Belle II status and Highlights

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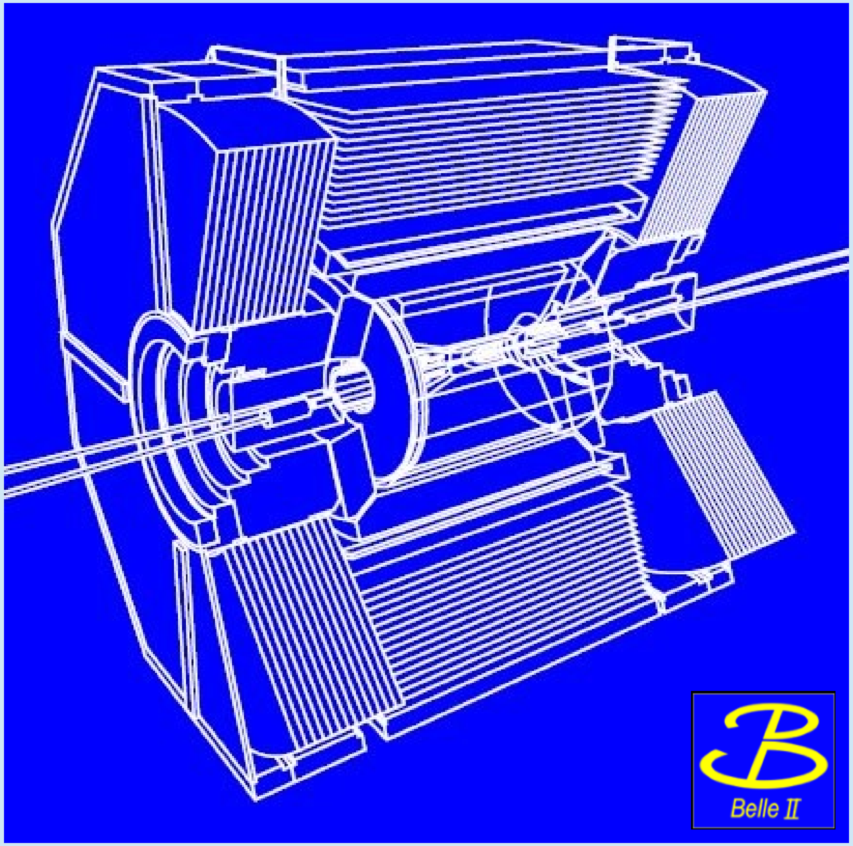
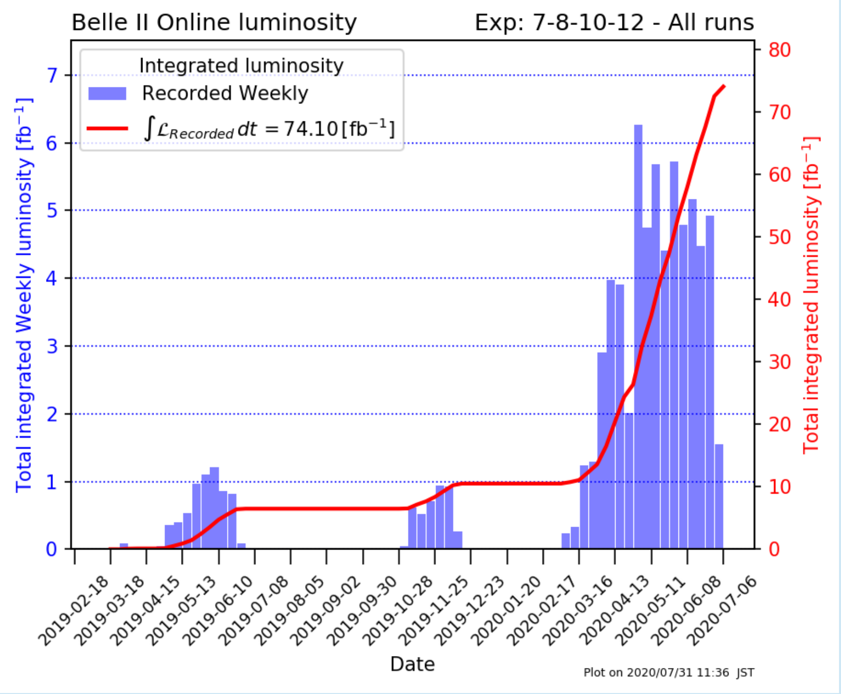




2020/10/23

The Geography of the International Belle II collaboration

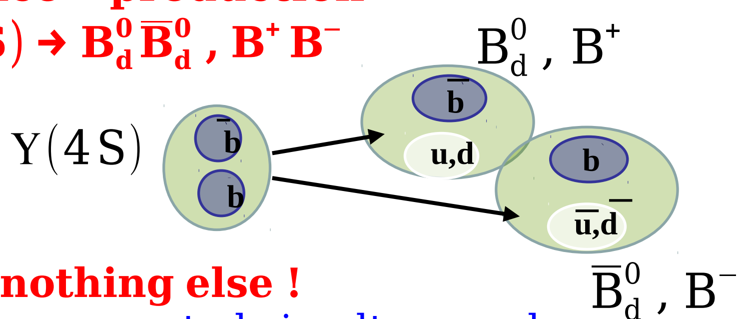
Belle II has grown to ~ 900 researchers from 26 countries

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

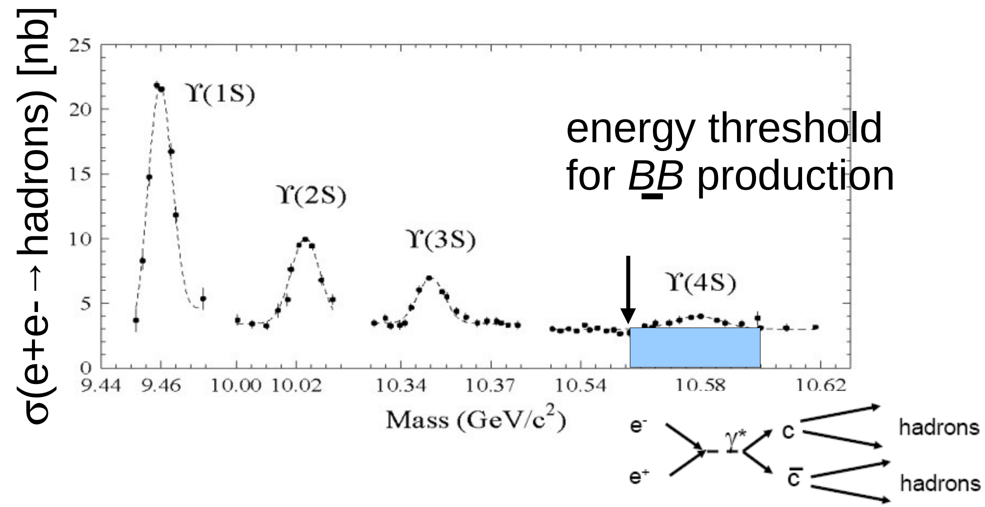
(Belle ~ 1 ab^{-1})

- 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 ($\sim 1.1 \times 10^9$ $B\bar{B}$ pairs per ab^{-1})**

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



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



- a (Super) charm factory ($\sim 1.3 \times 10^9$ $c\bar{c}$ 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

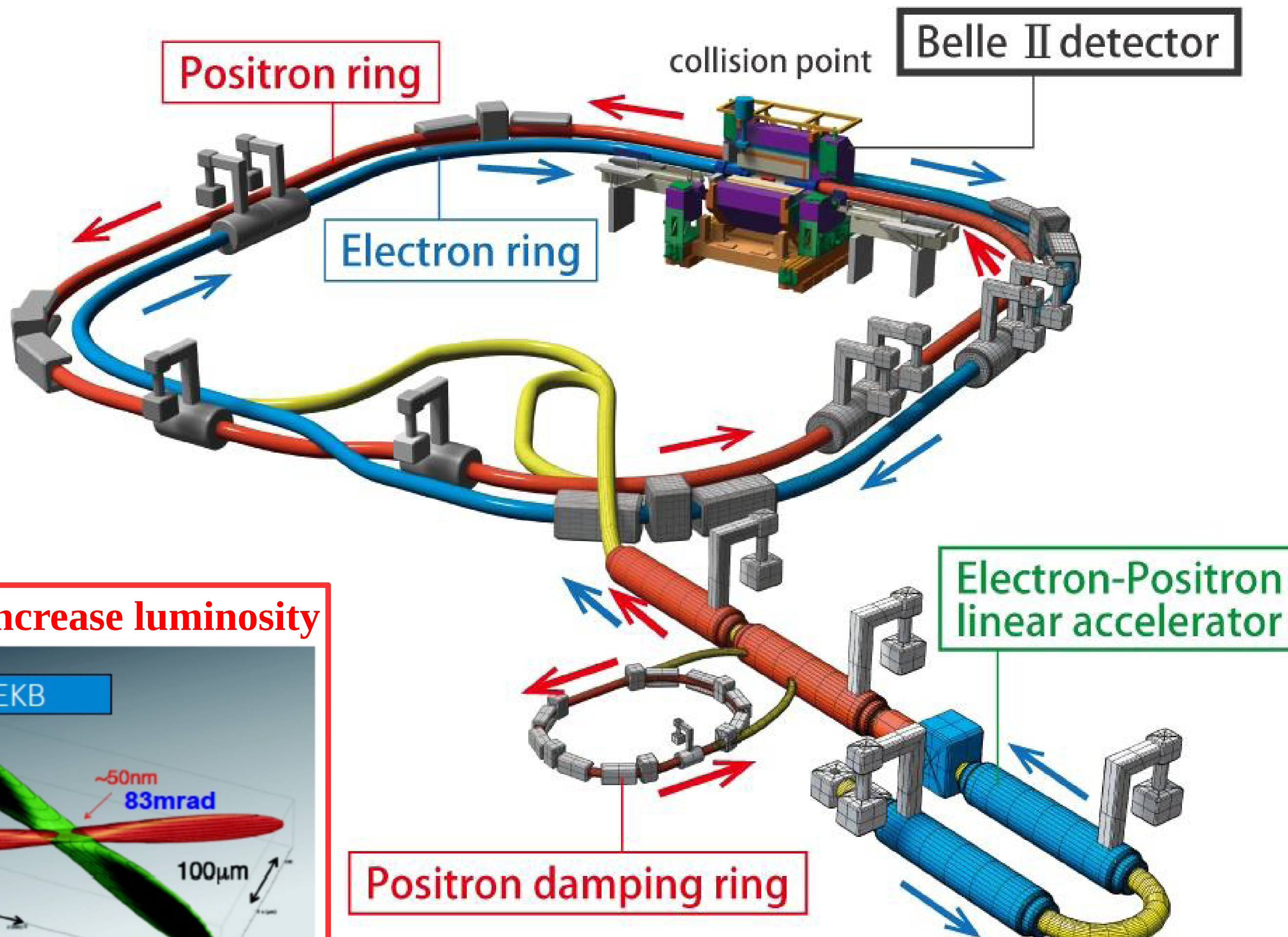
add positron damping ring

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

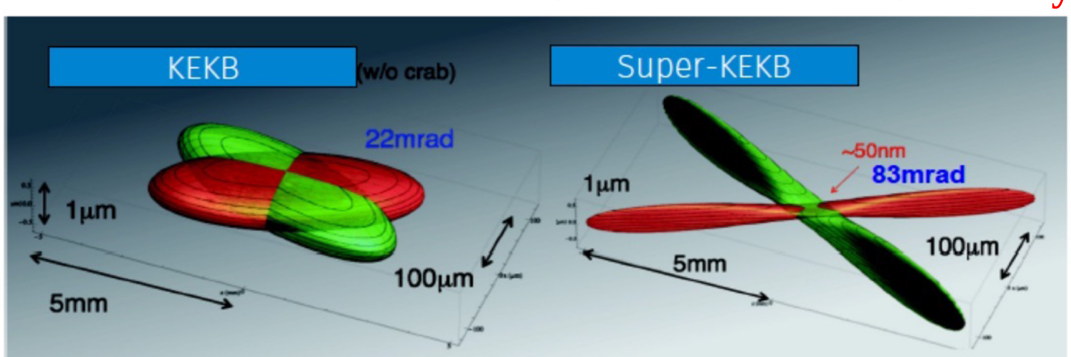
April 27 - July 17, **2018**

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 ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20   factor 2-3

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

$\Rightarrow$ **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

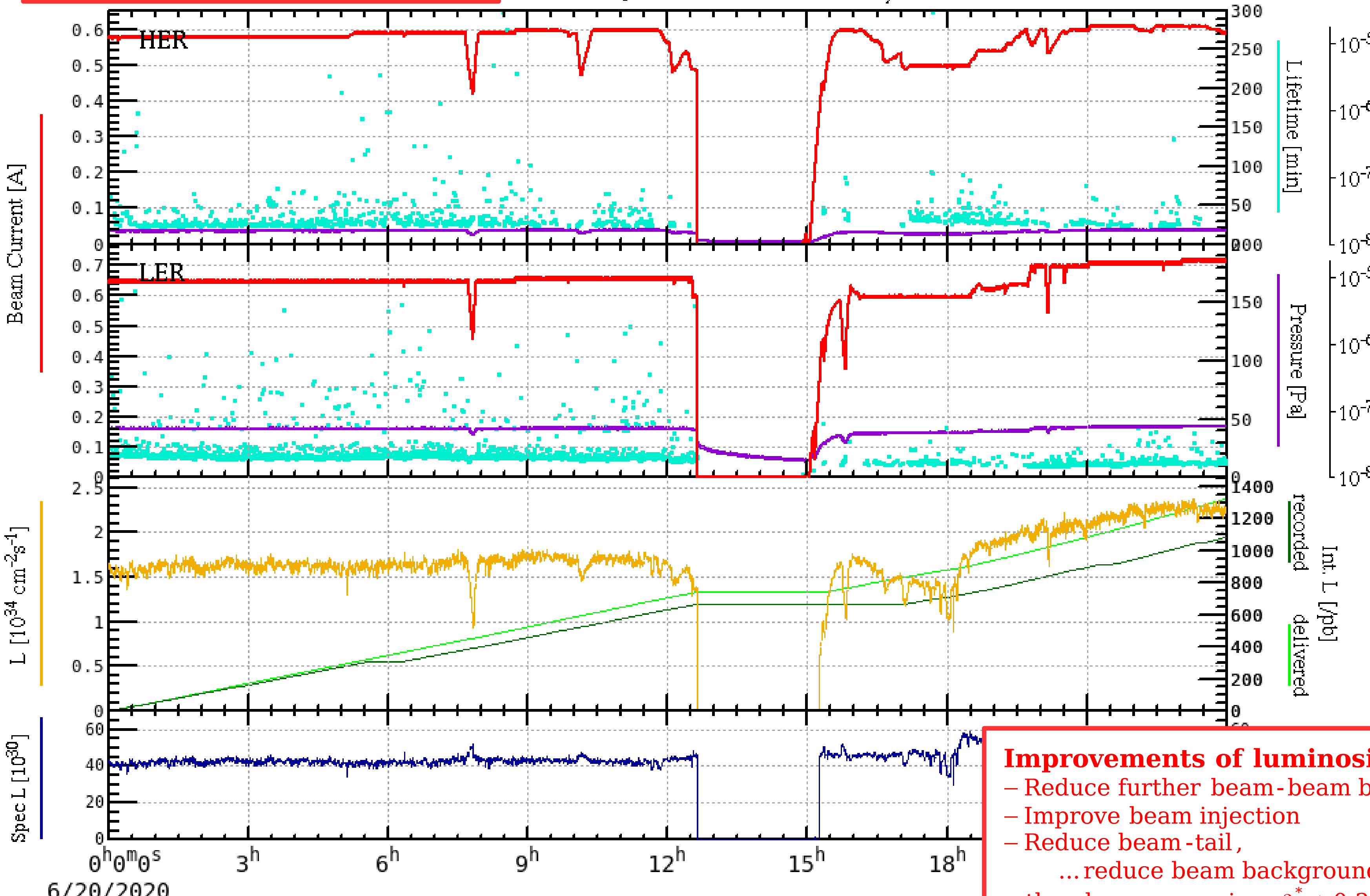
currents ~ 0.6–0.7 A

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

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

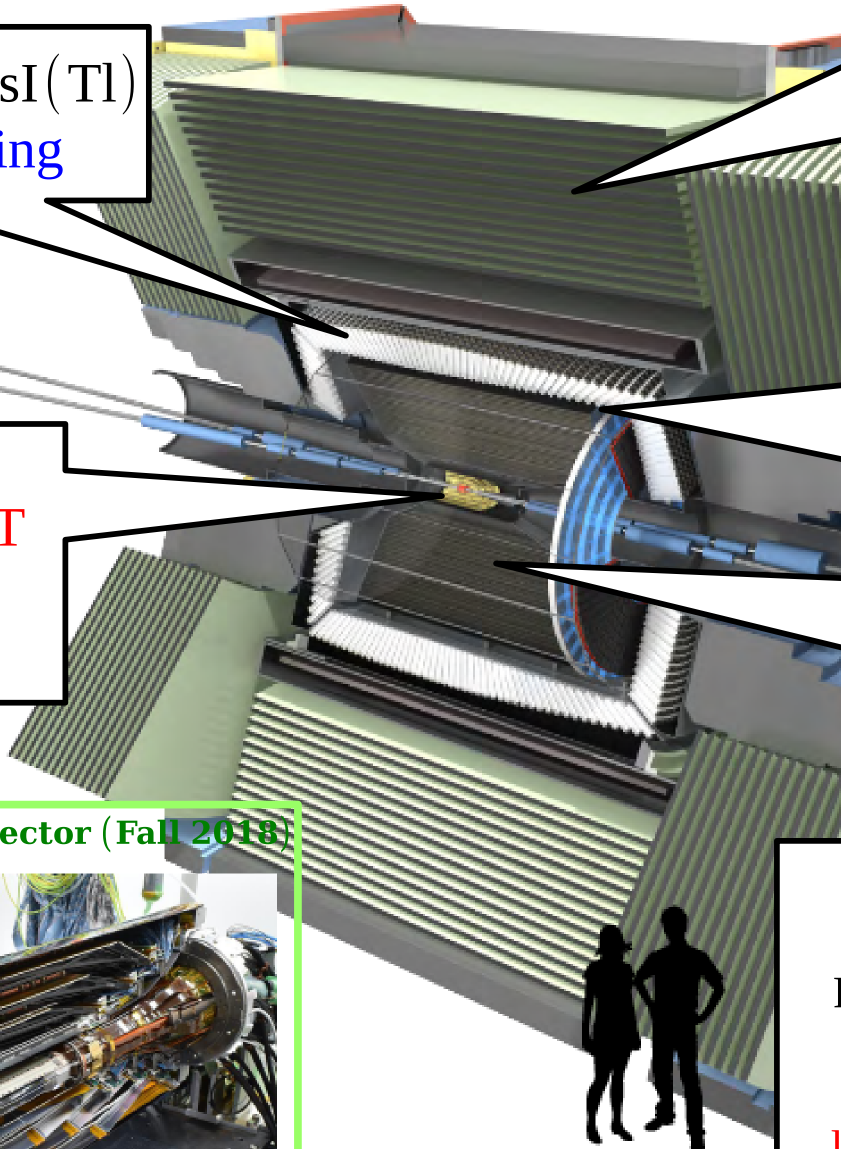
Peak L	2.393 [$10^{34}/cm^2/s$]	@ 2020-06-20 23:18
Int. L/day	1084.64 / 1324.42 [/pb]	

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



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

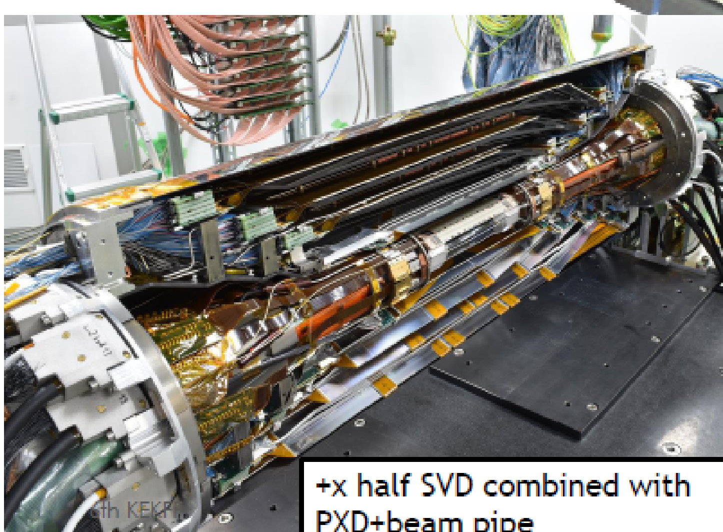
EM Calorimeter: CsI(Tl)
waveform sampling

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 fully installed in 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 (almost) entire Belle II detector**
(P.Robbe, D.Charlet et al)

⇒ now getting involved in VTX upgrade (2026)

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)

$\sigma_{b\bar{b}} \sim 1\,nb \Rightarrow 1\ fb^{-1}$ 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]	$\sigma_{b\bar{b}}$ / σ_{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},

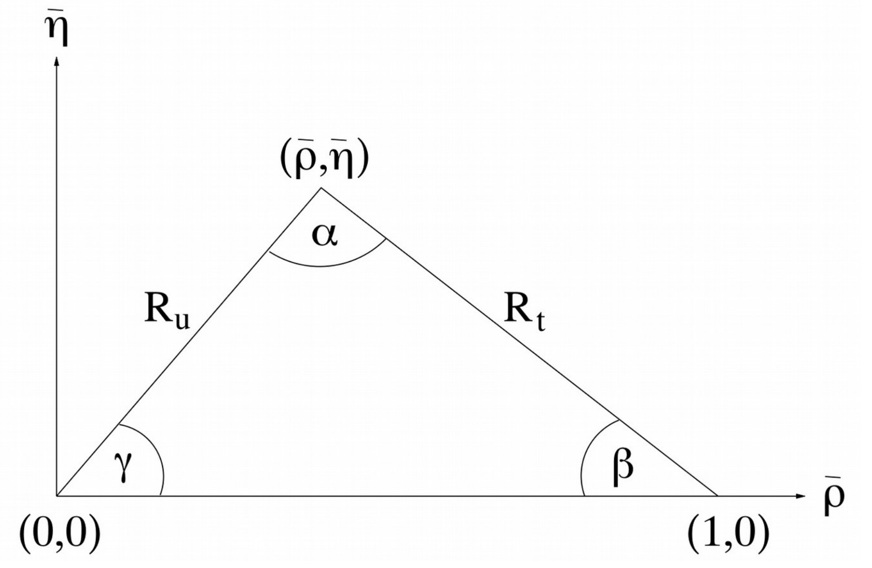
[run II: 2015-2018] = 6 fb^{-1}

(near) future

[Belle II from 2019] → 50 ab^{-1}

[LHCb upgrade from 2021]

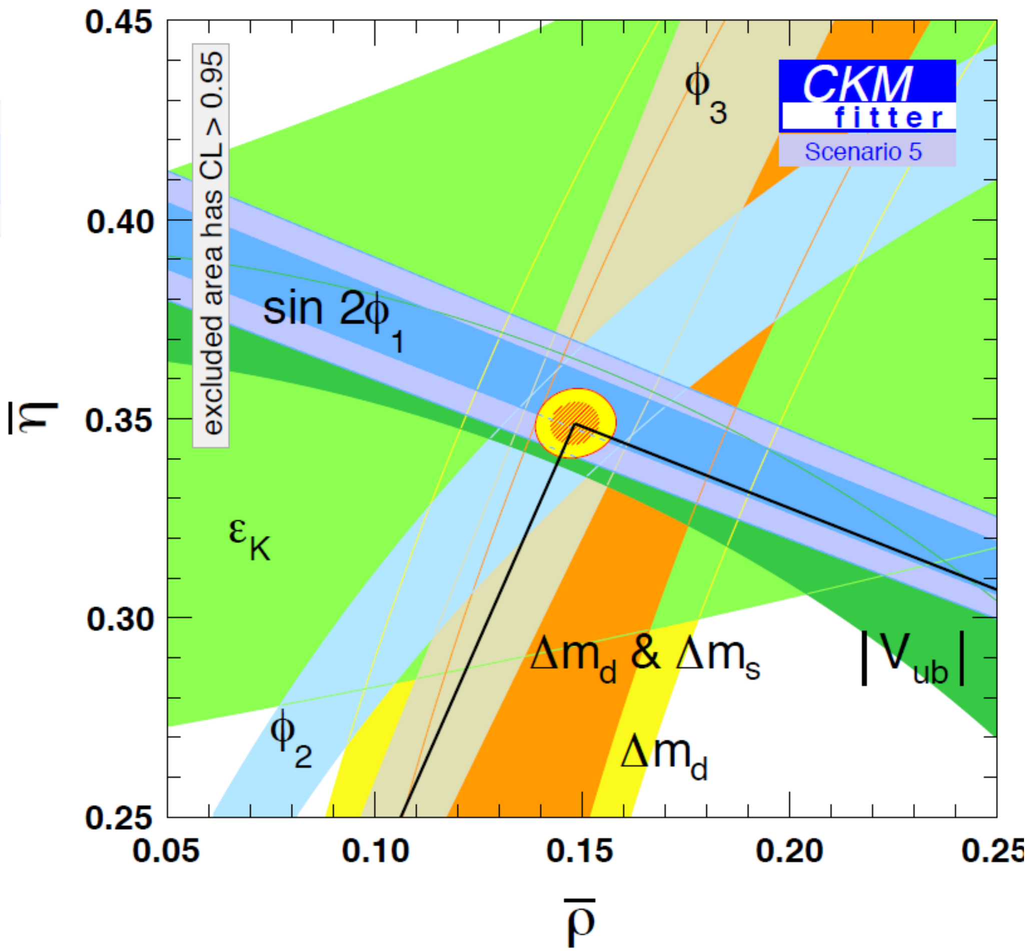
Precision measurements

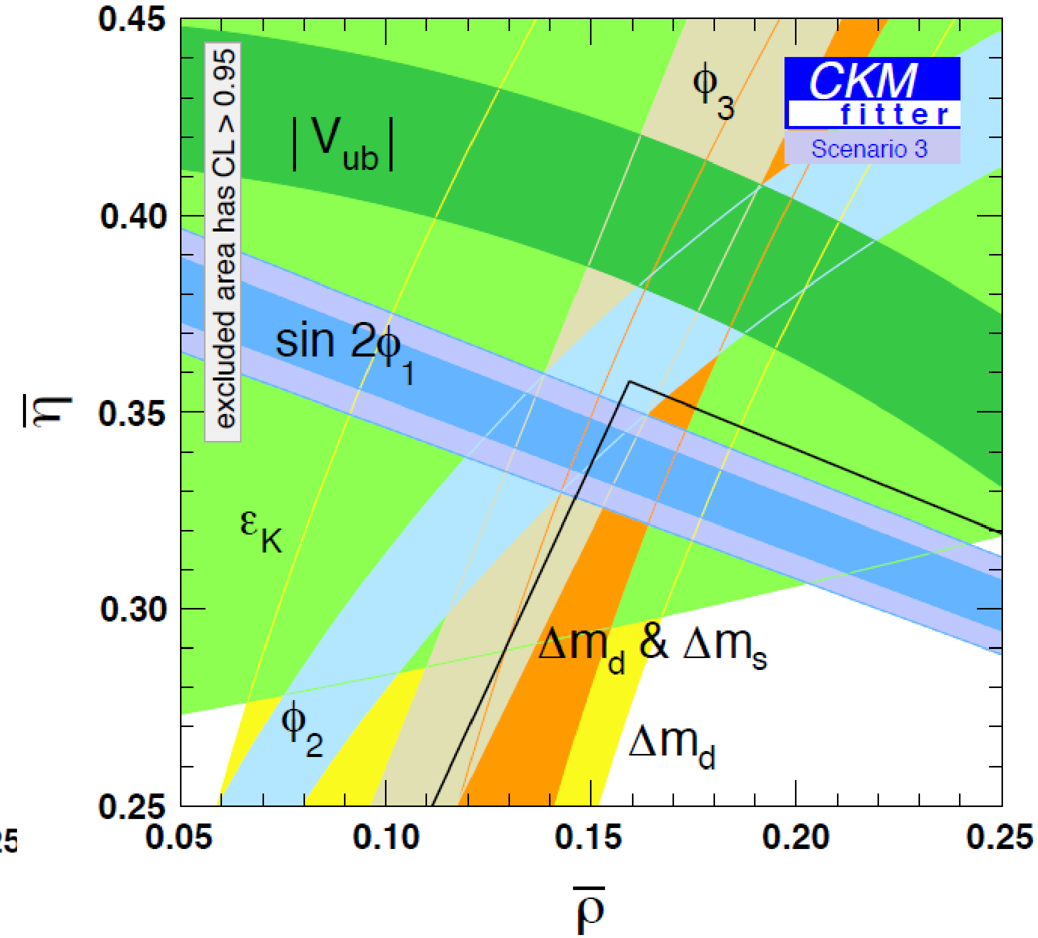


The Unitarity Triangle in the year 2030

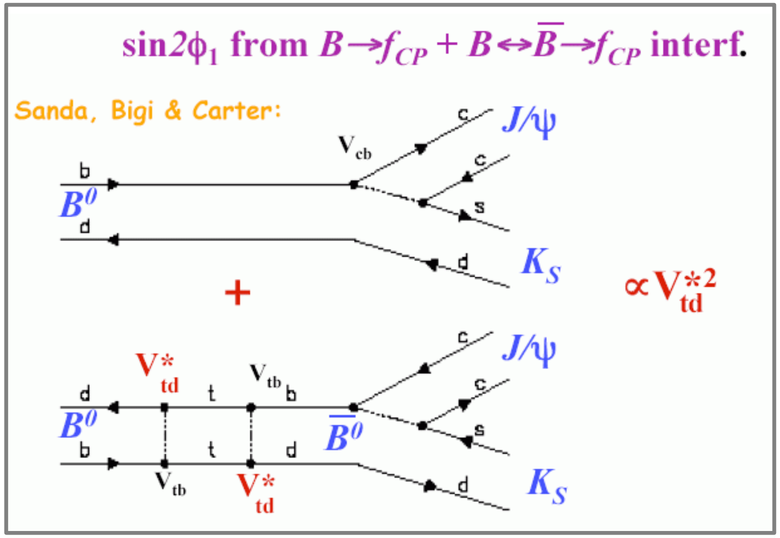
NB: α with couple of degrees @ Belle II

$\Rightarrow$ major updates for $|V_{ub}|$, $\sin 2\beta$, α, γ

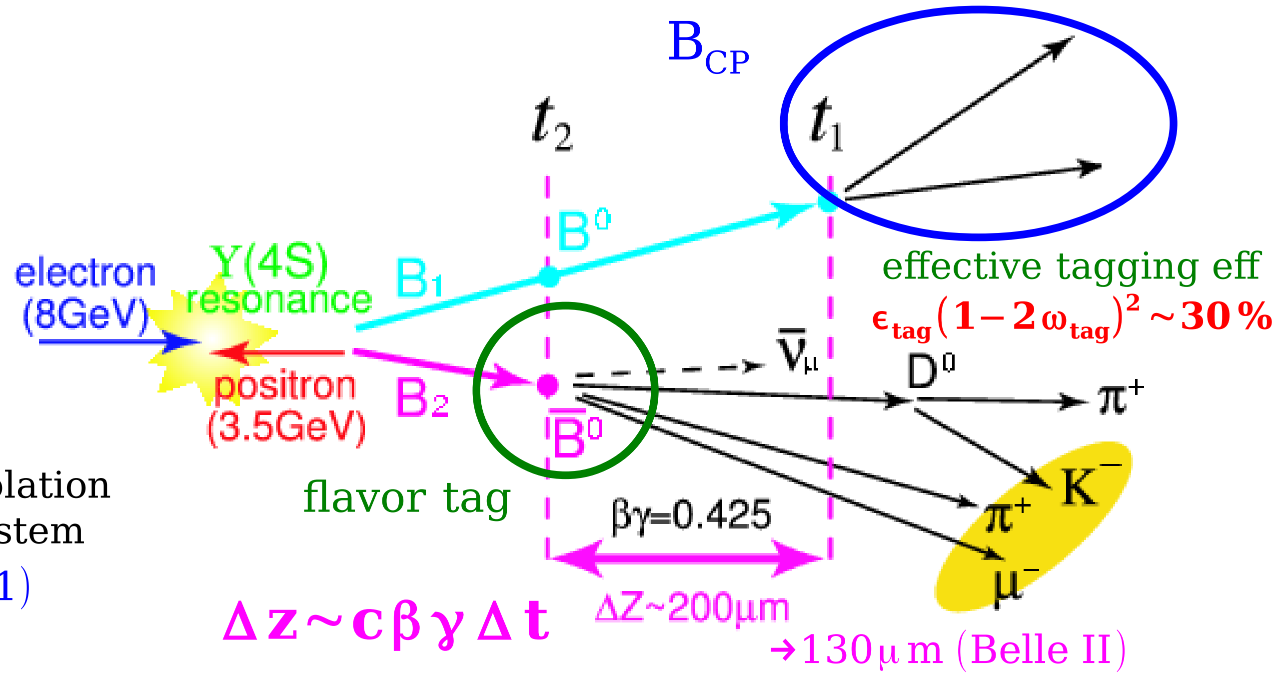




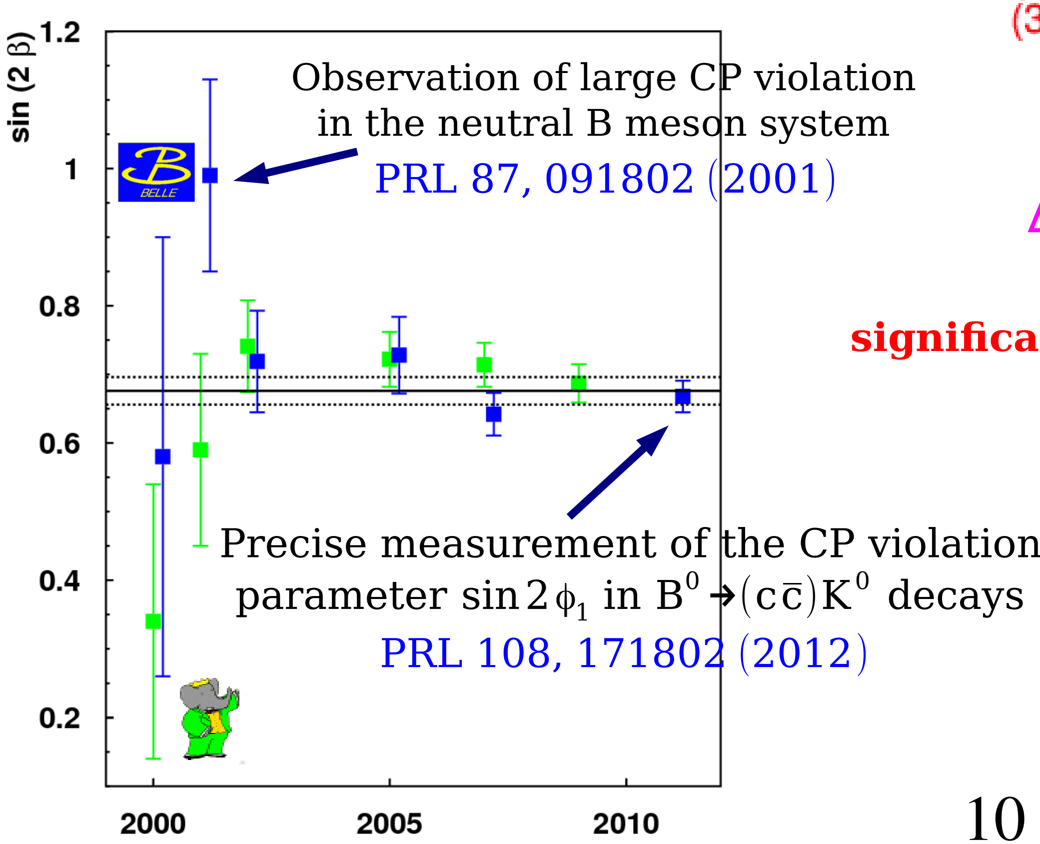
Time−dependent CP asymmetries in decays to CP eigenstates



$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}(1 + q(S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)))$$



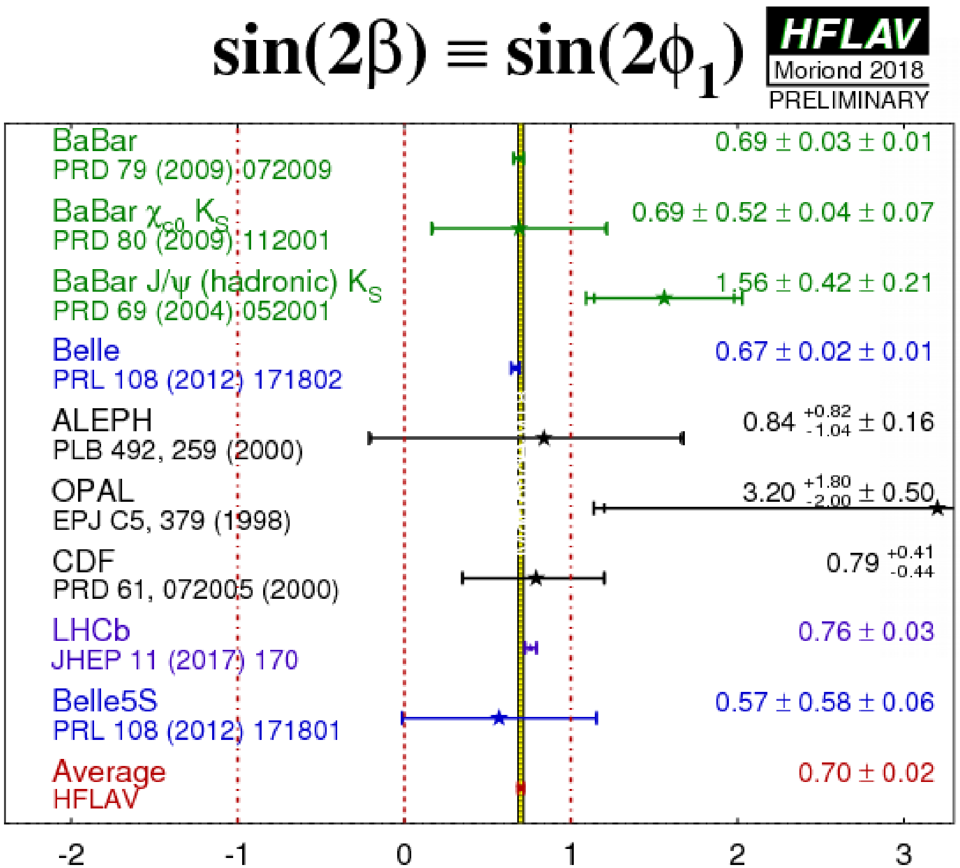
Raison d'être of SVD+PXD
significant resolution improvement for Belle II

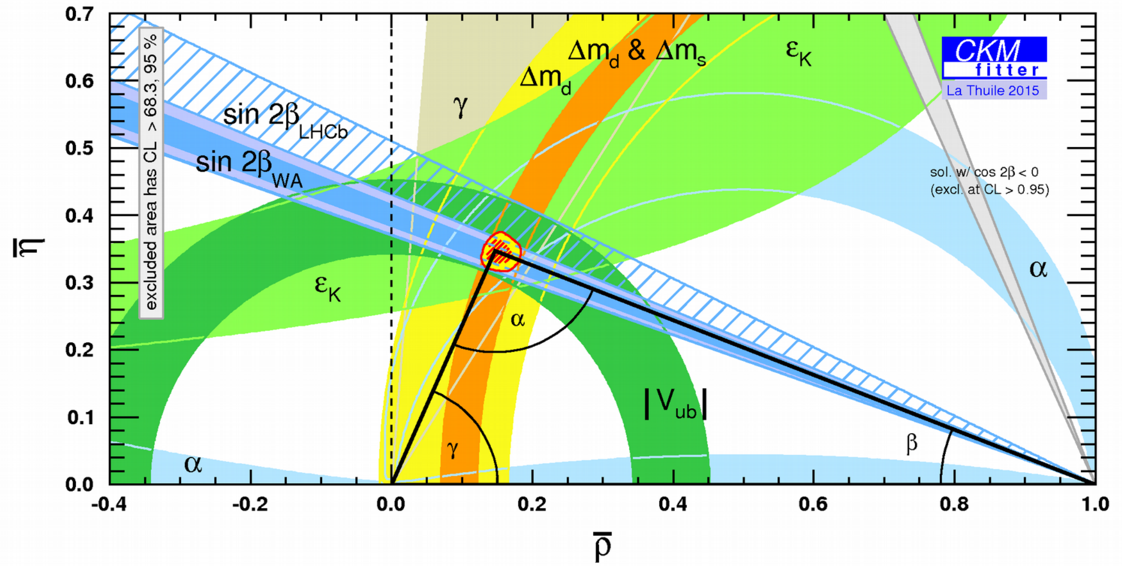


A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's

Critical role of the B factories in the verification of the KM hypothesis

Measurement of $\sin 2\beta$





WA 2016: $\beta = (21.9 \pm 0.7)^{\circ}$

$\sin 2\beta$ at Belle II

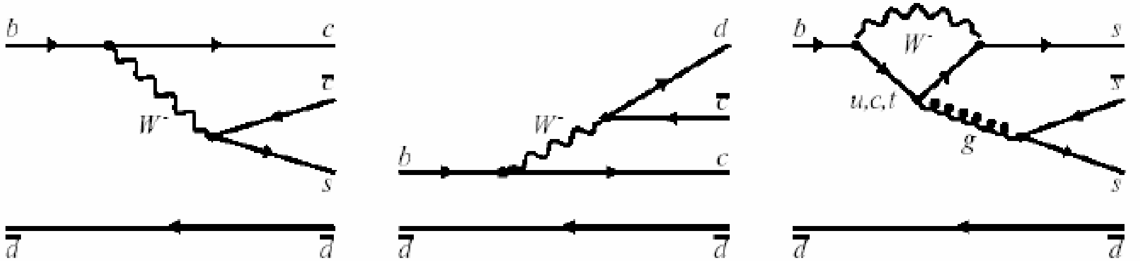
	Belle	Belle II (50 ab^{-1})
S	0.667 ± 0.023 ± 0.012	x.xxxx ± 0.0027 ± 0.0044
A	0.006 ± 0.016 ± 0.012	x.xxxx ± 0.0033 ± 0.0037

anchor of SM

will be dominated by systematic uncertainties

$\sin 2\beta$ with $b \to s$ penguins

dominated by B-factories

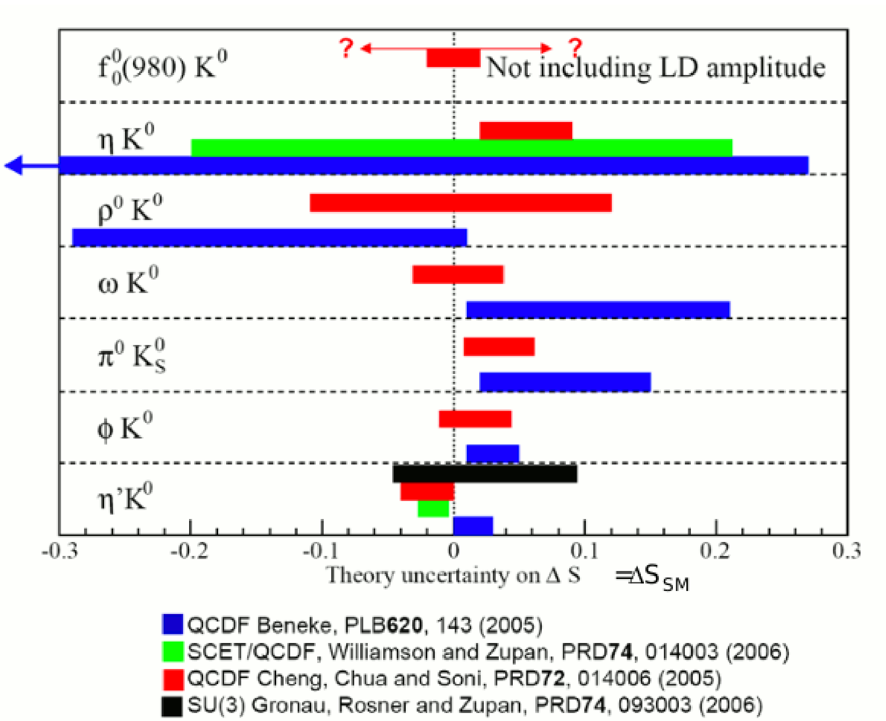


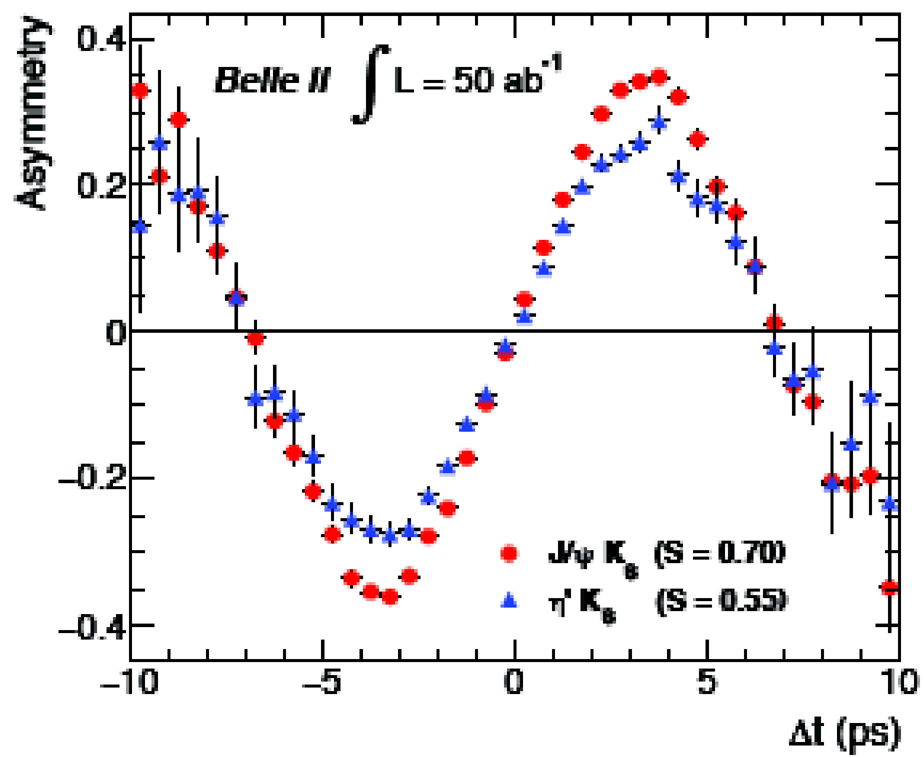
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0$, $\eta_c K_S^0, J/\psi K_L^0$, $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0$, $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0$, $\omega K_S^0, f_0(980)K_S^0$

← increasing tree diagram amplitude

increasing sensitivity to new physics →

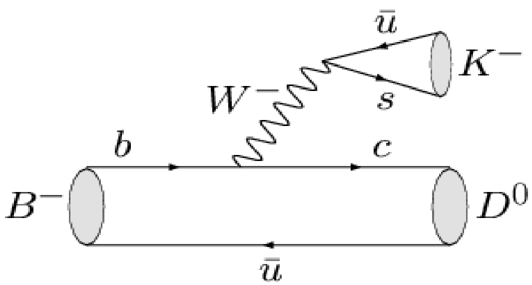
Channel	$\int \mathcal{L}$	Event yield	$\sigma(S)$	$\sigma(A)$
ϕK^0	5 ab^{-1}	5590	0.048	0.035
$\eta' K^0$	5 ab^{-1}	27200	0.027	0.020
ωK_S^0	5 ab^{-1}	1670	0.08	0.06
$K_S\pi^0\gamma$	5 ab^{-1}	1400	0.10	0.12
$K_S\pi^0$	5 ab^{-1}	5699	0.09	0.10





γ measurements from $B^{\pm} \rightarrow DK^{\pm}$

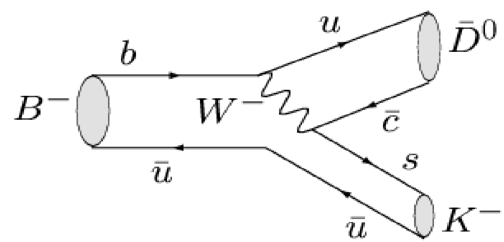
- Theoretically pristine B→DK approach
- Access γ via interference between $B^{-} \rightarrow D^{0}K^{-}$ and $B^{-} \rightarrow \overline{D}^{0}K^{-}$



color allowed

$B^{-} \rightarrow D^{0}K^{-} \sim V_{cb}V_{us}^{*}$

$\sim \mathbf{A\lambda^{3}}$



color suppressed

$B^{-} \rightarrow \overline{D}^{0}K^{-} \sim V_{ub}V_{cs}^{*}$

$\sim \mathbf{A\lambda^{3}(\rho + i\eta)}$

relative weak phase is γ

relative strong phase is δ_{B}

$$r_{B} = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub}V_{cs}^{*}|}{|V_{cb}V_{us}^{*}|} \times [\text{color supp}] = 0.1 - 0.2$$

$B^{\pm} \rightarrow DK^{\pm}$

$B^{\pm} \rightarrow D^{*}K^{\pm},\ D^{*} \rightarrow D\pi^{0}$

$B^{\pm} \rightarrow D^{*}K^{\pm},\ D^{*} \rightarrow D\gamma$

$B^{\pm} \rightarrow DK^{*\pm}$

$B^{0} \rightarrow DK^{*0}$

$B^{\pm} \rightarrow DK\pi\pi$

$B \rightarrow \ldots$

$D \rightarrow K^{+}K^{-},\ \pi^{+}\pi^{-} \ldots$

$D \rightarrow K_{S}\pi^{0},\ K_{S}\eta \ldots$

$D \rightarrow KK\pi^{0},\ \pi\pi\pi^{0} \ldots$

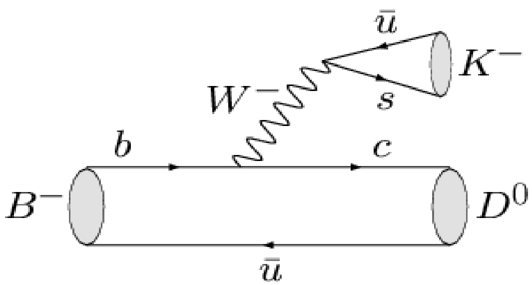
$D \rightarrow K_{S}\pi\pi, K_{S}KK$

$D \rightarrow K_{S}\pi\pi\pi^{0}$

$D \rightarrow \ldots$

γ measurements from $B^\pm \rightarrow DK^\pm$

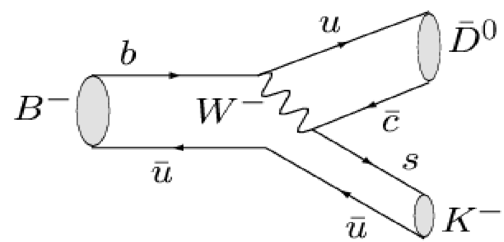
- Theoretically pristine $B \rightarrow DK$ approach
- Access γ via interference between $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \overline{D}^0 K^-$



color allowed

$B^- \rightarrow D^0 K^- \sim V_{cb} V_{us}^*$

$\sim A\lambda^3$



color suppressed

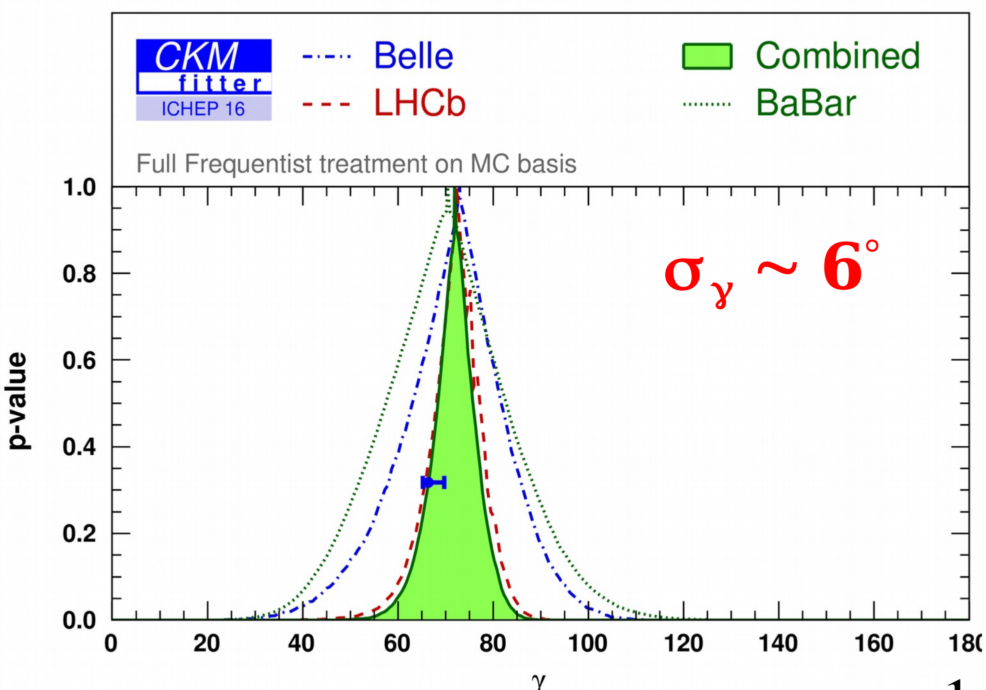
$B^- \rightarrow \overline{D}^0 K^- \sim V_{ub} V_{cs}^*$

$\sim A\lambda^3(\rho + i\eta)$

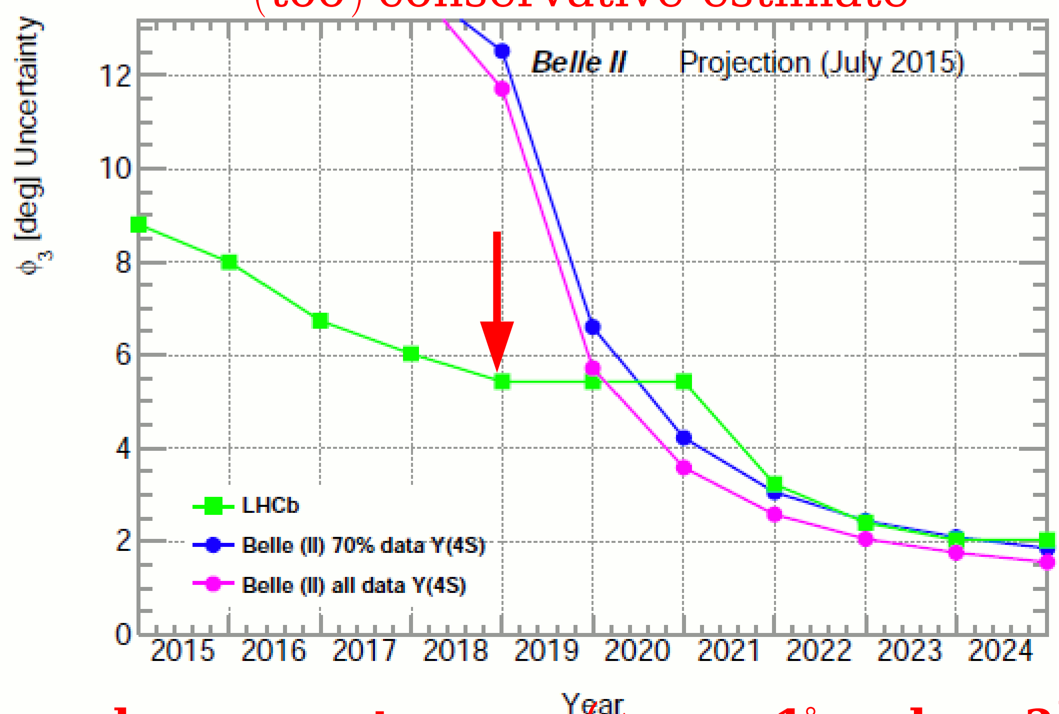
relative weak phase is γ

relative strong phase is δ_B

$r_B \simeq 0.1$

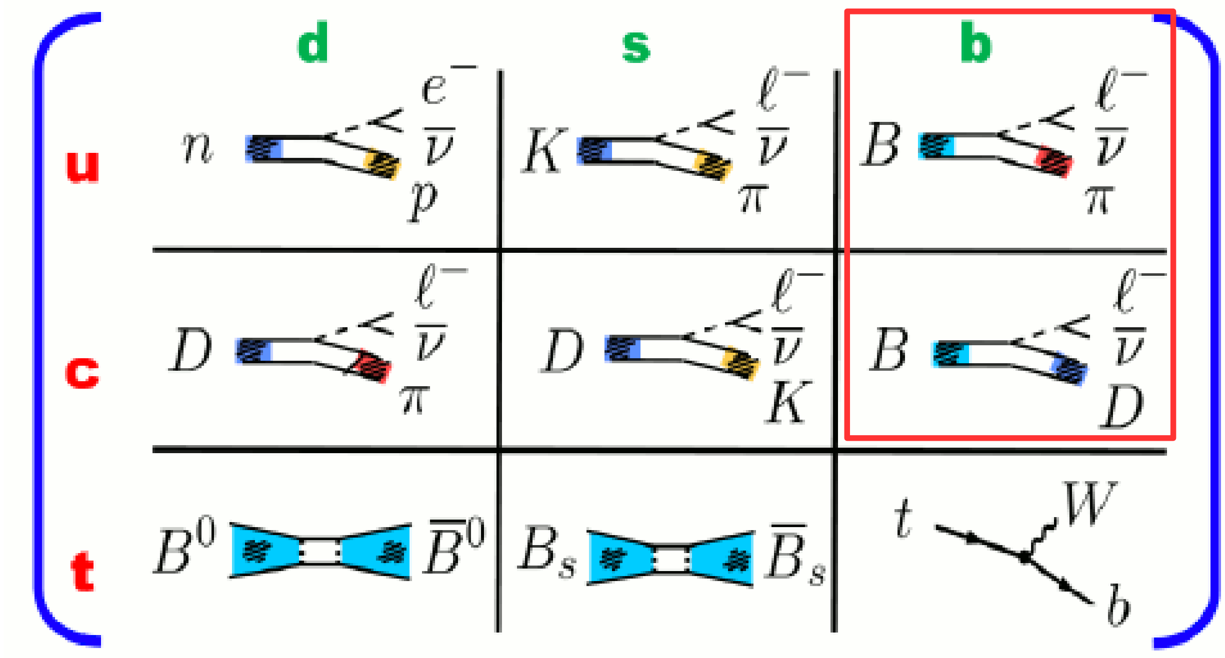


(too) conservative estimate

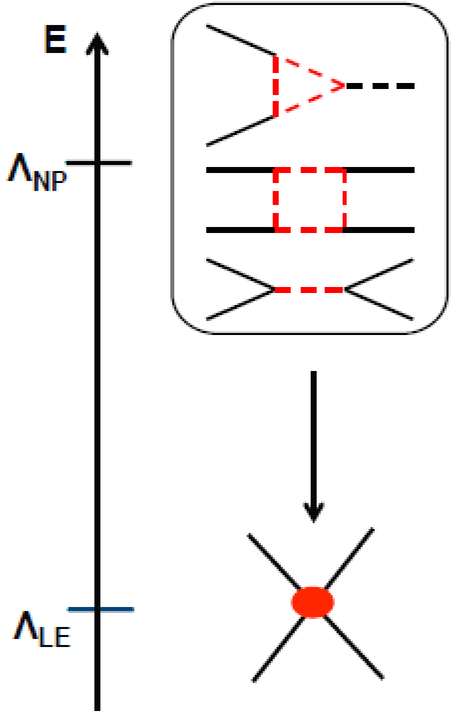


long way to go ... ($\rightarrow \sigma_\gamma = 1^\circ$ or less ?)

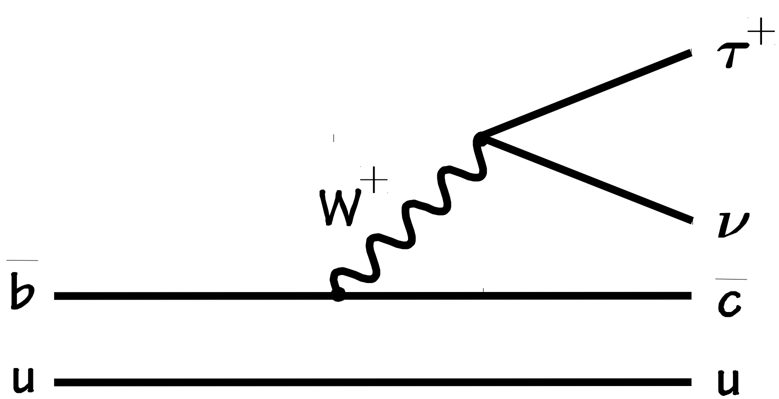
Semileptonic and leptonic

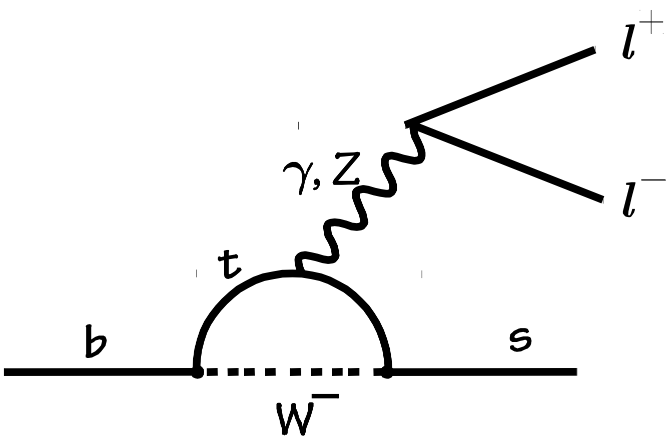


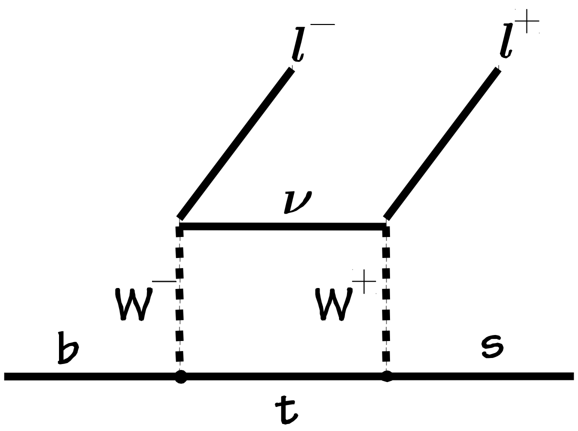
	Process	Obser.	Theory	Discovery (ab^{-1})	Sys. limit (ab^{-1})	vs LHCb BESIII	vs Belle	Anomaly	NP
●	$B \to \pi l \nu_l$	$\|V_{ub}\|$	⋆⋆⋆	-	10	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆
●	$B \to X_u l \nu_l$	$\|V_{ub}\|$	⋆⋆	-	2	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆
●	$B \to \tau\nu$	$Br.$	⋆⋆⋆	2	50	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \mu\nu$	$Br.$	⋆⋆⋆	5	50	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to D^{(*)} l \nu_l$	$\|V_{cb}\|$	⋆⋆⋆	-	1	⋆⋆⋆	⋆	⋆	
●	$B \to X_c l \nu_l$	$\|V_{cb}\|$	⋆⋆⋆	-	1	⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	⋆⋆⋆	-	5	⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	P_τ	⋆⋆⋆	-	15	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
●	$B \to D^{**} l \nu_l$	$\|V_{cb}\|$	⋆	-	-	⋆⋆	⋆⋆⋆	⋆⋆	



rare decays

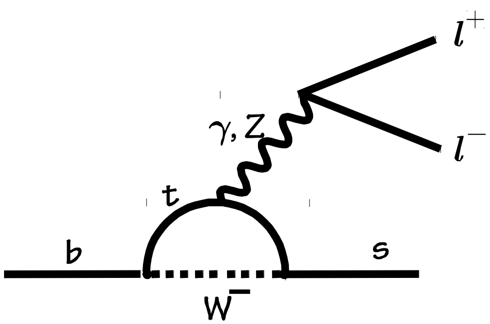


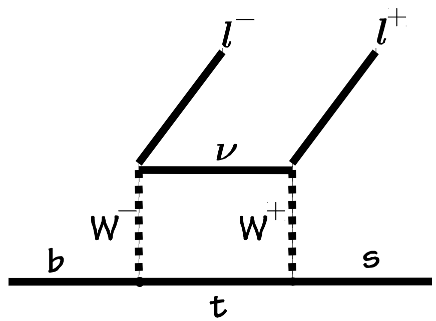




Lepton (non) universality using $B^+ \to K^{(*)} l^+ l^-$ decays

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



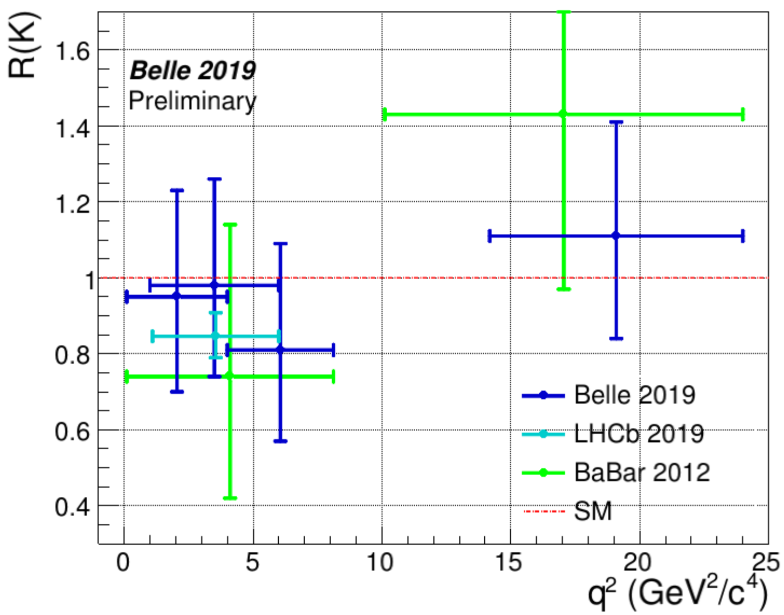


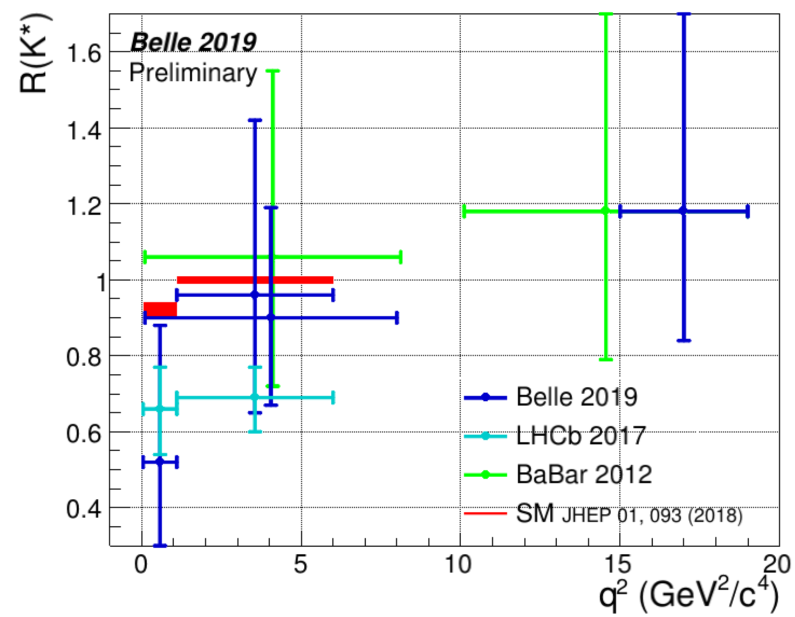
The ''clean'' Lepton Flavor Universality ratios:

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

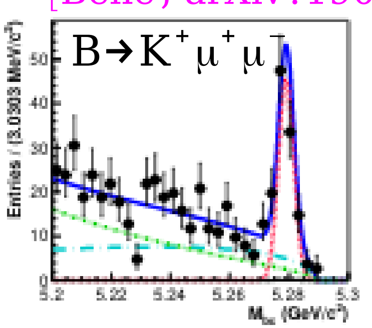
SM prediction very robust: $R_K(SM) = 1$

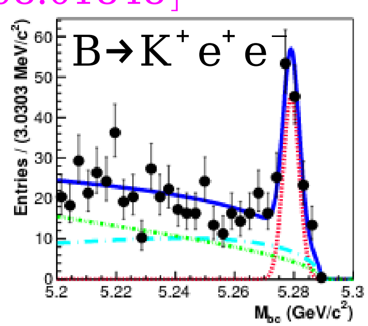
[up tiny QED and lepton mass effects]

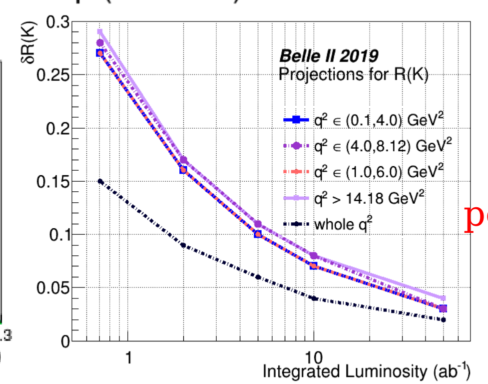




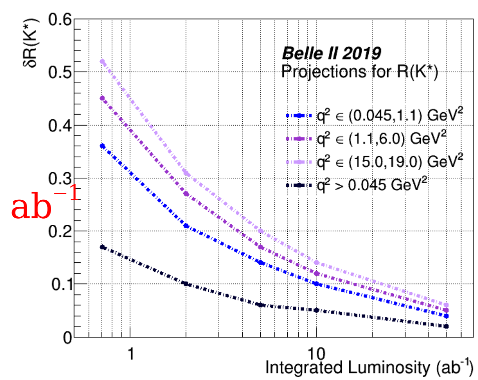
[Belle, arXiv:1908.01848]





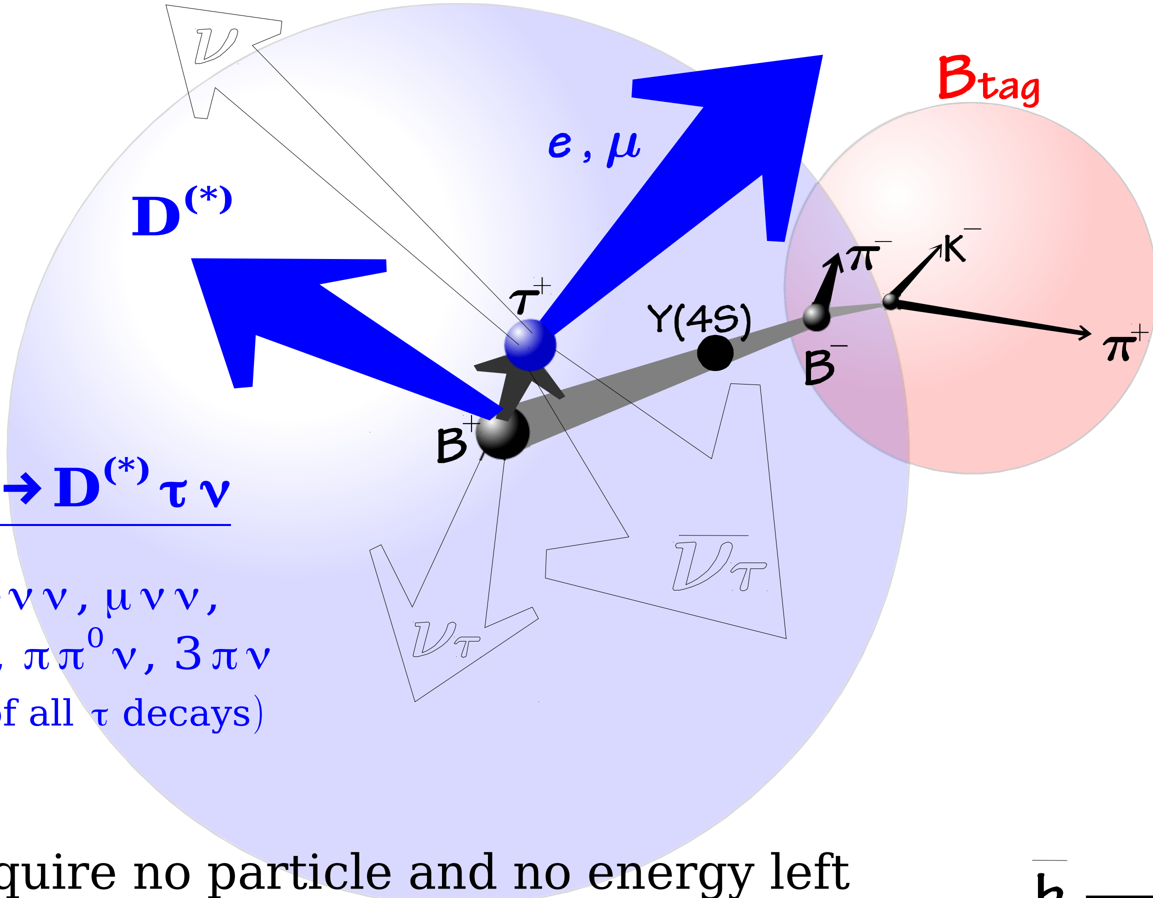


5σ confirmation possible with Belle II 20 ab^{-1}



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)

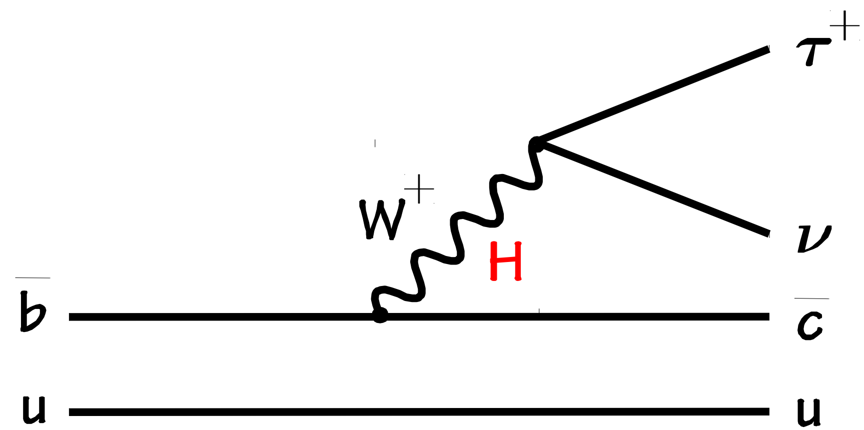
B_{tag}

hadronic tag

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

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}

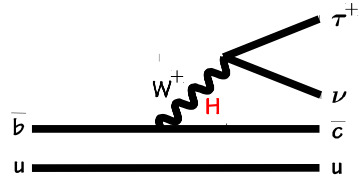
main signal-background discriminator

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

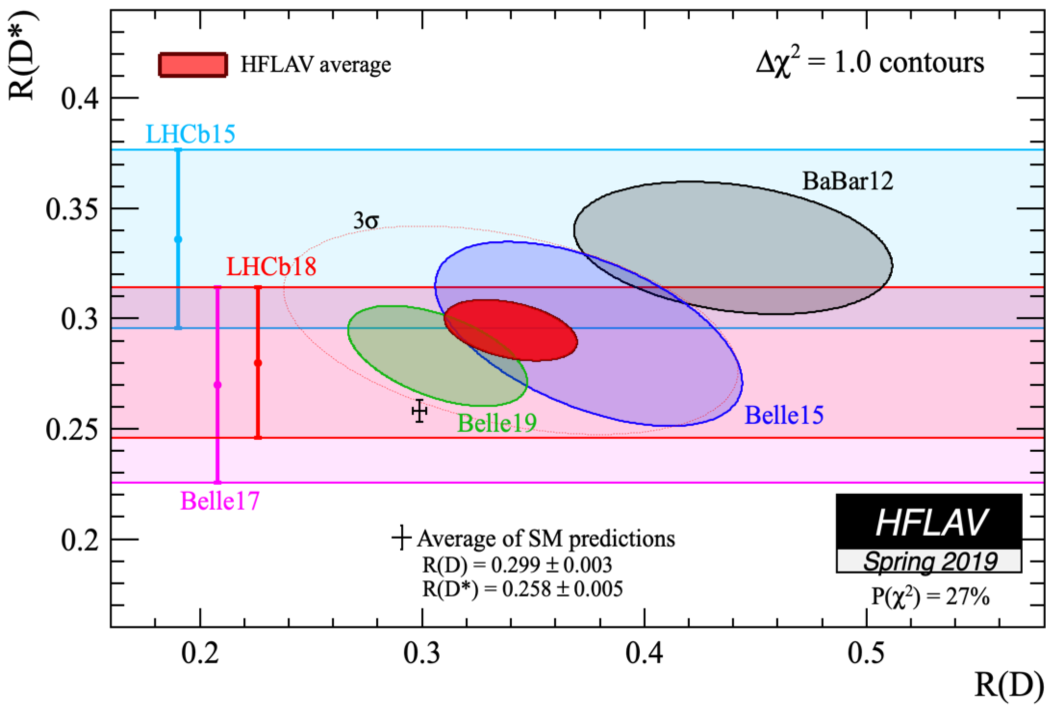
$$2HDM\ (type\ II):\ \mathcal{B}(B \to D \tau^+ \nu) = G_F^2\, \tau_B\, |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)$$

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

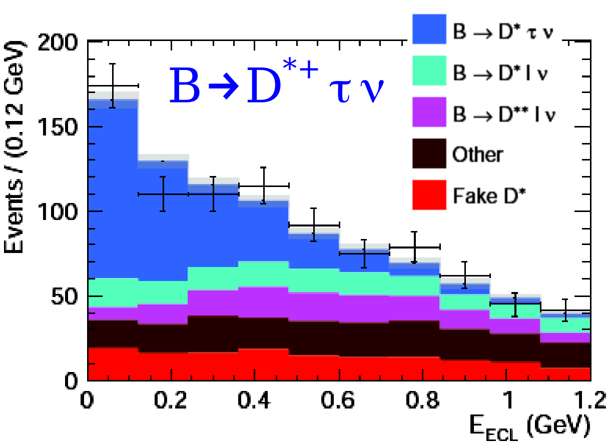
$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

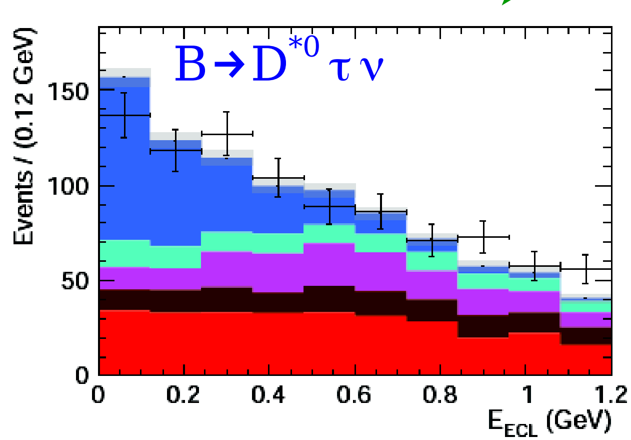
$R(D^*) = 0.270 \pm 0.035\,^{+0.028}_{-0.025}$

Belle 19 SL tag

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

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

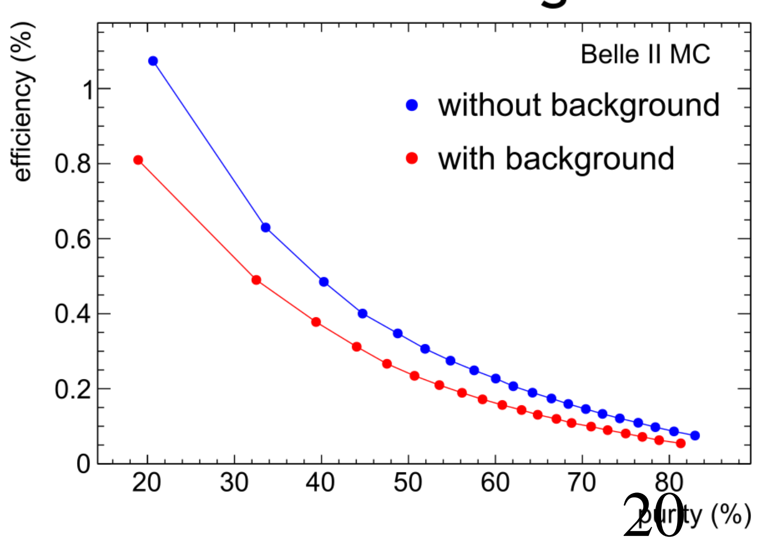
- More modes used for tag-side hadronic B than Belle, multiple classifiers

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

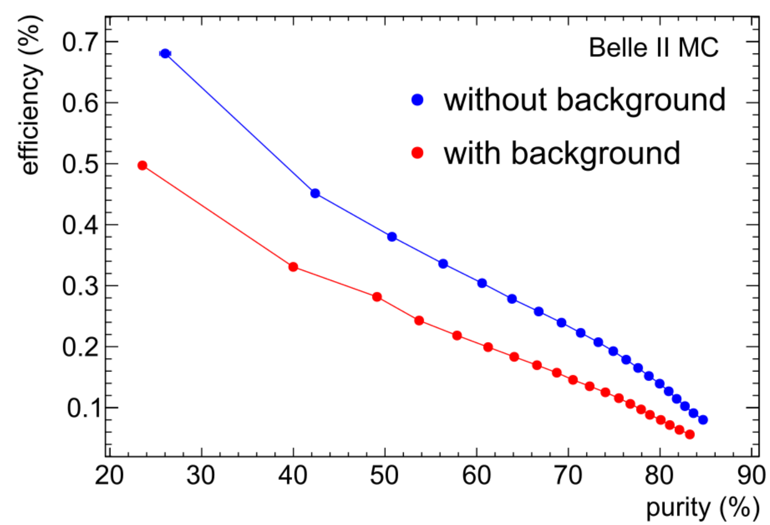
Improvement to tagging efficiency in Belle II

- Good performances on Belle II predicted beam background conditions:

Hadronic charged B



Hadronic neutral B



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

Model candidates

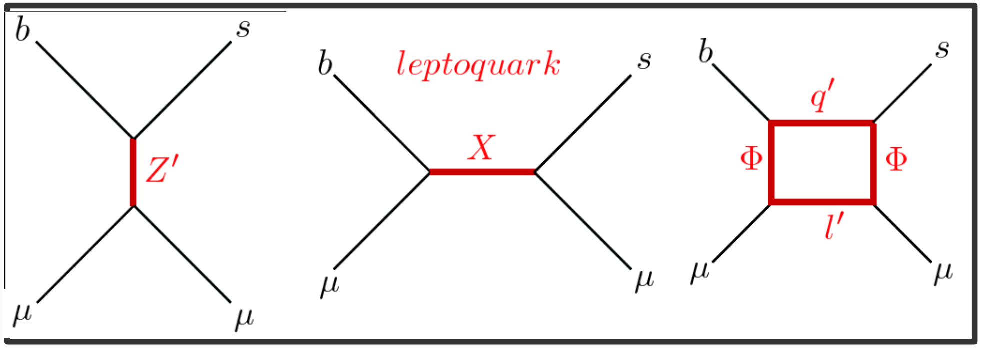
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **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 $b \to s e\mu$, $b \to s e\tau$,...

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

G.Isidori, FPCP 2020: correlations among b→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_π]	$B \to \pi \tau\tau$ → 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ → 10^{-7}	$B \to \pi \mu e$???

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

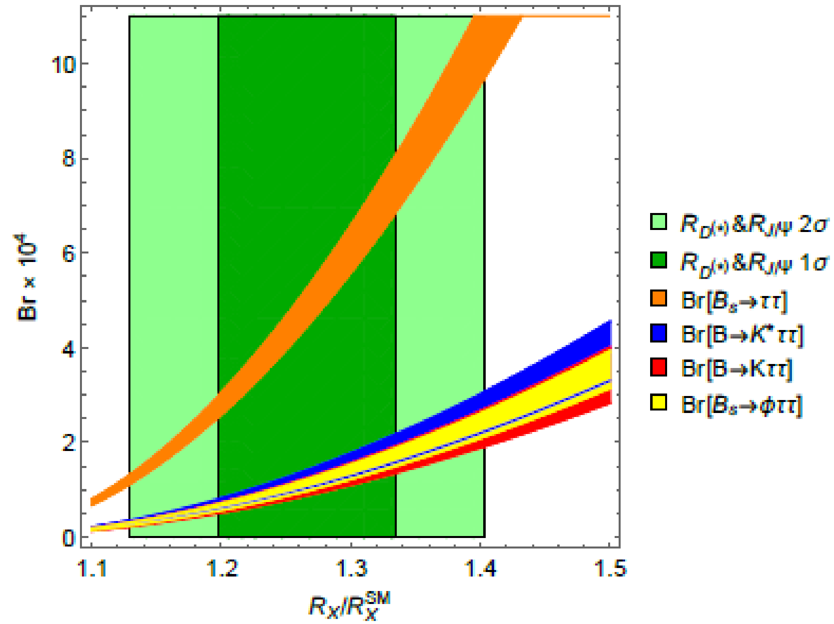
[B.Capdevila et al, arXiv:1712.01919]

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 $\psi(2S)$, $B \to H\psi(2S)$, $\psi(2S) \to \tau^+\tau^-$

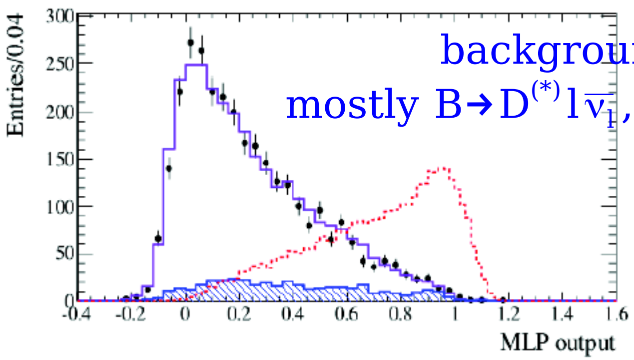
predictions restricted to $q^2 > 15$ GeV^2:

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

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

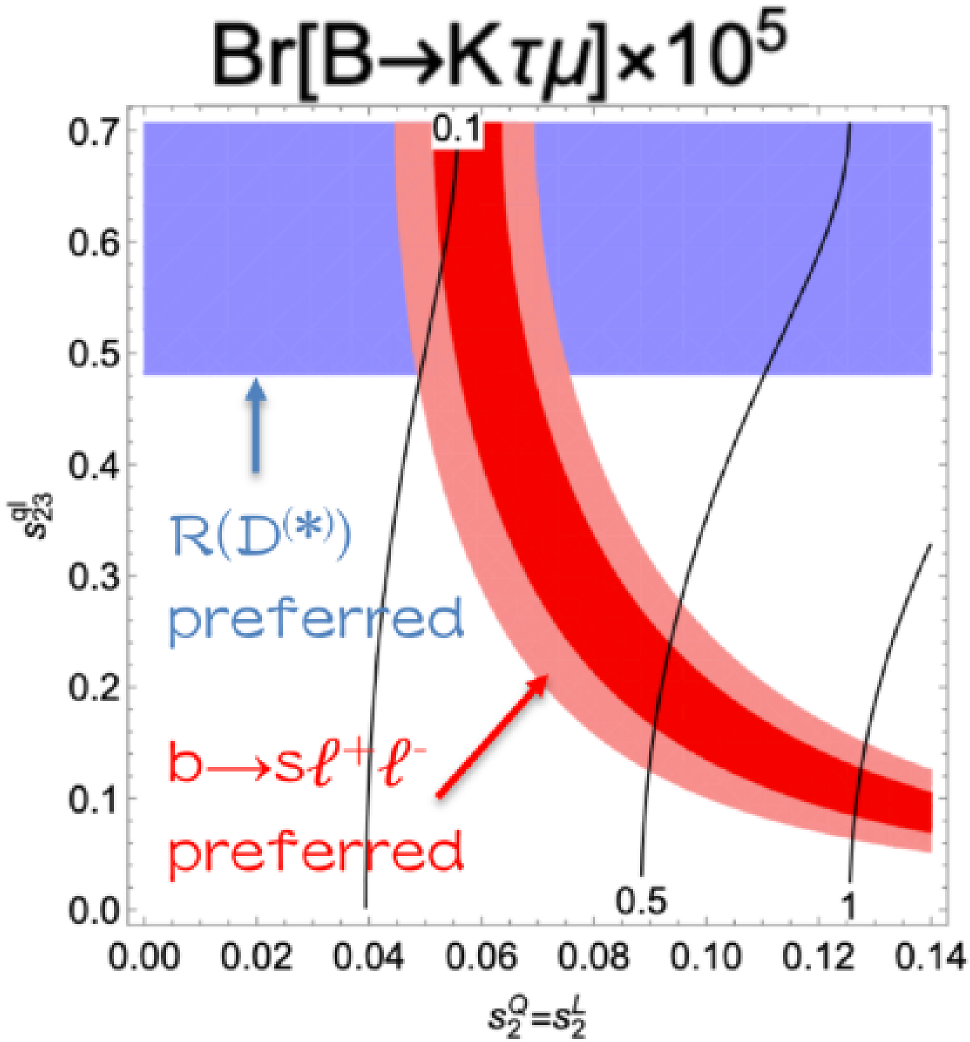
[Belle II, arXiv:1808.10567]

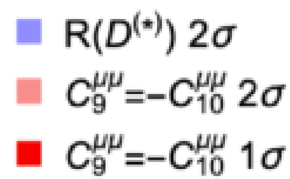
Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)\cdot 10^5$	< 32	< 6.5	< 2.0

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 PS³

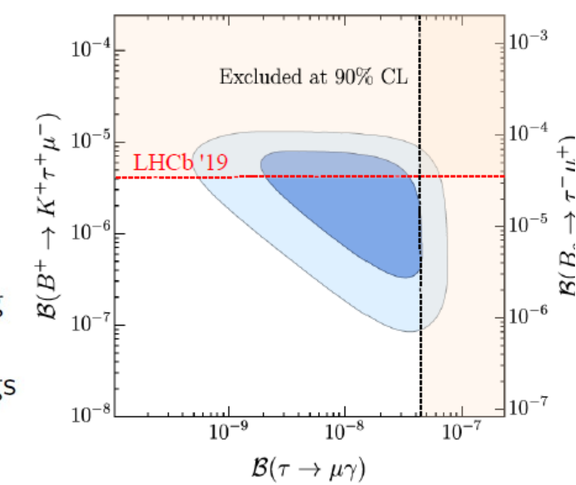
BORDONE, CORNELLA, FUENTES-MARTIN, ISIDORI (2017), (2018)

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



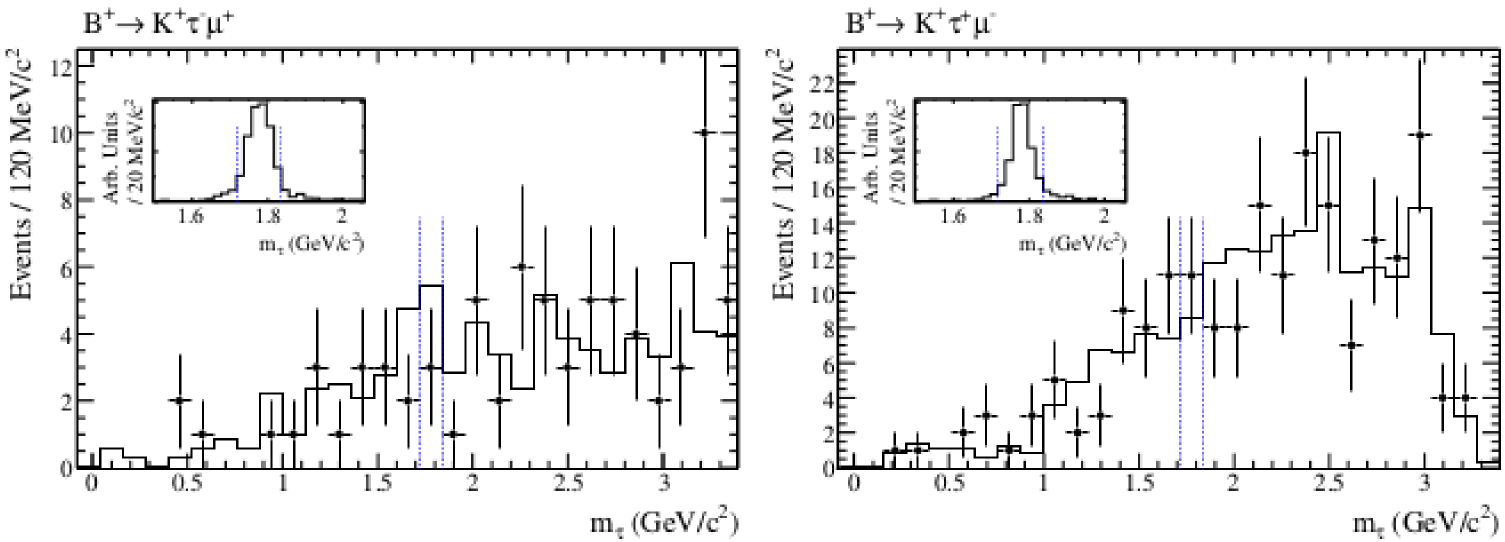
LFV $B \to K \tau l$ ($l = e, \mu$) decays

[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)

[LHCb, arXiv:2003.04352]

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

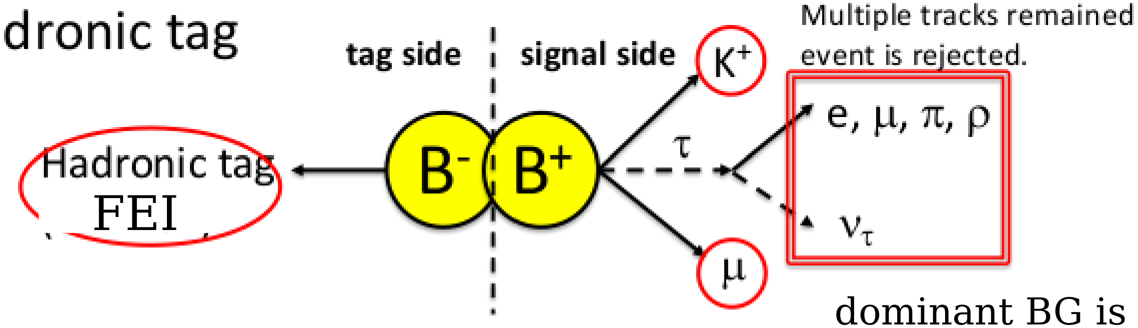
$Br(K^+ \tau^+ \mu^-) < 3.9 \times 10^{-5}$ at 90% CL

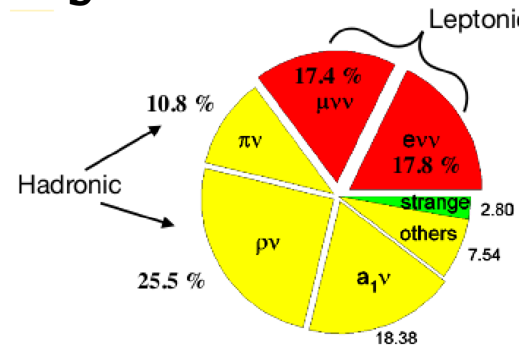
⇒ can we do better ? combining hadronic tag with an more inclusive tag ?...

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)

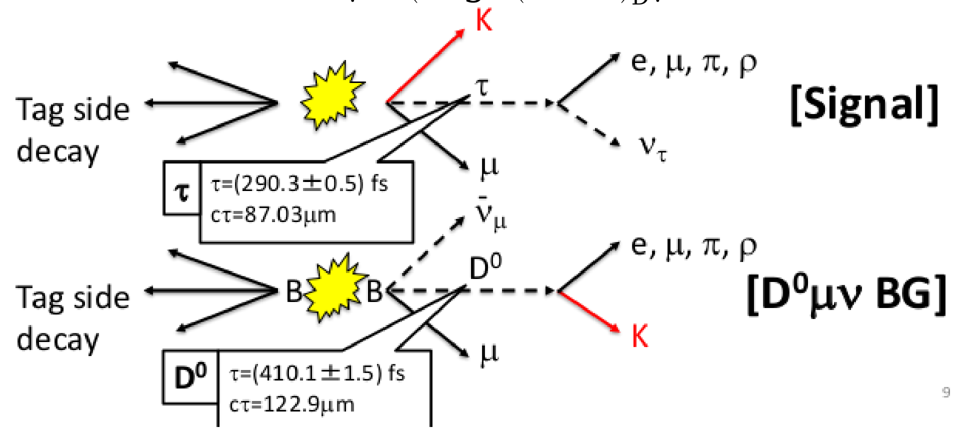
recoil mass of τ unique to $B \to K\tau^+ l^-$ mode

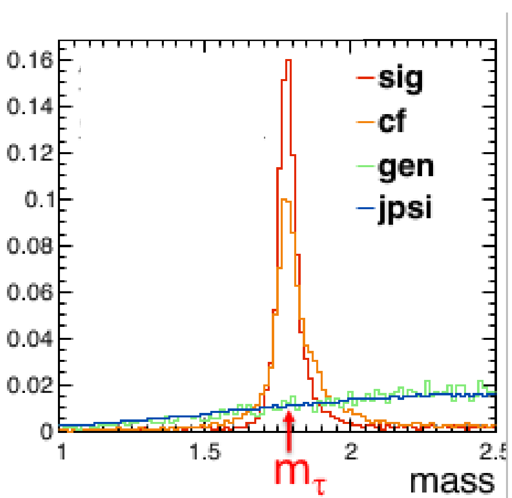
usually another neutrino companion ($B \to \tau\nu$, $D^*\tau\nu$...)

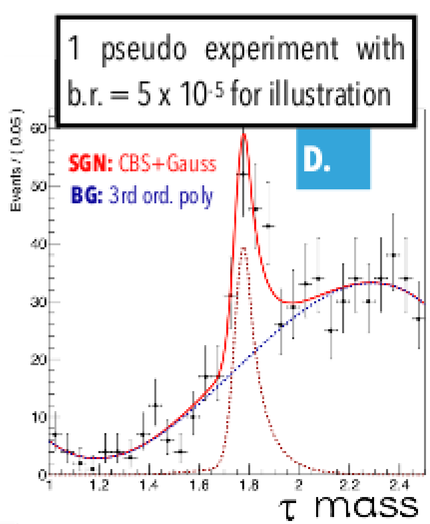
$$m_\tau^2 = m_B^2 + m_{Kl}^2 - 2(E_B^* E_{Kl}^* - |\vec{p}^{\,*}_{B_{sig}}||\vec{p}^{\,*}_{Kl}|\cos\theta)$$

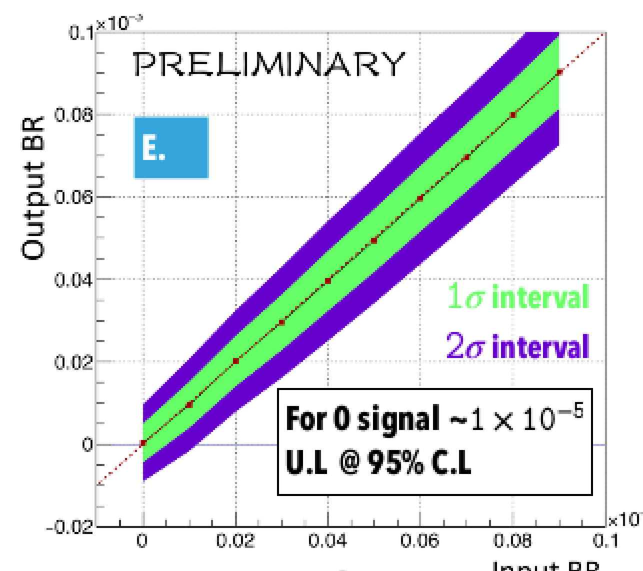
E^*_{beam} $\sqrt{(E^*_{beam})^2 - m_B^2}$

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







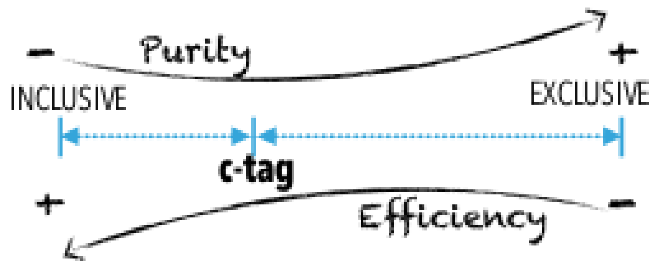


Stat. Error only! ⇒ **can we do better ?**

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

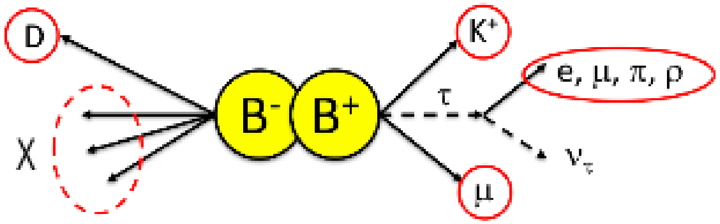
	$B^+ \to$	$B^0 \to$
$D^0 X$	(8.6±0.7)%	(8.1±1.5)%
$\overline{D}^0 X$	(79±4)%	(47.4±2.8)%
$D^+ X$	(2.5±0.5)%	(< 3.9%)
$D^- X$	(9.9±1.2)%	(36.9±3.3)%
$D_s^+ X$	(7.9±1.4)%	(10±2)%
$D_s^- X$	(1.10±0.40)%	(< 2.6%)
$\Lambda_c^+ X$	(2±1)%	(< 3.1%)
$\Lambda_c^- X$	(3±1)%	(5.0±2.0)%

- 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

cLFV : beyond the Standard Model

long-standing, and well motivated (particularly since the discovery of neutrino oscillations) programme of searches for charged Lepton Flavour Violation

less stringent limits in 3rd generation, but here BSM effects may be higher

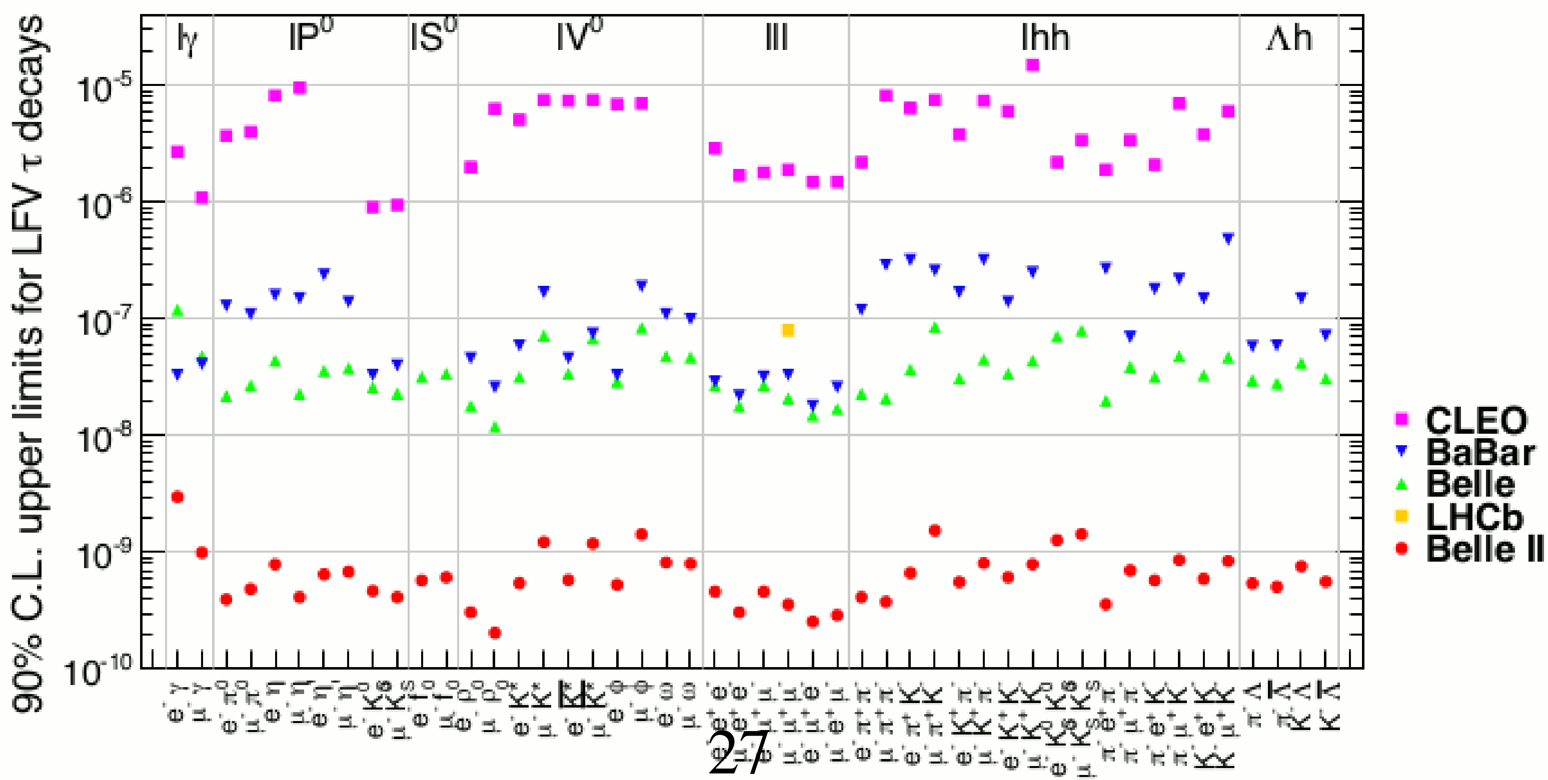
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$

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

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-40}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

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

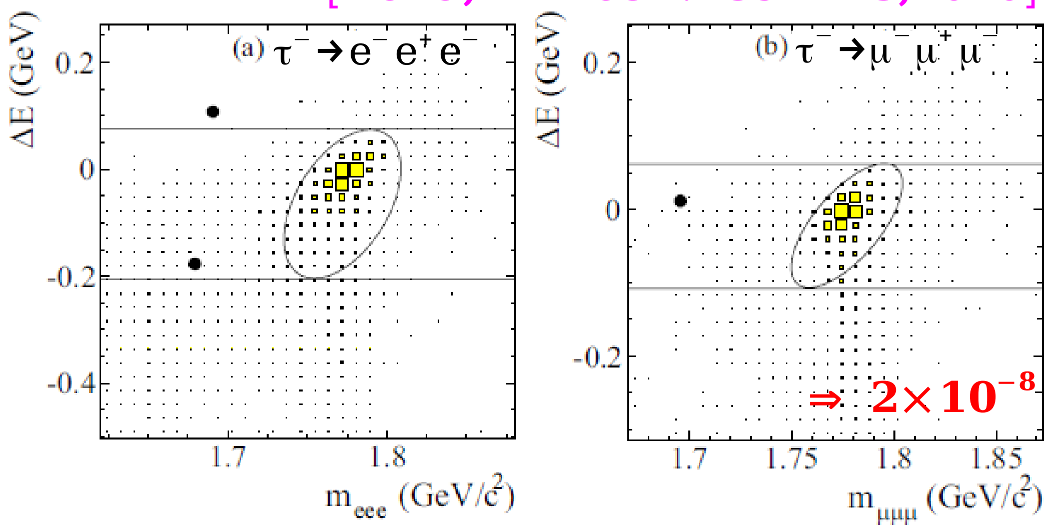
Celis, Cirigliano, Passemar (2014)



cLFV : beyond the Standard Model

τ LFV searches at Belle II will be extremely clean with very little background (if any), thanks to pair production and double-tag analysis technique.

[Belle, PLB 687:139–143,2010]



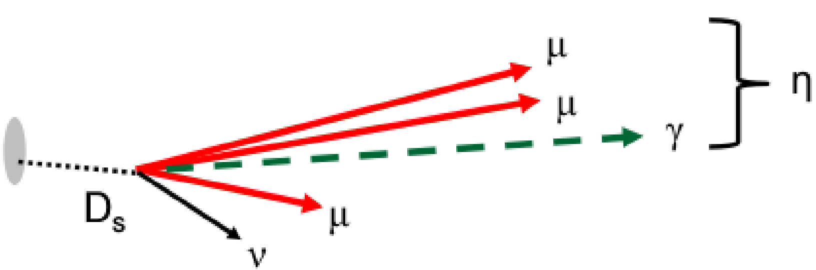
⇒ 2×10^{-8} at 90%CL

how to improve further ?

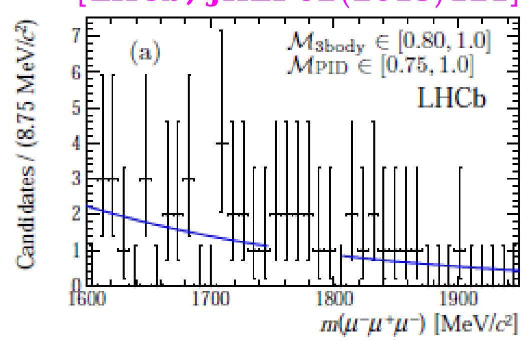
...considering $\tau\to\mu/e\,h^+h^-$ in function of one prong tag categories

...for $\tau\to3$ muons, improve μ-ID at low mom (ECL info)

In contrast, hadron collider experiments must contend with larger combinatorial and specific backgrounds



[LHCb, JHEP02(2015)121]



⇒ 5×10^{-8} at 90%CL

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

Decay channel	Relative abundance
$D_s\to\eta(\mu\mu\gamma)\mu\nu$	1
$D_s\to\phi(\mu\mu)\mu\nu$	0.87
$D_s\to\eta'(\mu\mu\gamma)\mu\nu$	0.13
$D\to\eta(\mu\mu\gamma)\mu\nu$	0.13
$D\to\omega(\mu\mu)\mu\nu$	0.06
$D\to\rho(\mu\mu)\mu\nu$	0.05

Most improvement in coming decade is expected from Belle II, which can reach 1×10^{-9} [arXiv:1011.0352] and will do even better if can achieve ~ zero bckgd

Many more interesting τ topics

CP asymmetry (CPV not yet observed in the lepton sector)

$$A_\tau \equiv \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

$$A_\tau = (-3.6 \pm 2.3 \pm 1.1)\, 10^{-3}$$

$(\geq 0\,\pi^0)$ [Babar, PRD85, 031102 (2012)]

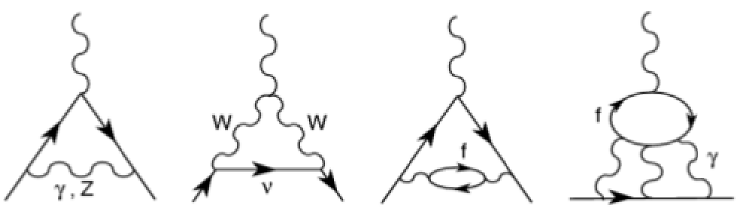
$$A_\tau^{SM} = (+3.6 \pm 0.1)\, 10^{-3}$$

(CPV in K^0 system)

[Bigi-Sanda, Grossman-Nir]

- Belle shows no indication of CP aymmetry in angular distribution of $\tau^- \to K_S \pi^- \nu_\tau$
- a variety of CPV observables to be studied: $\tau \to K\pi\pi\nu_\tau$, $\tau \to \pi\pi\pi\nu_\tau$ rate, angular asymmetries, triple products...

EDM (CPV in tau pair production), τ Anomalous Magnetic Moment



$$a_\mu^{exp} - a_\mu^{th} \sim 3.5\,\sigma$$

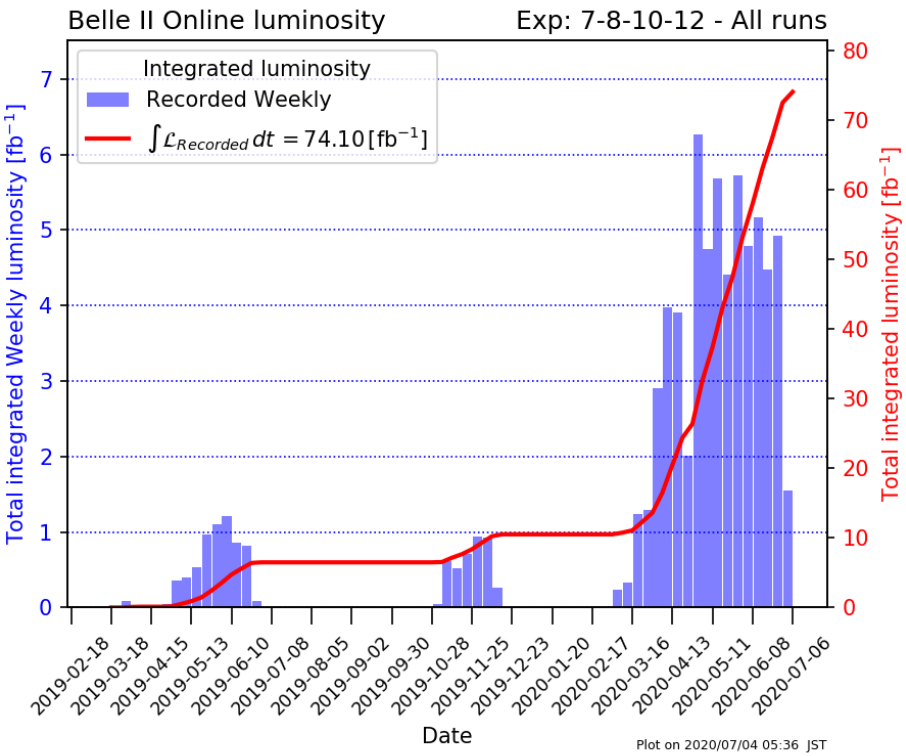
Enhanced sensitivity to new physics: $(m_\tau/m_\mu)^2 = 283$

S.Eidelman, M.Passera

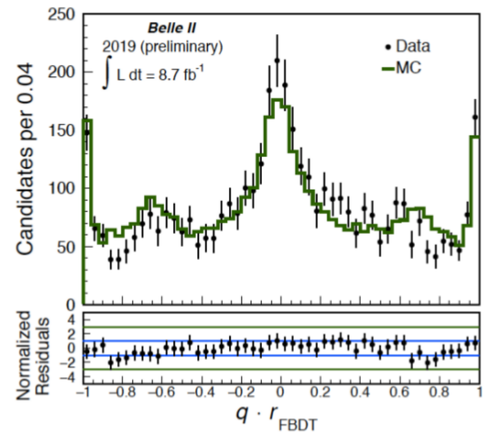
$10^8 \cdot\ a_\tau^{th} =$	117 324	± 2	QED
	+ 47.4	± 0.5	EW
	+ 337.5	± 3.7	hvp
	+ 7.6	± 0.2	hvp NLO
	+ 5	± 3	light-by-light
	= 117 721	**± 5**	

- difficult to measure, $a_\tau^{exp} = (-0.018 \pm 0.017)$, DELPHI, EPJC 35 (2004) 159

Belle II's first steps ...



Flavor Tagging (b quark or anti-b quark ?)



Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	l^-
Intermediate Kinetic Lepton	l^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum P*	l^-, π^-
Fast-Slow-Correlated (FSC)	l^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \to D^{*+}\, \overline{\nu}_\ell\, \ell^-$
$\quad \hookrightarrow D^0\, \pi^+$
$\qquad \hookrightarrow X\, K^-$

$\overline{B}^0 \to D^+\, \pi^-\, (K^-)$
$\quad \hookrightarrow K^0\, \nu_\ell\, \ell^+$

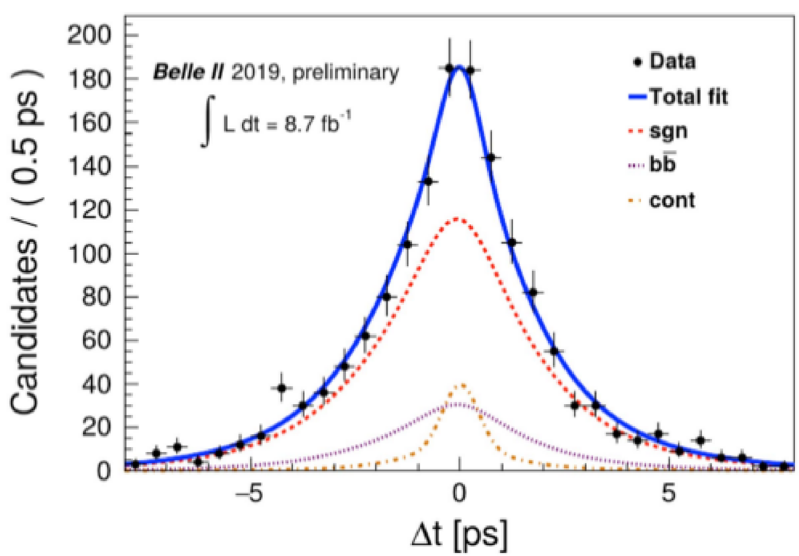
$\overline{B}^0 \to \Lambda_c^+\, X^-$
$\quad \hookrightarrow \Lambda\, \pi^+$
$\qquad \hookrightarrow p\, \pi^-$

We obtain epsilon_eff = epsilon(1-2 w^2)= **33.8+-3.9%**, which is a slight improvement over the Belle result of 30.1+-0.4%

Agreement of Data and MC

arXiv:2008.02707 [hep-ex]

B^0 Lifetime measurement ($B \rightarrow D^{(*)}$ h)

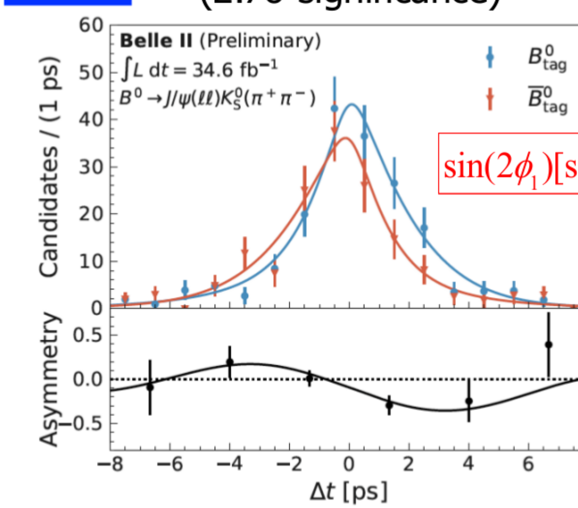


$\tau(B^0) = 1.48 \pm 0.28 \pm 0.06\, ps$

https://arxiv.org/pdf/2005.07507

Hint of time-dependent CPV from Belle II (2.7σ significance)

BELLE2-NOTE-PL-2020-011



$\sin(2\phi_1)[\sin(2\beta)] = 0.55 \pm 0.21 \pm 0.04$

(WA=0.691±0.017)

$B^0 \to f\ ;\ B^0 \to \overline{B^0} \to f$

$$N_{+/-} \quad \frac{\exp(-|\Delta t|/\tau)}{4\tau}\left\{1 \pm (1-2w)\sin(2\phi_1)\sin(\Delta m_d \Delta t)\right\} \otimes R(\Delta t)$$

V_{ub}: Exclusive $B \to \pi^- l^+ \nu$ with FEI

Measurements of the BF at q^2(max) combined with lattice QCD gives $|V_{ub}|$

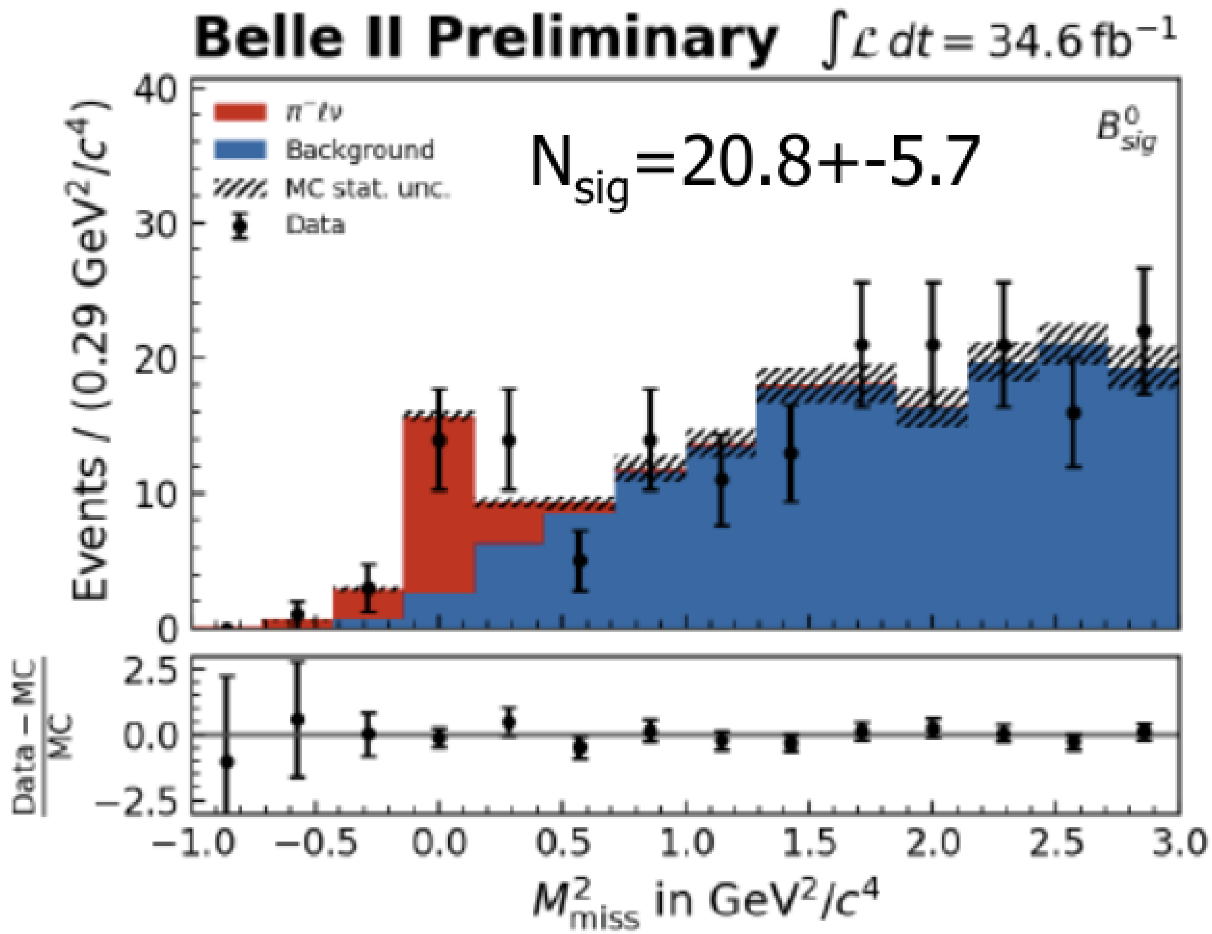


FIG. 4: Post-fit M^2_{miss} distribution in $34.6\,\mathrm{fb}^{-1}$ of data.

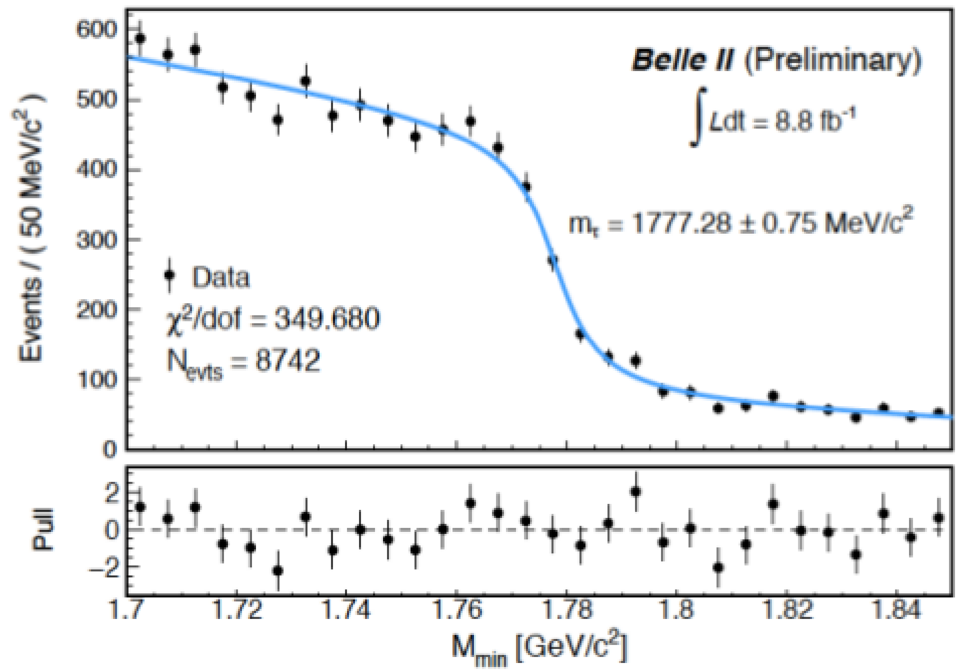
$$BF(B^0 \to \pi^- l^+ \nu) = [1.58 \pm 0.43(stat) \pm 0.07(sys)] \times 10^{-4}$$

arXiv:2008.08819 [hep-ex]

Tau Mass Measurement

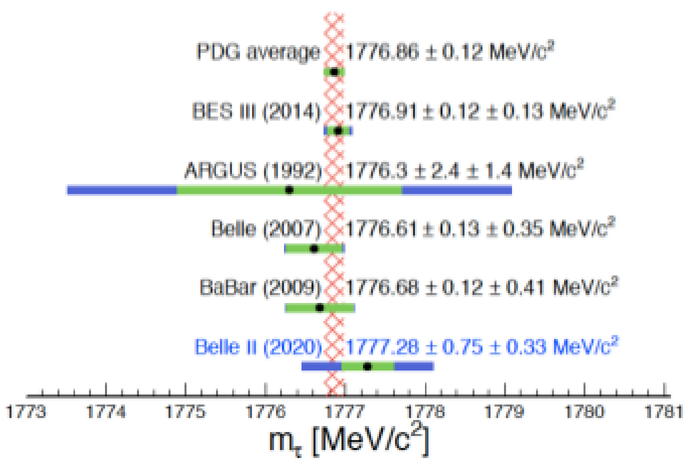
Use 1 prong vs 3-prong tau pair events from e+e- → $\tau^+ \tau^-$

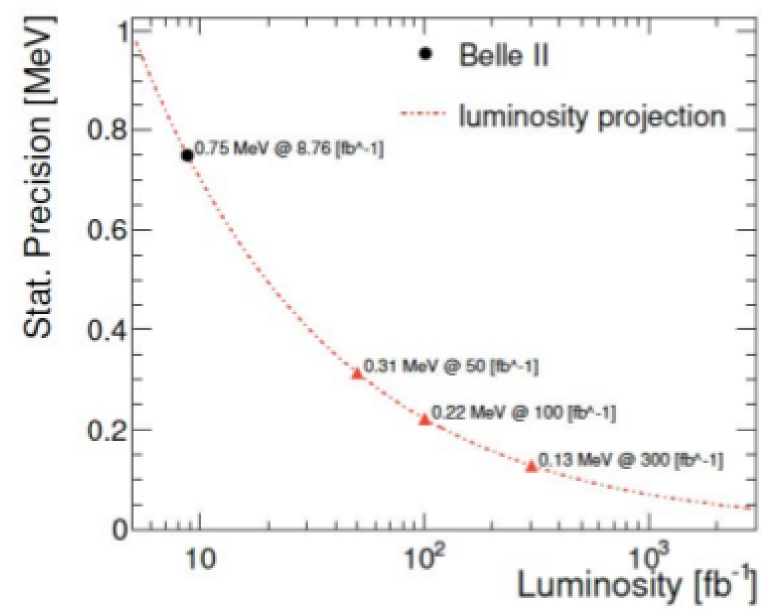
$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$



$$m(\tau) = 1777.28 \pm 0.75(stat) \pm 0.33(sys)\,\text{MeV/c}^2$$

arXiv:2008.04665 [hep-ex]





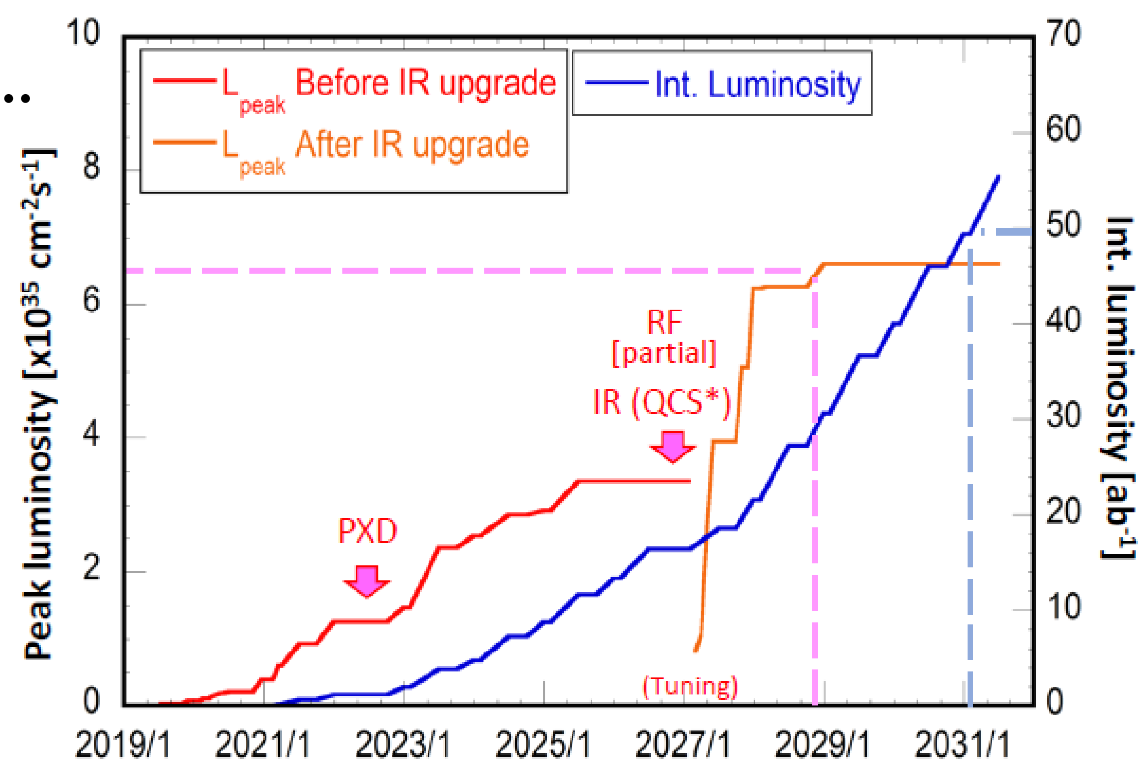
Currently BESIII dominates the world average.

Conclusion

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

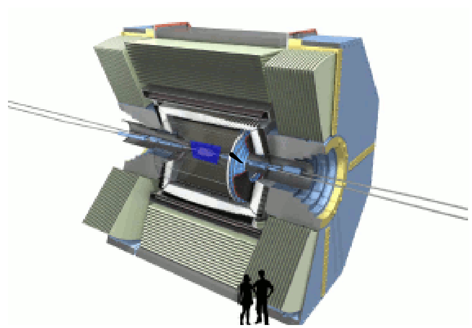
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

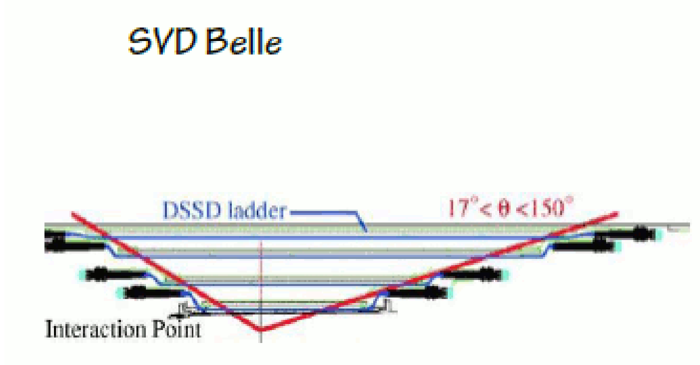
long way to go for 50 ab^{-1}…

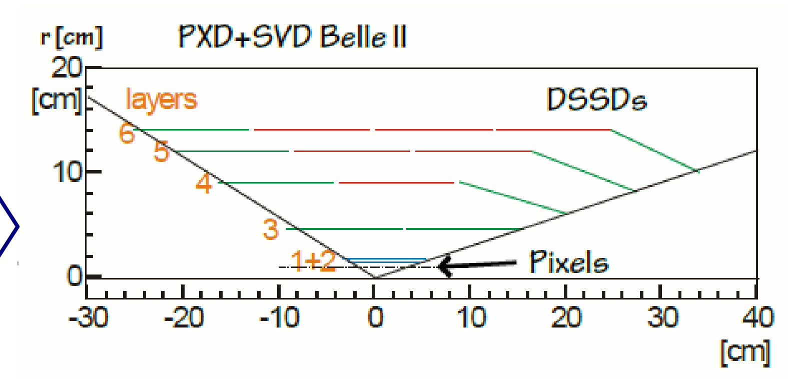


Few words on Belle II detector

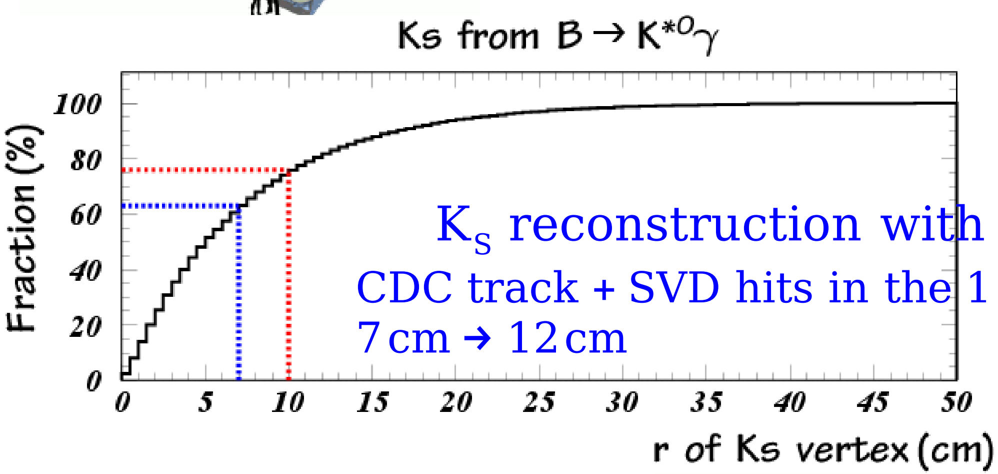
- collecting $50\,ab^{-1}$ from 2019 to 2030…(or until we get $50\,ab^{-1}$?)



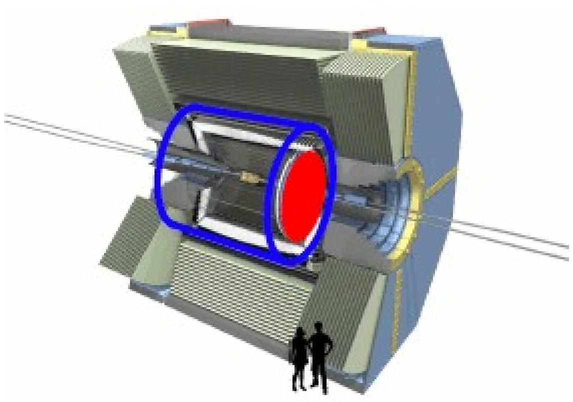


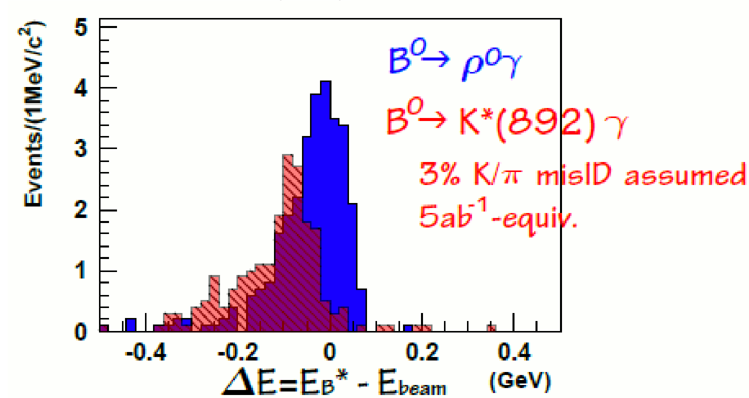


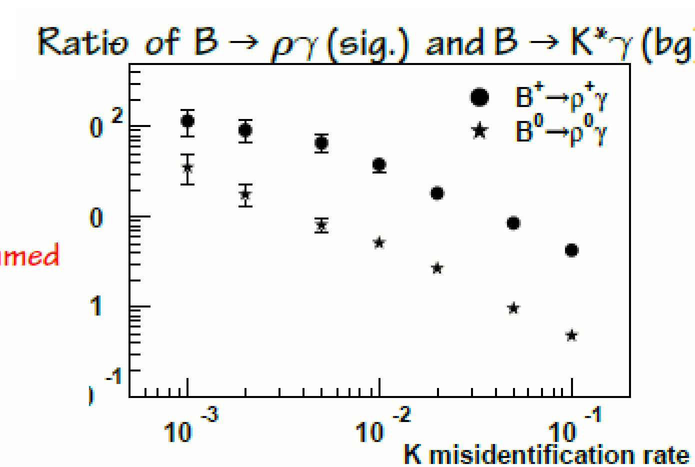
4 DSSD layers → 2 pixel layers + 4 DSSD layers
larger radius outermost layer (8.8 cm → 14 cm)



K_S reconstruction with PXD/SVD: $K^{*0}\gamma$ TCPV
CDC track + SVD hits in the 1st and 2nd outermost layers
7 cm → 12 cm

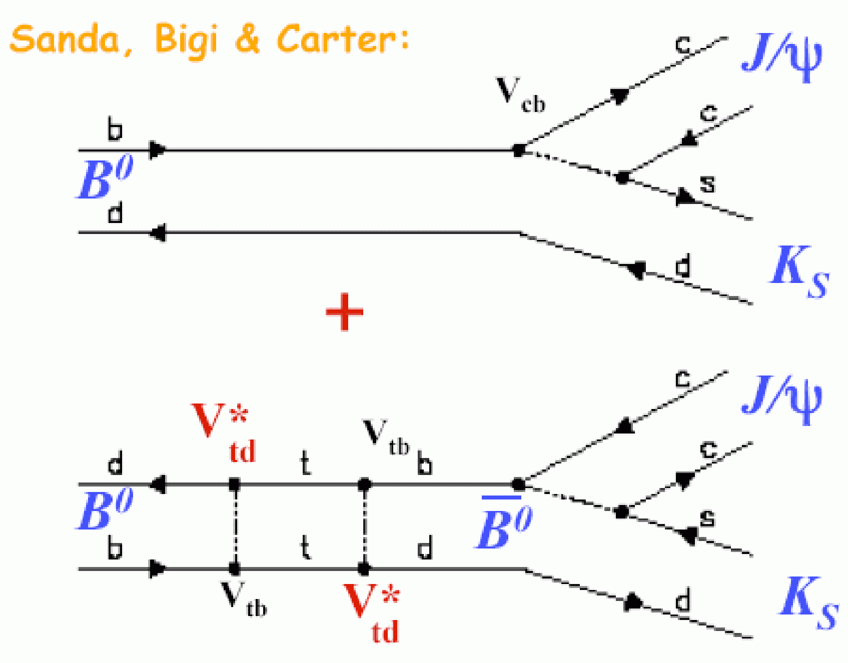






Time−dependent CP asymmetries in decays to CP eigenstates

$\sin 2\phi_1$ from $B \to f_{CP} + B \leftrightarrow \overline{B} \to f_{CP}$ interf.



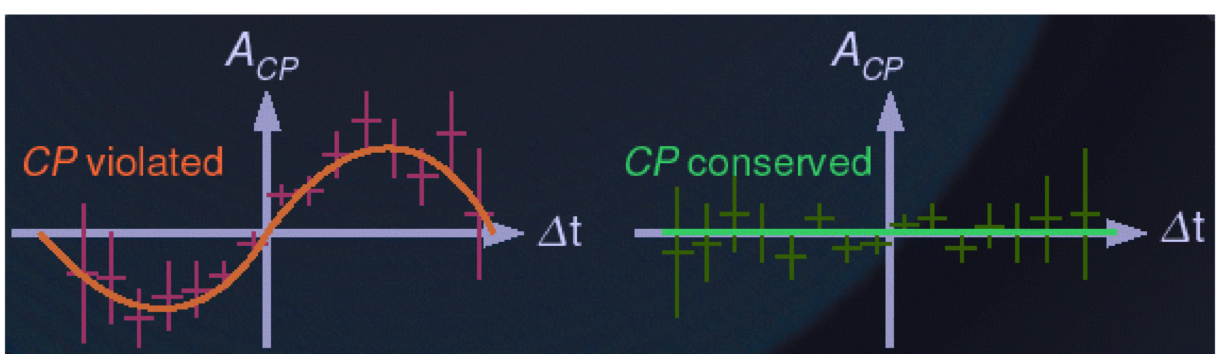
$$A_{CP}(f;t) = \frac{N(\overline{B}^0(t)\to f) - N(B^0(t)\to f)}{N(\overline{B}^0(t)\to f) + N(B^0(t)\to f)}$$

$$= \mathbf{S} \sin\Delta m_d t + \mathbf{A} \cos\Delta m_d t$$

$$= \frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1} \sin\Delta m_d t + \frac{|\lambda|^2-1}{|\lambda|^2+1} \cos\Delta m_d t$$

$$\lambda = \frac{q}{p}\,\frac{A(\overline{B}^0 \to f)}{A(B^0 \to f)} = e^{-i2\phi_i}\frac{\overline{A}_f}{A_f}$$

- $\mathbf{A} = 0$ and $\mathbf{S} = -\xi_f \sin 2\beta$ for $(c\bar{c})K_{S/L}$ $(\xi_f = \mp 1)$
- $\mathbf{A} = 0$ and $\mathbf{S} = \sin 2\alpha$ for $\pi^+\pi^-$ (if tree only)



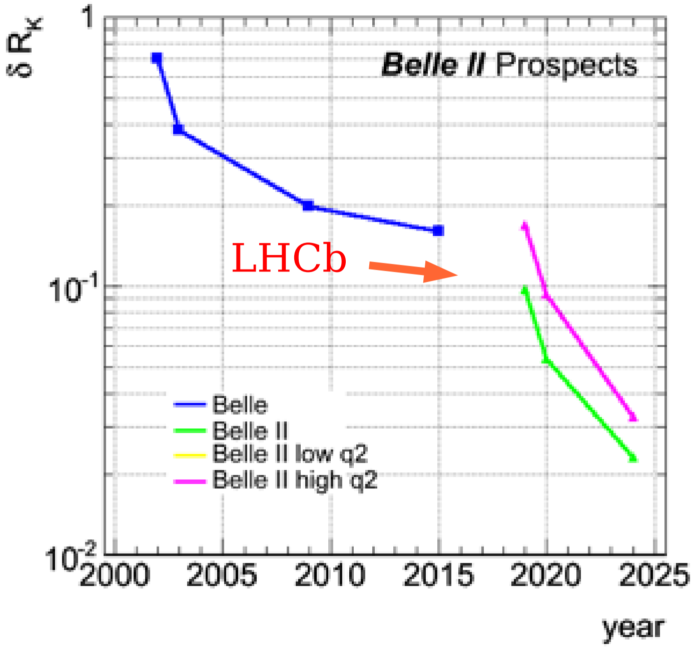
$\mathbf{C = -A}$

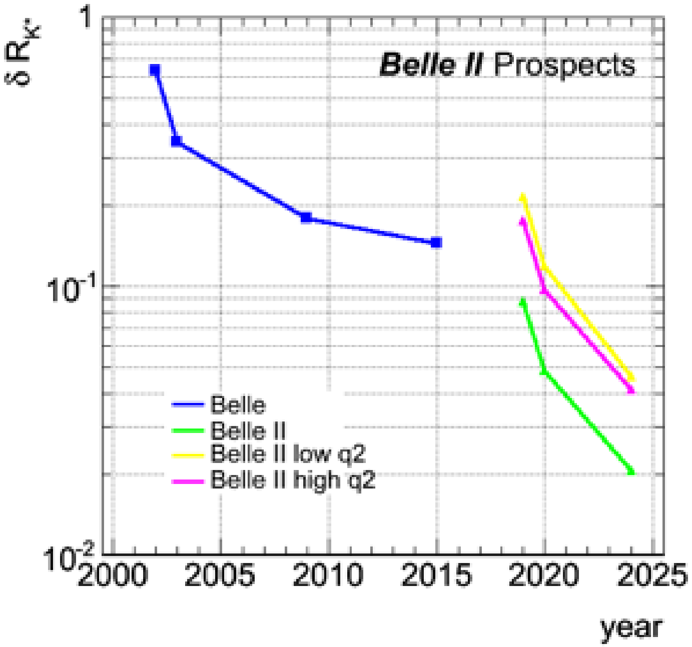
R_K, R_K^*, ...

[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}

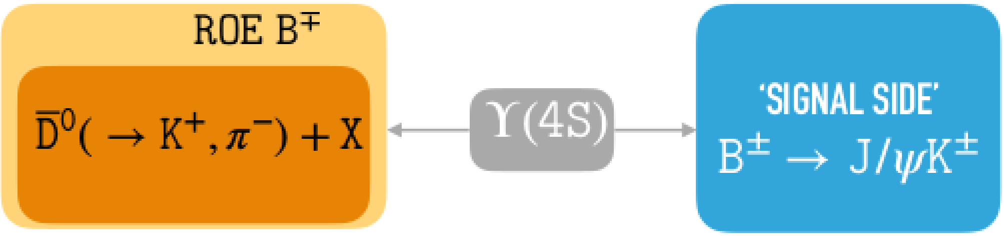


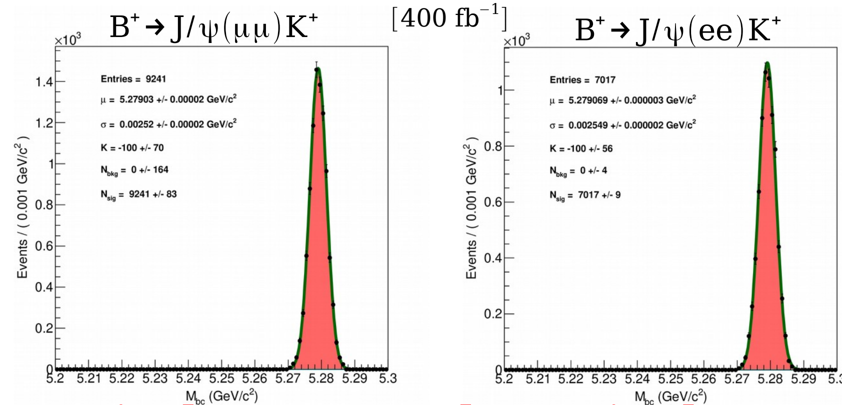


B-tagging ...

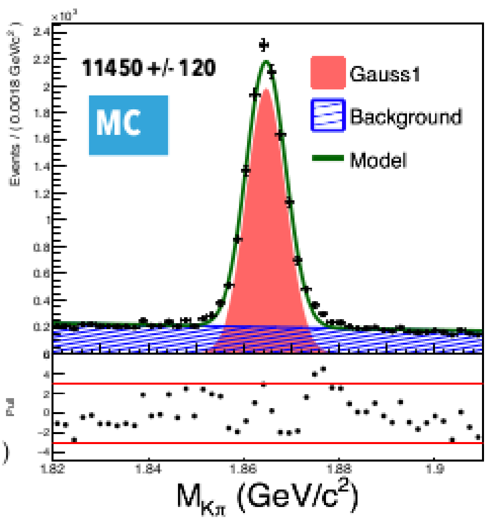
[Belle (II), G.de Marino]

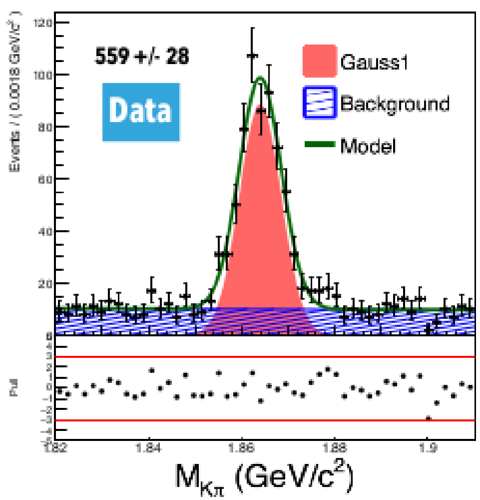
- probing the charged B^+ properties
- using $J/\psi K^{\pm}$ as signal side (high purity)

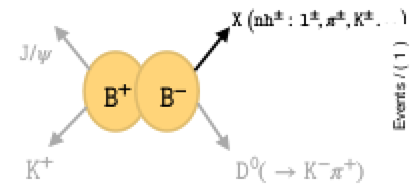


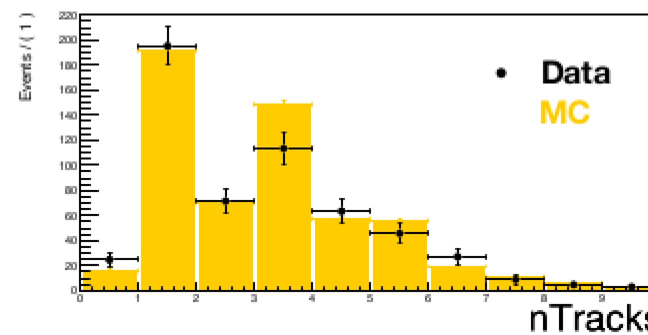


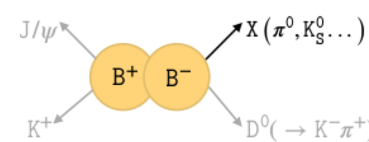
⇒ **isolate pure B beam in data !**

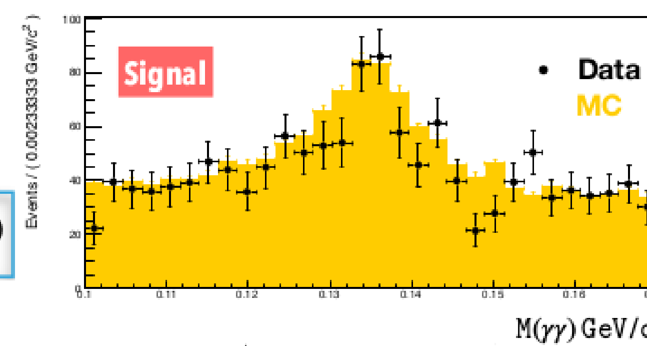






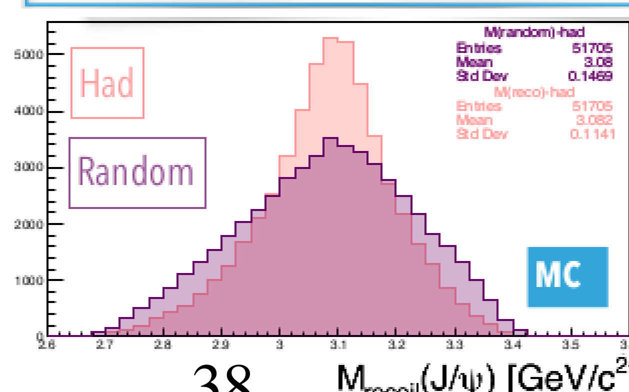






$$m^2_{J/\psi} = m^2_B + m^2_K - 2(E^*_B E^*_K - |\vec{p}^{\,*}_{B_{sig}}||\vec{p}^{\,*}_K|\cos\theta)$$

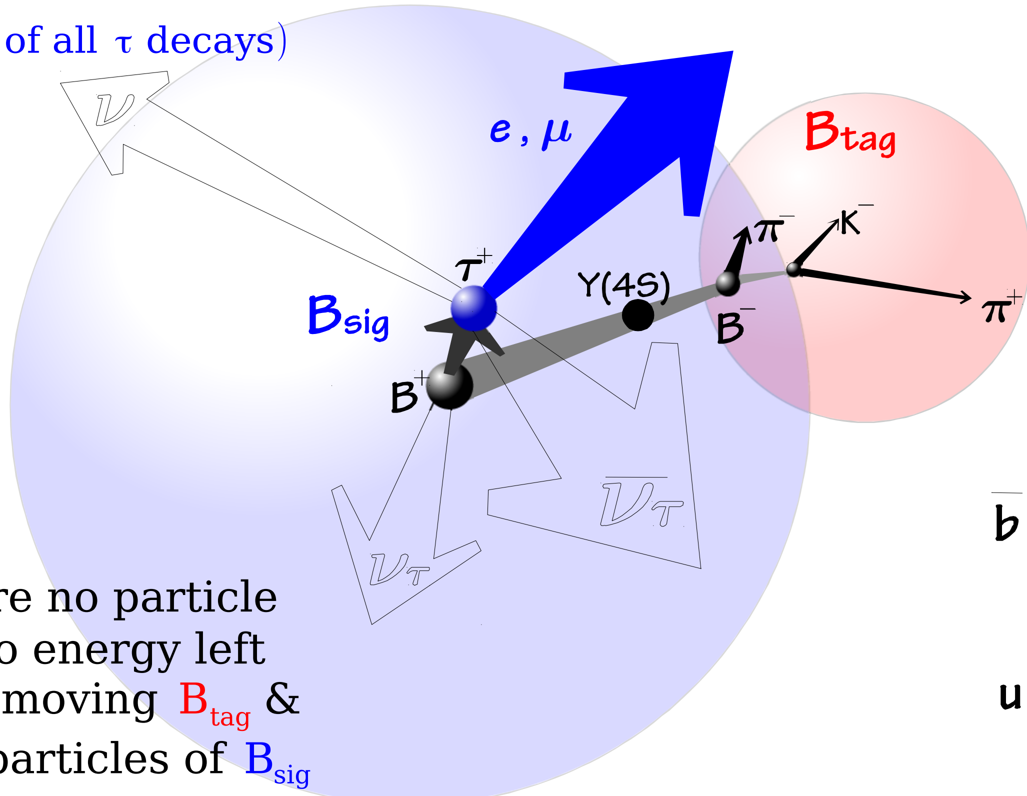
- J/ψ recoil mass poorly sensitive to $\vec{p}^{\,*}_{B_{tag}}$
- inclusive tag provides a recoil mass with similar resolution than hadronic tag !
- need to confirm that same happens for $B\rightarrow K\tau l$
-



Tauonic B decays: $B \to \tau\nu$

$B_{sig} \to \tau\nu$

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



B_{tag}

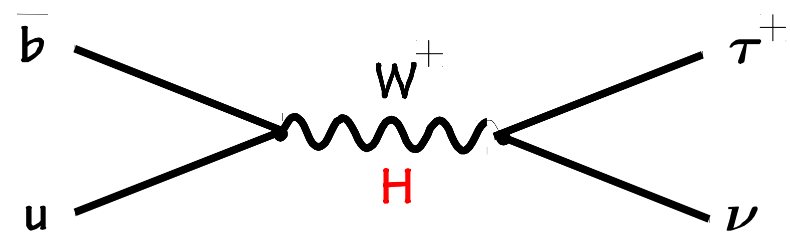
hadronic tag

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

$\epsilon \sim 0.2\%$

semileptonic tag

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



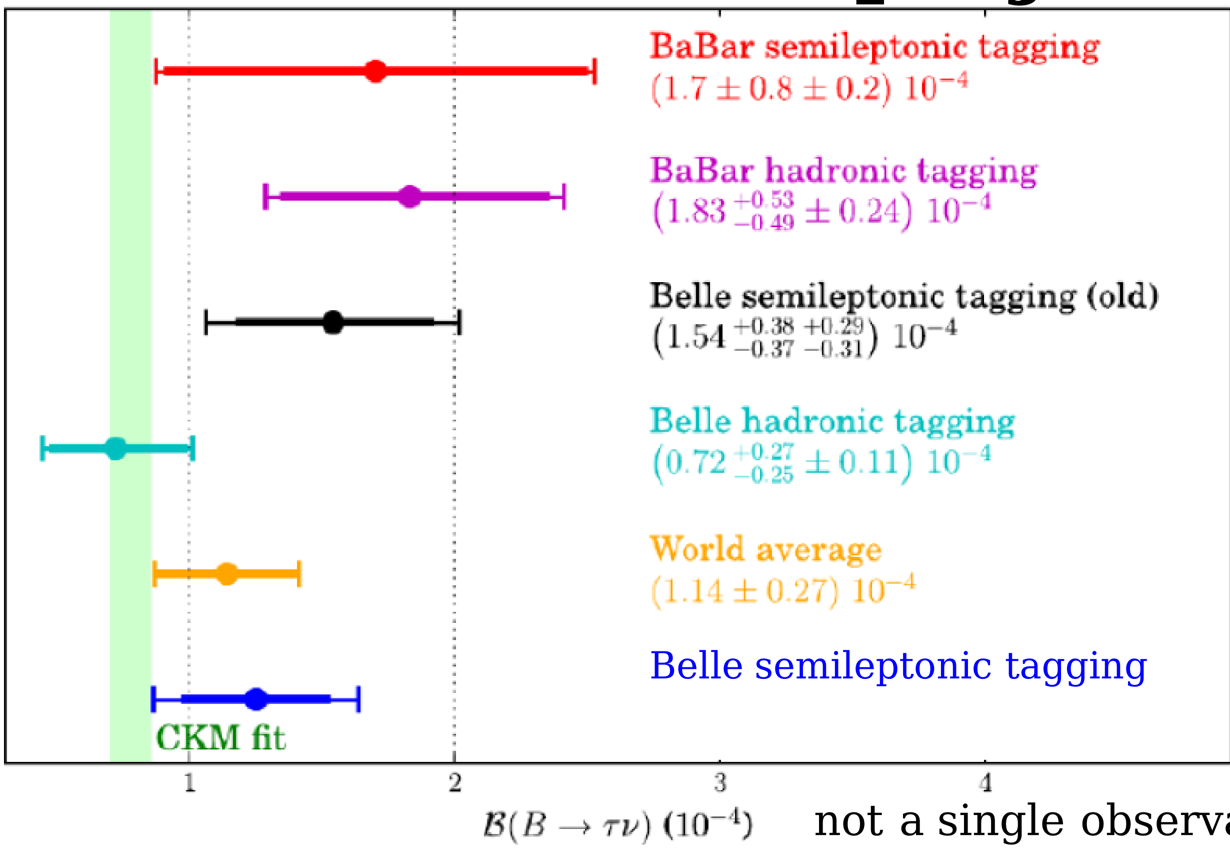
Require no particle and no energy left after removing B_{tag} & visible particles of B_{sig}

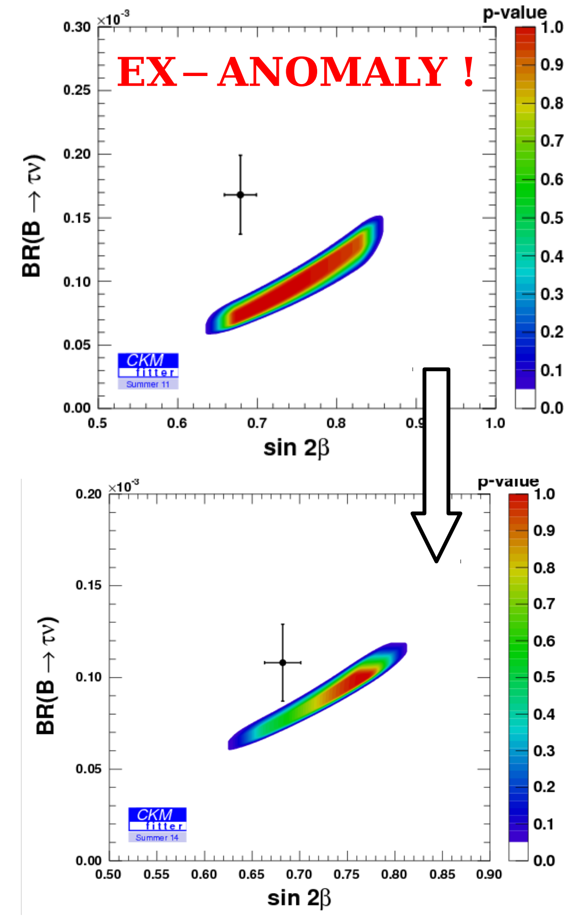
$$2\,\mathrm{HDM}\ (\text{type II}):\ \mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

$$\mathcal{B}_{SM}(B^+ \to \tau^+\nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2\ \tau_B$$

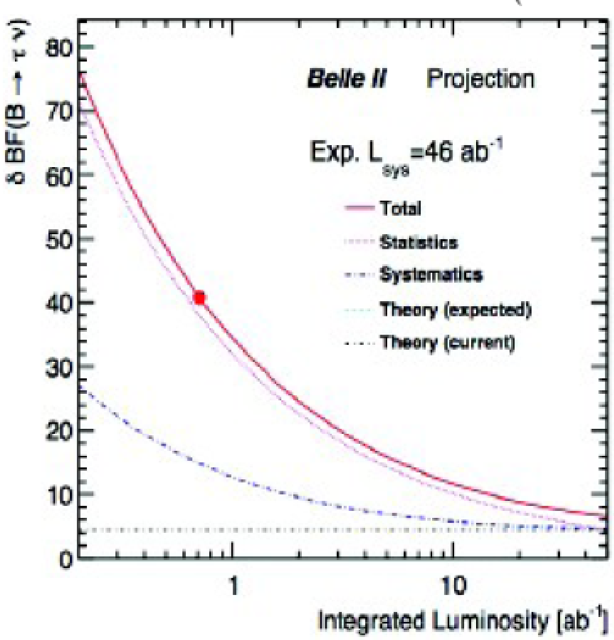
uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B and other CKM uncertainties by combining with precise Δm_d

B→τν status and projections





not a single observation ! !

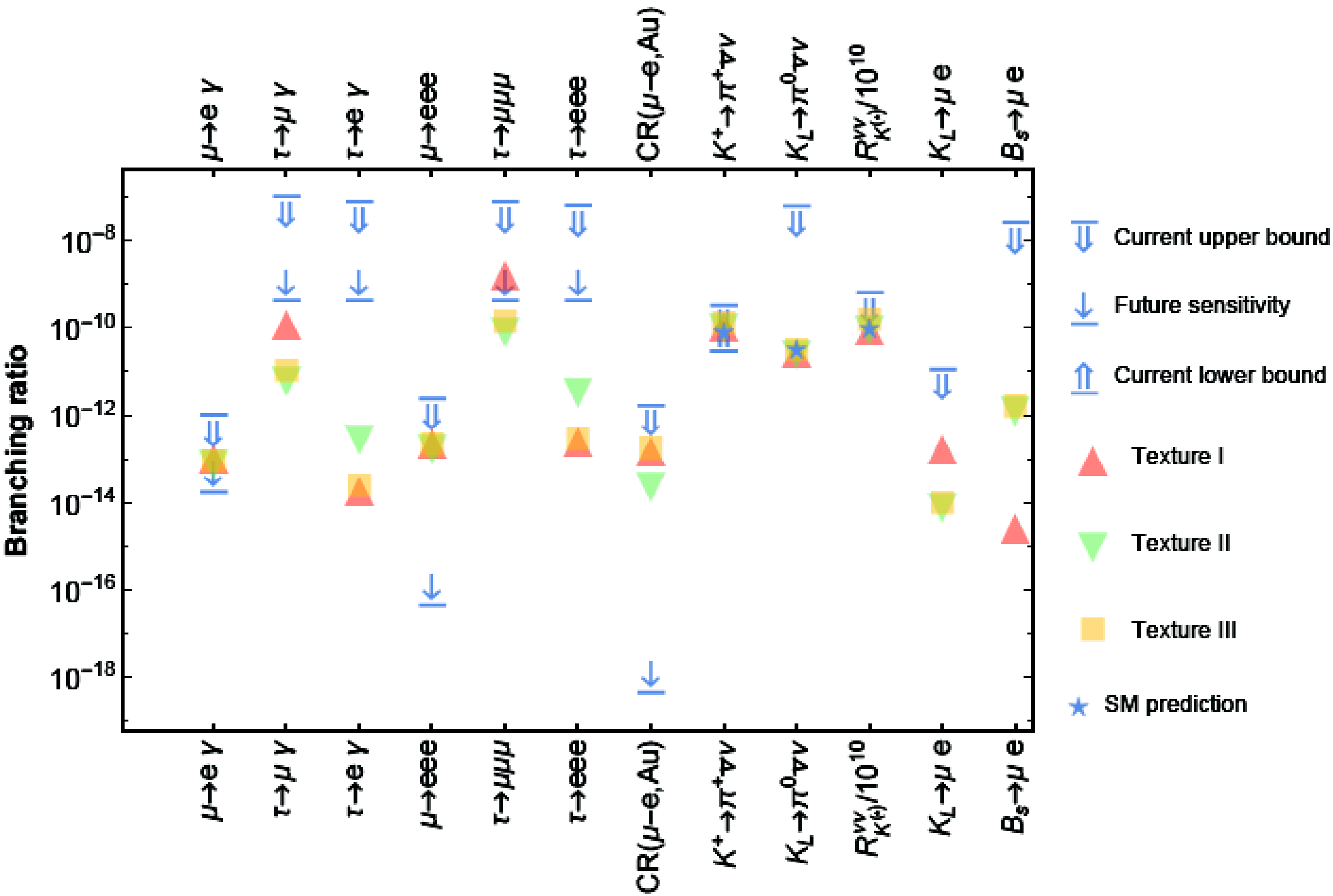


Belle II	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	19.0	(7.1, 2.2)	20.4	2.5	20.5
5 ab^{-1}	7.2	(2.7, 2.2)	7.9	1.5	8.1
50 ab^{-1}	2.3	(0.8, 2.2)	3.2	1.0	3.4
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
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	$^{+3.6}_{-5.2}$

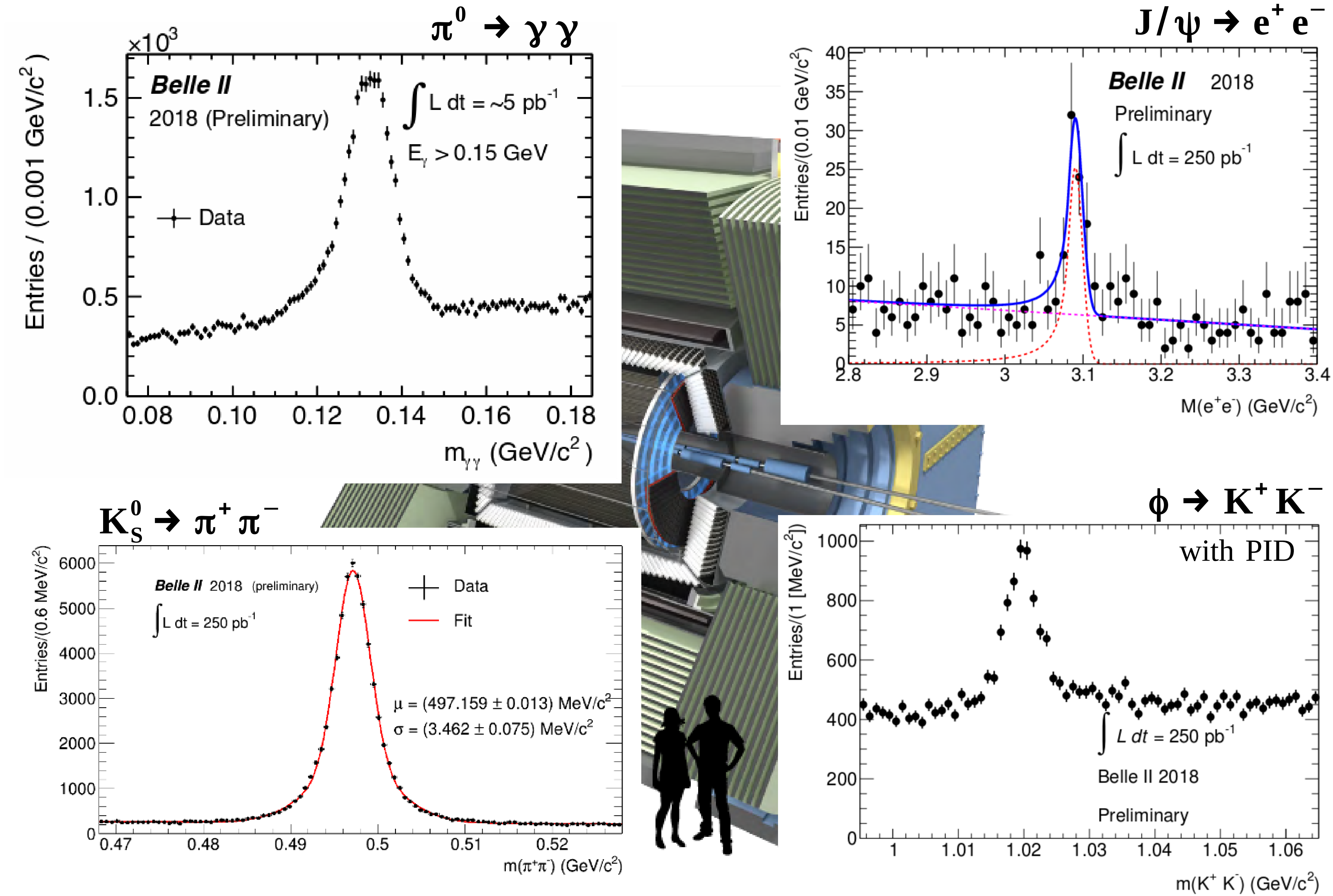
observation of B→μν is also expected (from 5 ab^{-1})

more observables…

C.Hati et al, arXiv:1806.10146



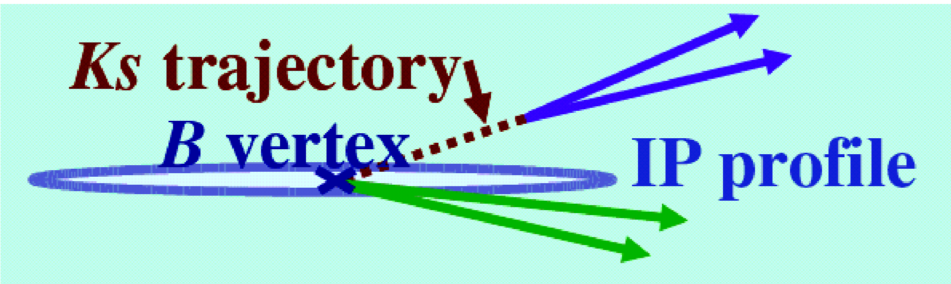
A.Datta et al, arXiv:1609.09078: interesting modes are $\tau\to3\mu$, and $\Upsilon(3S)\to\mu\tau$



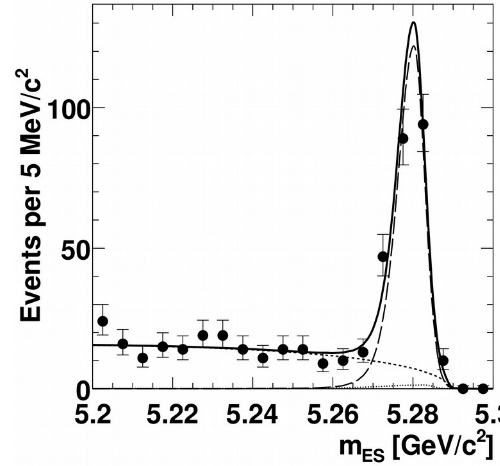
π0 → γ γ
Belle II
2018 (Preliminary)
∫L dt = ~5 pb-1
Eγ > 0.15 GeV
Data
×10^3
Entries / (0.001 GeV/c2)
mγγ (GeV/c2)
J/ψ → e+ e−
Belle II 2018
Preliminary
∫L dt = 250 pb-1
Entries/(0.01 GeV/c2)
M(e+e-) (GeV/c2)
K0S → π+ π−
Belle II 2018 (preliminary)
∫L dt = 250 pb-1
Data
Fit
μ = (497.159 ± 0.013) MeV/c2
σ = (3.462 ± 0.075) MeV/c2
Entries/(0.6 MeV/c2)
m(π+π-) (GeV/c2)
φ → K+ K−
with PID
∫L dt = 250 pb-1
Belle II 2018
Preliminary
Entries/(1 [MeV/c2])
m(K+ K-) (GeV/c2)

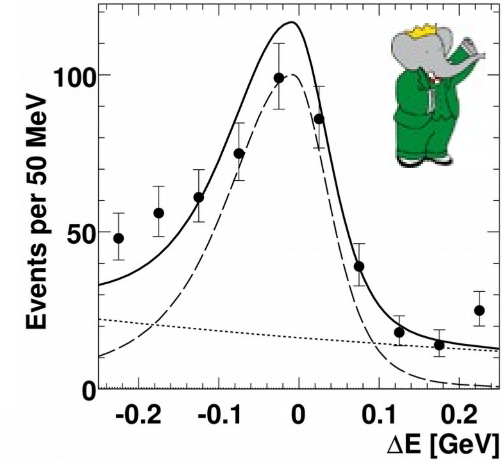
$B \to K^{*}(K^0_S \pi^0)\gamma$

time-dependent CPV



control sample is $J/\psi K^0_S$!!



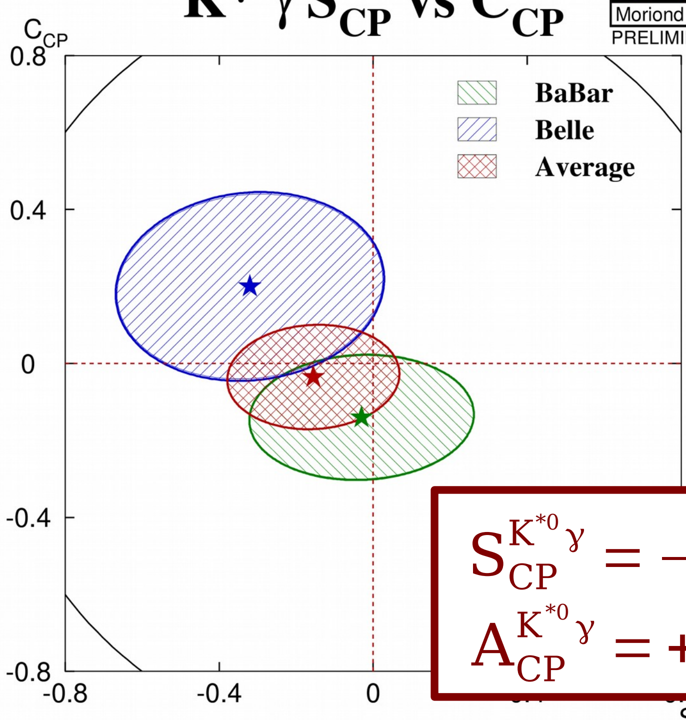


[467 MBB]
[arXiv:0807.3103]

[535 MBB]
[hep-ex/0608017]

$K^{*}\gamma\ S_{CP}$ vs C_{CP}

HFAG Moriond 2014 PRELIMINARY



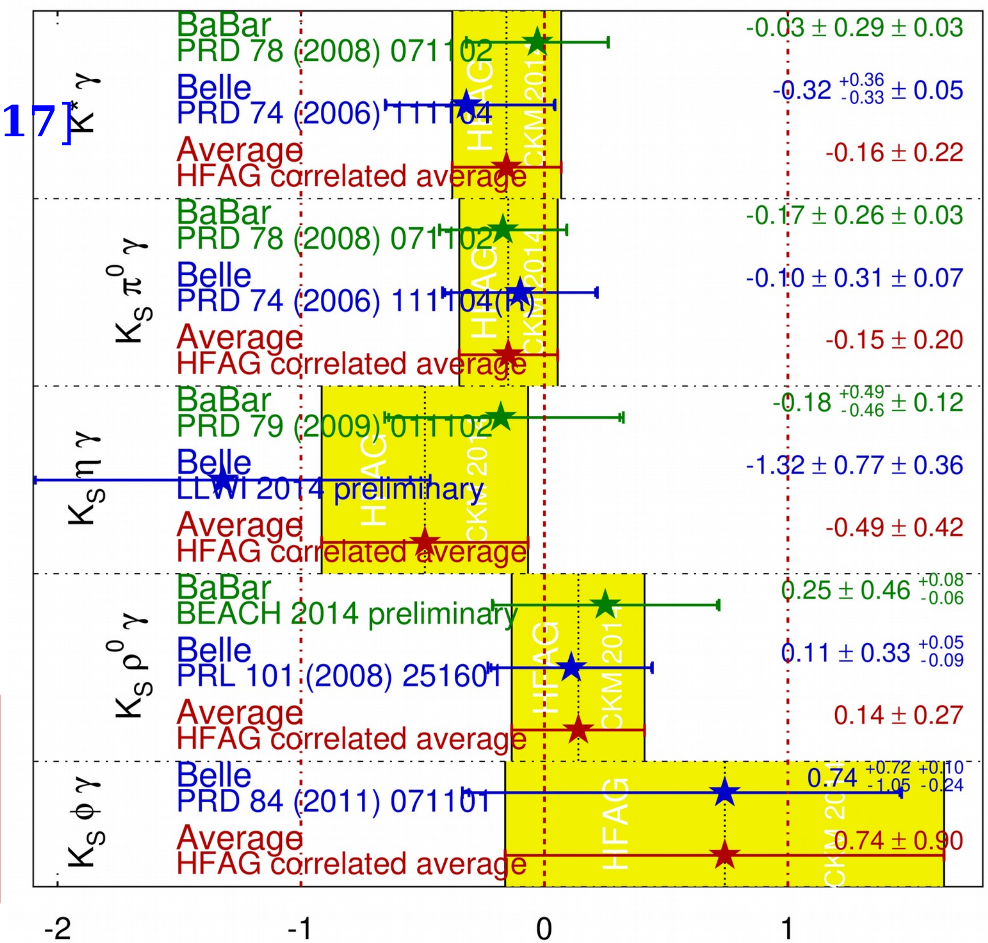
Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

$$S_{CP}^{K^{*0}\gamma} = -0.16 \pm 0.22$$
$$A_{CP}^{K^{*0}\gamma} = +0.04 \pm 0.14$$

HFAG

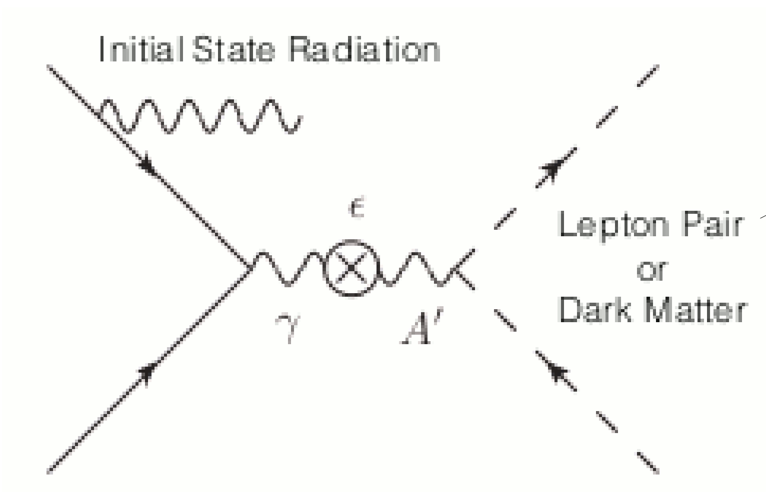
$b \to s\gamma\ S_{CP}$

HFAG CKM 2014 PRELIMINARY

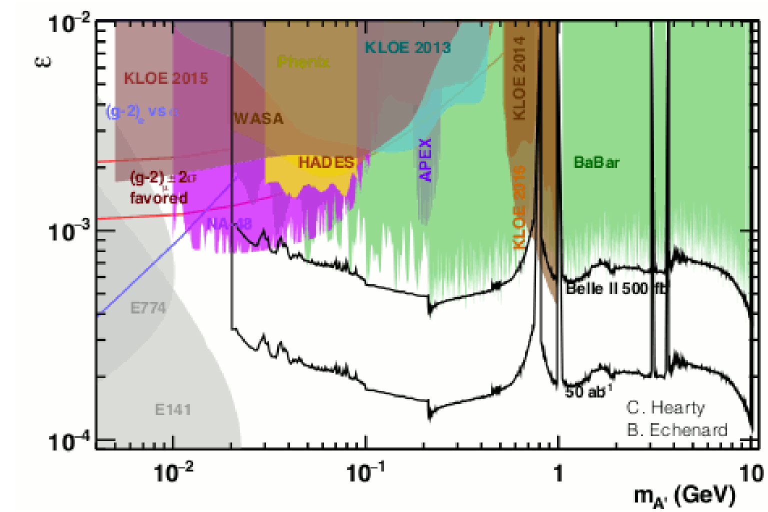


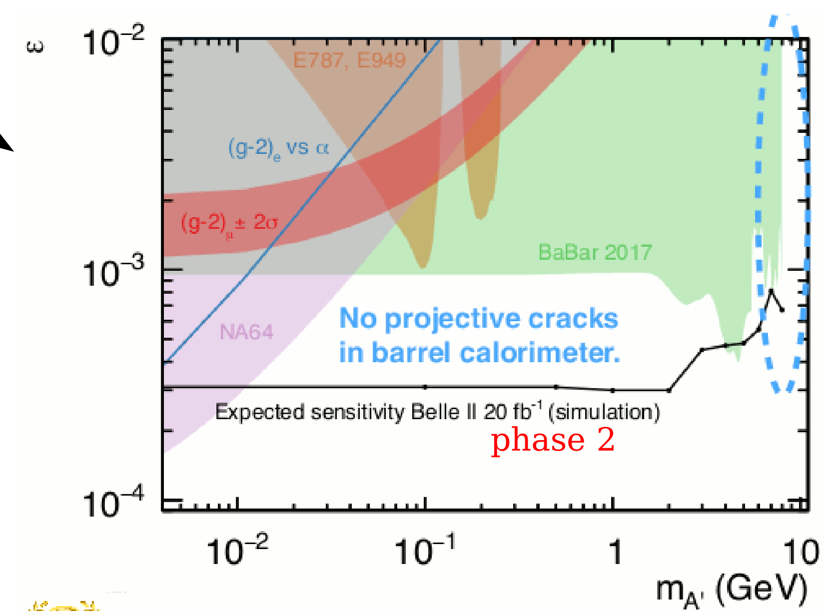
Dark Sector Physics

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



dark photon A' mixes with SM photon γ with strength ϵ





search for a dark photon decaying invisibly, and the search for an axion-like particle may be possible even in "Phase 2"