EFT & Heavy Flavours : an experimentalist point of view

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Disclaimer & simplifications

- Experimentalist's point of view
- I will restrict myself to FCNC modes
- Branching fractions of the order of 10^{-7} to 10^{-10} → LHC(b)-biased presentation
- But Belle-II can also play an important role

Outline of the lectures

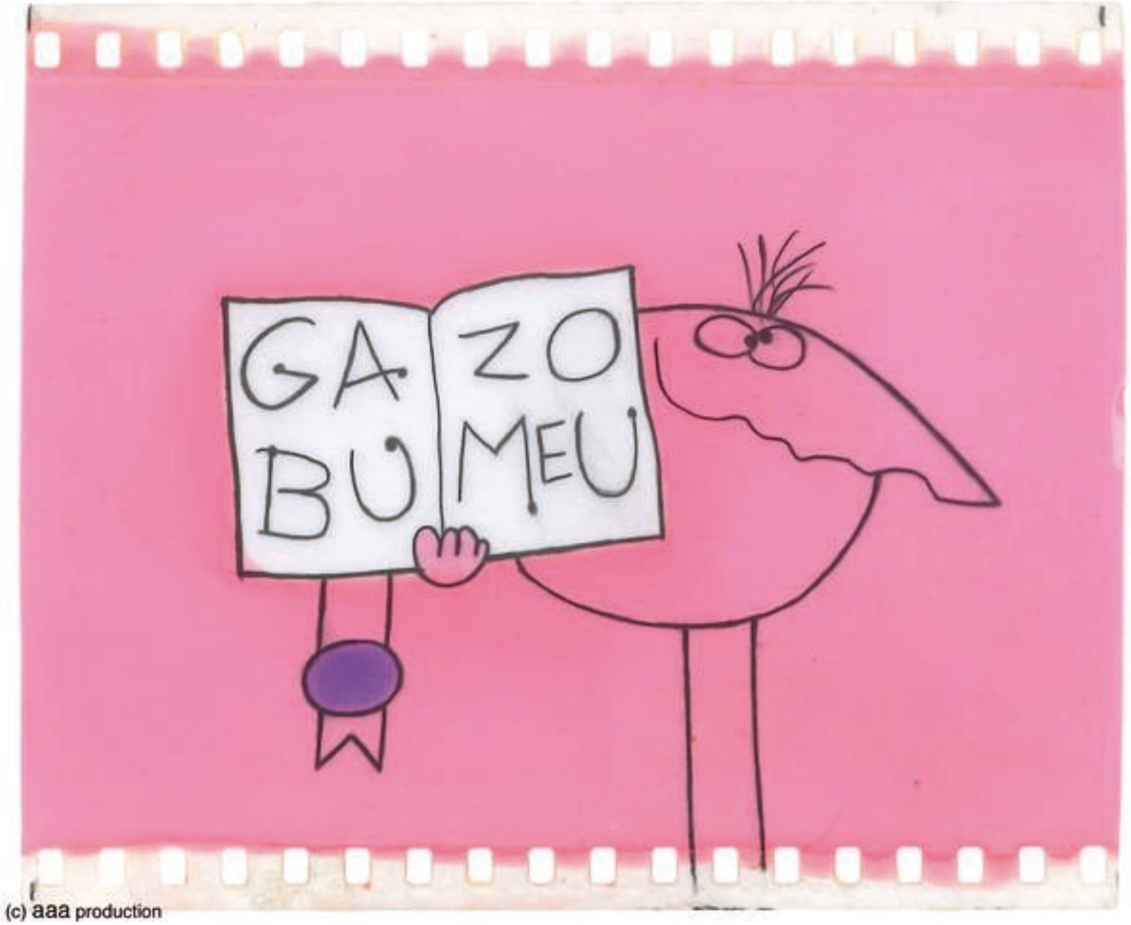
1

- Introduction (context, EFT as seen from an experimentalist, LHCb)
- $B \to \ell^+\ell^-$ what do we measure and how?
- $H_b \to H_s\, \ell^+\ell^-$ what do we measure and how?

2

- Why not electrons ?
- Some ideas to move forward

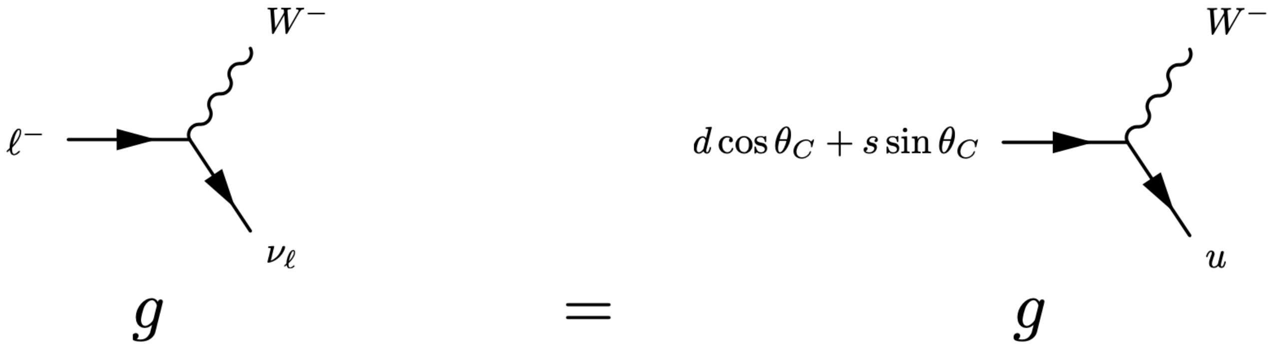
Introduction



(c) aaa production

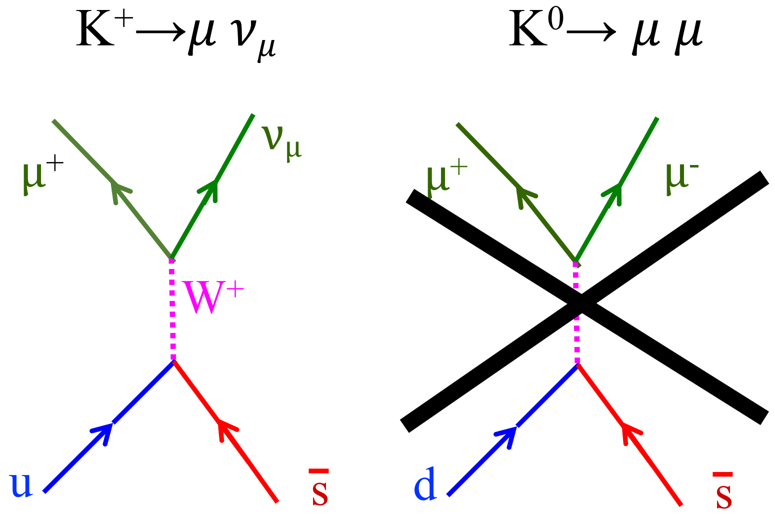
Rare K decay, FCNC and the GIM mechanism

- In the 1960's: 3 quarks and universality of couplings (Cabbibo)



- But problems with the $K^0 \rightarrow \mu\,\mu$ decay

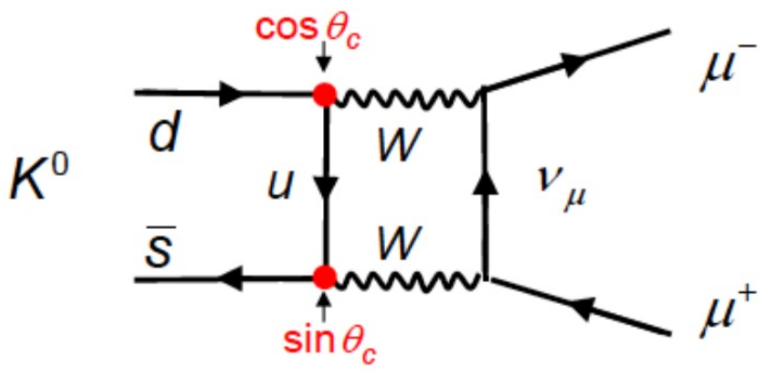
1st order



$$\frac{BR(K^0 \rightarrow \mu^+\mu^-)}{BR(K^+ \rightarrow \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

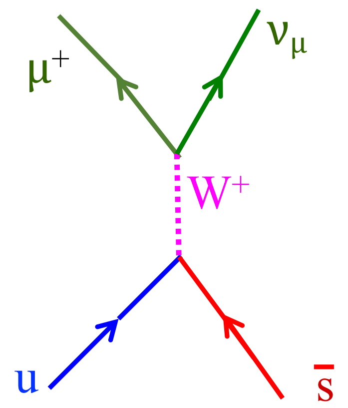
Second order

$K^0 \to \mu\,\mu$



$g^8 \sin^2\theta_C \cos^2\theta_C$ does not match experiment

$K^+ \to \mu\,\nu_\mu$

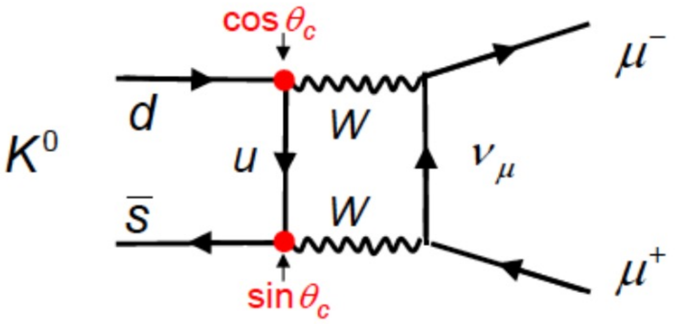


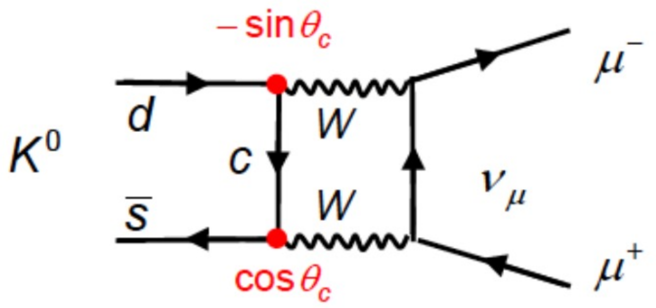
$g^4 \sin^2\theta_C$

GIM mechanism : add a fourth quark !

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$





$\text{Rate} \sim g^4\,(m_c^2 - m_u^2)\sin^2\theta_C\;\cos^2\theta_C$

First indirect "evidence" for Charm quark!

Good agreement with experimental value of BR($K^0 \rightarrow \mu\,\mu$) for a charm quark mass of 1.3 - 1.5 GeV

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

Directly observed in 1974

FCNC are forbidden at tree level in the SM

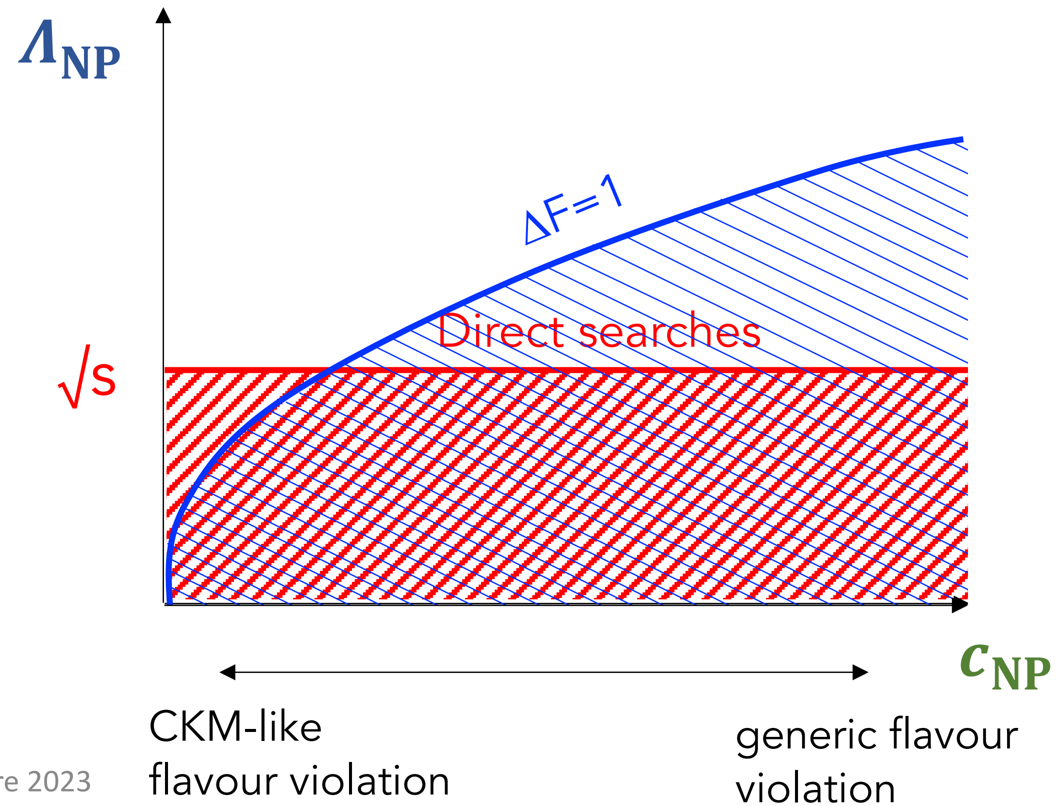
Mediated by box and loop diagrams ⇒ sensitive to indirect effects of New Physics (NP)

Access to larger scales than direct searches

Tests of couplings to 3rd generation (*b*-quarks)

$$\mathcal{H}_{NP} \propto \frac{c_{\mathrm{NP}}}{\Lambda^2_{\mathrm{NP}}}$$

NP scale and coupling



Flavour puzzle

$$\mathcal{H}_{NP} \propto \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2}$$

NP scale and coupling

Operator	Bounds on Λ in TeV ($c_{\mathrm{NP}}=1$) Re	Im	Bounds on c_{NP} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

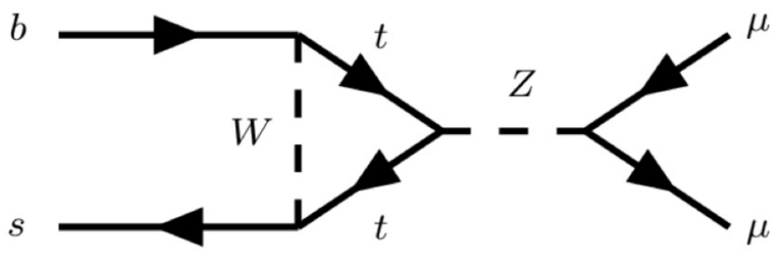
Ann. Rev. Nucl. Part. Sci. 60 (2010) 355, update from 2012

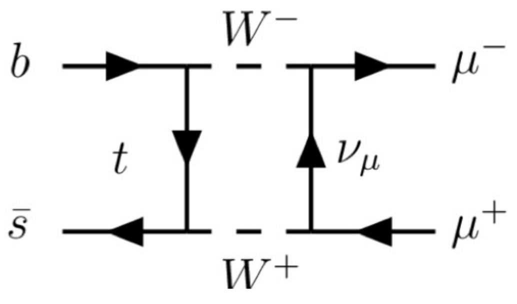
Large limits on the New Physics scale

why should NP follow the same flavour couplings (including same phase) as SM ?

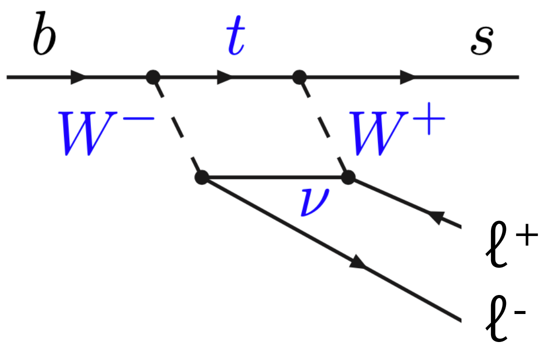
$b \to s\, \ell^+ \ell^-$ transitions: what are we talking about ?

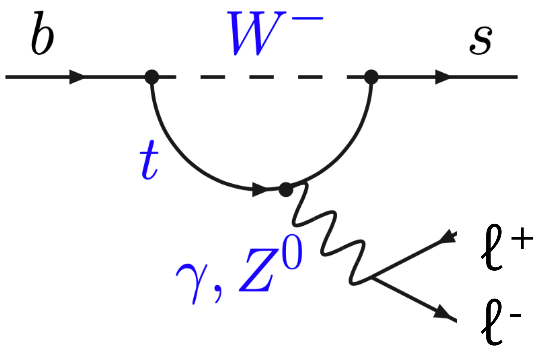
$B_s \to \ell^+ \ell^-$





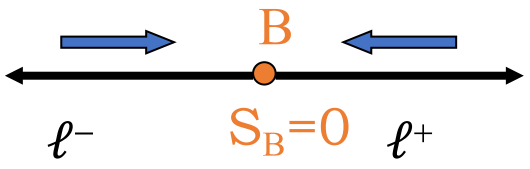
$H_b \to H_s\, \ell^+ \ell^-$



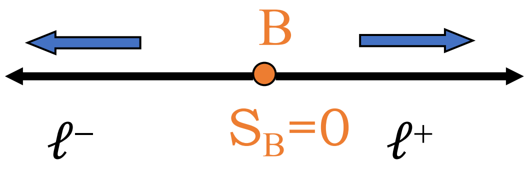


$B_{s/d} \rightarrow \ell^+ \ell^-$

ℓ = e or μ



left-handed particle
left-handed anti-particle



right-handed particle
right-handed anti-particle

SM : very rare (V_{tq}, helicity suppression)

In the SM, in the massless limit: left-handed anti-particle &right-handed particle are forbidden

$$\mathcal{B}(B_s^0 \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$

$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

JHEP10 (2019) 232

SM

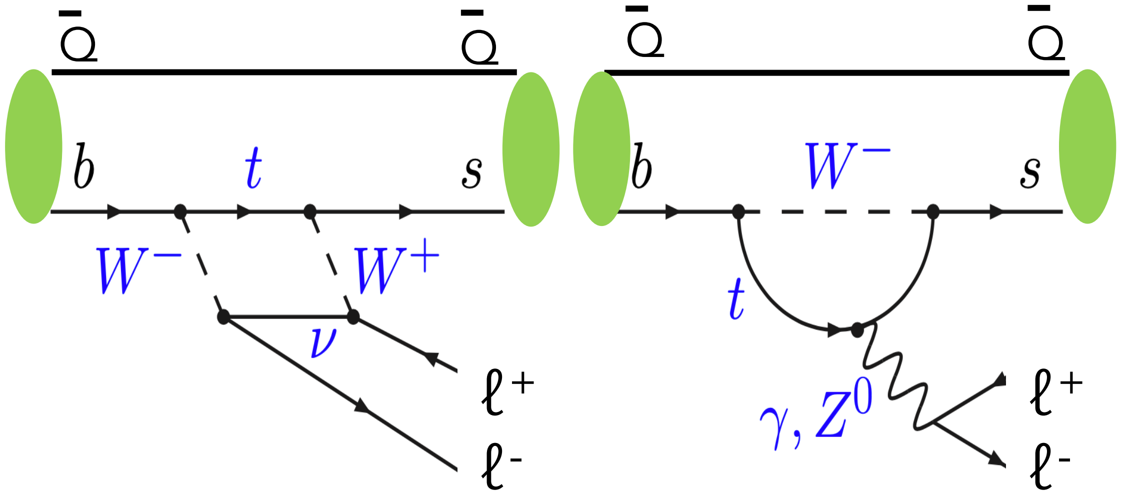
Due to CKM, the B_d modes are further suppressed by a factor 1/30

Sensitive to the scalar sector
New Physics models with an extended Higgs sector $BR^{MSSM} \propto \tan^6\beta / M_A{}^4$

ratio of the vevs of the two Higgs doublets

First searches in 1985 (!) : CLEO BR < 10^{-4} @ 90% CL

$H_b \to H_s\, \ell^+ \ell^-$



Q=u	Q=d	Q=s
$B^- \to K^- \ell\ell$ $B^- \to K^{*-} \ell\ell$	$B^0 \to K_s \ell\ell$ $B^0 \to K^{*0} \ell\ell$	$B_s \to \phi \ell\ell$

+ *b*-baryons ….
(and B_c)

$q^2 = M^2(\ell\ell)$

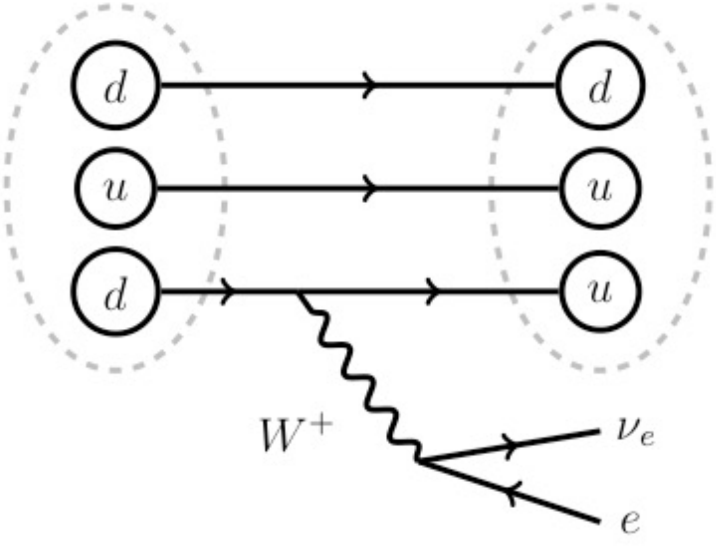
Contributions of the various diagrams vary

- with q^2
- with the different decay modes

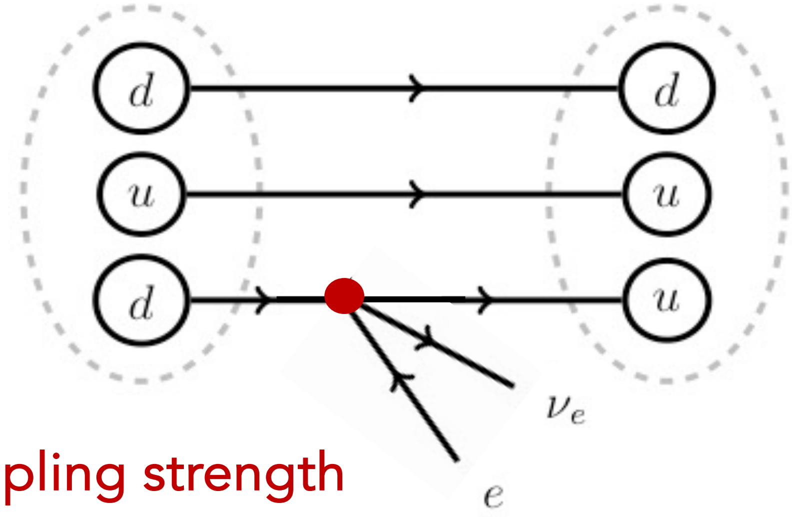
] eg : photon pole

EFT for Heavy Flavours in a nutshell

neutron β decay



Expansion in q^2/M_W^2:



coupling strength

$$i\mathcal{A} = \left(\frac{ie}{\sqrt{2}\sin\theta_W}\right)^2 V_{ud}^*(\bar{\nu}_l\gamma_\nu P_L \ell)\frac{ig_{\mu\nu}}{q^2 - M_W^2 + i\epsilon}(\bar{d}\gamma_\mu P_L u)$$

$$i\mathcal{A} = i\frac{4G_F}{\sqrt{2}}V_{ud}^*(\bar{\nu}_l\gamma^\mu P_L \ell)(\bar{d}\gamma_\mu P_L u) + \mathcal{O}\left(\frac{q^2}{M_W^2}\right)$$

$$G_F \equiv \sqrt{2}\frac{e^2}{8\sin^2\theta_W M_W^2} \equiv \sqrt{2}\frac{g}{8M_W^2}$$

Measurement of the effective coupling ⇒ constraints on g/M_W^2

$$\mathcal{H}_{NP} \propto \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2}$$

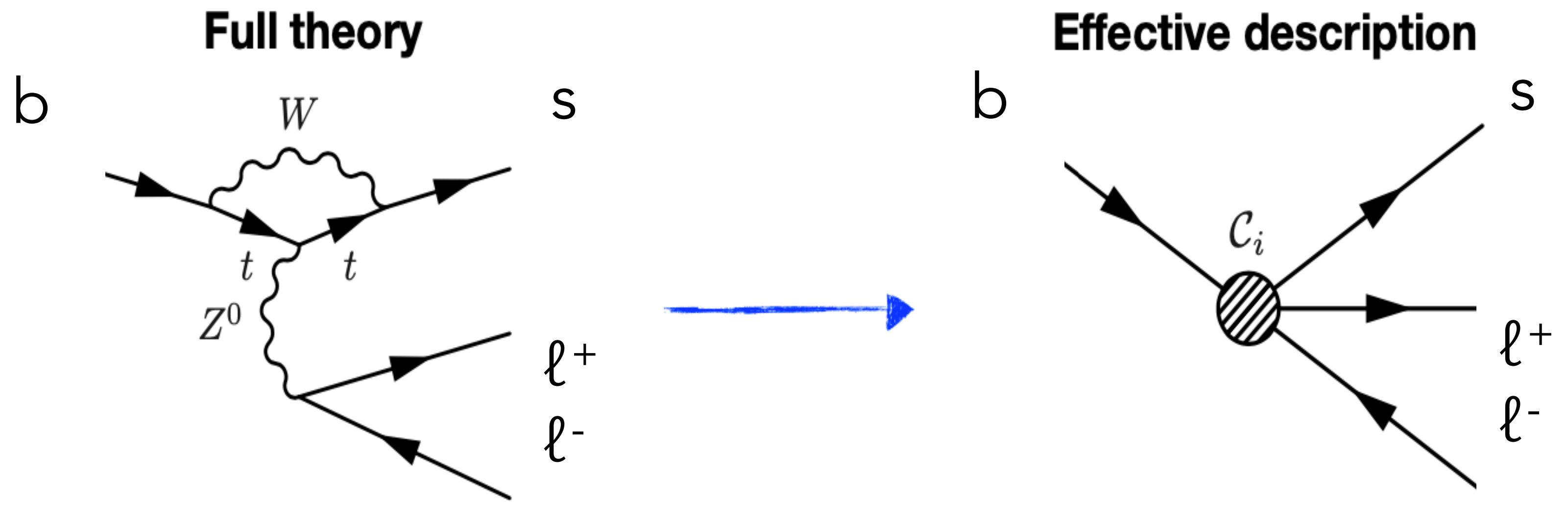
Assuming a coupling value one can say something on the scale of the heavy particle involved without detailed knowledge of them …

$$i\,\mathcal{A} = \frac{i\,g}{2M_W^2} V_{ud}^* (\bar{\nu}_l \gamma^\mu P_L \ell)(\bar{d}\gamma_\mu P_L u)$$

Effective coupling:
Wilson coefficient

low energy interaction
non-perturbative QCD etc …

Weak Effective Theory



W, Z, top, …
integrated out

~ Fermi's description of neutron β decay

$$\mathcal{L}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

$C_i^{(')} = C_i^{SM\,(')} + C_i^{NP\,(')}$ perturbative, contains the short distance physics. q^2 independent. Heavy NP

$O_i^{(')}$ non-perturbative, Lorentz structure, long distance physics.. q^2 dependent.

Which operators and Wilson coefficients ?

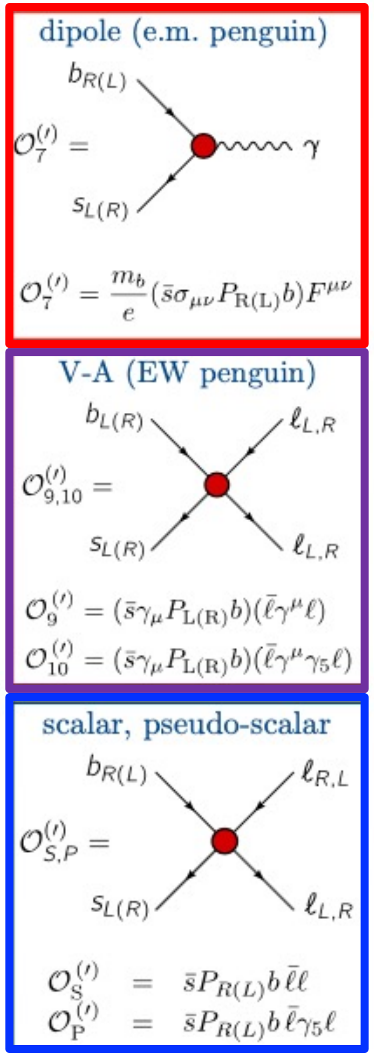
$O_7^{(')} \propto (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$

$O_9^{(')} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu l)$

$O_{10}^{(')} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{l}\gamma_\mu\gamma_5 l)$

$O_S^{(')} \propto (\bar{s}P_{L(R)}b)(\bar{l}l)$

$O_P^{(')} \propto (\bar{s}P_{L(R)}b)(\bar{l}\gamma_5 l)$



Coupling	$b \to s\gamma$	$b \to s\ell\ell$	$B \to \ell\ell$
$C_7^{(')}$	■	■	
$C_9^{(')}$		■	
$C_{10}^{(')}$		■	■
$C_S^{(')}$ & $C_P^{(')}$			■

A priori different for ℓ = e and $\ell=\mu$

Primed operators and Wilson Coefficients:
$P_L \to P_R$ and $m_b \to m_s$

In the SM

$\mathcal{O}_{7,9,10}$ (and $\mathcal{O}'_7$)

$$\mathcal{C}_7^{\rm SM}(\mu_b) = -0.29, \quad \mathcal{C}_9^{\rm eff\,SM}(\mu_b) = 4.1, \quad \mathcal{C}_{10}^{\rm SM}(\mu_b) = -4.3$$

$$\mathcal{C}_{7'}^{\rm SM}(\mu_b) \simeq -0.006$$

m_s/m_b suppression

$\mu_b = \mathcal{O}(m_b)$

if there is New Physics :

$$C_i = C_i^{SM} + C_i^{NP}$$

real — can be imaginary

- No need to specific a precise model (Leptoquark, Z ' , …)
- Approach working for heavy New Physics (> M_W)

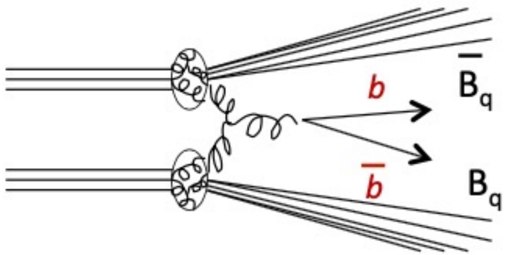
Experimental set-up

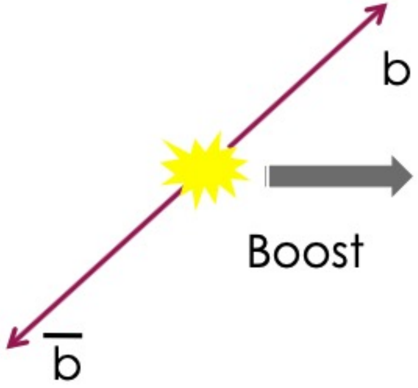
LHC:
- ATLAS, CMS & LHCb for $B_{s/d} \to \mu\mu$
- mostly LHCb for the rest except for some specific results

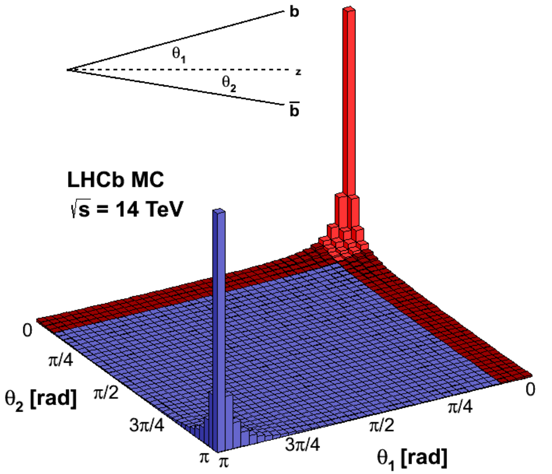
B-factories:
- BaBar and Belle: pioneering results but very statistically limited
- Belle-II integrated luminosity not yet large enough

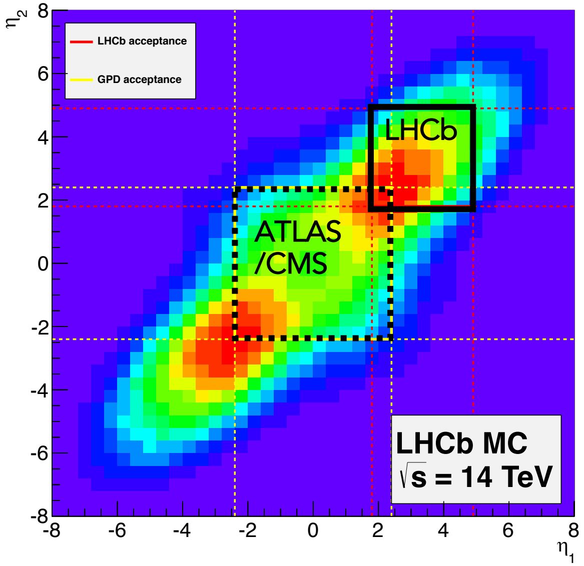
⇒few details on LHCb in the following slides

The b and $\bar{b}$ quarks are produced in the same direction, close to the beam axis

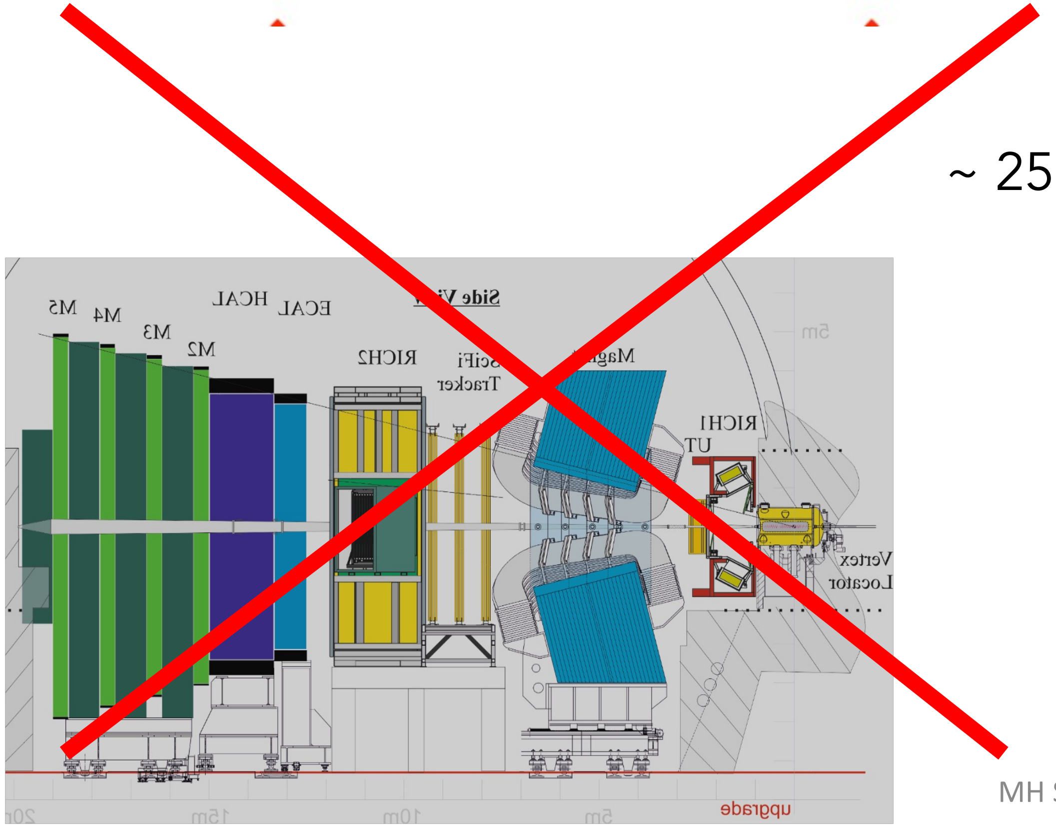


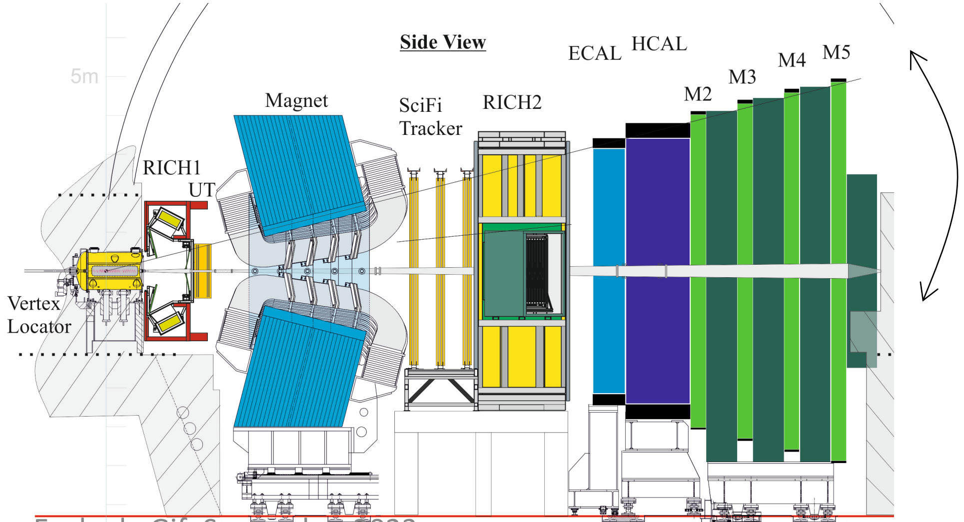






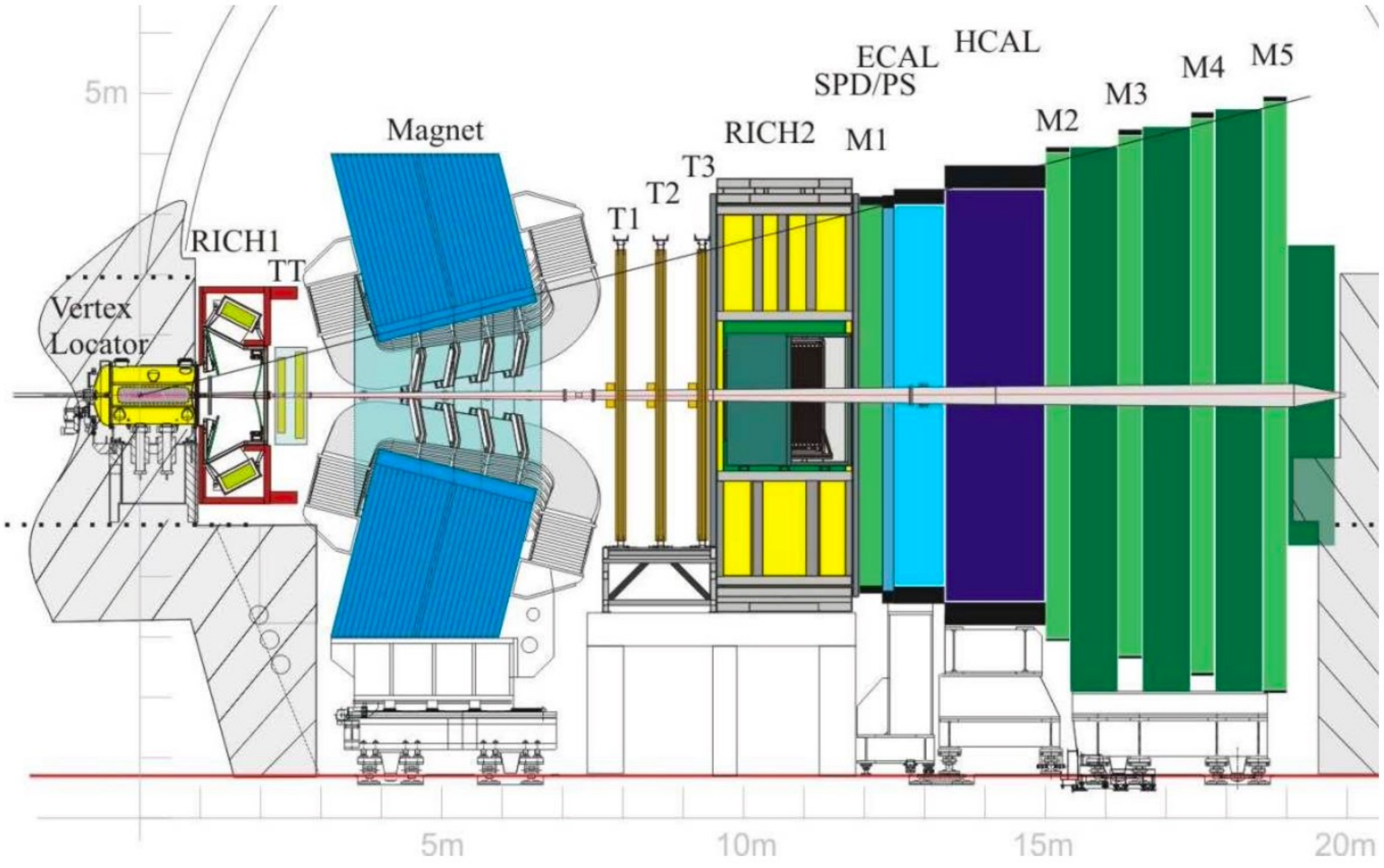
~ 25% of the $b\bar{b}$ production between 15 and 300 mrad





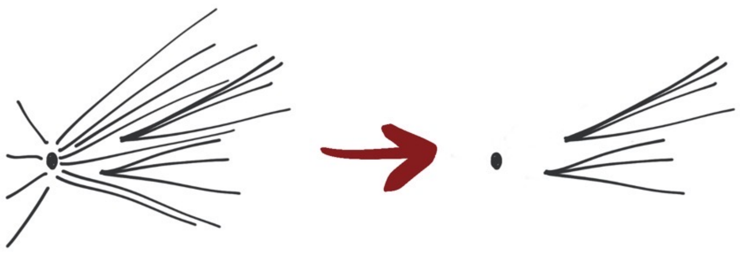
16 deg

Experimental set-up and datasets



$\Delta p / p = 0.5 - 1.0\%$

$\Delta IP = (15 + 29/p_T[GeV]) \mu m$



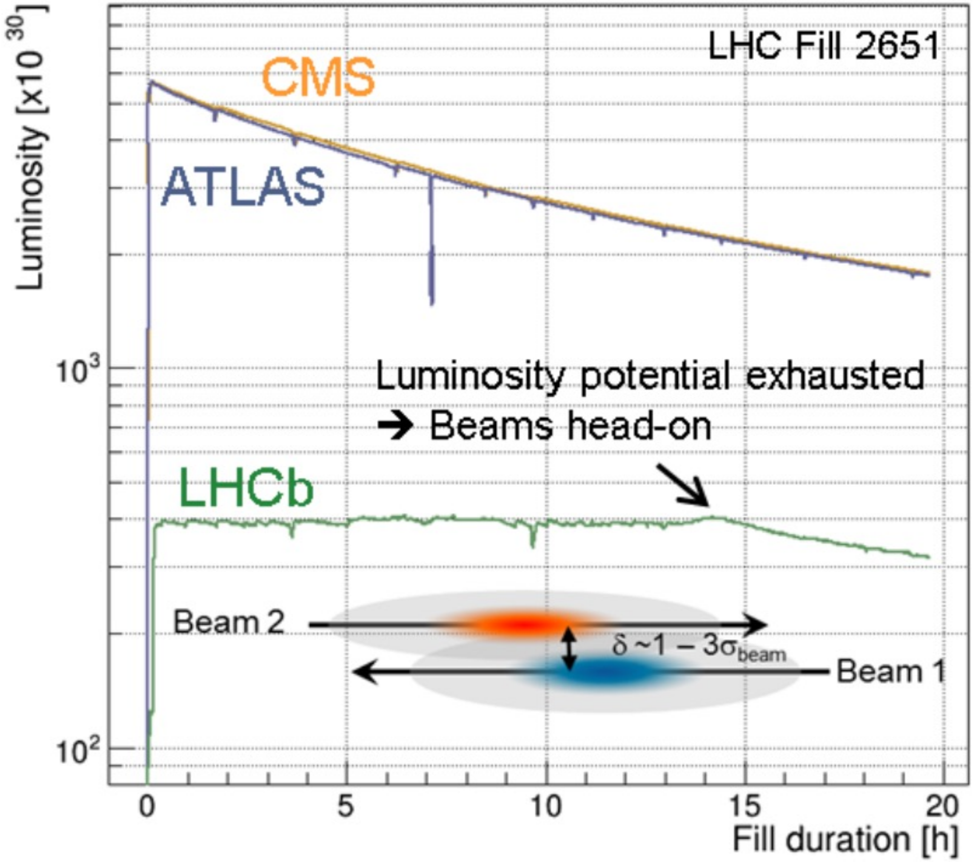
$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[GeV])}$

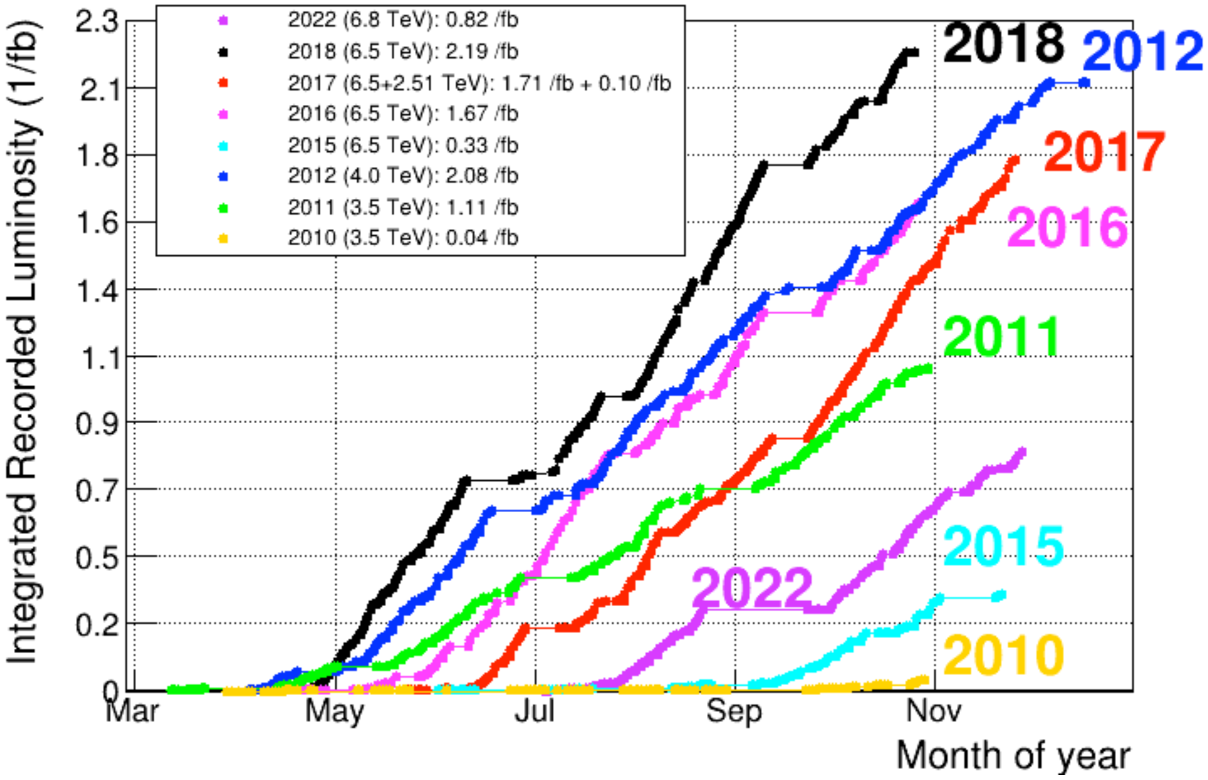
Electron ID ~90% for ~5% $h \to e^{\pm}$ mis-id probability

Muon ID ~ 97% for 1-3% $\pi \to \mu$ mis-id probability

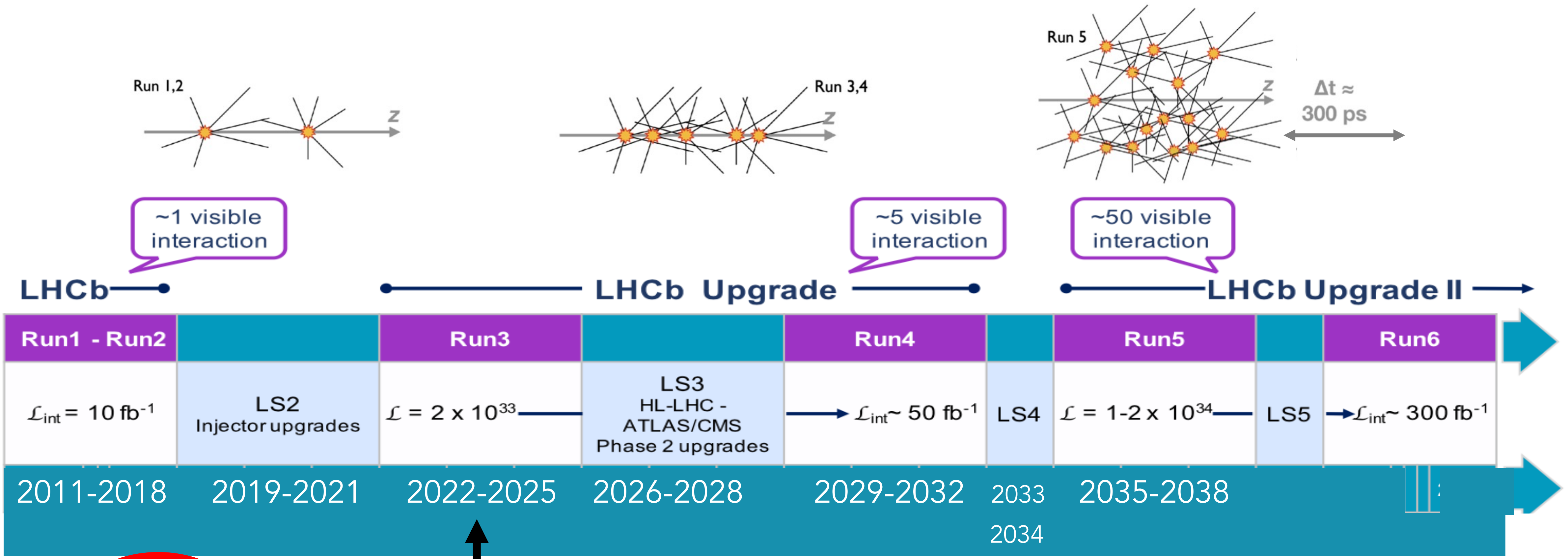
Run1 and Run2 data taking

- Running with luminosity levelling at 4. 10^{32} $cm^{-2}s^{-1}$ (x2 design luminosity)
- About 1.5 interaction per bunch crossing
- 9 fb^{-1} collected by LHCb





Schedule and datasets



9 fb^{-1}

the current results

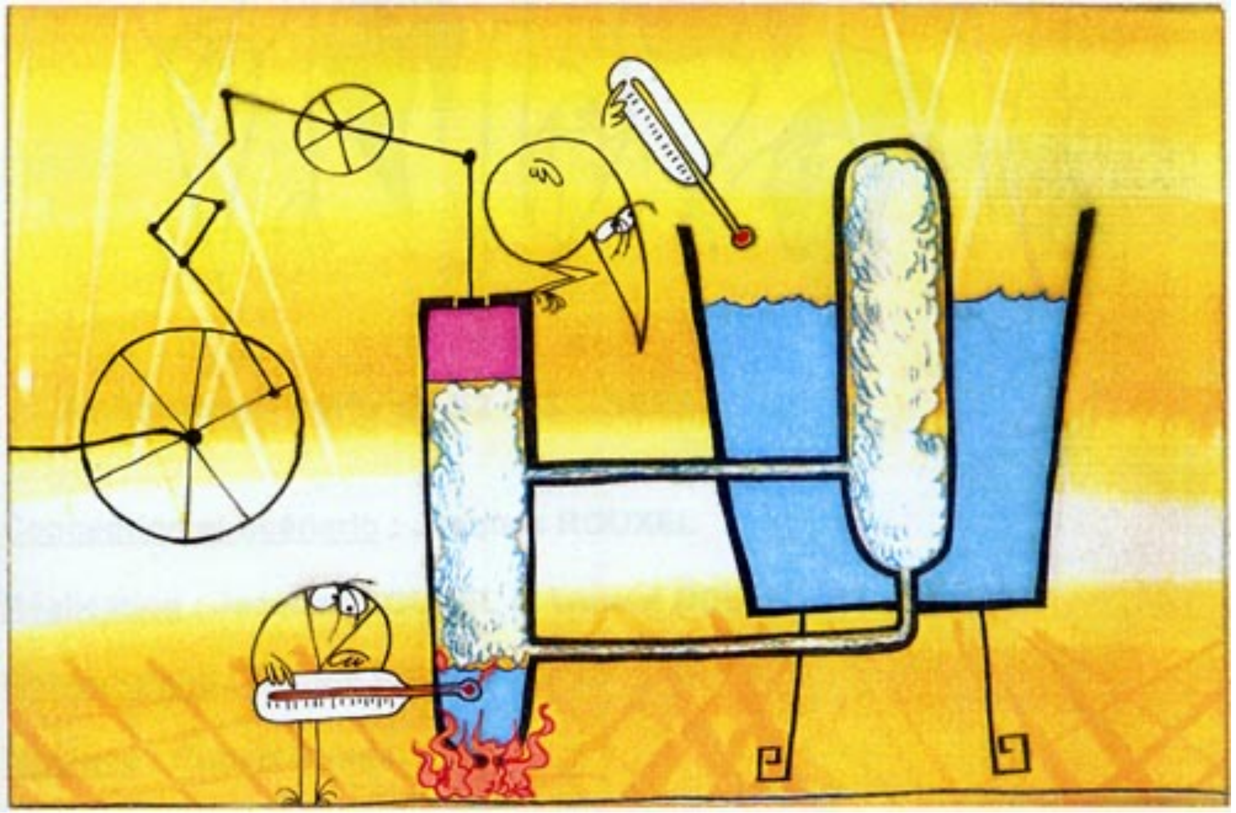
We are here, commissioning our new detector

23 fb^{-1}

50 fb^{-1}

~300 fb^{-1}

$B_{s/d} \longrightarrow \ell^+\ell^-$: what do we measure and how?



$B_{s/d} \to \ell^+\ell^-$ observables

Branching fraction in the SM:

$$\mathcal{B}(B_s^0 \to \ell^+\ell^-) = \frac{1 + y_s \mathcal{A}_{\Delta\Gamma}}{1 - y_s^2} \times \mathcal{B}(B_s^0 \to \ell^+\ell^-)_{t=0}$$

$$\mathcal{A}_{\Delta\Gamma} = \frac{\Gamma_{B^0_{s,H} \to \ell^+\ell^-} - \Gamma_{B^0_{s,L} \to \ell^+\ell^-}}{\Gamma_{B^0_{s,H} \to \ell^+\ell^-} + \Gamma_{B^0_{s,L} \to \ell^+\ell^-}}$$ =1 in the SM

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

$$\mathscr{B}(B_q^0 \to \mu^+\mu^-)_{SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{SM} V_{tb} V_{tq}^*|^2 f_{B_q}^2 m_{B_q} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_q}^2}} \frac{1}{1 - y_q} \qquad q = d, s$$

Only one Wilson Coeff.

hadronic parameter
Computed by LQCD, known to 0.5%

A precise measurement of the BF ⇒ constraint on C_{10}

Going beyond the SM:

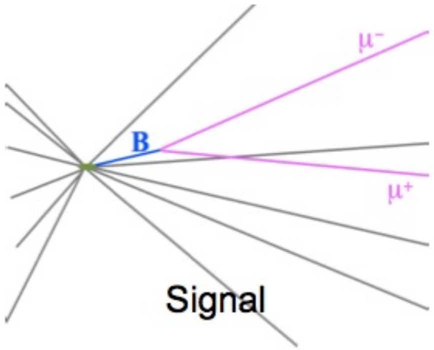
NP ?   NP ?

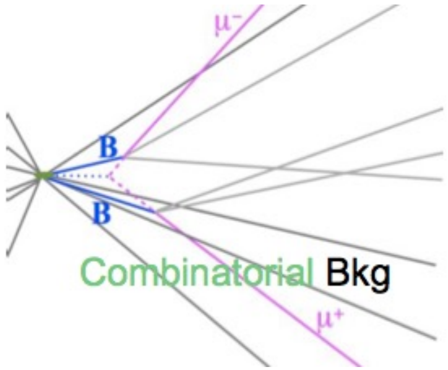
$$\mathcal{B}(\mathrm{B_s^0} \to \ell^+\ell^-) = \frac{1 + y_s \mathcal{A}_{\Delta\Gamma}}{1 - y_s^2} \times \mathcal{B}(\mathrm{B_s^0} \to \ell^+\ell^-)_{t=0}$$

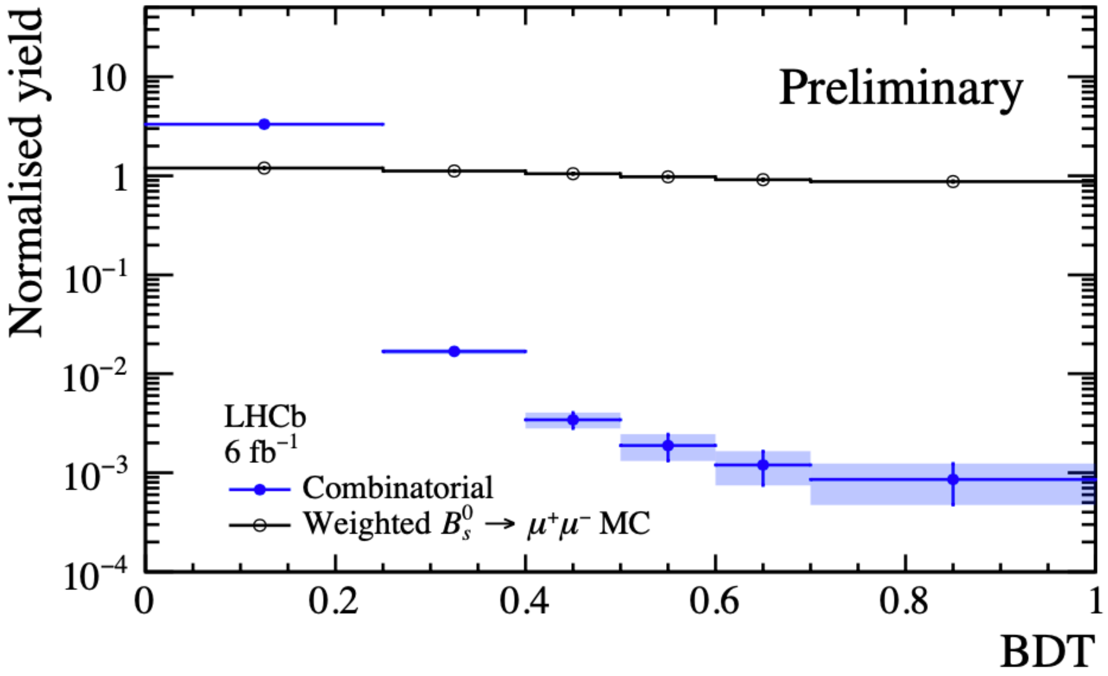
$$\mathcal{B}(\mathrm{B^0_{(s)}}(\mathrm{t}) \to \ell^+\ell^-)_{t=0} \propto \left(1 - \frac{4m_\ell^2}{m_\mathrm{B}^2}\right)|C_S - C_S'|^2 + \left|(C_P - C_P') + 2\frac{m_\ell}{m_\mathrm{B}^2}(C_{10} - C_{10}')\right|^2$$

Analysis in a nutshell

- Huge sample of B mesons
- Efficient trigger
- Powerful selection
  - Vertex resolution
  - Mass resolution
  - Muon ID
- BDT algorithm



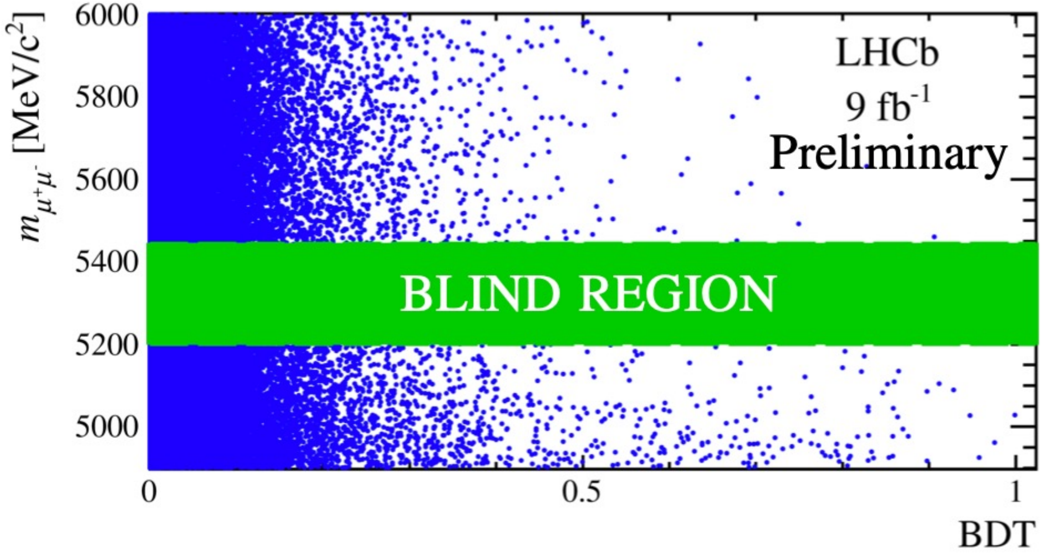




- Branching fraction estimated from a fit in 5 BDT bins (first one excluded since it's background dominated) and two run periods (Run1 & Run2)

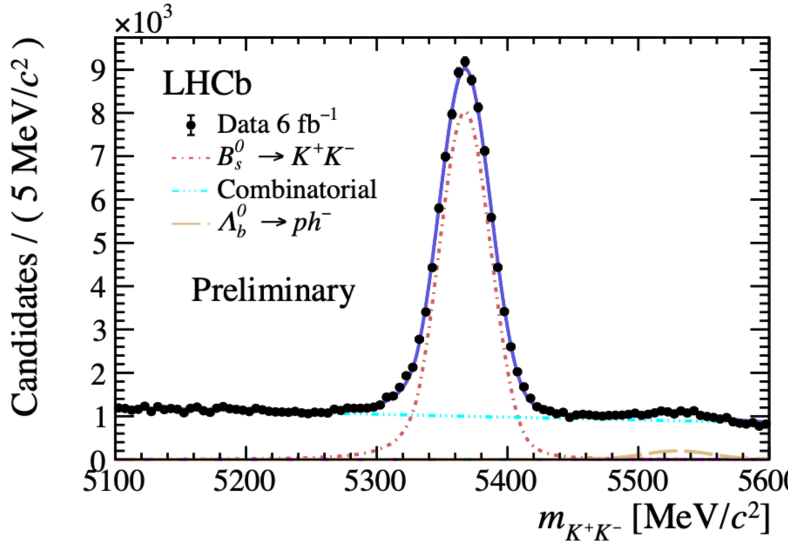
Select $M(\mu+\mu-) \in [4900,6000]$ MeV forming a displaced vertex

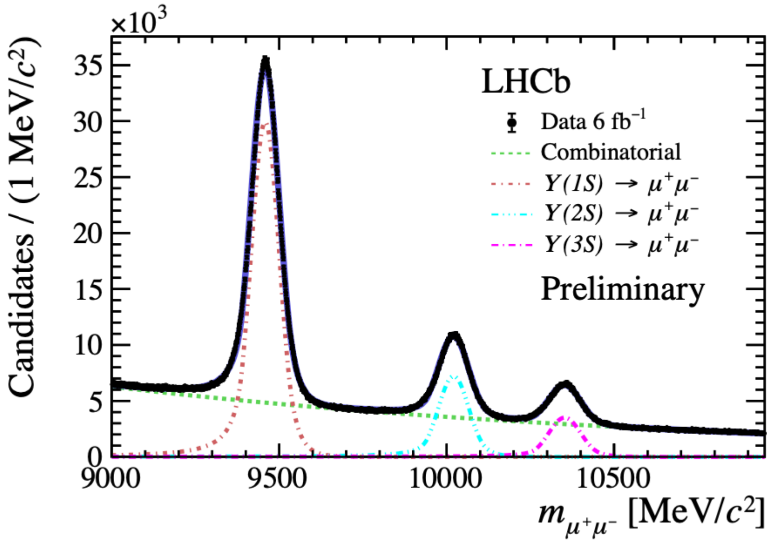
Signal mass region blinded



Signal shape: mass and resolution obtained from data

- The mean is obtained from $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$ data for $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$
- The resolution is interpolated from mass fits to $c\bar{c}$ and $b\bar{b}$ resonances: $\sigma_{m(\mu^+\mu^-)} = 21.96 \pm 0.63$ MeV (Run 2)

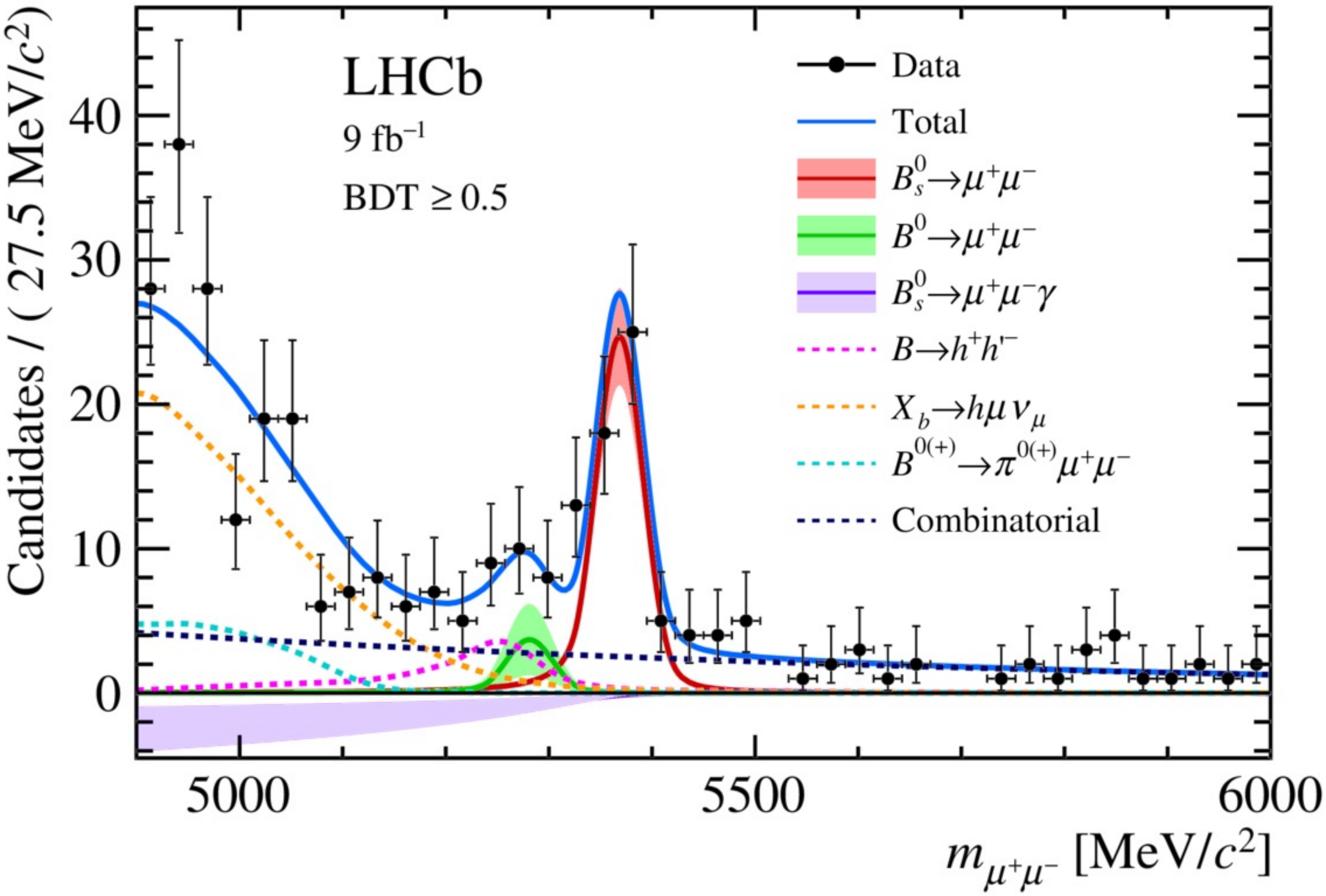




Expectations (from SM)

$N(B_s^0 \to \mu^+\mu^-)_{SM} = 147 \pm 8$

$N(B^0 \to \mu^+\mu^-)_{SM} = 16 \pm 1$


LHCb
9 fb^{-1}
BDT ≥ 0.5
Data
Total
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B_s^0 \to \mu^+\mu^-\gamma$
$B \to h^+h'^-$
$X_b \to h\mu\nu_\mu$
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$
Combinatorial
Candidates / (27.5 MeV/c^2)
$m_{\mu^+\mu^-}$ [MeV/c^2]

From a yield to a BR

Number of observed decay

Efficiency

$$BR(B_s \to \mu\mu) = \frac{N(B_s \to \mu\mu)_{real}}{N(B_s)_{produced}} = \frac{N(B_s \to \mu\mu)_{obs} / \varepsilon}{L_{\text{int}} \times \sigma_{bb} \times f_s}$$

Integrated luminosity

bb cross section

Fraction of b quarks that hadronize into a B_s

$L_{\text{int}}, \sigma_{bb}, \varepsilon$ have large systematic errors

Normalize with respect to another decay with a very well known BR (BFactories crucial inputs) :

$B^+ \to J/\psi K^+$ or $B^0 \to K^+\pi^-$

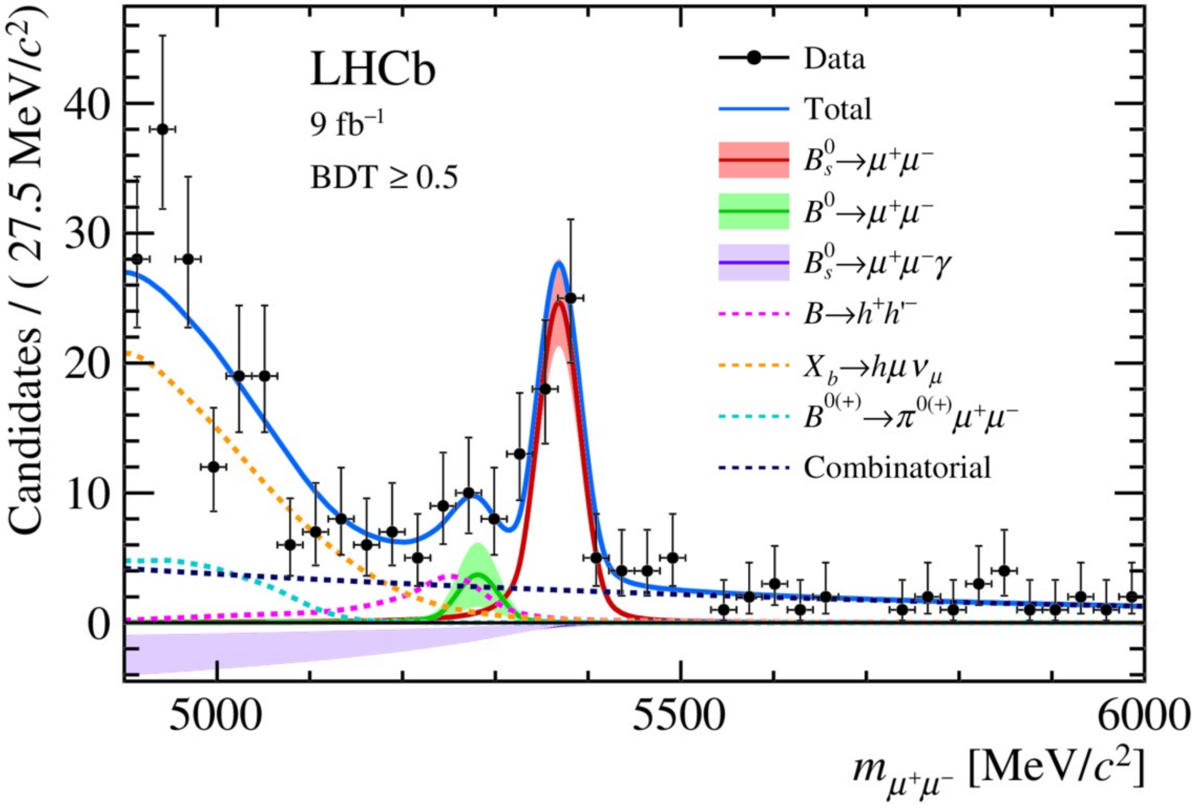
$$\frac{BR(B_s \to \mu\mu)}{BR(B^+ \to J\Psi K^+)} = \frac{N(B_s \to \mu\mu)_{obs}}{N(B \to J\Psi K)_{obs}} \times \frac{\varepsilon_{B \to J\Psi K}}{\varepsilon_{B_s \to \mu\mu}} \times \frac{f_u}{f_s}$$

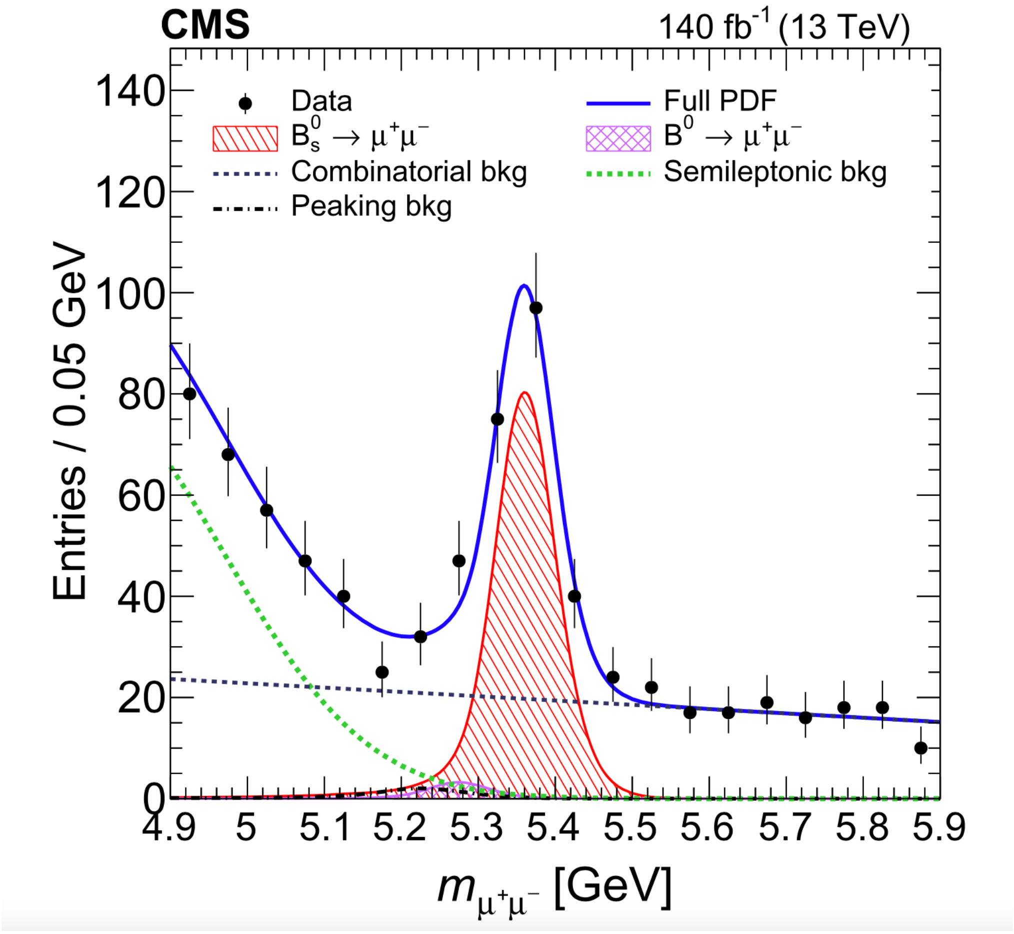
Most of systematic uncertainties cancel in the ratio of efficiency

This cancellation is very efficient if you have a normalization channel similar to your signal and selected in the same way!

Two most precise measurements: CMS & LHCb

https://doi.org/10.1016/j.physletb.2023.137955





LHCb-PAPER-2021-007

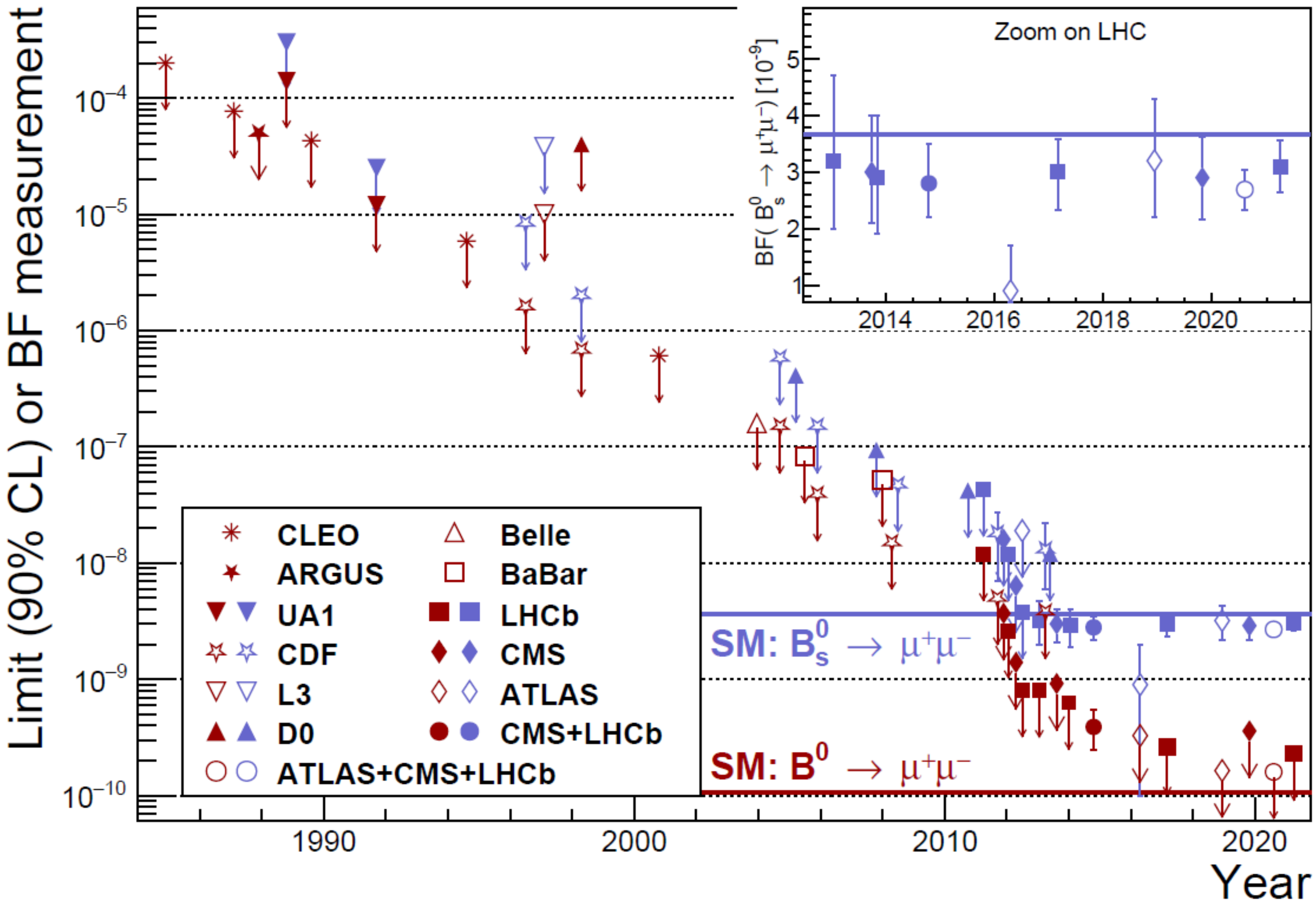
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$

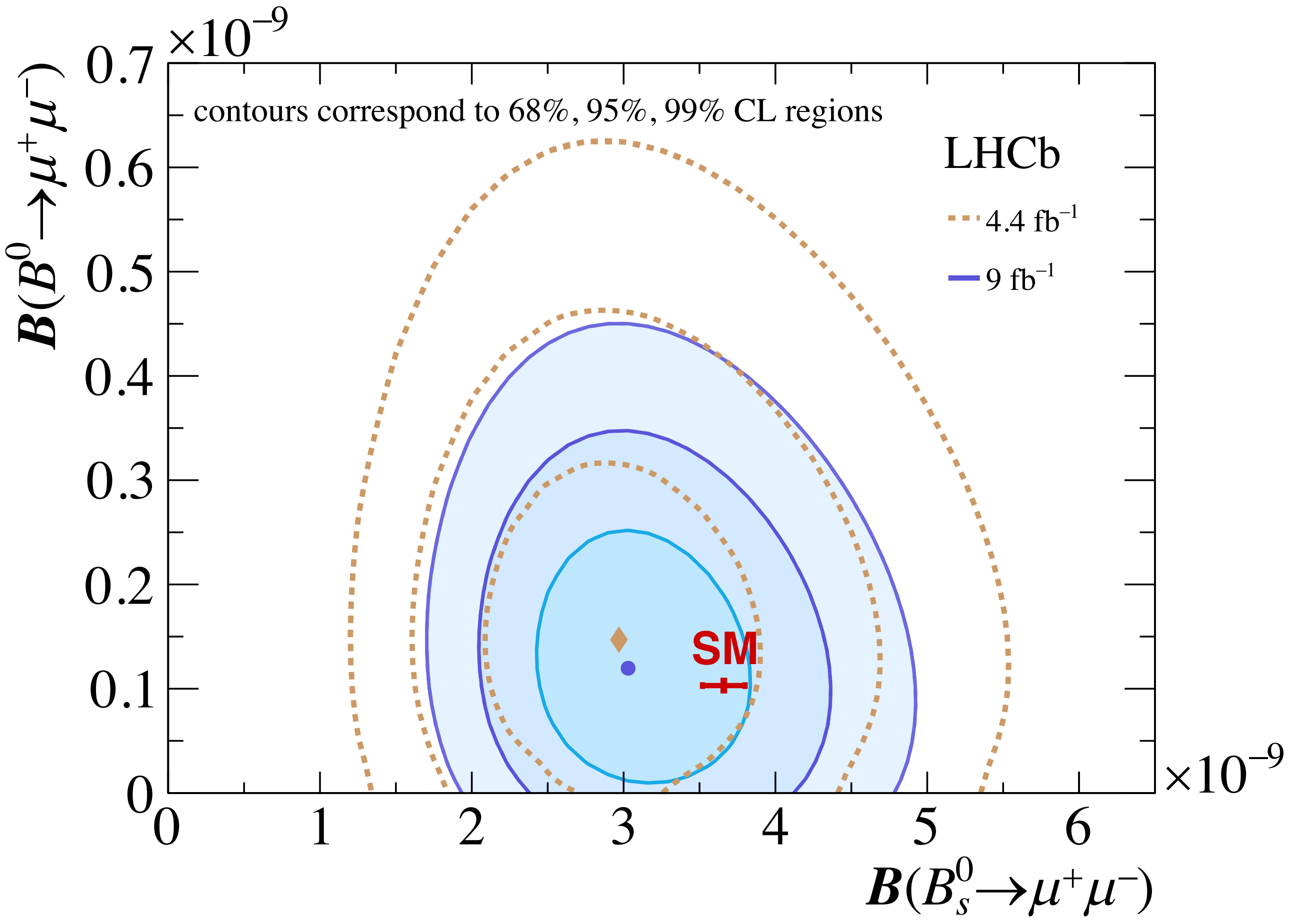
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$ @ 95 % CL

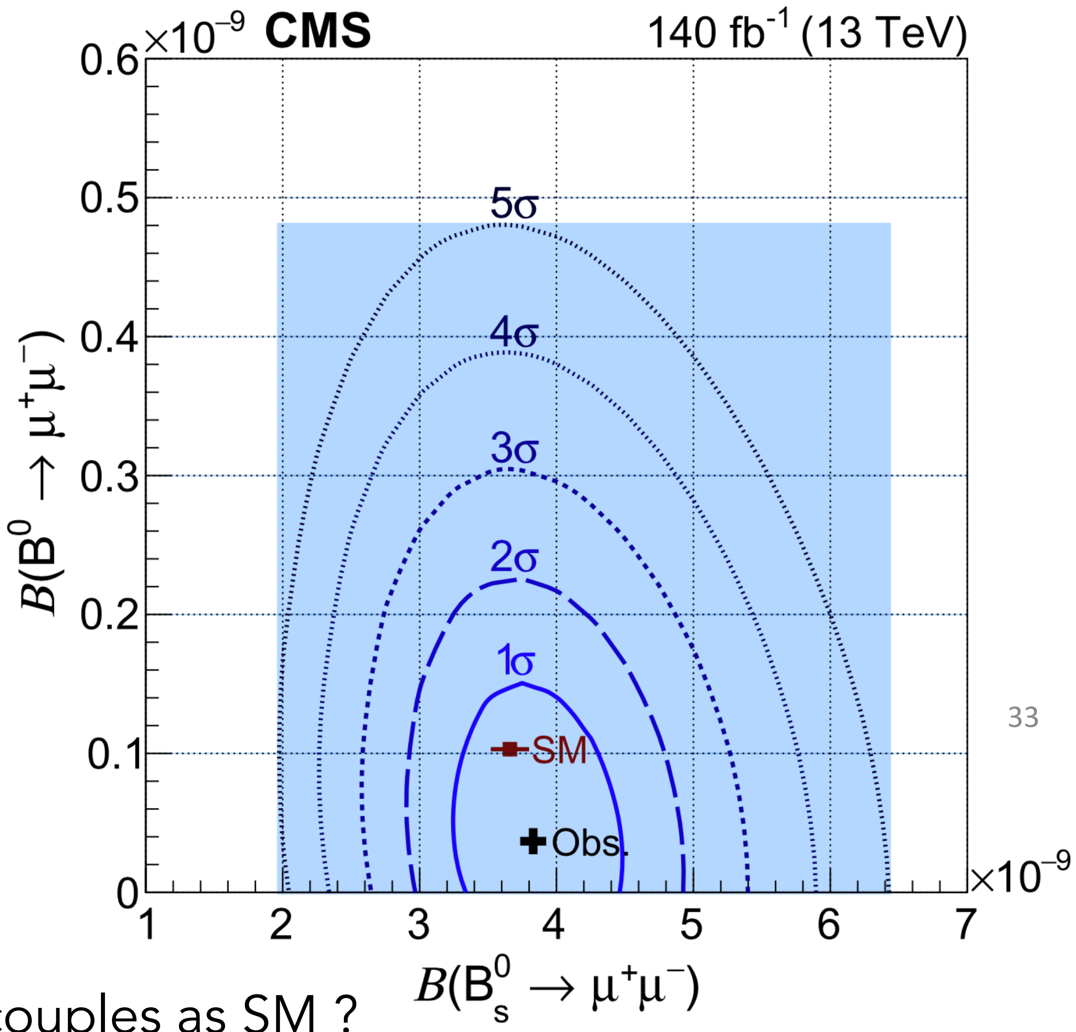
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL.}$$

Searched for during ~ 30 years. First evidence in Nov 2012 (LHCb)







Important to check B_d vs B_s : if there is New Physics does it couples as SM ?

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.52^{+0.32}_{-0.30} \times 10^{-9}$$

Combination from arXiv:2210.07221

SM-like given the current precision

$H_b \rightarrow H_s \ell^+ \ell^-$: what do we measure and how?

$H_b \rightarrow H_s \ell^+\ell^-$ observables

Branching Fractions

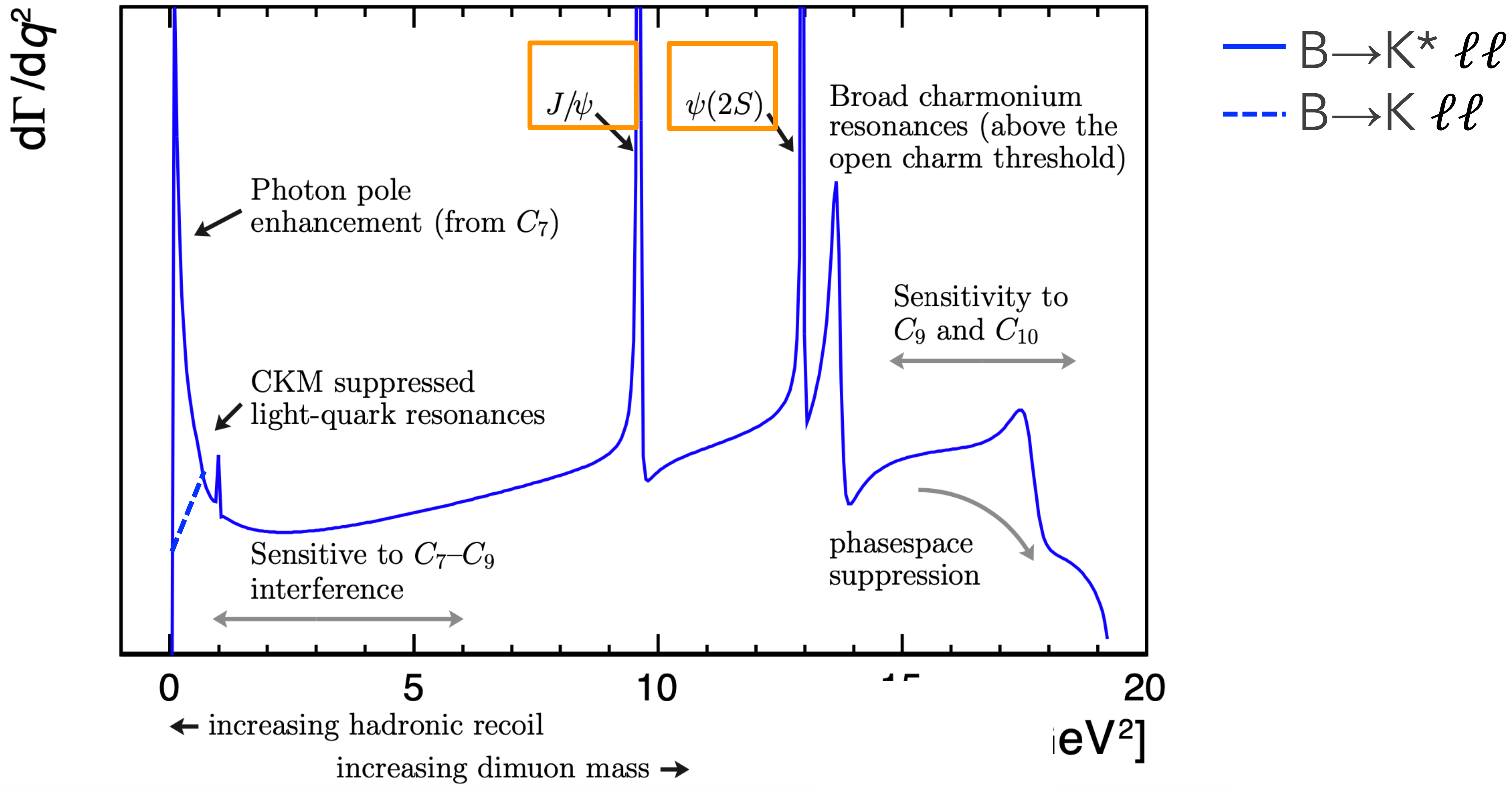
Angular observables

Lepton Flavour Universality observables:
Branching Fractions ratios
angular observables ratios

theoretical cleanness

there is no free lunch

resonant (control) modes



One example of a BF measurement: $B_s \to \phi\, \mu\, \mu$

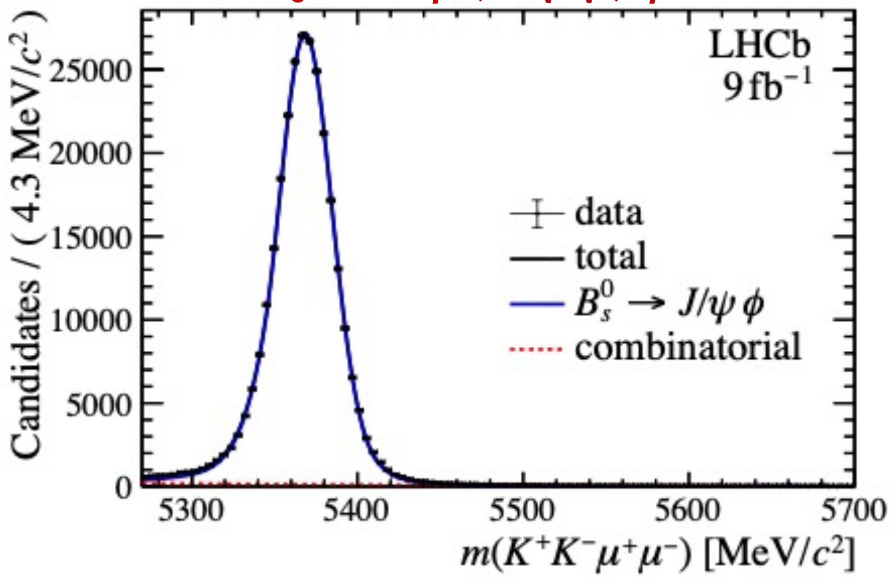
Experimentally 'easy' for LHCb
- two muons
- ϕ →KK and is a narrow resonance

Use of $B_s \to J/\psi\, (\to \mu\, \mu)\, \phi$ as a normalisation mode

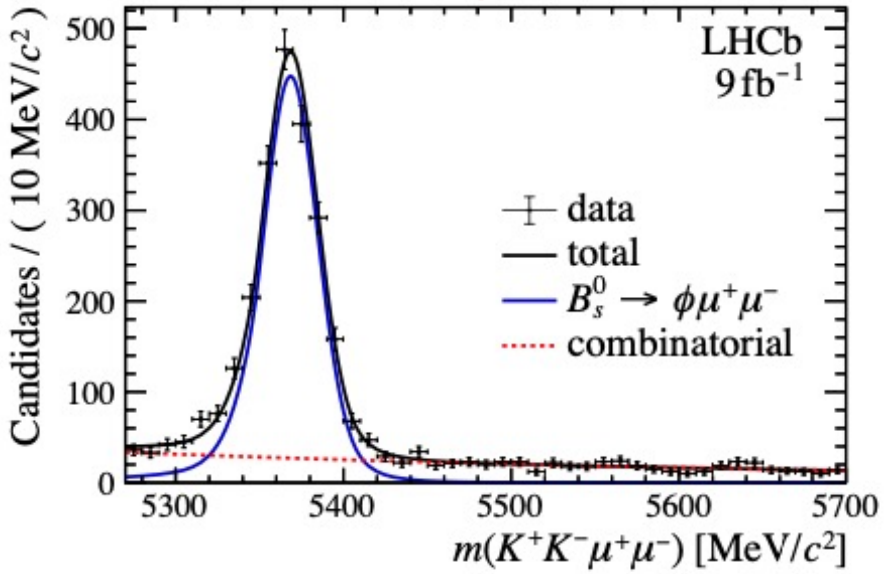
$$\mathcal{B}(B_s^0 \to J/\psi\phi) = (1.018 \pm 0.032 \pm 0.037) \times 10^{-3}$$

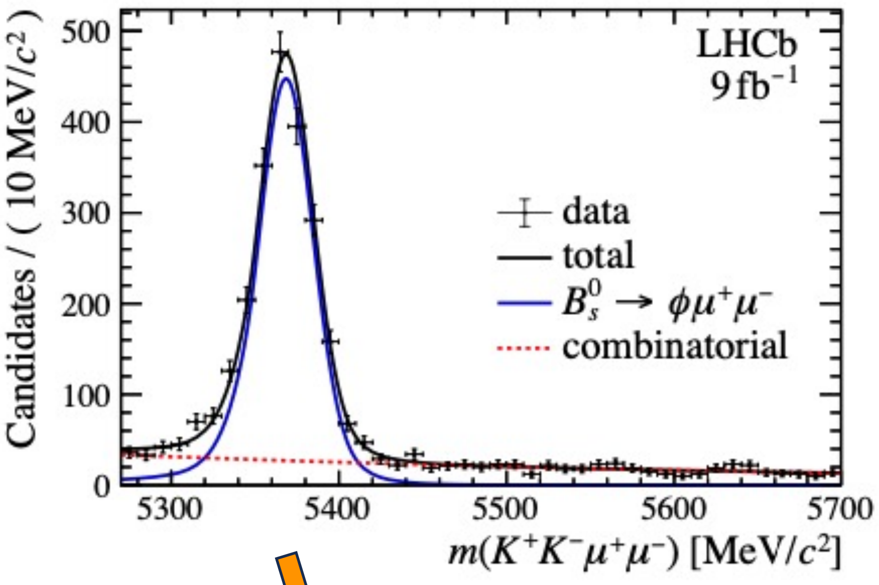
$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = \frac{\mathcal{B}(B_s^0 \to J/\psi\phi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{q^2_{\max} - q^2_{\min}} \times \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu^+\mu^-}}$$

$B_s \to J/\psi\, (\to \mu\, \mu)\, \phi$

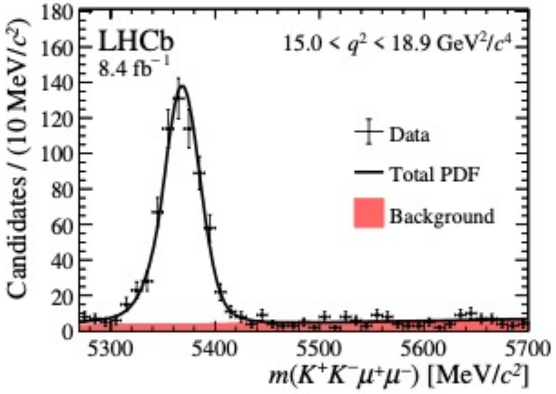


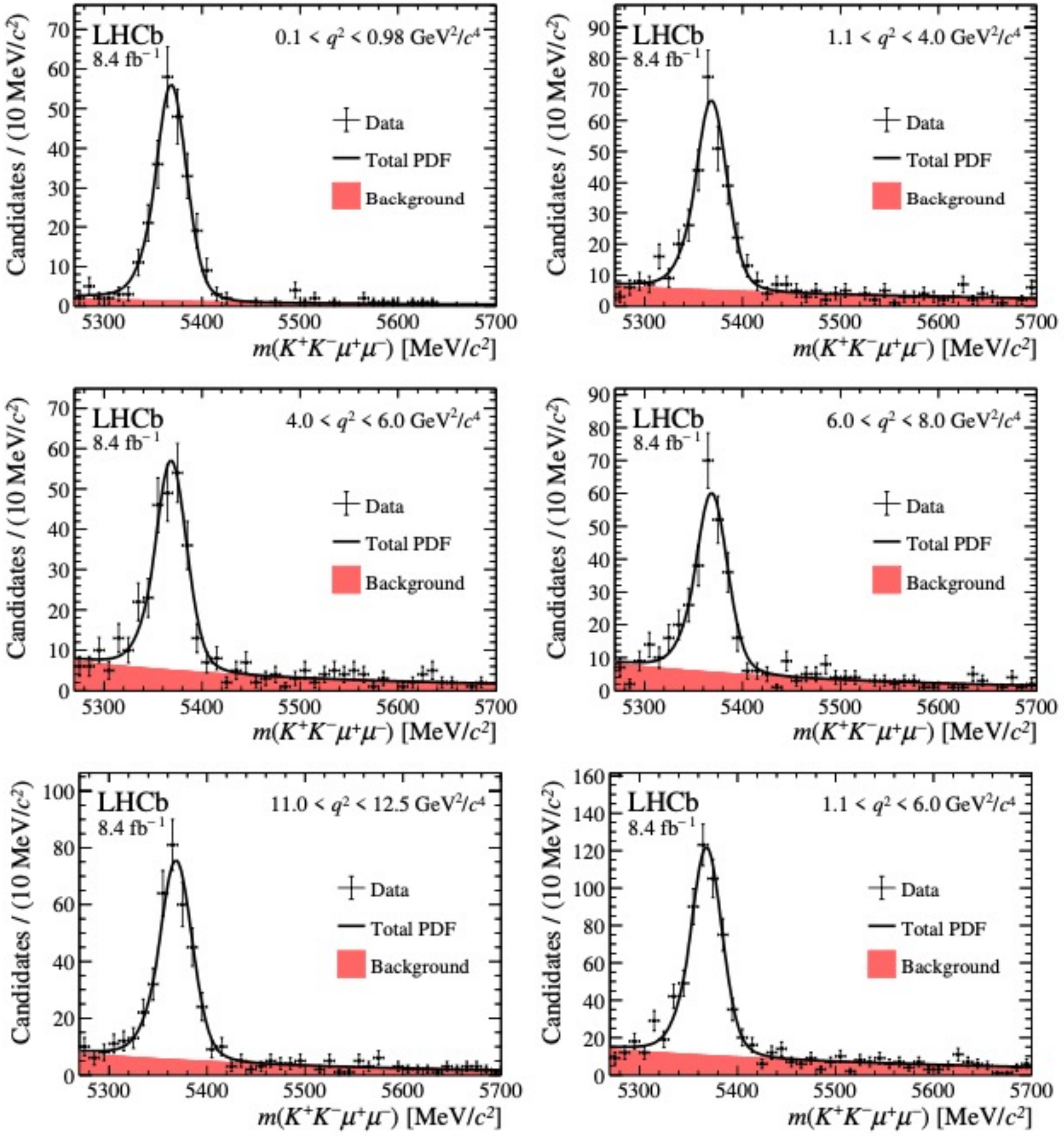
$B_s \to \phi\, \mu\, \mu$

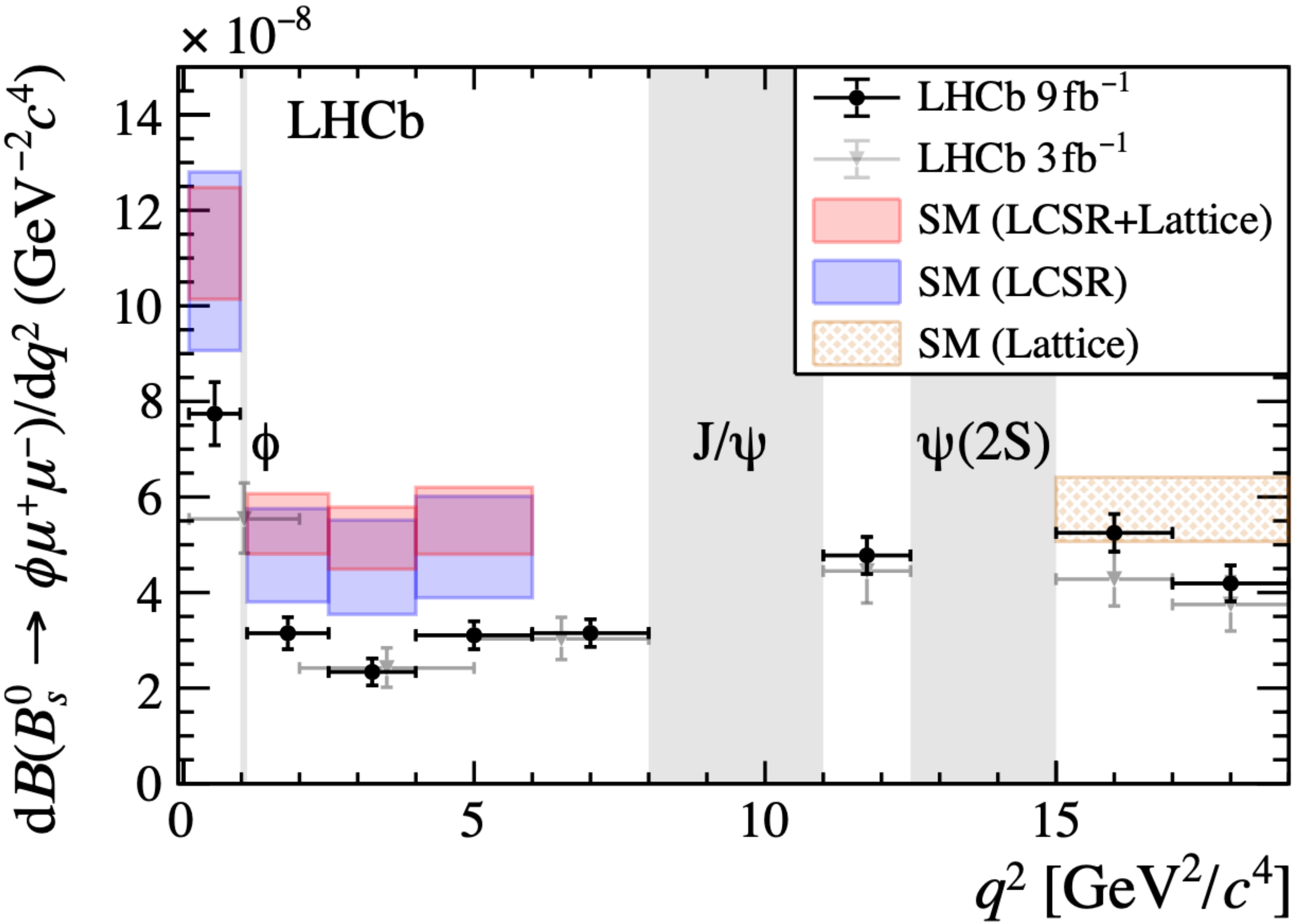




Split in 7 q^2 bins





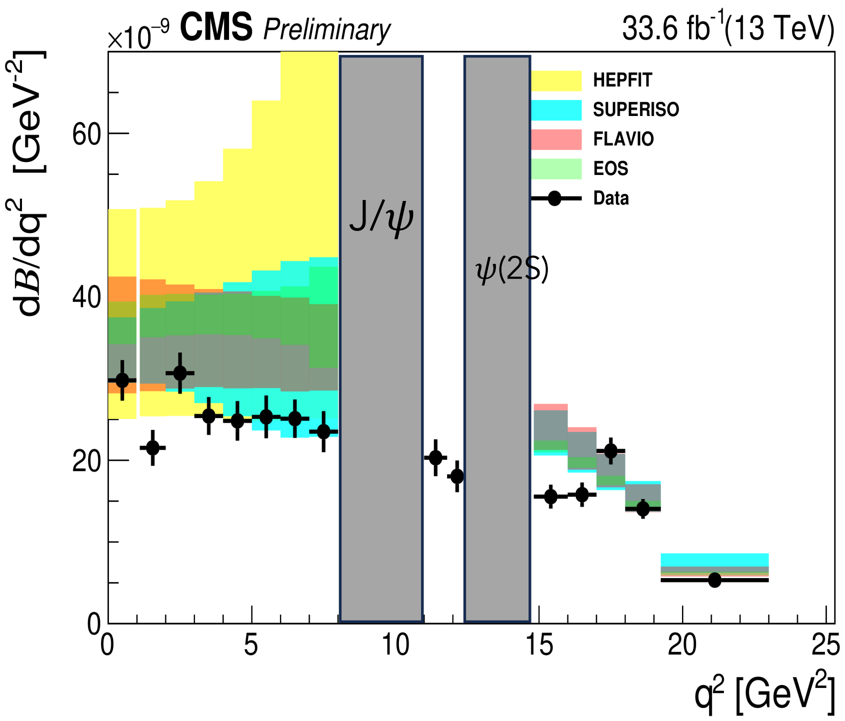


Measurements below predictions
Predictions correlated from a bin to another
Better agreement at higher-q^2 (LQCD)

Branching fractions for b→s $\mu\mu$ transitions

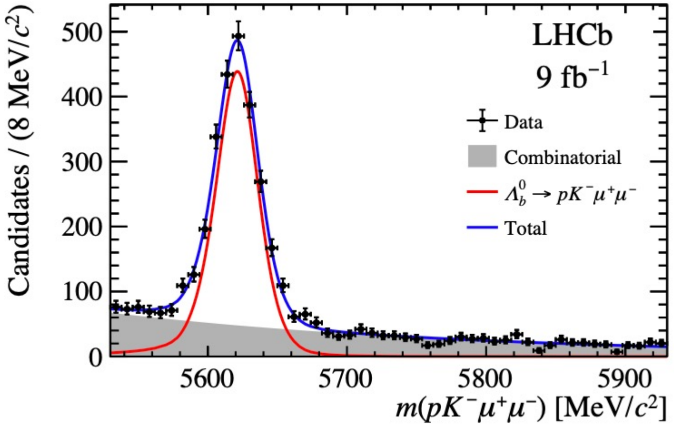
$B_d \to K^{*0}\, \mu\, \mu$

CMS-PAS-BPH-22-005

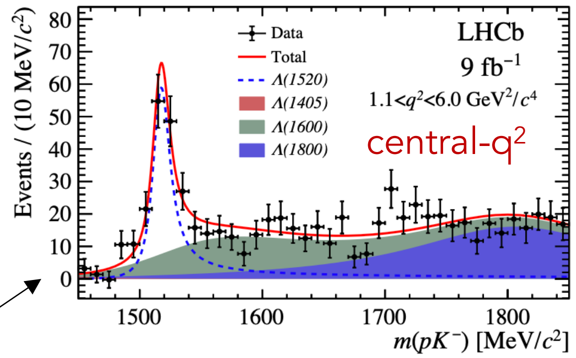


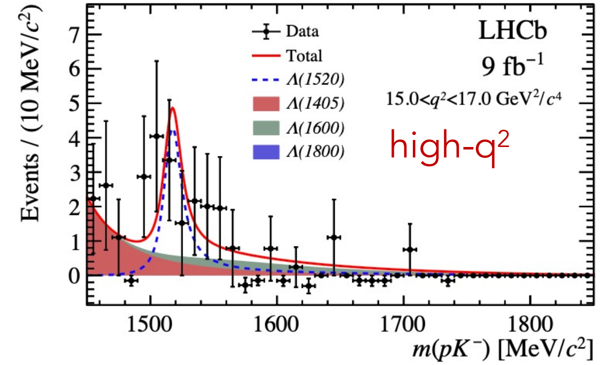
$\Lambda_b \to \Lambda(1520)\, \mu\mu$

arXiv:2302.08262

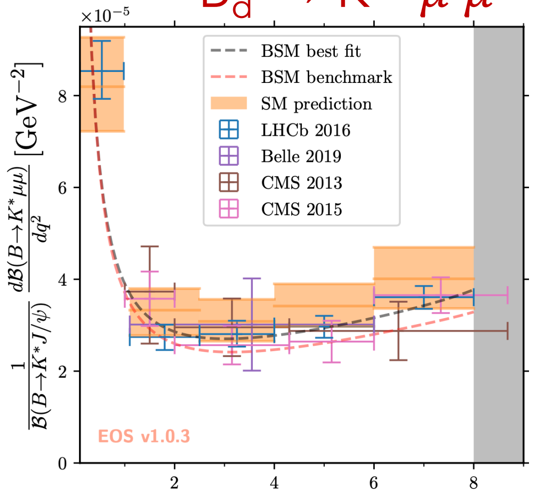


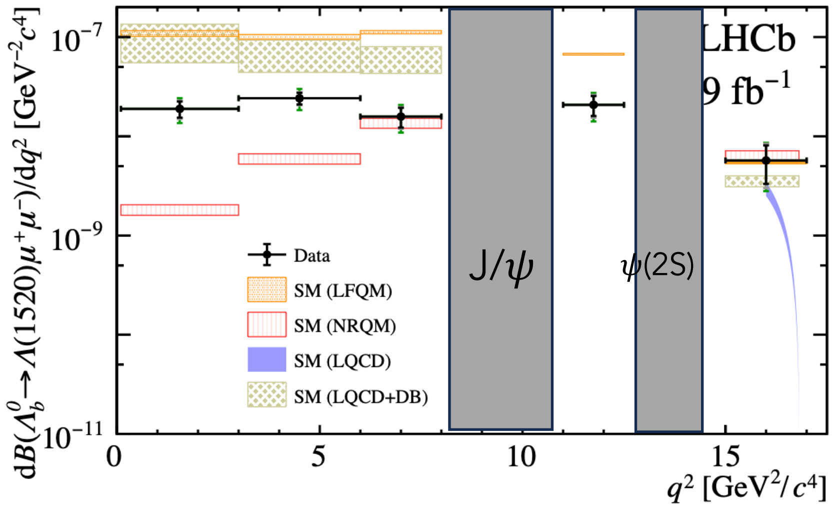
$N(\Lambda_b \to pK^-\mu^+\mu^-) = 2250 \pm 57\text{(stat)}$





$B_d \to K^{*0}\, \mu\, \mu$



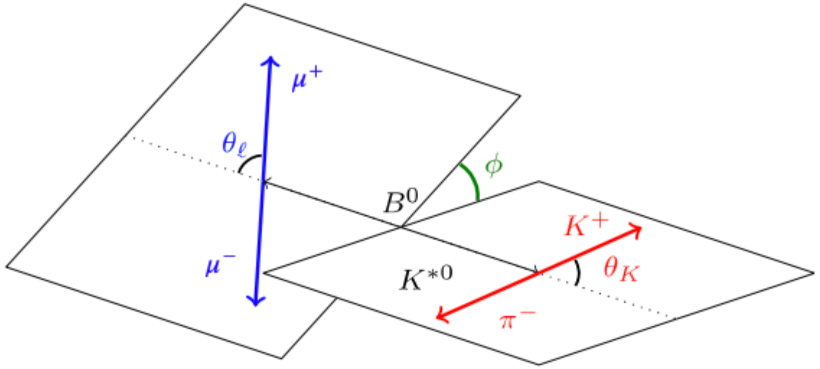


Very clean signal peaks
Measurements below predictions
Predictions correlated from a bin to another
Better agreement at higher-q² (LQCD)

To have more information: angular analyses

3 angles and $q^2 = M^2(\ell\ell)$

$B \to V \ell\ell$



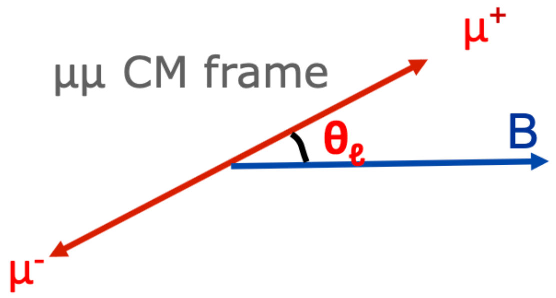
$\Lambda_b \to \Lambda^* \ell\ell$

$\Lambda_b \to \Lambda \ell\ell$

Assuming that the Λ_b is produced unpolarized at LHC

one angle and q^2

$B \to PS \ell\ell$



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

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

$$\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$$

I_i (i=1,9) are encoding the matrix elements of the decay

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K$$
$$+ I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi$$
$$+ I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell$$
$$+ I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi$$
$$+ I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$

The I_i depend on the amplitudes

$$I_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\mu^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right),$$

$$\beta_\mu = \sqrt{1 - 4m_\mu^2/q^2}.$$

=1 in most of the q^2 range

$$I_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\mu^2|A_S|^2,$$

$$I_2^s = \frac{\beta_\mu^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right],$$

$$I_2^c = -\beta_\mu^2\left[|A_0^L|^2 + (L\to R)\right],$$

$$I_3 = \frac{1}{2}\beta_\mu^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R)\right],$$

$$I_4 = \frac{1}{\sqrt{2}}\beta_\mu^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*}) + (L\to R)\right],$$

$$I_5 = \sqrt{2}\beta_\mu\left[\mathrm{Re}(A_0^L A_\perp^{L*}) - (L\to R) - \frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^R A_S^*)\right]$$

$$I_6^s = 2\beta_\mu\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*}) - (L\to R)\right],$$

$$I_6^c = 4\beta_\mu\frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}\left[A_0^L A_S^* + (L\to R)\right],$$

$$I_7 = \sqrt{2}\beta_\mu\left[\mathrm{Im}(A_0^L A_\parallel^{L*}) - (L\to R) + \frac{m_\mu}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* + A_\perp^R A_S^*)\right]$$

$$I_8 = \frac{1}{\sqrt{2}}\beta_\mu^2\left[\mathrm{Im}(A_0^L A_\perp^{L*}) + (L\to R)\right],$$

$$I_9 = \beta_\mu^2\left[\mathrm{Im}(A_\parallel^{L*} A_\perp^L) + (L\to R)\right].$$

0, L, R K* transversity

Do not pay too much attention to the details and using EFT one can write the amplitudes:

Wilson Coefficient

FF, q^2 dependent

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\left[\left[(C_9^{\text{eff}} + C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} + C_{10}^{\text{eff}\prime})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7^{\text{eff}\prime})T_1(q^2)\right]$$

$$A_{\parallel L,R} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left[\left[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime})\right]\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} - C_7^{\text{eff}\prime})T_2(q^2)\right],$$

photon pole

$$A_{0L,R} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(C_9^{\text{eff}} - C_9^{\text{eff}\prime}) \mp (C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime})\right] \times \left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\right] + 2m_b(C_7^{\text{eff}} - C_7^{\text{eff}\prime})\left[(m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\right]\right\}$$

$$A_t = \frac{N}{\sqrt{q^2}}\lambda^{1/2}\left[2(C_{10}^{\text{eff}} - C_{10}^{\text{eff}\prime}) + \frac{q^2}{m_\mu}(C_P - C_P')\right]A_0(q^2),$$

$$A_S = -2N\lambda^{1/2}(C_S - C_S')A_0(q^2),$$

$$N = V_{tb}V_{ts}^*\left[\frac{G_F^2\alpha^2}{3\cdot 2^{10}\pi^5 m_B^3}q^2\lambda^{1/2}\beta_\mu\right]^{1/2},$$

with $\lambda = m_B^4 + m_{K^*}^4 + q^4 - 2(m_B^2 m_{K^*}^2 + m_{K^*}^2 q^2 + m_B^2 q^2)$ and $\beta_\mu = \sqrt{1 - 4m_\mu^2/q^2}$.

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K$$
$$+ I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi$$
$$+ I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell$$
$$+ I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi$$
$$+ I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$

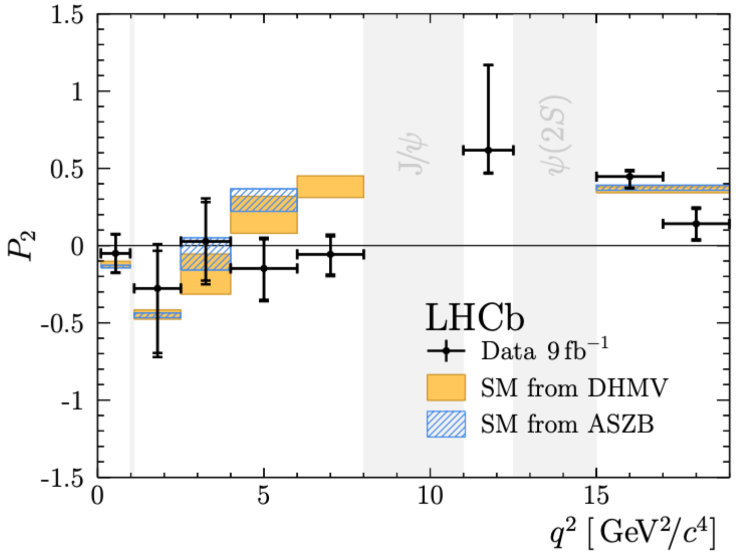
The $C^{(\prime)}_{7..10}$ are encoded in the $I_{i=1,..9}$

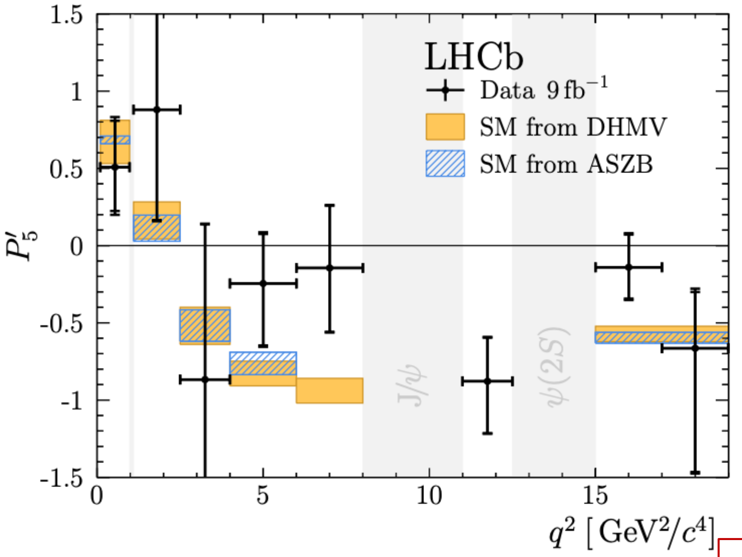
Ratios of I_i can be built to remove FF dependence

Many parameters extracted in a large number of bins

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

[Phys. Rev. Lett.126 (2021) 161802]





Optimized variables
(less FF dependent)

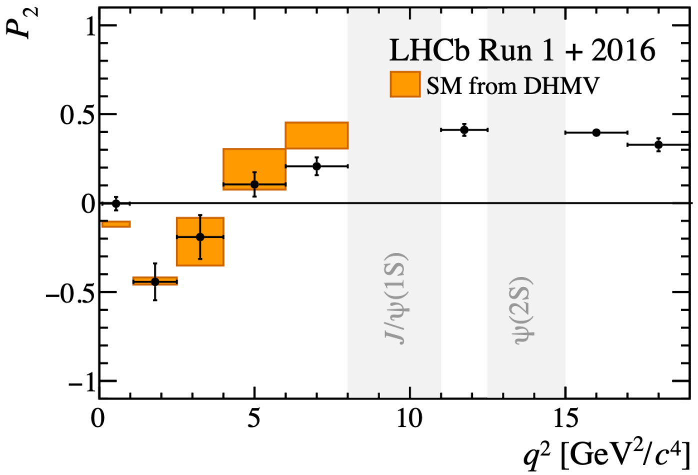
$$P_2 = \tfrac{2}{3} A_{\mathrm{FB}}/(1 - F_{\mathrm{L}})$$

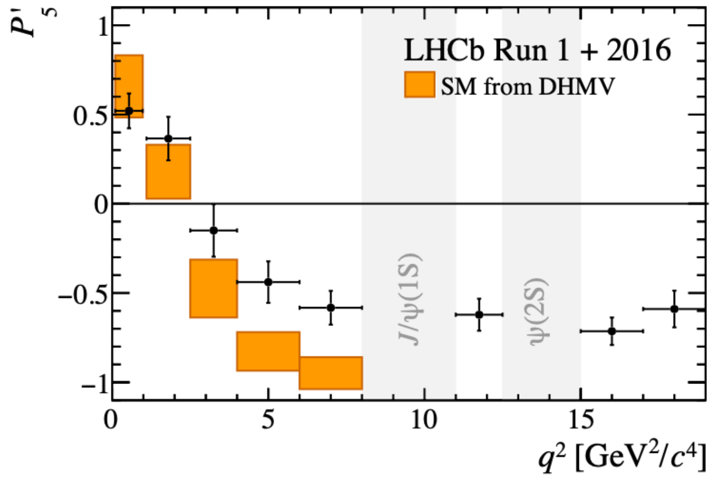
$$P_5' = S_5/\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}$$

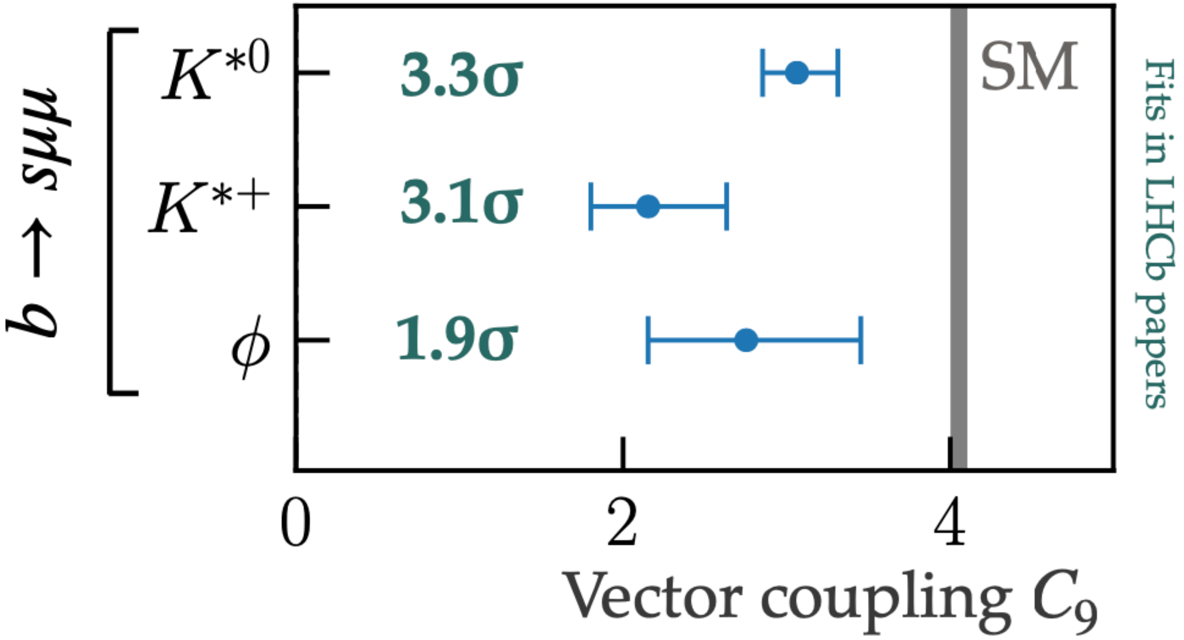
$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}} A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}} A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

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

[Phys. Rev. Lett. 125 (2020) 011802]





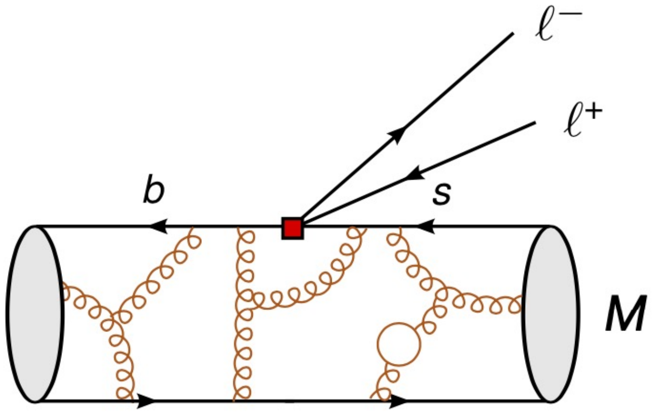


From Martino Borsato (SUSY2022)

?

Life is not that simple …

$$\mathcal{L}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_{i=7,9,10} (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$



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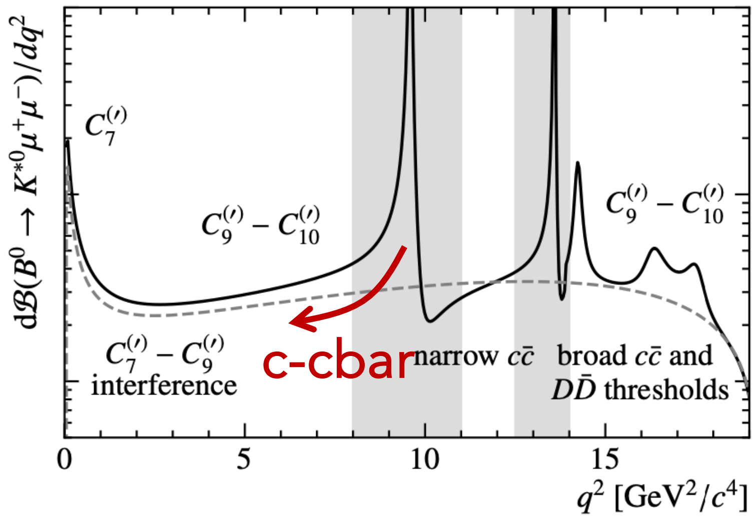
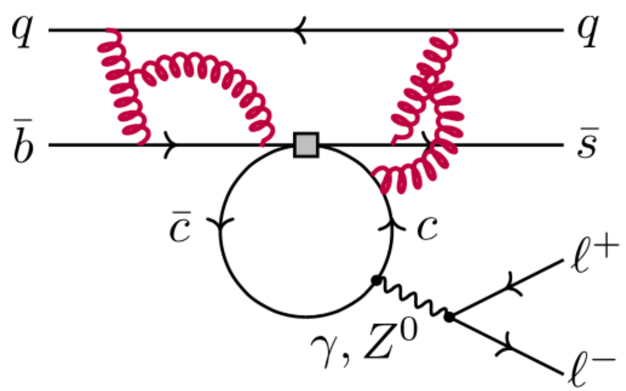


non-local contributions



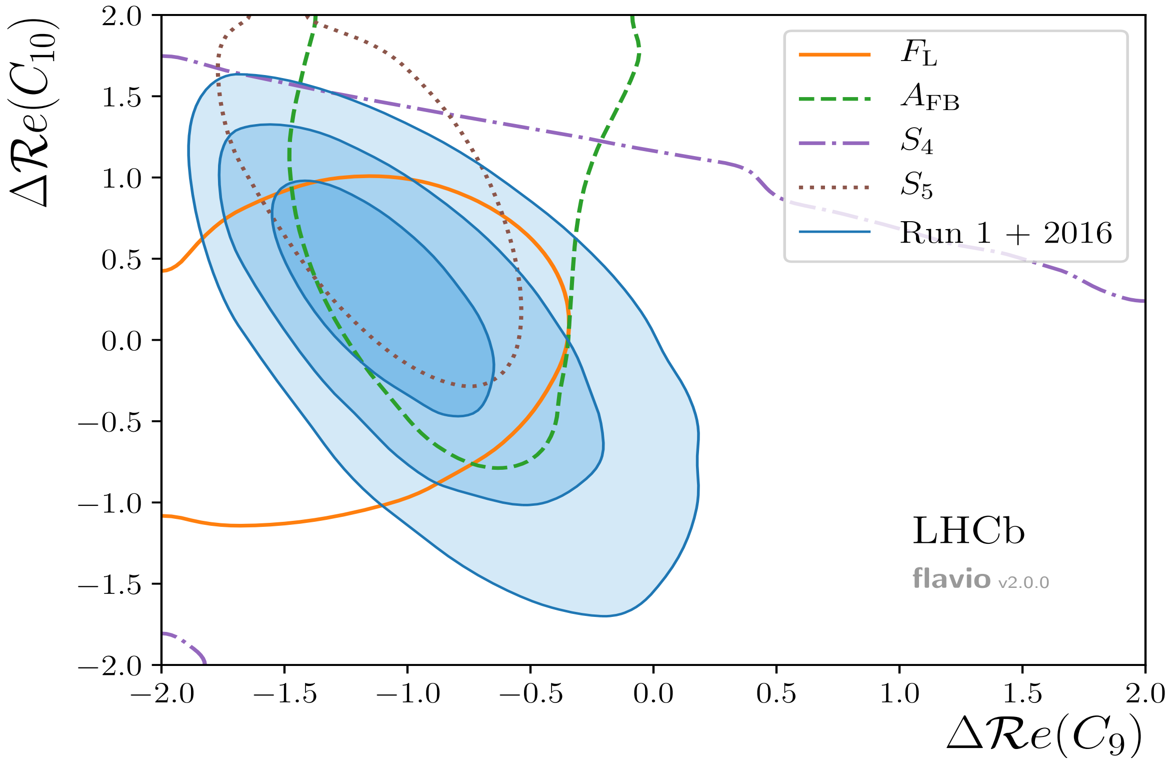
Would appear as a shift in C_9
Varying as function of q^2 (not the case for NP)

$$C_i = C_i^{SM} + C_i^{NP}$$

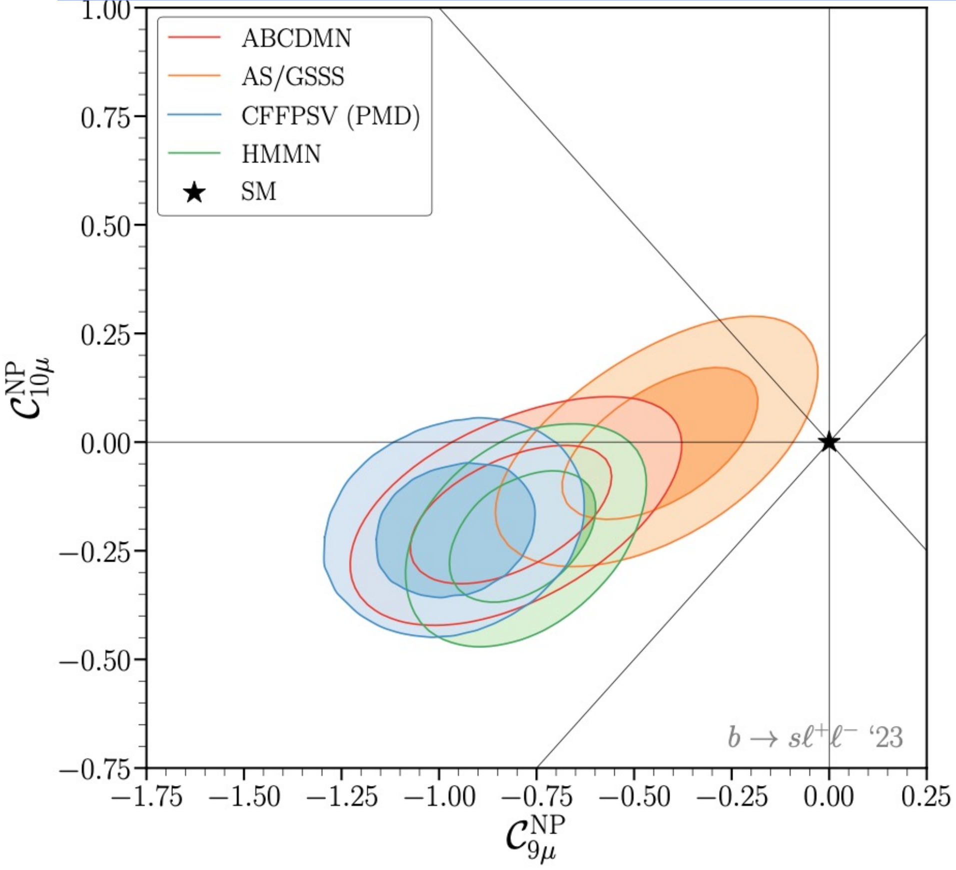
- In the SM Wilson coefficients are real, no necessarily the case for New Physics
- Many parameters fit… reduced configurations
- Several fitters, they differs by:
  - Choice of experimental inputs
  - Form factors modelling
  - Treatment on non-local nuisance parameters
  - Statistical frameworks

B→ K*μμ alone

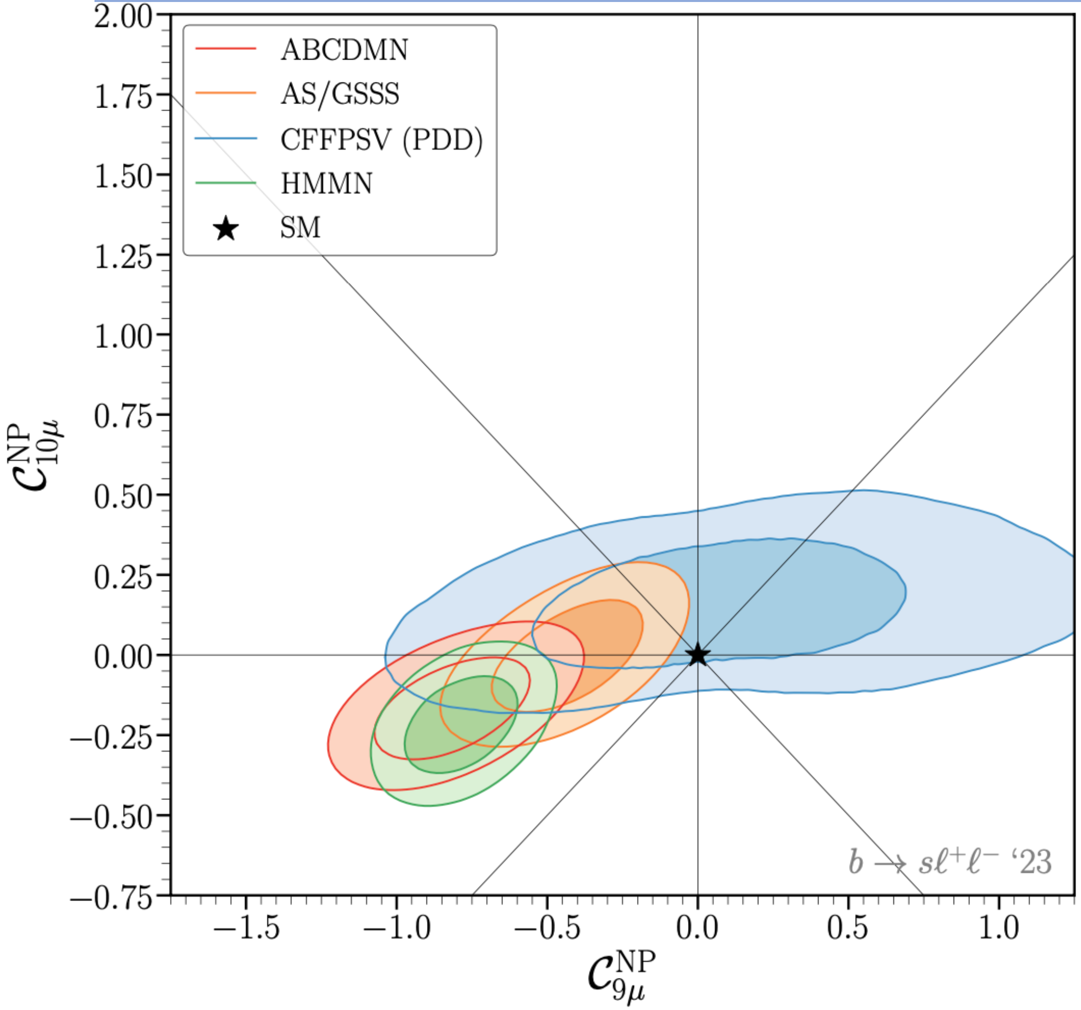
PRL. 125 (2020) 011802



with TH input for the non-local contributions



No TH input for the non-local contributions



- ABCDMN (M. Algueró, A. Biswas, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code arXiv:2304.07330
- AS / GSSS (W. Altmannshofer, P. Stangl / A. Greljo, J. Salko, A. Smolkovic, P. Stangl)
  Statistical framework: χ^2-fit, based on public code `flavio` arXiv:2212.10497.
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code `HEPfit` arXiv:2212.10516
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code `SuperIso` arXiv:23xx.xxxxx

From B. Capdevila
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