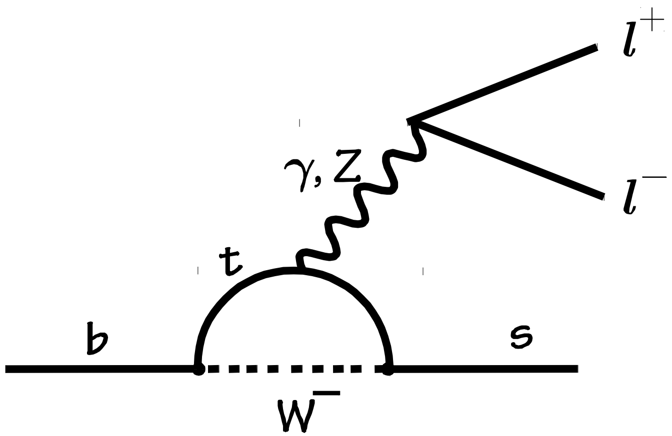
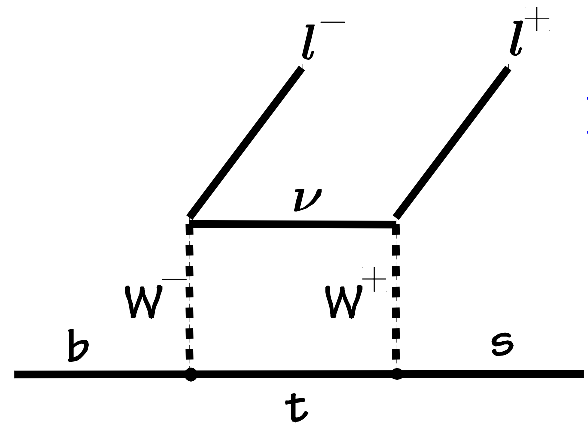
Beautiful paths to probe physics beyond the standard model of particles





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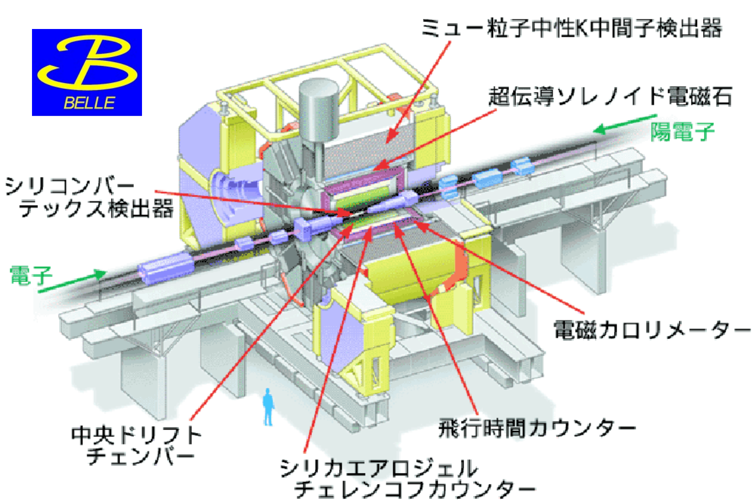
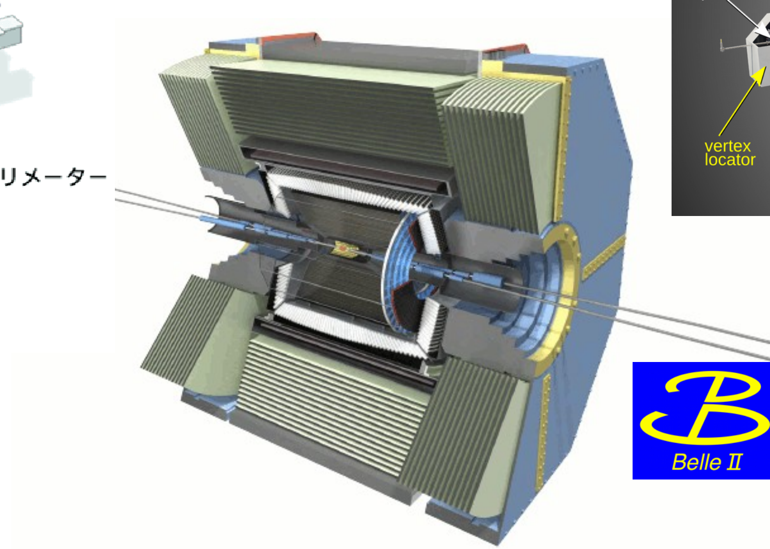
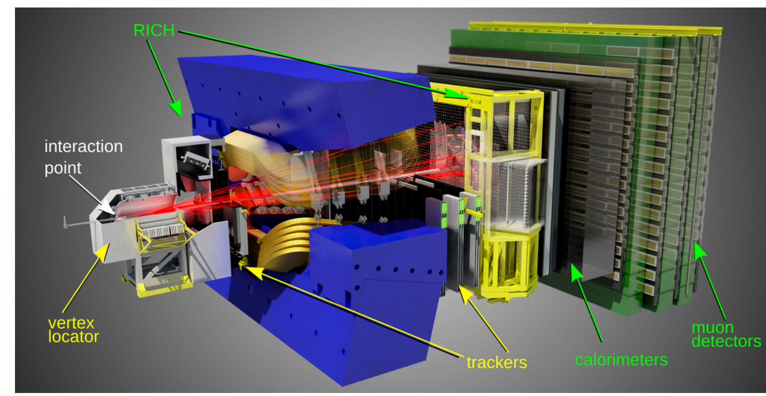
Laboratoire de Physique des 2 Infinis

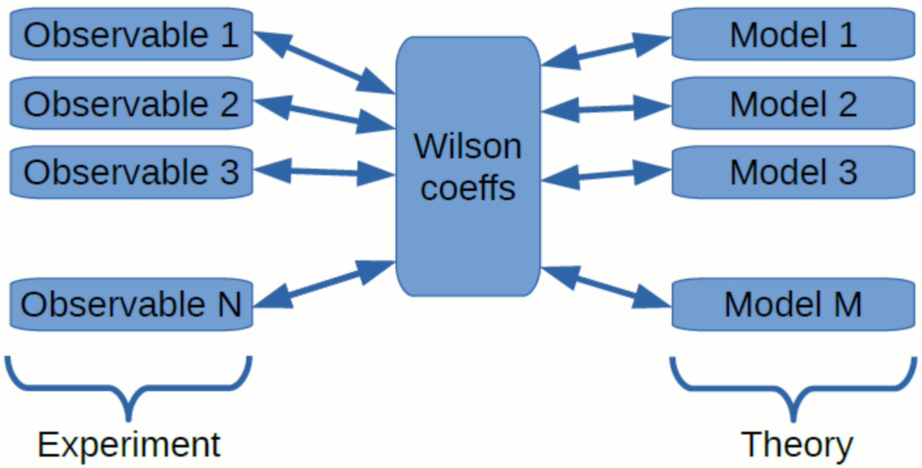






Jennifer school, July 23rd 2020

Sensitivity to new physics in rare B decays



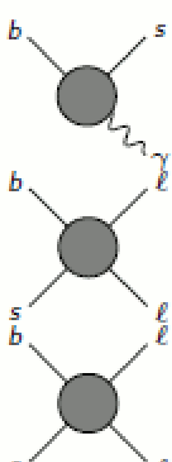
M.Ciuchini et al, arXiv:1512.07157
T.Hurth et al, arXiv:1603.00865
S.Descotes-Genon et al, arXiv:1510.04239...

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

- Model-independent description in effective field theory

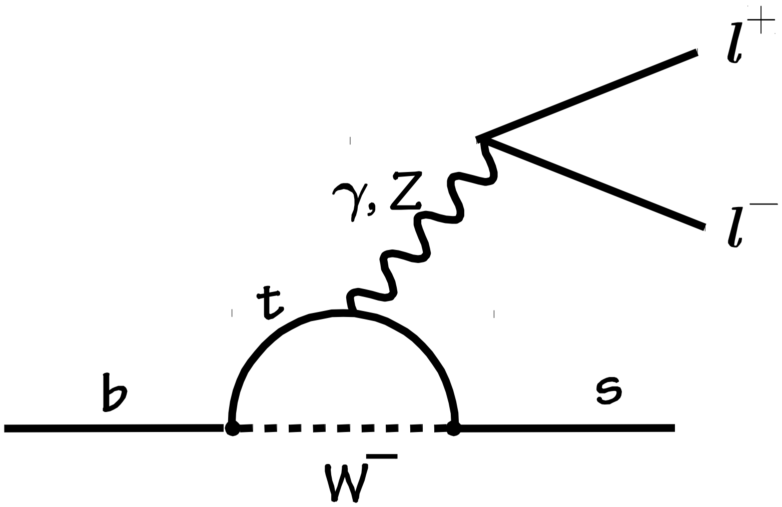
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm ts}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

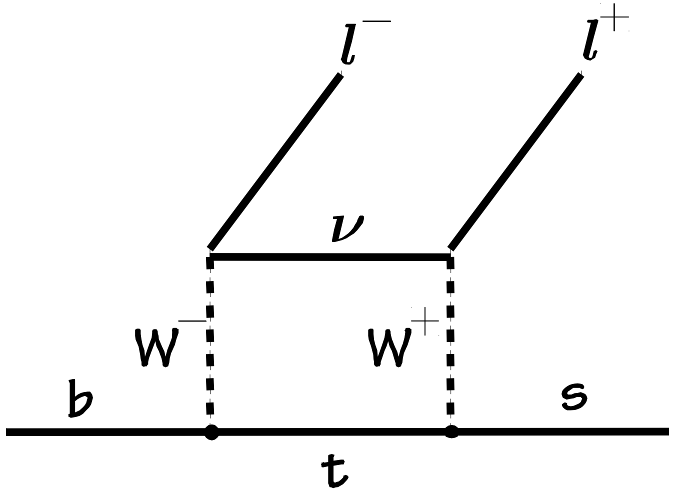
- Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators



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

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





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

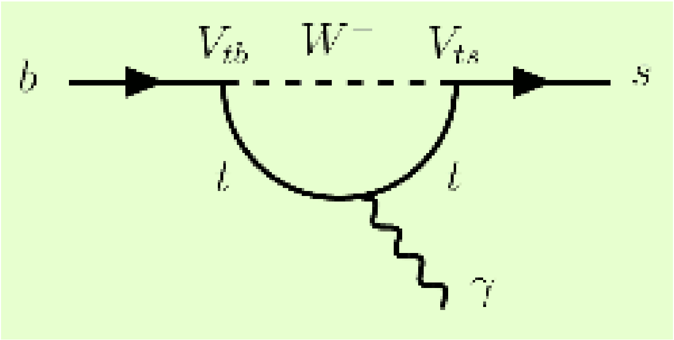
Amplitudes from
- ◦ electromagnetic penguin: C_7
- ◦ vector electroweak: C_9
- ◦ axial-vector electroweak: C_{10}

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...

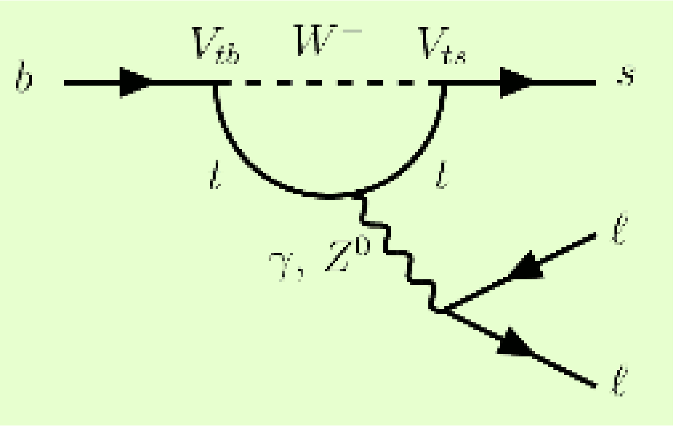
⇒ Exclusive ($B \to K^{(*)} l^+ l^-$), Inclusive ($B \to X_s\, l^+ l^-$)

b→lls



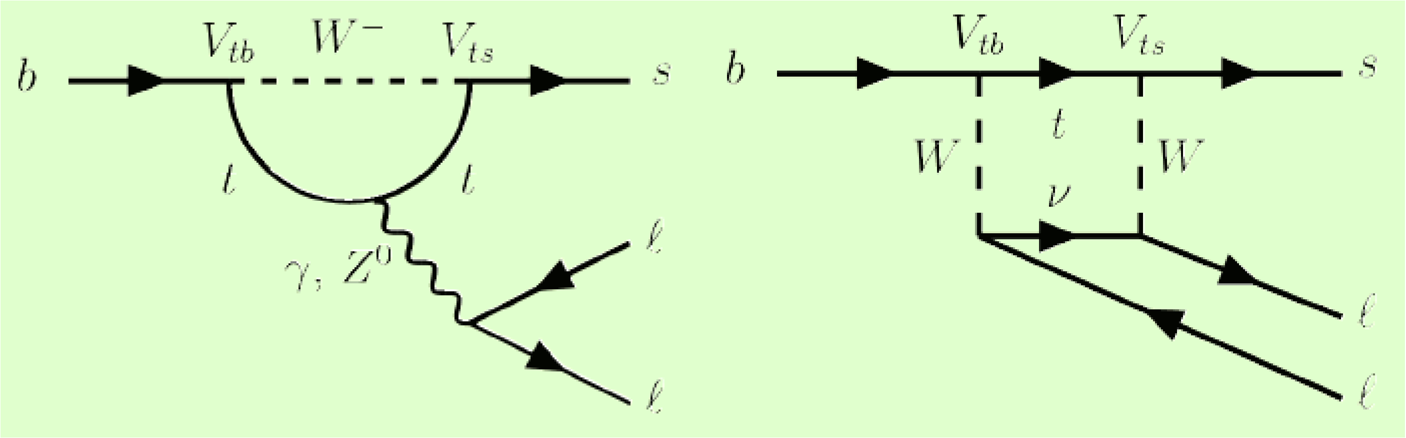
- Start with b→s γ

b→lls



- Start with b→s γ, pay a factor $\alpha_{EM} = \frac{1}{137}$
  - → Decay the γ into 2 leptons

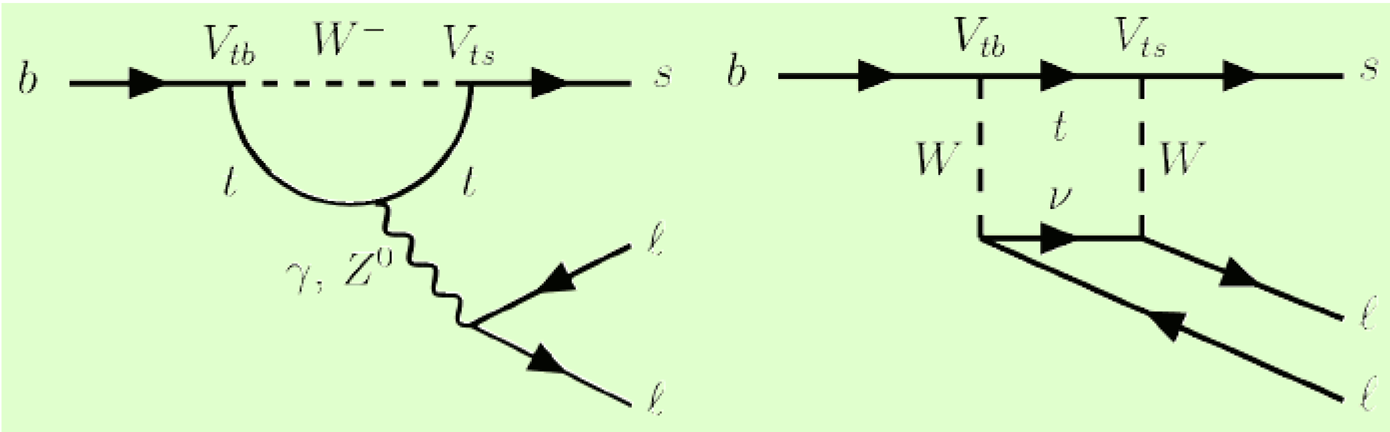
b→lls



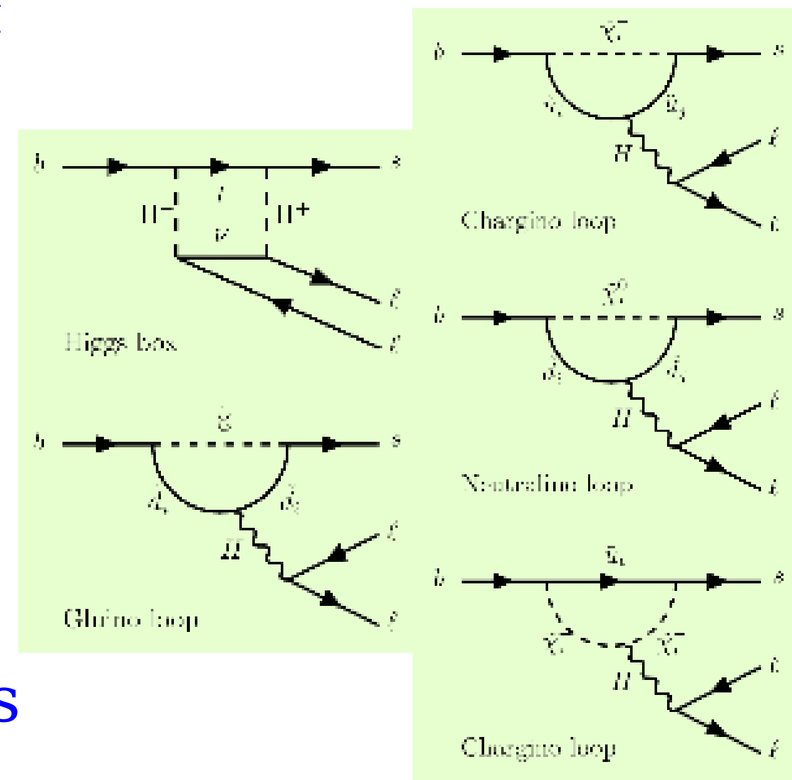
- Start with b→sγ, pay a factor α_{EM}
  - → Decay the γ into 2 leptons
- Add an interfering box diagram
  - → b→lls, very rare in the SM

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

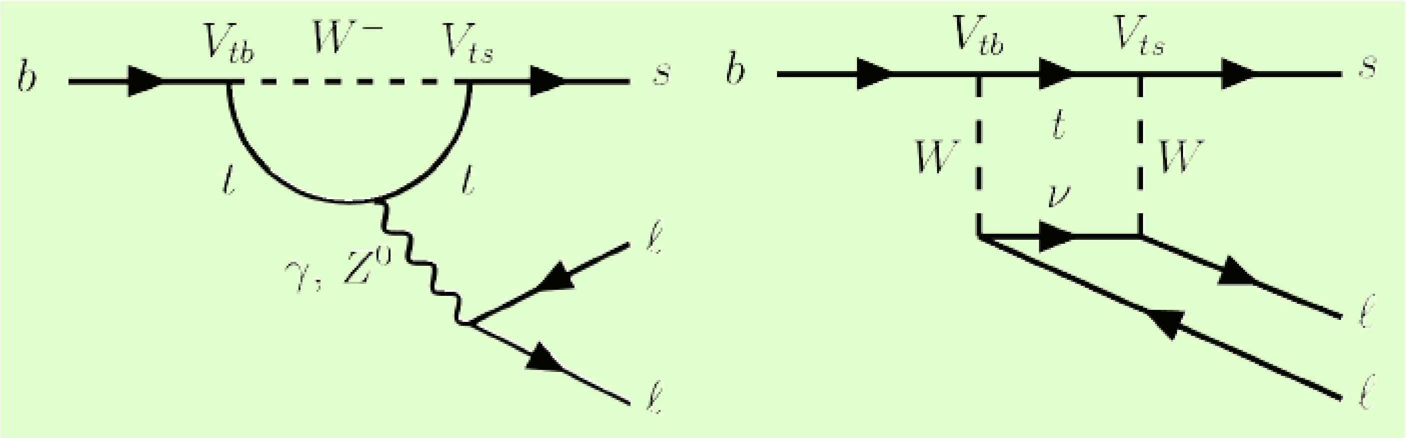
b→lls



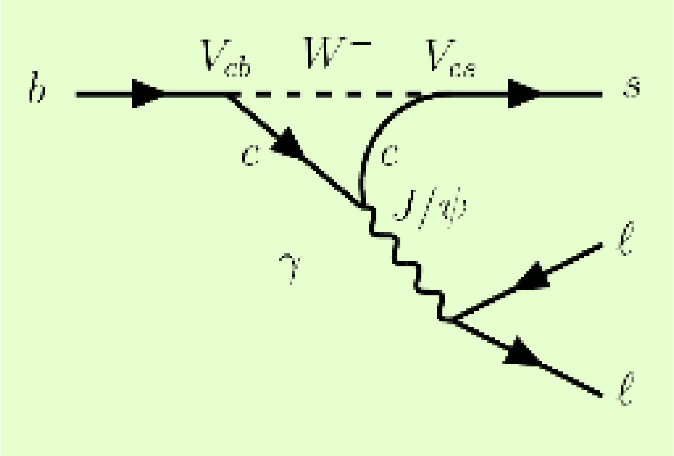
- Start with b→sγ, pay a factor α_{EM}
  - → Decay the γ into 2 leptons
  - Add an interfering box diagram
  - → b→lls, very rare in the SM
  - $B(\mathrm{B \to llK^*}) = (3.3 \pm 1.0) \cdot 10^{-6}$
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions…
- Ideal place to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



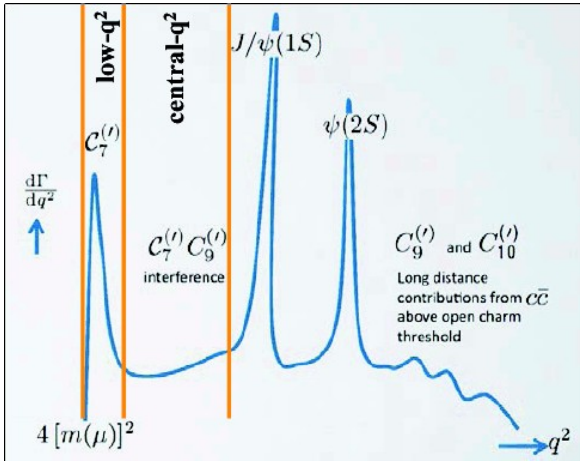
b→lls



- Start with b→sγ, pay a factor α_{EM}
  → Decay the γ into 2 leptons
  - Add an interfering box diagram
  → b→lls, very rare in the SM
  $B(B \to llK^*) = (3.3 \pm 1.0) \, . \, 10^{-6}$

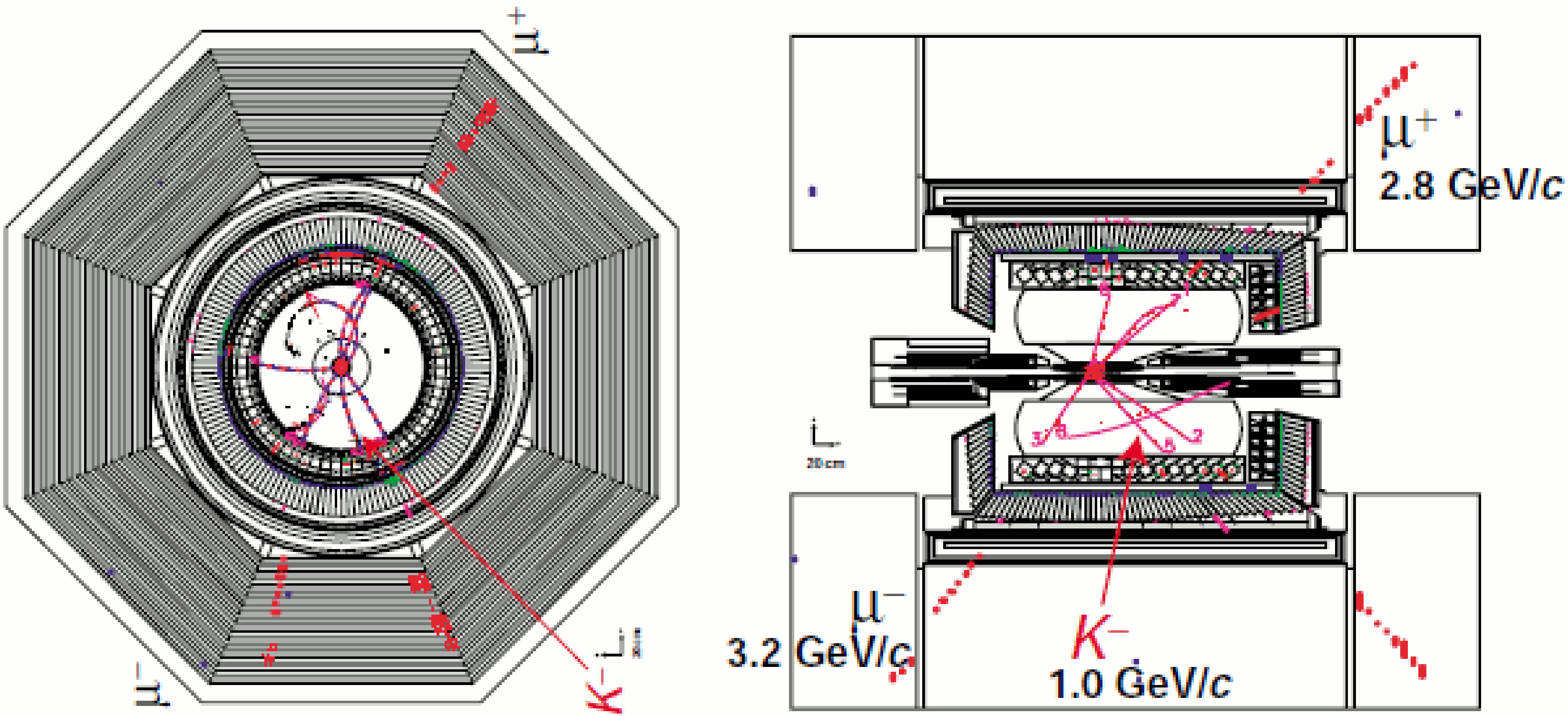


- But beware of LD effects:
  - Tree b→c$\bar{c}$s, (c$\bar{c}$)→ll
  - Can be removed by mass cuts
  - Interferes elsewhere



First observation

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

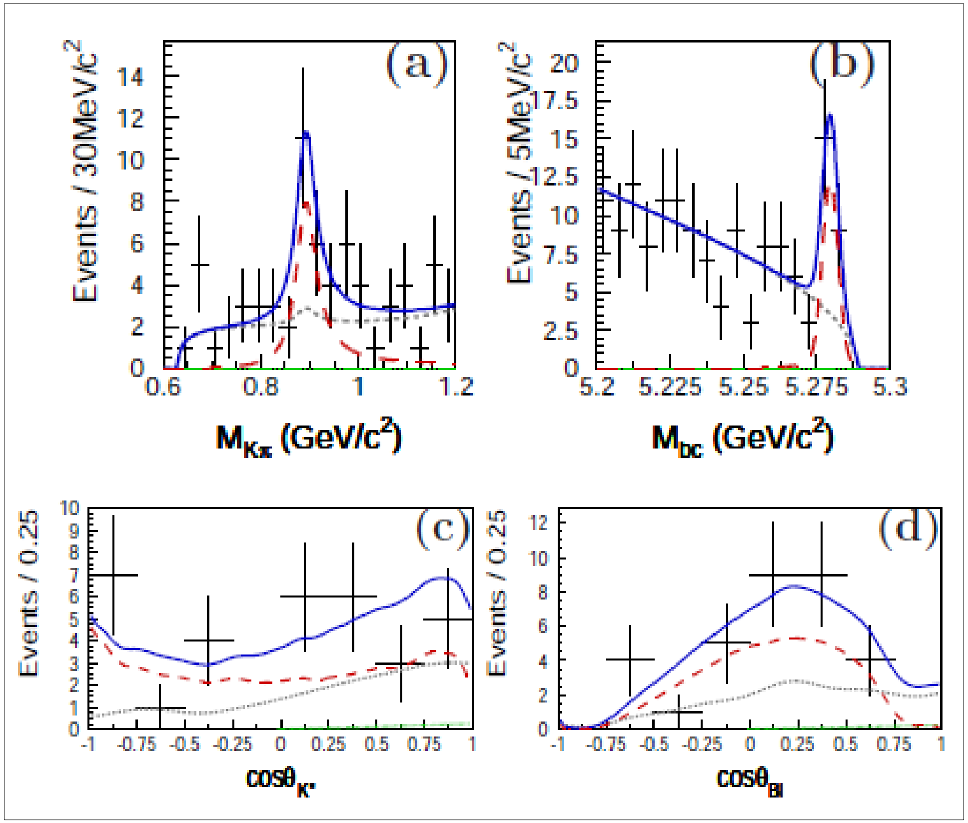


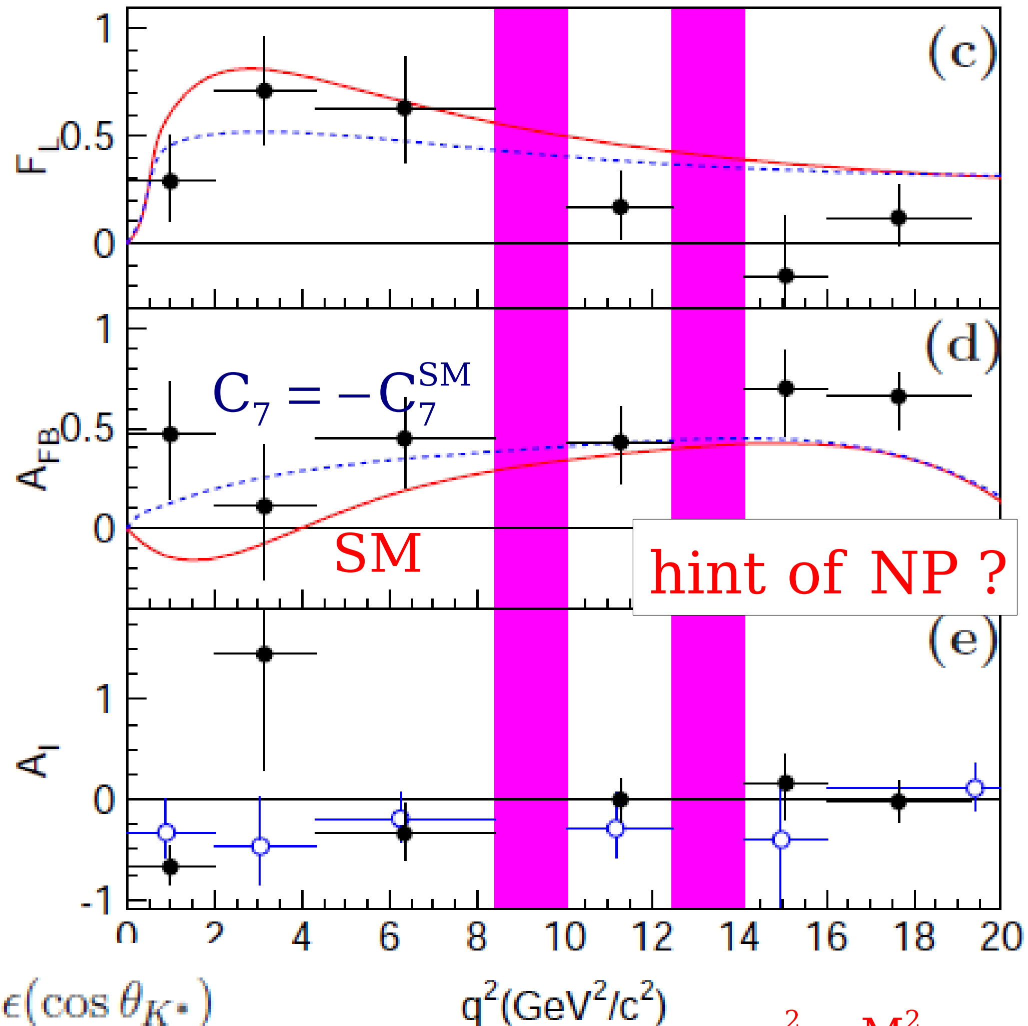
$B \to K^* l^+ l^-$ decays

[arXiv:0904.0770]

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

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





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

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

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

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

$R_K = 1.03 \pm 0.19 \pm 0.06$

Lepton flavor universality (LFU)

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

Universality in neutral current interactions

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

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

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

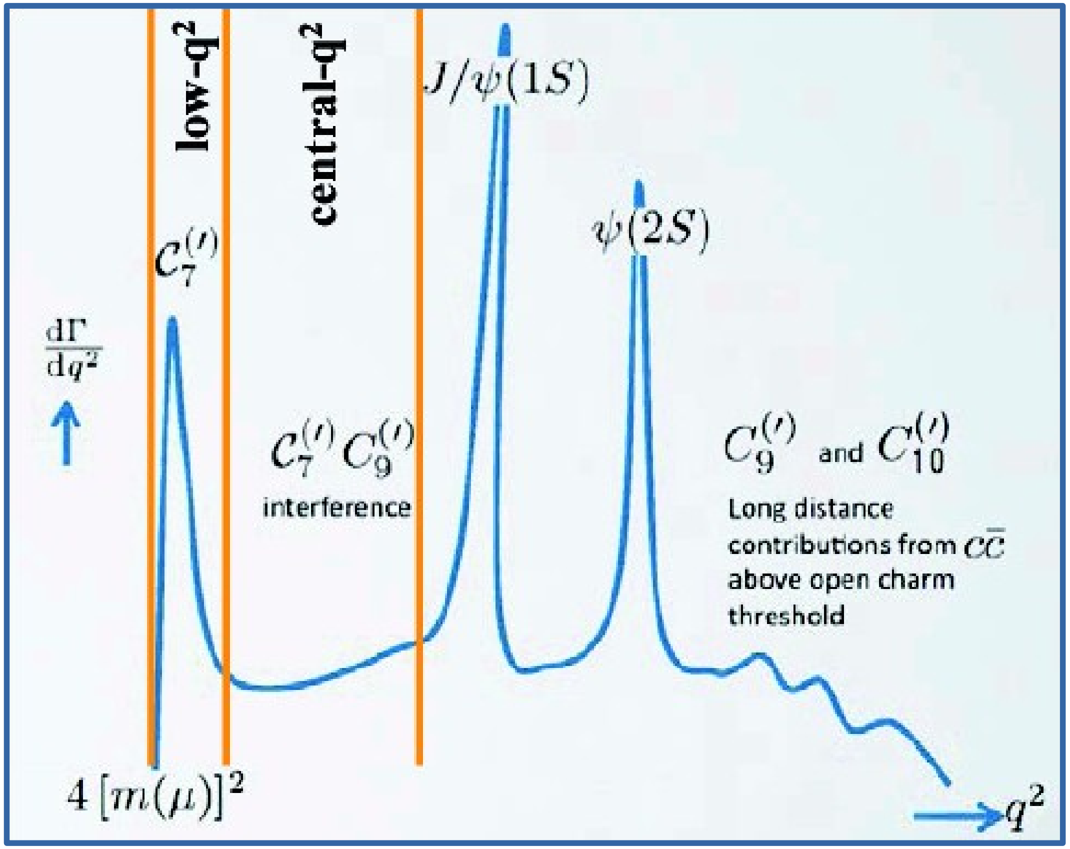
Experimental results

We'll see...

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 $B^0 \rightarrow K^{*0} J/\psi(ll)$ 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

Strategy

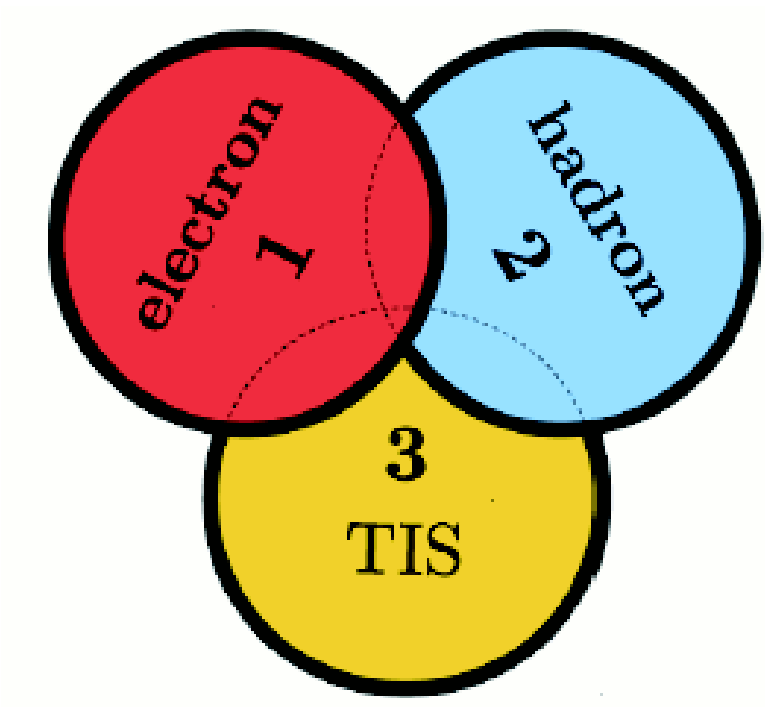
- Measured relative to $B^0 \rightarrow K^{*0} J/\psi(ll)$ in order to reduce systematics

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

- High occupancy of calorimeters (compared to muon stations)

⇒ hardware thresholds on electron E_T higher than on muon p_T

(L0 Muon , $p_T > 1.5$, 1.8 GeV)



3 exclusive trigger categories:

- L0 Electron: electron hardware trigger fired by clusters associated to at least one of the two electrons (E_T >2.5 GeV)

- L0 Hadron: hadron hardware trigger fired by clusters associated to at least one of the K^{*0} decay products (E_T >2.5 GeV)

- L0 TIS(*): any hardware trigger fired by particles in the event not associated to the signal candidate

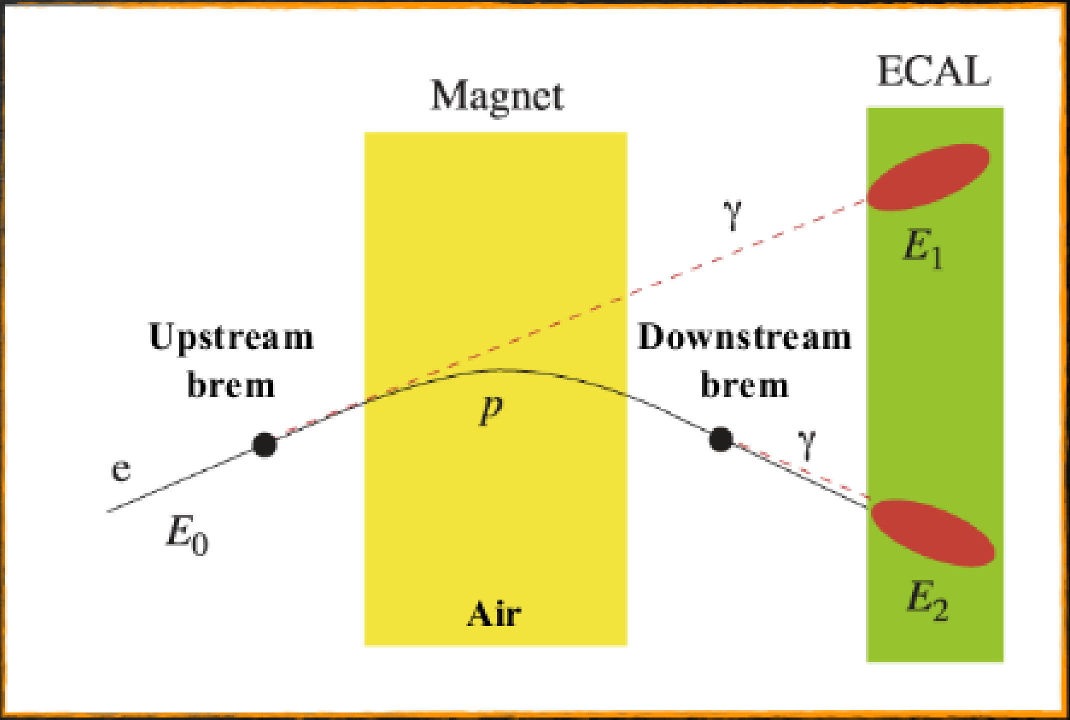
(*) TIS = Trigger Independent of Signal

Bremsstrahlung – ee

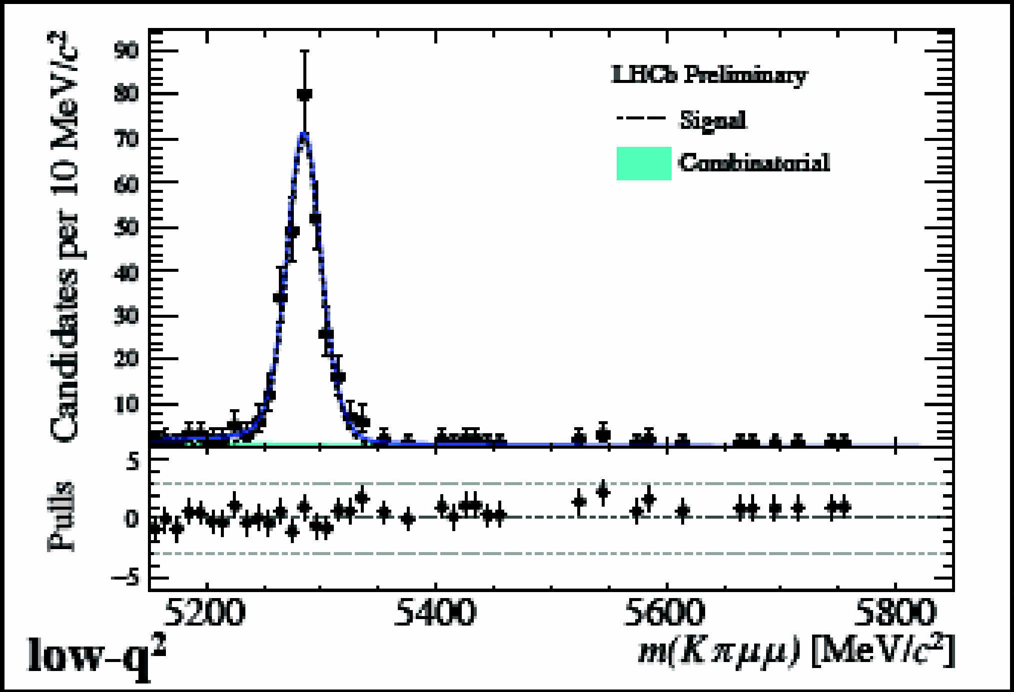
S.Bifani (LHCb)

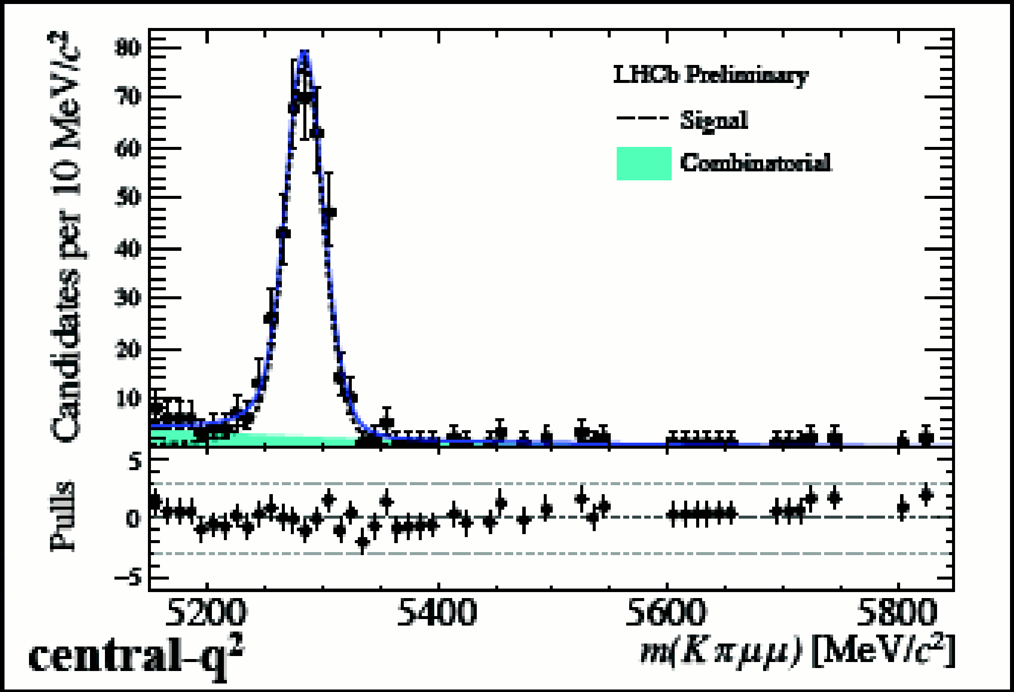
- Electrons emit a large amount of bremsstrahlung that results in degraded momentum and mass resolutions

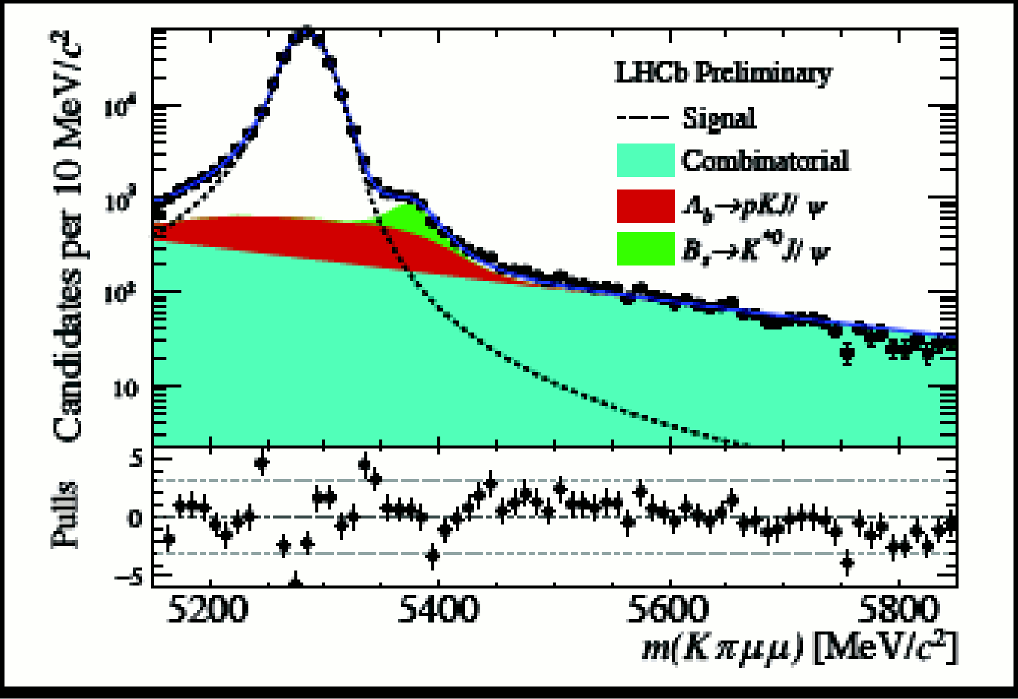
- Two types of bremsstrahlung
  - » Downstream of the magnet
    - photon energy in the same calorimeter cell as the electron
    - momentum correctly measured
  - » Upstream of the magnet
    - photon energy in different calorimeter cells than electron
    - momentum evaluated after bremsstrahlung



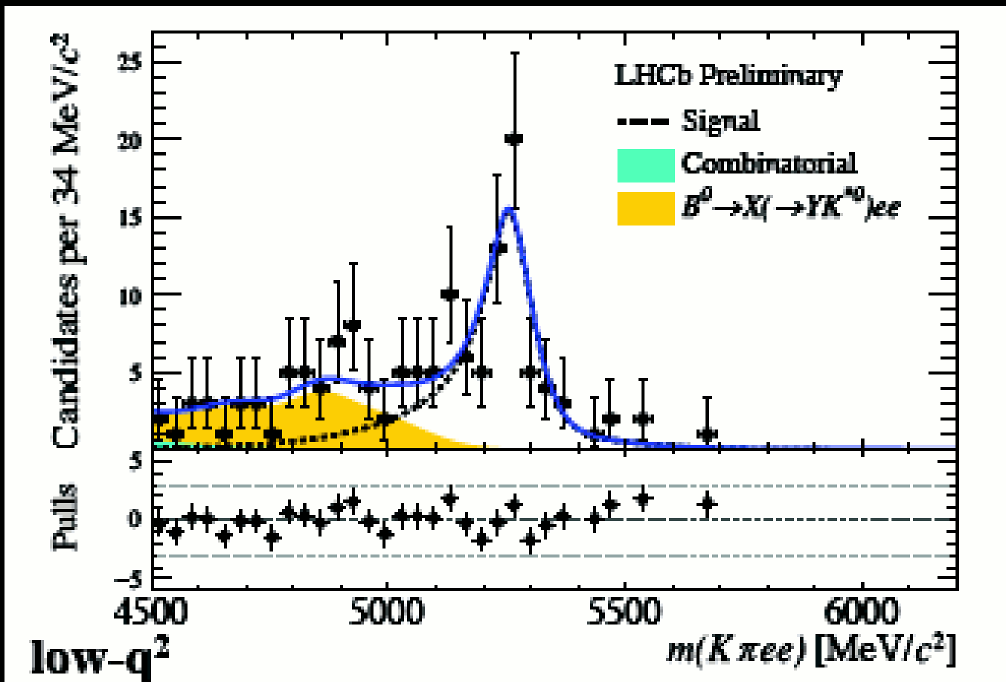
Fit results – μμ

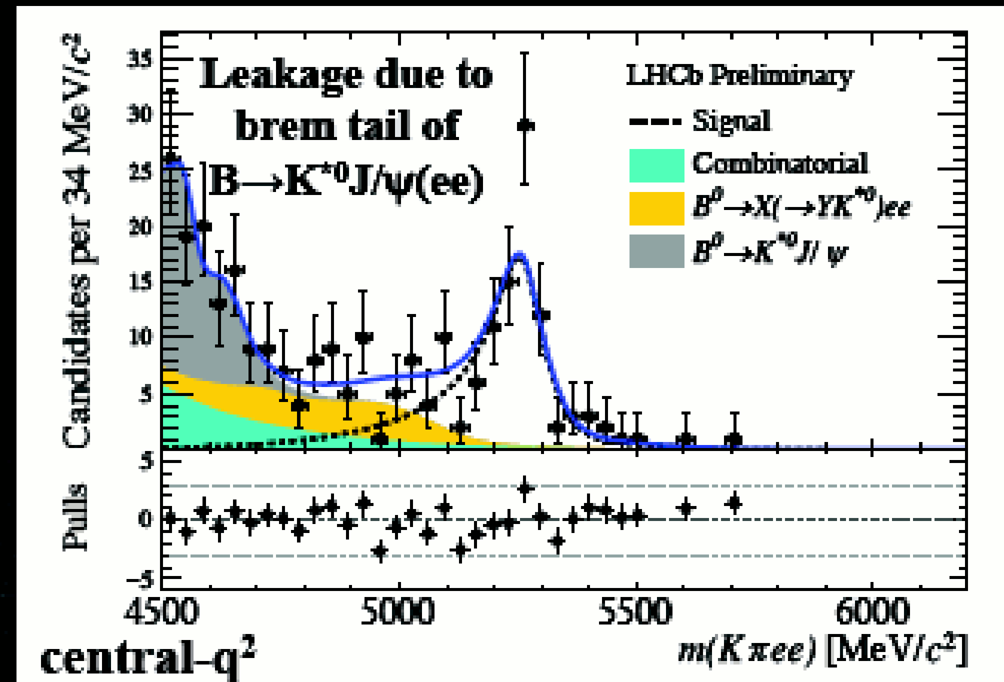


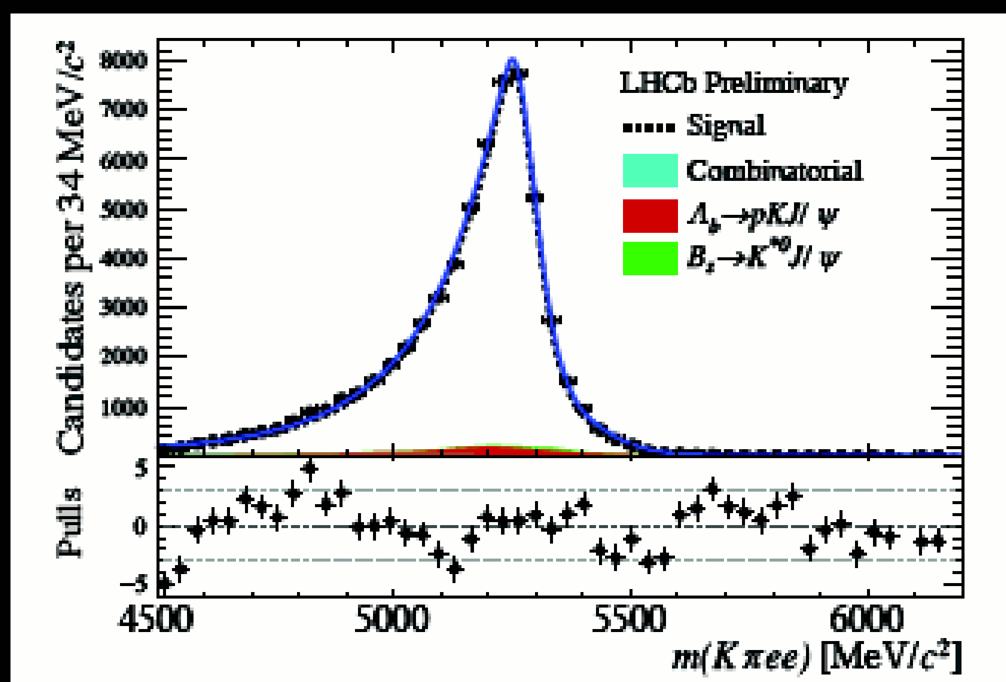




Fit results – ee







Yields

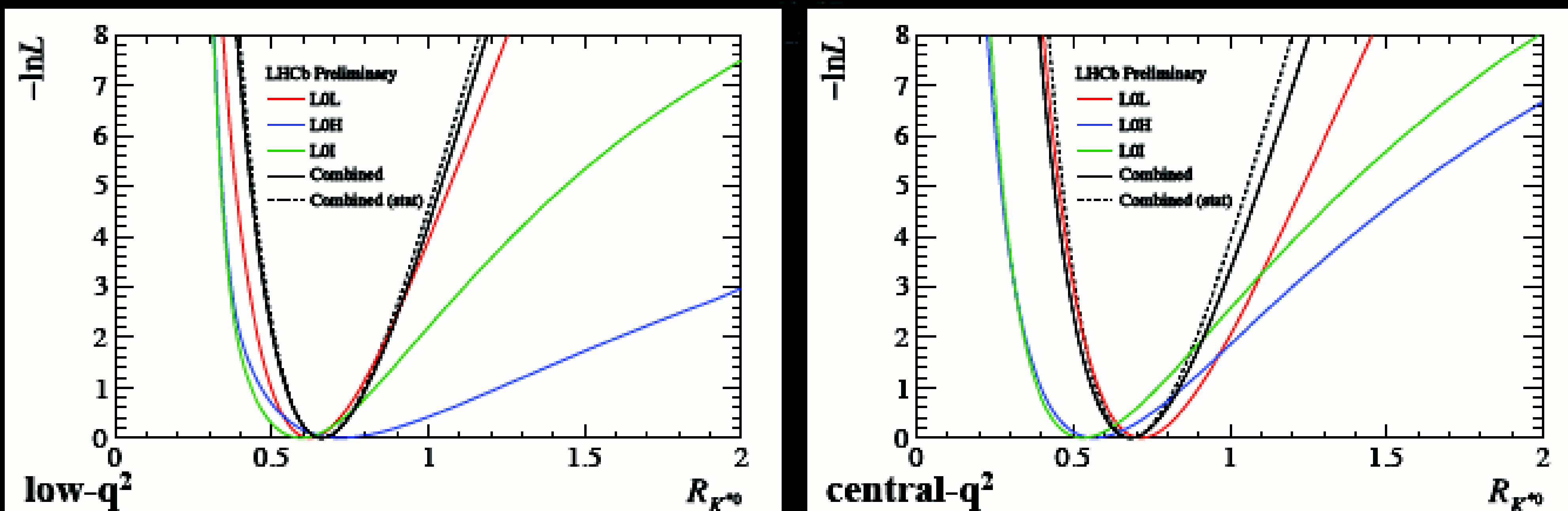
Precision of the measurement driven by the statistics of the electron samples

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi (\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	$285 \,^{+\,18}_{-\,18}$	$353 \,^{+\,21}_{-\,21}$	$274416 \,^{+\,602}_{-\,654}$
e^+e^- (L0E)	$55 \,^{+\,9}_{-\,8}$	$67 \,^{+\,10}_{-\,10}$	$43468 \,^{+\,222}_{-\,221}$
e^+e^- (L0H)	$13 \,^{+\,5}_{-\,5}$	$19 \,^{+\,6}_{-\,5}$	$3388 \,^{+\,62}_{-\,61}$
e^+e^- (L0I)	$21 \,^{+\,5}_{-\,4}$	$25 \,^{+\,7}_{-\,6}$	$11505 \,^{+\,115}_{-\,114}$

In total, about 90 and 110 $B^0 \to ee$ candidates at low- and central-q^2, respectively

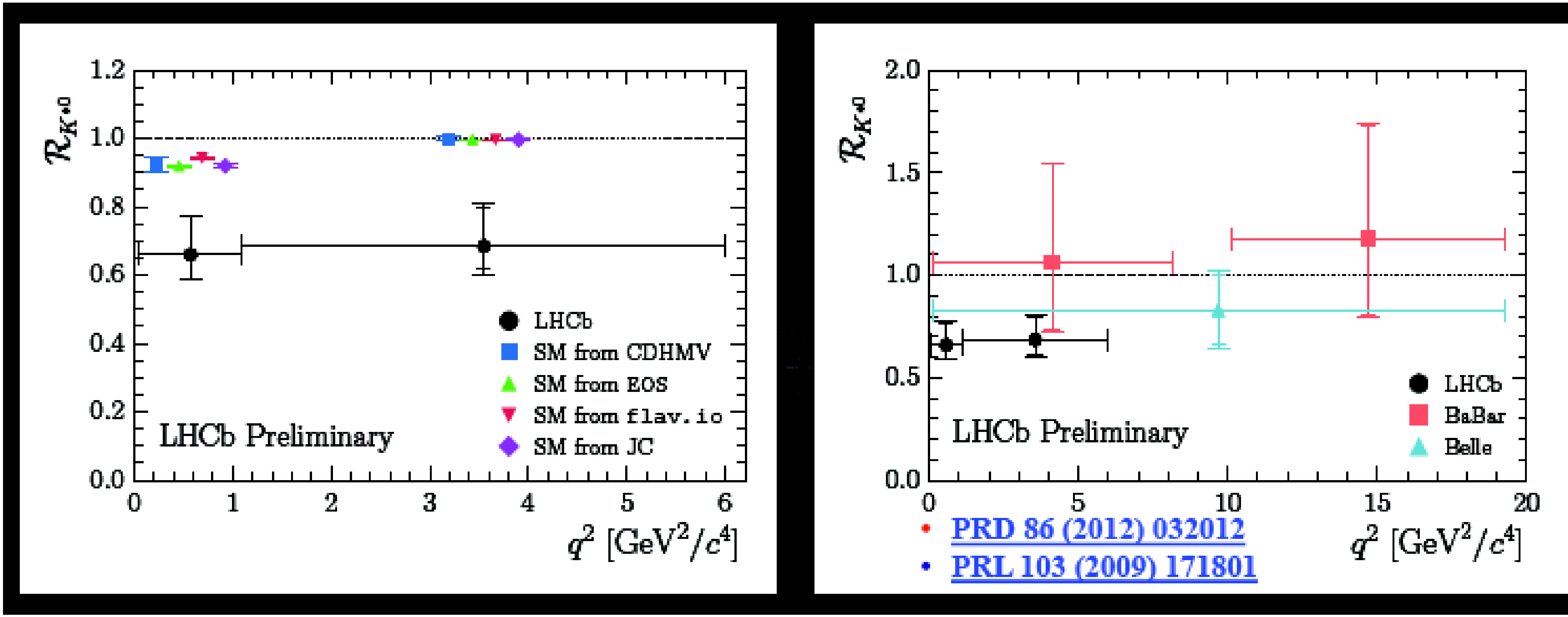
Results

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ {}^{+\,0.110}_{-\,0.070} \pm 0.024$	$0.685\ {}^{+\,0.113}_{-\,0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]



The measured values of $R_{K^{*0}}$ are found to be in good agreement among the three trigger categories in both q^2 regions

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

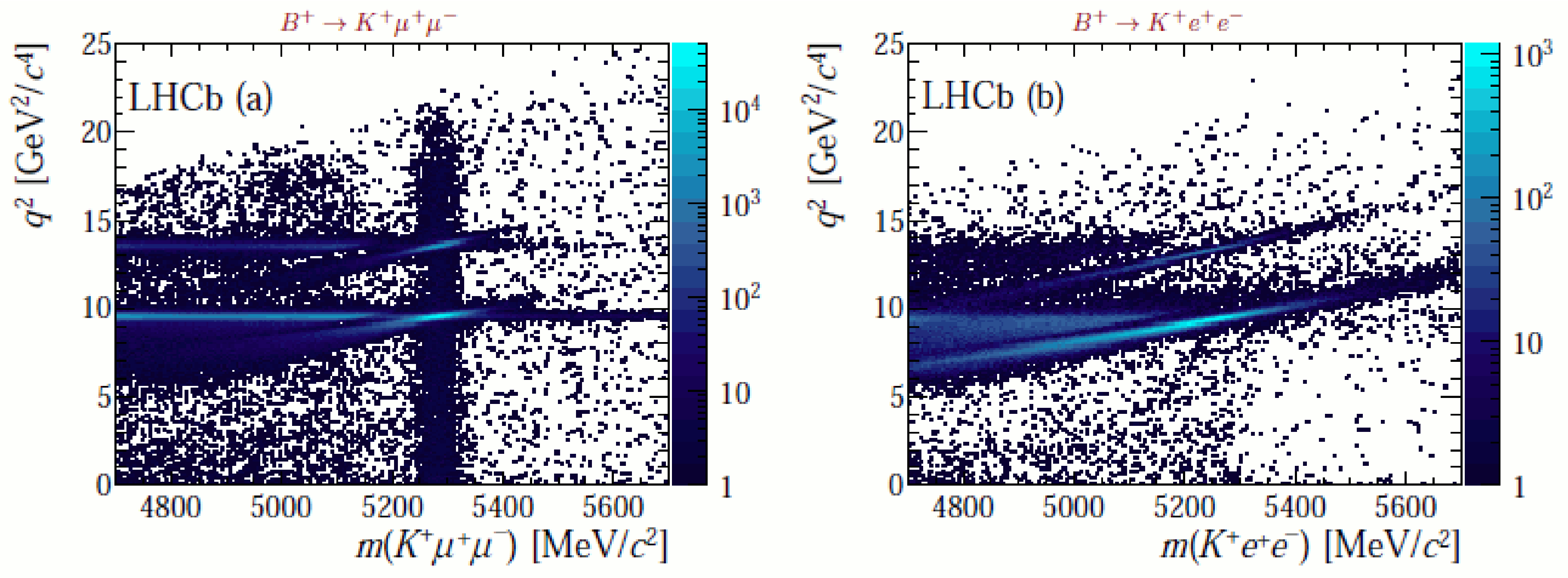
arXiv:1406.6482

- Ratio of branching fractions of $B^+ \to K^+ e^+ e^-$ and $B^+ \to K^+ \mu^+ \mu^-$ sensitive to lepton universality

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)]}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[\mathcal{B}(B^+ \to K^+ e^+ e^-)]}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right) \left(\frac{N_{J/\psi(ee)K}}{N_{J/\psi(\mu\mu)K}}\right) \left(\frac{\varepsilon_{Kee}}{\varepsilon_{K\mu\mu}}\right) \left(\frac{\varepsilon_{J/\psi(ee)K}}{\varepsilon_{J/\psi(\mu\mu)K}}\right)$$

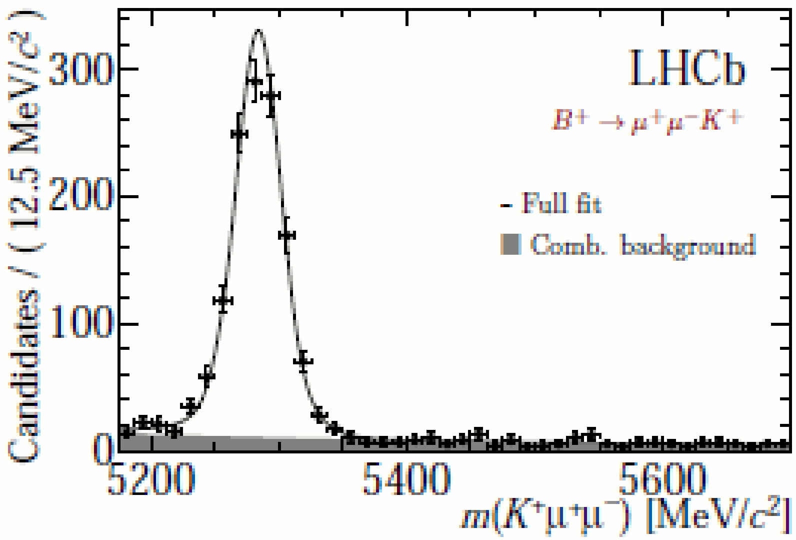
- SM prediction is $R_K = 1$ with an uncertainty of $O(10^{-3})$

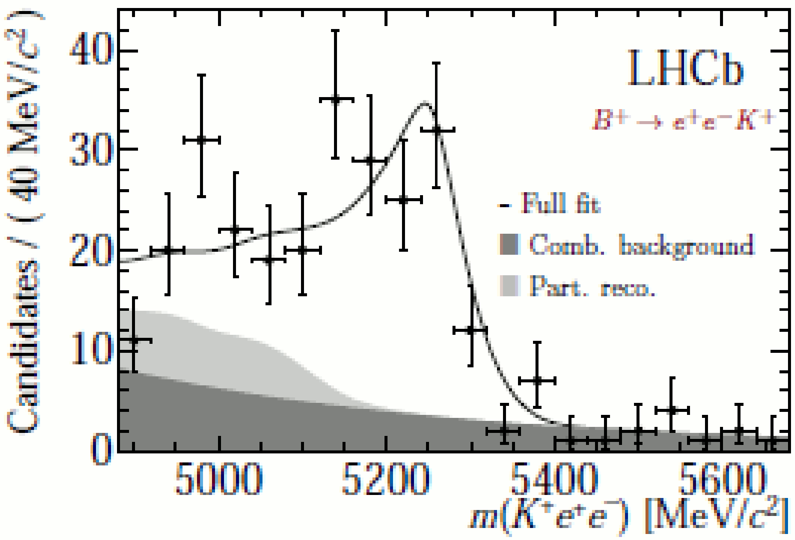
- Measurement relative to resonant $B \to J/\psi K$ modes



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

[arXiv:1406.6482]





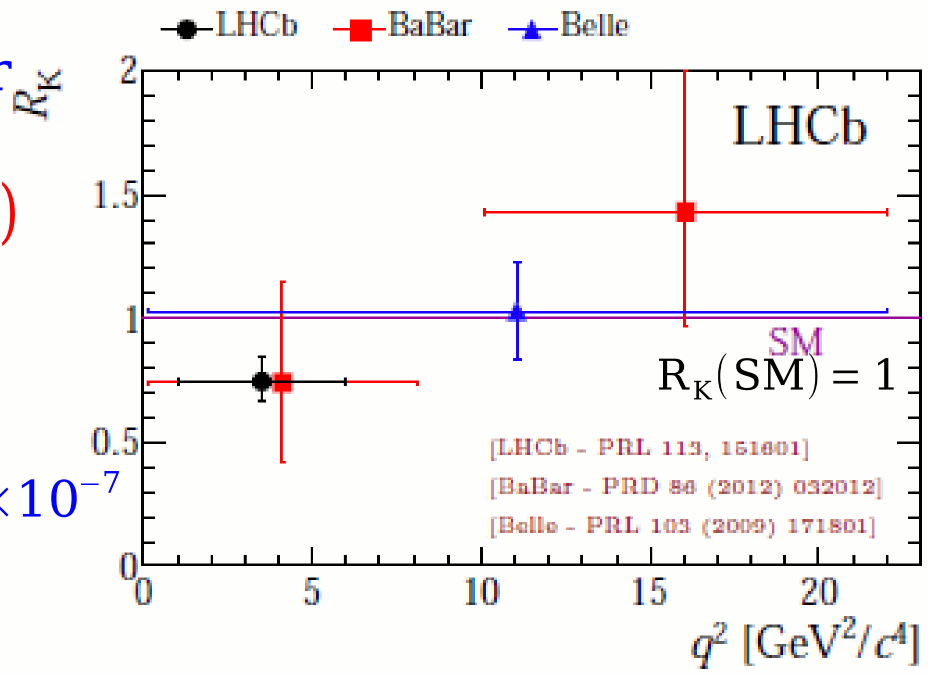
R_K: ratio of branching fractions for dilepton invariant mass squared range $1<q^2<6\,\mathrm{GeV}^2/c^4$

- The combination of the various trigger channels gives:

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

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

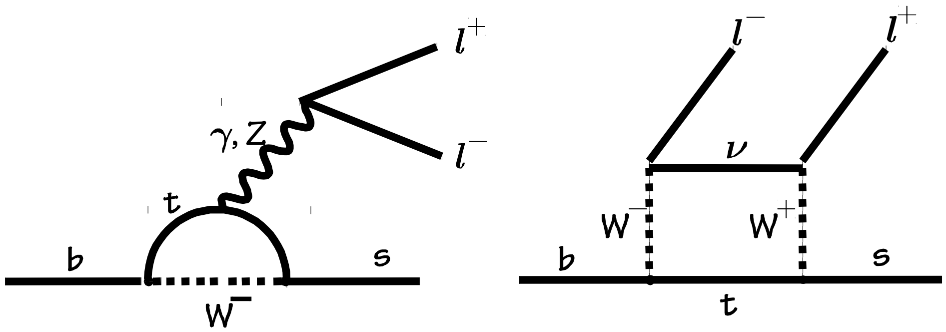
$\Rightarrow$ $B(B^+ \to e^+e^-K^+) = (1.56\,^{+0.19}_{-0.15}(\mathrm{stat})\,^{+0.06}_{-0.05}(\mathrm{syst}))\times 10^{-7}$ compatible with SM predictions



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 ...

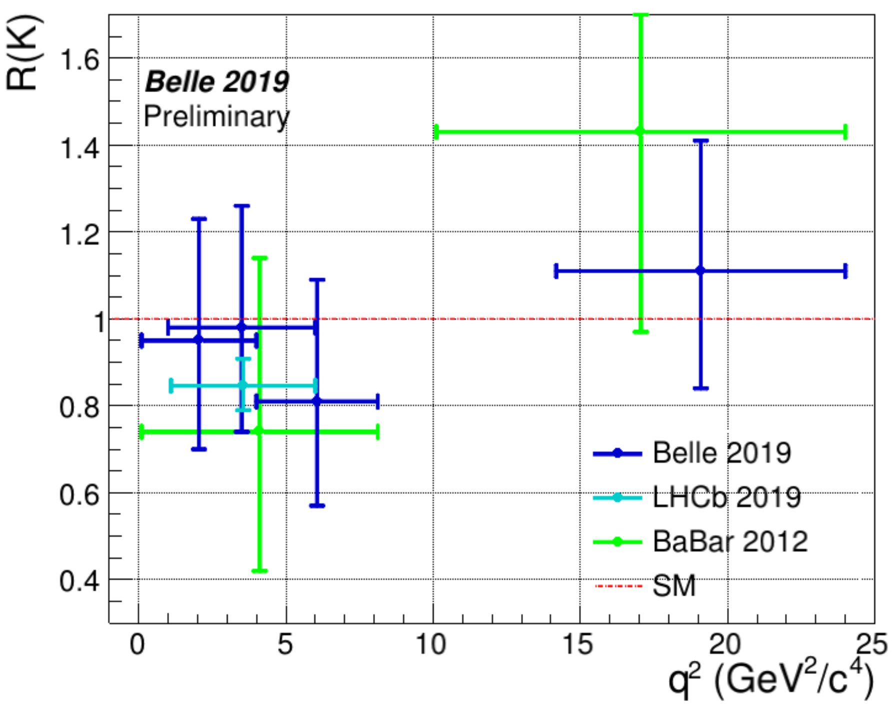


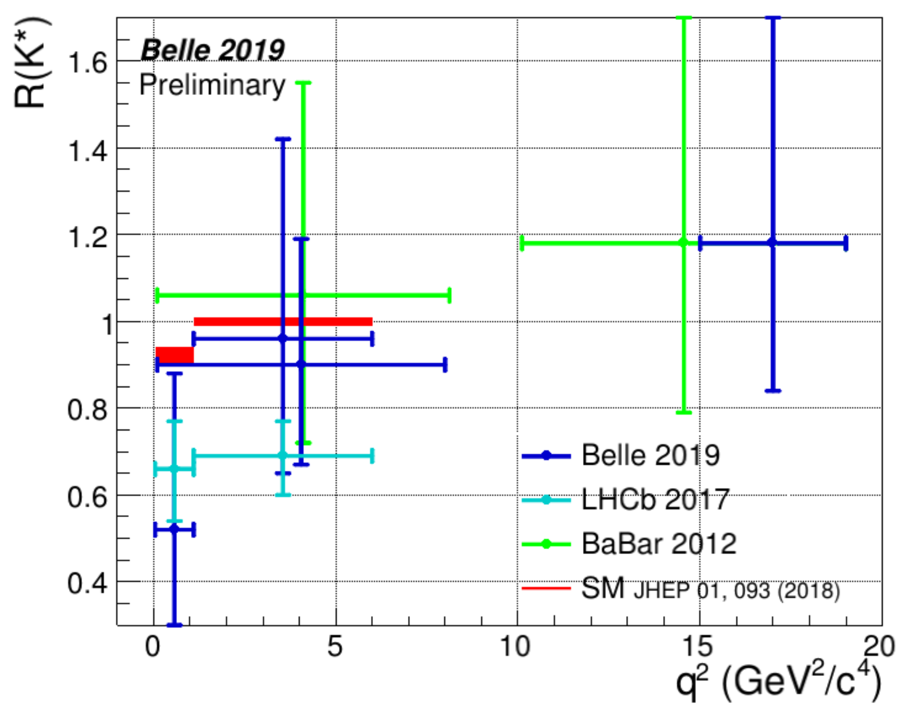
The ''clean'' Lepton Flavor Universality ratios:

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

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

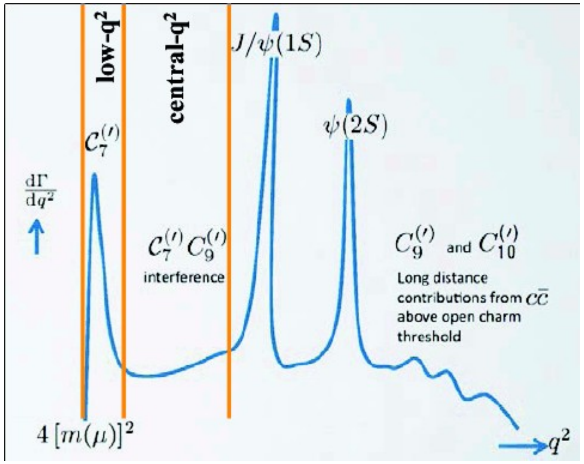
[up tiny QED and lepton mass effects]

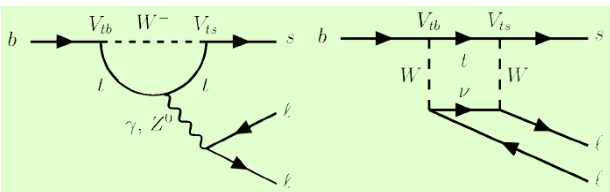


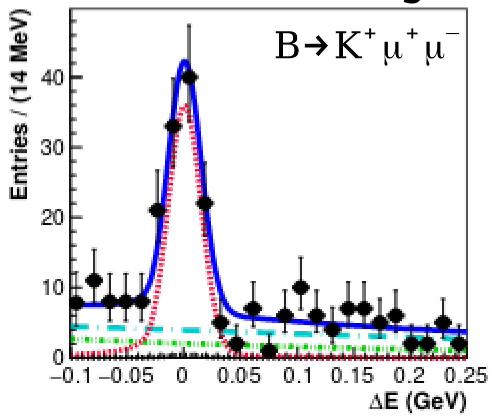


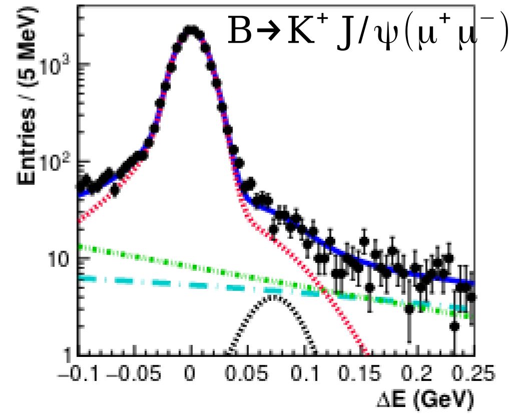
Test of lepton universality using $B^+ \to K l^+ l^-$ decays

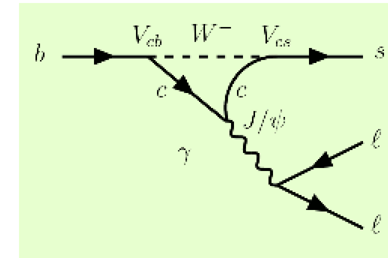
[Belle, arXiv:1908.01848]

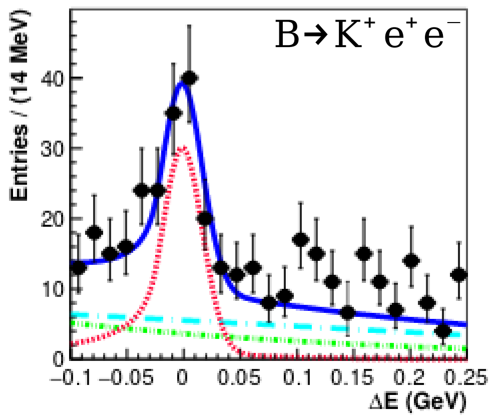


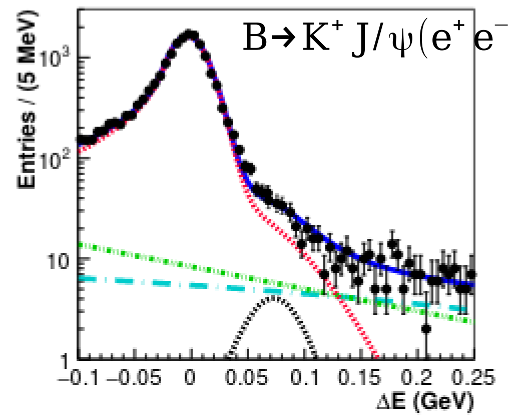


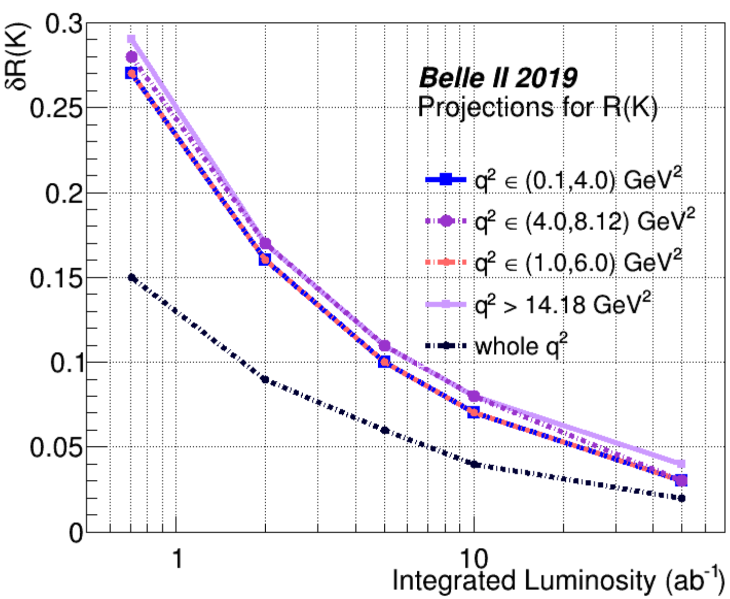


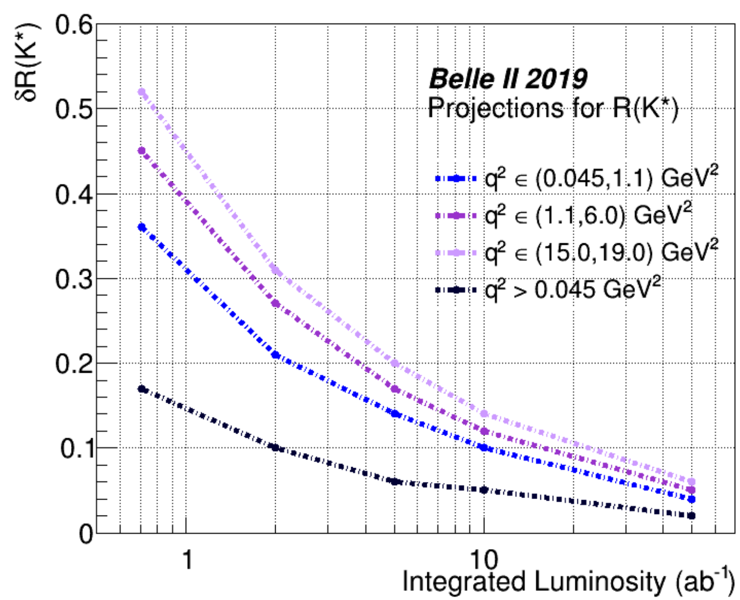




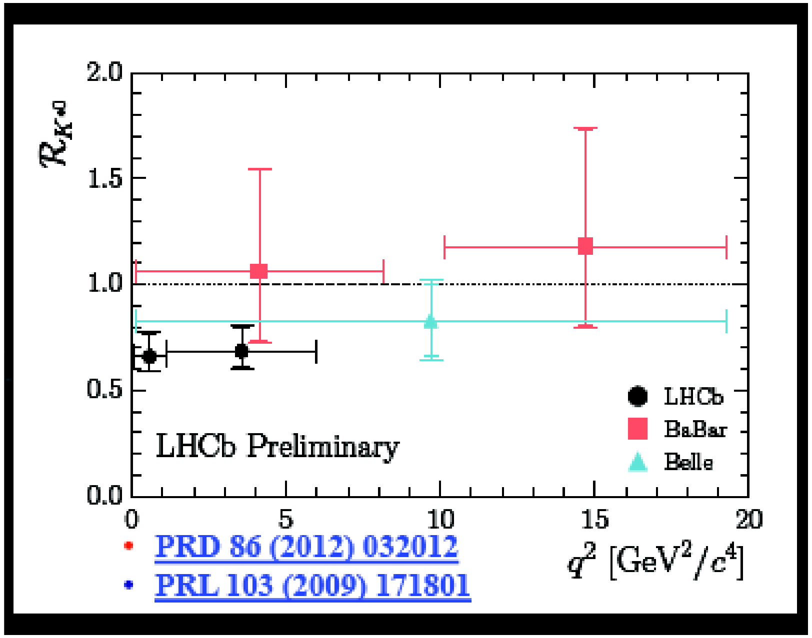


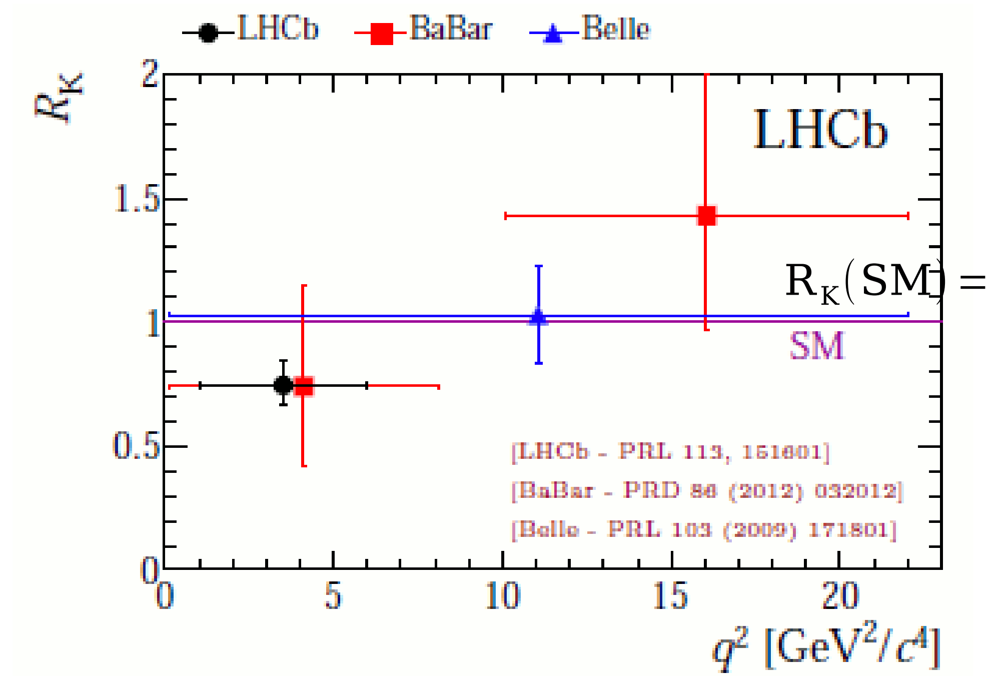






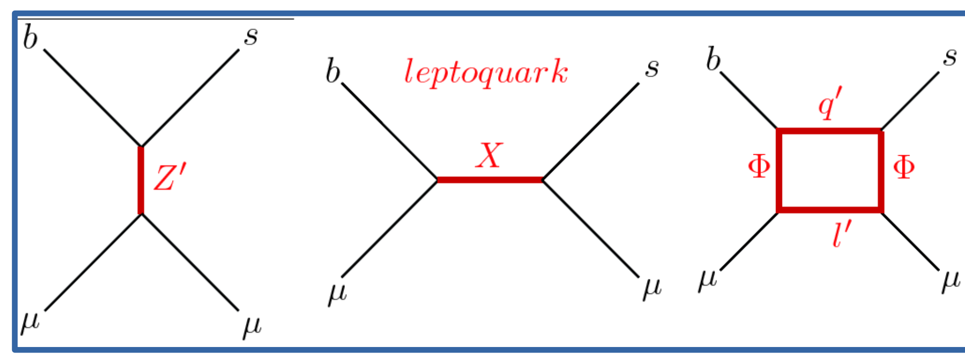
Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays





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

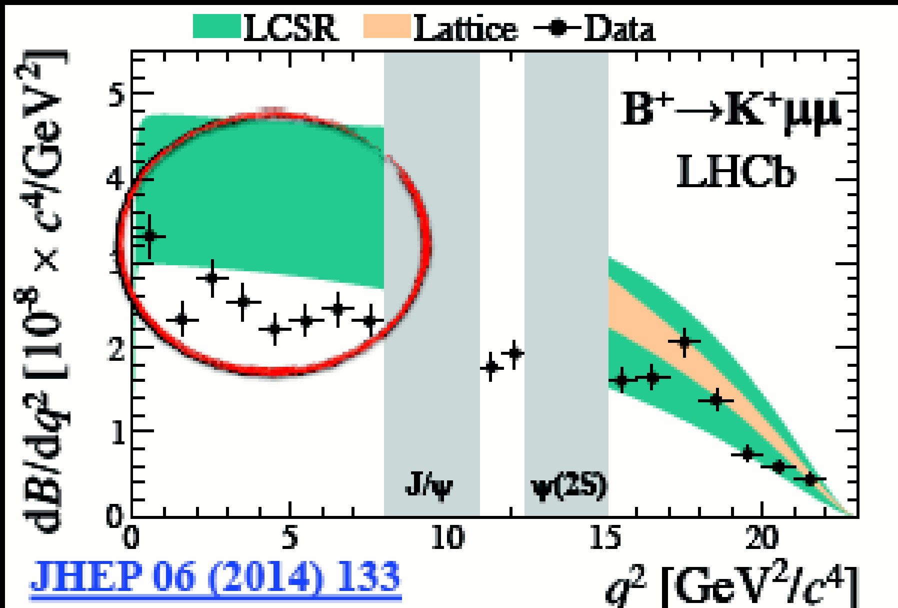


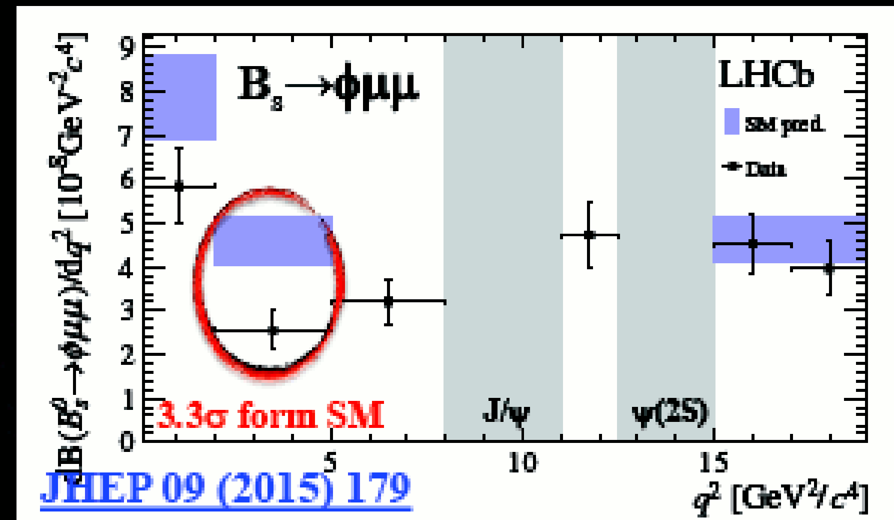
Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

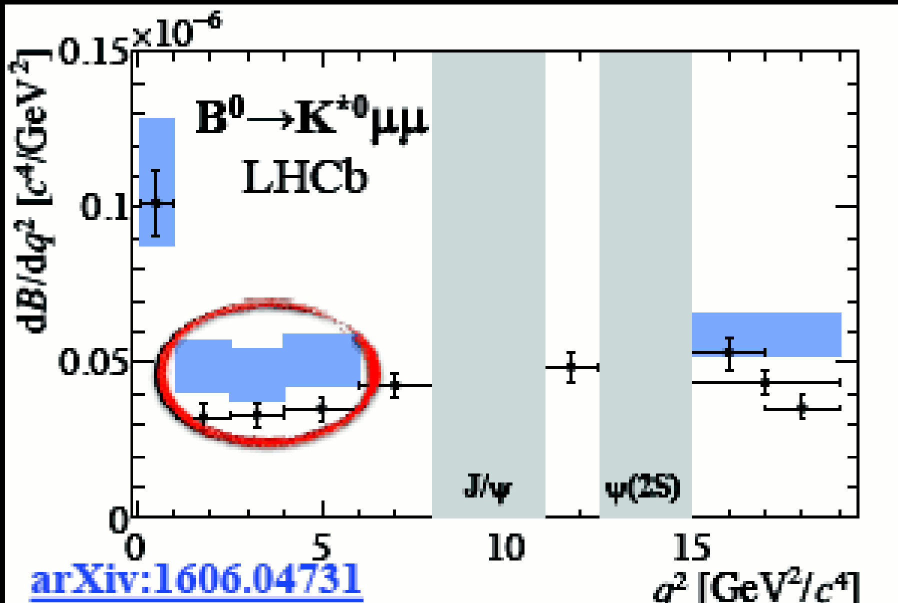
Lot of those models predict also LFV $b \to s e \mu, b \to s e \tau, \ldots$

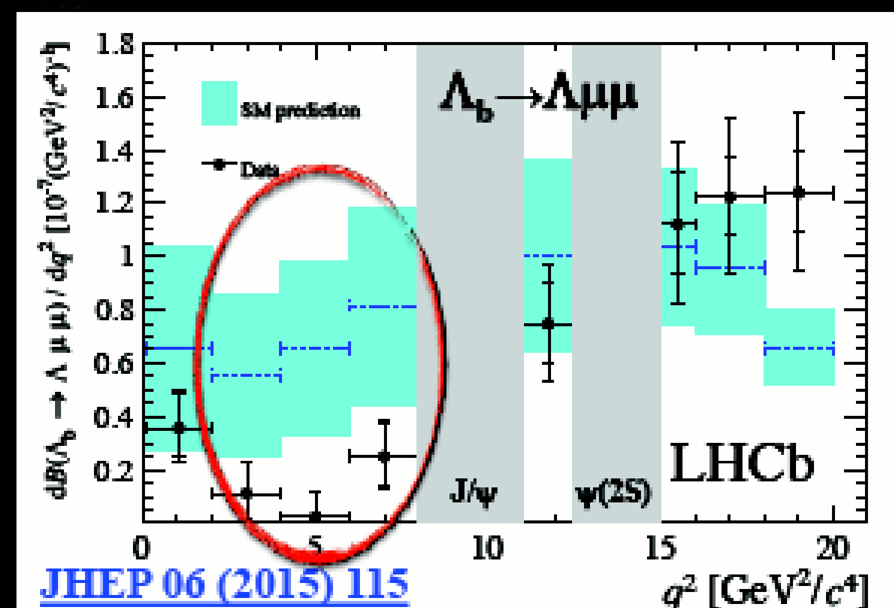
Differential Branching Fractions

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

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

Model candidates

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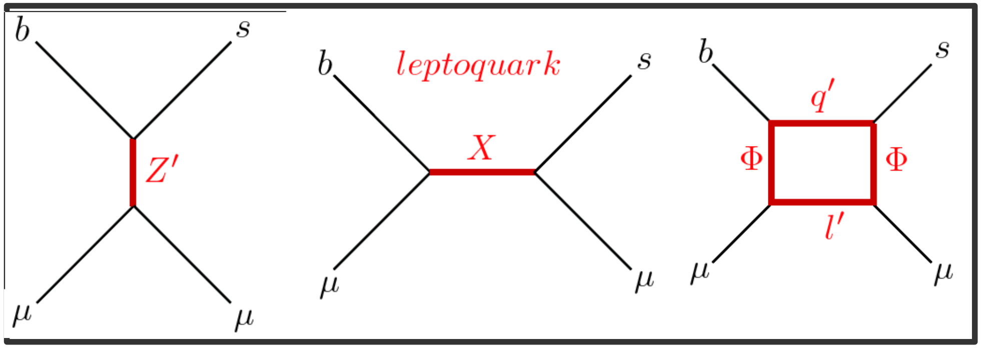

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Lot of those models predict also LFV $b \to s e\mu$, $b \to s e\tau$,...

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

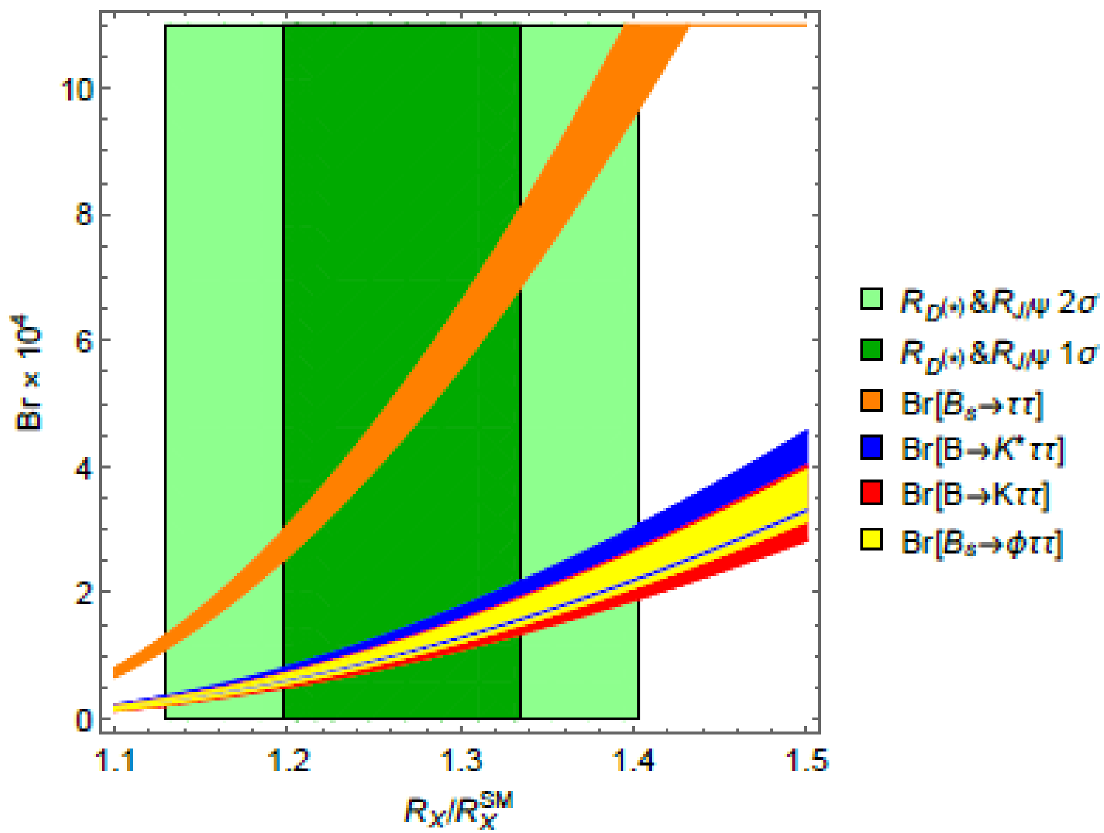
$B \to K^{(*)} \tau \tau$

[B.Capdevila et al, arXiv:1712.01919]

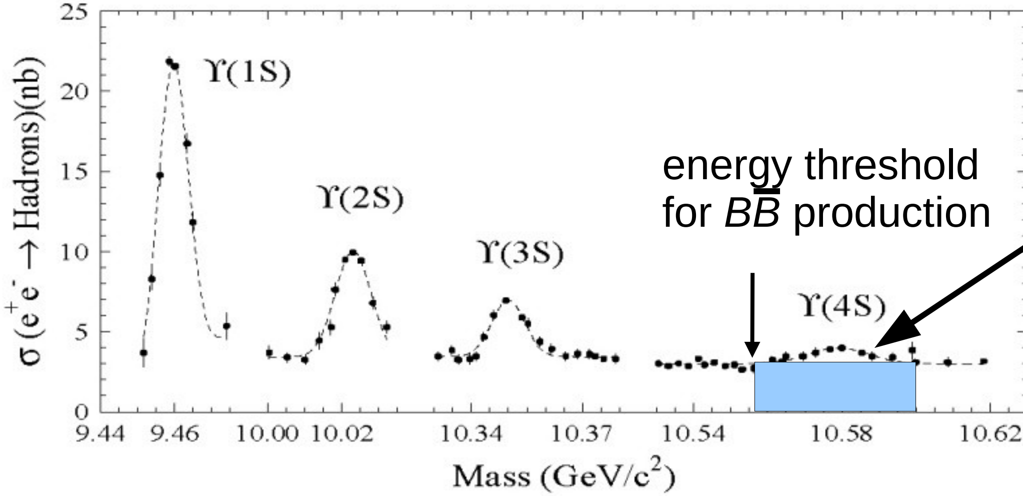
q^2 range for predictions for $B \to H \tau^+ \tau^-$: from $4\, m_\tau^2$ (~ 12.6 GeV^2) to $(m_B - m_H)^2$
to avoid contributions from resonant decay
through $\psi(2S)$, $B \to H \psi(2S)$, $\psi(2S) \to \tau^+ \tau^-$
predictions restricted to $q^2 > 15$ GeV^2:

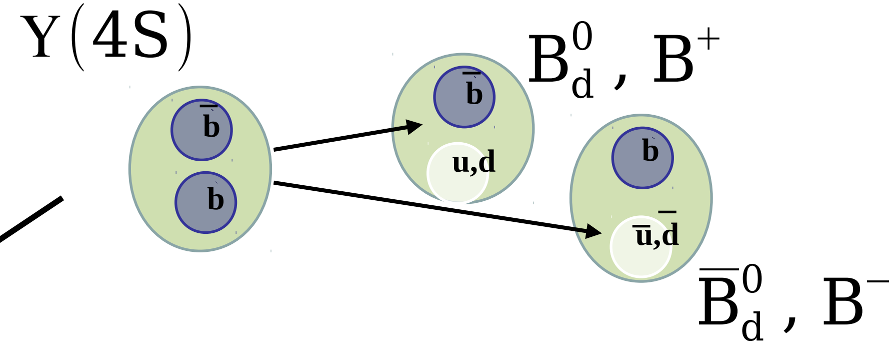
$$B(B \to K \tau^+ \tau^-)_{SM} = (1.2 \pm 0.1)\, 10^{-7}$$
$$B(B \to K^* \tau^+ \tau^-)_{SM} = (1.0 \pm 0.1)\, 10^{-7}$$

greatly enhanced in NP models...



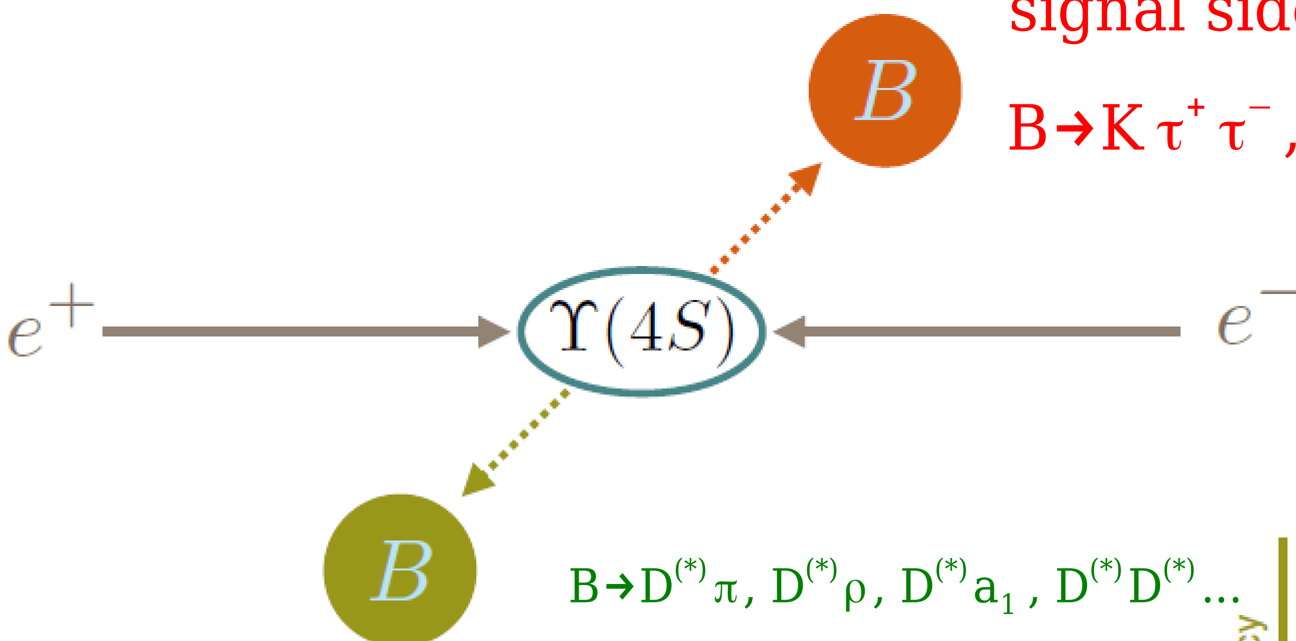
$B \to K^{(*)} \tau \tau$





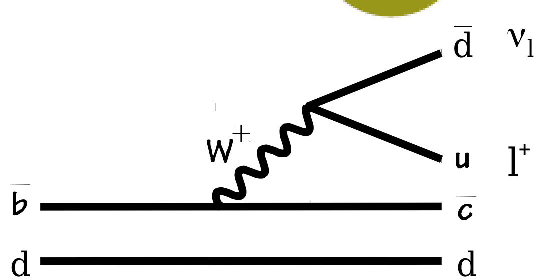
signal side

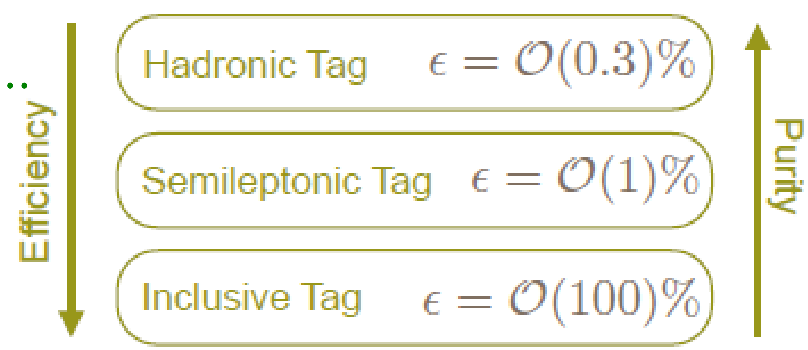
$B \to K \tau^+ \tau^-$, $\tau^+ \to \mu^+ \nu \nu$, $\tau^- \to e^- \nu \nu$



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

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





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

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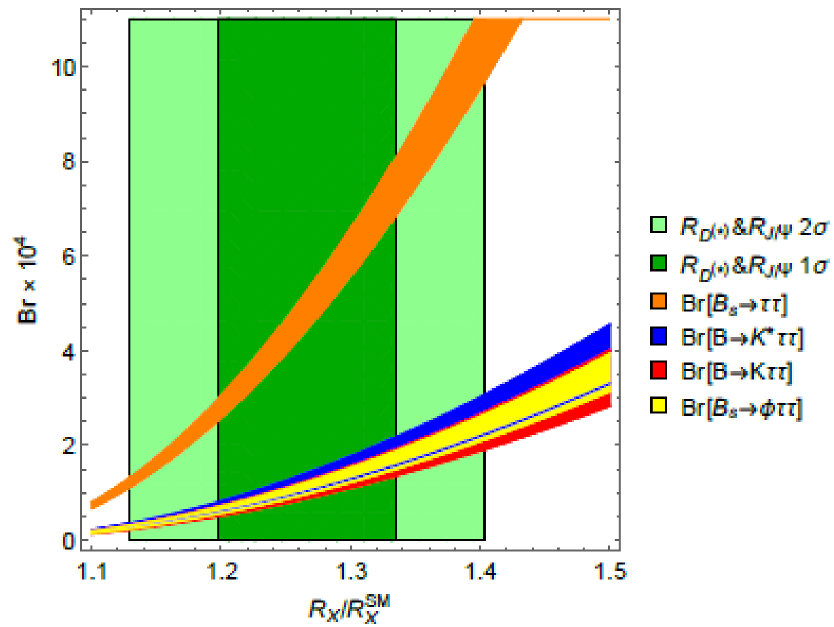
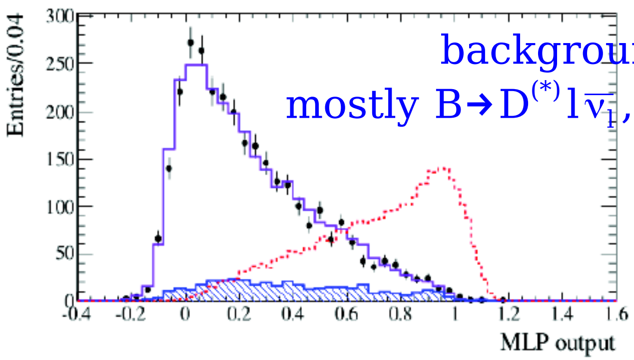


strategy used: [BaBar, arXiv:1605.09637]
B fully reconstructed (had tag), $\tau^+ \to l^+ \nu_l \nu_\tau$



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

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

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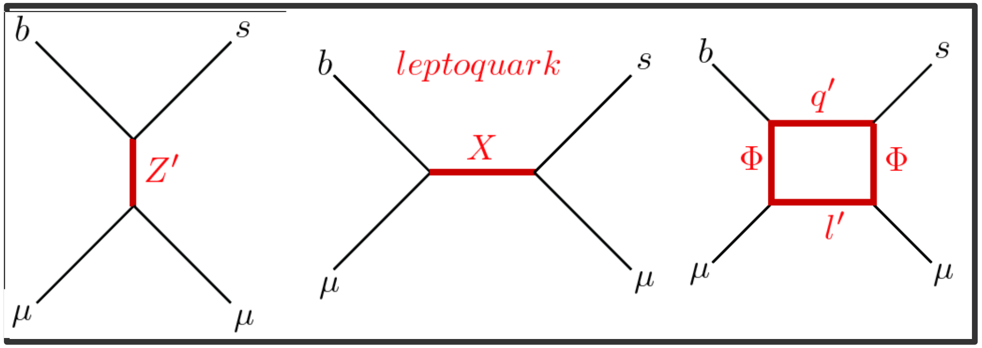

Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

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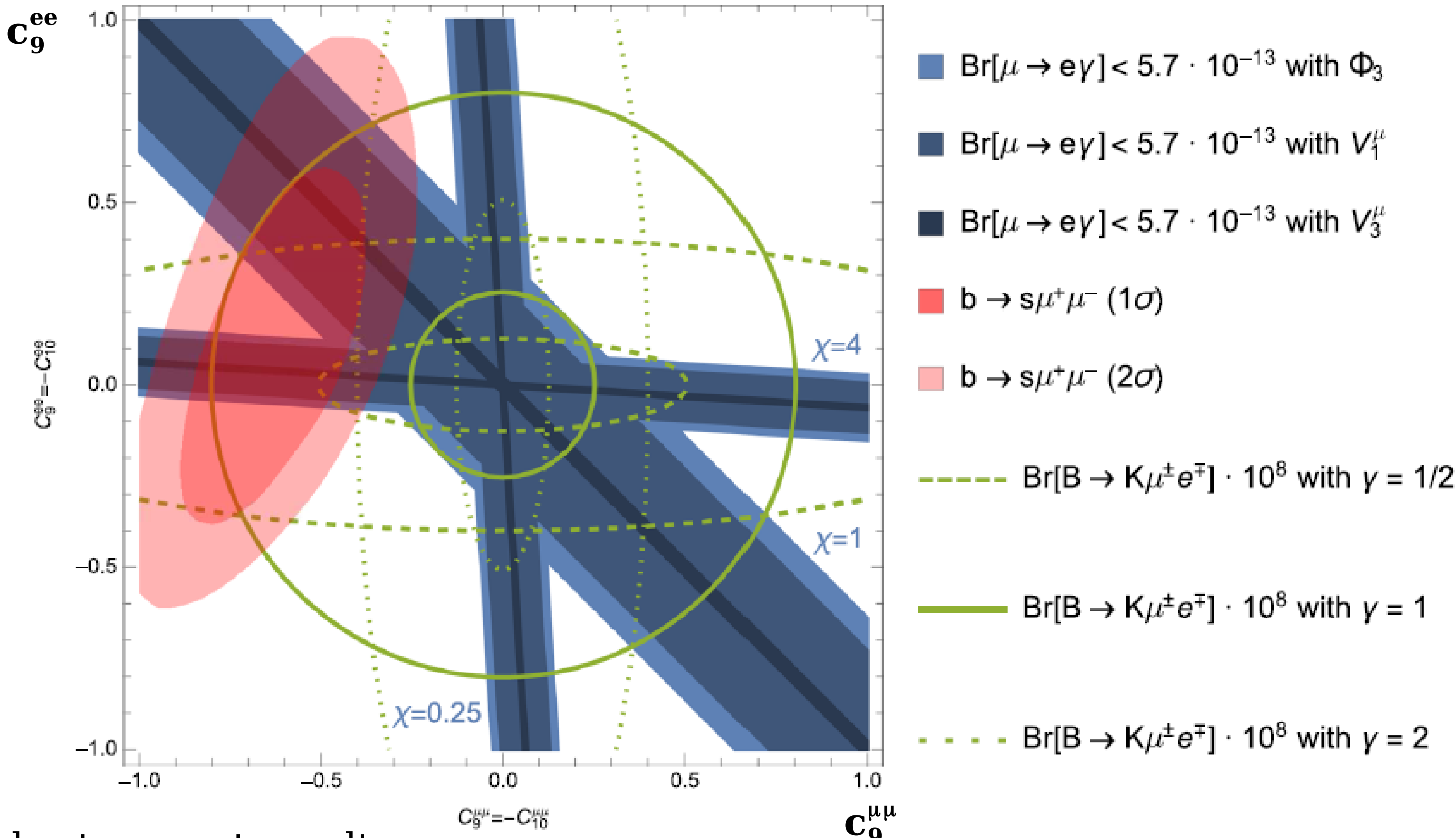
G.Isidori, FPCP 2020: correlations among $b \to s(d) l l'$ within the U(2)-based EFT

	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_π]	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → 10^{-7}	$B \to \pi \mu e$???

LFV b→sll'decays

Glashow, Guadagnoli and Lane, 1411.0565, LUV ⇒ LFV, such as B→Kμe, Kμτ are also generated...

A.Crivellin et al, 1706.08511



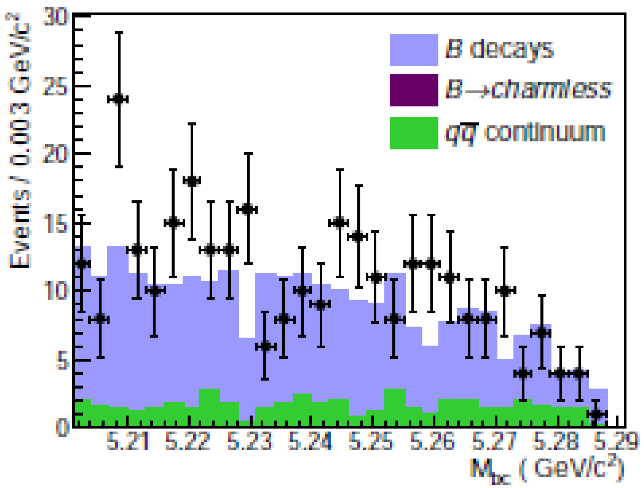
⇒ best current results:

- BaBar: $BF(B \to K\mu^{\pm}e^{\mp}) < 3.8\times10^{-8}$ at 90%CL (arXiv:hep-ex/0604007)
- Belle: $BF(B \to K^{*0}\mu^{\pm}e^{\mp}) < 1.8\times10^{-7}$ at 90%CL (arXiv:1807.03267)

LFV $B \to K^{*} l l'$ decays

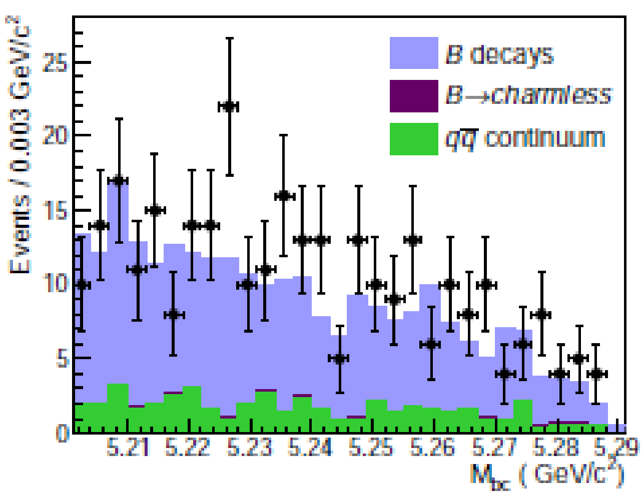
S.Sandilya (UC), KT (LAL)

[Belle, arXiv:1807.03267]



Mode	ε (%)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{\rm UL}$ (10^{-7})
$B^0 \to K^{*0}\mu^+e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2
$B^0 \to K^{*0}\mu^-e^+$	9.3	$0.40^{+4.8}_{-4.5}$	7.4	1.6
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ (combined)	9.0	$-1.18^{+6.8}_{-6.2}$	8.0	1.8

$B(B^0 \to K^{*0}\mu^+e^-) < 1.2 \times 10^{-7}$ at 90% CL

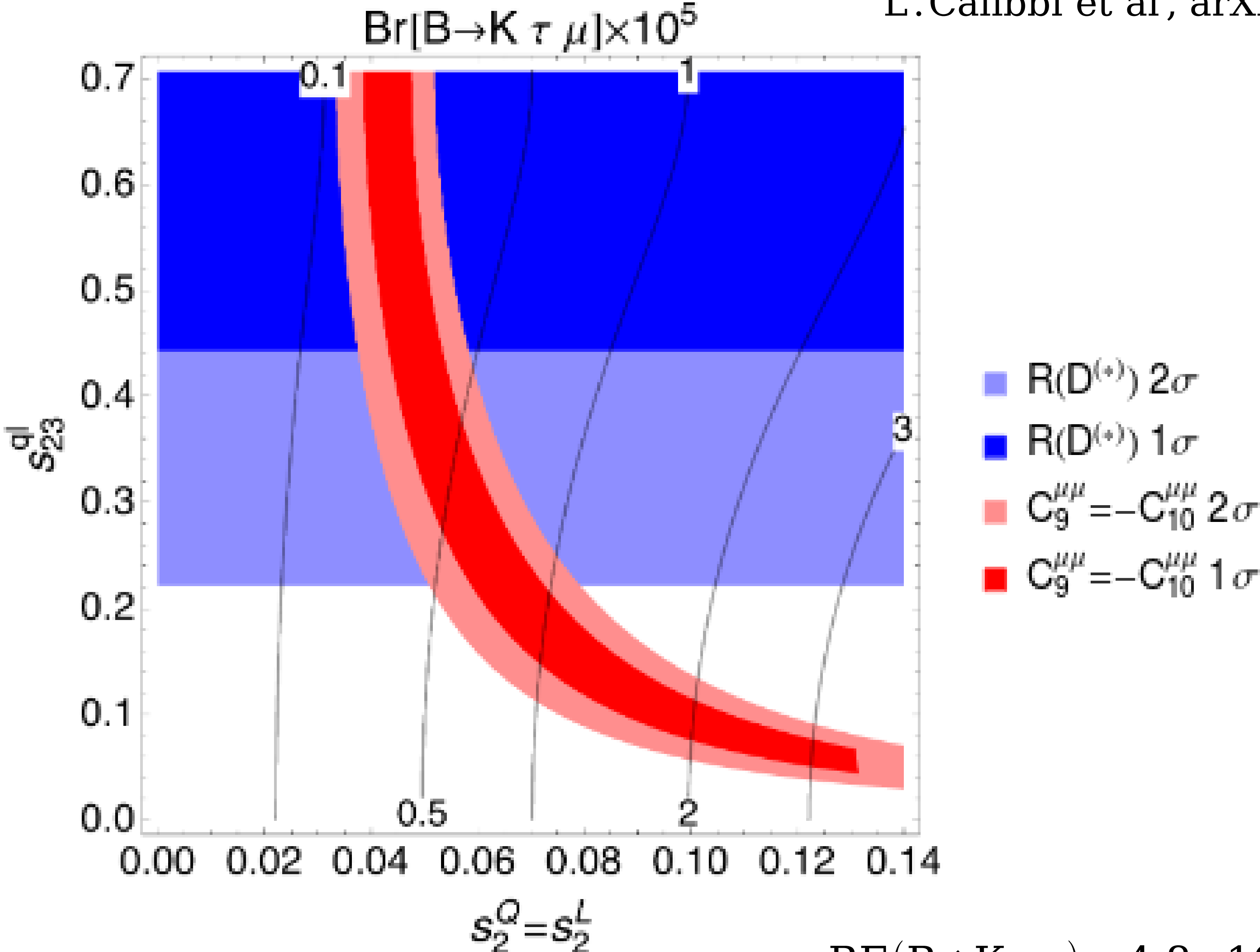


$B(B^0 \to K^{*0}\mu^+e^-) < 1.6 \times 10^{-7}$ at 90% CL

Belle II can get 90% UL at 10^{-8} level with 50 ab^{-1}

R(D*) and b→sμμ

L.Calibbi et al, arXiv:1709.00692

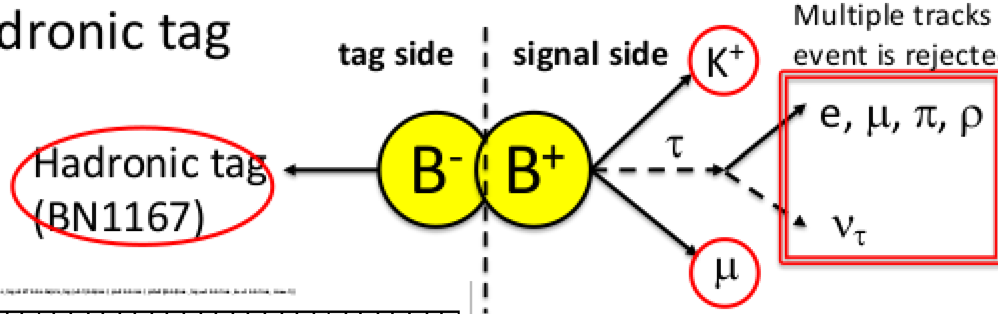


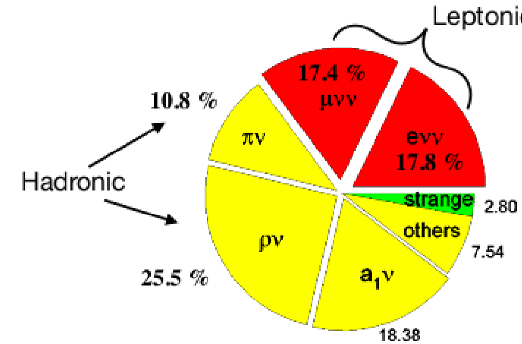
$BF(B\to K\tau\mu) < 4.8\times10^{-5}$ @ 90% CL
BaBar, arXiv:1204.2852
hadronic tag

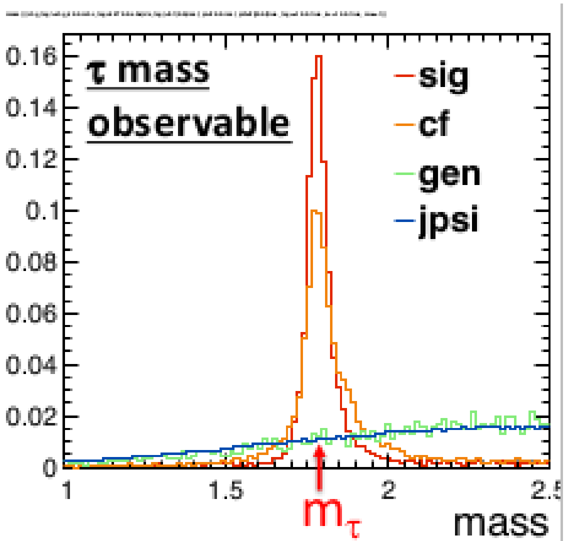
LFV B→Kτl (l = e, μ) decays

focus on K (K^+ or K^0_S), $\tau \to e\nu\nu, \mu\nu\nu, \pi\nu, \rho\nu$ **[Belle & Belle II]**

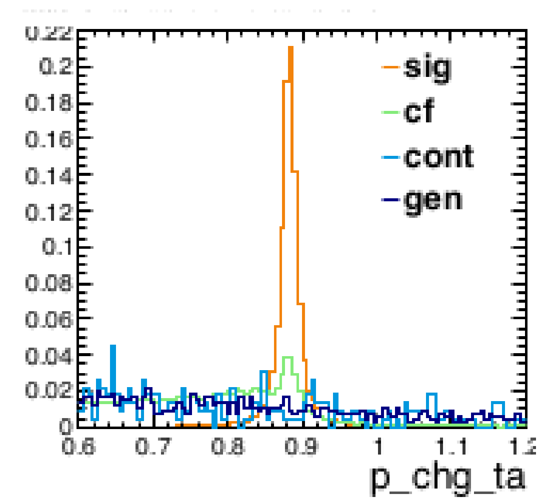
- Hadronic tag



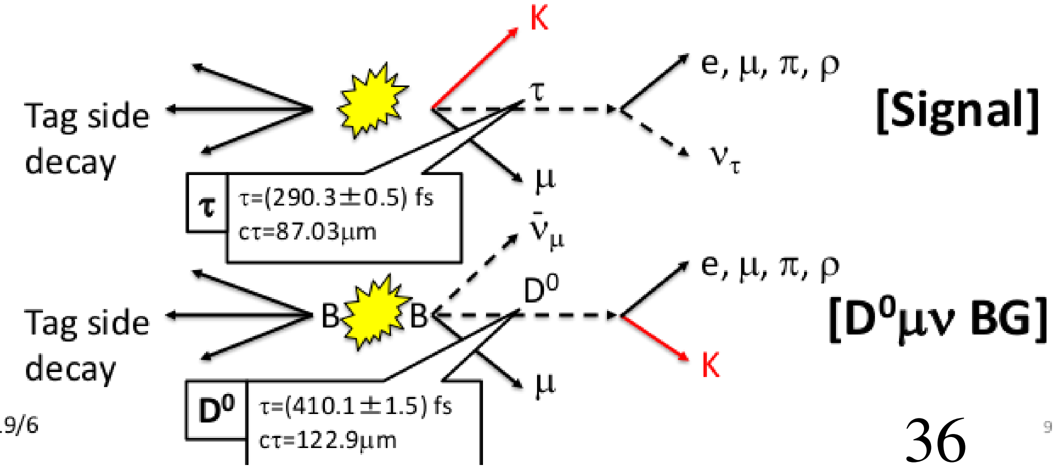


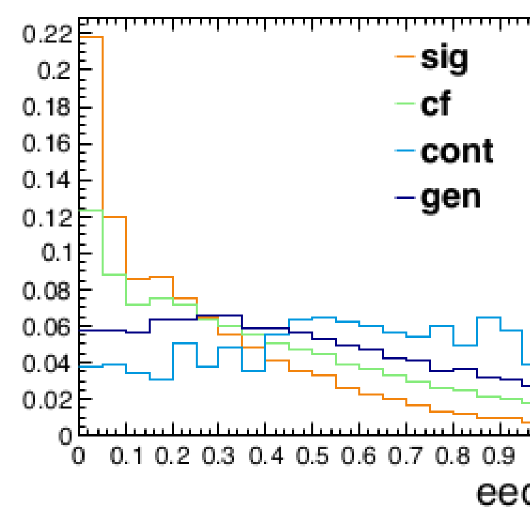


- For τ→πν, ρν channel, kinematic cut is useful to suppress BG.
- τ→πν
  - Monochromatic momentum of π in τ rest frame
- τ→ρν→ππ⁰ν
  - Monochromatic momentum of ρ in τ rest frame
  - Invariant mass of ππ⁰



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





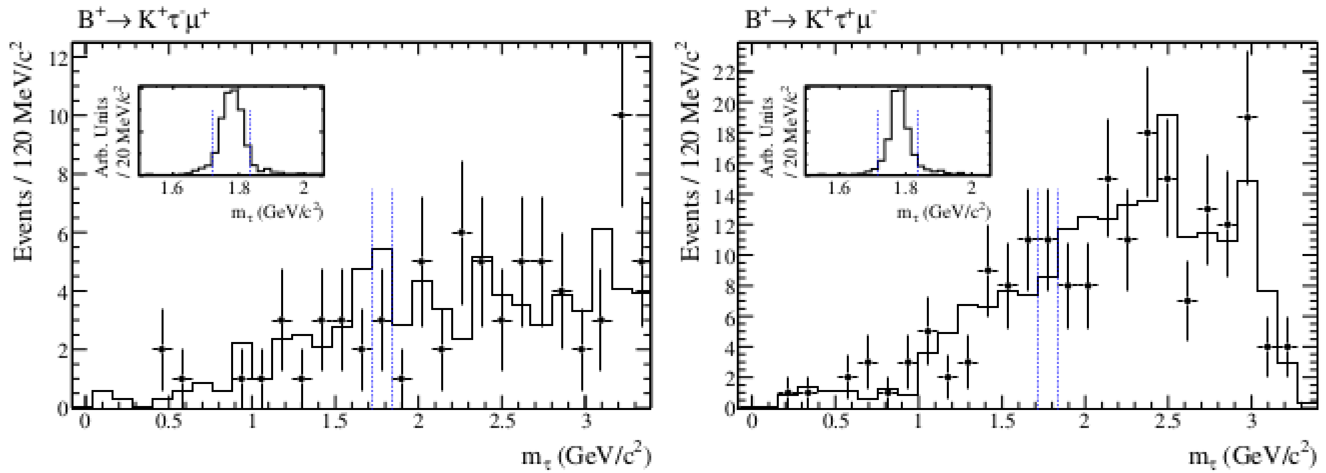
LFV $B \to K \tau l$ ($l = e, \mu$) decays

[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

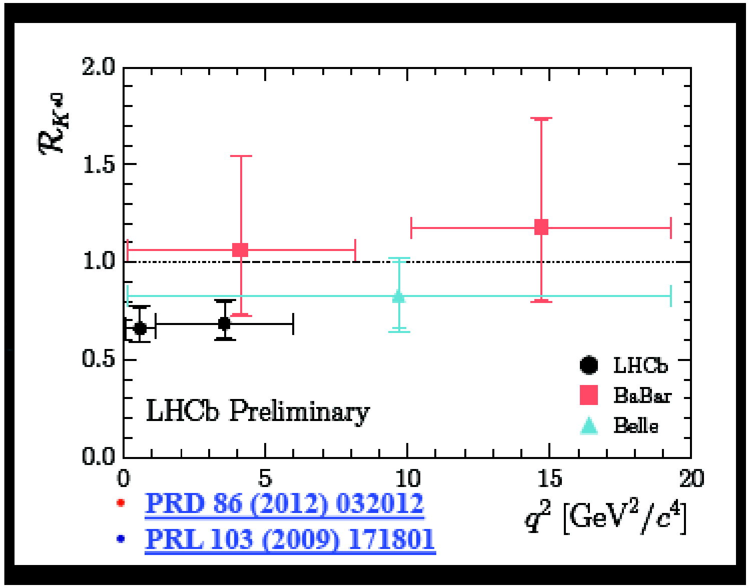
(also results for $B \to K^+ \tau^\pm e^\mp$, $B \to \pi^+ \tau^\pm \mu^\mp$, $B \to \pi^+ \tau^\pm e^\mp$ modes)

[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...**



anything else ?

b → s anomalies

Found by LHCb (and perhaps hinted by Belle)

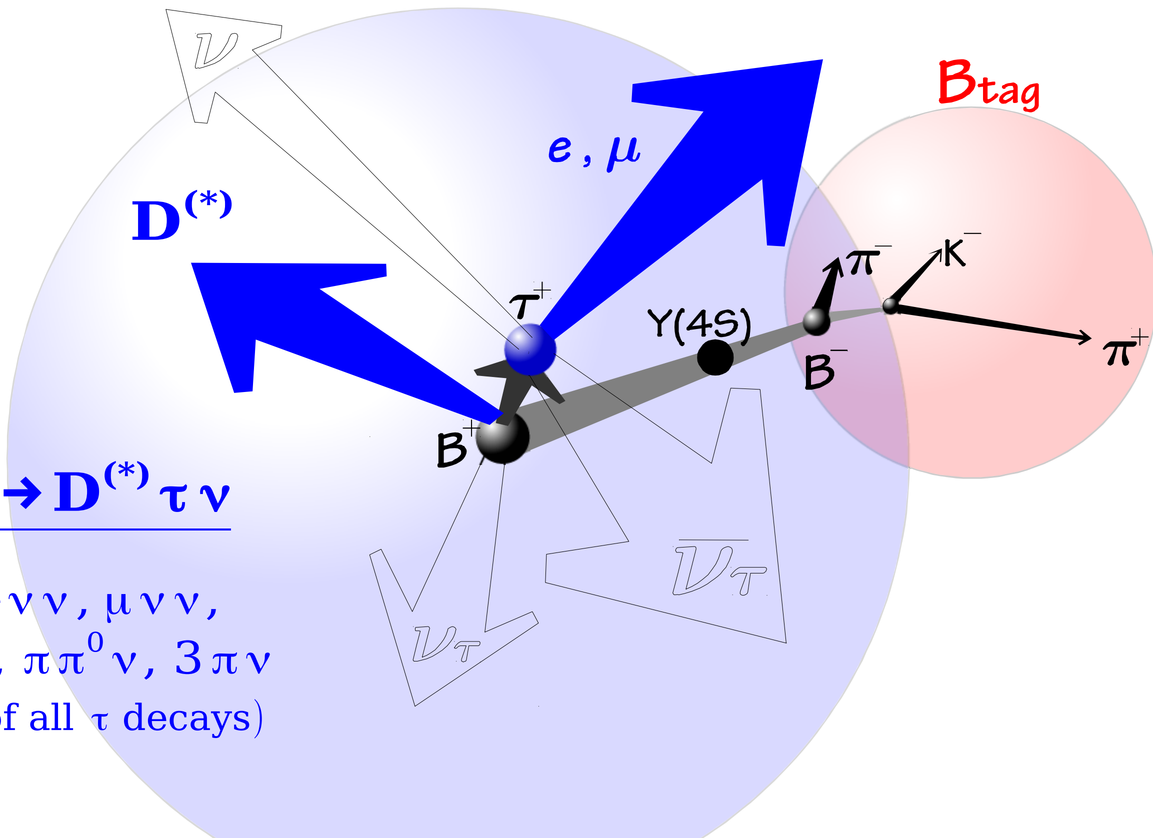
Many observables: global pattern

Neutral current

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

The New Physics can be heavy

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



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

$\tau \to e\nu\nu,\ \mu\nu\nu,$
$\tau \to \pi\nu,\ \pi\pi^0\nu,\ 3\pi\nu$
(70 % of all τ decays)

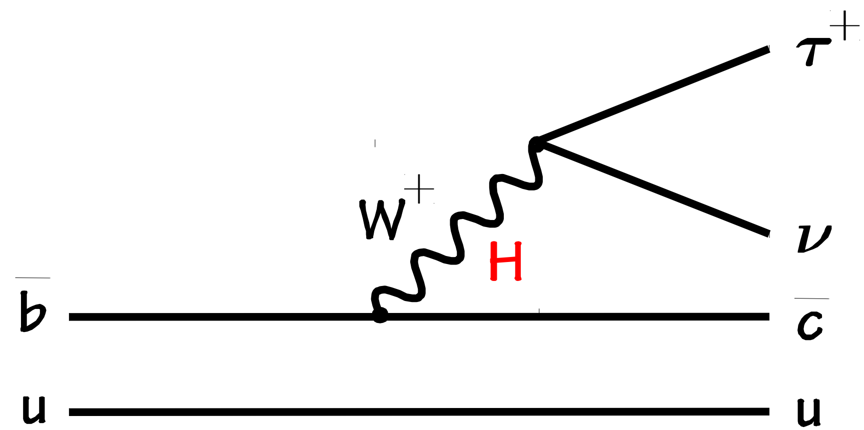
B_{tag}

hadronic tag

$B \to D^{(*)}\pi,\ D^{(*)}\rho \ldots$
$\epsilon \sim 0.2\,\%$

semileptonic tag

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



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

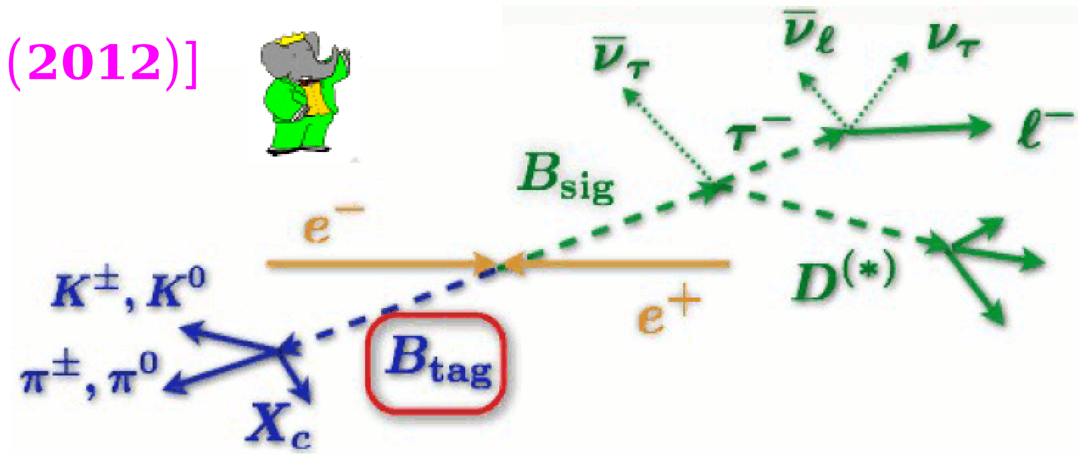
main signal-background discriminator

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

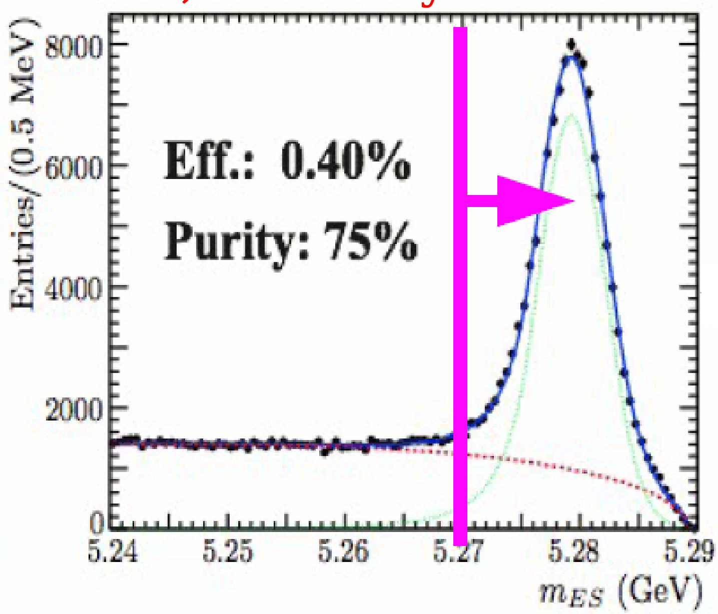
$$2\mathrm{HDM\ (type\ II)}: \mathcal{B}(B \to D \tau^+ \nu) = G_F^2\, \tau_B\, |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

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

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

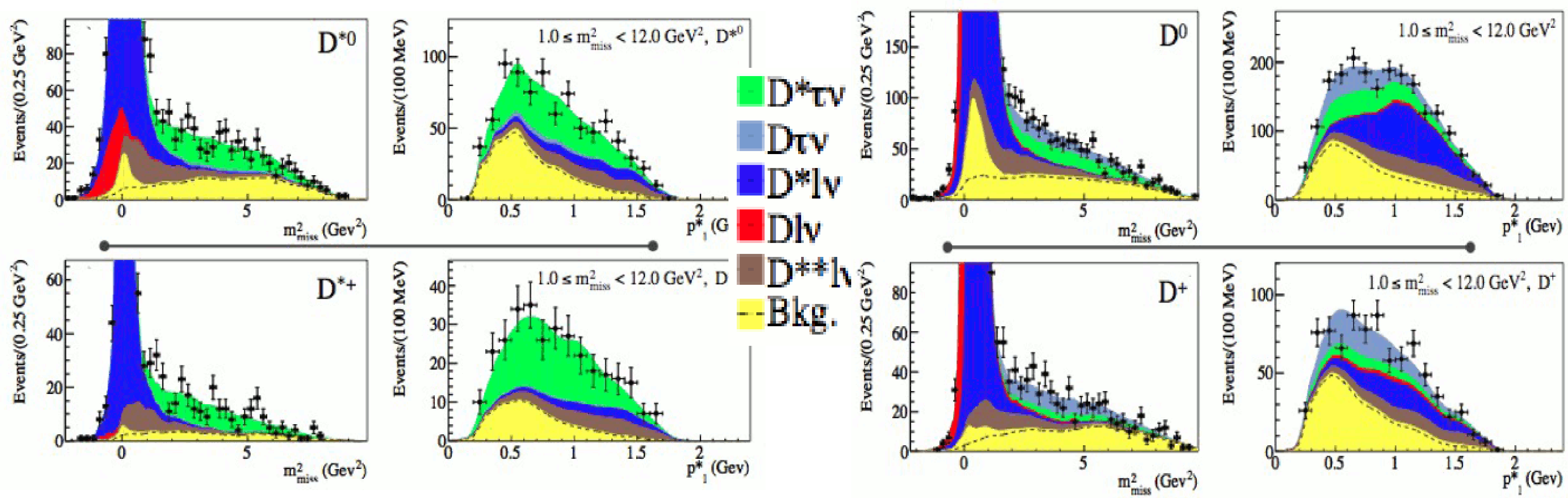


1,768 decay chains

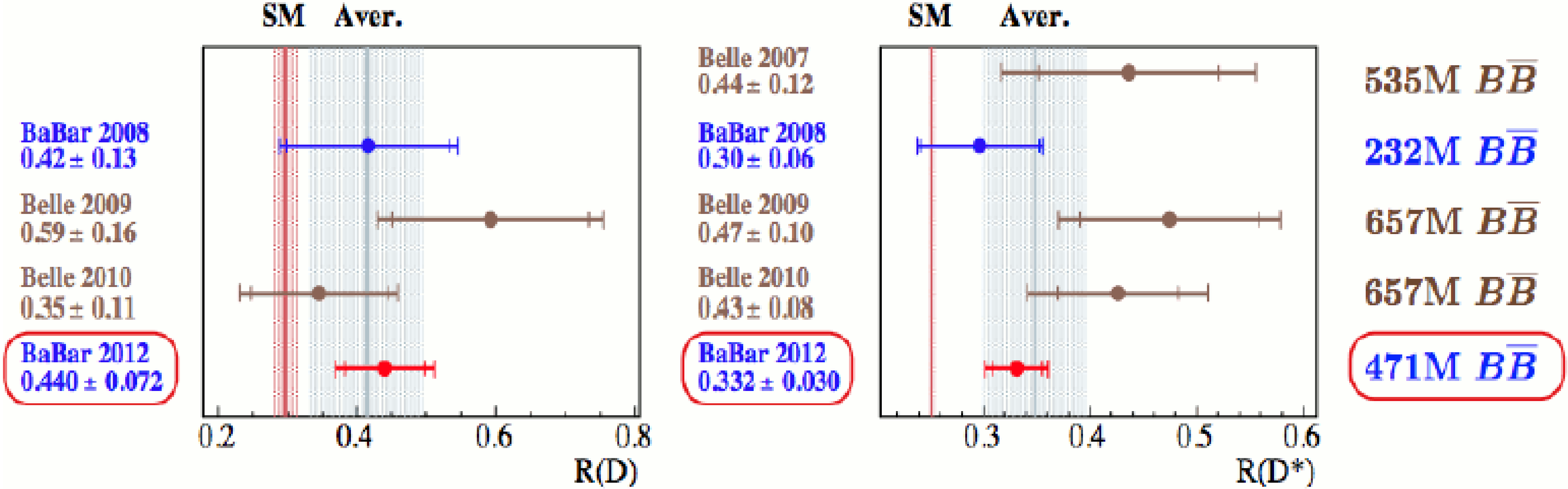


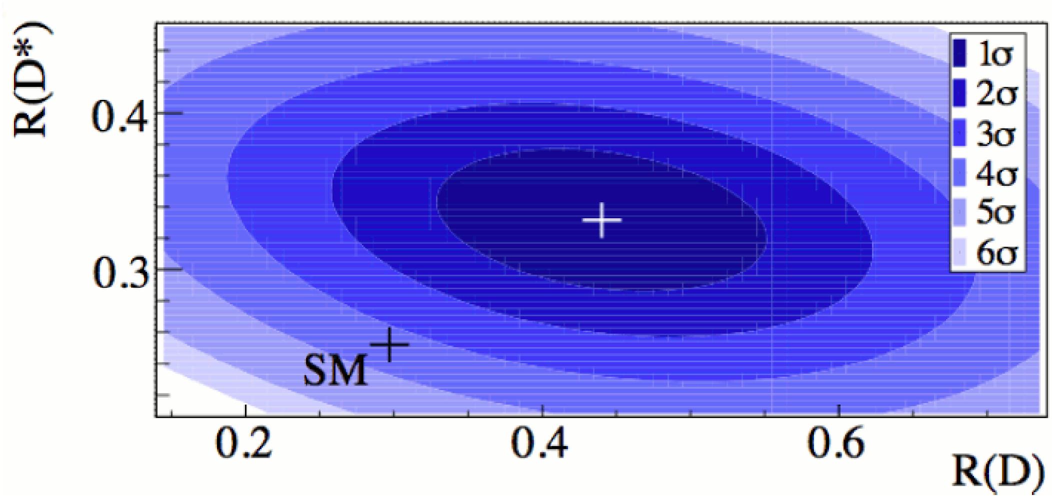
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

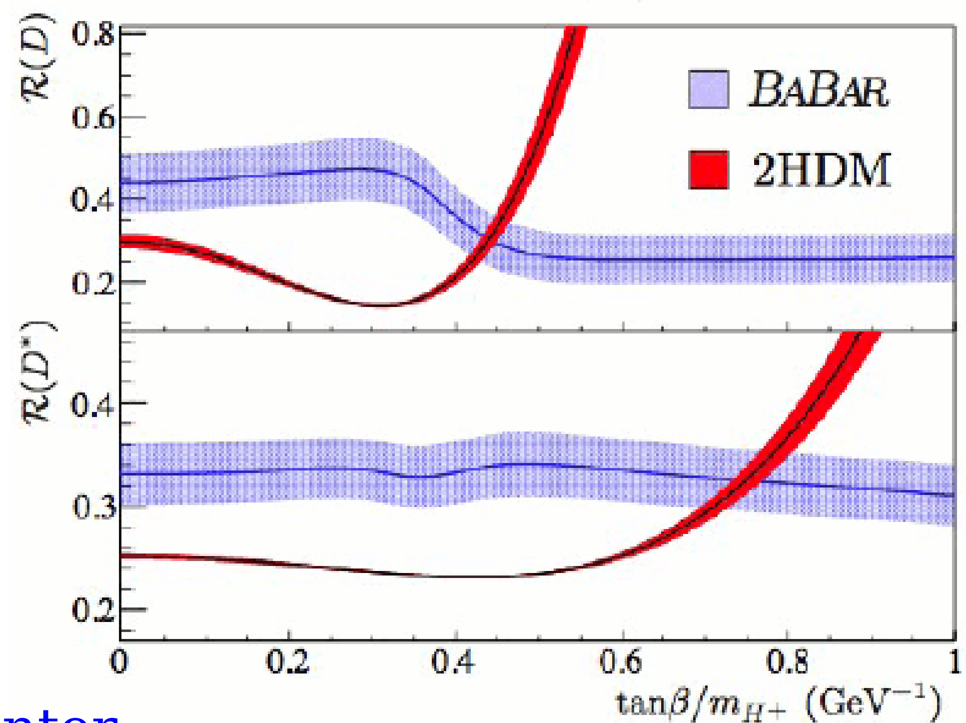
⇒ $D\tau\nu$ and $D^*\tau\nu$ clearly observed



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



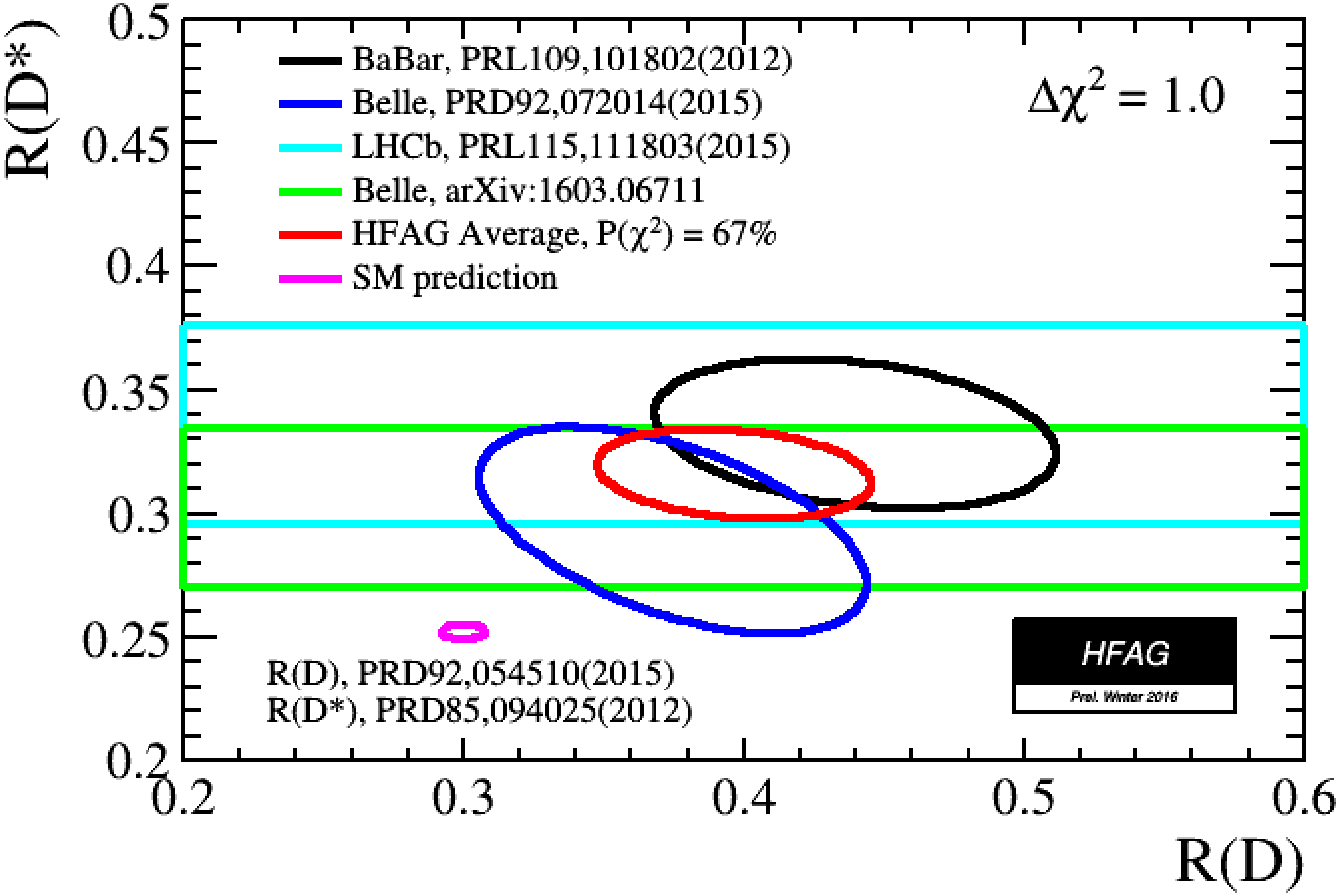




- combined 3.4 σ away from SM
- doesn't fit 2HDM Type II
- Belle will show its new result this winter

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

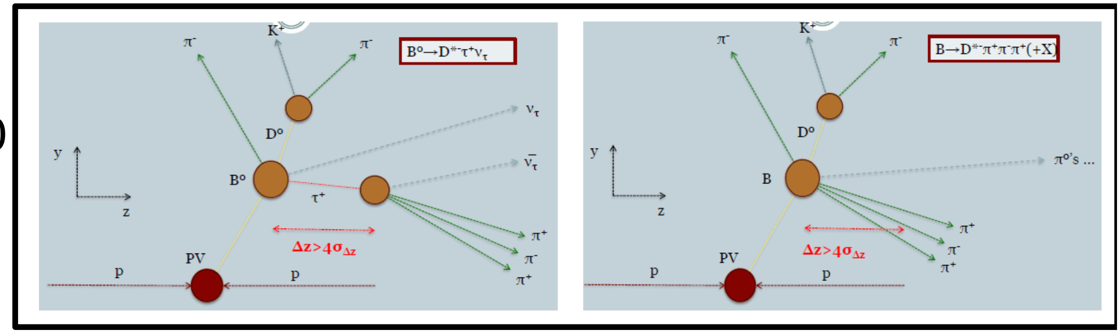
$R(D) = 0.397 \pm 0.040 \pm 0.028$
$R(D^*) = 0.316 \pm 0.016 \pm 0.010$

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

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

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

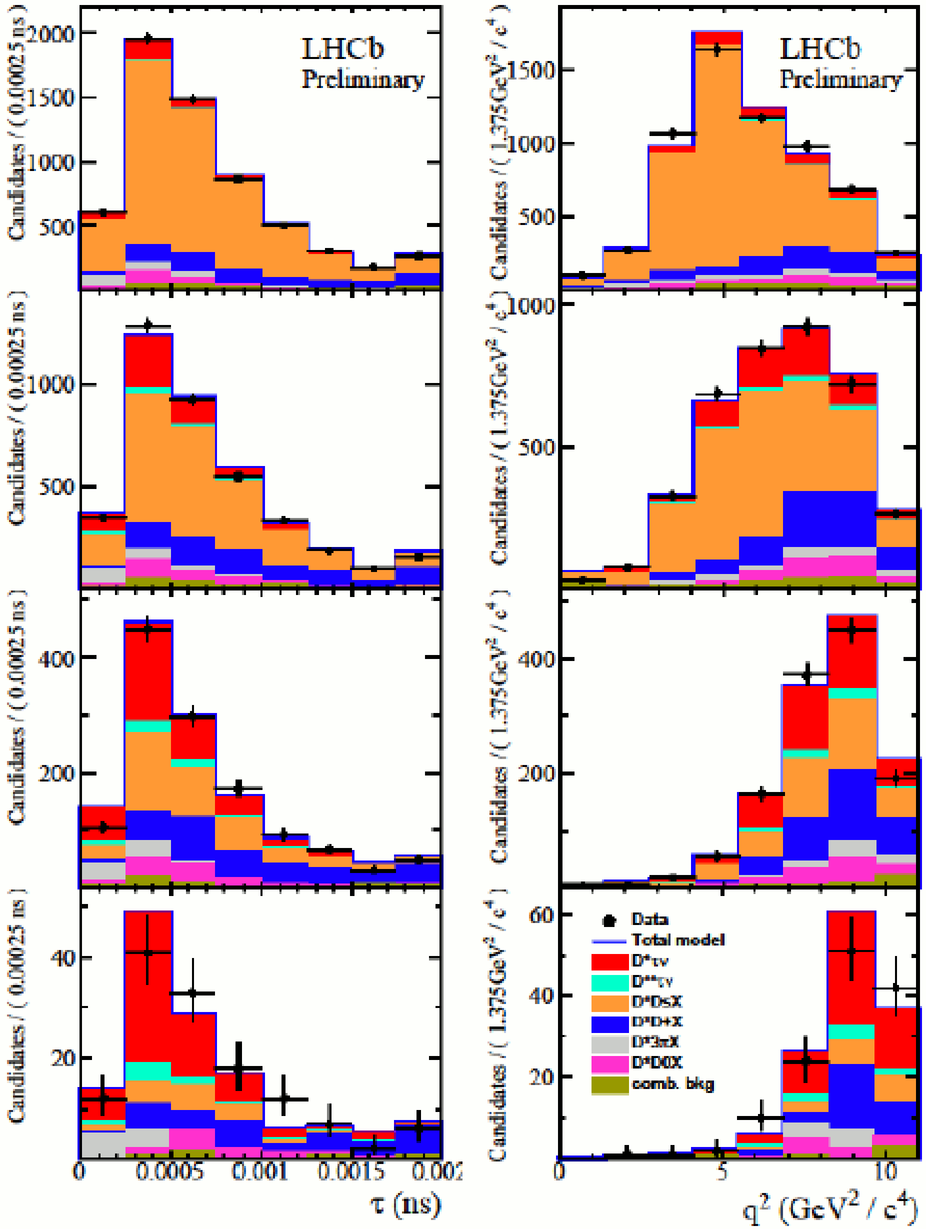
[LHCb-PAPER-2017-017]

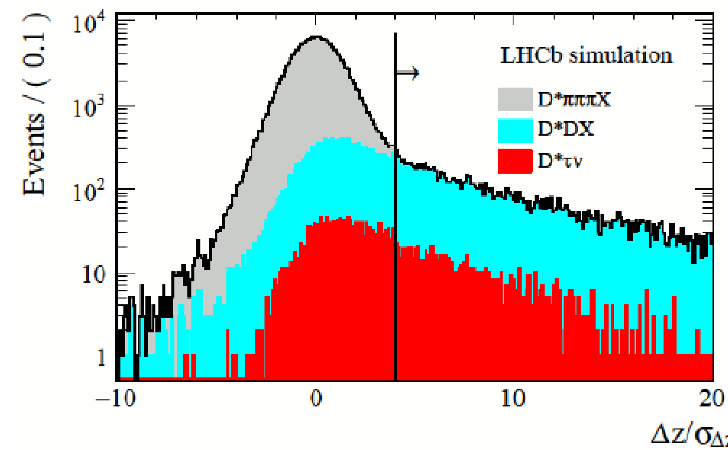


need a strong background suppression:

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

⇒ 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

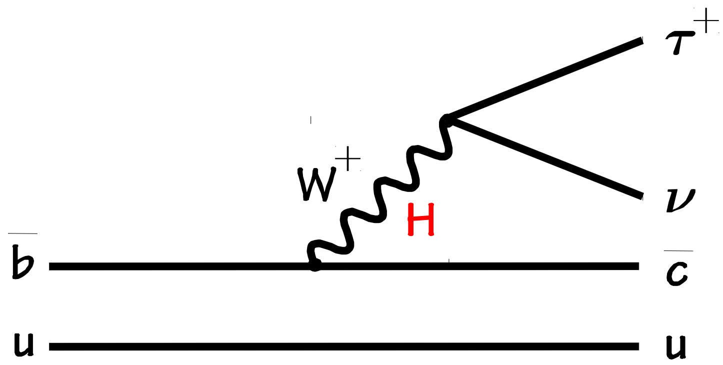
$B(B^0 \to D^* \tau\nu)/B(B^0 \to D^* 3\pi) = (1.93 \pm 0.13 \pm 0.17)$

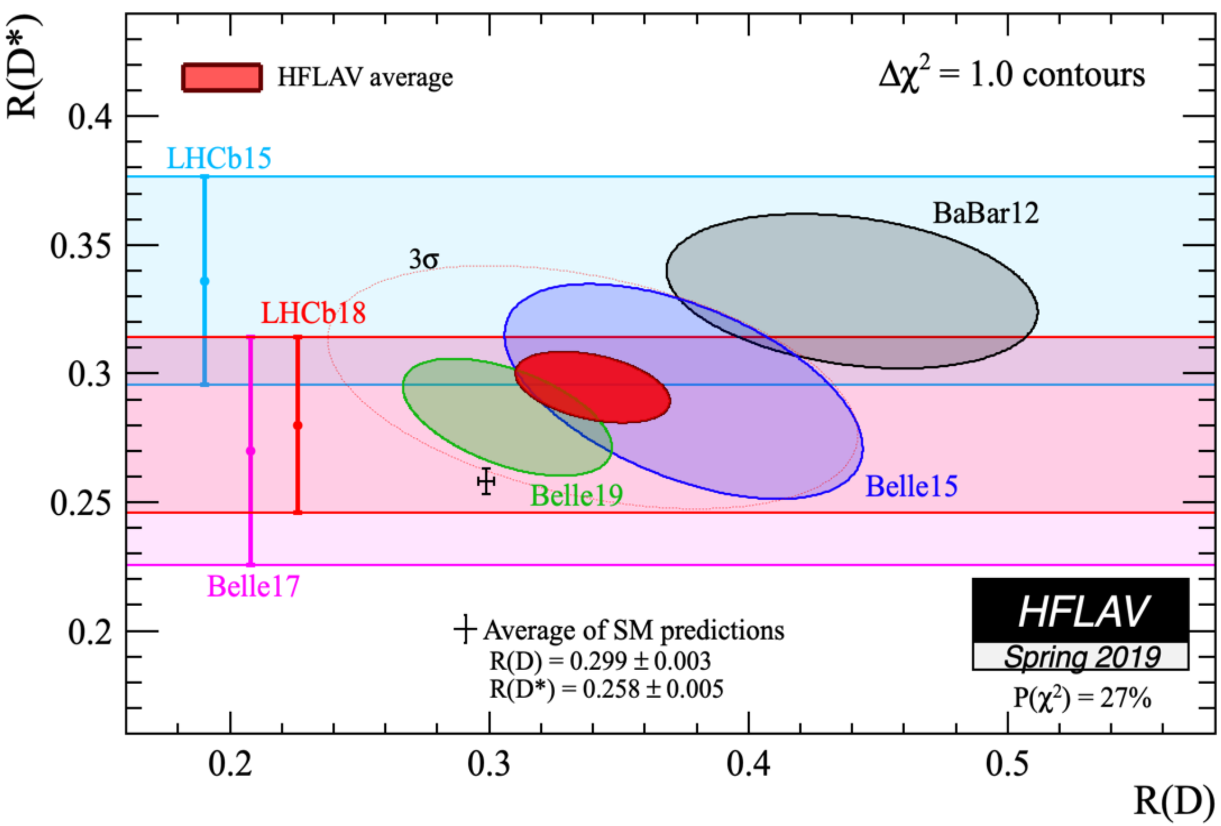
⇒ **$R(D^*) = 0.285 \pm 0.019 \pm 0.025 \pm 0.014$**

$R(D)$, $R(D^*)$ 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

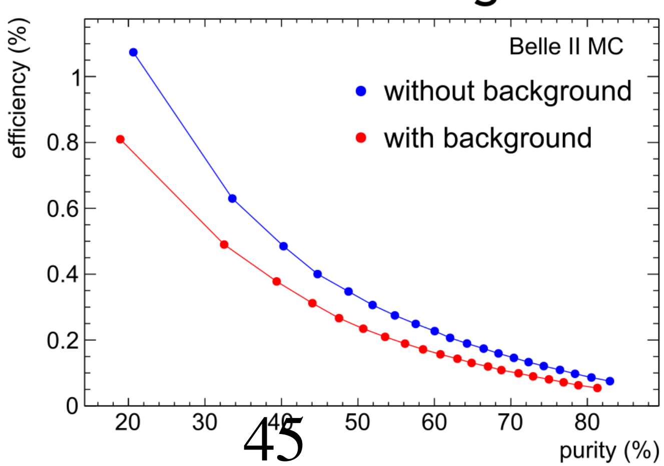
- More modes used for tag-side hadronic B than Belle, multiple classifiers

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

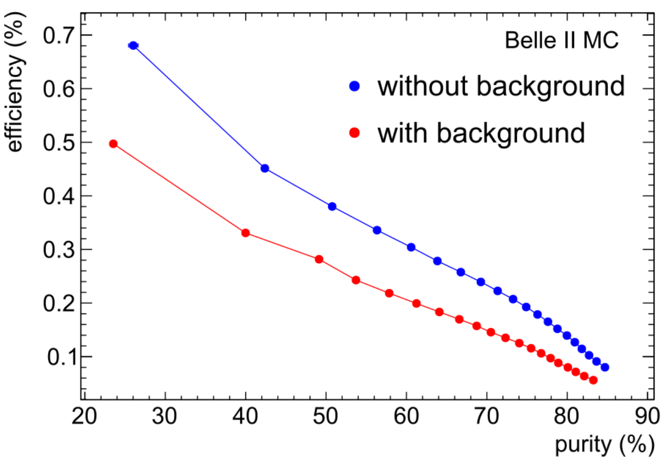
Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:

Hadronic charged B



Hadronic neutral B

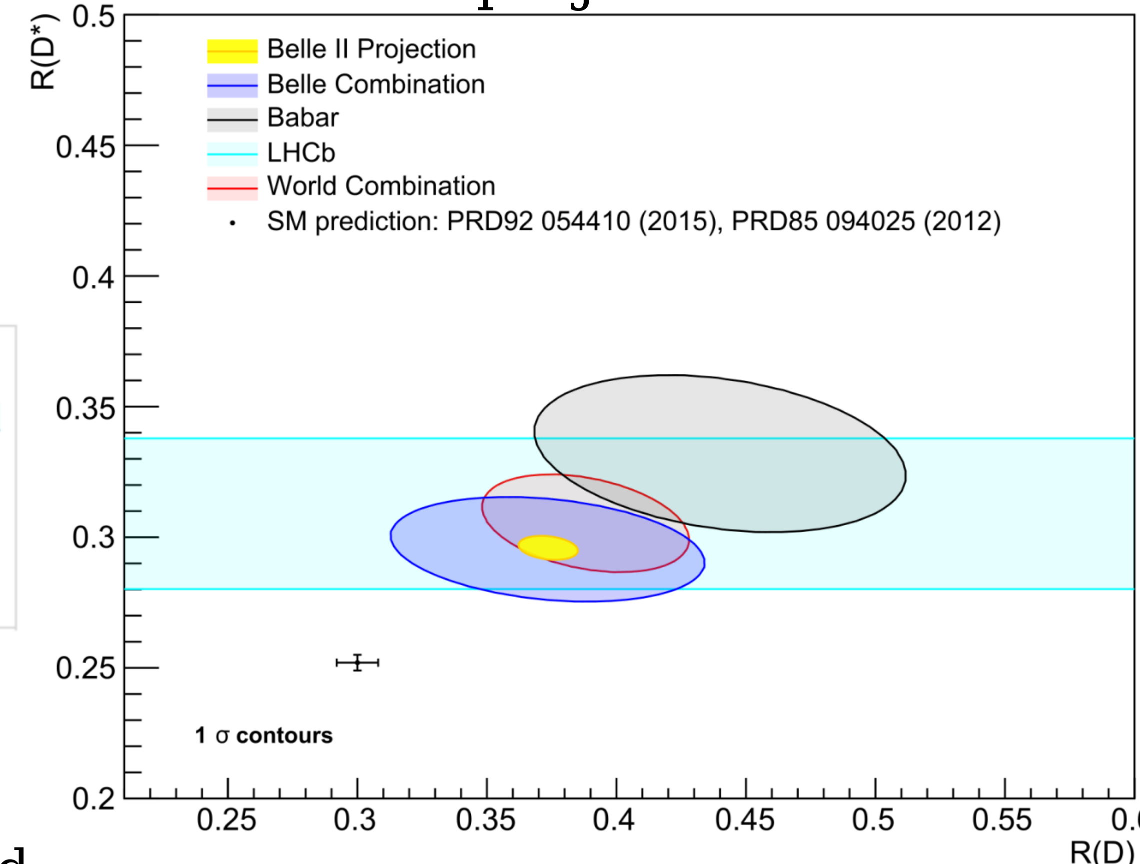


Projections for Belle II $R(D^{(*)})$

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

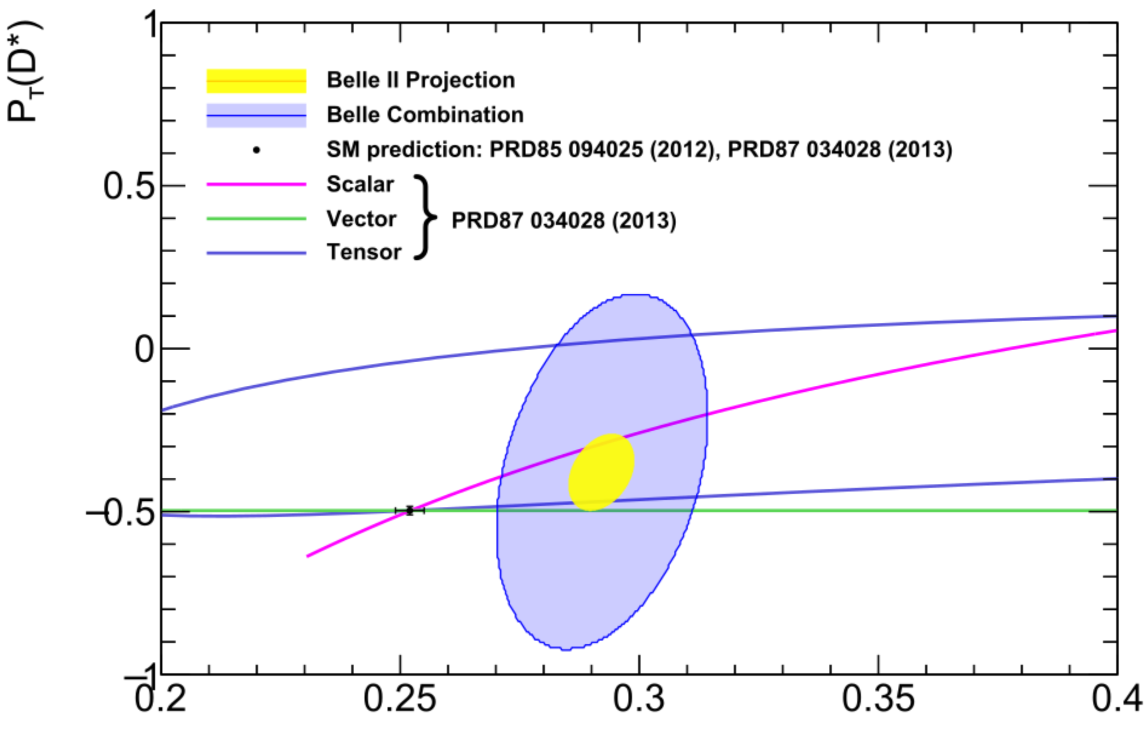
Additional observables as $P_\tau(D^*)$ ($F_L(D^*)$) and q^2 distribution can help discriminate between New Physics models

[Belle, arXiv:1612.00529]

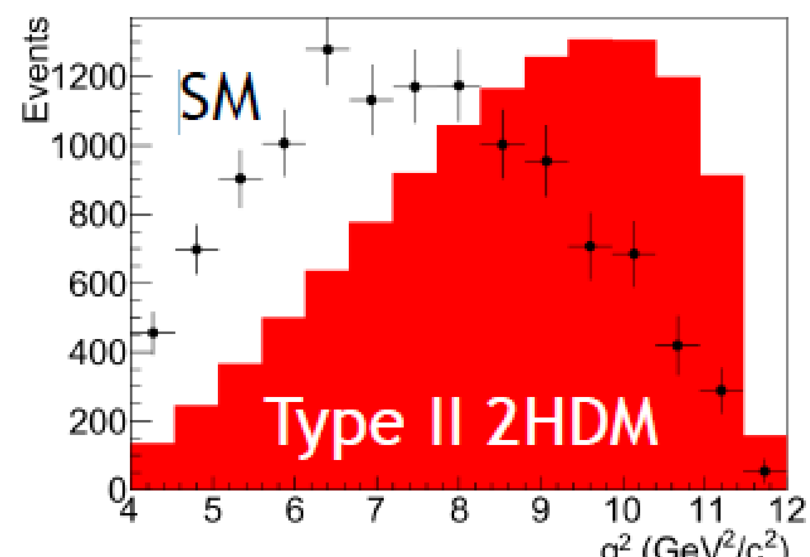
$$P_\tau(D^*) = -0.38 \pm 0.51\,^{+0.21}_{-0.16}$$

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

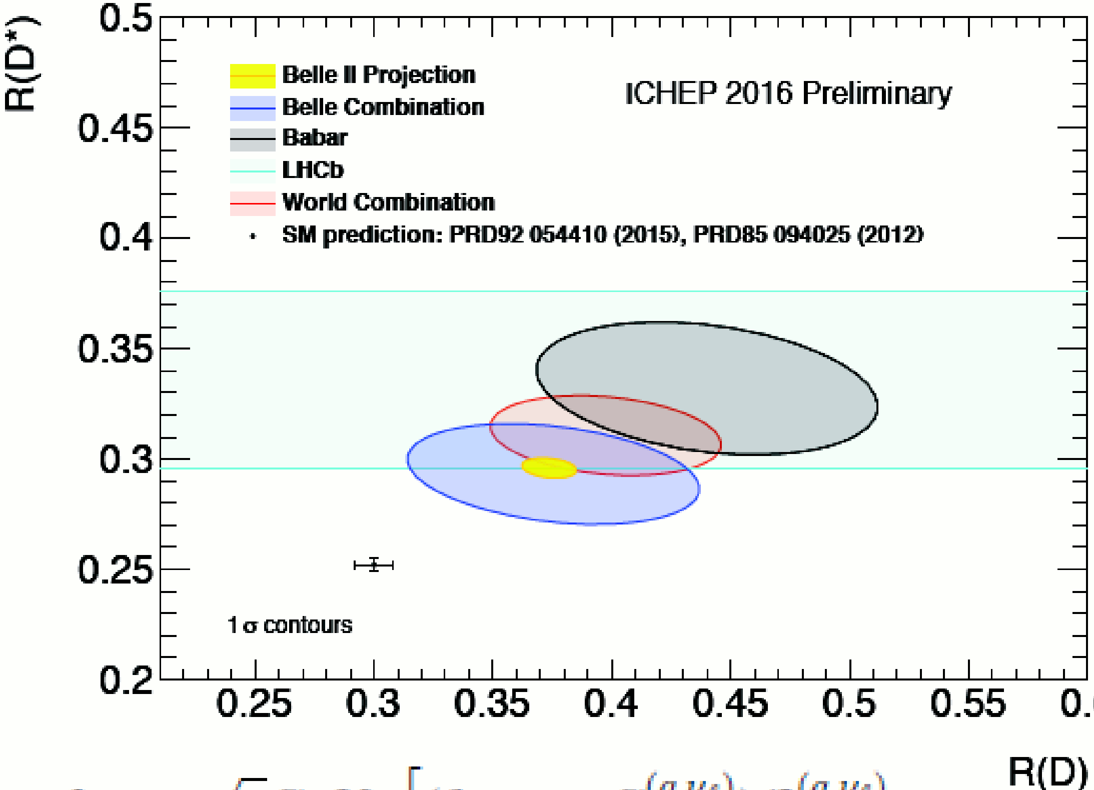
$P_\tau(D^*)$	Stat. uncertainty	Sys. uncertainty
at 5 ab^{-1}	0.18	0.08
at 50 ab^{-1}	0.06	0.04



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



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

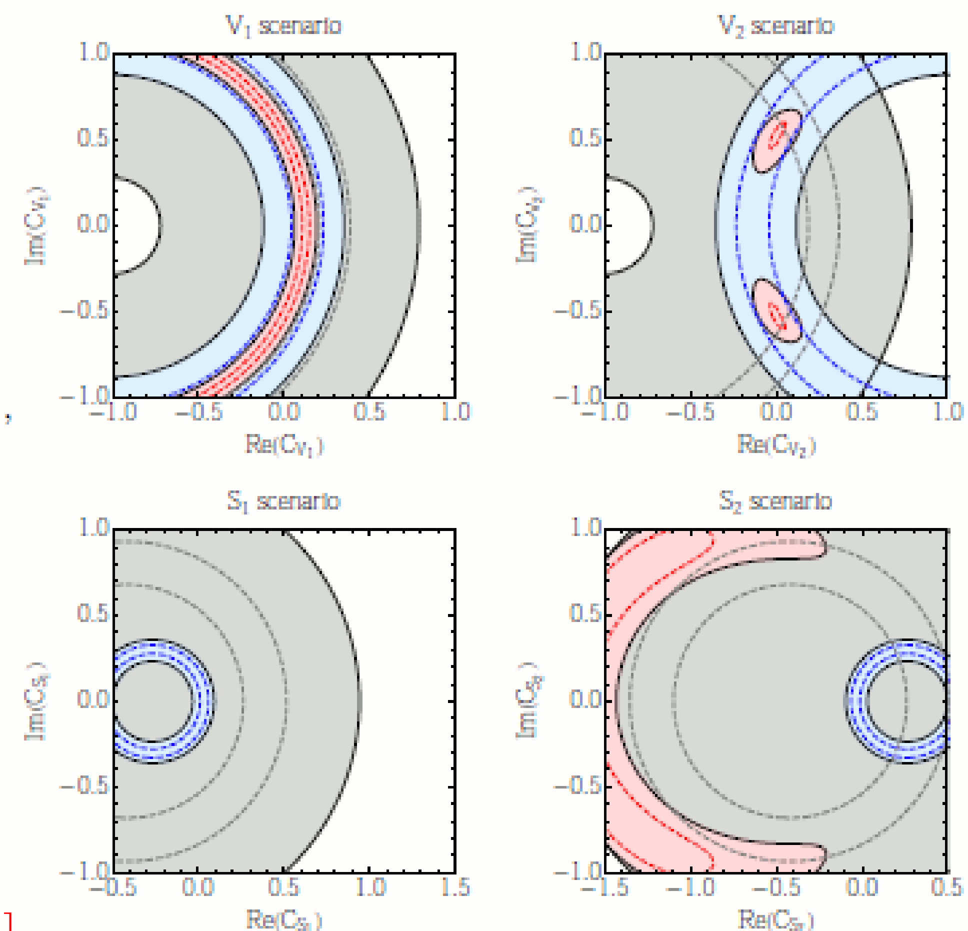


$$R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}, \text{ in red}$$

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

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

Dashed: Belle II

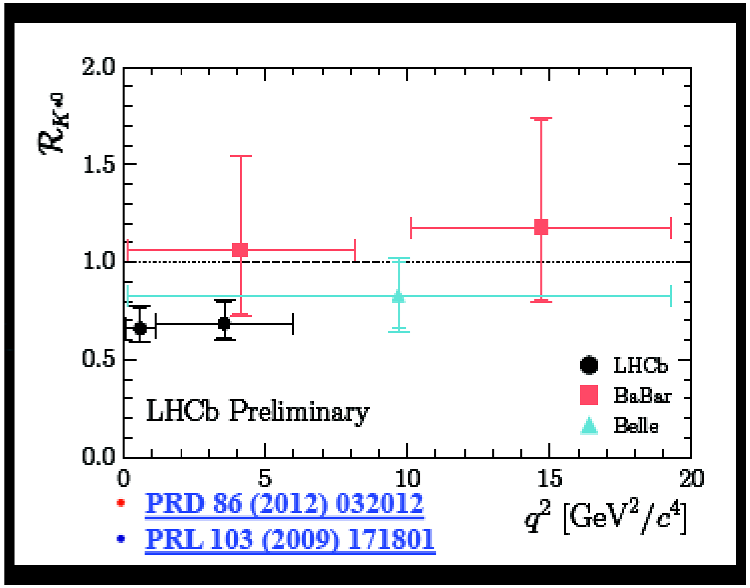


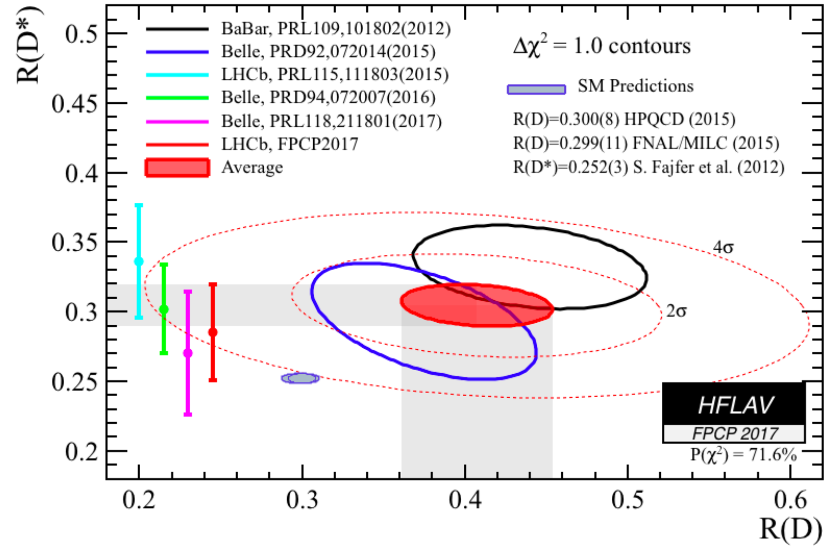
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{qb}\Big[(\delta_{\nu_\tau,\nu_\ell} + C_{V_1}^{(q,\nu_\ell)})\mathcal{O}_{V_1}^{(q,\nu_\ell)} + \sum_{X=}^{V_2,S_1,S_2,T} C_X^{(q,\nu_\ell)}\mathcal{O}_X^{(q,\nu_\ell)}\Big],$$

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)	Found by several experiments (LHCb, BaBar and Belle)
Many observables: global pattern	Two observables: R(D) and R(D*)
Neutral current	Charged current
1-loop (and CKM-suppressed) in the SM	Tree-level in the SM
The New Physics can be heavy	The New Physics must be light

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

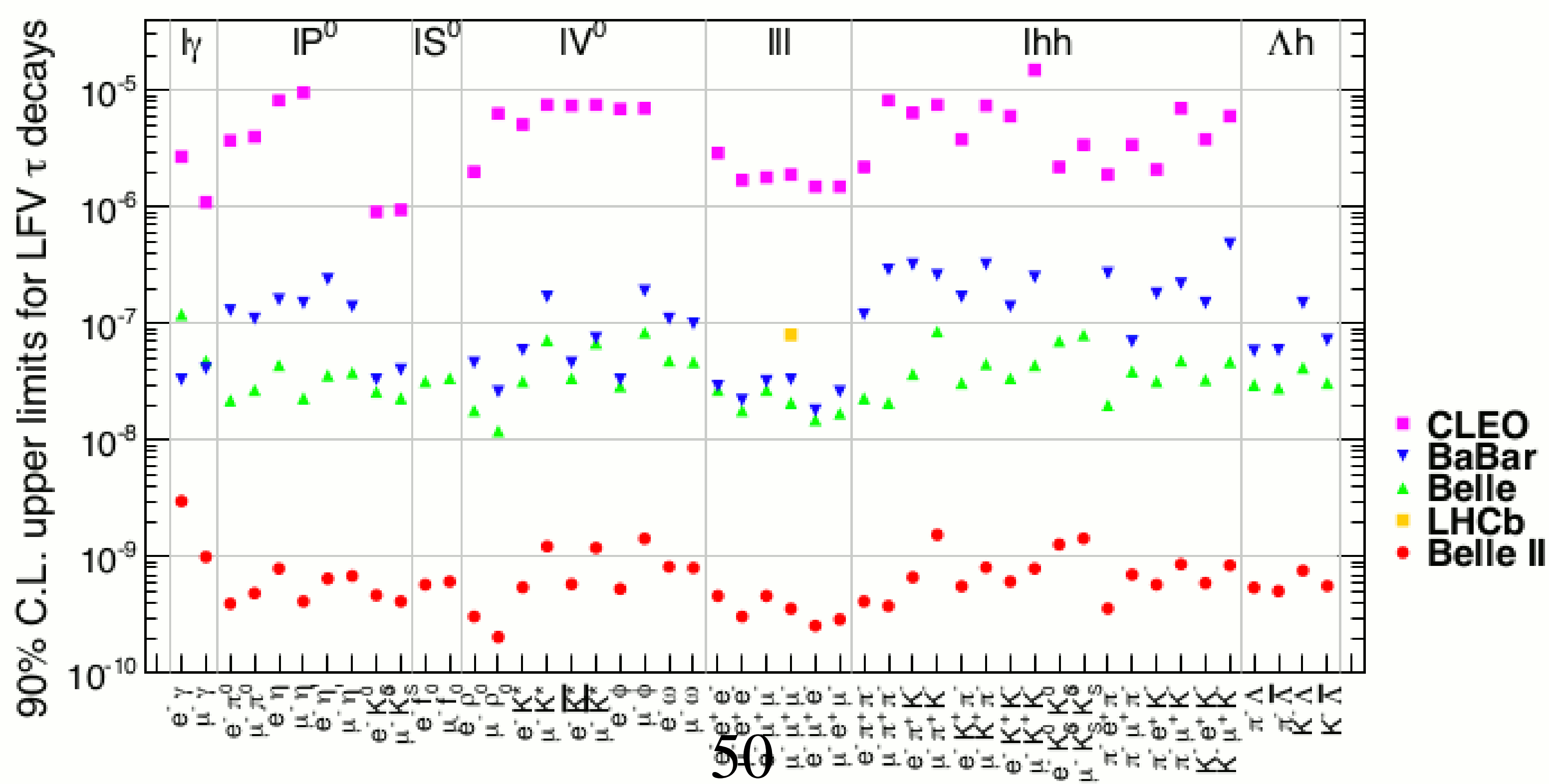
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left| U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \right|^2 < 10^{-40}$$

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

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	$\tau\to 3\mu$	$\tau\to\mu\gamma$	$\tau\to\mu\pi^+\pi^-$	$\tau\to\mu K\bar{K}$	$\tau\to\mu\pi$	$\tau\to\mu\eta^{(\prime)}$
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	$O_{G\tilde{G}}$	–	–	–	–	–	✓

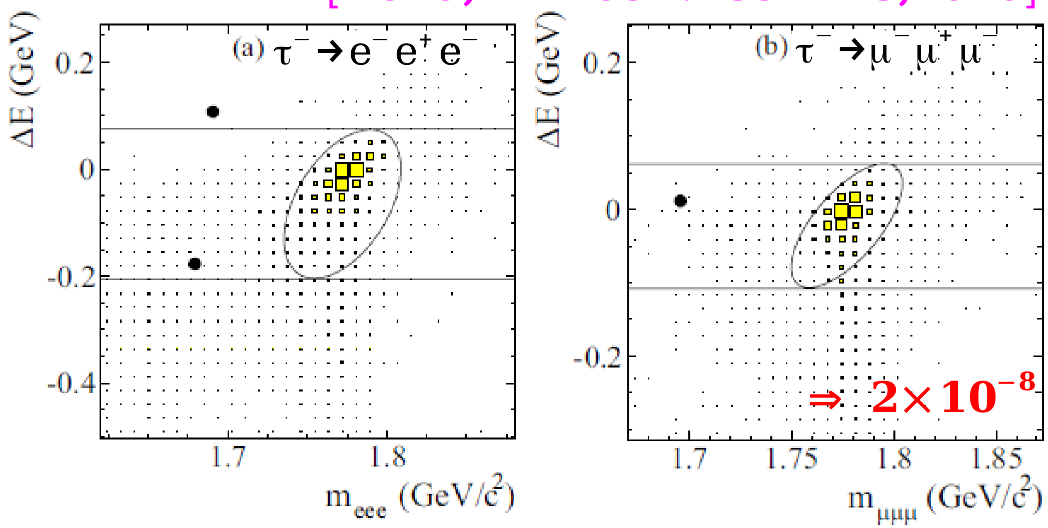
Celis, Cirigliano, Passemar (2014)



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]



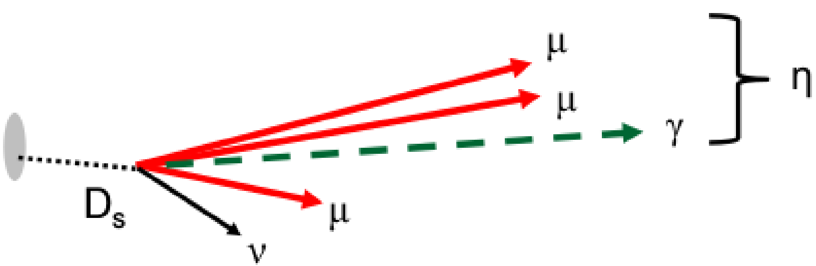
⇒ 2×10^{-8} at 90%CL

how to improve further ?

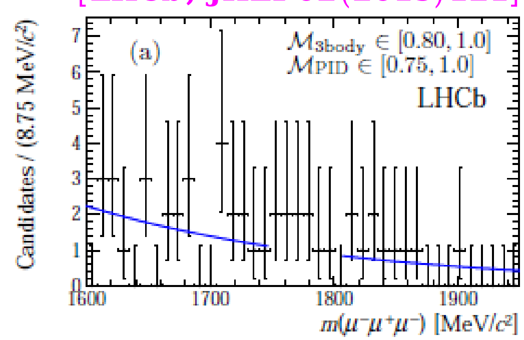
...considering $\tau\to\mu/e\,h^+h^-$
in function of one prong tag categories

...for $\tau\to3$ muons,
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

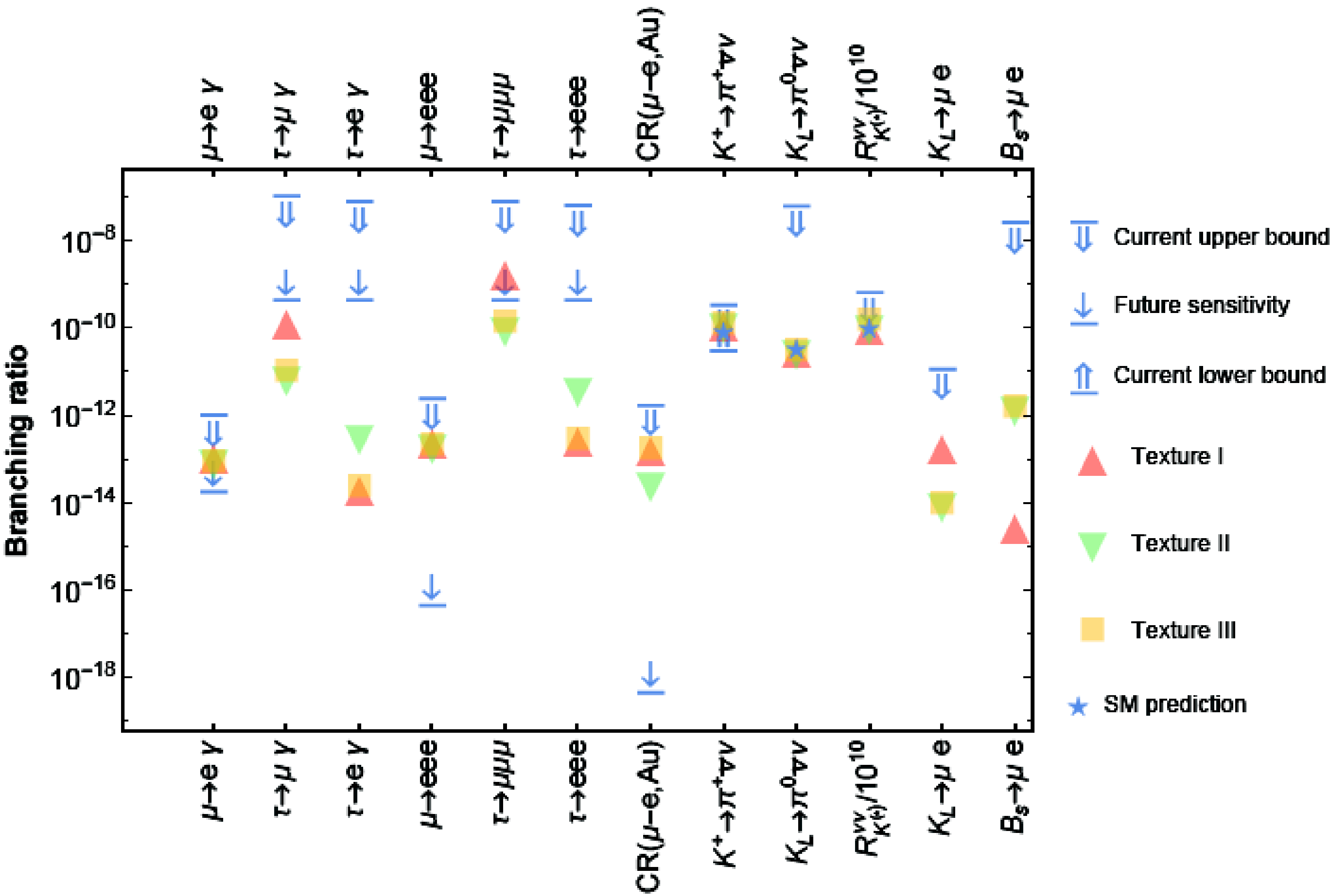
Background modes normalised to $D_s\to\eta(\mu\mu\gamma)\mu\nu$ (BR ~ 10^{-5})

Decay channel	Relative abundance
$D_s\to\eta(\mu\mu\gamma)\mu\nu$	1
$D_s\to\phi(\mu\mu)\mu\nu$	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

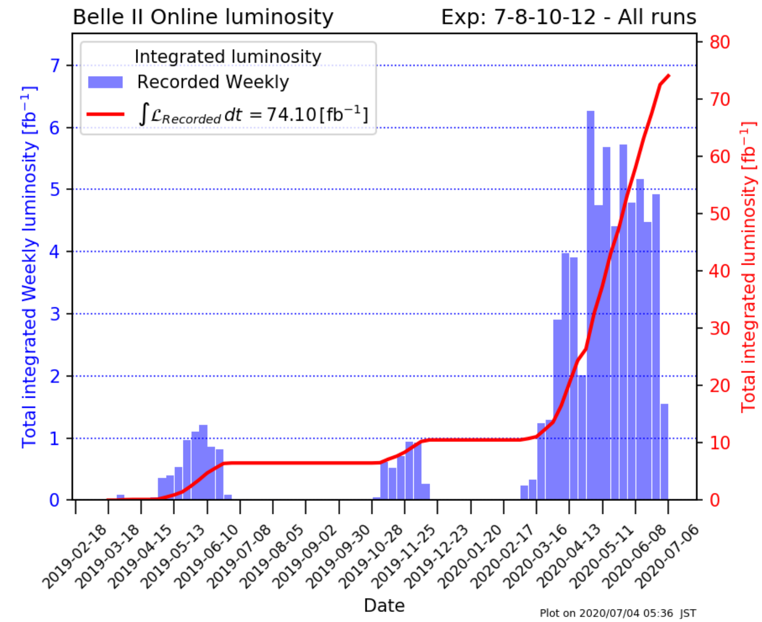
more observables…

C.Hati et al, arXiv:1806.10146



A.Datta et al, arXiv:1609.09078: interesting modes are $\tau \to 3\mu$, and $\Upsilon(3S) \to \mu\tau$

Belle II's first steps…



long way to go for 50 ab^{-1}…

Publication opportunities with 75-200 fb^{-1}

A.Gaz @ BPAC

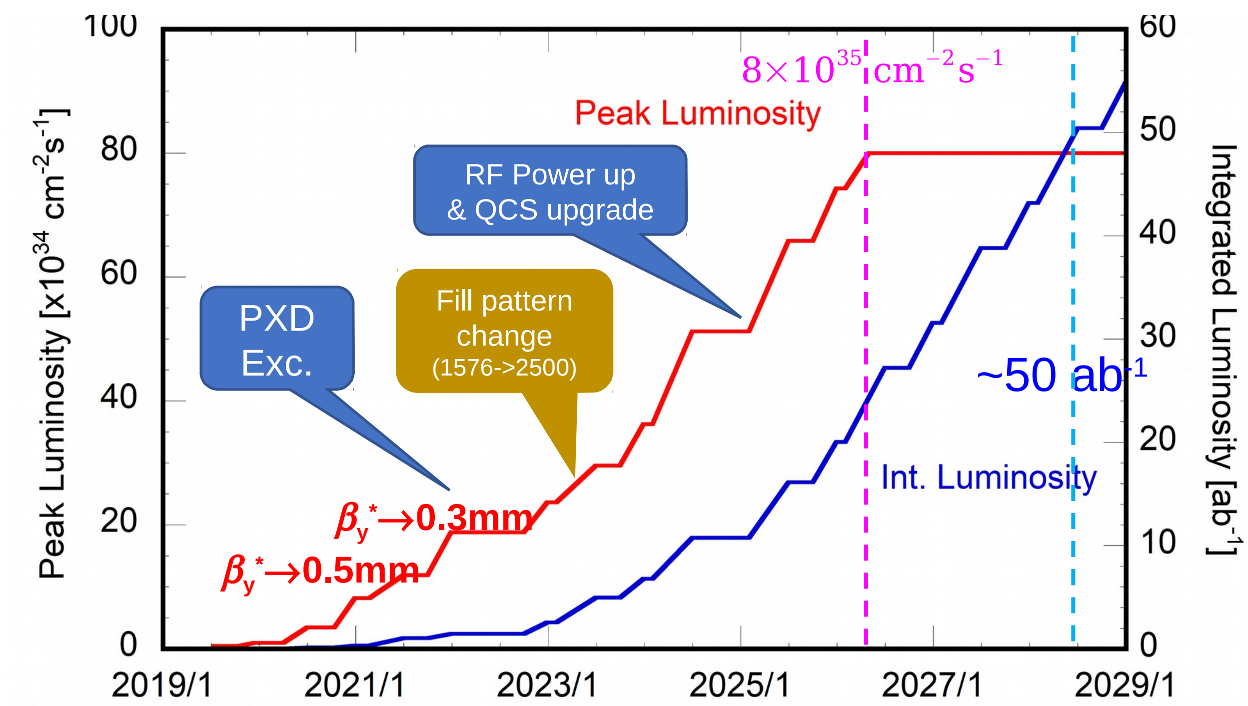
- FEI performance;
- $|V_{cb}|$ from hadronic q^2 moments, inclusive $|V_{ub}|$ from lepton endpoint;
- Inclusive and FEI tagged $b \to s\gamma$;
- Inclusive $B^+ \to K^+ \nu \nu$;
- FlavorTagger performance;
- B lifetime and mixing;
- First combined Belle + Belle II analysis on BPGGSZ ϕ_3;
- D^0, D^+, (D_s, Λ_c) lifetimes;
- $B \to \Lambda_c$ + invisible;
- τ mass measurement;
- $\tau \to l\,\alpha$;
- Z' → visible and invisible, Dark Higgsstrahlung;
- ALPs → $\gamma\gamma(\gamma)$, Dark Photon, … ;
- …

Consider also "non competitive" physics channels that display good Belle II performance

Conclusion

- Few tantalizing results on rare decays in B sector covered in this talk… but much more in B decays: LFV searches, $B \to K^{(*)} \nu \bar{\nu}$, $B \to \tau \nu$, $\mu \nu$… also in charm, charmonium, bottomonium, light Higgs, τ, DS, kaon sectors…
- Definitely not only complementary, but stimulating competition between (super) B-factory and LHCb (upgrade):
  - for the expected: results on $B_{(s)} \to \mu\mu$, $B \to K^{*} \mu\mu$, γ angle…
  - for the less expected: results on $|V_{ub}|$, $D^{*} \tau \nu$…

LHC era		HL-LHC era		
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}



Lepton flavor universality in the Standard Model

Fermion masses

In the SM, fermions get their masses via Yukawa couplings with the Higgs doublet Φ

For example, for the leptons:

$$\mathcal{L}_Y^\ell = Y_e \bar{\ell}_L \Phi e_R + \text{h.c.} = \frac{1}{\sqrt{2}}(v+h) Y_e \begin{pmatrix} \bar{\nu} & \bar{e} \end{pmatrix}_L \begin{pmatrix} 0 \\ 1 \end{pmatrix} e_R + \text{h.c.}$$

$$= \mathcal{M}_e \bar{e}_L e_R + \frac{\mathcal{M}_e}{v} h \bar{e}_L e_R + \text{h.c.}$$

where

$$\mathcal{M}_e = \frac{v}{\sqrt{2}} Y_e$$

3x3 charged lepton mass matrix

Similarly, one obtains

$$\mathcal{L}_m^F = \mathcal{M}_e \bar{e}_L e_R + \mathcal{M}_u \bar{u}_L u_R + \mathcal{M}_d \bar{d}_L d_R + \text{h.c.}$$

$$\mathcal{M}_f = \frac{v}{\sqrt{2}} Y_f$$

$$f = e, u, d$$

Fermion masses

- It is remarkable that the same mechanism that gives mass to the gauge bosons (SSB), also gives a mass to the fermions
- Neutrinos do not get a mass. This can be traced back to the absence of right-handed neutrinos.
- In general, these mass mass matrices are <u>not</u> diagonal: they must be diagonalized to get the mass eigenstates and eigenvalues

Biunitary transformations

$$f_L = U_f \widehat{f}_L \qquad f_R = V_f \widehat{f}_R \quad \Longrightarrow \quad \widehat{\mathcal{M}}_f = U_f^\dagger \mathcal{M}_f V_f$$

↑ gauge eigenstates (f_L, f_R)

↑ mass eigenstates ($\widehat{f}_L$, $\widehat{f}_R$)

For example, for the charged leptons:

$$\widehat{\mathcal{M}}_e = U_e^\dagger \mathcal{M}_e V_e = \mathrm{diag}\,(m_e, m_\mu, m_\tau)$$

The electroweak currents

In order to find the fermionic currents we must expand the fermion kinetic Lagrangian:

$$\mathcal{L}_{\rm kin} \supset \bar{\ell}_L \left(g\frac{\vec{\tau}}{2}\vec{W}_\mu - \frac{g'}{2}B_\mu \right)\gamma^\mu \ell_L + \bar{q}_L \left(g\frac{\vec{\tau}}{2}\vec{W}_\mu + \frac{g'}{6}B_\mu \right)\gamma^\mu q_L$$

$$-\bar{e}_R g' B_\mu \gamma^\mu e_R + \bar{u}_R \,\frac{2}{3}\, g' B_\mu \gamma^\mu u_R - \bar{d}_R \,\frac{1}{3}\, g' B_\mu \gamma^\mu d_R$$

$$= \underbrace{g J^1_\mu W^{1\mu} + g J^2_\mu W^{2\mu}}_{\text{Charged current}} + \underbrace{g J^3_\mu W^{3\mu} + g' J^Y_\mu B^\mu}_{\text{Neutral current}}$$

Charged current

Neutral current

The neutral current

$$\mathcal{L}_{\rm nc} = g J^3_\mu W^{3\mu} + g' J^Y_\mu B^\mu$$

$$\begin{cases} J^3_\mu = \frac{1}{2}\left(\overline{\nu}_L\gamma_\mu\nu_L - \overline{e}_L\gamma_\mu e_L + \overline{u}_L\gamma_\mu u_L - \overline{d}_L\gamma_\mu d_L\right) \\ J^Y_\mu = \frac{1}{2}\left(-3\,\overline{\nu}_L\gamma_\mu\nu_L - 3\,\overline{e}_L\gamma_\mu e_L + \overline{u}_L\gamma_\mu u_L + \overline{d}_L\gamma_\mu d_L \right. \\ \qquad \left. -6\,\overline{e}_R\gamma_\mu e_R + 4\,\overline{u}_R\gamma_\mu u_R - 2\,\overline{d}_R\gamma_\mu d_R\right) \end{cases}$$

After some basic algebra:

$$\boxed{\mathcal{L}_{\rm nc} = e J^{\rm em}_\mu A^\mu + \frac{g}{\cos\theta_W}\left(J^3_\mu - \sin^2\theta_W J^{\rm em}_\mu\right) Z^\mu}$$

with $J^{\rm em}_\mu = J^3_\mu + J^Y_\mu = \sum_f q_f \overline{f}\gamma_\mu f$ $\qquad$ $\boxed{e = g\sin\theta_W = g'\cos\theta_W}$

An observation about the neutral current:

$$U^\dagger U = V^\dagger V = \mathbb{I}_{3\times 3} \quad \Rightarrow \quad \overline{f}_X\gamma_\mu f_X = \overline{\widehat{f}}_X\gamma_\mu \widehat{f}_X$$

(X = L or R)

The neutral currents are diagonal (<u>and universal</u>) in flavor space

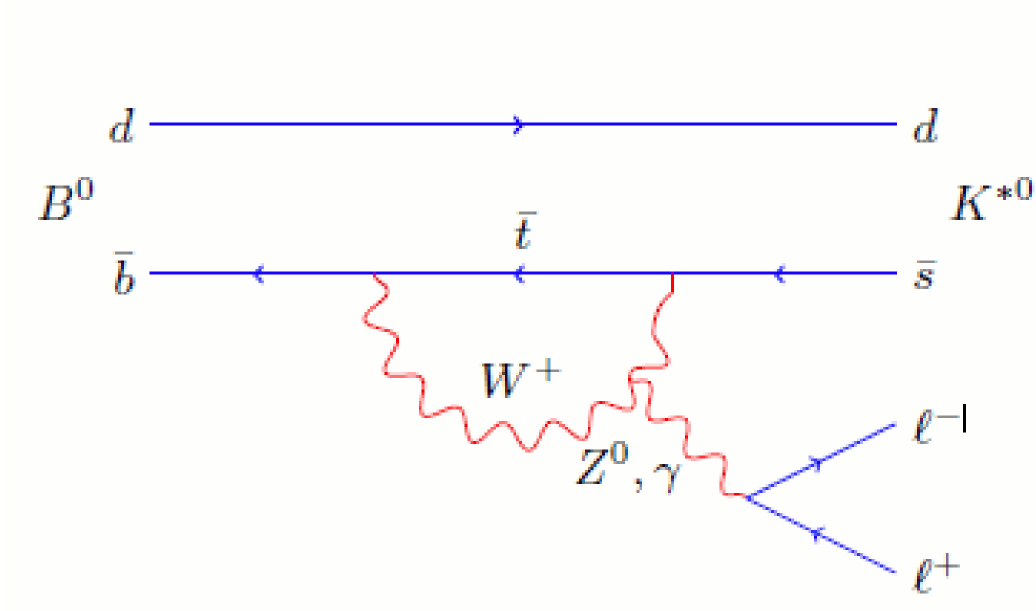
There are no flavor changing neutral currents (FCNC) at tree-level

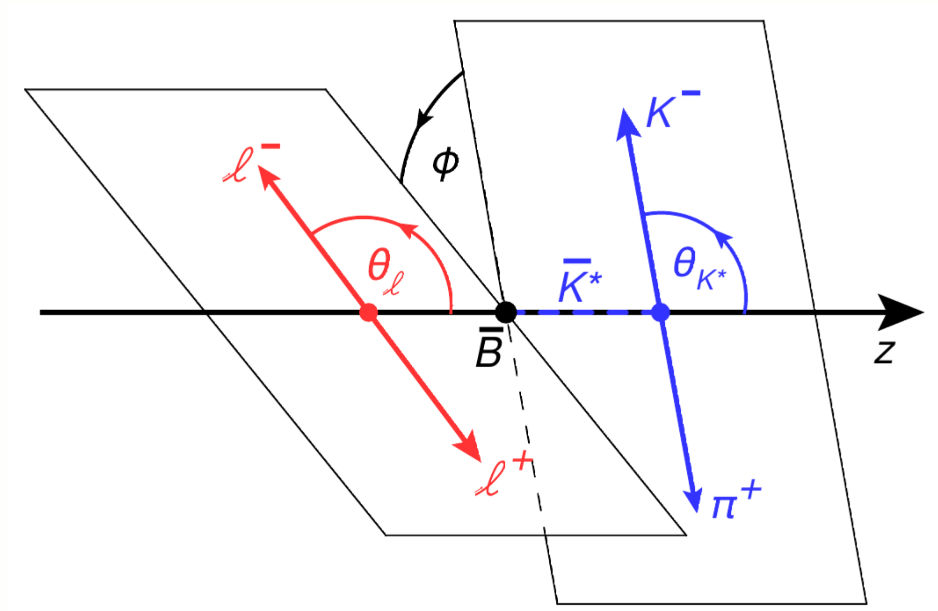
$Z \not\to \overline{u}c$ $\qquad$ in contrast to $W \to \overline{s}u$

Fundamentally this is caused by the fact that fermion families are exact replicas. This was the original motivation that led Glashow, Iliopoulos and Maiani (GIM) to postulate the existence of the <u>charm quark</u>.

Angular analysis of $B_d^0 \rightarrow K^* l^+ l^-$ decays

- Final state described by $q^2 = m_{ll}^2$ and three angles $\Omega = (\theta_l, \theta_K, \phi)$



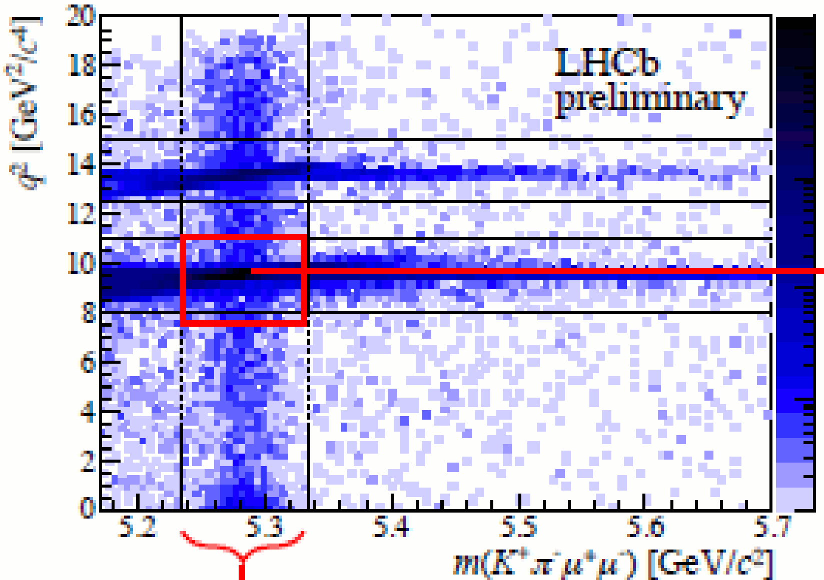


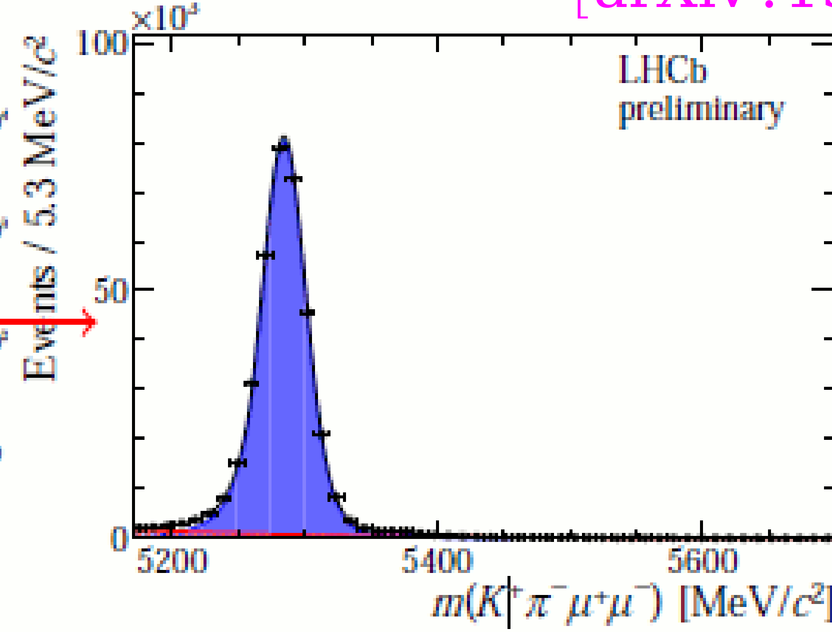
$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\
&-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

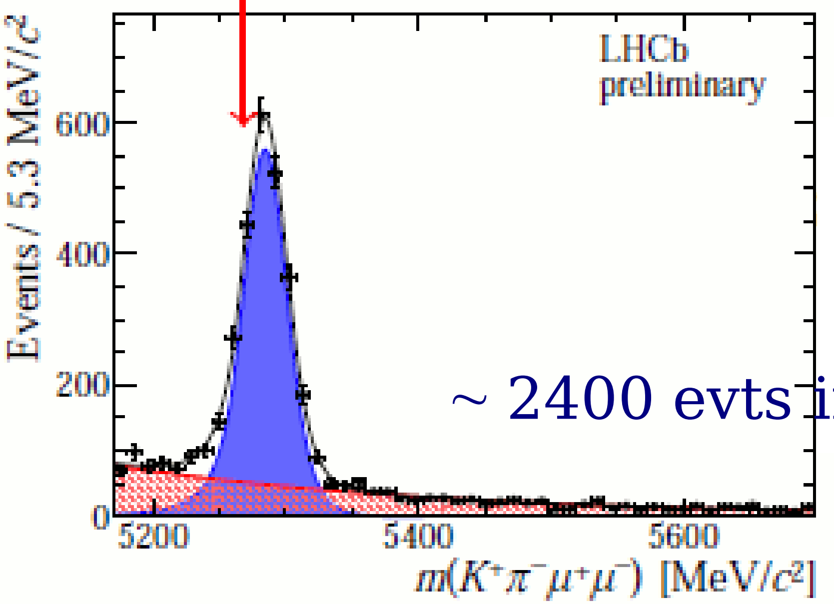
- F_L, A_{FB}, S_i sensitive to $C_7^{(')}$, $C_9^{(')}$, $C_{10}^{(')}$

Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

◦ Channel: $B \to K^{*0}(\to K^+ \pi^-)\mu\mu$ [arXiv:1512.04442]







Selection:

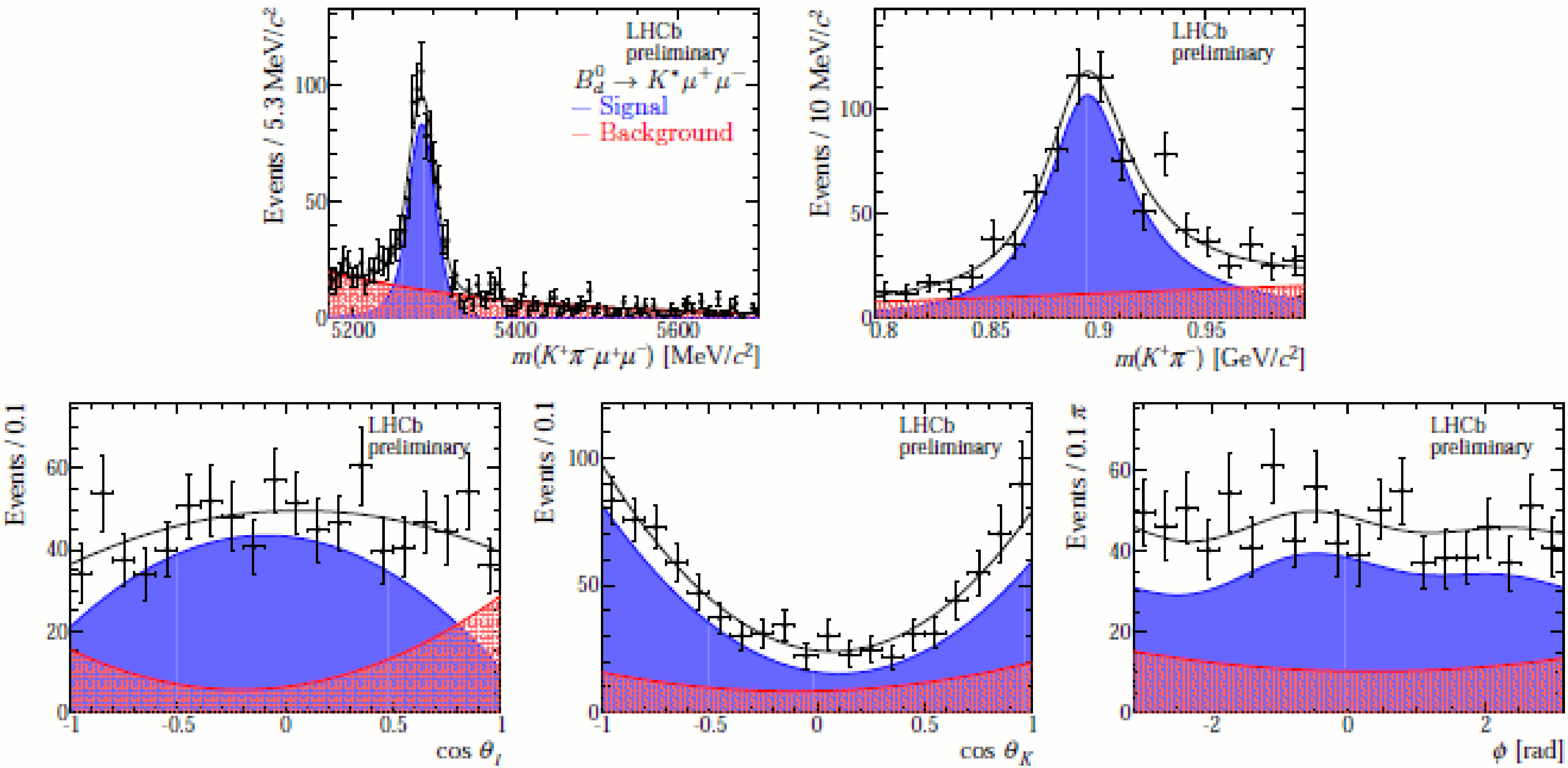
BDT to reject combinatorial background
Veto of resonant modes (control modes)

~ 2400 evts in the full q^2 range

Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

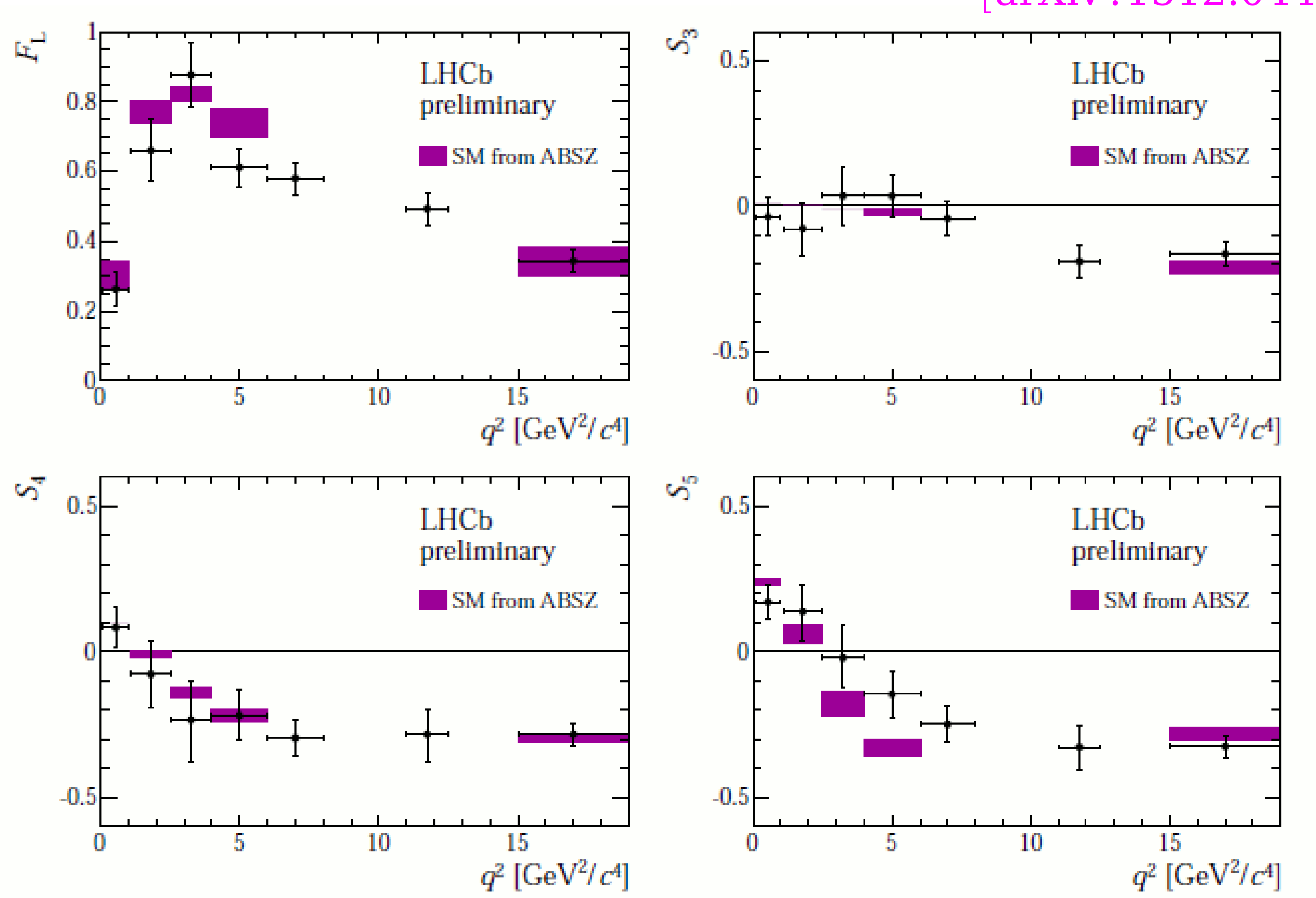
[arXiv:1512.04442]

- Projections of fit results for $q^2 \in [1.1, 6.0]$ GeV^2
- Good agreement of PDF projections with data in every bin of q^2



Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

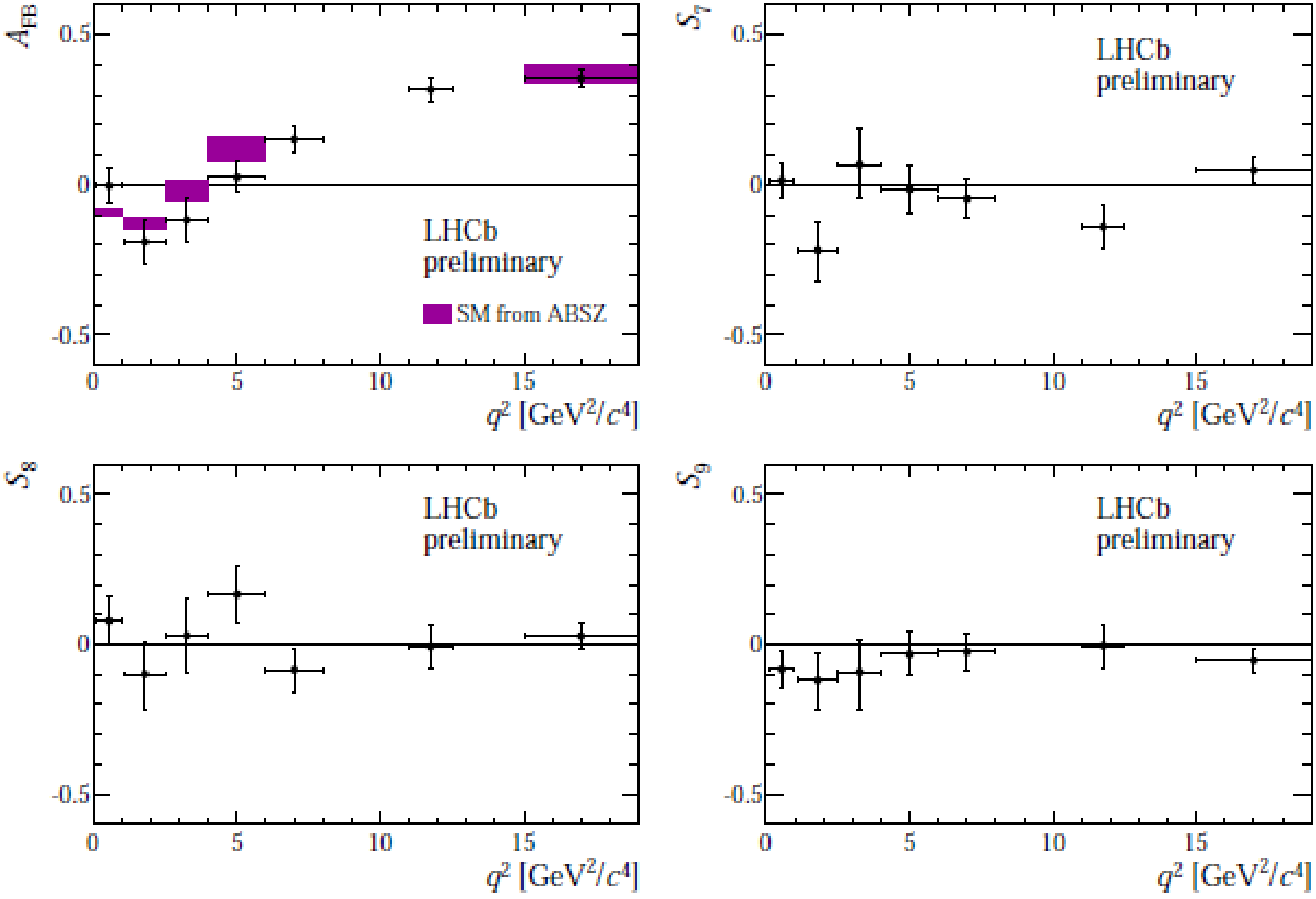
[arXiv:1512.04442]



Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

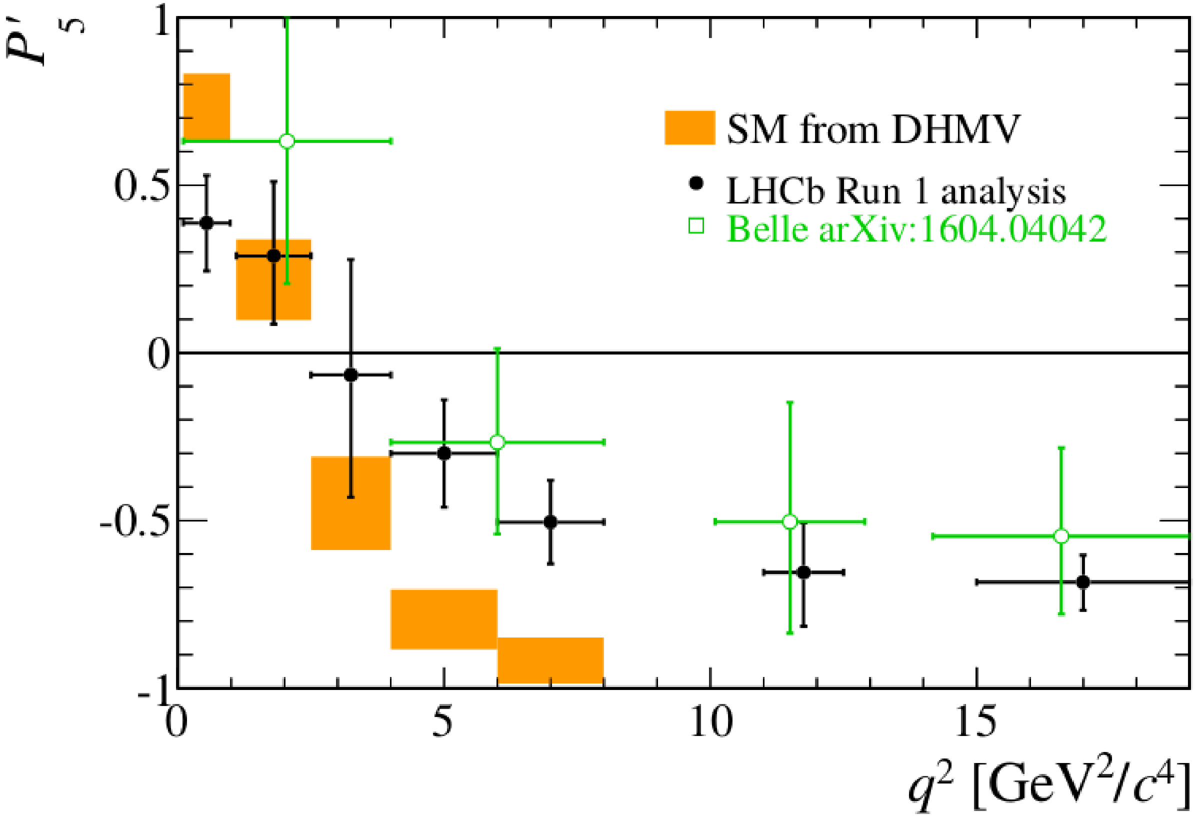
[arXiv:1512.04442]

data points systematically lower than SM



Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

- Form-factor less dependent observables $P_5^{'} = \frac{S_5}{\sqrt{F_L(1-F_L)}}$



[LHCb, arXiv:1512.04442]

- Tension in $P_5^{'}$ seen with $1\,fb^{-1}$ is confirmed
- Local deviations of 2.9σ and 3.0σ for $q^2 \in [4.0,\, 6.0]$ and $[6.0,\, 8.0]\,GeV^2$
- Naive combination of the two gives local significance of 3.7σ

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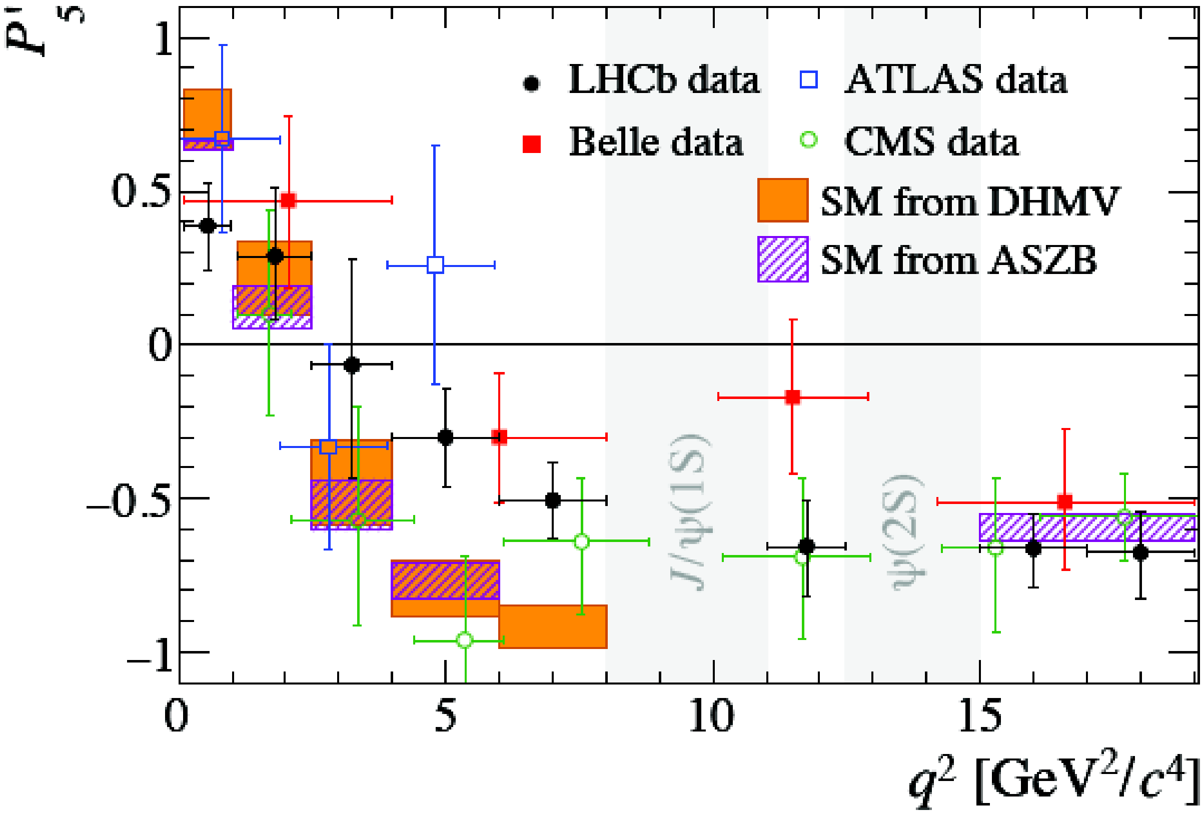

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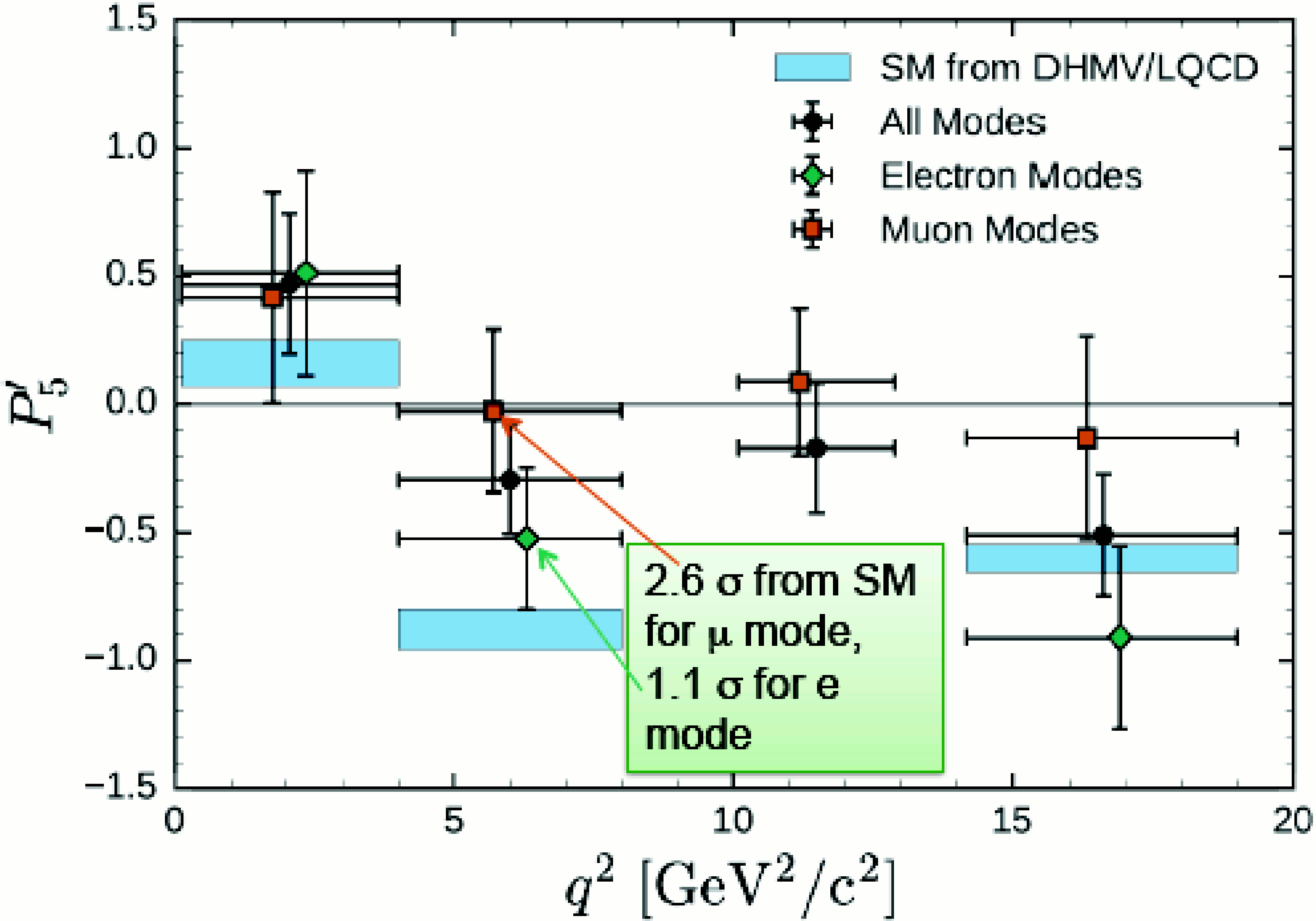
- LHCb, Belle and ATLAS show deviations in $4 < q^2 < 8$ GeV^2/c^4
- CMS shows better agreement

- Belle does both e's & μ's (PRL 118, 111801, 2017)

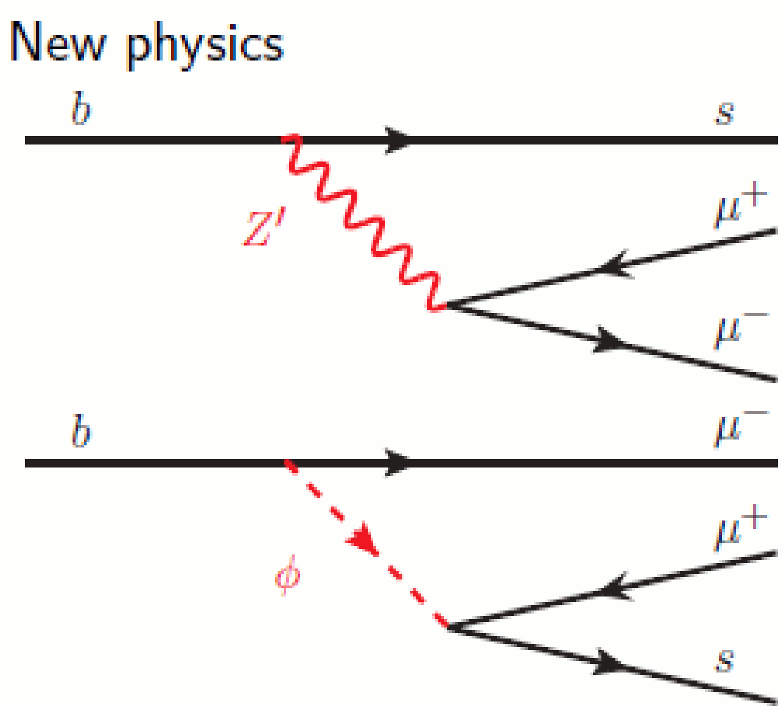


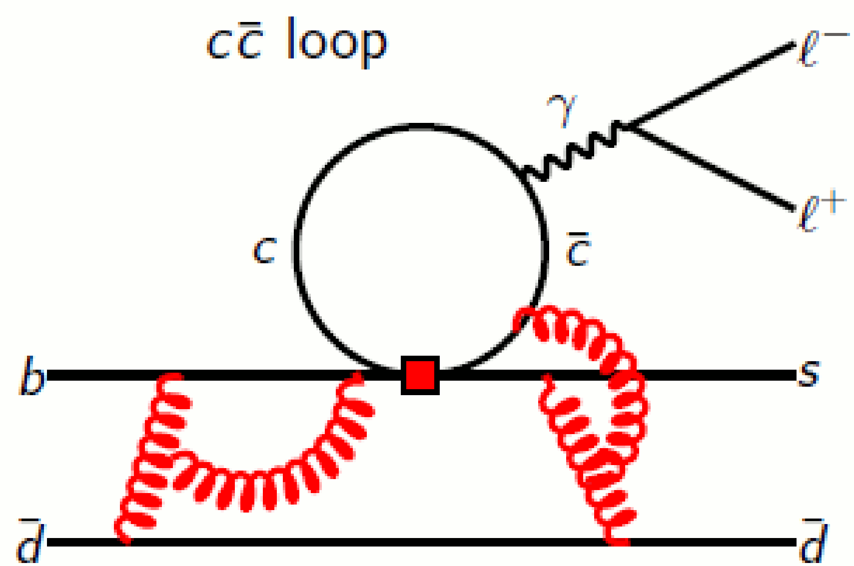
NP or hadronic effect ?

Possible explanations for shift in C_9:

a potential new physics contribution C_9^{NP} enters amplitudes always with a charm-loop contribution $C_9^{c\bar{c}\,i}(q^2)$

⇒ **spoiling an unambiguous interpretation of the fit result in terms of NP**





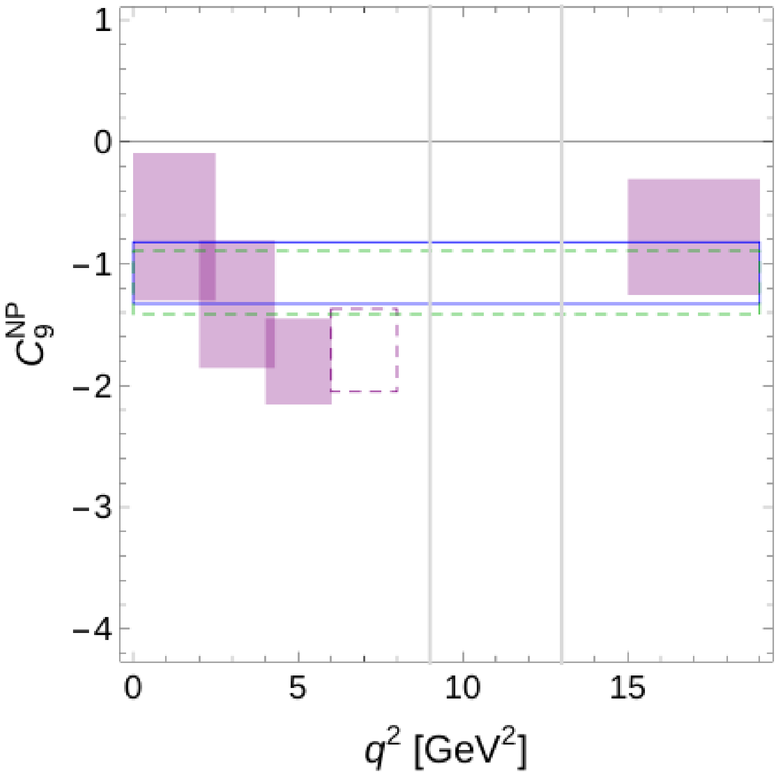
NP e.g. Z', leptoquarks

hadronic charm loop contributions

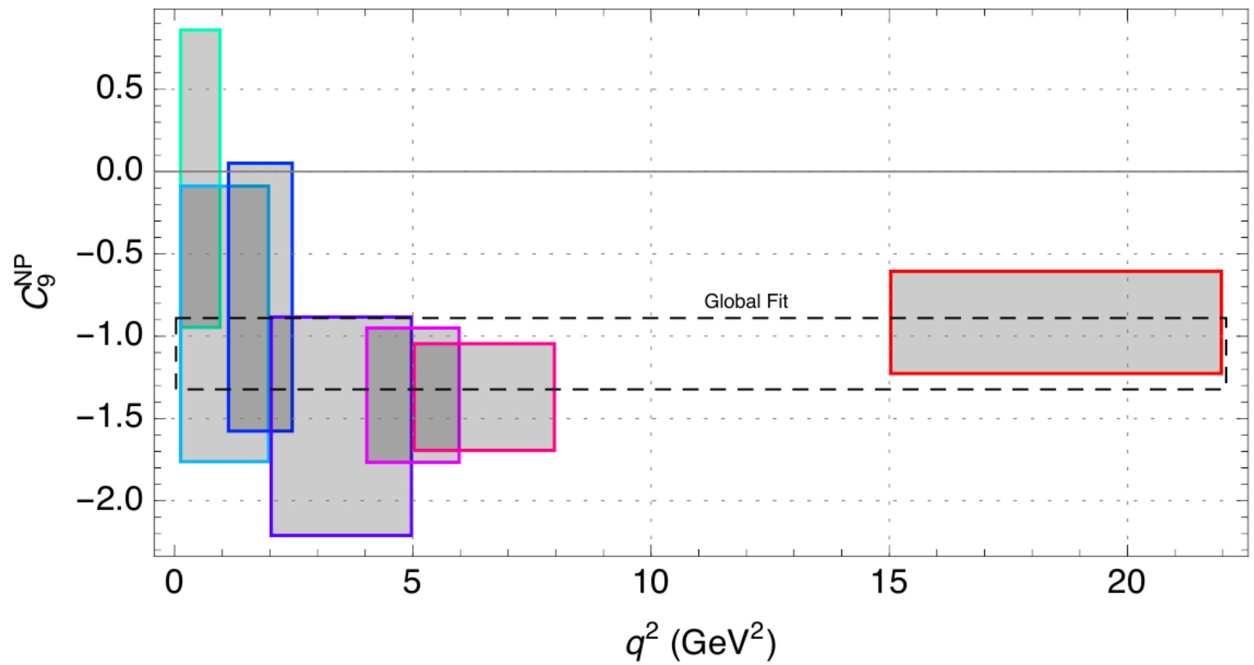
NP or hadronic effect ?

Bin-by-bin fit of the one-parameter scenario with a single coefficient $\mathbf{C_9^{NP}}$

[W.Altmannshofer et al, arXiv:1503.06199]



[S.Descotes-Genon et al, arXiv:1510.04239]



C_9^{NP} doesn't depend on q^2,

$C_9^{c\bar{c}\,i}(q^2)$ expected to exhibit a non-trivial q^2 dependence

⇒ definitely need more stat.