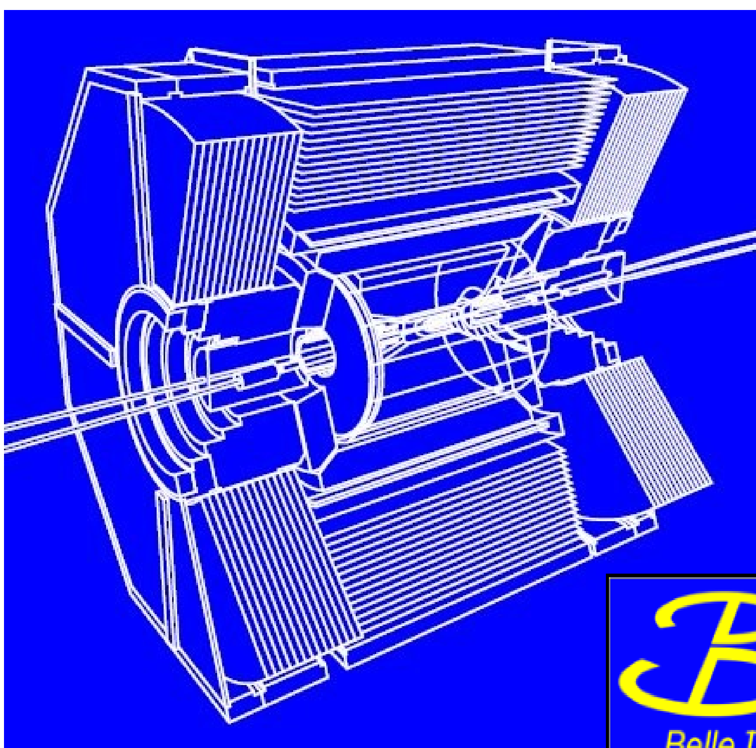
LFV+LFU in neutral-current b/c decays at Belle II

''penguin highway and the third lepton''



Karim Trabelsi

karim.trabelsi@ijclab.in2p3.fr

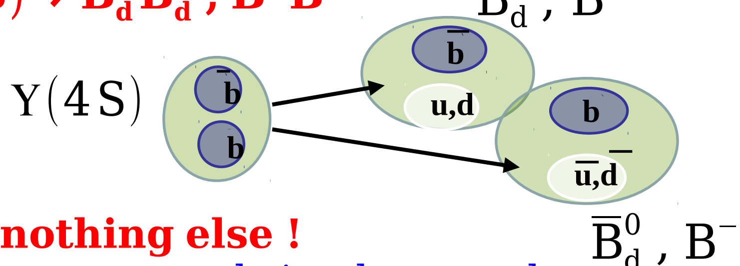
2020/09/28

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

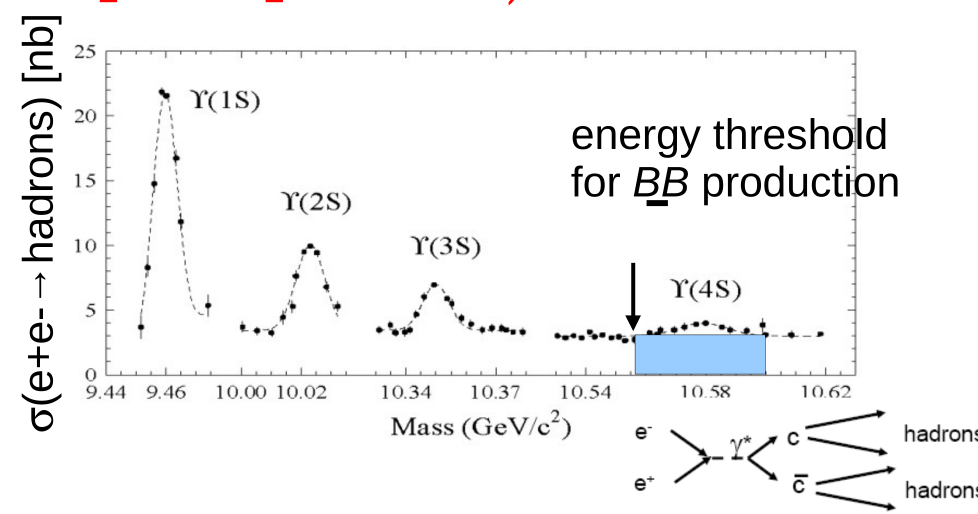
- We plan to collect (**at least**) 50 ab^{-1} of e^+e^- collisions at (or close to) the $\Upsilon(4S)$ resonance, so that we have:
  - **a (Super) B-factory ($\sim 1.1 \times 10^9$ $B\overline{B}$ pairs per ab^{-1})**

''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})**

(**but also charmonium, X, Y, Z, pentaquarks, tetraquarks, bottomonium...**)

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

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

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

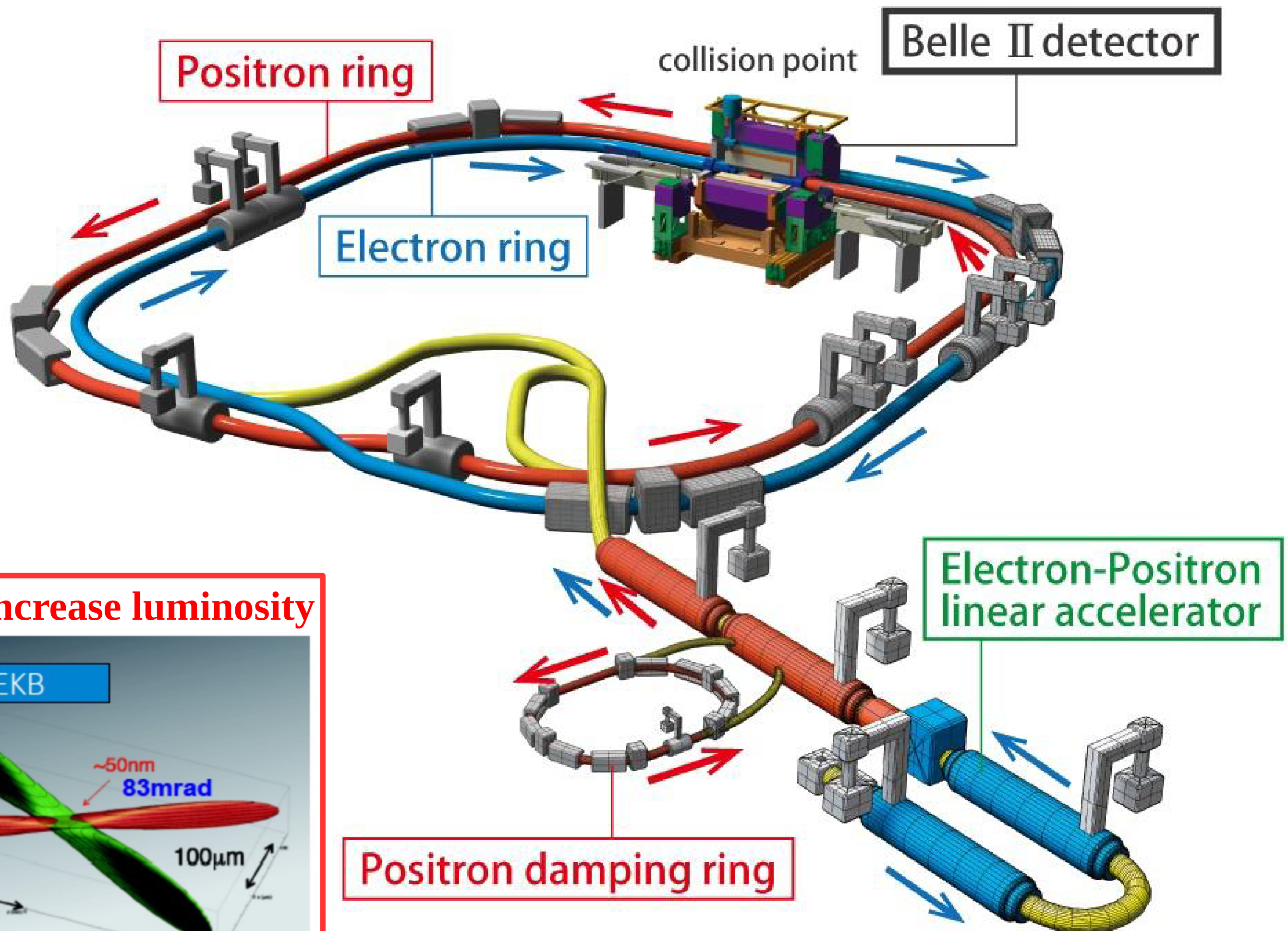
Background, Optics commissioning
Feb - June **2016**
Brand new 3 km positron ring

Phase 2: Pilot run

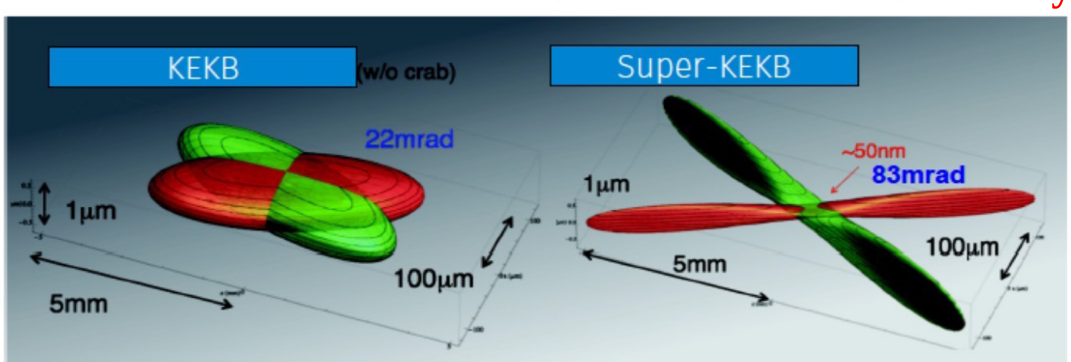
Superconducting Final Focus
add positron damping ring
First Collisions $(0.5\ fb^{-1})$
April 27 - July 17, **2018**

Phase 3: Physics run

Since April, **2019**



Nano-beams and more beam current to increase luminosity



	E (GeV) LER/HER	β*y (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 $8 \times 10^{35}\ cm^{-2} s^{-1}$

⇒ cumulate 50 ab^{-1} by ~2030

SuperKEKB/Belle II status

- successfully introduced this spring, crab waist for LER/HER
- despite difficult conditions, continued to take data since March !

beyond to $2.4\times10^{34}/cm^2/s$!

$> 1\,fb^{-1}$ per day

June 20, 2020

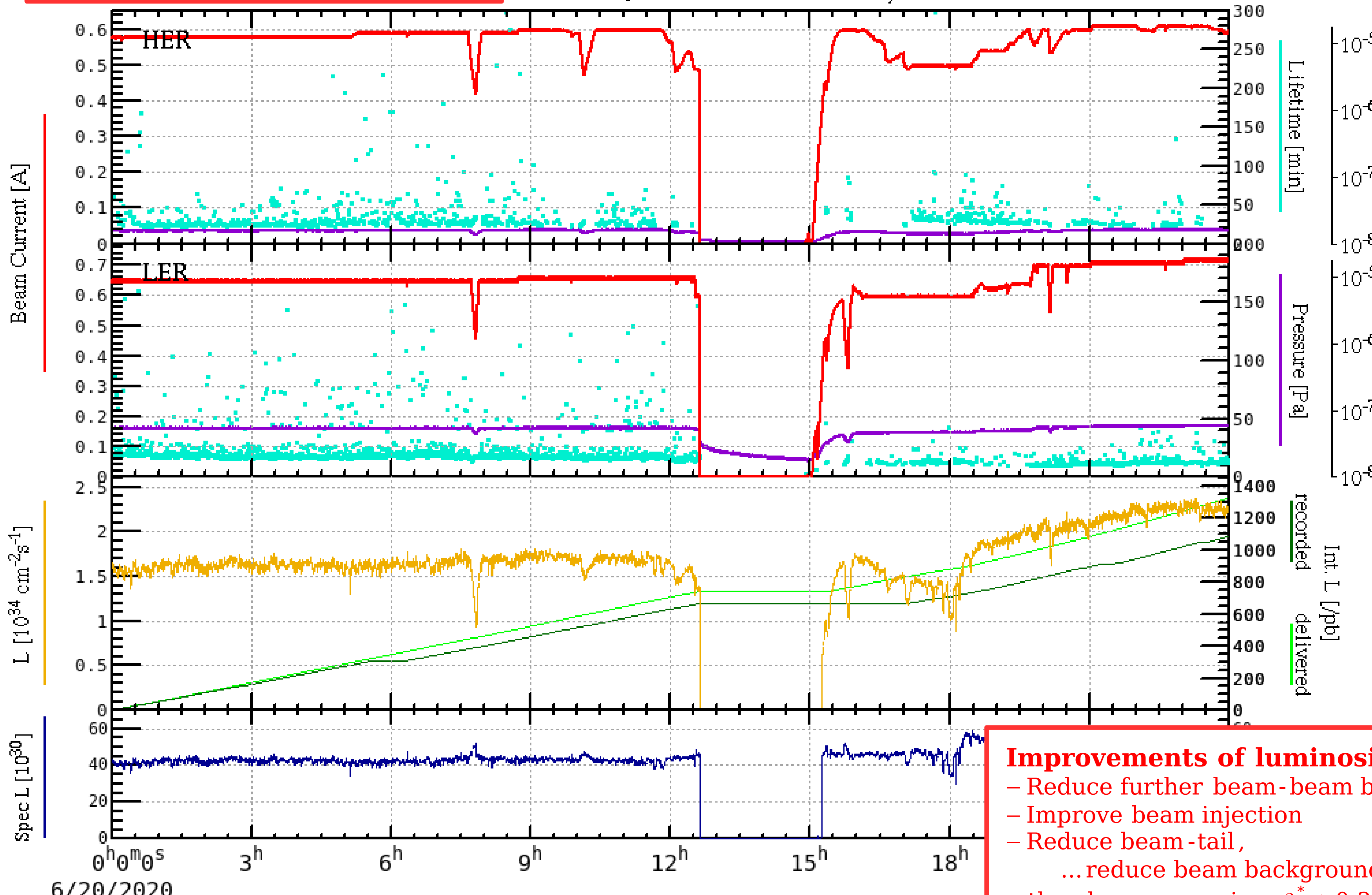
currents ~ 0.6−0.7 A

record of KEKB/Belle
$2.1\times10^{34}/cm^2/s$ currents > 1 A
record of PEPII/BaBar
$1.2\times10^{34}/cm^2/s$ currents > 2 A

Peak L	2.393 [$10^{34}/cm^2/s$]	@ 2020-06-20 23:18
Int. L/day	1084.64 / 1324.42 [/pb]	

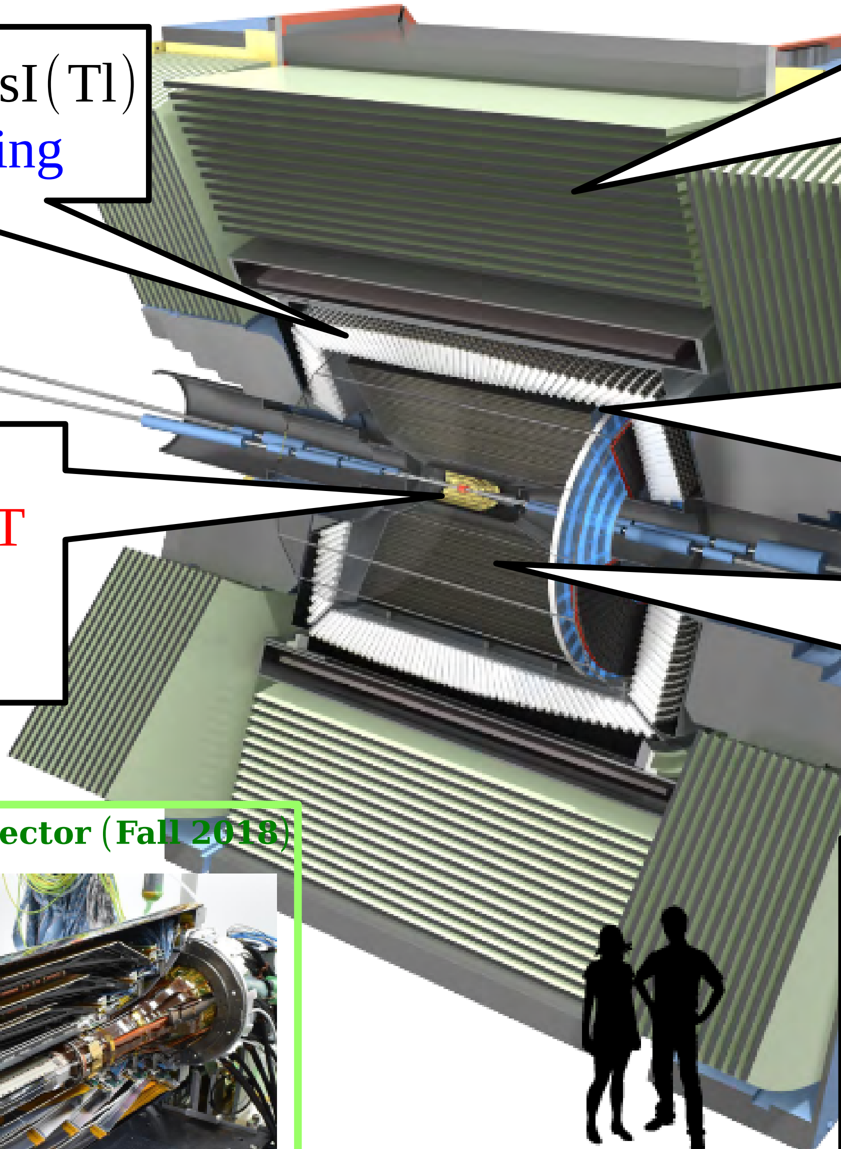
06/19/2020 23:59 - 06/20/2020 23:59 JST

HER I_{peak}:	610.1 [mA]	$\beta_{x/y}^*$:	60./ 1.00 [mm]	n_b:	978	Physics Run
LER I_{peak}:	720.5 [mA]	$\beta_{x/y}^*$:	80./ 1.00 [mm]	n_b:	978	Physics Run



Improvements of luminosity performance
- Reduce further beam-beam blowup
- Improve beam injection
- Reduce beam-tail,
  ... reduce beam background
- then keep squeezing: $\beta_y^* \rightarrow 0.3$ mm

Belle II detector



EM Calorimeter: CsI(Tl)
waveform sampling

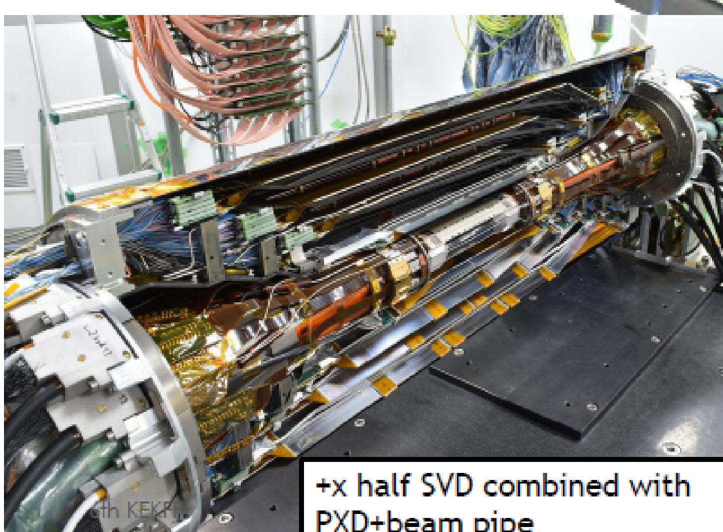
K_L and muon detector
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (endcaps)

Particle Identification
Time-Of-Propagation counter (barrel)
Prox. focusing Aerogel RICH

Vertex Detector
1/2 layers DEPFET
+
4 layers DSSD

Central Drift Chamber
He(50%):C_2H_6(50%)
small cells, long level arm, fast electronics

Installation of Vertex Detector (Fall 2018)



on-going DAQ upgrade
(to be installed in 2020-2021)
PCIe40 board, capable of reading via high speed optical links and to write to computer at rate of 100 Gb/s:
limited number of boards (20) enough **to read entire Belle II detector**
(P.Robbe, D.Charlet et al)

considering now VTX upgrade (2025 or later)
(also luminometer LumiBelle2, P.Bambade et al)

Belle(II), LHCb side by side

Belle (II)

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

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

(flavour tagging, B tagging, missing energy)

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

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

LHCb

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

production of B^+, B^0, B_s, B_c, Λ_b...

but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

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

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

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

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

⇒ lower trigger efficiencies

B mesons live relativey long

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

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

(displaced vertices)

data taking period(s)

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

[2019-...] = ...

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

[run II: 2015-2018] = 6 fb^{-1}

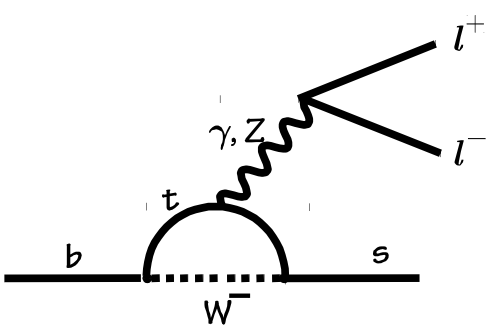
(near) future

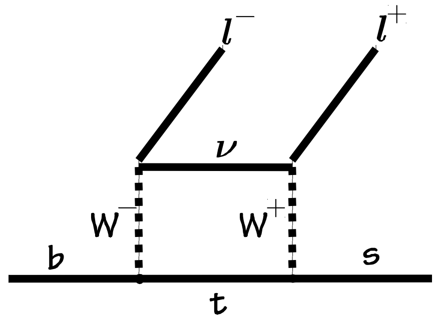
[Belle II from 2019] → 50 ab^{-1}

[LHCb upgrade from 2021]

Lepton (non) universality using $B^+ \to K^{(*)} l^+ l^-$ decays

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



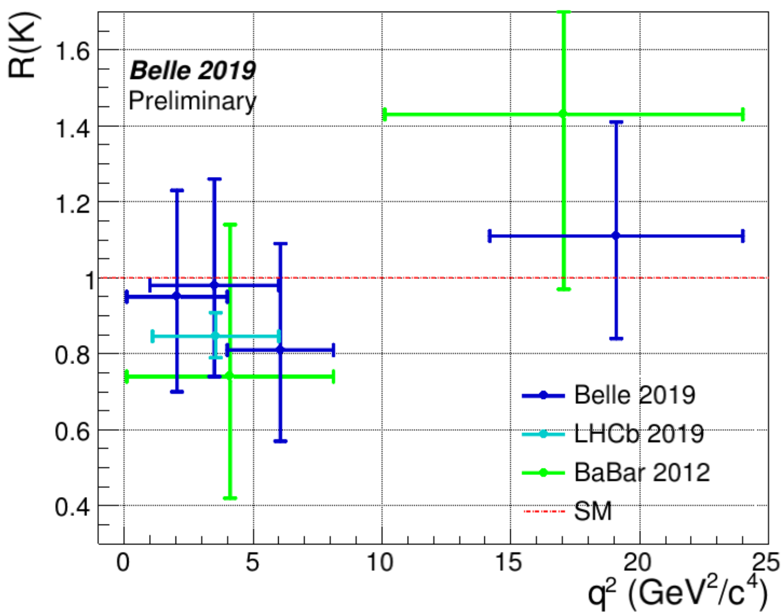


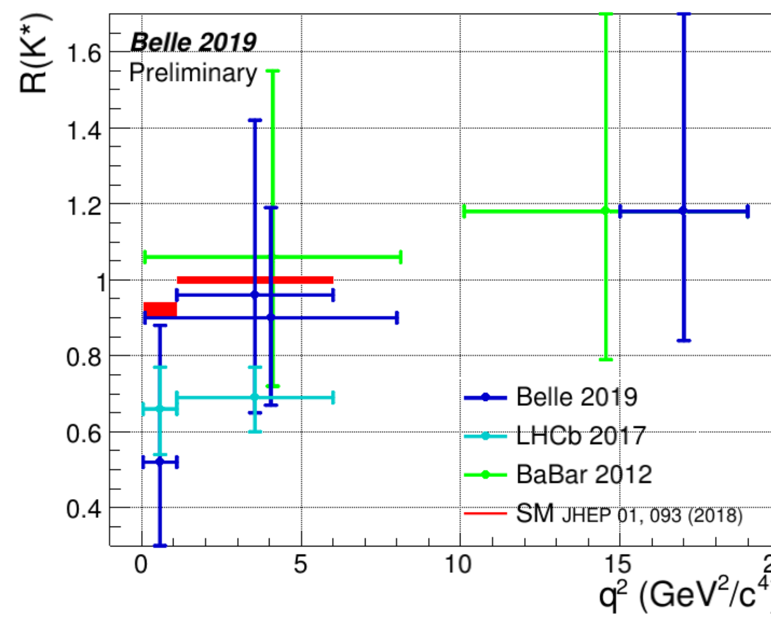
The ''clean'' Lepton Flavor Universality ratios:

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

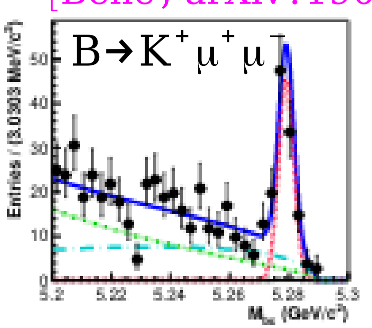
SM prediction very robust: $R_K(SM) = 1$

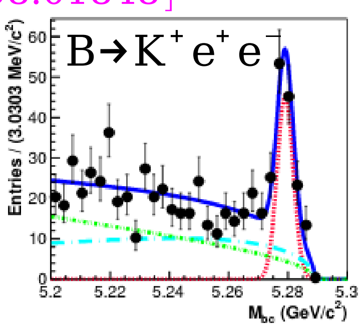
[up tiny QED and lepton mass effects]

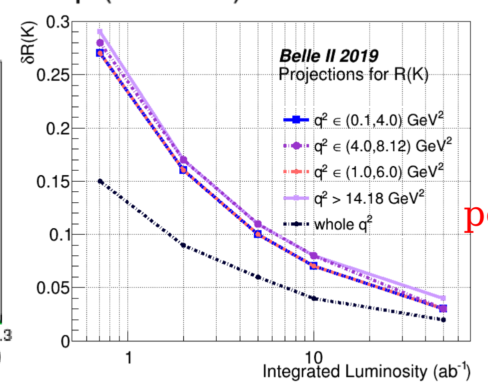




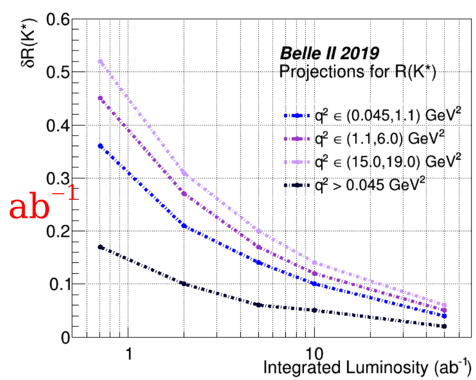
[Belle, arXiv:1908.01848]







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



Lepton (non) universality using $B^+ \to K^{(*)} l^+ l^-$ decays

Model candidates

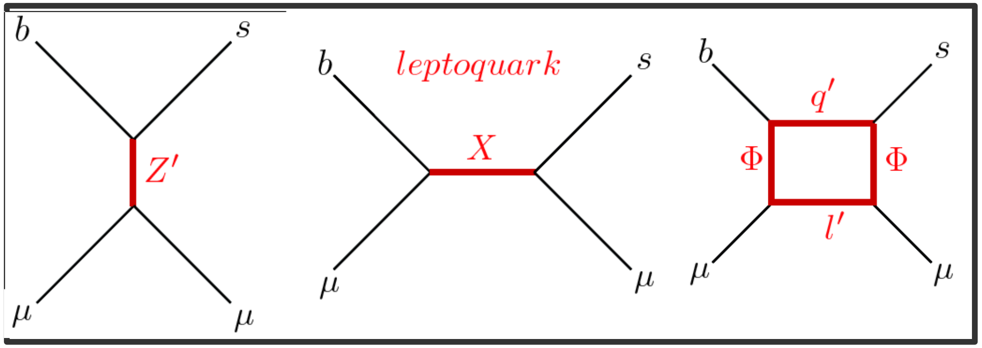
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **Models with leptoquarks**

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

✧ **Models with loop induced effective operator**

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



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

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

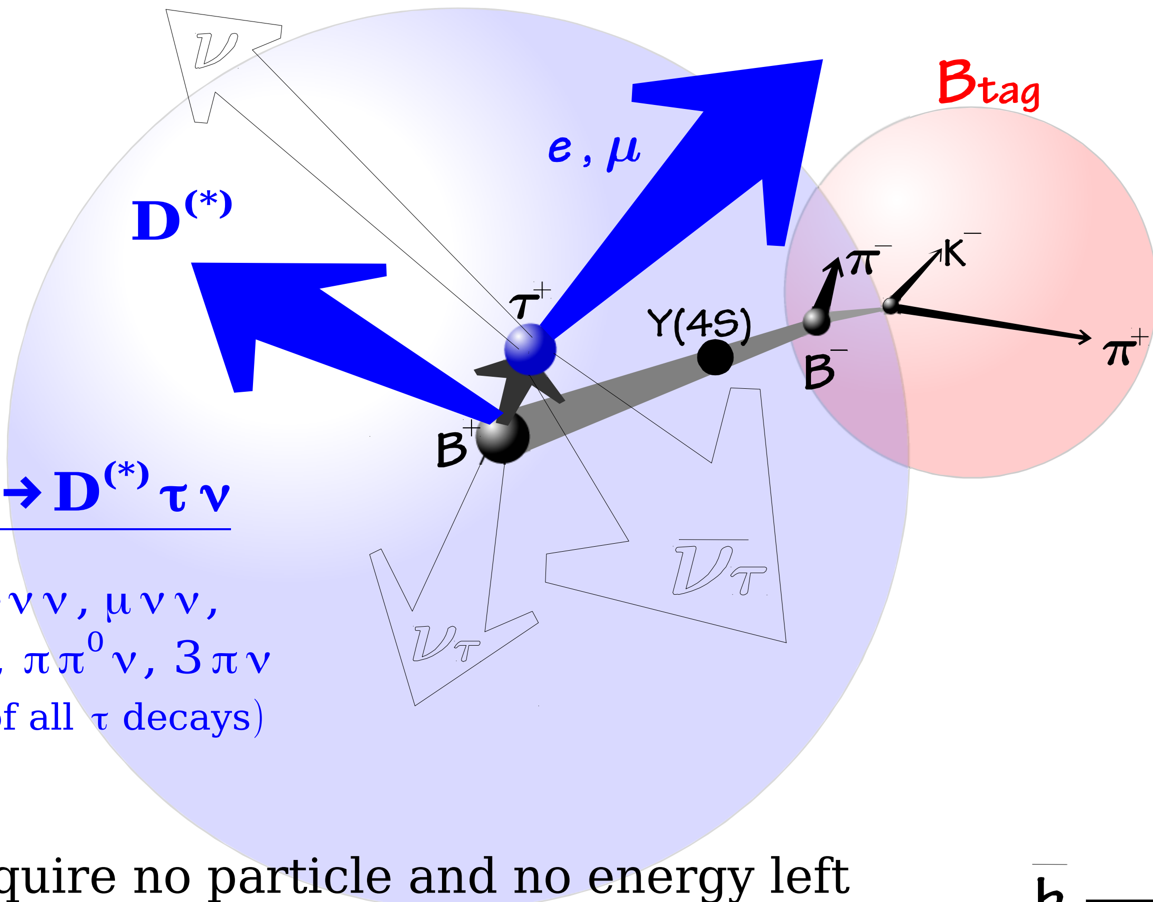
(see D.Becirevic, S.Descotes-Genon's work)

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

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

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

(another B anomaly !)



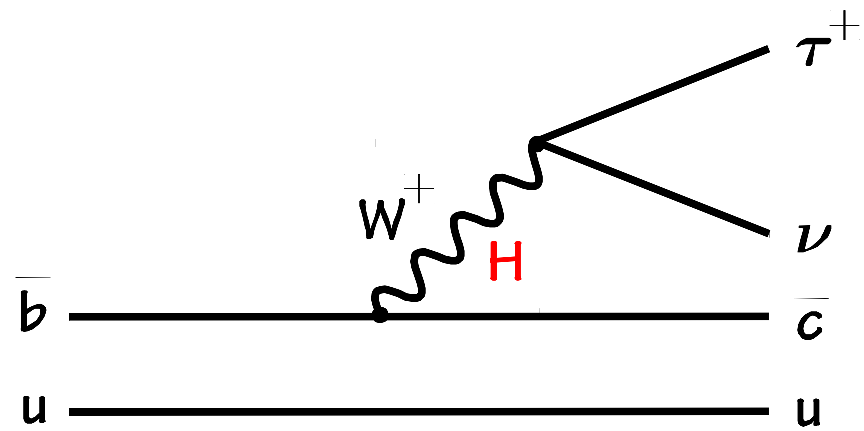
$B_{sig} \to D^{(*)} \tau \nu$

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

B_{tag}

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

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



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

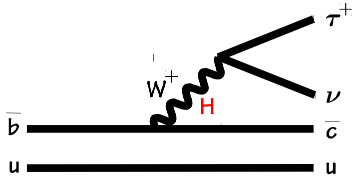
main signal-background discriminator

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

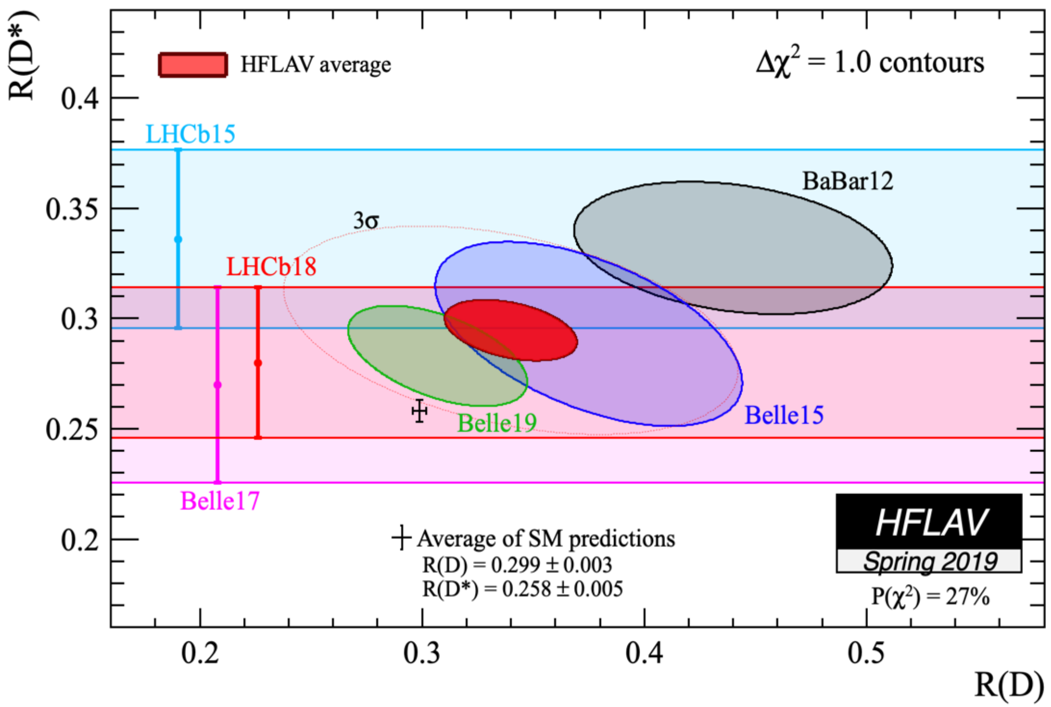
$$\text{2HDM (type II)}: \mathcal{B}(B \to D\tau^+\nu) = G_F^2\,\tau_B\,|V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

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

Belle 15 had tag

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

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

Belle 19 SL tag

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

LHCb

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

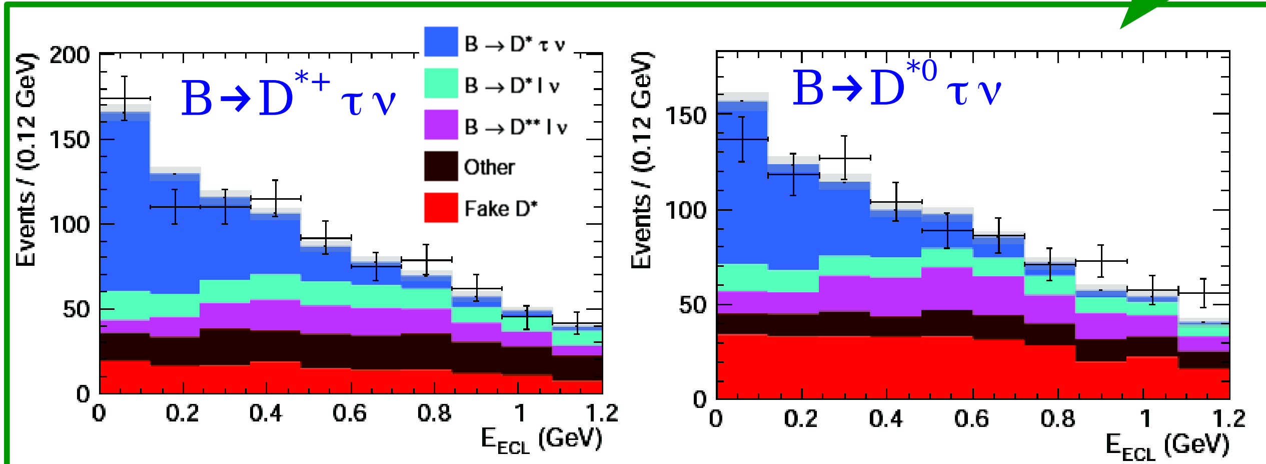
$R(D^*) = 0.280 \pm 0.018 \pm 0.029$

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

semi-leptonic tag, PRL 124, 161803 [arXiv:1904.08794]



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

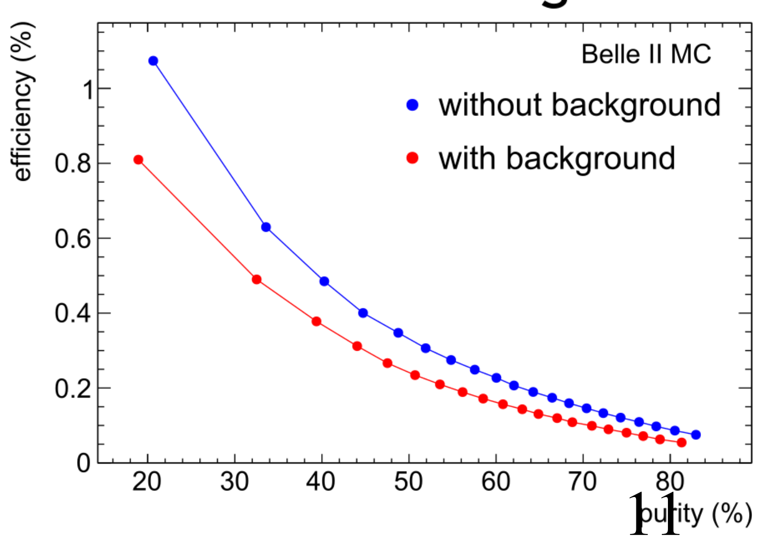
- More modes used for tag-side hadronic B than Belle, multiple classifiers

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

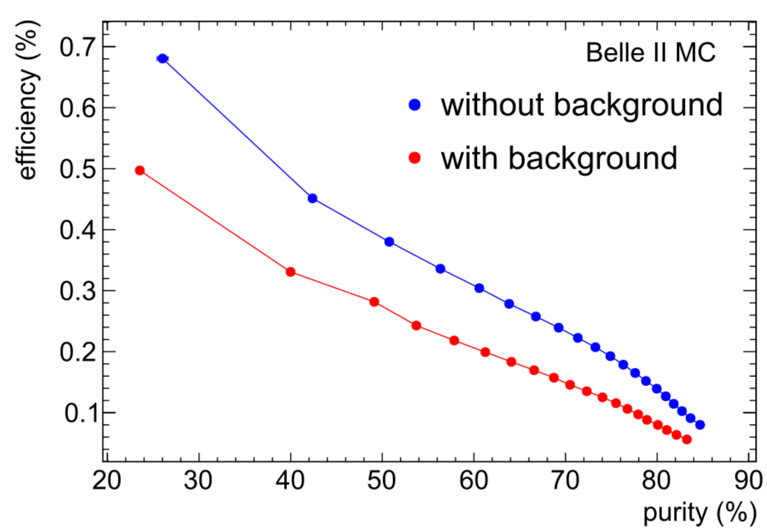
Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:

Hadronic charged B



Hadronic neutral B



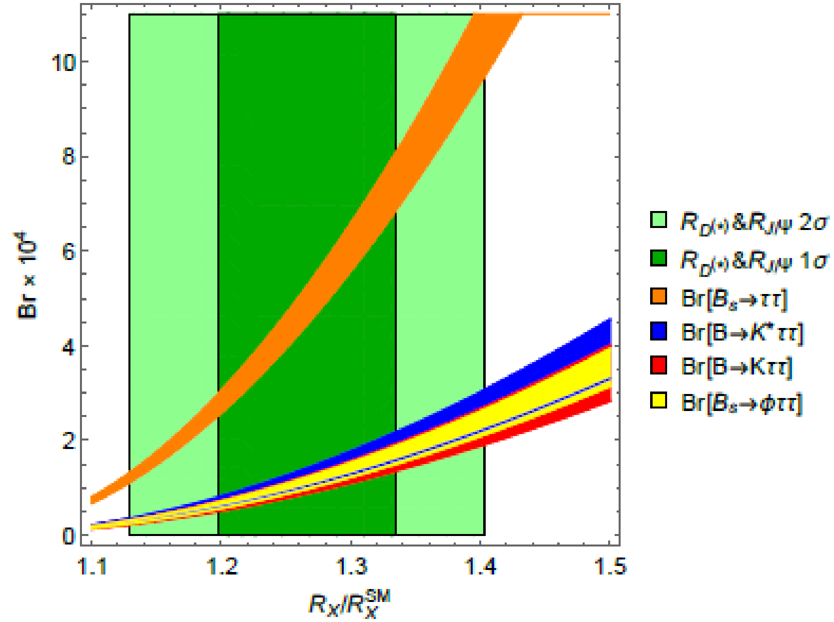
$B \to K^{(*)} \tau\tau$

[B.Capdevila et al, arXiv:1712.01919]

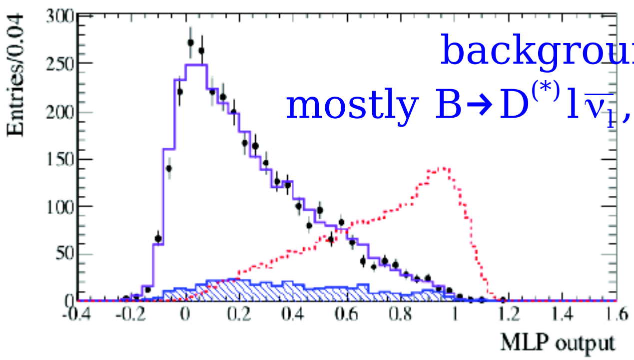
q^2 range for predictions for $B \to H \tau^+ \tau^-$: from $4\, m_\tau^2$ (~ 12.6 GeV^2) to $(m_B - m_H)^2$
to avoid contributions from resonant decay through $\psi(2S)$, $B \to H \psi(2S)$, $\psi(2S) \to \tau^+ \tau^-$
predictions restricted to $q^2 > 15$ GeV^2:

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

greatly enhanced in NP models...



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



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

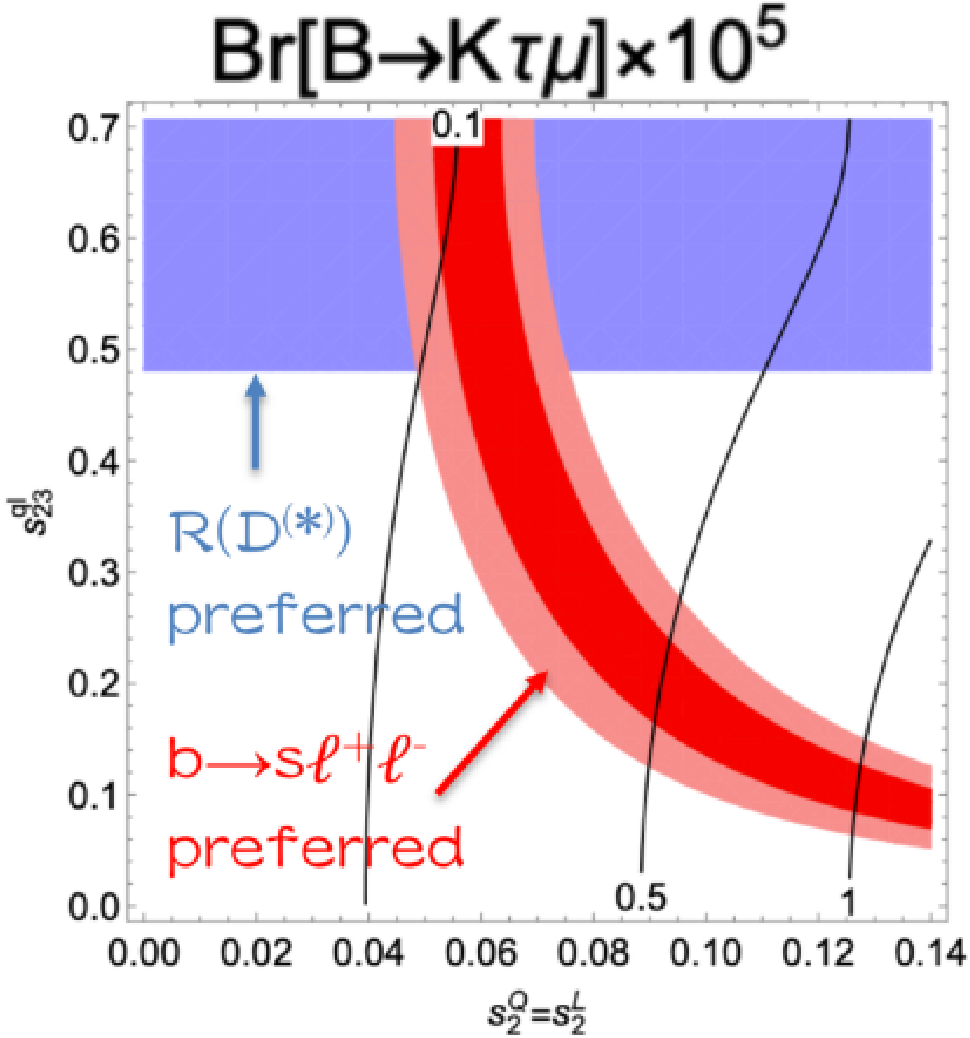
BaBar's result with had tag: $B(B^+ \to K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3}$ at 90% CL

[Belle II, arXiv:1808.10567]

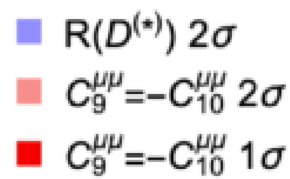
Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+ \tau^+ \tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0

this is the result with had tag.... (on-going thesis at IJCLab from G.de Marino)

R(D*) and b→sμμ ⇒ B→Kτμ



L.Calibbi et al, arXiv:1709.00692



Key Features of PS[3]

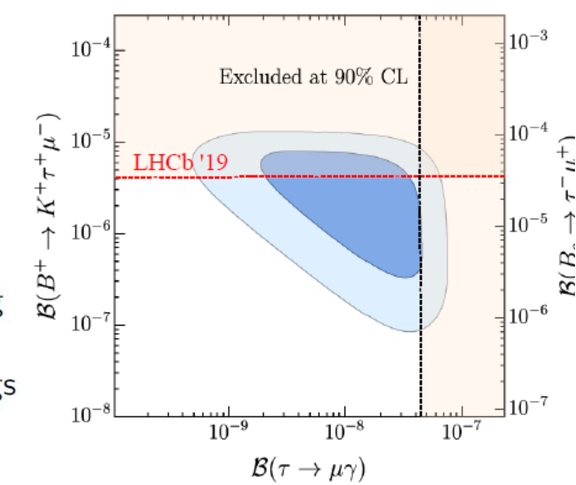
Bordone, Cornella, Fuentes-Martin, Isidori (2017), (2018)

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



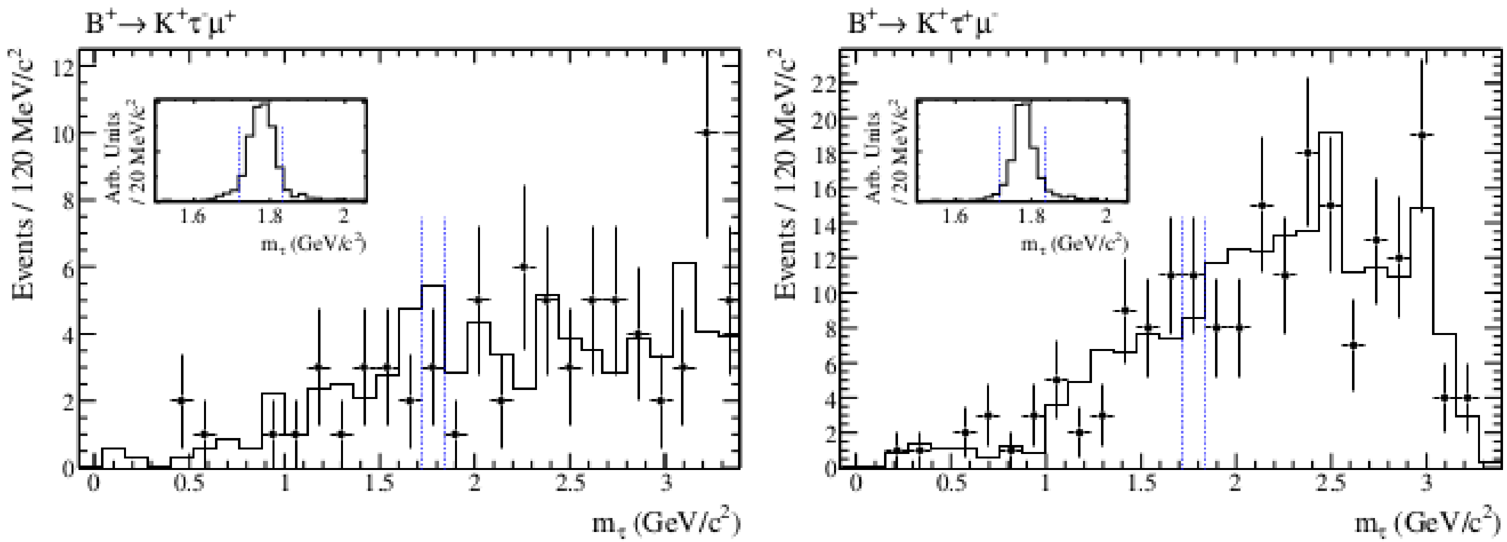
LFV $B \to K \tau l$ ($l = e, \mu$) decays

[BaBar, arXiv:1204.2852]

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

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

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



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

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

[LHCb, arXiv:2003.04352]

Search for the lepton favour violating decay $B^+ \to K^+ \mu^- \tau^+$ using B_{s2}^{*0} decays, $B_{s2}^{*0} \to B^+ K^-$

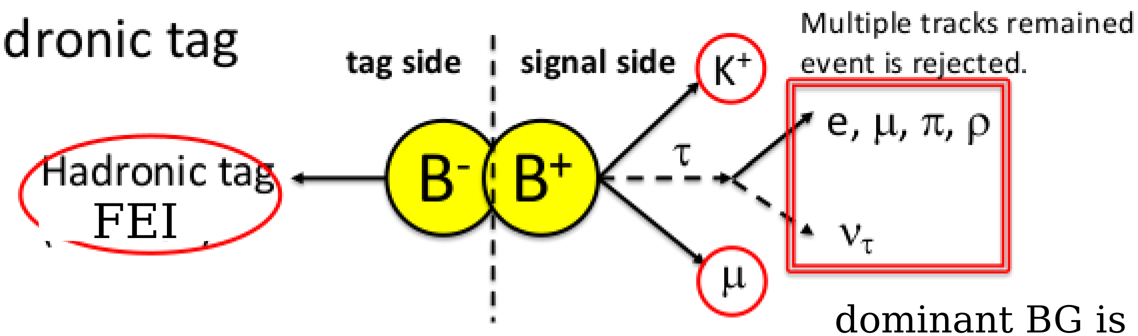
$Br(K^+ \tau^+ \mu^-) < 3.9 \times 10^{-5}$ at 90% CL

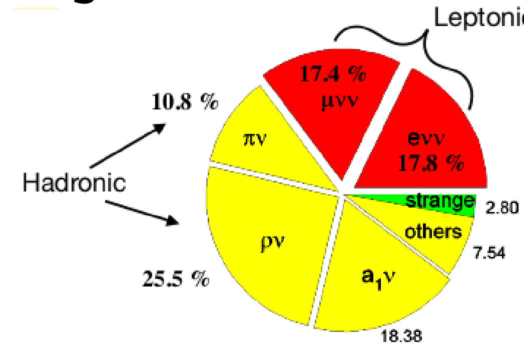
⇒ can we do better ? combining hadronic tag with an more inclusive tag ?...

LFV $B \to K \tau l$ ($l = e, \mu$) decays [Belle, S.Watanuki]

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

- Hadronic tag





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

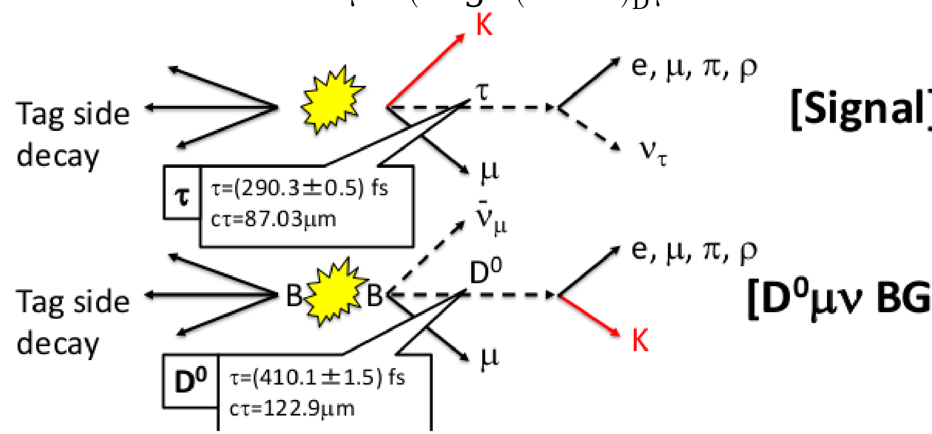
recoil mass of τ unique to $B \to K\tau^+ l^-$ mode

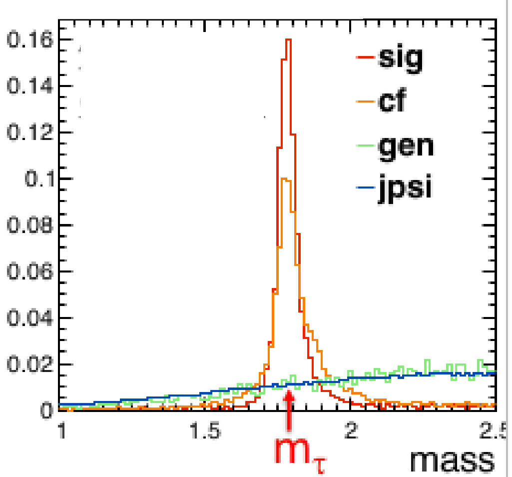
usually another neutrino companion ($B \to \tau\nu$, $D^*\tau\nu$...)

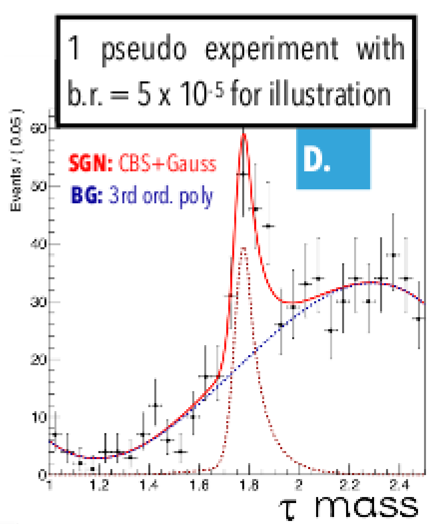
$$m_\tau^2 = m_B^2 + m_{Kl}^2 - 2(E_B^* E_{Kl}^* - |\vec{p}^{\,*}_{B_{sig}}||\vec{p}^{\,*}_{Kl}|\cos\theta)$$

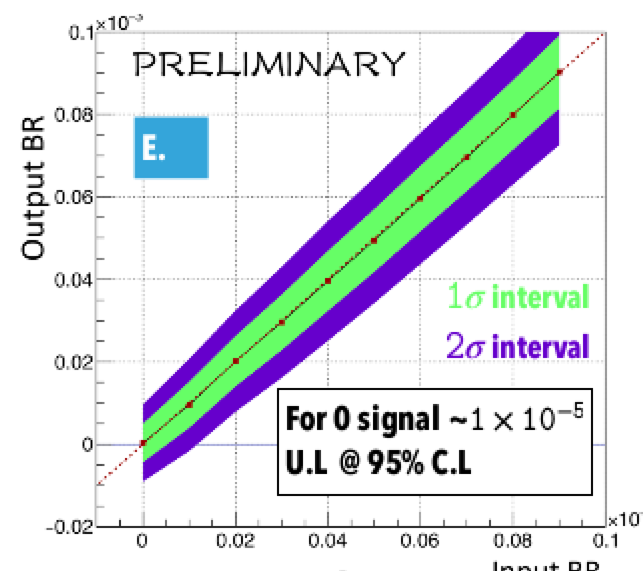
E^*_{beam} $\quad \sqrt{(E^*_{beam})^2 - m_B^2}$

θ angle between $\vec{p}^{\,*}_{B_{sig}}$ ($= -\vec{p}^{\,*}_{B_{tag}}$) and $\vec{p}^{\,*}_K$





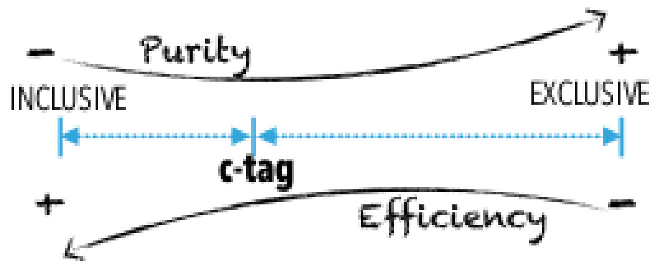




Stat. Error only! ⇒ **can we do better ?**

B-tagging ... [Belle (II), G.de Marino]

standard tagging methods: hadronic and semi-leptonic
other possibilities ? semi-inclusive, a.k.a **c-tag** ...
⇒ B-tagging ... but better to talk about charged B tag or neutral B tag



- semi-inclusive, intermediate tagging method
- way to probe the tag side

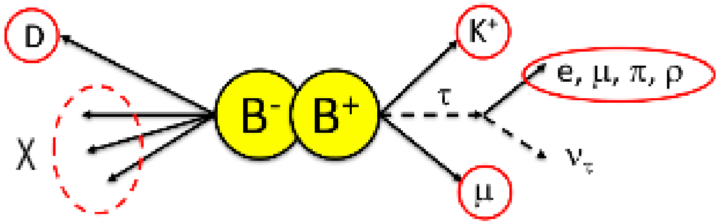
	$B^+ \to$	$B^0 \to$
$D^0 X$	$(8.6 \pm 0.7)\%$	$(8.1 \pm 1.5)\%$
$\overline{D}^0 X$	$(79 \pm 4)\%$	$(47.4 \pm 2.8)\%$
$D^+ X$	$(2.5 \pm 0.5)\%$	$(< 3.9\%)$
$D^- X$	$(9.9 \pm 1.2)\%$	$(36.9 \pm 3.3)\%$
$D_s^+ X$	$(7.9 \pm 1.4)\%$	$(10 \pm 2)\%$
$D_s^- X$	$(1.10 \pm 0.40)\%$	$(< 2.6\%)$
$\Lambda_c^+ X$	$(2 \pm 1)\%$	$(< 3.1\%)$
$\Lambda_c^- X$	$(3 \pm 1)\%$	$(5.0 \pm 2.0)\%$

- Exploit the high B.R. of $B^+ \to \overline{D}^0 X$

→ reconstruct D^0 + inclusive X

- Application in $B \to K \tau l$, where the topology with K+l allows looser reconstruction in B_{tag} side

1) D is reconstructed
2) Primary K and l, and τ decay prong are chosen
3) ''D + X'' provides the tag side B

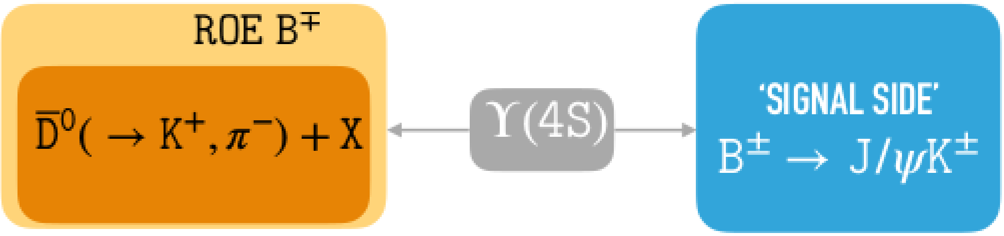


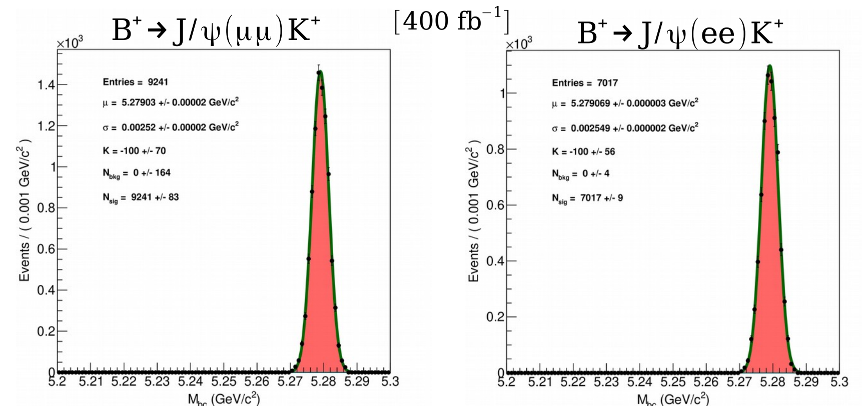
⇒ promising avenue as much higher efficiency, though with larger background

B-tagging…

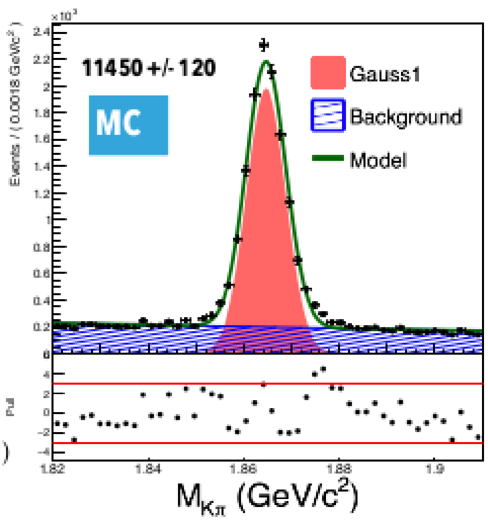
[Belle (II), G.de Marino]

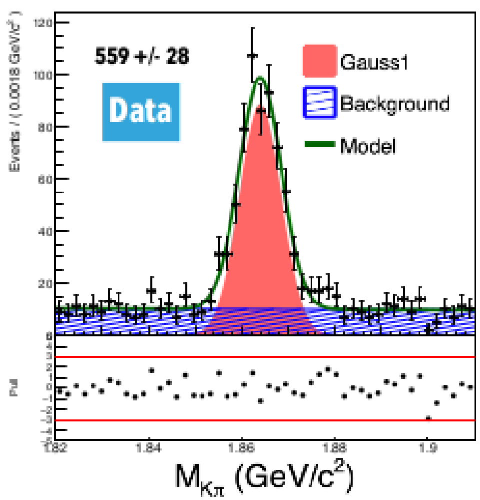
- probing the charged B^+ properties
- using $J/\psi K^\pm$ as signal side (high purity)

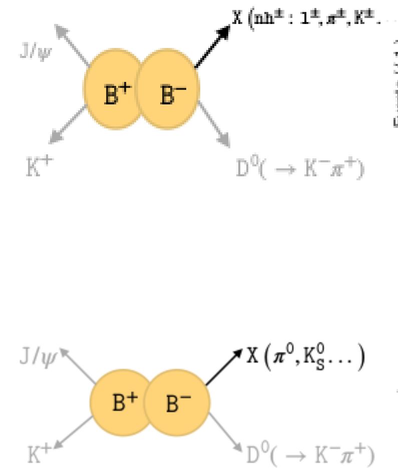


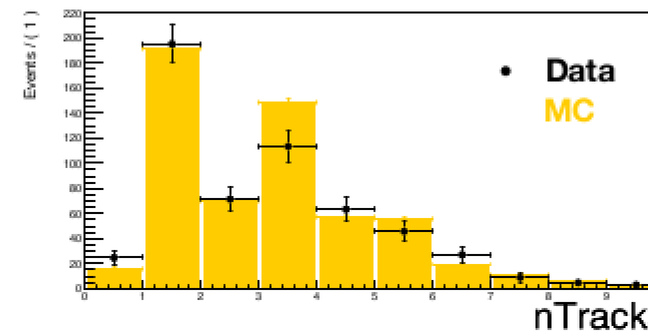


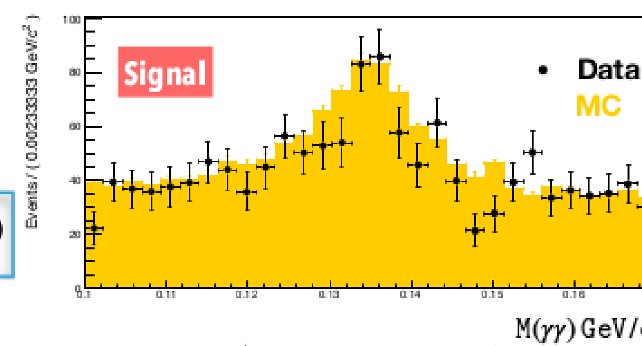
⇒ isolate pure B beam in data !





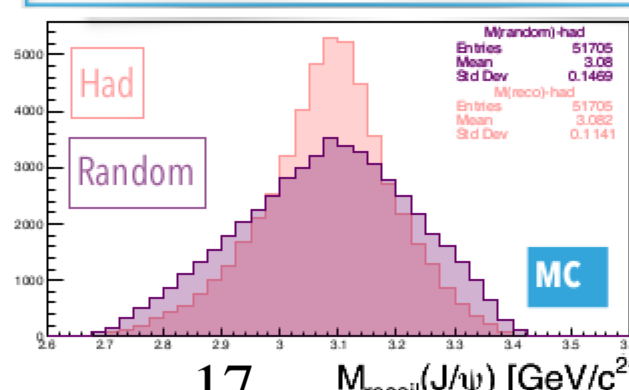






$$m^2_{J/\psi} = m^2_B + m^2_K - 2(E^*_B E^*_K - |\vec{p}^{\,*}_{B_{sig}}||\vec{p}^{\,*}_K|\cos\theta)$$

- J/ψ recoil mass poorly sensitive to $\vec{p}^{\,*}_{B_{tag}}$
- inclusive tag provides a recoil mass with similar resolution than hadronic tag !
- need to confirm that same happens for $B \to K\tau l$
-



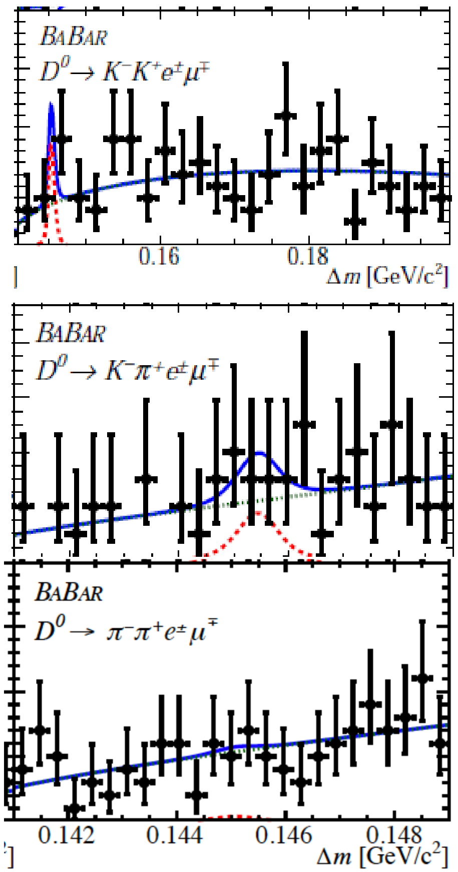
LFU and LFV in $c \to u l^+ l^-$

recent efforts from BaBar [PRL 122, 081802, 2019]

$B(D^0 \to K^- \pi^+ e^- e^+) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$ with $0.675 < m_{e^- e^+} < 0.875$

consistent with LHCb result on corresponding muon channel

$(4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$



$D^0 \to h'^- h^+ e^\pm \mu^\mp$, where h and h' = K, π [PRL 124, 071802, 2020]

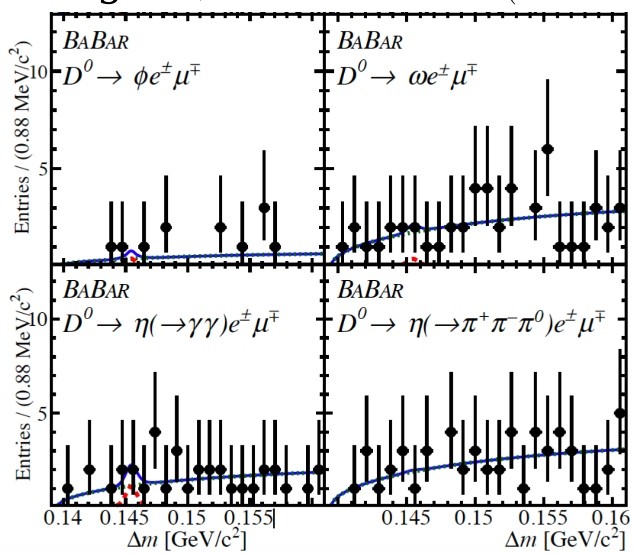
no signal, UL obtained $(1\text{-}2) \times 10^{-6}$

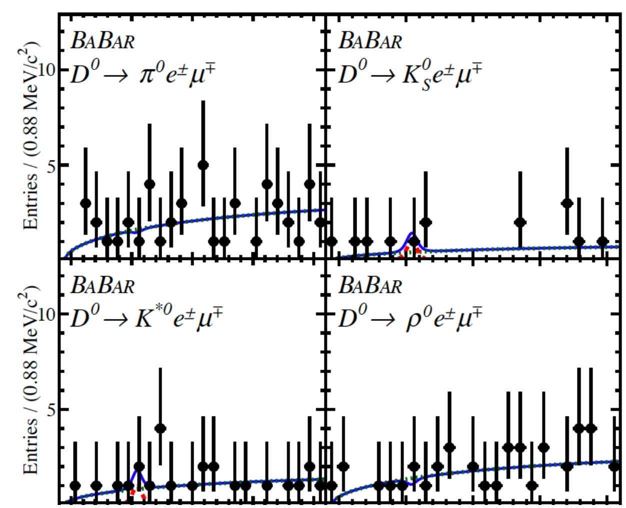
[PRD 101, 112003, 2020]

Search for lepton-flavor-violating decays $D^0 \to X^0 e^\pm \mu^\mp$,

where $X^0 = \pi^0, K^0_S, K^{*0}, \rho^0, \phi, \omega, \eta$

no signal, UL obtained $(0.5\text{-}2.2) \times 10^{-6}$

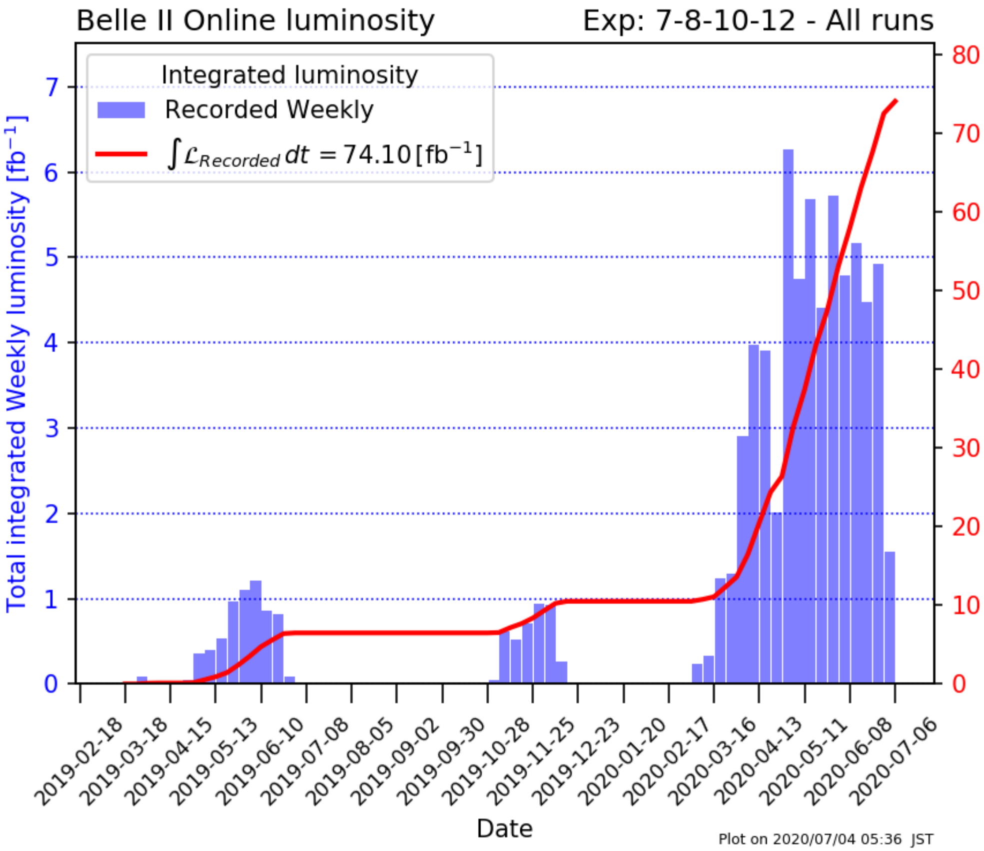




⇒ 1-2 orders of magnitude more stringent constraints !

⇒ Belle II should provide ULs at 10^{-7}

La Belle (II) aventure



- SuperKEKB/Belle II just started their journey to 50 ab^{-1}
- NP searches in B physics with τ leptons
  - Sharpening our tools: B tagging is the key
  - exclusive approach: hadronic/semi-leptonic tags
  - more inclusive approach is promising