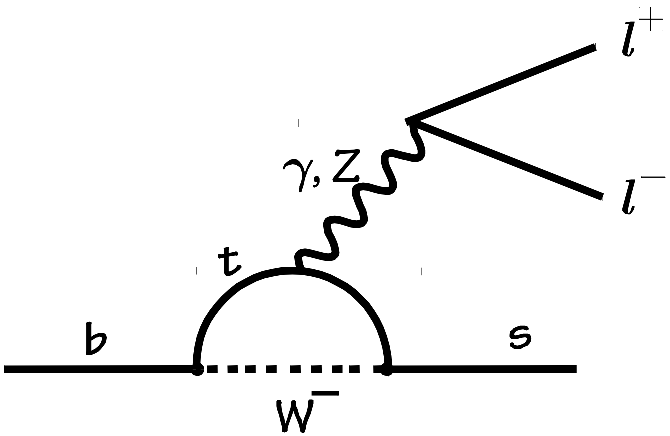
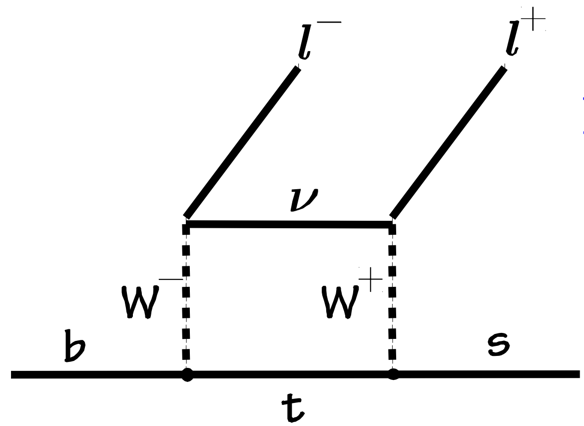
Beautiful paths to probe physics beyond the standard model of particles





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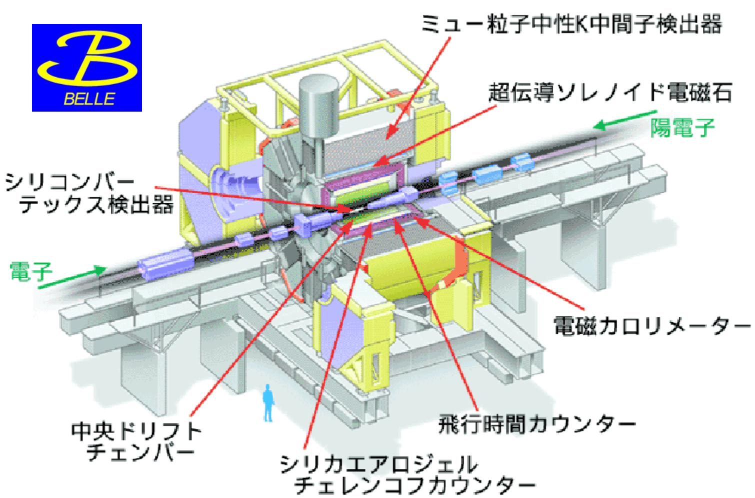
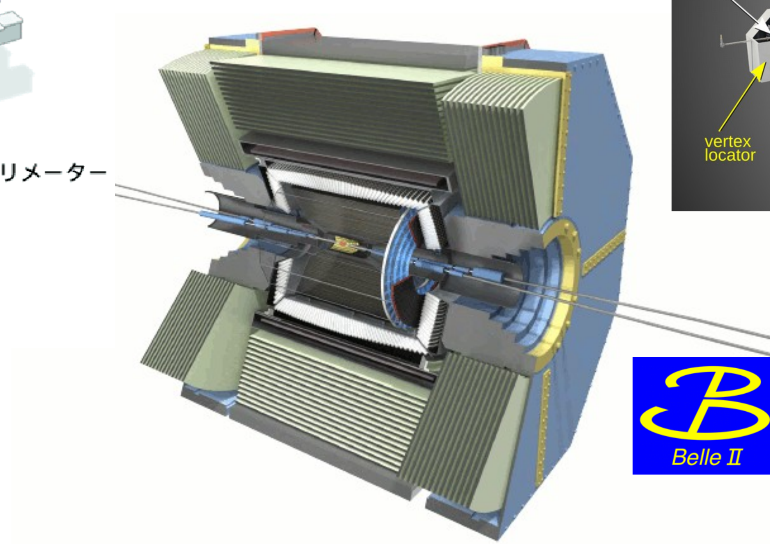
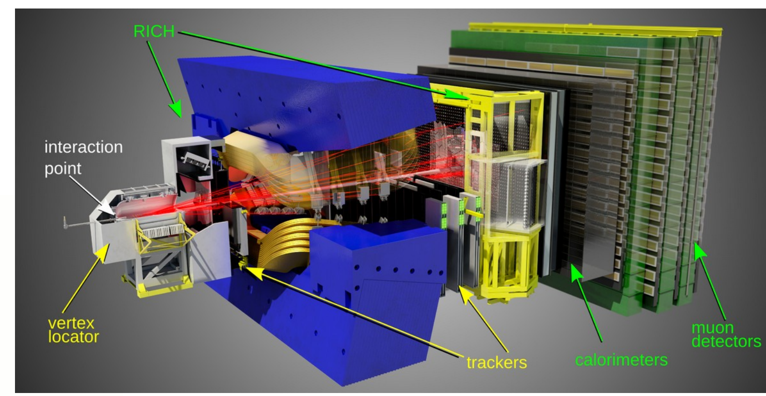


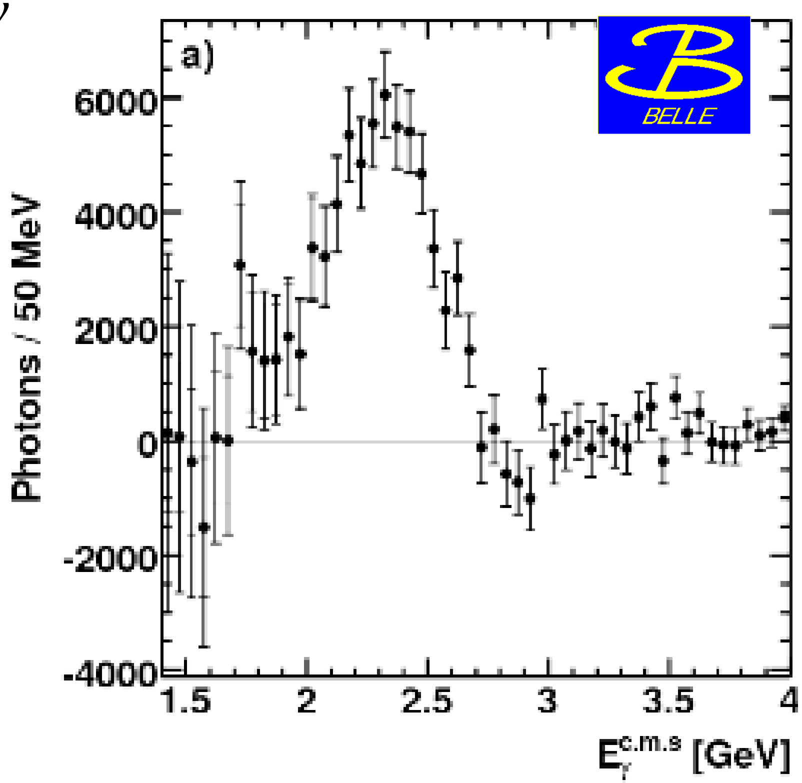


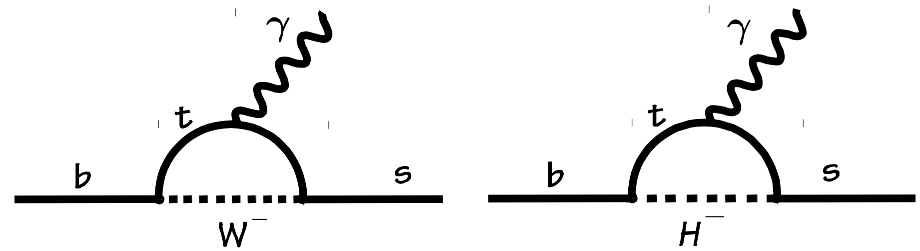


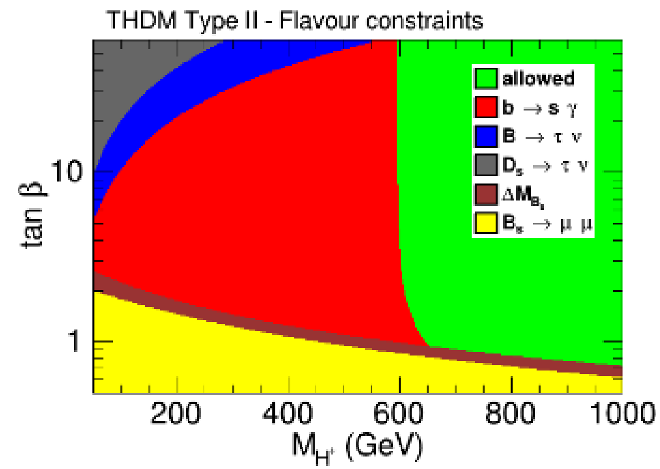
Future Flavours: Prospects for Beauty, Charm and Tau Physics , April 2022

Recent rare B decays results

$b \to s\gamma$

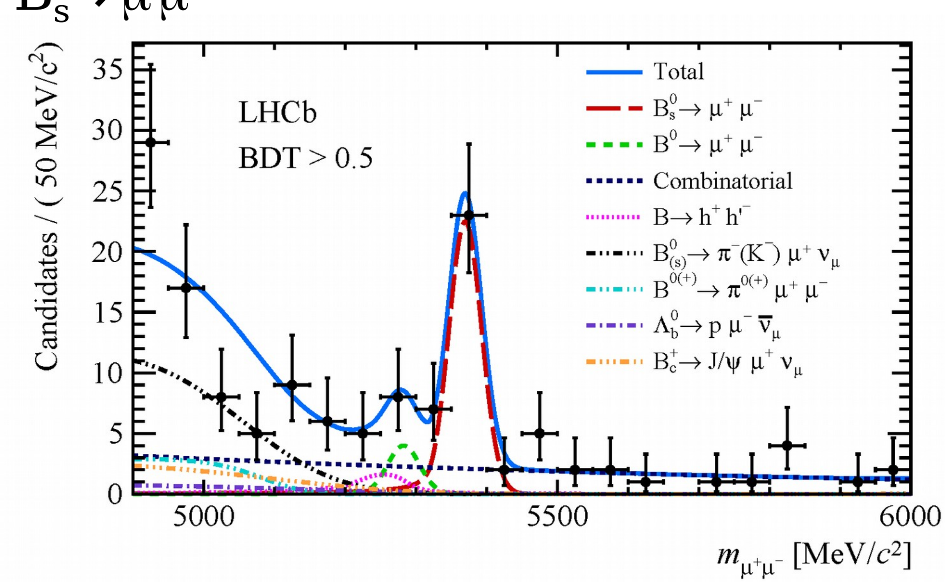


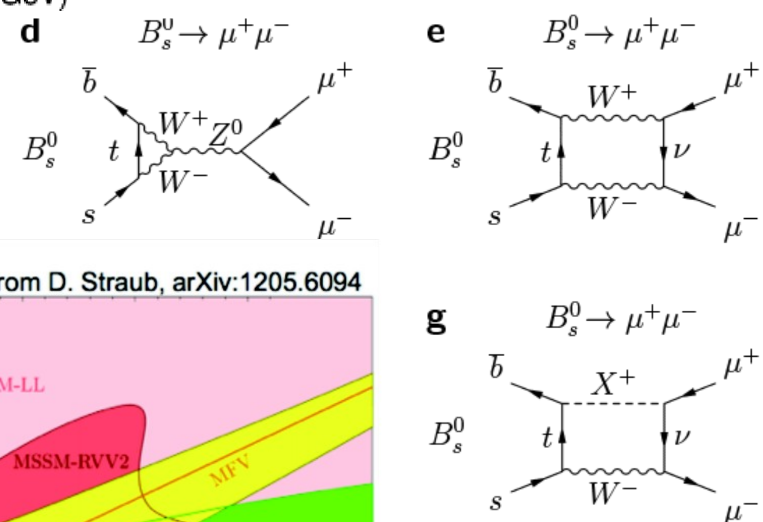


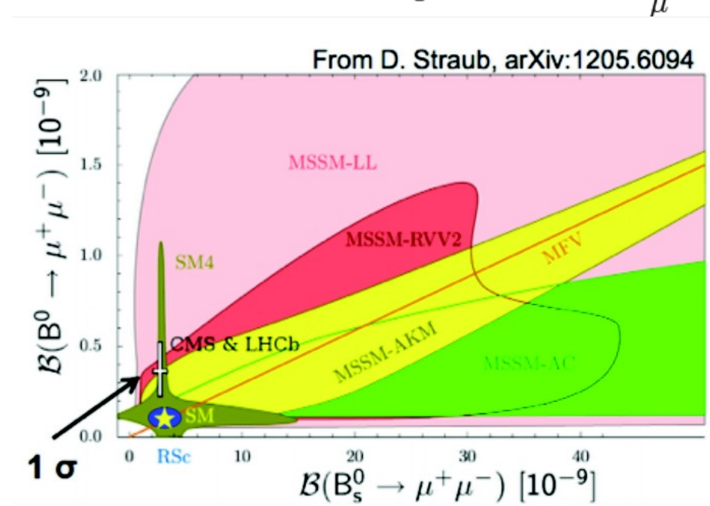


arXiv : 1706.07414]

$B_s \to \mu\mu$







Belle(II), LHCb side by side

Belle (II)

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow b\bar{b}$

at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events

(flavour tagging, B tagging, missing energy)

$\sigma_{b\bar{b}} \sim 1\,\text{nb} \Rightarrow 1\ \text{fb}^{-1}$ produces $10^6\ B\bar{B}$

$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$

LHCb

$pp \rightarrow b\bar{b}X$

production of B^+, B^0, B_s, B_c, Λ_b...
but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

$\sigma_{b\bar{b}}$ much higher than at the $\Upsilon(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
HERA pA	42 GeV	~30	~10^{-6}
Tevatron	2 TeV	5000	~10^{-3}
LHC	8 TeV	~3×10^5	~ 5×10^{-3}
	14 TeV	~6×10^5	~10^{-2}

$b\bar{b}$ production cross-section at LHCb ~ 500,000 × BaBar/Belle !!

$\sigma_{b\bar{b}}/\sigma_{total}$ much lower than at the $\Upsilon(4S)$

⇒ lower trigger efficiencies

B mesons live relativey long

mean decay length $\beta\gamma c\tau \sim 200\ \mu m$

mean decay length $\beta\gamma c\tau \sim 7$ mm

(displaced vertices)

data taking period(s)

[1999-2010] = 1 ab^{-1}
[2019-...] = ...

[run I: 2010-2012] = 3 fb^{-1},
[run II: 2015-2018] = 6 fb^{-1}

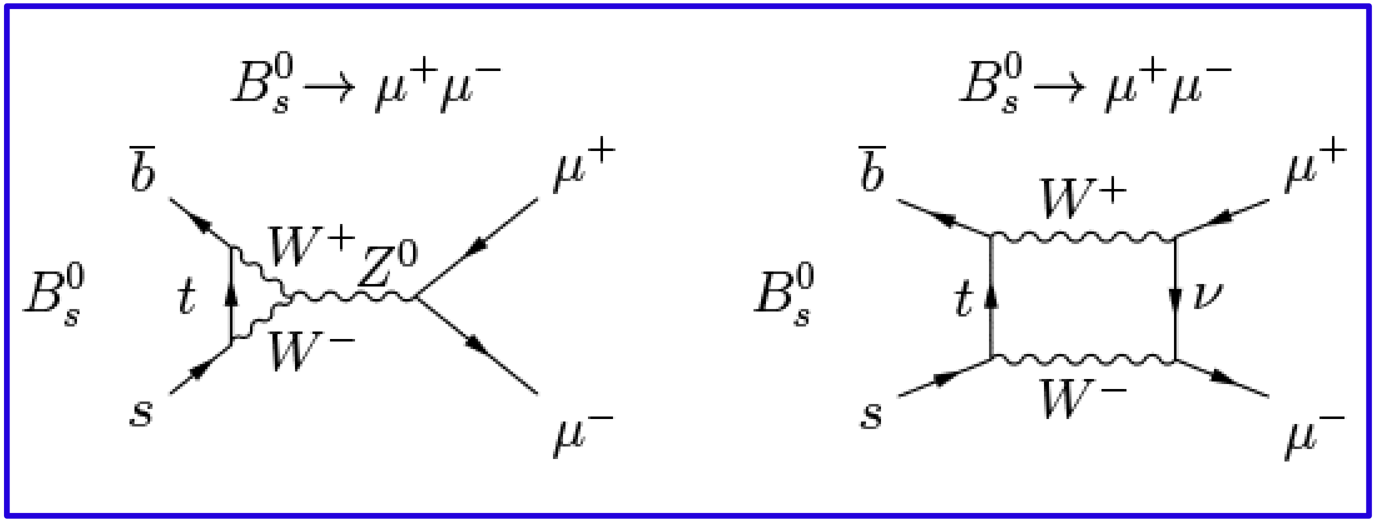
(near) future

[Belle II from 2019] → 50 ab^{-1}

[LHCb upgrade from 2021]

$B_{(s)} \to \mu\mu$: ultra rare processes…

loop diagram + suppressed in SM + theoretically clean =
an excellent place to look for new physics

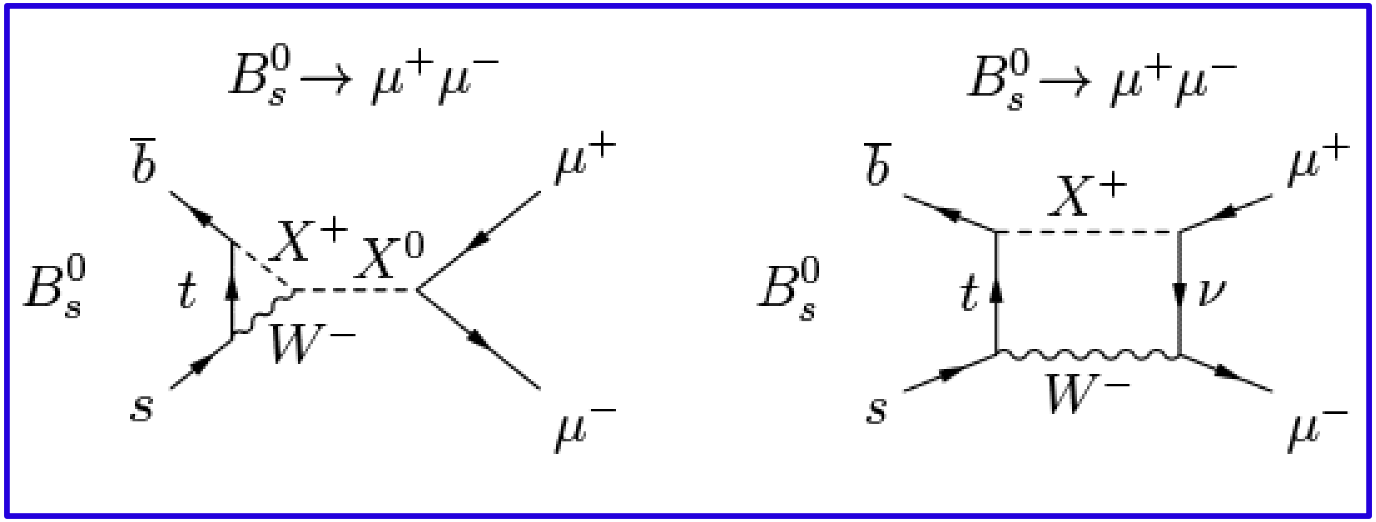


higher-order FCNC allowed in SM

$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[Bobeth et al, PRL 112 (2014) 101801]



same decay in theories extending the SM (some of NP scenarios may boost the $B \to \mu\mu$ decay rates)

Leptonic decays

$$B^0_{(s)} \to \ell^+\ell^-$$

$$BR(B^0_{(q)} \to \ell^+\ell^-) = \frac{\tau_B G_F^4 M_W^2 \sin^4\theta_W}{8\pi^5} |C_{10} V_{tb} V^*_{tq}| F_B^2 m_B m_\ell^2 \times \left| \sqrt{1 - \frac{4m_\ell^2}{m_B^2}} \right.$$

Branching ratio proportional to the lepton mass squared

$$\frac{BR(B^0_{(q)} \to \tau^+\tau^-)}{BR(B^0_{(q)} \to \mu^+\mu^-)} \sim \frac{m_\tau^2}{m_\mu^2} \qquad \frac{BR(B^0_{(q)} \to \mu^+\mu^-)}{BR(B^0_{(q)} \to e^+e^-)} \sim \frac{m_\mu^2}{m_e^2}$$

Helicity suppression, same reason why the pion decays into muon instead of electron ⇒ true only in SM

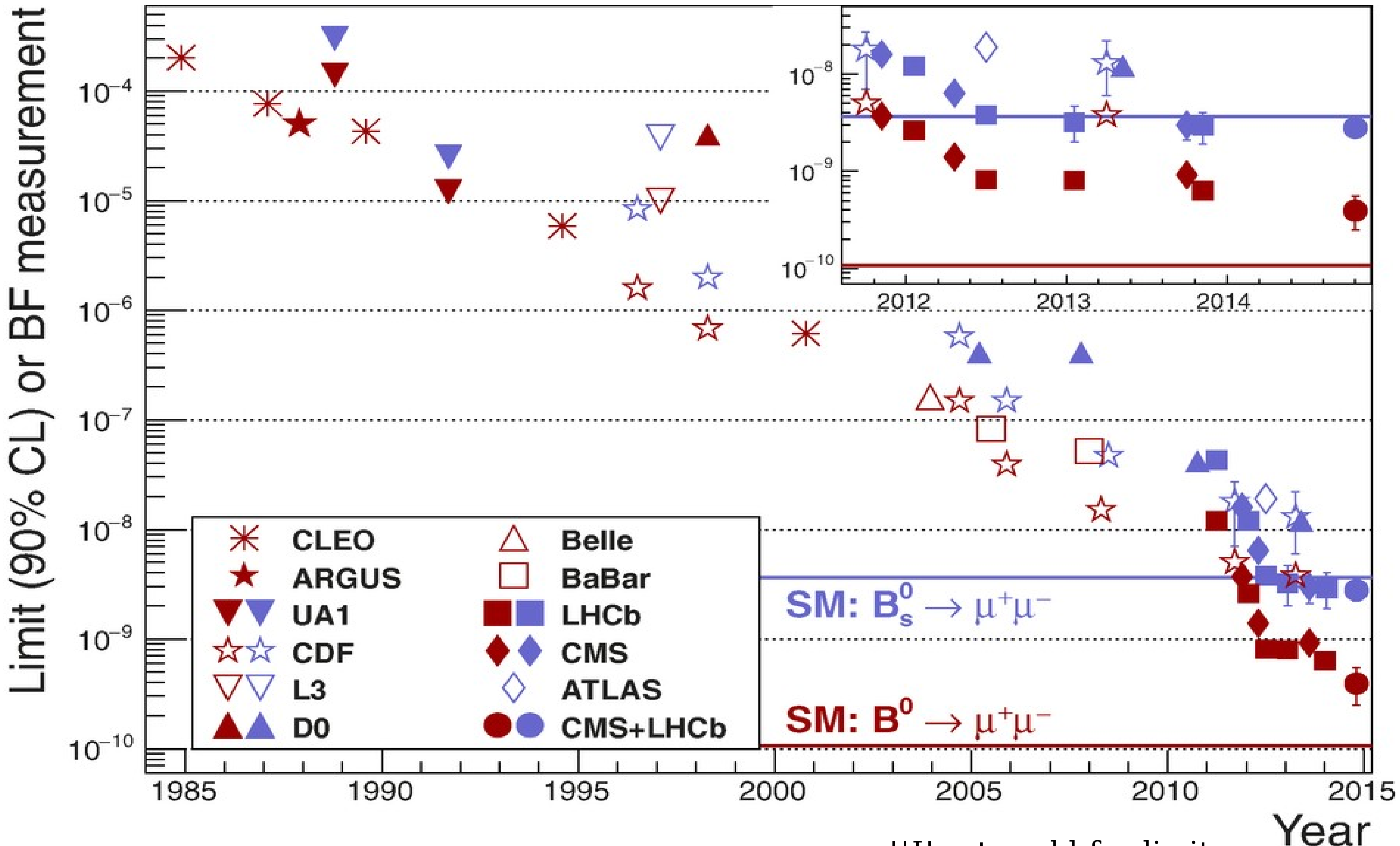
$$\frac{BR(B^0_{(d)} \to \mu^+\mu^-)}{BR(B^0_{(s)} \to \mu^+\mu^-} = \frac{\tau_{B^0_d}}{\tau_{B^0_s}} \frac{m_{B^0_d}}{m_{B^0_s}} \frac{F_{B^0_d}}{F_{B^0_s}} (\frac{V_{td}}{V_{ts}})^2$$

All parameters either measurable or calculable with high precision valid only in Minimal Flavour Violating Models
(where the flavour structure is described only by CKM)

In a ''general'' NP scenarios, the branching ratio of B leptonic decay is given by

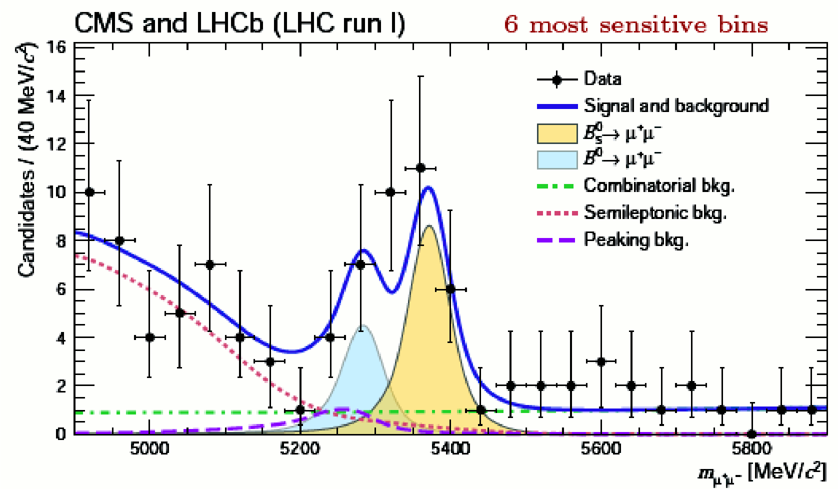
$$BR(B^0_s \to \mu^+\mu^-) \propto (1 - \frac{4m_\ell^2}{m_B^2})|C_S - C'_S|^2 + |(C_P - C'_P)^2 + 2\frac{m_\ell^2}{m_B^2}(C_{10} - C'_{10})|^2$$

$B_{(s)} \rightarrow \mu\mu$: ultra rare processes...



''I'm too old for limits,
I want to see signals''
(Francis Halzen)

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



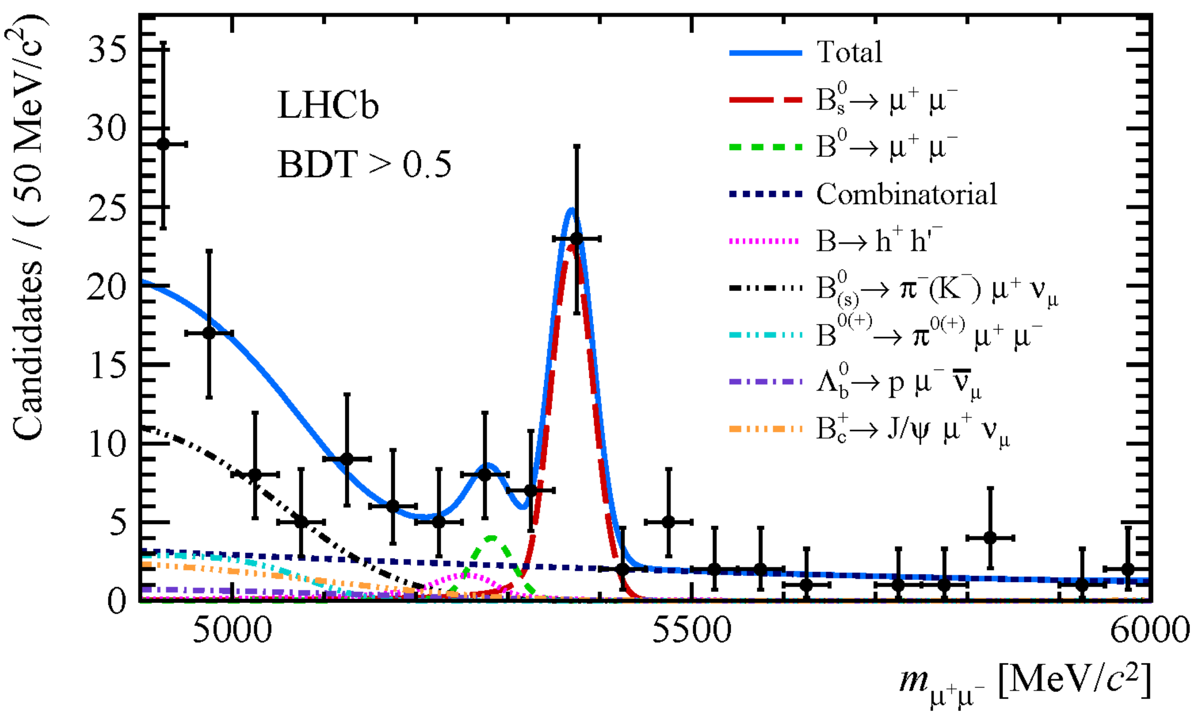
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$

first observation: 6.2σ significance

$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$

first evidence: 3.0σ significance

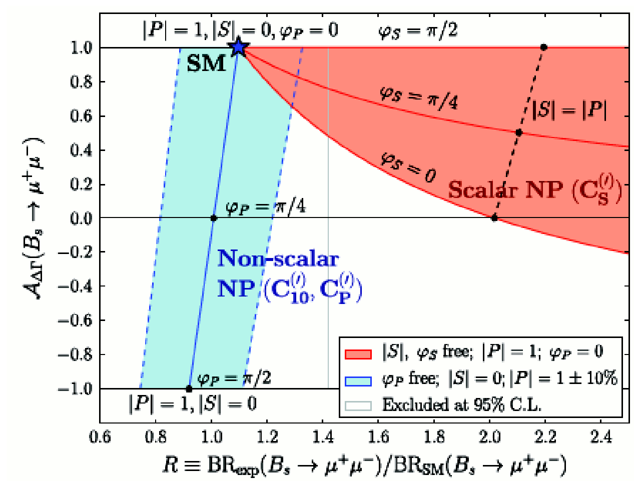
[arXiv:1703.05747]



SM: heavy state decays to $\mu^+\mu^-$

first lifetime measurement:

$\tau(B_s \to \mu^+\mu^\pm) = 2.04 \pm 0.44 \pm 0.05$ ps

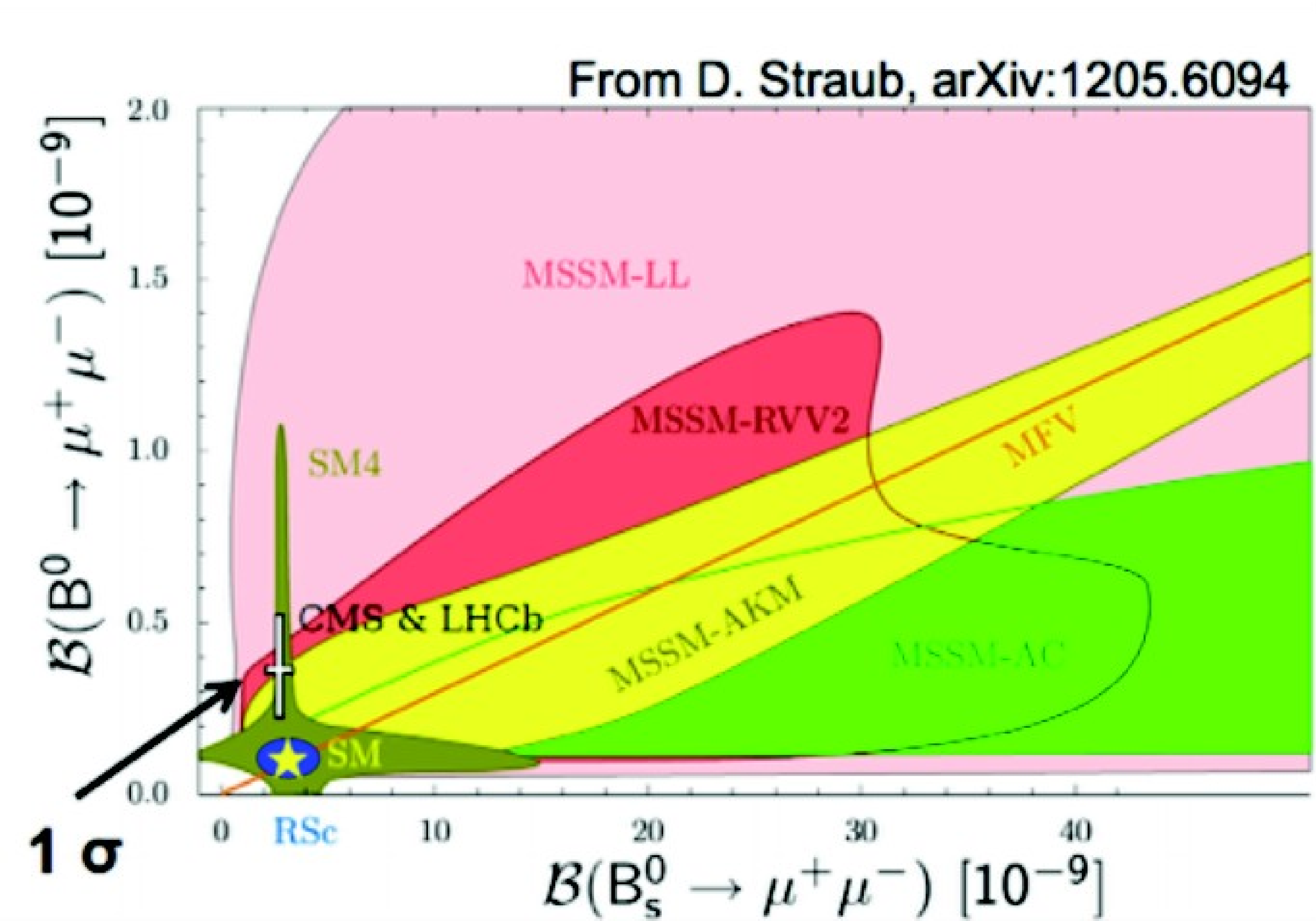


[De Bruyn et al., PRL 109, 041801 (2012)]

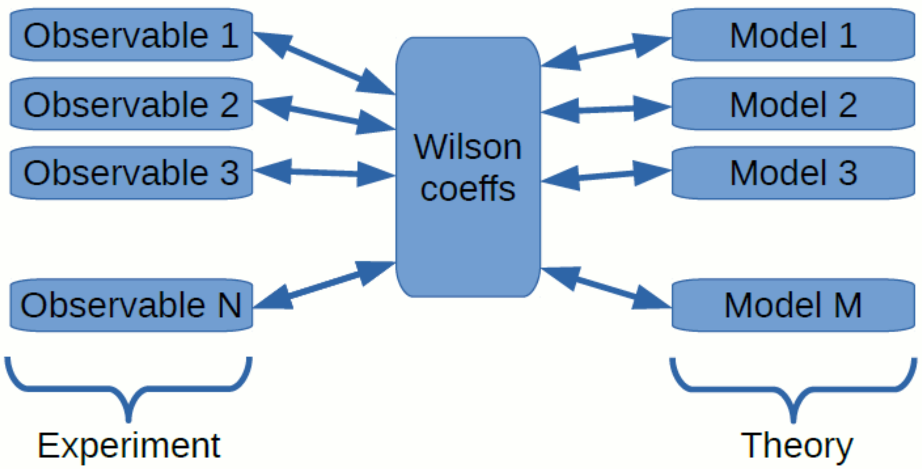
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$ (7.8σ significance)

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 90% CL

Constraints on NP models



Sensitivity to new physics in rare B decays



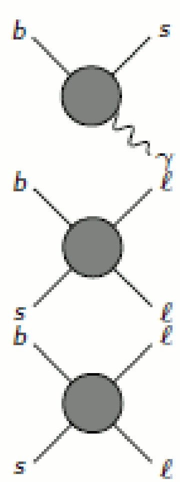
M.Ciuchini et al, arXiv:1512.07157
T.Hurth et al, arXiv:1603.00865
S.Descotes-Genon et al, arXiv:1510.04239...

NP changes short-distance C_i and/or add new long-distance ops O'_i

- Model-independent description in effective field theory

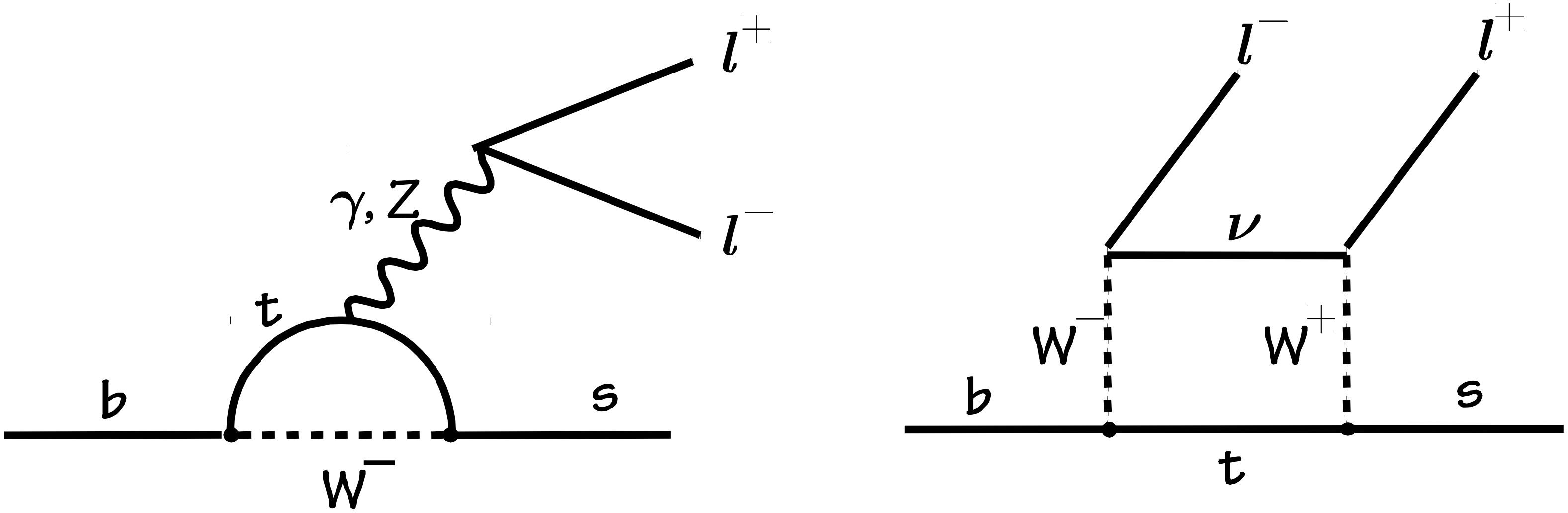
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

- Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators



		$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$	photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$	vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$	axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$	(pseudo)scalar penguin		✓	

$\mathbf{b \rightarrow s\, l^+ l^-}$



⇒ 2 orders of magnitude smaller than $b \rightarrow s\gamma$ but rich NP search potential

Amplitudes from

- ∘ electromagnetic penguin: C_7
- ∘ vector electroweak: C_9
- ∘ axial-vector electroweak: C_{10}

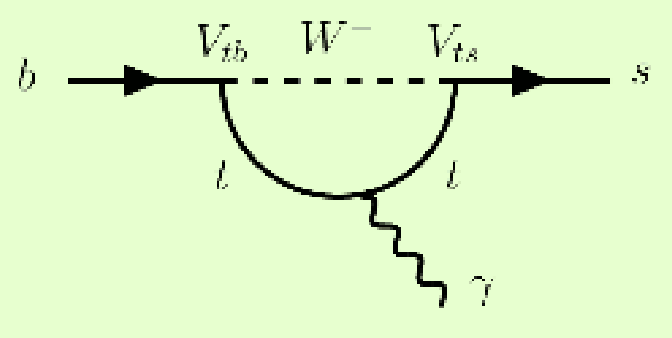
may interfere w/ contributions from NP

Many observables:

- ∘ Branching fractions
- ∘ Isospin asymmetry (A_I), Lepton forward-backward asymmetry (A_{FB}), CP asymmetry ...
- ∘ and much more...

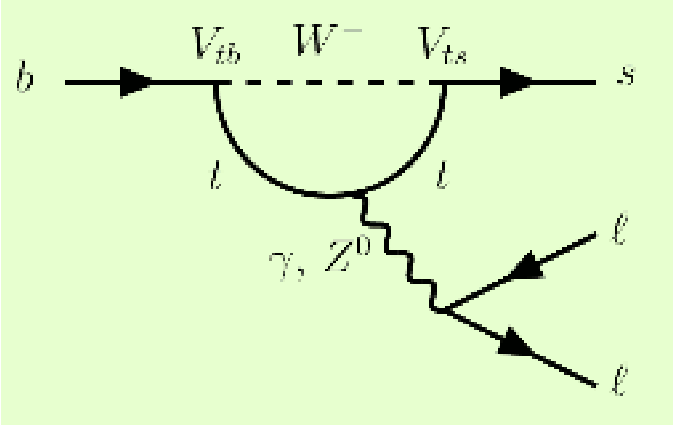
⇒ Exclusive $(B \rightarrow K^{(*)} l^+ l^-)$, Inclusive $(B \rightarrow X_s\, l^+ l^-)$

b→lls



- Start with b→s γ

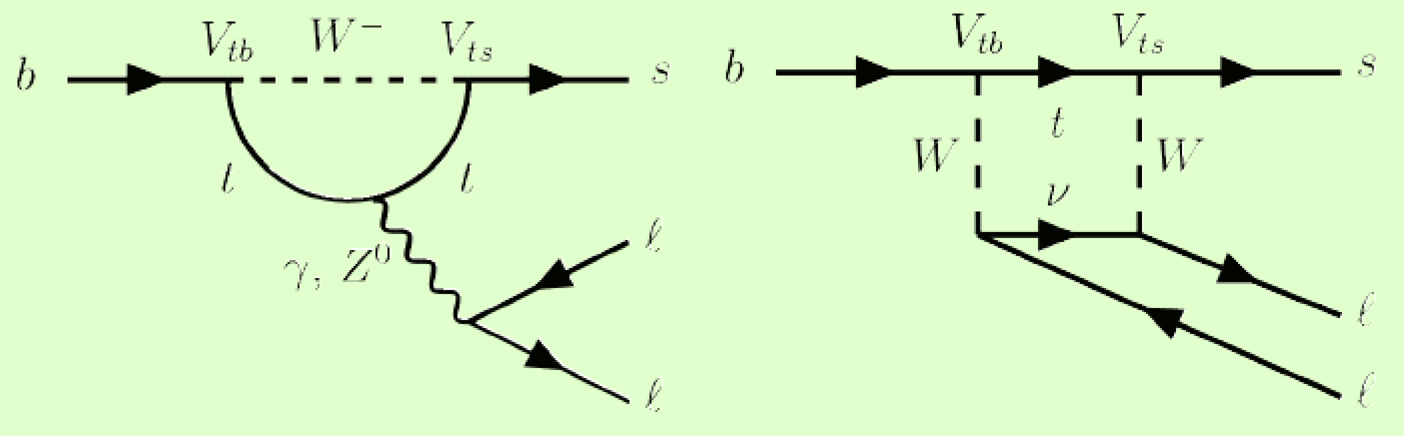
b→lls



- Start with b→s γ, pay a factor $\alpha_{EM} = \frac{1}{137}$

  → Decay the γ into 2 leptons

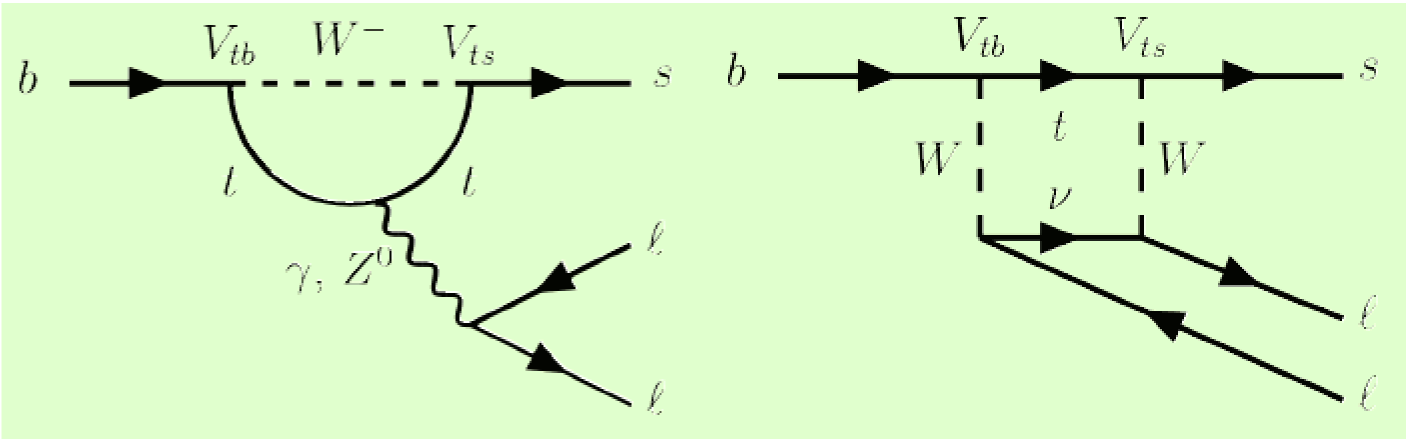
b→lls



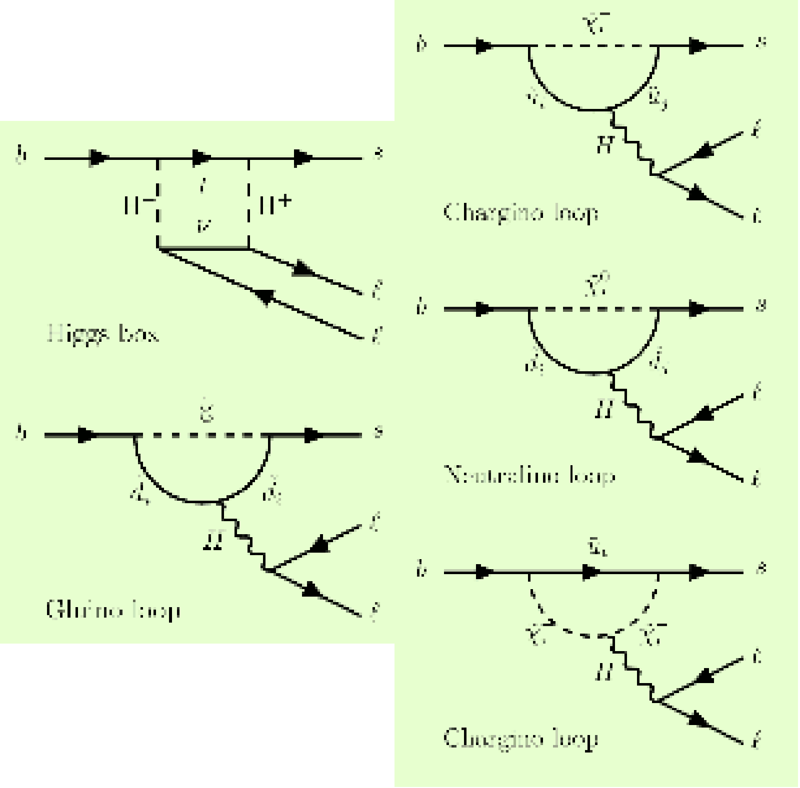
- Start with b→s γ, pay a factor α_{EM}
  - → Decay the γ into 2 leptons
- Add an interfering box diagram
  - → b→lls, very rare in the SM

$$B(\mathrm{B \to llK^*}) = (3.3 \pm 1.0) \,.\, 10^{-6}$$

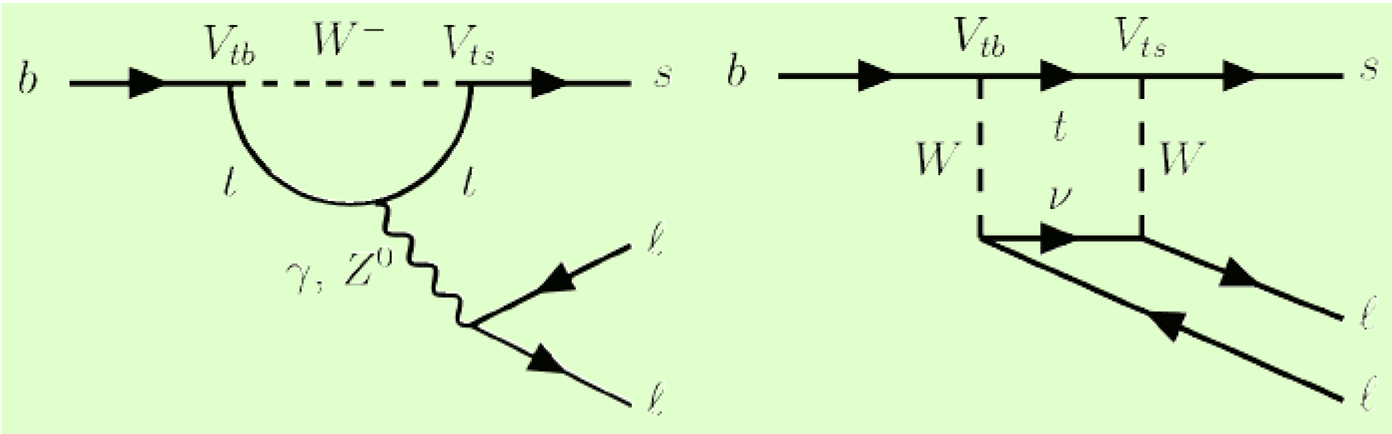
b→lls



- Start with b→sγ, pay a factor α_{EM}
  - → Decay the γ into 2 leptons
- Add an interfering box diagram
  - → b→lls, very rare in the SM
  - $B(B \to llK^*) = (3.3 \pm 1.0) \cdot 10^{-6}$
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions…
- Ideal place to look for new physics



b→lls



- Start with b→sγ, pay a factor α_{EM}
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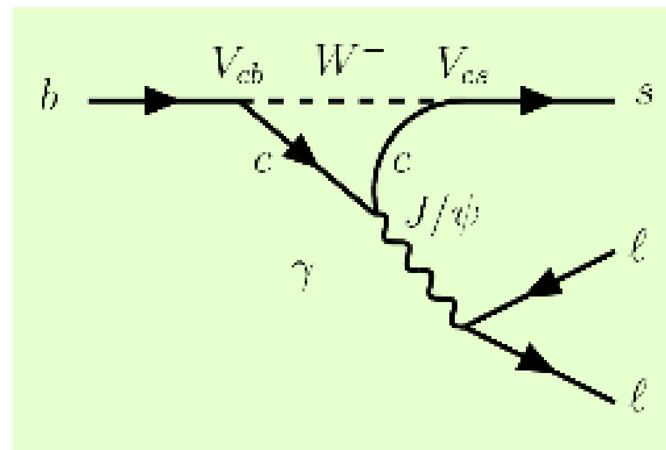
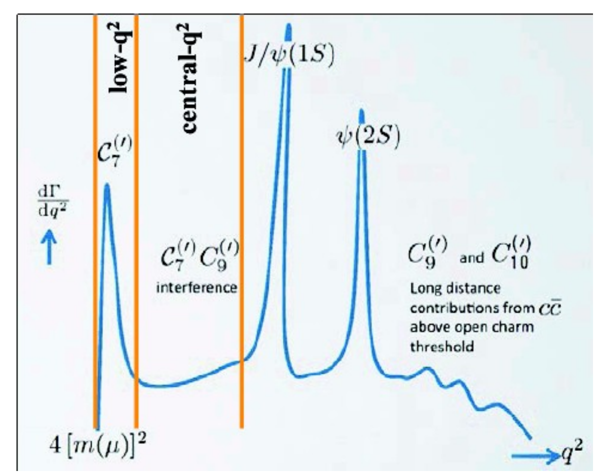
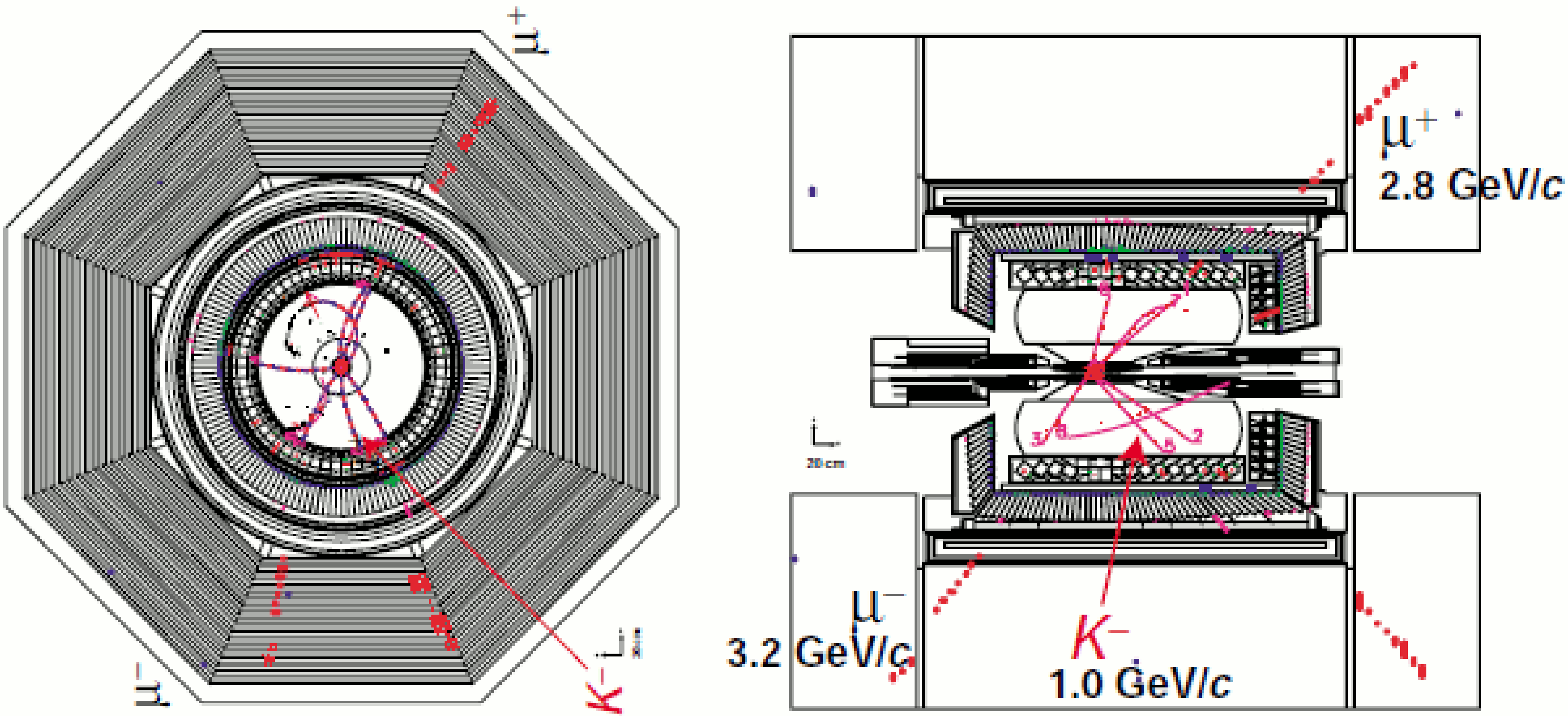


- But beware of LD effects:
  - Tree $b \to c\bar{c}s$, $(c\bar{c}) \to ll$
  - Can be removed by mass cuts
  - Interferes elsewhere



First observation

$B^+ \to K^+ \mu^+ \mu^-$ Event



Lepton flavor universality (LFU)

How do the SM gauge bosons couple to charged leptons of different flavors?

Universality in neutral current interactions

$$U^\dagger U = V^\dagger V = \mathbb{I}_{3\times 3} \;\Rightarrow\; \mathcal{L}^{\ell}_{\rm nc} \equiv \left(\overline{\hat{e}}\gamma_\mu \hat{e} + \overline{\hat{\mu}}\gamma_\mu \hat{\mu} + \overline{\hat{\tau}}\gamma_\mu \hat{\tau}\right)\left(g_\gamma A^\mu + g_Z Z^\mu\right)$$

The photon and Z-boson couple with the same strength to the three lepton families

Universality

How do we test this feature of the Standard Model?

$$R_Y = \frac{\mathrm{BR}\left(X \to Y e_i^+ e_i^-\right)}{\mathrm{BR}\left(X \to Y e_j^+ e_j^-\right)} \qquad i \neq j$$

SM expectation

$$R_Y = 1 + \mathcal{O}\left(\frac{m^n_{i,j}}{m^n_X}\right)$$

Experimental results

We'll see...

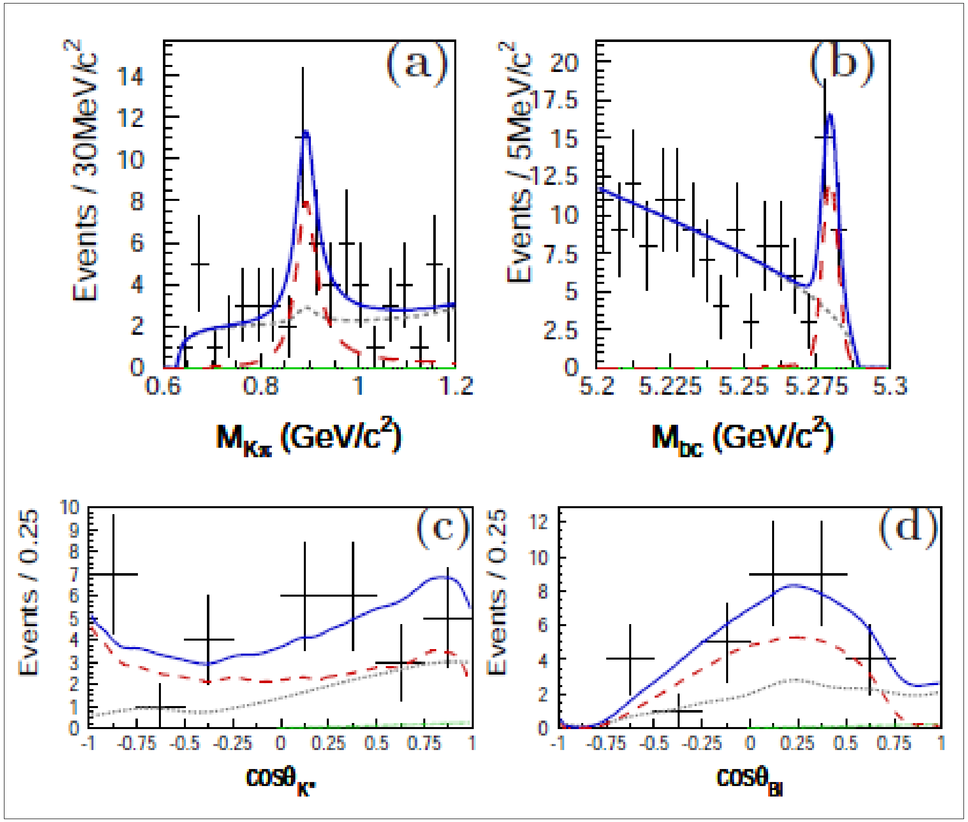
Situation pre-LHCb

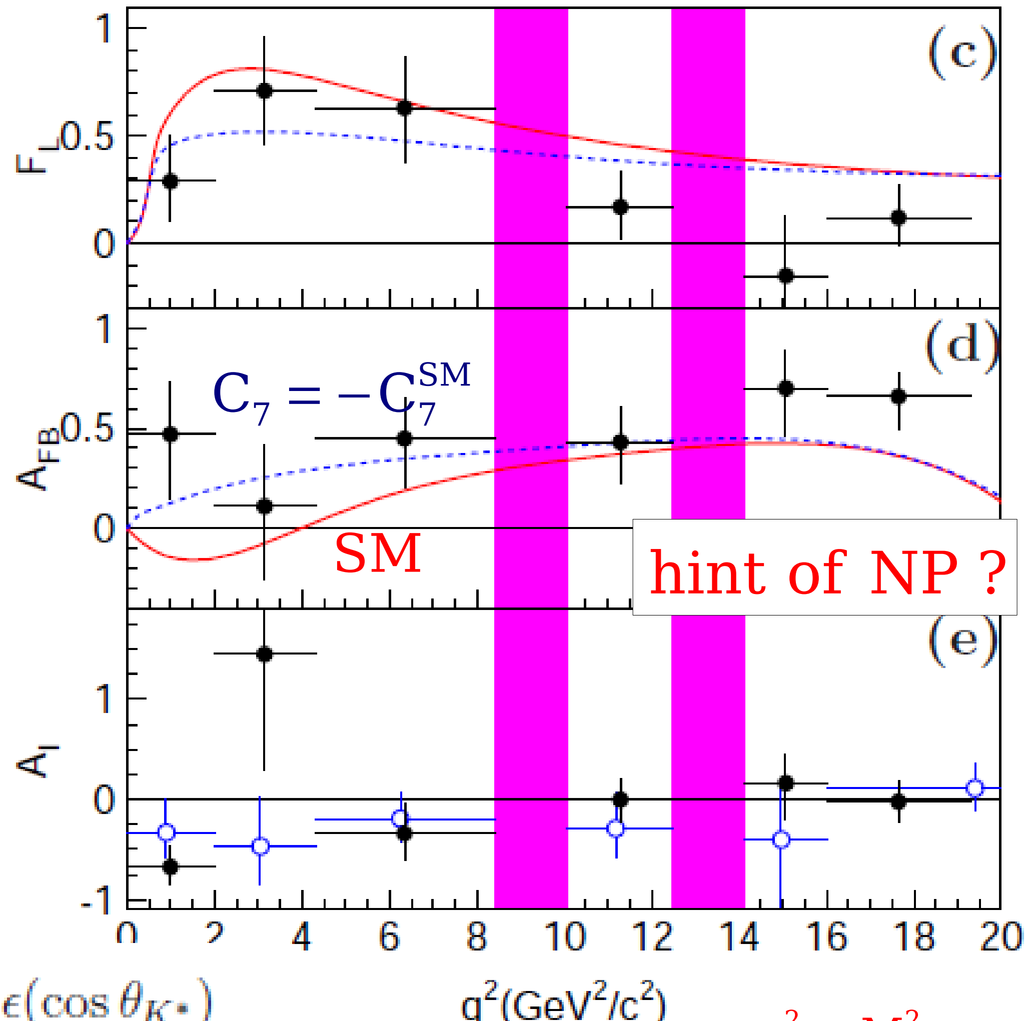
$B \to K^* l^+ l^-$ decays

[arXiv:0904.0770]

- Channels: $K^* \to K^+\pi^-$, $K^0_S\pi^+$, $K^+\pi^0$, $l = e$ or μ

illustration: $q^2 \in [0.0, 2,0]$ GeV^2





$$\left[\ \tfrac{3}{2}F_L\cos^2\theta_{K^*} + \tfrac{3}{4}(1-F_L)(1-\cos^2\theta_{K^*})\ \right] \times \epsilon(\cos\theta_{K^*})$$

$$\left[\ \tfrac{3}{4}F_L(1-\cos^2\theta_{B\ell}) + \tfrac{3}{8}(1-F_L)(1+\cos^2\theta_{B\ell}) + A_{FB}\cos\theta_{B\ell}\ \right] \times \epsilon(\cos\theta_{B\ell}) \,,$$

$q^2 = M^2_{l^+l^-}$

$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$

$R_K = 1.03 \pm 0.19 \pm 0.06$

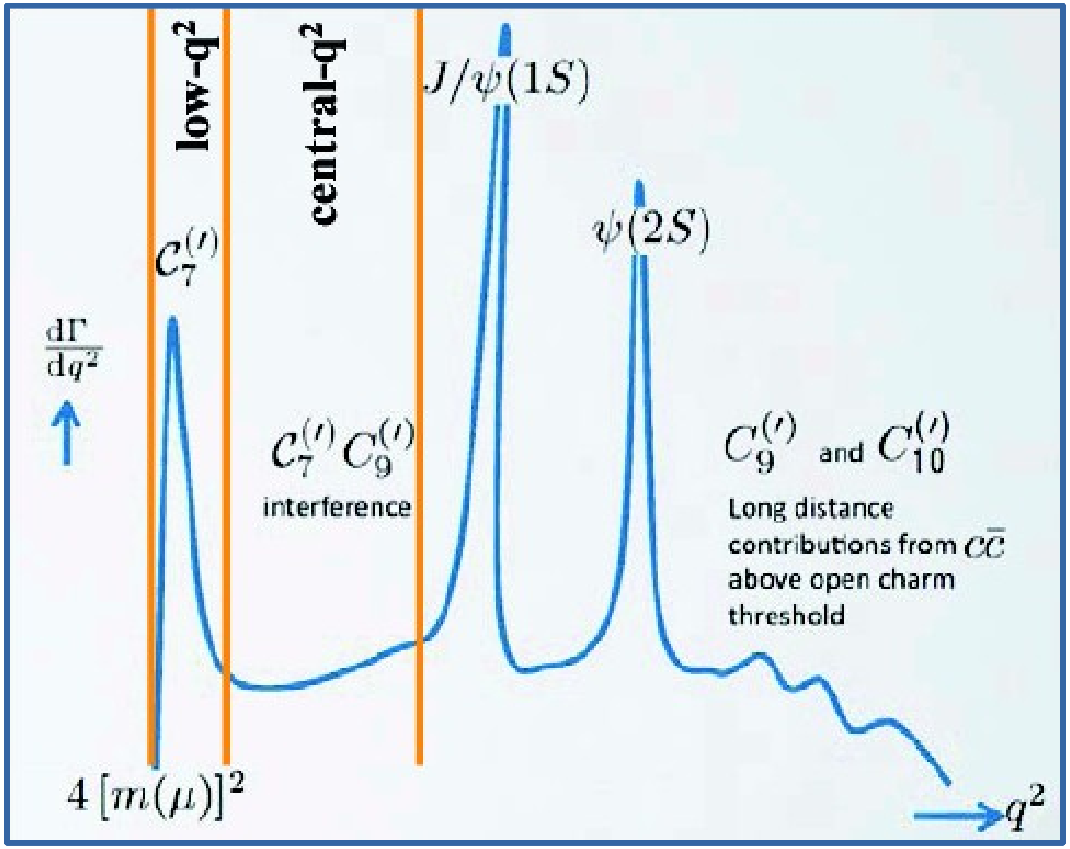
Test of LFU with $B \to K^{*0}\mu\mu$ and $B \to K^{*0}ee$, $R_{K^{*0}}$

Two regions of q^2

- Low [0.045-1.1] GeV^2/c^4
- Central [1.1-6.0] GeV^2/c^4

Different q^2 regions probe
different processes
in the OPE framework
short distance contributions
described by Wilson coefficients

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \frac{\alpha_e}{4\pi} \sum [C_i\mathcal{O}_i + C_i'\mathcal{O}_i']$$



- Measured relative to $B^0 \to K^{*0} J/\psi(ll)$ in order to reduce systematics

- Challenging:
  - due to significant differences in the way μ and e interact with detector
  - Bremsstrahlung
  - Trigger

Strategy

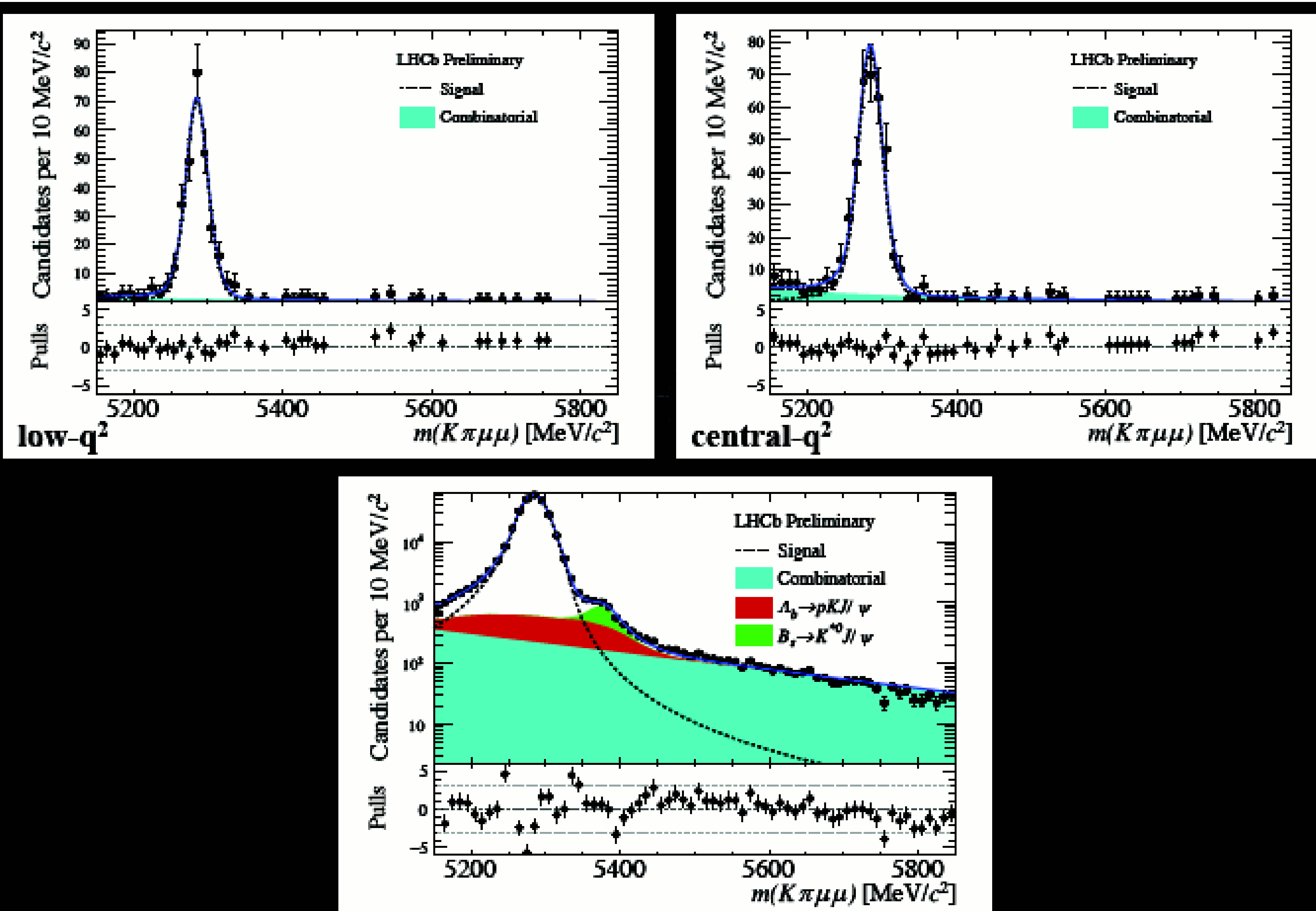
- Measured relative to $B^0 \to K^{*0} J/\psi(ll)$ in order to reduce systematics

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

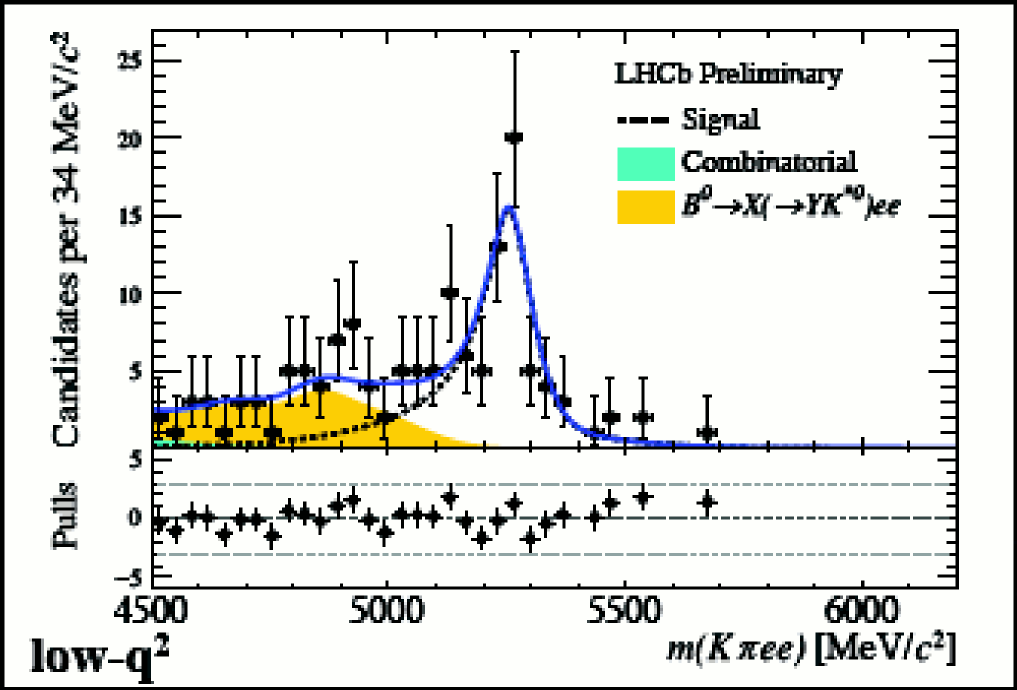
› Selection as similar as possible between μμ and ee
  » Pre-selection requirements on trigger and quality of the candidates
  » Cuts to remove the peaking backgrounds
  » Particle identification to further reduce the background
  » Multivariate classifier to reject the combinatorial background
  » Kinematic requirements to reduce the partially-reconstructed backgrounds
  » Multiple candidates randomly rejected (1-2%)

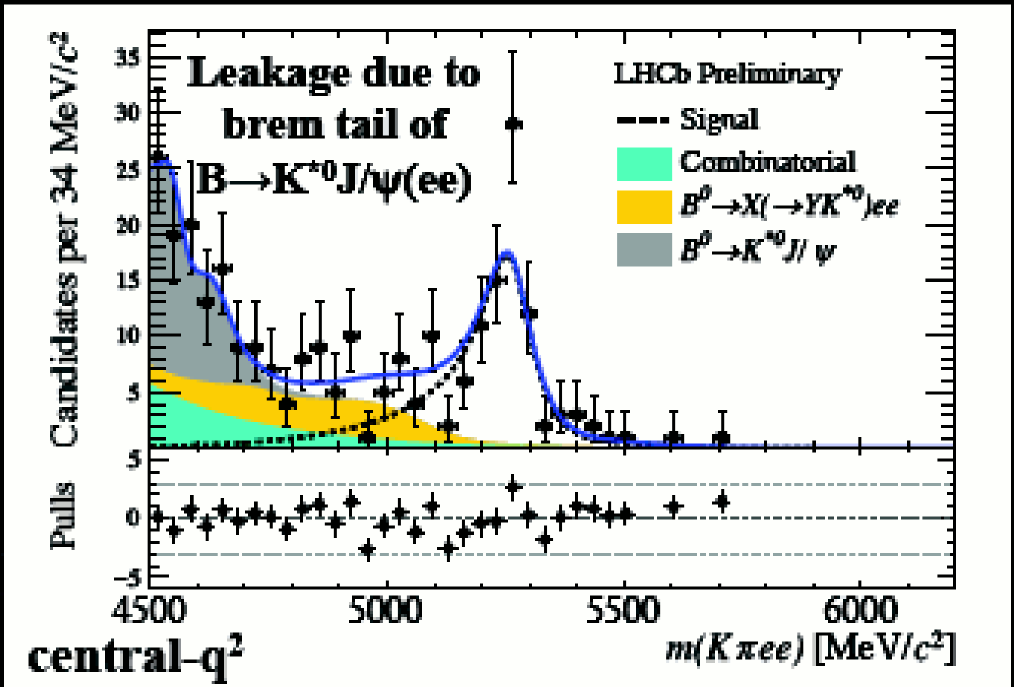
› Efficiencies
  » Determined using simulation, but tuned using data

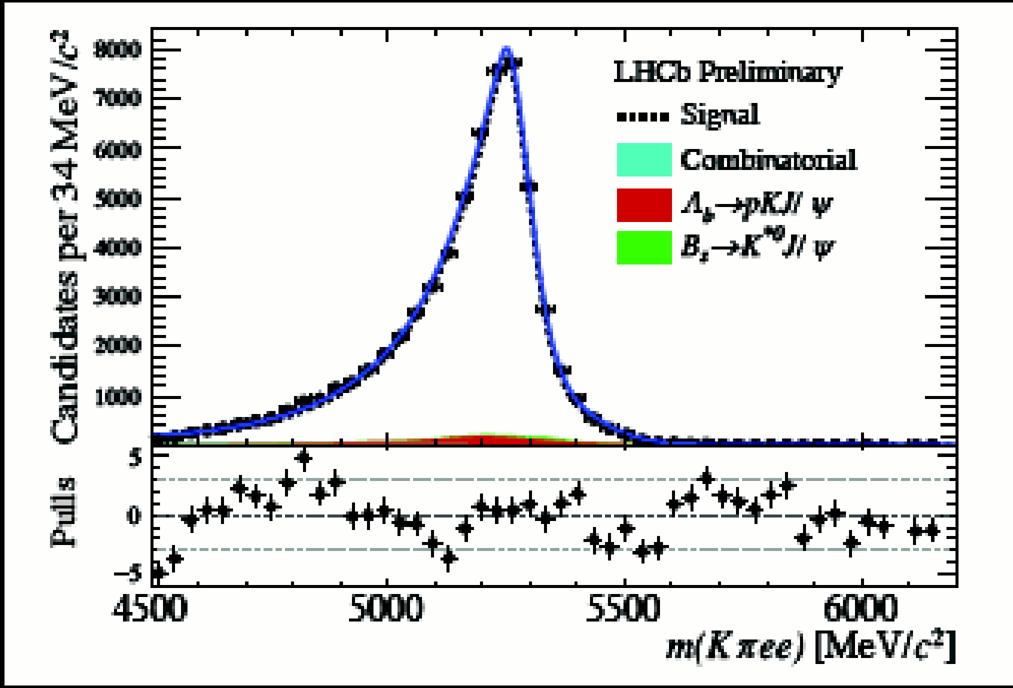
Fit results – μμ



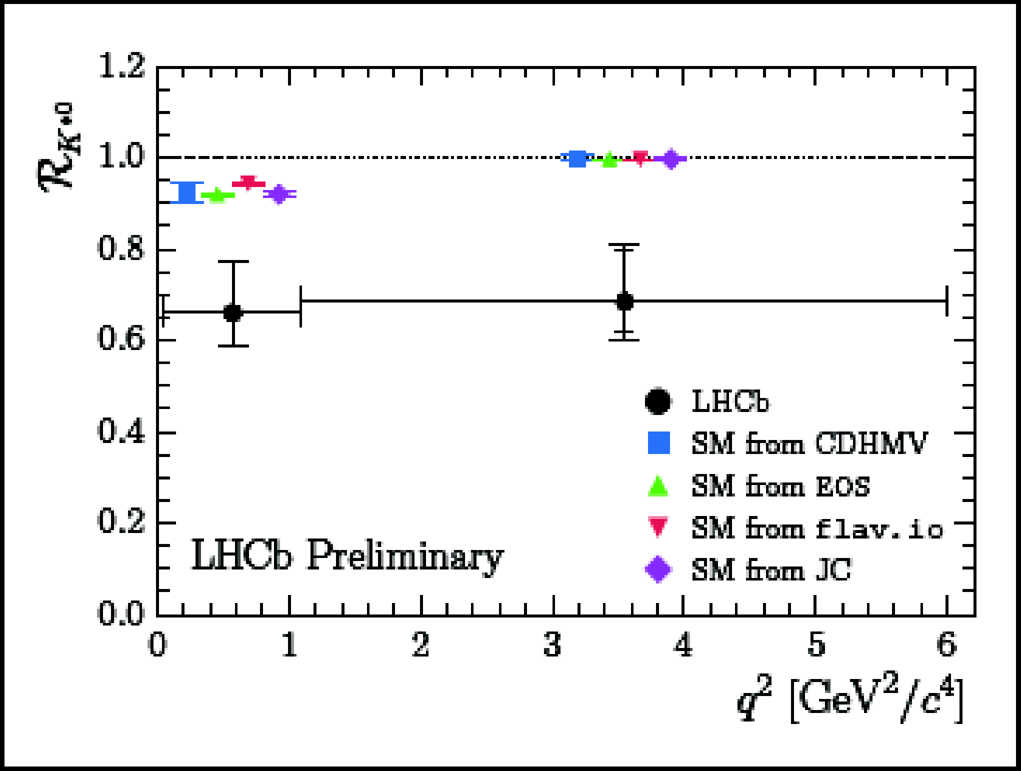
Fit results – ee

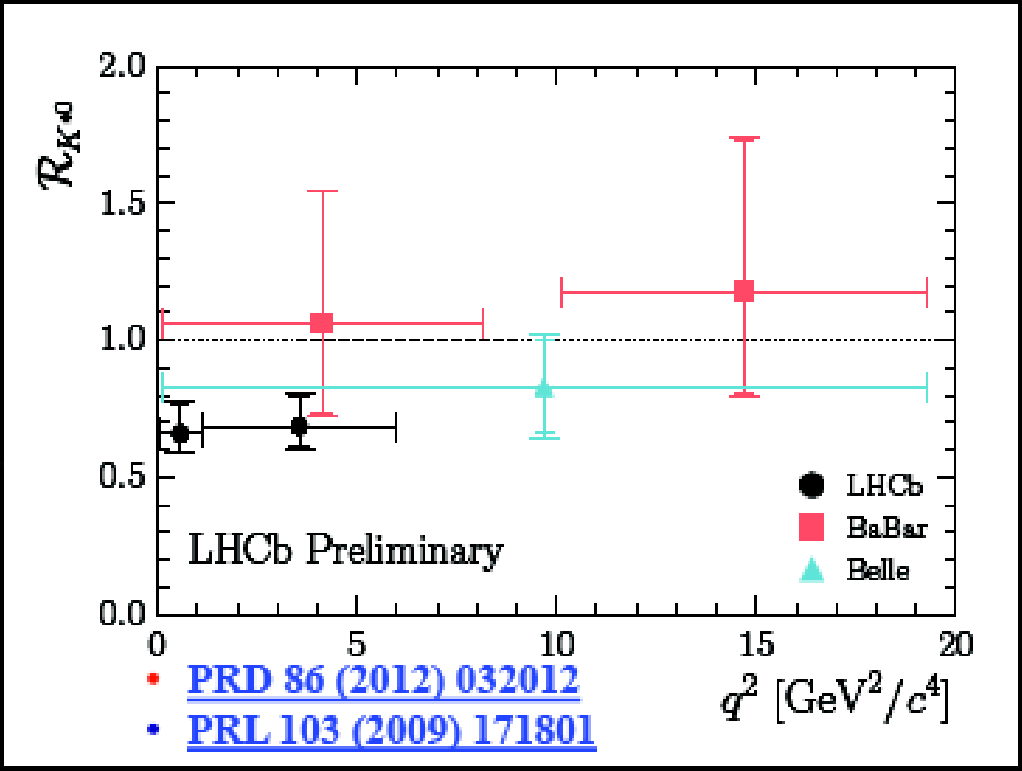






Results

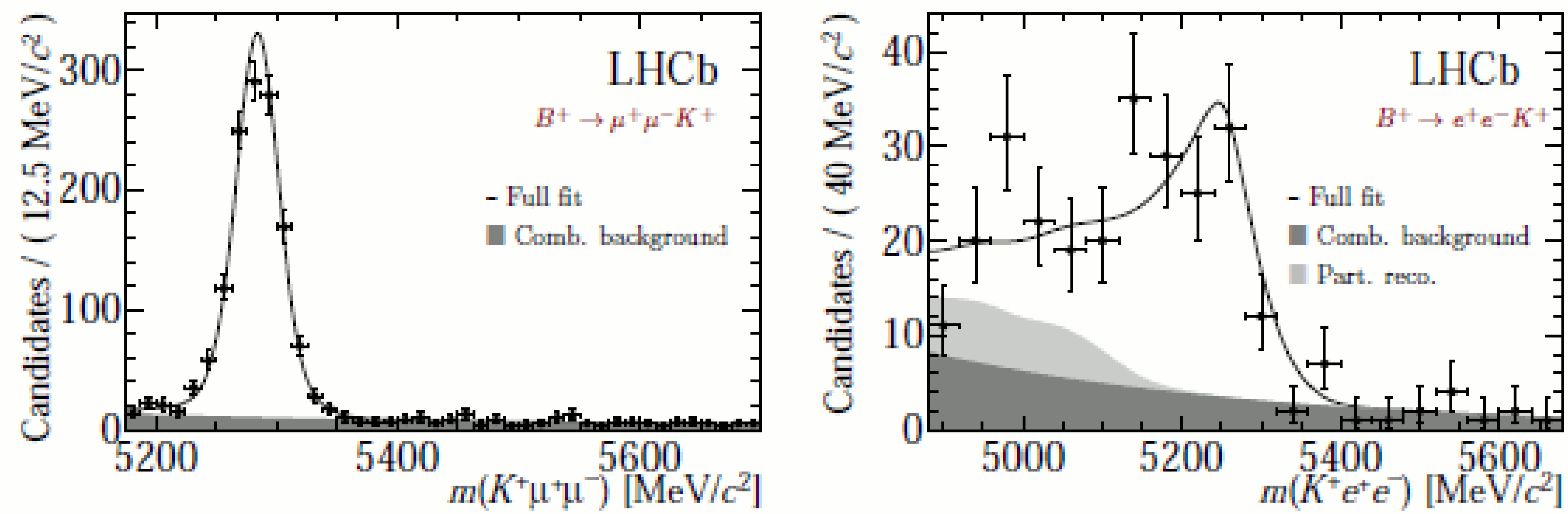




- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

Test of lepton universality using $B^+ \to K^+ l^+ l^-$ decays

[arXiv:1406.6482]



$q^2 \in [1, 6]\,\mathrm{GeV}^2/c^4$

Electron Trigger

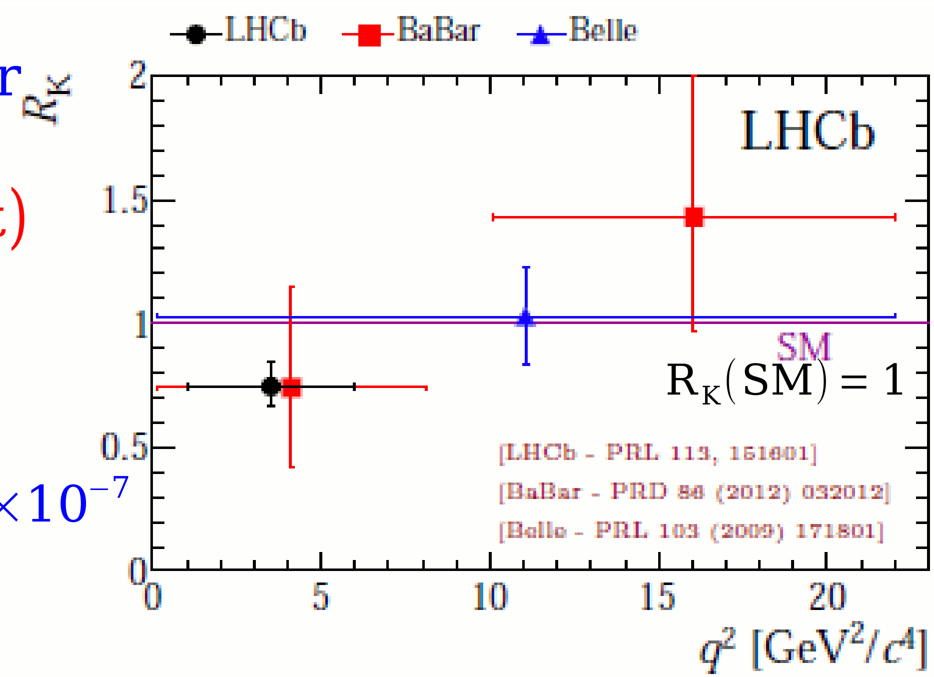
R_K: ratio of branching fractions for dilepton invariant mass squared range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

- The combination of the various trigger channels gives:

  $$\mathbf{R_K = 0.745\,^{+0.090}_{-0.074}(stat) \pm 0.036(syst)}$$

- Most precise measurement to date, disagreement with SM at 2.6σ level

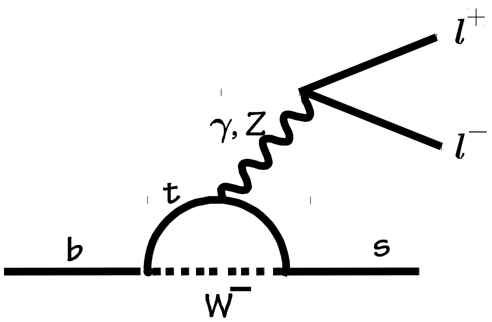
$\Rightarrow$ $\mathcal{B}(B^+ \to e^+e^-K^+) = (1.56\,^{+0.19}_{-0.15}(\mathrm{stat})\,^{+0.06}_{-0.05}(\mathrm{syst})) \times 10^{-7}$ compatible with SM predictions

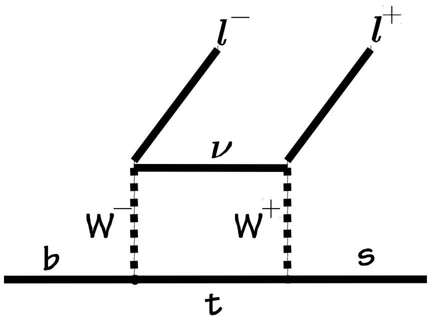


BSM LFNU and effect is in $\mu\mu$, not ee

Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays

no evidence of New Physics in a series of ''clean'' flavor-changing observables, such as $\Delta F=2$, but also $b \to s\gamma$ but ...



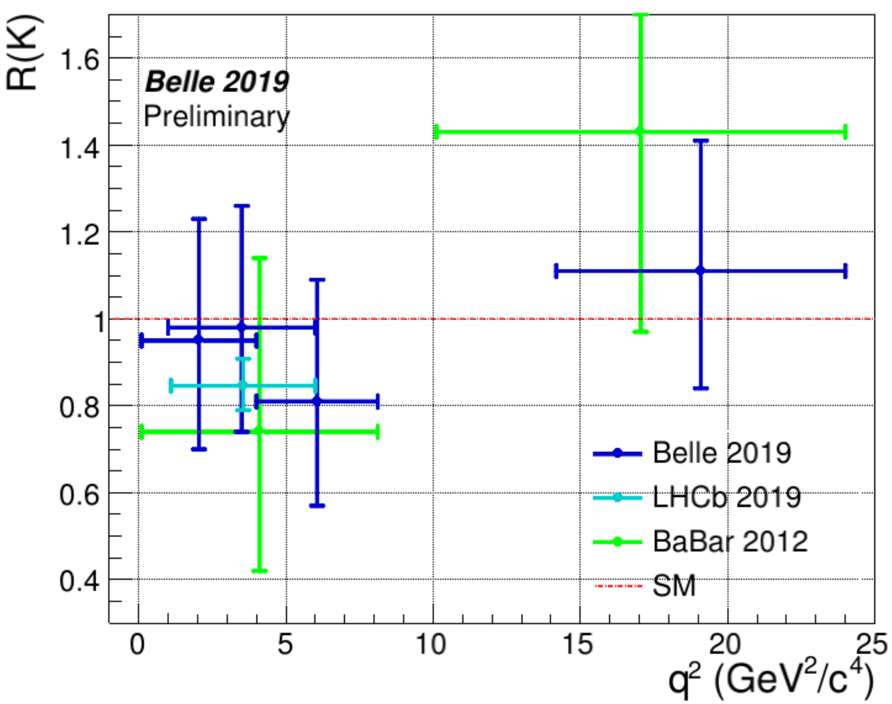


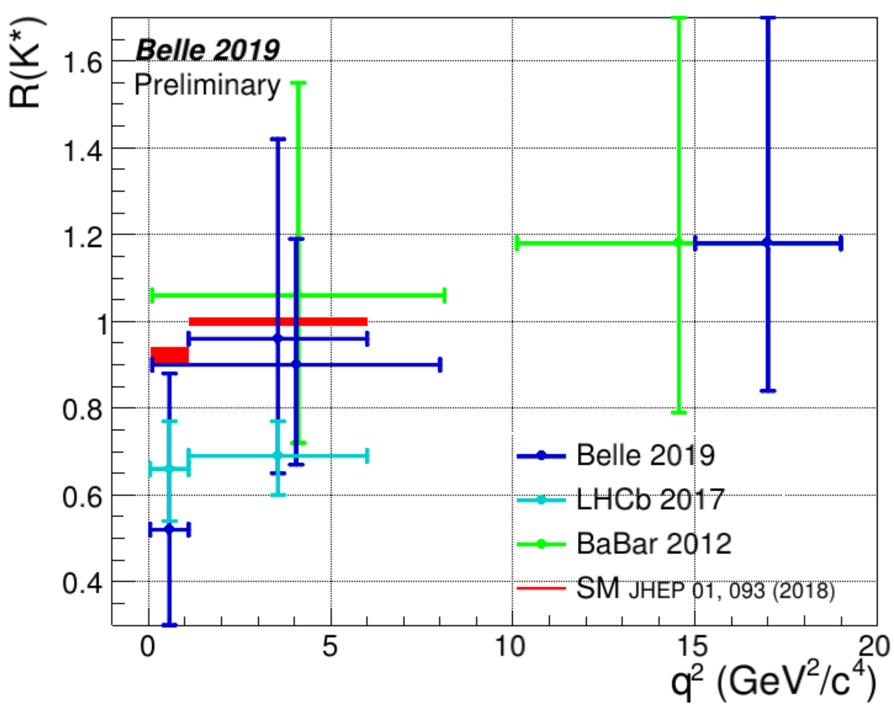
The ''clean'' Lepton Flavor Universality ratios:

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

SM prediction very robust: $R_K(SM) = 1$

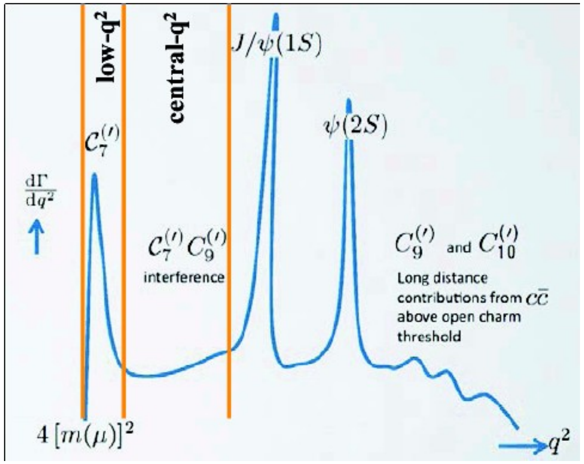
[up tiny QED and lepton mass effects]

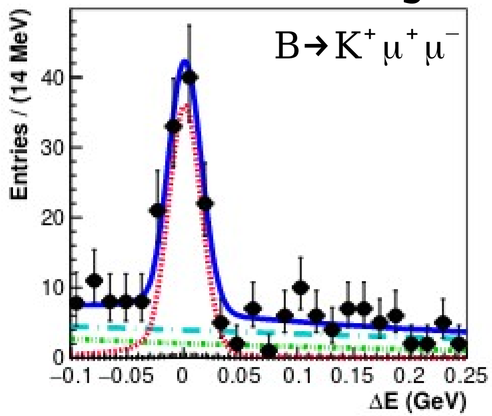


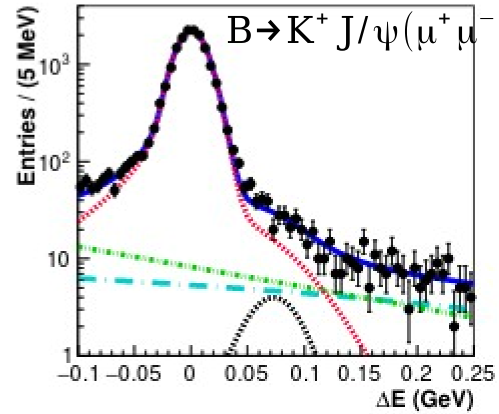


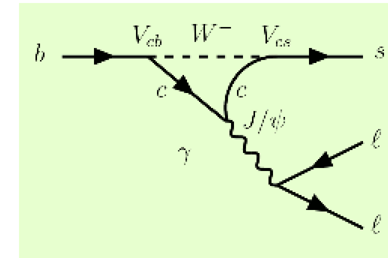
Test of lepton universality using $B^+ \to K l^+ l^-$ decays

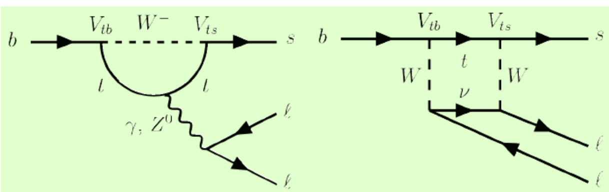
[Belle, arXiv:1908.01848]

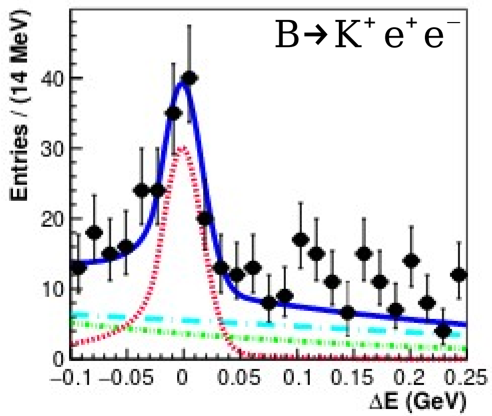


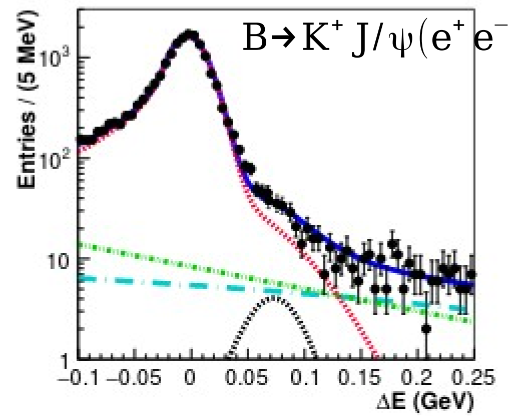


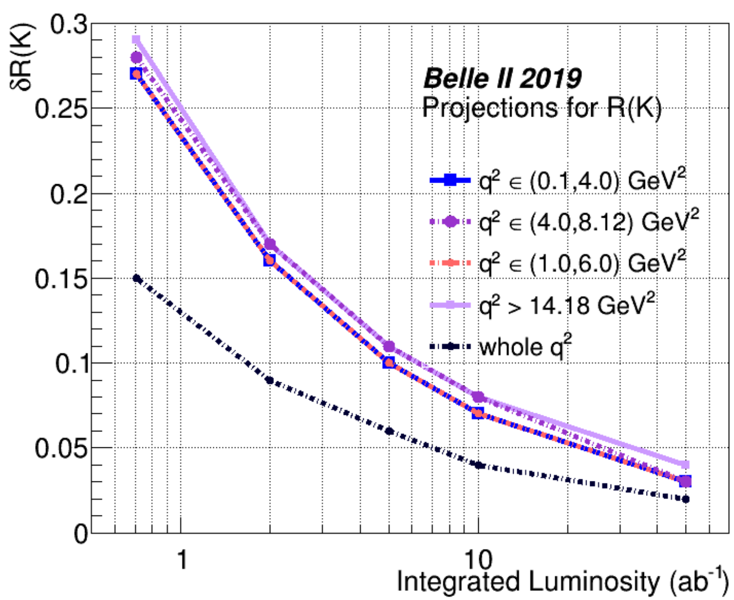


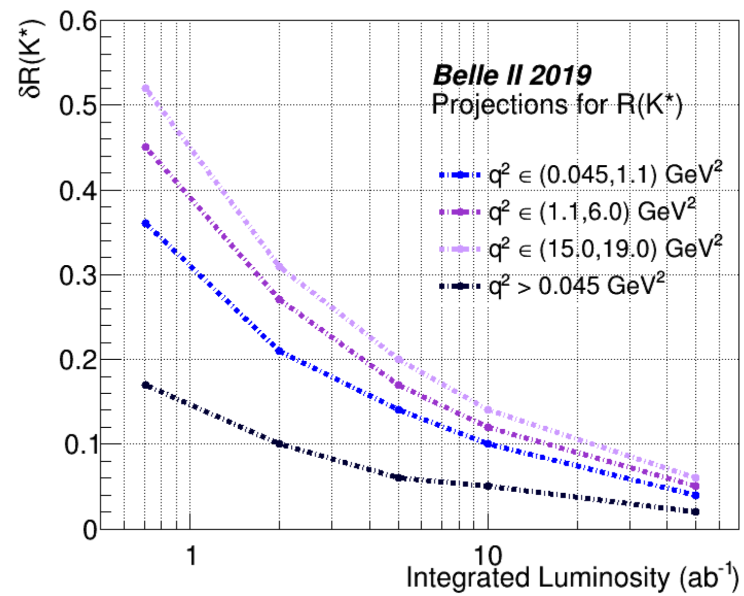




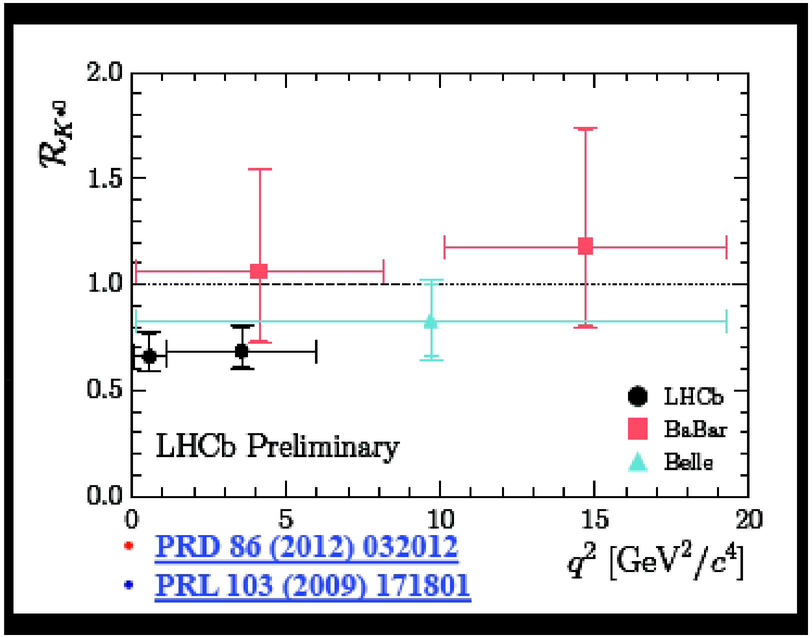


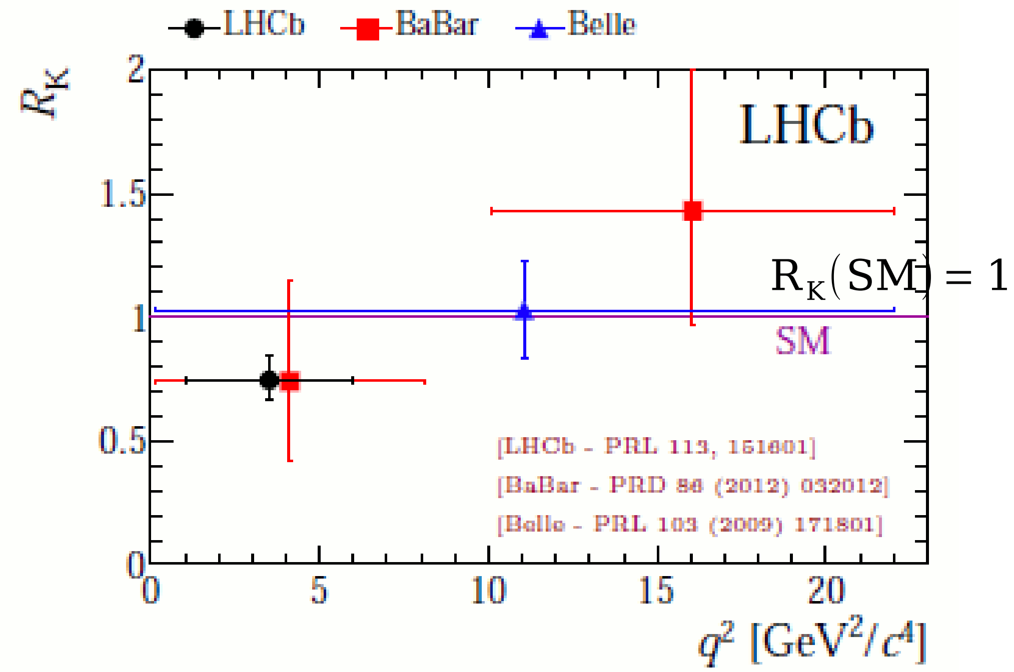






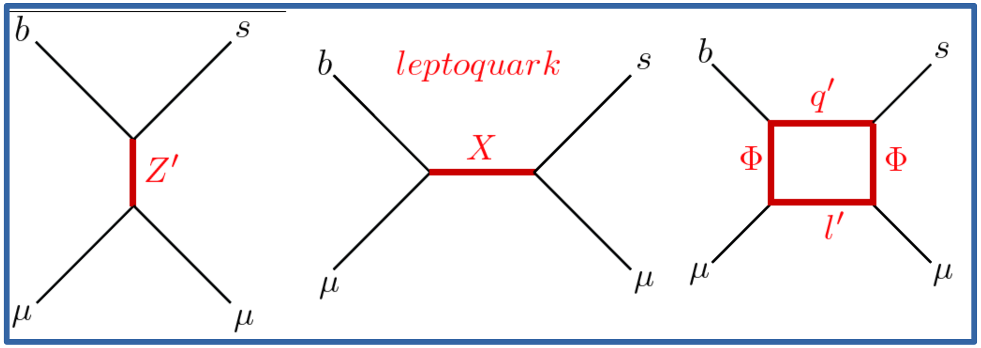
Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays





Model candidates

- ✧ **Model with extended gauge symmetry**
  - ✓ Effective operator from Z' exchange
  - ✓ Extra U(1) symmetry with flavor dependent charge
- ✧ **Models with leptoquarks**
  - ✓ Effective operator from LQ exchange
  - ✓ Yukawa interaction with LQs provide flavor violation
- ✧ **Models with loop induced effective operator**
  - ✓ With extended Higgs sector and/or vector like quarks/leptons
  - ✓ Flavor violation from new Yukawa interactions

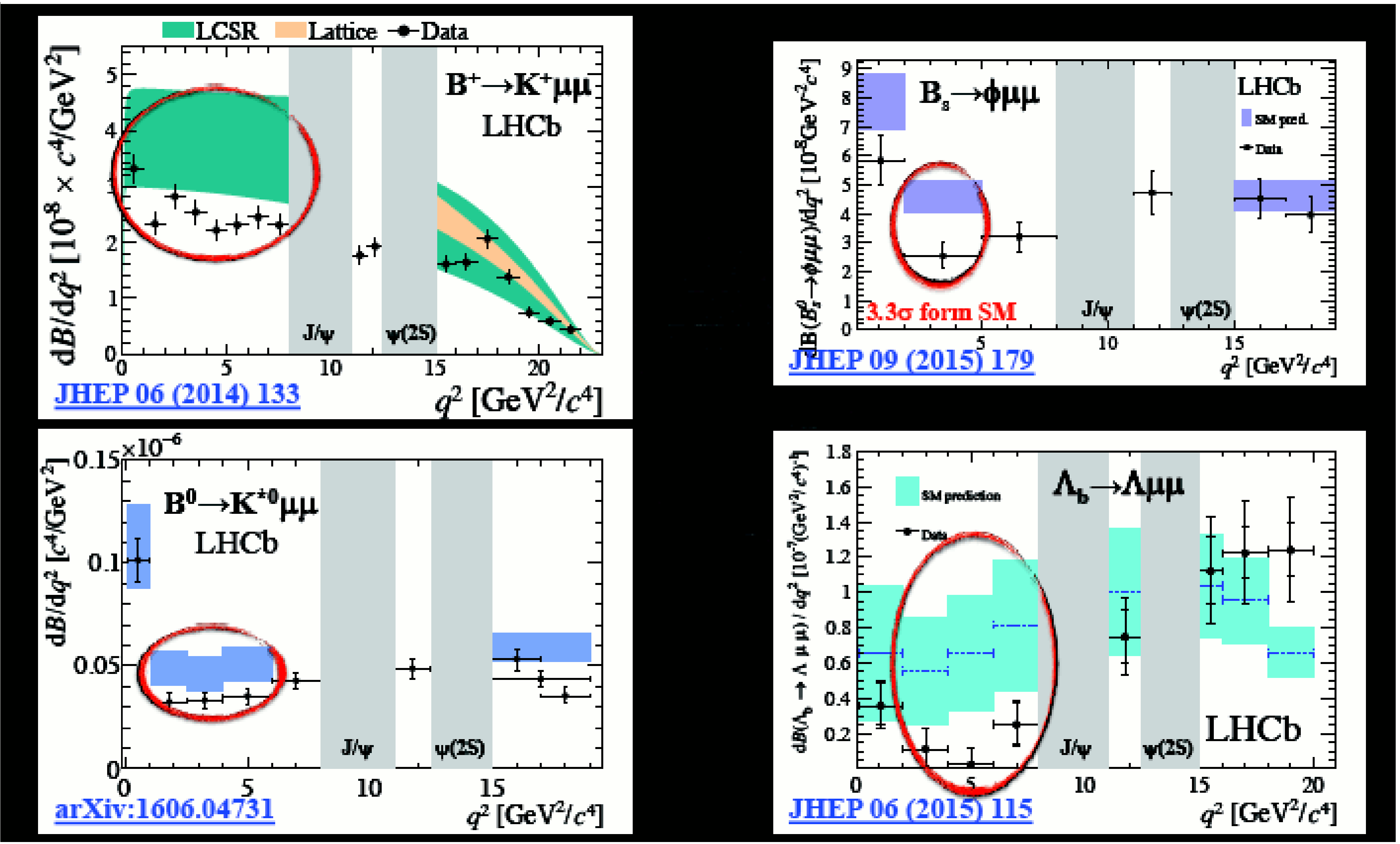


Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

Lot of those models predict also LFV $b \to s e\mu, b \to s e\tau, \ldots$

Differential Branching Fractions

Results consistently lower than SM predictions



Sheldon Stone (LHCb)

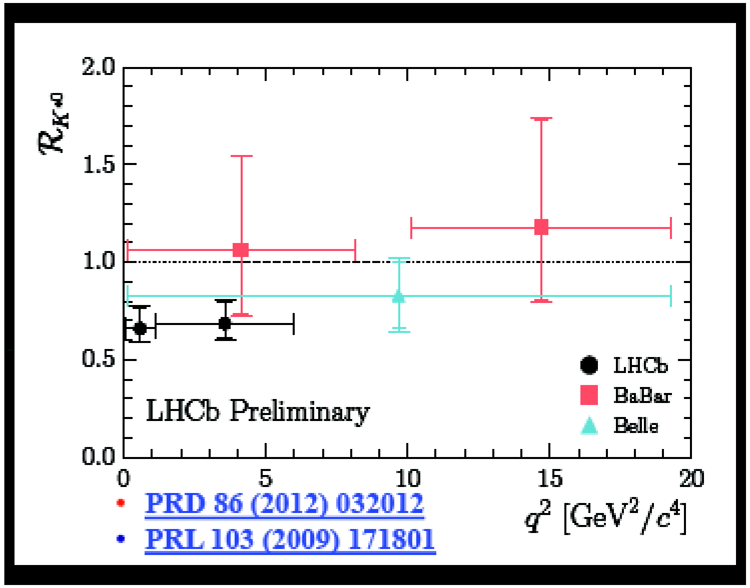
Should we believe LFU violation?

Yes

- R measurements are double ratio's to J/ψ, check with $K^*J/\psi\to{}^{-}e^+e^-/\mu^+\mu^-$ $=1.043\pm0.006\pm0.045$
- $\mathcal{B}(B^-\to K^-e^+e^-)$ agrees with SM prediction, puts onus on muon mode which is well measured and low
- Both R_K & R_{K^*} are different than ~1
- Supporting evidence of effects in angular distributions

No, not yet

- Statistics are marginal in each measurement
- Need confirming evidence in other experiments for R_K & R_{K^*}
- Disturbing that R_{K^*} is not ~1 in lowest q^2, which it should be, because of the photon pole
- Angular distribution evidence is also statistically weak



b → s anomalies

anything else ?

Found by LHCb (and perhaps hinted by Belle)

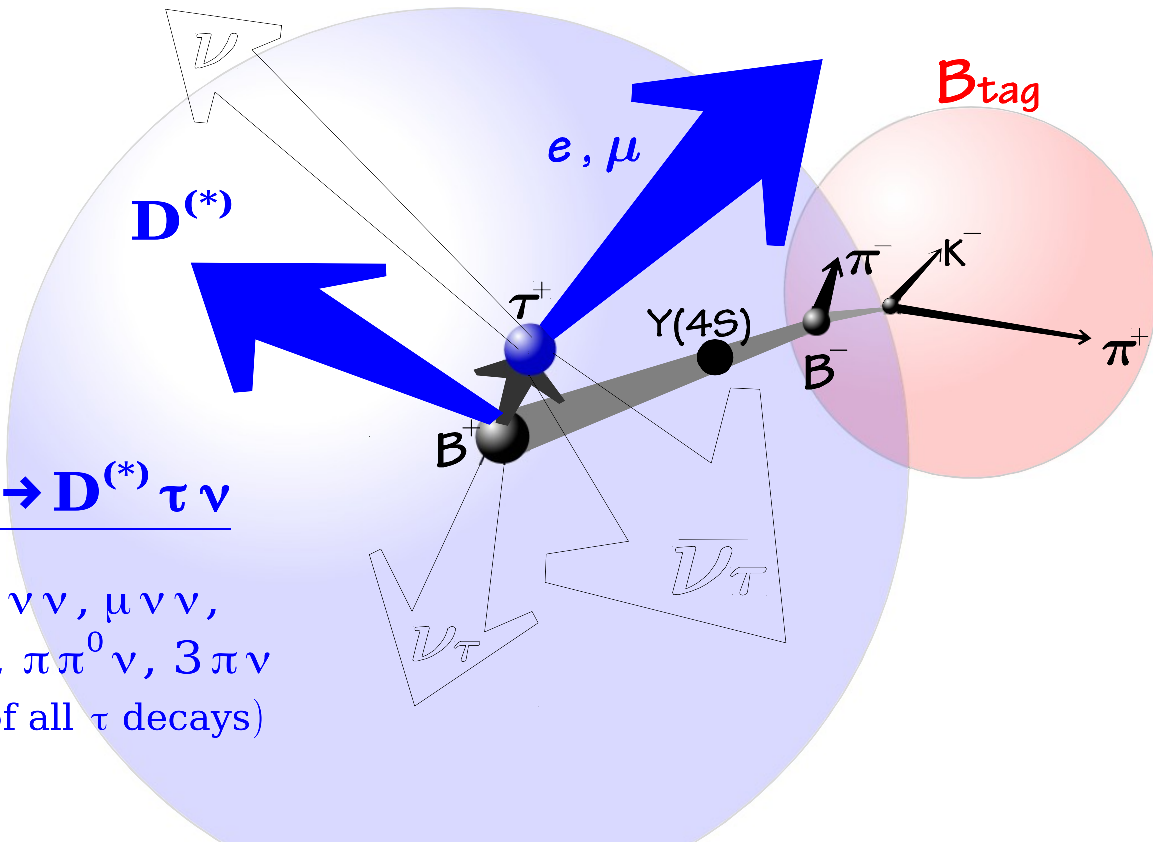
Many observables: global pattern

Neutral current

1-loop (and CKM-suppressed) in the SM

The New Physics can be heavy

Event reconstruction in $B \to D^{(*)} \tau \nu$ at B factories



B_{tag}

hadronic tag

$B \to D^{(*)} \pi,\ D^{(*)} \rho \ldots$

$\epsilon \sim 0.2\,\%$

semileptonic tag

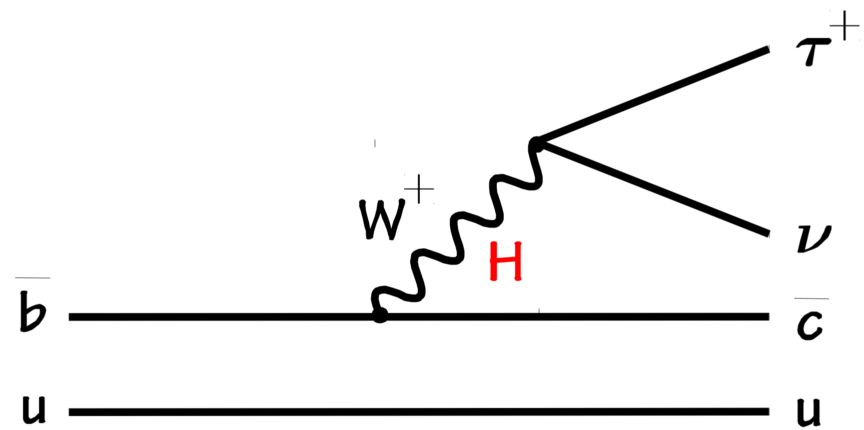
$B \to D^{(*)} l \nu\ X$

$B_{sig} \to D^{(*)} \tau \nu$

$\tau \to e \nu \nu,\ \mu \nu \nu,$

$\tau \to \pi \nu,\ \pi \pi^0 \nu,\ 3 \pi \nu$

(70 % of all τ decays)



Require no particle and no energy left after removing B_{tag} and visible particles of B_{sig}

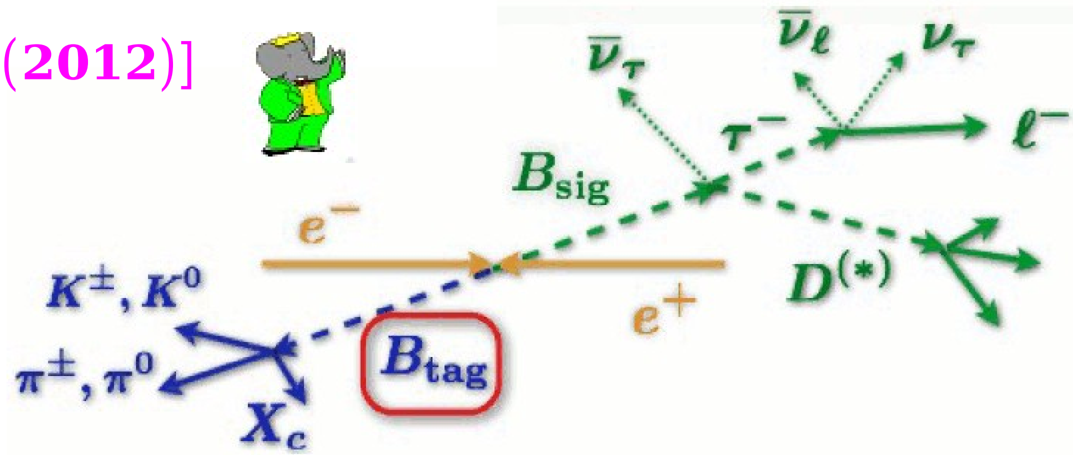
main signal-background discriminator

$$\mathbf{m^2_{miss} = (p_{ee} - p_{tag} - p_{D^{(*)}} - p_l)^2}$$

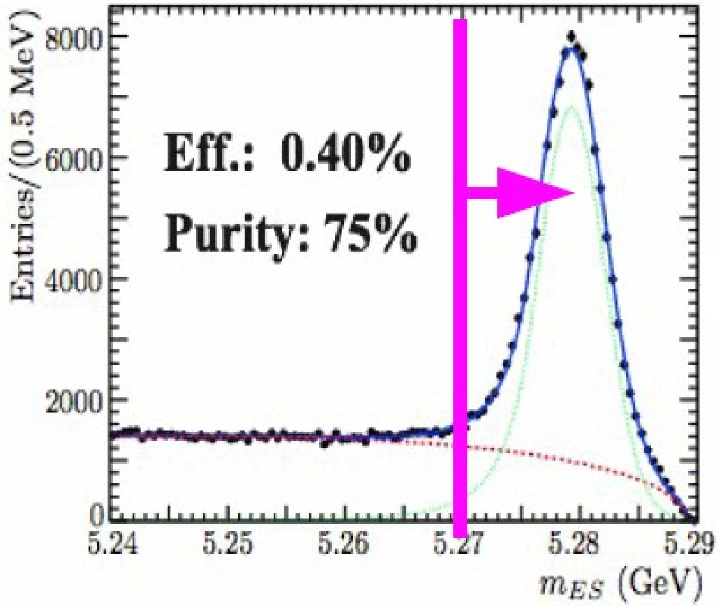
$$2\,\mathrm{HDM\ (type\ II)}:\ \mathcal{B}(B \to D \tau^+ \nu) = G_F^2\, \tau_B\, |V_{cb}|^2 f\left(F_V,\ F_S,\ \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)$$

uncertainties from form factors F_V and F_S can be studied with $B \to D l \nu$ (more form factors in $B \to D^* \tau \nu$)

$B \rightarrow D^{(*)} \tau \nu$ [PRL 109, 101802 (2012)]

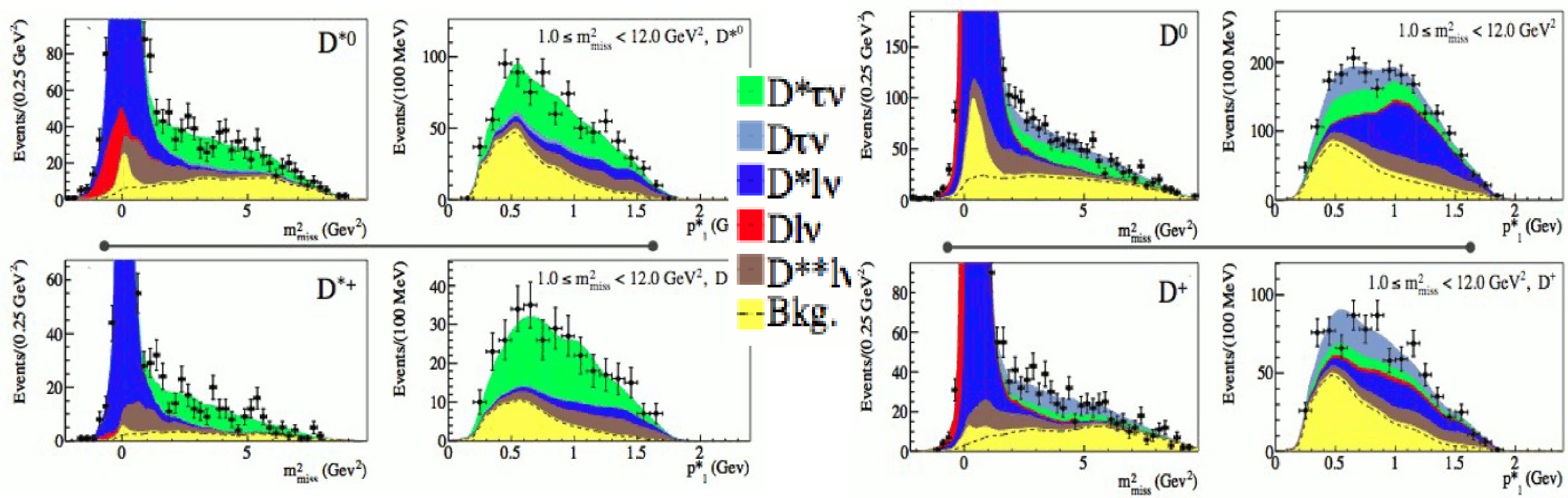


1,768 decay chains

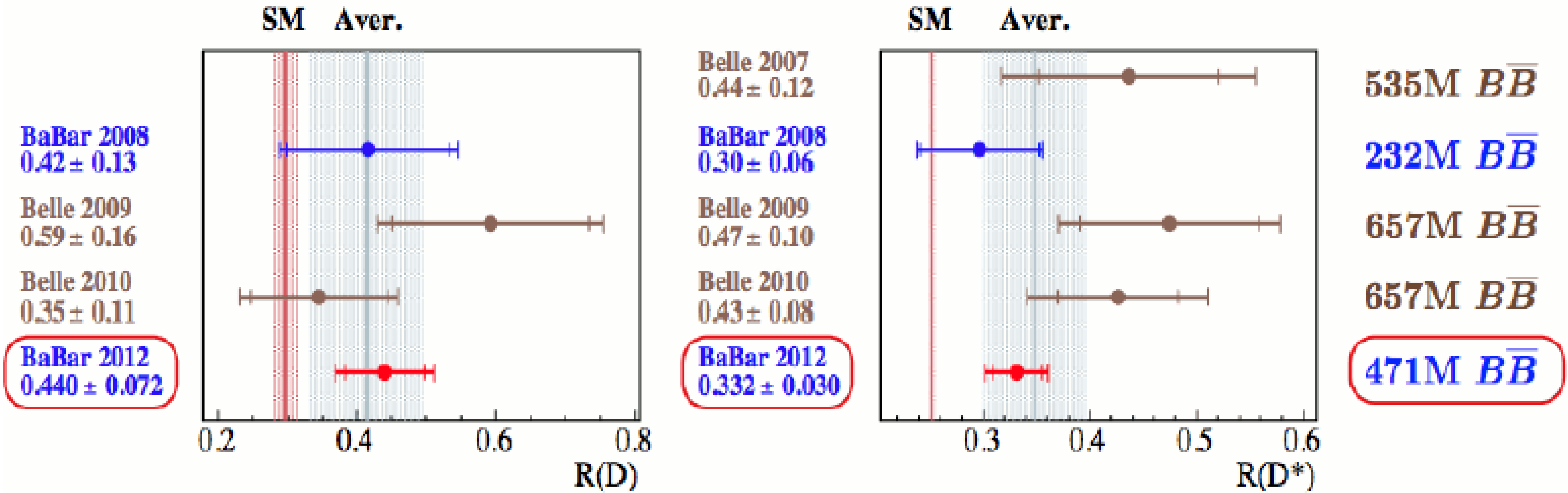


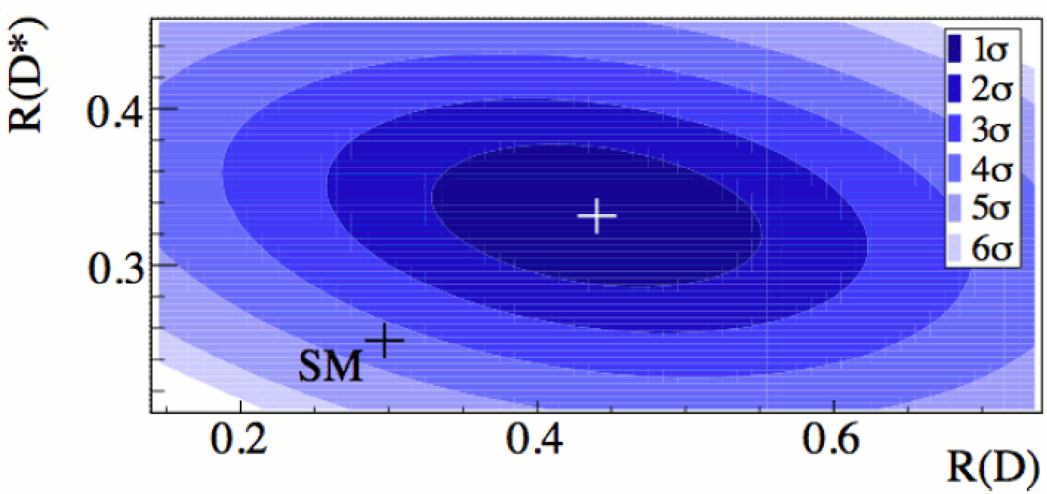
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

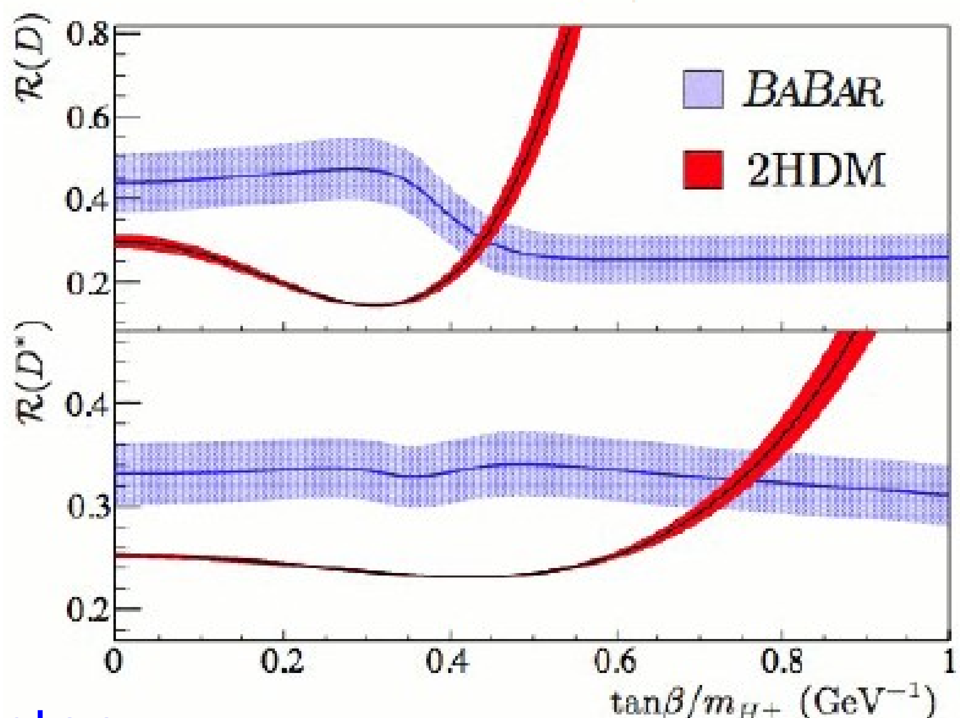
⇒ $D\tau\nu$ and $D^*\tau\nu$ clearly observed



$B \to D^{(*)} \tau \nu$



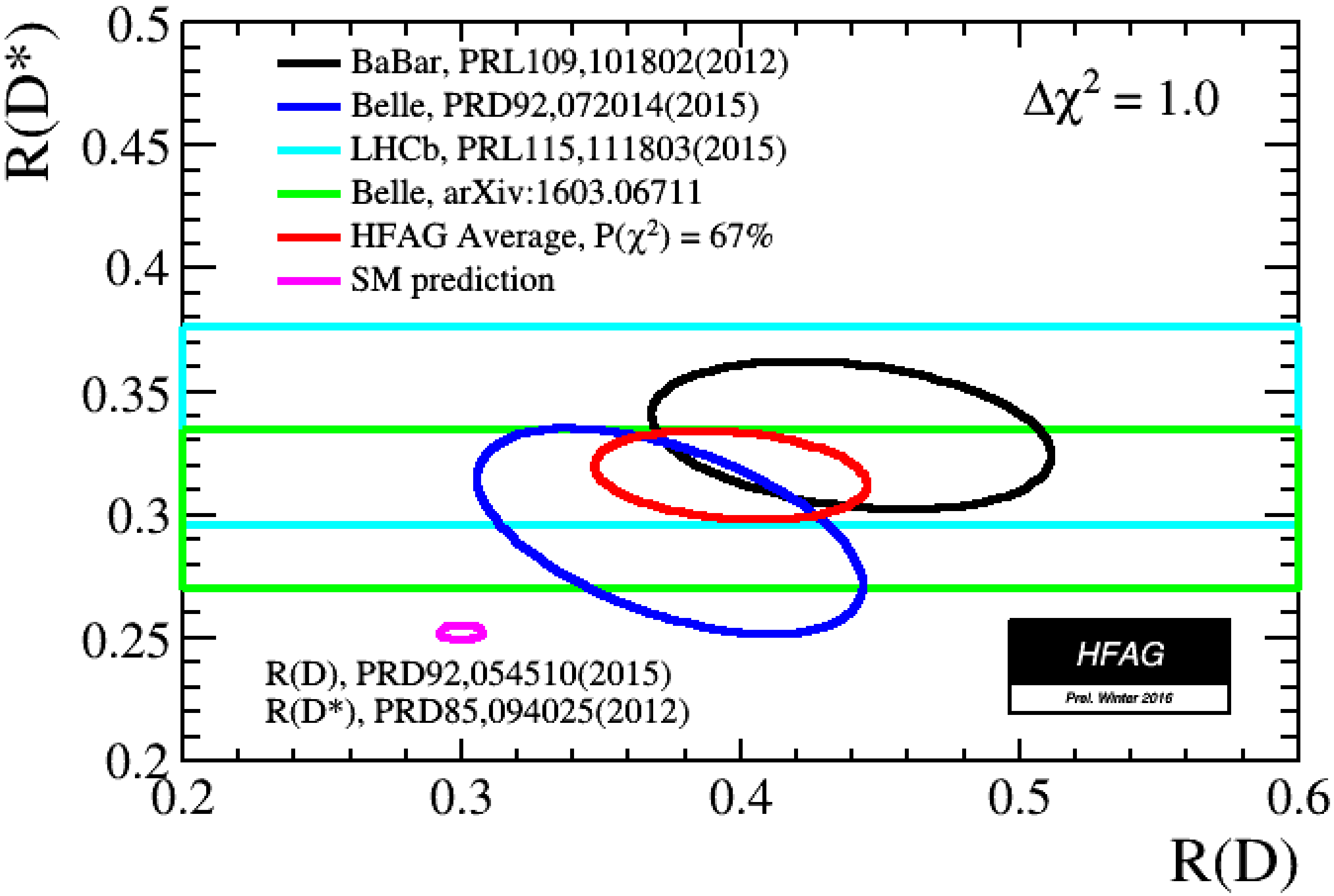




- combined 3.4 σ away from SM
- doesn't fit 2HDM Type II
- Belle will show its new result this winter

Summary for $B \to D^{(*)} \tau \nu$ in 2016

$$\Rightarrow R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$



BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

LHCb

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

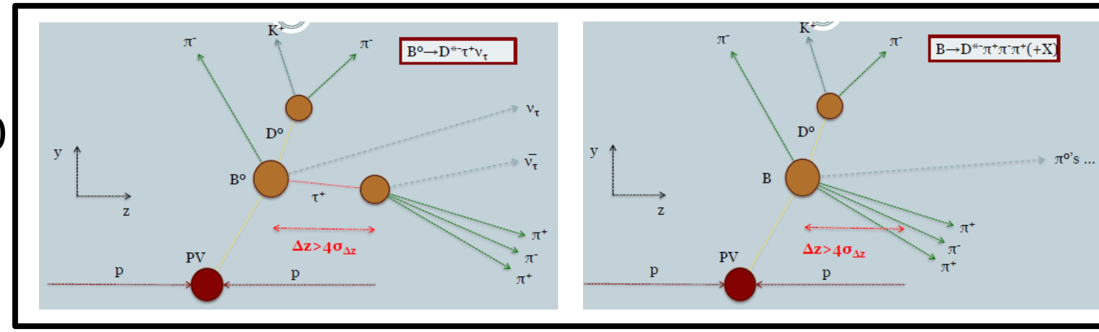
$R(D) = 0.397 \pm 0.040 \pm 0.028$
$R(D^*) = 0.316 \pm 0.016 \pm 0.010$

difference with SM predictions is at **4.0**σ level

$B \to D^{*+} \tau \nu$ at LHCb

$\tau \to 3\pi(\pi^0)$

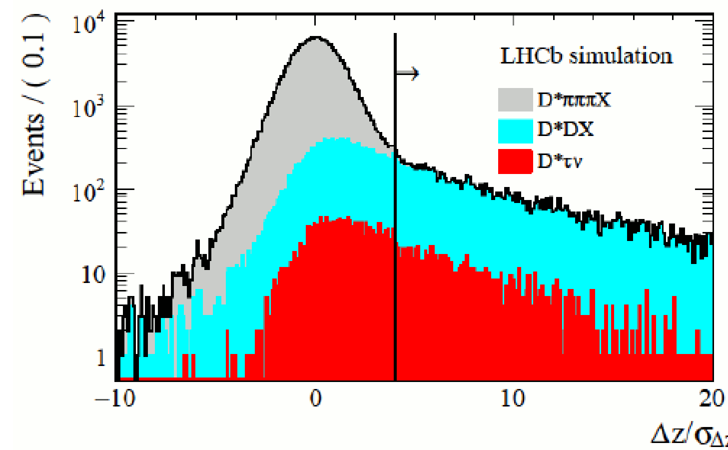
[LHCb-PAPER-2017-017]

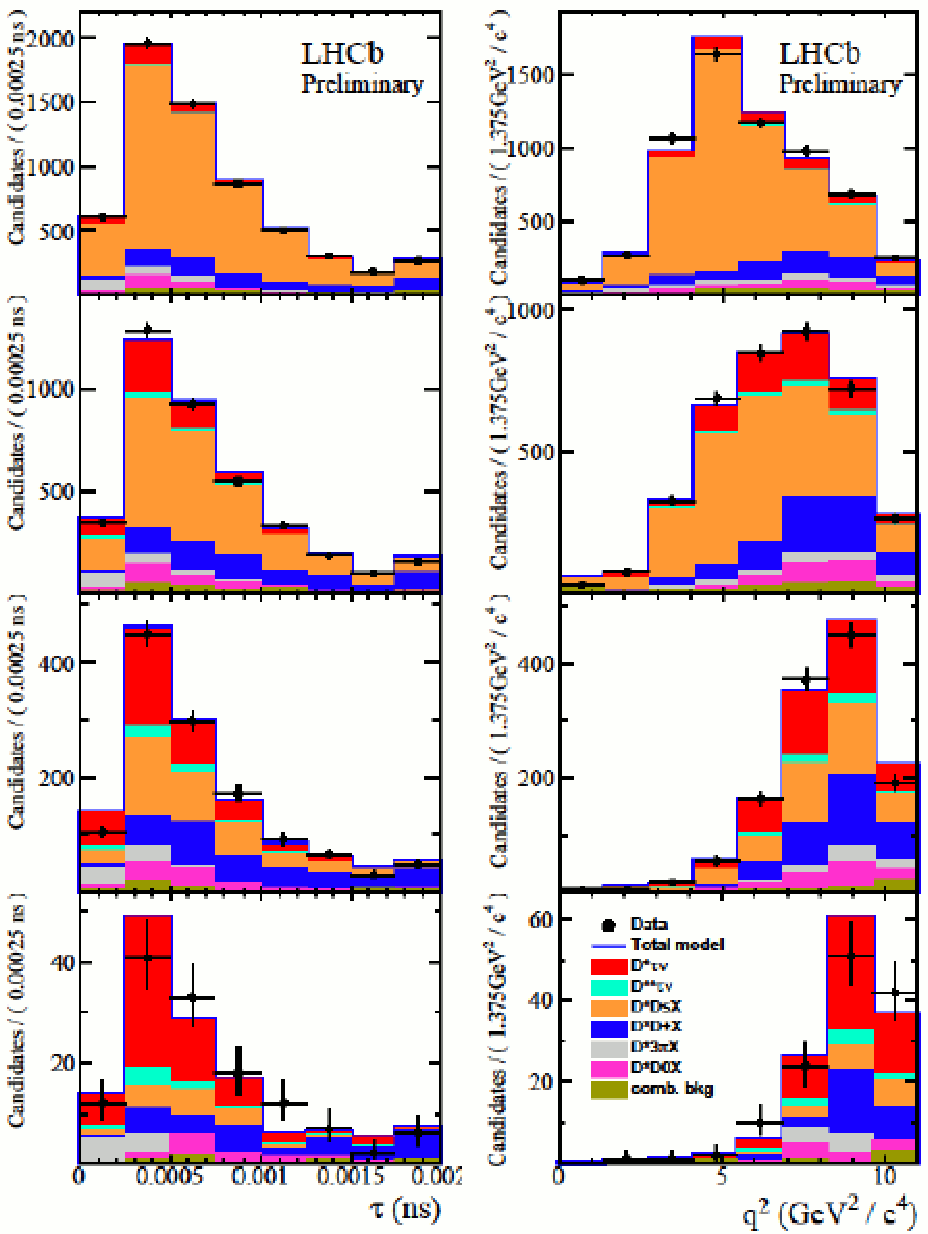


need a strong background suppression:

$\mathcal{B}(B^0 \to D^* 3\pi + X)/\mathcal{B}(B^0 \to D^* \tau\nu;\ \tau \to 3\pi)_{SM} \sim 100$

⇒ detached vertex method





components of 3D fit (q^2, 3π decay time, BDT):

anti-D_s

$\tau \to \pi^-\pi^+\pi^-\nu_\tau,\ \pi^-\pi^+\pi^-\pi^0\nu_\tau$

$X_b \to D^{**}\tau\nu_\tau$

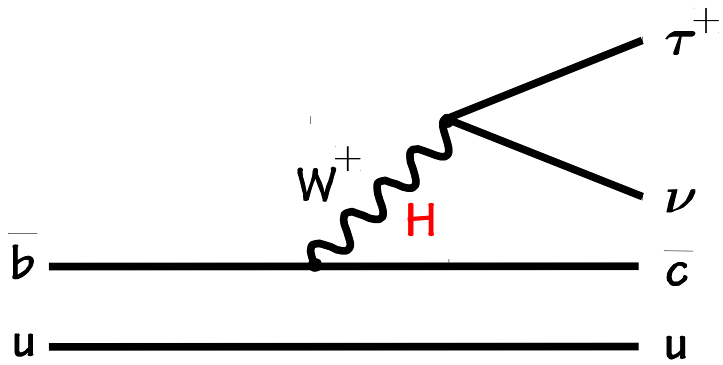
$B \to D D_{s(J)} X$
$X_b \to D D X$
} (relative) yields constrained from control samples

$\mathcal{B}(B^0 \to D^*\tau\nu)/\mathcal{B}(B^0 \to D^* 3\pi) = (1.93 \pm 0.13 \pm 0.17)$

⇒ $R(D^*) = 0.285 \pm 0.019 \pm 0.025 \pm 0.014$

$R(D)$, $R(D^*)$ still at 4σ away from SM

Summary for $B \to D^{(*)} \tau \nu$



$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

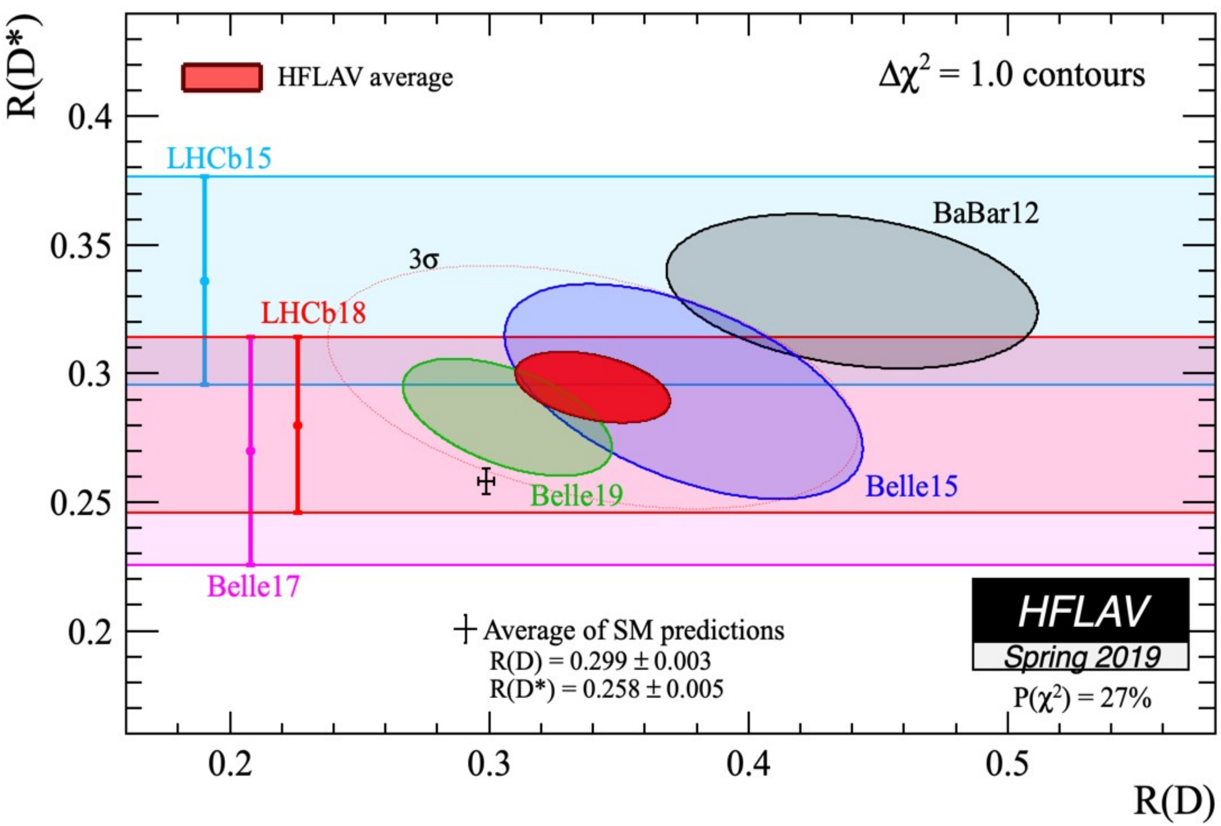
$R(D^*) = 0.270 \pm 0.035\ ^{+0.028}_{-0.025}$

$R(D) = 0.307 \pm 0.037 \pm 0.016$
$R(D^*) = 0.283 \pm 0.018 \pm 0.014$

LHCb

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

$R(D^*) = 0.280 \pm 0.018 \pm 0.029$



average

$R(D) = 0.340 \pm 0.027 \pm 0.013$
$R(D^*) = 0.295 \pm 0.011 \pm 0.008$

difference with SM predictions is at **3σ** level

Hadronic full reconstruction at Belle II

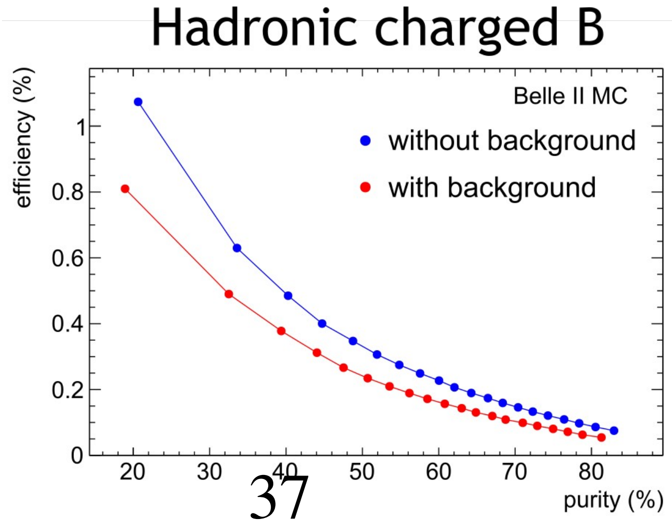
Particle	# channels (Belle)	# channels (Belle II)
$D^+/D^{*+}/D_s^+$	18	26
D^0/D^{*0}	12	17
B^+	17	29
B^0	14	26

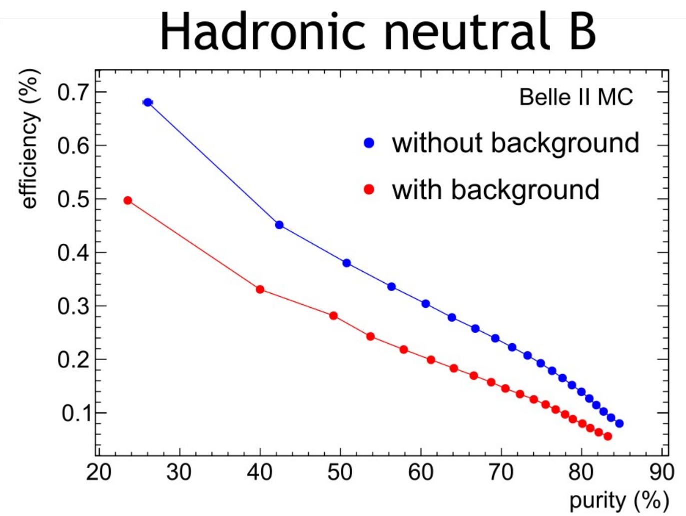
- More modes used for tag-side hadronic B than Belle, multiple classifiers

Algorithm	MVA	Efficiency	Purity
Belle v1 (2004)	Cut based (Vcb)		
Belle v3 (2007)	Cut based	0.1	0.25
Belle NB (2011)	Neurobayes	0.2	0.25
Belle II FEI (2017)	Fast BDT	0.5	0.25

Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:



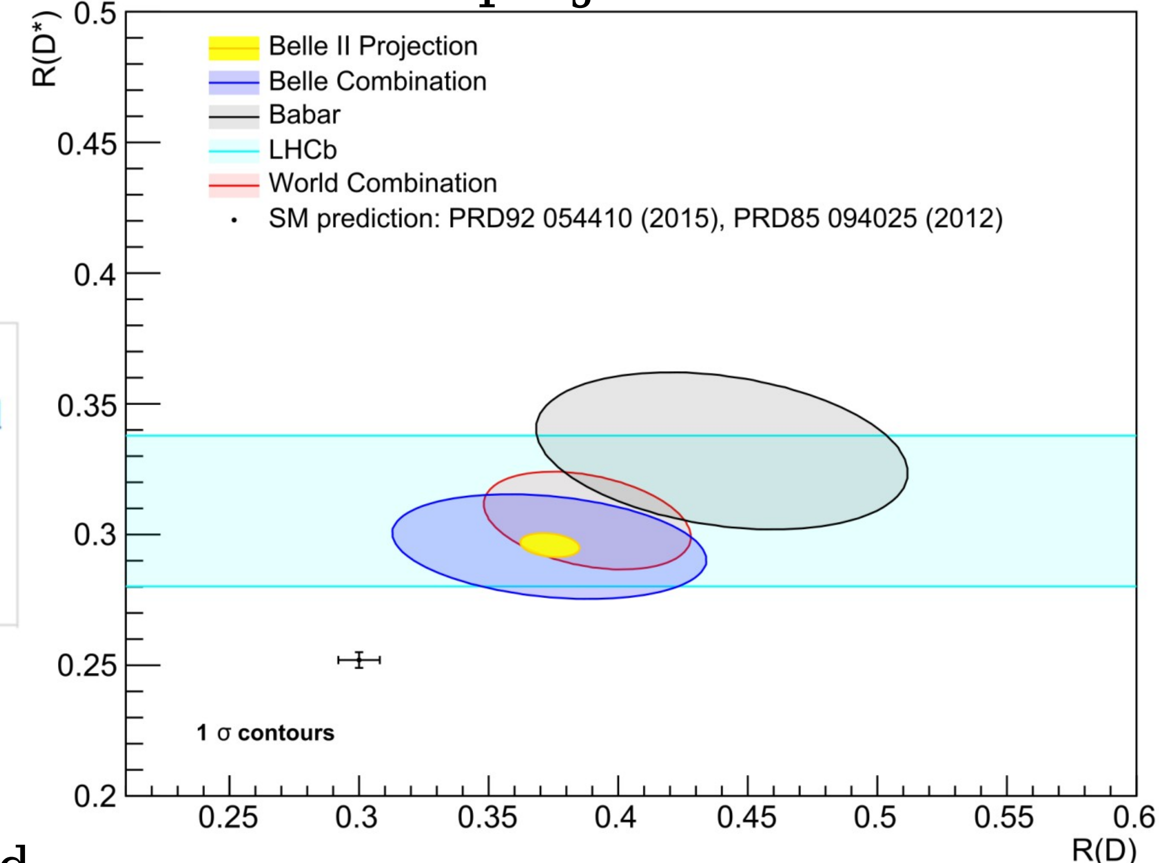


Projections for Belle II $R(D^{(*)})$

Predictions of uncertainty using hadronic full reconstruction:

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

projection for 50 ab^{-1}



Systematic uncertainty dominated by D^{**} and missed soft pions:

- Studies of $D^{**} l \nu$ and $D^{**} \tau \nu$ planned
- Branching ratios and decay modes from data

Other observables from $B \to D^{(*)} \tau \nu$

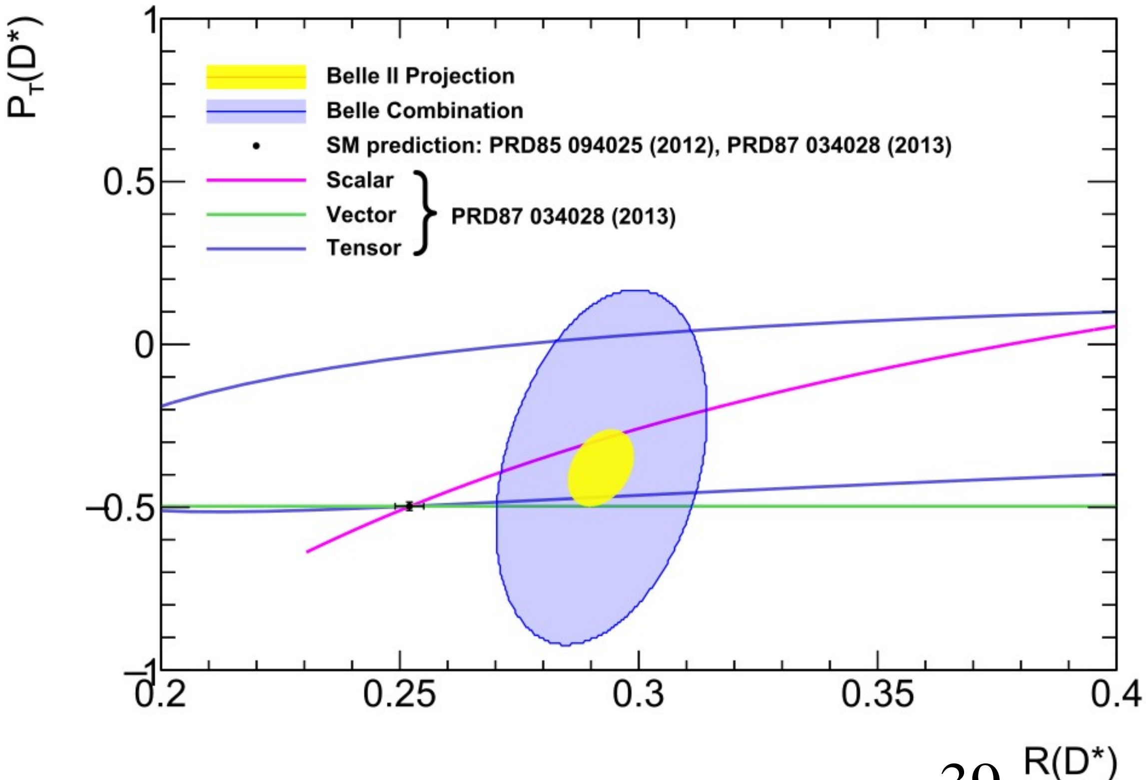
Additional observables as $P_\tau(D^*)$ ($F_L(D^*)$) and q^2 distribution can help discriminate between New Physics models

[Belle, arXiv:1612.00529]

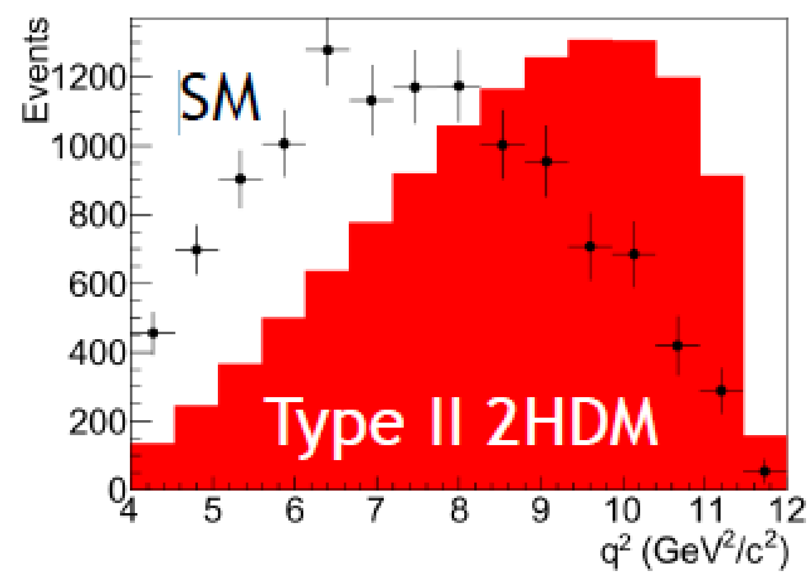
$$P_\tau(D^*) = -0.38 \pm 0.51 \,^{+0.21}_{-0.16}$$

Projections for $P_\tau(D^*)$ at Belle II

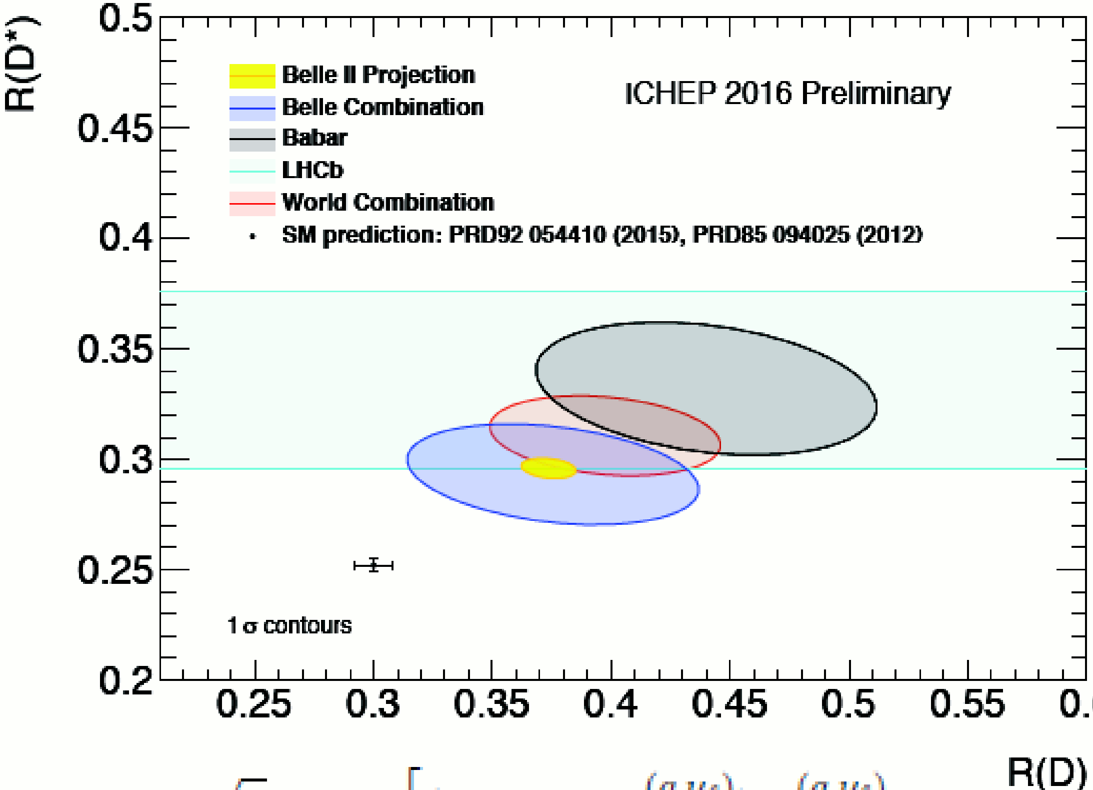
$P_\tau(D^*)$	Stat. uncertainty	Sys. uncertainty
at 5 ab^{-1}	0.18	0.08
at 50 ab^{-1}	0.06	0.04



q^2 spectrum $B \to D^* \tau\nu$ 50ab^{-1} projection



$B \to D^{(*)} \tau \nu$ and other observables



$$R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}, \text{ in red}$$

$$R_{ps} = \frac{\tau_{B^0}}{\tau_{B^-}} \frac{B(B \to \tau^- \nu)}{B(B \to \pi^+ l^- \nu)}, \text{ in blue}$$

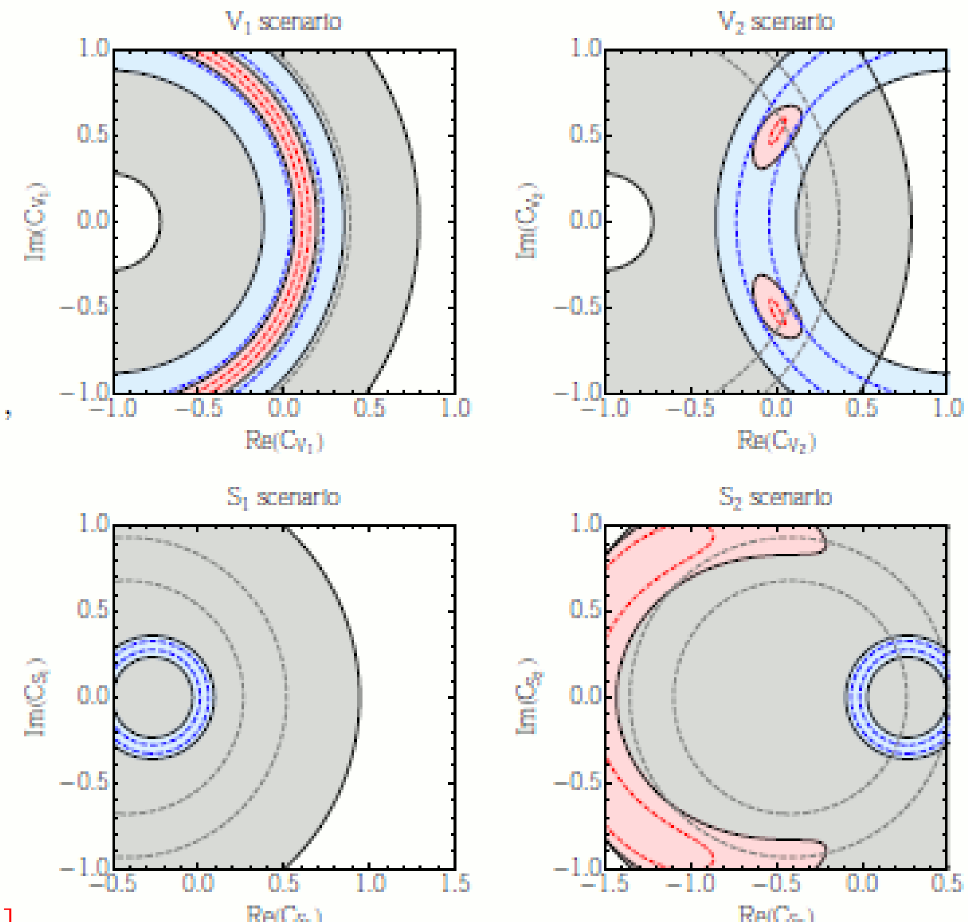
$$R(\pi) = \frac{B(B \to \pi \tau \nu)}{B(B \to \pi l \nu)}, \text{ in grey}$$

Dashed : Belle II

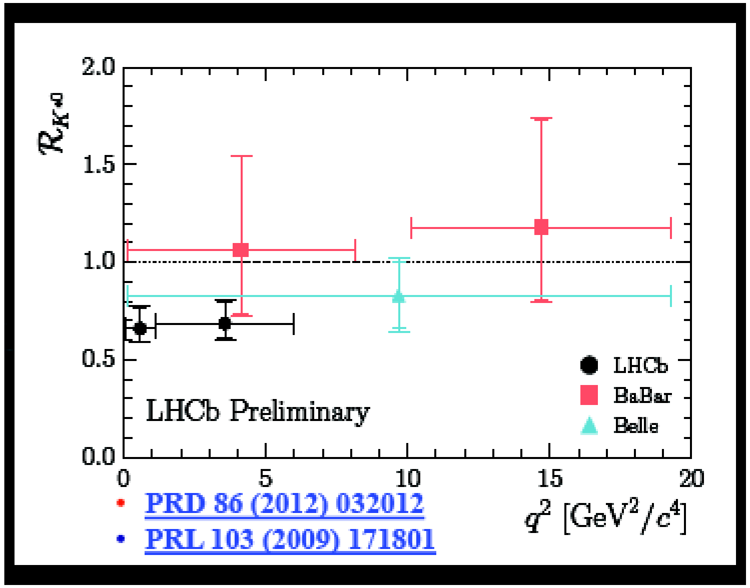
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{qb} \Big[(\delta_{\nu_\tau,\nu_\ell} + C_{V_1}^{(q,\nu_\ell)}) \mathcal{O}_{V_1}^{(q,\nu_\ell)} + \sum_{X=}^{V_2,S_1,S_2,T} C_X^{(q,\nu_\ell)} \mathcal{O}_X^{(q,\nu_\ell)} \Big],$$

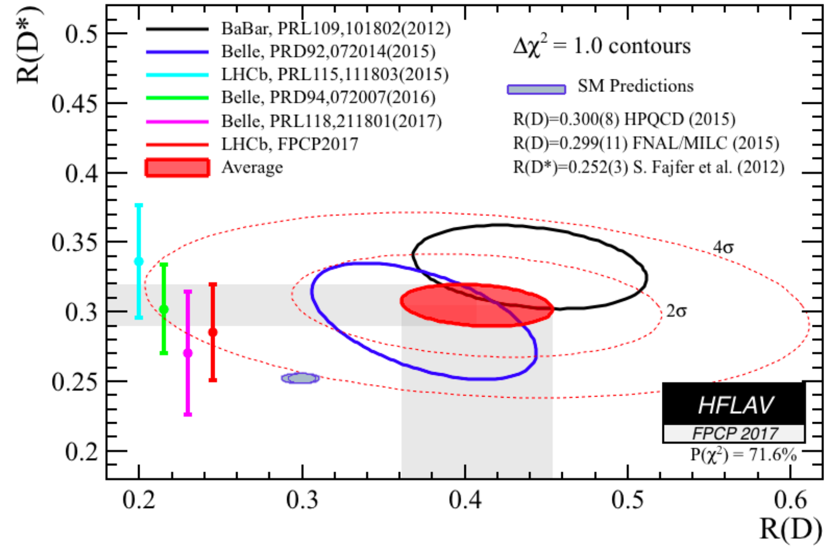
where the four-Fermi operators:

$$\mathcal{O}_{V_1}^{(q,\nu_\ell)} = (\bar{q}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\ell),$$
$$\mathcal{O}_{V_2}^{(q,\nu_\ell)} = (\bar{q}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\ell),$$
$$\mathcal{O}_{S_1}^{(q,\nu_\ell)} = (\bar{q} P_R b)(\bar{\tau} P_L \nu_\ell),$$
$$\mathcal{O}_{S_2}^{(q,\nu_\ell)} = (\bar{q} P_L b)(\bar{\tau} P_L \nu_\ell),$$
$$\mathcal{O}_{T}^{(q,\nu_\ell)} = (\bar{q}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\ell)$$



[Details in Watanabe et al, B2TiP theory]





b → s anomalies

b → c anomalies

Found by LHCb (and perhaps hinted by Belle)

Many observables: global pattern

Neutral current

1-loop (and CKM-suppressed) in the SM

The New Physics can be heavy

Found by several experiments (LHCb, BaBar and Belle)

Two observables: R(D) and R(D*)

Charged current

Tree-level in the SM

The New Physics must be light

Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays

Model candidates

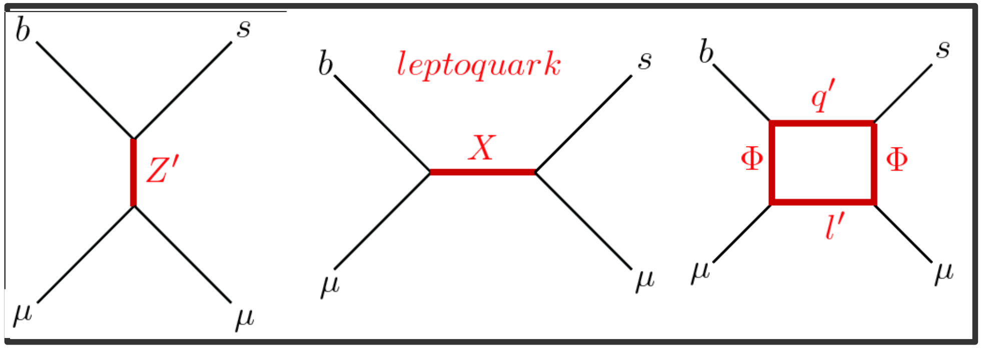
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ Models with leptoquarks

- ✓ Effective operator from LQ exchange
- ✓ Yukawa interaction with LQs provide flavor violation

✧ Models with loop induced effective operator

- ✓ With extended Higgs sector and/or vector like quarks/leptons
- ✓ Flavor violation from new Yukawa interactions



Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

Lot of those models predict also LFV $b \to s e\mu$, $b \to s e\tau$, ...

G.Isidori, FPCP 2020: correlations among $b \to s(d) l l'$ within the U(2)-based EFT

	μμ (ee)	ττ
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [R_K=R_π]	$B \to \pi \tau\tau$ → 100×SM

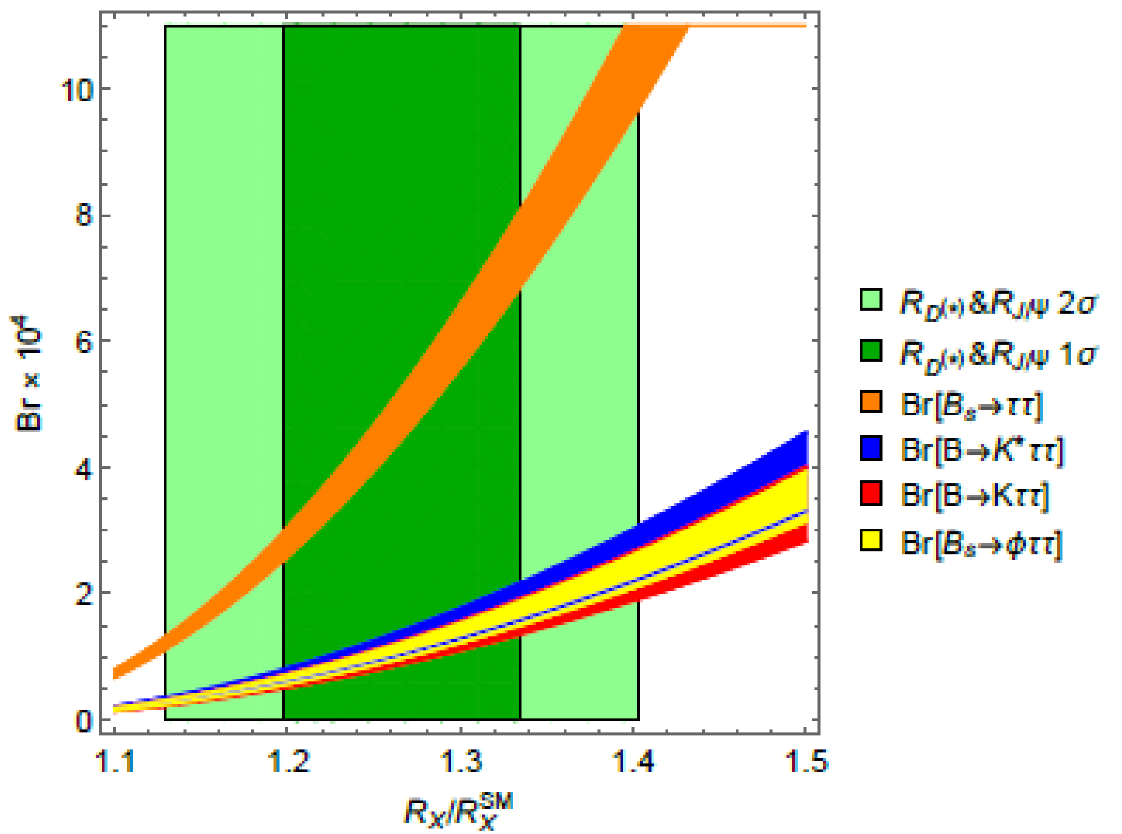
$B \to K^{(*)} \tau \tau$

[B.Capdevila et al, arXiv:1712.01919]

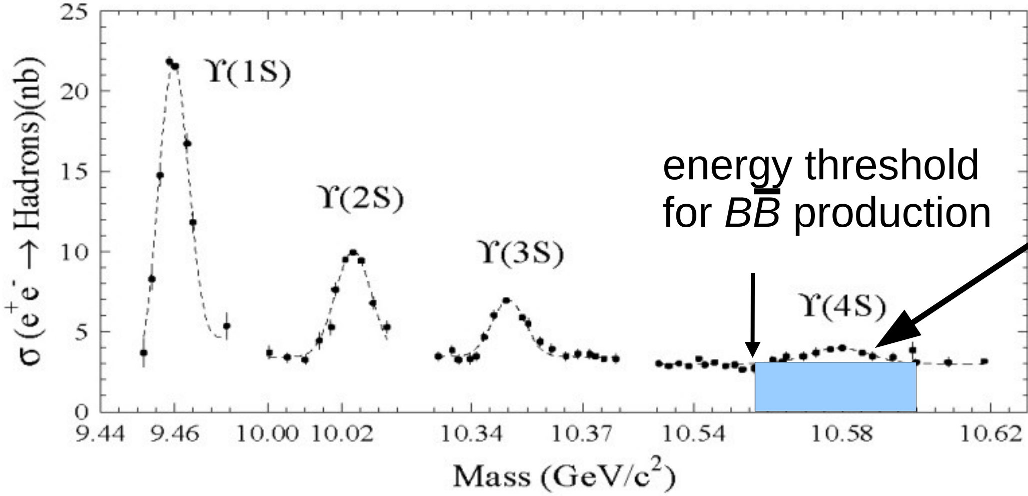
q^2 range for predictions for $B \to H \tau^+ \tau^-$: from $4\, m_\tau^2$ (~ 12.6 GeV^2) to $(m_B - m_H)^2$
to avoid contributions from resonant decay
through $\psi(2S)$, $B \to H \psi(2S)$, $\psi(2S) \to \tau^+ \tau^-$
predictions restricted to $q^2 > 15$ GeV^2:

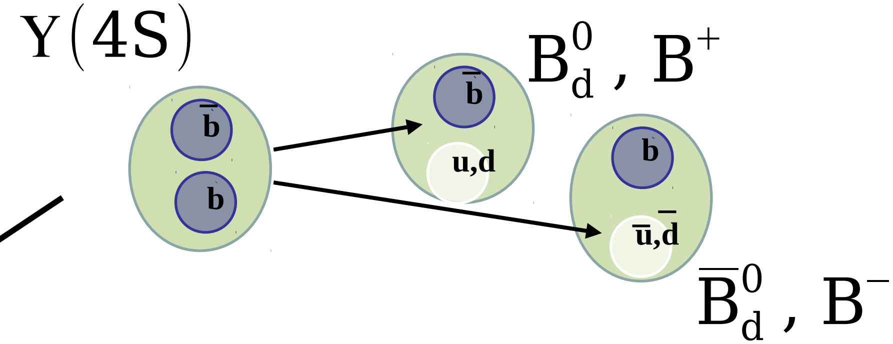
$B(B \to K \tau^+ \tau^-)_{SM} = (1.2 \pm 0.1)\, 10^{-7}$
$B(B \to K^* \tau^+ \tau^-)_{SM} = (1.0 \pm 0.1)\, 10^{-7}$

greatly enhanced in NP models…

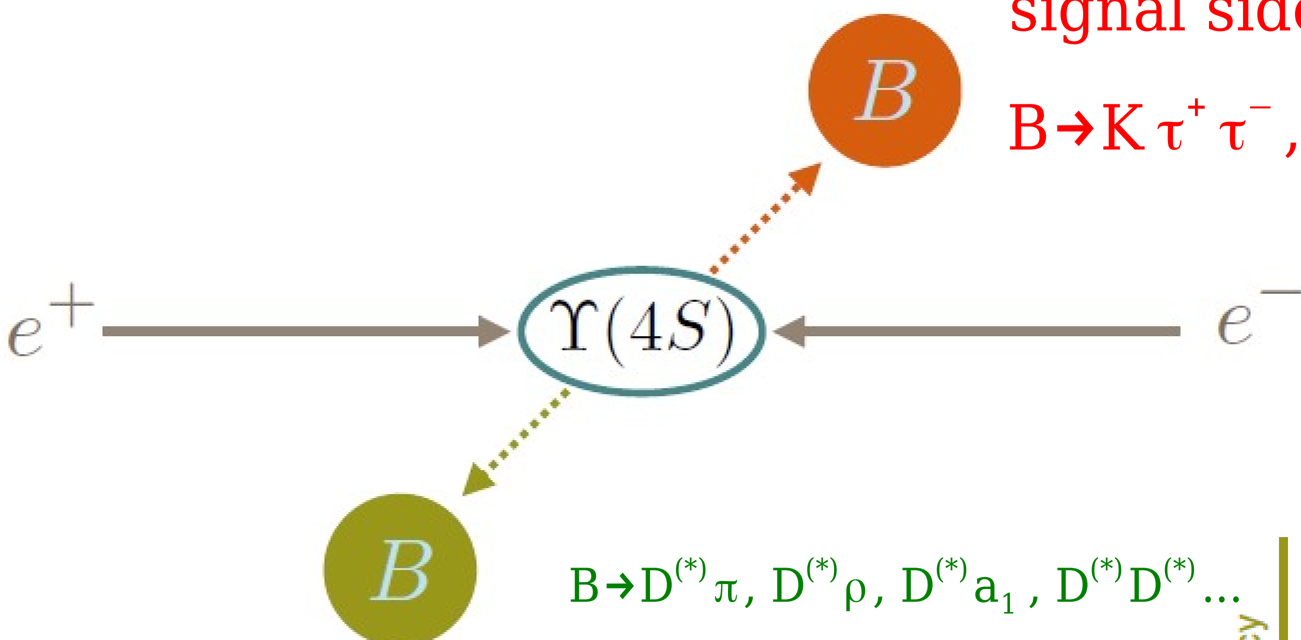


$B \to K^{(*)} \tau \tau$





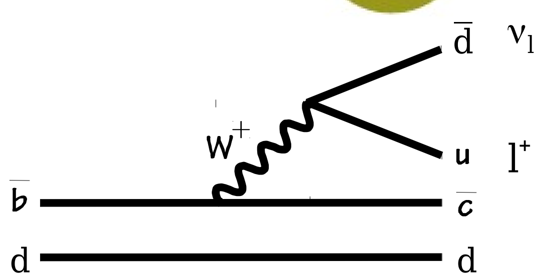
signal side

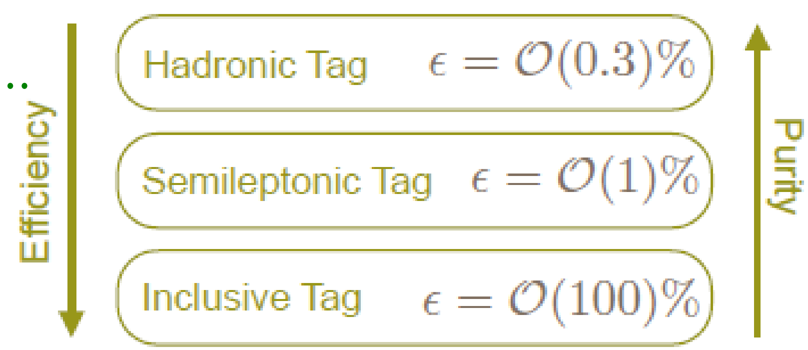


$B \to K \tau^+ \tau^-$, $\tau^+ \to \mu^+ \nu \nu$, $\tau^- \to e^- \nu \nu$

$B \to D^{(*)}\pi$, $D^{(*)}\rho$, $D^{(*)}a_1$, $D^{(*)}D^{(*)}$...

$B \to D^{(*)}e\nu$, $D^{(*)}\mu\nu$...





$B \to K^{(*)}\tau\tau$

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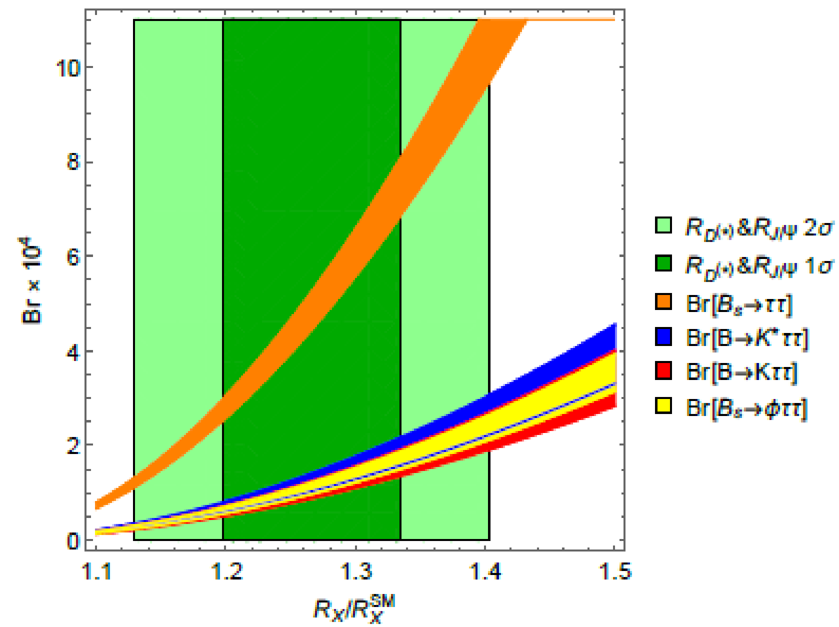
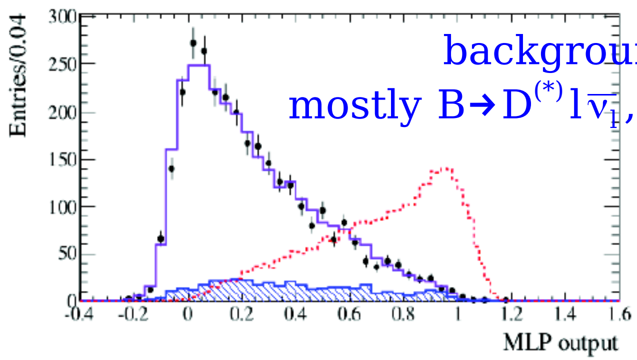


$$B(B \to K\tau^+\tau^-)_{SM} = (1.2 \pm 0.1)\,10^{-7}$$
$$B(B \to K^*\tau^+\tau^-)_{SM} = (1.0 \pm 0.1)\,10^{-7}$$

strategy used: [BaBar, arXiv:1605.09637]
B fully reconstructed (had tag), $\tau^+ \to l^+ \nu_l \nu_\tau$



background:
mostly $B \to D^{(*)} l \overline{\nu_l}$, $D^{(*)} \to K l' \overline{\nu_{l'}}$

BaBar's result with had tag: $B(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at 90%CL

[Belle II, arXiv:1808.10567]

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0

Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays

Model candidates

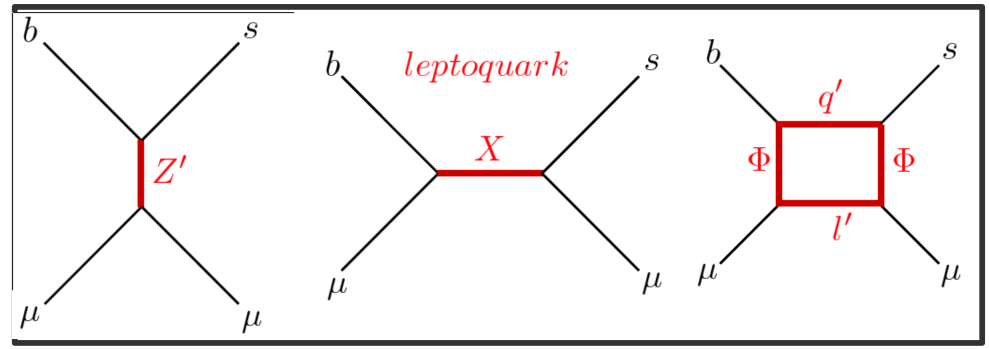
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **Models with leptoquarks**

- ✓ Effective operator from LQ exchange
- ✓ Yukawa interaction with LQs provide flavor violation

✧ **Models with loop induced effective operator**

- ✓ With extended Higgs sector and/or vector like quarks/leptons
- ✓ Flavor violation from new Yukawa interactions



Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

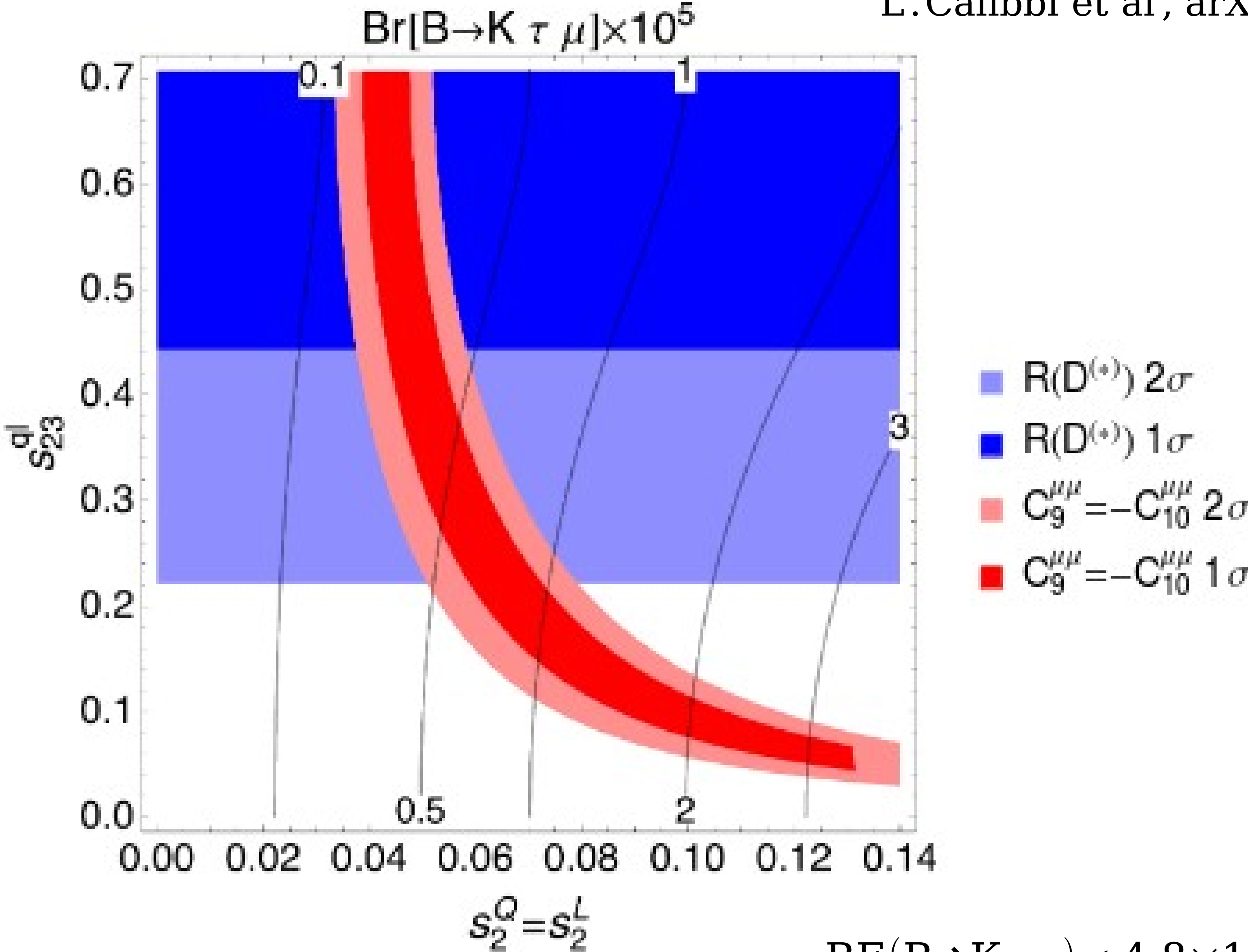
Lot of those models predict also LFV $b \to se\mu$, $b \to se\tau$, ...

G.Isidori, FPCP 2020: correlations among $b \to s(d)ll'$ within the U(2)-based EFT

	μμ (ee)	ττ	νν	τμ	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ → 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ → 10^{-6}	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) $[R_K=R_\pi]$	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → 10^{-7}	$B \to \pi \mu e$???

$R(D^*)$ and $b \to s\mu\mu$

L. Calibbi et al, arXiv:1709.00692



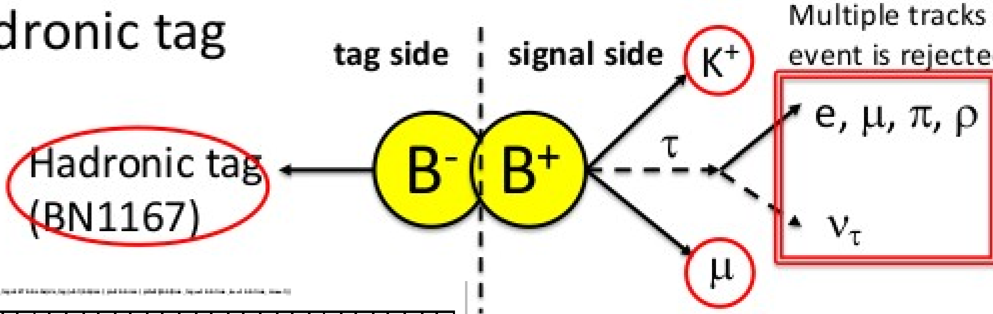
$BF(B \to K\tau\mu) < 4.8 \times 10^{-5}$ @ 90% CL
BaBar, arXiv:1204.2852
hadronic tag

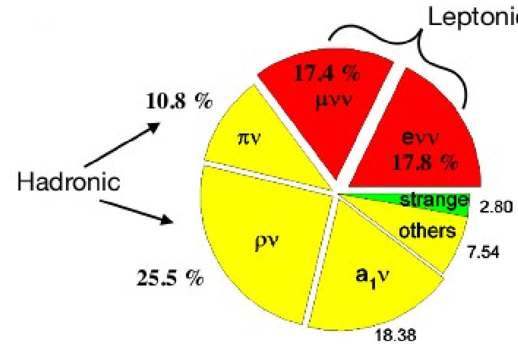
LFV $B \to K \tau l$ ($l = e, \mu$) decays

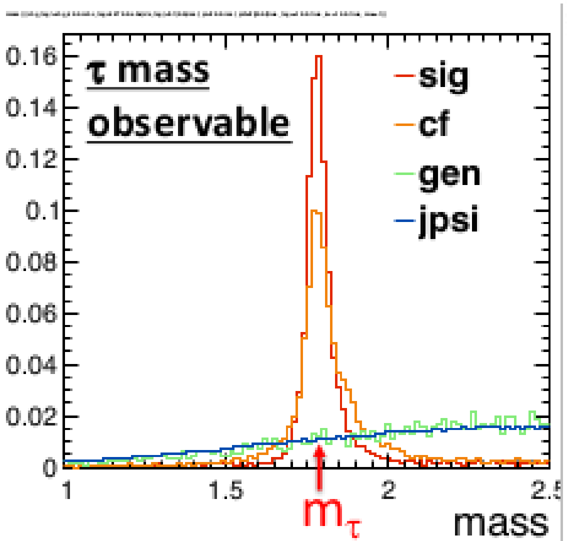
focus on K (K^+ or K^0_S), $\tau \to e\nu\nu, \mu\nu\nu, \pi\nu, \rho\nu$

[Belle & Belle II]

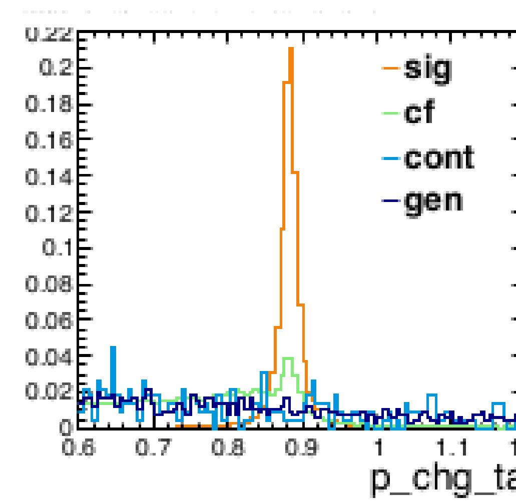
- Hadronic tag



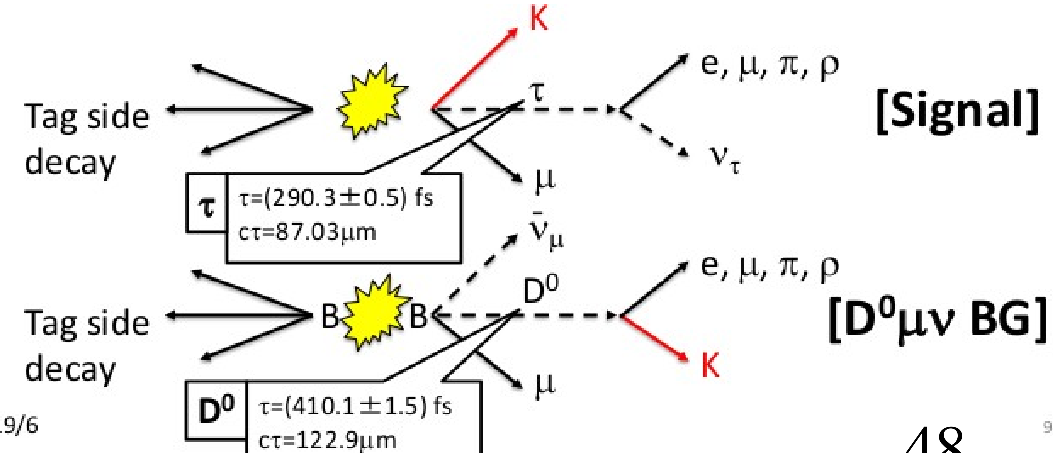


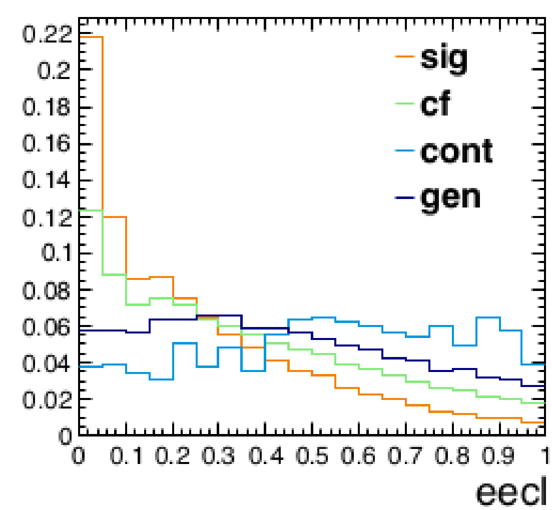


- For $\tau \to \pi\nu$, $\rho\nu$ channel, kinematic cut is useful to suppress BG.
- $\tau \to \pi\nu$
  - Monochromatic momentum of π in τ rest frame
- $\tau \to \rho\nu \to \pi\pi^0\nu$
  - Monochromatic momentum of ρ in τ rest frame
  - Invariant mass of $\pi\pi^0$



dominant BG is $B^+ \to D^{(*)0}\mu\nu$ (e.g. $(K\pi X)_D \mu\nu$ in $\tau \to \pi\nu$ case)





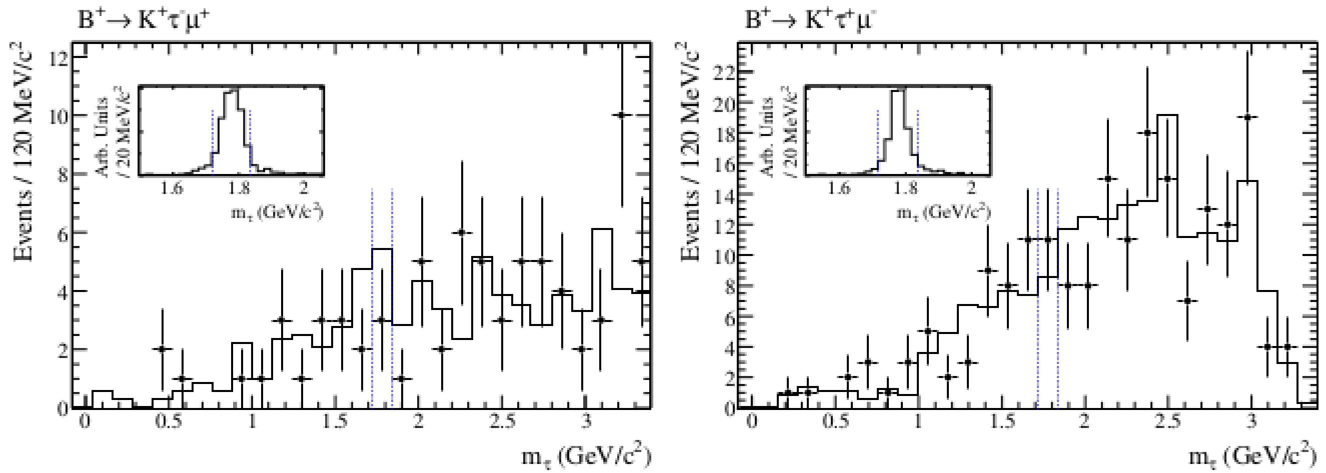
LFV $B \to K \tau l$ ($l = e, \mu$) decays

[BaBar, arXiv:1204.2852]

strategy used: B fully reconstructed (had tag), $\tau^+ \to l^+ \nu_l \nu_\tau$, $(n\pi^0)\pi\nu$, with $n \geq 0$

using momenta of K, l and B, **can fully determine the τ four-momentum**

unique system: no other neutrino than the ones from one tau ($\neq B \to \tau\nu$, $D^{(*)}\tau\nu$...)



$B(B^+ \to K^+ \tau^- \mu^+) < 4.5 \times 10^{-5}$ at 90%CL, $B(B^+ \to K^+ \tau^+ \mu^-) < 2.8 \times 10^{-5}$ at 90%CL

(also results for $B \to K^+ \tau^\pm e^\mp$, $B \to \pi^+ \tau^\pm \mu^\mp$, $B \to \pi^+ \tau^\pm e^\mp$ modes)

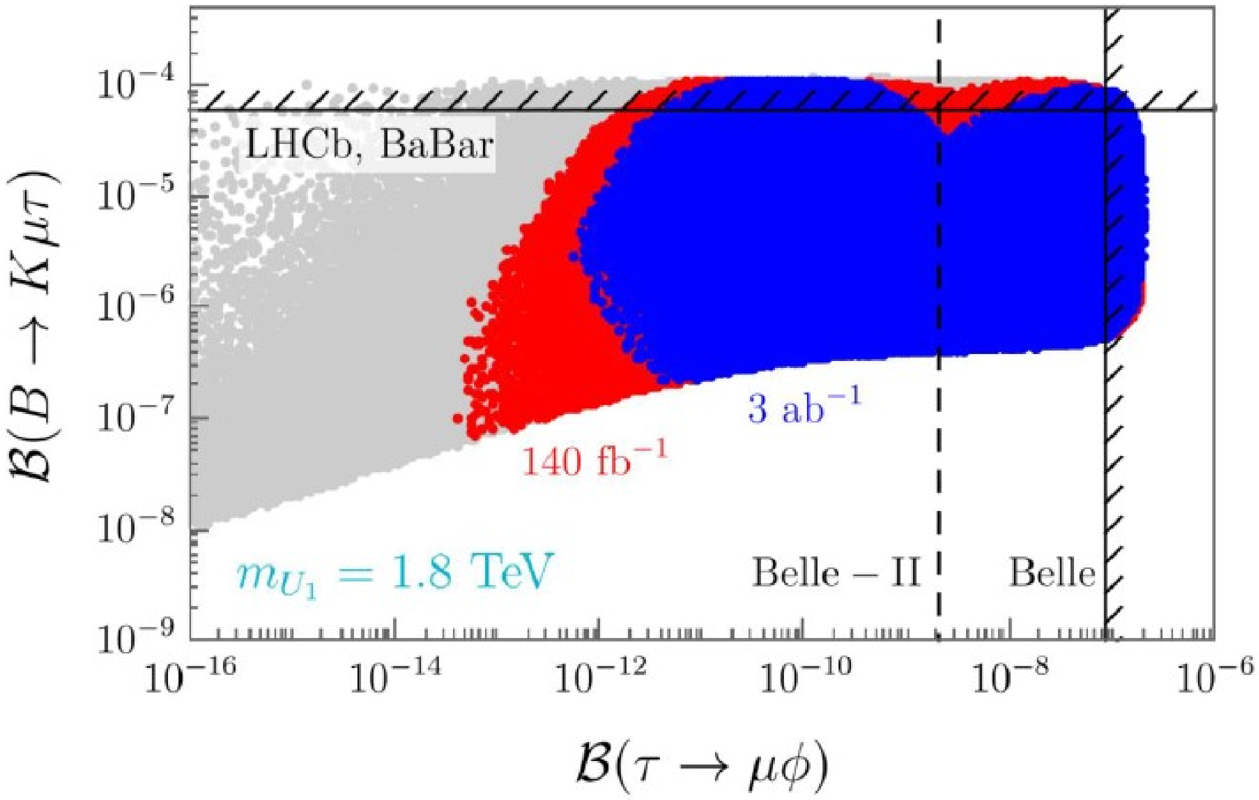
[Belle II, arXiv:1808.10567]

Observables	Belle $0.71\,ab^{-1}$ ($0.12\,ab^{-1}$)	Belle II $5\,ab^{-1}$	Belle II $50\,ab^{-1}$
$Br(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	–	< 2.1
$Br(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	–	–	< 3.3
$Br(B^0 \to \tau^\pm e^\mp) \cdot 10^5$	–	–	< 1.6
$Br(B^0 \to \tau^\pm \mu^\mp) \cdot 10^5$	–	–	< 1.3

⇒ **can we do better ? combining hadronic tag with an more inclusive tag...**

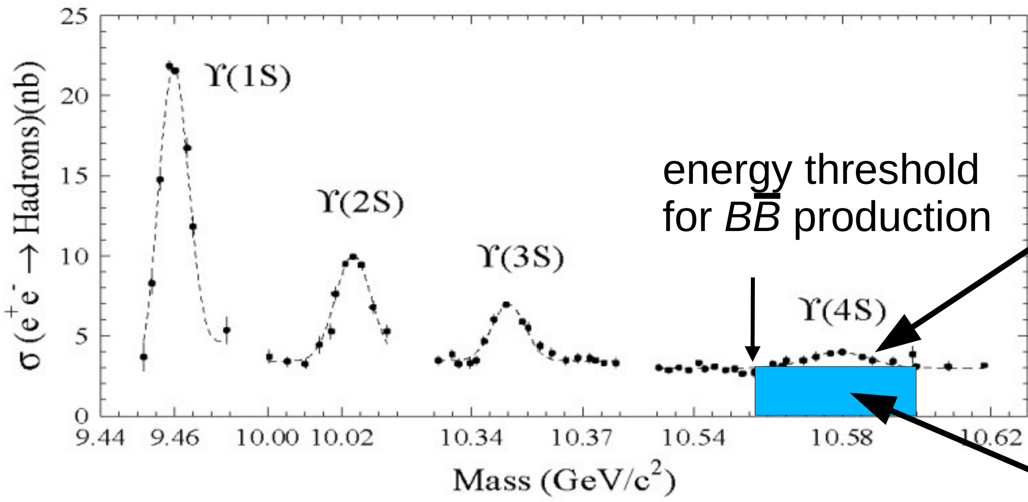
⇒ **can do $K^*\tau e$, $K^*\tau\mu$ with similar sensitivity...**

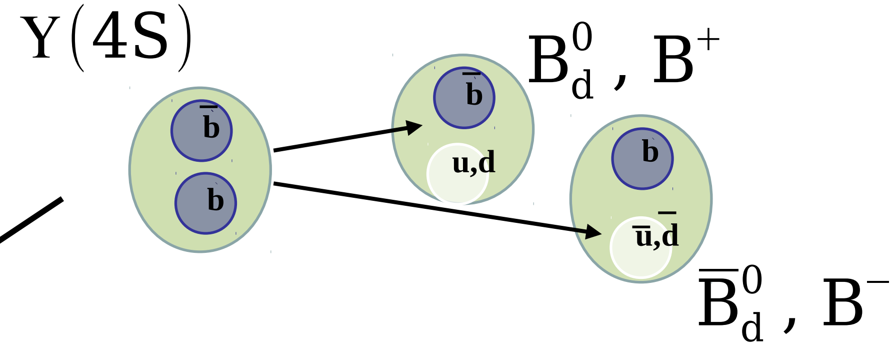
Nice complementarity

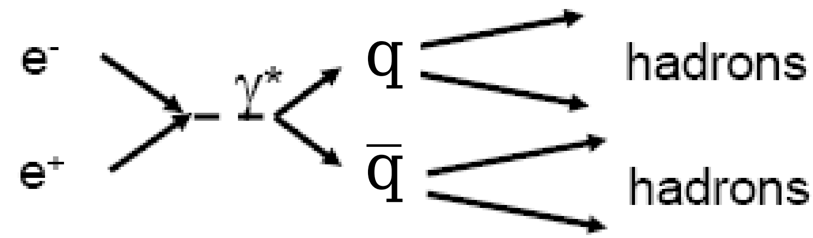


A. Angelescu et al., arXiv:2103.12504v2 (21 Apr 2021)

$\Upsilon(4S)$ B-factory







- **"on resonance" production**

  $e^+e^- \to \Upsilon(4S) \to B_d^0 \overline{B}_d^0 \,,\, B^+B^-$

  $\sigma(e^+e^- \to B\overline{B}) \simeq 1.1$ nb

- **"continuum" production ($q\overline{q} = u\overline{u}, d\overline{d}, s\overline{s}, c\overline{c}$)**

  $\sigma(e^+e^- \to c\overline{c}) = 1.3$ nb

  $\sigma(e^+e^- \to s\overline{s}) = 0.4$ nb

  $\sigma(e^+e^- \to u\overline{u}) = 1.6$ nb

  $\sigma(e^+e^- \to d\overline{d}) = 0.4$ nb

- **$\sigma(e^+e^- \to \tau^+\tau^-) \sim 1$ nb**
- **$\sigma(e^+e^- \to \mu^+\mu^-) \sim 1$ nb (calibration)**
- **bhabha: $\sigma(e^+e^- \to e^+e^-) \sim 100$ nb (luminosity)**

cLFV : beyond the Standard Model

long-standing, and well motivated (particularly since the discovery of neutrino oscillations) programme of searches for charged Lepton Flavour Violation

less stringent limits in 3rd generation, but here BSM effects may be higher

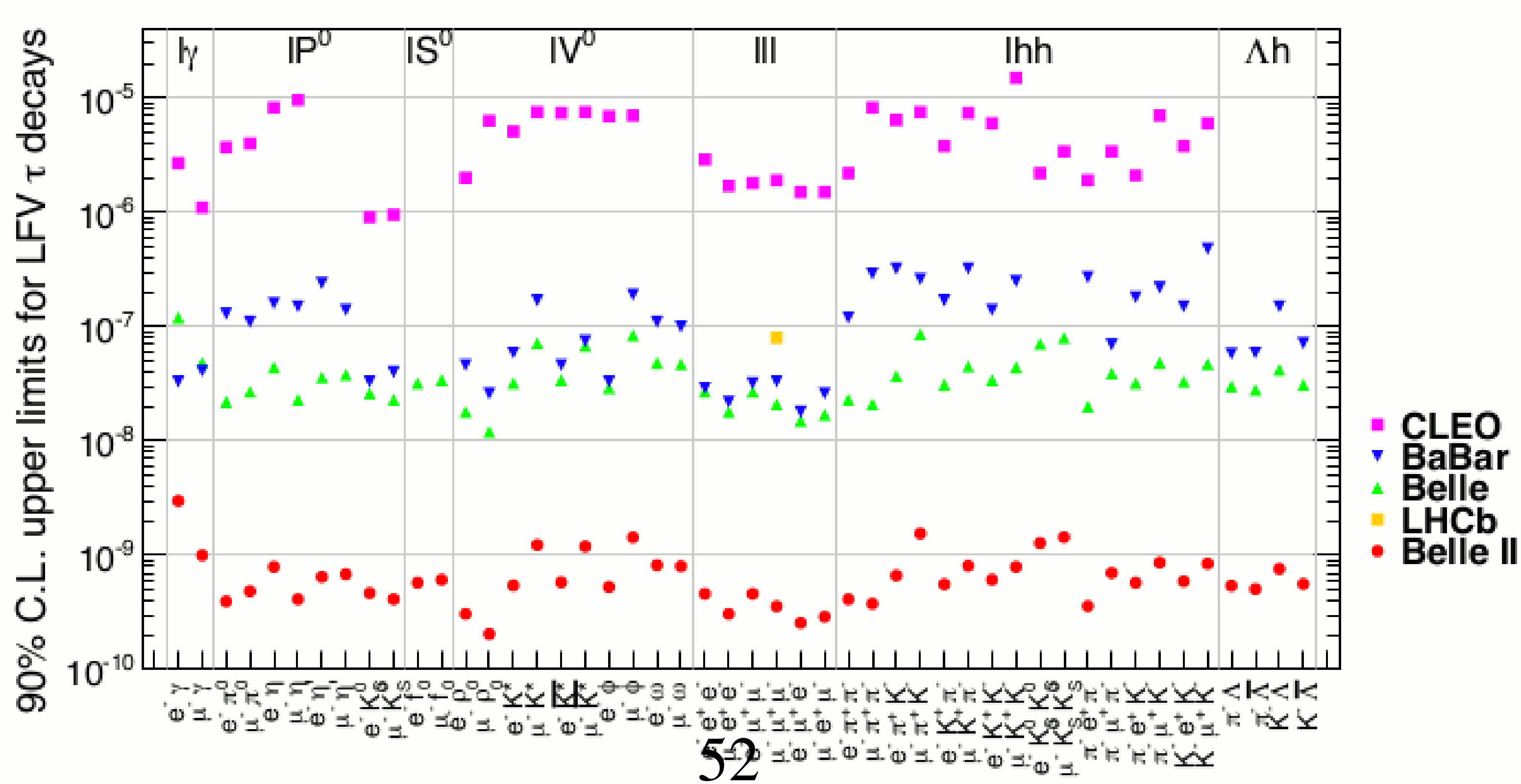
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda}O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}O_i^{(6)} + \ldots$$

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-40}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

	Operator	$\tau\to3\mu$	$\tau\to\mu\gamma$	$\tau\to\mu\pi^+\pi^-$	$\tau\to\mu K\bar{K}$	$\tau\to\mu\pi$	$\tau\to\mu\eta^{(\prime)}$
4-lepton	$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
dipole	O_D	✓	✓	✓	✓	–	–
lepton-quark	O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
lepton-quark	O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
lepton-quark	O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-quark	O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-gluon	$O_{G\tilde{G}}$	–	–	–	–	–	✓

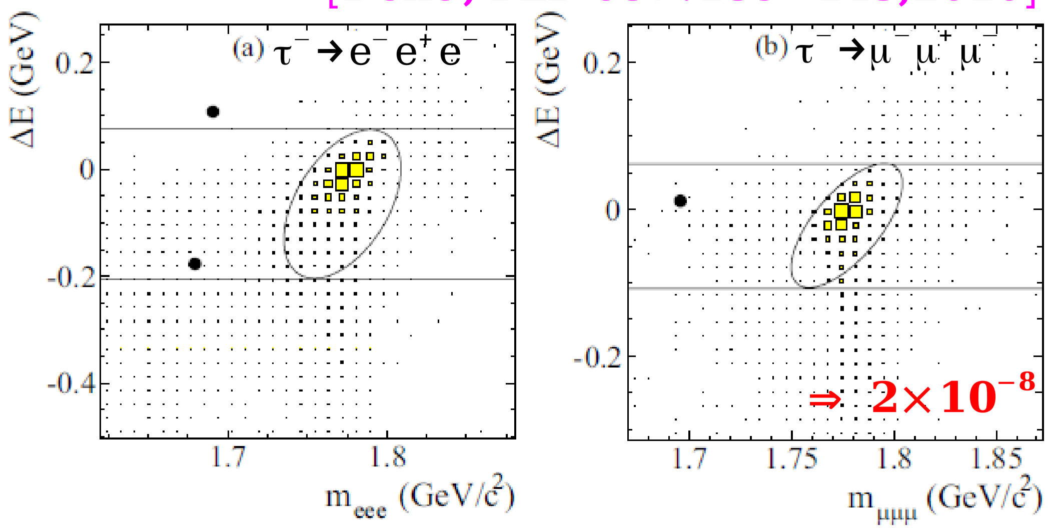
Celis, Cirigliano, Passemar (2014)



cLFV : beyond the Standard Model

τ LFV searches at Belle II will be extremely clean with very little background (if any), thanks to pair production and double-tag analysis technique.

[Belle, PLB 687:139−143,2010]

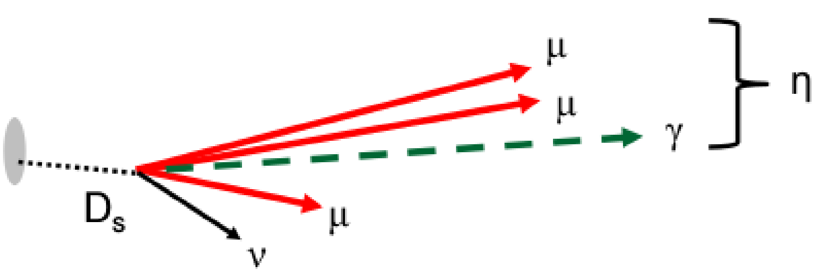


⇒ 2×10^{-8} at 90%CL

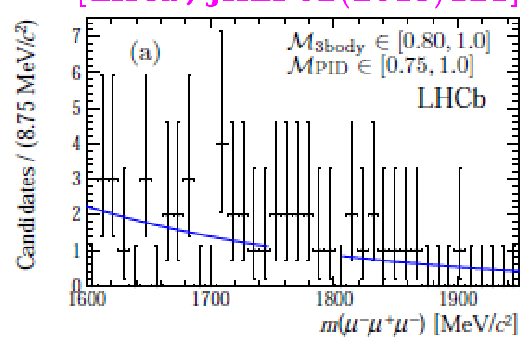
how to improve further ?

...considering $\tau\to\mu/e\,h^+h^-$
in function of one prong tag categories
...for τ→3muons,
improve μ-ID at low mom (ECL info)

In contrast, hadron collider experiments must contend with larger combinatorial and specific backgrounds



[LHCb, JHEP02(2015)121]



⇒ 5×10^{-8} at 90%CL

Background modes normalised to $D_s\to\eta(\mu\mu\gamma)\mu\nu$ (BR ~ 10^{-5})

Decay channel	Relative abundance
$D_s\to\eta(\mu\mu\gamma)\mu\nu$	1
$D_s\to\varphi(\mu\mu)\mu\nu$	0.87
$D_s\to\eta'(\mu\mu\gamma)\mu\nu$	0.13
$D\to\eta(\mu\mu\gamma)\mu\nu$	0.13
$D\to\omega(\mu\mu)\mu\nu$	0.06
$D\to\rho(\mu\mu)\mu\nu$	0.05

Most improvement in coming decade is expected from Belle II, which can reach 1×10^{-9} [arXiv:1011.0352] and will do even better if can achieve ~ zero bckgd