Missing energy modes
$(B \to \tau\nu,\ B \to D^{(*)}\tau\nu,\ B \to K\nu\nu,\ B \to K\tau^+\tau^-,\ B \to K\tau^+ l^-)$
and B-tagging
at Belle II

Karim Trabelsi
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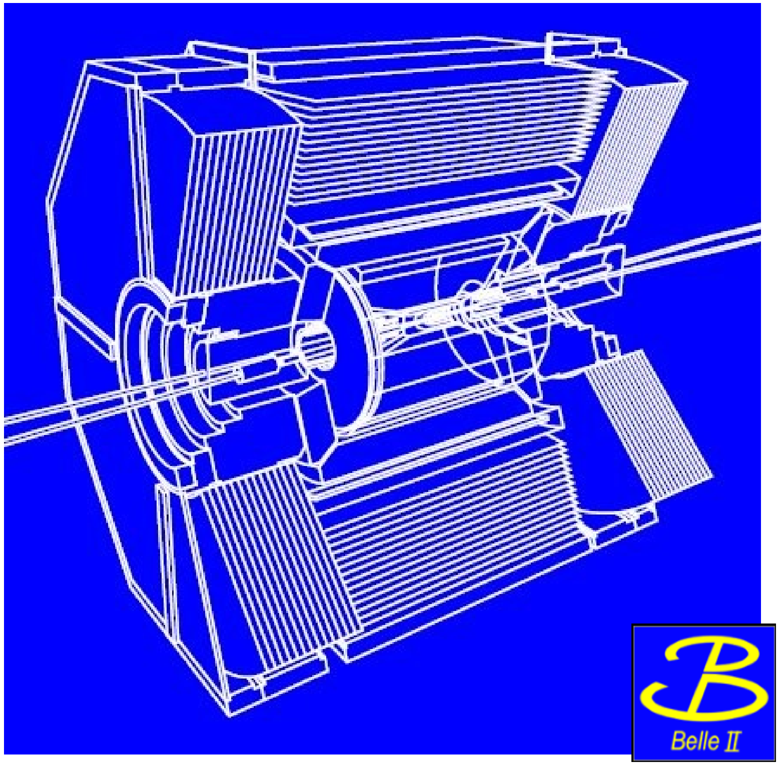


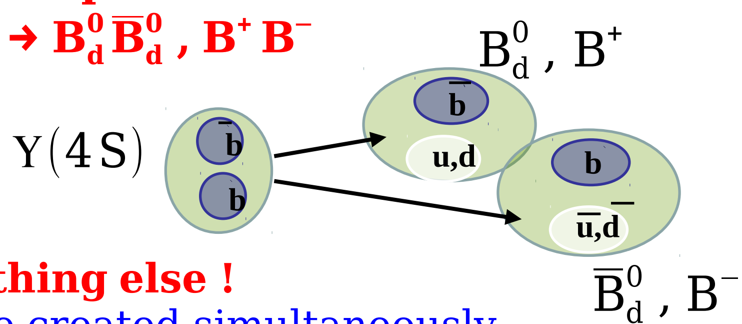
2020/05/15

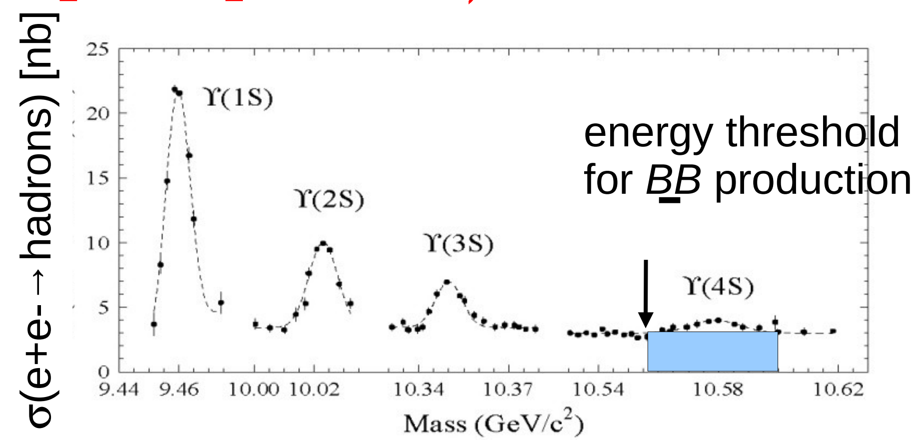
Belle II, a flavour-factory,
a rich physics program…

- 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:

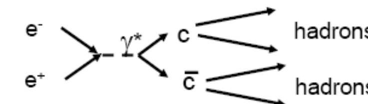
  - **a (Super) B-factory ($\sim 1.1 \times 10^9$ $B\overline{B}$ pairs per ab^{-1})**

''on resonance'' production
$e^+e^- \to \Upsilon(4S) \to B^0_d \overline{B}^0_d$, 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 $e^+e^- \to$ 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

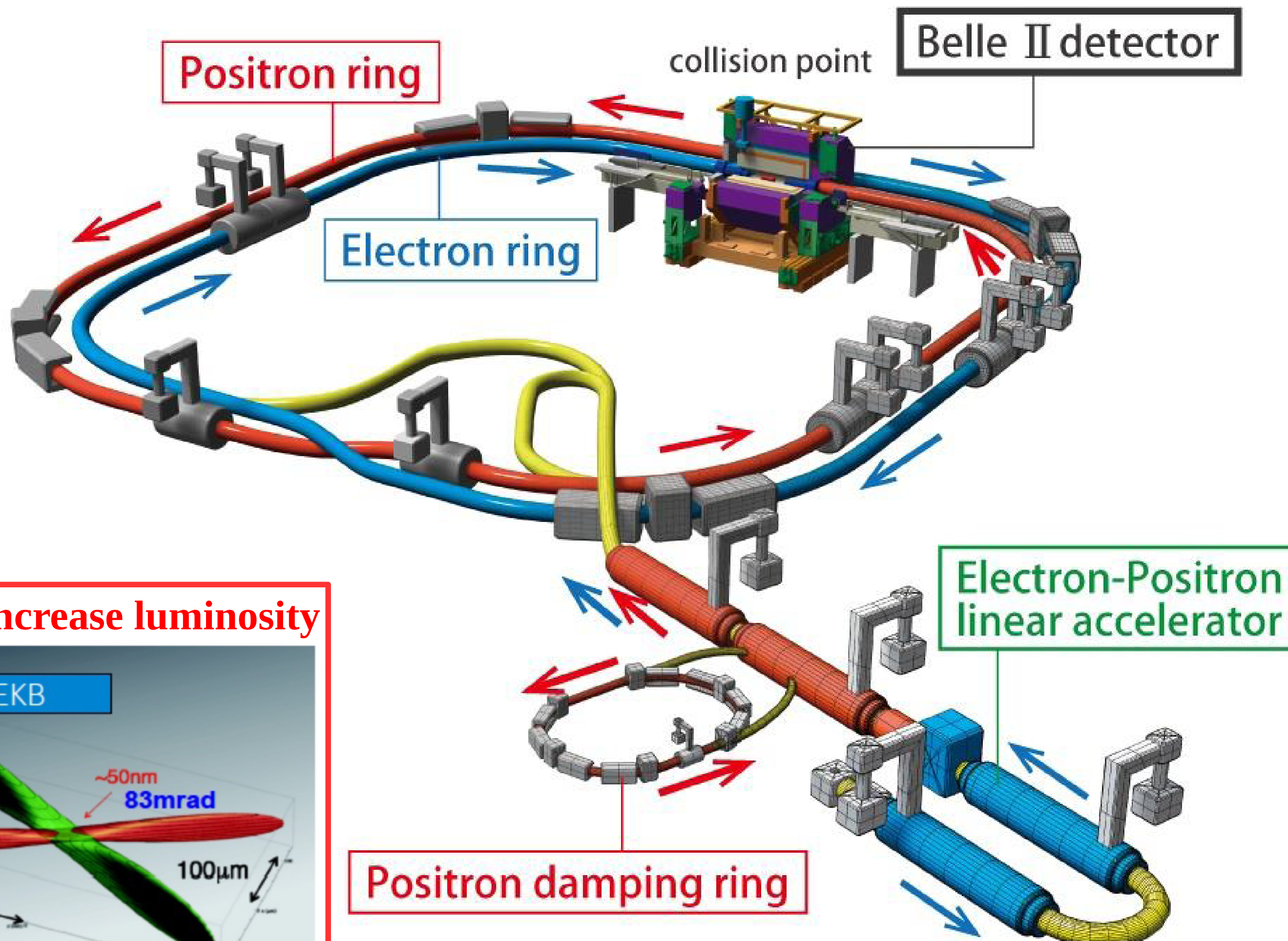
add positron damping ring

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

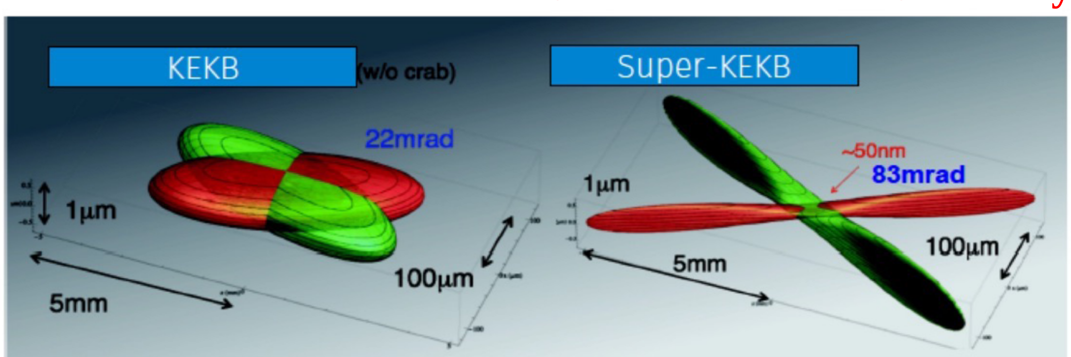
April 27 - July 17, **2018**

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 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20 factor 2-3

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

$\Rightarrow$ **cumulate 50 ab^{-1} by ~2029**

SuperKEKB/Belle II status

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

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

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

May 13, 2020

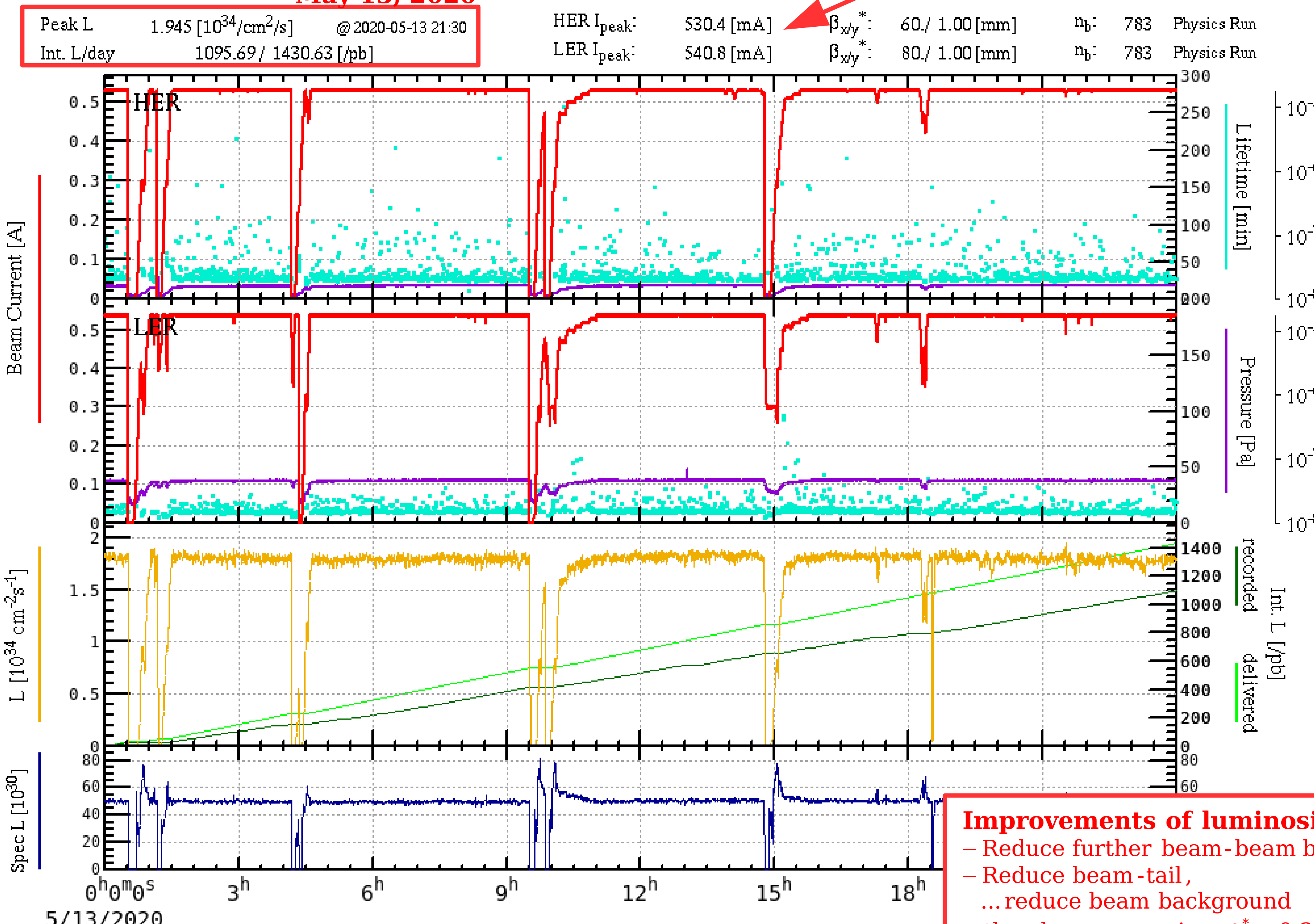
currents ~ 0.5 A

record of KEKB/Belle

$2.1\times10^{34}/cm^2/s$ currents > 1 A

record of PEPII/BaBar

$1.1\times10^{34}/cm^2/s$ currents > 2 A



Improvements of luminosity performance

– Reduce further beam-beam blowup

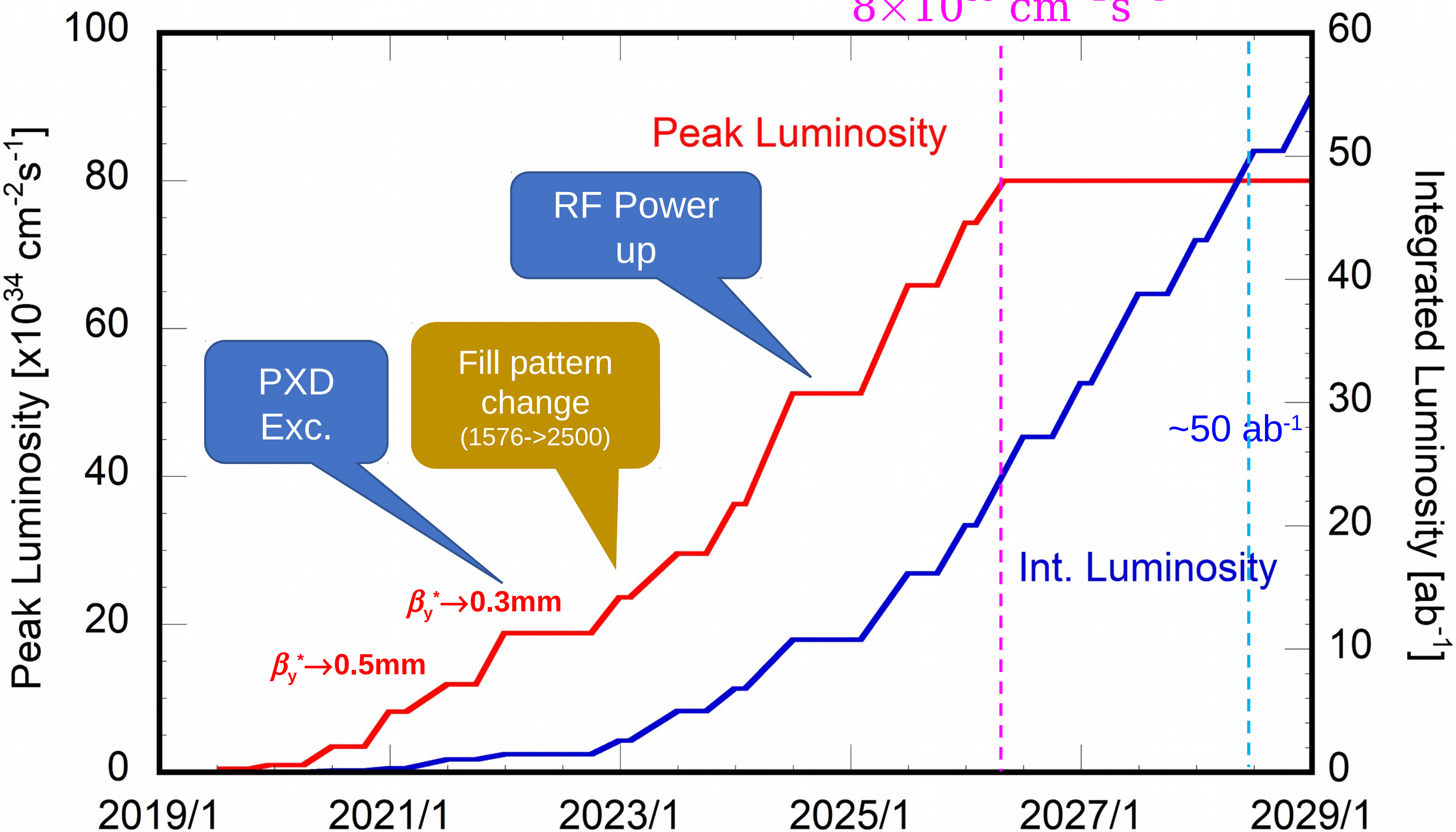
– Reduce beam-tail,

...reduce beam background

– then keep squeezing: $\beta_y^* \rightarrow 0.3$ mm

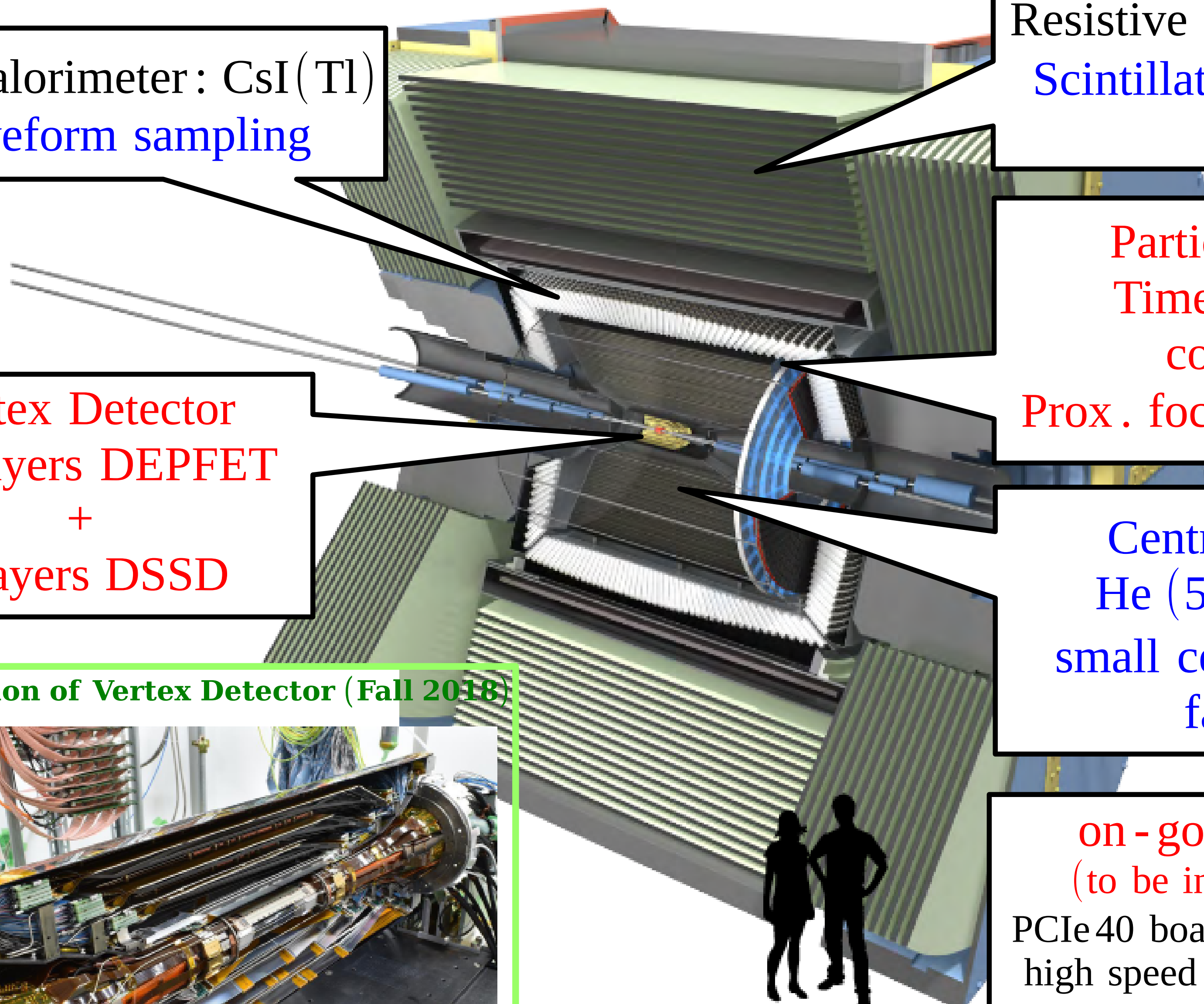
Operation plan and luminosity projection

- long term (~ 2029)
- PXD exc. 2022, RF upgrade 2024



just started to consider an upgrade → 250 ab^{-1}, polarized beams…

Belle II detector



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

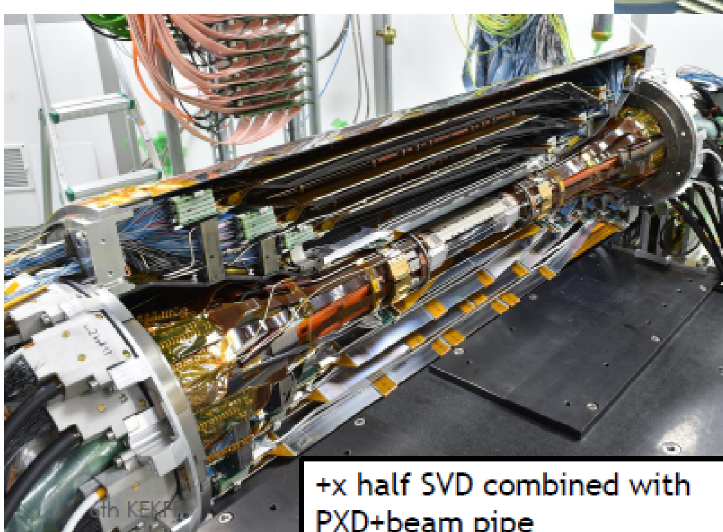
EM Calorimeter: CsI(Tl)
waveform sampling

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

considering now VTX upgrade (2025 or later)

Belle(II), LHCb side by side

(in the context of B anomalies)

Belle (II)	**LHCb**
$e^+e^- \to \Upsilon(4S) \to b\bar{b}$	$pp \to b\bar{b}X$
at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events	production of B^+, B^0, B_s, B_c, Λ_b... but also a lot of other particles in the event
$\sigma_{b\bar{b}} \sim 1\,\text{nb} \Rightarrow 1\ \text{fb}^{-1}$ produces $10^6\ B\bar{B}$	⇒ lower reconstruction efficiencies
$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$	$\sigma_{b\bar{b}}$ 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 ~ 5× Tevatron, ~ 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

Belle (II)	LHCb
mean decay length $\beta\gamma c\tau \sim 200\ \mu m$	**mean decay length $\beta\gamma c\tau \sim 7$ mm**

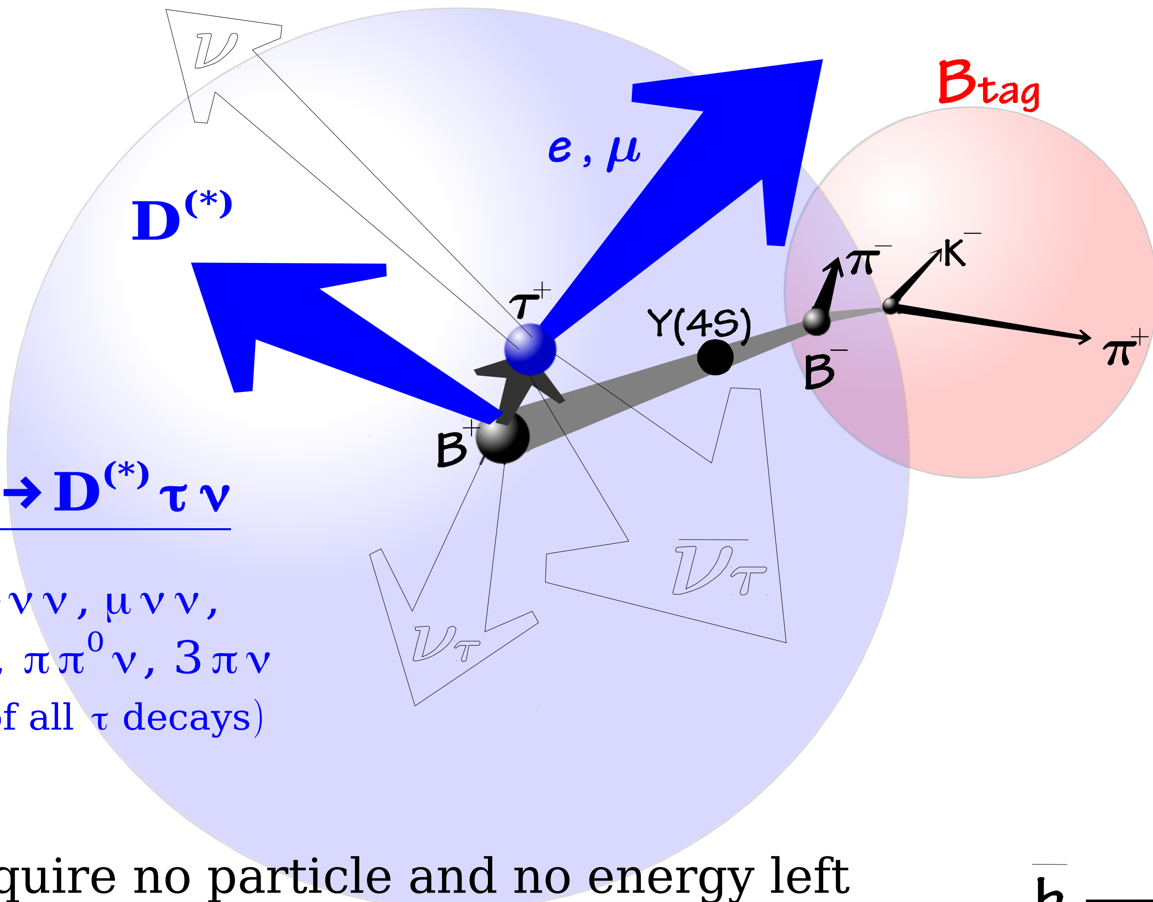
data taking period(s)

Belle (II)	LHCb
[1999-2010] = 1 ab^{-1}	[run I: 2010-2012] = 3 fb^{-1}, [run II: 2015-2018] = 8 fb^{-1}

(near) future

Belle (II)	LHCb
[Belle II from 2019] → 50 ab^{-1}	[LHCb upgrade from 2020]

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



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

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

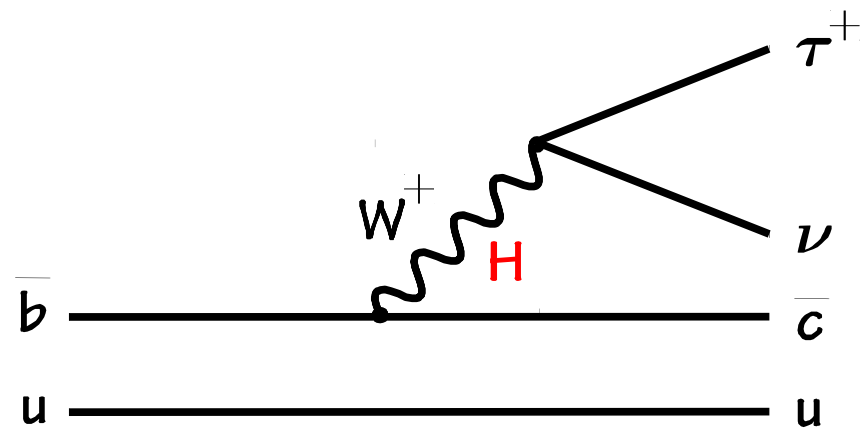
B_{tag}

hadronic tag

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

semileptonic tag

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



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

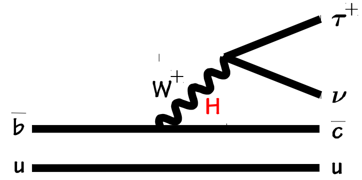
main signal-background discriminator

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

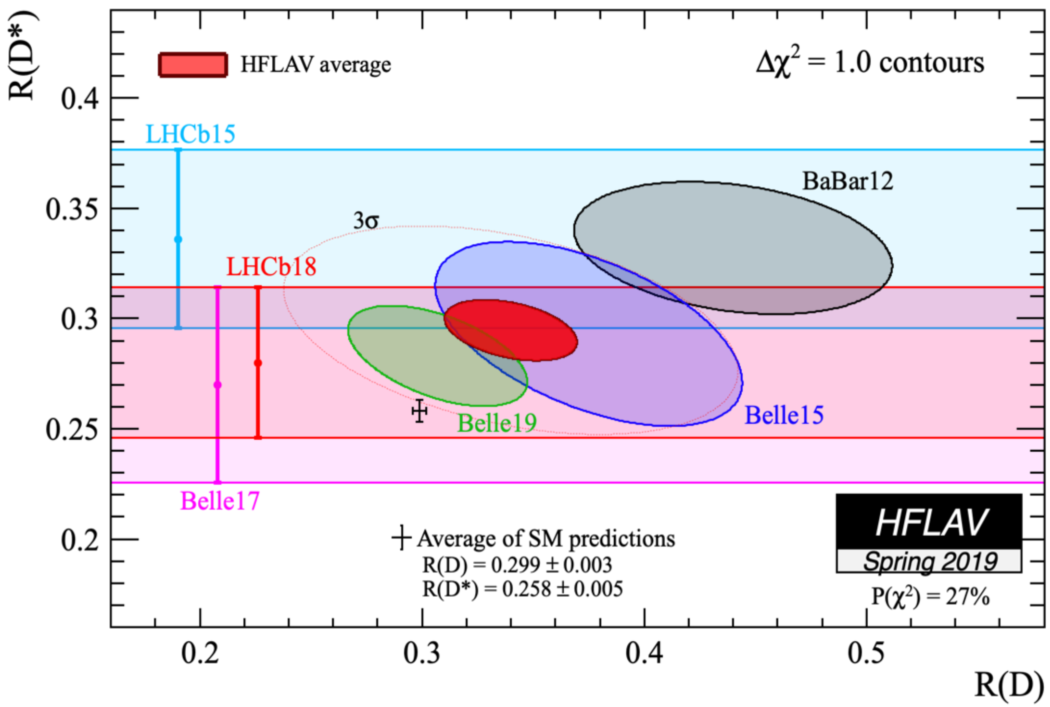
$$2\mathrm{HDM\ (type\ II)}: \mathcal{B}(B \to D \tau^+ \nu) = G_F^2 \, \tau_B \, |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)$$

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

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

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

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

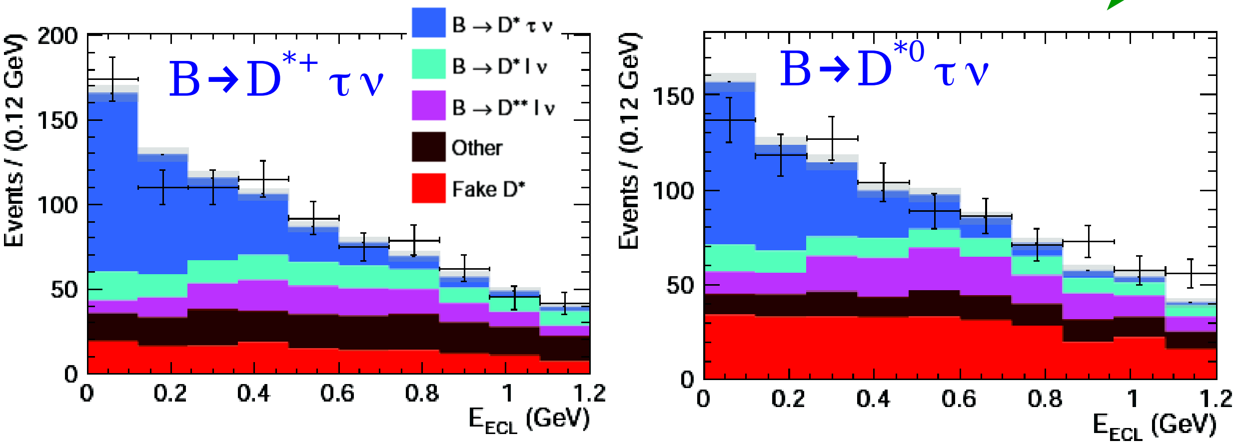
$R(D^*) = 0.270 \pm 0.035 ^{+0.028}_{-0.025}$

Belle 19 SL tag

$R(D) = 0.307 \pm 0.037 \pm 0.016$

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

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



LHCb

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

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

average

$R(D) = 0.340 \pm 0.027 \pm 0.013$

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

difference with SM predictions is at 3σ level

Hadronic full reconstruction at Belle II

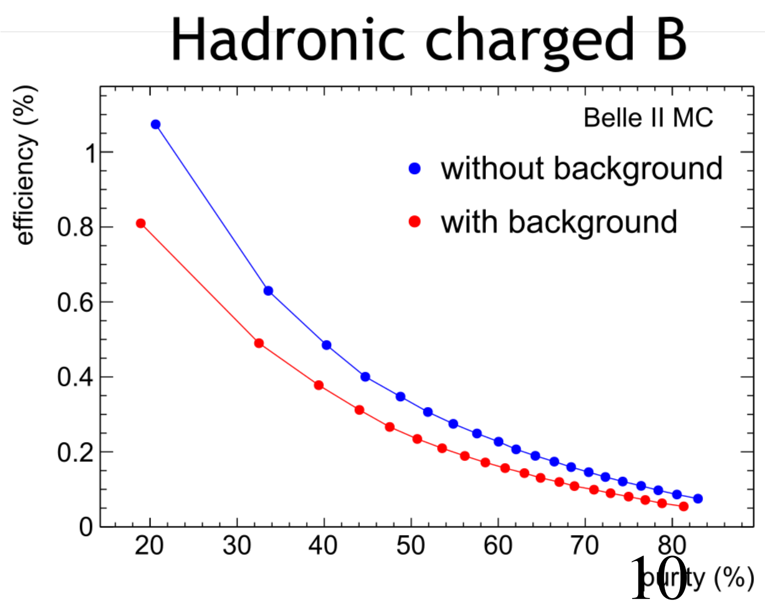
Particle	# channels (Belle)	# channels (Belle II)
$D^+/D^{*+}/D_s^+$	18	26
D^0/D^{*0}	12	17
B^+	17	29
B^0	14	26

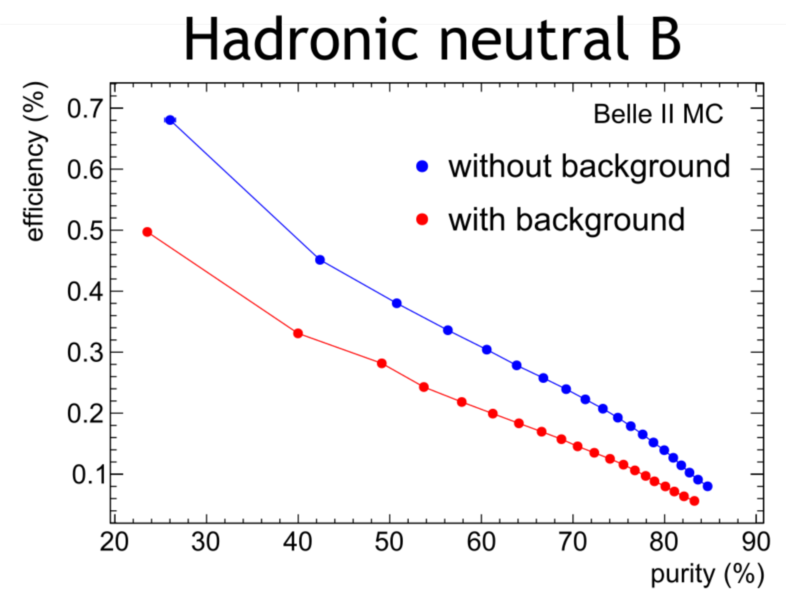
- More modes used for tag-side hadronic B than Belle, multiple classifiers

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

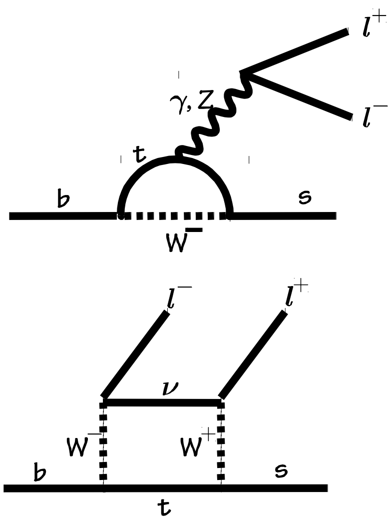
Improvement to tagging efficiency in Belle II

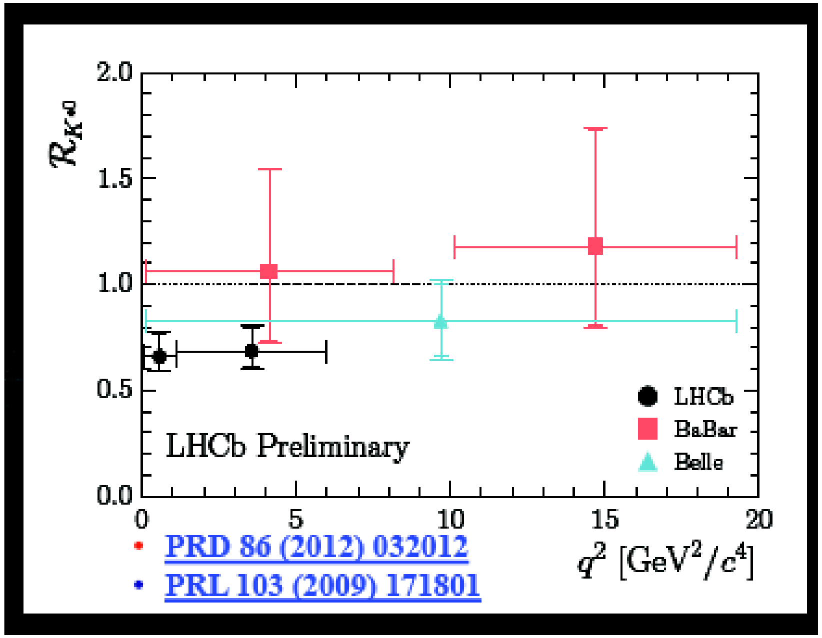
- Good performances on Belle II predicted beam background conditions:

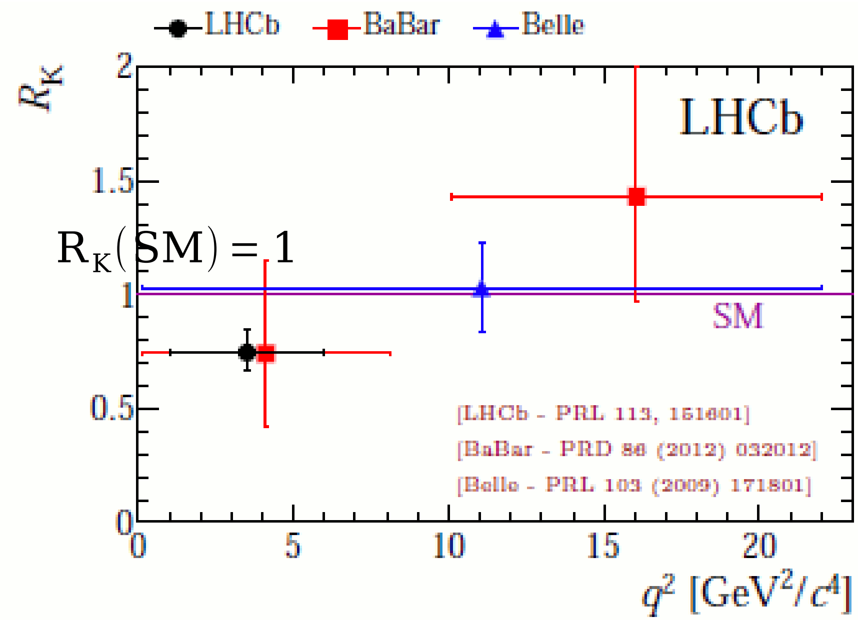




Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays

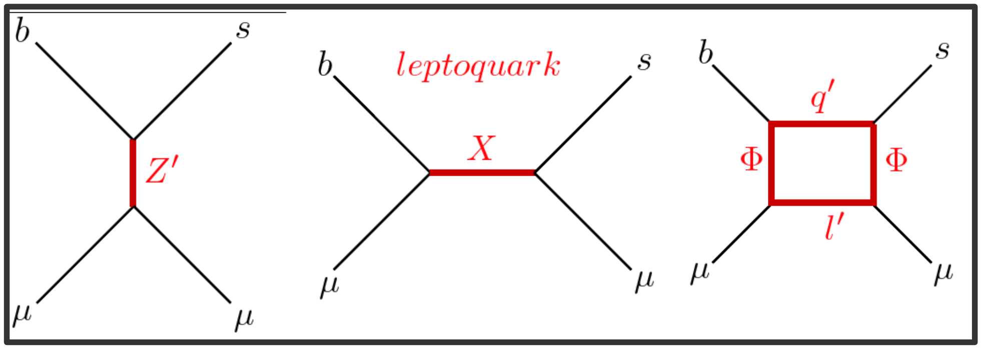






Model candidates

- ✧ **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

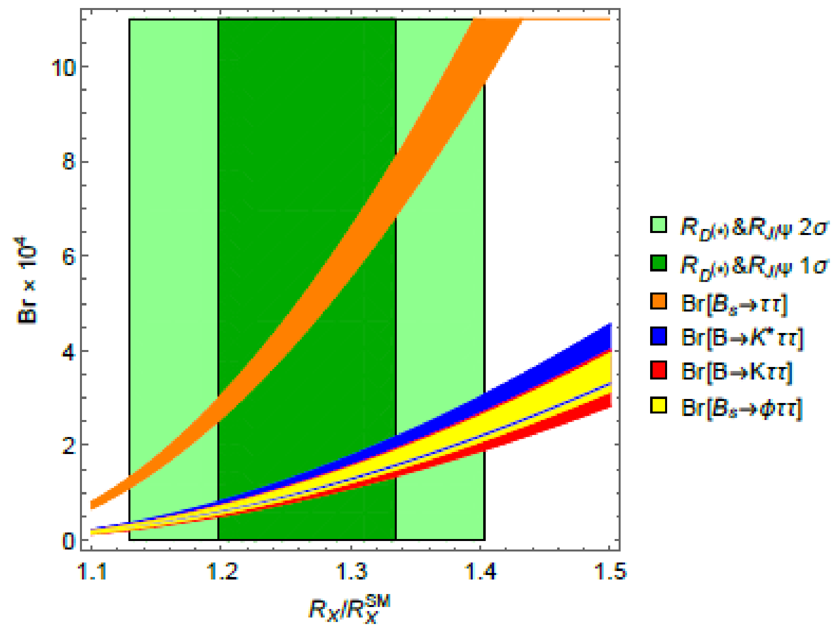
Lot of those models predict also LFV $b \to s e \mu$, $b \to s e \tau$, ...

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

[B.Capdevila et al, arXiv:1712.01919]

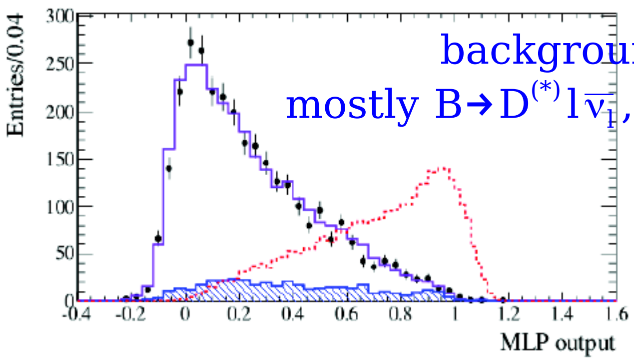
q^2 range for predictions for $B \to H\tau^+\tau^-$: from $4\, m_\tau^2$ ($\sim 12.6\ \mathrm{GeV}^2$) to $(m_B - m_H)^2$
to avoid contributions from resonant decay through $\psi(2S)$, $B \to H\psi(2S)$, $\psi(2S) \to \tau^+\tau^-$
predictions restricted to $q^2 > 15\ \mathrm{GeV}^2$:

greatly enhanced in NP models...



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

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



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

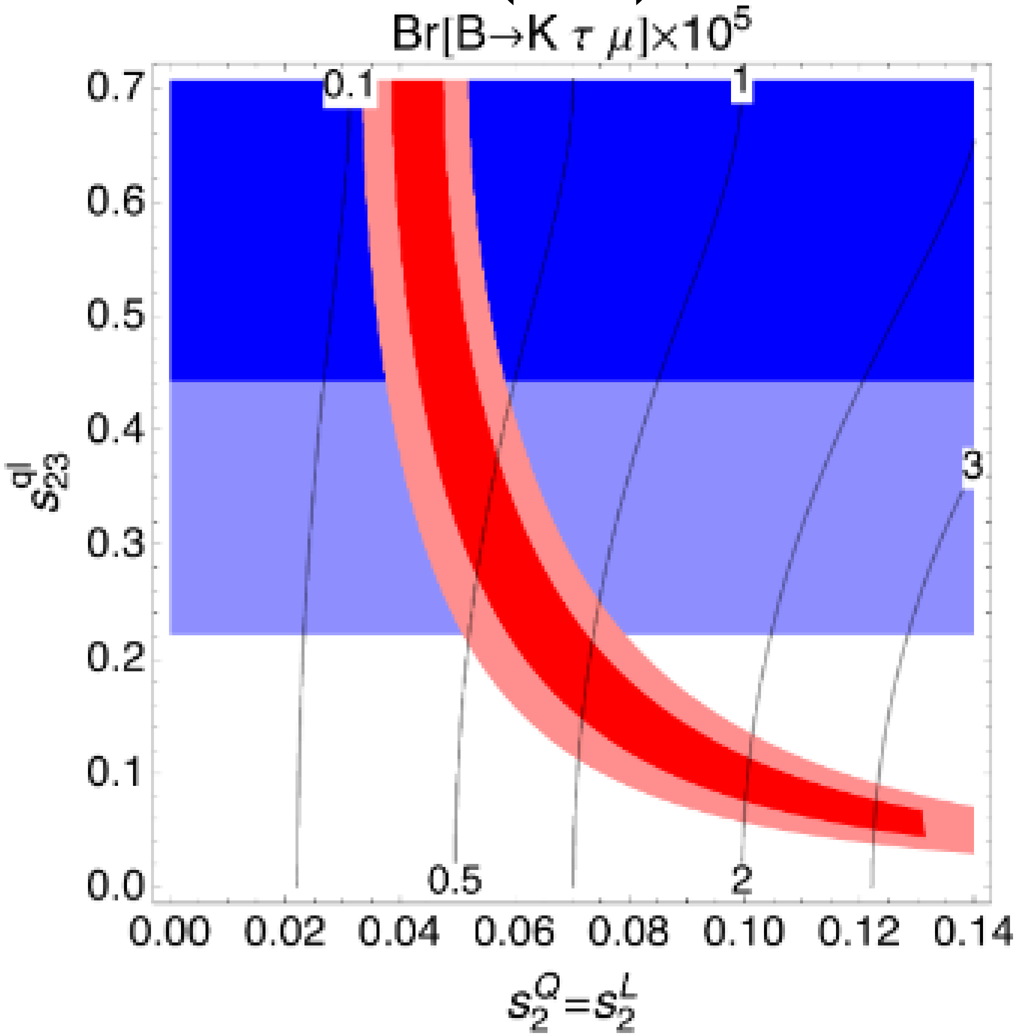
BaBar's result with had tag: $B(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at 90%CL

[Belle II, arXiv:1808.10567]

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

this is the result with had tag.... (on-going thesis at IJCLab from G.de Marino)
⇒ exploring additional tags in $B \to K^+\tau\mu/e$ (see following slides)

R(D*) and b→sμμ ⇒ B→Kτμ



L.Calibbi et al, arXiv:1709.00692

Key Features of PS³

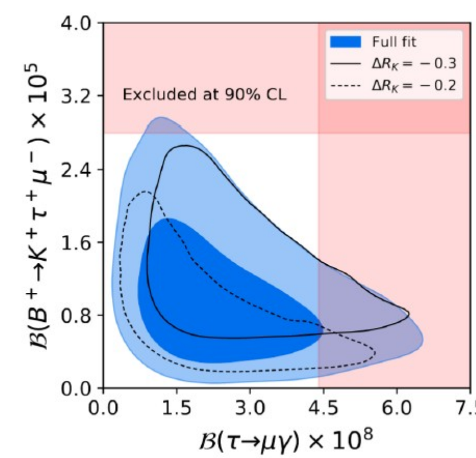
Bordone, Cornella, Fuentes-Martin, Isidori (2017), (2018)

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 PS³

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



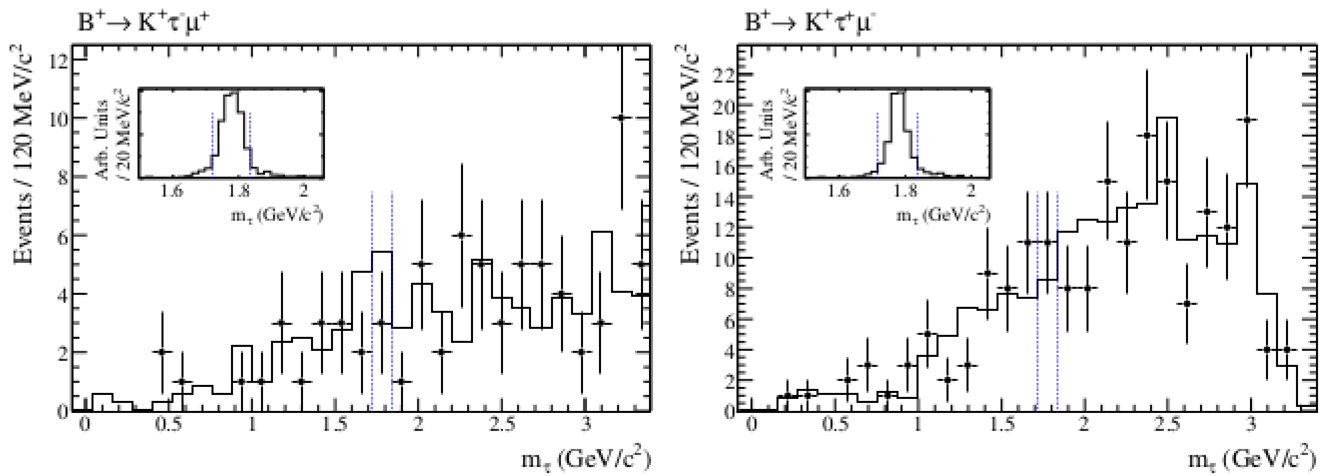
LFV $B \to K \tau l$ ($l = e, \mu$) decays

[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)

[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

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

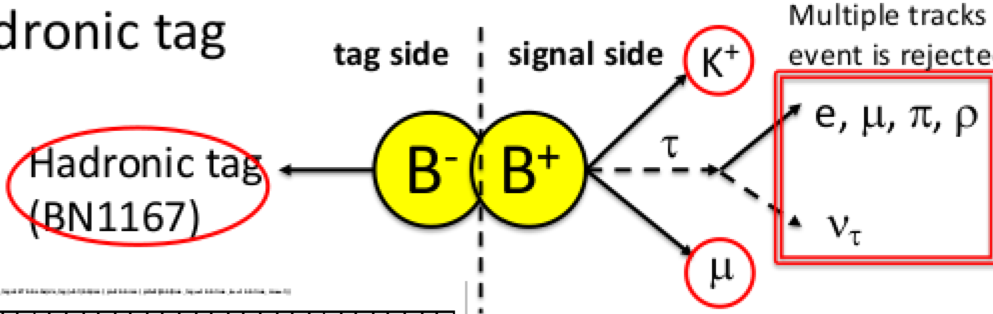
⇒ **can do $K^*\tau e$, $K^*\tau\mu$ with similar sensitivity...**

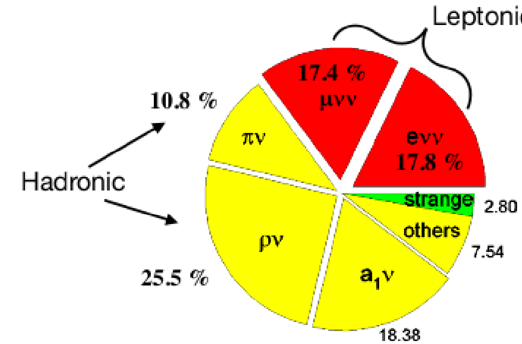
LFV $B \to K \tau l$ ($l = e, \mu$) decays

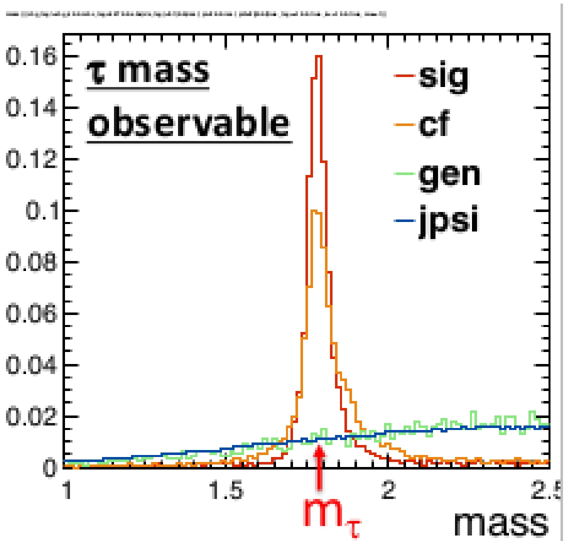
[Belle & Belle II]

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

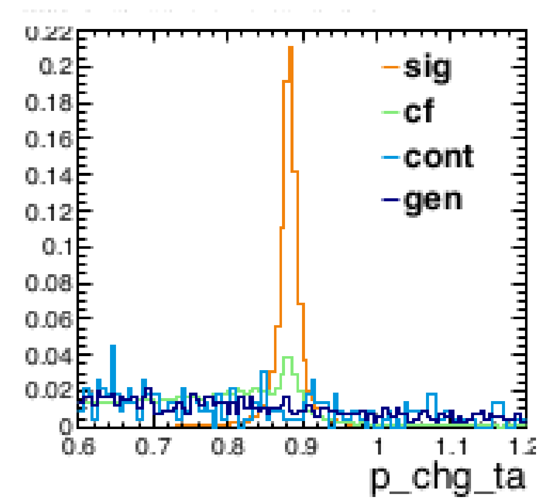
- Hadronic tag



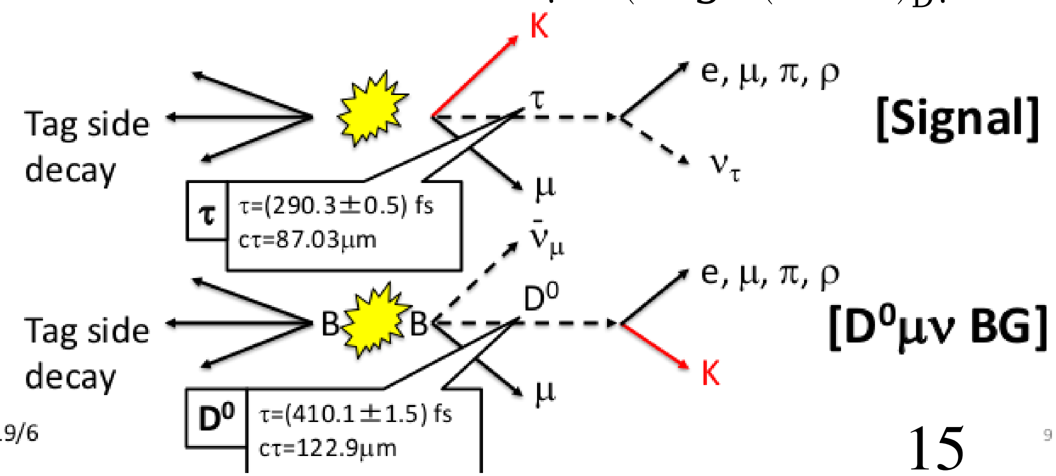


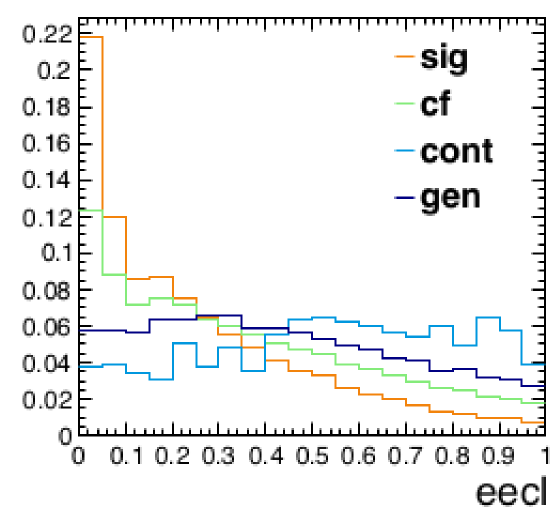


- For $\tau \to \pi\nu$, $\rho\nu$ channel, kinematic cut is useful to suppress BG.
- $\tau \to \pi\nu$
  - Monochromatic momentum of π in τ rest frame
- $\tau \to \rho\nu \to \pi\pi^0\nu$
  - Monochromatic momentum of ρ in τ rest frame
  - Invariant mass of $\pi\pi^0$



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





B-tagging...

standard tagging methods: hadronic and semi-leptonic

other possibilities ? semi-inclusive, a.k.a **c-tag**...

signal side: K+2 leptons (especially $K\tau l$) allows looser selection in B_{tag} side ?

⇒ flavour tagging combines information as charge/momentum of lepton, charge of kaon, charge of soft pion etc... ⇒ output (qr): B or $\overline{B}$

⇒ B-tagging... but better to talk about charged B tag or neutral B tag

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

- $B^+ \to \overline{D}^0 X$ BR is high
  - reconstruct exclusively D^0 ($20\% \sim \epsilon \times BR$, $D \to K\pi, K\pi\pi^0$, K3pi, $K_S\pi\pi$, KK...), p_{CM}...
  - exploit ''Dalitz'' properties of $D \to K n\pi$
- D^+ would be a veto !
- D_s^+: additional info (but $BR(D_s \to \phi(K^+K^-)\pi) \sim 2.3\%$ only), $\phi + D^0$? ($BR(D_s \to \phi(K^+K^-)X) \sim 8\%$
- in fact think as $B^+ \to \overline{D}^0[\mu\nu]X$, $\to \overline{D}^0[e\nu]X$, $\to \overline{D}^0[c\bar{s}]X$ (here $\overline{D}^0 D_s X$ or $\overline{D}^0 \phi X$), $\overline{D}^0[u\bar{d}]X$
- not forgetting $B^+ \to J/\psi K X$ (K^+ and K_S^0)
- study of X: presence of leptons, kaons, π^0, clusters... ⇒ BDT, DNN...

⇒ charged Btag info with a quality information, ≠ neutral Btag algorithm

B-tagging ... using data directly

[Belle & Belle II, G. de Marino]

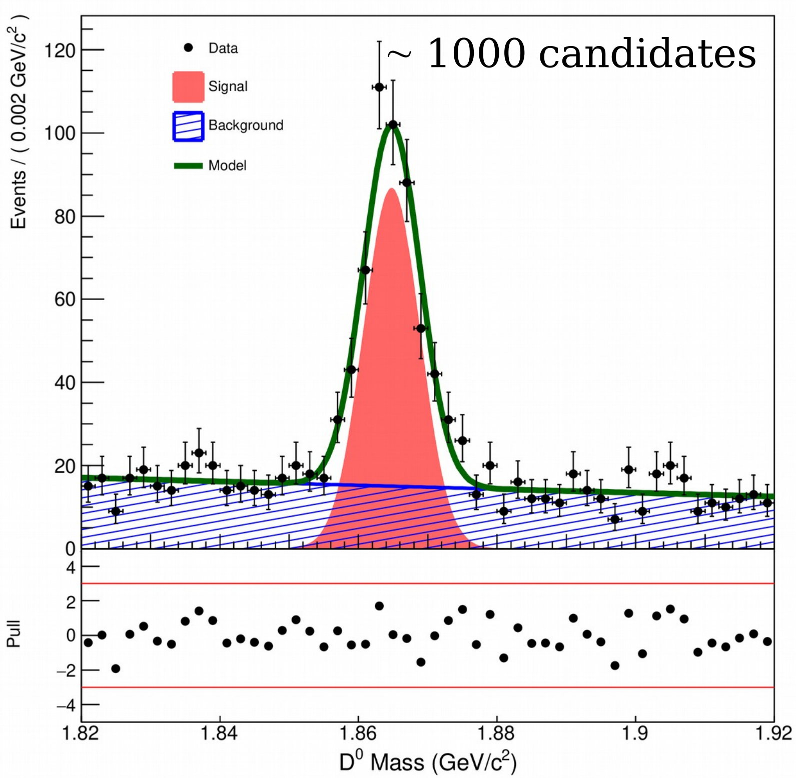
- reconstruct the signal side as $B^+ \to J/\psi K^+$

$\Rightarrow$ extremely pure sample, pure B beam

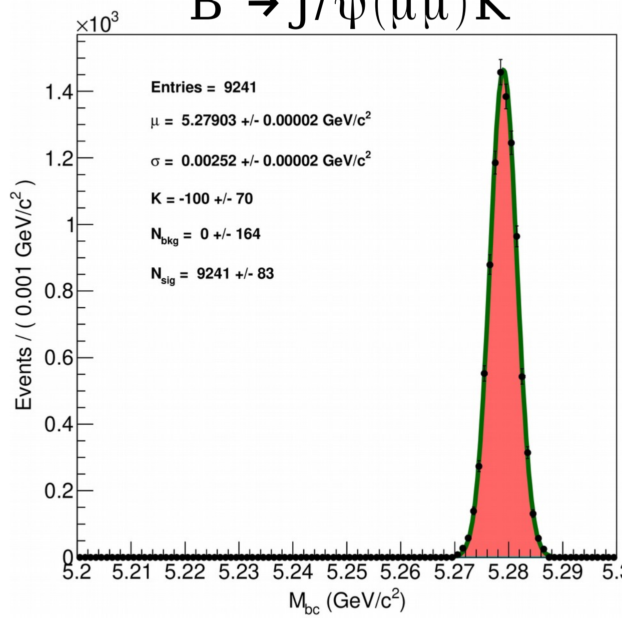
$\sim 40\,\mathrm{k}$ candidates $B^+ \to J/\psi K^+$ per 1 ab^{-1}

isolate pure B beam in data !

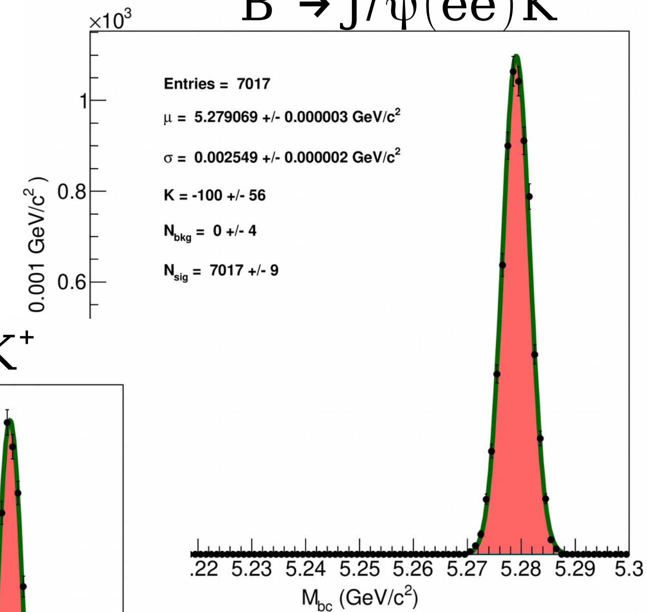
within those events looking as a $D\,(\to K\pi)$ in the other 'side':



$B^+ \to J/\psi(\mu\mu)K^+$



$B^+ \to J/\psi(ee)K^+$

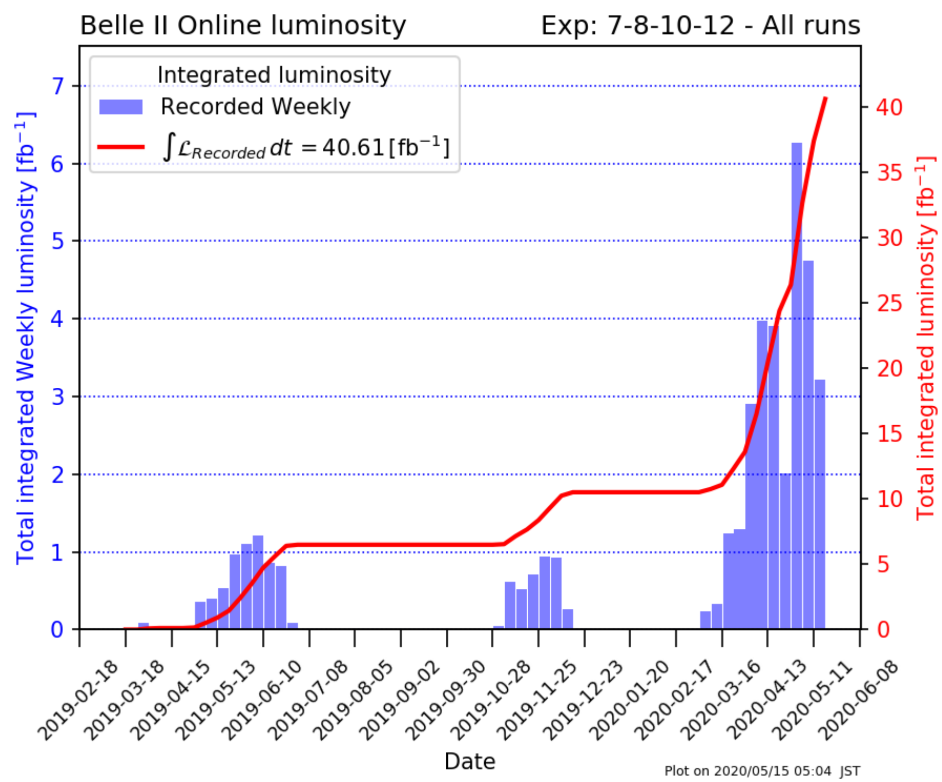


[400 fb^{-1}]

- more studies on going on D_s, other D, ϕ, and X
- track, π^0, K^0_S multiplicity, ...

$\Rightarrow$ establish a more inclusive tagging using data

La Belle aventure (Tome II)

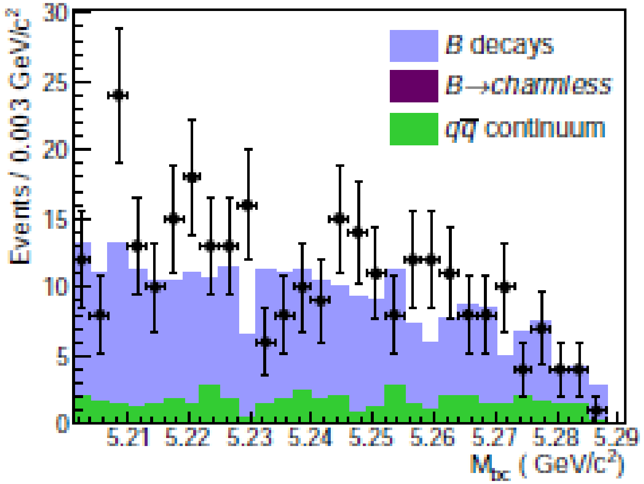


- SuperKEKB/Belle II just started their journey to 50 ab^{-1}
- NP searches with missing energy B modes
- Sharpening our tools: B-tagging is the key
  - exclusive approach: hadronic/semi-leptonic tags
  - more inclusive approach is promising
- Large data samples will allow to perfect the art of B-tagging

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

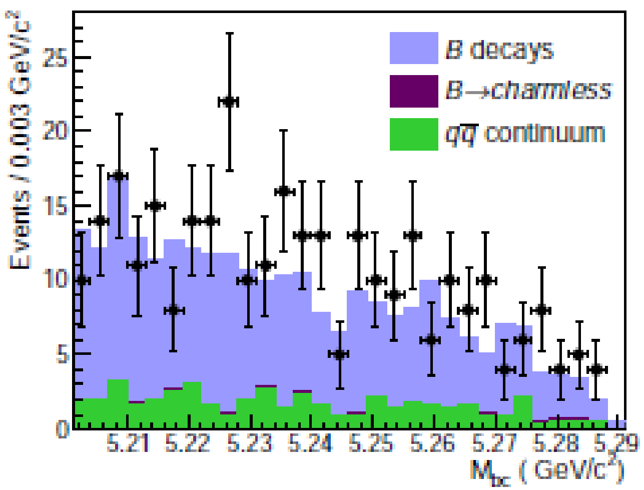
S.Sandilya (UC), KT (LAL)

[Belle, arXiv:1807.03267]



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

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



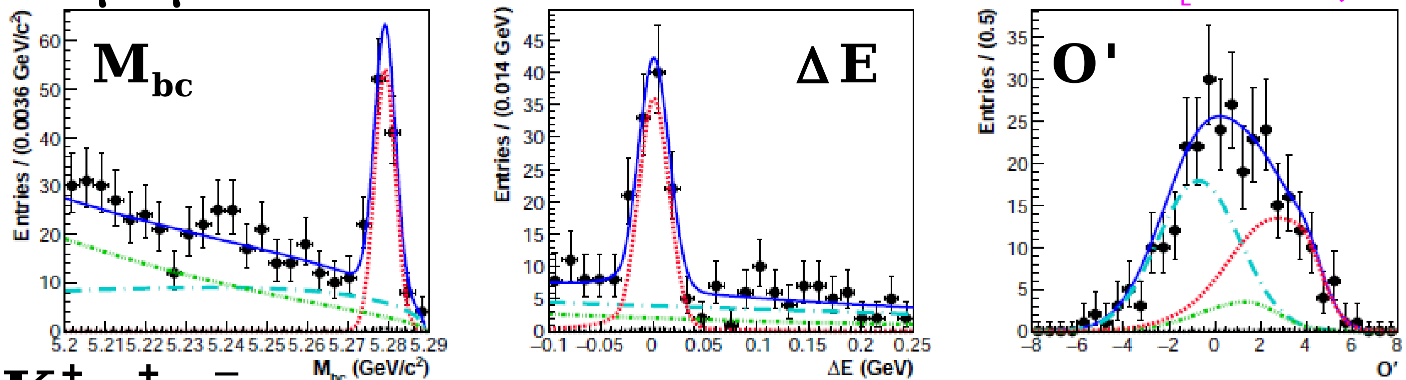
$B(B^0 \to K^{*0}\mu^+e^-) < 1.6 \times 10^{-7}$ at 90% CL

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

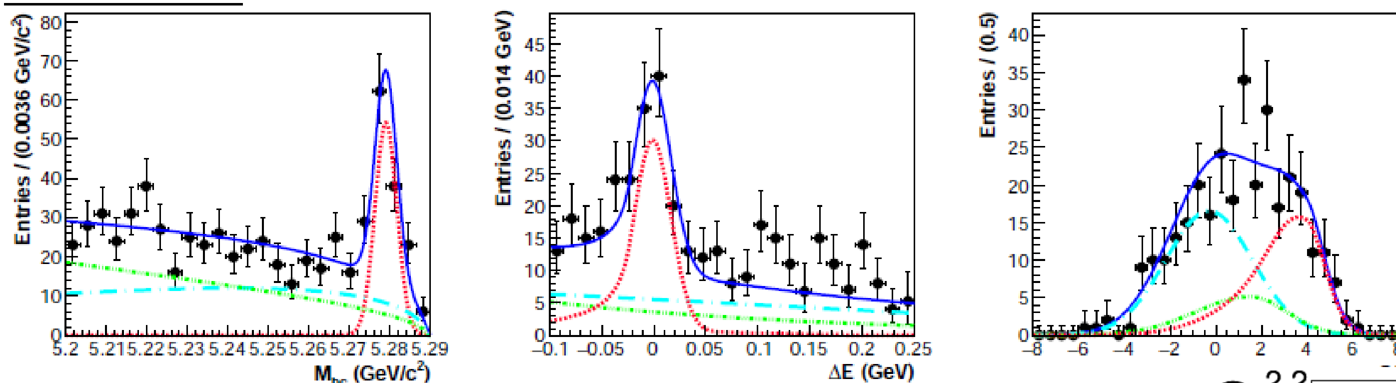
R_K...

S.Choudhury (IITH), S.Sandilya (UC), KT (LAL)
[Belle, arXiv:1908.01848]

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



$K^+e^+e^-$

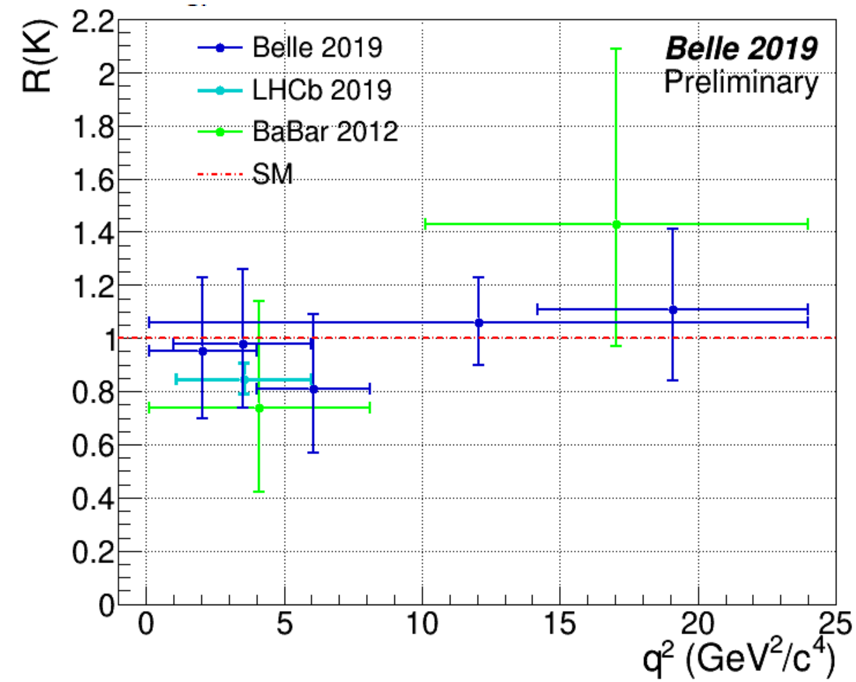


for the whole q^2 range: of course excluding the ψ...

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

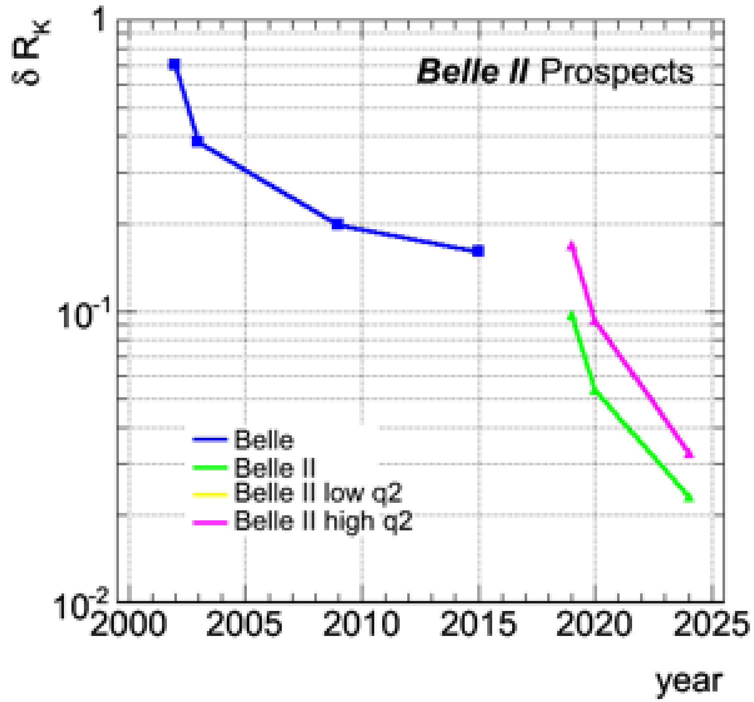
$q^2 \in [1.0,\, 6.0]\ \mathrm{GeV}^2/c^4$

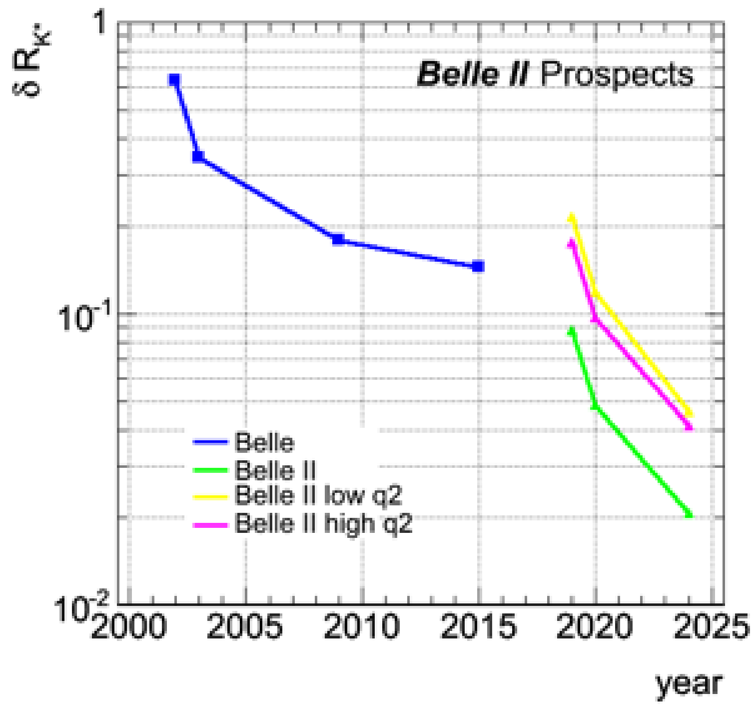
$$R_K = 0.98\,^{+0.27}_{-0.23} \pm 0.06$$



R_K, R_K^*, ...

[Belle II, arXiv:1808.10567]





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

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