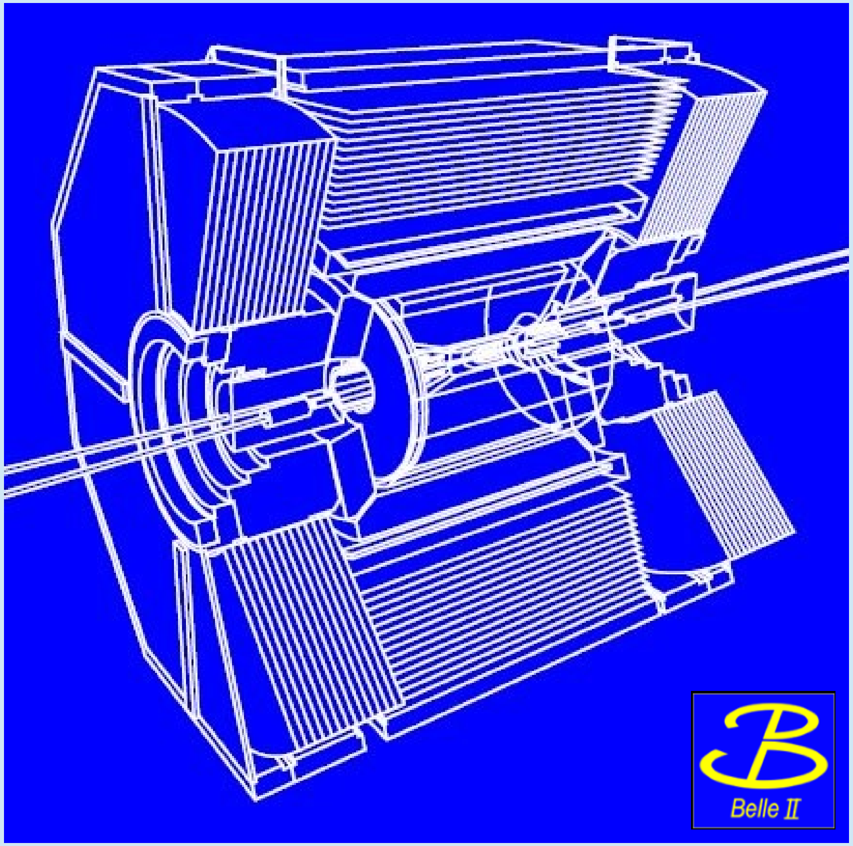
Belle II status and prospects

Karim Trabelsi
karim.trabelsi@lal.in2p3.fr



2019/02/19

Scope of this talk

- brief reminder of Belle II's goals…
- …in light of what is observed/obtained at LHCb
- …in light of recent Belle results
- …in light of phase 2 results

Outline

- Belle II
- CPV and V_{xb}, $B \to \tau \nu$
- $B \to D^{(*)} \tau \nu$
- $b \to s \gamma$, $b \to s l^+ l^-$
- LFV B and τ decays

precision measurements

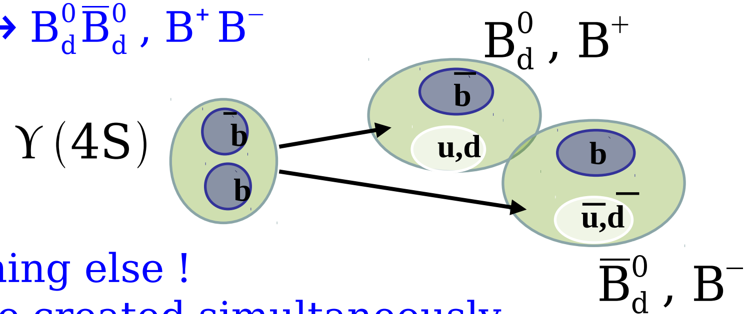
rare decays

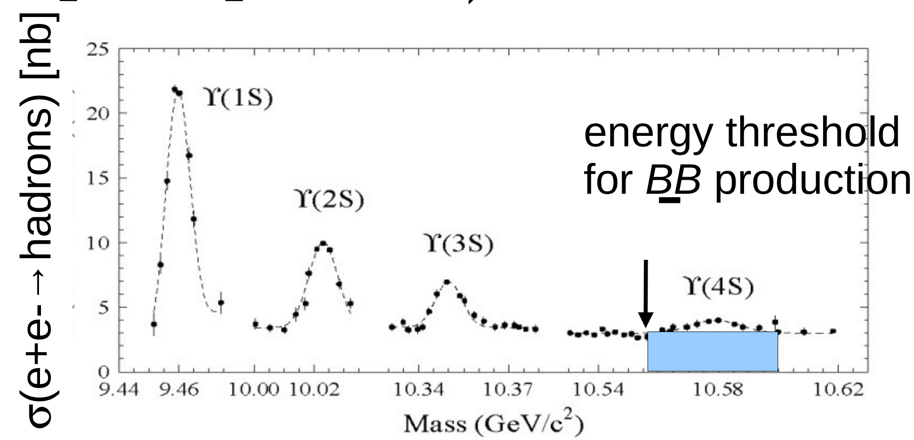
Belle II, a flavour-factory,
a rich physics program...

- 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:

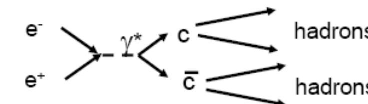
  – **a (Super) B-factory ($\sim 1.1 \times 10^9$ $B\bar{B}$ pairs per ab^{-1})**

''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})**
  ➔ Y.Kato's talk

  – **a (Super) τ factory ($\sim 1.3 \times 10^9$ $\tau^+\tau^-$ pairs per ab^{-1})**
  ➔ K.Hayasaka's talk

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

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

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
$\sigma_{b\bar{b}} \sim 1\,nb \Rightarrow 1\ fb^{-1}$ 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**

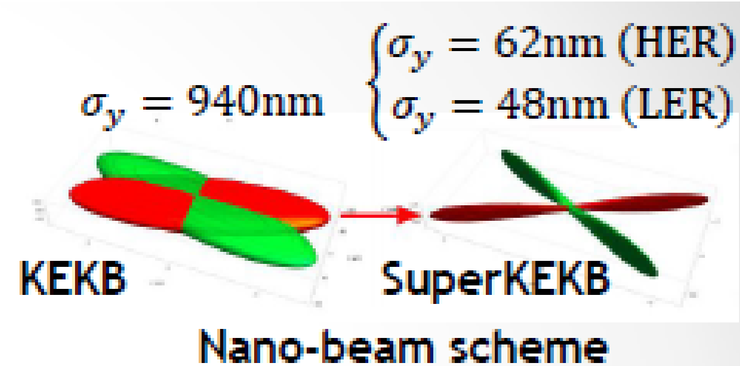
data taking period(s)

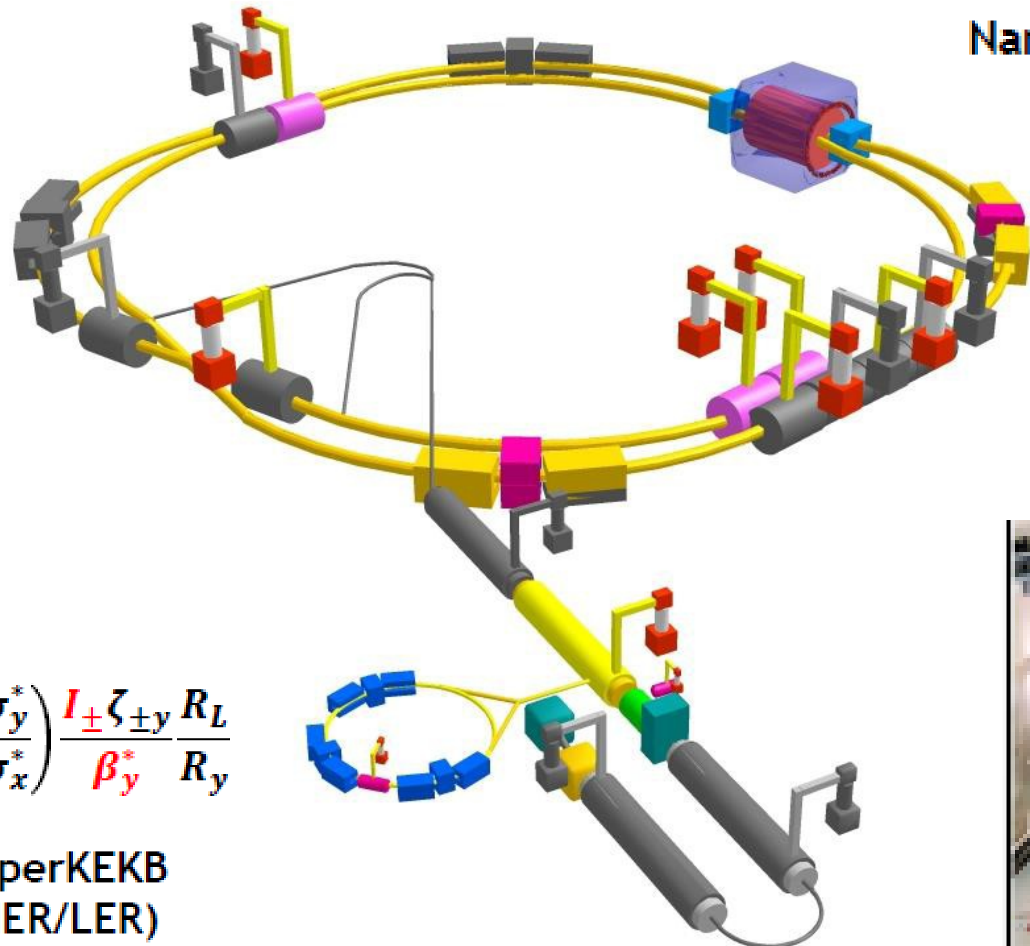
Belle (II)	LHCb
[1999-2010] = 1 ab^{-1}	[run I: 2010-2012] = 3 fb^{-1}, [run II: 2015-2018] = 2 fb^{-1} → 8 fb^{-1} ?

(near) future

Belle (II)	LHCb
[Belle II from 2018] → 50 ab^{-1}	[LHCb upgrade from 2020]

SuperKEKB accelerator





new final focusing magnets

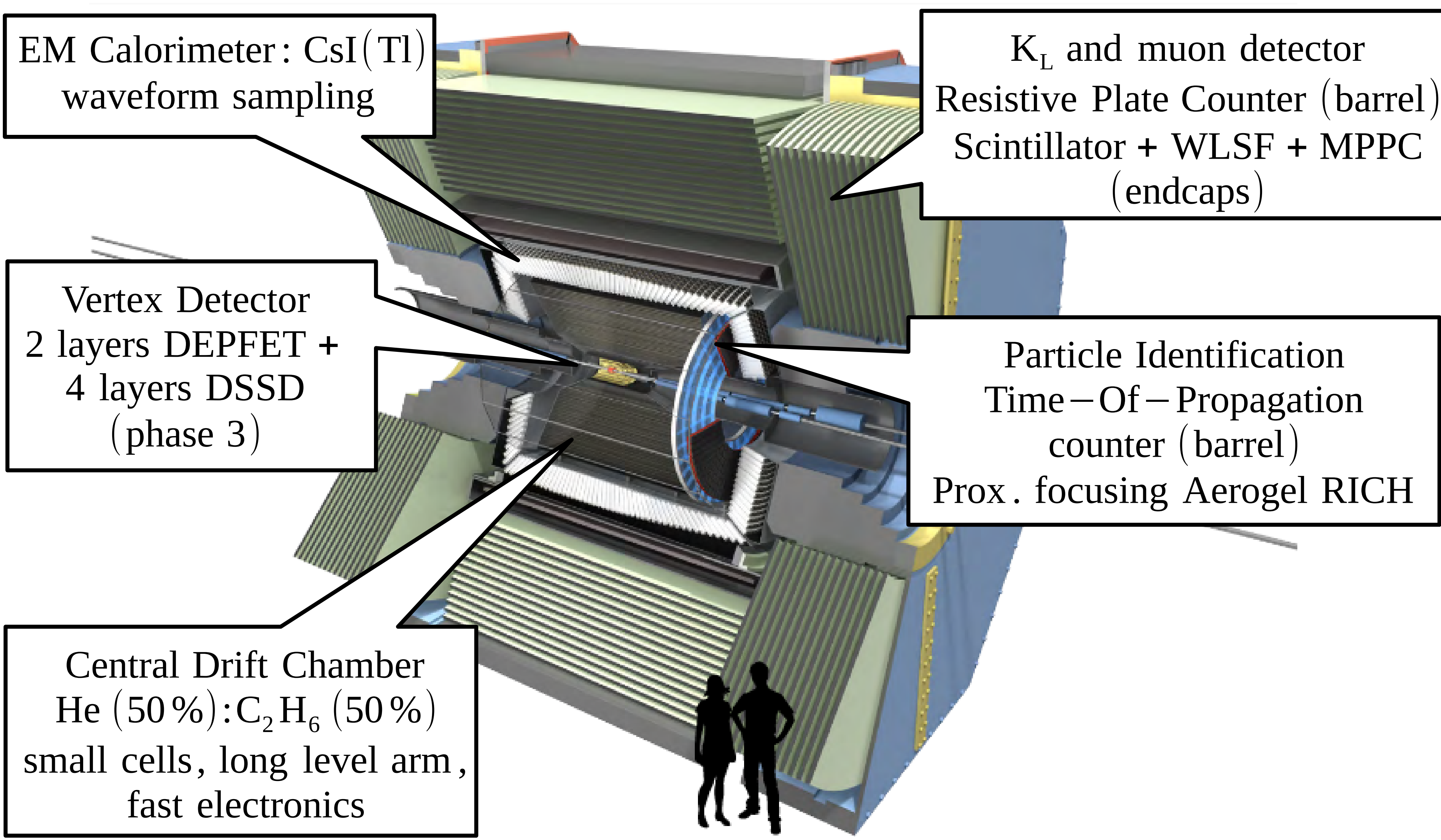
more RF cavities to increase beam currents

Key upgrades:

$$\text{Luminosity} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \zeta_{\pm y}}{\beta_y^*}\frac{R_L}{R_y}$$

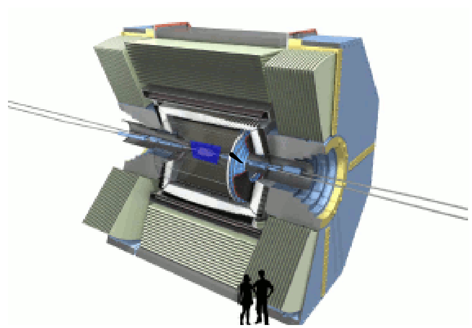
	KEKB (HER/LER)	SuperKEKB (HER/LER)	
β_y* (mm)	5.9/5.9	0.30/0.27	x20
I_{beam} (A)	1.19/1.64	2.6/3.6	x2
$\mathcal{L}$ (cm^{-2}s^{-1})	2.11x10^{34}	80x10^{34}	x40
$\int \mathcal{L}dt$ (ab^{-1})	1	50	x50

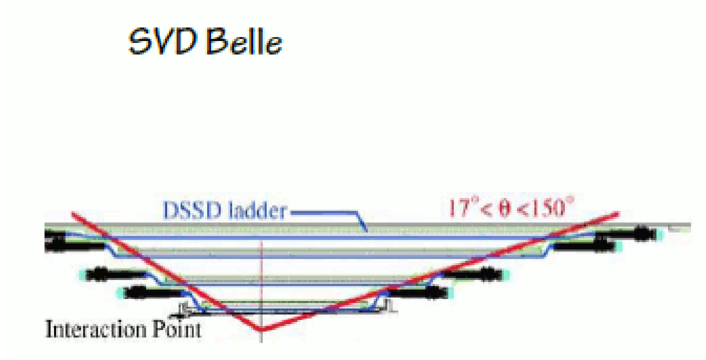
Belle II detector

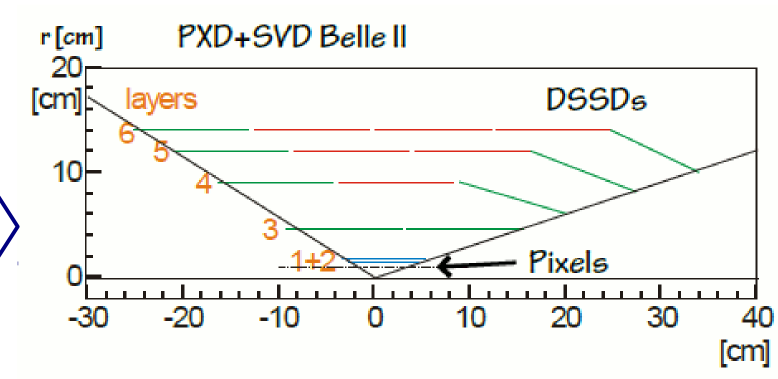


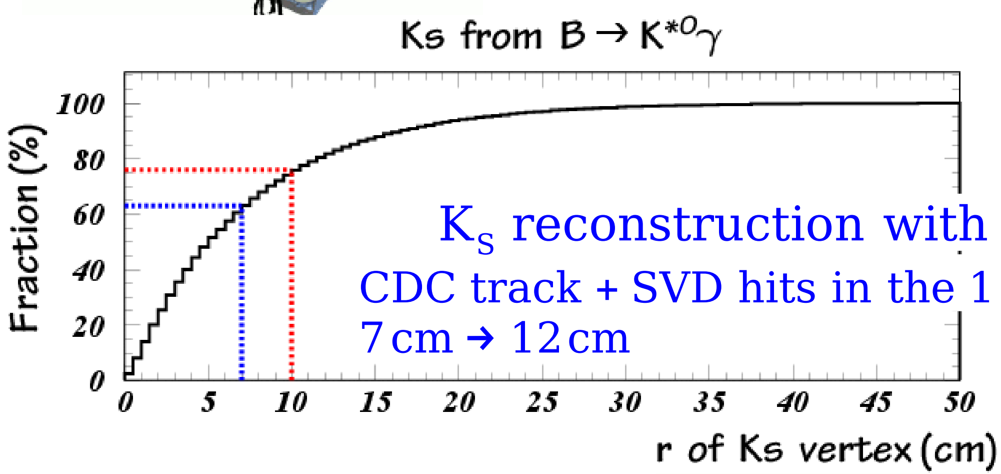
Few words on Belle II detector

- collecting $50\,ab^{-1}$ from 2019 to 2026…(or until we get $50\,ab^{-1}$?)







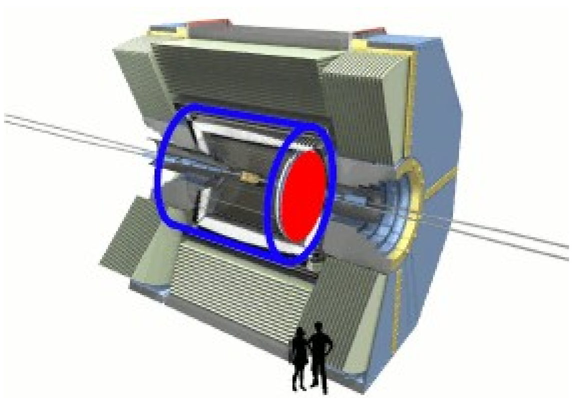


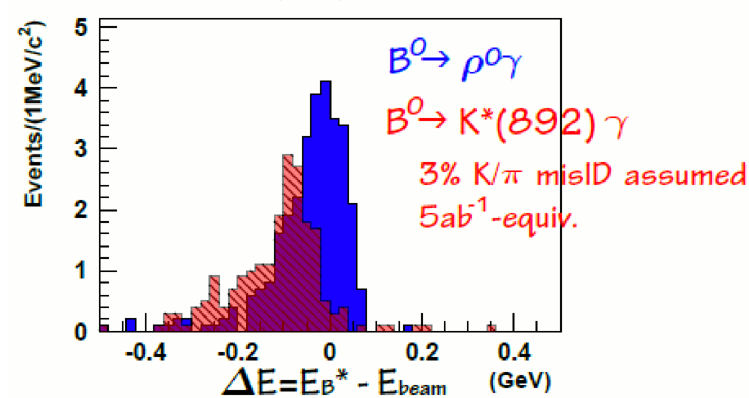
4 DSSD layers → 2 pixel layers + 4 DSSD layers
larger radius outermost layer (8.8 cm → 14 cm)

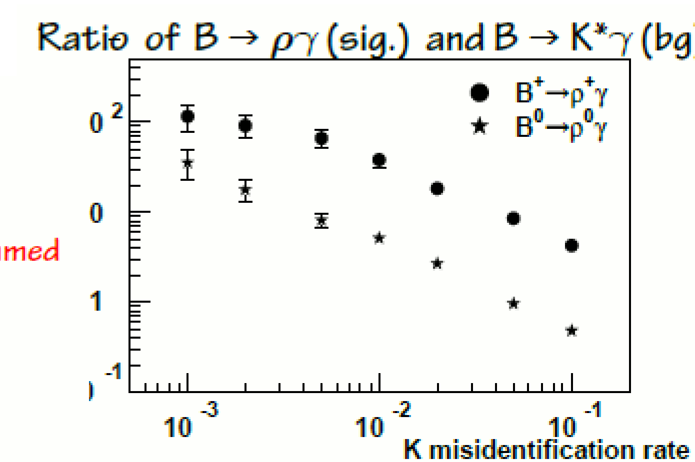
K_S reconstruction with PXD/SVD: $K^{*0}\gamma$ TCPV

CDC track + SVD hits in the 1st and 2nd outermost layers

7 cm → 12 cm



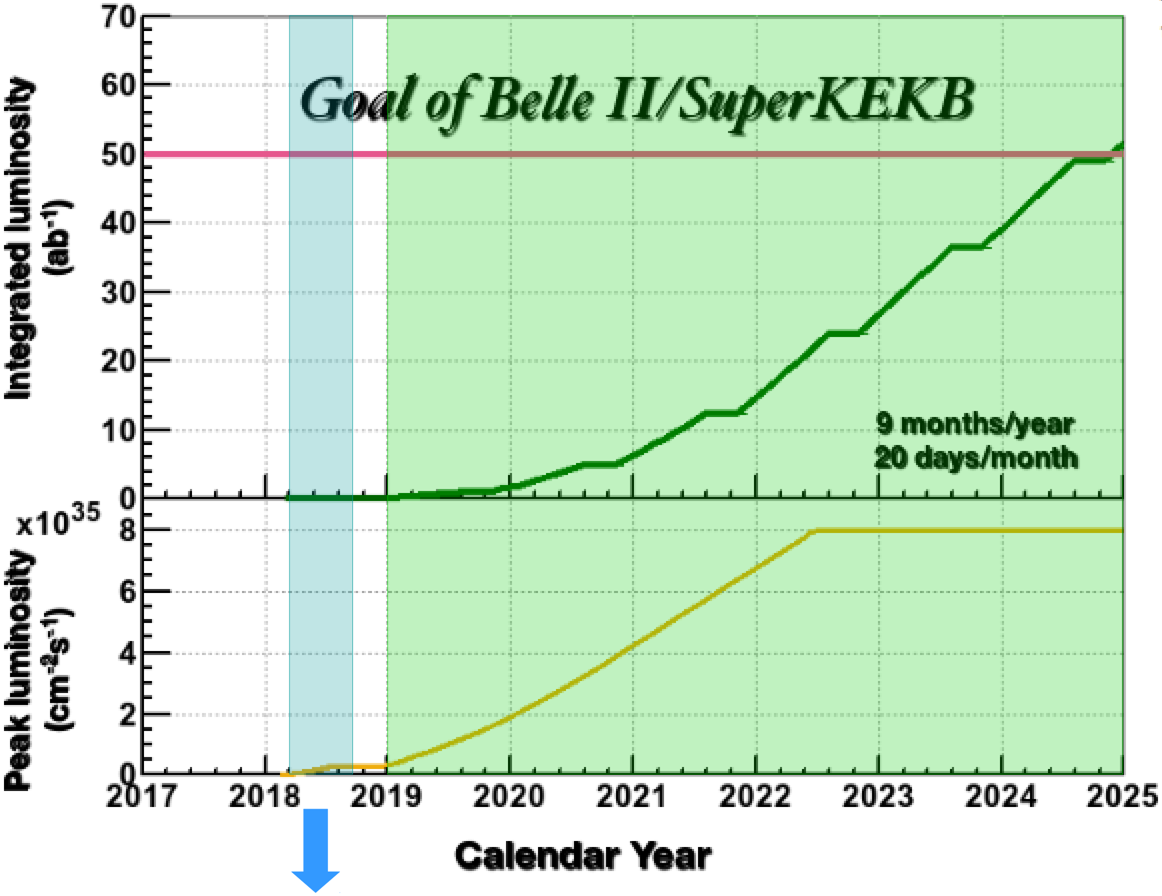




phase 2 → phase 3

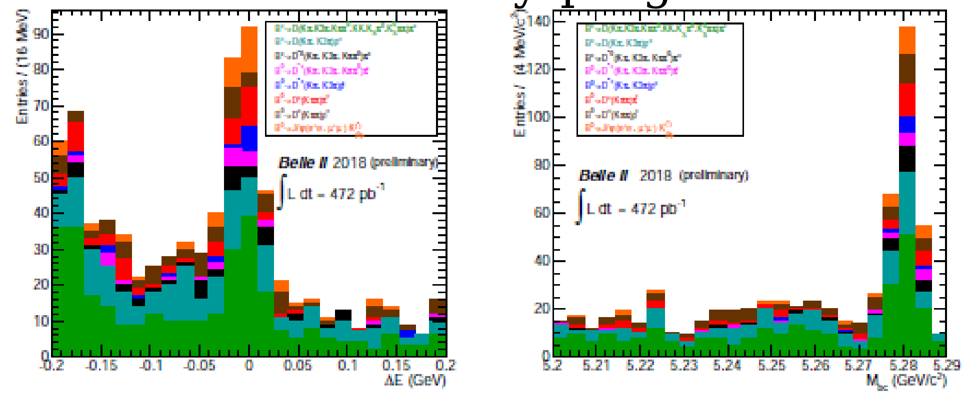
Phase2, BEAST II
collision + partial Belle II

Phase3, physics run

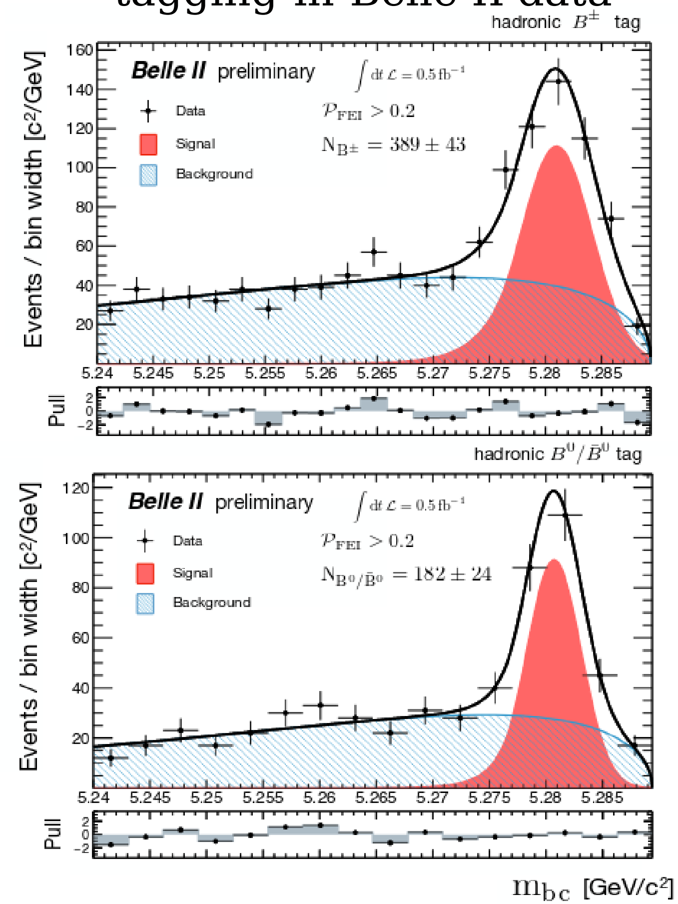


First collisions May to July
$\sim 500\ \mathrm{pb}^{-1}$

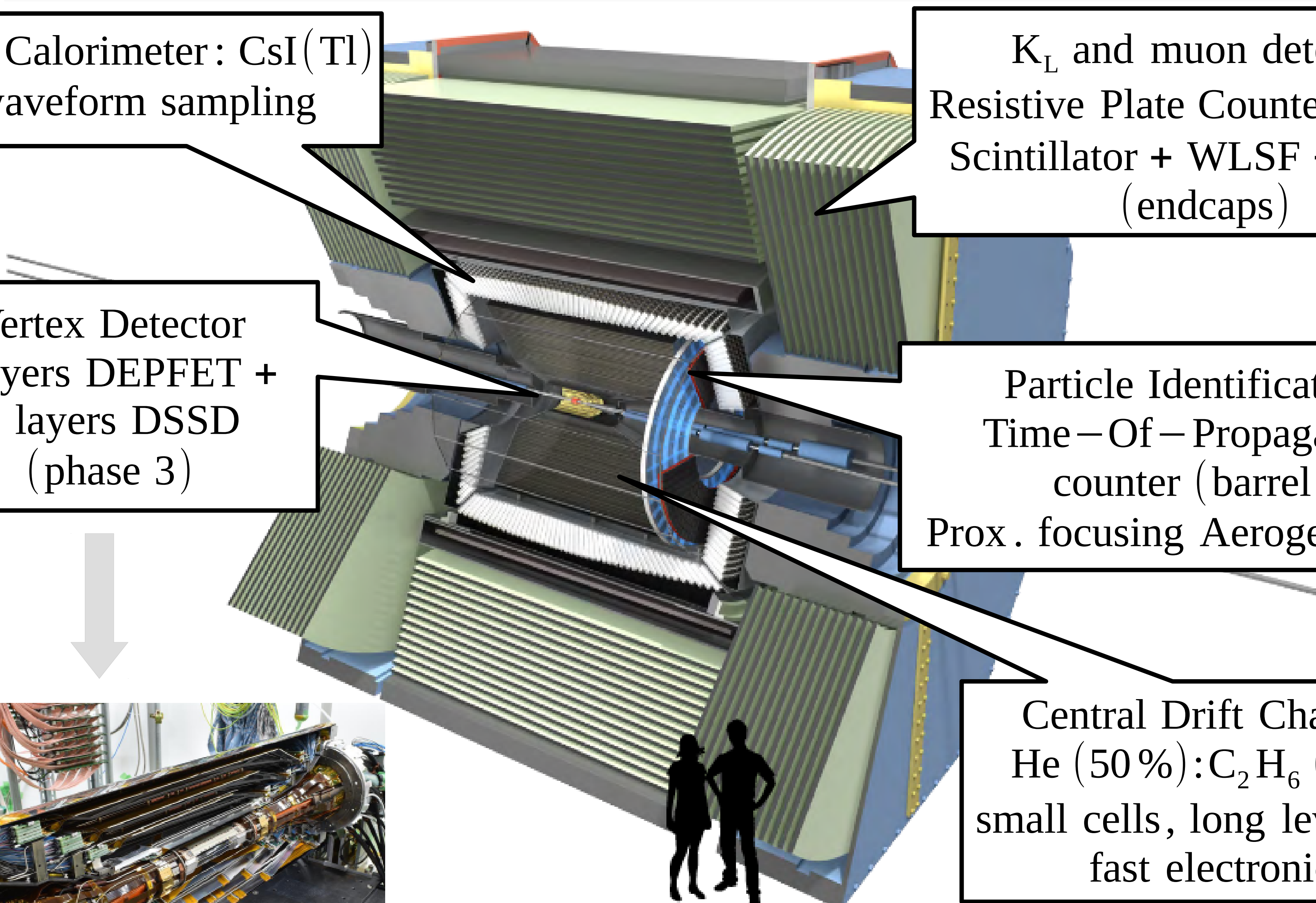
B rediscovery program

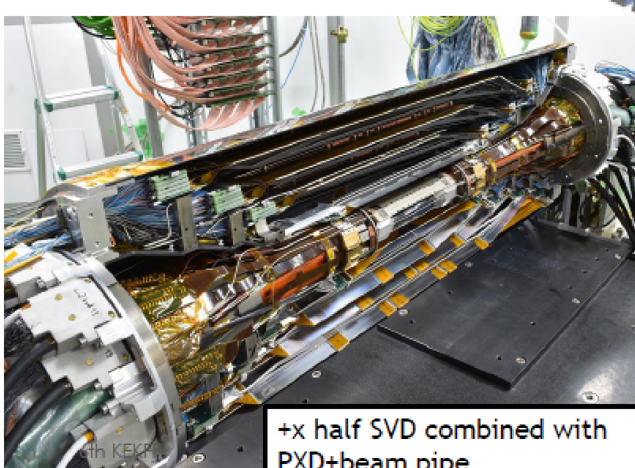


first studies of performance of hadronic tagging in Belle II data

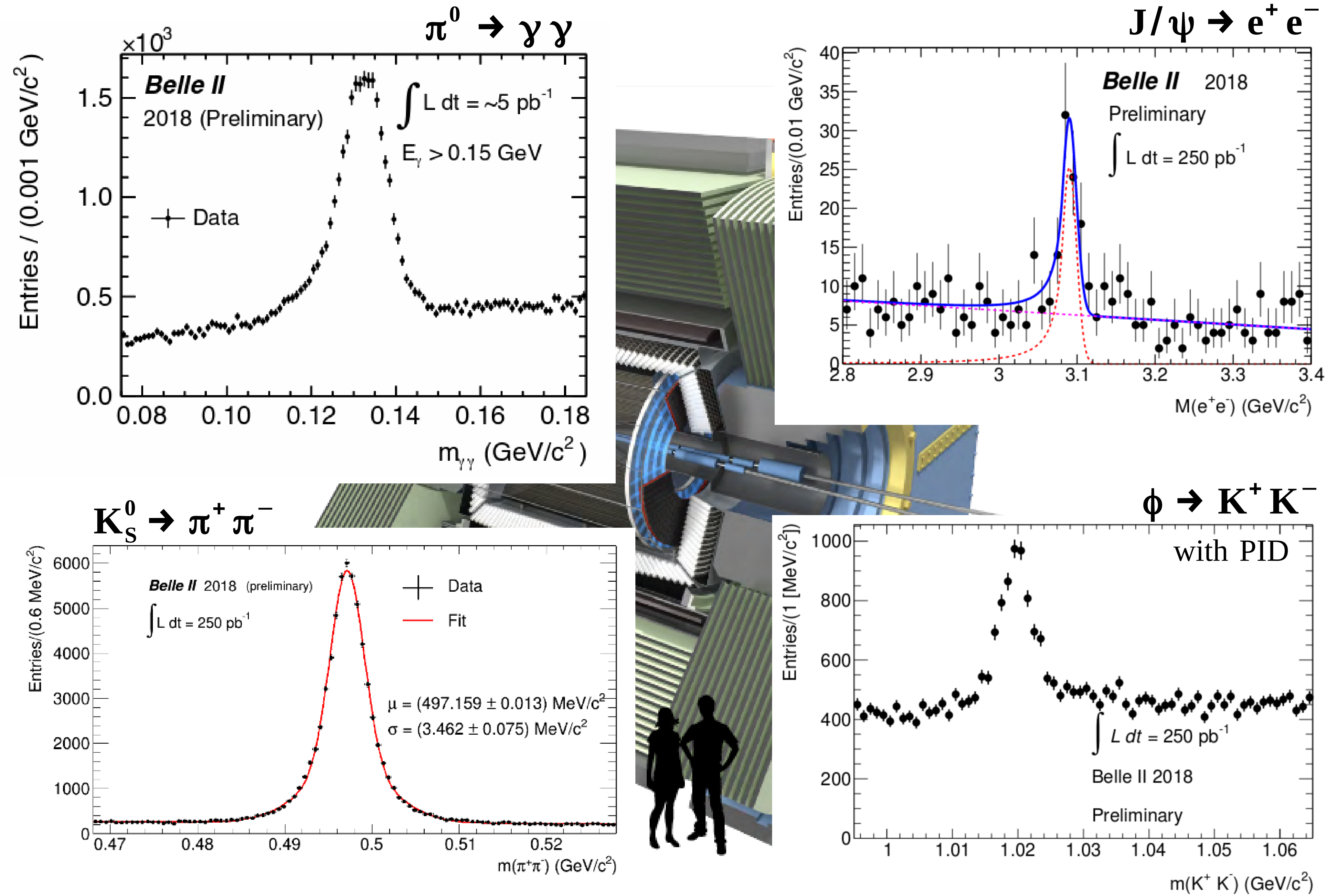


Belle II detector

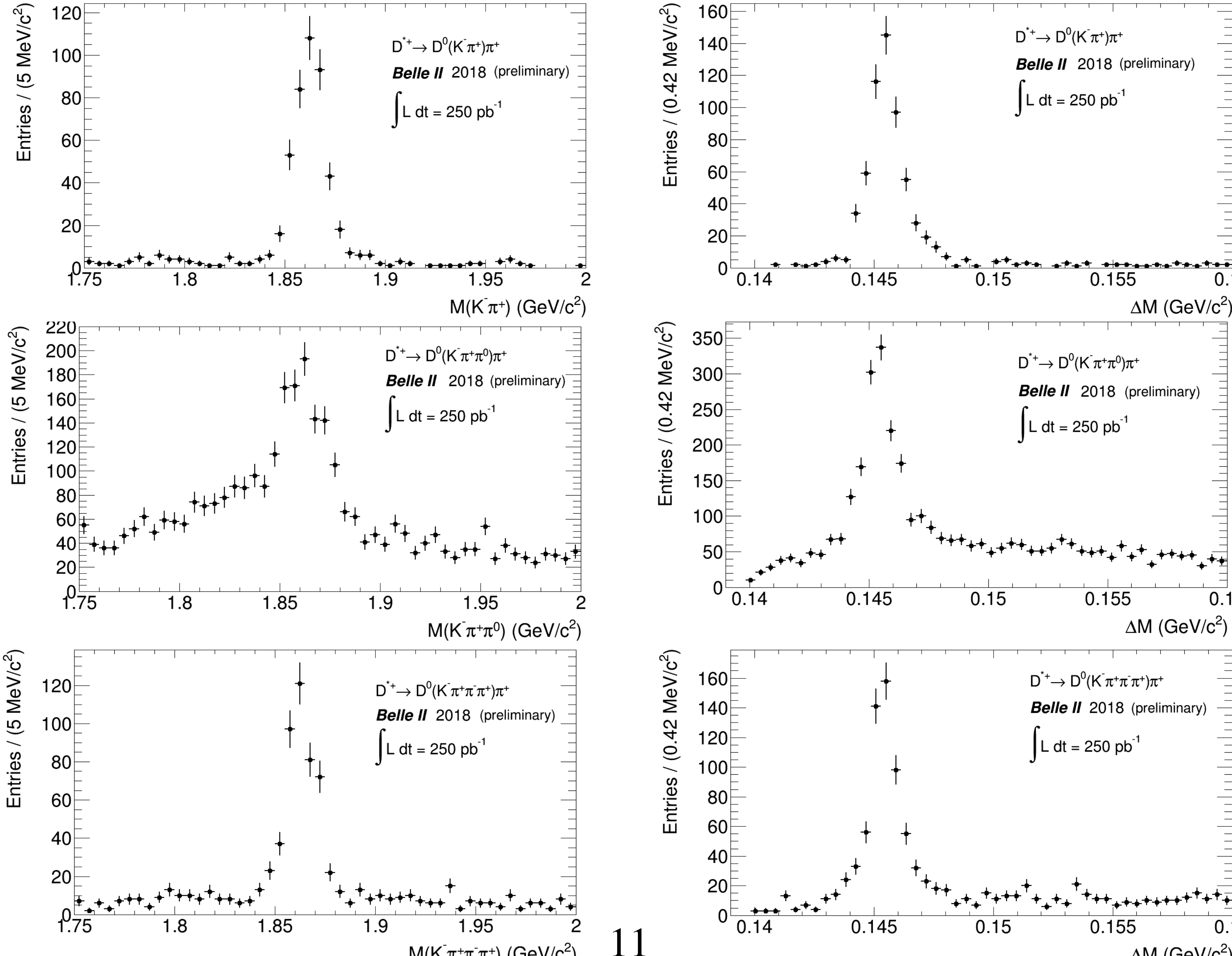




+x half SVD combined with PXD+beam pipe

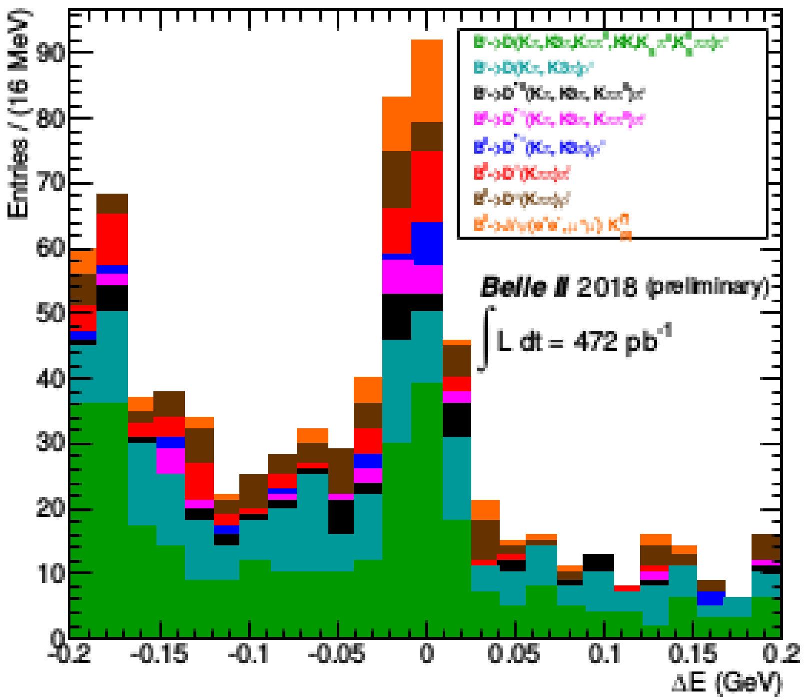

π0 → γ γ
Belle II
2018 (Preliminary)
∫L dt = ~5 pb-1
Eγ > 0.15 GeV
Data
Entries / (0.001 GeV/c2)
×10^3
mγγ (GeV/c2)
J/ψ → e+ e−
Belle II 2018
Preliminary
∫L dt = 250 pb-1
Entries/(0.01 GeV/c2)
M(e+e-) (GeV/c2)
K0S → π+ π−
Belle II 2018 (preliminary)
∫L dt = 250 pb-1
Data
Fit
μ = (497.159 ± 0.013) MeV/c2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

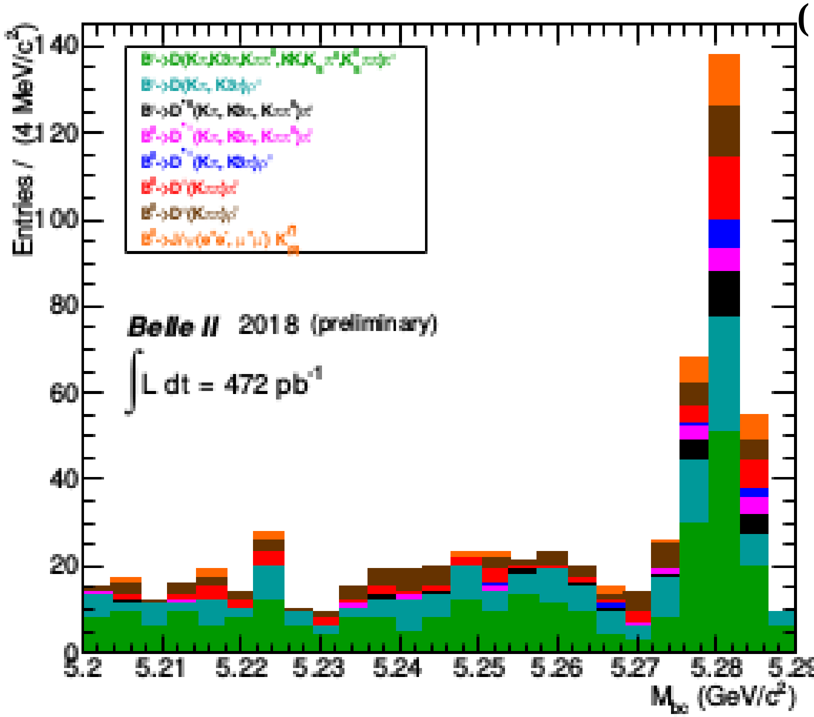
Rediscovering charm: $D^{*+} \rightarrow D\pi^+$, $D \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^- \pi^+$



Rediscovering beauty : $B \to D^{(*)} h$ + $B \to J/\psi K^{(*)}$

Results for 0.5 fb^{-1}





Candidates in signal box

(M_{bc} > 5.27 GeV/c^2, |Δ E| < 0.050 GeV)

Mode	yield
$B^\pm \to D\pi^\pm$	116
$B^\pm \to D\rho^\pm$	61
$B^\pm \to D^*\pi^\pm$	22
$B^0 \to D^{*\pm}\pi^\mp$	13
$B^0 \to D^{*\pm}\rho^\mp$	10
$B^0 \to D^\pm\pi^\mp$	25
$B^0 \to D^\pm\rho^\mp$	33
$B \to J/\psi K^{(*)}_{(S)}$	29

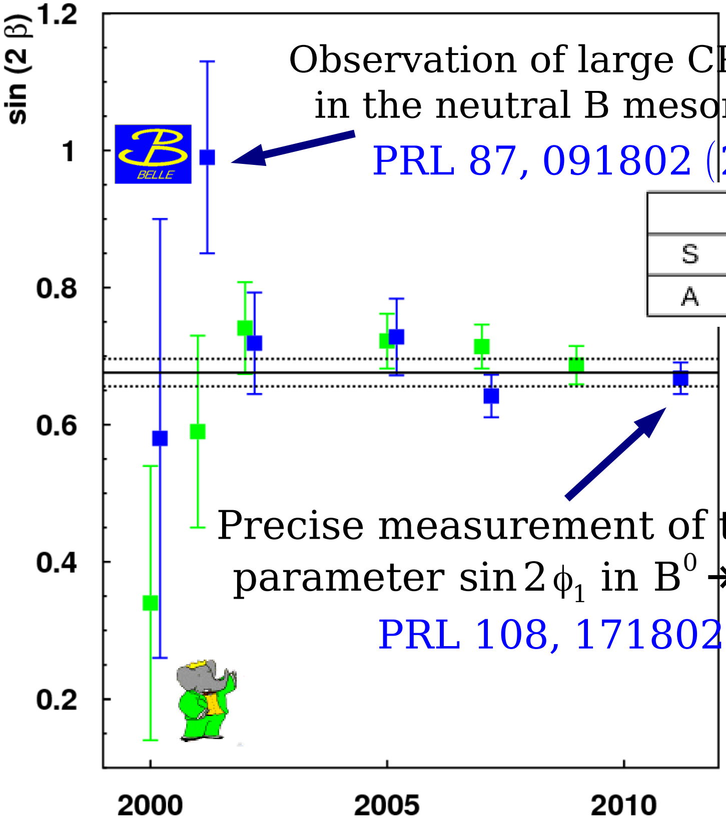
Show capacity for charm physics in $e^+ e^- \to c\bar{c}$

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

...for B-physics

- hadronic modes from $b \to c$
- semileptonic decay modes from $b \to c$

Precision measurements for UT



Observation of large CP violation in the neutral B meson system
PRL 87, 091802 (2001)

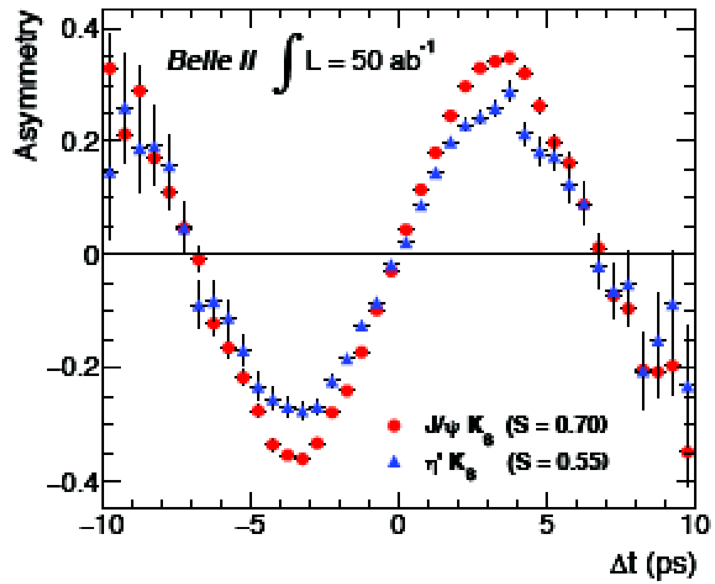
Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays
PRL 108, 171802 (2012)

anchor of SM

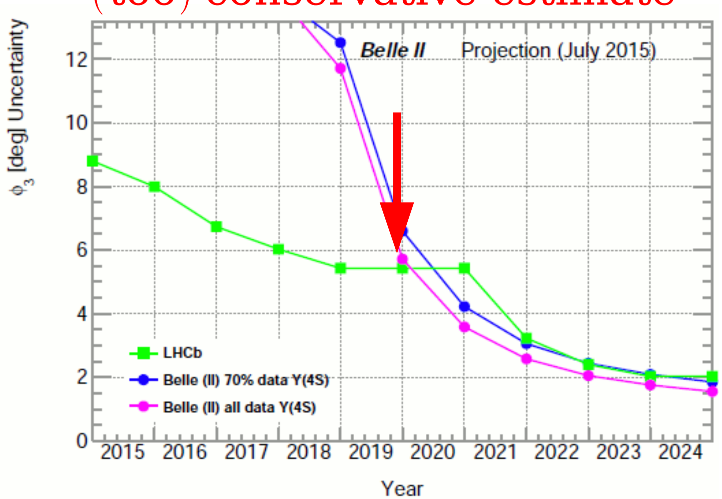
	Belle	Belle II (50 ab^{-1})
S	0.667 ± 0.023 ± 0.012	x.xxxx ± 0.0027 ± 0.0044
A	0.006 ± 0.016 ± 0.012	x.xxxx ± 0.0033 ± 0.0037

will be dominated by systematic uncertainties

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

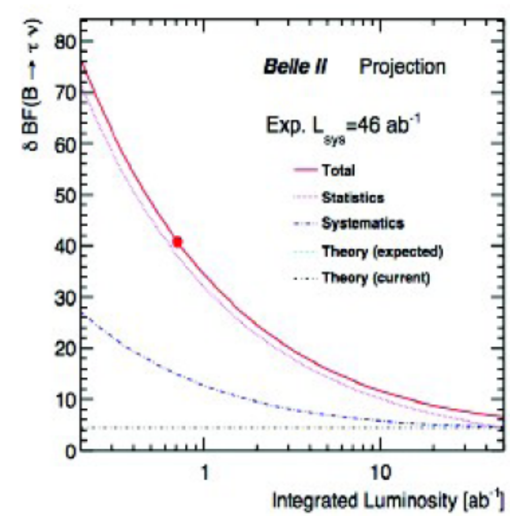


(too) conservative estimate



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

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

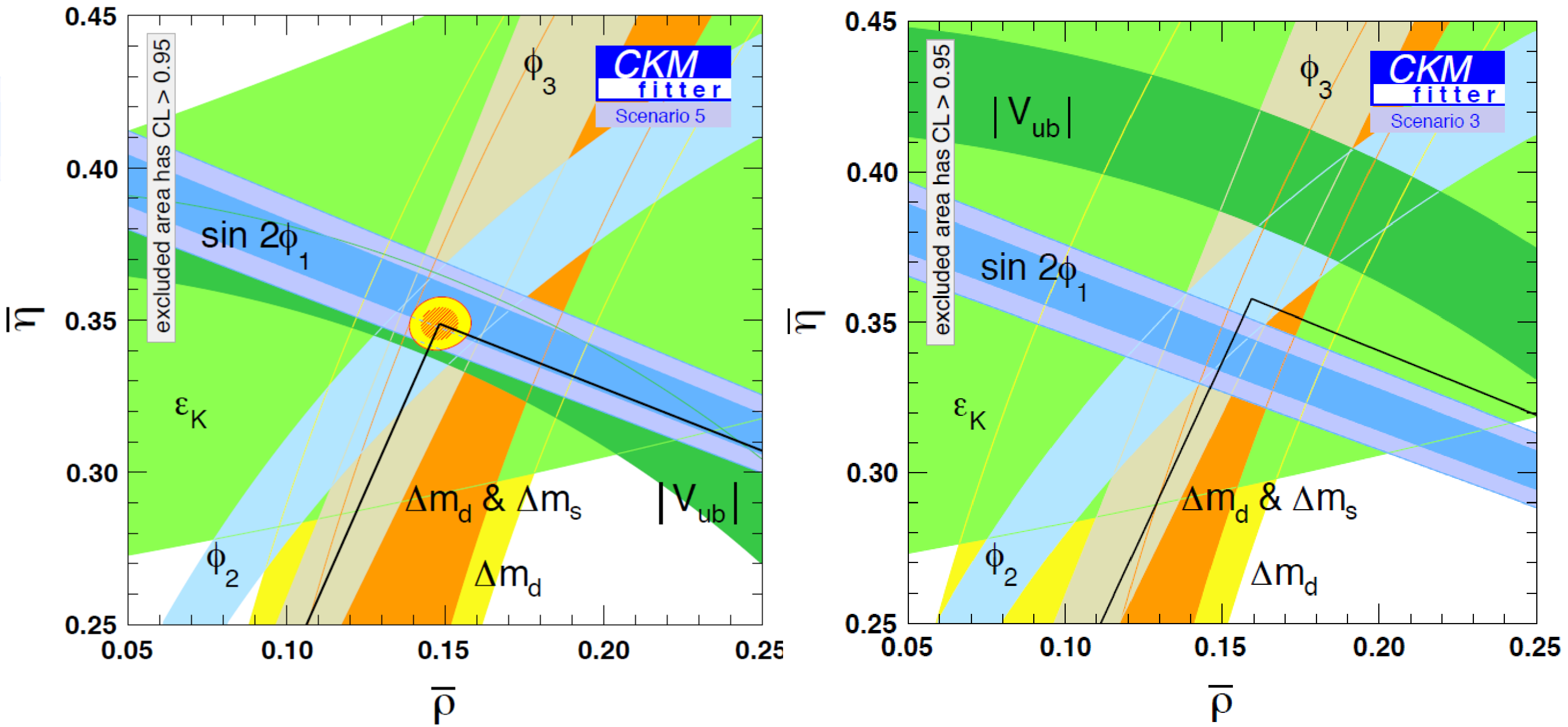


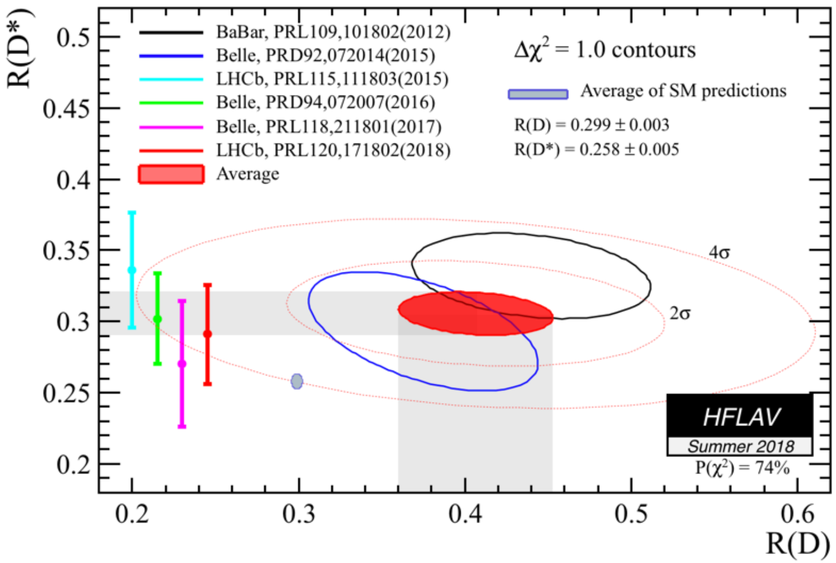
observation of $B \to \mu\nu$ is also expected (from 5 ab^{-1})

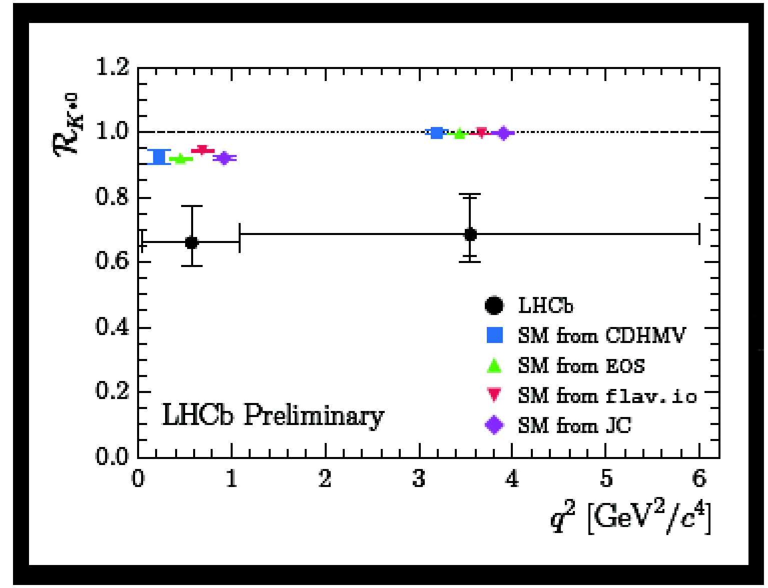
The Unitarity Triangle in the year 2026

NB: α with couple of degrees @ Belle II

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







b → c anomalies

b → s anomalies

Found by several experiments (LHCb, BaBar and Belle)

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

Charged current

Tree-level in the SM

The New Physics must be light

Found by LHCb

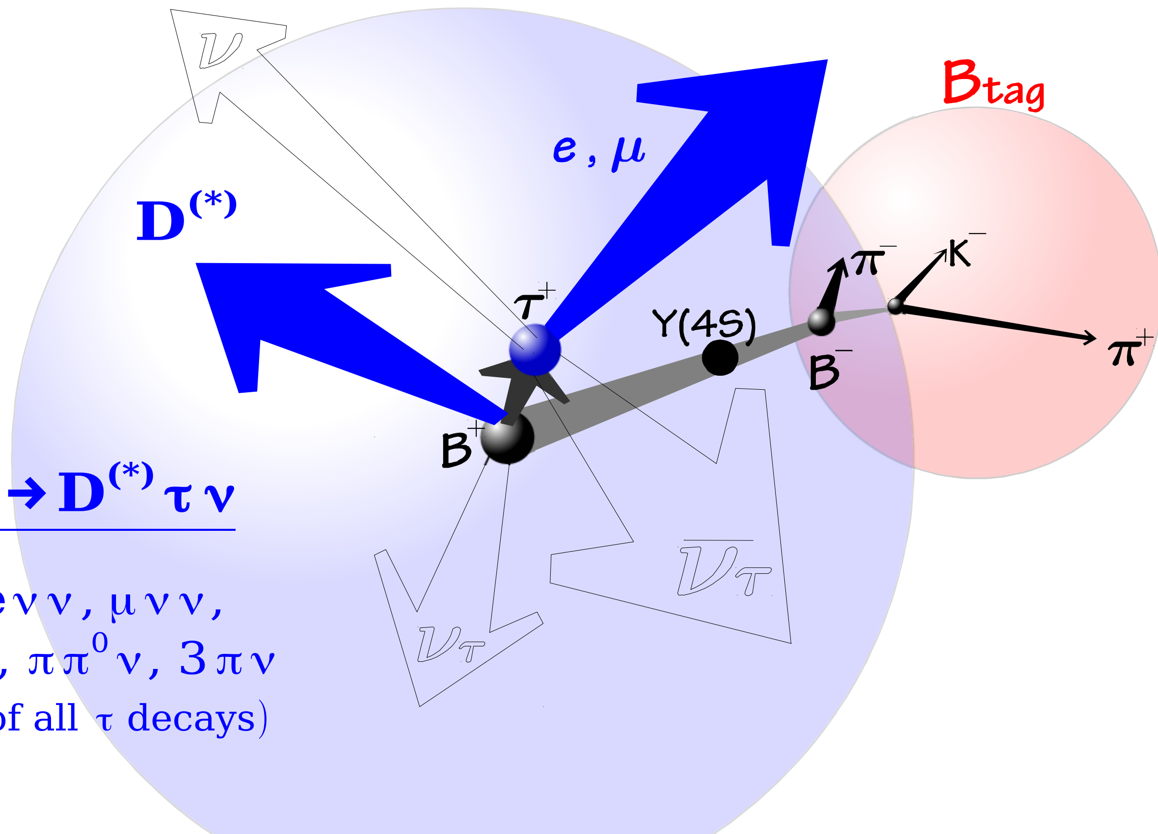
Many observables: global pattern

Neutral current

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

The New Physics can be heavy

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



B_{tag}

hadronic tag

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

$\epsilon \sim 0.2\,\%$

semileptonic tag

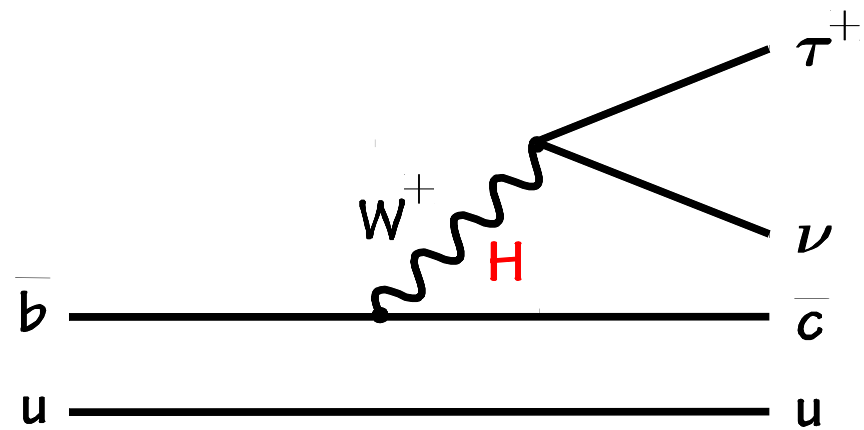
$B \to D^{(*)} l \nu\ X$

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

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

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

(70 % of all τ decays)



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

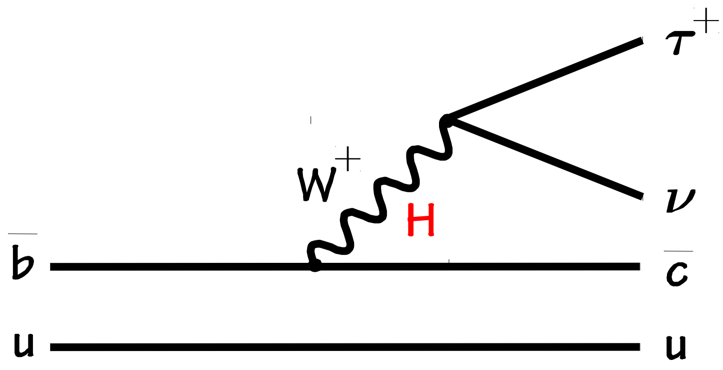
main signal-background discriminator

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

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

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

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



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

BaBar

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

Belle

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

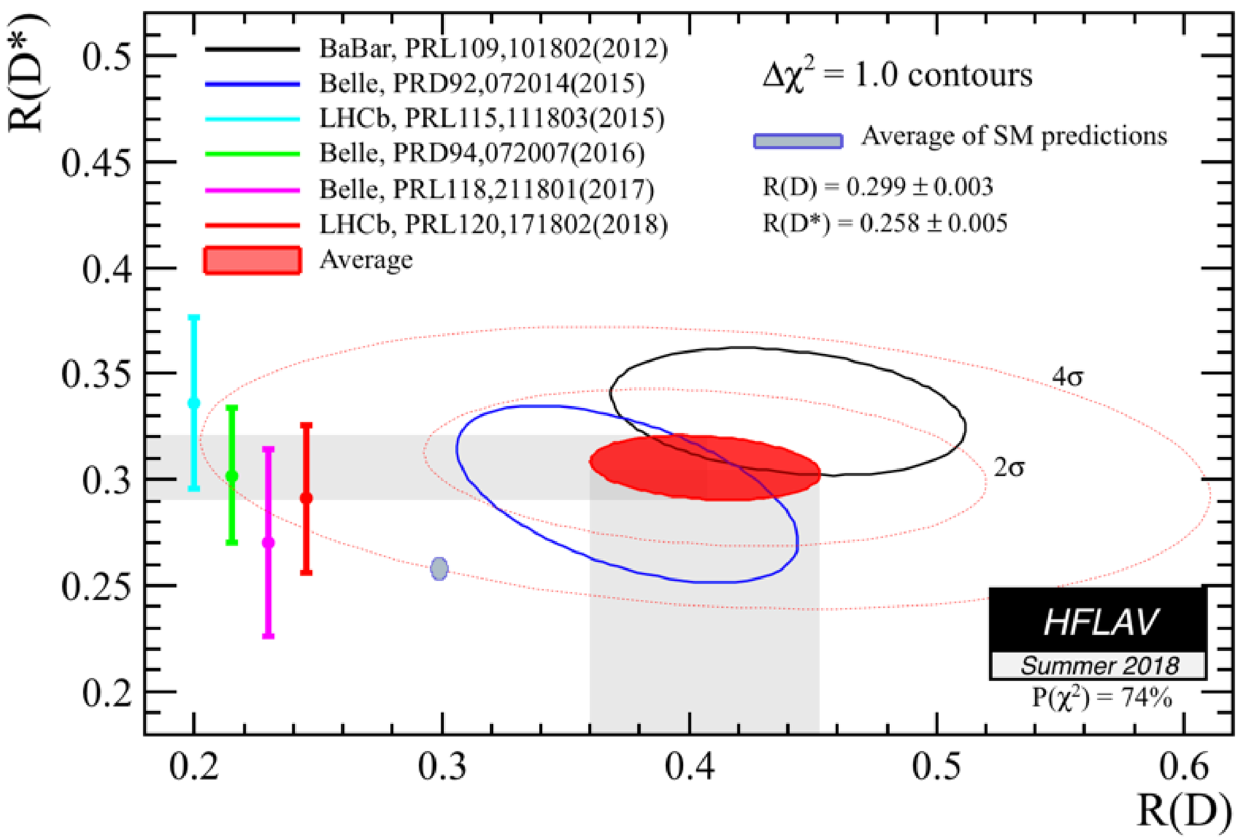
$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

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

LHCb

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

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



average

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

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

Hadronic full reconstruction at Belle II

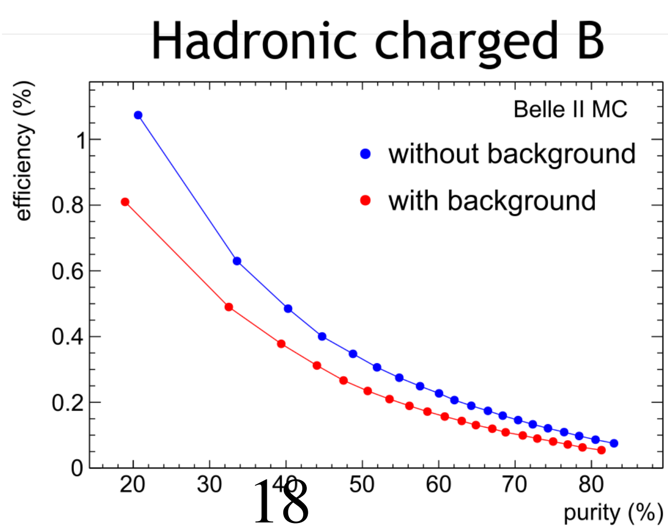
Particle	# channels (Belle)	# channels (Belle II)
$D^+/D^{*+}/D_s^+$	18	26
D^0/D^{*0}	12	17
B^+	17	29
B^0	14	26

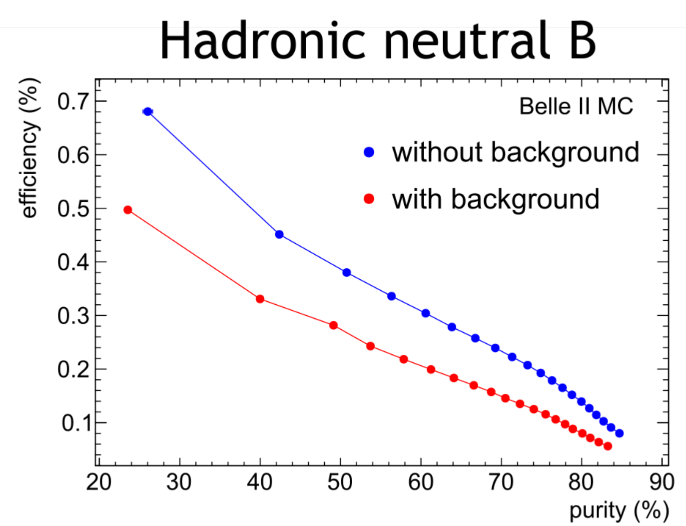
◦ More modes used for tag-side hadronic B than Belle, multiple classifiers

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

Improvement to tagging efficiency in Belle II

◦ Good performances on Belle II predicted beam background conditions:



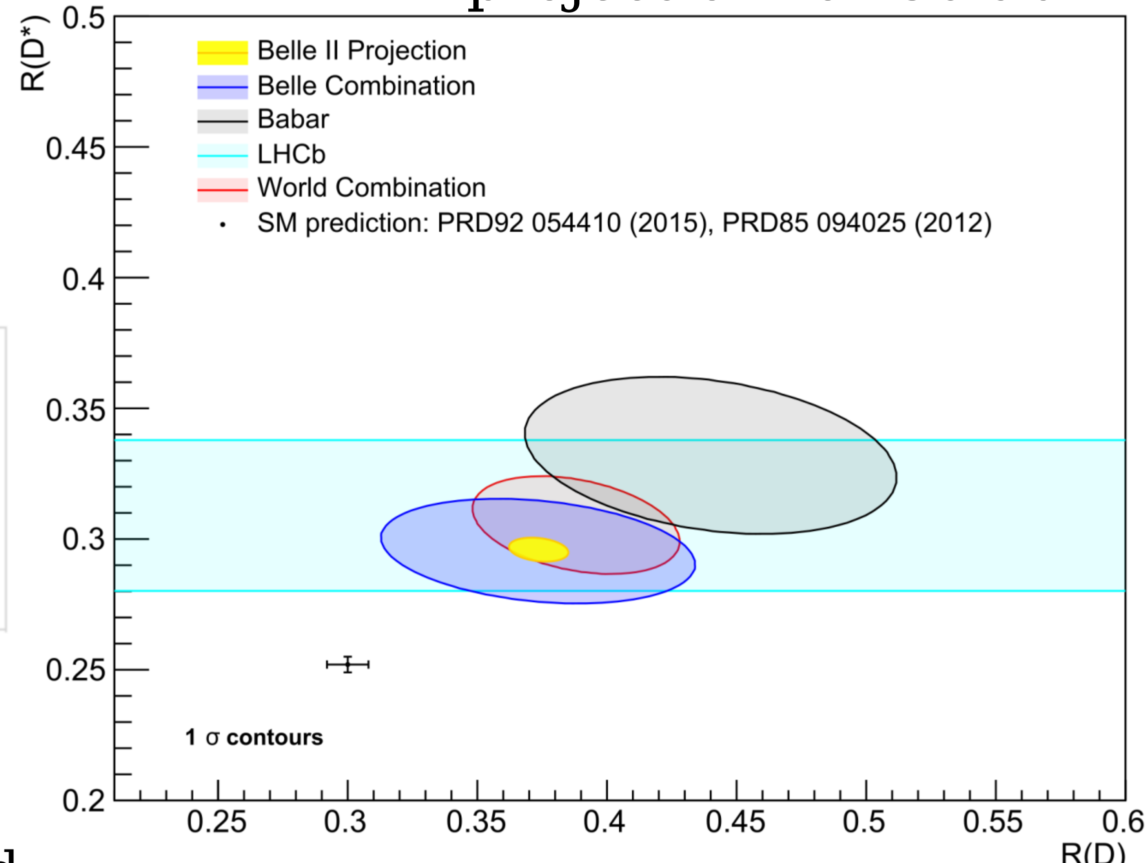


Projections for Belle II $R(D^{(*)})$

Predictions of uncertainty using hadronic full reconstruction:

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

projection for 50 ab^{-1}



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

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

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

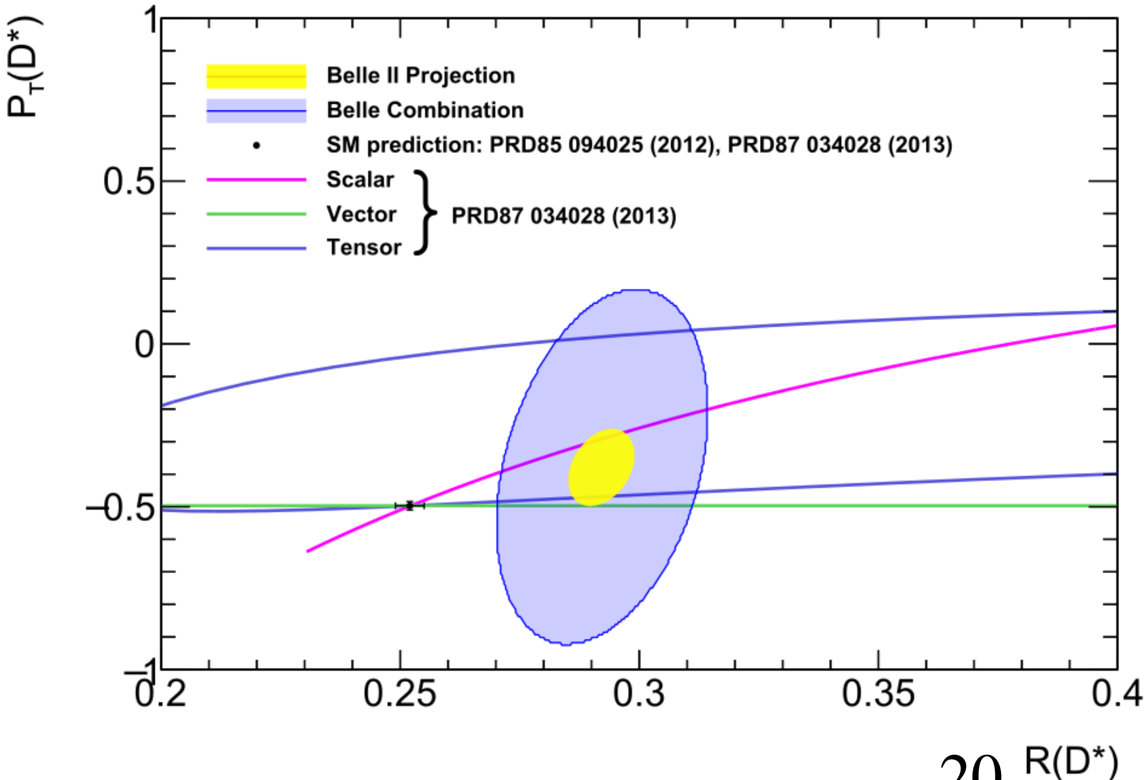
Additional observables as $P_\tau(D^*)$ ($F_L(D^*)$) and q^2 distribution can help discriminate between New Physics models

[Belle, arXiv:1612.00529]

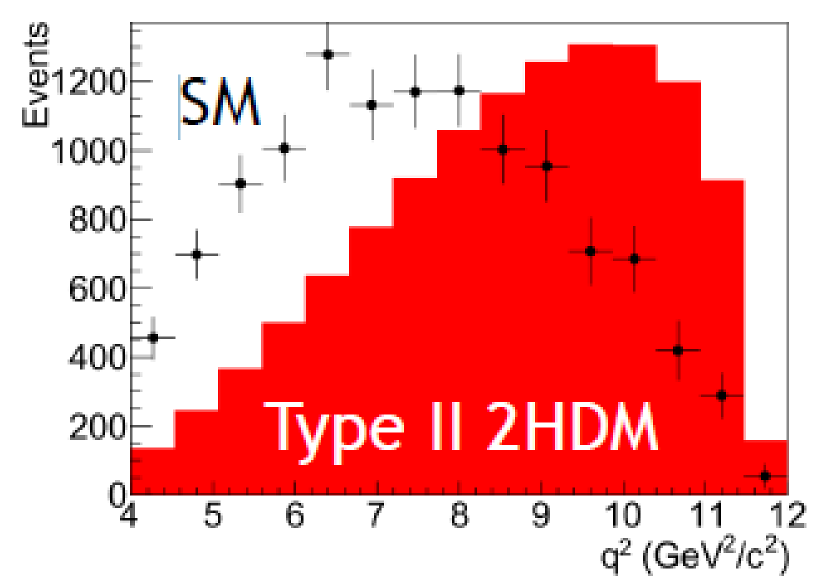
$$P_\tau(D^*) = -0.38 \pm 0.51\,^{+0.21}_{-0.16}$$

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

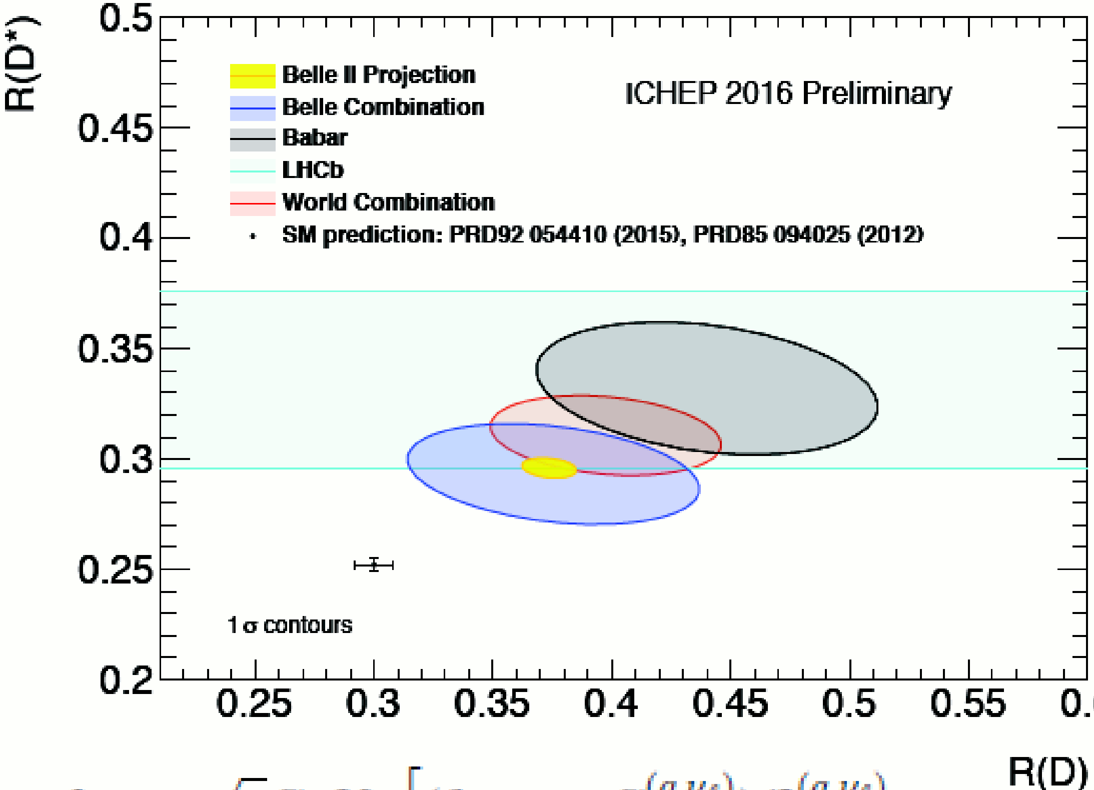
$P_\tau(D^*)$	Stat. uncertainty	Sys. uncertainty
at 5 ab^{-1}	0.18	0.08
at 50 ab^{-1}	0.06	0.04



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



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

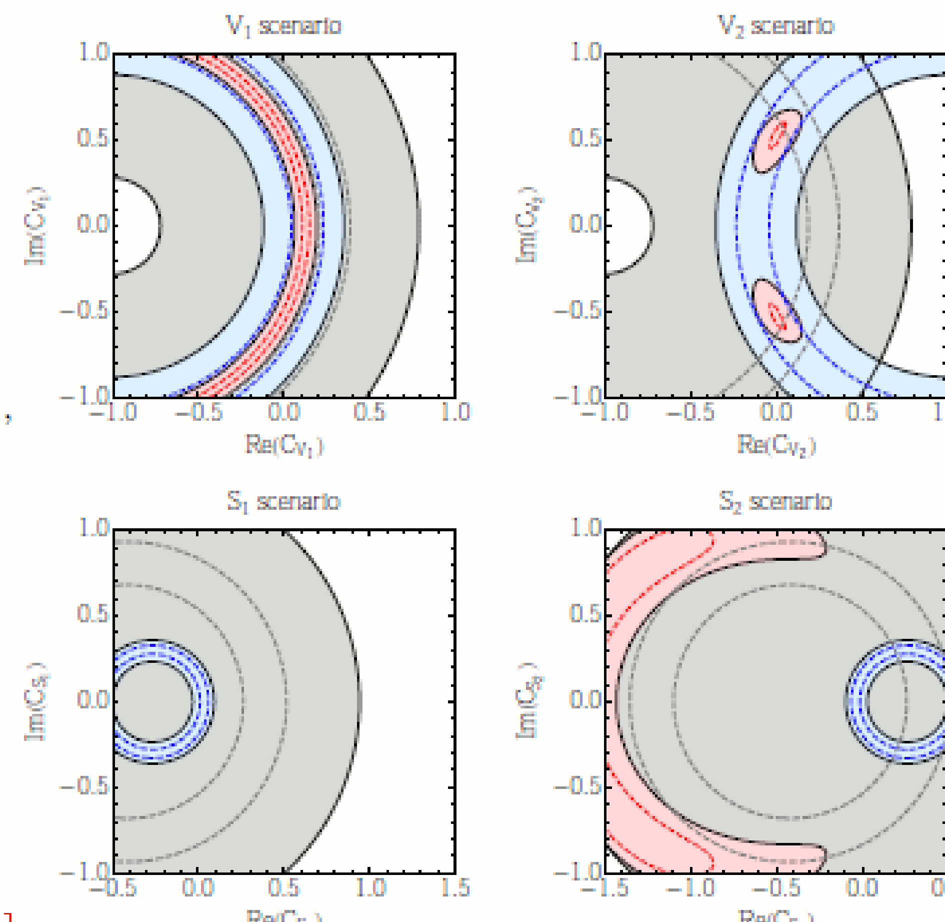


$$R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}, \text{ in red}$$

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

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

Dashed: Belle II



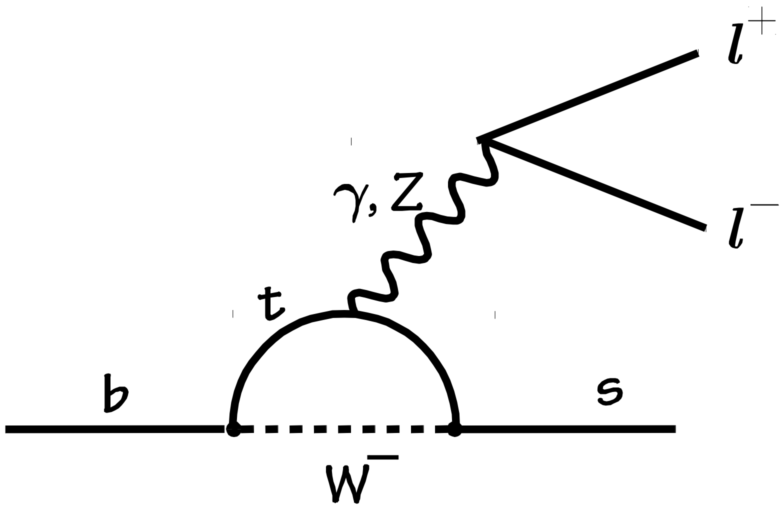
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{qb} \Big[(\delta_{\nu_\tau,\nu_\ell} + C_{V_1}^{(q,\nu_\ell)}) \mathcal{O}_{V_1}^{(q,\nu_\ell)} + \sum_{X=}^{V_2,S_1,S_2,T} C_X^{(q,\nu_\ell)} \mathcal{O}_X^{(q,\nu_\ell)} \Big],$$

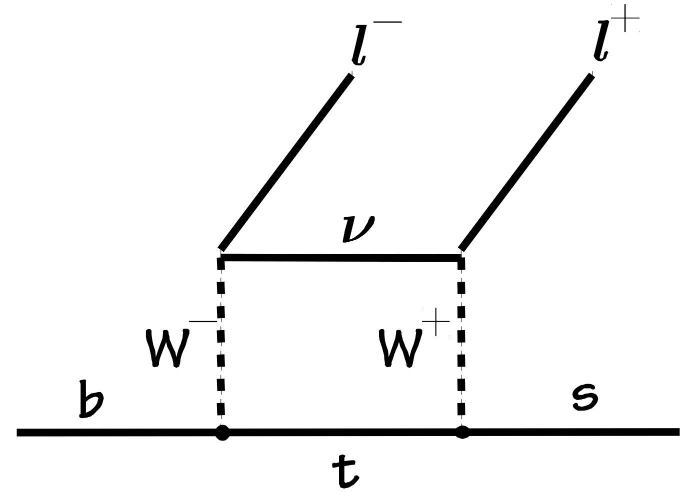
where the four-Fermi operators:

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

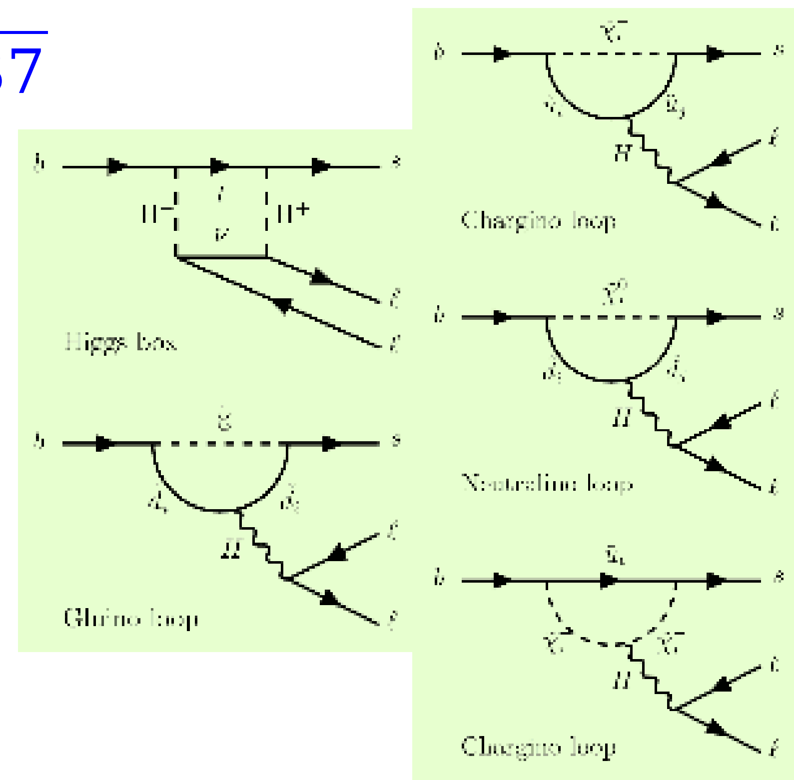
[Details in Watanabe et al, B2TiP theory]

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

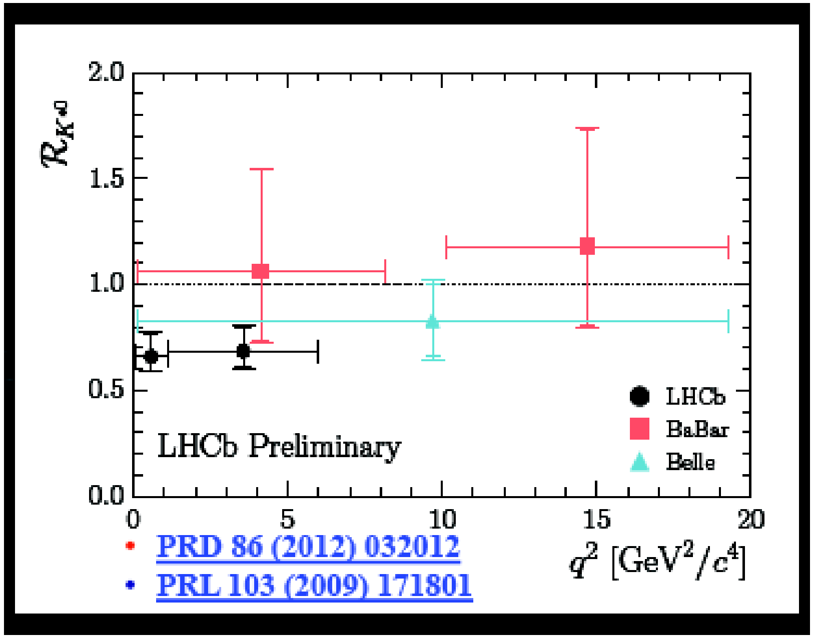


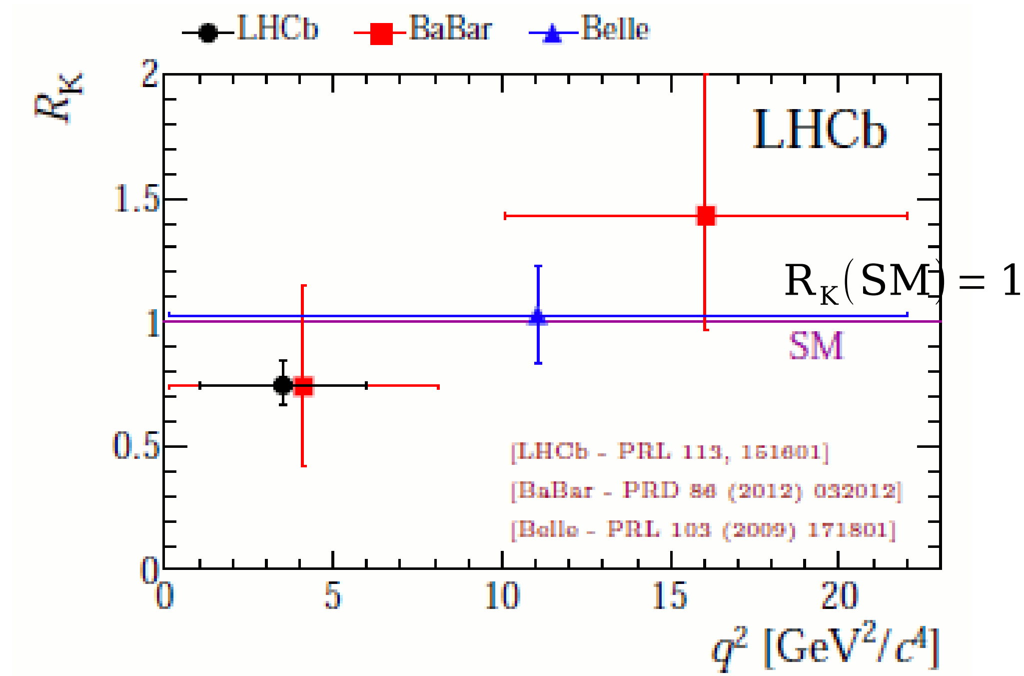


- Start with $b \to s\gamma$, pay a factor $\alpha_{EM} = \frac{1}{137}$
  - → Decay the γ into 2 leptons
  - Add an interfering box diagram
    → $b \to l l s$, very rare in the SM
    $\mathcal{B}(B \to l l K^*) = (3.3 \pm 1.0)\,.\,10^{-6}$
- Sensitive to Supersymmetry, Any 2HDM, Fourth generation, Extra dimensions, Axions…
- Ideal place to look for new physics



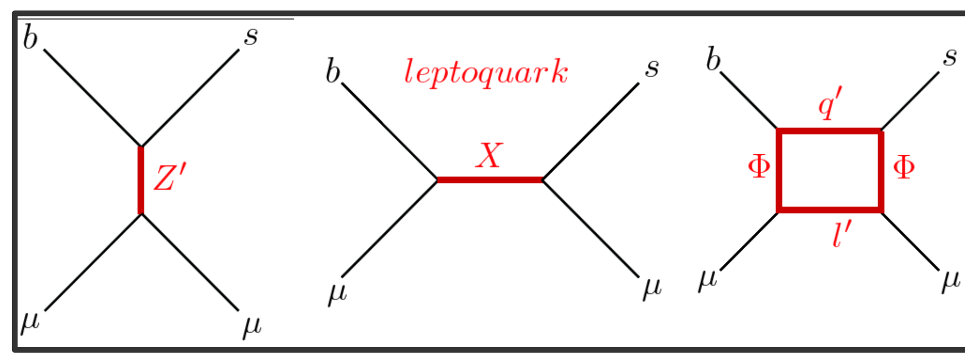
Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays





Model candidates

- ✧ **Model with extended gauge symmetry**
  - ✓ Effective operator from Z' exchange
  - ✓ Extra U(1) symmetry with flavor dependent charge
- ✧ **Models with leptoquarks**
  - ✓ Effective operator from LQ exchange
  - ✓ Yukawa interaction with LQs provide flavor violation
- ✧ **Models with loop induced effective operator**
  - ✓ With extended Higgs sector and/or vector like quarks/leptons
  - ✓ Flavor violation from new Yukawa interactions



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

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

$\mathbf{R_K}$, $\mathbf{R_K^*}$, ...

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

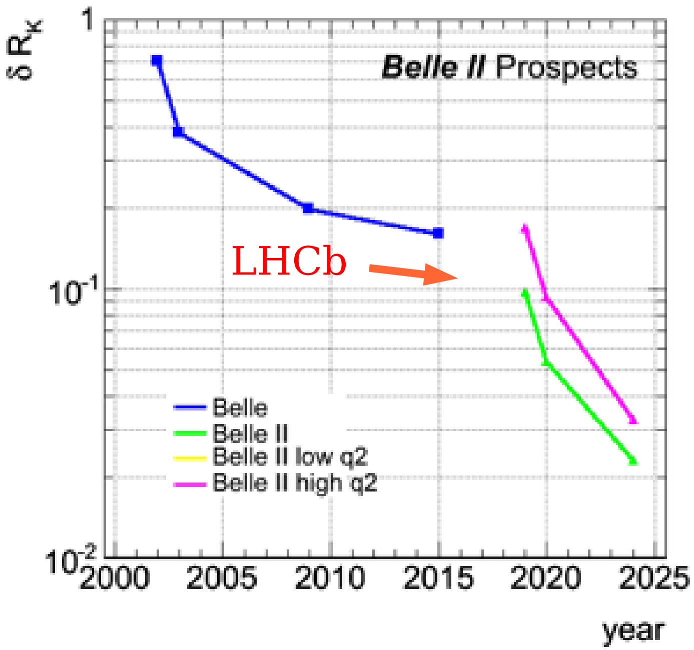
$$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$$
$$R_K = 1.03 \pm 0.19 \pm 0.06$$

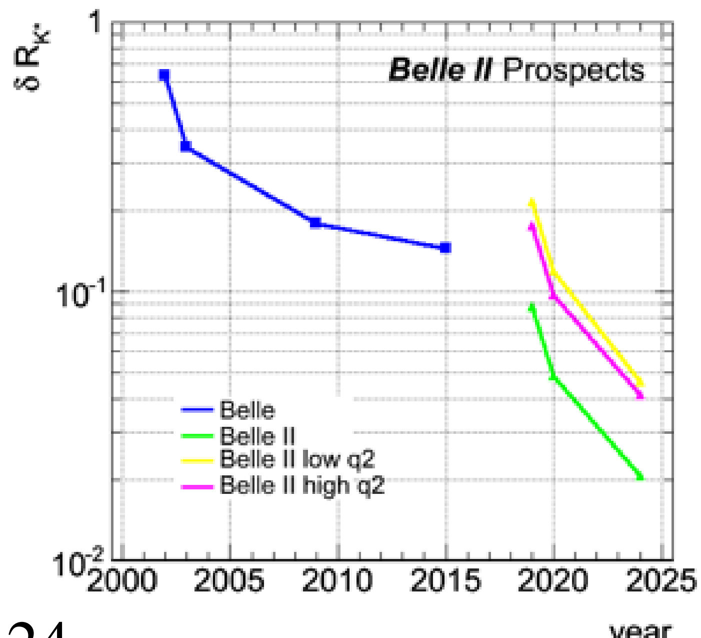
[Belle, arXiv:0904.0770]

[Belle II, arXiv:1808.10567]

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

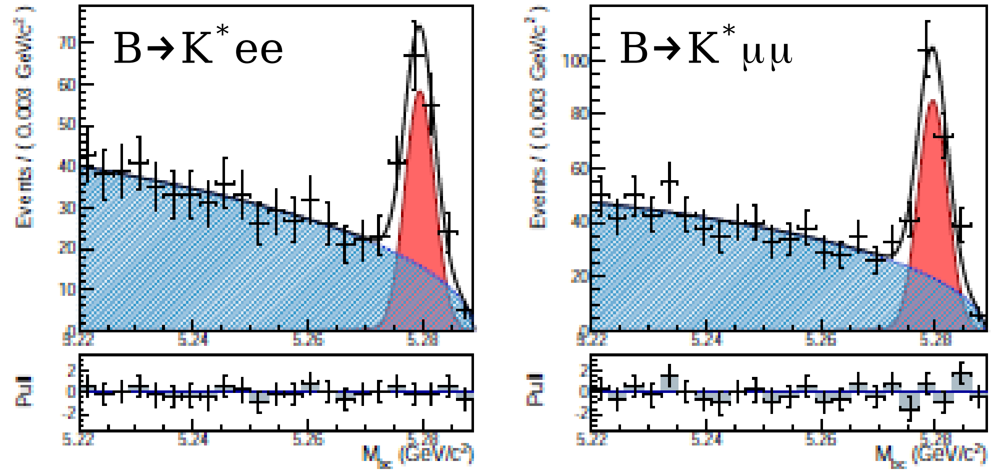
5σ confirmation possible with Belle II $20\,\text{ab}^{-1}$

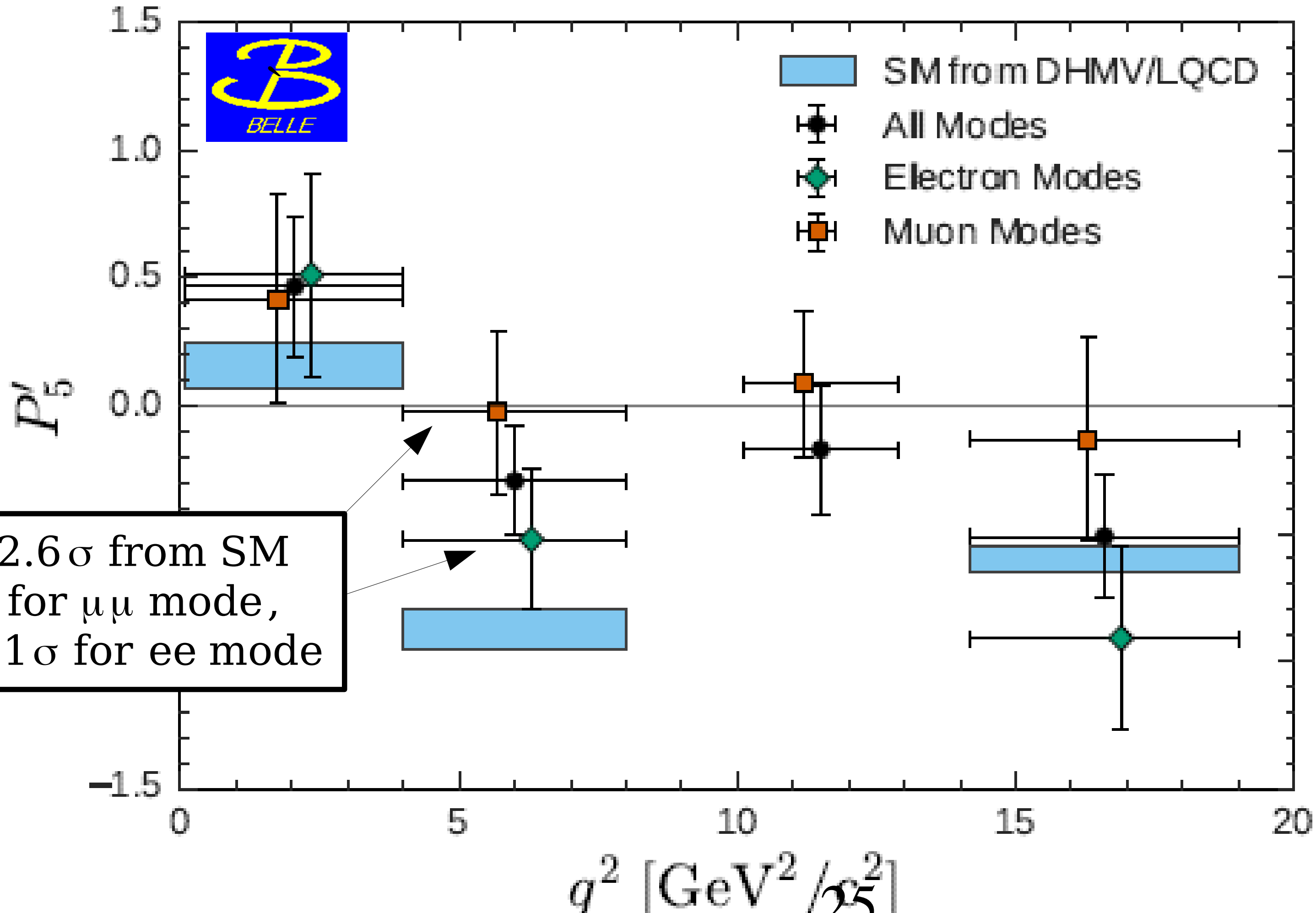




Belle results for both ee and μμ

[Belle, arXiv:1612.05014]





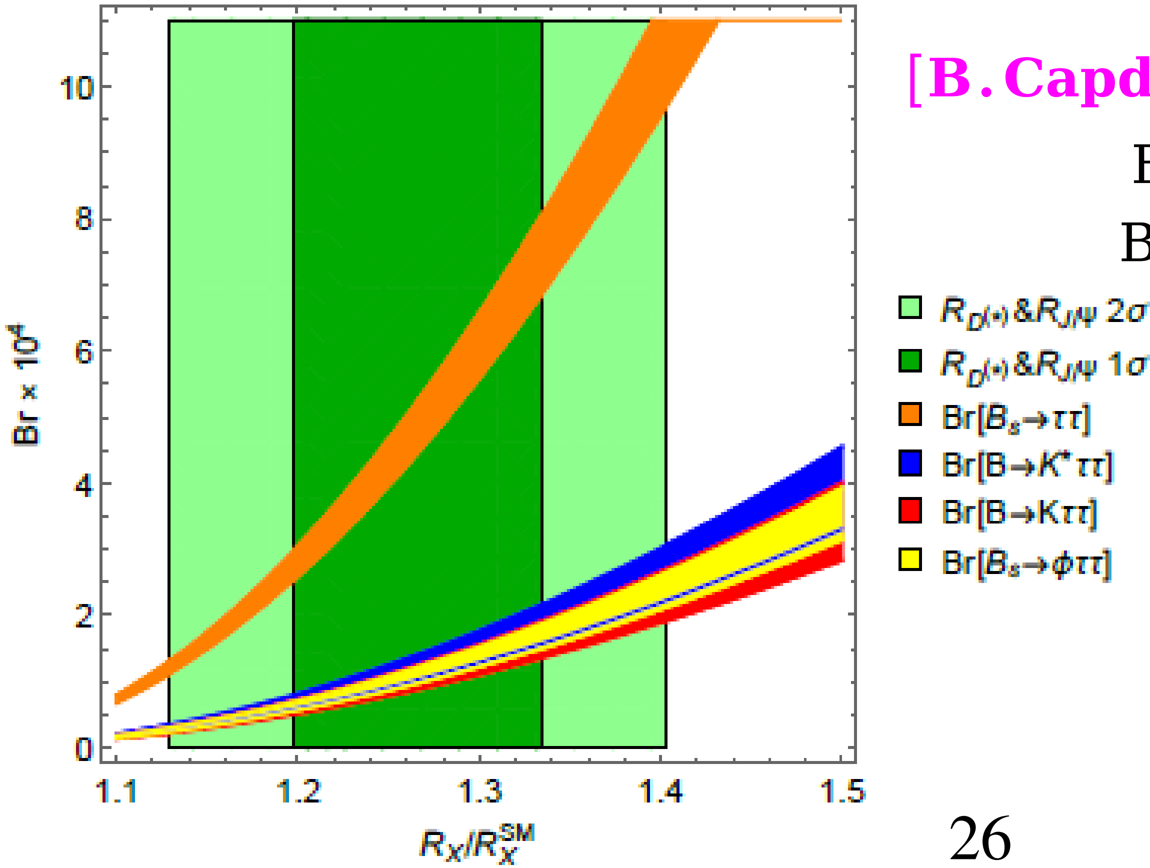
2.6σ from SM for μμ mode, 1.1σ for ee mode

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

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

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

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



[B.Capdevila et al, arXiv:1712.01919]

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

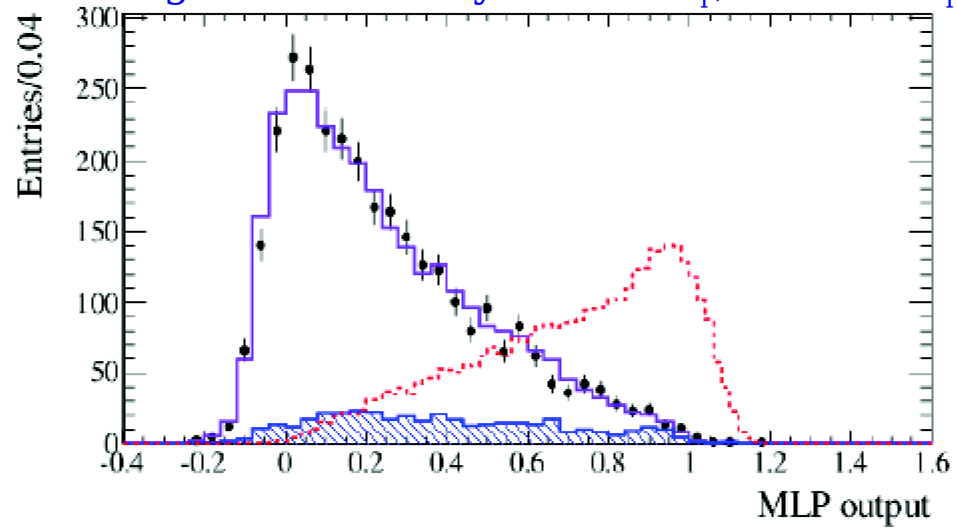
$B \to K^{(*)} \tau \tau$

[BaBar, arXiv:1605.09637]

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

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

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



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

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

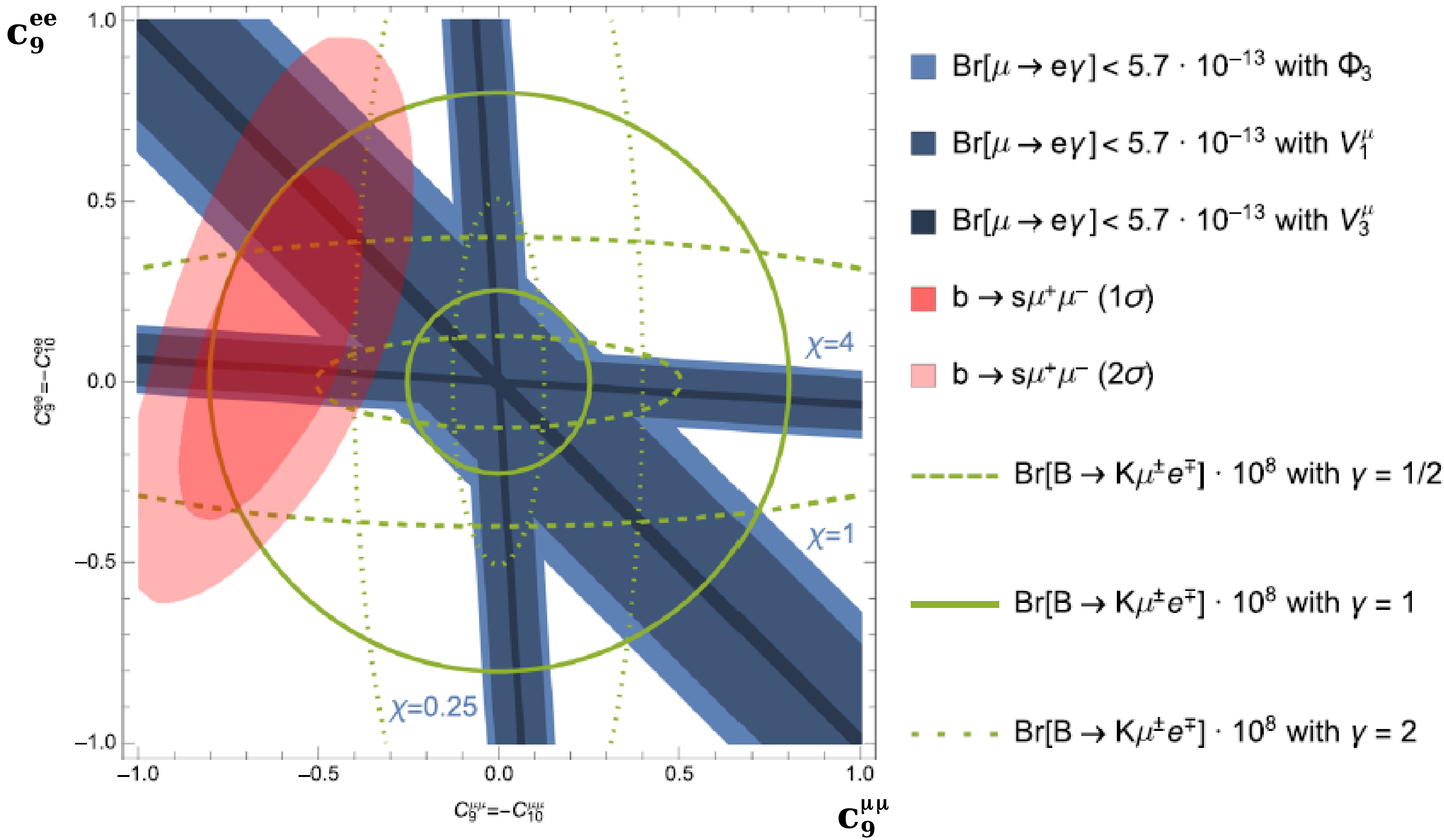
[Belle II, arXiv:1808.10567]

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

LFV b→sll'decays

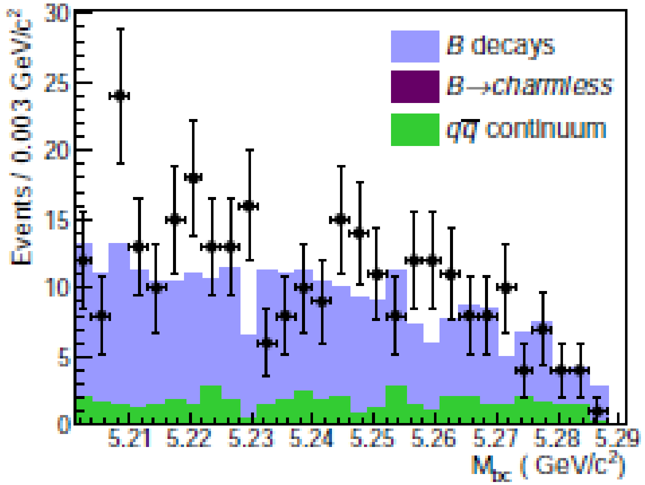
Glashow, Guadagnoli and Lane, 1411.0565, LUV ⇒ LFV, such as B→Kμe, Kμτ could also be generated ...

A.Crivellin et al, 1706.08511



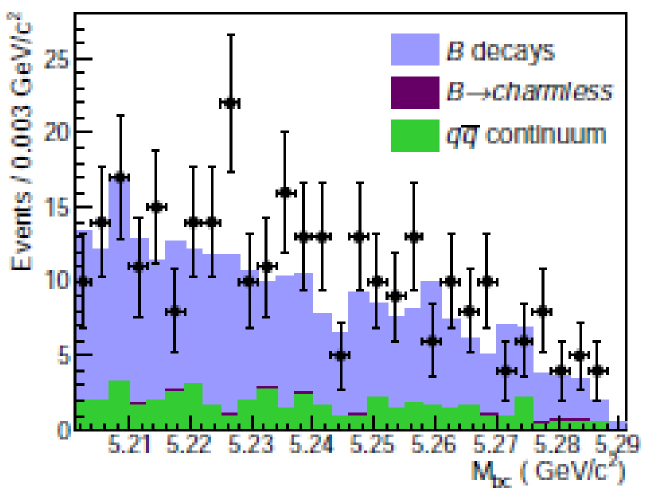
LFV $B \to K^* l l'$ decays

[Belle, arXiv:1807.03267]



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

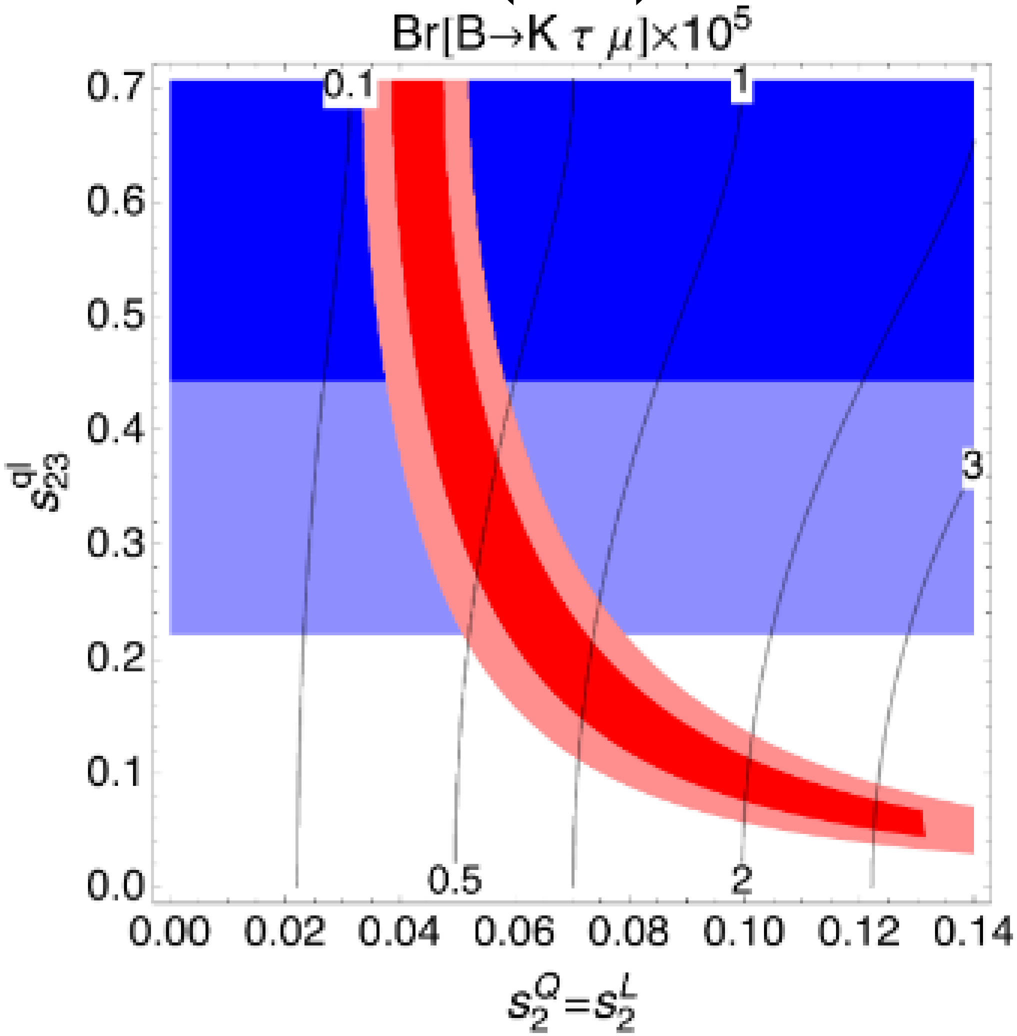
$\mathcal{B}(B^0 \to K^{*0}\mu^+ e^-) < 1.2 \times 10^{-7}$ at 90%CL



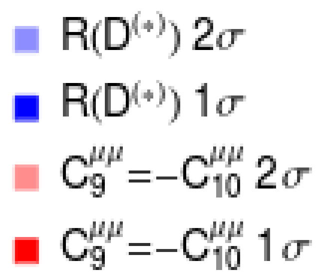
$\mathcal{B}(B^0 \to K^{*0}\mu^+ e^-) < 1.6 \times 10^{-7}$ at 90%CL

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

R(D*) and b→sμμ ⇒ B→Kτμ



L.Calibbi et al, arXiv:1709.00692



Key Features of PS³

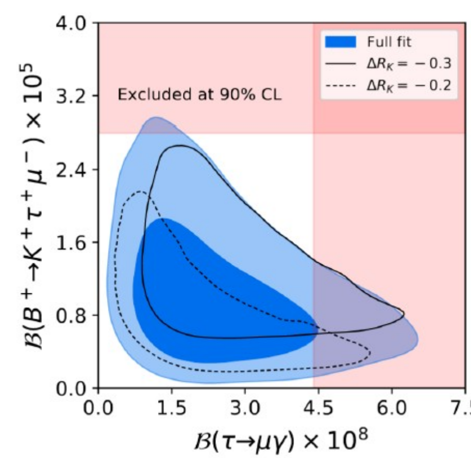
BORDONE, CORNELLA, FUENTES-MARTIN, ISIDORI (2017), (2018)

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

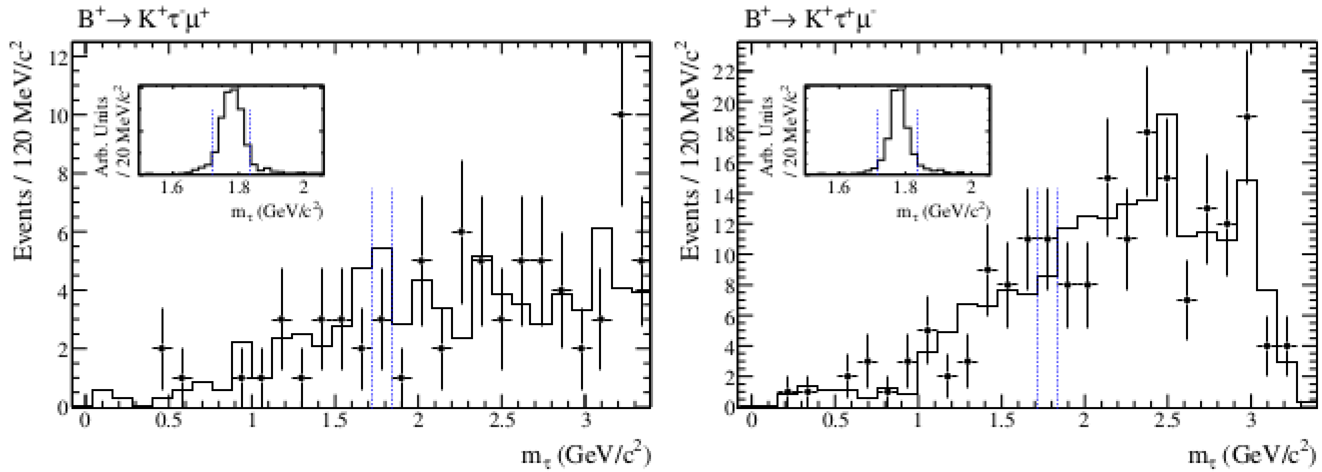


LFV B→Kτl decays

[BaBar, arXiv:1204.2852]

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

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



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

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

[Belle II, arXiv:1808.10567]

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+ \tau^\pm e^\mp) \cdot 10^6$	–	–	< 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 inclusive tag ?

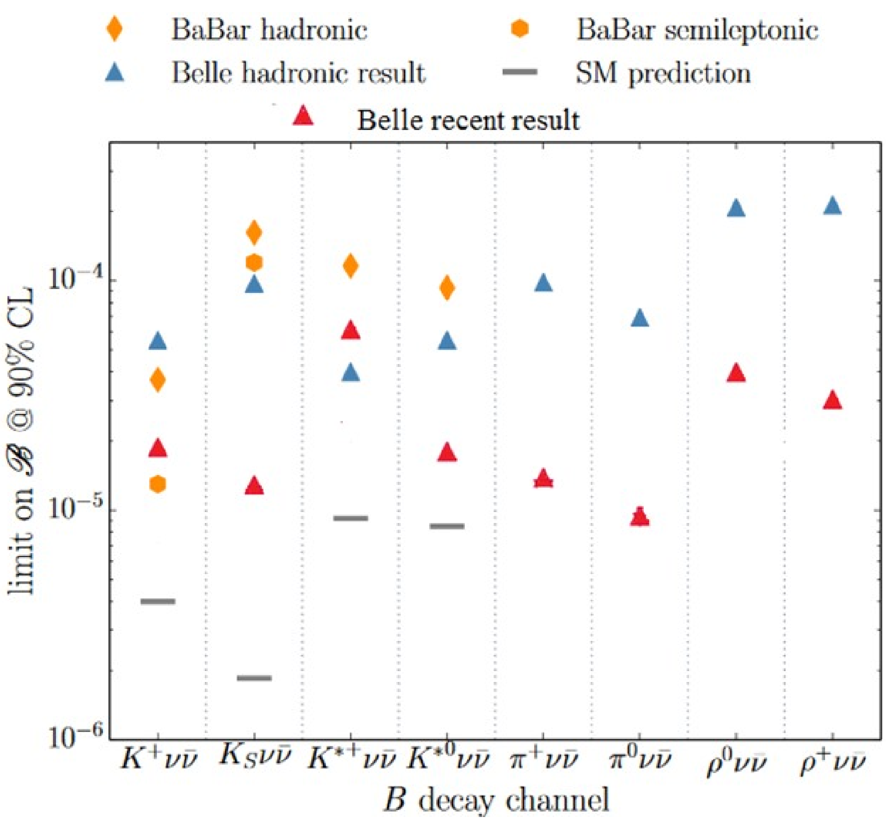
⇒ can do $K^*\tau e$, $K^*\tau\mu$ with similar sensitivity...

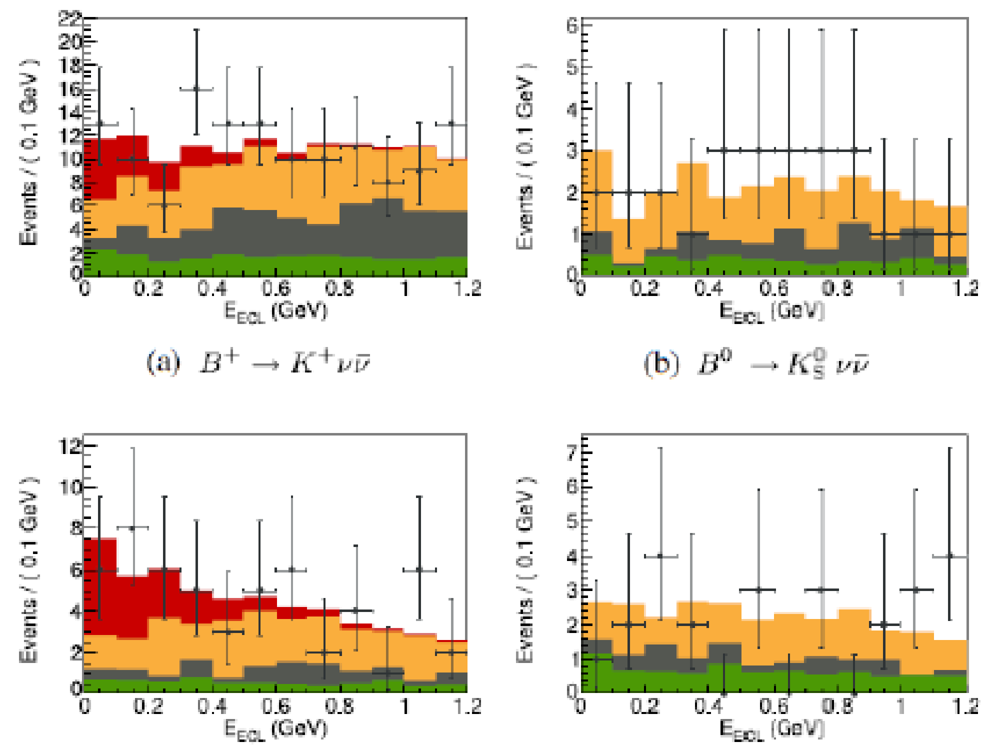
$B \to h \nu \bar{\nu}$ decays

– semi-leptonic tag
– signal extracted in extra energy in calorimeter

[Belle, arXiv:1702.03224]

Channel	Observed signal yield	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	1.9σ
$K^0_S\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	0.0σ
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	2.3σ
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	0.0σ
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	0.0σ
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	0.0σ
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	0.3σ
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	1.2σ





(a) $B^+ \to K^+\nu\bar{\nu}$ (b) $B^0 \to K^0_S\,\nu\bar{\nu}$
(c) $B^+ \to K^{*+}\nu\bar{\nu}$ (d) $B^0 \to K^{*0}\nu\bar{\nu}$

– Belle II able to observe $B \to K^{(*)}\nu\bar{\nu}$ (charged+neutral) with 5 ab^{-1}
– with 50 ab^{-1}, uncertainty on BF comparable to SM predictions (10%)

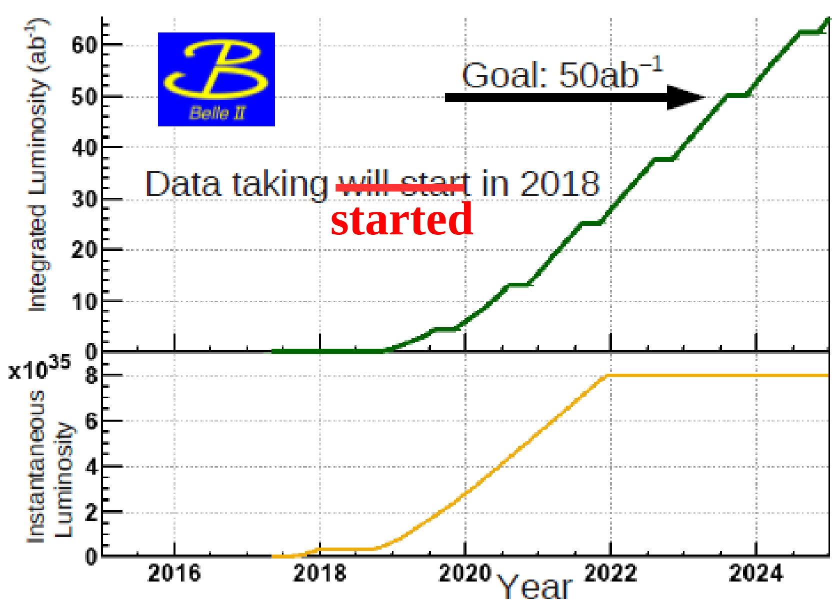
Conclusion

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

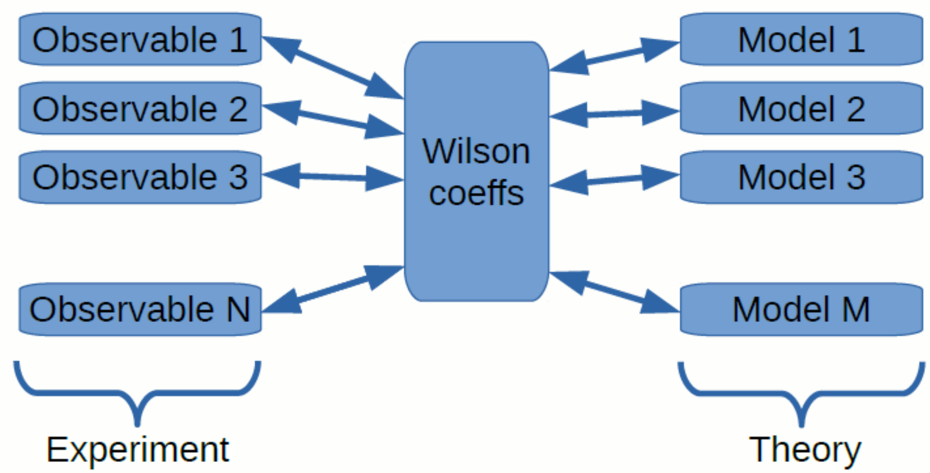
  also in charm, charmonium, bottomonium, light Higgs, τ, DS, kaon sectors…

- Definitely not only complementary, but stimulating competition between (super) B-factories and LHCb (upgrade):
  - for the expected: results on $B_{(s)} \to \mu\mu$, $B \to K^* \mu\mu$, $B_s \to J/\psi \phi$, 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}



Sensitivity to new physics in rare B decays



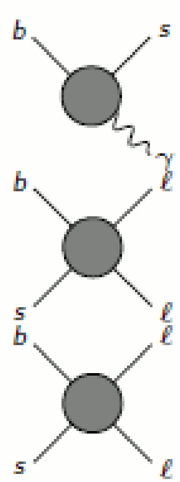
M.Ciuchini et al, arXiv:1512.07157
T.Hurth et al, arXiv:1603.00865
S.Descotes-Genon et al, arXiv:1510.04239...

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

- Model-independent description in effective field theory

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

- Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators



	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

$\mathbf{B \to X_s \gamma}$

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

vs

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

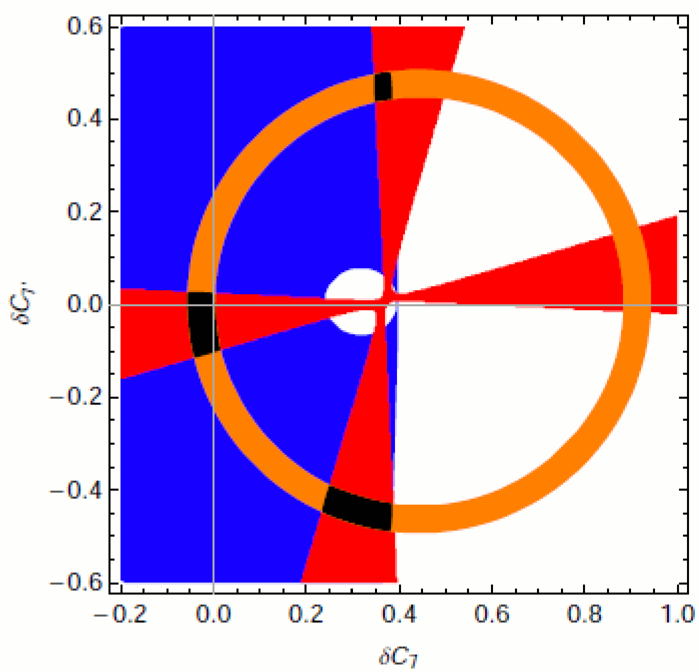
[Misiak et al, arXiv:1503.01789]

[model – dependent]

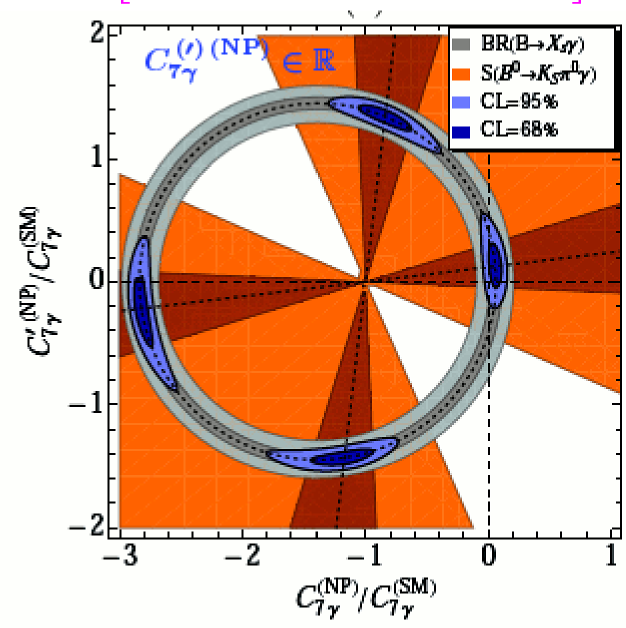
Charged Higss bound (2HDM TypeII): $M_{H^+} > 400$ GeV @ 95% C.L.

Exploring New Physics in the C_7-C_7' plane [model – independent]

S.Descotes-Genon et al
[arXiv:1104.3342]



D.Becirevic et al
[arXiv:1206.1502]

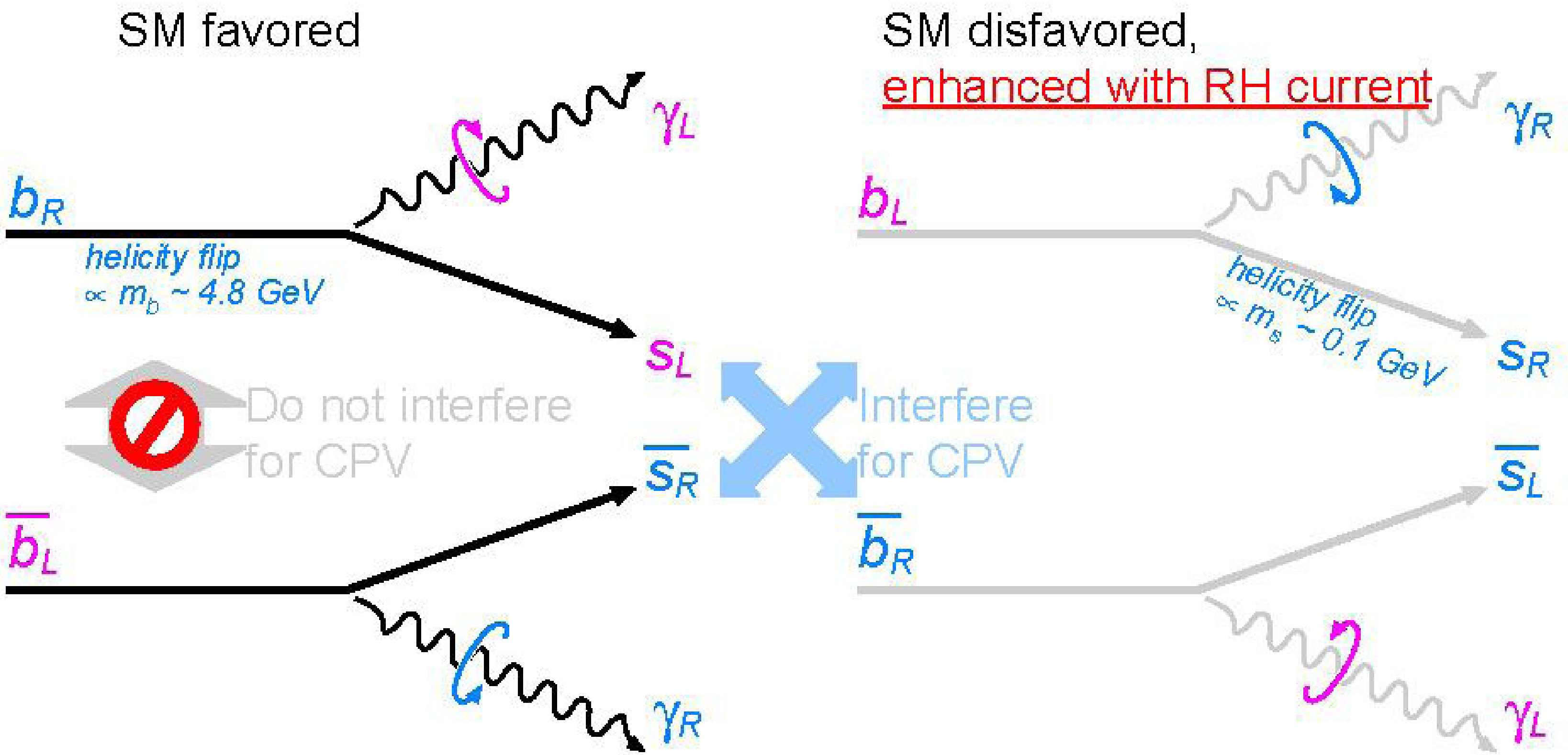


...

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

time−dependent decays rate of $B \to f_{CP}\gamma$
S and A: CP violating parameters

In SM, the photon from $b \to s\gamma$ is (mostly) lefthanded (polarized).
⇒ Mixing induced (time-dependent) CPV does not occur in $B \to f_{CP}\gamma$



$$\text{SM: } S_{CP}^{K^*\gamma} \sim -(2\,m_s/m_b)\sin 2\beta \sim -0.04$$

$$\text{Left-Right Symmetric Models: } S_{CP}^{K^*\gamma} \sim 0.5$$

[D. Atwood et al, PRL 79, 185 (1997)]

Constraints on NP from radiative B decays

At Belle II, expect significant improvement in the determination of $A_{CP}(t)$ in $K_S^0 \pi^0 \gamma$

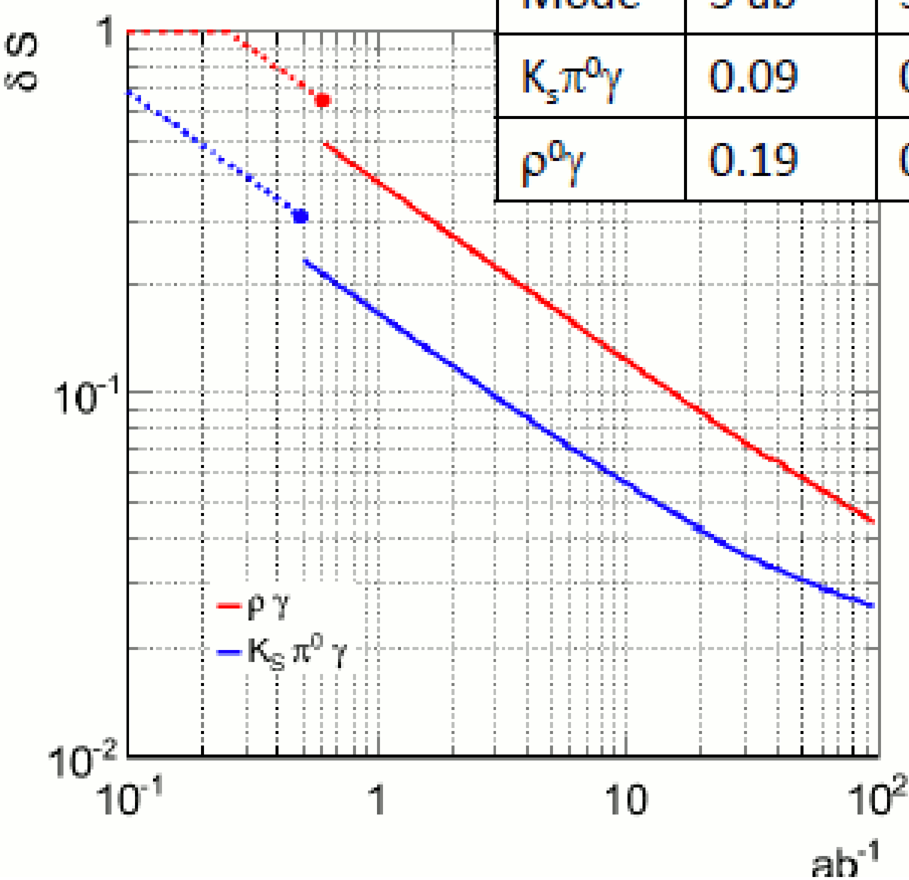
- **Belle II SVD larger than Belle (6 → 11.5 cm)**

$\Rightarrow$ 30% more K_S with vertex hits available, effective tagging eff. 13% better

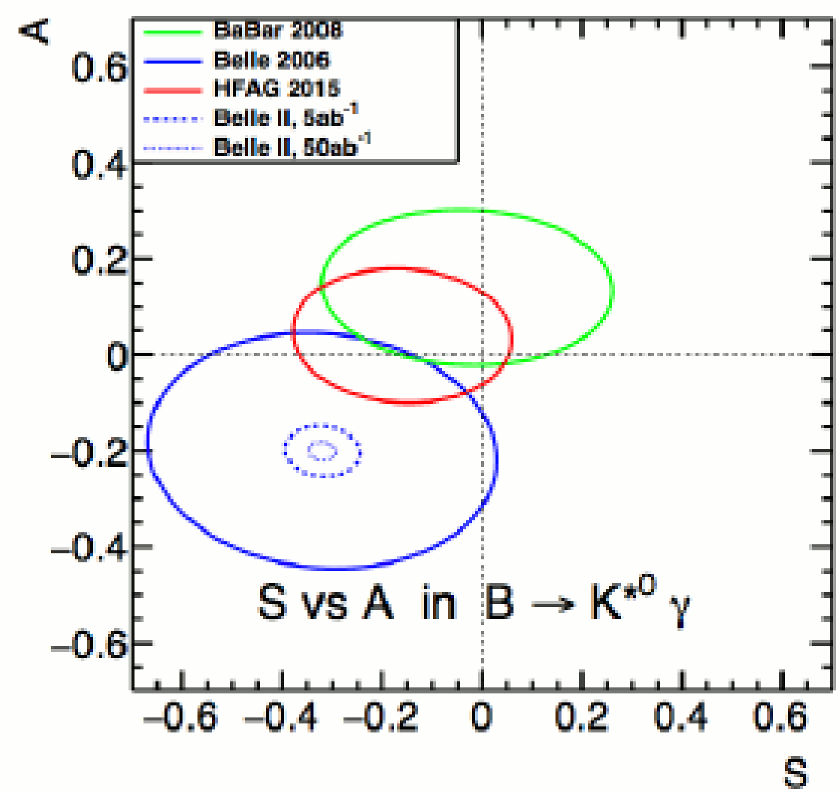
HFLAV

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

- Expected errors for ***S*** measurements of $K_s\pi^0\gamma$ and $\rho^0\gamma$.

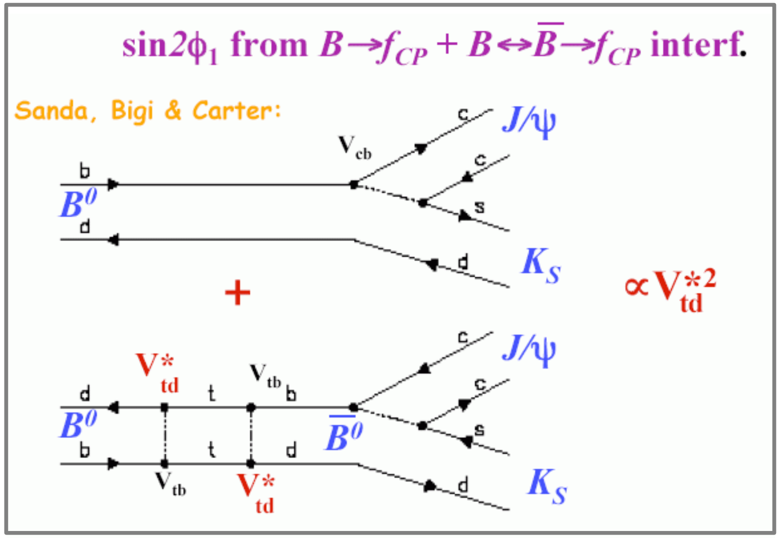


Mode	5 ab^{-1}	50 ab^{-1}
$K_s\pi^0\gamma$	0.09	0.030
$\rho^0\gamma$	0.19	0.064

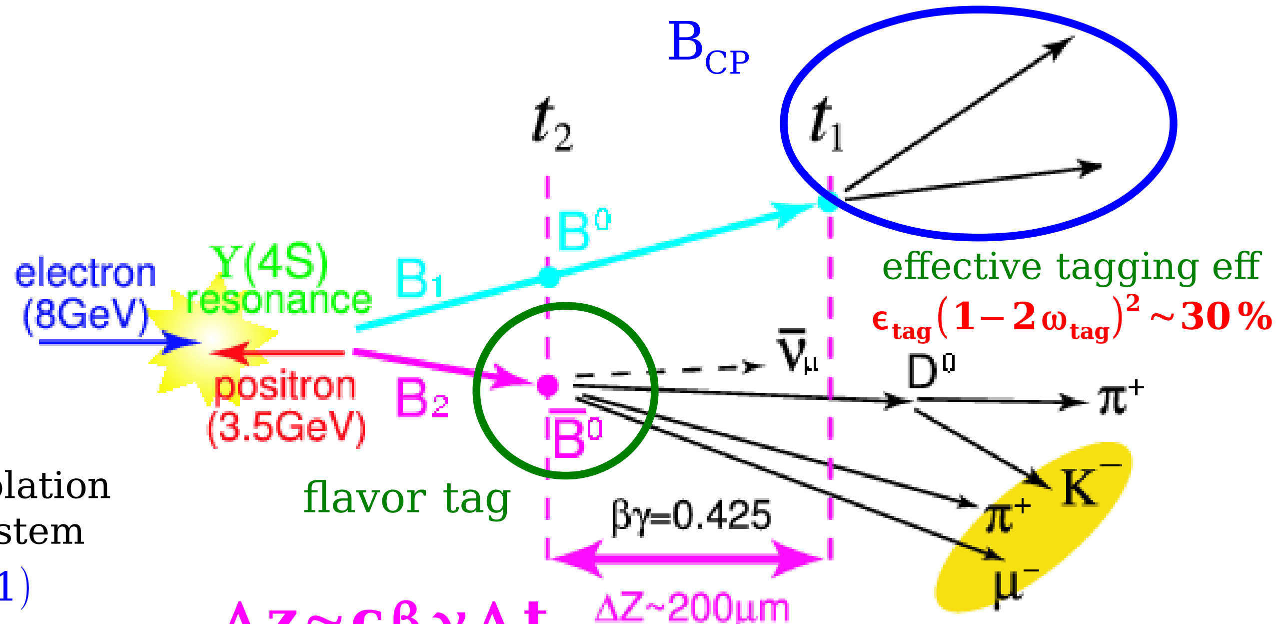


16σ deviation with 50 ab^{-1}.

Time−dependent CP asymmetries in decays to CP eigenstates

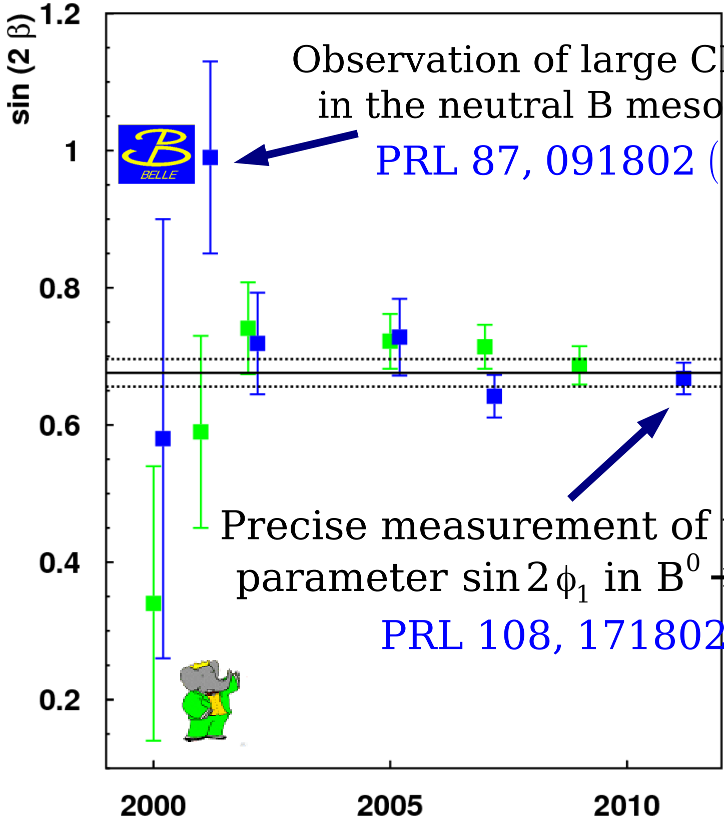


$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}(1 + q(S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)))$$



$\Delta z \sim c\beta\gamma\Delta t$

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



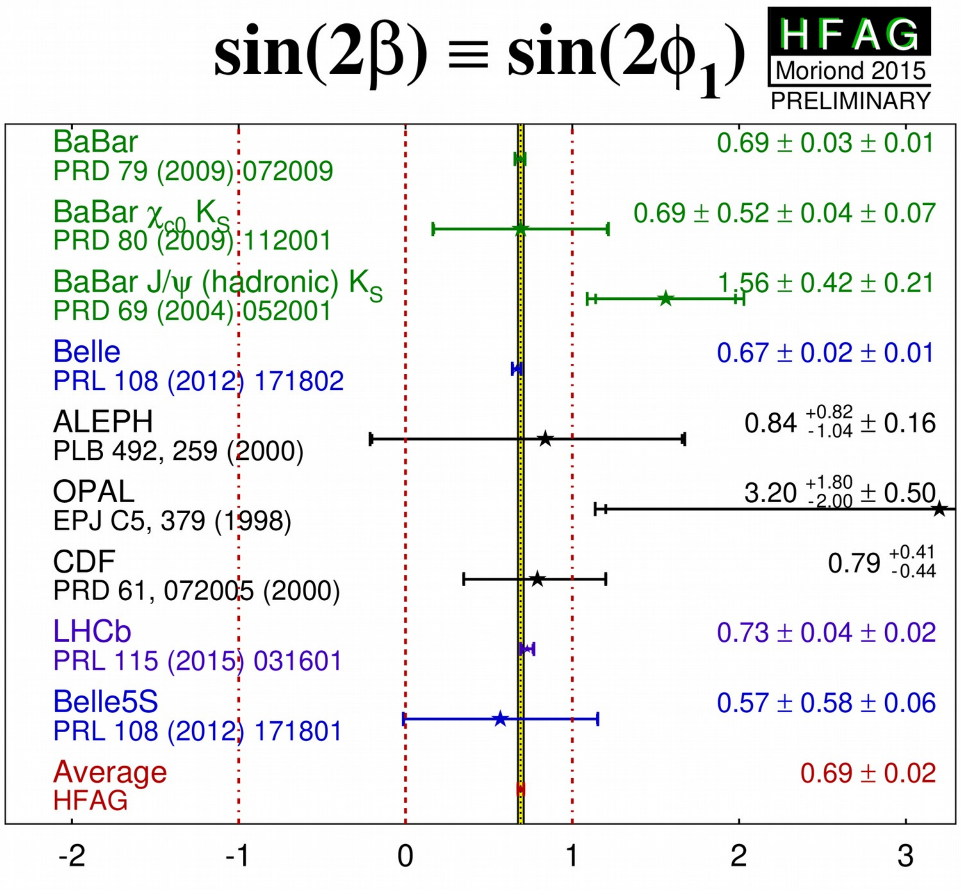
Observation of large CP violation in the neutral B meson system
PRL 87, 091802 (2001)

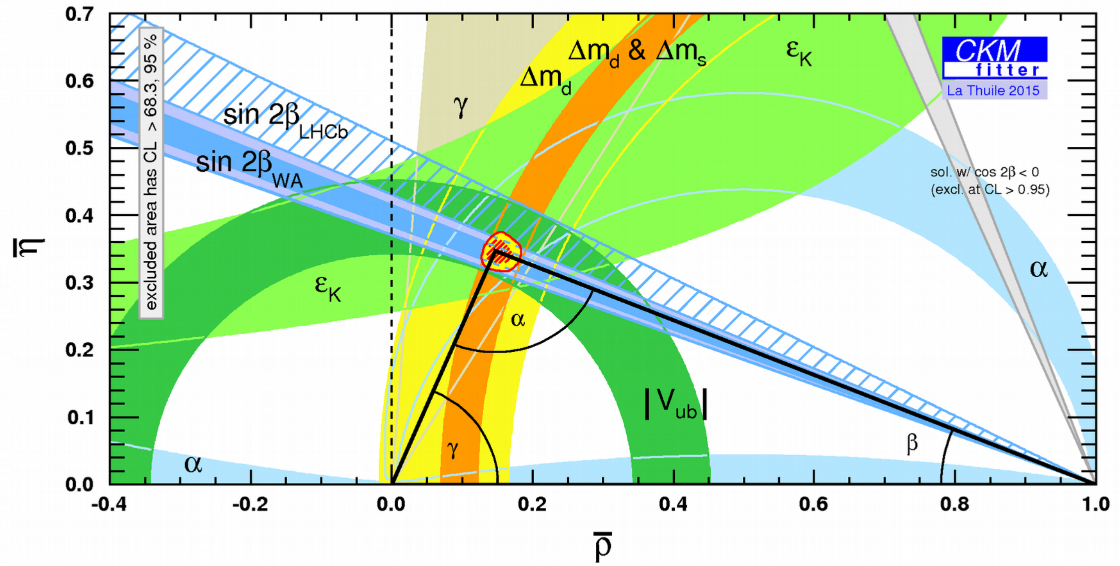
Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays
PRL 108, 171802 (2012)

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: $\beta = (21.9 \pm 0.7)^\circ$

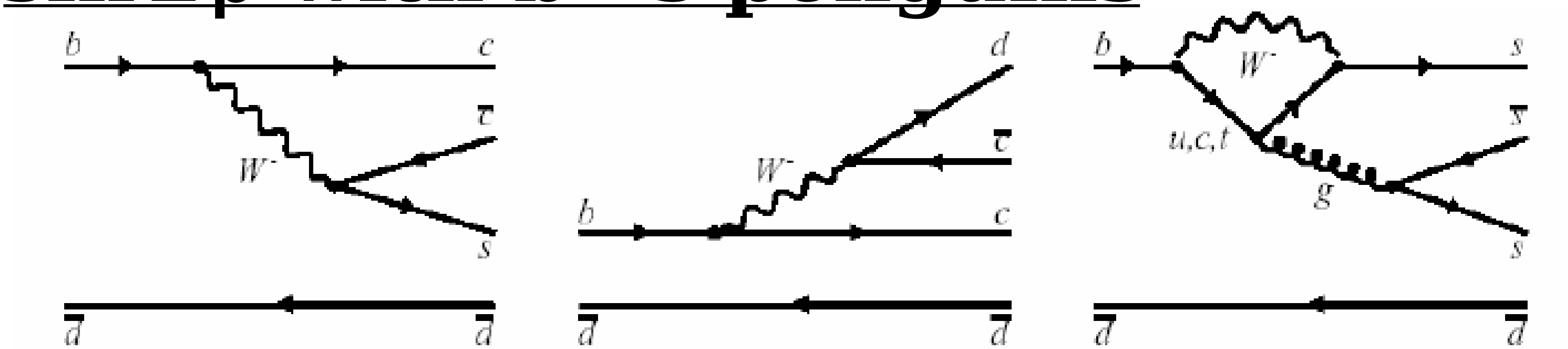
$\sin 2\beta$ at Belle II

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

anchor of SM

will be dominated by systematic uncertainties

sin 2β with b→s penguins



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

increasing tree diagram amplitude ←

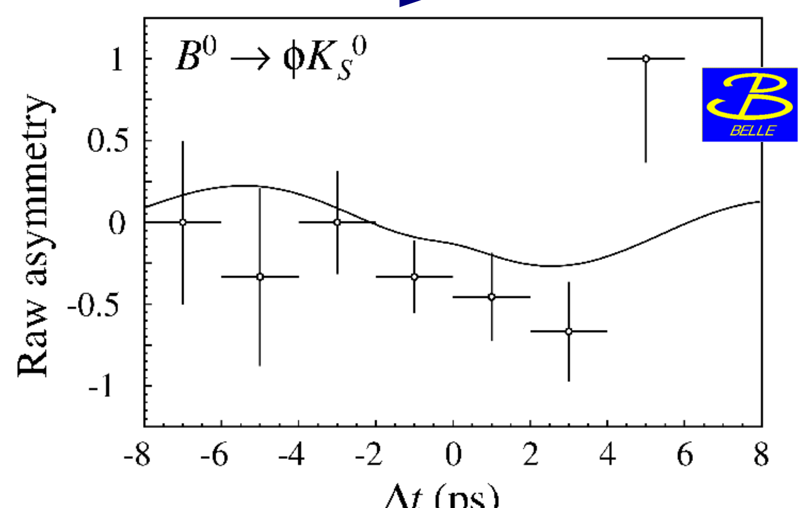
increasing sensitivity to new physics →

EX−ANOMALY !

first reported in Moriond EW 2002

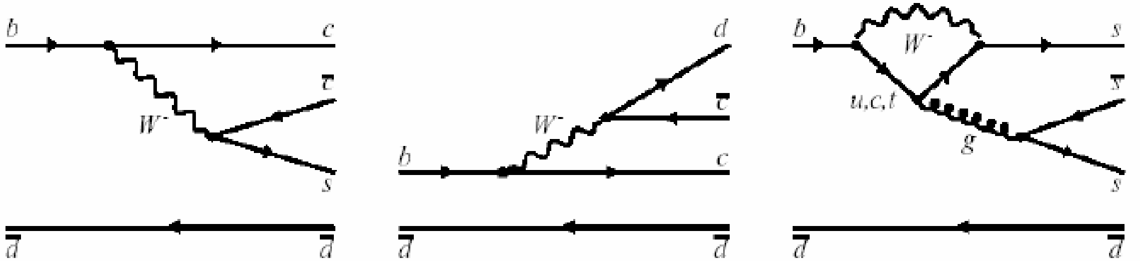
"$\sin 2\beta$" $= -0.73 \pm 0.64 \pm 0.22$

[PRD 67, 031102 (2003)]



sin 2β with b→s penguins

dominated by B-factories



$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$

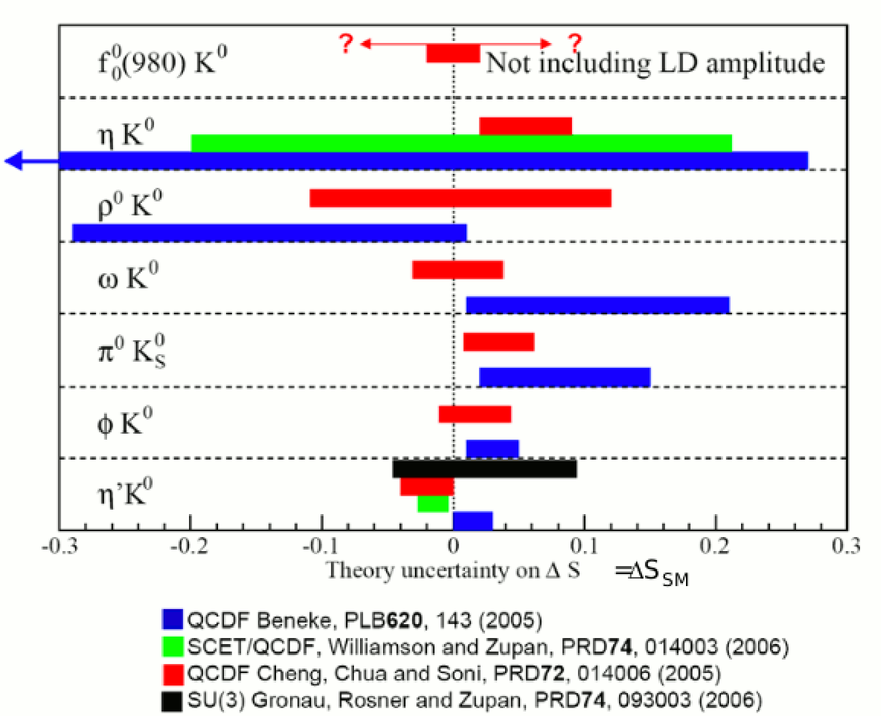
$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$

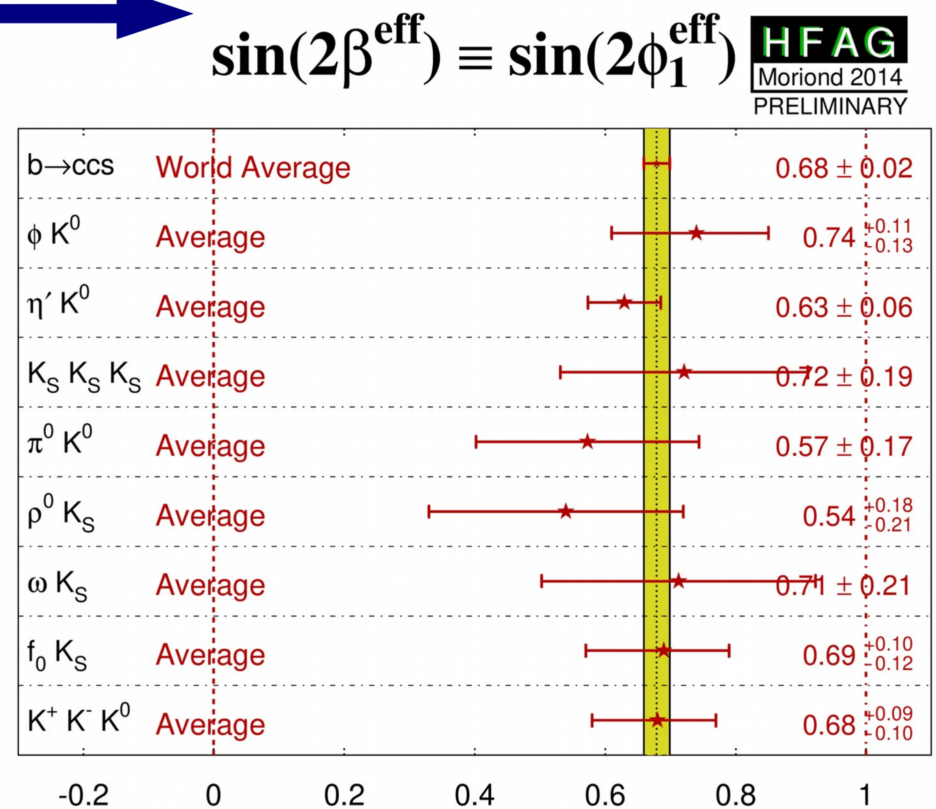
$\phi K^0, K^+K^-K_S^0,$ $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$

increasing tree diagram amplitude

increasing sensitivity to new physics

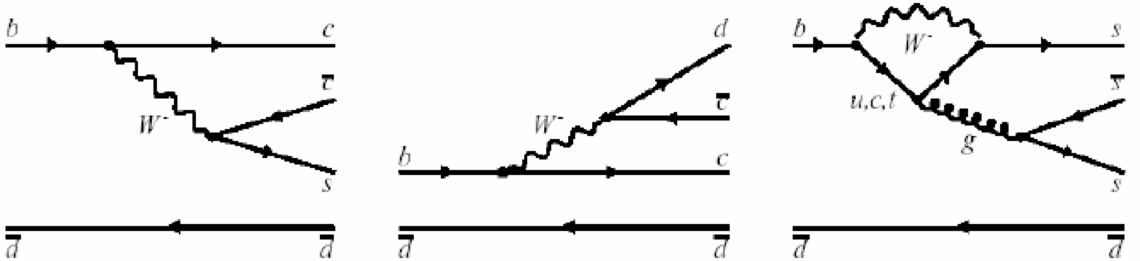
More statistics crucial for mode-by-mode studies





sin 2β with b→s penguins

dominated by B-factories

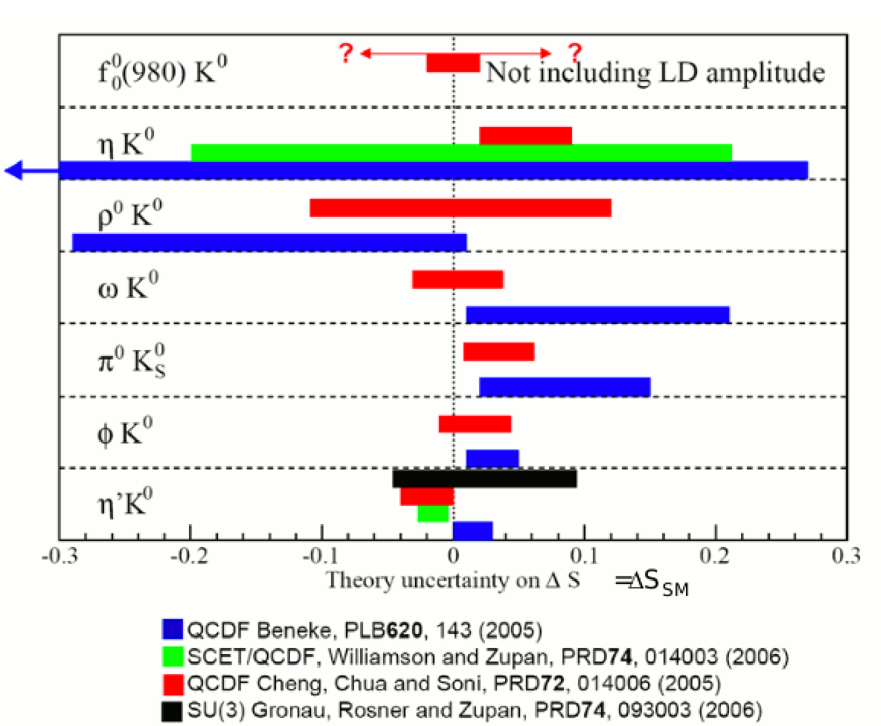


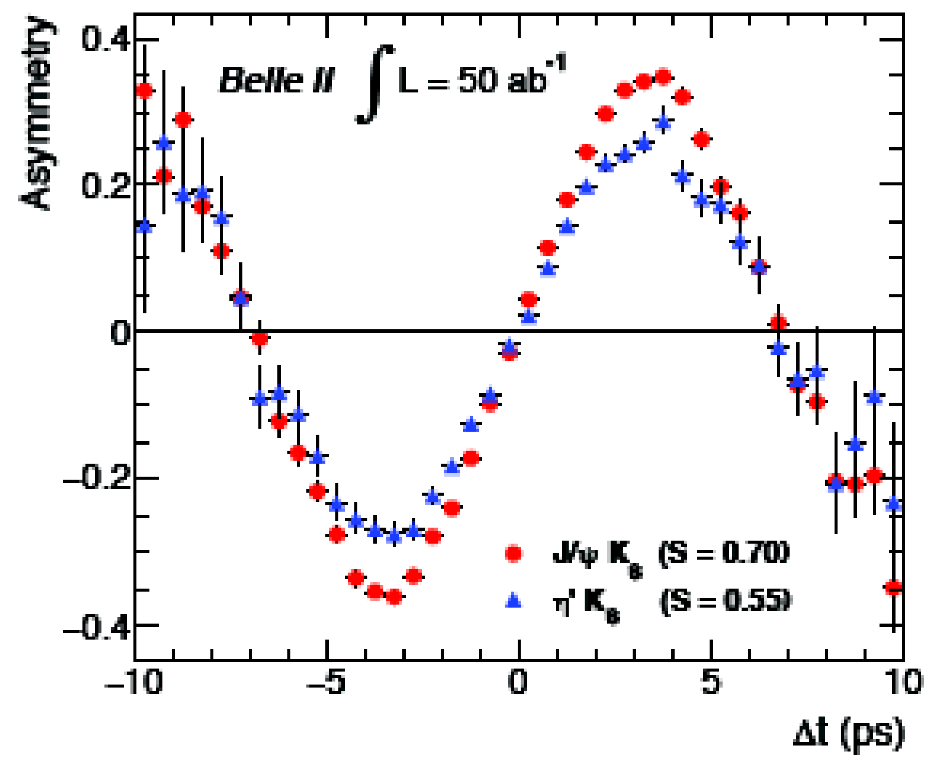
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0$, $\eta_c K_S^0, J/\psi K_L^0$, $J/\psi K^{*0}(K^{*0} \to K_S^0 \pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi \pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0$, $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0$, $\omega K_S^0, f_0(980)K_S^0$

← increasing tree diagram amplitude

increasing sensitivity to new physics →

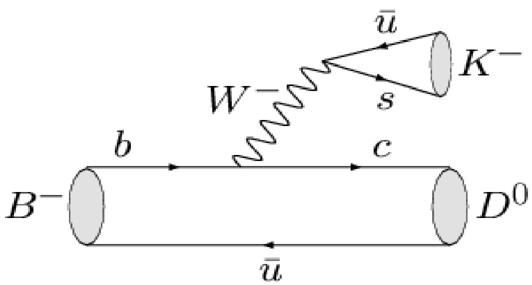
Channel	$\int \mathcal{L}$	Event yield	$\sigma(S)$	$\sigma(A)$
ϕK^0	5 ab^{-1}	5590	0.048	0.035
$\eta' K^0$	5 ab^{-1}	27200	0.027	0.020
ωK_S^0	5 ab^{-1}	1670	0.08	0.06
$K_S \pi^0 \gamma$	5 ab^{-1}	1400	0.10	0.12
$K_S \pi^0$	5 ab^{-1}	5699	0.09	0.10





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

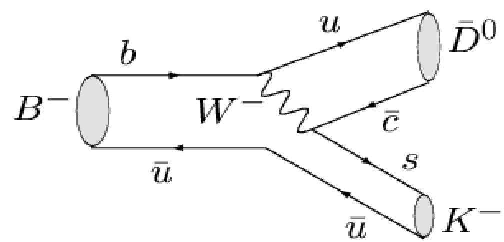
- Theoretically pristine $B \to DK$ approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



color allowed

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

$\sim A\lambda^3$



color suppressed

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

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

relative weak phase is γ

relative strong phase is δ_B

$r_B \simeq 0.1$

$B^{\pm} \to D K^{\pm}$

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

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

$B^{\pm} \to D K^{*\pm}$

$B^0 \to D K^{*0}$

$B^{\pm} \to D K\pi\pi$

$B \to \ldots$

$D \to K^+ K^-$, $\pi^+ \pi^- \ldots$

$D \to K_S \pi^0$, $K_S \eta \ldots$

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

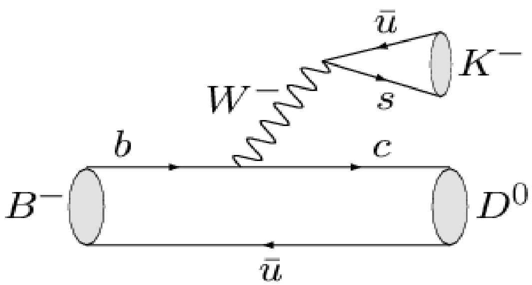
$D \to K_S \pi\pi$, $K_S K K$

$D \to K_S \pi\pi\pi^0$

$D \to \ldots$

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

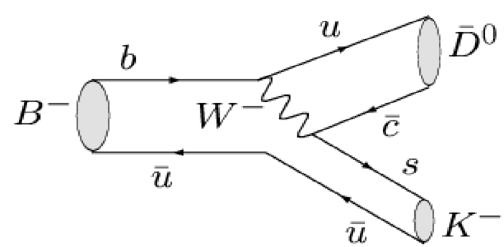
- Theoretically pristine B→DK approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$



color allowed

$B^- \to D^0 K^- \sim V_{cb} V^*_{us}$

$\sim A\lambda^3$



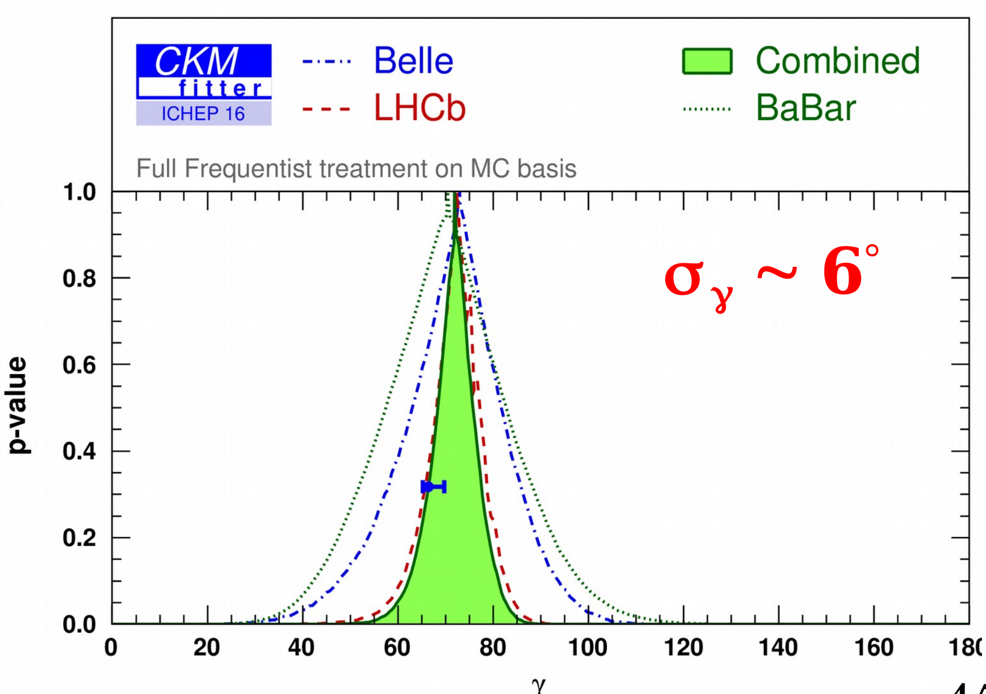
color suppressed

$B^- \to \bar{D}^0 K^- \sim V_{ub} V^*_{cs}$

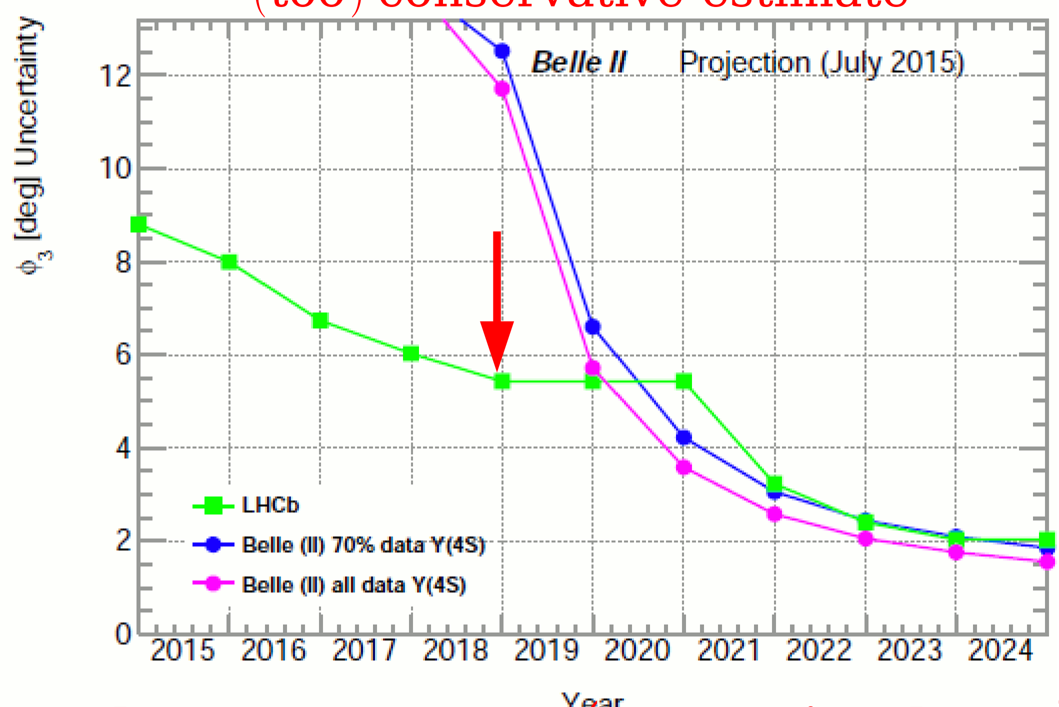
$\sim A\lambda^3(\rho + i\eta)$

relative weak phase is γ
relative strong phase is δ_B

$r_B \simeq 0.1$

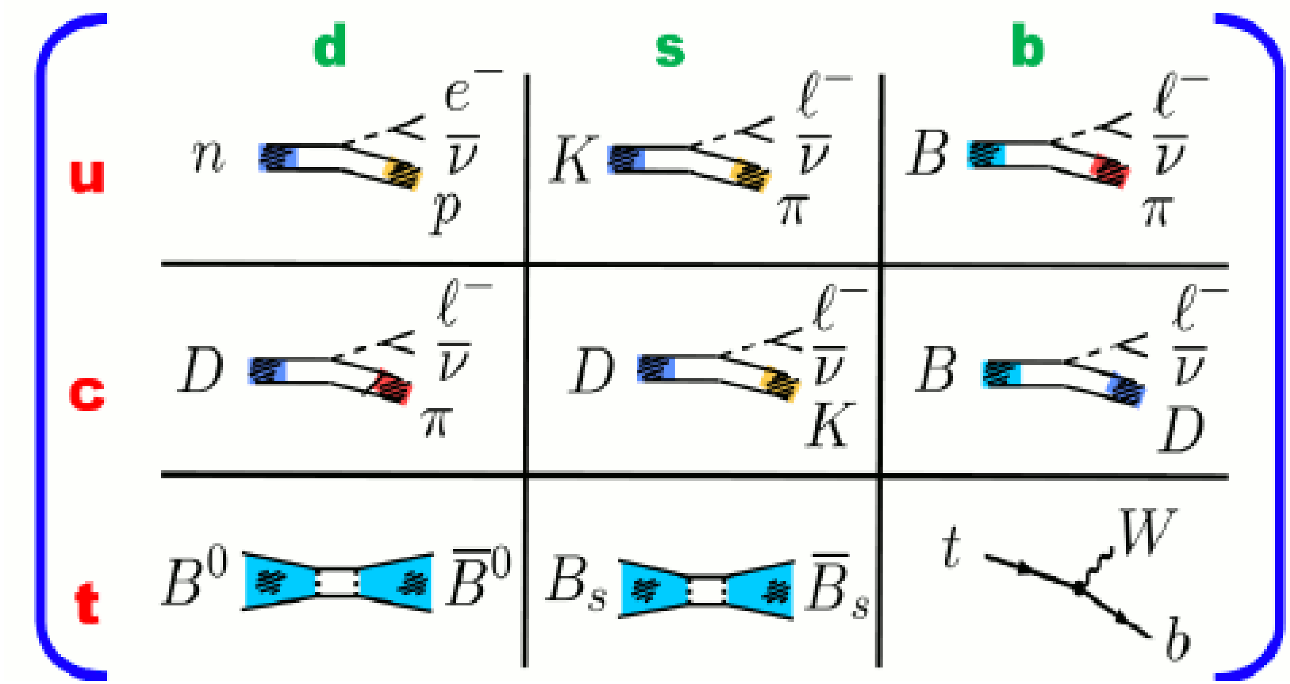


(too) conservative estimate



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

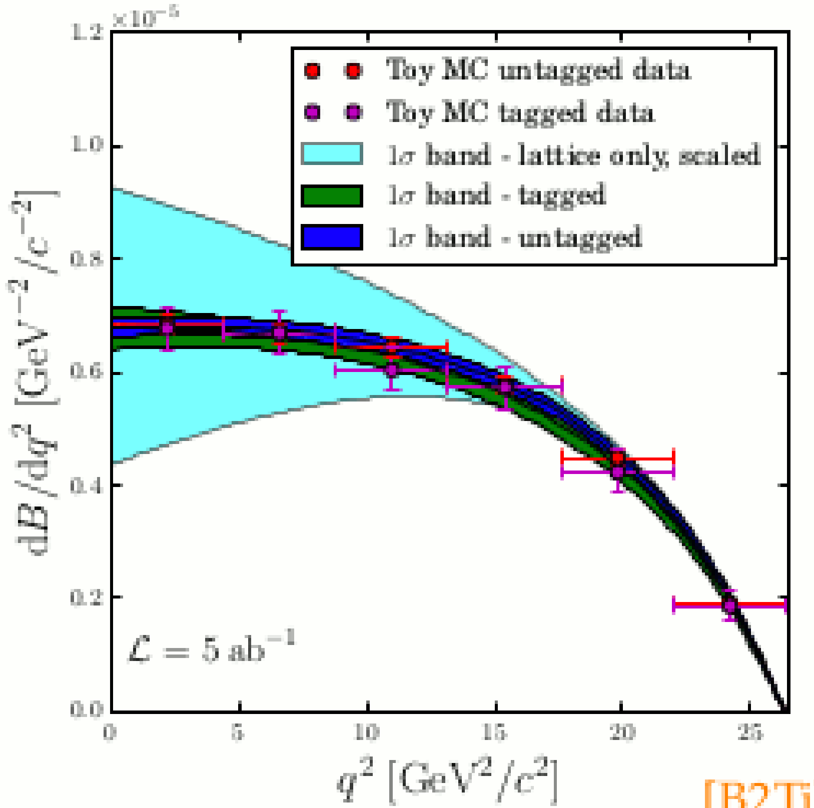
Semileptonic and leptonic

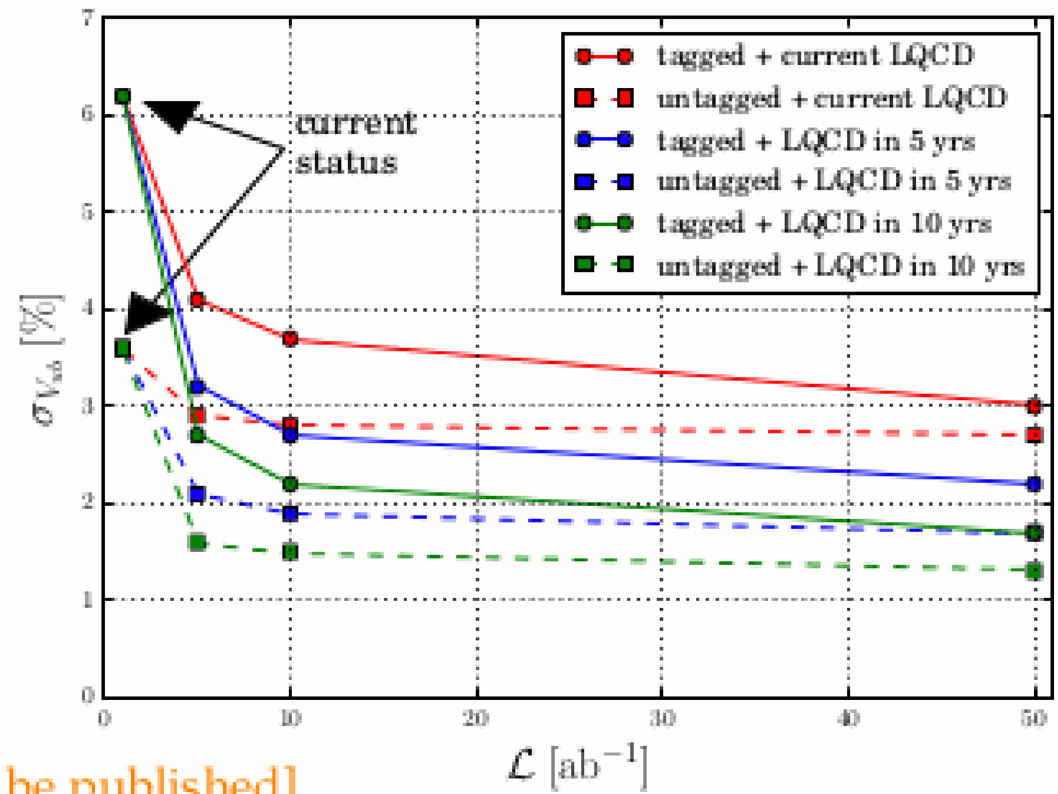


Process	Obser.	Theory	Discovery (ab^{-1})	Sys. limit (ab^{-1})	vs LHCb BESIII	vs Belle	Anomaly	NP
$B \to \pi l \nu_l$	$\lvert V_{ub} \rvert$	★★★	-	10	★★★	★★★	★★	★
$B \to X_u l \nu_l$	$\lvert V_{ub} \rvert$	★★	-	2	★★★	★★	★★★	★
$B \to \tau \nu$	$Br.$	★★★	2	50	★★★	★★★	★	★★★
$B \to \mu \nu$	$Br.$	★★★	5	50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

$|V_{ub}|$ from $B \to \pi l \nu$ at Belle II

Toy MC studies based on Belle II MC, LQCD forecasts estimated at 5 years (5, 10 ab^{-1}) and 10 years (50 ab^{-1})





[B2TiP, to be published]

$|V_{ub}|^{\pi \ell \nu}$ from simultaneous fit for $\mathcal{L} = 5\ \mathrm{ab}^{-1}$, including lattice forecasts and error scaling.

$\delta_{|V_{ub}|^{\pi \ell \nu}}$ estimates for 5, 10 and 50 ab^{-1}:
Tagged: 3.2, 2.7 and 1.7 %
Untagged: 2.1, 1.9 and 1.3 %

LQCD forecasts: [A. Kronfeld, T. Kaneko, S. Simula]

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}

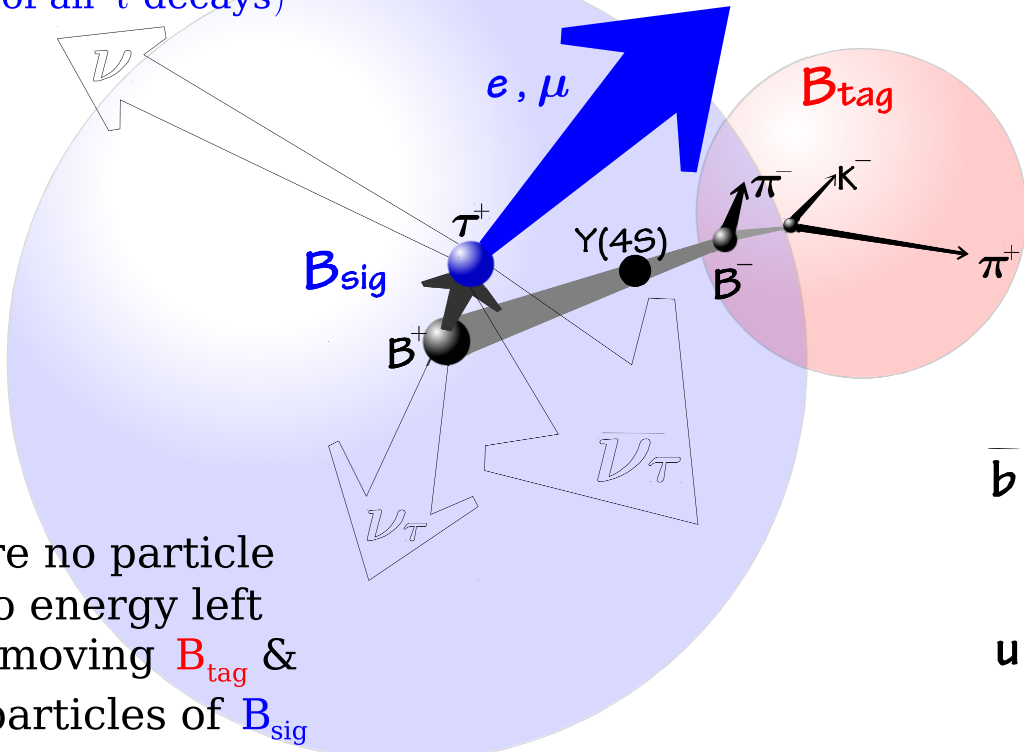
hadronic tag

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

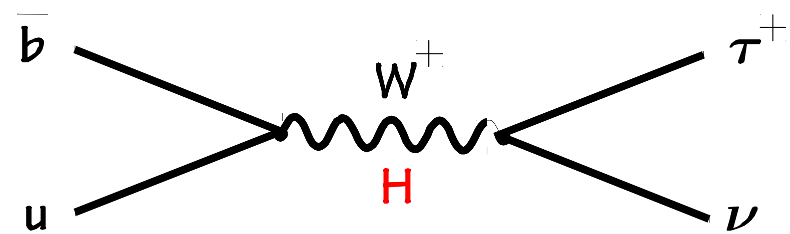
$\epsilon \sim 0.2\%$

semileptonic tag

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



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

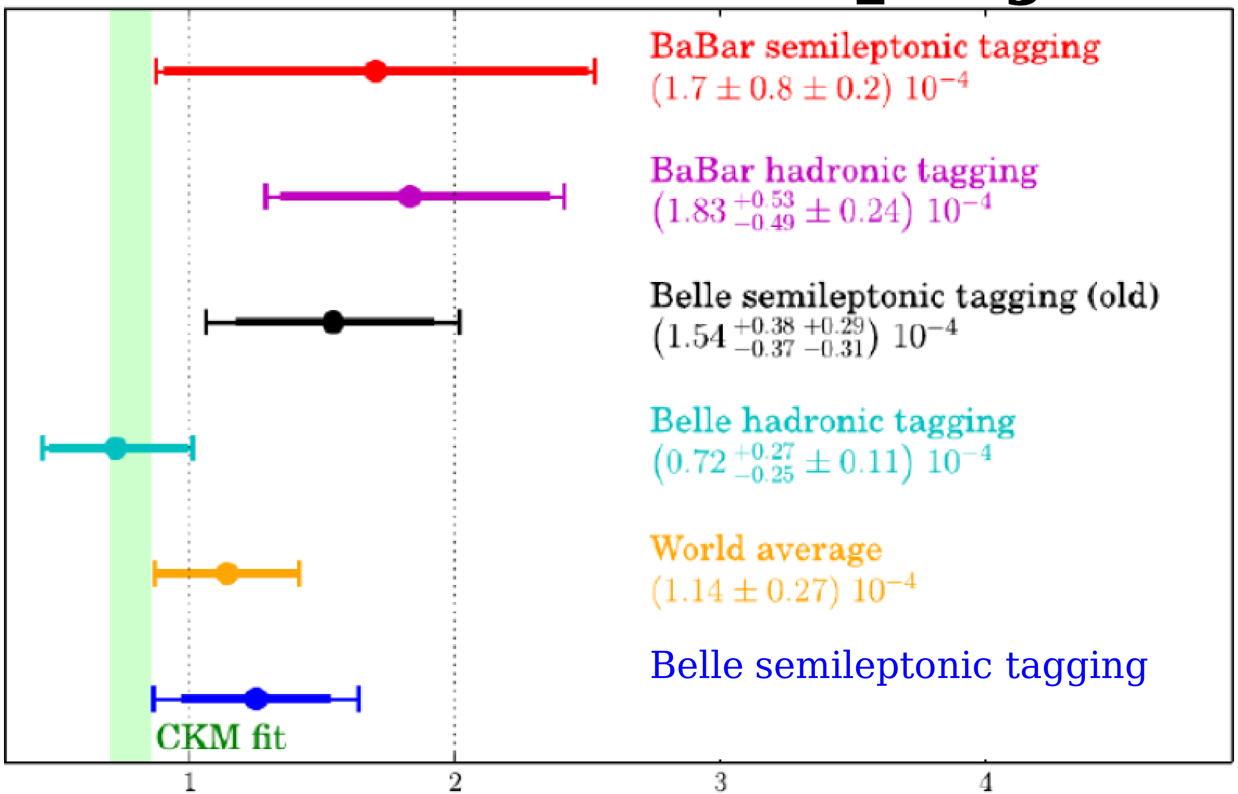


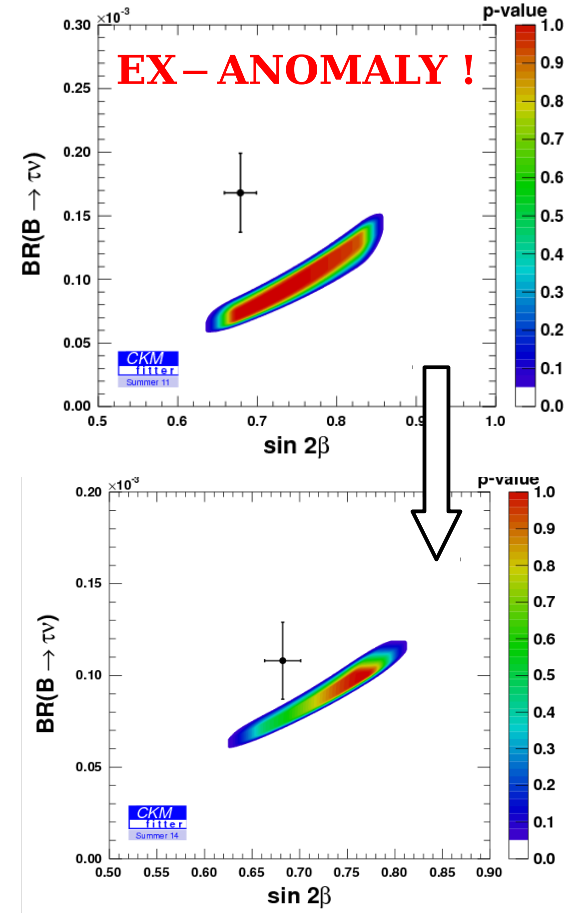
$$\text{2HDM (type II)}: \quad \mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

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

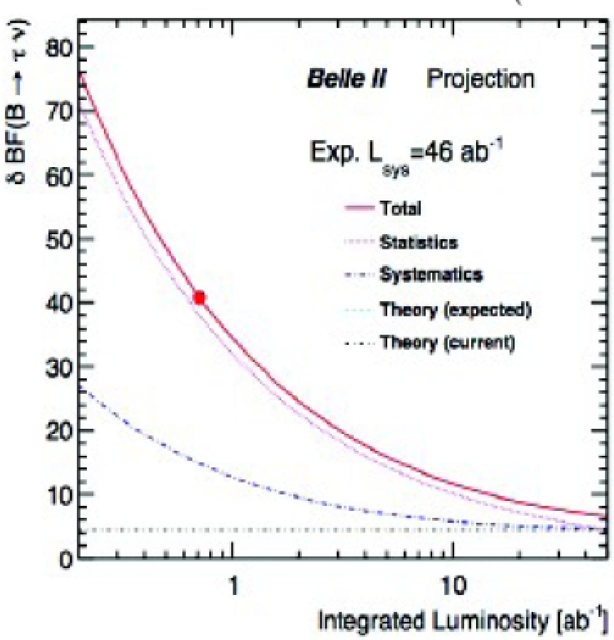
uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B and other CKM uncertainties by combining with precise Δm_d

$B \to \tau \nu$ status and projections





not a single observation !!

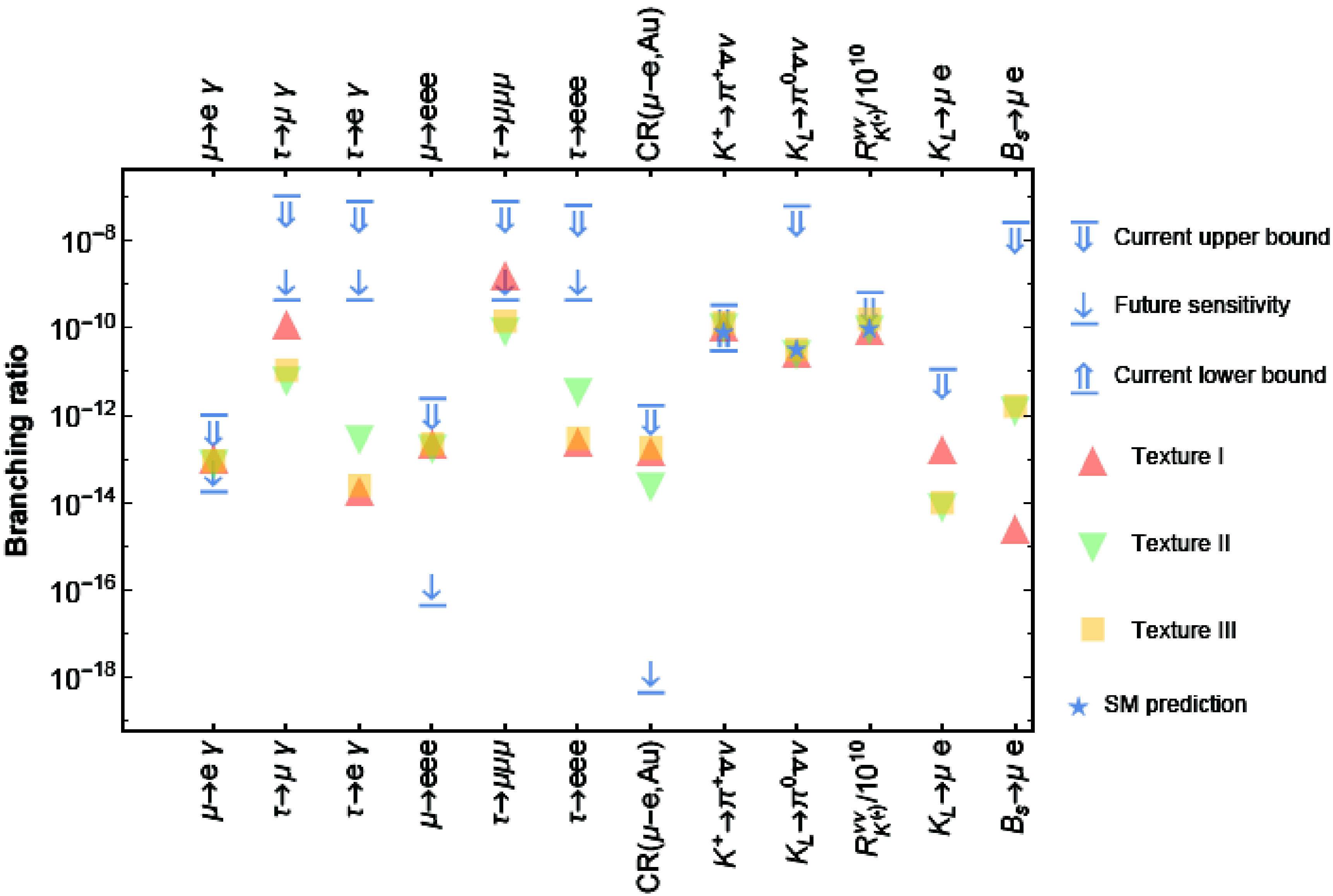


Belle II	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	19.0	(7.1, 2.2)	20.4	2.5	20.5
5 ab^{-1}	7.2	(2.7, 2.2)	7.9	1.5	8.1
50 ab^{-1}	2.3	(0.8, 2.2)	3.2	1.0	3.4
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
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 $B \to \mu\nu$ 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 $\tau \to 3\mu$, and $\Upsilon(3S) \to \mu\tau$

cLFV : beyond the Standard Model

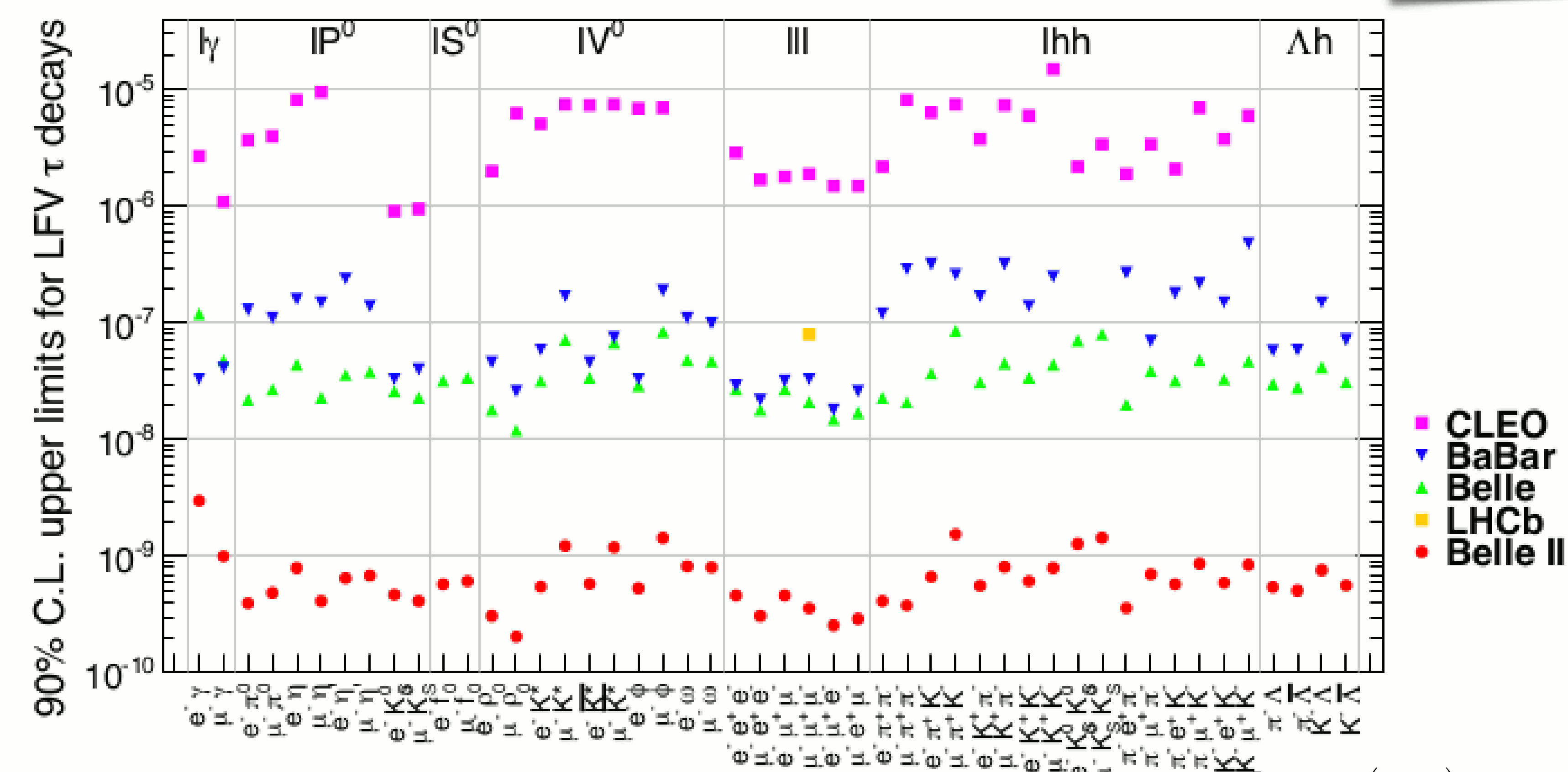
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$

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

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

	Operator	$\tau\to 3\mu$	$\tau\to\mu\gamma$	$\tau\to\mu\pi^+\pi^-$	$\tau\to\mu K\bar{K}$	$\tau\to\mu\pi$	$\tau\to\mu\eta^{(\prime)}$
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	$O_{G\tilde{G}}$	–	–	–	–	–	✓

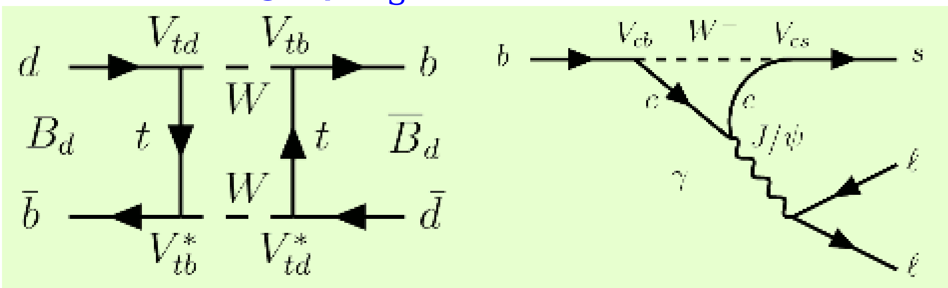
Celis, Cirigliano, Passemar (2014)



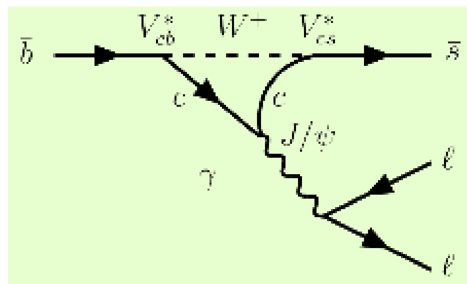
…also Υ(nS) LFV decays

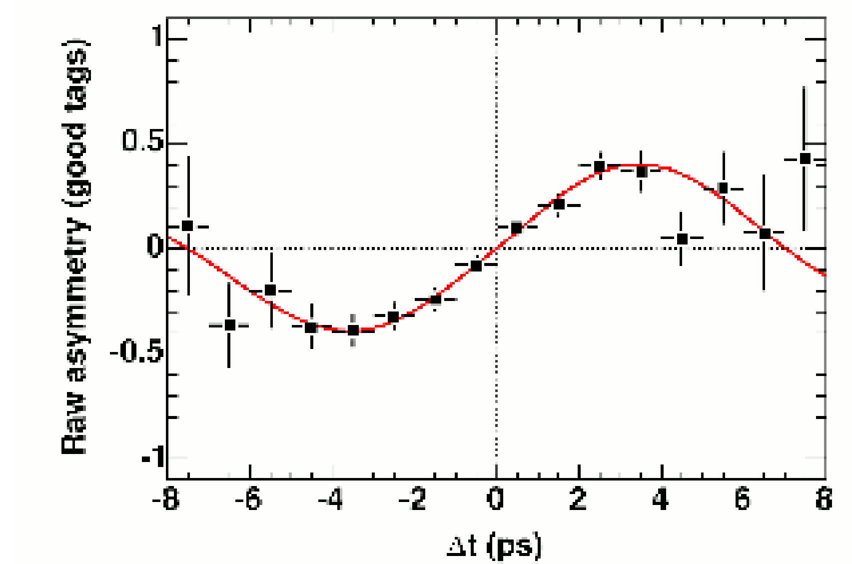
Mixing-induced CP violation

Remember $B^0 \to J/\psi K^0_S$:

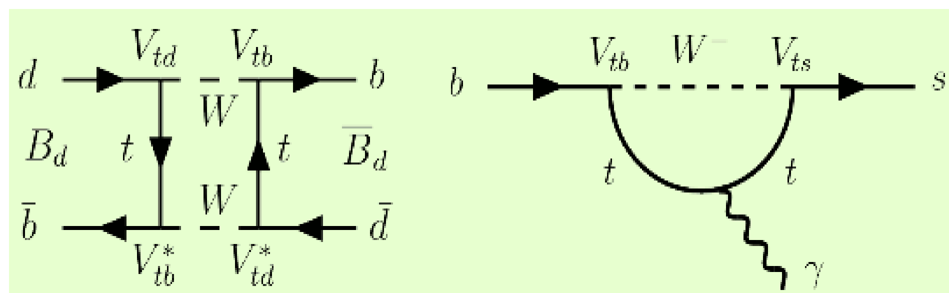


interferes with

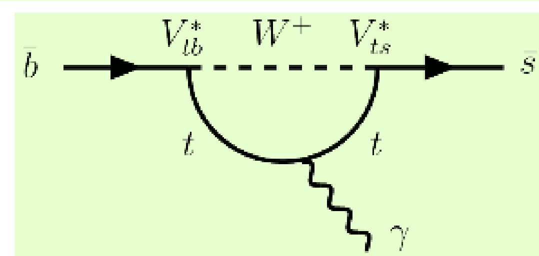




What about $B^0 \to \gamma K^0_S \pi^0$?



interferes with right-handed component of

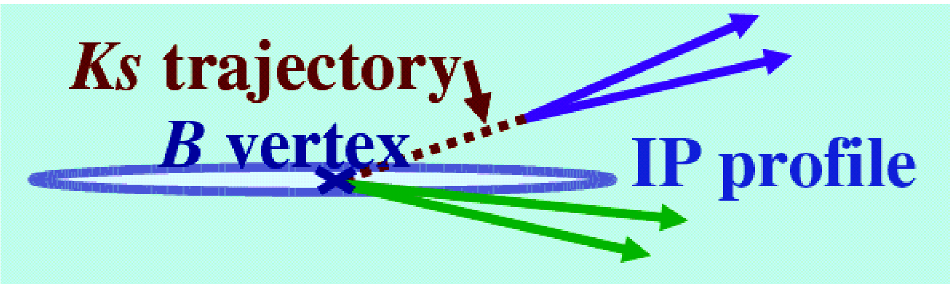


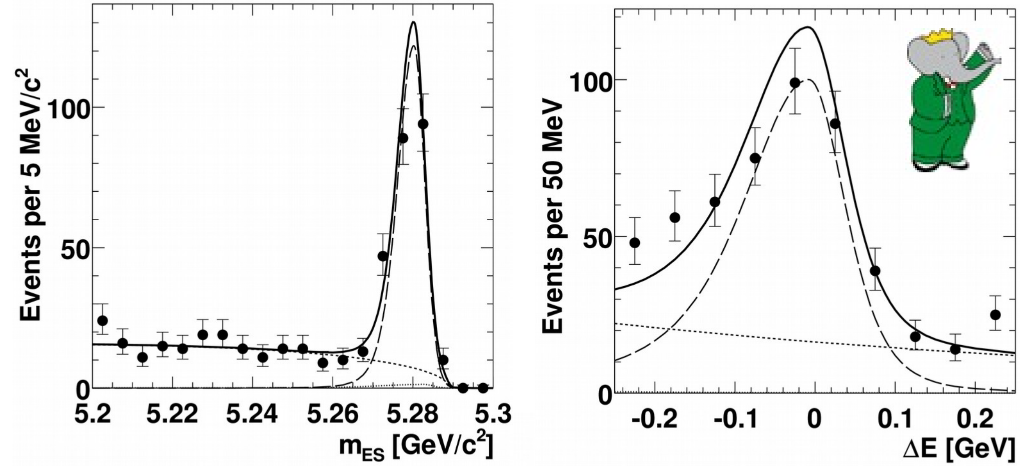
In SM mainly $B^0 \to K^0_S \pi^0 \gamma_R$ and $\overline{B}^0 \to K^0_S \pi^0 \gamma_L$: $K^0_S \pi^0 \gamma$ behaves like an effective flavor eigenstate,

⇒ mixing-induced CP violation is expected to be small $S \sim -2(m_s/m_b)\sin(2\phi_1)$

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

time-dependent CPV





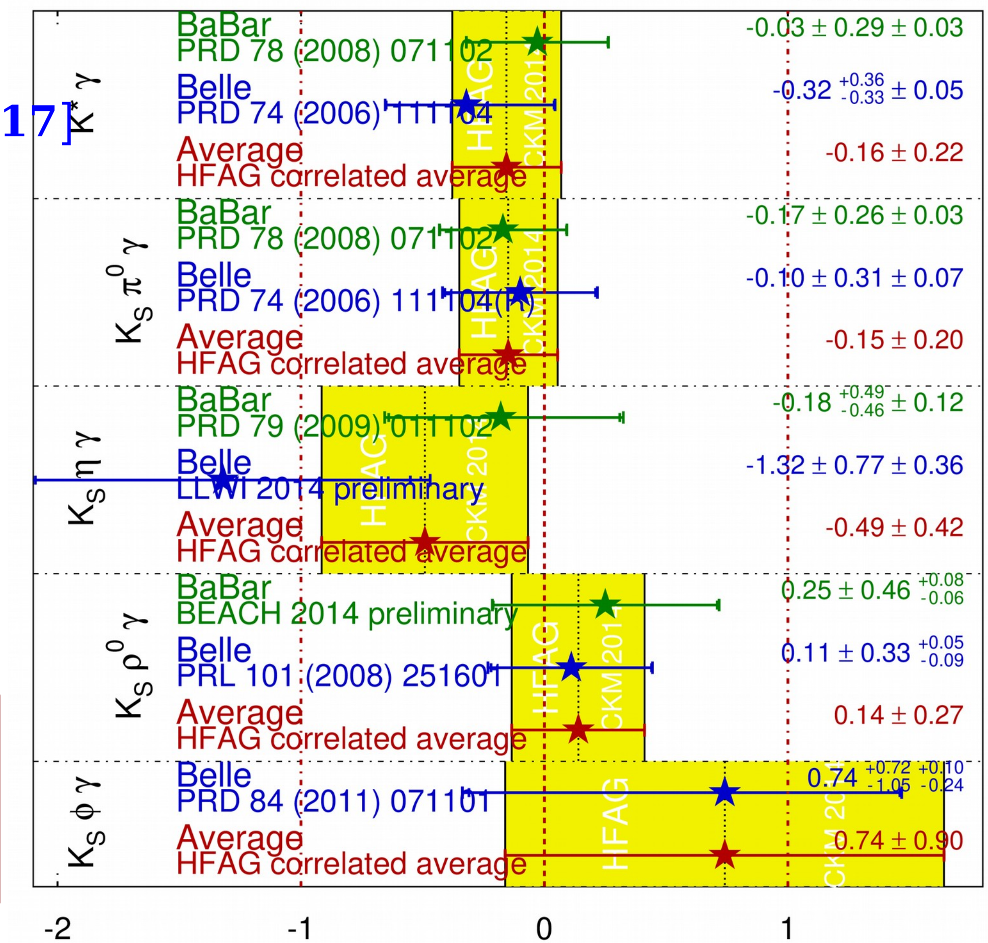
control sample is $J/\psi K^0_S$!!

[467 MBB]
[arXiv:0807.3103]

[535 MBB]
[hep-ex/0608017]

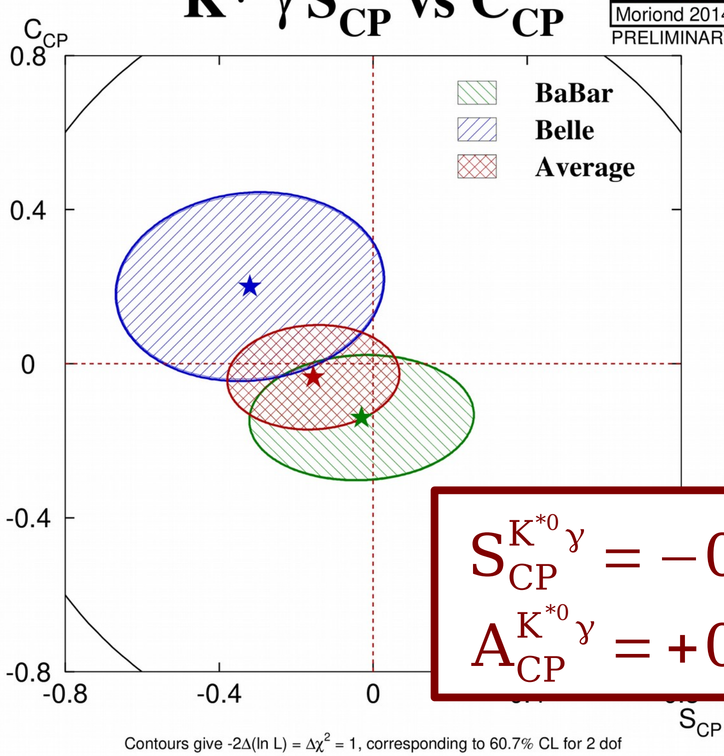
$b \to s\gamma$ S_{CP}

HFAG CKM 2014 PRELIMINARY



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

HFAG Moriond 2014 PRELIMINARY

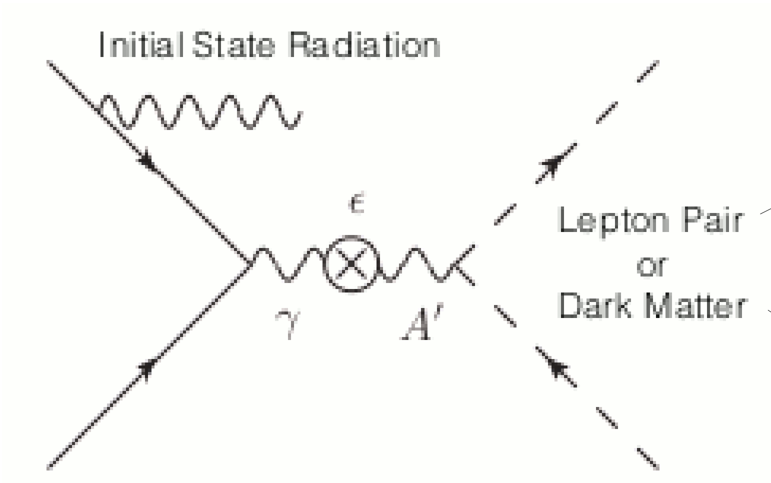


$$S_{CP}^{K^{*0}\gamma} = -0.16 \pm 0.22$$
$$A_{CP}^{K^{*0}\gamma} = +0.04 \pm 0.14$$

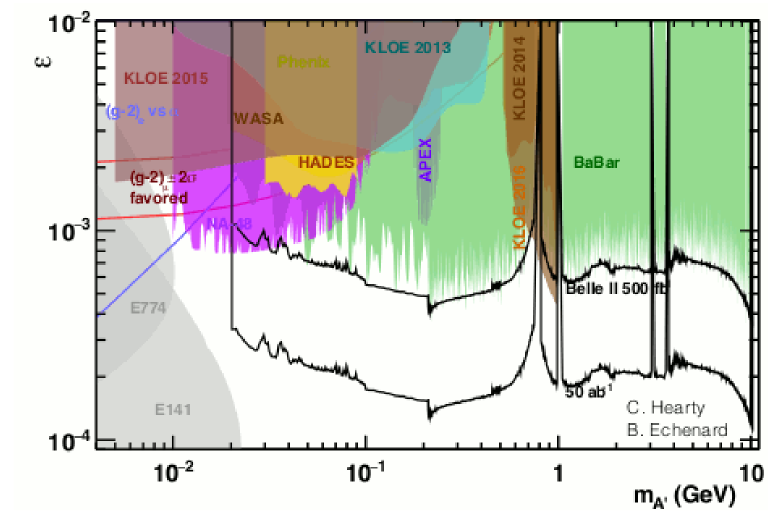
HFAG

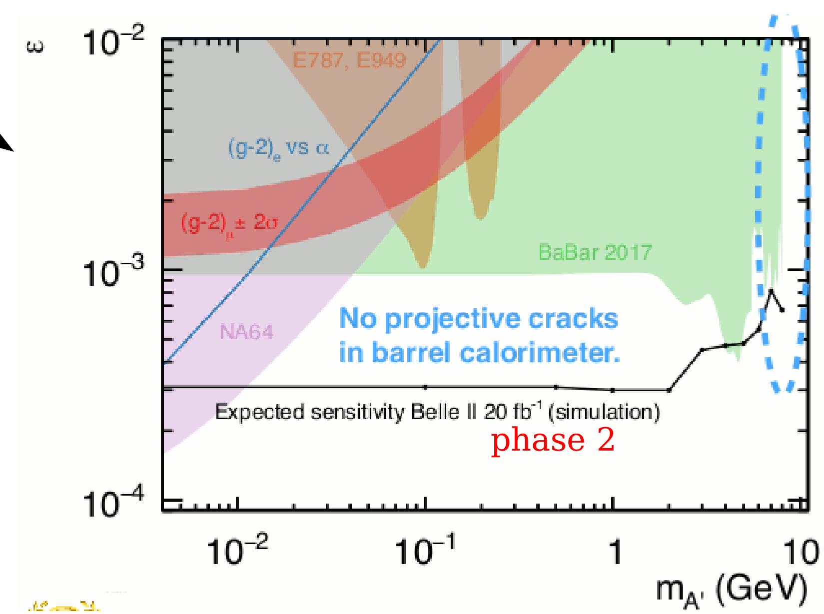
Dark Sector Physics

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



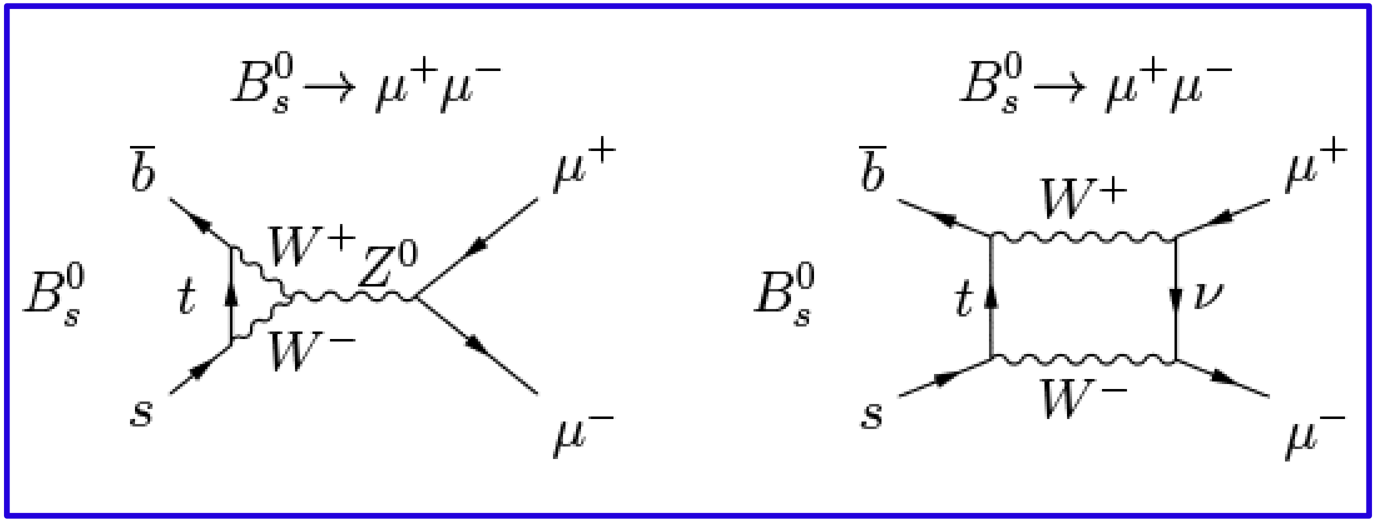


search for a dark photon decaying invisibly, and the search for an axion-like particle may be possible even in "Phase 2"

$B_{(s)} \to \mu\mu$: ultra rare processes…

loop diagram + suppressed in SM + theoretically clean =

an excellent place to look for new physics

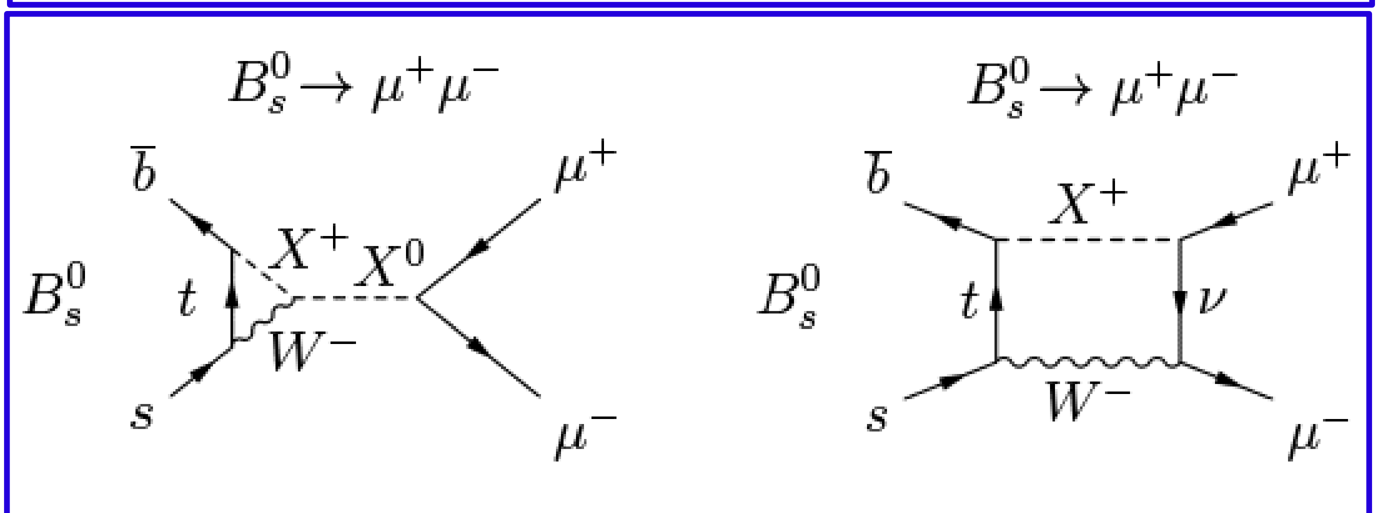


higher-order FCNC allowed in SM

$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

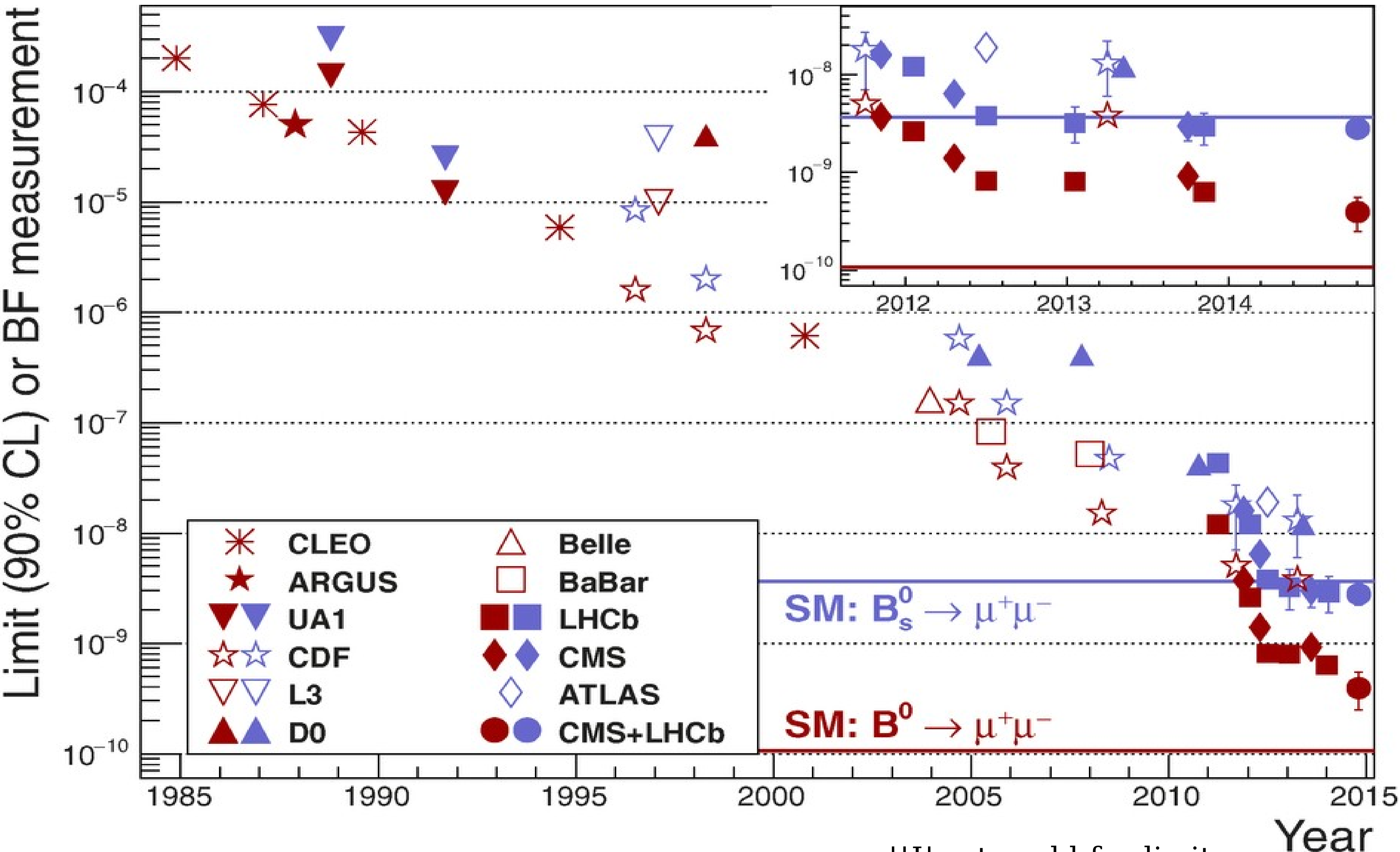
$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[Bobeth et al, PRL 112 (2014) 101801]



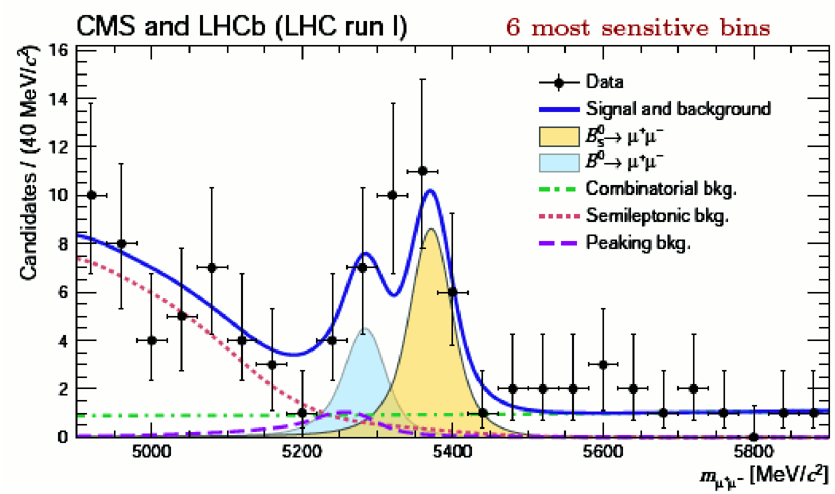
same decay in theories extending the SM (some of NP scenarios may boost the $B \to \mu\mu$ decay rates)

$B_{(s)} \to \mu\mu$: ultra rare processes…



''I'm too old for limits,
I want to see signals''
(Francis Halzen)

$B_s \to \mu^+\mu^-$ results



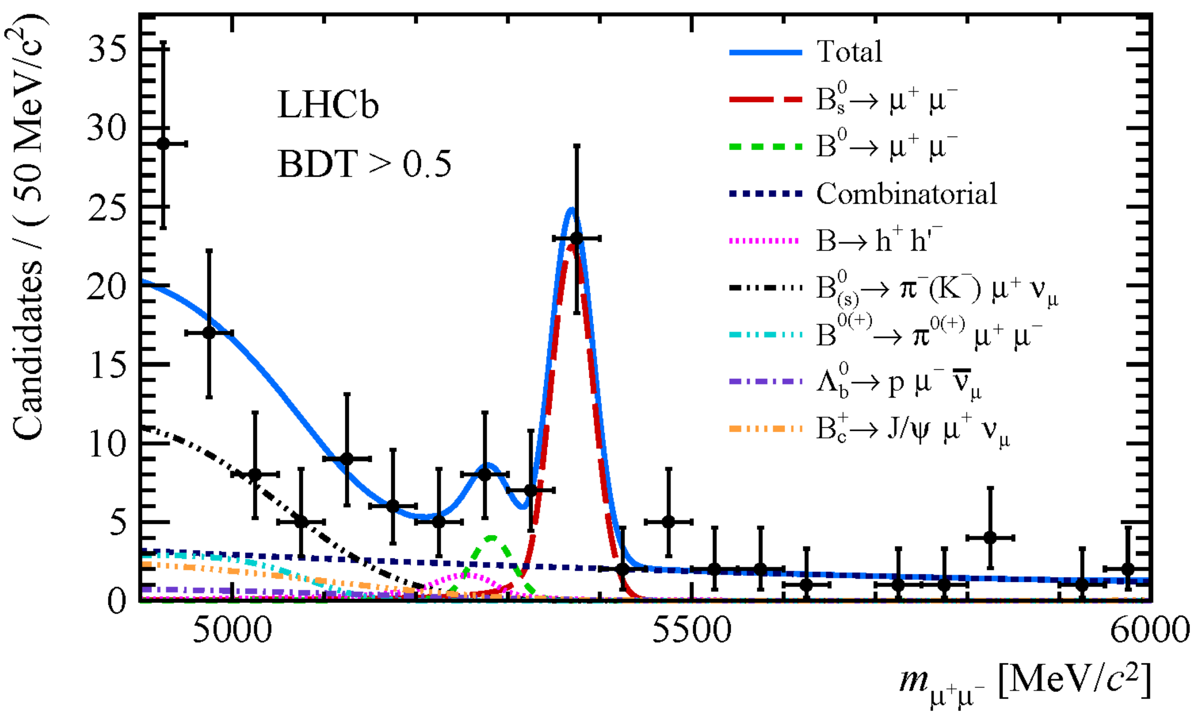
$$B(B^0_s \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

first observation: 6.2σ significance

$$B(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

first evidence: 3.0σ significance

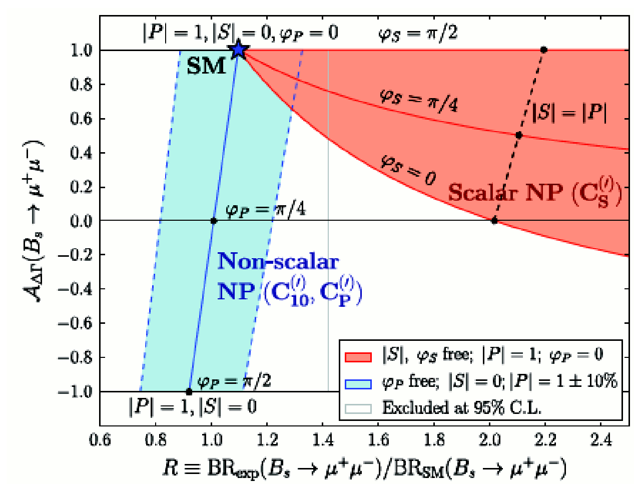
[arXiv:1703.05747]



SM: heavy state decays to $\mu^+\mu^-$

first lifetime measurement:

$\tau(B_s \to \mu^+\mu^\pm) = 2.04 \pm 0.44 \pm 0.05$ ps

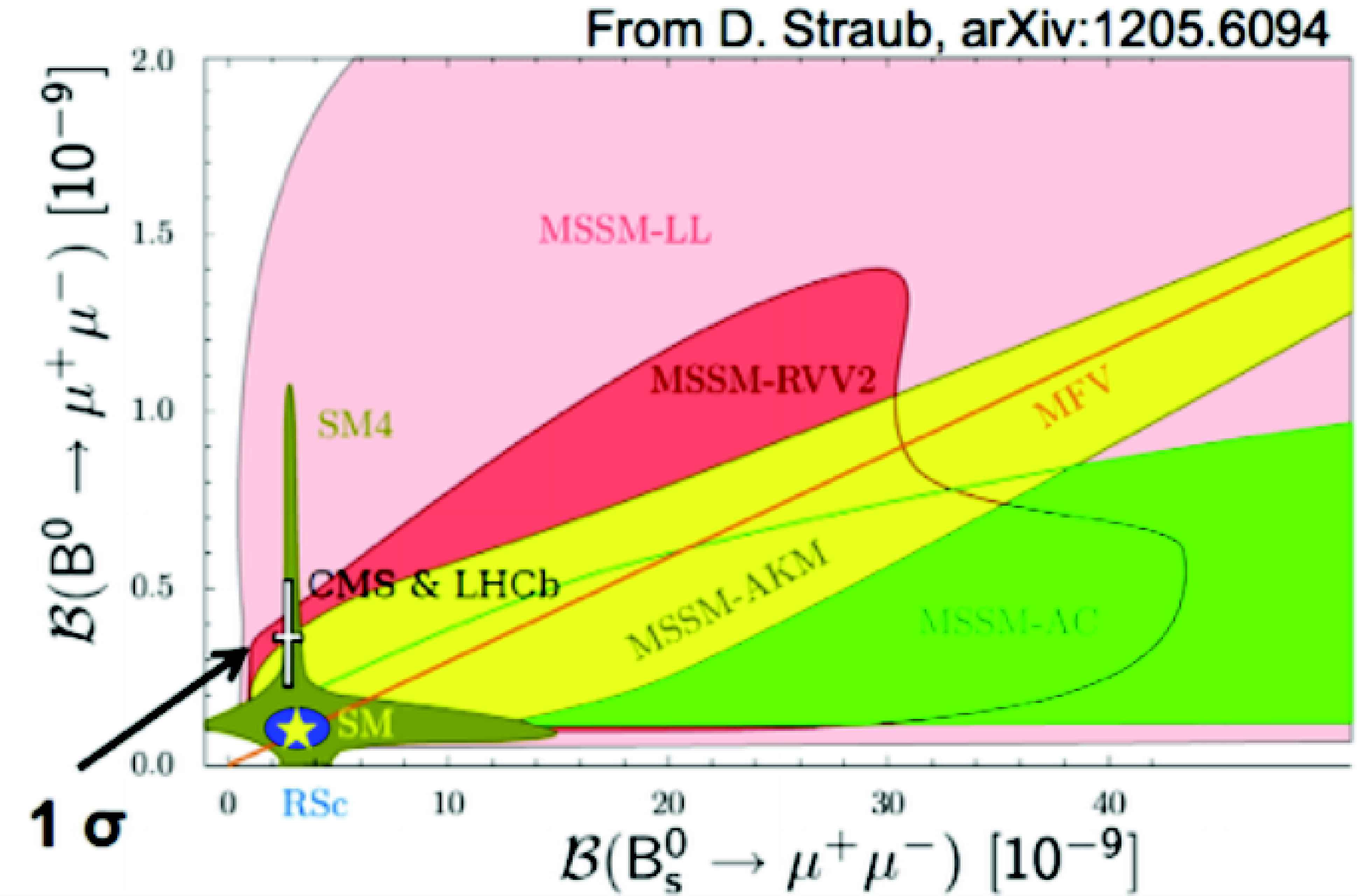


[De Bruyn et al., PRL 109, 041801 (2012)]

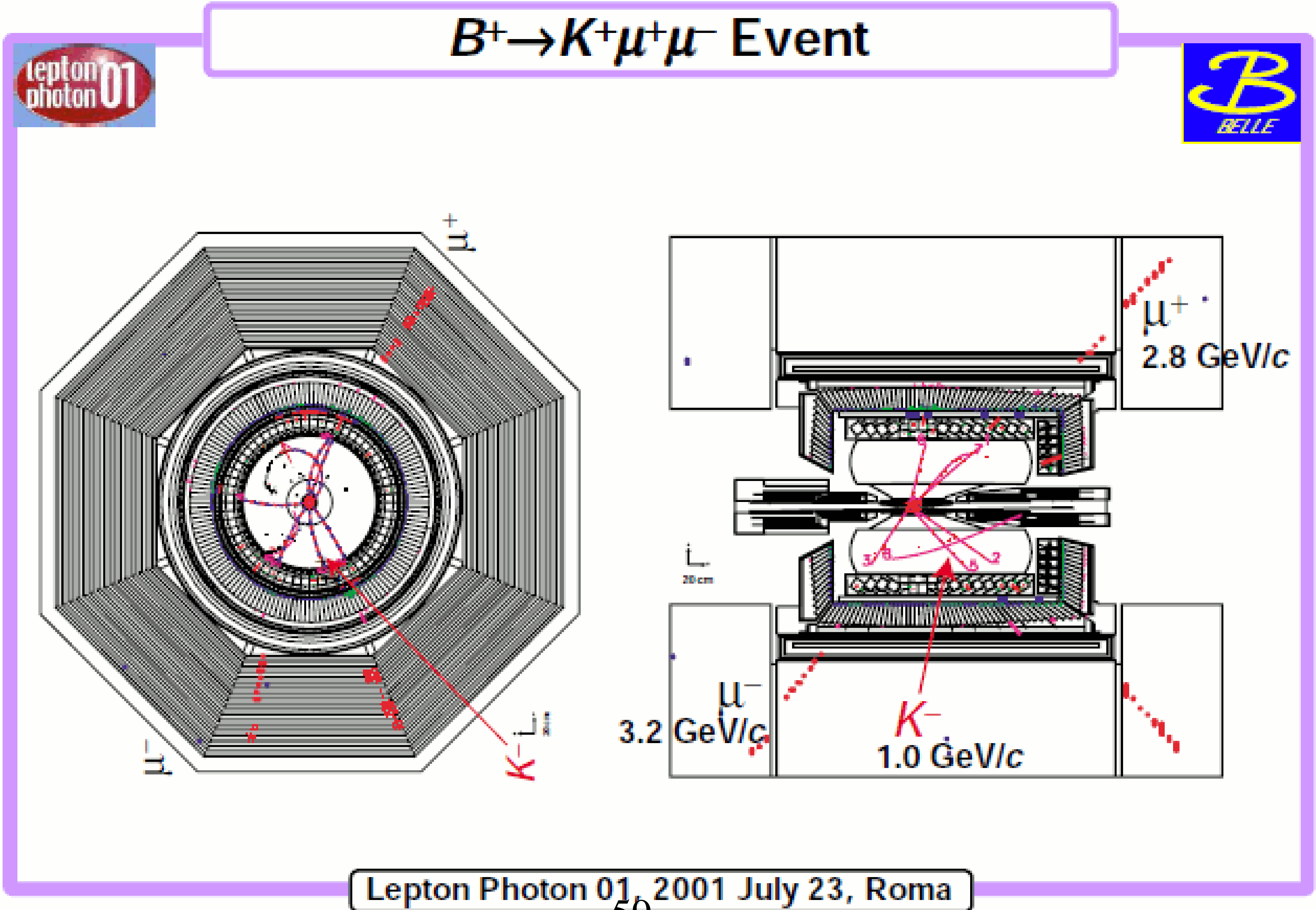
$$\mathbf{B(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}\ (7.8\sigma\ significance)}$$

$$\mathbf{B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}\ @\ 90\%\,CL}$$

Constraints on NP models



First observation



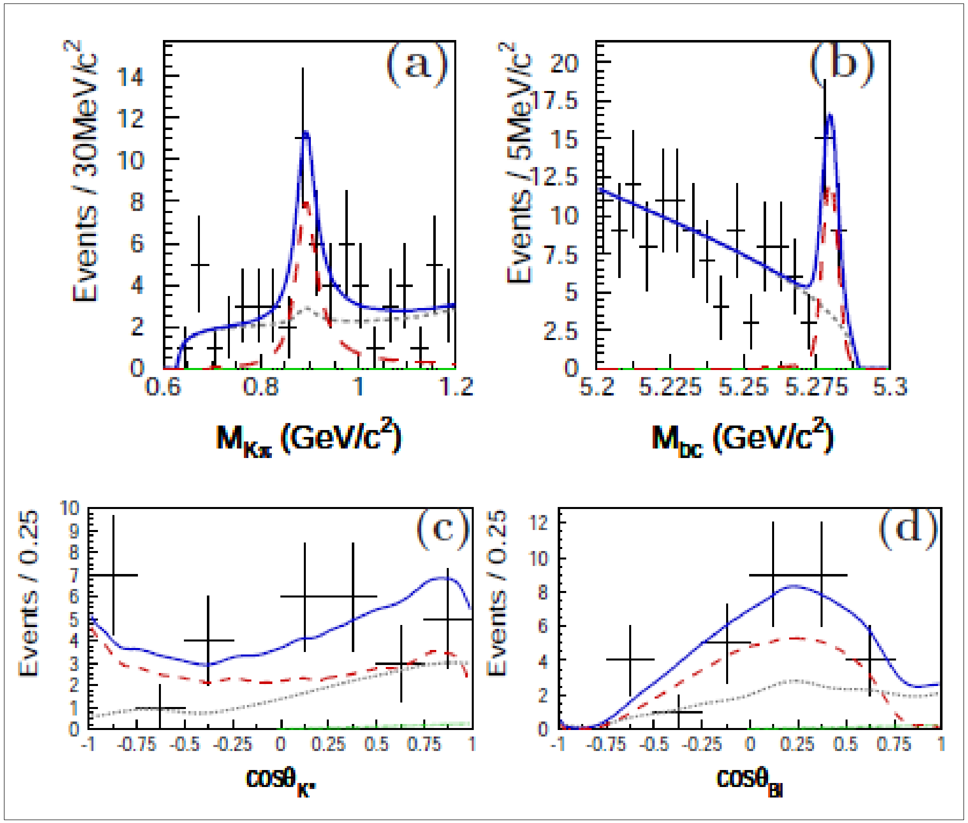
Situation pre-LHCb

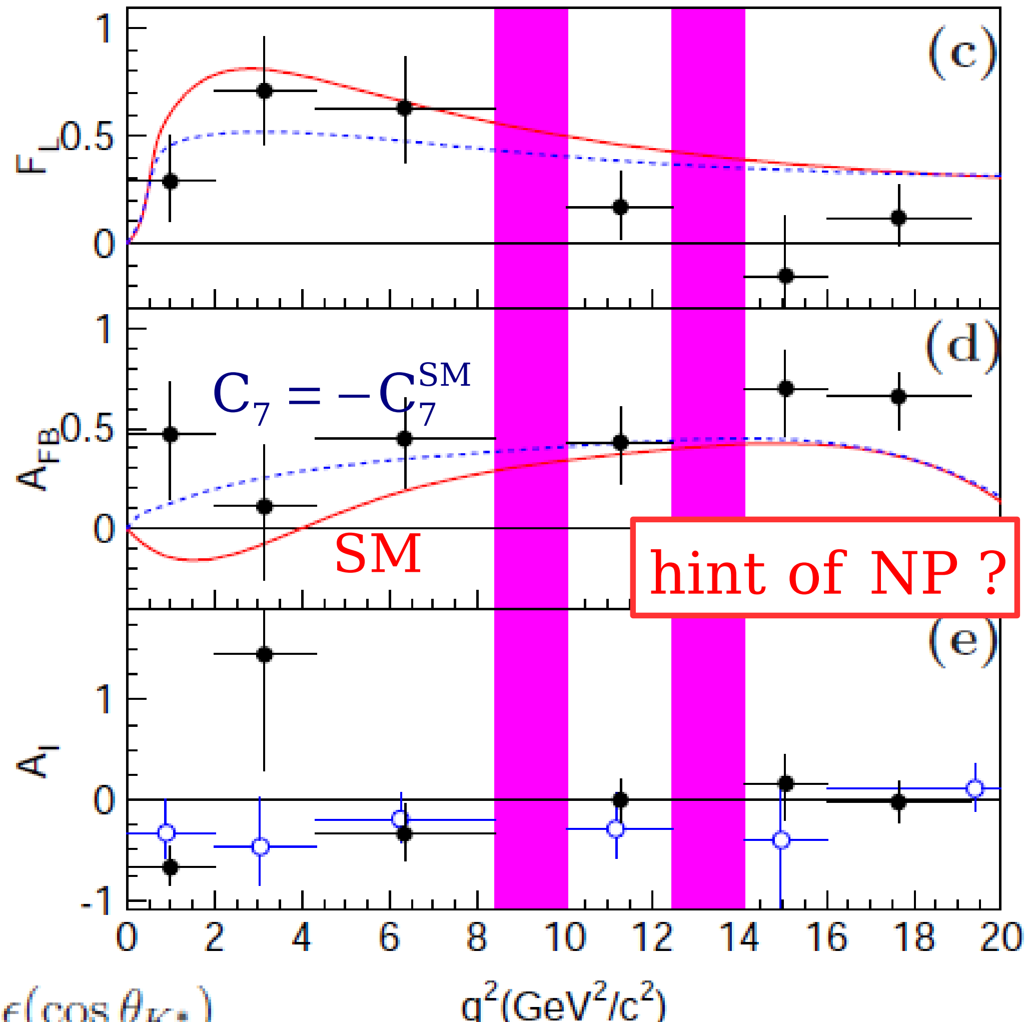
$B \to K^* l^+ l^-$ decays

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

[Belle, arXiv:0904.0770]

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





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

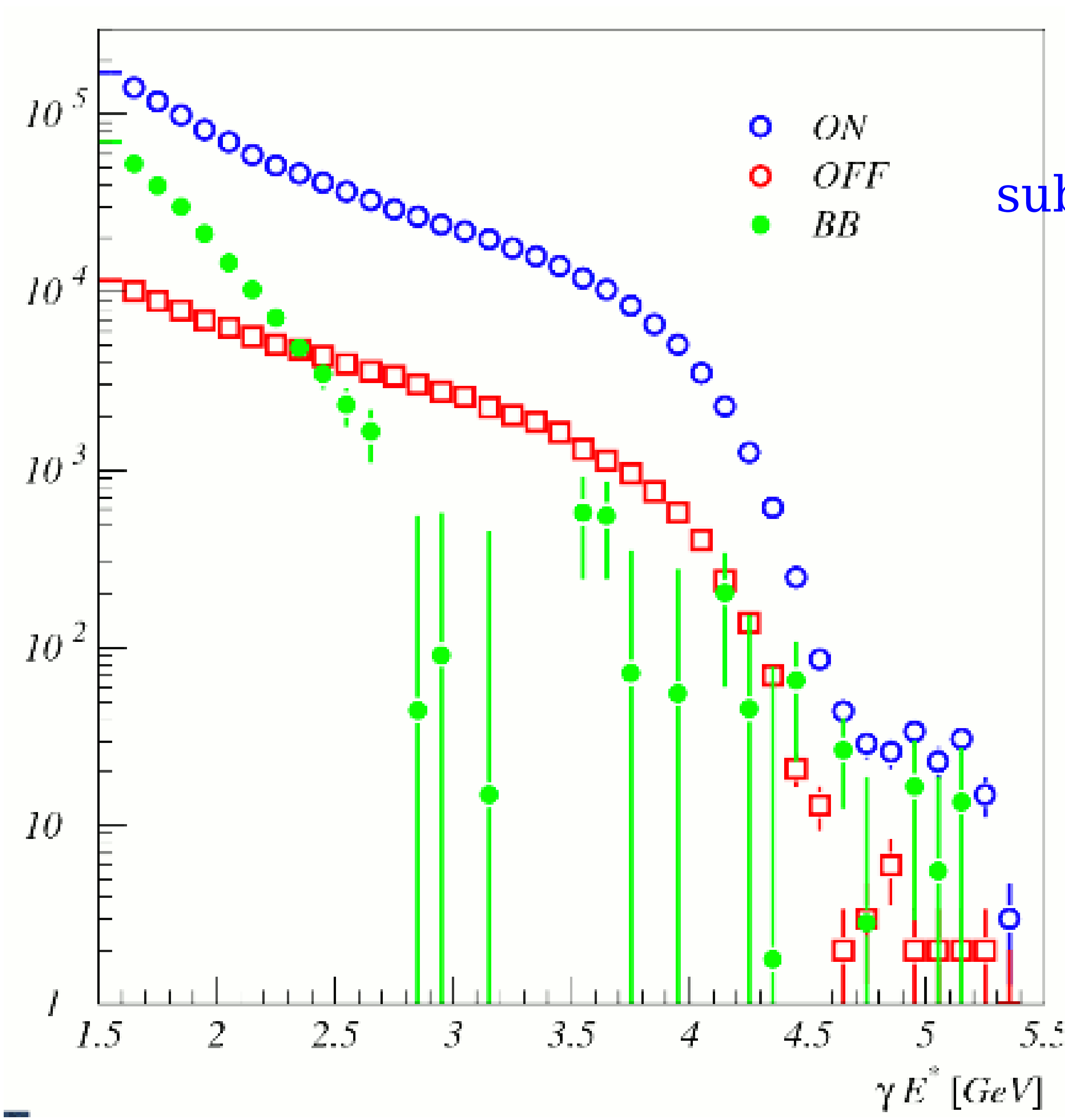
$$\left[\ \tfrac{3}{4}F_L(1-\cos^2\theta_{B\ell}) + \tfrac{3}{8}(1-F_L)(1+\cos^2\theta_{B\ell}) + A_{FB}\cos\theta_{B\ell}\ \right] \times \epsilon(\cos\theta_{B\ell}) ,$$

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

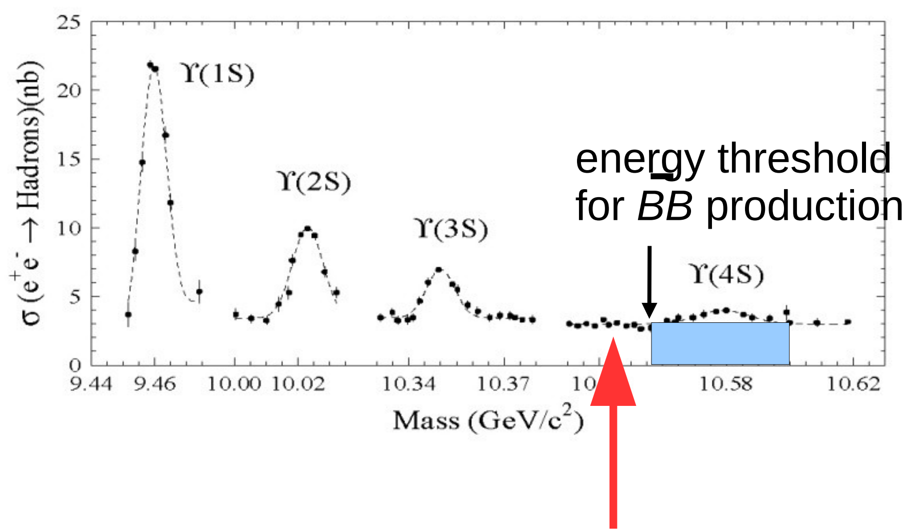
$R_K = 1.03 \pm 0.19 \pm 0.06$

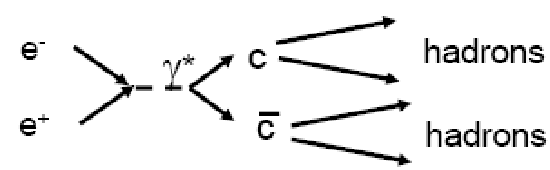
what about inclusive b → sll ?

as done in b→sγ ?



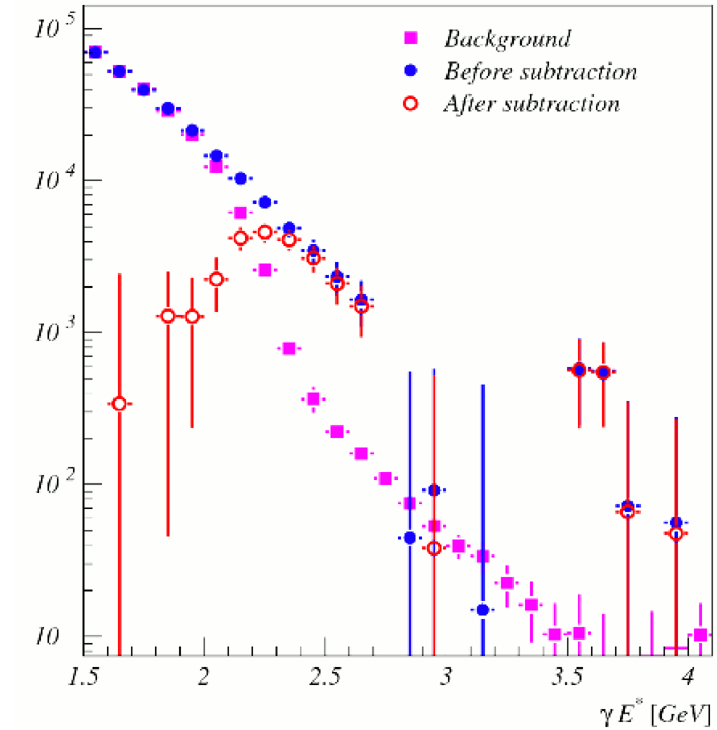
OFF-resonance data is scaled according to luminosities and subtracted from ON-resonance data



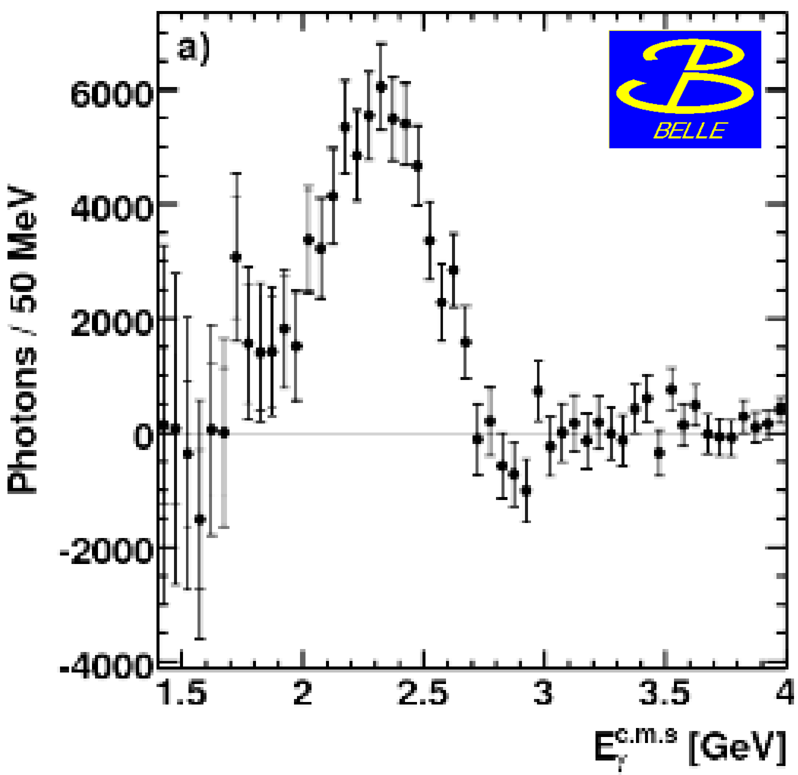


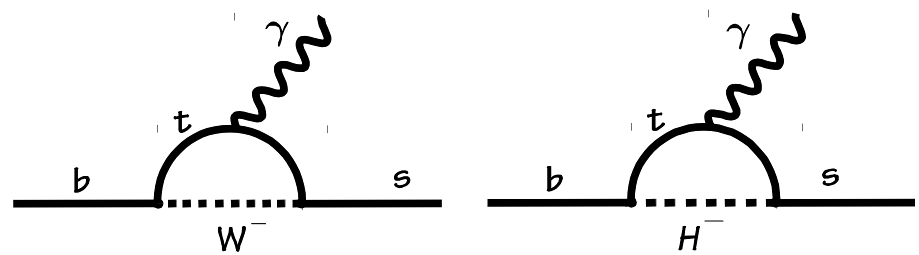
what about inclusive b → sll?

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

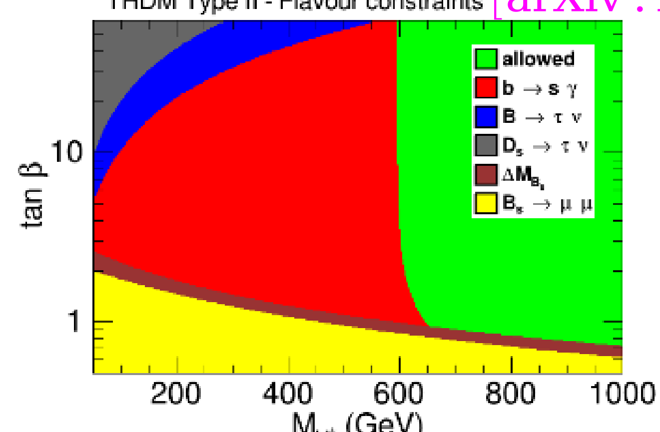


for $E_\gamma^* > 1.7$ GeV,
$\mathcal{B}(B \to X_s \gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$





THDM Type II - Flavour constraints [arXiv:1706.07414]



what about inclusive b → sll ?

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

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

and lot of leptons in B decays…

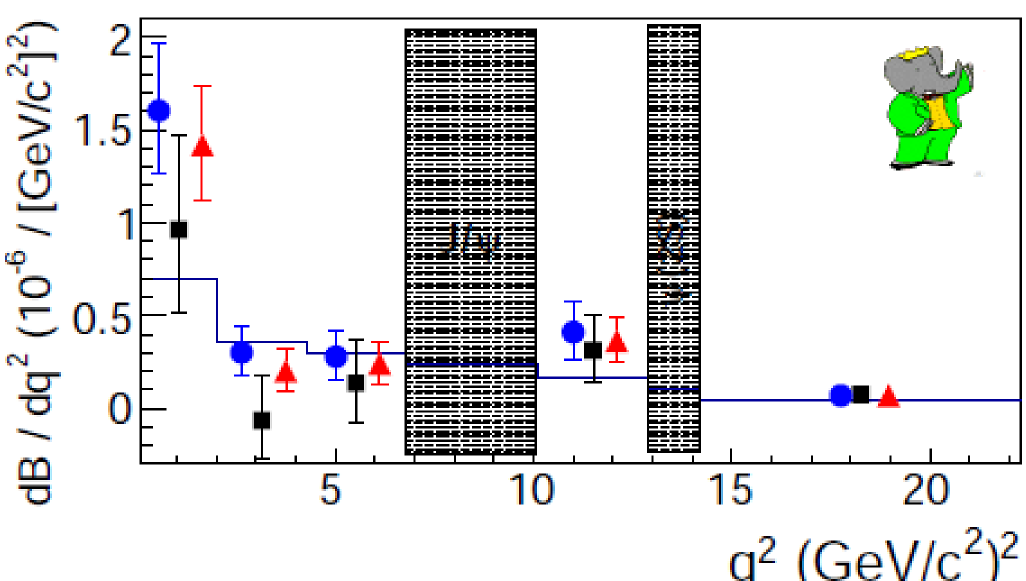
- difficult to achieve using inclusive method (à la $b \to s\gamma$)
- some on-going efforts using full had. tag, but $\epsilon < 1\%$…

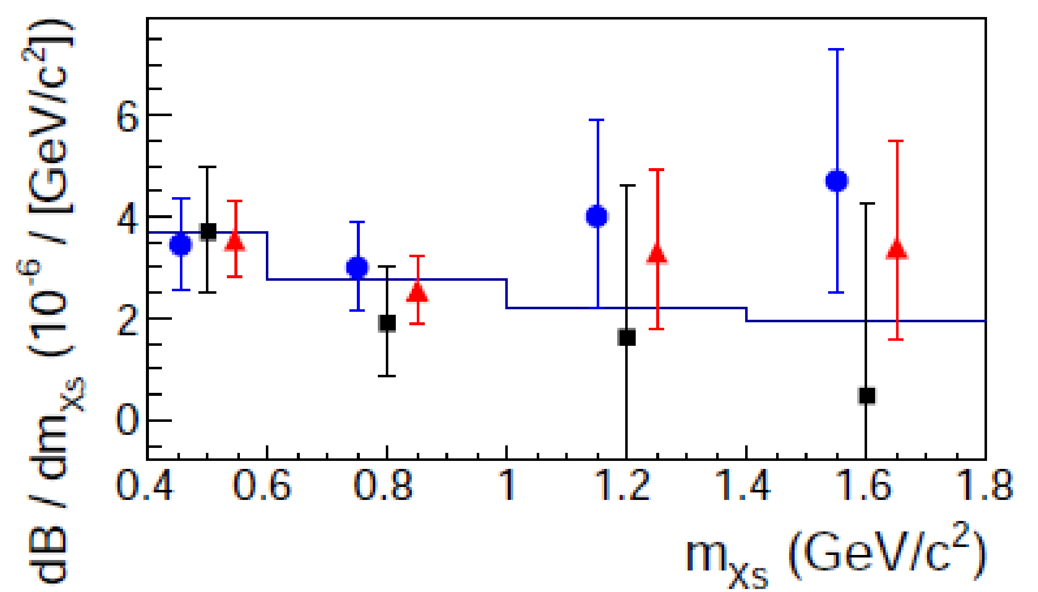
sum-of-exclusive method instead…

[BaBar, arXiv:1312.5364]

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

Bin	Range	$B \to X_s e^+e^-$	$B \to X_s \mu^+\mu^-$	$B \to X_s \ell^+\ell^-$	$A_{CP\,B\to X_s\ell^+\ell^-}$
q^2_0	$1.0 < q^2 < 6.0$	$1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18$ (1.71)	$0.66^{+0.82+0.30}_{-0.76-0.24} \pm 0.07$ (1.78)	$1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18$	$-0.06 \pm 0.22 \pm 0.01$





inclusive as sum-of-exclusive

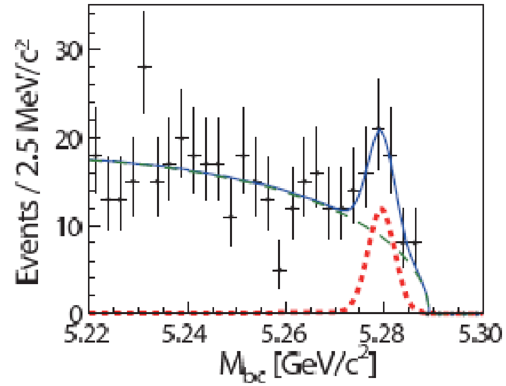
[Belle, arXiv:1402.7134]

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

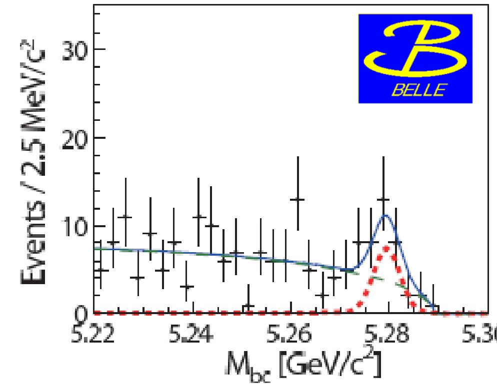
50% of total inclusive rate

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

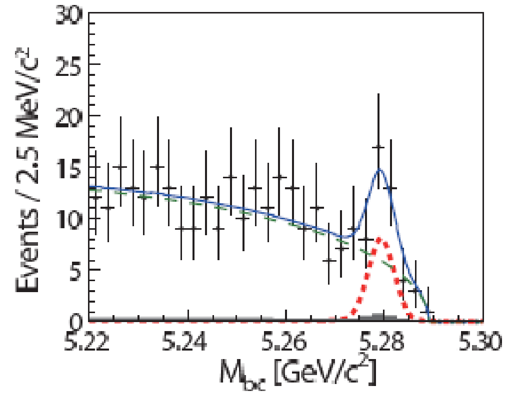
$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$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



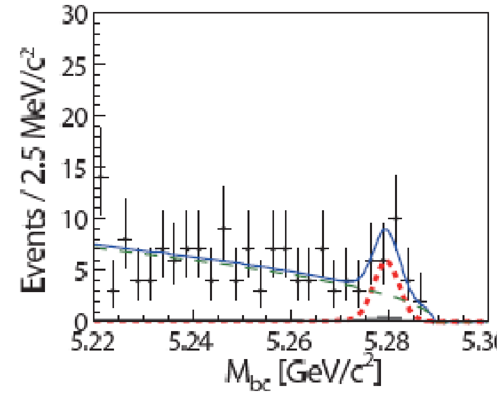
(a) $B \to X_s e^+e^-$ candidates with $\cos\theta > 0$



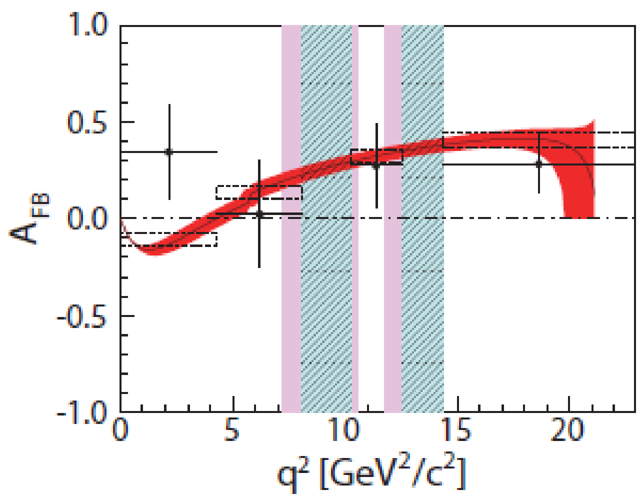
(b) $B \to X_s e^+e^-$ candidates with $\cos\theta < 0$



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



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

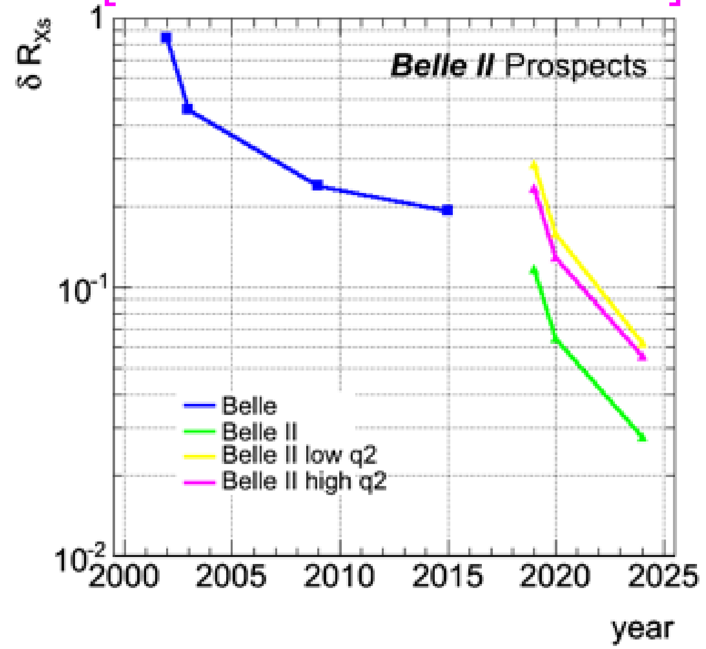


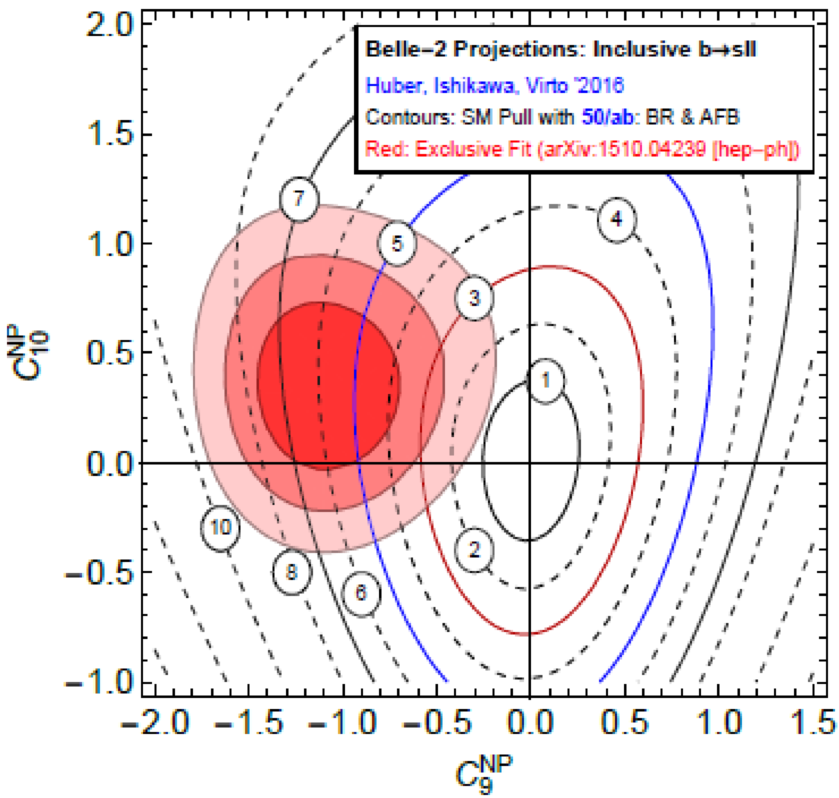
	1st q^2 bin	2nd q^2 bin	3rd q^2 bin	4th q^2 bin	
q^2 range [GeV$^2/c^2$]	[0.2,4.3]	$[4.3,7.3]_{X_s e^+e^-}$ $[4.3,8.1]_{X_s \mu^+\mu^-}$	$[10.5,11.8]_{X_s e^+e^-}$ $[10.2,12.5]_{X_s \mu^+\mu^-}$	[14.3, 25.0]	[1.0, 6.0]
$\mathcal{A}_{FB}$	$0.34 \pm 0.24 \pm 0.03$	$0.04 \pm 0.31 \pm 0.05$	$0.28 \pm 0.21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

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

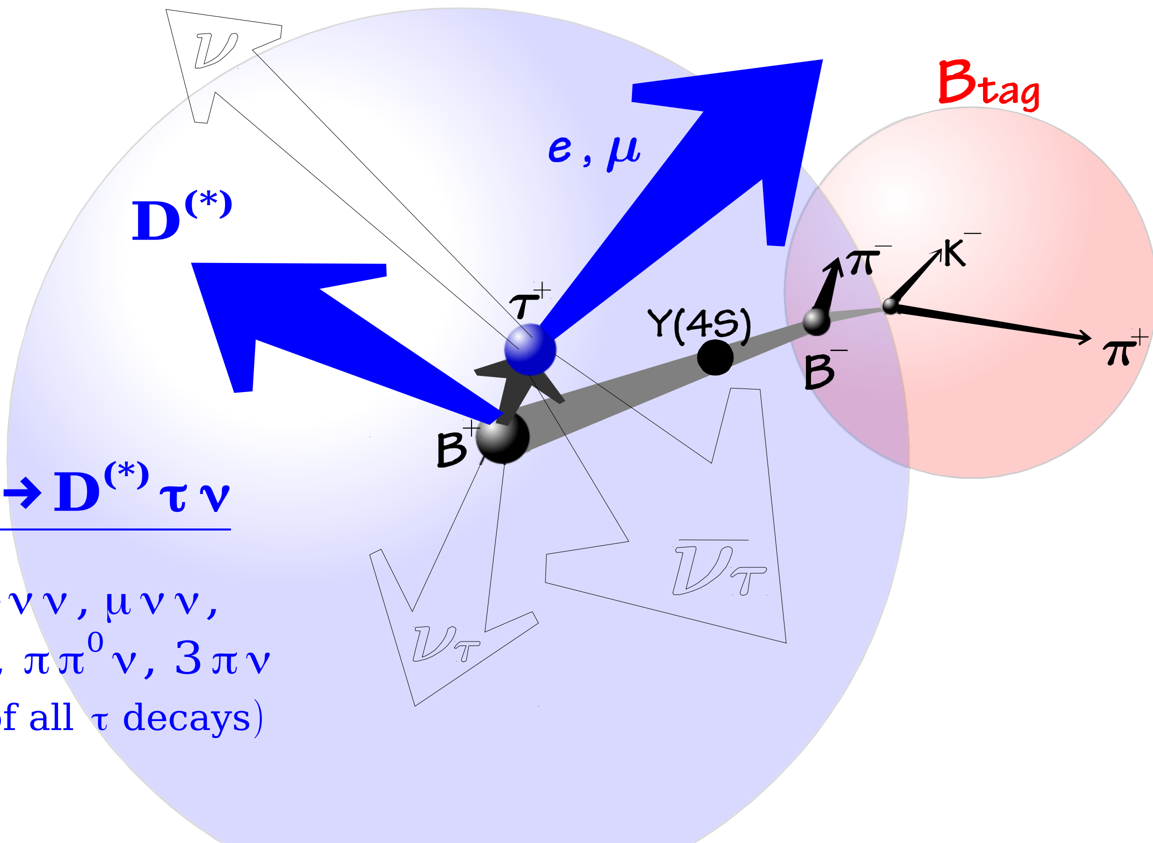
[arXiv:1808.10567]

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





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)

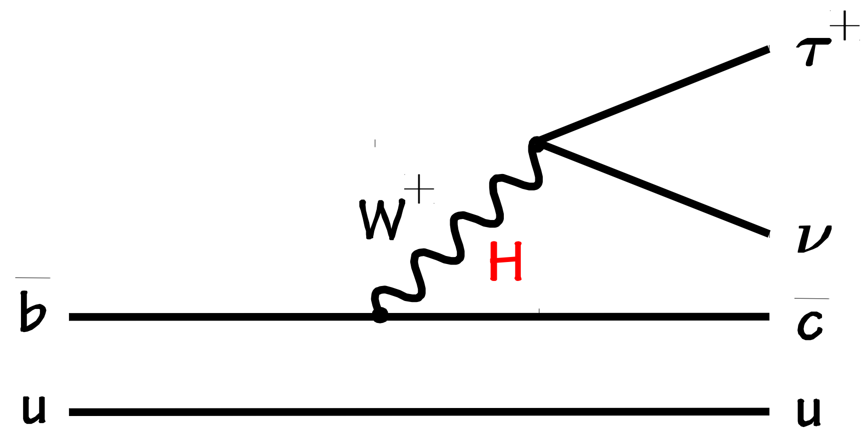
B_{tag}

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}

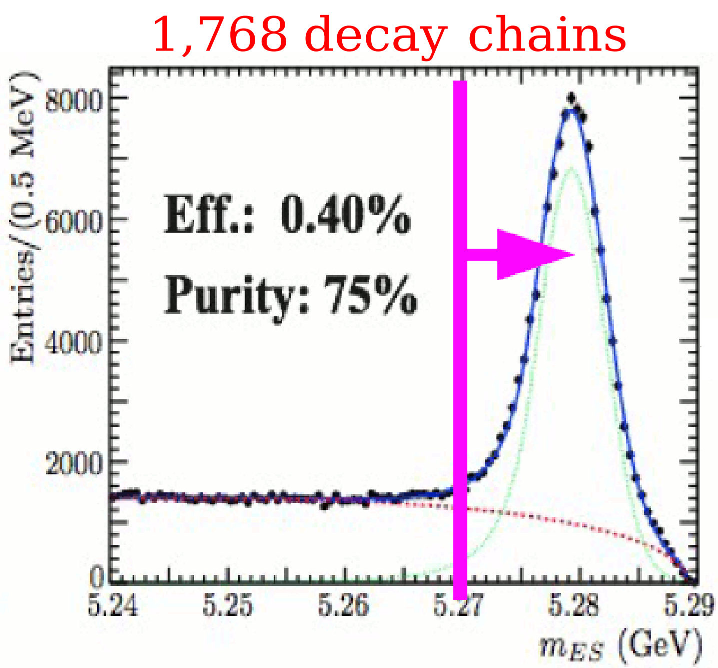
main signal-background discriminator

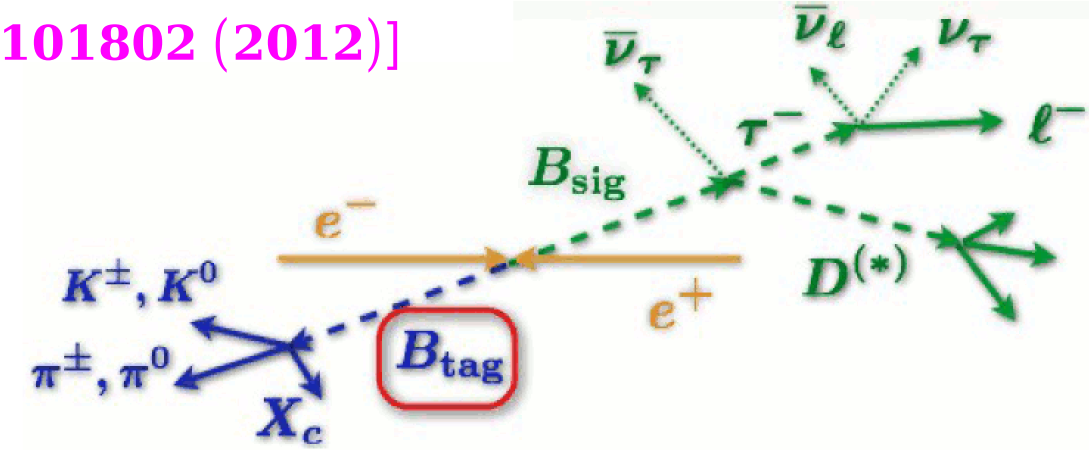
$$\mathbf{m_{miss}^2 = (p_{ee} - p_{tag} - p_{D^{(*)}} - p_l)^2}$$

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

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

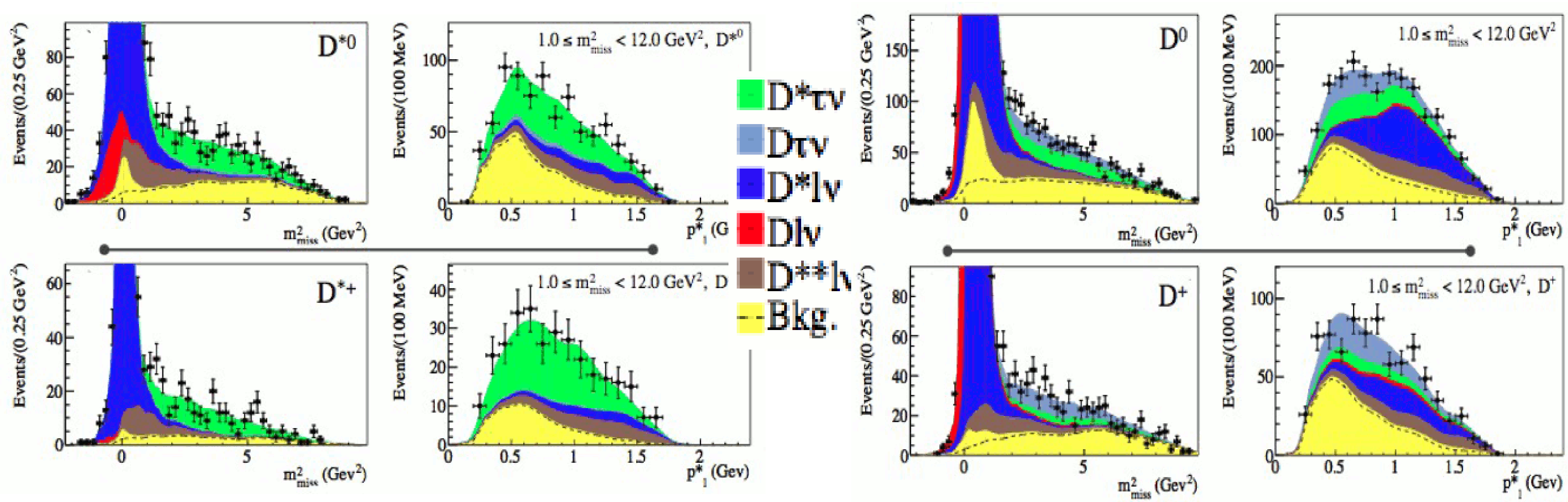
$B \to D^{(*)} \tau \nu$ [BaBar, PRL 109, 101802 (2012)]



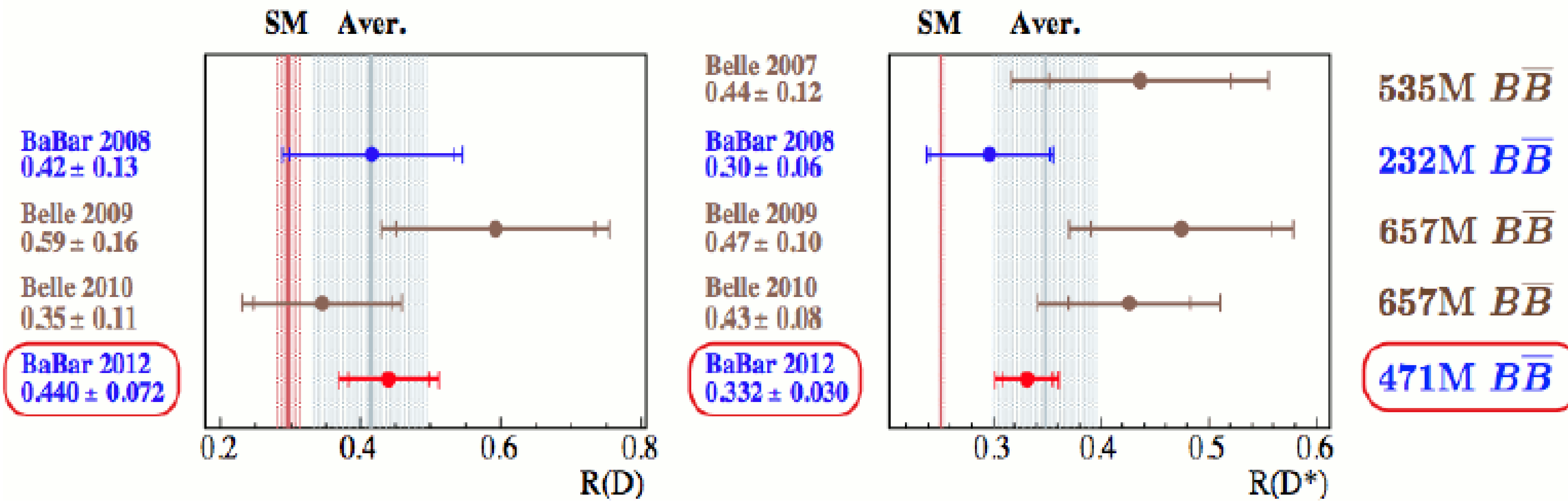


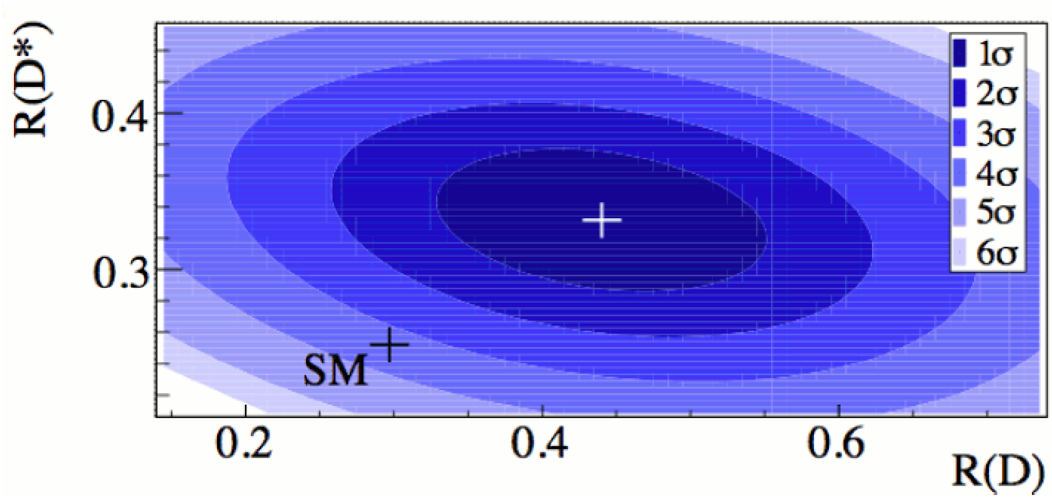
- 2D unbinned fit to m^2_{miss} and p^*_l
- fitted samples
  - 4 $D^{(*)}l$ samples ($D^0 l$, $D^{*0} l$, $D^+ l$ and $D^{*+} l$)
  - 4 $D^{(*)}\pi^0 l$ control samples ($D^{**}(l/\tau)\nu$)

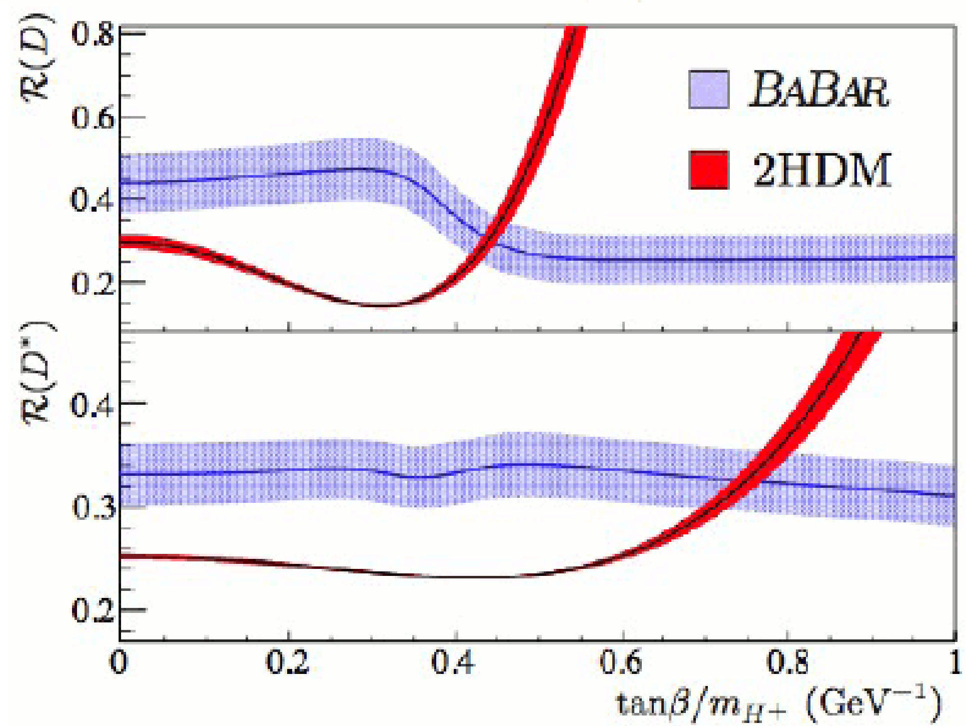
⇒ $D\tau\nu$ and $D^*\tau\nu$ clearly observed



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







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

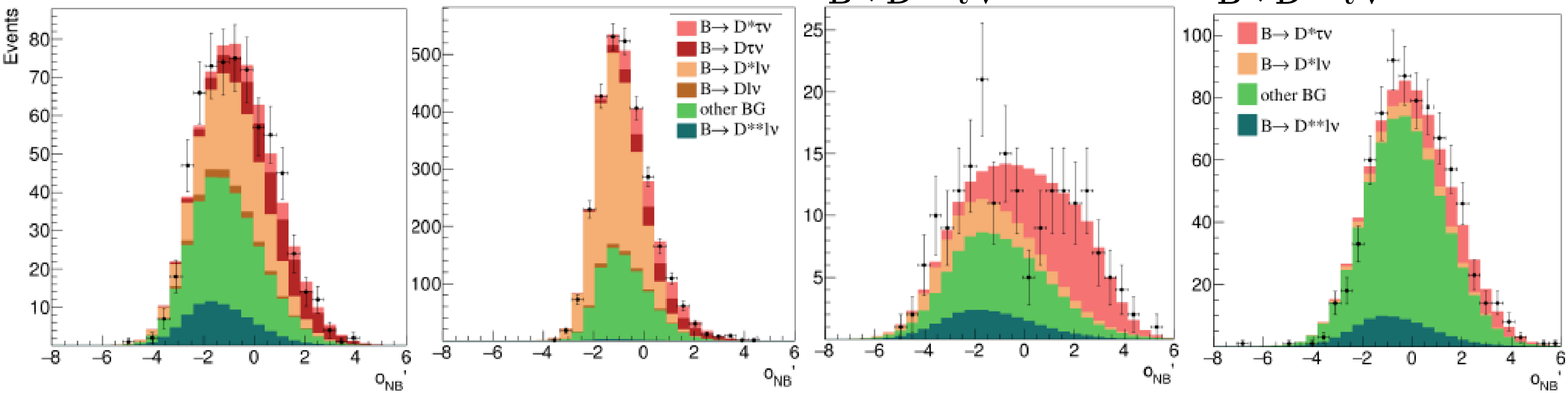
$B \to D^{(*)} \tau \nu$ at Belle

[Belle, arXiv:1507.03233]

(with hadronic tagging)

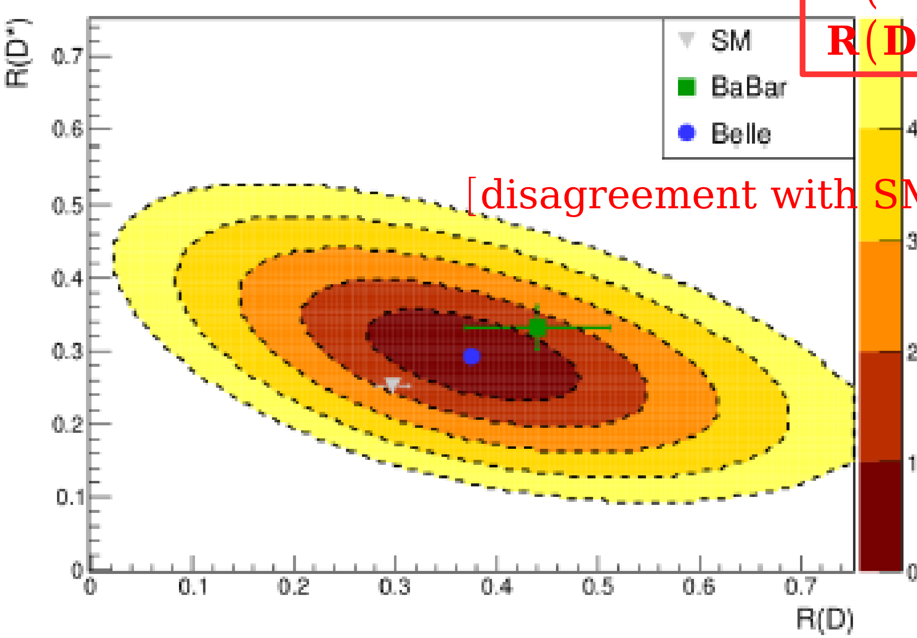
projections for large M^2_{miss} region, $N(D\tau\nu) \sim 300$, $N(D^*\tau\nu) \sim 500$

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



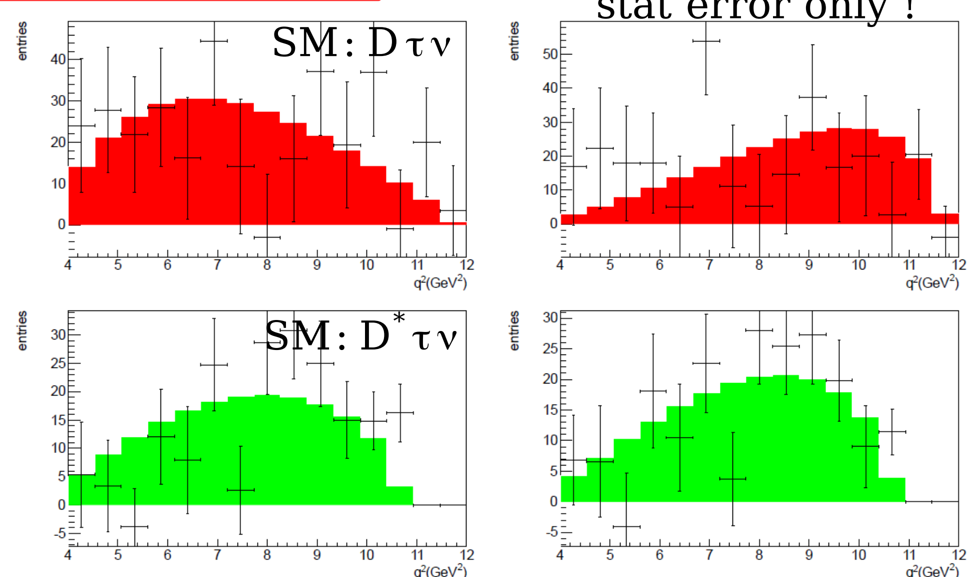
$R(D) = 0.375 \pm 0.064 \pm 0.026$

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



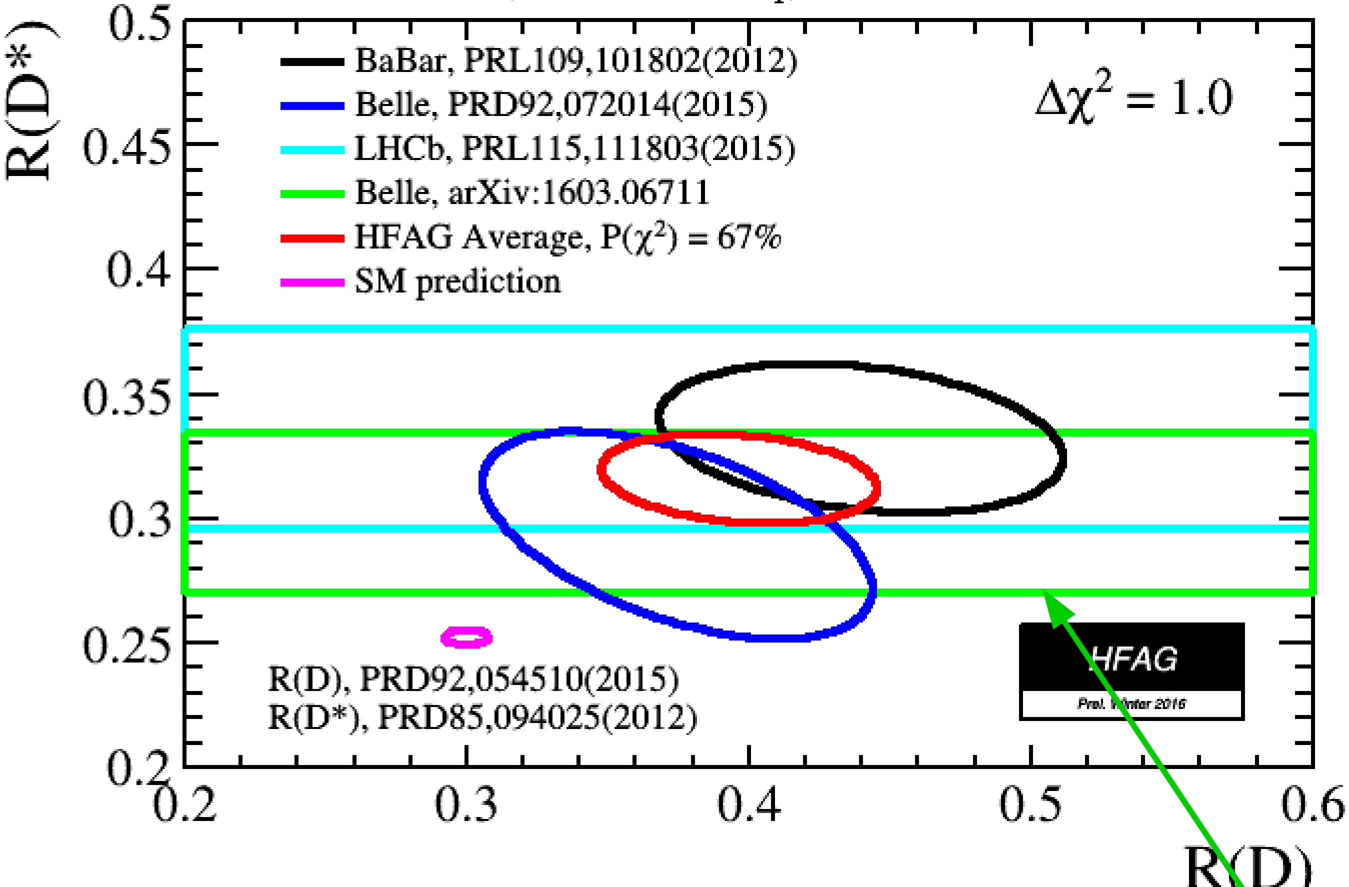
[disagreement with SM at 1.5σ]

stat error only !



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

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



BaBar

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

Belle

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

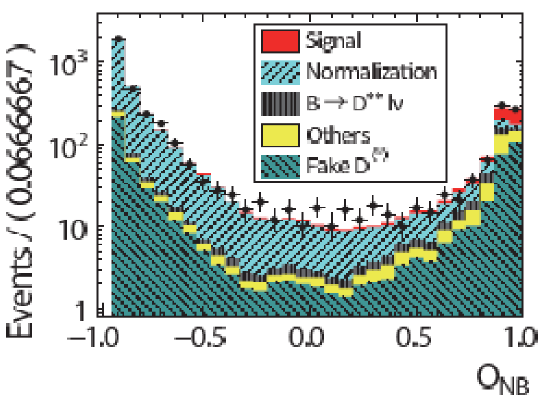
LHCb

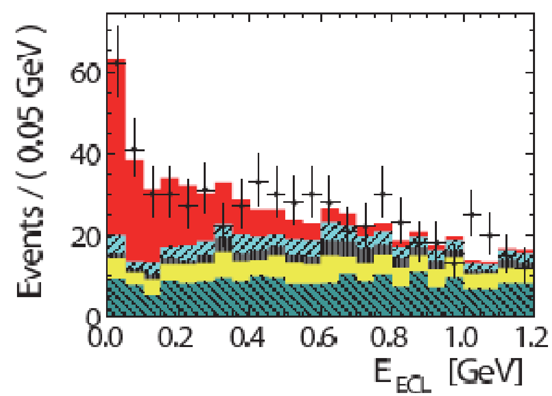
$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

$R(D) = 0.397 \pm 0.040 \pm 0.028$
$R(D^*) = 0.316 \pm 0.016 \pm 0.010$

difference with SM predictions is at **4.0**σ level





[Belle, arXiv:1607.07923]

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

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

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

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

[Belle, arXiv:1612.00529]

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

τ polarization result using:

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

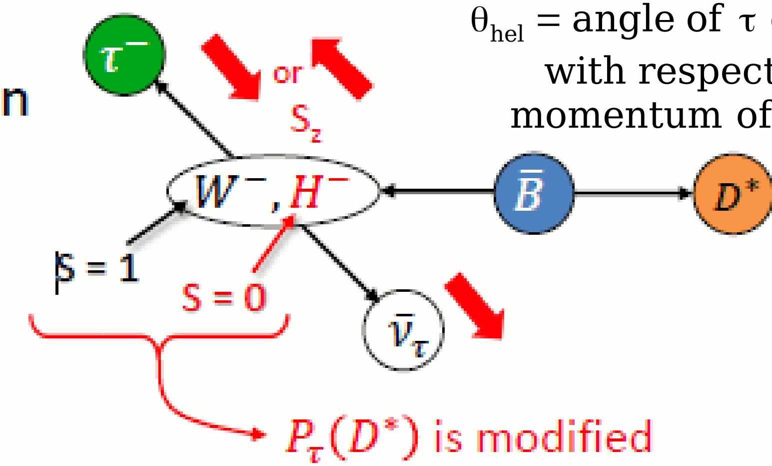
- $\tau^- \to \pi^- \nu_\tau$, $\rho^- \nu_\tau$ are good polarimeter for τ polarization

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

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

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

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

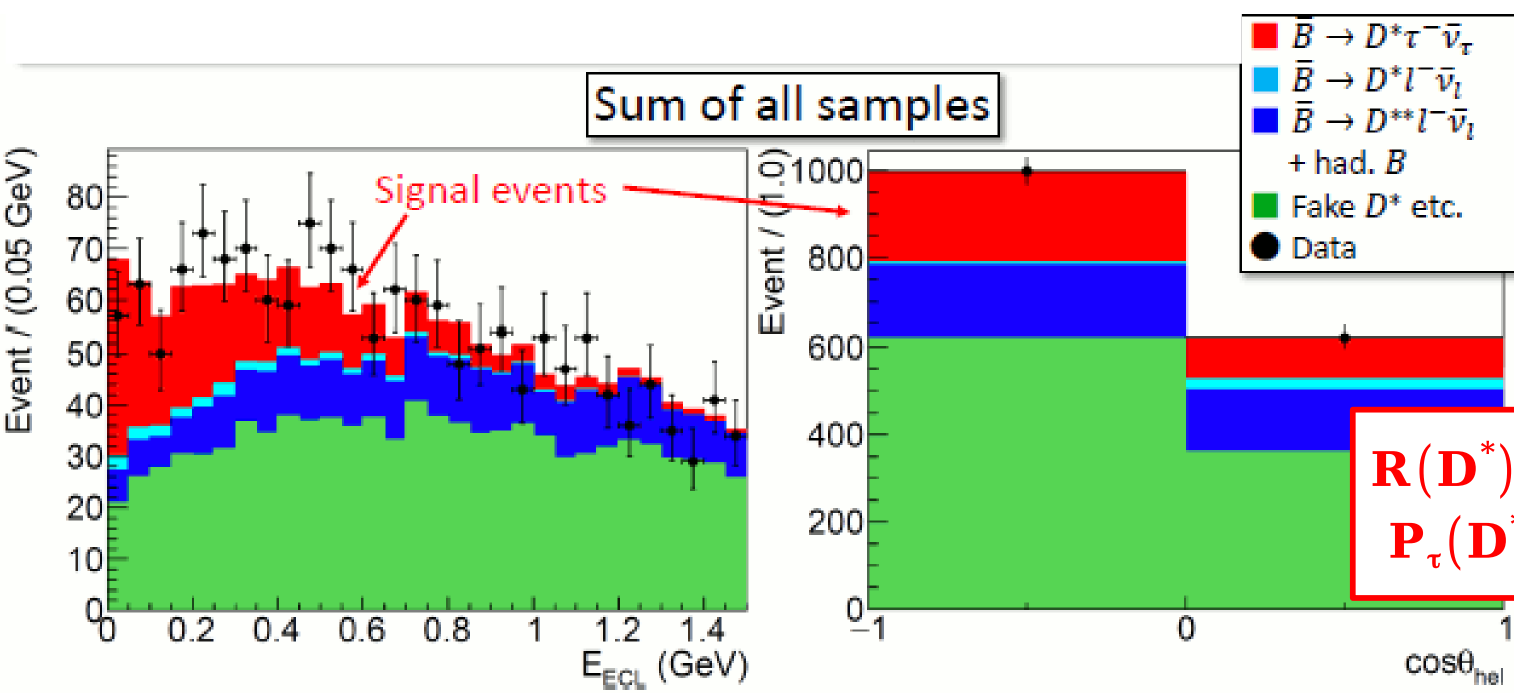


θ_{hel} = angle of τ daughter meson momentum with respect to direction opposite to momentum of $\tau\nu$ system in τ rest frame

τ polarization is a variable sensitive to NP

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

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



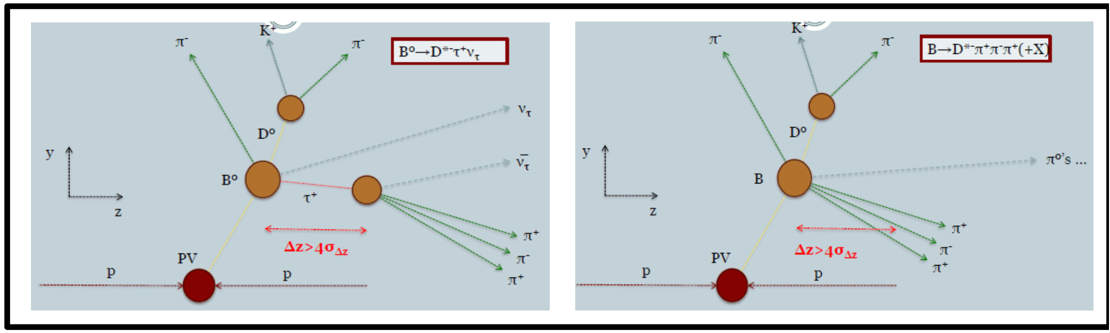
$$R(D^*) = 0.270 \pm 0.035 \,^{+0.028}_{-0.025}$$

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

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

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

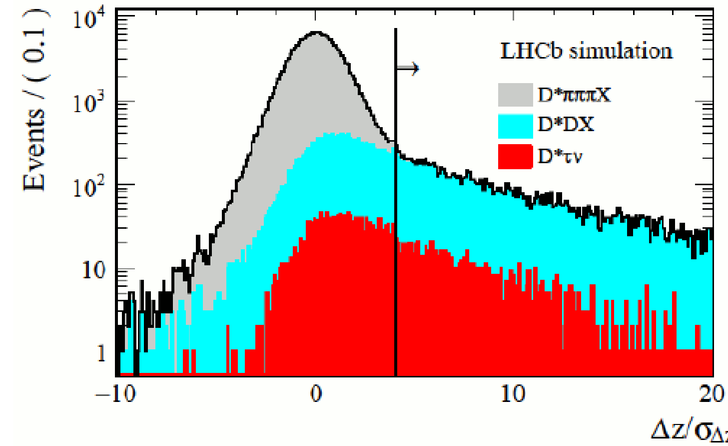
[LHCb-PAPER-2017-017]

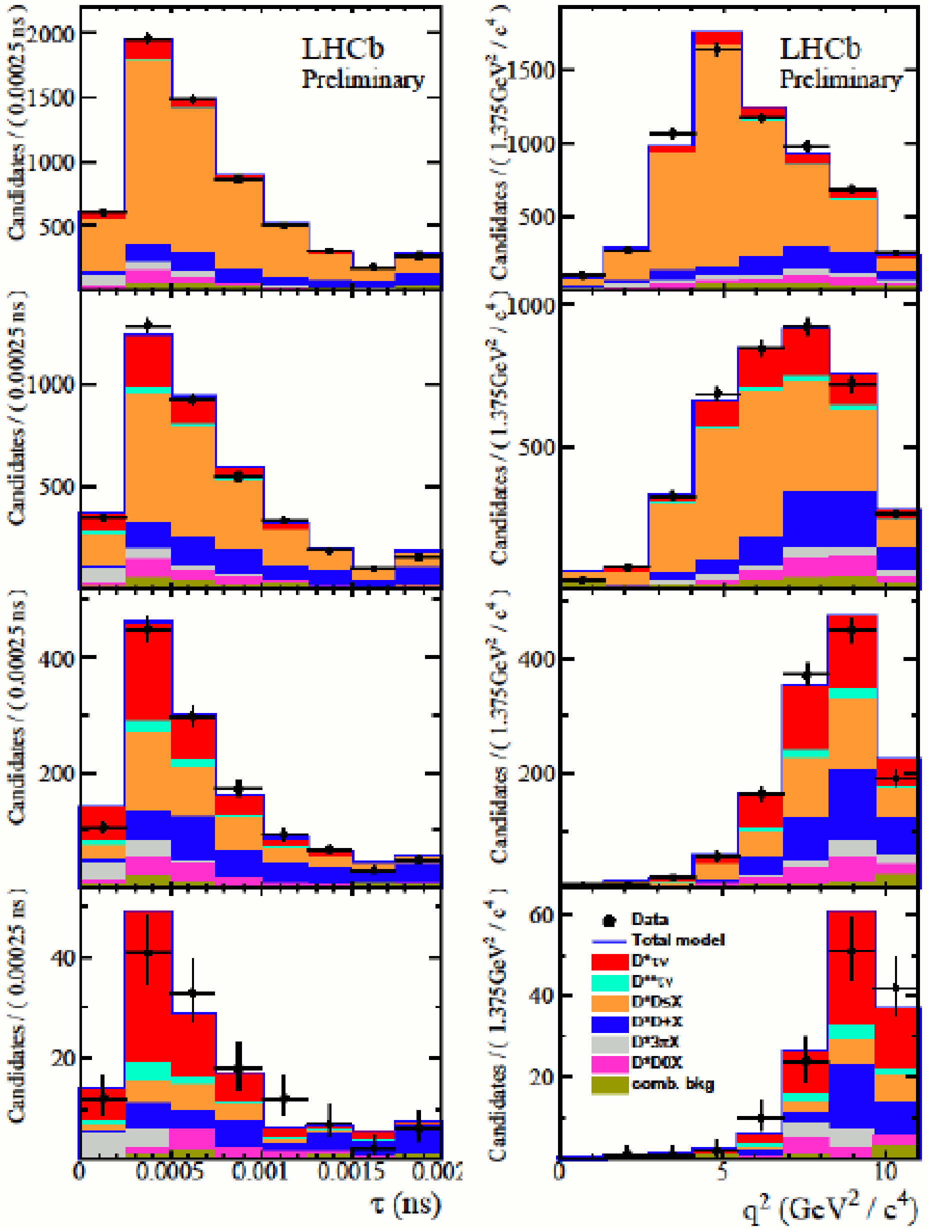


need a strong background suppression:

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

$\Rightarrow$ detached vertex method





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

anti-D_s

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

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

$B \to D D_{s(J)} X$
$X_b \to D D X$ } (relative) yields constrained from control samples

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

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

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