Belle II perspectives on lepton flavour universality, lepton flavour violation

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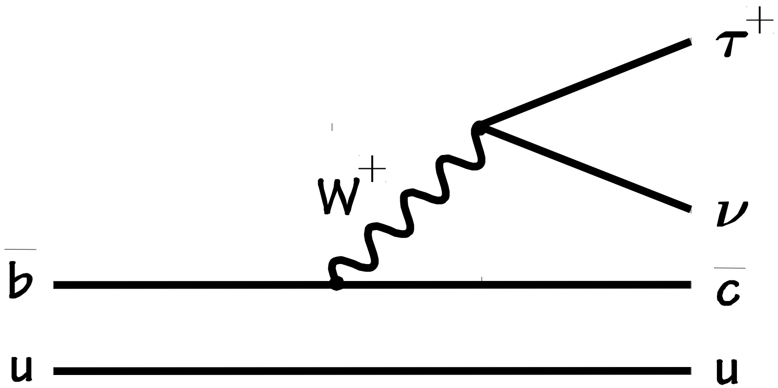
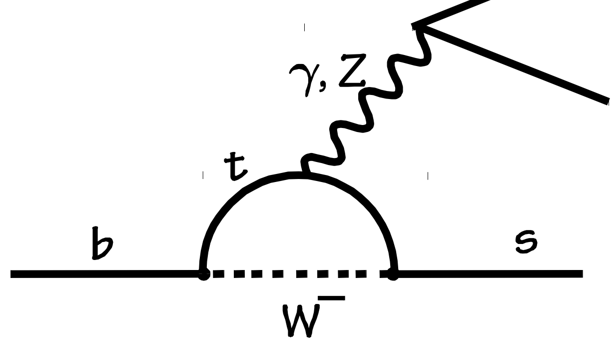
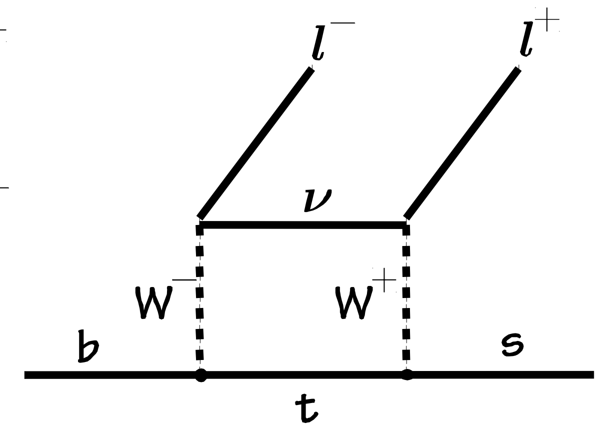
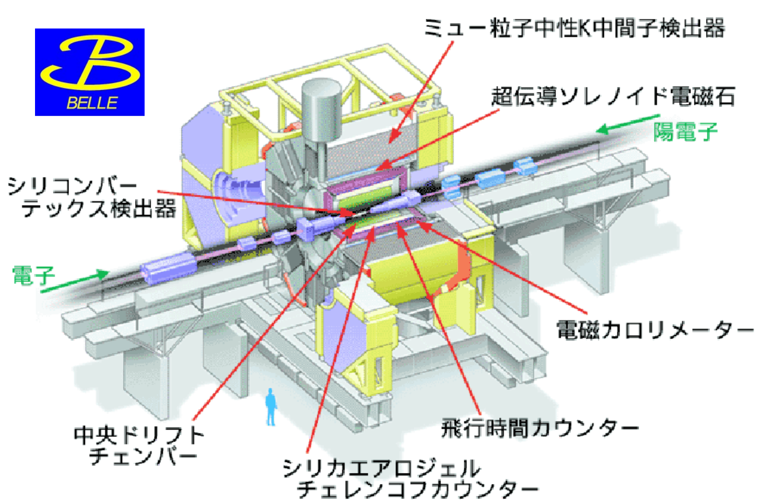
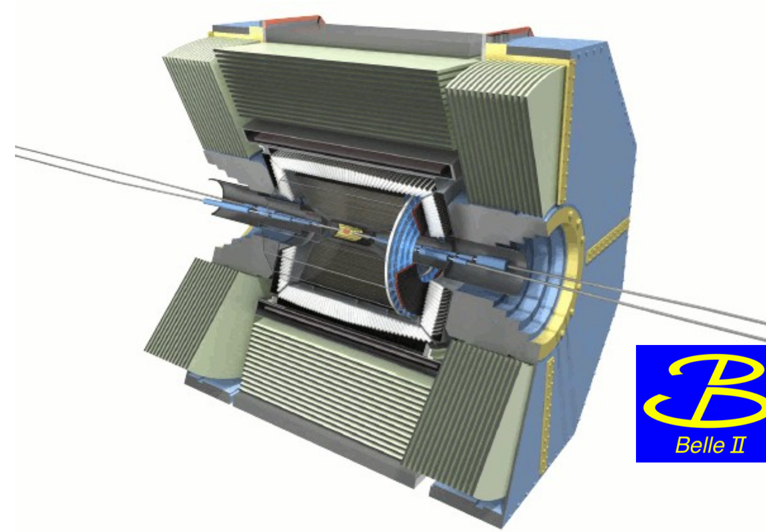


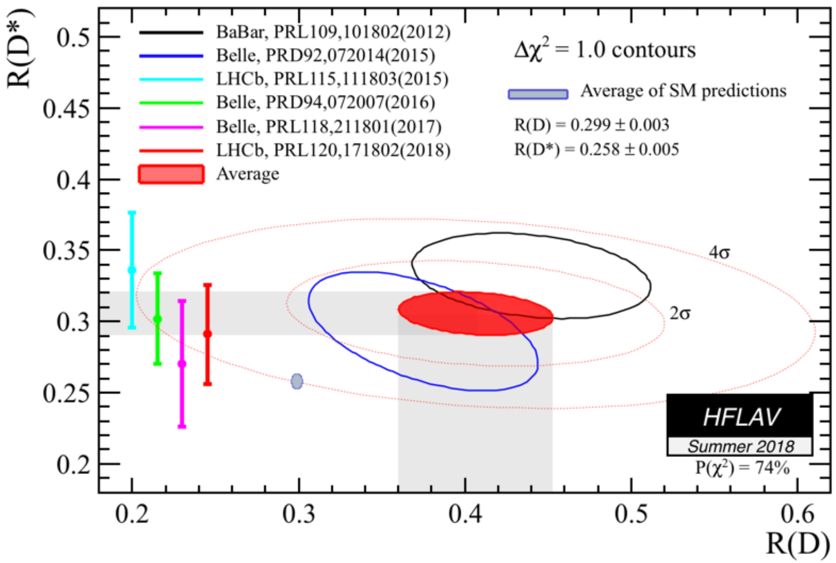








Synergy between LHC and SuperKEB in the quest of New Physics
XIII Meeting on B physics, Marseille, October 2nd 2018



b → c anomalies

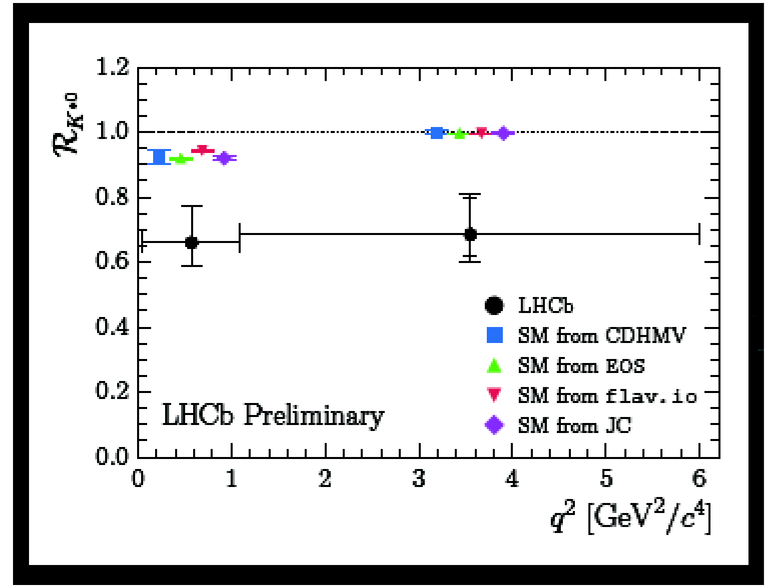
Found by several experiments (LHCb, BaBar and Belle)

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

Charged current

Tree-level in the SM

The New Physics must be light



b → s anomalies

Found by LHCb

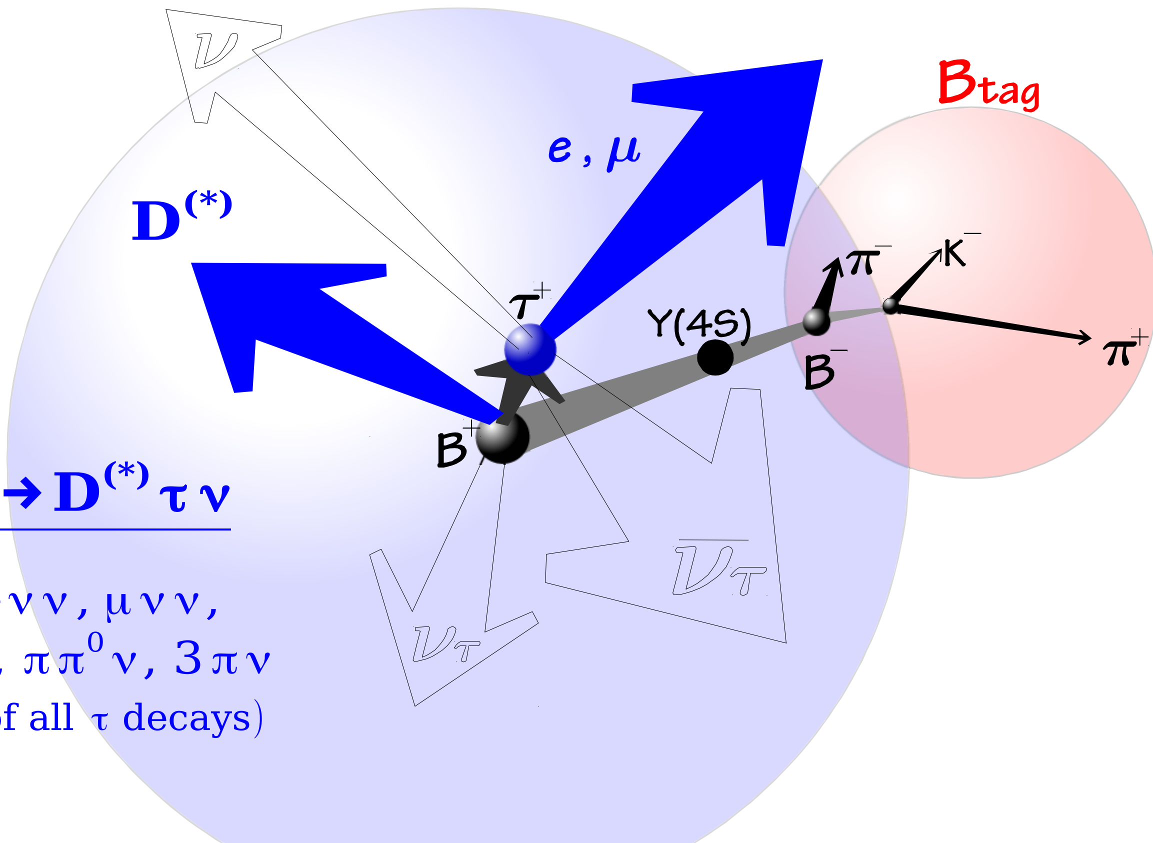
Many observables: global pattern

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



$\mathbf{B_{tag}}$

hadronic tag

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

$\epsilon \sim 0.2\,\%$

semileptonic tag

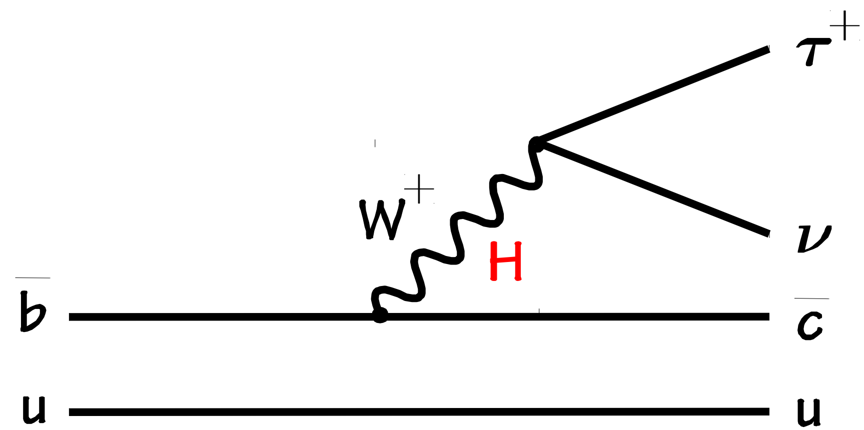
$B \to D^{(*)} l \nu\, X$

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

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

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

(70 % of all τ decays)



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

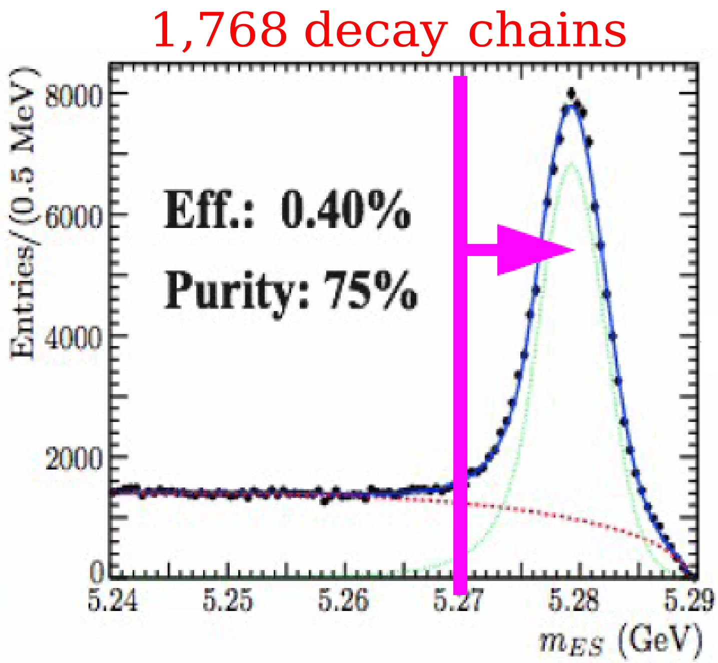
main signal - background discriminator

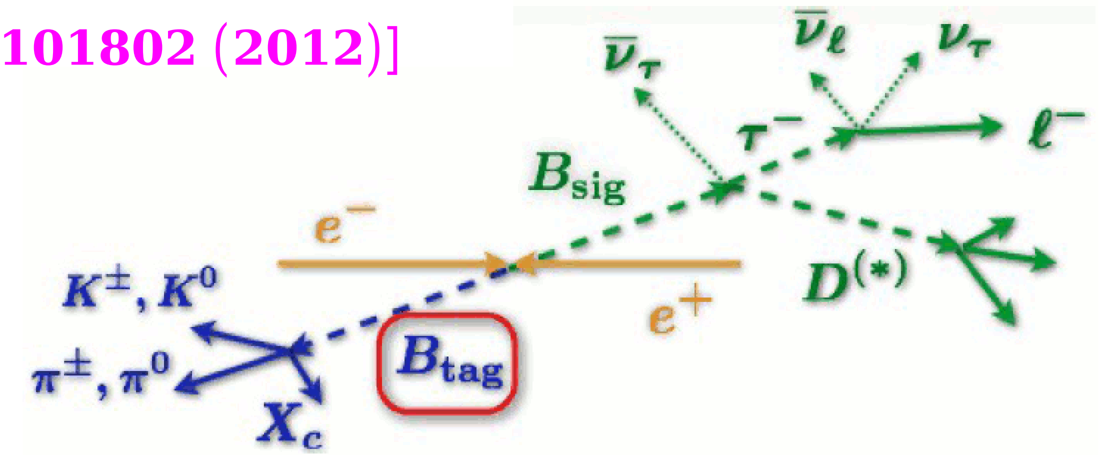
$$\mathbf{m^2_{miss} = (p_{ee} - p_{tag} - p_{D^{(*)}} - p_l)^2}$$

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

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

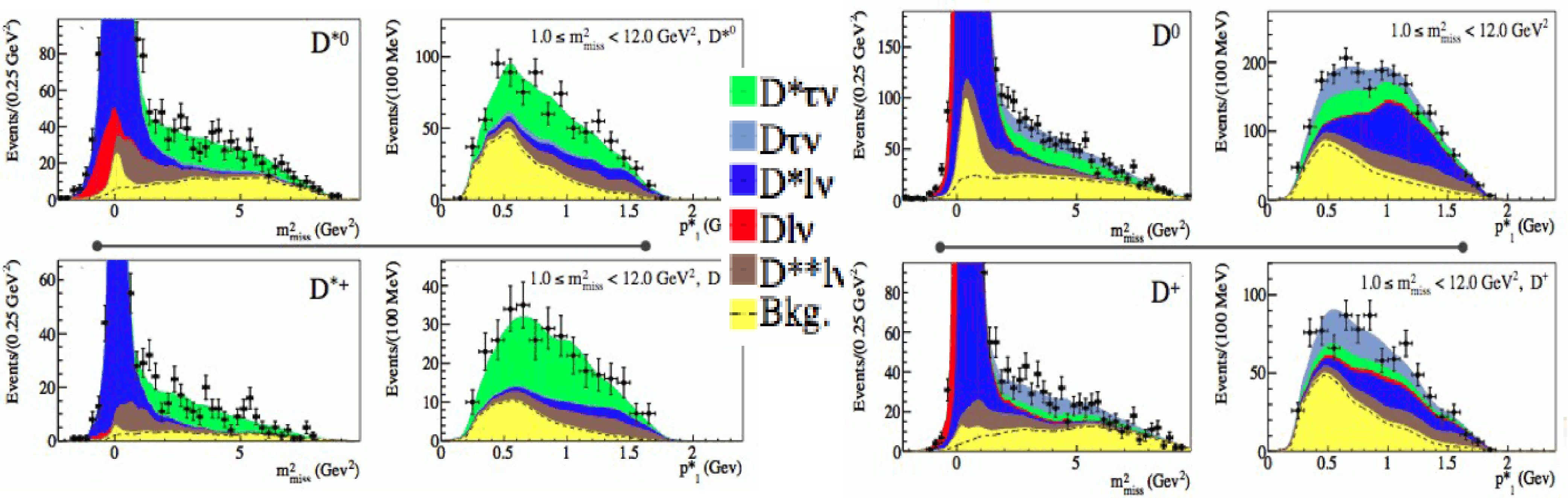
$B \to D^{(*)} \tau \nu$ [BaBar, PRL 109, 101802 (2012)]



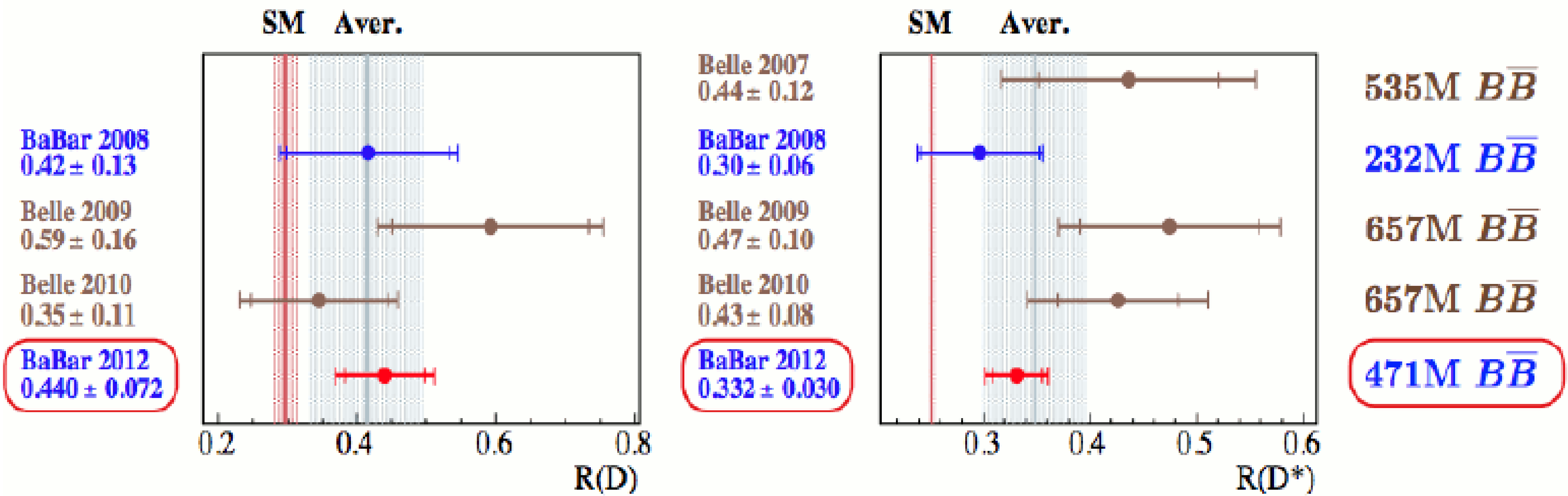


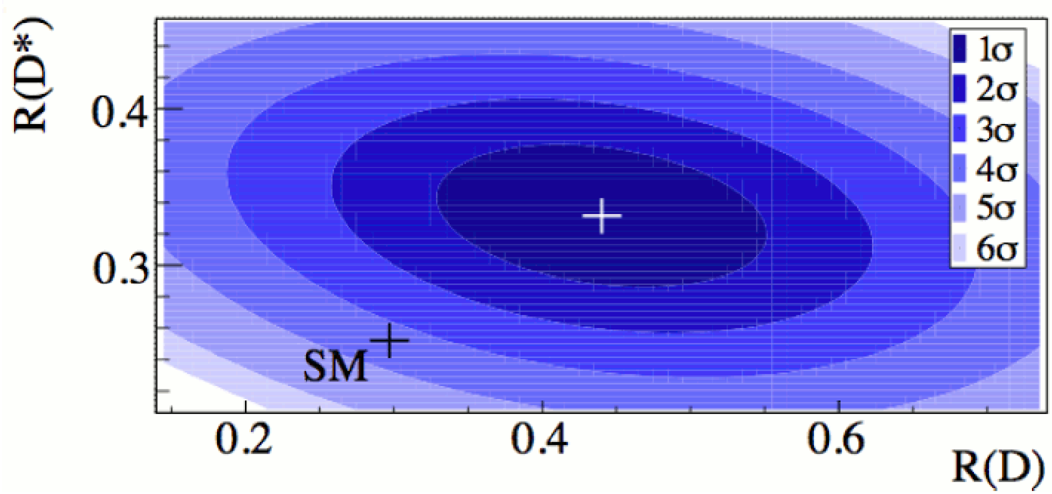
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

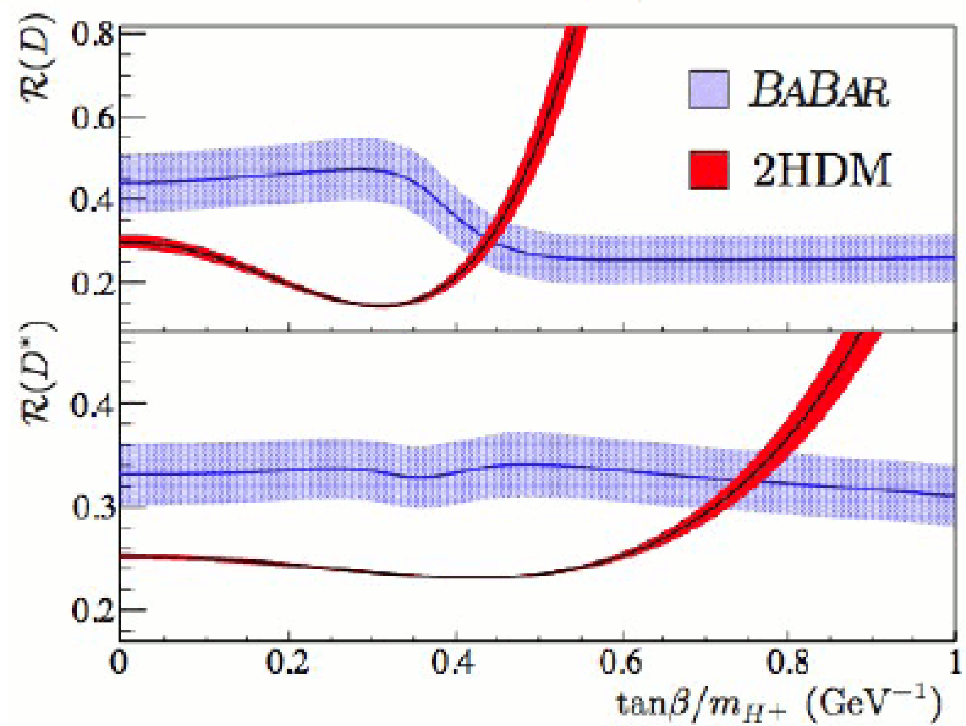
$\Rightarrow$ $D\tau\nu$ and $D^*\tau\nu$ clearly observed



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







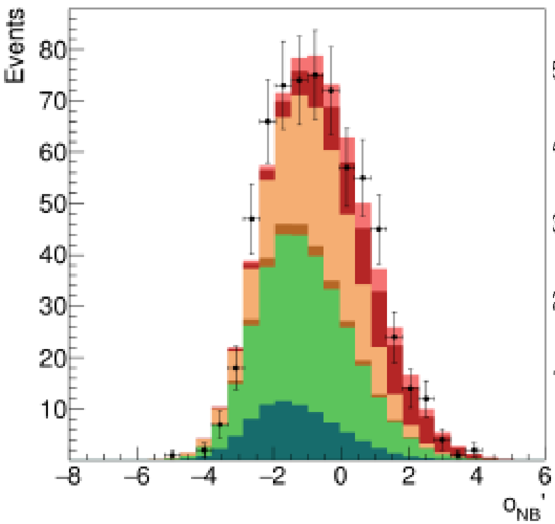
- combined 3.4 σ away from SM
- doesn't fit 2HDM Type II

$B \to D^{(*)} \tau \nu$ at Belle [Belle, arXiv:1507.03233]

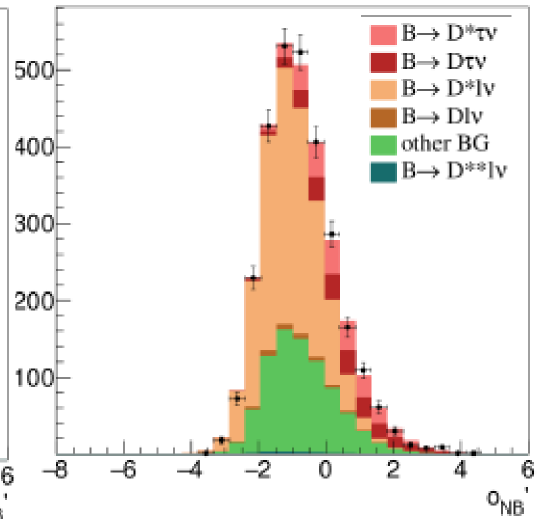
(with hadronic tagging)

projections for large M^2_{miss} region, $N(D\tau\nu) \sim 300$, $N(D^*\tau\nu) \sim 500$

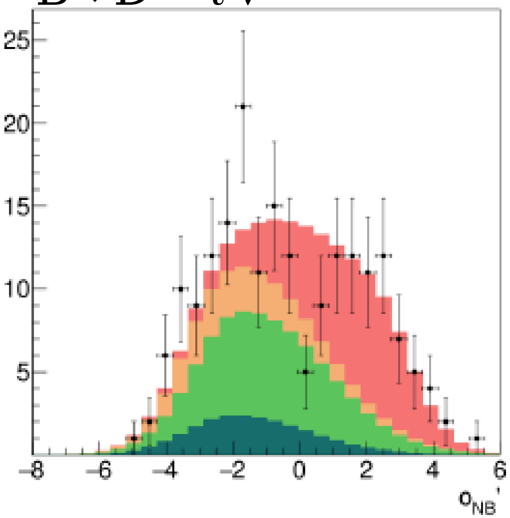
$B \to D^+ \tau \nu$



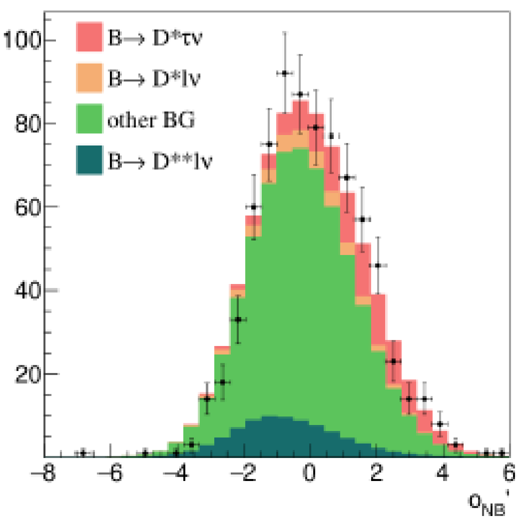
$B \to D^0 \tau \nu$



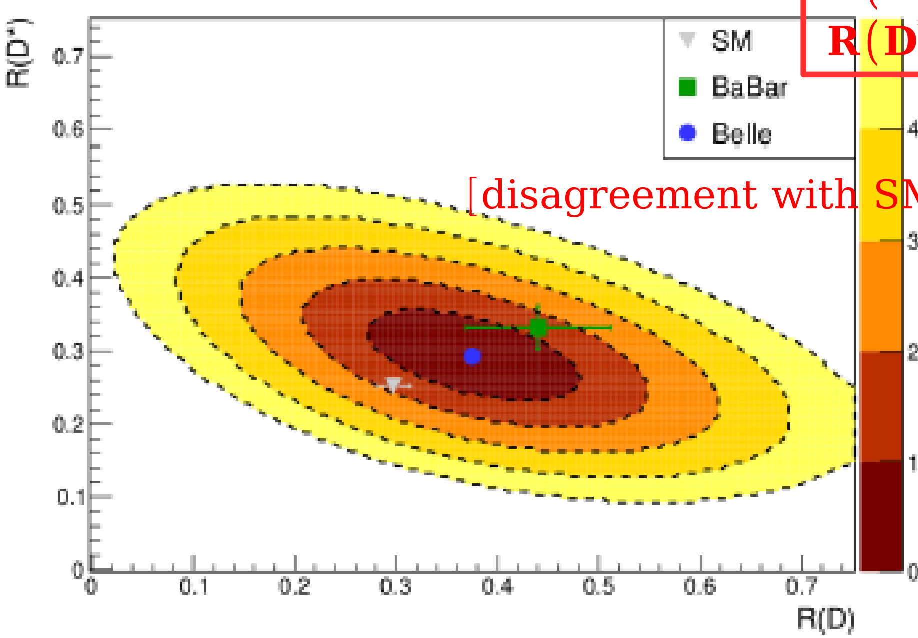
$B \to D^{*+} \tau \nu$



$B \to D^{*0} \tau \nu$

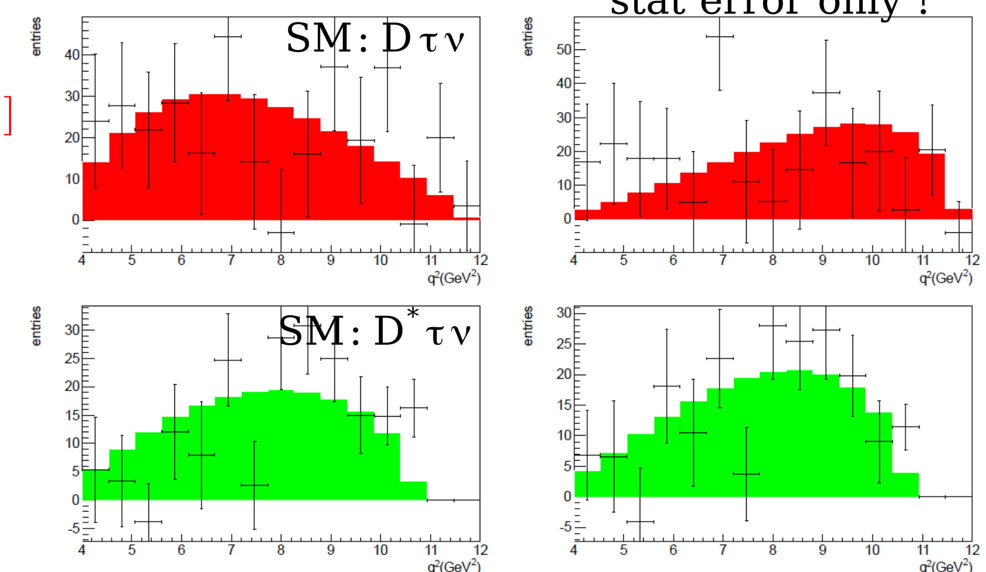


$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$



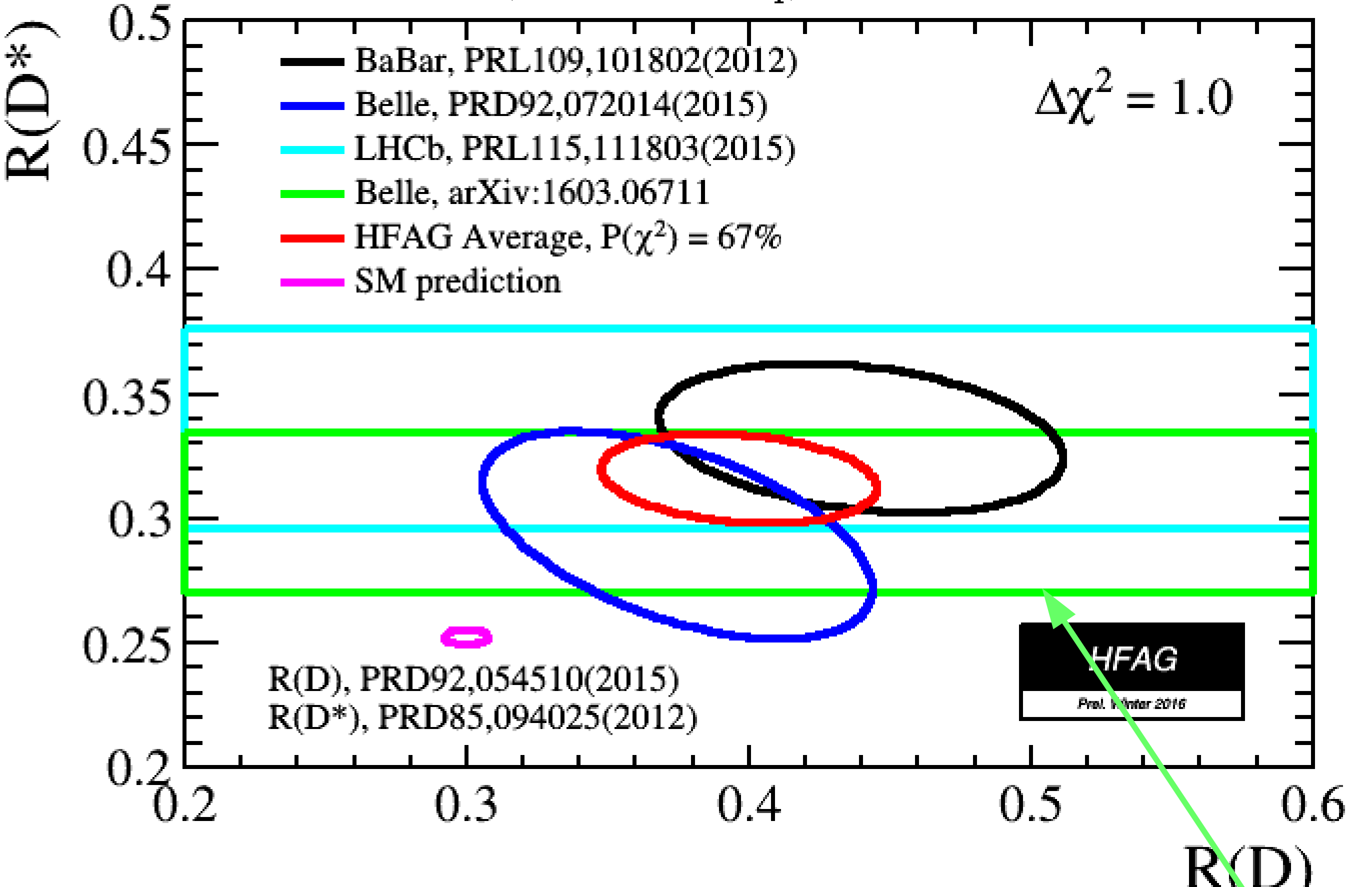
[disagreement with SM at 1.5σ]

stat error only !



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

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



BaBar

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

Belle

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

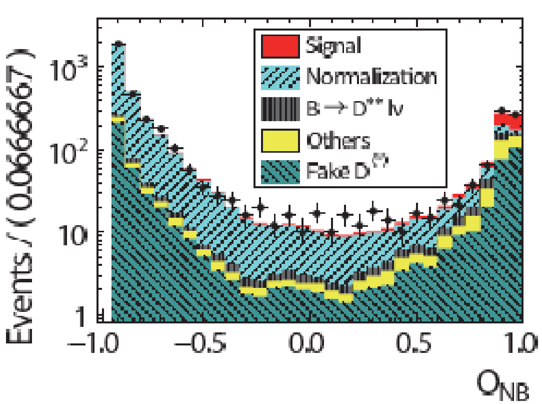
LHCb

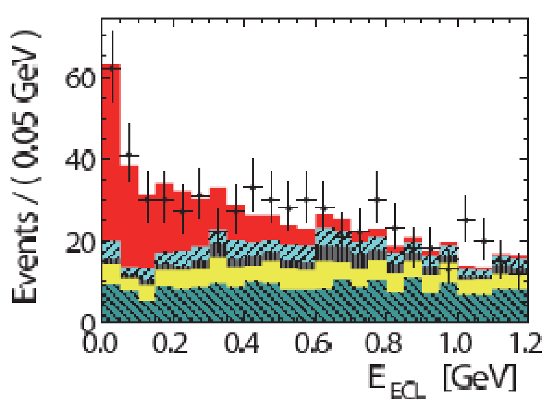
$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

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





[Belle, arXiv:1607.07923]

semileptonic tagging $(B \to D^{*+} l^- \nu)$

sig: $B \to D^{*+} \tau^- \nu$, $\tau \to l \nu_l \nu_\tau$

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

$B \to D^* \tau \nu$ at Belle

[Belle, arXiv:1612.00529]

$D^{(*)}$ leptonic with hadronic tagging, arXiv:1507.03233
D^* with semileptonic tagging, arXiv:1607.07923

τ polarization result using:

- hadronic decays of τ: $\tau^- \to \pi^- \nu_\tau$, $\rho^- \nu_\tau$
- hadronic tagging

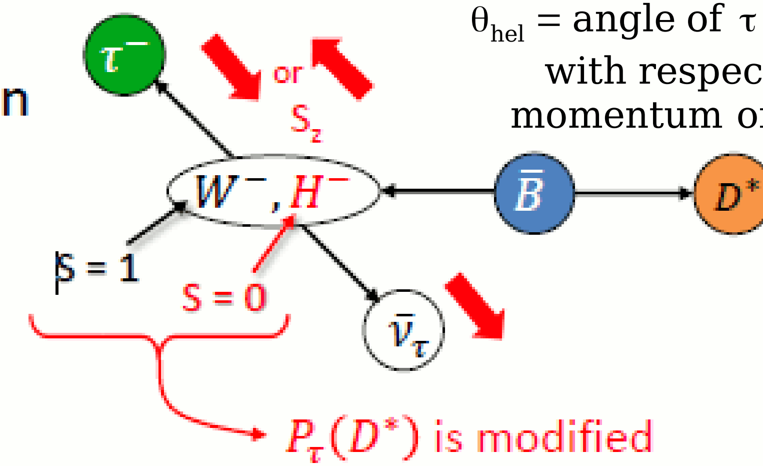
- $\tau^- \to \pi^- \nu_\tau$, $\rho^- \nu_\tau$ are good polarimeter for τ polarization

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^{+(-)}$ for right-(left-)handed τ

$$P_\tau(D^*)_{SM} = -0.497 \pm 0.013$$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)

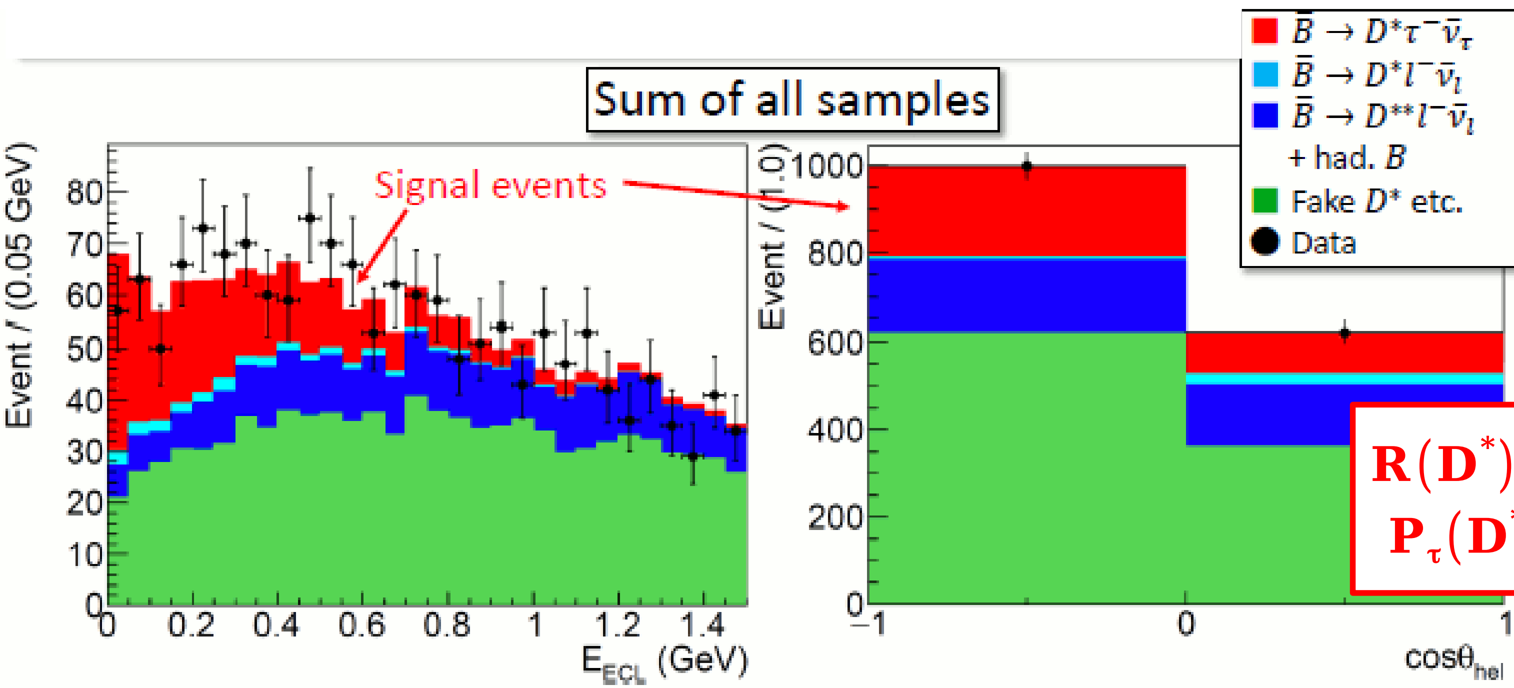


θ_{hel} = angle of τ daughter meson momentum with respect to direction opposite to momentum of $\tau\nu$ system in τ rest frame

τ polarization is a variable sensitive to NP

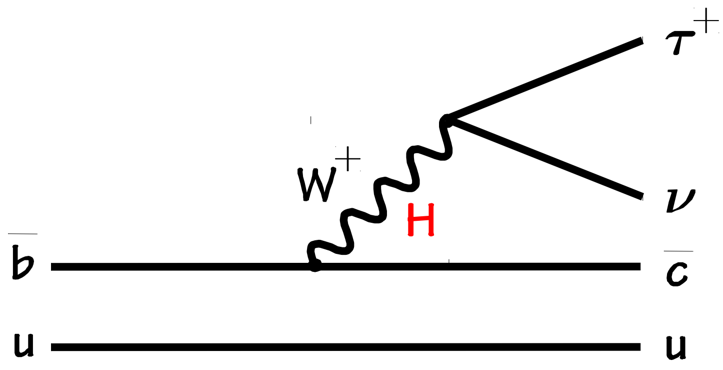
$$\frac{1}{\Gamma(D^*)}\frac{d\Gamma(D^*)}{d\cos\theta_{hel}} = \frac{1}{2}[1+\alpha P_\tau(D^*)\cos\theta_{hel}]$$

$\alpha = 1$ for $\tau^- \to \pi^- \nu_\tau$
$\alpha = 0.45$ for $\tau^- \to \rho^- \nu_\tau$



$$R(D^*) = 0.270 \pm 0.035 \,^{+0.028}_{-0.025}$$
$$P_\tau(D^*) = -0.38 \pm 0.51 \,^{+0.21}_{-0.16}$$

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

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

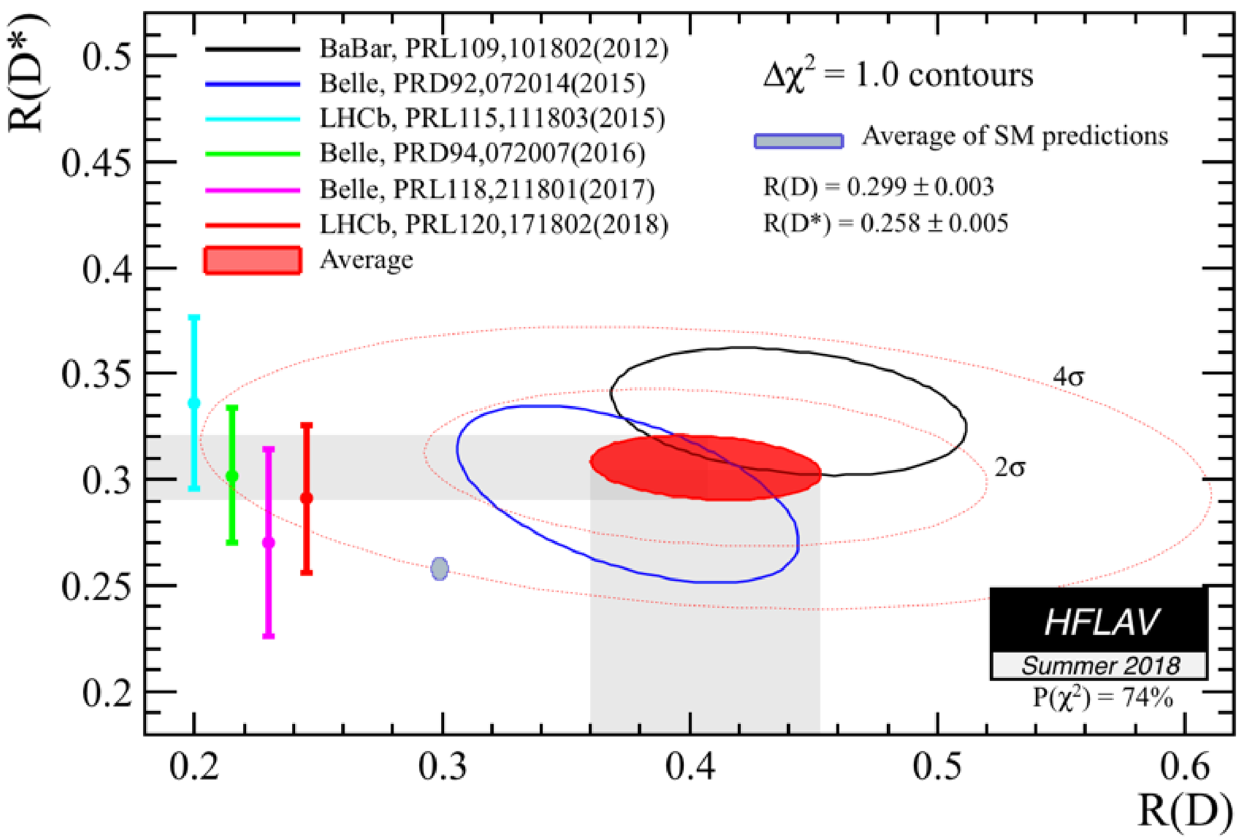
$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

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

LHCb

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

$R(D^*) = 0.291 \pm 0.019 \pm 0.029$



average

$R(D) = 0.407 \pm 0.039 \pm 0.024$
$R(D^*) = 0.306 \pm 0.013 \pm 0.007$

difference with SM predictions is at **3.8σ** 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

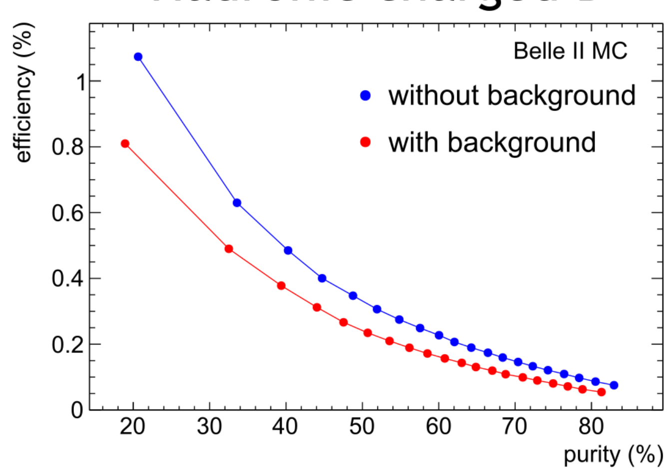
- More modes used for tag-side hadronic B than Belle, multiple classifiers

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

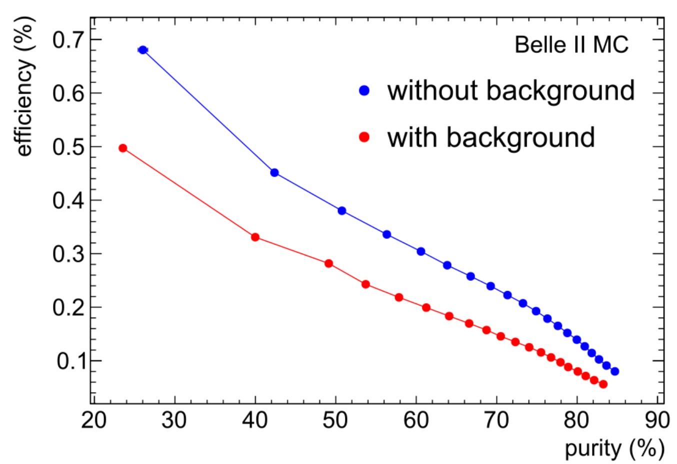
Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:

Hadronic charged B



Hadronic neutral B

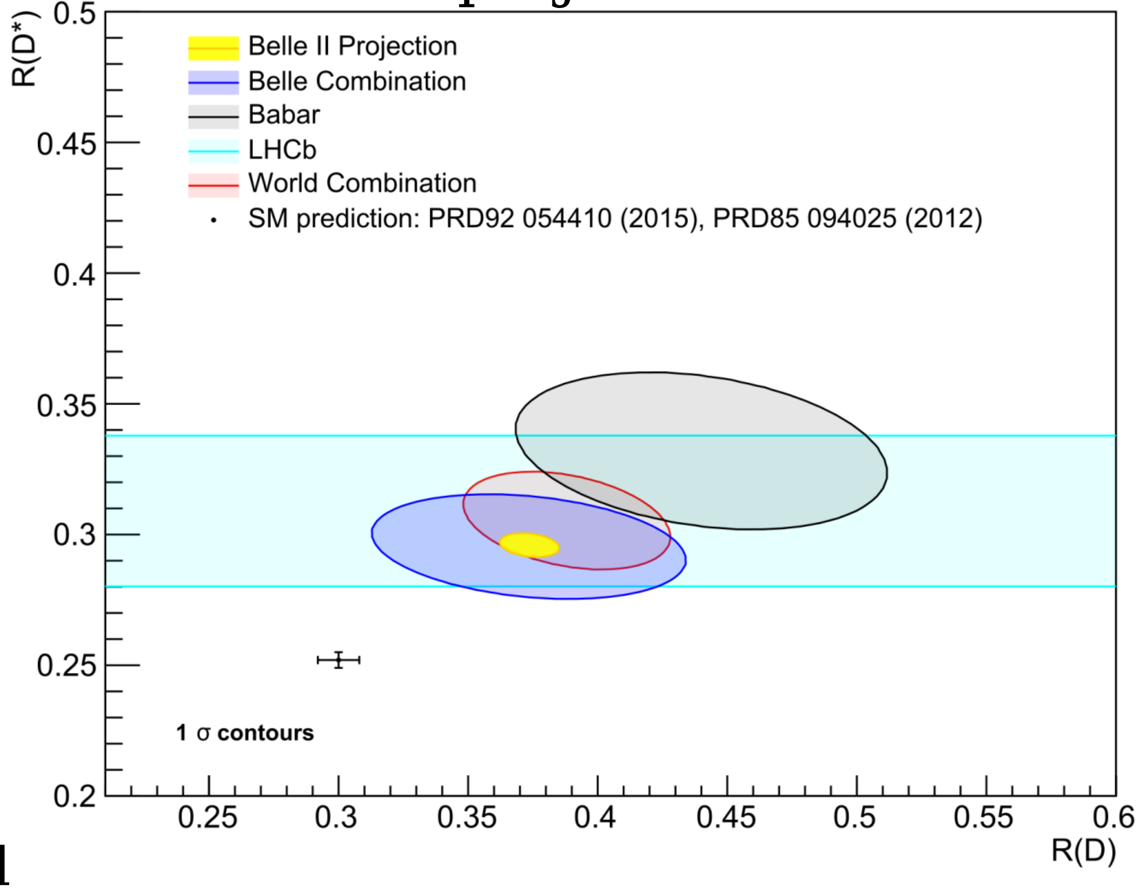


Projections for Belle II $R(D^{(*)})$

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

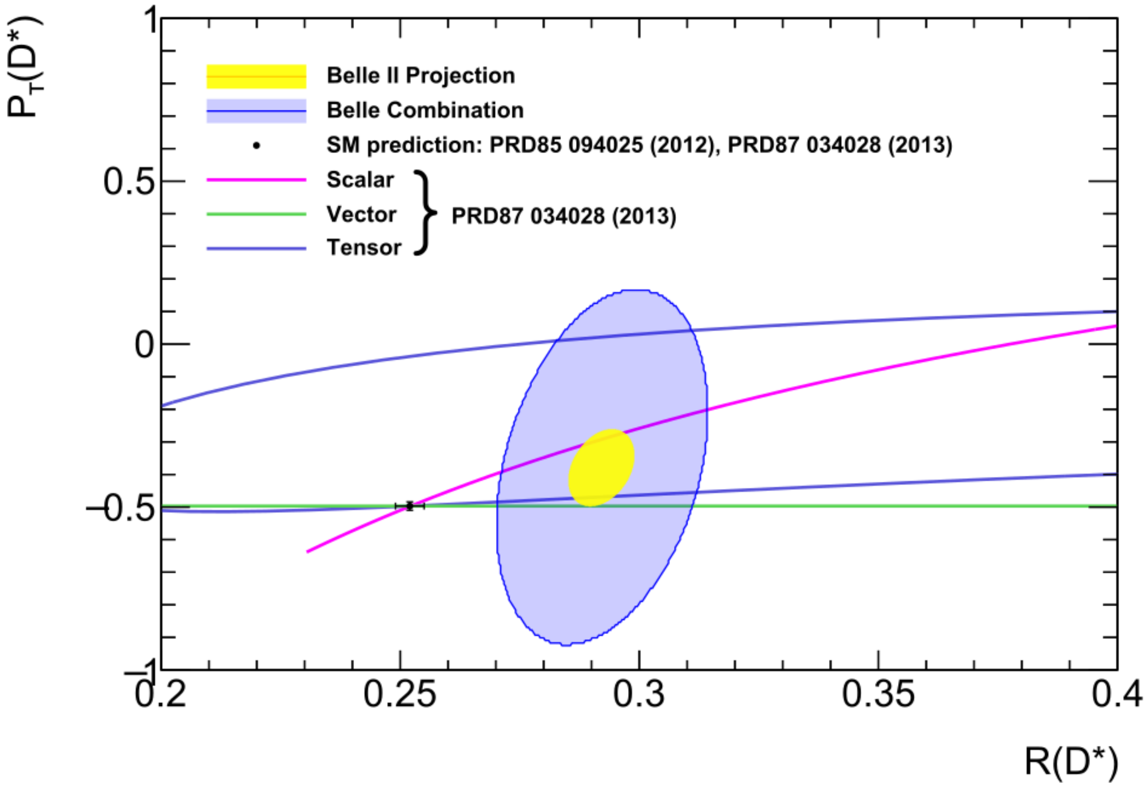
Additional observables as $P_\tau(D^*)$ ($F_L(D^*)$) and q^2 distribution can help discriminate between New Physics models

[Belle, arXiv:1612.00529]

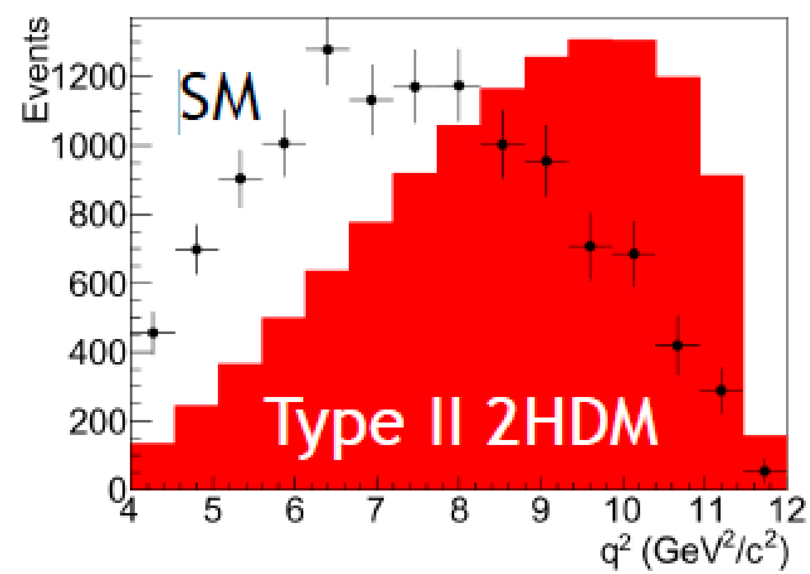
$$P_\tau(D^*) = -0.38 \pm 0.51\,^{+0.21}_{-0.16}$$

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



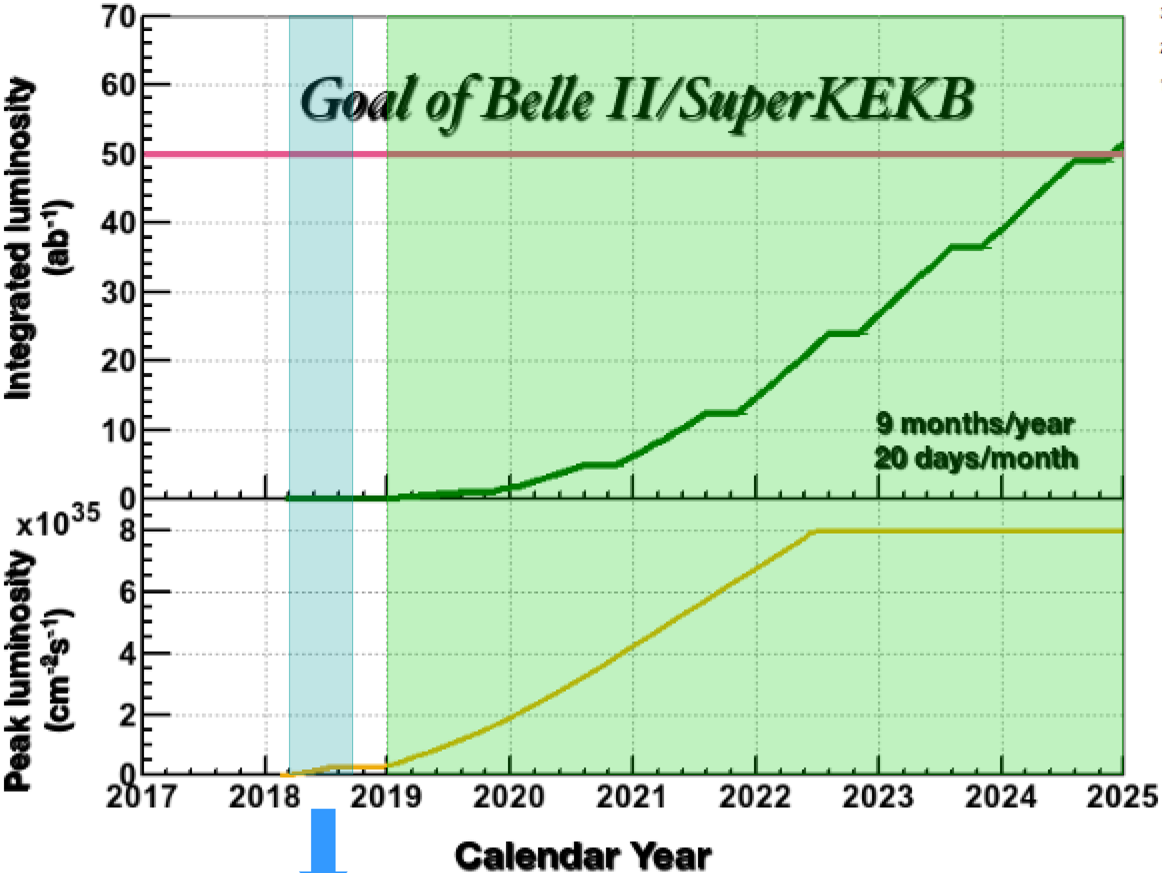
q² spectrum B →D* τν
50ab⁻¹ projection



phase 2 → phase 3

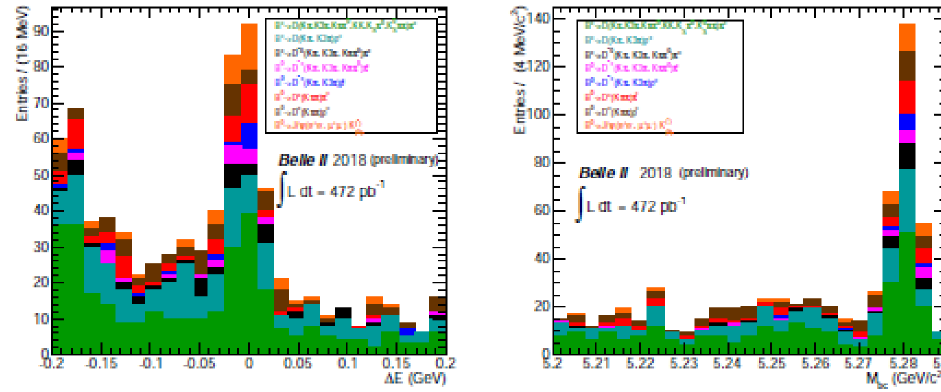
Phase2, BEAST II
collision + partial Belle II

Phase3, physics run

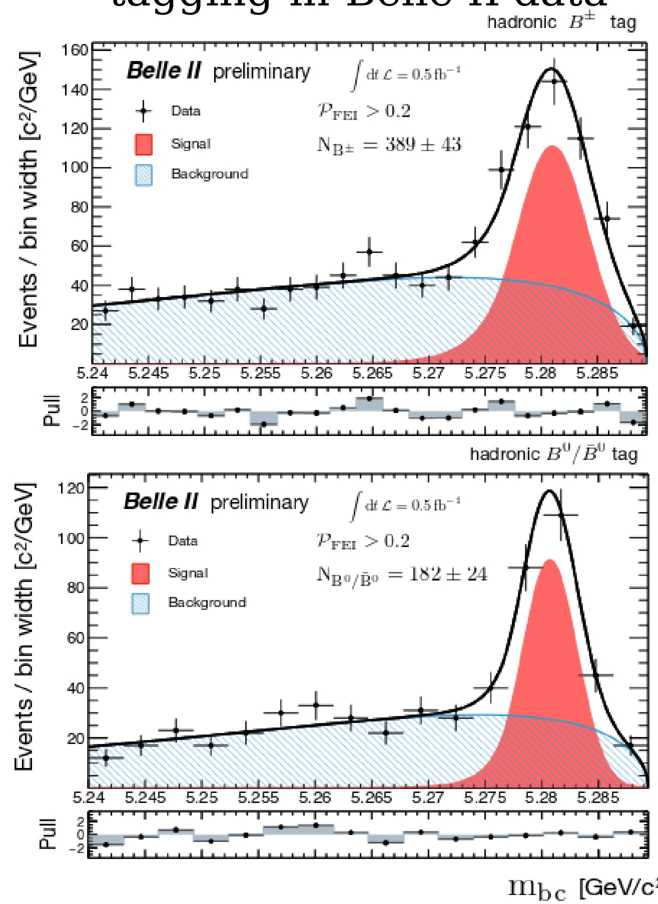


First collisions May to July
$\sim 500\ \mathrm{pb}^{-1}$

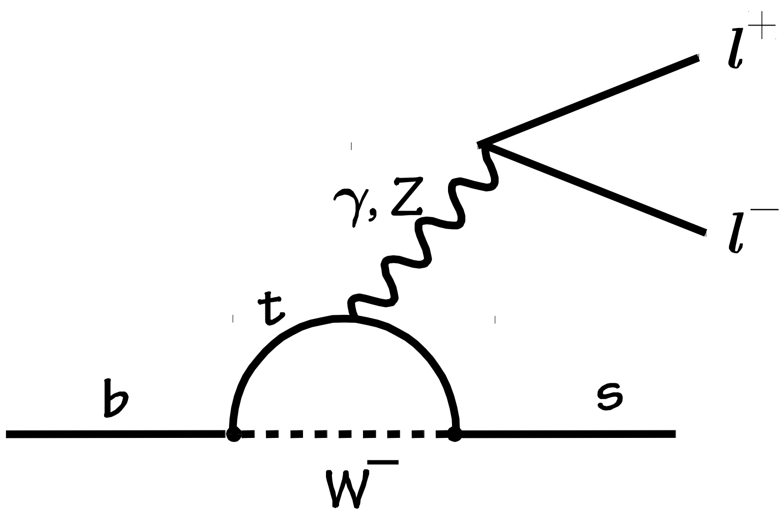
B rediscovery program

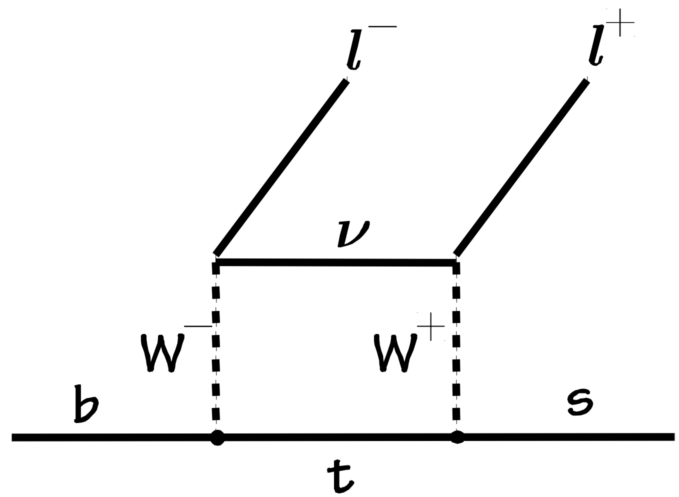


first studies of performance of hadronic tagging in Belle II data



b→lls





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

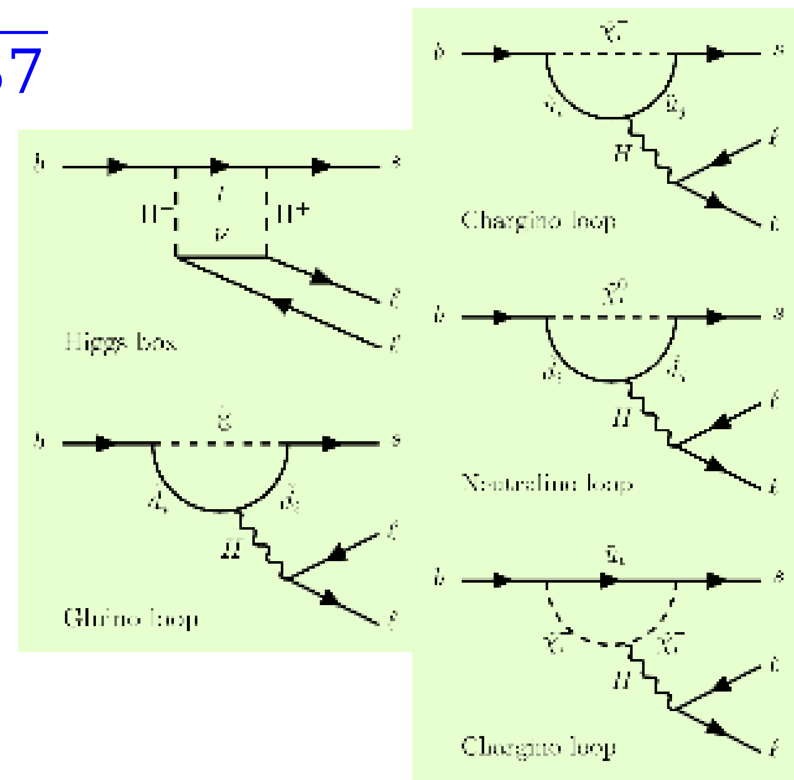
  → Decay the γ into 2 leptons
  - Add an interfering box diagram

    → b→lls, very rare in the SM

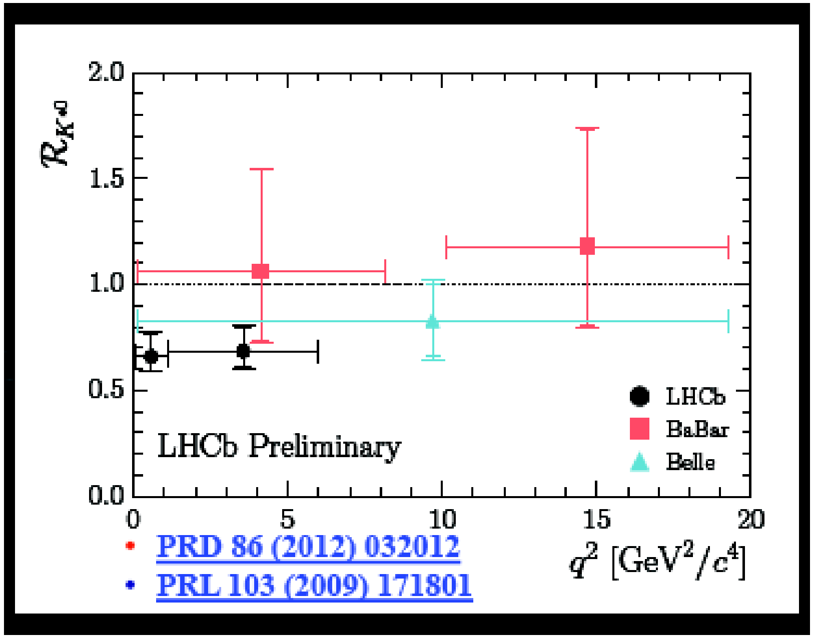
    $B(\mathrm{B \to llK^*}) = (3.3 \pm 1.0)\ .\ 10^{-6}$

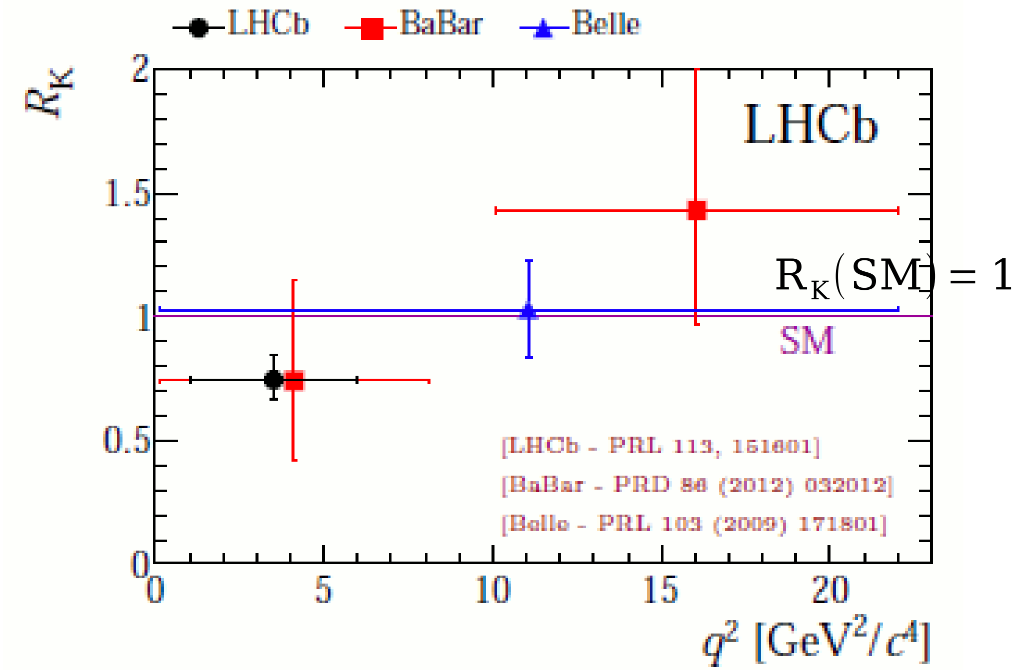
  - Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions…

- Ideal place to look for new physics



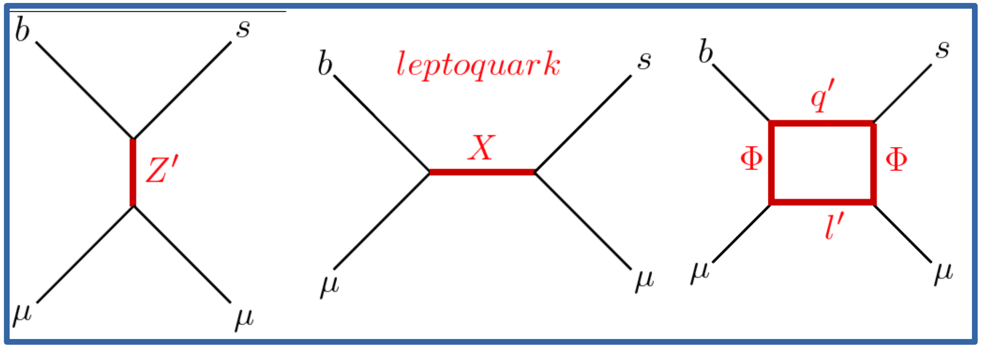
Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays





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

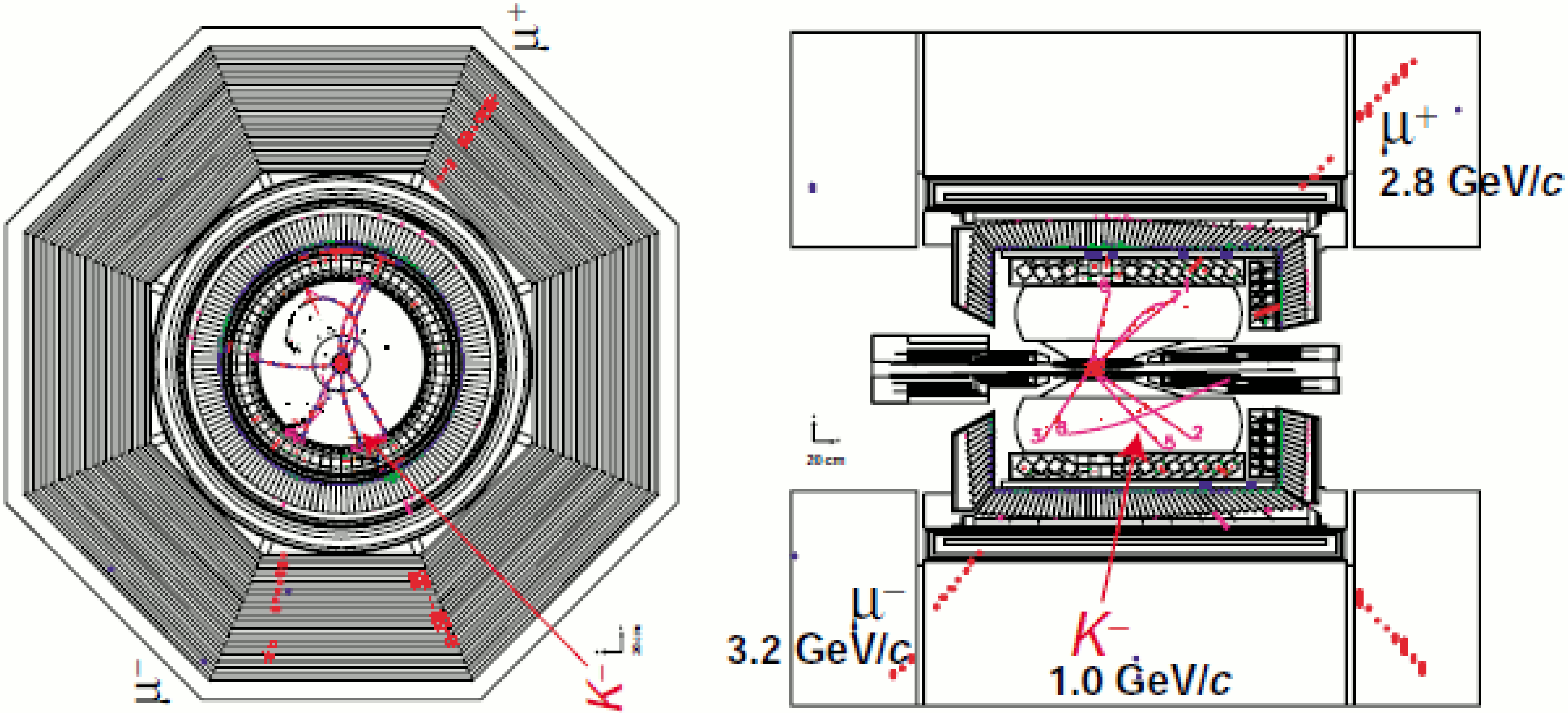


Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

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

First observation

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



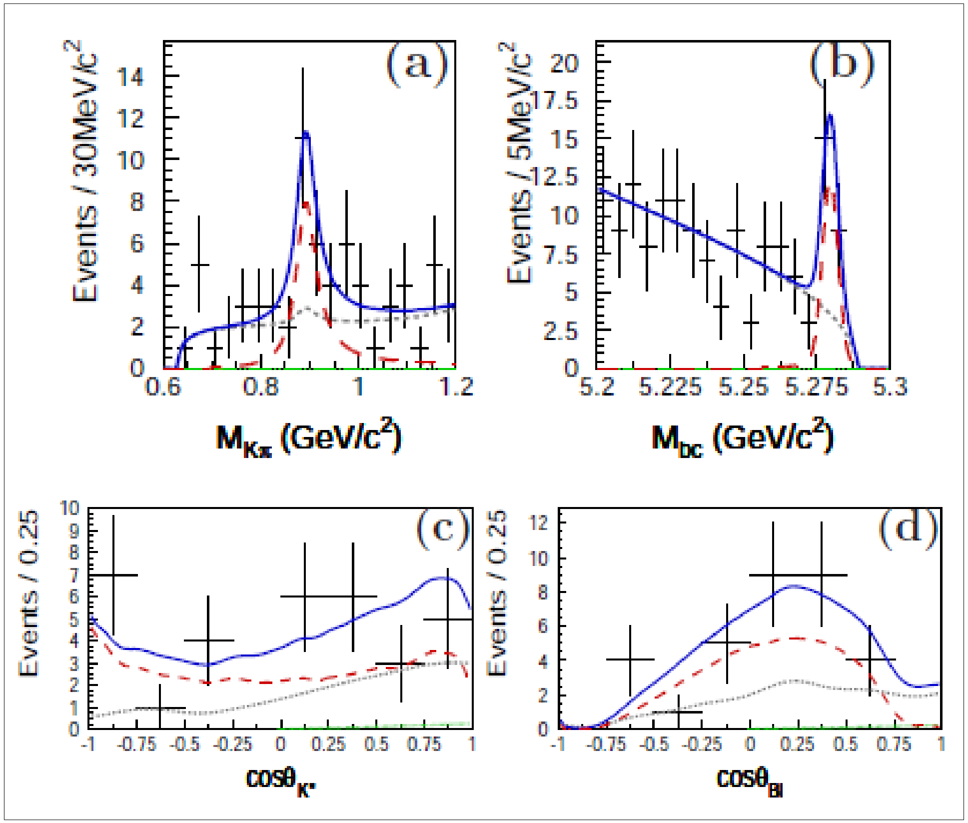
Situation pre-LHCb

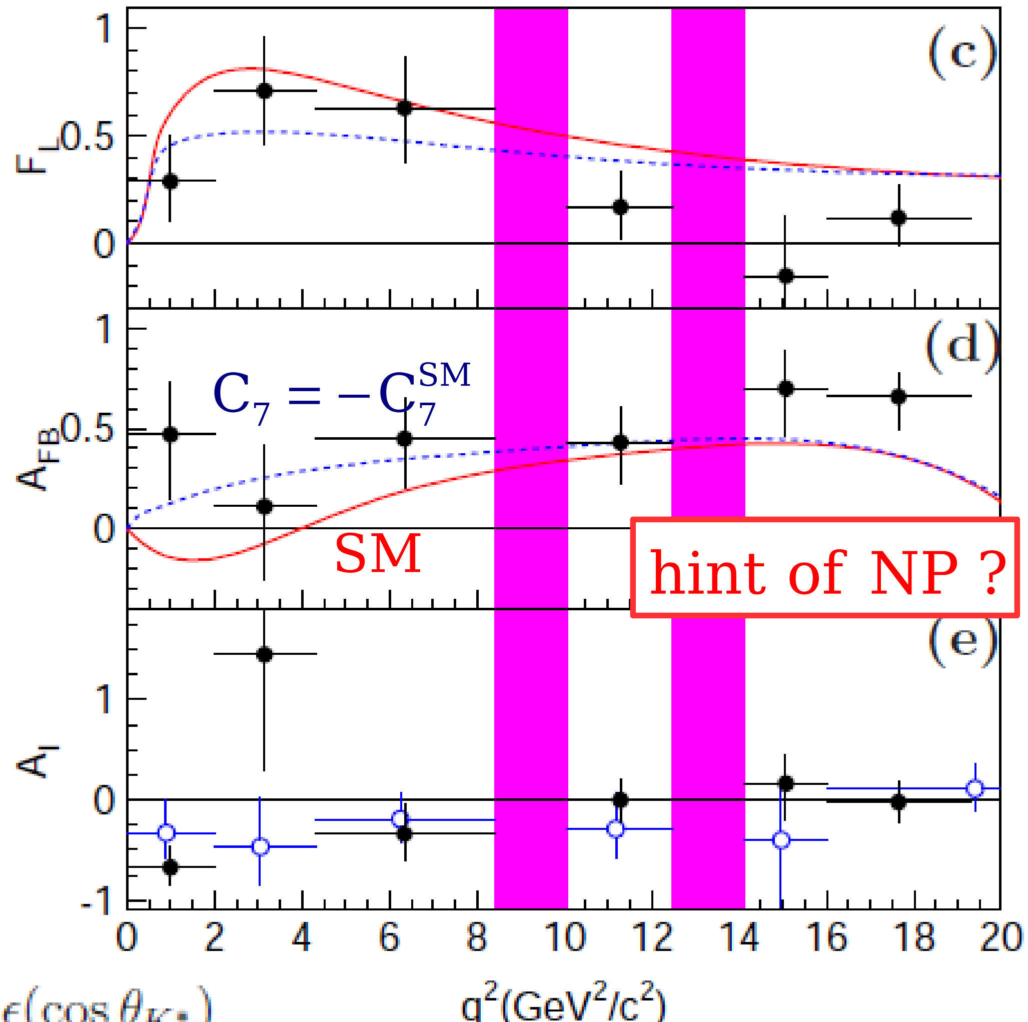
$B \to K^{*} l^{+} l^{-}$ decays

[Belle, arXiv:0904.0770]

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

illustration: $q^2 \in [0.0,\, 2.0]\ \mathrm{GeV}^2$





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

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

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

$R_K = 1.03 \pm 0.19 \pm 0.06$

R_K , R_K^* ,...

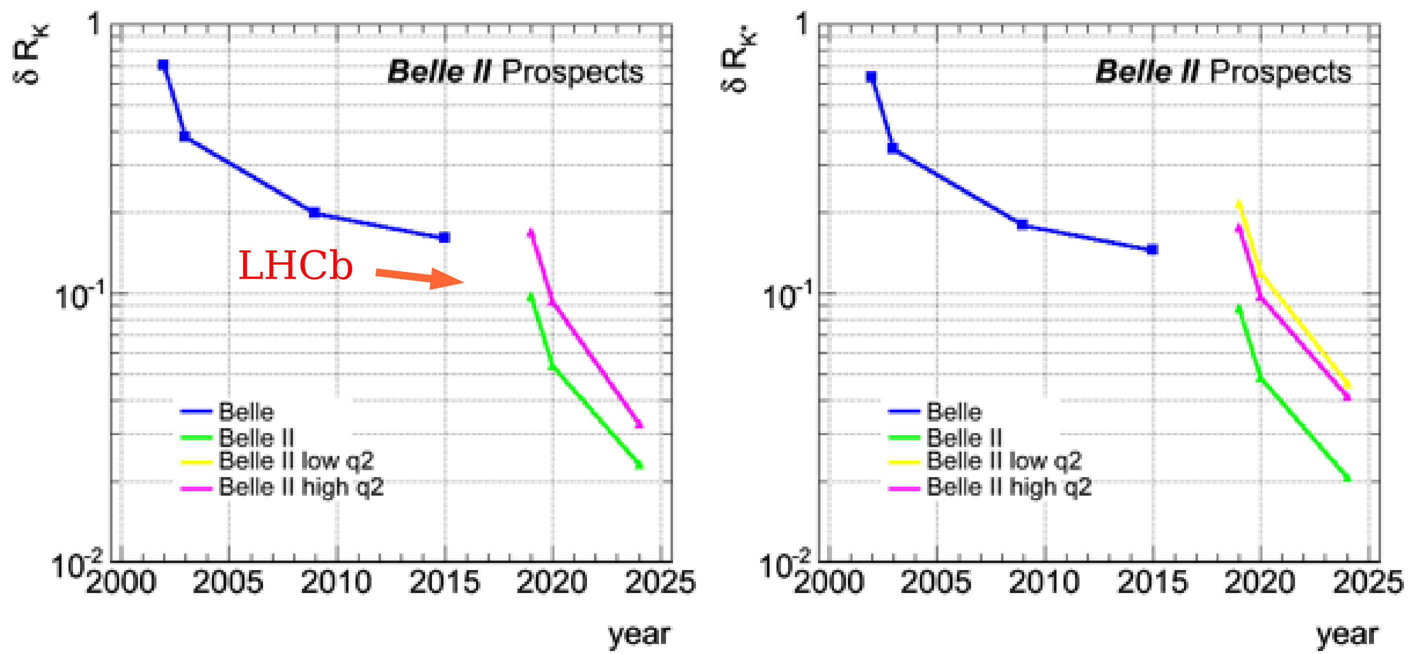
for the whole q^2 range:

$$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$$
$$R_K = 1.03 \pm 0.19 \pm 0.06$$

[Belle, arXiv:0904.0770]

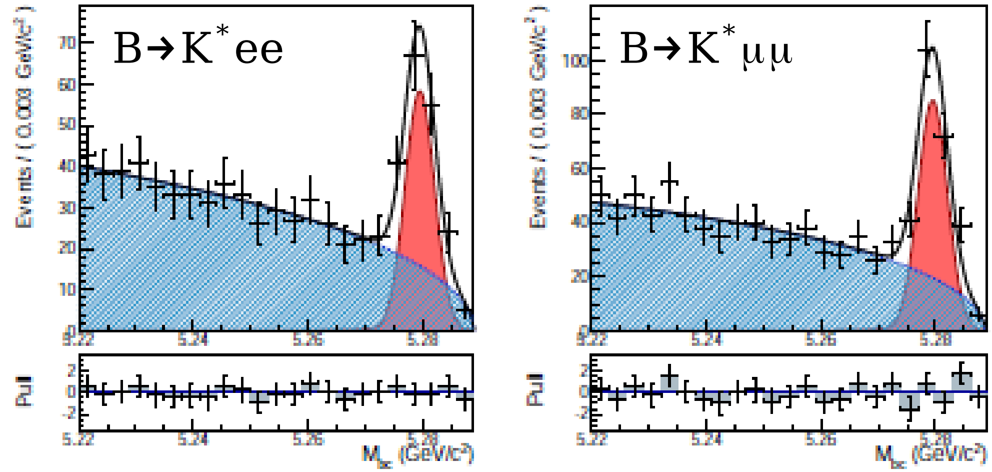
[Belle II, arXiv:1808.10567]

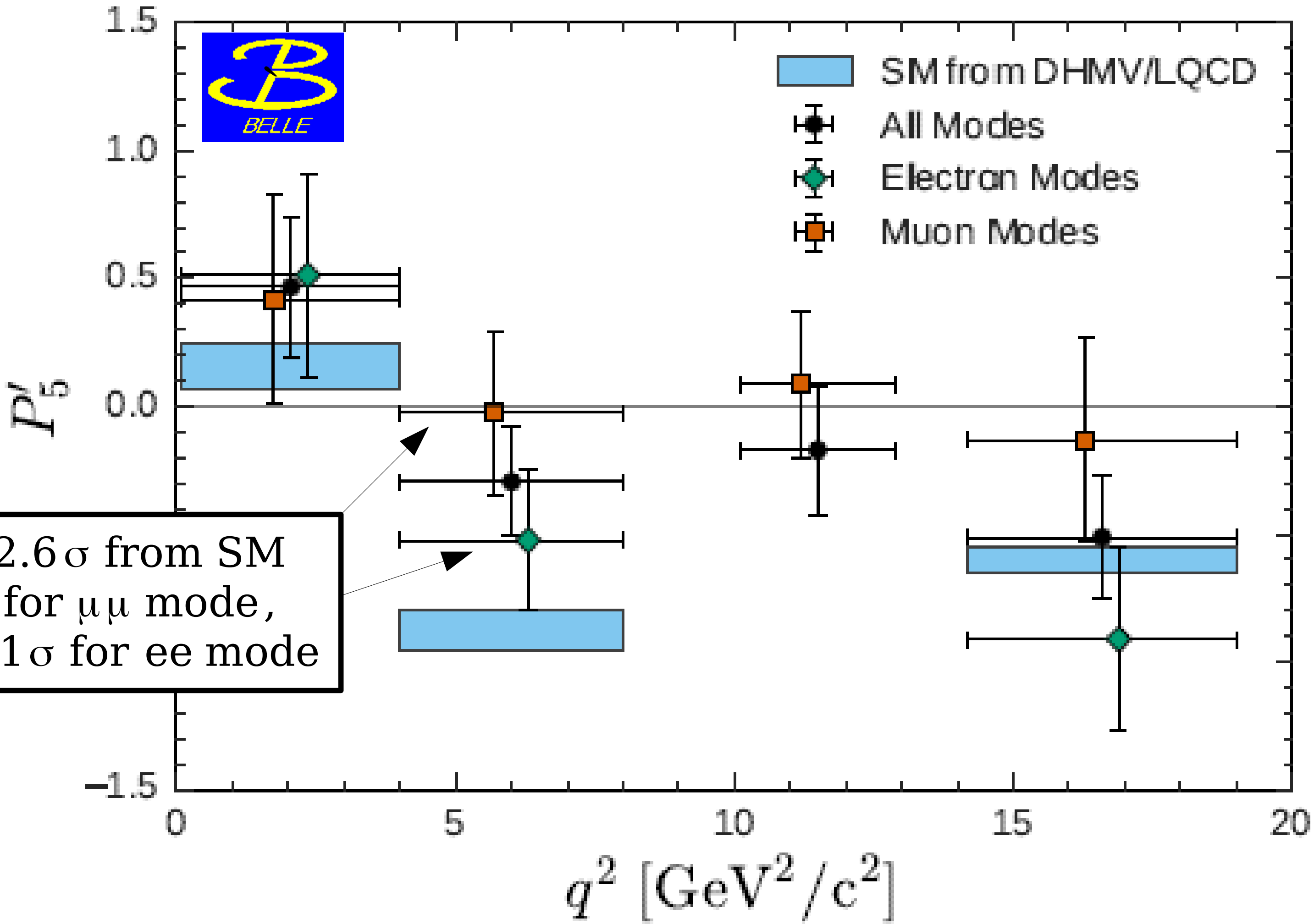
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%



Belle results for both ee and $\mu\mu$

[Belle, arXiv:1612.05014]

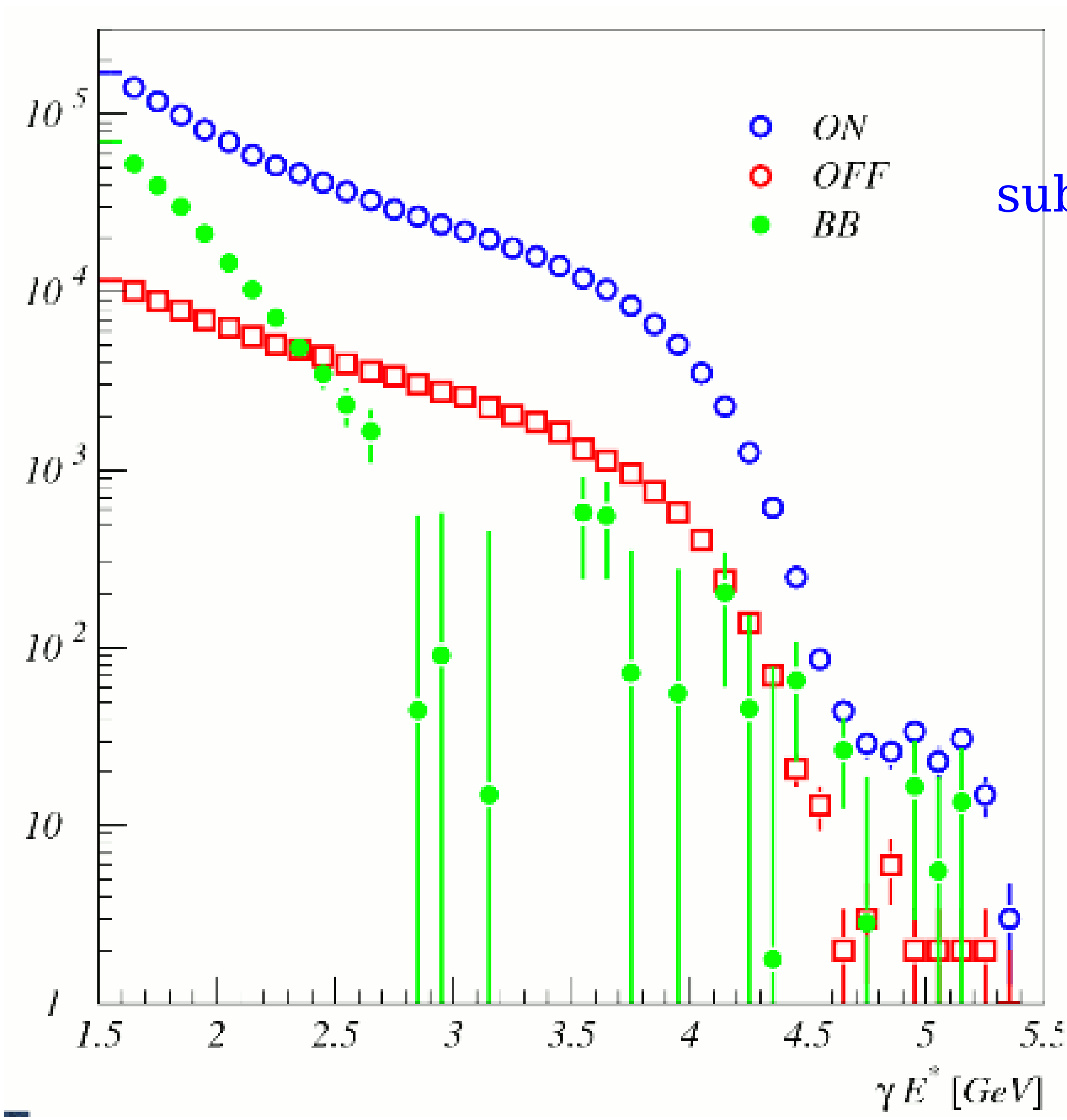




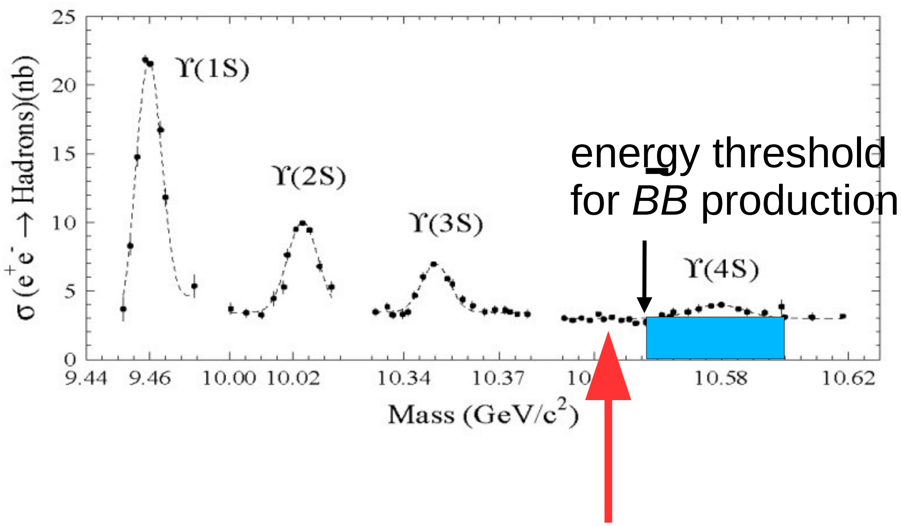
2.6σ from SM
for $\mu\mu$ mode,
1.1σ for ee mode

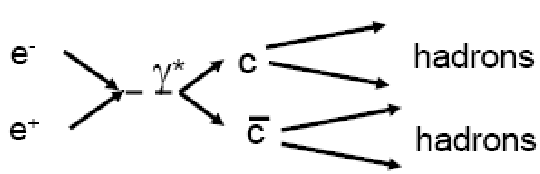
what about inclusive b ➔ sll?

as done in b➔sγ ?



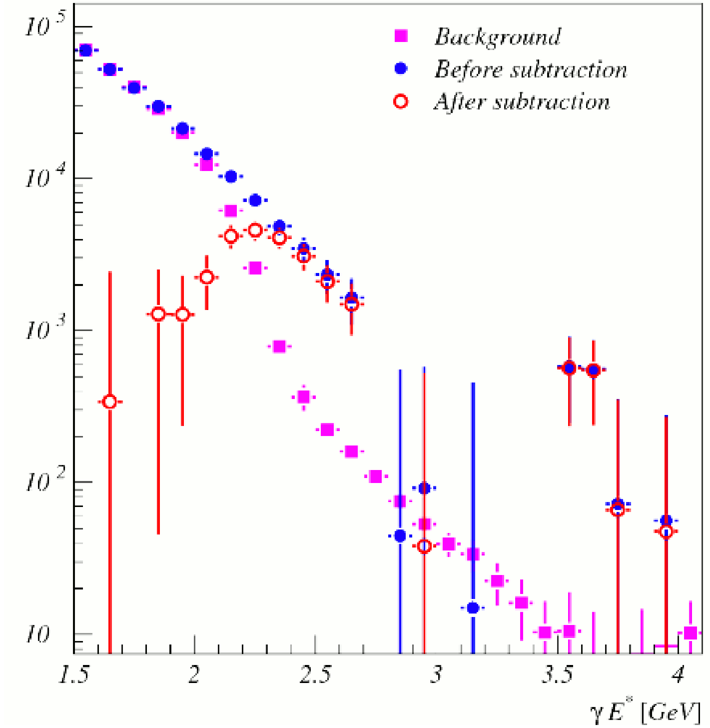
OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data



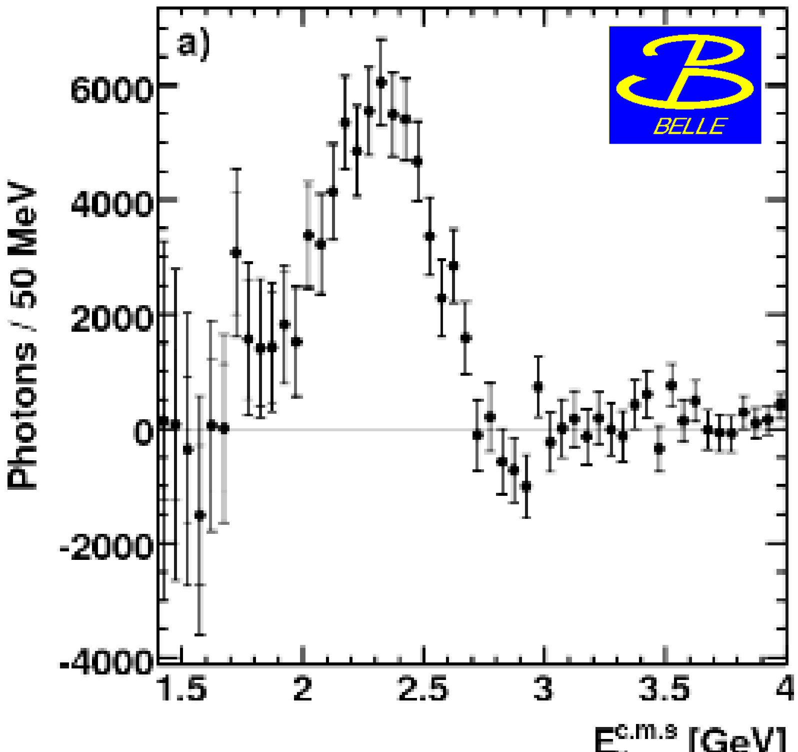


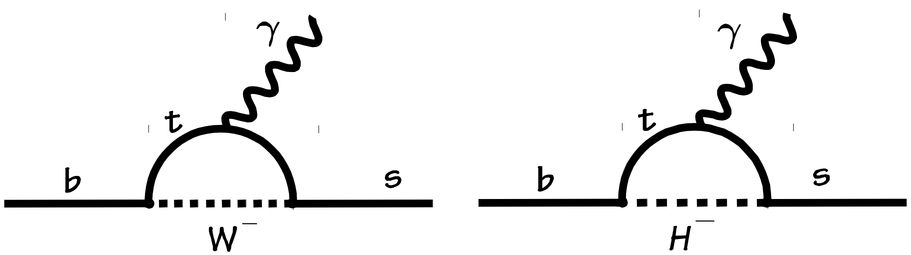
what about inclusive b → sll?

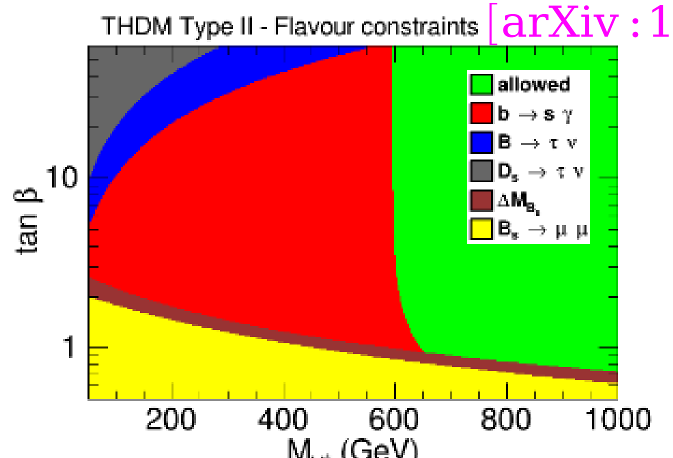
$B\overline{B}$ subtraction:
Use measured π^0 and η spectra
and some efficiency-corrected MC



for $E^*_\gamma > 1.7$ GeV,
$\mathcal{B}(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$







[arXiv:1706.07414]

what about inclusive $b \to sll$?

for $E_\gamma^* > 1.7$ GeV, $\mathcal{B}(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$

predicted BF for $1 < q^2 < 6\ \text{GeV}^2$, $\mathcal{B}(B \to X_s ll) = (1.62 \pm 0.09) \times 10^{-6}$

and lot of leptons in B decays...

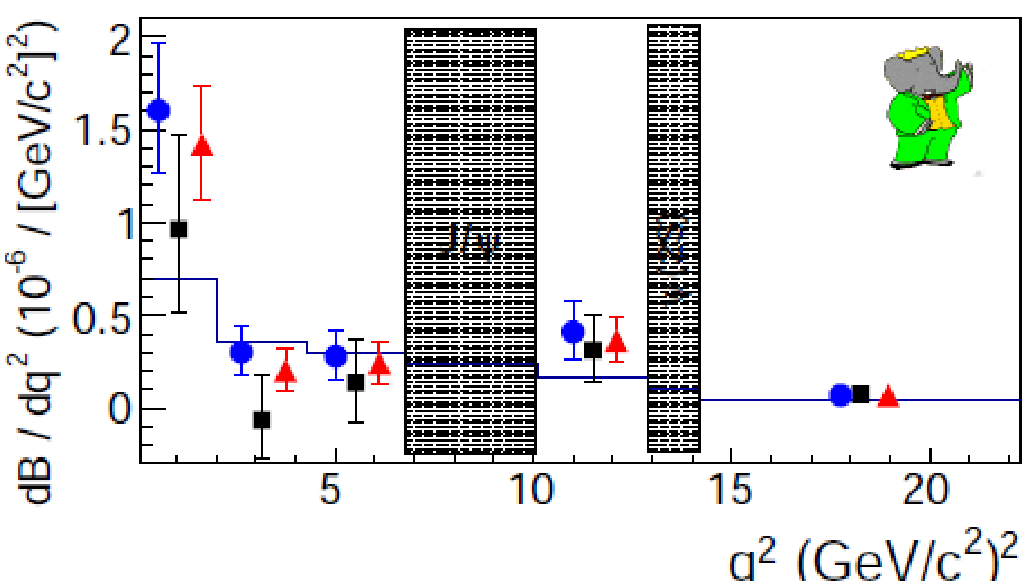
- difficult to achieve using inclusive method (à la $b \to s\gamma$)
- some on-going efforts using full had. tag, but $\epsilon < 1\%$...

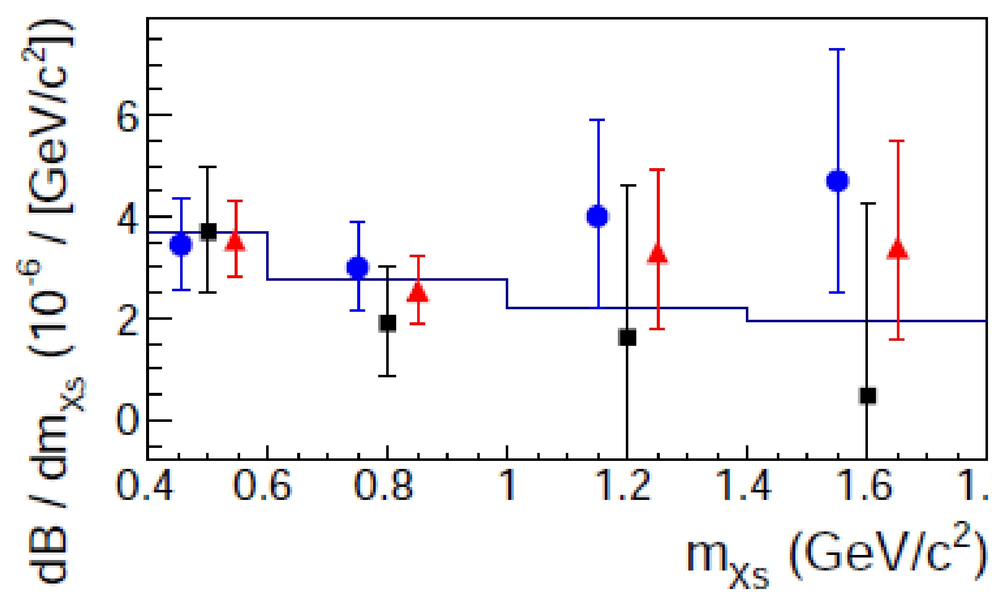
sum-of-exclusive method instead...

[BaBar, arXiv:1312.5364]

10 modes for X_s: K^+, $K^+\pi^0$, $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+$, K^0_S, $K^0_S\pi^0$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, $K^0_S\pi^+\pi^-$ } $M(X_s) < 1.8$ GeV, 70% of total inclusive rate

Bin	Range	$B \to X_s e^+e^-$	$B \to X_s \mu^+\mu^-$	$B \to X_s \ell^+\ell^-$	$A_{CP\,B\to X_s\ell^+\ell^-}$
q_0^2	$1.0 < q^2 < 6.0$	$1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18$ (1.71)	$0.66^{+0.82+0.30}_{-0.76-0.24} \pm 0.07$ (1.78)	$1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18$	$-0.06 \pm 0.22 \pm 0.01$





inclusive as sum-of-exclusive

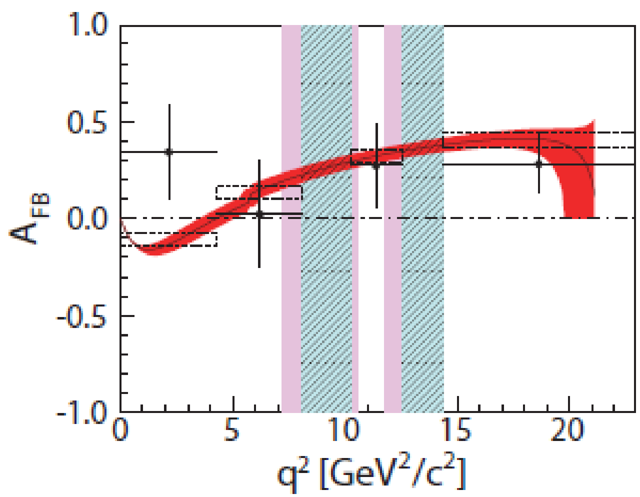
[Belle, arXiv:1402.7134]

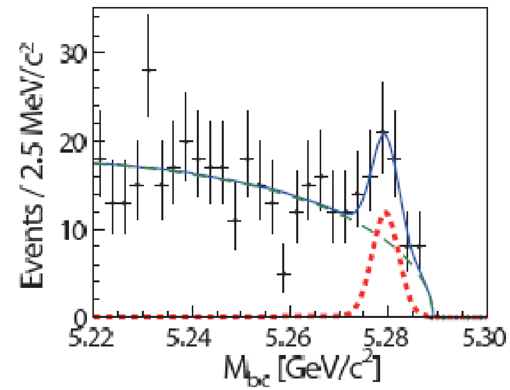
10 modes, $M(X_s) < 2.0$ GeV

50% of total inclusive rate

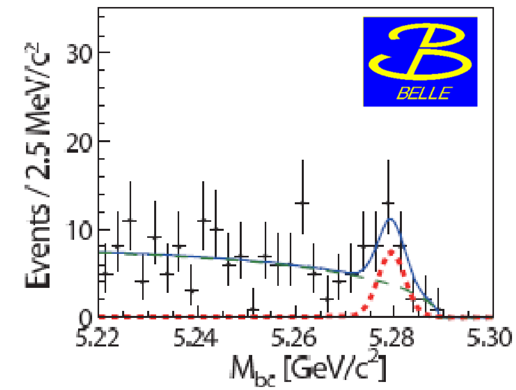
(goal here was A_{FB}, flavor of B needed)

$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$

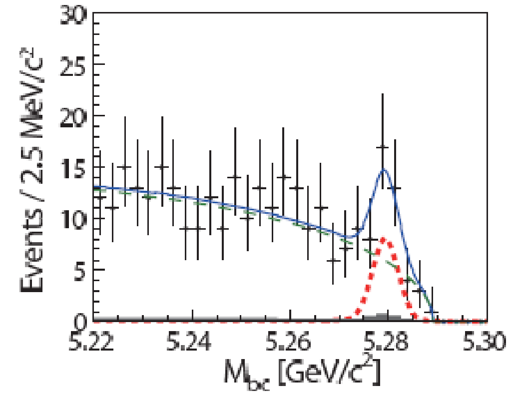




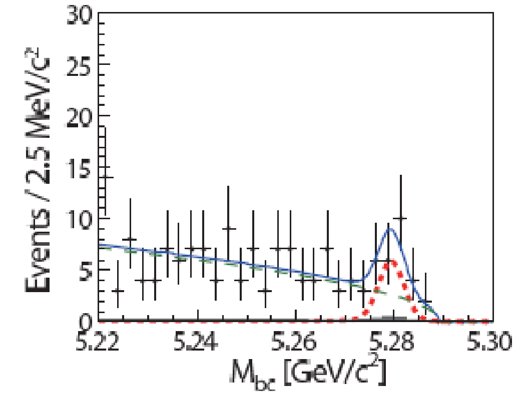
(a) $B \to X_s e^+e^-$ candidates with $\cos\theta > 0$



(b) $B \to X_s e^+e^-$ candidates with $\cos\theta < 0$



(c) $B \to X_s \mu^+\mu^-$ candidates with $\cos\theta > 0$



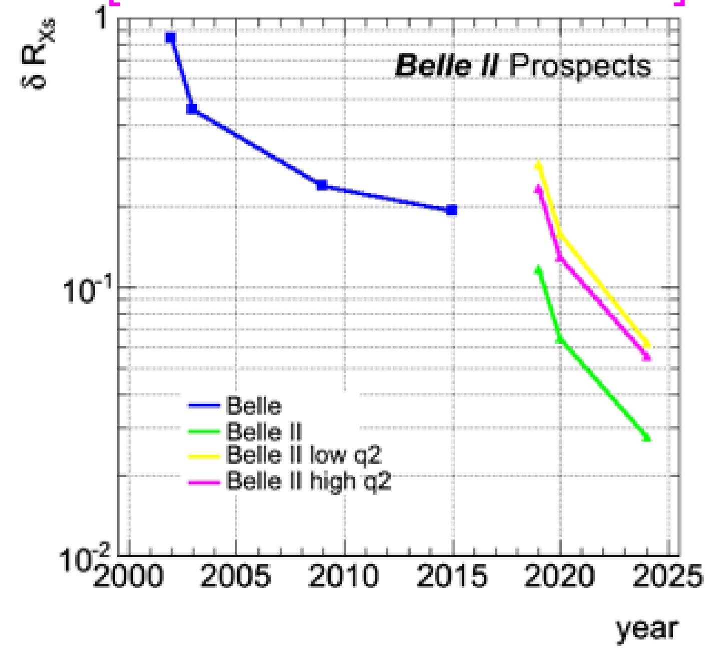
(d) $B \to X_s \mu^+\mu^-$ candidates with $\cos\theta < 0$

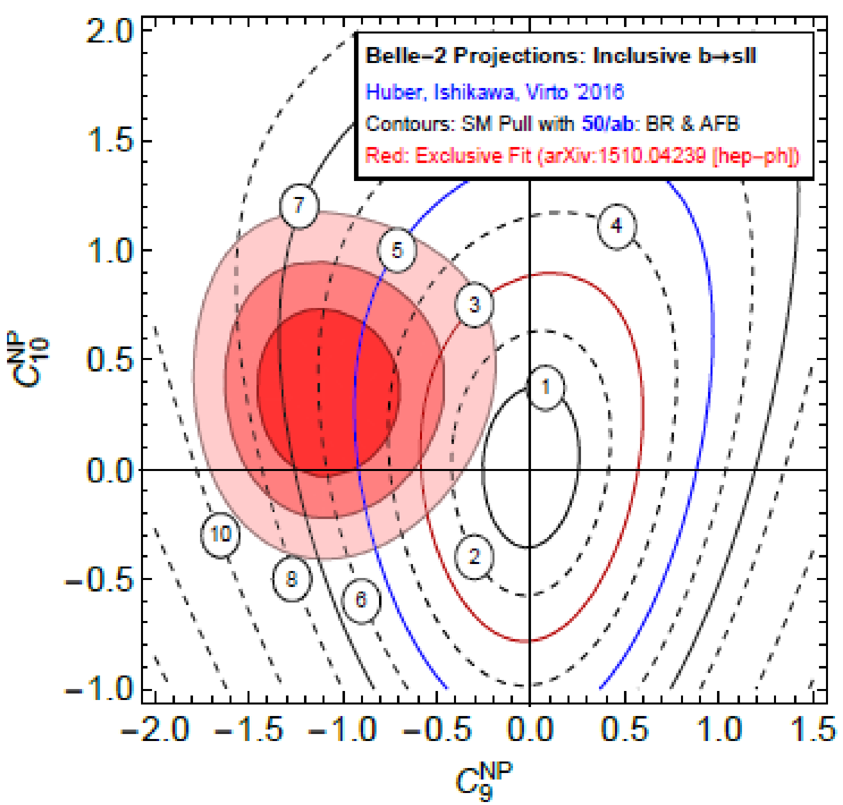
	1st q^2 bin	2nd q^2 bin	3rd q^2 bin	4th q^2 bin	
q^2 range [GeV$^2/c^2$]	[0.2,4.3]	$[4.3,7.3]_{X_se^+e^-}$ $[4.3,8.1]_{X_s\mu^+\mu^-}$	$[10.5,11.8]_{X_se^+e^-}$ $[10.2,12.5]_{X_s\mu^+\mu^-}$	[14.3, 25.0]	[1.0, 6.0]
$\mathcal{A}_{FB}$	$0.34 \pm 0.24 \pm 0.03$	$0.04 \pm 0.31 \pm 0.05$	$0.28 \pm 0.21 \pm 0.02$	$0.28 \pm 0.15 \pm 0.02$	$0.30 \pm 0.24 \pm 0.04$
$\mathcal{A}_{FB}$ (theory)	-0.11 ± 0.03	0.13 ± 0.03	0.32 ± 0.04	0.40 ± 0.04	-0.07 ± 0.04
N_{sig}^{ee}	45.6 ± 10.9	30.0 ± 9.2	25.0 ± 7.0	39.2 ± 9.6	50.3 ± 11.4
$N_{sig}^{\mu\mu}$	43.4 ± 9.2	23.9 ± 10.4	30.7 ± 9.9	62.8 ± 10.4	35.3 ± 9.2

Inclusive di-lepton, $B \to X_s l^+ l^-$ (at Belle II)

Observables	Belle $0.71\,\mathrm{ab}^{-1}$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	23%	10%	4.7%
$A_{\mathrm{CP}}(B \to X_s \ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7 %	3.1 %
$A_{\mathrm{CP}}(B \to X_s \ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9 %	2.6 %
$A_{\mathrm{CP}}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	21%	8.1 %	2.6 %
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7%	3.1%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9%	2.6%
$A_{\mathrm{FB}}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	19%	7.3%	2.4%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($[1.0, 3.5]$ GeV^2)	52%	19%	6.1%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ ($[3.5, 6.0]$ GeV^2)	42%	16%	5.2%
$\Delta_{\mathrm{CP}}(A_{\mathrm{FB}})$ (> 14.4 GeV^2)	38%	15%	4.8%

[arXiv:1808.10567]





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

[D.Du et al, arXiv:1510.02349]
[D.Straub, Flavio]

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:

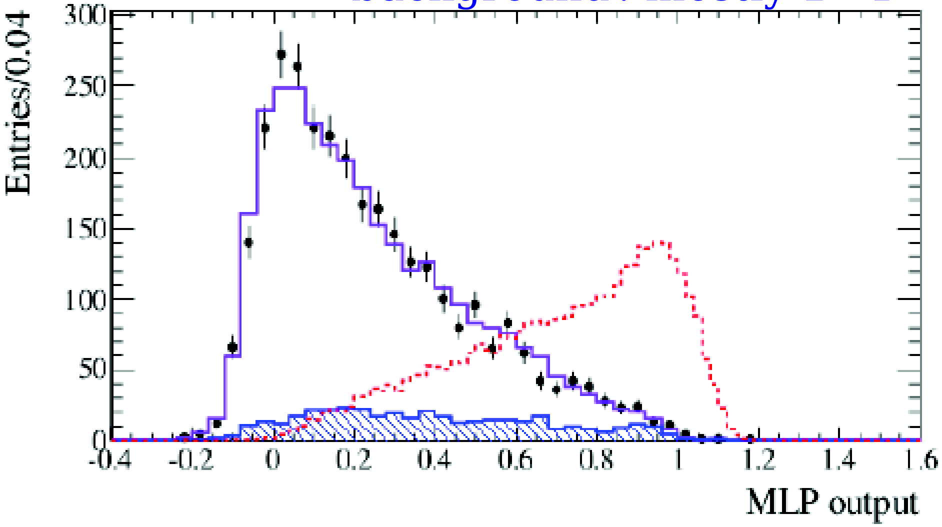
$$B(B^+ \to K^+ \tau^+ \tau^-)_{SM} = (1.22 \pm 0.10)\, 10^{-7}$$
$$B(B^0 \to K^0 \tau^+ \tau^-)_{SM} = (1.13 \pm 0.09)\, 10^{-7}$$
$$B(B^+ \to K^{*+} \tau^+ \tau^-)_{SM} = (0.99 \pm 0.12)\, 10^{-7}$$
$$B(B^0 \to K^{*0} \tau^+ \tau^-)_{SM} = (0.91 \pm 0.11)\, 10^{-7}$$

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

[BaBar, arXiv:1605.09637]

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

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



	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
$N^i_{\rm bkg}$	49.4±2.4±2.9	45.8±2.4 ±3.2	59.2±2.8 ±3.5
$\epsilon^i_{\rm sig}(\times 10^{-5})$	1.1 ±0.2±0.1	1.3±0.2±0.1	2.1±0.2±0.2
$N^i_{\rm obs}$	45	39	92
Significance (σ)	-0.6	-0.9	3.7

$$B(B^+ \to K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3} \text{ at } 90\%\,\text{CL}$$

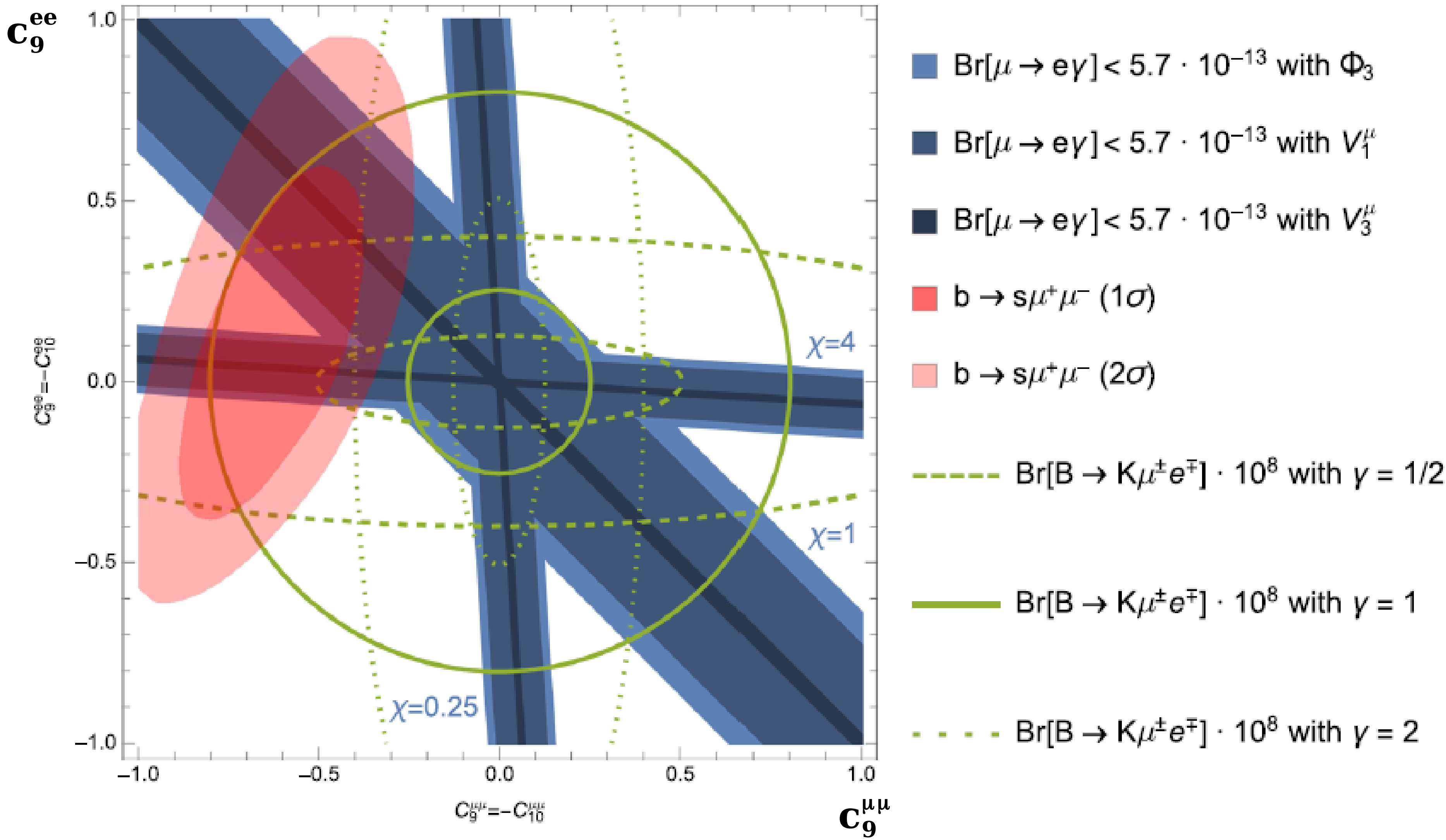
[Belle II, arXiv:1808.10567]

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\text{Br}(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$\text{Br}(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$\text{Br}(B^0_s \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	–

LFV b→sll'decays

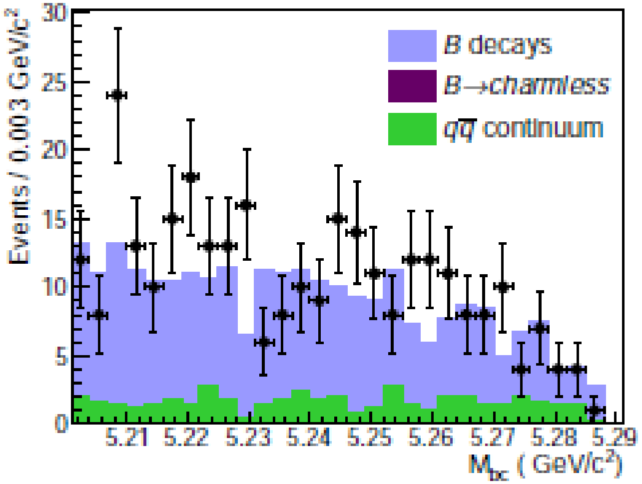
Glashow, Guadagnoli and Lane, 1411.0565, LUV ⇒ LFV, such as B→Kμe, Kμτ could also be generated ...

A.Crivellin et al, 1706.08511



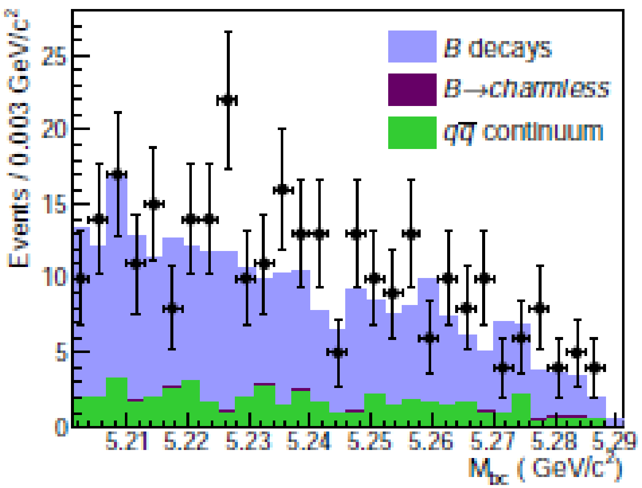
LFV $B \to K^* l l'$ decays

[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

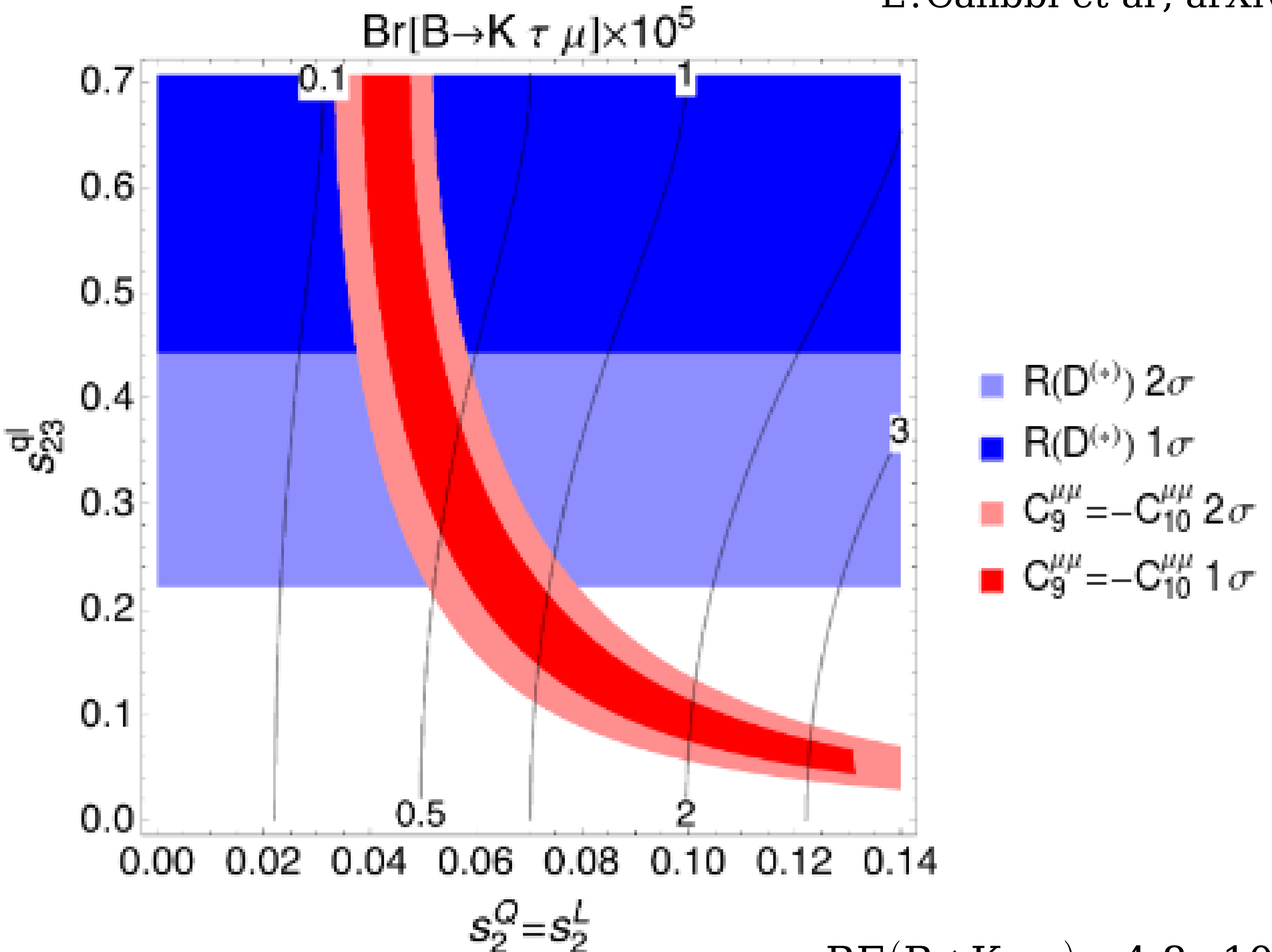


$B(B^0 \to K^{*0}\mu^+e^-) < 1.6 \times 10^{-7}$ at 90%CL

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

$R(D^*)$ and $b \to s\mu\mu \Rightarrow B \to K\tau\mu$

L. Calibbi et al, arXiv:1709.00692

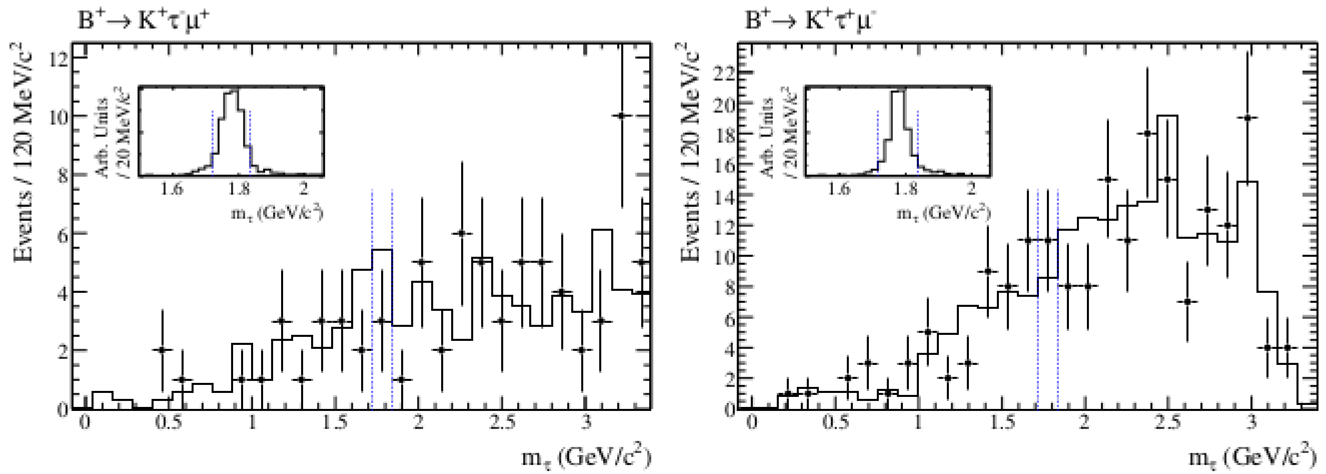


$BF(B \to K\tau\mu) < 4.8 \times 10^{-5}$ @ 90% CL
BaBar, arXiv:1204.2852
hadronic tag

LFV B→Kτl 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



$B(B^+ \to K^+ \tau^- \mu^+) < 4.5 \times 10^{-5}$ 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)

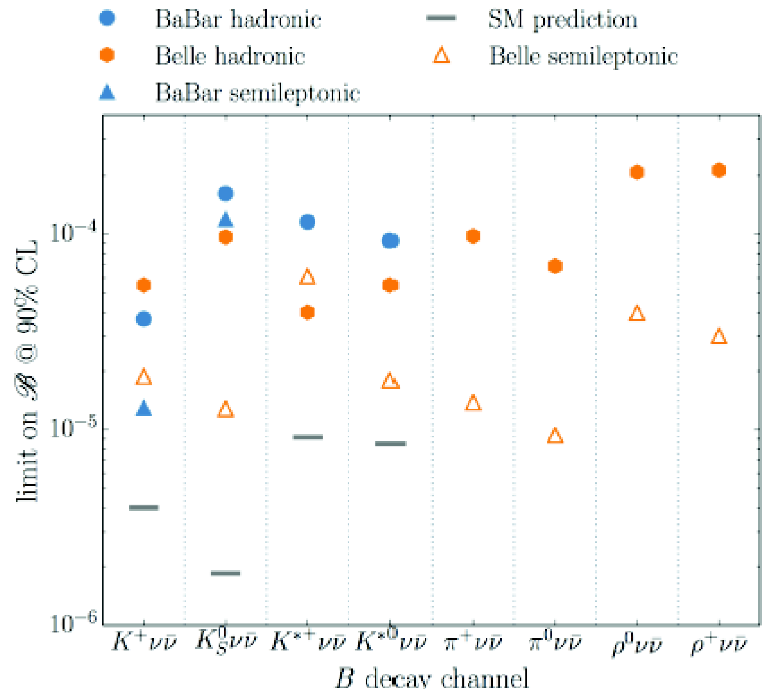
[Belle II, arXiv:1808.10567]

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

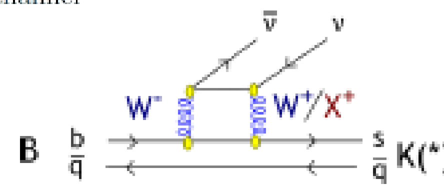
and more…

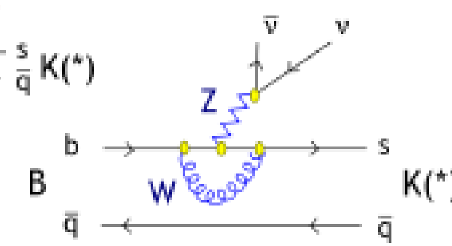
$B \rightarrow K^{(*)} \nu \bar{\nu}$

Current limits



- Standard Model:
  - Flavour changing neutral current prohibited at tree level
  - Measurement of $B \rightarrow K^{(*)} \nu\bar{\nu}$ would allow high accuracy extraction of $B \rightarrow K^{(*)}$ form factors
  - SM estimate of branching fraction known to ~10% uncertainty
- New Physics:
  - Contribution from NP may be similar in size to SM contributions, decreasing time required to make discovery.
  - Light dark matter scenarios:
    - $B \rightarrow K \nu\bar{\nu}$ is identical in the detector to $B \rightarrow K$ + invisible searches for light dark matter
    - Increased $B \rightarrow K \nu\bar{\nu}$ branching ratio may suggest a light dark matter component





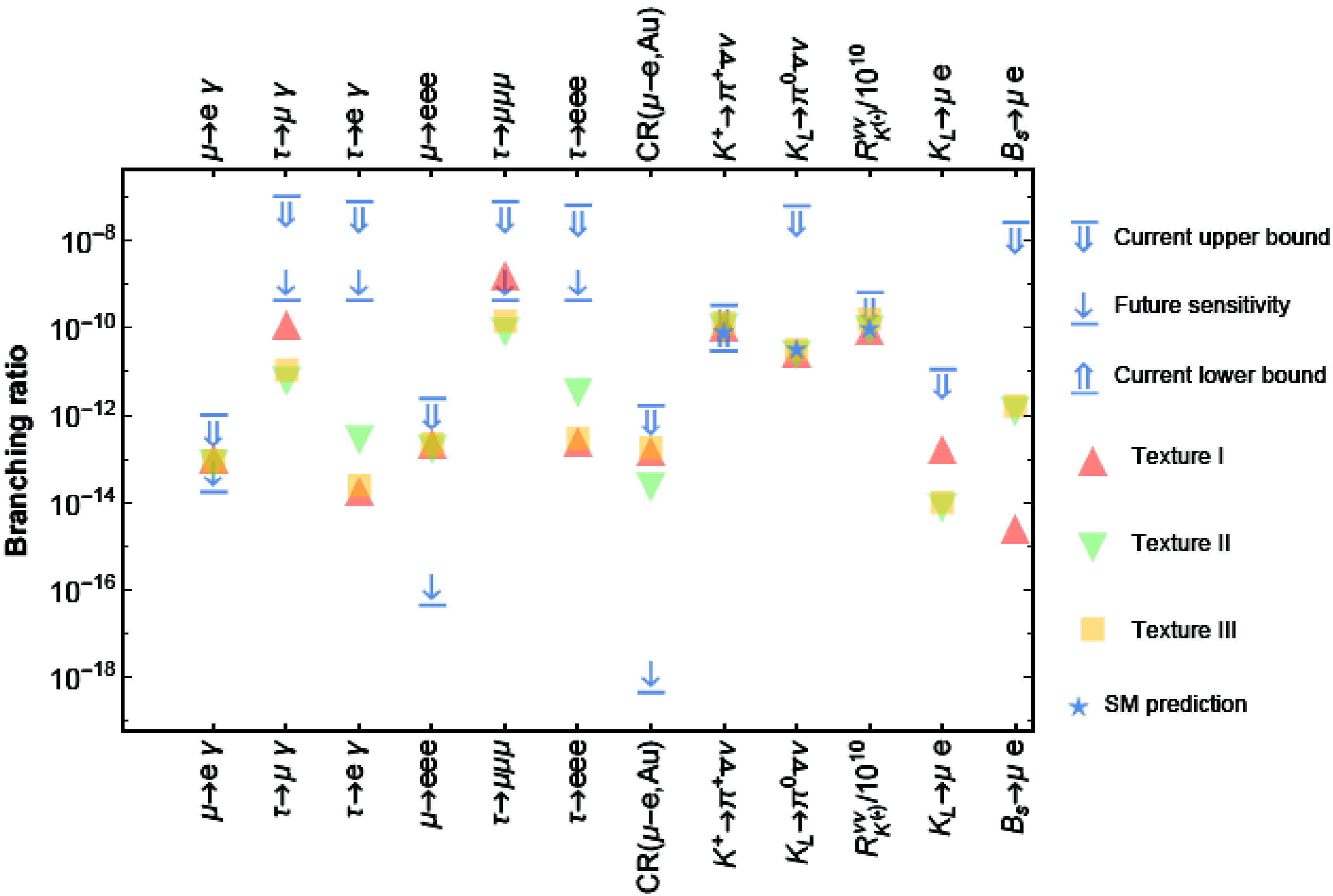
Projected precision on branching ratios at 50 ab^{-1} Belle II data, with FEI hadronic tag

Mode	Stat. uncertainty	Total uncertainty
$B^+ \rightarrow K^+ \nu\bar{\nu}$	9.5%	10.7%
$B^+ \rightarrow K^{*+} \nu\bar{\nu}$	7.9%	9.3%
$B^+ \rightarrow K^{*0} \nu\bar{\nu}$	8.2%	9.6%

Standard model observations of these modes could be made with ~18 ab^{-1}

more observables...

C.Hati et al, arXiv:1806.10146



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

cLFV : beyond the Standard Model

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

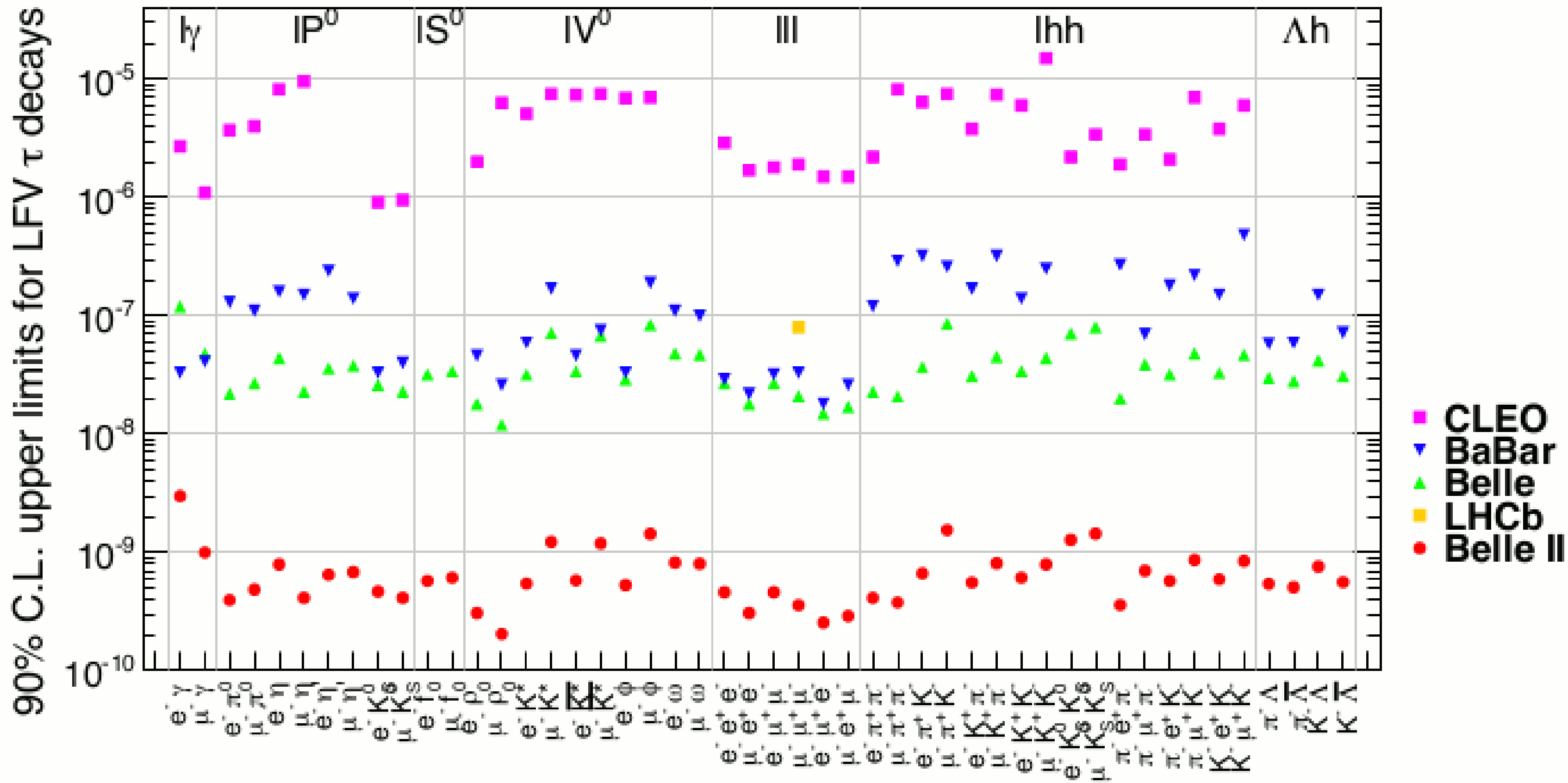
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda}O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}O_i^{(6)} + \ldots$$

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
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}

		$\tau\to 3\mu$	$\tau\to\mu\gamma$	$\tau\to\mu\pi^+\pi^-$	$\tau\to\mu K\bar{K}$	$\tau\to\mu\pi$	$\tau\to\mu\eta^{(\prime)}$
4-lepton	$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
dipole	O_D	✓	✓	✓	✓	–	–
	O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
	O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
	O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
	O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
	$O_{G\tilde{G}}$	–	–	–	–	–	✓

lepton-quark

Celis, Cirigliano, Passemar (2014)

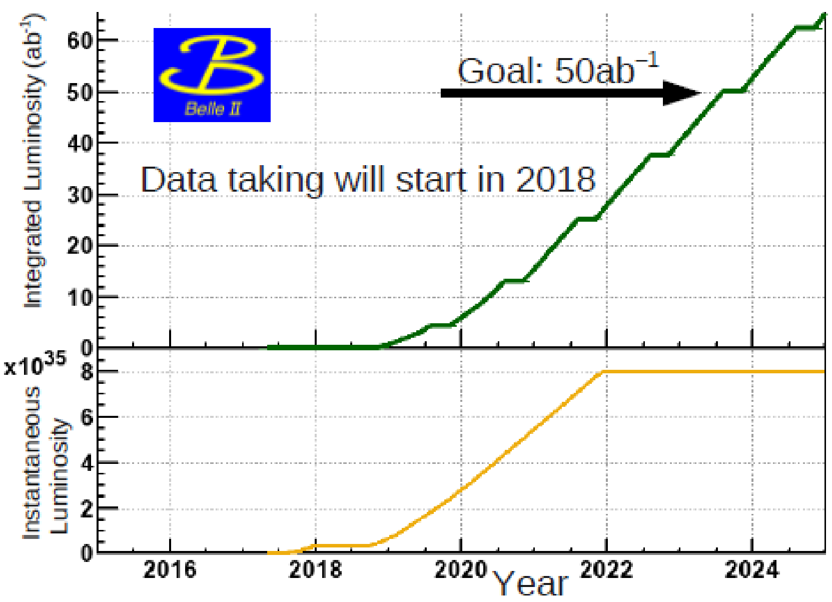


Summary

- Tantalizing results on R_D, R_D^*, R_K, R_K^*
- Belle II has a wide programme of LU tests based on similar ratios
- including B decays with tau in final states,

  as well as searches for LFV decays (including τ, Υ decays)
- Many improvements and new results to come..

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}

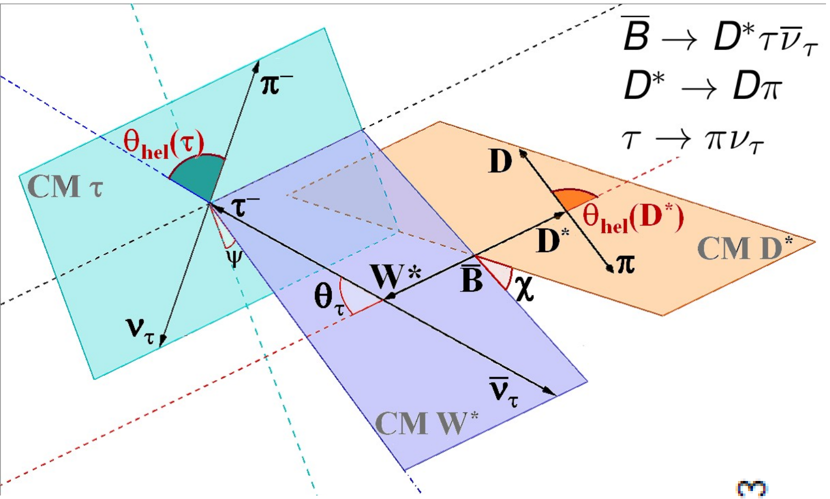


$F_L^{D^*}$ for $B^0 \to D^* \tau \nu$

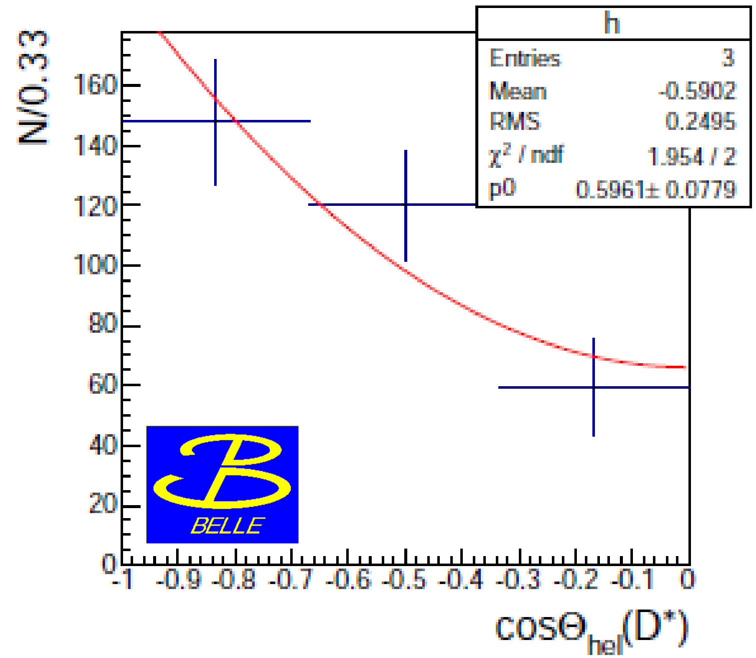
[Belle, preliminary]

Measure $F_L^{D^*}$ from fit to $\cos\theta_{hel}(D^*)$ distribution:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{hel}(D^*)) + (1 - F_L^{D^*})\sin^2(\theta_{hel}(D^*))]$$



- Employ **inclusive** B_{tag} reconstruction method
- Select clean decay chains:
  $B^0 \to D^{*-}(\to \overline{D^0}\pi^-)\tau^+\nu$;
  $D^0 \to K\pi, K\pi\pi^0, K\pi\pi\pi$;
  $\tau \to e\nu\nu; \mu\nu\nu; \pi\nu$



Number of events in:
I bin: 151 ± 21
II bin: 125 ± 19
III bin: 55 ± 15
- signal yields corrected for accaptance variations

Dominant systematics:
- MC statistics (AR shape and peaking backgroud) $= \pm 0.03$

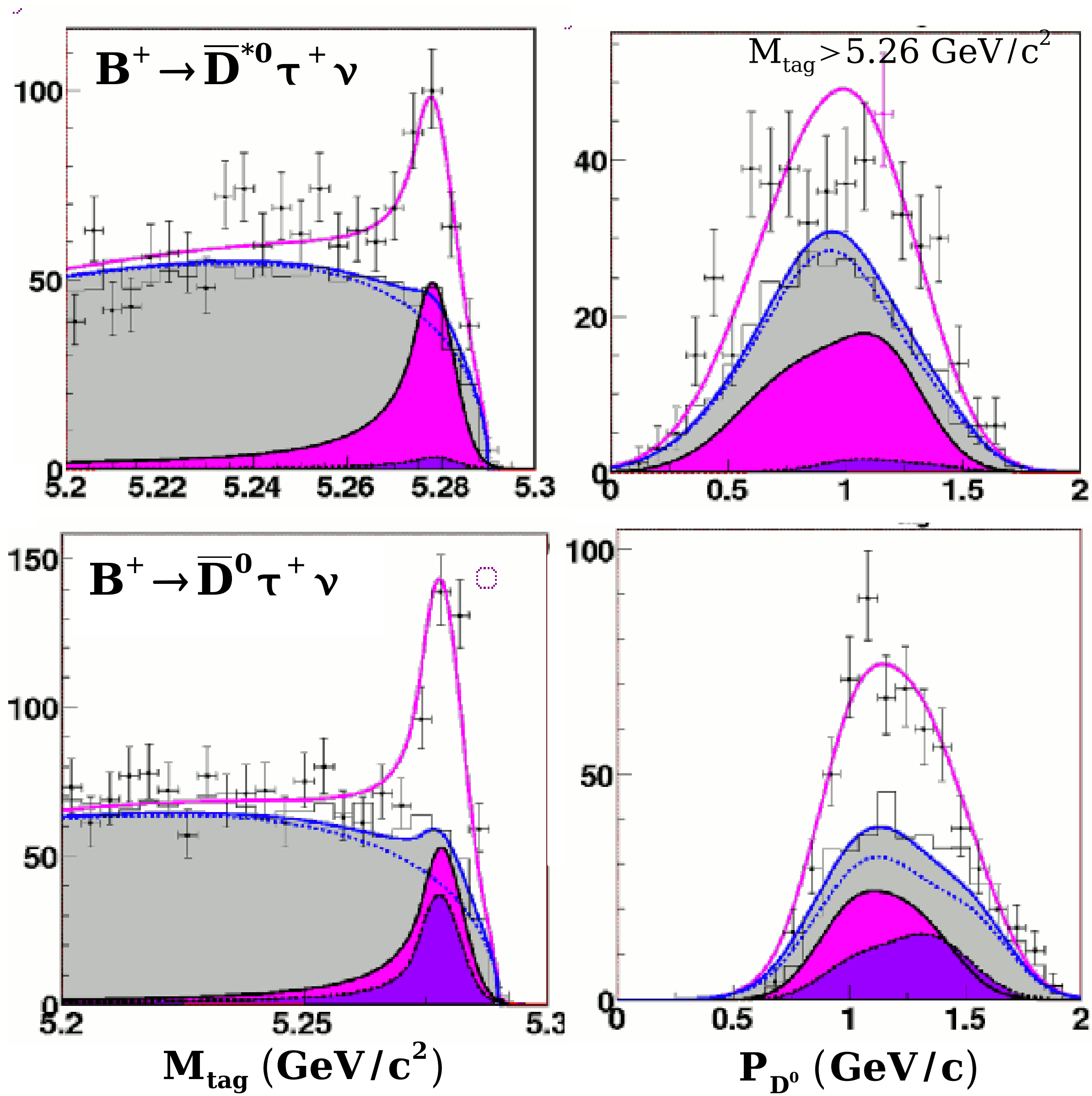
$$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$$

SM: $F_L^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D **95**, 115038 (2017), A.K. Alok, et al) ($1.5\ \sigma$)

SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) ($1.8\ \sigma$)

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

PRD 82, 072005 (2010)
arXiv:1005.2302



- 657M $B\overline{B}$
- same method than for $B^0 \to D^{*-} \tau^+ \nu$

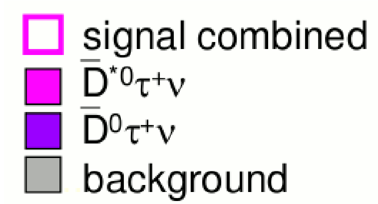
B_{sig}:

$D^0 \to K\pi,\ K\pi\pi^0$

$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau,\ \mu^+ \nu_\mu \bar{\nu}_\tau,\ \pi^+ \bar{\nu}_\tau,\ \rho^+ \bar{\nu}_\tau$

13 different decay chains

B_{tag}: all remaining particles



First $B^+ \to \overline{D}^0 \tau \nu$ evidence !

	N_S	$\mathcal{B}(\%)$	$\Sigma(\sigma)$
$B^+ \to \overline{D}^{*0} \tau^+ \nu$	446^{+58}_{-56} (226)	$2.12^{+0.28}_{-0.27} \pm 0.29$	8.1
$B^+ \to \overline{D}^{0} \tau^+ \nu$	146^{+42}_{-41} (15)	$0.77 \pm 0.22 \pm 0.12$	3.5

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

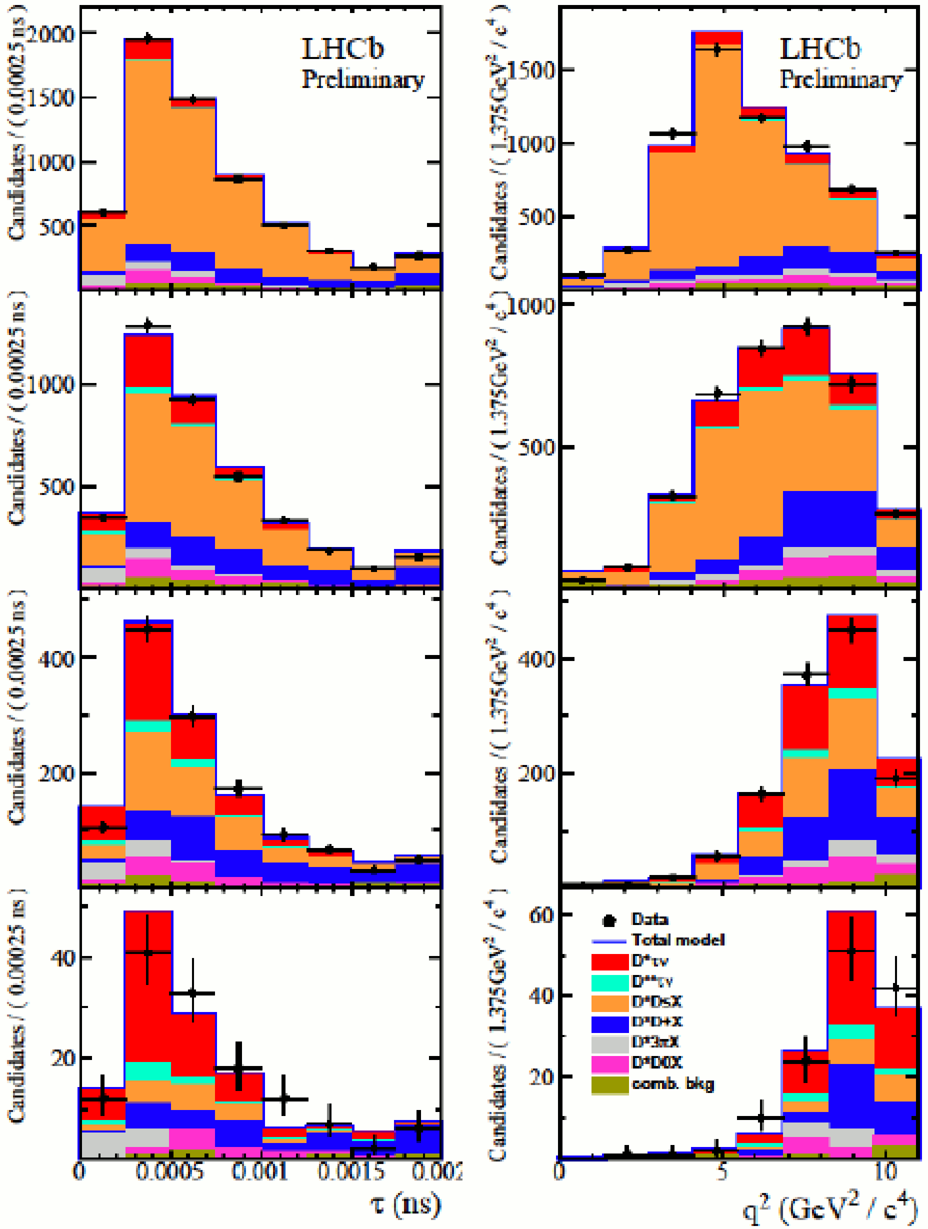
$\tau \to 3\pi(\pi^0)$

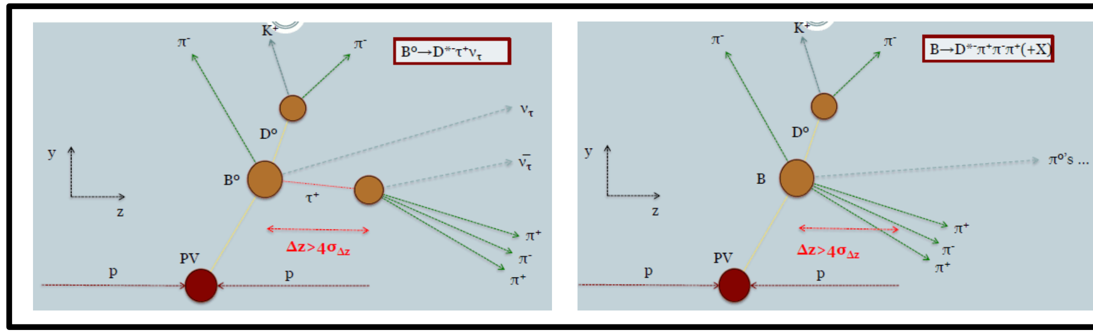
[LHCb-PAPER-2017-017]

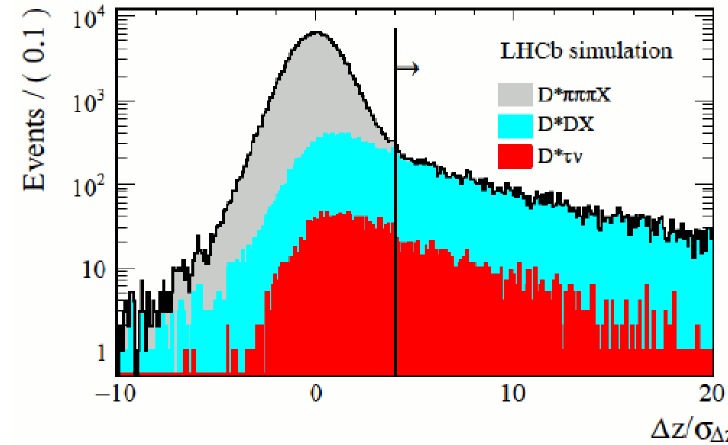
need a strong background suppression:

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

$\Rightarrow$ detached vertex method







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

anti-D_s

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

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

$B \to D D_{s(J)} X$

$X_b \to D D X$

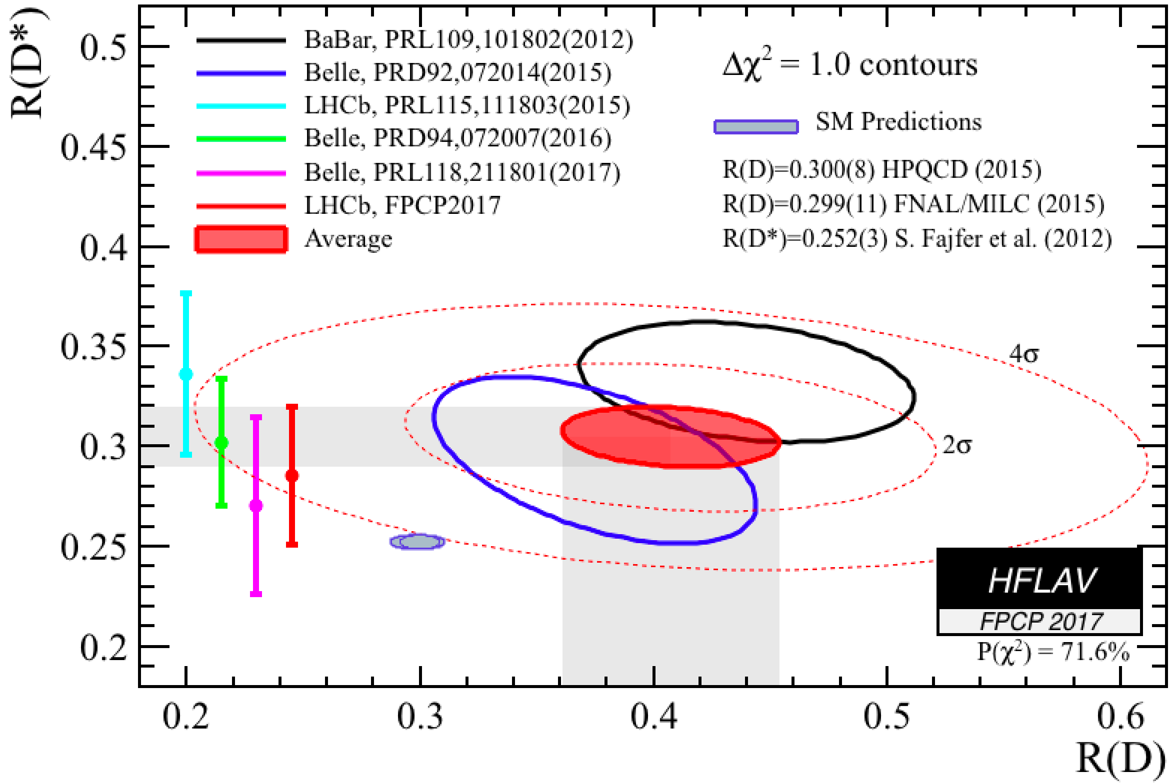
(relative) yields constrained from control samples

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

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

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

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



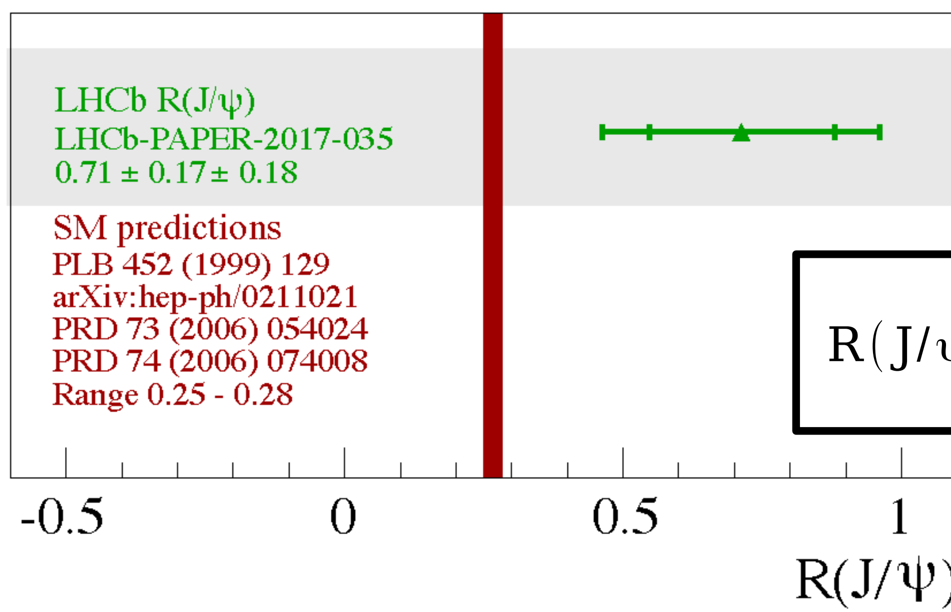
$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

$R(D) = 0.407 \pm 0.039 \pm 0.024$

$R(D^*) = 0.304 \pm 0.013 \pm 0.007$

difference with SM predictions is at **4.1σ** level

$B_c \to J/\psi \tau \nu$



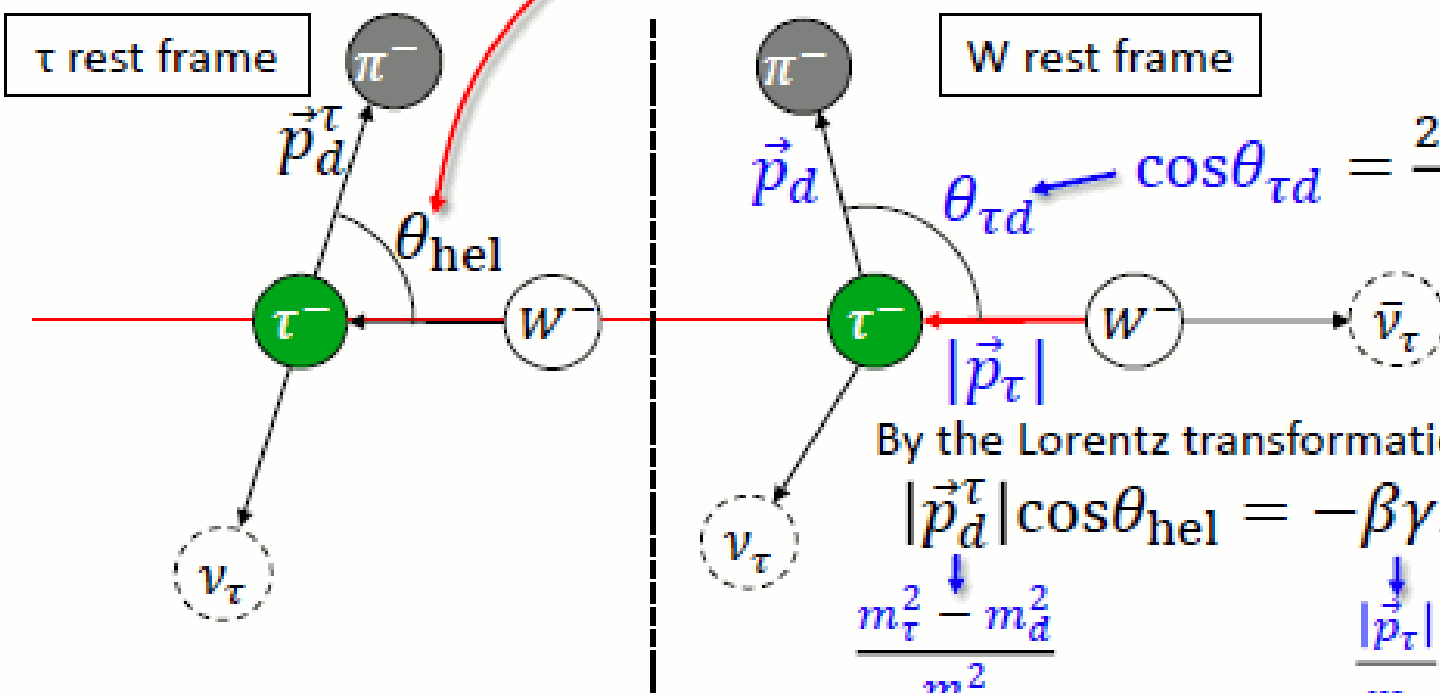
$$R(J/\psi) = \frac{BF(B_c \to J/\psi \tau \nu_\tau)}{BF(B_c \to J/\psi l \nu_l)}$$

Belle Collaboration, Phys. Rev. Lett. 118, 211801 (2017)

■ $P_\tau(D^*)$ Measurement Method

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{1}{2}\left(1 + \alpha P_\tau(D^*)\cos\theta_{\mathrm{hel}}\right)$$

$$\alpha = \begin{cases} 1 & \text{for } \tau^- \to \pi^-\nu_\tau \\ \sim 0.45 & \text{for } \tau^- \to \rho^-\nu_\tau \end{cases}$$



$$\cos\theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_d|}$$

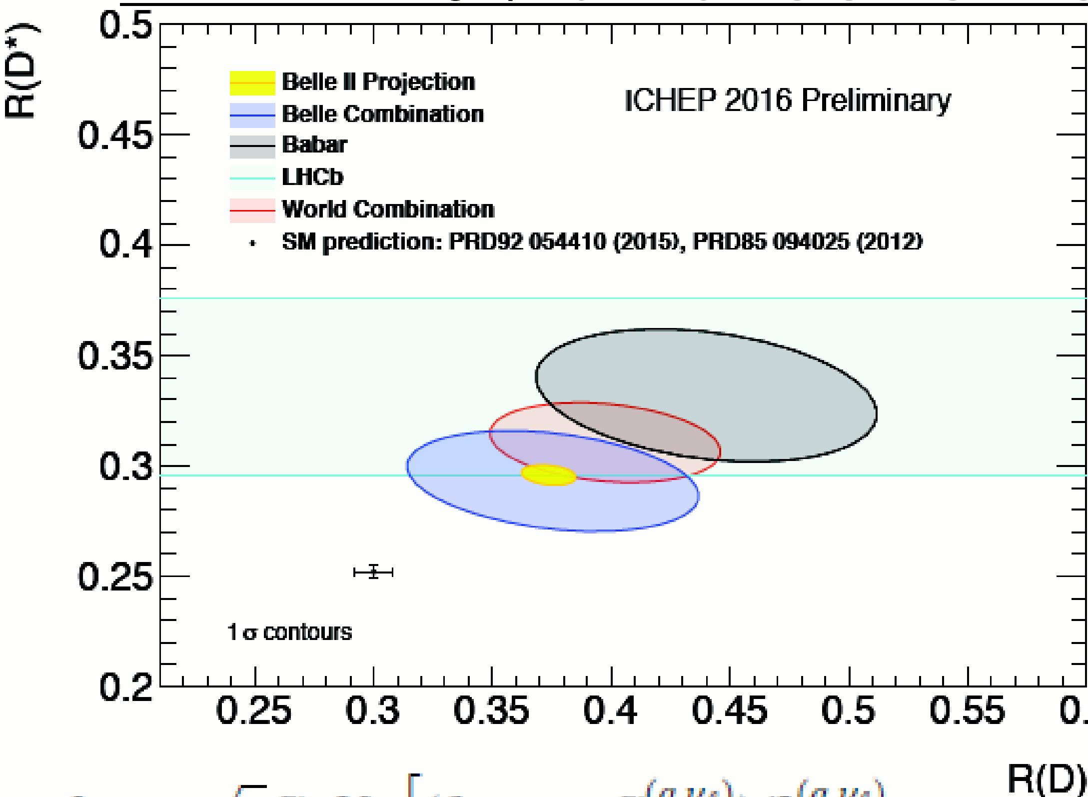
By the Lorentz transformation,

$$|\vec{p}_d^{\,\tau}|\cos\theta_{\mathrm{hel}} = -\beta\gamma E_d + \gamma|\vec{p}_d|\cos\theta_{\tau d}$$

$$\frac{m_\tau^2 - m_d^2}{m_\tau^2} \qquad \frac{|\vec{p}_\tau|}{m_\tau} \qquad \frac{E_\tau}{m_\tau}$$

Solving the equation, $\cos\theta_{\mathrm{hel}}$ is obtained

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

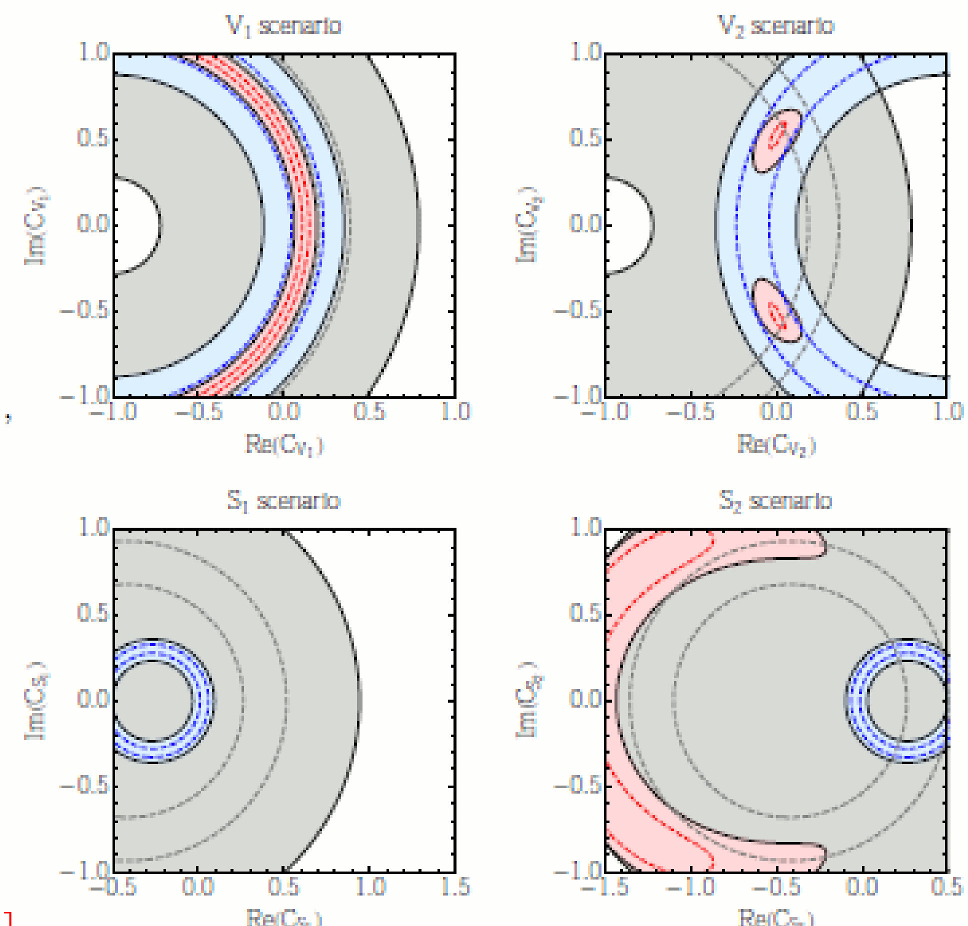


$$R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}, \text{ in red}$$

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

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

Dashed: Belle II



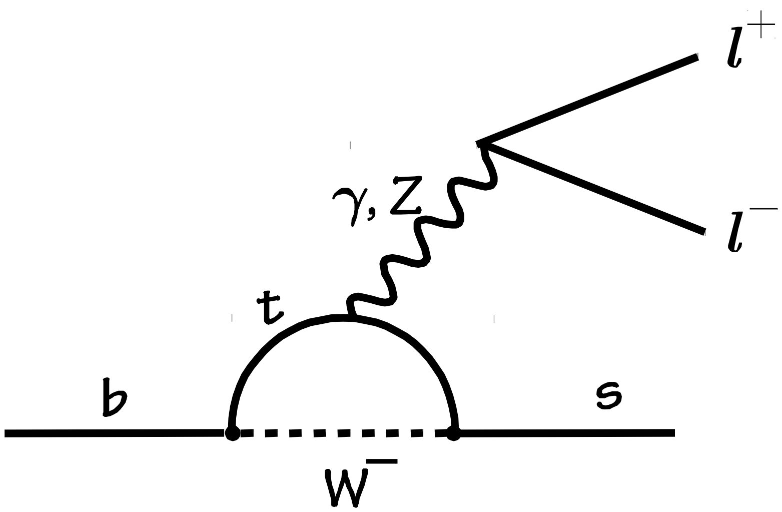
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{qb} \Big[(\delta_{\nu_\tau,\nu_\ell} + C_{V_1}^{(q,\nu_\ell)}) \mathcal{O}_{V_1}^{(q,\nu_\ell)} + \sum_{X=}^{V_2,S_1,S_2,T} C_X^{(q,\nu_\ell)} \mathcal{O}_X^{(q,\nu_\ell)} \Big],$$

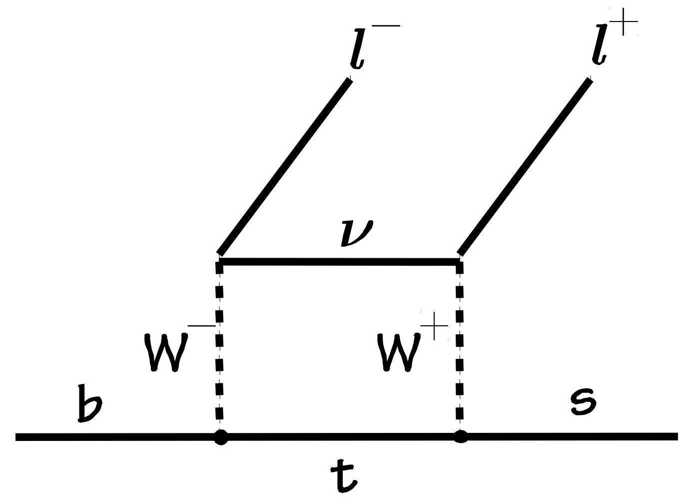
where the four-Fermi operators:

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

[Details in Watanabe et al, B2TiP theory]

$b \rightarrow s\, l^+ l^-$





$\Rightarrow$ 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...

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

Lepton flavor universality (LFU)

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

Universality in neutral current interactions

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

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...

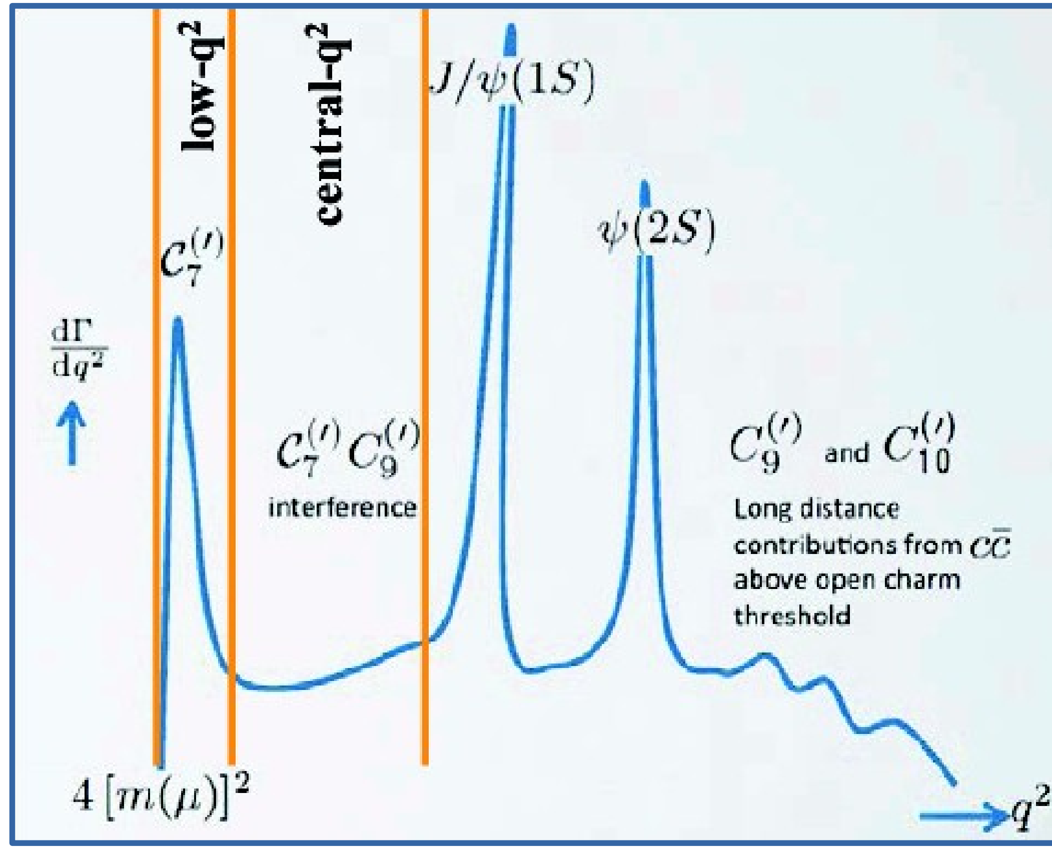
Test of LFU with $B \to K^{*0}\mu\mu$ and $B \to K^{*0}ee$, $R_{K^{*0}}$

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

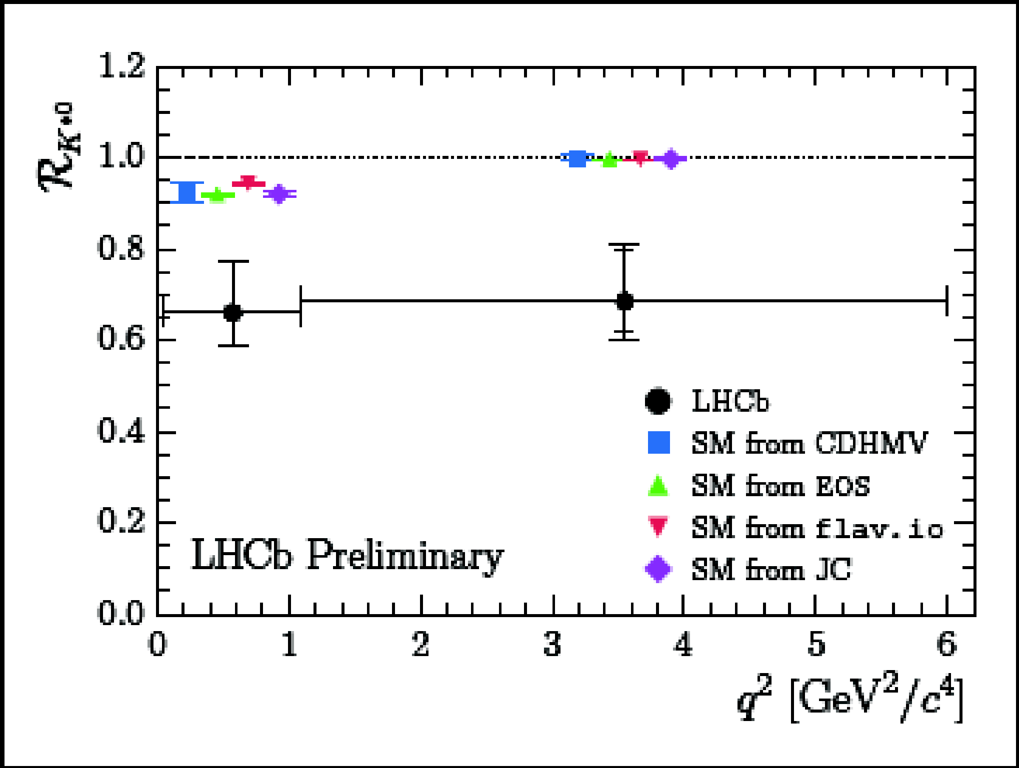
$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \frac{\alpha_e}{4\pi} \sum \left[C_i \mathcal{O}_i + C_i' \mathcal{O}_i'\right]$$

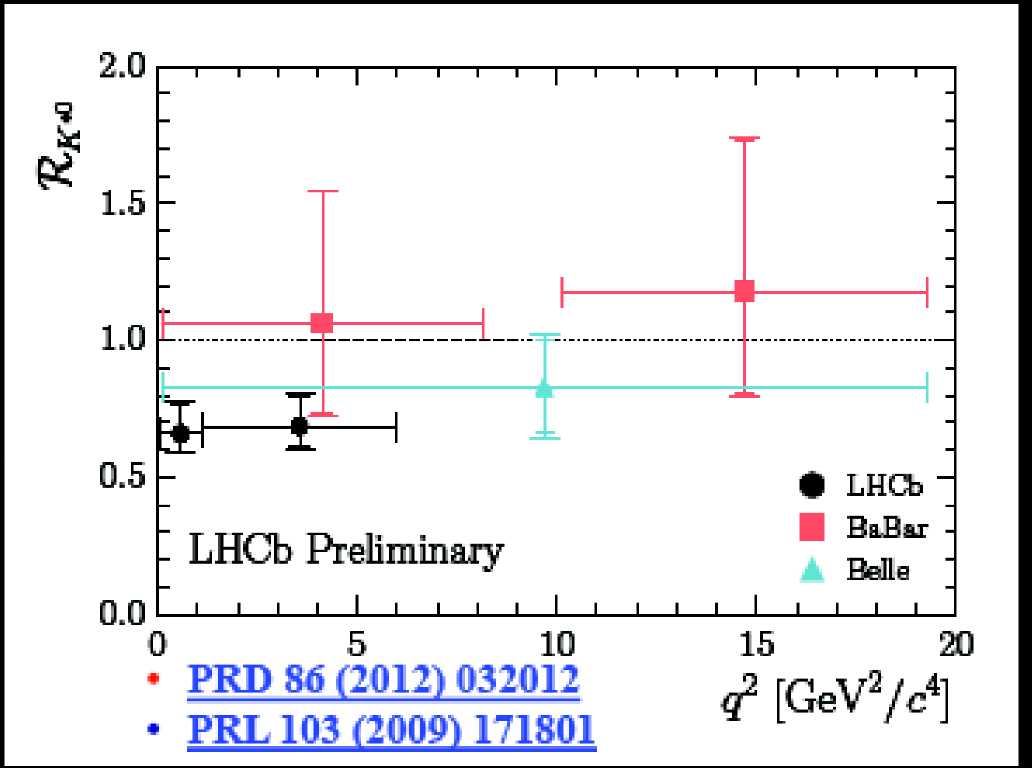


- Measured relative to $B^0 \to K^{*0} J/\psi(ll)$ in order to reduce systematics

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

Results

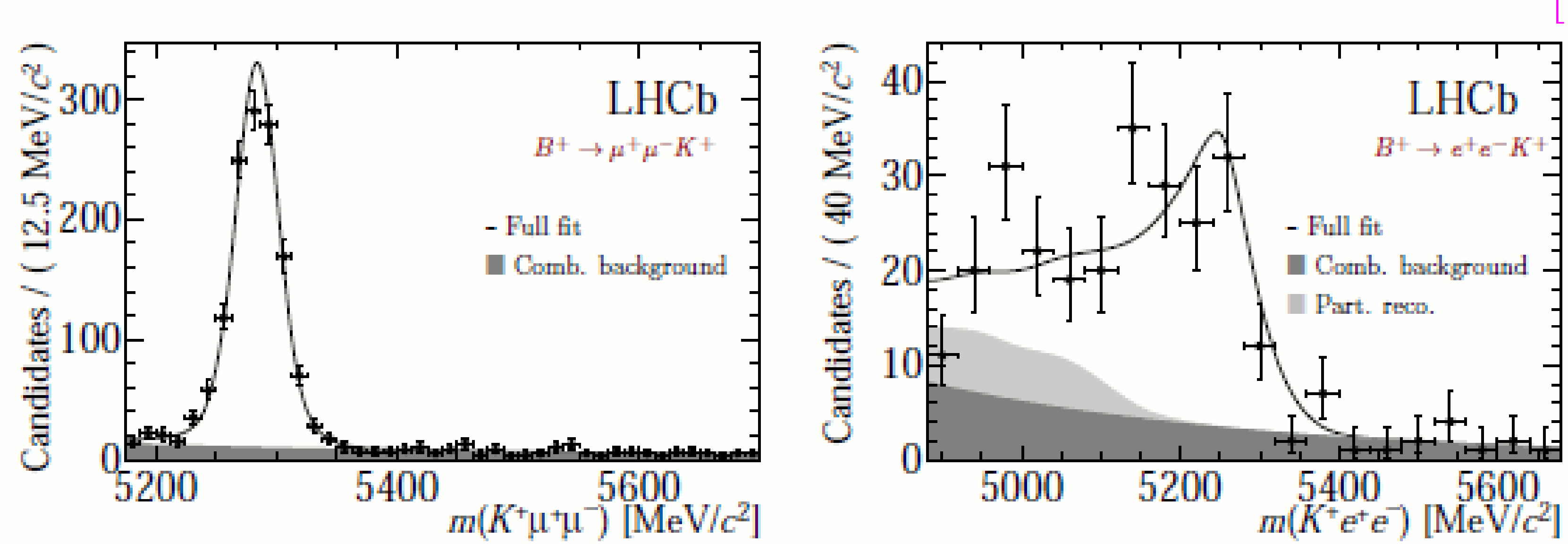




- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

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

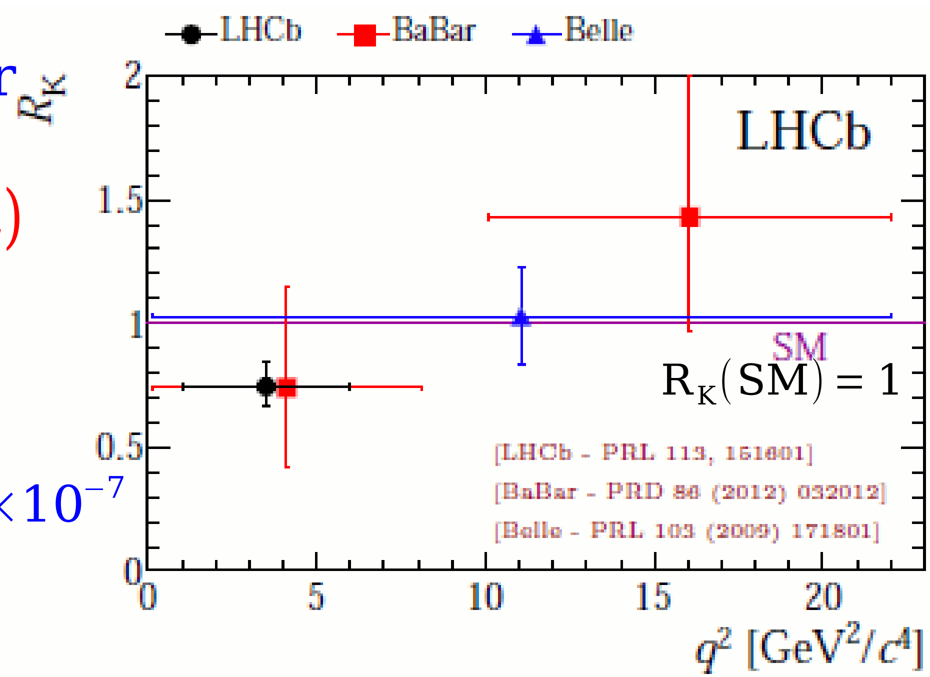
R_K: ratio of branching fractions for dilepton invariant mass squared range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

- 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

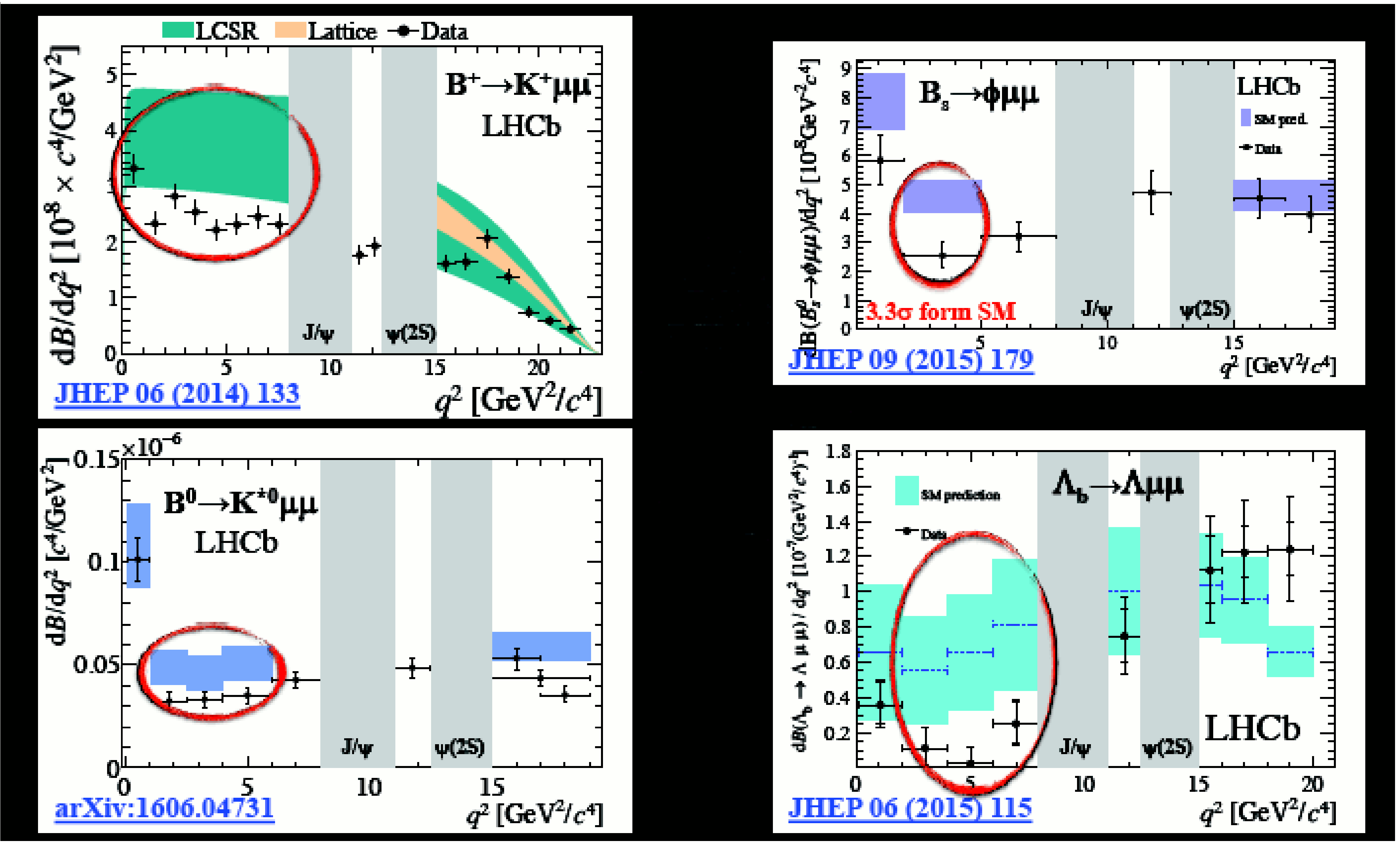
$\Rightarrow$ $B(B^+ \to e^+ e^- K^+) = (1.56\,^{+0.19}_{-0.15}(\text{stat})\,^{+0.06}_{-0.05}(\text{syst})) \times 10^{-7}$ compatible with SM predictions



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

Differential Branching Fractions

Results consistently lower than SM predictions



Should we believe LFU violation?

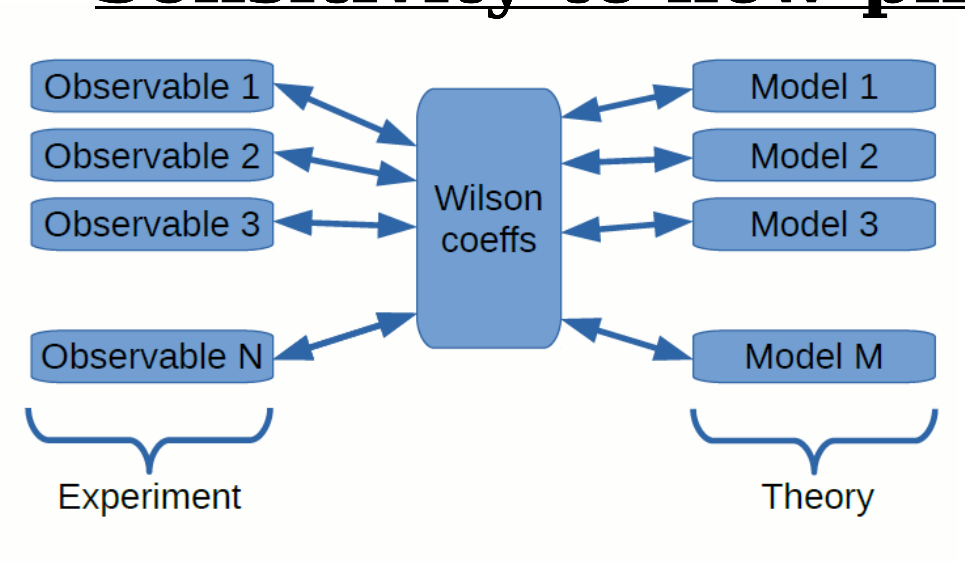
Yes

- R measurements are double ratio's to J/ψ, check with $K^* J/\psi \rightarrow e^+e^-/\mu^+\mu^-$ $=1.043\pm0.006\pm0.045$
- $\mathcal{B}(B^-\rightarrow K^-e^+e^-)$ 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

Sensitivity to new physics in rare B decays



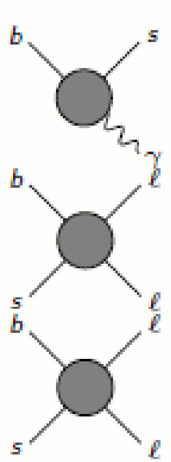
M.Ciuchini et al, arXiv:1512.07157
T.Hurth et al, arXiv:1603.00865
S.Descotes-Genon et al, arXiv:1510.04239...

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

- Model-independent description in effective field theory

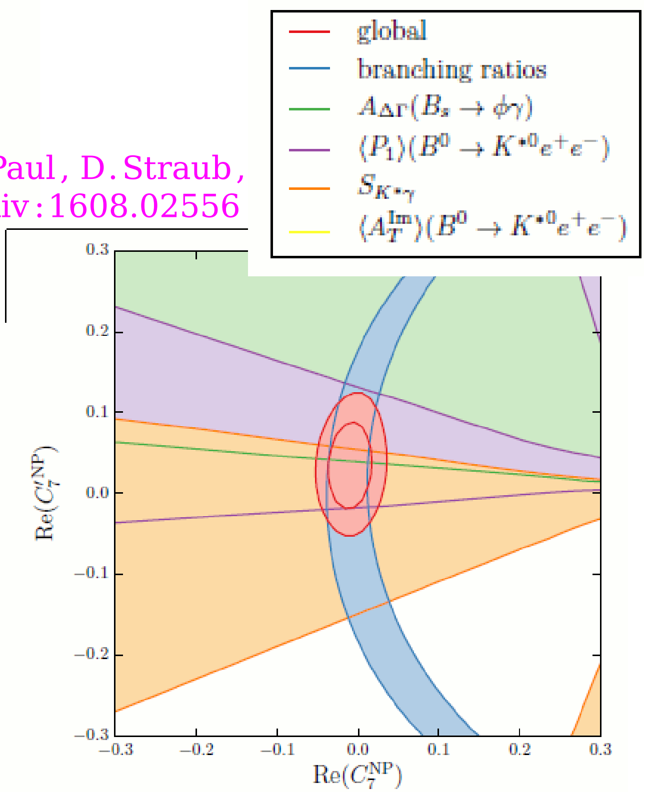
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V^*_{\rm ts} \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

- 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		✓	

A.Paul, D.Straub,
arXiv:1608.02556



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

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

$$f = e, u, d$$

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

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 not diagonal: they must be diagonalized to get the mass eigenstates and eigenvalues

Biunitary transformations

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

gauge eigenstates

mass eigenstates

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:

$$
\begin{aligned}
\mathcal{L}_{\rm kin} \supset\ & \bar{\ell}_L \left(g\frac{\vec{\tau}}{2}\vec{W}_\mu - \frac{g'}{2}B_\mu \right)\gamma^\mu \ell_L + \bar{q}_L \left(g\frac{\vec{\tau}}{2}\vec{W}_\mu + \frac{g'}{6}B_\mu \right)\gamma^\mu q_L \\
& -\bar{e}_R g' B_\mu \gamma^\mu e_R + \bar{u}_R \frac{2}{3} g' B_\mu \gamma^\mu u_R - \bar{d}_R \frac{1}{3} g' B_\mu \gamma^\mu d_R \\
& = \underbrace{g J^1_\mu W^{1\mu} + g J^2_\mu W^{2\mu}}_{\text{Charged current}} + \underbrace{g J^3_\mu W^{3\mu} + g' J^Y_\mu B^\mu}_{\text{Neutral current}}
\end{aligned}
$$

The neutral current

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

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

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

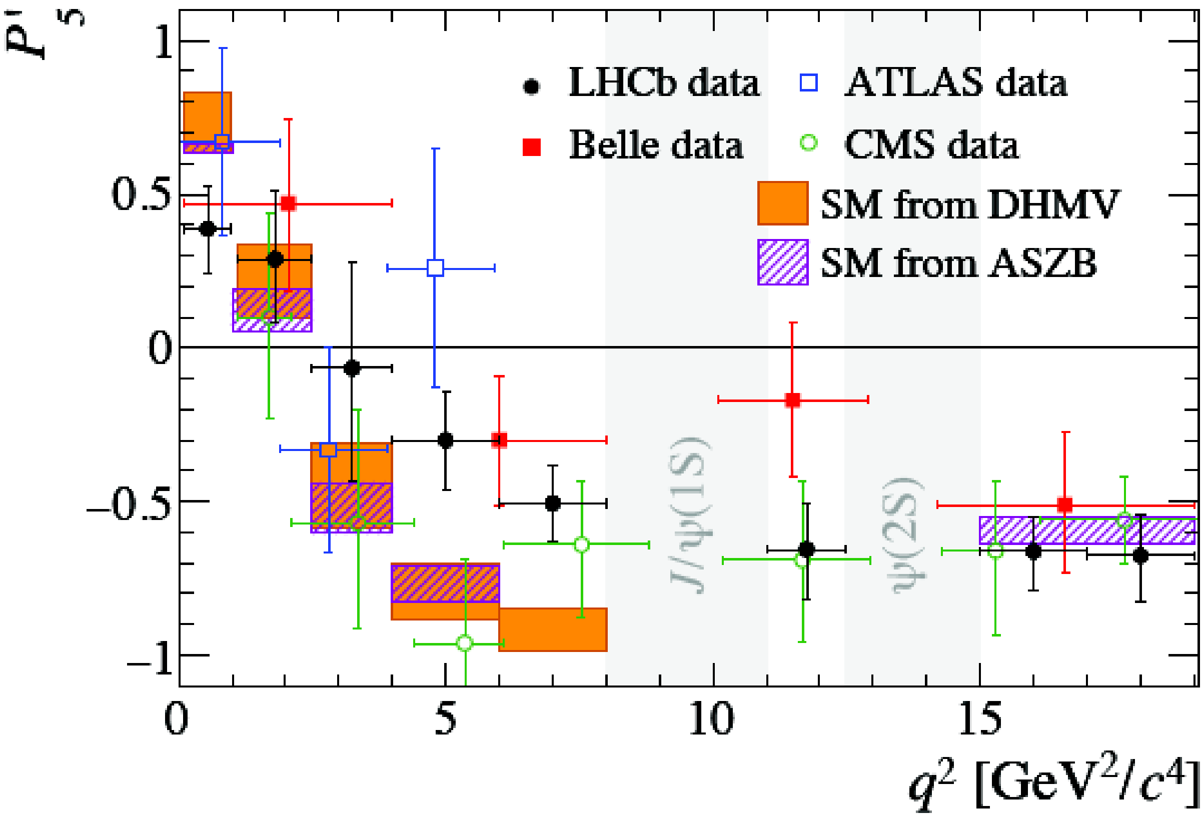
There are no flavor changing neutral currents (FCNC) at tree-level

$Z \not\to \overline{u}c$ 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 charm quark.

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

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

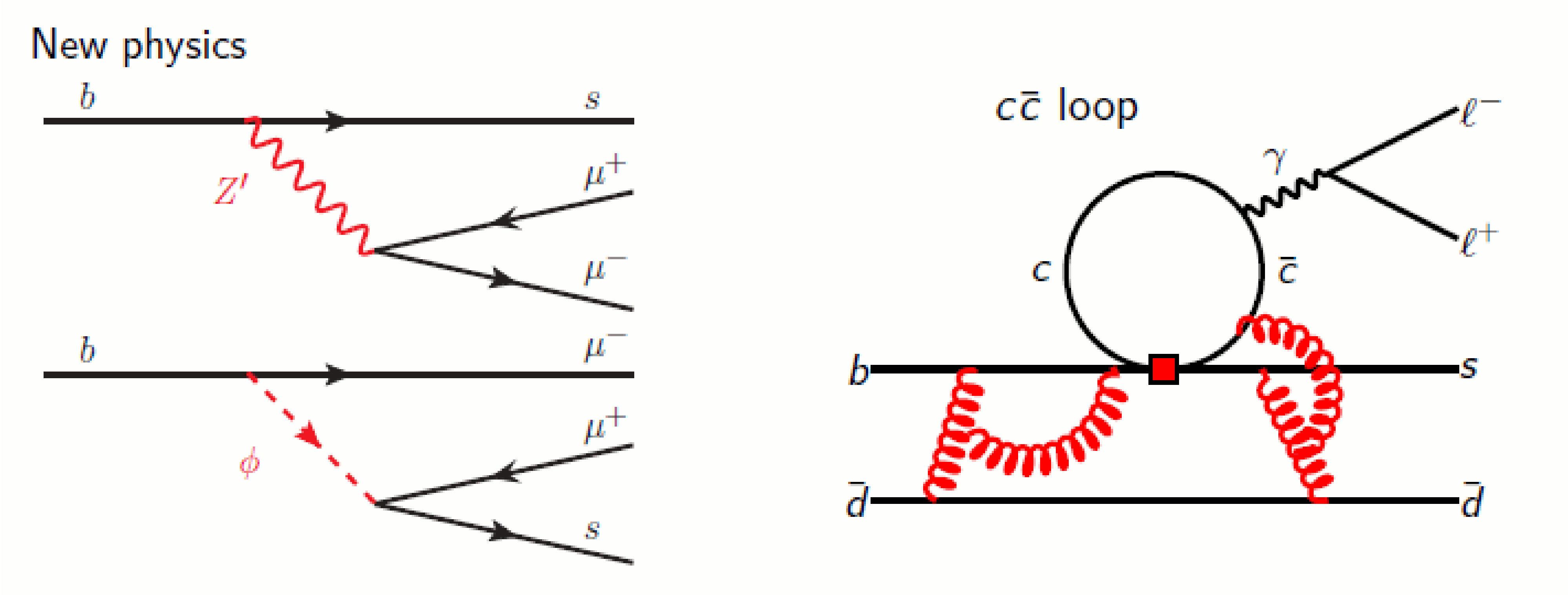
NP or hadronic effect ?

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**



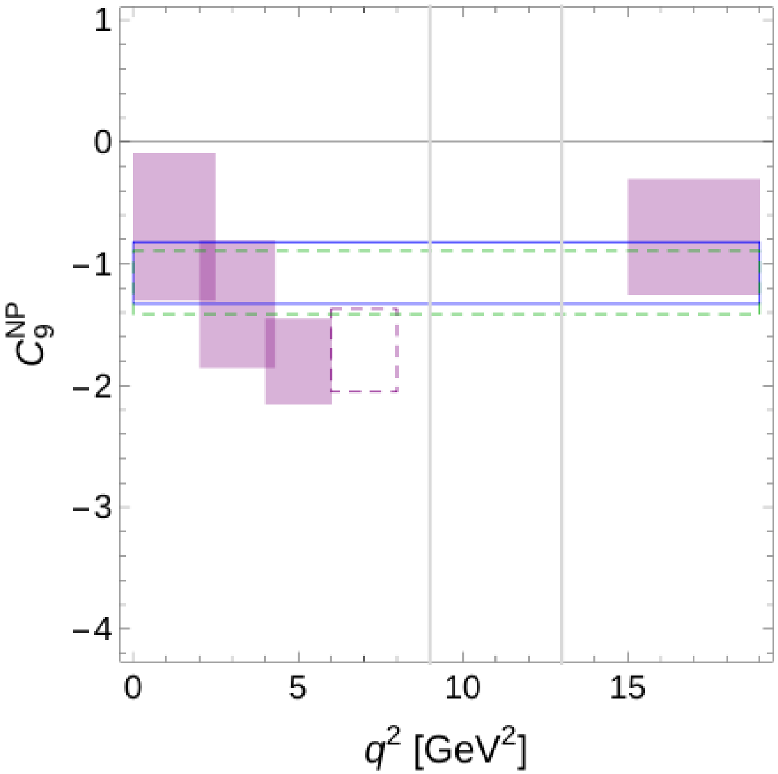
NP e.g. Z', leptoquarks

hadronic charm loop contributions

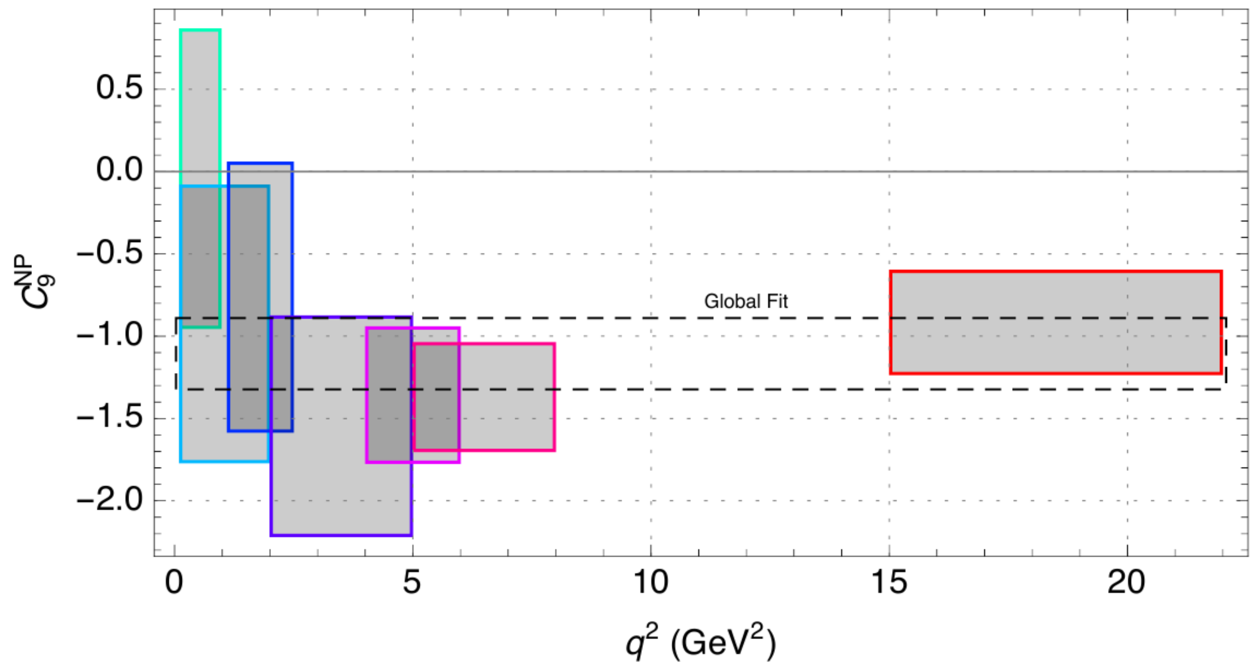
NP or hadronic effect ?

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]



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

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

$\Rightarrow$ definitely need more stat.