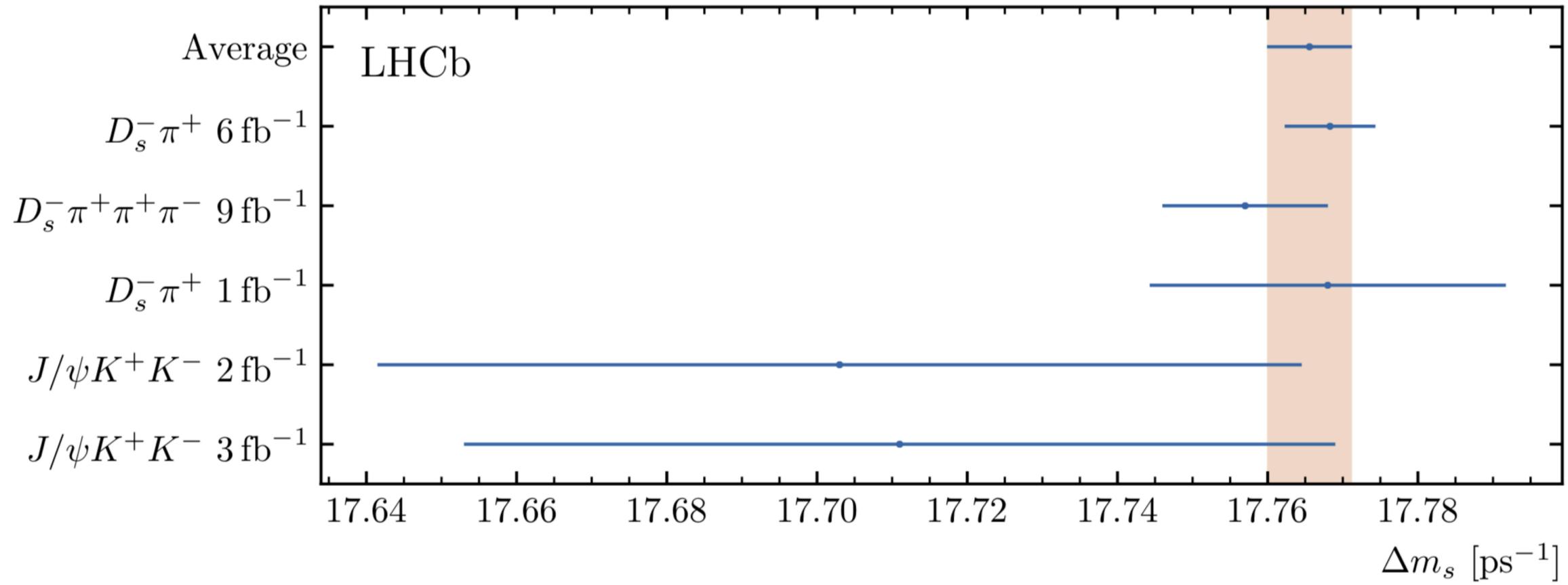


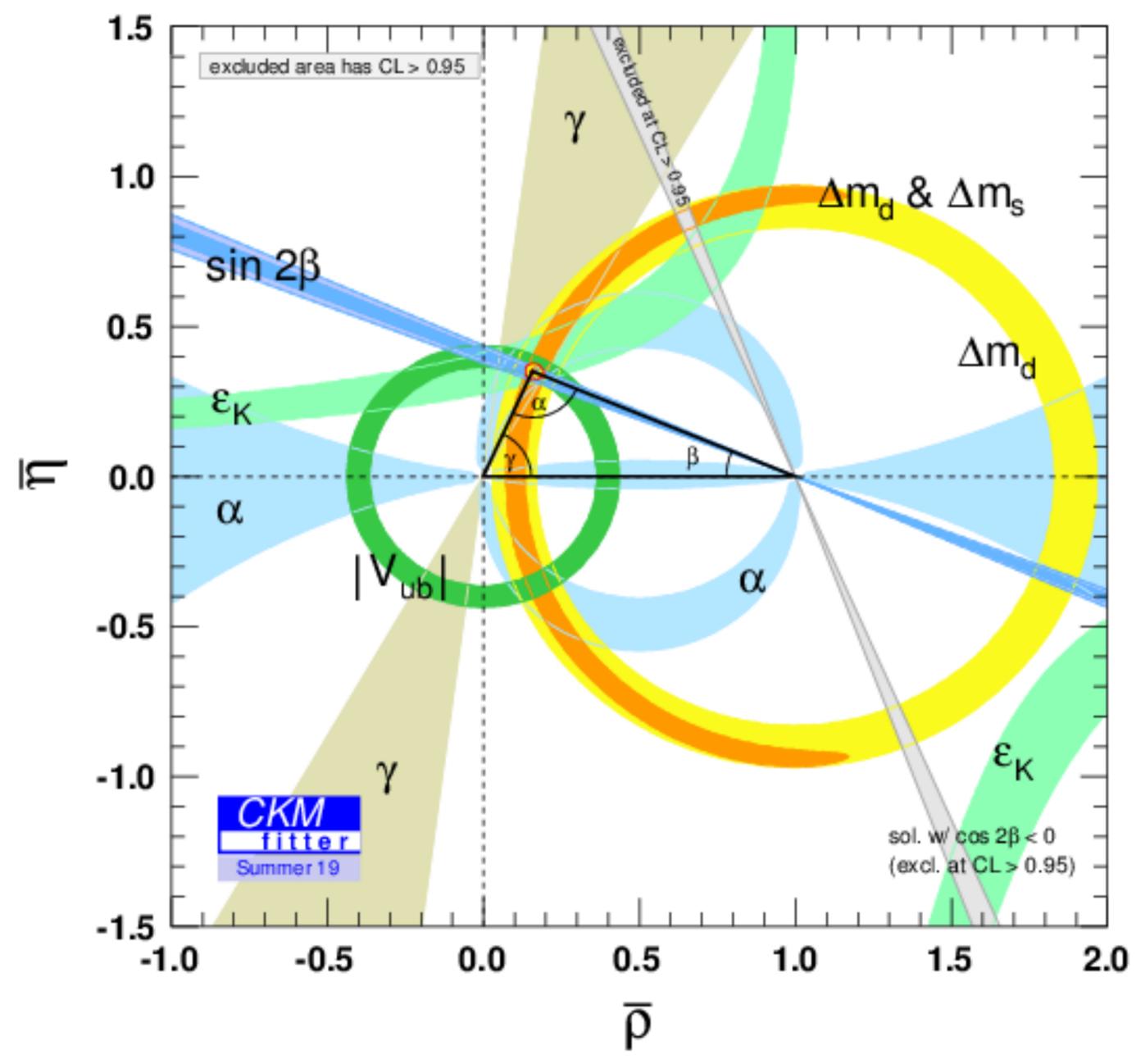
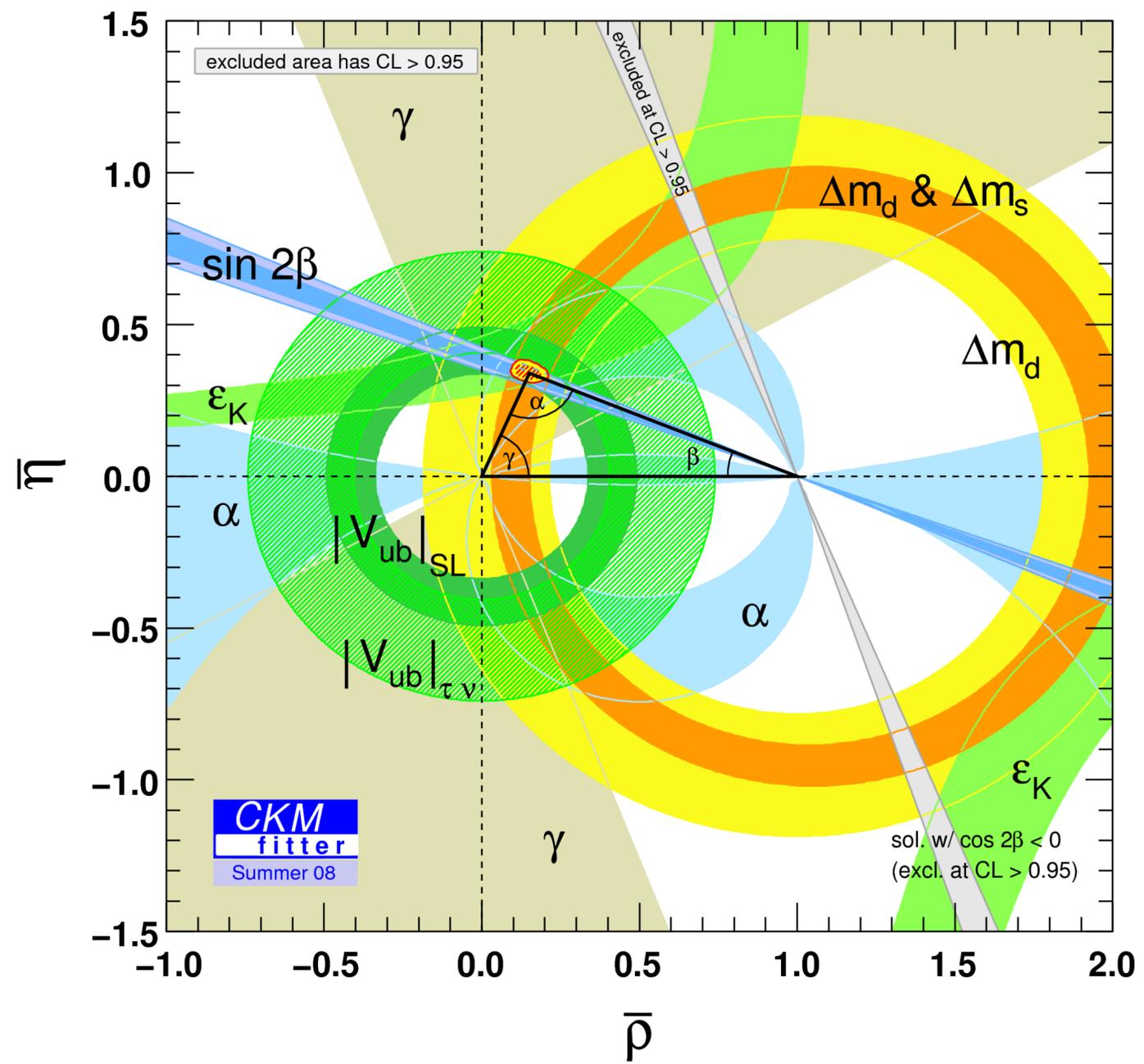
$$R_{K_S^0} = 0.66_{-0.14}^{+0.20} (\text{stat.})_{-0.04}^{+0.02} (\text{syst.}),$$

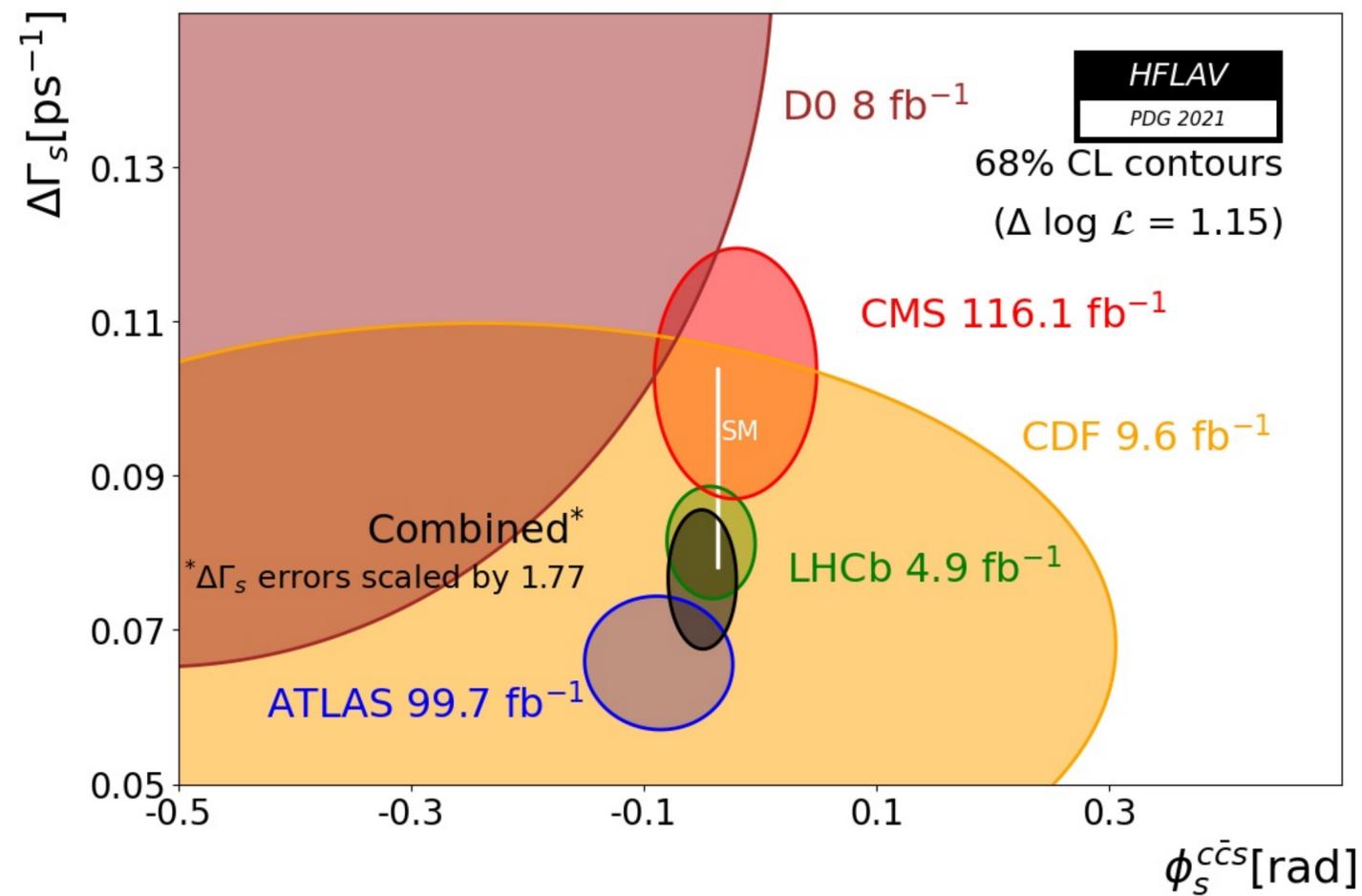
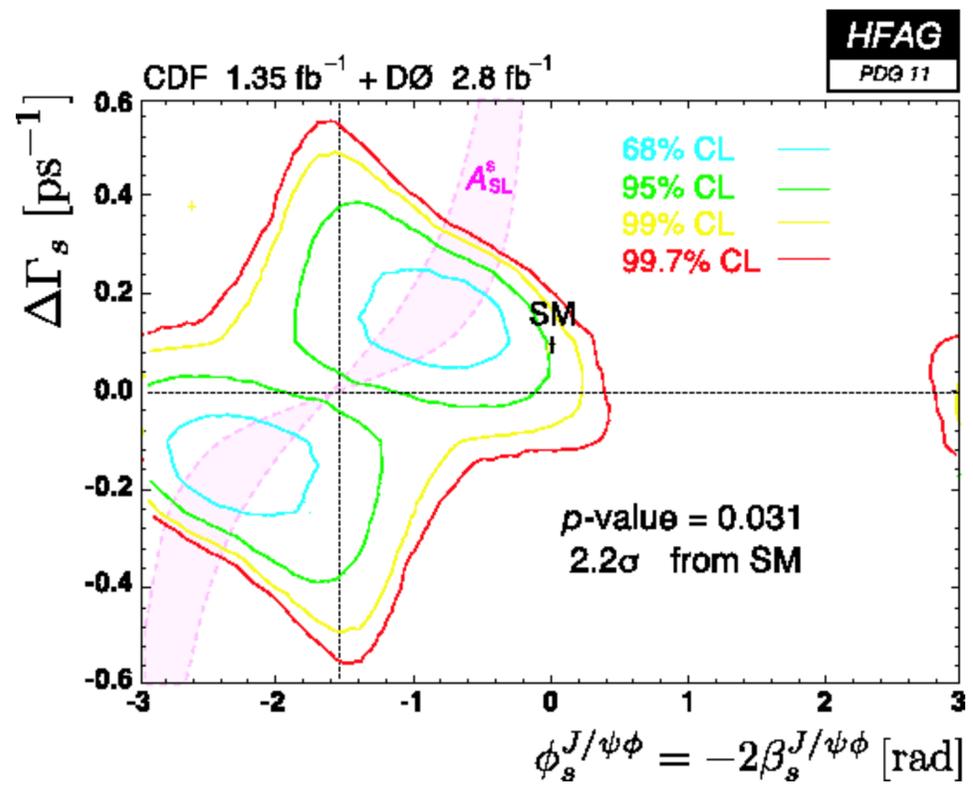
$$R_{K^{*+}} = 0.70_{-0.13}^{+0.18} (\text{stat.})_{-0.04}^{+0.03} (\text{syst.}).$$

— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow D_s^- \pi^+$ — Untagged

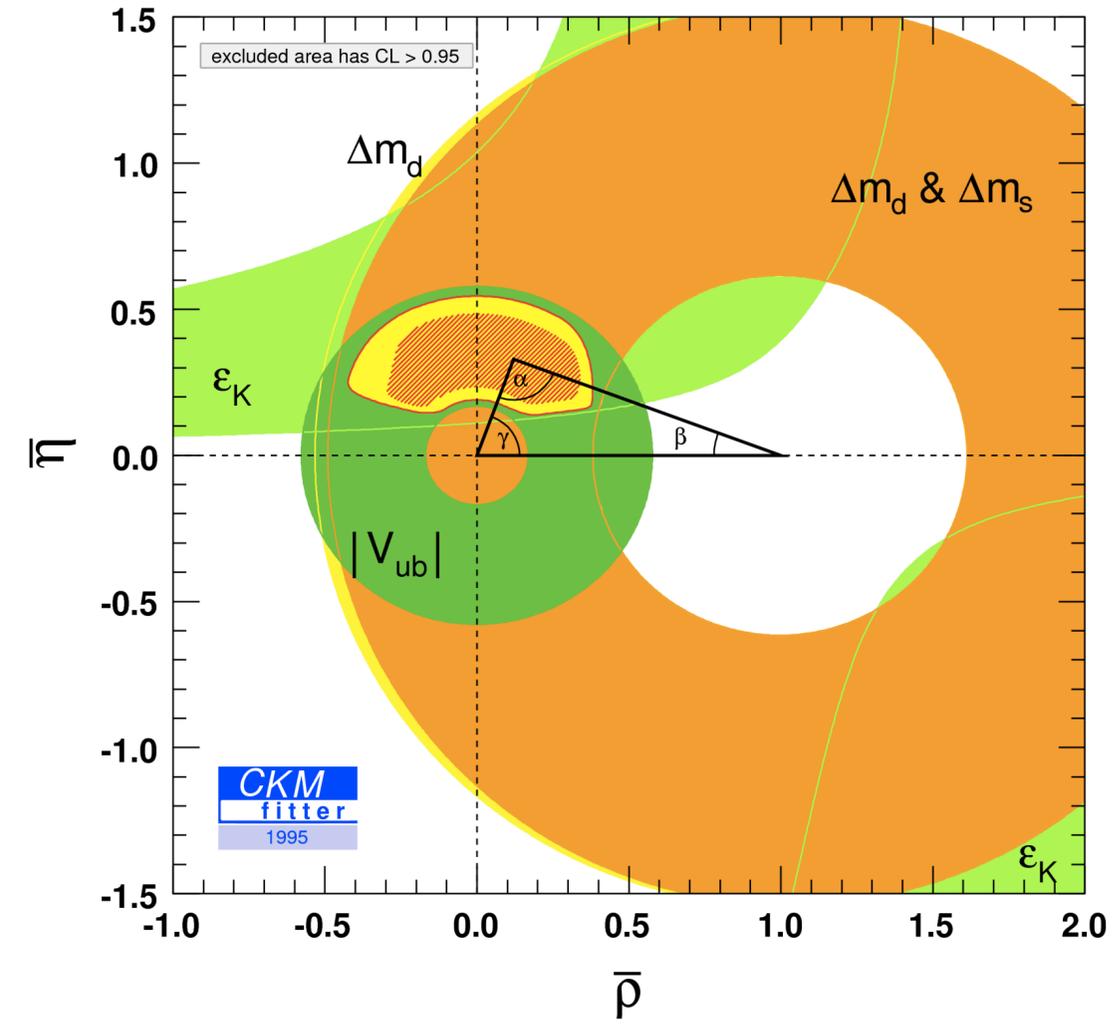


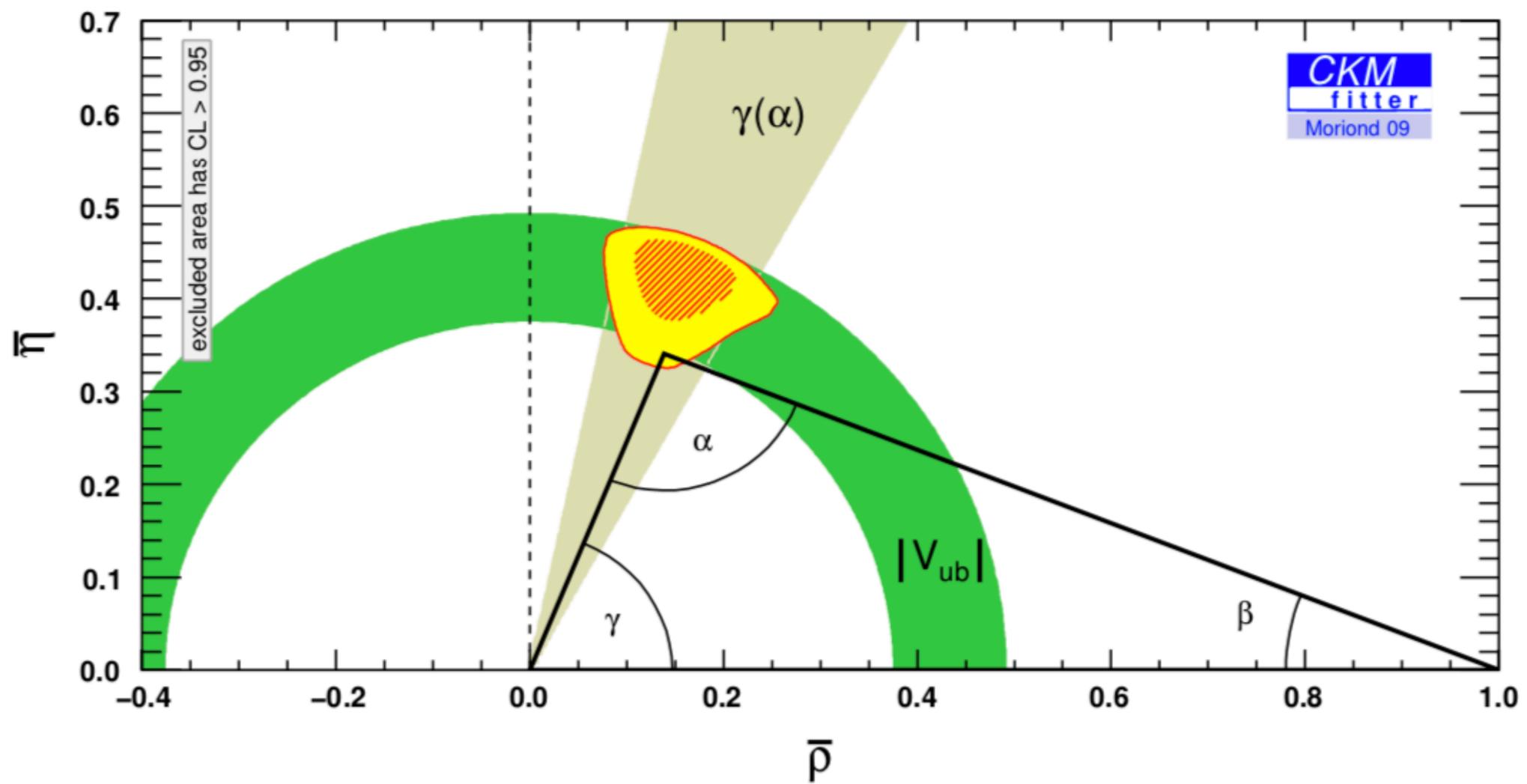




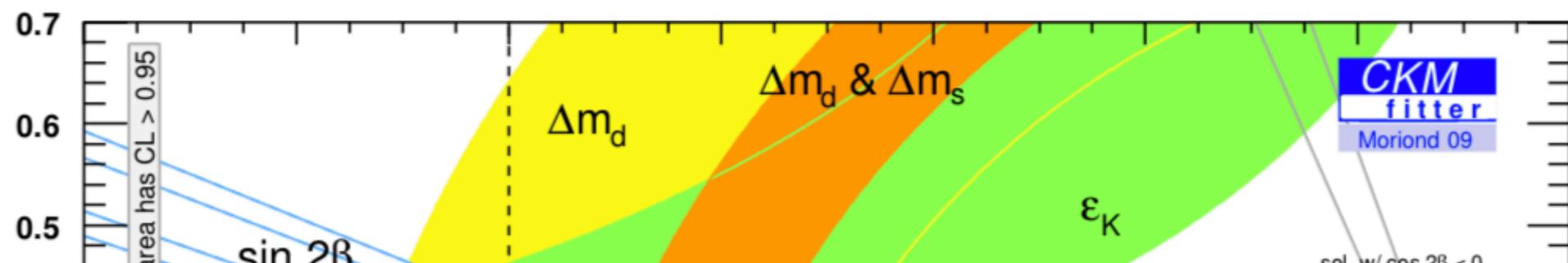


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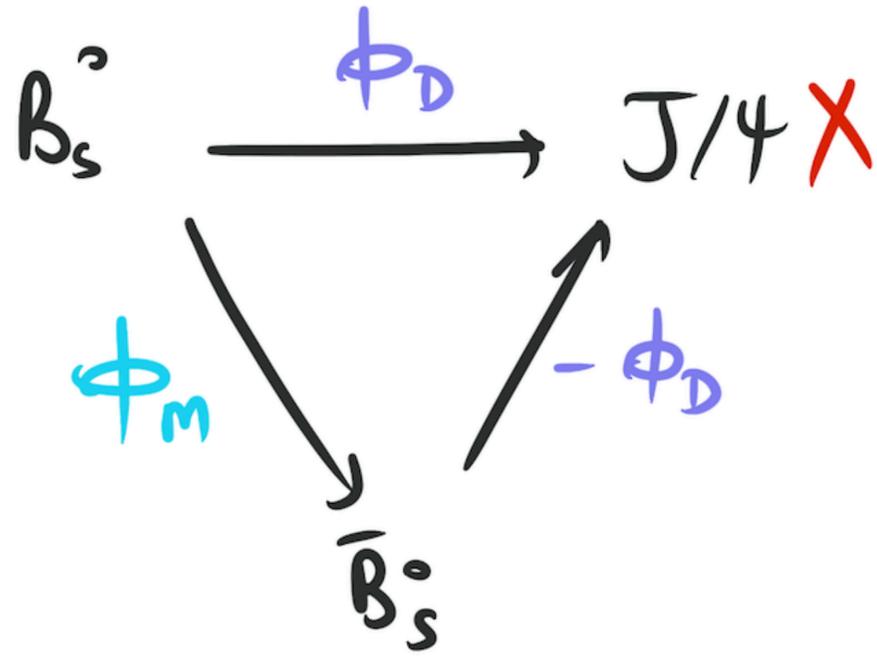




(a)



B_s phases



$$\phi_s = \phi_m - 2\phi_D$$

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$