

第九届中国LHC物理年会

The 9th China LHC Physics Workshop

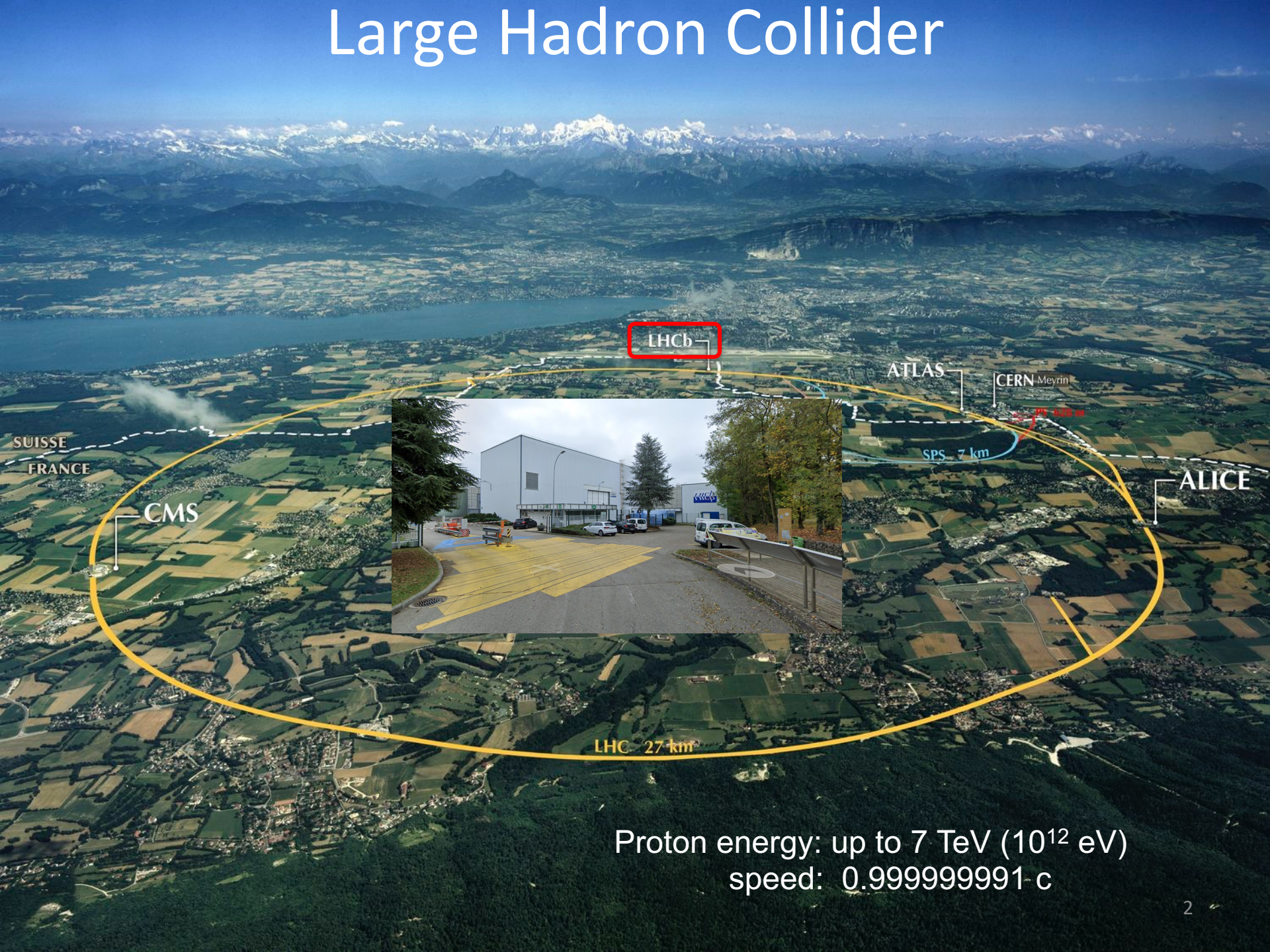
2023年11月16日-20日 @TDLI, SJTU

Rare decays at LHCb

Jibo HE/何吉波

(UCAS/中国科学院大学)

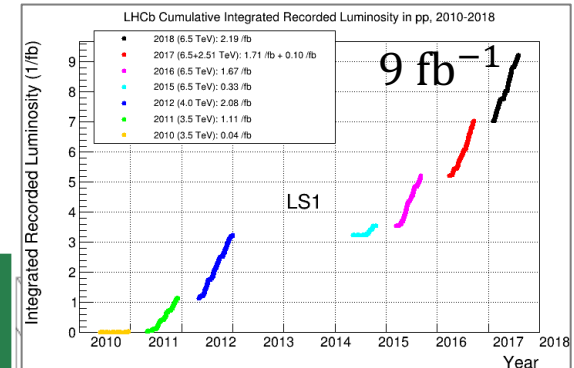
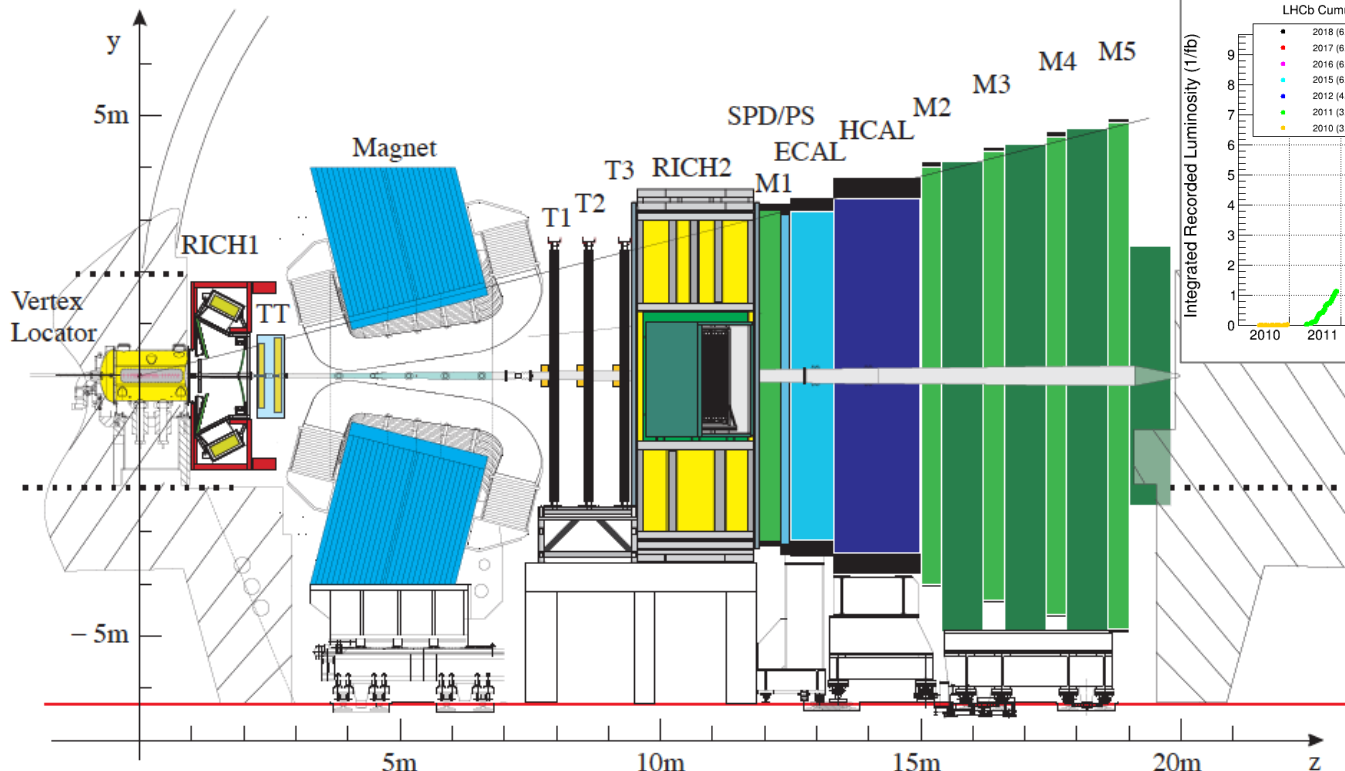
Large Hadron Collider



Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

The LHCb experiment

[JINST 3 (2008) S080005]



Vertex Locator

Tracking (TT, T1-T3)

RICHs

Muon system (M1-M5)

ECAL

HCAL

$$\sigma_{PV,x/y} \sim 10 \mu\text{m}, \sigma_{PV,z} \sim 60 \mu\text{m}$$

$$\Delta p/p: 0.4\% \text{ at } 5 \text{ GeV}/c, \text{ to } 0.6\% \text{ at } 100 \text{ GeV}/c$$

$$\varepsilon(K \rightarrow K) \sim 95\%, \text{ mis-ID rate } (\pi \rightarrow K) \sim 5\%$$

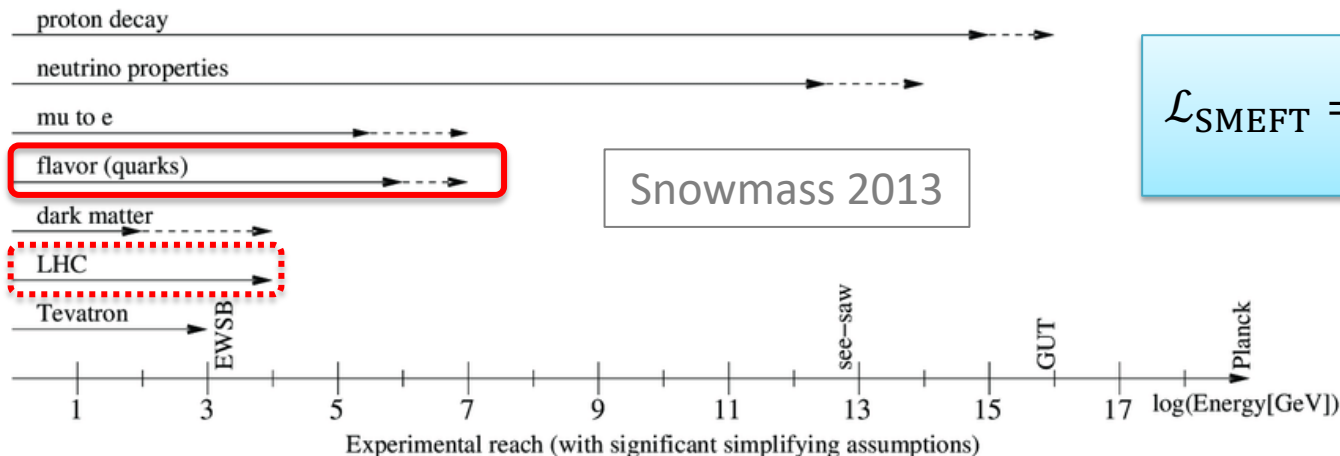
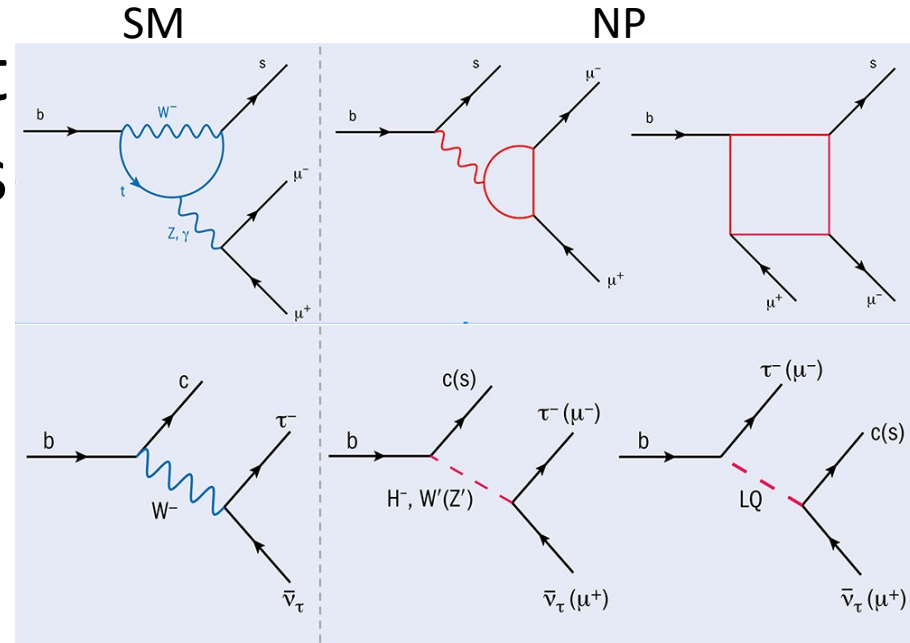
$$\varepsilon(\mu \rightarrow \mu) \sim 97\%, \text{ mis-ID rate } (\pi \rightarrow \mu) = 1 - 3\%$$

$$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\% (E \text{ in GeV})$$

$$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\% (E \text{ in GeV})$$

Indirect search for New Physics

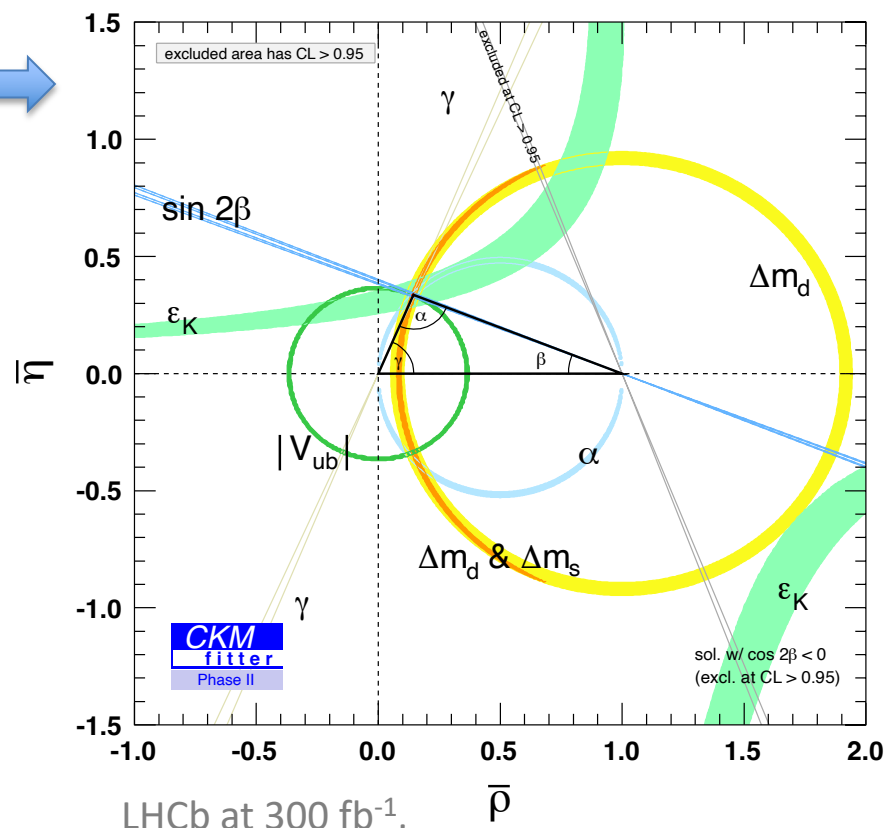
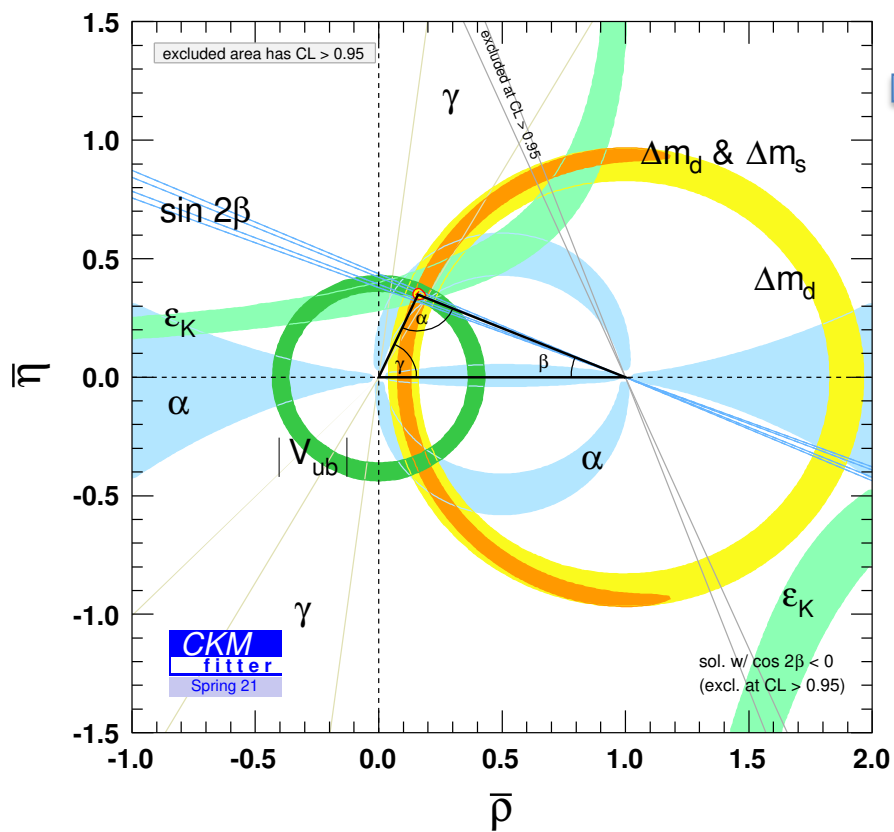
- Precision measurement of heavy hadron decays
 - Flavour-Changing NC
 - Flavour-Changing CC
- Probe New Physics at high energy scale



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

Indirect search for NP (cont.)

- Overconstrain the CKM triangle



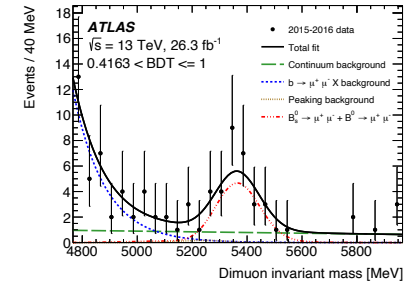
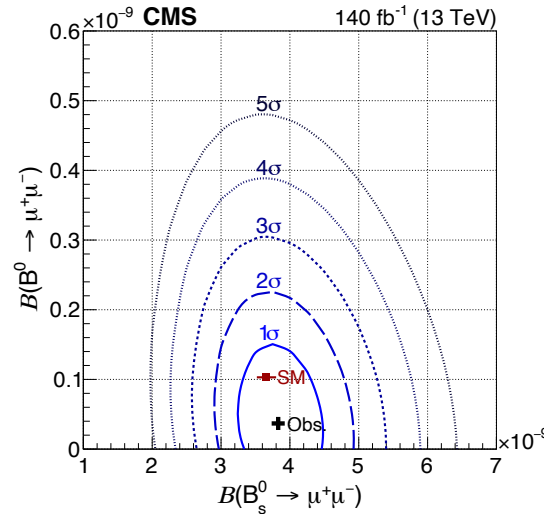
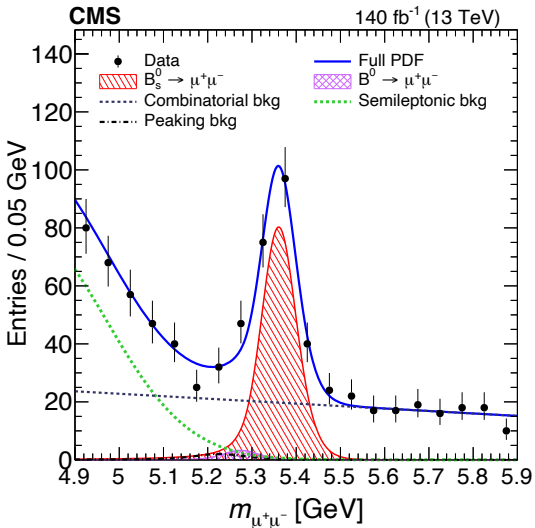
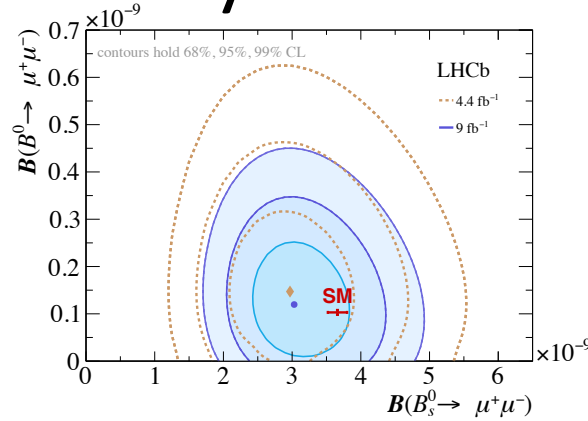
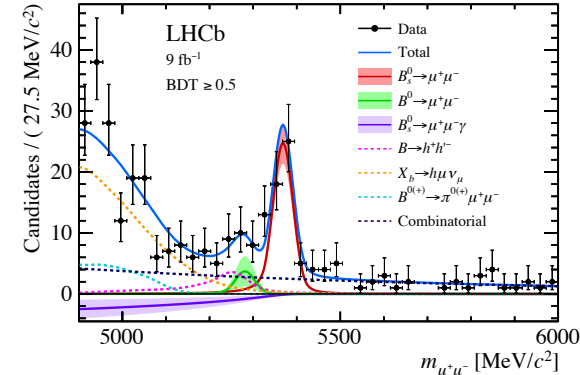
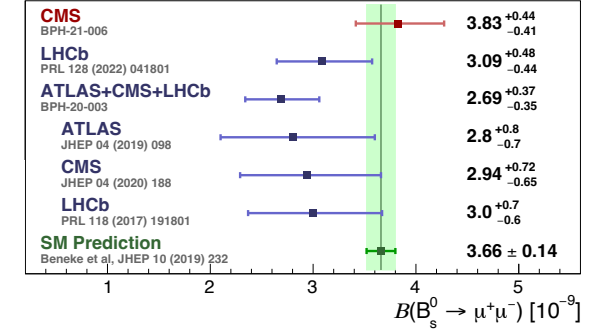
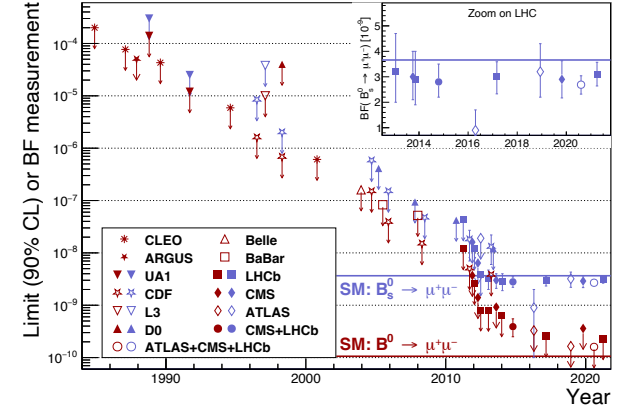
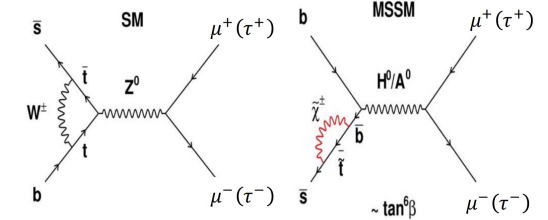
LHCb at 300 fb⁻¹,

CMS/ATLAS at 3000 fb⁻¹, Belle II at 50 ab⁻¹.

Please see W. Qian's talk

$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$

- Suppressed in SM, could be enhanced by New Physics



$$B_s^0 \rightarrow \mu^+ \mu^- \text{ eff. } \tau$$

- B_s^0 mixing $\Rightarrow$ effective τ

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s}}{1 - y_s^2} \left[\frac{1 + 2A_{\Delta\Gamma}^{\mu^+\mu^-} y_s + y_s^2}{1 + A_{\Delta\Gamma}^{\mu^+\mu^-} y_s} \right]$$

$$A_{\Delta\Gamma}^{\mu^+\mu^-} \equiv \frac{R_H^{\mu^+\mu^-} - R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-} + R_L^{\mu^+\mu^-}} \quad A_{\Delta\Gamma} = 1 \text{ in SM}$$

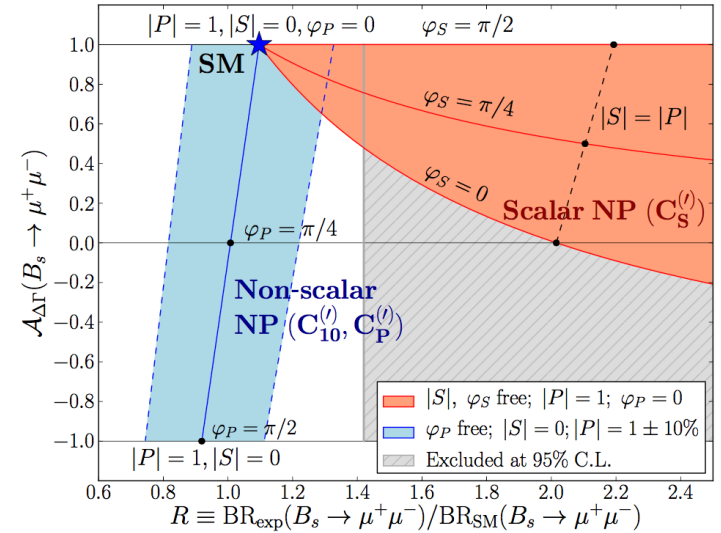
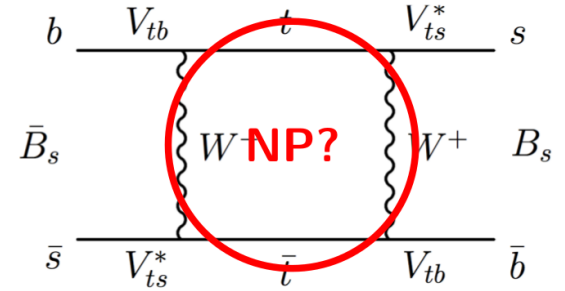
$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

- Measured by LHCb, CMS, ATLAS, not-yet sensitive to $A_{\Delta\Gamma}$

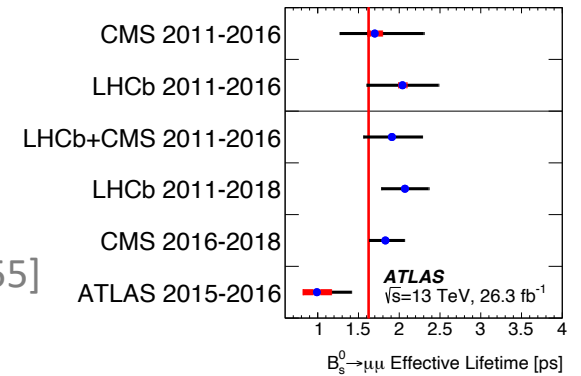
$$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$$

$$1.83_{-0.20}^{+0.23} \pm 0.04 \text{ ps [CMS, PLB 842 (2023) 137955]}$$

$$0.99_{-0.07}^{+0.42} \pm 0.17 \text{ ps [ATLAS, arXiv:2308.01171]}$$

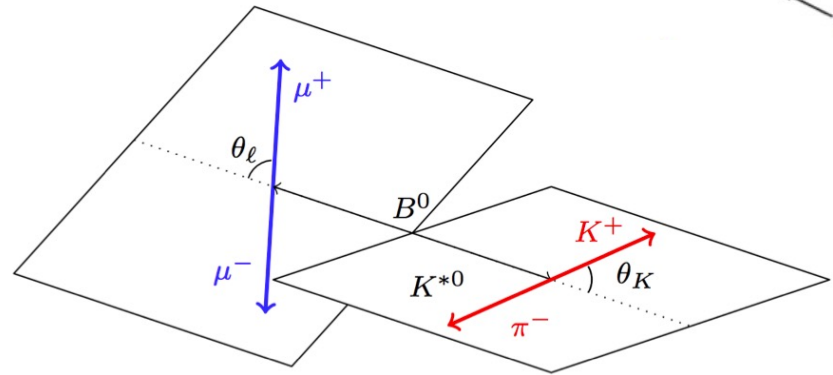
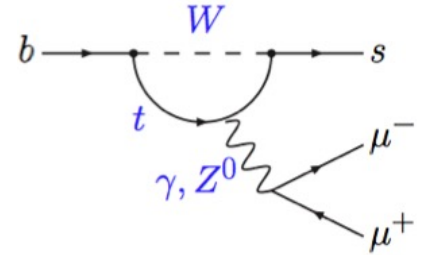


[De Bruyn et al., PRL 109 (2012) 041801]



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

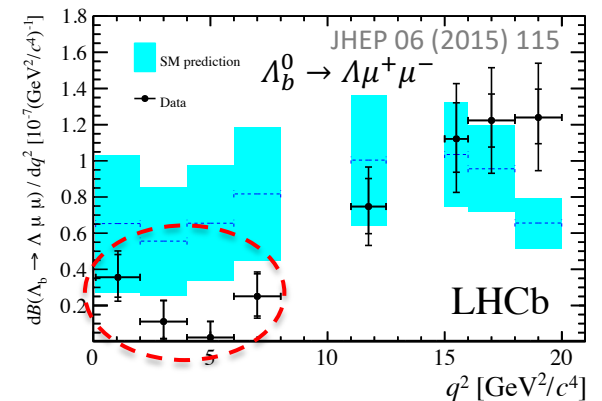
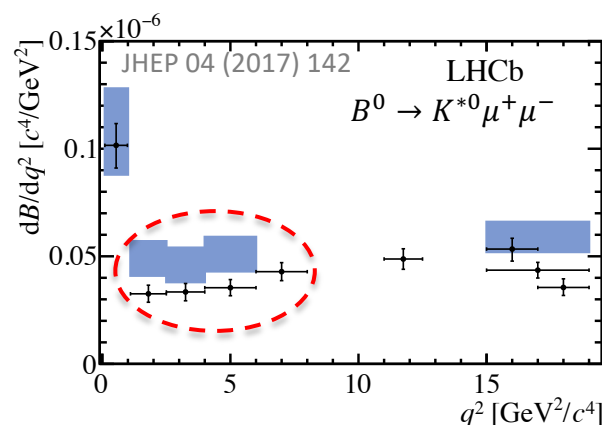
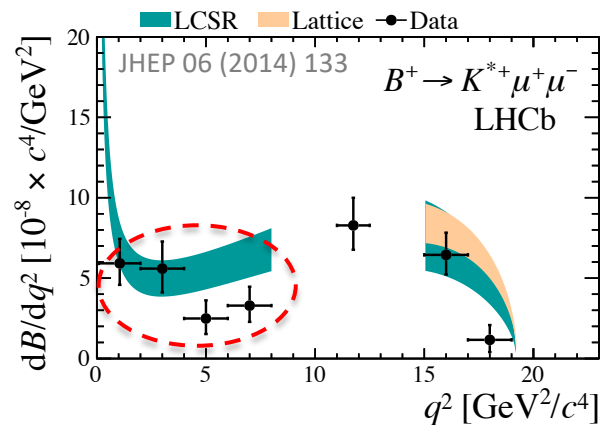
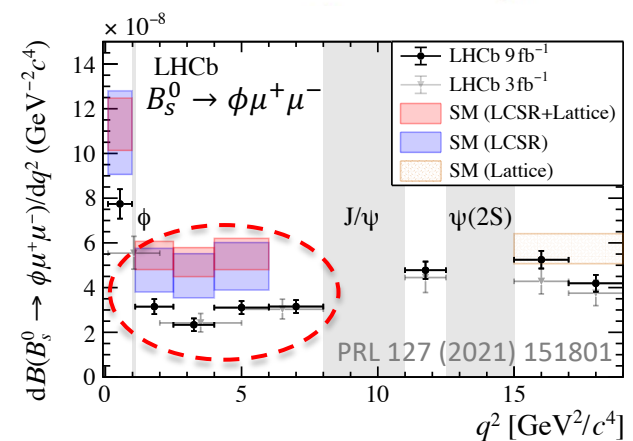
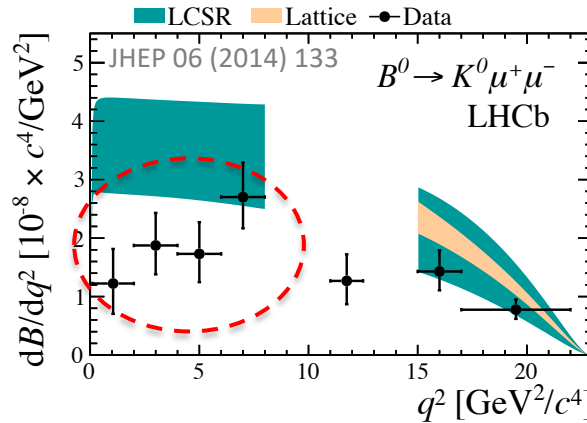
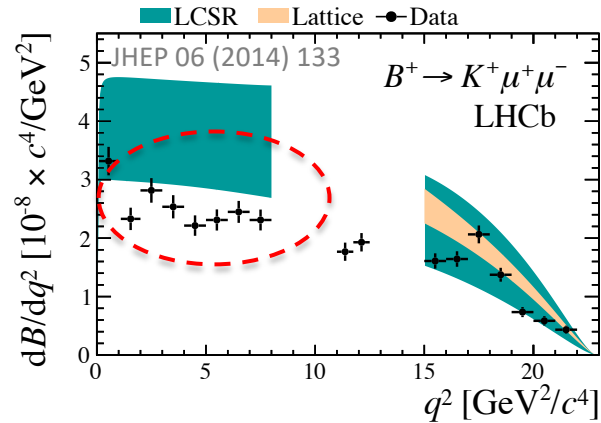
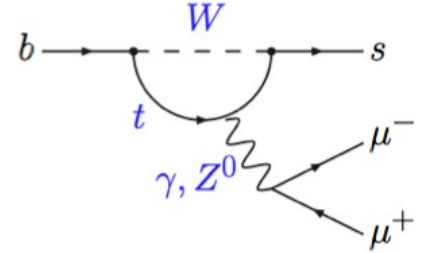
- Described by $q^2 = m^2(\ell^+ \ell^-)$ and $\theta_\ell, \theta_K, \phi$
- Many observables!



$$\begin{aligned} \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = & \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right. \\ & - F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \\ & + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \\ & + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\ & \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \end{aligned}$$

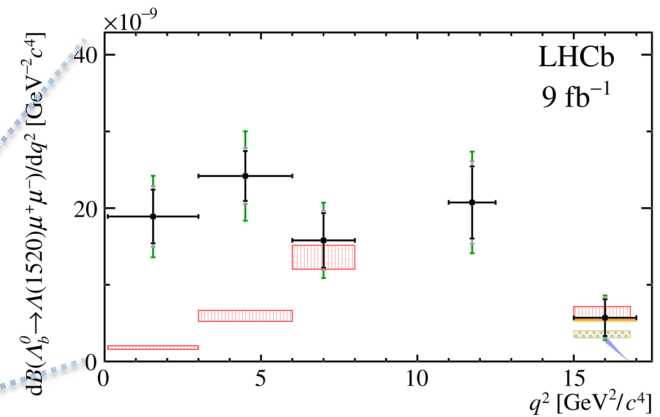
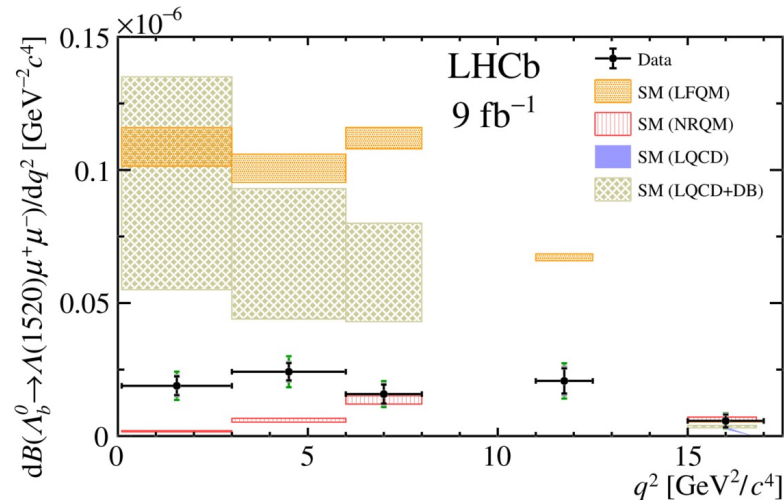
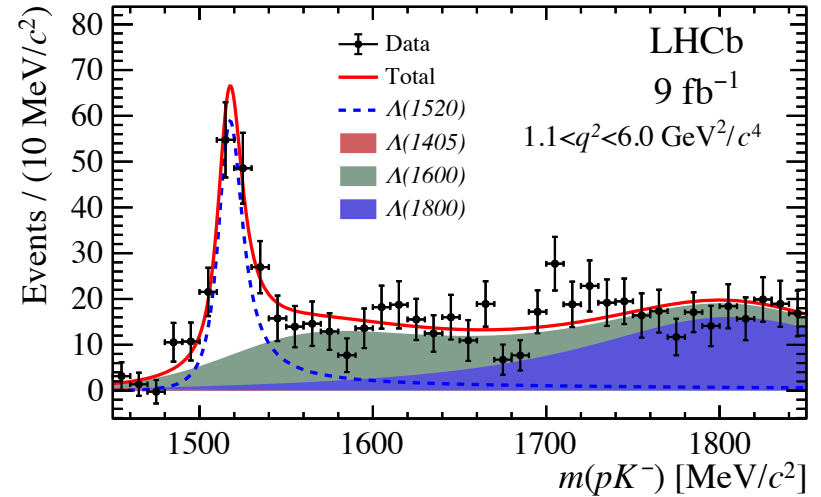
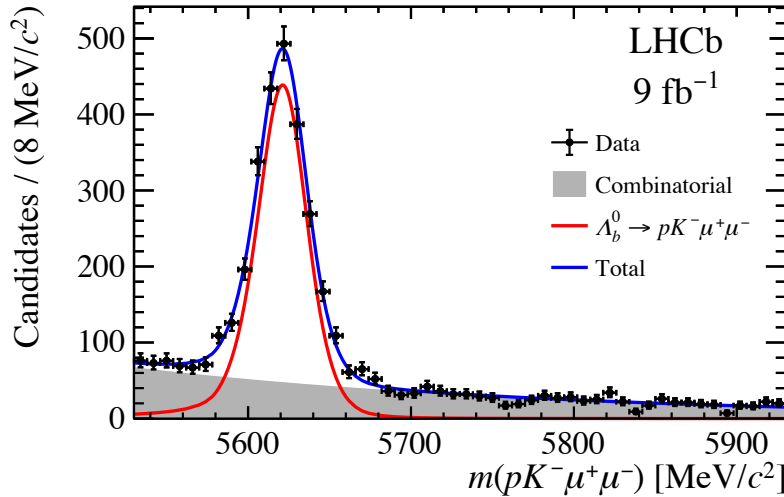
Branching fraction of $b \rightarrow s\mu^+\mu^-$

- Pattern of tensions seen, theoretical uncertainty?



BR of $\Lambda_b^0 \rightarrow \Lambda(1520)\mu^+\mu^-$

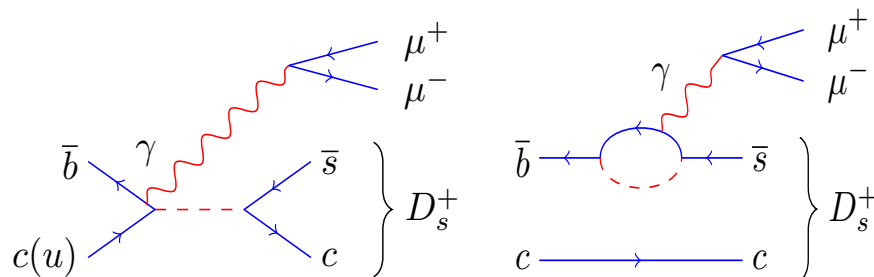
- First measurement w/ excited baryon, “milestone”



More details in Y. Zhou's talk

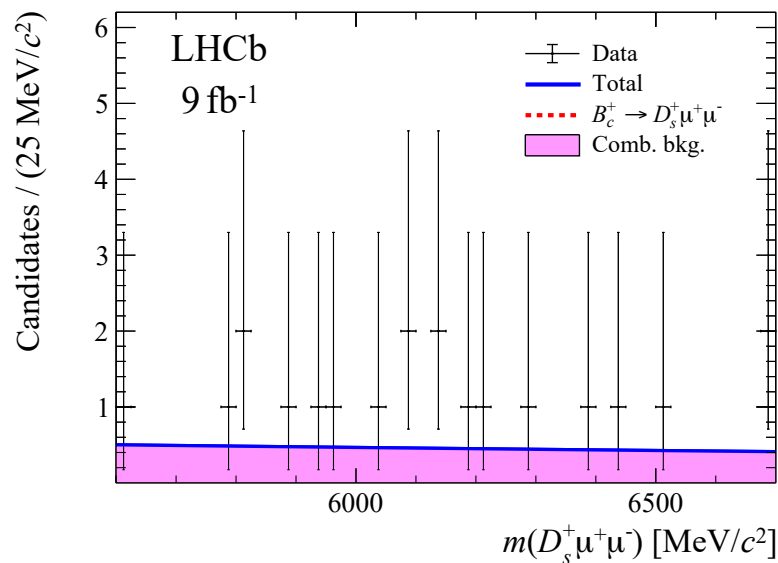
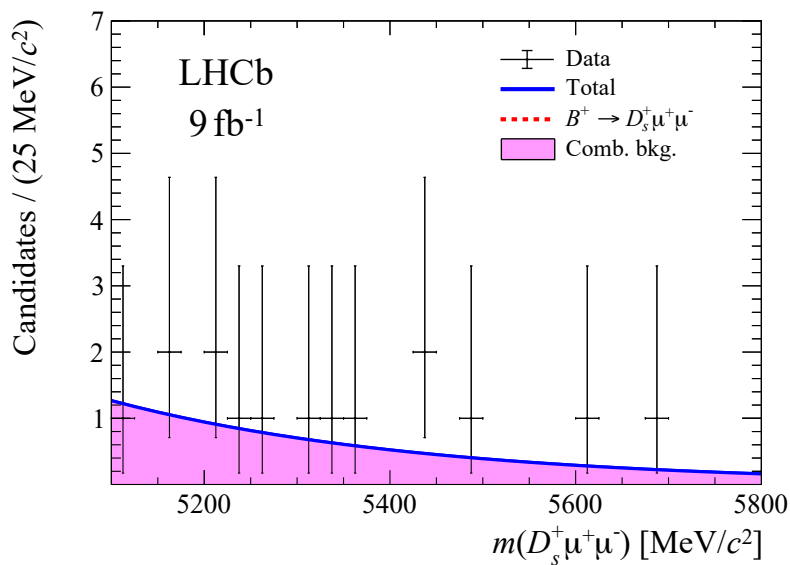
Search for $B \rightarrow D\mu^+\mu^-$

- Performed w/ all data, no signal yet
- Upper limits at 95% CL



$$\mathcal{B}(B^+ \rightarrow D_s^+ \mu^+ \mu^-) < 3.2 \times 10^{-8}$$

$$\frac{f_c}{f_u} \cdot \mathcal{B}(B_c^+ \rightarrow D_s^+ \mu^+ \mu^-) < 9.6 \times 10^{-8}$$

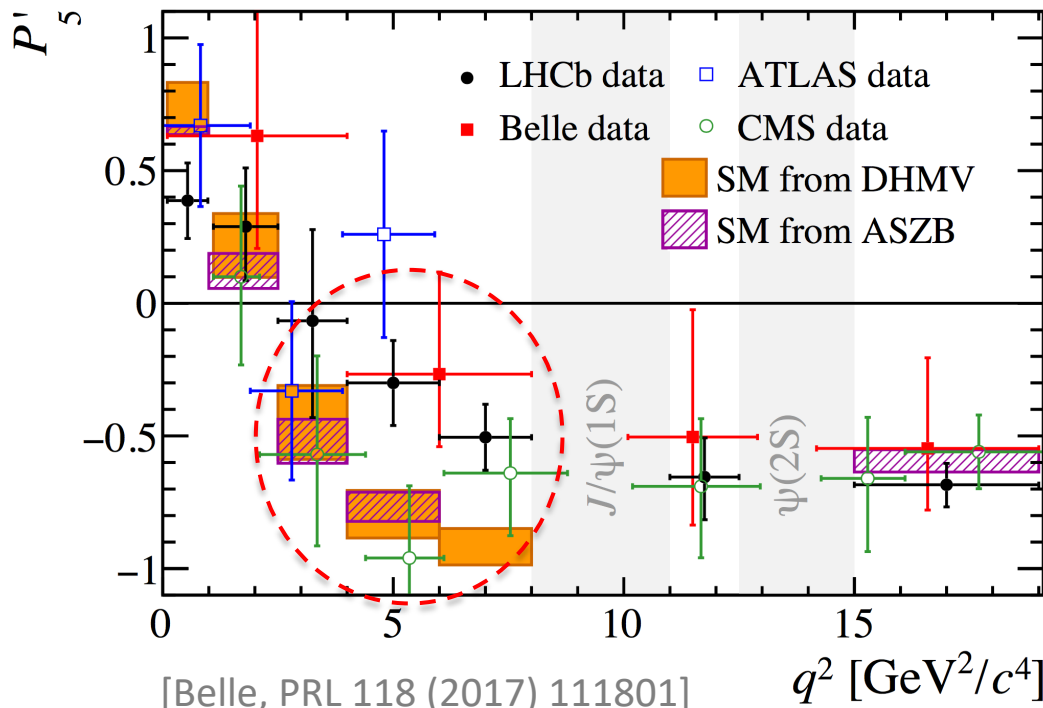


P'_5 with $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, less form-factor dependent

[S. Descotes-Genon, *et al.*, JHEP 01 (2013) 048]

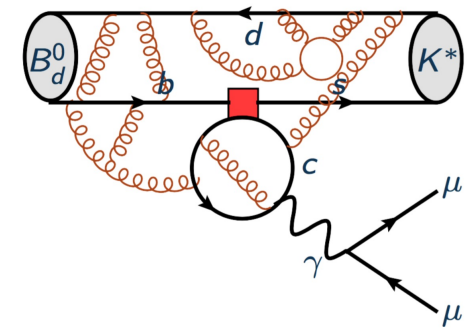
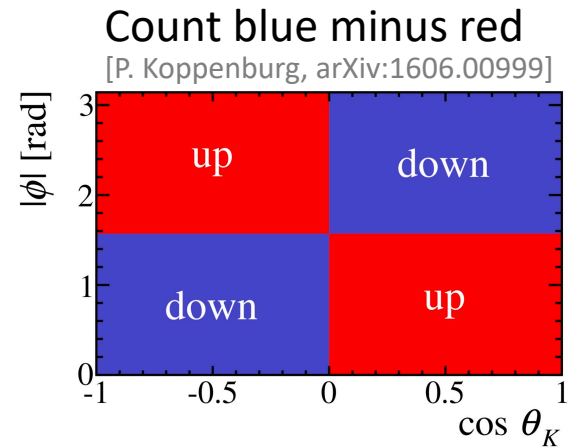
- Also measured by Belle, ATLAS, CMS



[Belle, PRL 118 (2017) 111801]

[ATLAS, JHEP 10 (2018) 047]

[CMS, PLB 781 (2018) 517]

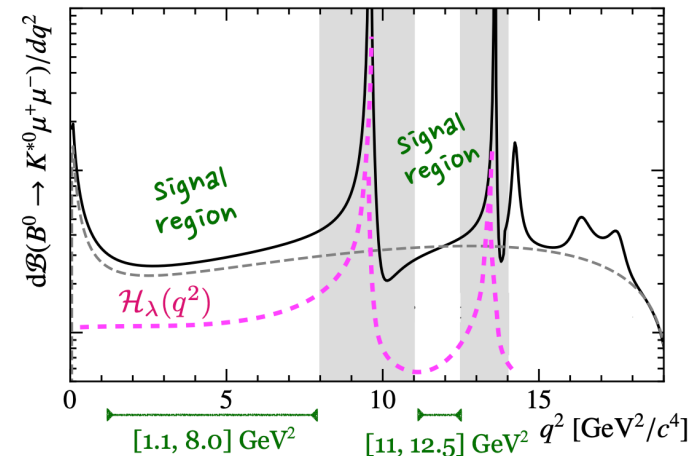


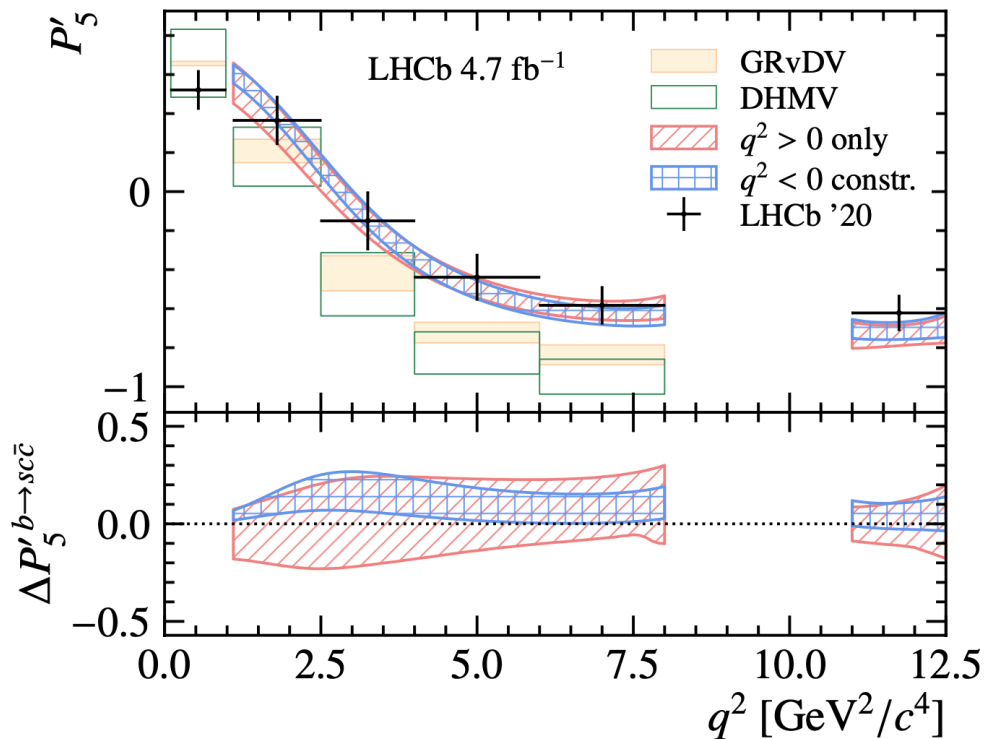
Amplitude analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Parametrise the decay amplitudes, choices of parametrisation introduce model-dependence

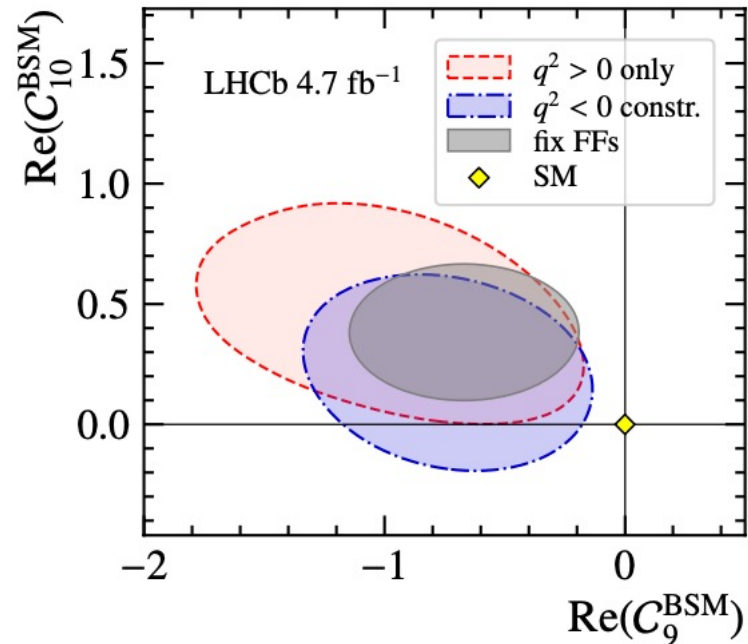
$$\mathcal{A}_\lambda^{L,R} = \mathcal{N} \left\{ \left[(C_9 \pm C'_9) \mp (C_{10} \pm C'_{10}) \right] \mathcal{F}_\lambda(q^2, k^2) + \frac{2m_b M_B}{q^2} \left[(C_7 \pm C'_7) \mathcal{F}_\lambda^T(q^2, k^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2, k^2) \right] \right\}$$

- $C_9^{(\prime)}, C_{10}^{(\prime)}$ float, $C_7^{(\prime)}$ fixed to SM
- Local FF, const. to LCSR+LQCD
- Charm loop parameters $\mathcal{H}_\lambda$, constrained using info
 - Exp. info of $B^0 \rightarrow \psi_n K^{*0}$ decays
 - Theo. predictions at $q^2 < 0$





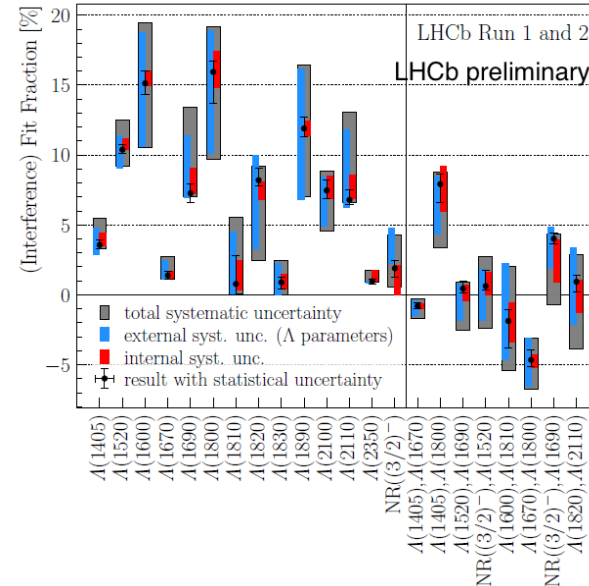
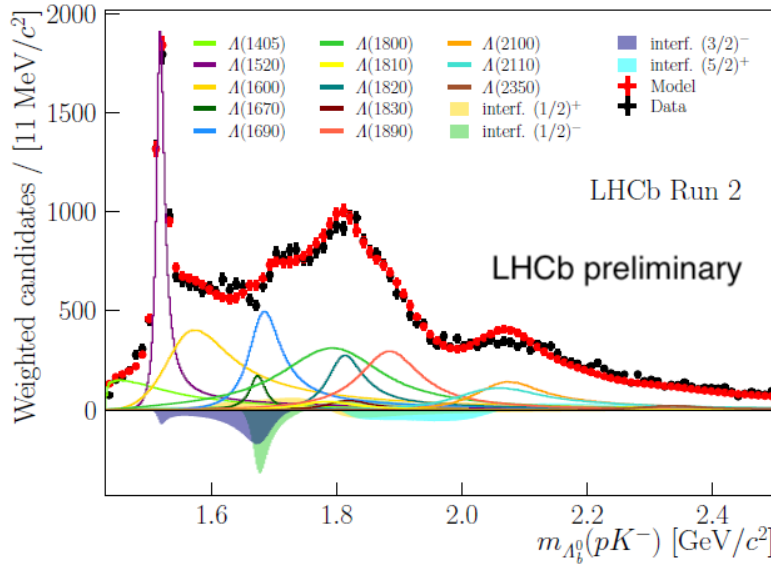
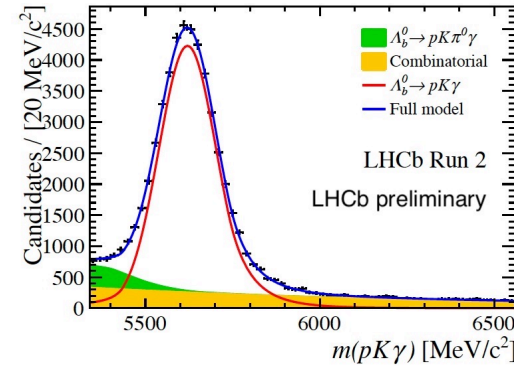
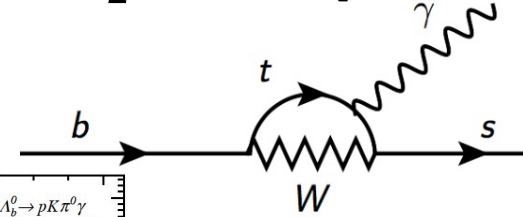
- Impact of charm loops consistent with predictions.



- With extra freedom given by $c\bar{c}$, a shift in C_9 still preferred
- Compatibility with SM, 1.8σ in C_9 and 1.4σ global

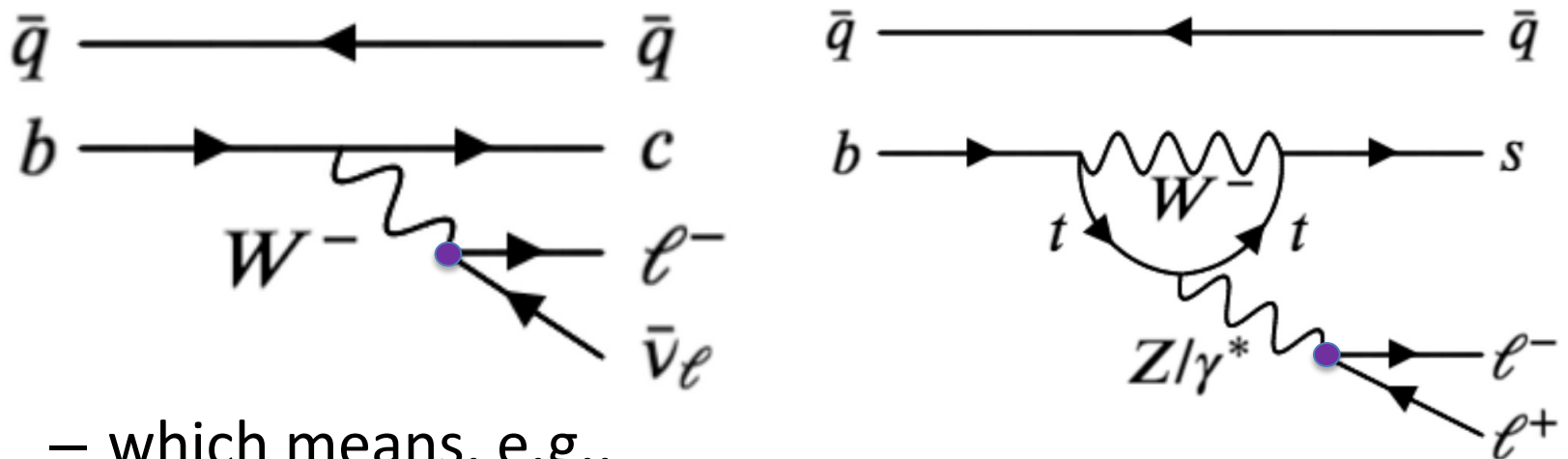
Amplitude analysis of $\Lambda_b^0 \rightarrow pK^- \gamma$

- Contributions from many Λ^* , dominated by $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1800)$, $\Lambda(1890)$



Lepton flavour universality

- In SM, three lepton families (e, μ, τ) have identical couplings to the gauge bosons



– which means, e.g.,

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \cong 1$$

$\mathcal{O}(10^{-4})$ uncertainty

[C. Bobeth *et al.*, JHEP 12 (2007) 040]

$\mathcal{O}(1\%)$ QED correction

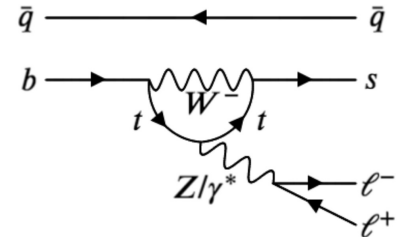
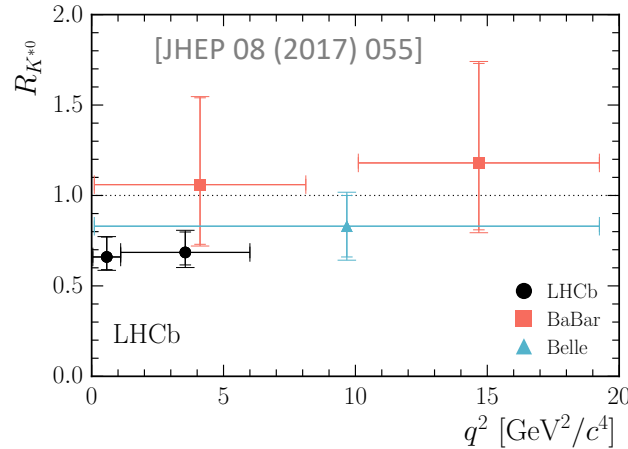
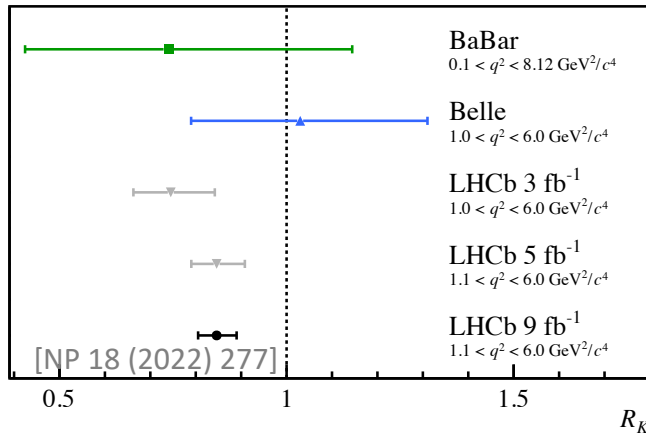
[M. Bordone *et al.*, EJPC 76 (2016) 440]

- Lepton flavour universality violation? **New Physics!**

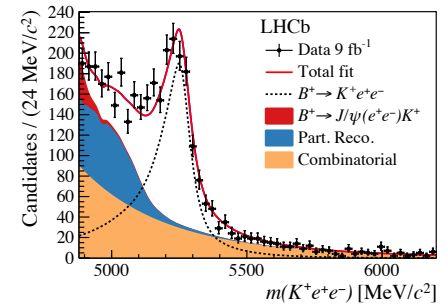
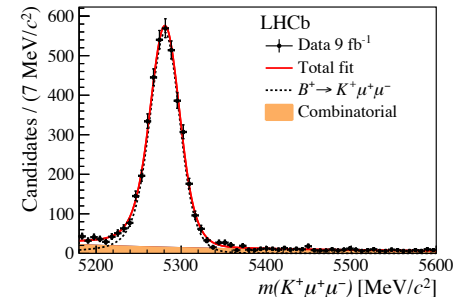
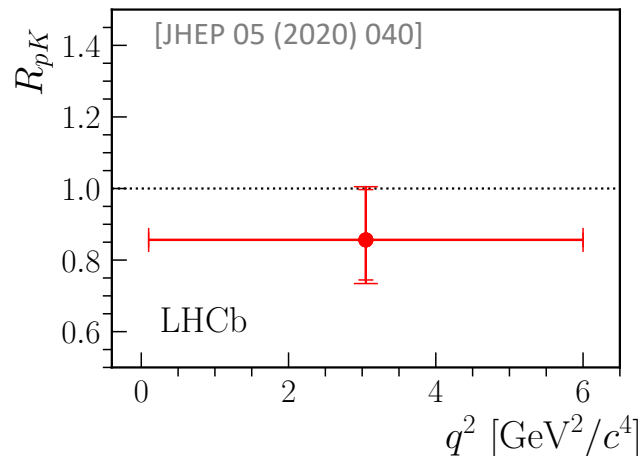
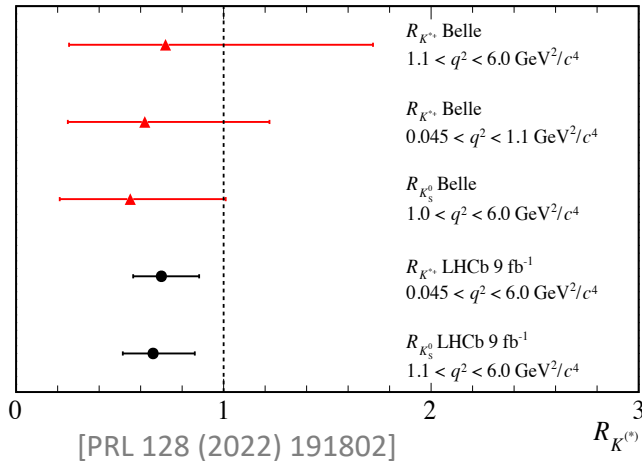
LFU in $b \rightarrow s \ell^+ \ell^-$ decays

- Deviations from SM seen by LHCb

before Dec 2022



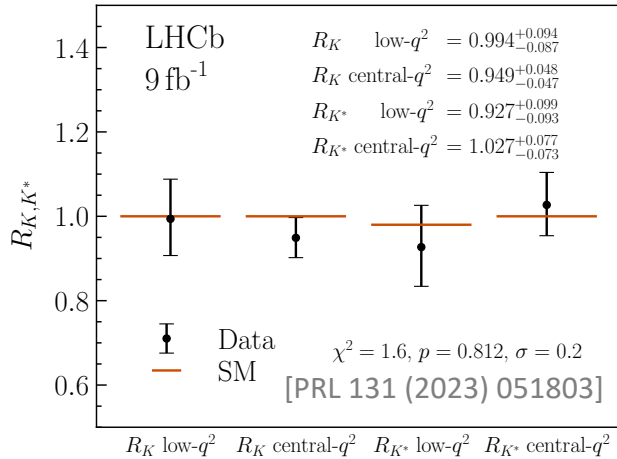
$$R_X = \frac{B(H_b \rightarrow X \mu^+ \mu^-)}{B(H_b \rightarrow X e^+ e^-)}$$



LFU in $b \rightarrow s \ell^+ \ell^-$ decays

after Dec 2022

- Deviations mostly gone

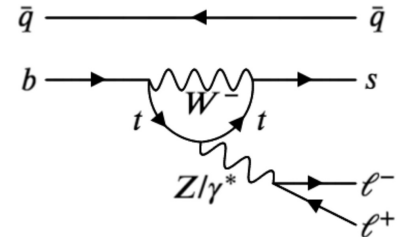
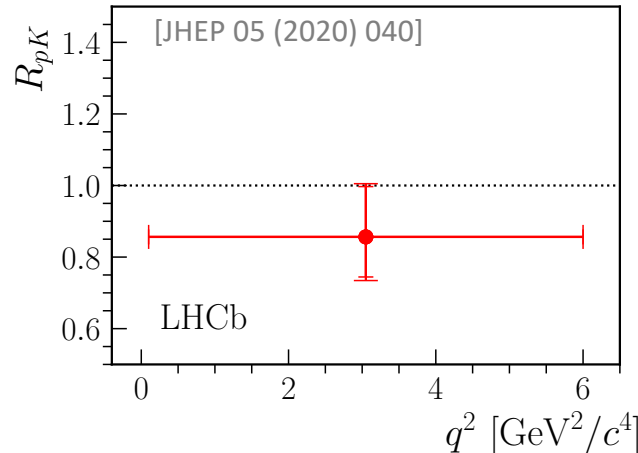
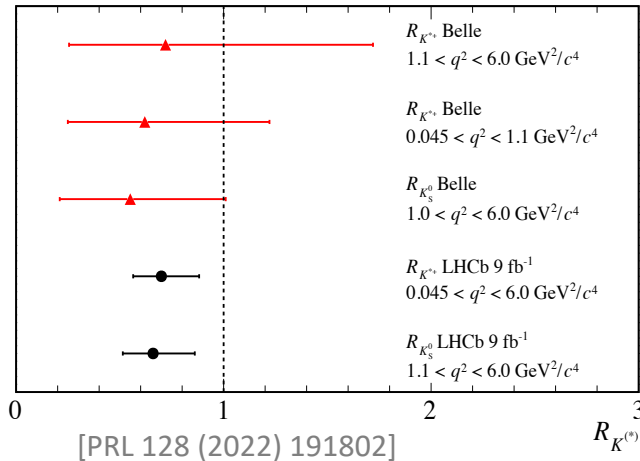


Precision at 5-10%

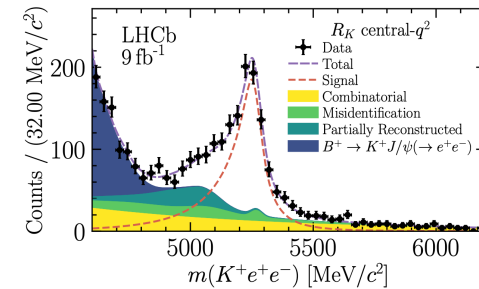
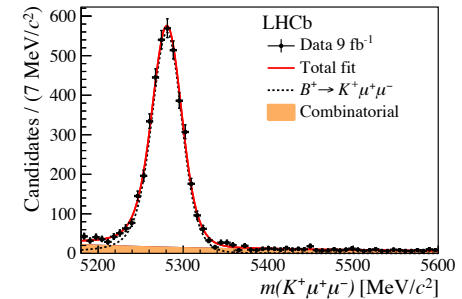
$\mathcal{O}(1\%)$ LFUV still possible

路漫漫其修远兮，吾将上下而求索
The road ahead will be long and our climb will be steep

$$R_K = 0.78^{+0.46}_{-0.23} {}^{+0.09}_{-0.05} \quad [\text{CMS, BPH-22-005-PAS}]$$

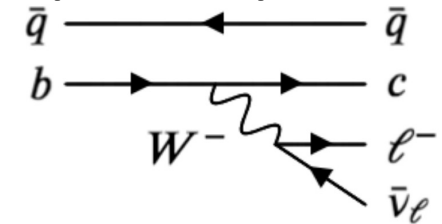
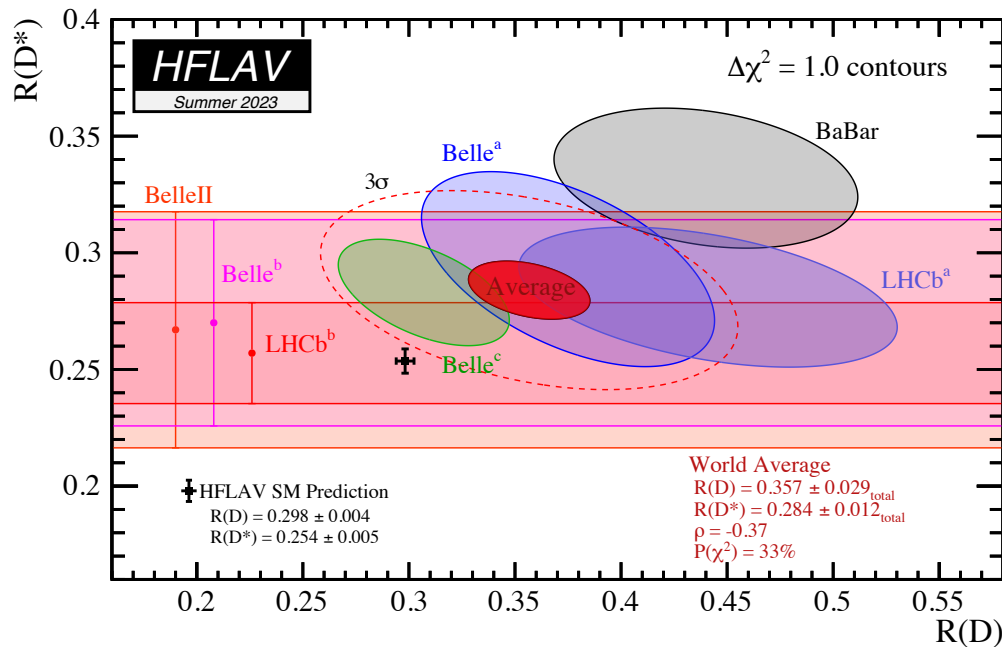


$$R_X = \frac{B(H_b \rightarrow X \mu^+ \mu^-)}{B(H_b \rightarrow X e^+ e^-)}$$

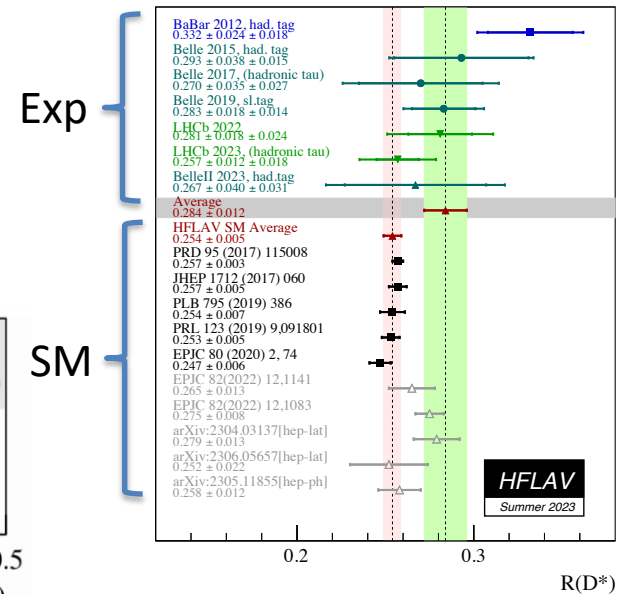
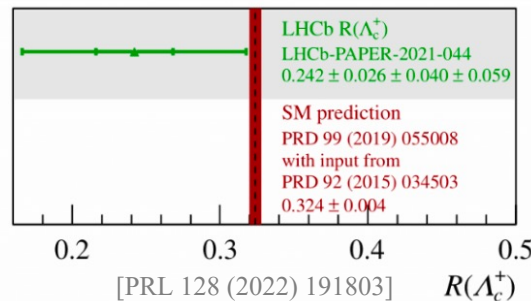
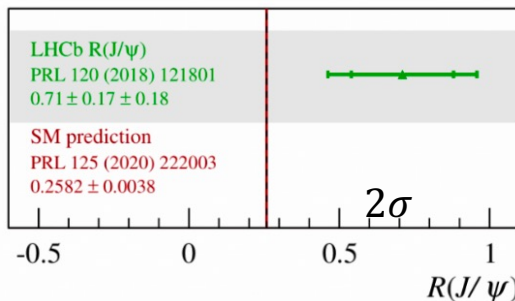


LFU in $b \rightarrow c \ell \nu$ decays

- Deviations from SM seen by Babar/Belle/LHCb



$$R(H_c) = \frac{B(H_b \rightarrow H_c \tau^- \bar{\nu}_\tau)}{B(H_b \rightarrow H_c \mu^- \bar{\nu}_\mu)}$$



$R(D^{(*)})$ using muonic τ decays

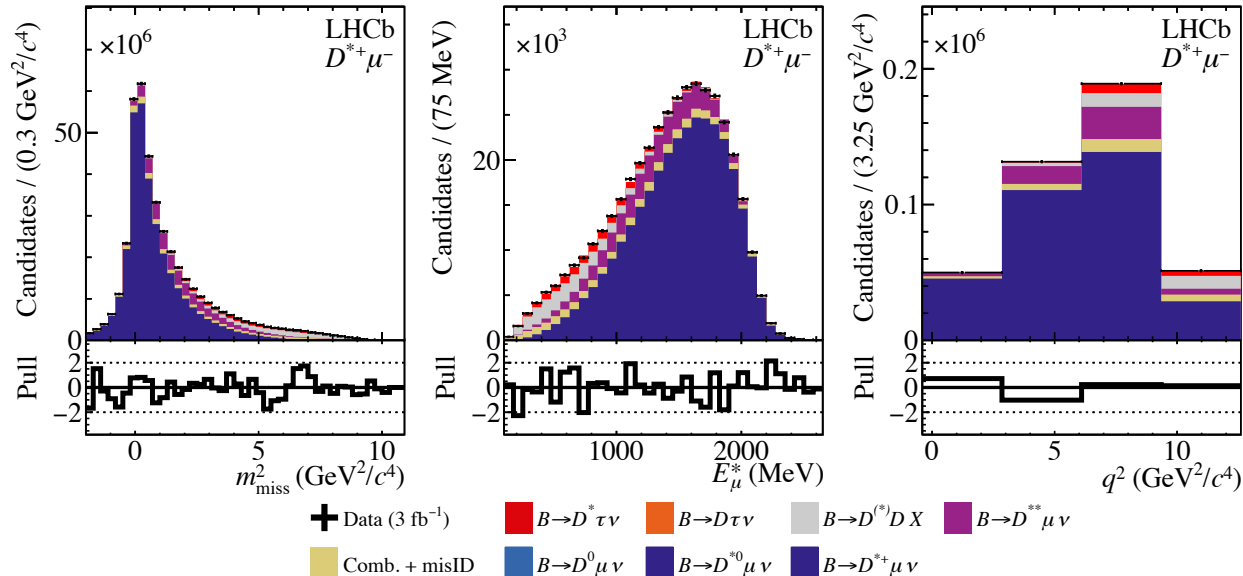
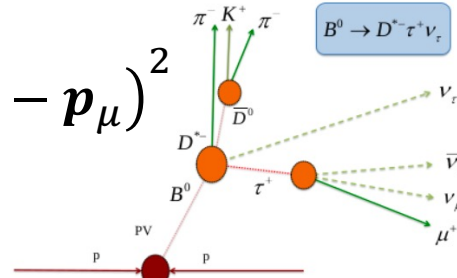
- $\mathcal{B}(\tau \rightarrow \mu X) \sim 17.4\%$

- 3D fits

– Signal yields: 44 000

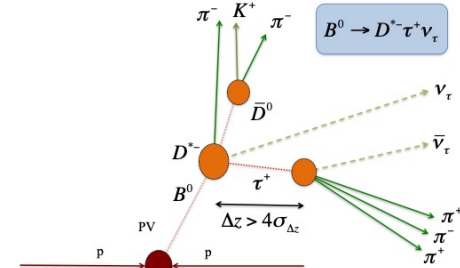
– Systematics: Simulation size, form factors, ...

$$R(D^*) = 0.281 \pm 0.018 \pm 0.023$$



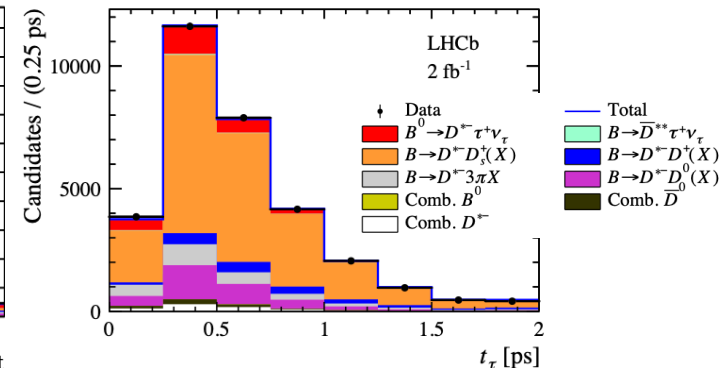
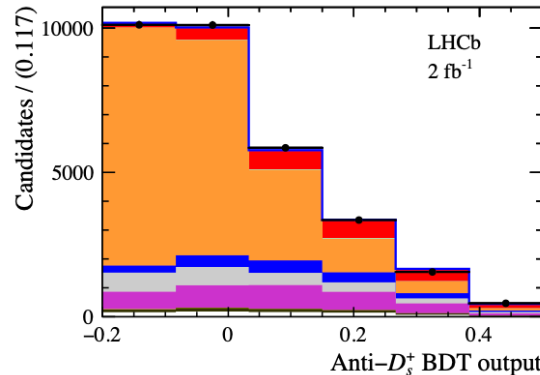
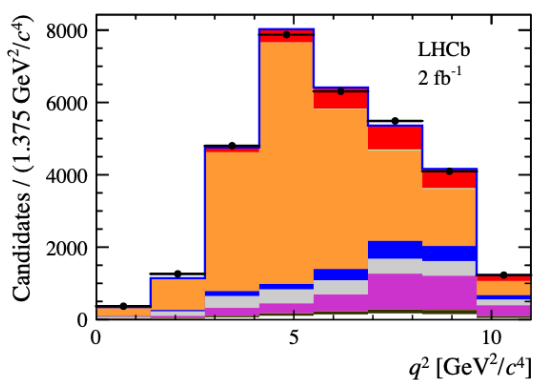
$R(D^*)$ using 3-prong τ decays

- $\mathcal{B}(\tau \rightarrow 3\pi^\pm X) \sim 9\% + 4\% (\geq 1\pi^0)$
- Normalized to $B^0 \rightarrow D^{*-} 3\pi$



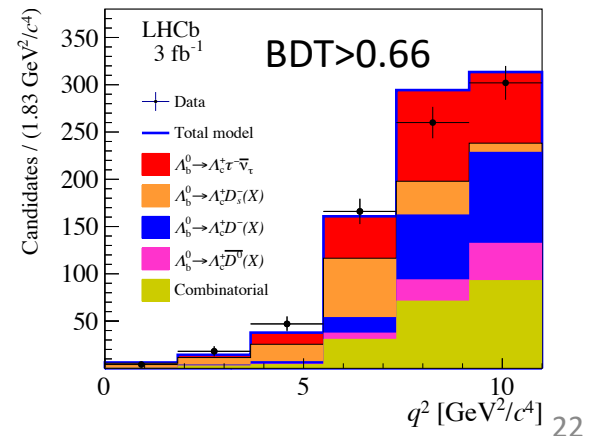
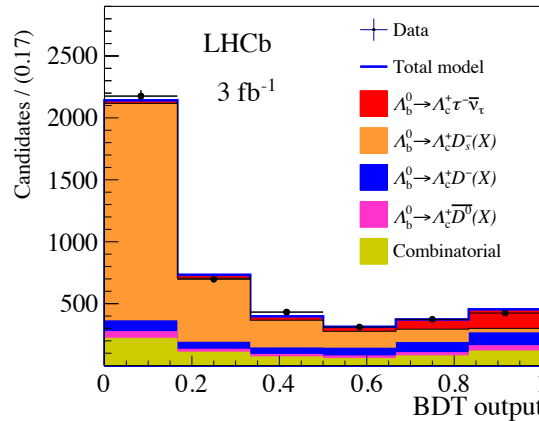
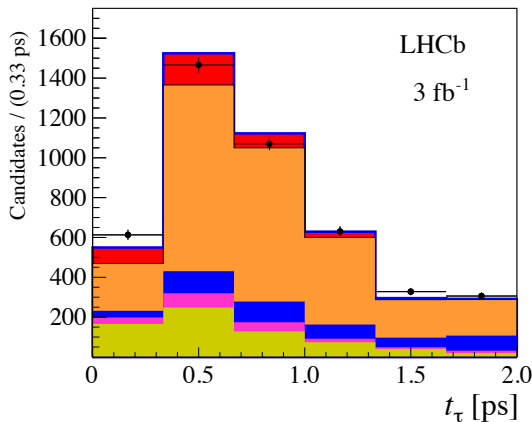
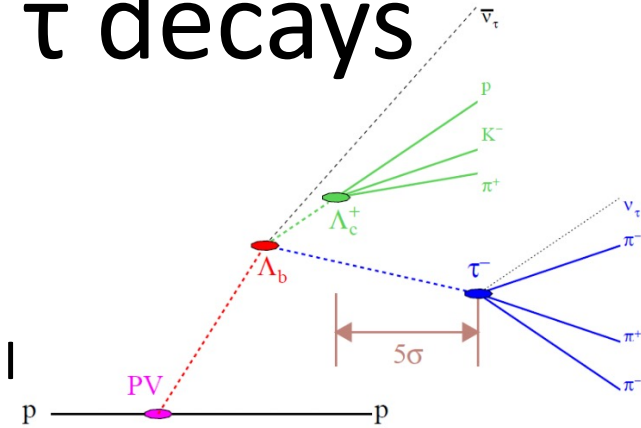
$$R_{had}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)} \quad R(D^*) = R_{had}(D^*) \times \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^- \nu_\mu)}$$

- 3D fits, $R(D^*) = 0.247 \pm 0.015 \pm \mathbf{0.015} \pm 0.012$
 - Signal yields: 2469 ± 154
 - Systematics: Simulation size, $D \rightarrow 3\pi X$ template, ...



$R(\Lambda_c^+)$ using 3-prong τ decays

- Normalized to $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$
 $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu) = (6.2 \pm 1.4)\%$ by DELPHI
- 3D fits, $R(\Lambda_c^+) = 0.242 \pm 0.026 \pm \mathbf{0.040} \pm 0.059$
 - Signal yields: 349 ± 40
 - Systematics: $D \rightarrow 3\pi X$ template, $\Lambda_b^0 \rightarrow \Lambda_c^+ DX$



$R(J/\psi)$ using muonic τ decays

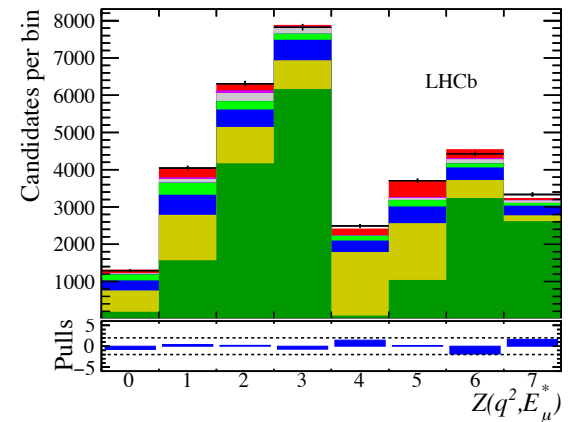
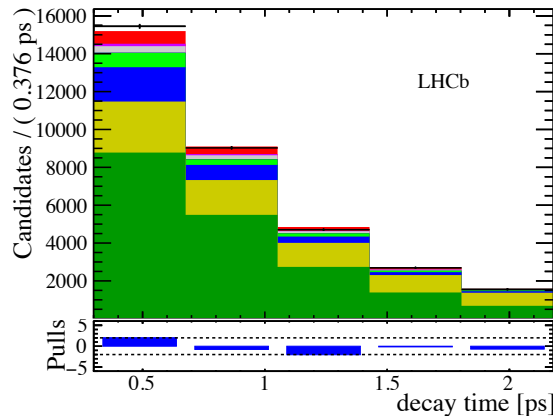
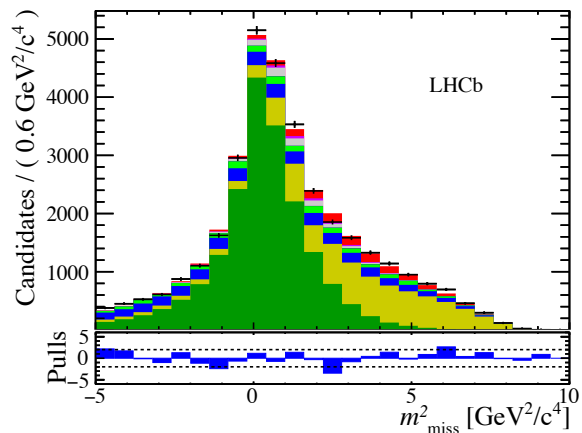
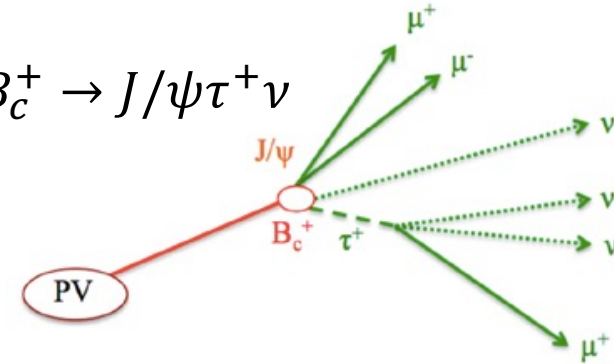
- Run-I, 1400 ± 300 signal (3σ) $B_c^+ \rightarrow J/\psi \tau^+ \nu$

– Pros: 3μ , $\mathcal{B}(\tau \rightarrow \mu X) \sim 17.4\%$

– Cros: small $\sigma(B_c^+)$, no τ vertex

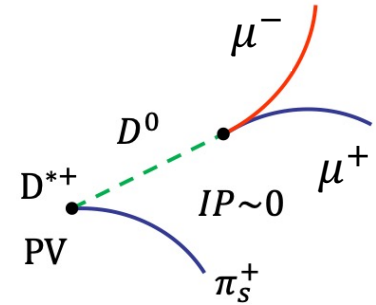
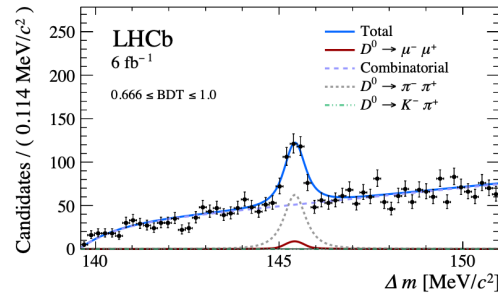
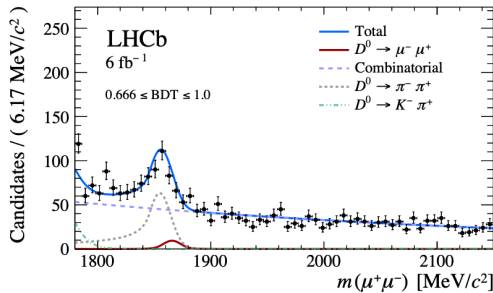
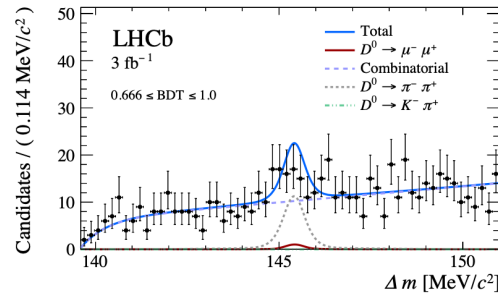
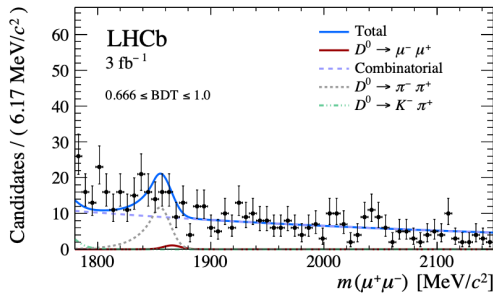
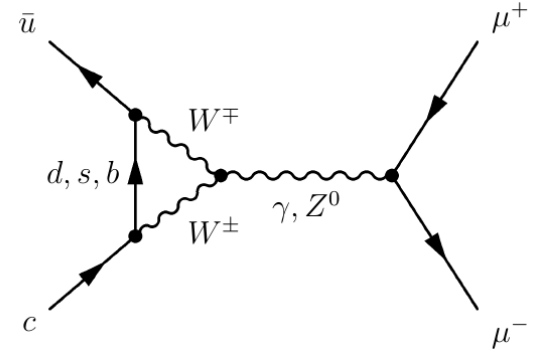
- $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$

$$= 0.17_{-0.17}^{+0.18} {}^{+0.21}_{-0.22} \pm 0.19 \text{ (theo.)} \quad [\text{CMS, BPH-22-012-PAS}]$$



$$D^0 \rightarrow \mu^+ \mu^-$$

- Very rare decay: FCNC+helicity suppression, contributions in SM
 - SD, $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) \sim 10^{-18}$
 - LD, $\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) \sim 10^{-11}$

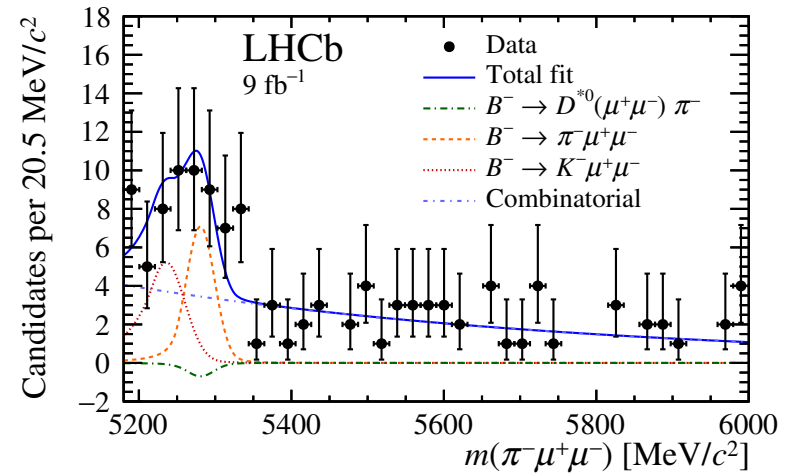
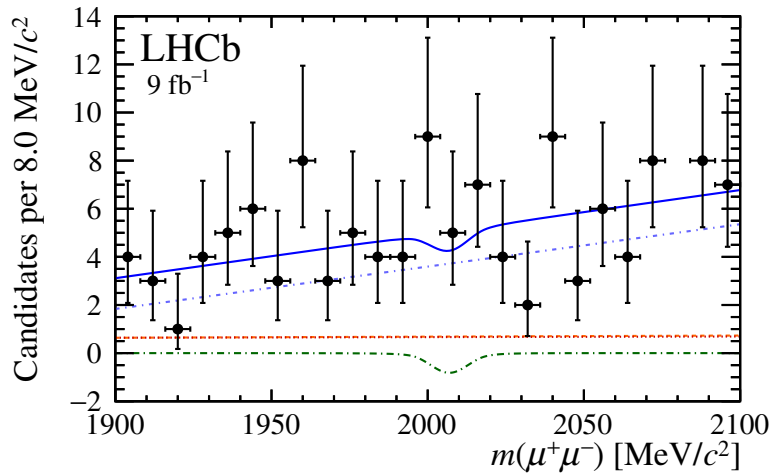


$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 3.1 \times 10^{-9} \text{ @ 90\% CL}$$

$$D^*(2007)^0 \rightarrow \mu^+ \mu^-$$

- Complementary to $D^0 \rightarrow \mu^+ \mu^-$ (same operators), no chiral suppression, but can decay via EM and strong interactions, BR in SM $\mathcal{O}(10^{-19})$
- Searched in $B^- \rightarrow \pi^- \mu^+ \mu^-$ decay, no signal yet, upper limit at 90% CL

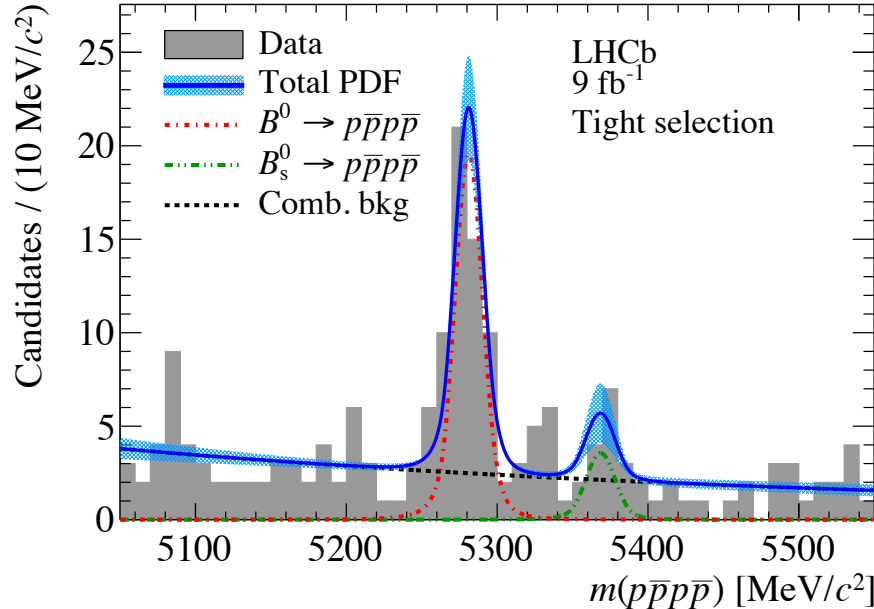
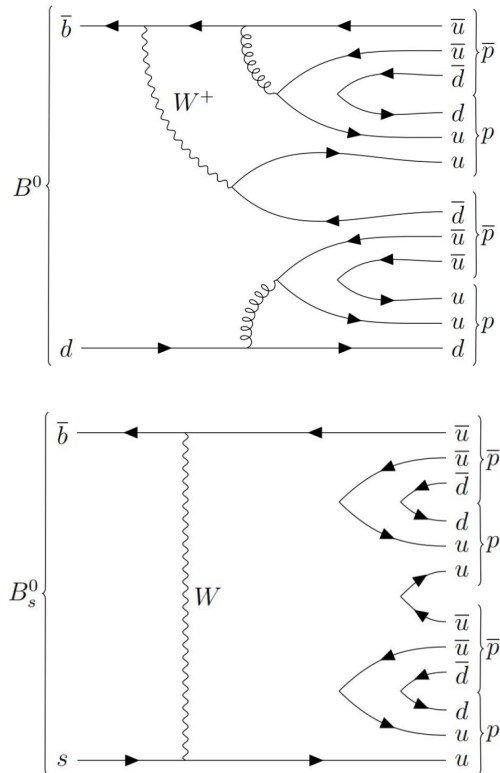
$$\mathcal{B}(D^*(2007)^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-8}$$



Search for $B_{(s)}^0 \rightarrow pp\bar{p}\bar{p}$

- Non-pert. + weak, threshold enhancement?
- First observation (evidence) of $B_{(s)}^0 \rightarrow pp\bar{p}\bar{p}$

[PRL 131 (2023) 091901]

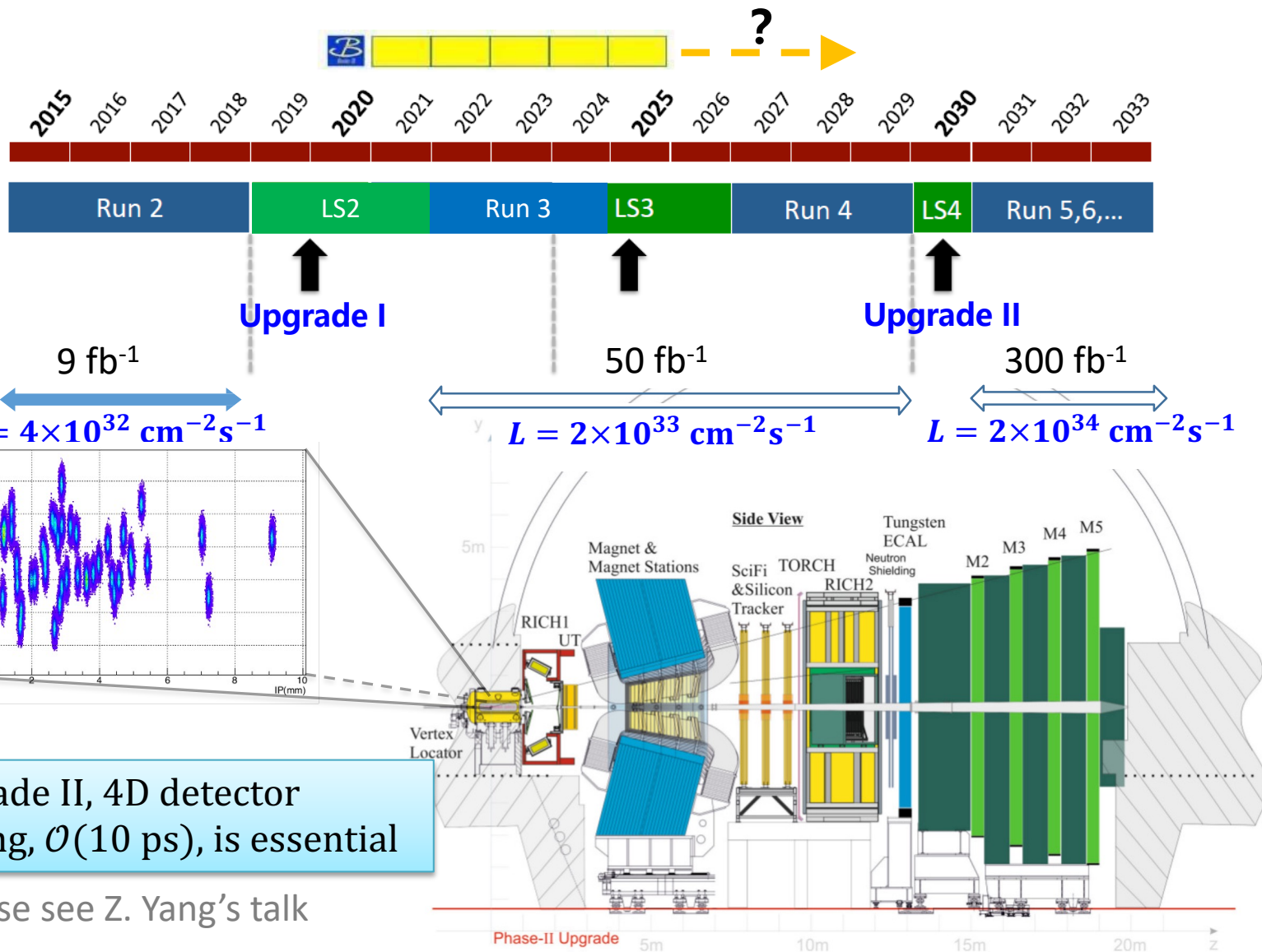


$$\mathcal{B}(B^0 \rightarrow p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$$

$$\mathcal{B}(B_s^0 \rightarrow p\bar{p}p\bar{p}) = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$$

$$B_s^0 \rightarrow p\bar{p}p\bar{p} \text{ higher than } \left| \frac{V_{us}}{V_{ud}} \right|^2 \sim 5\% ?$$

The LHCb upgrades



Upgrade II, 4D detector
Timing, $\mathcal{O}(10 \text{ ps})$, is essential

Please see Z. Yang's talk

Prospects

• LHCb upgrades

(2025: 23 fb⁻¹, Upgrade-II: 300 fb⁻¹)

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K ($1 < q^2 < 6 \text{ GeV}^2 c^4$)	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} ($1 < q^2 < 6 \text{ GeV}^2 c^4$)	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ , with $B_s^0 \rightarrow D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ , all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \rightarrow J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
ϕ_s^{ss} , with $B_s^0 \rightarrow \phi \phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [608]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$ V_{ub} / V_{cb} $	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \rightarrow \mu^+ \mu^-$					
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \rightarrow c \ell^- \bar{\nu}_\ell$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
$A_\Gamma (\approx x \sin \phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin \phi$ from multibody decays	–	($K3\pi$) 4.0×10^{-5}	($K_S^0 \pi\pi$) 1.2×10^{-4}	($K3\pi$) 8.0×10^{-6}	–

Summary

- Many interesting results from LHCb
 - Flavour anomalies, $b \rightarrow s\mu^+\mu^-$ BR, $\mathcal{R}_{K^{(*)0}}, \mathcal{R}_{D^*}$, to be confirmed or refuted with more data
 - Rare decays, $D^{(*)0} \rightarrow \mu^+\mu^-$, $B \rightarrow pp\bar{p}\bar{p}$
- With LHCb upgrade (50 fb⁻¹) & upgrade-II (300 fb⁻¹), much more will be done
- Your continued and strong supports are always appreciated!
 - Form factors, non-form-factor contributions
 - New observables?