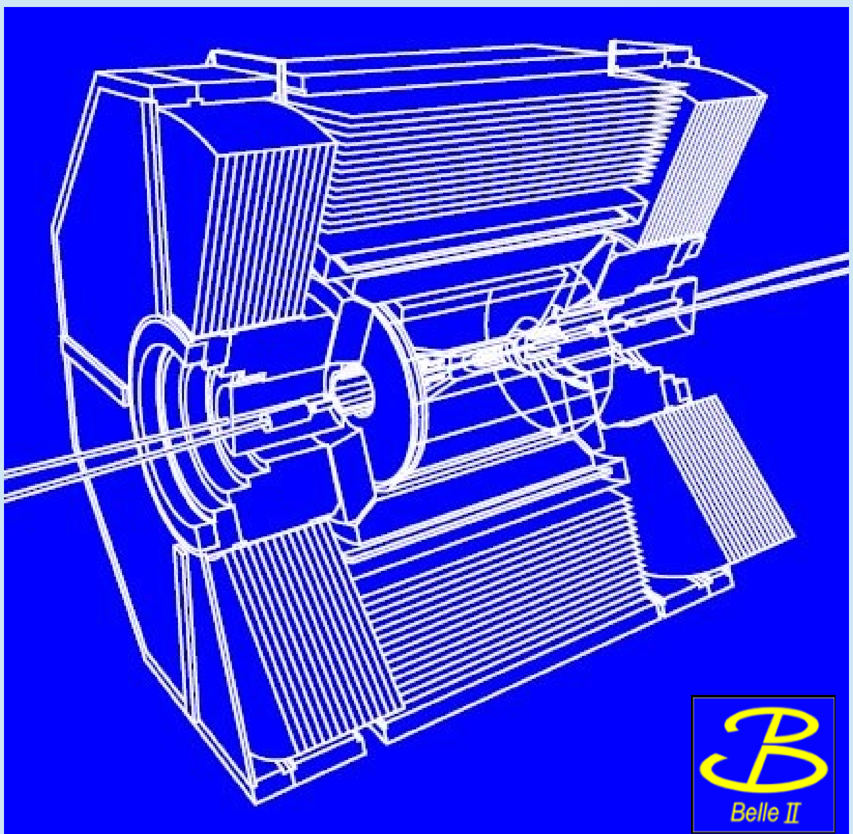
$b \to s \tau^+ \tau^-$ and LFV B and τ decays Perspectives at Belle II

Karim Trabelsi
karim.trabelsi@lal.in2p3.fr



Outline

- Belle II and phase 3
- Anomalies in $B \to D^{(*)} \tau \nu$ and $b \to s l^+ l^-$
- **$b \to s l^+ l^-$, $l = e, \mu, \tau$**
- **LFV B and τ decays**

2019/11/04

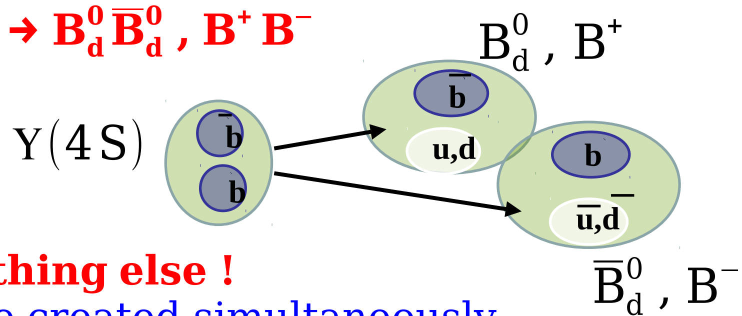
Belle II, a flavour-factory, a rich physics program...

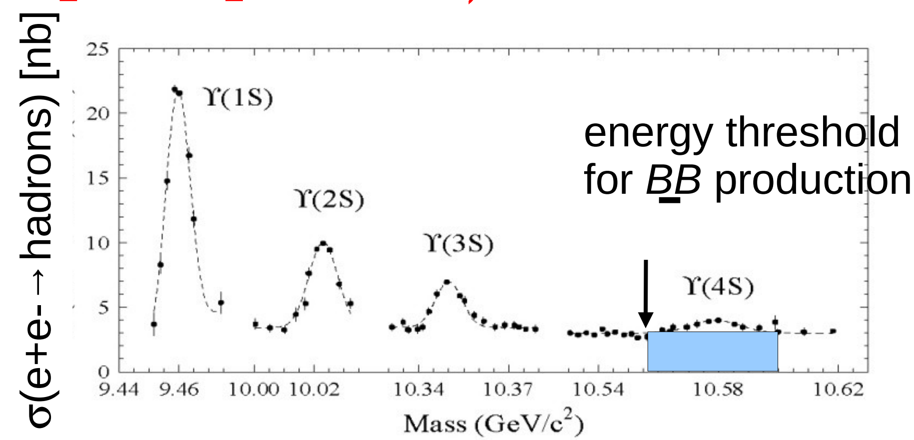
- We plan to collect (**at least**) 50 ab^{-1} of e^+e^- collisions at (or close to) the $\Upsilon(4S)$ resonance, so that we have:

  – **a (Super) B-factory ($\sim 1.1 \times 10^9$ $B\overline{B}$ pairs per ab^{-1})**

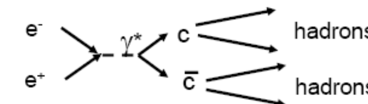
"on resonance" production

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





- **2 B's and nothing else !**
- 2 B mesons are created simultaneously in a L=1 coherent state



  – **a (Super) charm factory ($\sim 1.3 \times 10^9$ $c\overline{c}$ pairs per ab^{-1})**

  – **a (Super) τ factory ($\sim 0.9 \times 10^9$ $\tau^+\tau^-$ pairs per ab^{-1})**

  – with Initial State Radiation, effectively scan the range [0.5 – 10] GeV and measure the $e^+e^- \rightarrow$ light hadrons cross section very precisely

  – exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ...

SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (p-p)

Phase 1

Background , Optics commissioning

Feb - June **2016**

Brand new 3 km positron ring

Phase 2: Pilot run

Superconducting Final Focus

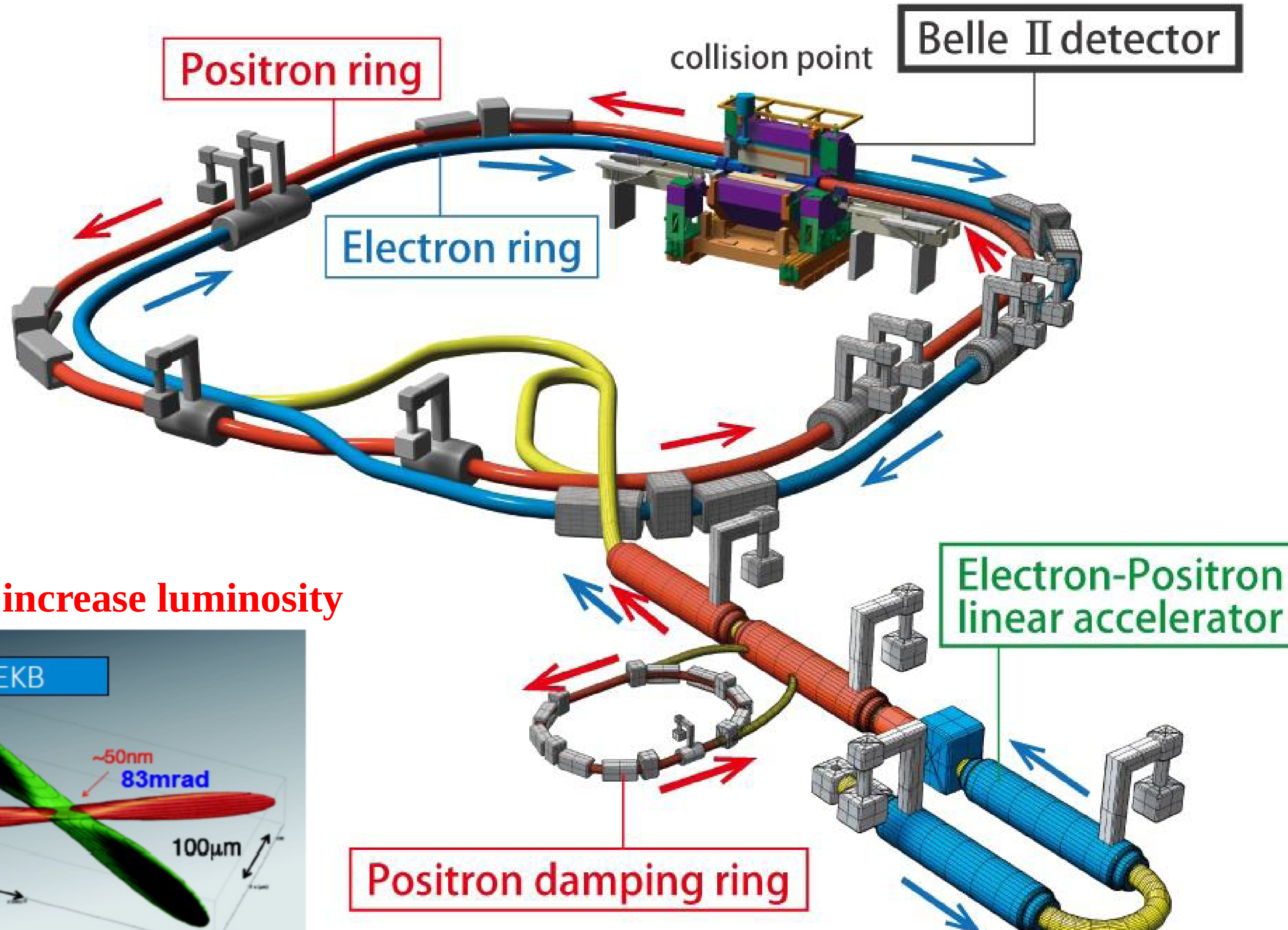
add positron damping ring

First Collisions $(0.5\ \text{fb}^{-1})$

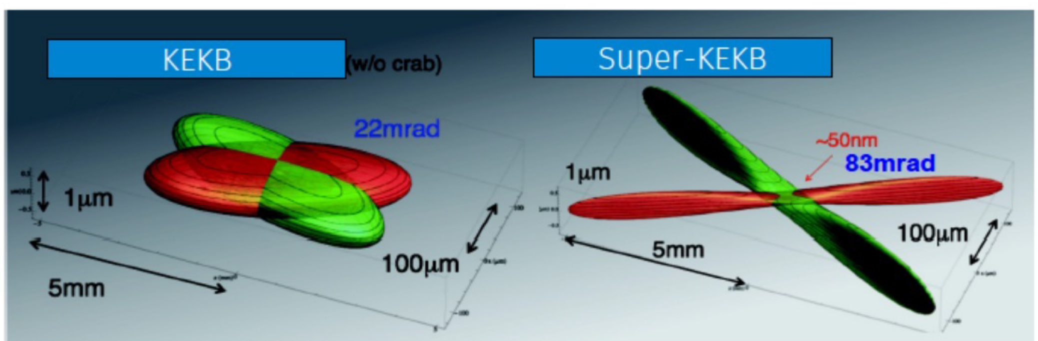
April 27 - July 17, **2018**

Phase 3: Physics run

March 27 - June 30, **2019**



Nano-beams and more beam current to increase luminosity



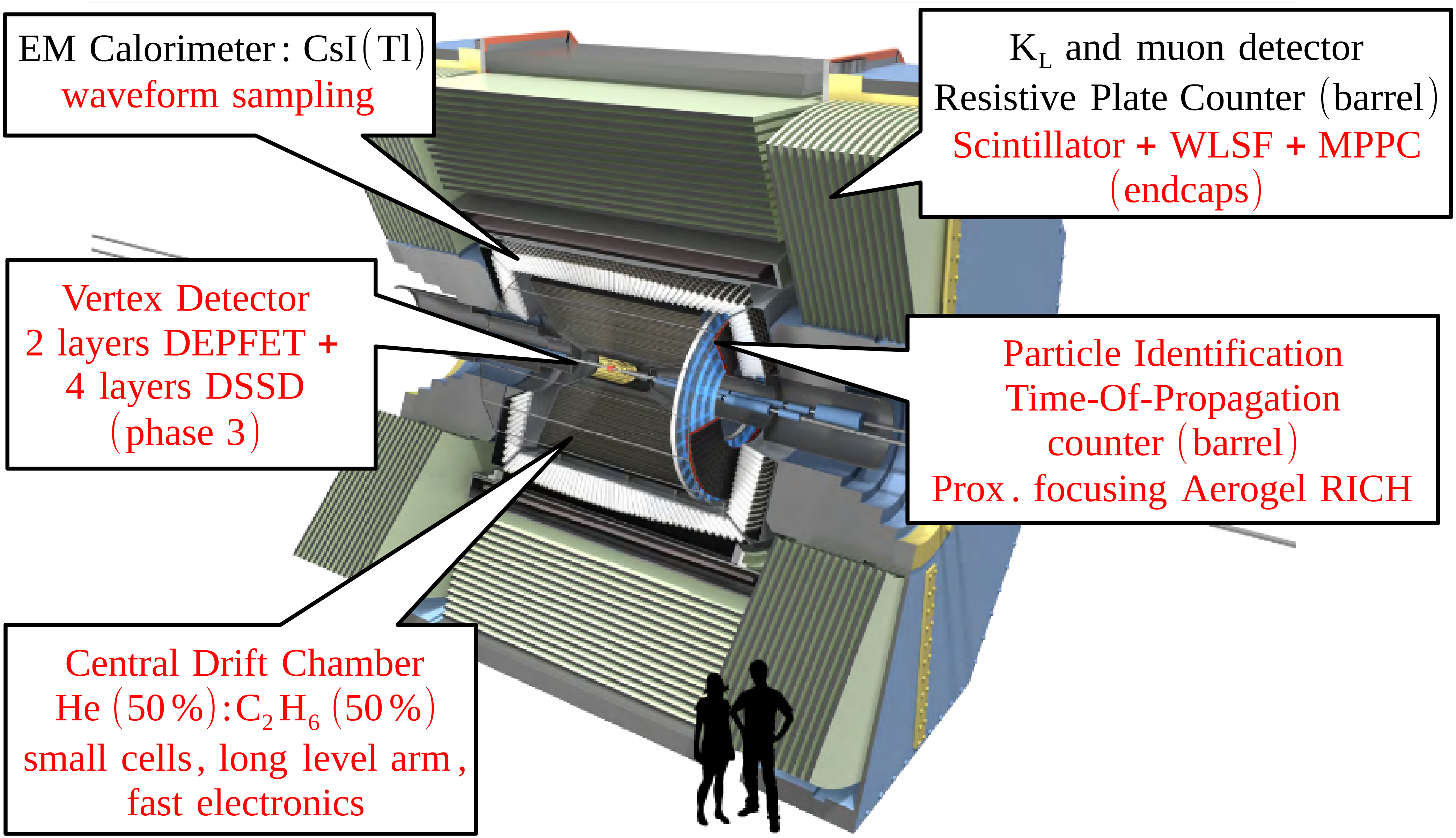
	E (GeV) LER/HER	β*ᵧ (mm) LER/HER	β*ₓ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10³⁴
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10³⁴

factor 20 factor 2-3

⇒ to reach $8 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$

⇒ cumulate 50 ab^{-1} by ~2027

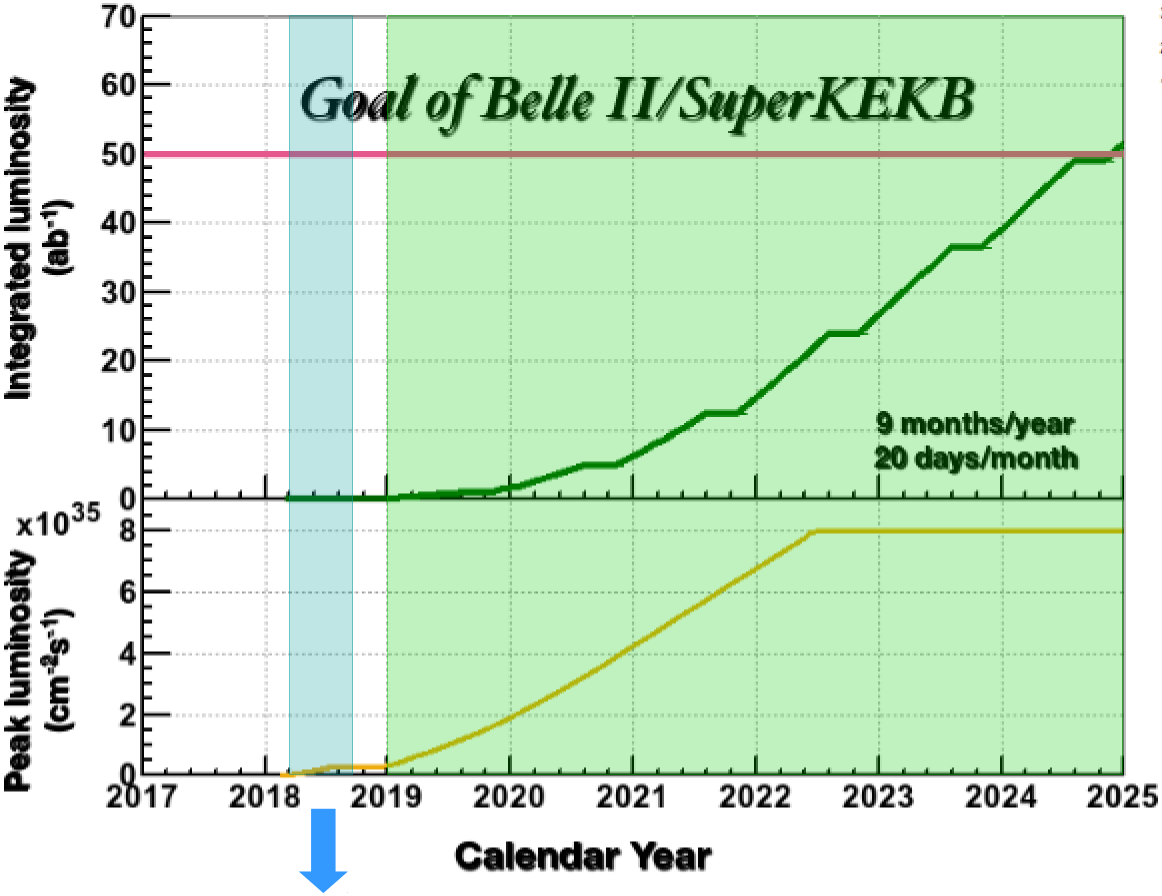
Belle II detector



phase 2 → phase 3

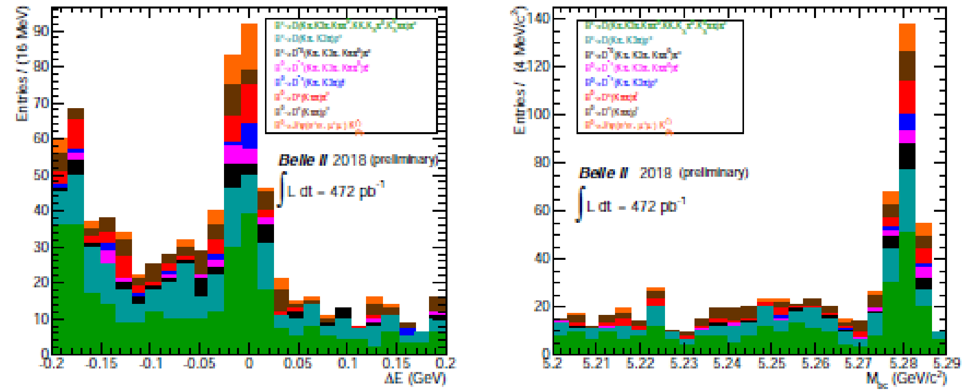
Phase2, BEAST II
collision + partial Belle II

Phase3, physics run

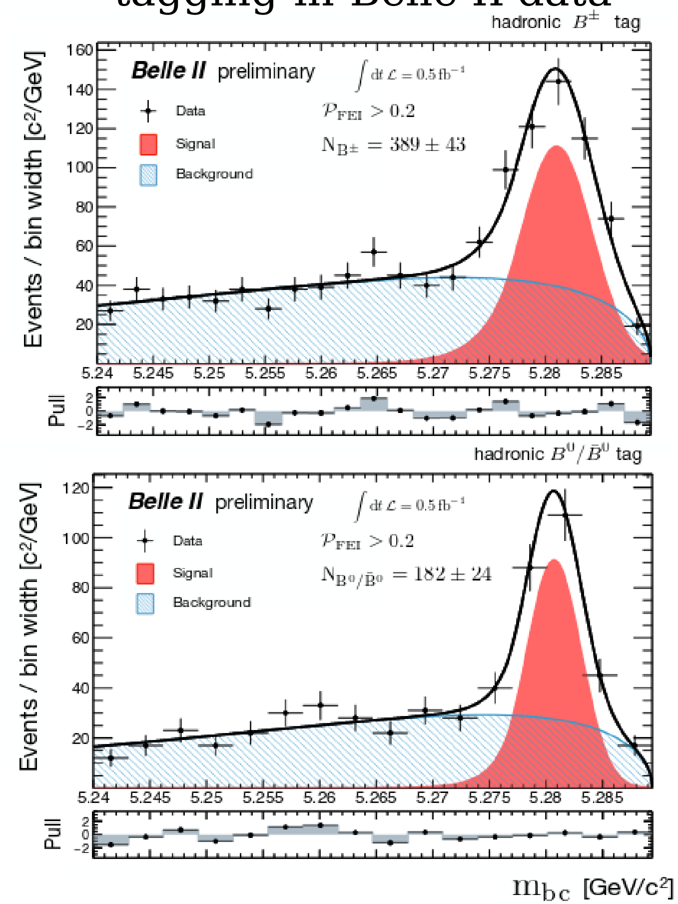


First collisions May to July
$\sim 500\ \text{pb}^{-1}$

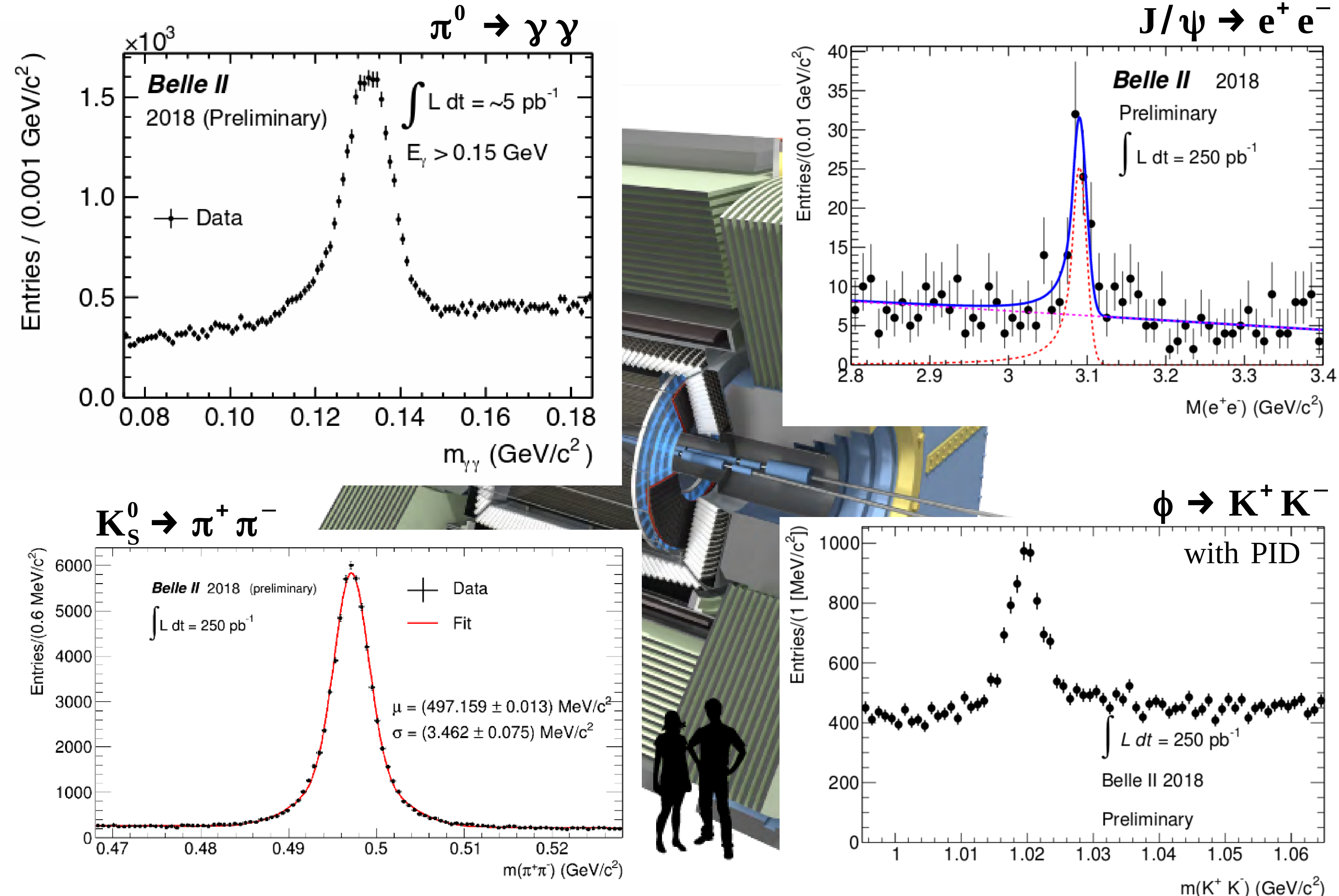
B rediscovery program



first studies of performance of hadronic tagging in Belle II data



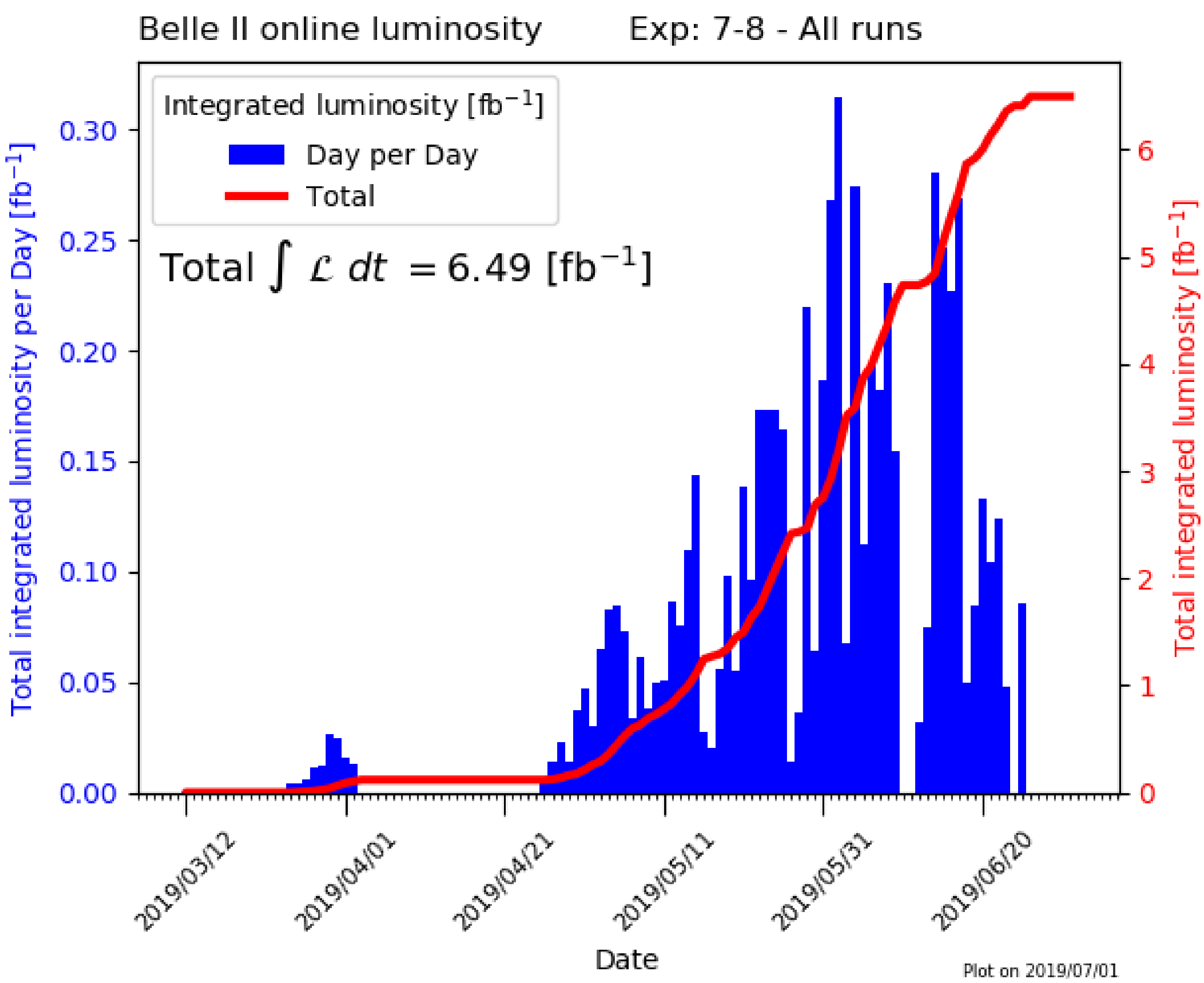
Detector performance with data…




Fall 2019,
Installation of vertex detector


Belle II VXD installed on Nov 21, 2018

Spring 2019, first phase 3 physics run



Only 2 months of collisions

$L(\text{peak}) \sim 5.5 \times 10^{33}/\text{cm}^2/\text{sec}$

$(\beta_y^* = 3\ \text{mm})$

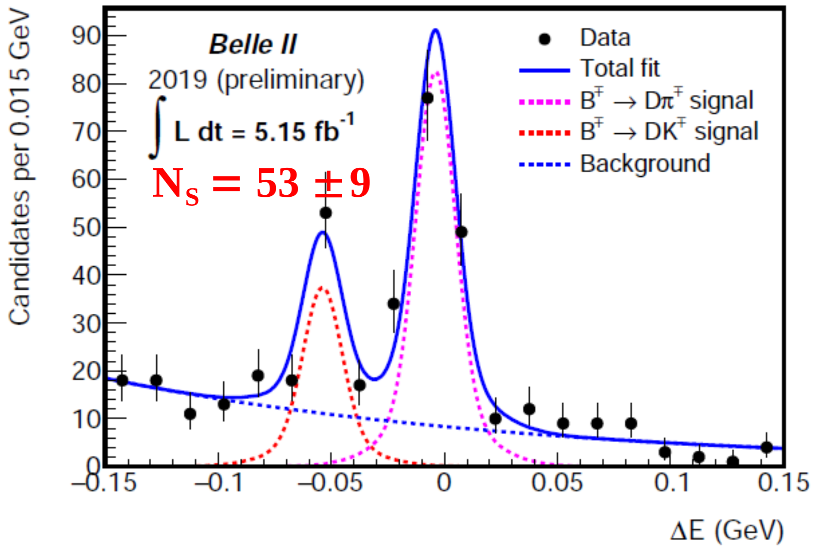
$L(\text{SuperKEKB peak}) \sim 1.2 \times 10^{34}/\text{cm}^2/\text{sec}$

$(\beta_y^* = 2\ \text{mm})$

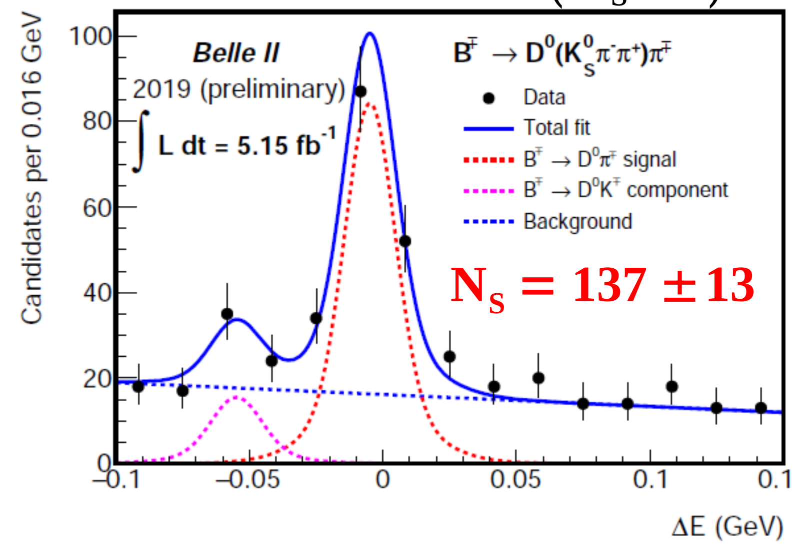
Comparable to PEP−II best but bkgs × 3 too large to turn on Belle II

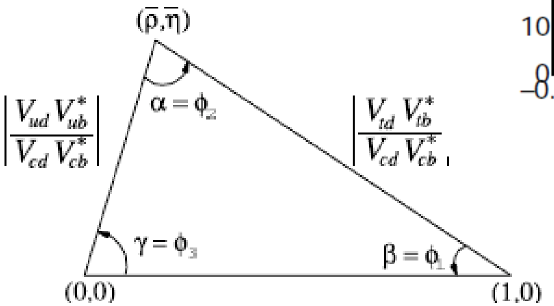
First results of phase 3… shown at LP 2019, Beauty 2019

step by step… observation of $B \to DK$



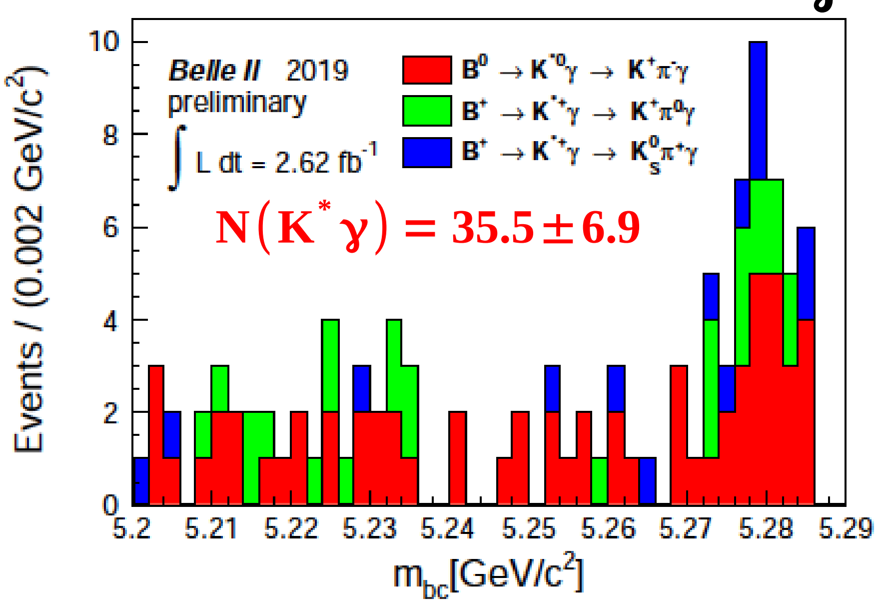
… observation of $B \to D(K_S\pi\pi)\pi$



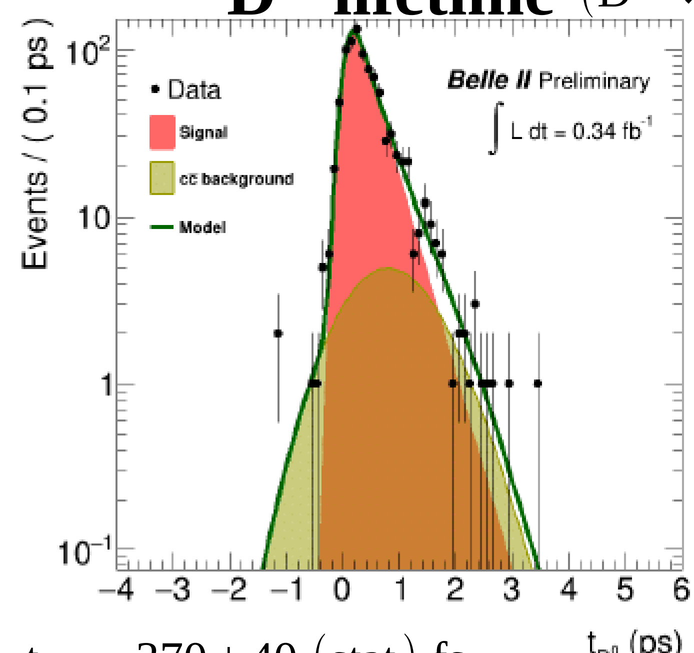


Demonstration of Belle II high momentum PID on a decay mode to be used for future determinations of the unitarity angle γ (a.k.a ϕ_3)

Observation of $B \to K^* \gamma$

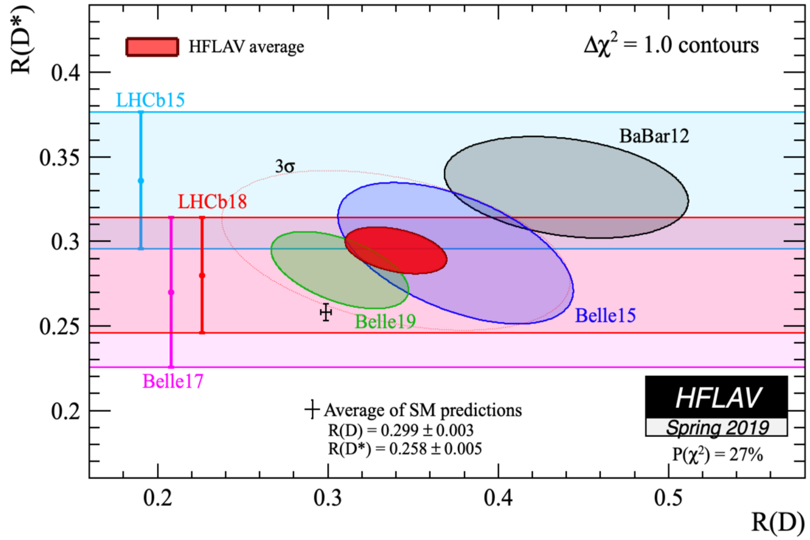


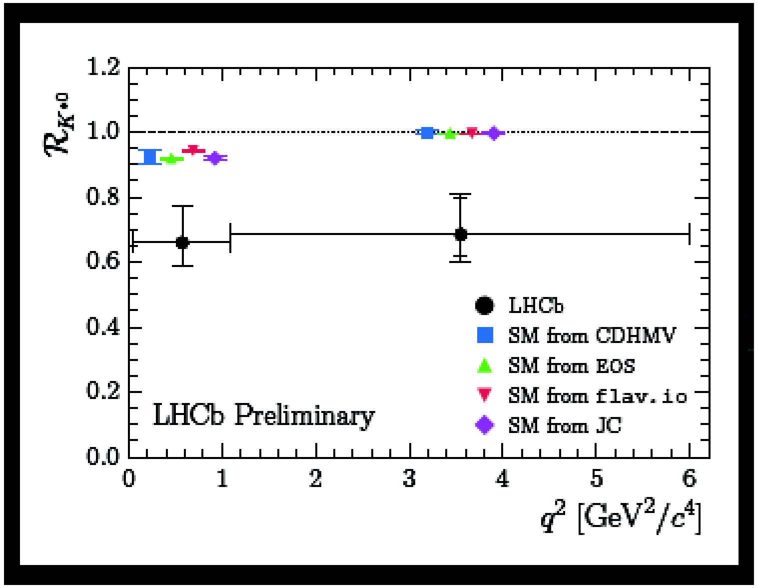
D^0 lifetime ($D^0 \to K\pi$)



$t_{D^0} = 370 \pm 40$ (stat) fs

In the context of B anomalies ...





b → c anomalies

b → s 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 <u>must be light</u>

Found by LHCb

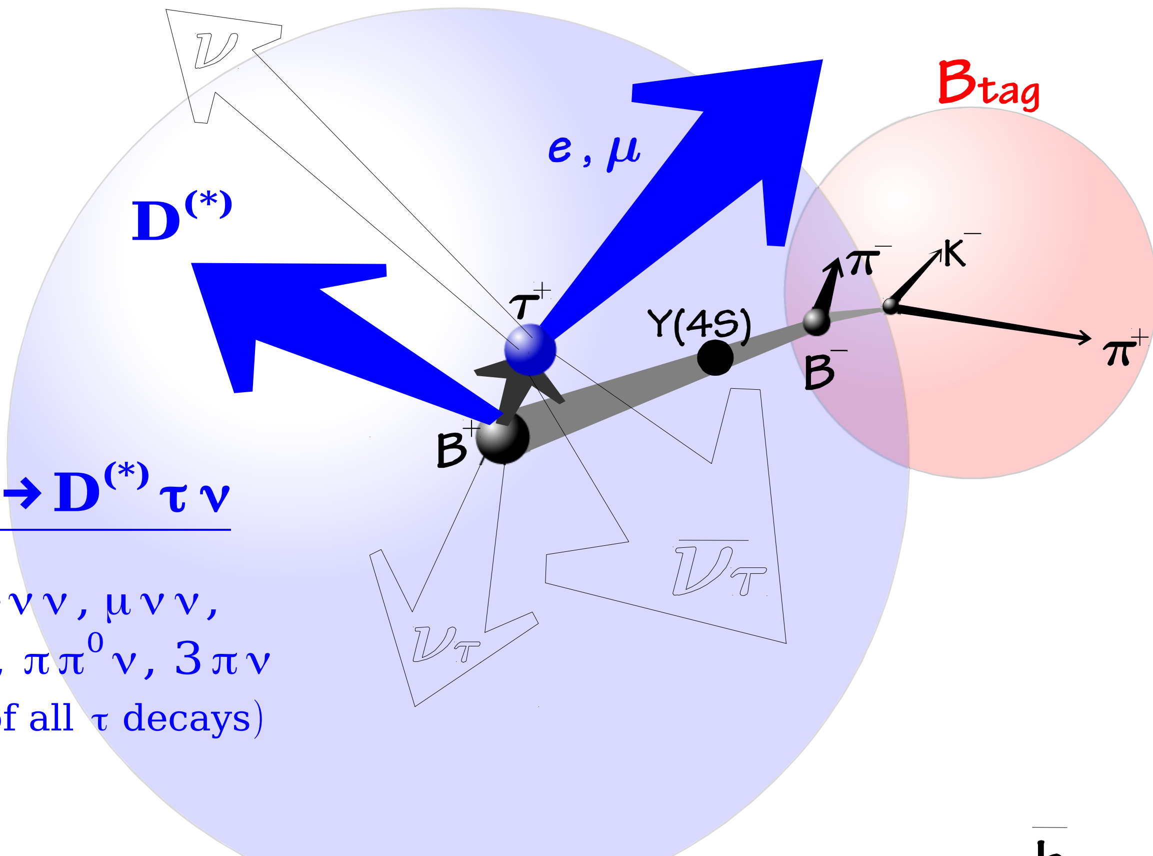
Many observables: <u>global pattern</u>

Neutral current

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

The New Physics <u>can be heavy</u>

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



B_{tag}

hadronic tag

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

$\epsilon \sim 0.2\,\%$

semileptonic tag

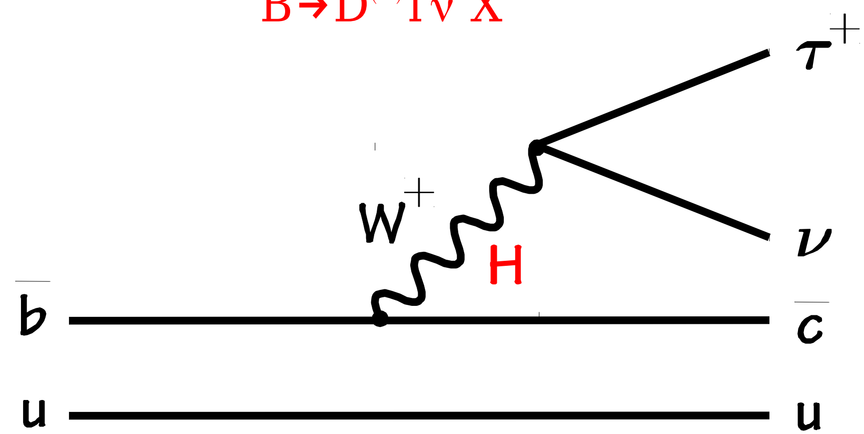
$B \to D^{(*)} l \nu X$

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

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

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

(70 % of all τ decays)



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

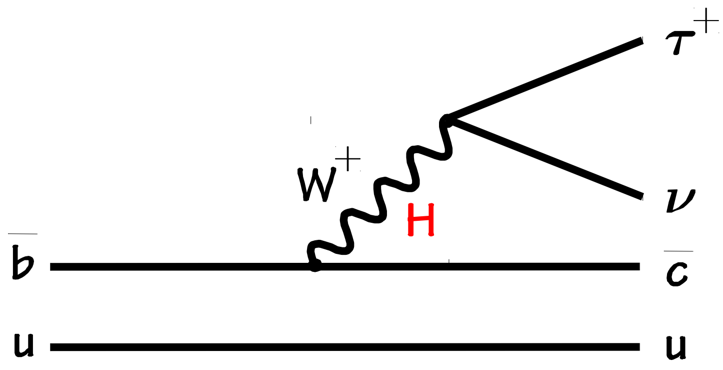
main signal-background discriminator

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

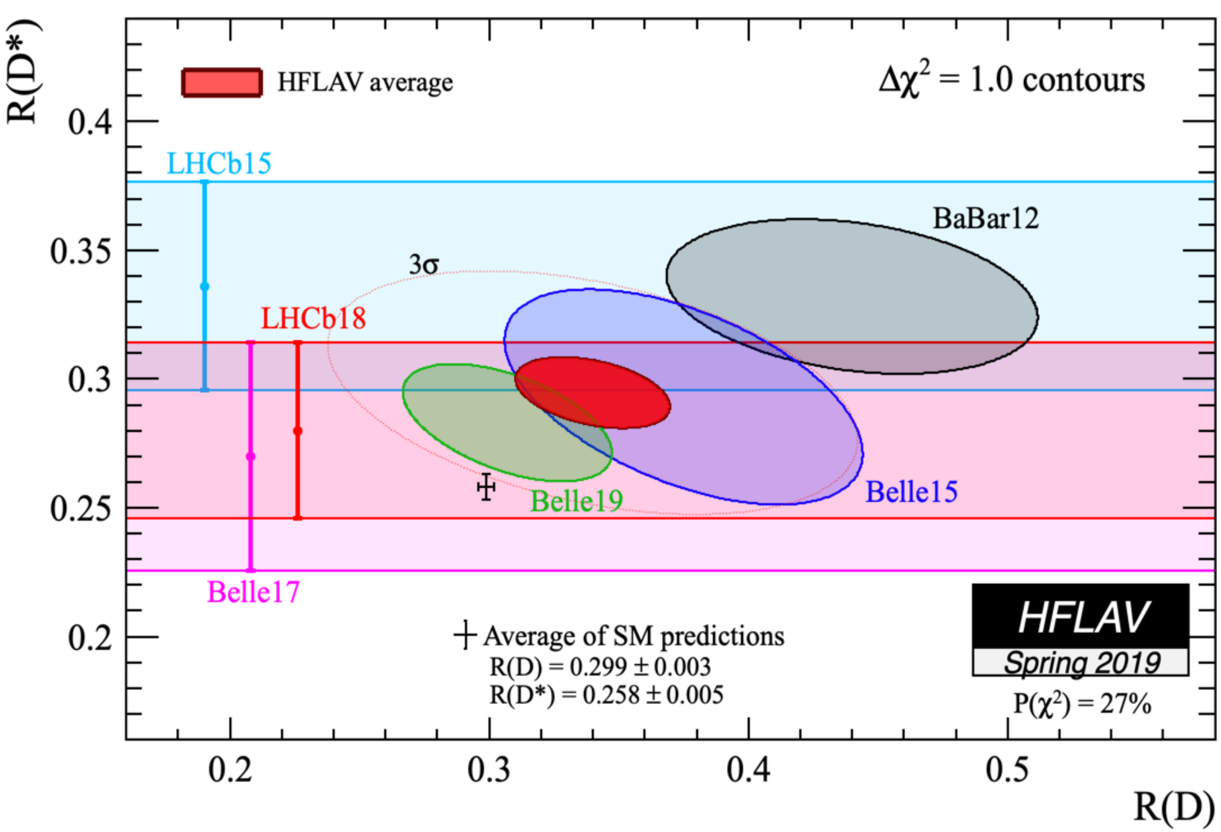
$$\text{2HDM (type II)}: \mathcal{B}(B \to D\tau^+\nu) = G_F^2\,\tau_B\,|V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

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

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

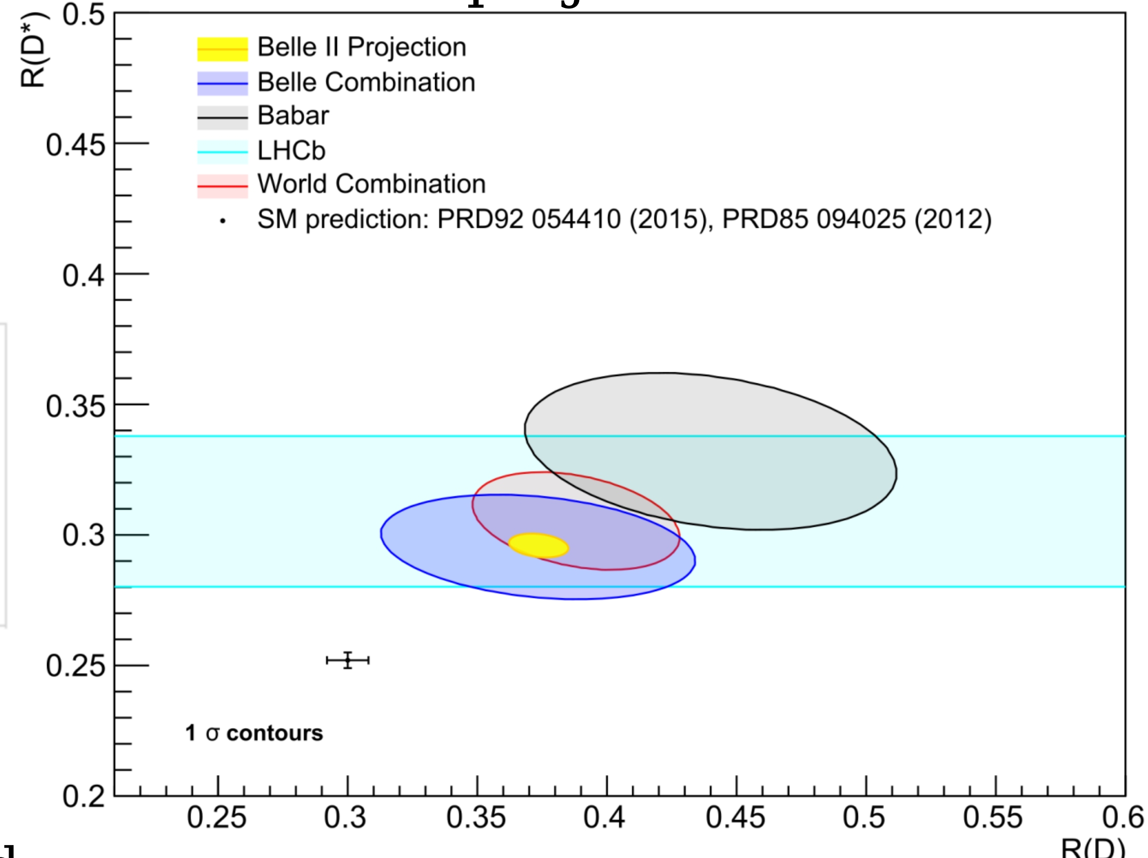
$R(D) = 0.340 \pm 0.027 \pm 0.013$
$R(D^*) = 0.295 \pm 0.011 \pm 0.008$
difference with SM predictions is at **3σ** level

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

Predictions of uncertainty using hadronic full reconstruction:

	$\Delta R(D)$ [%]			$\Delta R(D^*)$ [%]		
	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

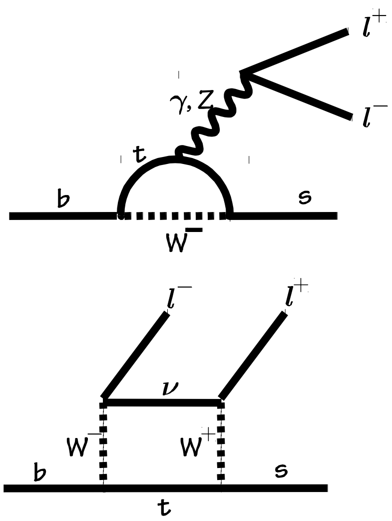
projection for 50 ab^{-1}

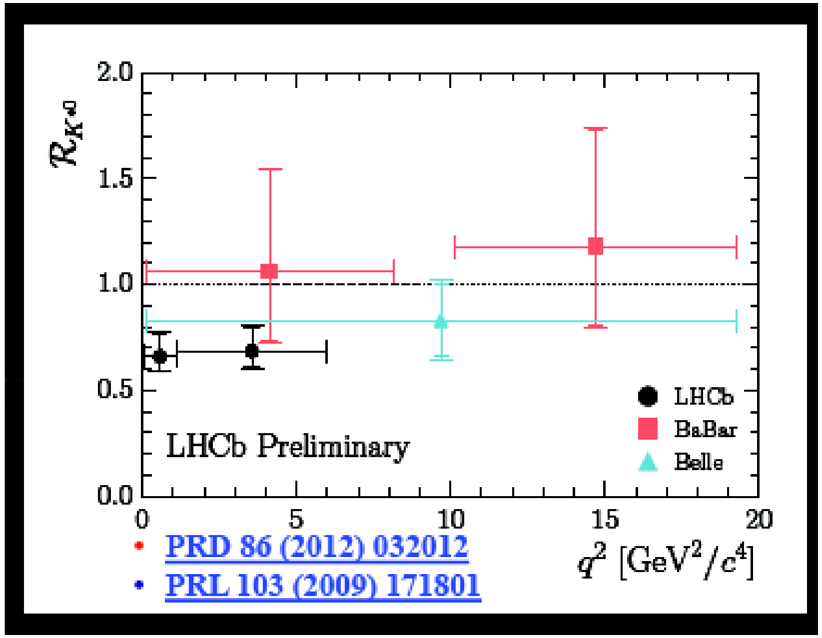


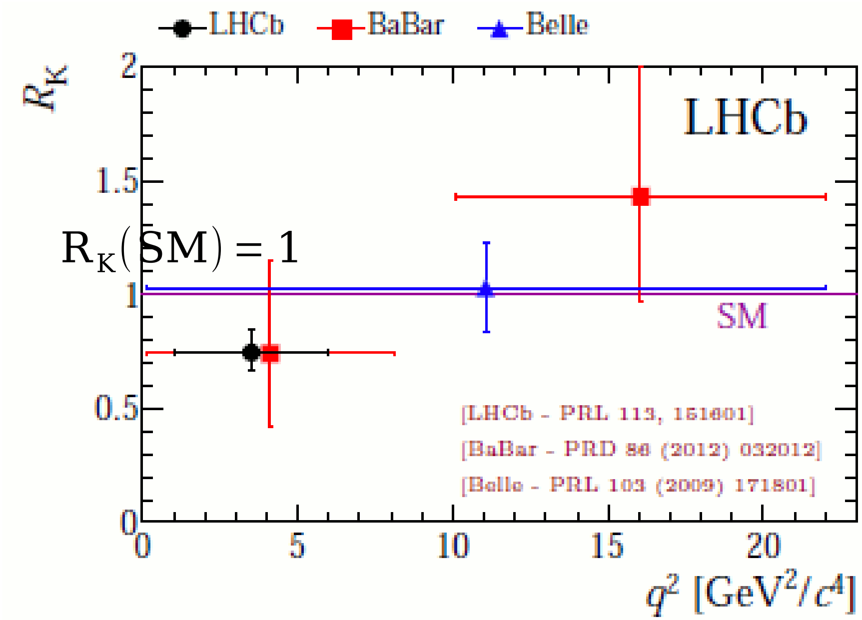
Systematic uncertainty dominated by D^{**} and missed soft pions:

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

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







Model candidates

✧ **Model with extended gauge symmetry**

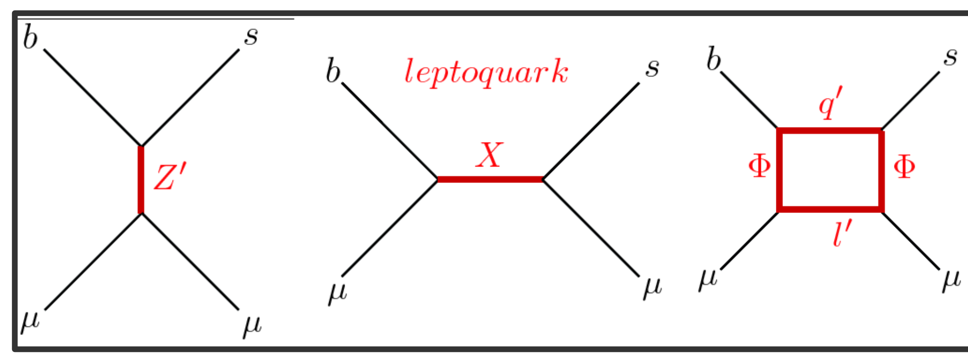
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **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



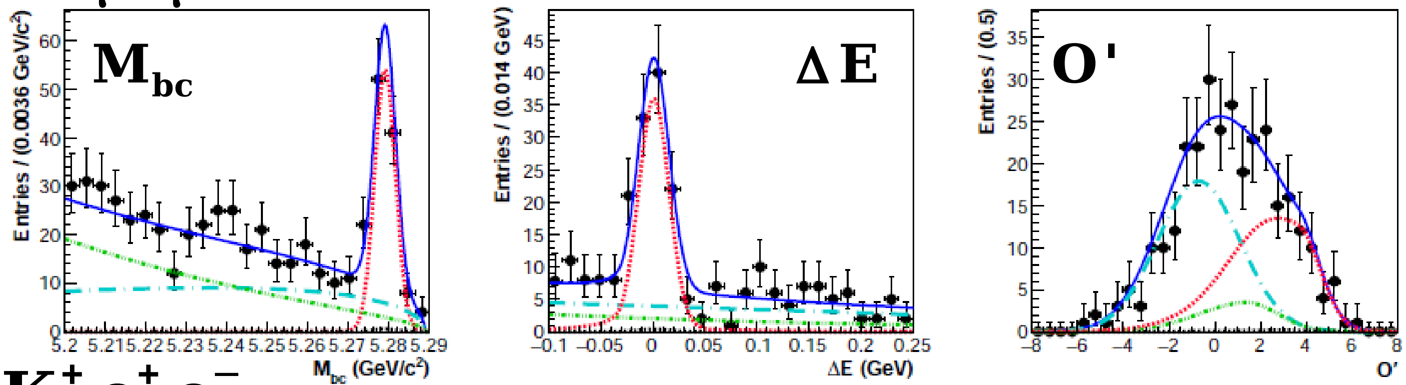
Leptoquarks are color-triplet bosons that carry both lepton and baryon numbers

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

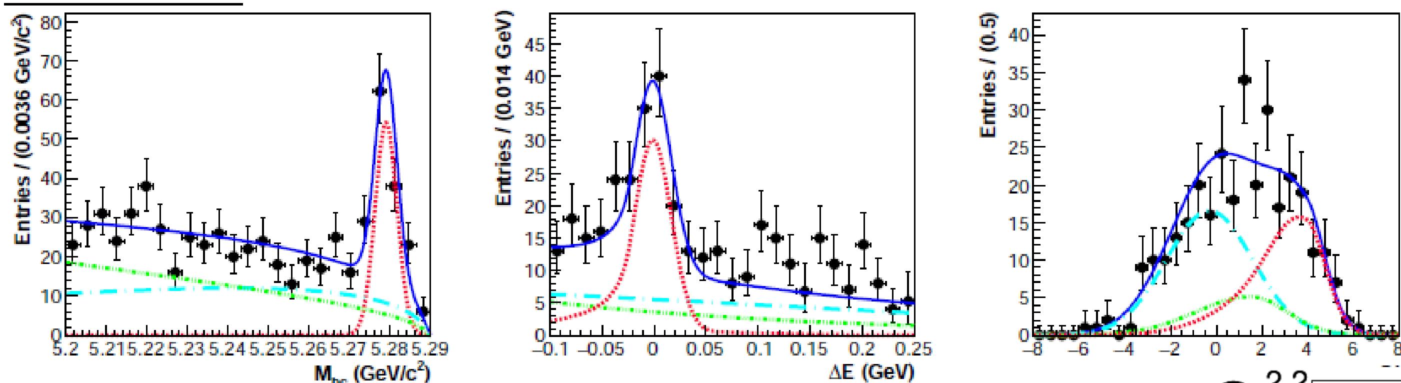
R_K, R_{K}^{*}, ...

[Belle, arXiv:1908.01848]

$K^+\mu^+\mu^-$



$K^+e^+e^-$

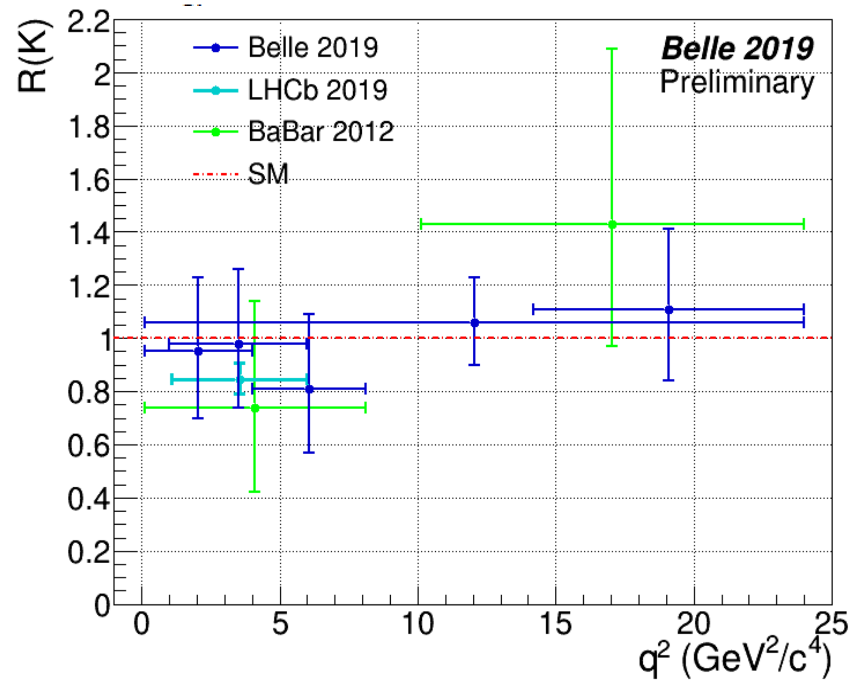


for the whole q^2 range: of course excluding the ψ...

$$R_K = 1.06\,^{+0.15}_{-0.14} \pm 0.07$$

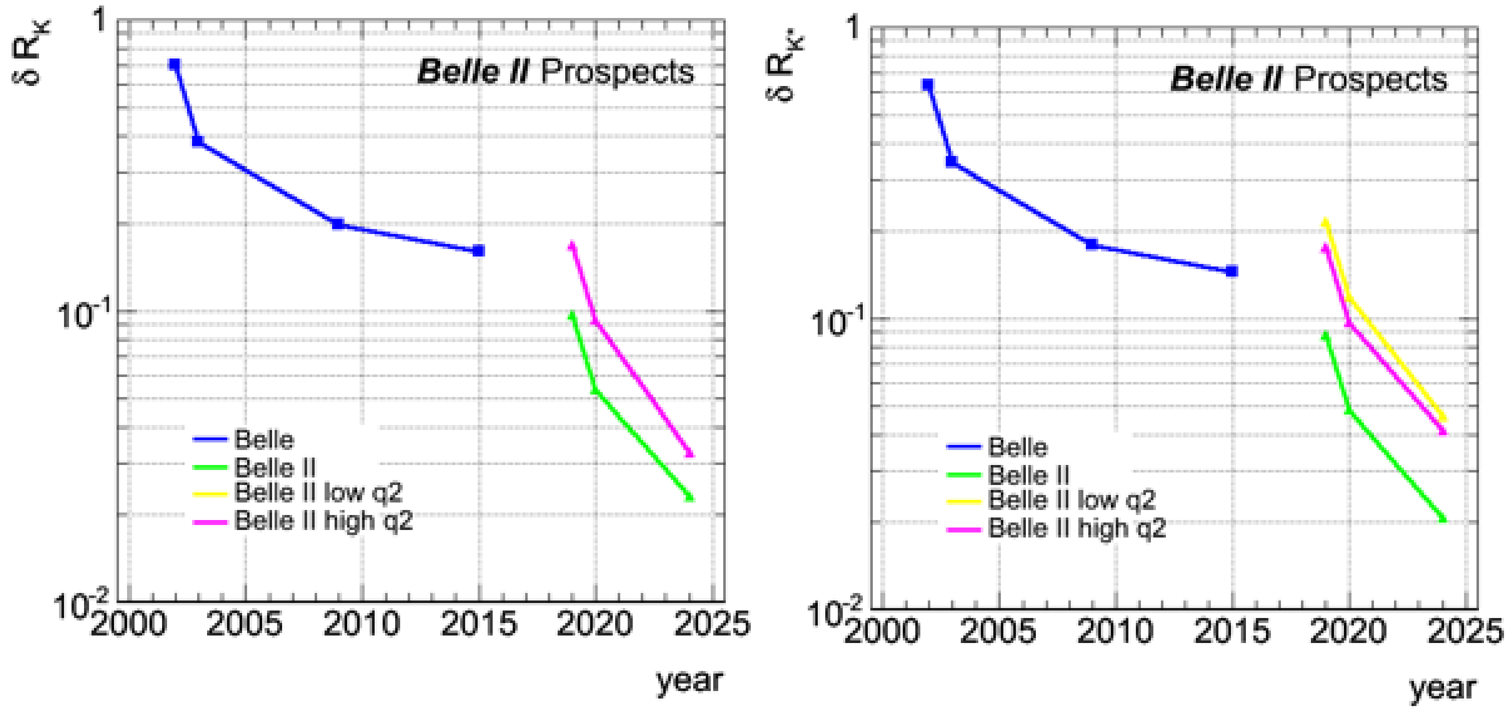
$q^2 \in [1.0,\, 6.0]\ \mathrm{GeV}^2/c^4$

$$R_K = 0.98\,^{+0.27}_{-0.23} \pm 0.06$$



R_K, R_K^*, ...

[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%

5σ confirmation possible with Belle II 20 ab^{-1}

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

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

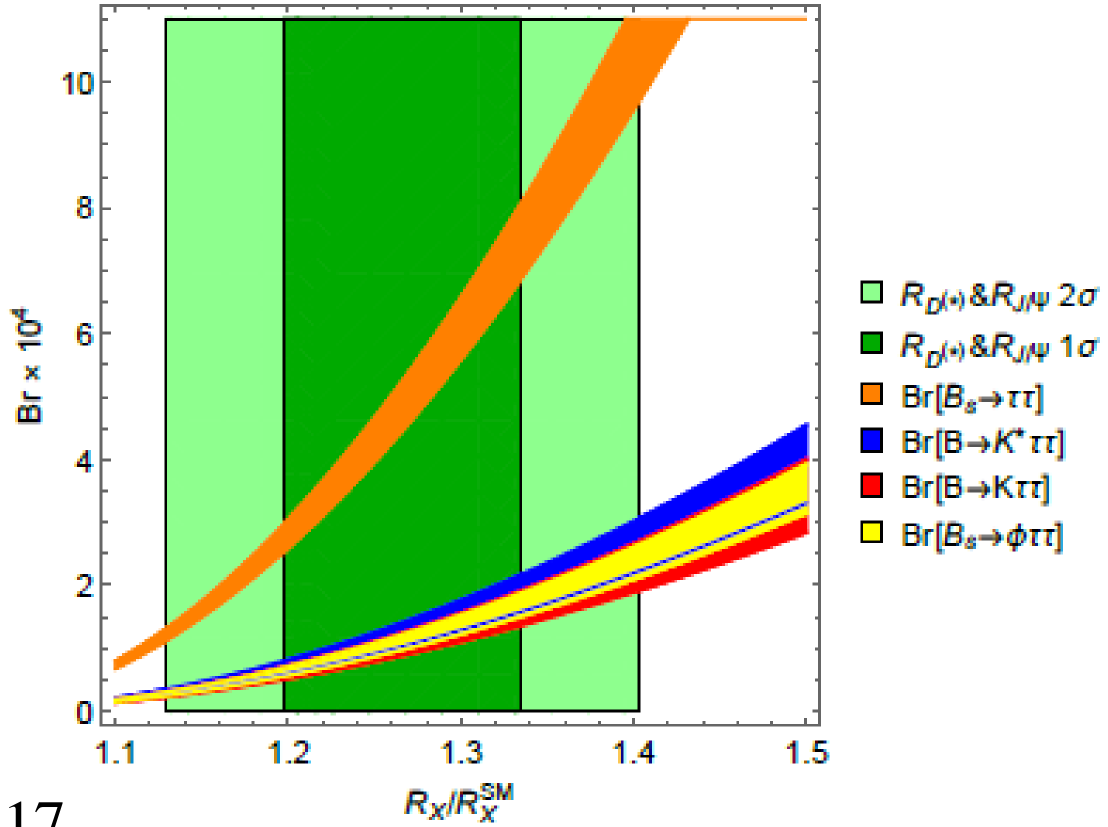
q^2 range for predictions for $B \to H \tau^+ \tau^-$: from $4\, m_\tau^2$ (~ 12.6 GeV^2) to $(m_B - m_H)^2$ to avoid contributions from resonant decay through $\psi(2S)$, $B \to H \psi(2S)$, $\psi(2S) \to \tau^+ \tau^-$ predictions restricted to $q^2 > 15$ GeV^2:

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

[B.Capdevila et al, arXiv:1712.01919]

$$B(B \to K \tau^+ \tau^-)_{SM} = (1.20 \pm 0.12)\, 10^{-7}$$
$$B(B \to K^* \tau^+ \tau^-)_{SM} = (0.98 \pm 0.10)\, 10^{-7}$$

greatly enhanced in NP models...



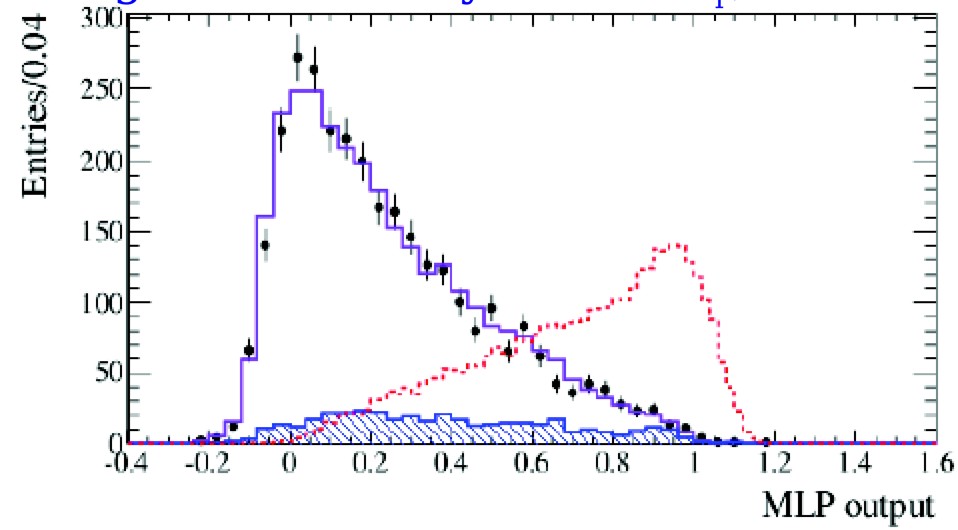
$B \to K^{(*)}\tau\tau$

[BaBar, arXiv:1605.09637]

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

ground. The input variables are: the angle between the kaon and the oppositely charged lepton, the angle between the two leptons, and the momentum of the lepton with charge opposite to the K, all in the $\tau^+\tau^-$ rest frame, which is calculated as $p_{B_{\rm sig}} - p_K$; the angle between the $B_{\rm sig}$ and the oppositely charged lepton, the angle between the K and the low-momentum lepton, and the invariant mass of the $K^+\ell^-$ pair, all in the CM frame. Furthermore, the final input variables to the neural network are $E^*_{\rm extra}$ and the residual energy, $E_{\rm res}$, which here is effectively the missing energy associated with the $\tau^+\tau^-$ pair and is calculated as the energy component of $p^\tau_{\rm residual} = p^\tau_{B_{\rm sig}} - p^\tau_K - p^\tau_{\ell^+\ell^-}$, where $p^\tau_{B_{\rm sig}}$, p^τ_K and $p^\tau_{\ell^+\ell^-}$ are the four-momenta vectors in the $\tau^+\tau^-$ rest frame of the $B_{\rm sig}$, K, and lepton pair in the event,

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

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

[Belle II, arXiv:1808.10567]

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

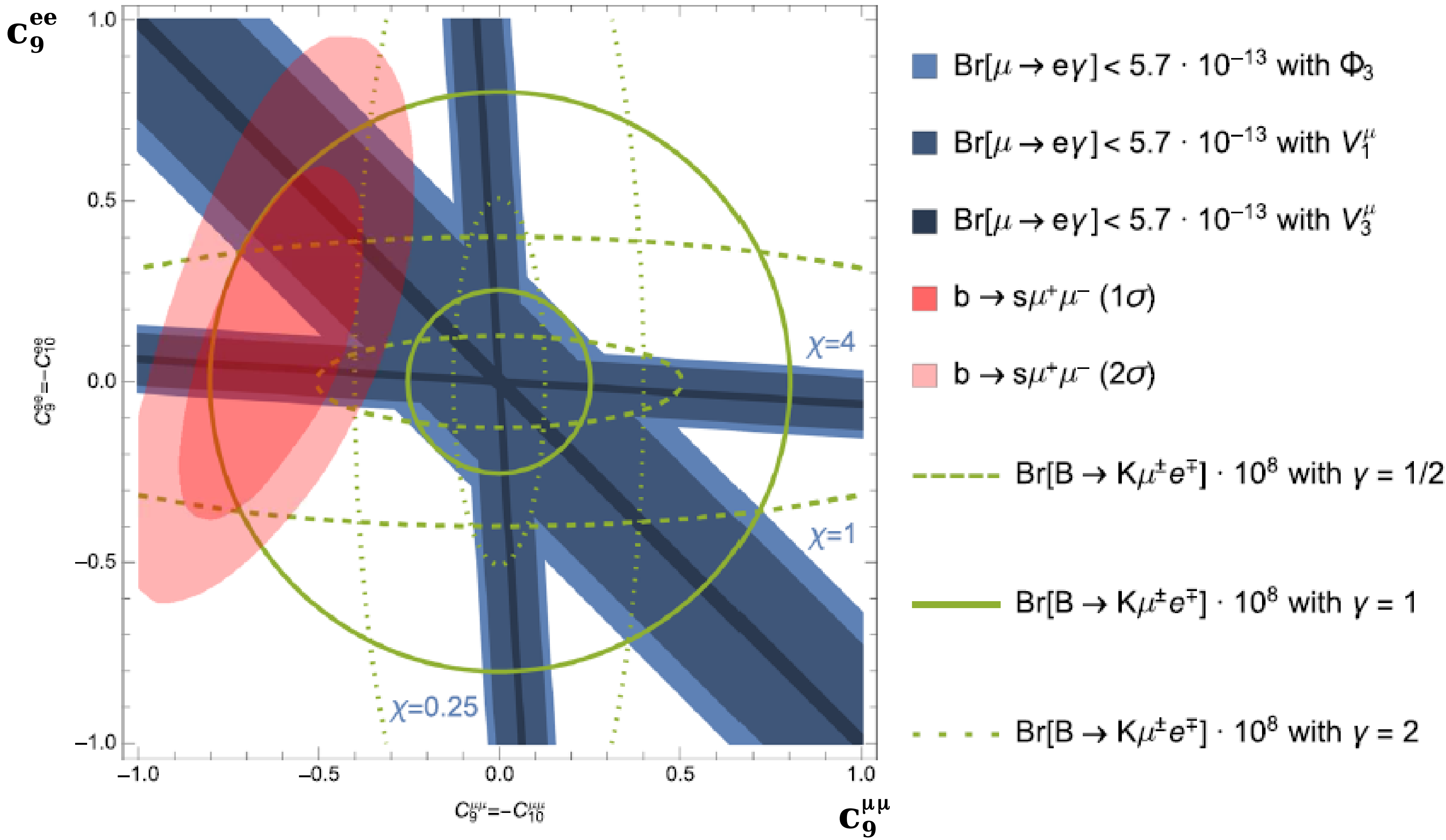
result with had tag only.... (on−going thesis at LAL)

⇒ exploring additional tags in $B \to K^+ \tau \mu / e$ (see following slides)

LFV b→sll'decays

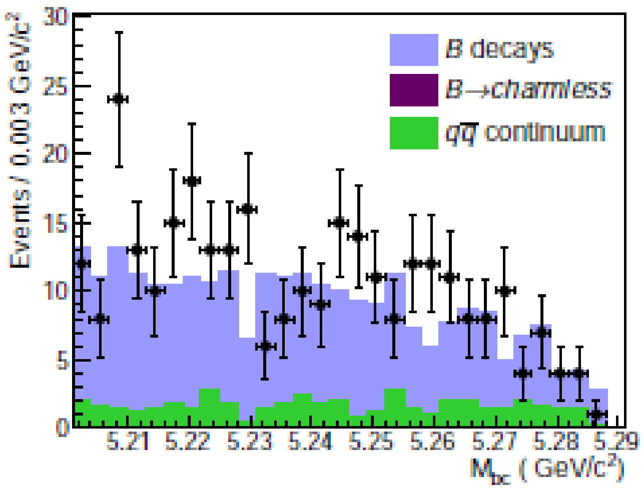
Glashow, Guadagnoli and Lane, 1411.0565, LUV ⇒ LFV, such as B→Kμe, Kμτ could also be generated ...

A.Crivellin et al, 1706.08511



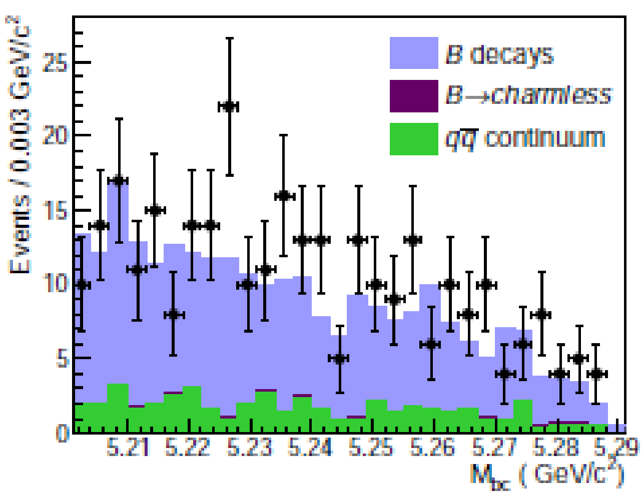
LFV $B \to K^* l l'$ decays

[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

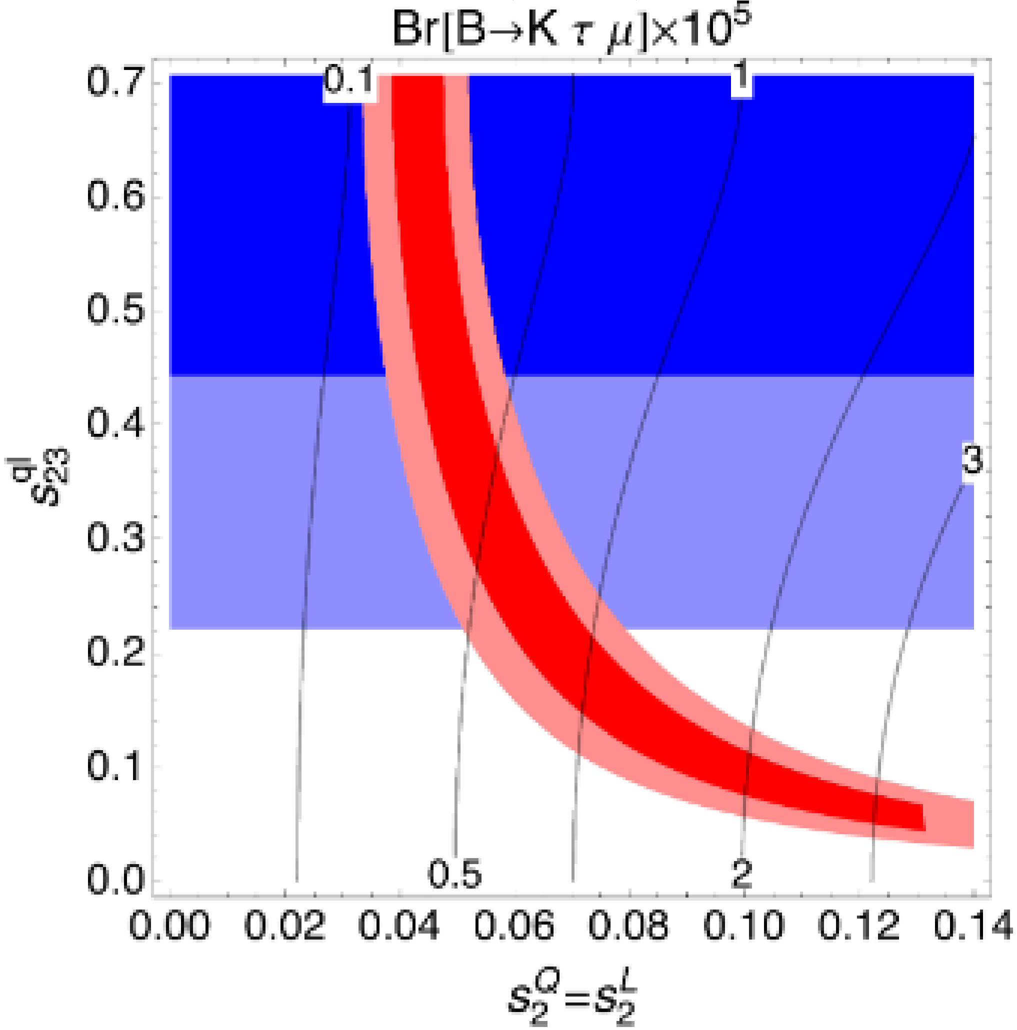
$\mathrm{B}(B^0 \to K^{*0}\mu^+ e^-) < 1.2 \times 10^{-7}$ at 90% CL



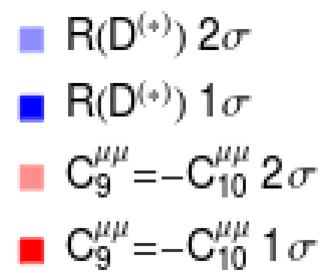
$\mathrm{B}(B^0 \to K^{*0}\mu^+ e^-) < 1.6 \times 10^{-7}$ at 90% CL

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

R(D*) and b→sμμ ⇒ B→Kτμ



L.Calibbi et al, arXiv:1709.00692



Key Features of PS^3

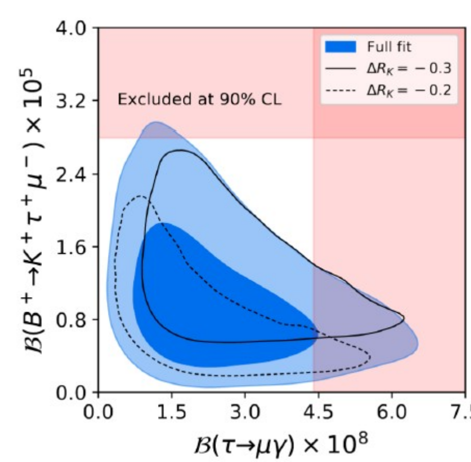
Bordone, Cornella, Fuentes-Martin, Isidori (2017), (2018)

common to all PS-type models

- TeV-scale LQ, colour-octet vector and Z'
- decent fit to low-energy data
- large $\tau \to \mu$ LFV effects

specific to PS^3

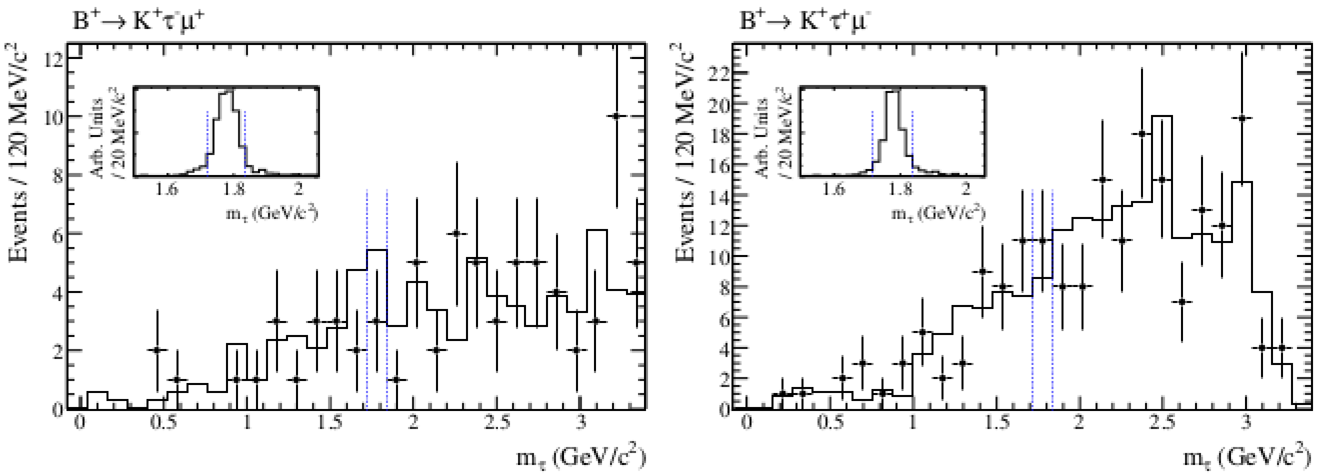
- hierarchical symmetry breaking pattern relates flavour-dependent LQ couplings to Yukawa hierarchies
- LQ coupling also to right-handed fermions



LFV $B \to K \tau l$ 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}
$Br(B^+ \to K^+ \tau^\pm e^\mp) \cdot 10^6$	–	–	< 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 inclusive tag...

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

cLFV : beyond the Standard Model

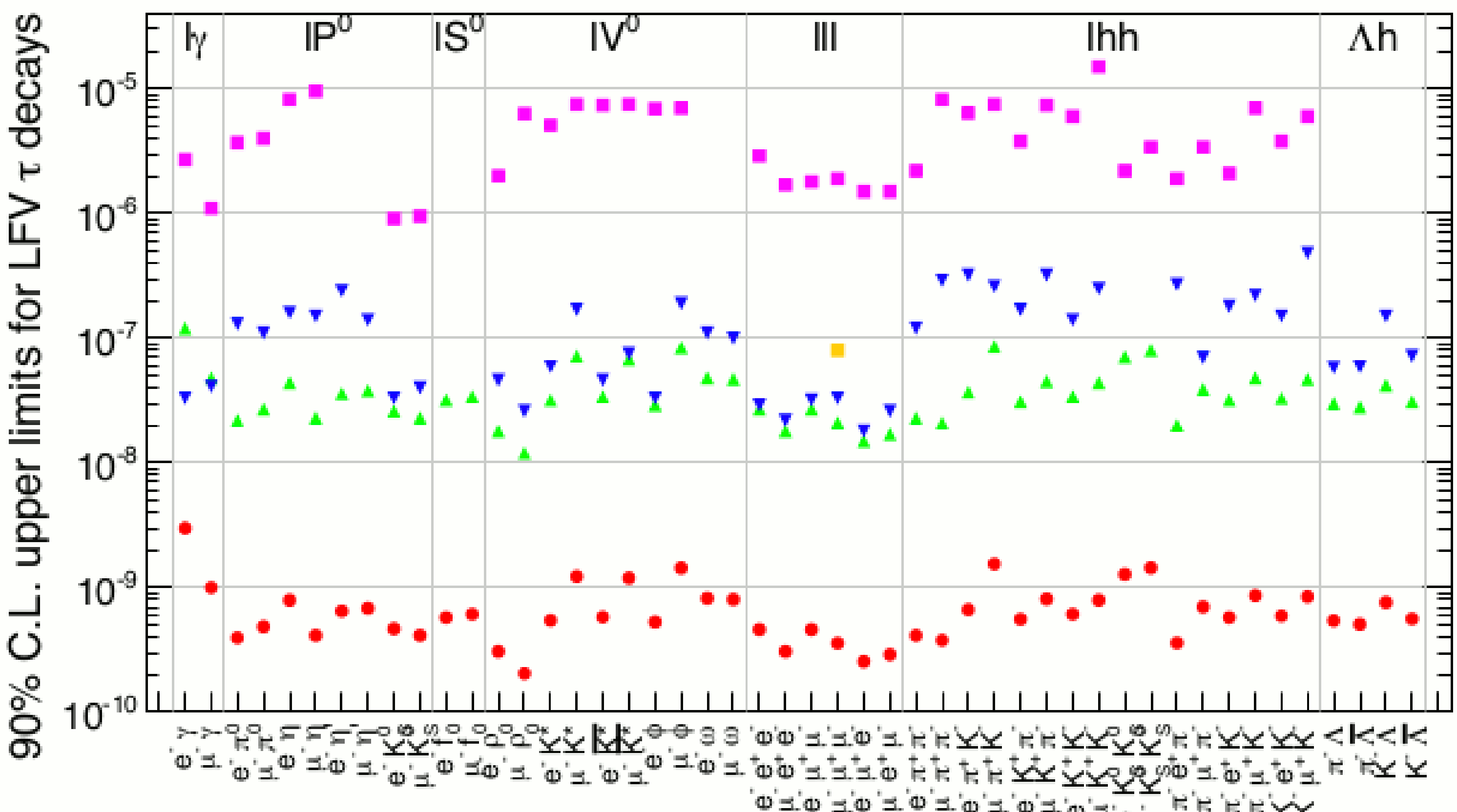
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$

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

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

		$\tau\to 3\mu$	$\tau\to\mu\gamma$	$\tau\to\mu\pi^+\pi^-$	$\tau\to\mu K\bar{K}$	$\tau\to\mu\pi$	$\tau\to\mu\eta^{(\prime)}$
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)



how to improve ?

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

…for $\tau\to 3$ muons, improve μ−ID at low mom (ECL info)

- CLEO
- BaBar
- Belle
- LHCb
- Belle II

Conclusion

- Few tantalizing results on rare decays in B sector covered in this talk… but much more in B decays: LFV searches, $B \to K^{(*)} \nu \bar{\nu}$, $B \to \tau \nu$, $\mu \nu$…

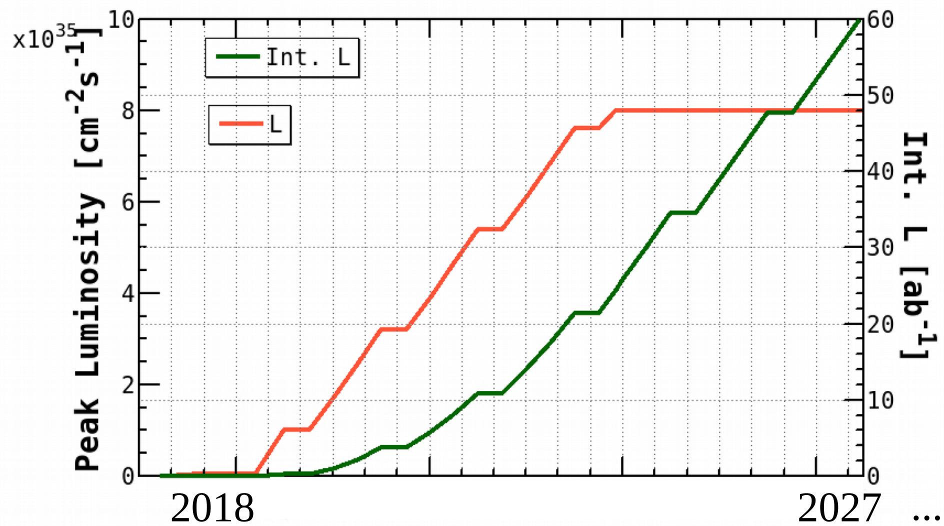
  also in charm, charmonium, bottomonium, light Higgs, τ, DS, kaon sectors…

- Not only complementary, but stimulating competition between (super) B-factories and LHCb (upgrade)…

  … especially for the modes with τ

  $B \to K^{(*)} \tau \tau$, LFV $B \to K^{(*)} (\mu, e) \tau$, LFV τ decays

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}



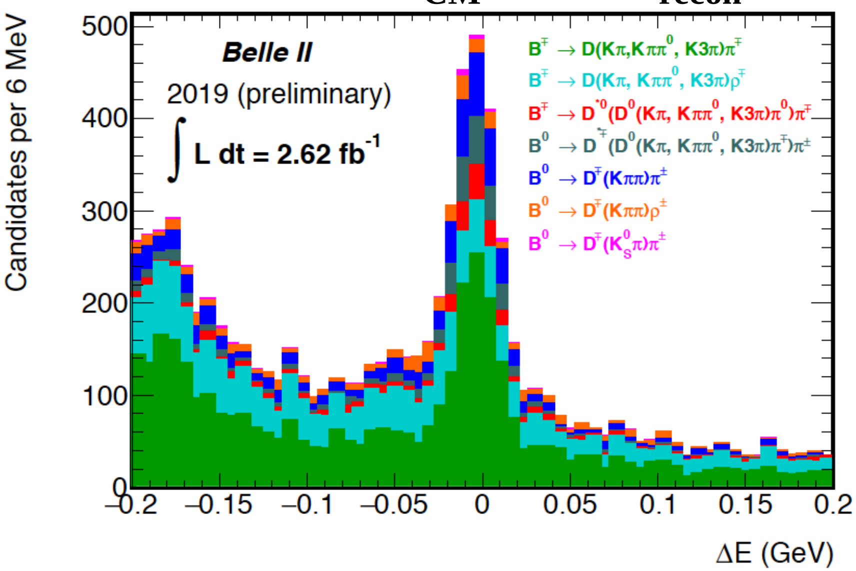
… and beyond 50 ab^{-1} ?

Rediscovering beauty : $B \to D^{(*)} h$ ...

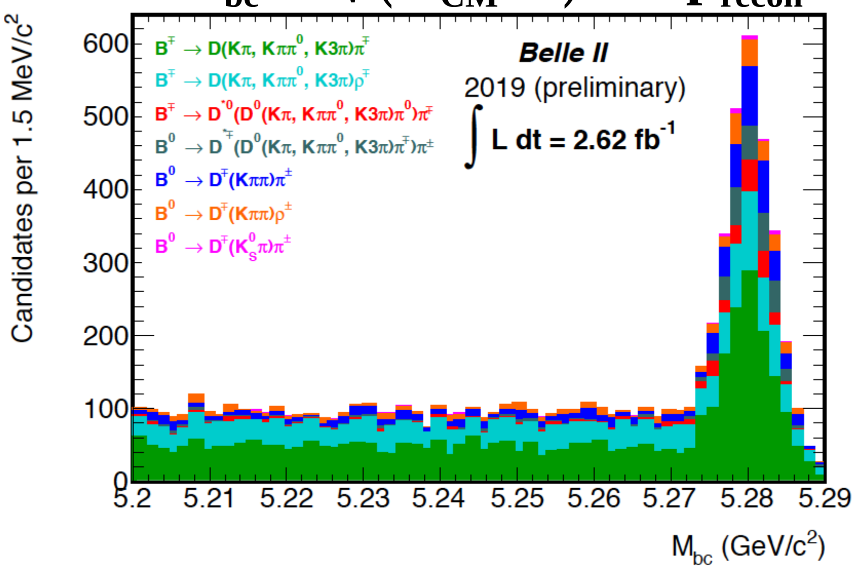
Results for 2.6 fb^{-1}

Candidates in signal box
($M_{bc} > 5.27\ GeV/c^2$, $|\Delta E| < 0.050\ GeV$)

$$\Delta E = E_{CM}/2 - E_{recon}$$



$$M_{bc} = \sqrt{(E_{CM}/2)^2 - p^2_{recon}}$$



2200 fully reconstructed hadronic B decays

Show capacity for charm physics in $e^+ e^- \to c\bar{c}$

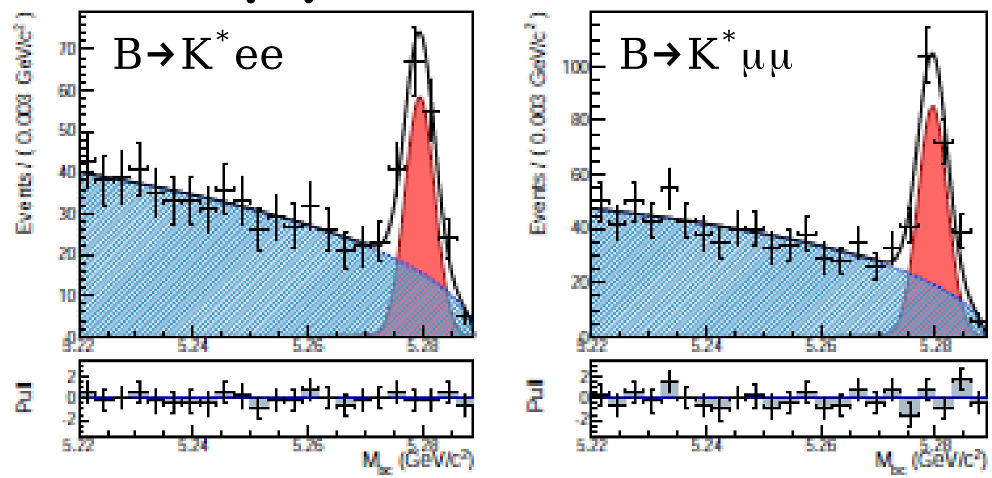
- D^0 , D^+, D^*
- Cabibbo favoured and suppressed modes

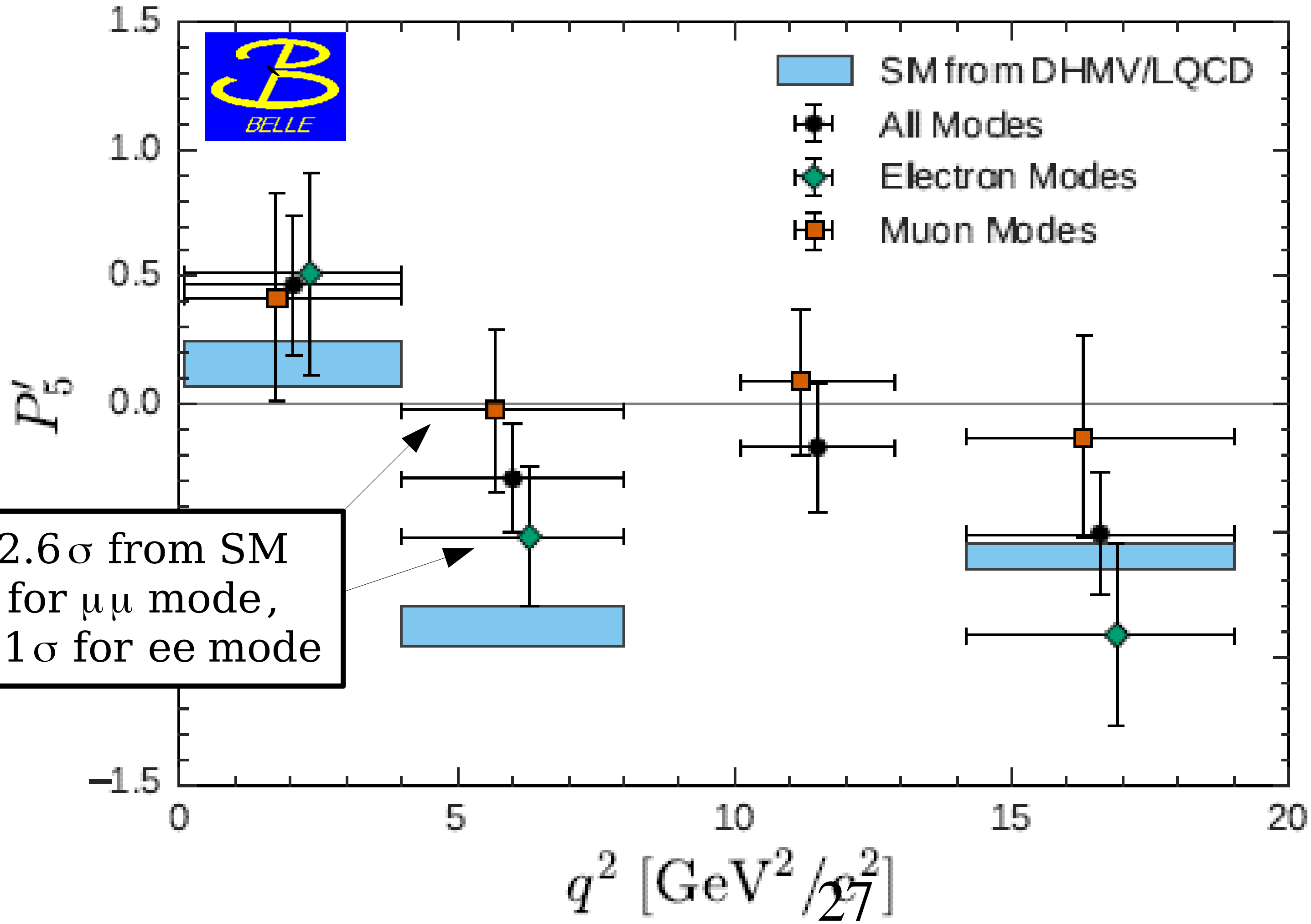
... for B - physics

- hadronic modes from $b \to c$, including modes with neutrals and K^0_S
- semileptonic decay modes from $b \to c$

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

[Belle, arXiv:1612.05014]



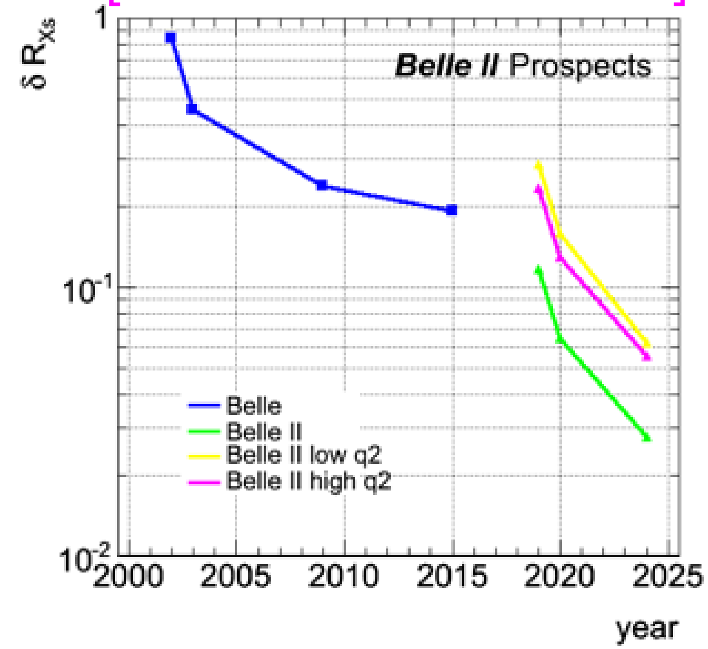


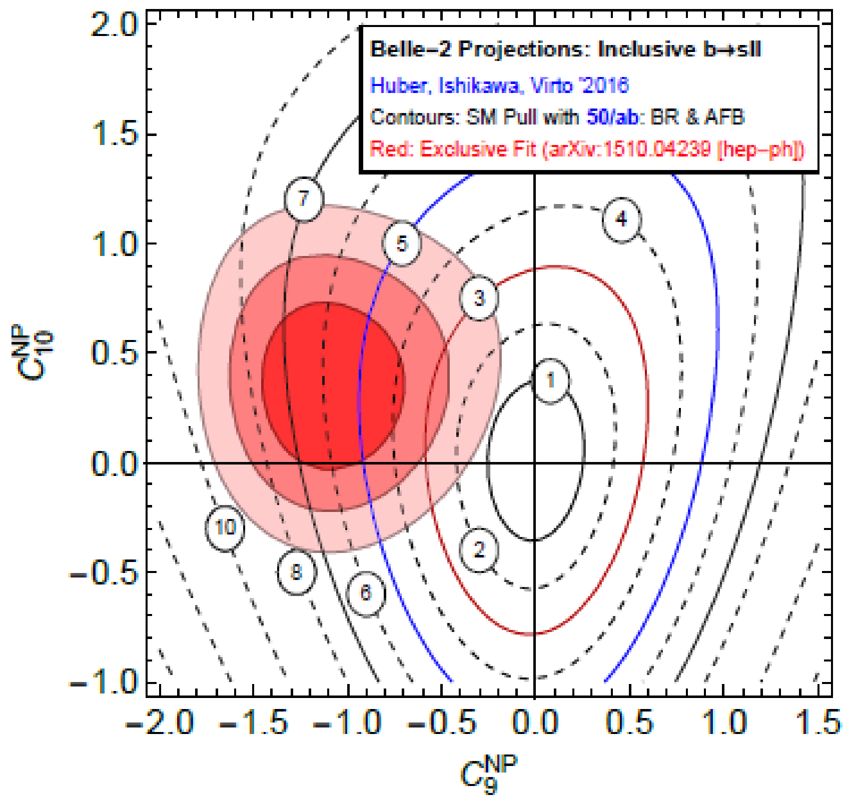
2.6σ from SM
for $\mu\mu$ mode,
1.1σ for ee mode

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

[arXiv:1808.10567]

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 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%





what about inclusive b → 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 $1 < q^2 < 6$ GeV^2, $\mathcal{B}(B \to X_s ll) = (1.62 \pm 0.09) \times 10^{-6}$

and lot of leptons in B decays…

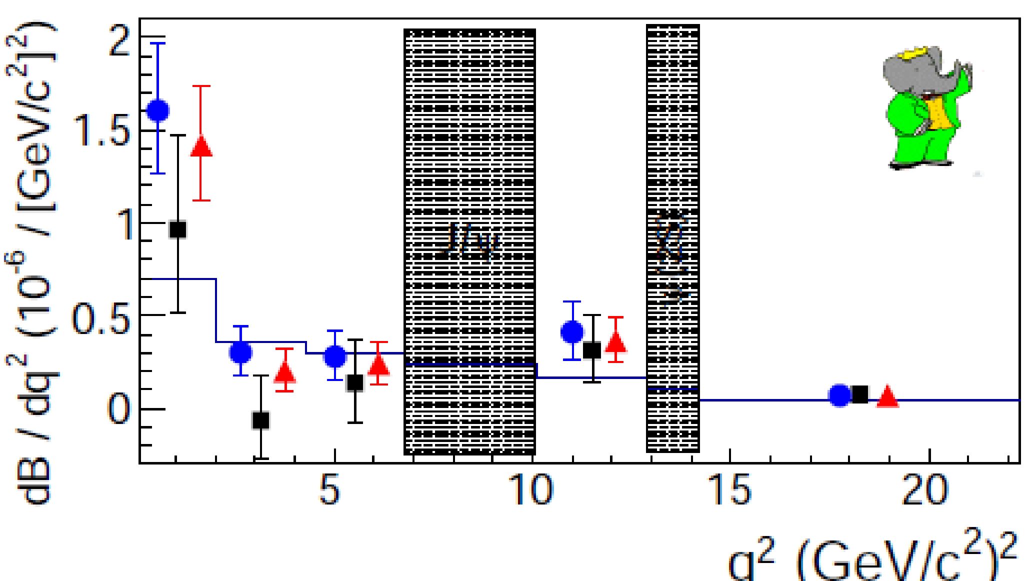
- difficult to achieve using inclusive method (à la $b \to s\gamma$)
- some on-going efforts using full had. tag, but $\epsilon < 1\%$…

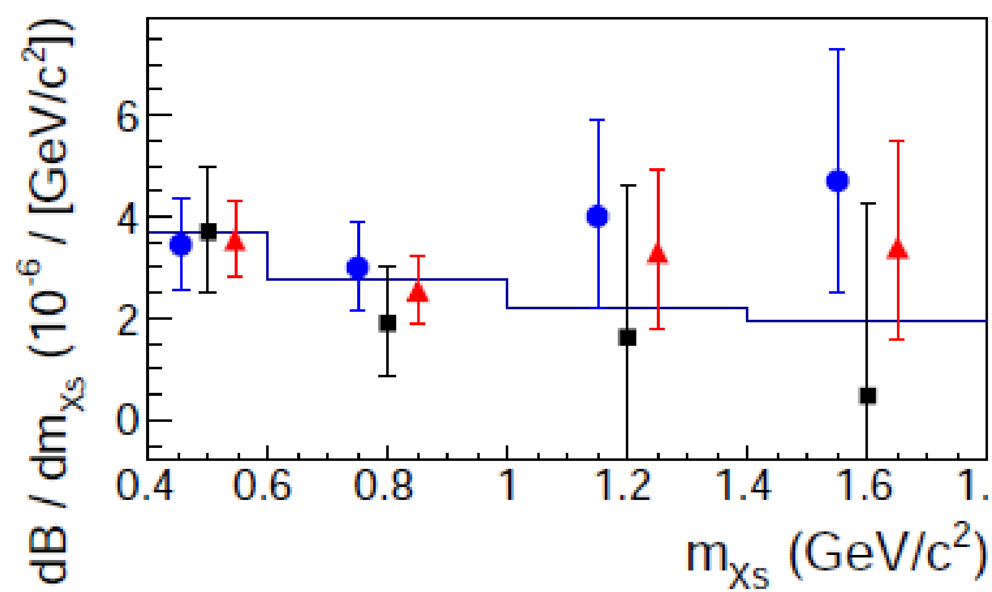
sum-of-exclusive method instead…

[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^2_0	$1.0 < q^2 < 6.0$	$1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18$ (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

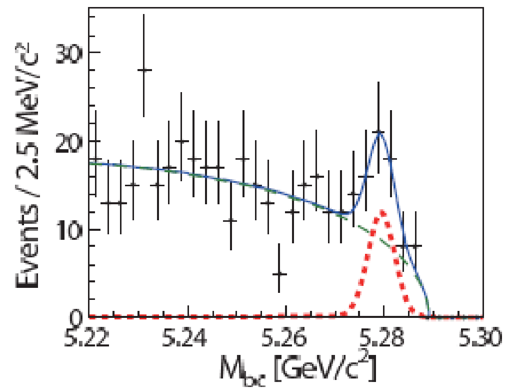
[Belle, arXiv:1402.7134]

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

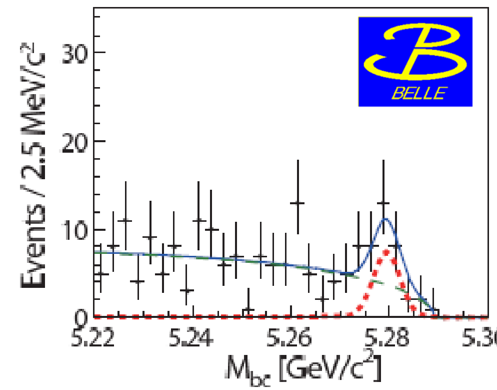
50% of total inclusive rate

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

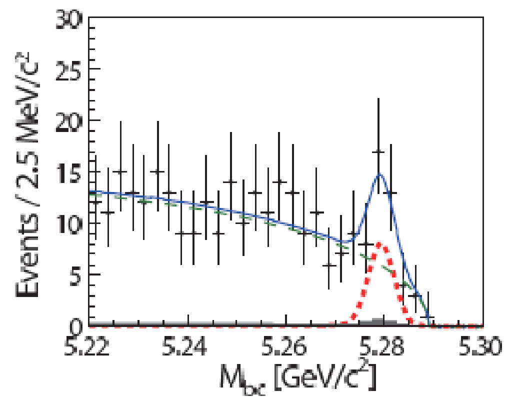
$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$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



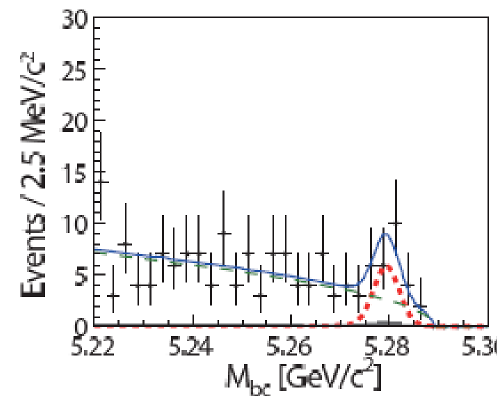
(a) $B \to X_s e^+e^-$ candidates with $\cos\theta > 0$



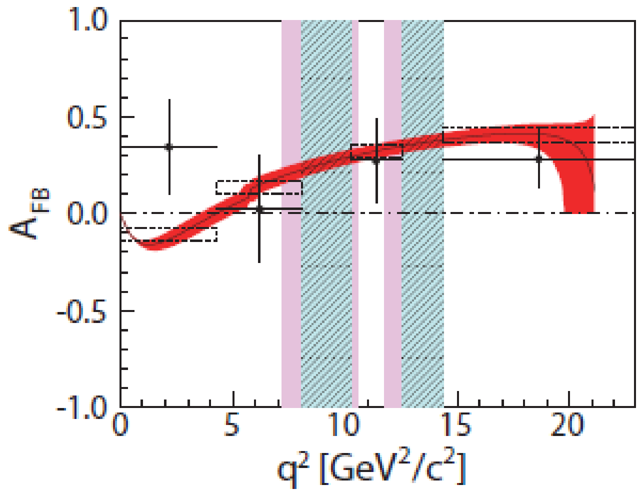
(b) $B \to X_s e^+e^-$ candidates with $\cos\theta < 0$



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



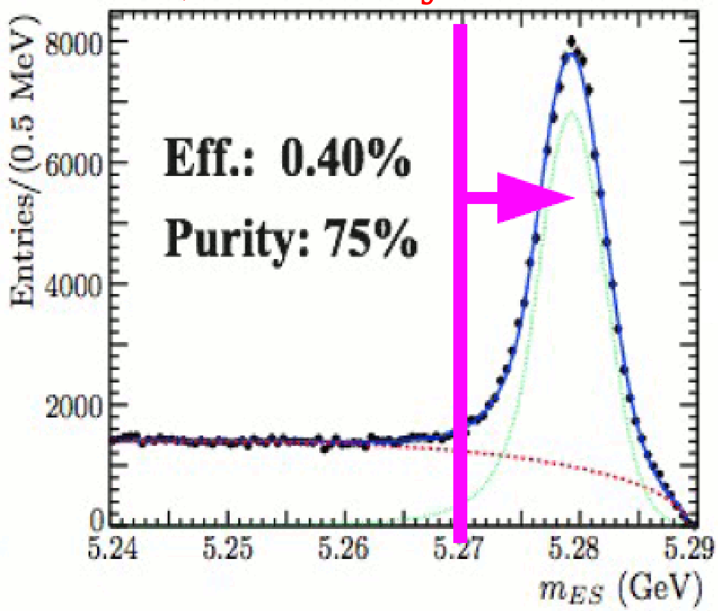
(d) $B \to X_s \mu^+\mu^-$ candidates with $\cos\theta < 0$

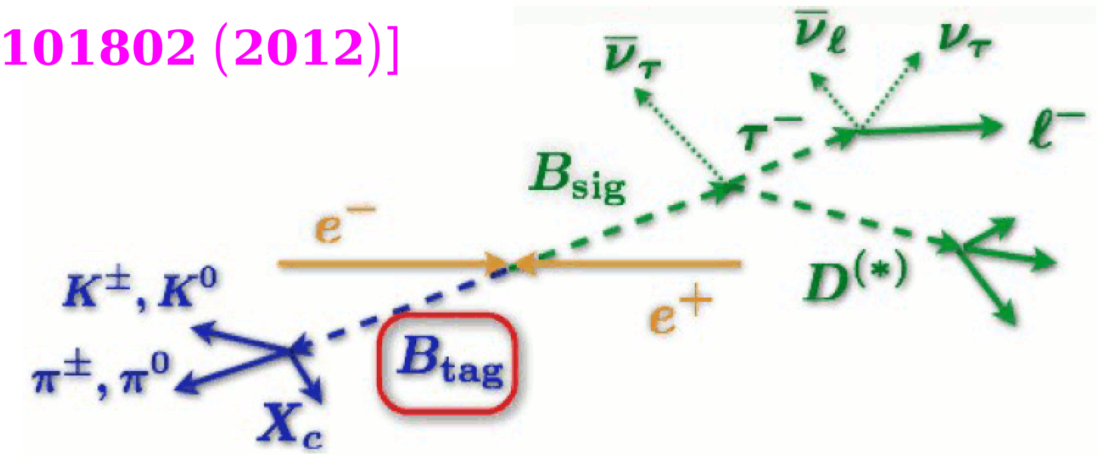


	1st q^2 bin	2nd q^2 bin	3rd q^2 bin	4th q^2 bin	
q^2 range [GeV$^2/c^2$]	[0.2,4.3]	$[4.3,7.3]_{X_s e^+e^-}$ $[4.3,8.1]_{X_s \mu^+\mu^-}$	$[10.5,11.8]_{X_s e^+e^-}$ $[10.2,12.5]_{X_s \mu^+\mu^-}$	[14.3, 25.0]	[1.0, 6.0]
$\mathcal{A}_{\rm FB}$	$0.34 \pm 0.24 \pm 0.03$	$0.04 \pm 0.31 \pm 0.05$	$0.28 \pm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

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

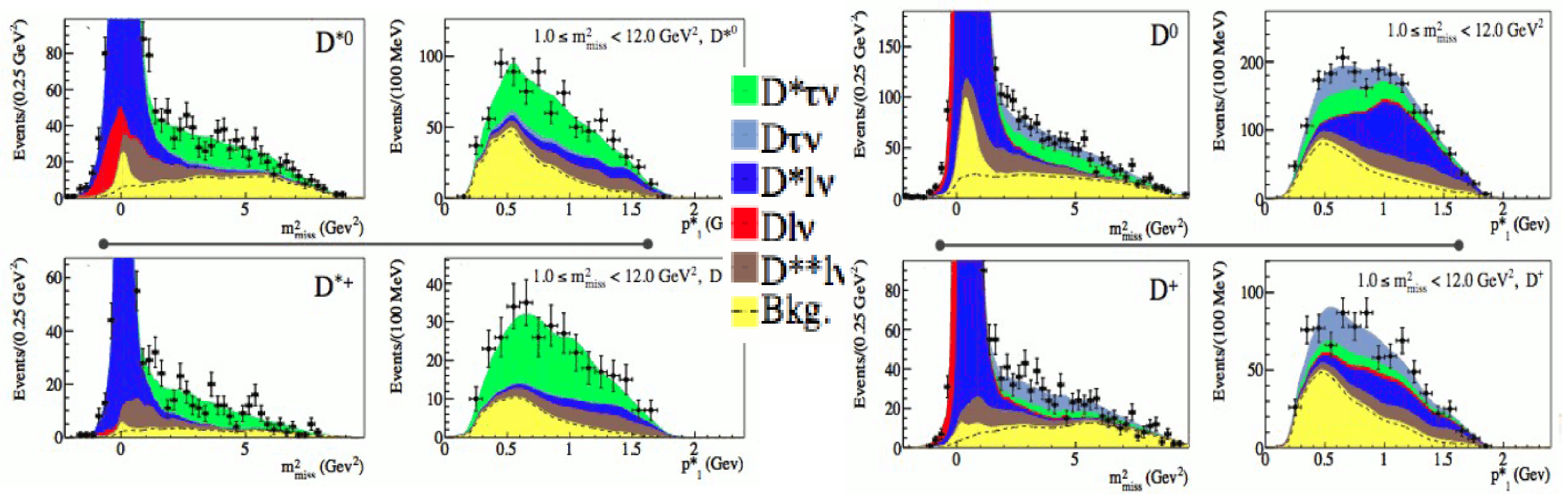
1,768 decay chains



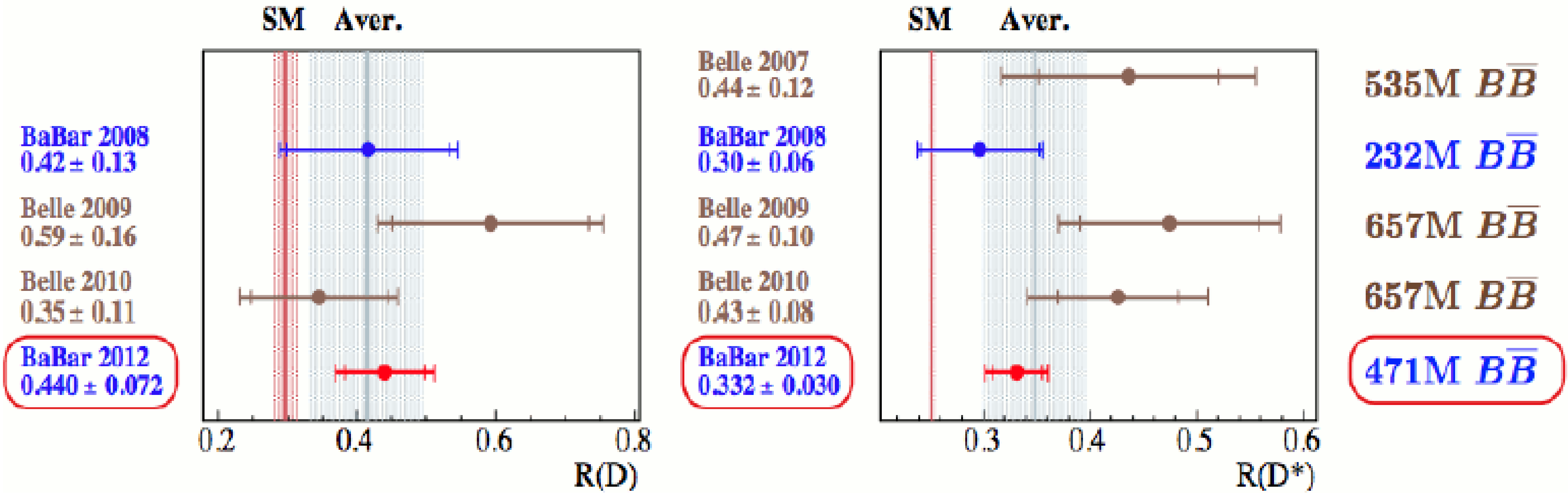


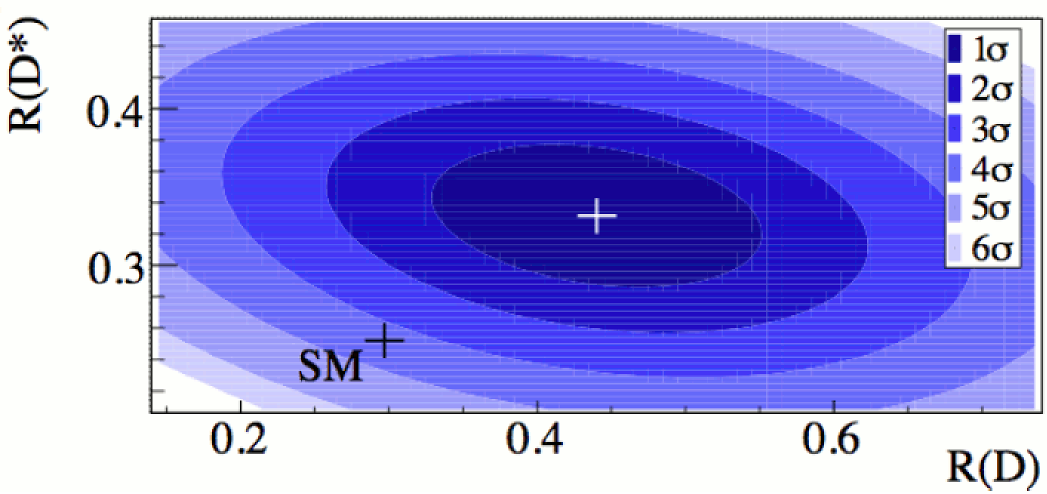
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

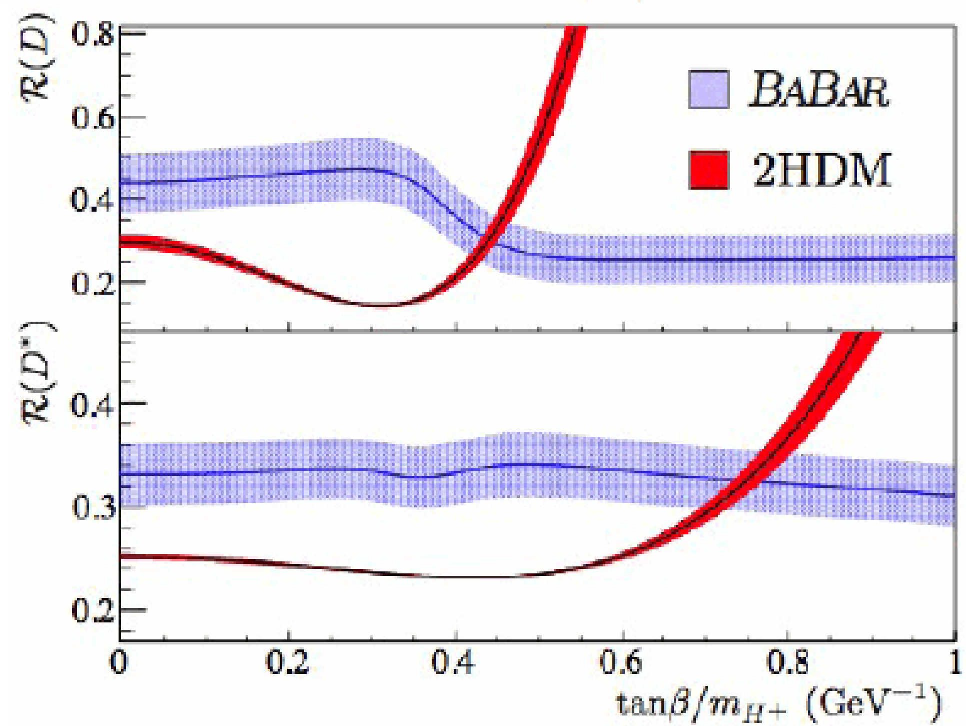
⇒ **$D\tau\nu$ and $D^*\tau\nu$ clearly observed**



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







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

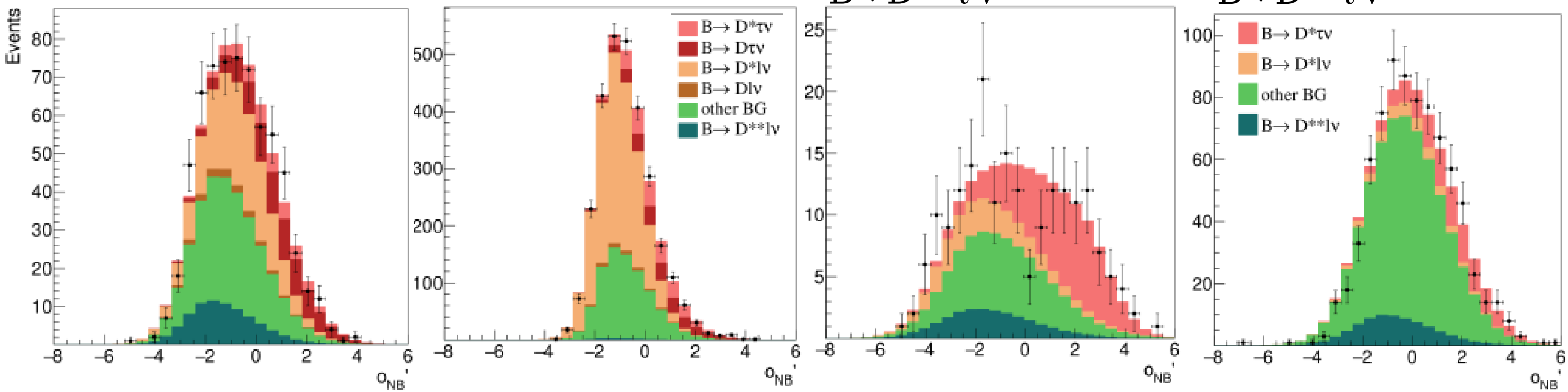
$B \to D^{(*)} \tau \nu$ at Belle

[Belle, arXiv:1507.03233]

(with hadronic tagging)

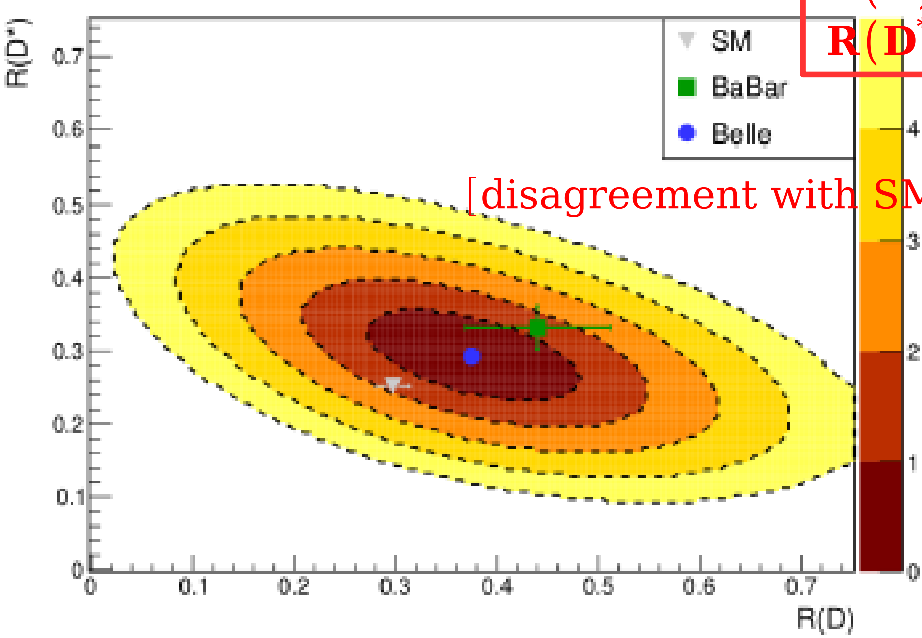
projections for large M^2_{miss} region, $N(D\tau\nu) \sim 300$, $N(D^*\tau\nu) \sim 500$

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



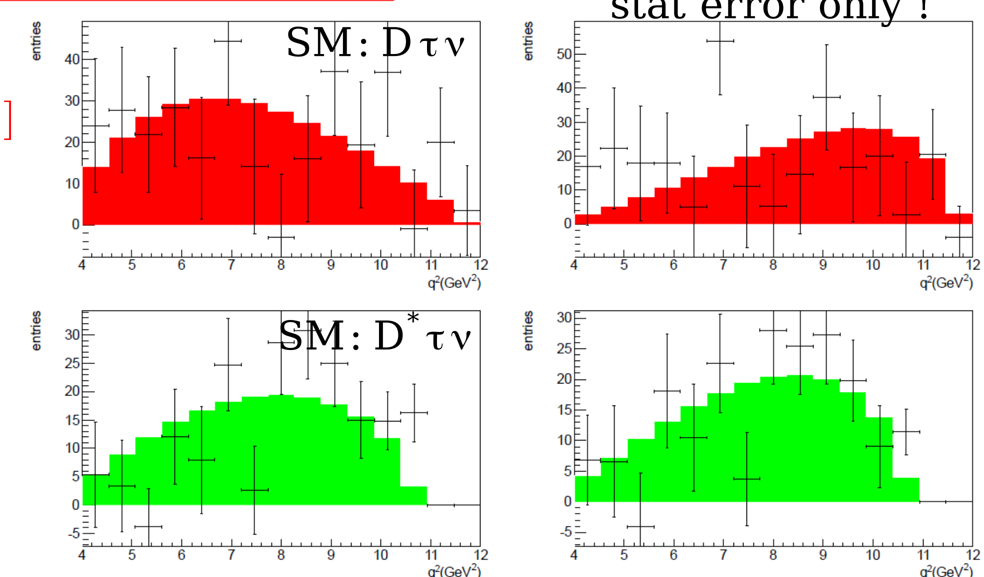
$R(D) = 0.375 \pm 0.064 \pm 0.026$

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



[disagreement with SM at 1.5 σ]

stat error only !



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

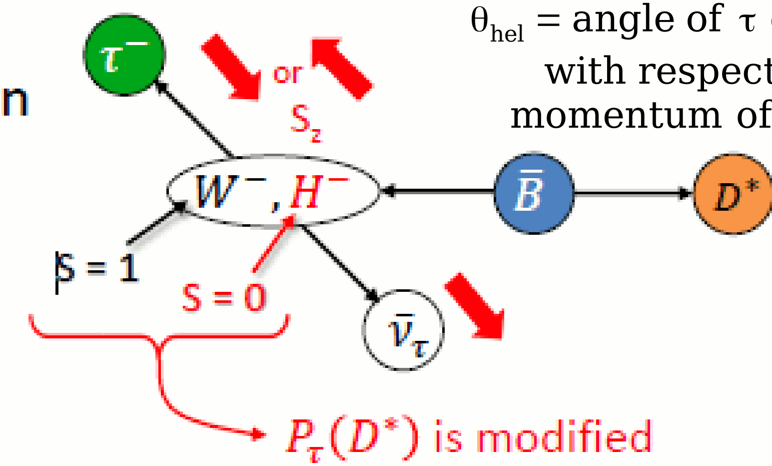
- $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$ are good polarimeter for τ polarization

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

$\Gamma^{+(-)}$ 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)

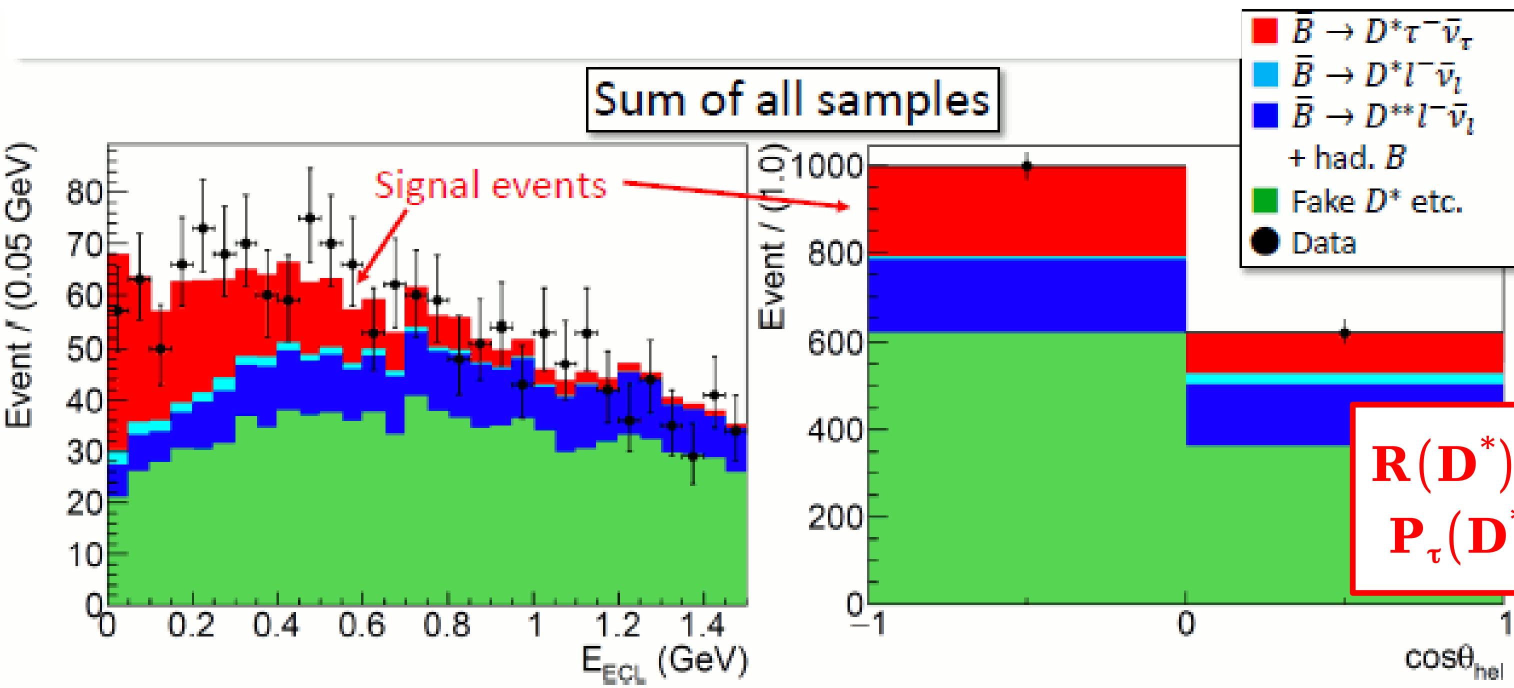


θ_{hel} = angle of τ daughter meson momentum with respect to direction opposite to momentum of $\tau\nu$ system in τ rest frame

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 $\tau^- \to \rho^- \nu_\tau$



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

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

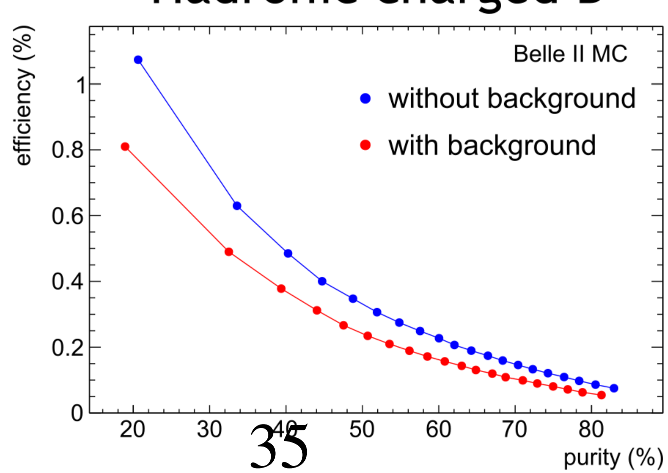
- More modes used for tag-side hadronic B than Belle, multiple classifiers

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

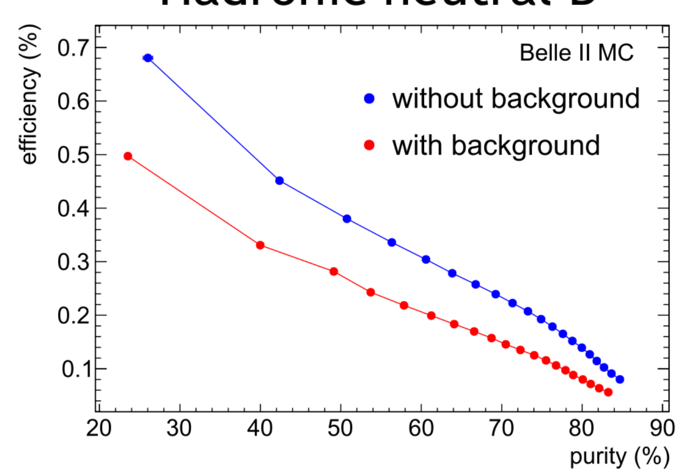
Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:

Hadronic charged B



Hadronic neutral B



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

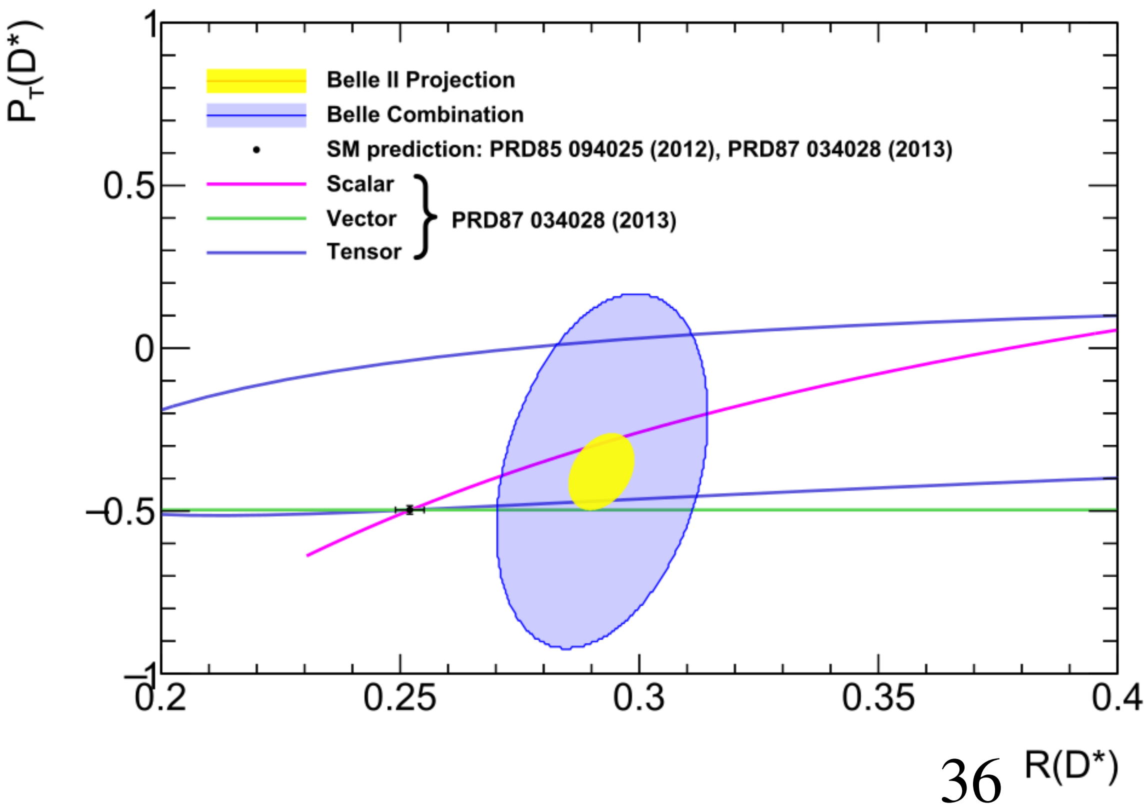
Additional observables as $P_\tau(D^*)$ ($F_L(D^*)$) and q^2 distribution can help discriminate between New Physics models

[Belle, arXiv:1612.00529]

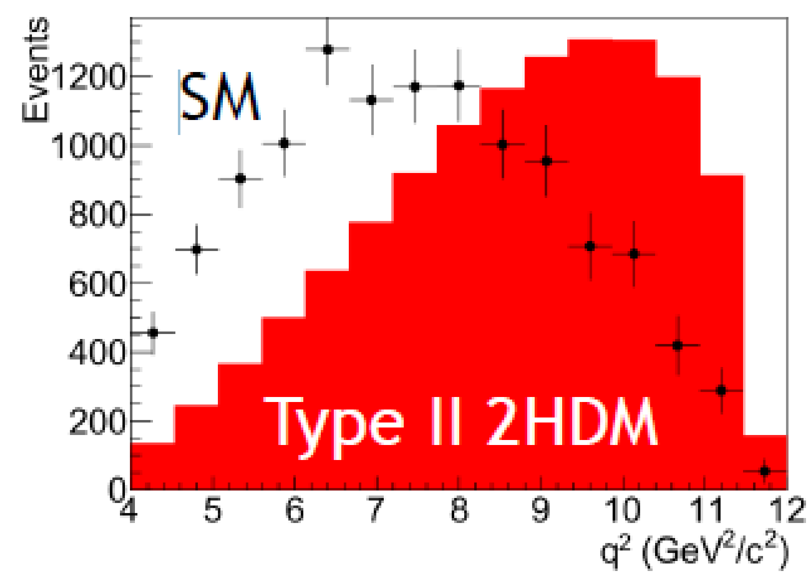
$$P_\tau(D^*) = -0.38 \pm 0.51\ ^{+0.21}_{-0.16}$$

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

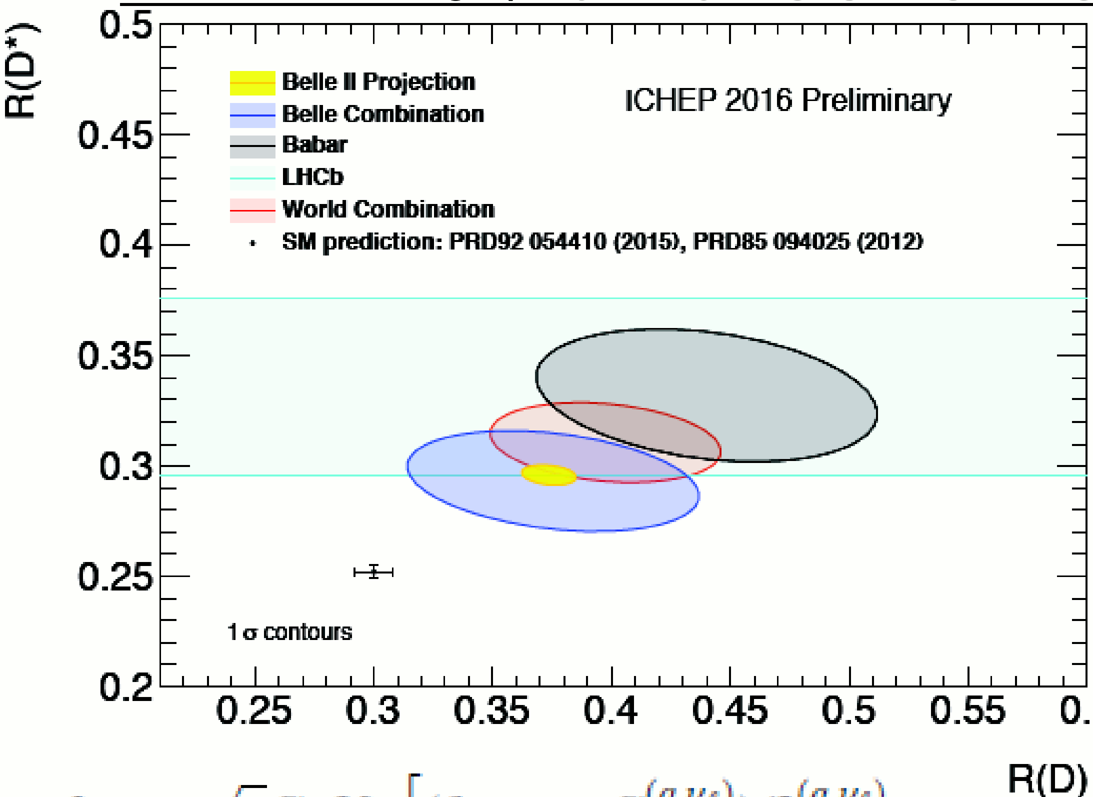
$P_\tau(D^*)$	Stat. uncertainty	Sys. uncertainty
at 5 ab^{-1}	0.18	0.08
at 50 ab^{-1}	0.06	0.04



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



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



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

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

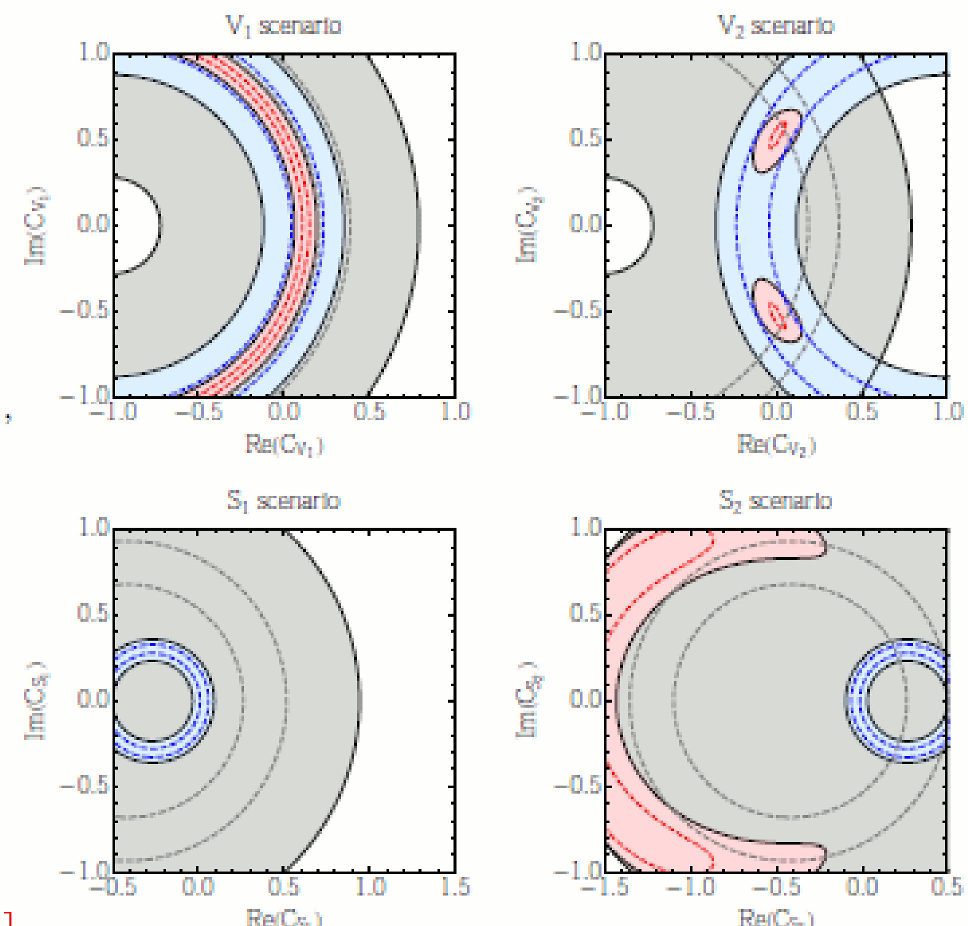
$$R(\pi) = \frac{B(B \to \pi \tau \nu)}{B(B \to \pi l \nu)}, \text{ in grey}$$

Dashed : Belle II

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

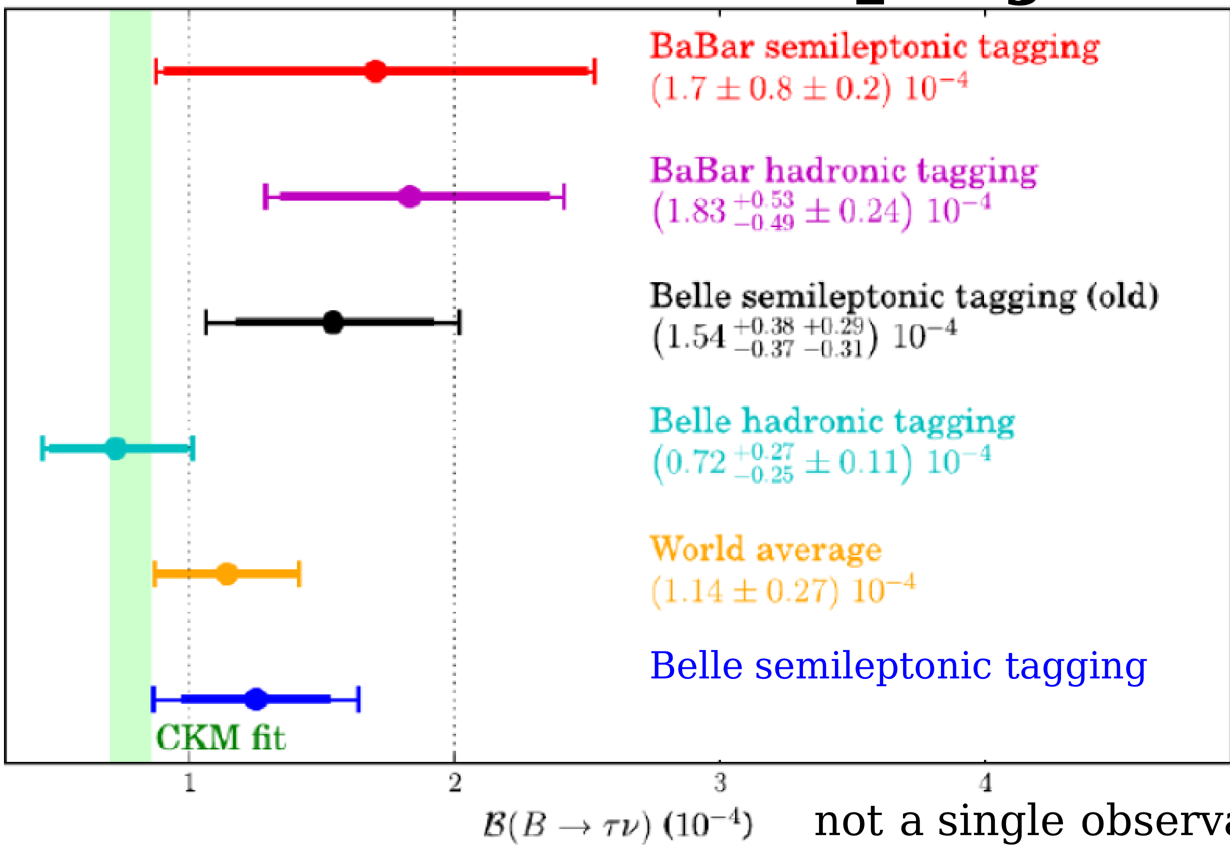
where the four-Fermi operators:

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

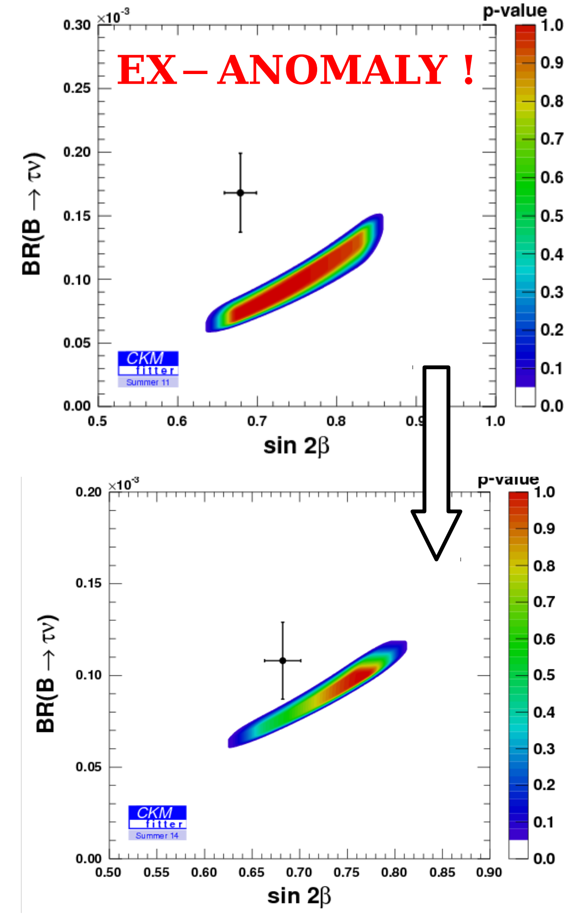


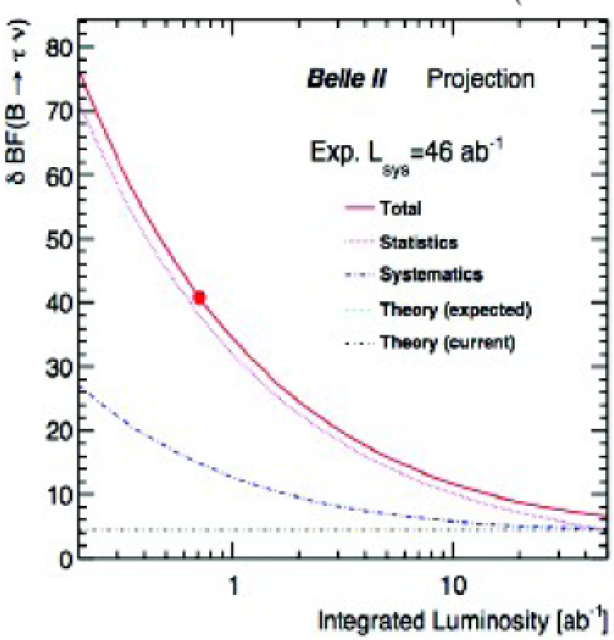
[Details in Watanabe et al, B2TiP theory]

B→τν status and projections



not a single observation ! !

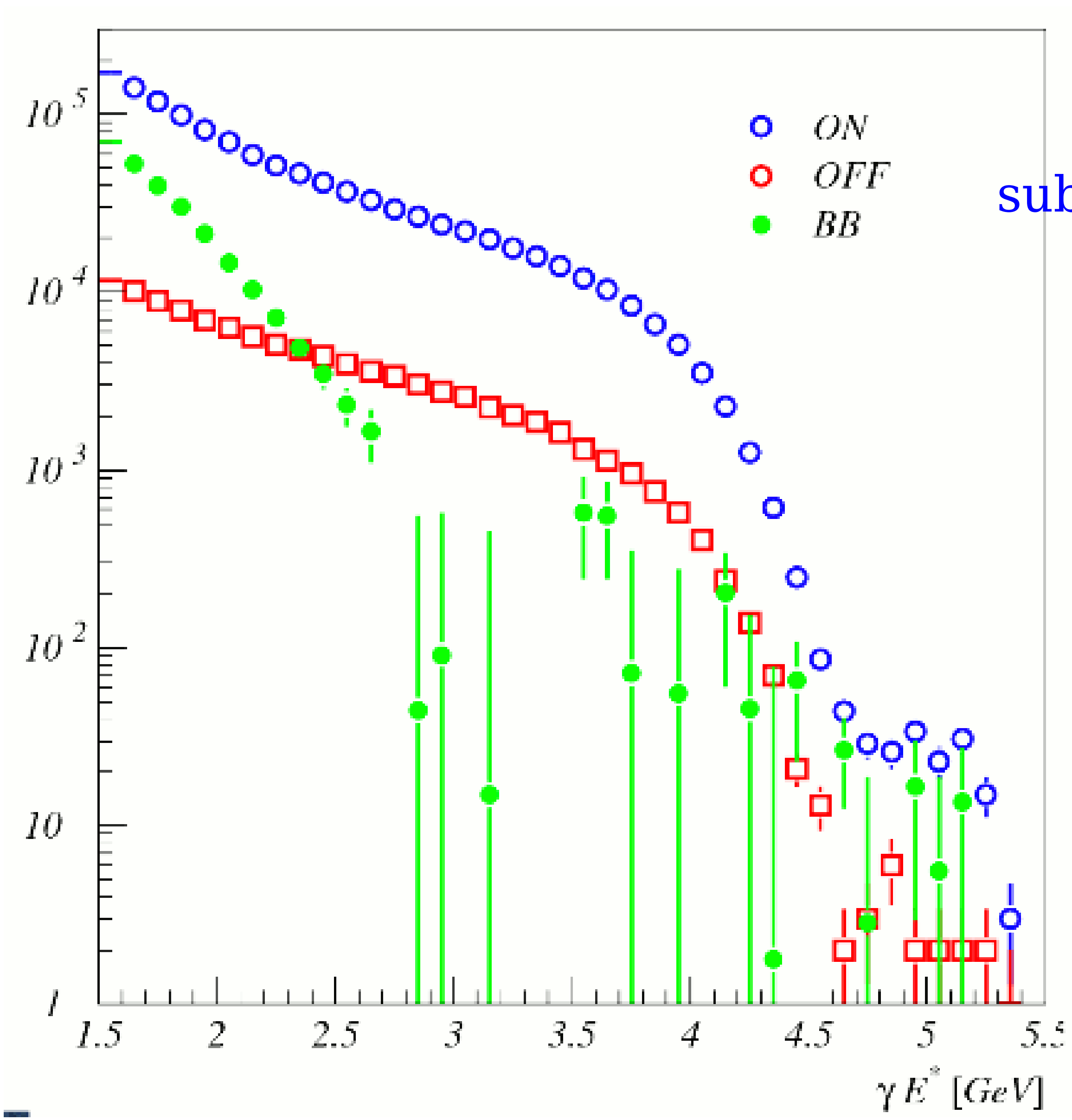




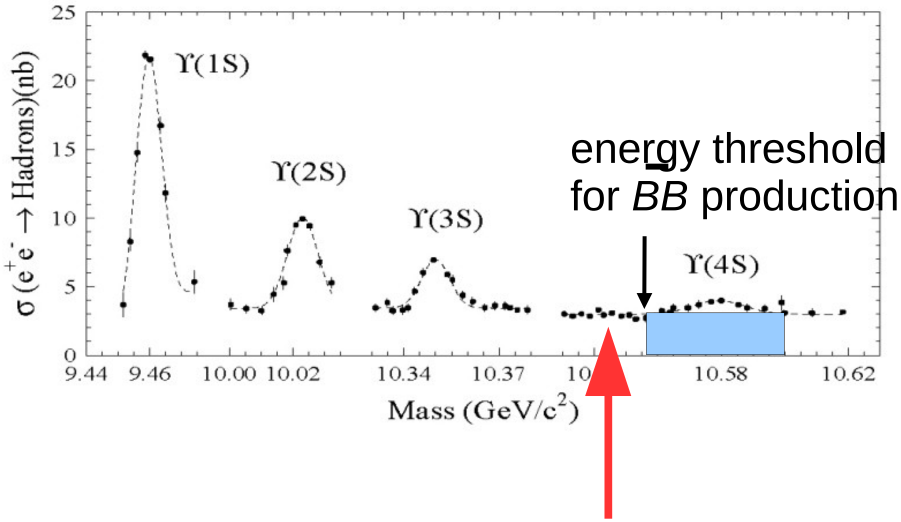
Belle II	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	19.0	(7.1, 2.2)	20.4	2.5	20.5
5 ab^{-1}	7.2	(2.7, 2.2)	7.9	1.5	8.1
50 ab^{-1}	2.3	(0.8, 2.2)	3.2	1.0	3.4
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
605 fb^{-1}	12.4	$(9.0, {}^{+3.0}_{-4.8})$	${}^{+15.6}_{-16.1}$	2.5	${}^{+15.8}_{-16.2}$
5 ab^{-1}	4.3	$(3.1, {}^{+3.0}_{-4.8})$	${}^{+6.1}_{-7.2}$	1.5	${}^{+6.3}_{-7.3}$
50 ab^{-1}	1.4	$(1.0, {}^{+3.0}_{-4.8})$	${}^{+3.4}_{-5.1}$	1.0	${}^{+3.6}_{-5.2}$

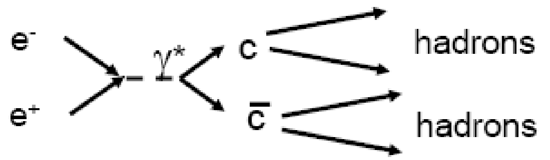
observation of B→μν is also expected (from 5 ab^{-1})

what about inclusive b → s γ ?



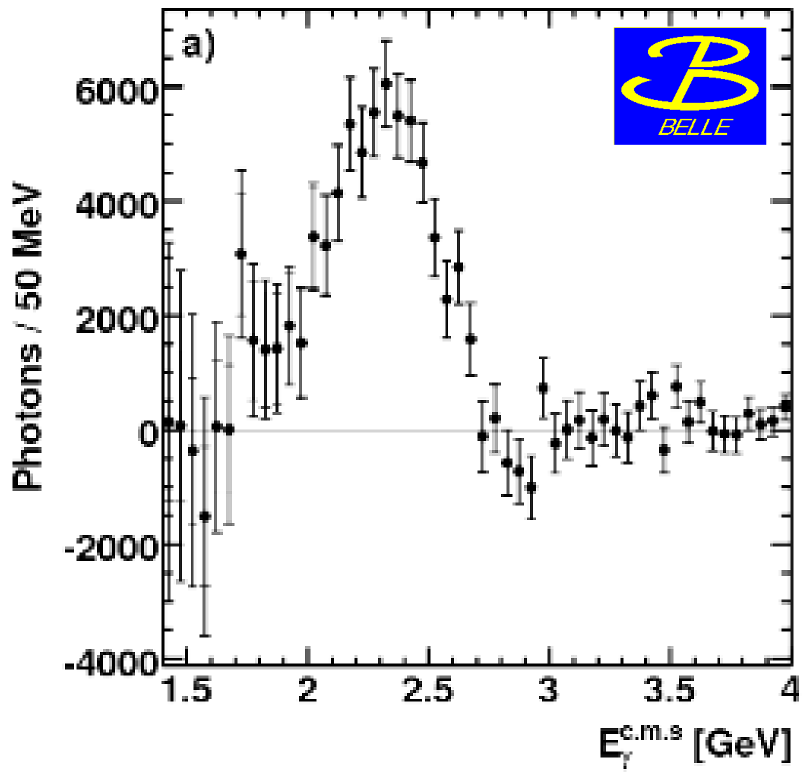
OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data

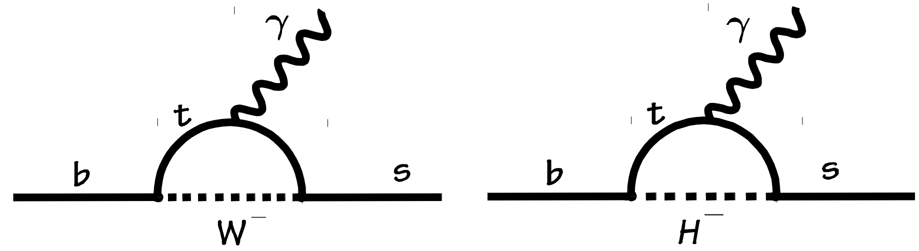


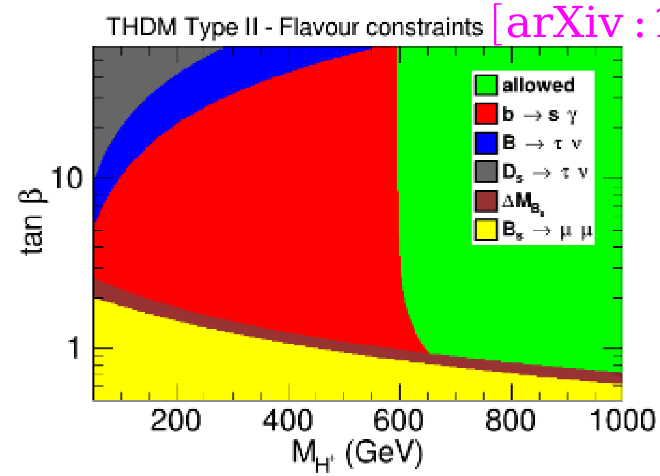


for $E_\gamma^* > 1.7$ GeV,

$\mathcal{B}(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$







[arXiv:1706.07414]

WA: $\mathcal{B}(B \to X_s \gamma) = (3.49 \pm 0.20) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

vs

SM: $\mathcal{B}(B \to X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV)

[Misiak et al, arXiv:1503.01789]

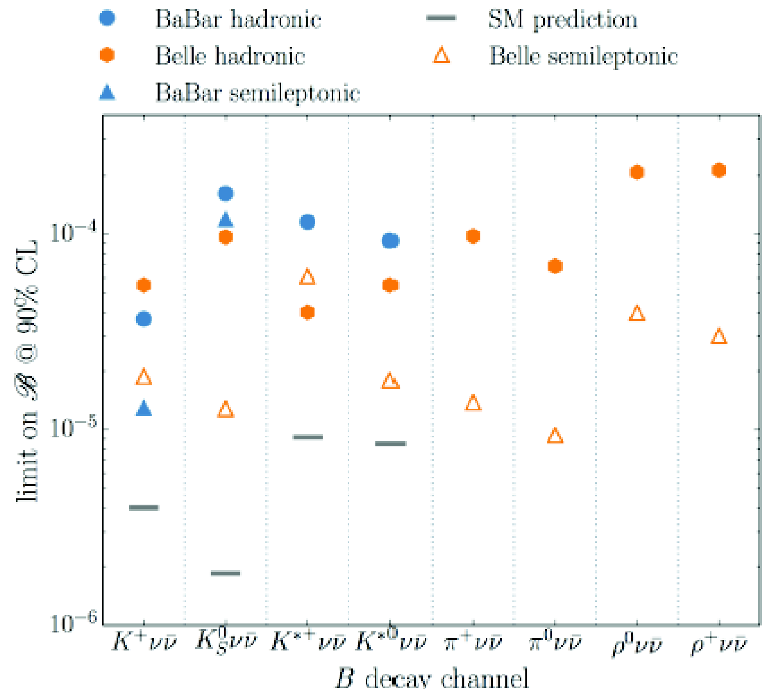
[model – dependent]

Charged Higss bound (2HDM TypeII): $M_{H^+} > 400$ GeV @ 95% C.L.

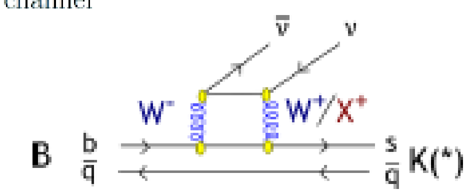
and more…

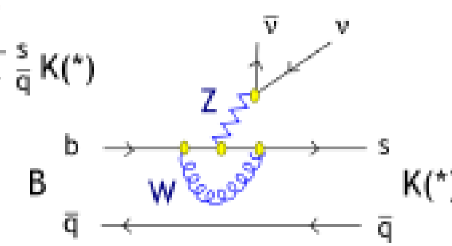
B→K$^{(*)}$ν $\bar{\nu}$

Current limits



- Standard Model:
  - Flavour changing neutral current prohibited at tree level
  - Measurement of B → K(*) $\nu\bar{\nu}$ would allow high accuracy extraction of B → 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 → K $\nu\bar{\nu}$ is identical in the detector to B → K + invisible searches for light dark matter
    - Increased B → 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
$B^+ \to K^+ \nu\bar{\nu}$	9.5%	10.7%
$B^+ \to K^{*+} \nu\bar{\nu}$	7.9%	9.3%
$B^+ \to K^{*0} \nu\bar{\nu}$	8.2%	9.6%

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