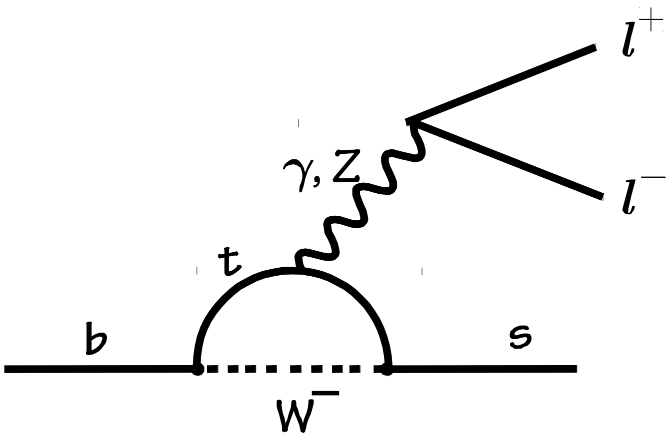
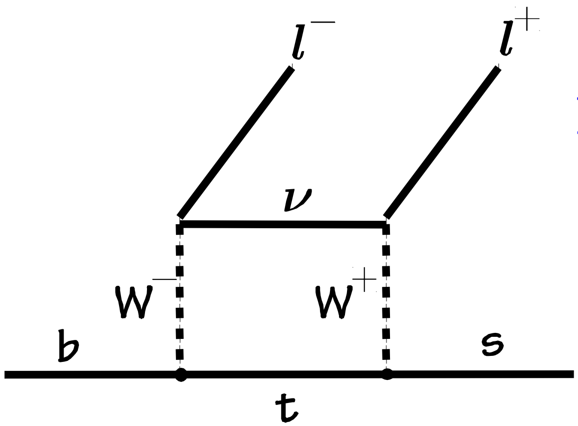
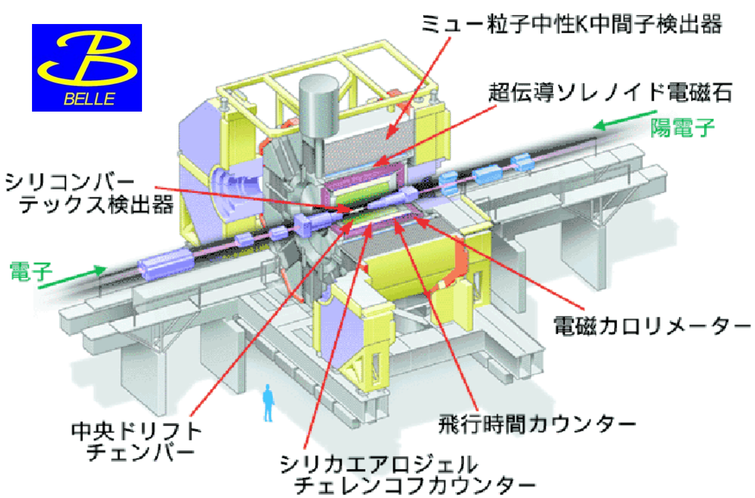
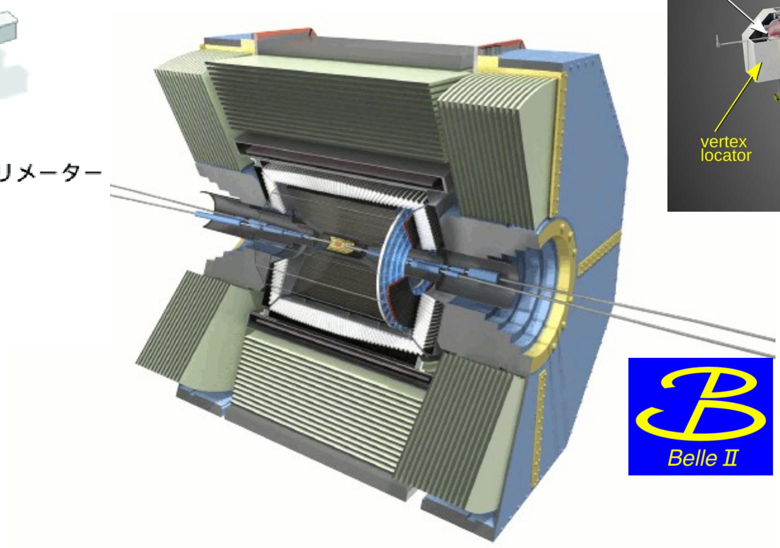
Beautiful paths to probe physics beyond the standard model of particles

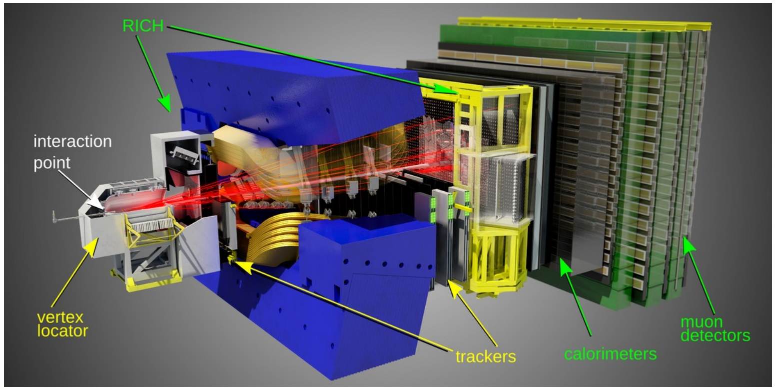




K. Trabelsi
karim.trabelsi@in2p3.fr
université PARIS-SACLAY
cnrs
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis





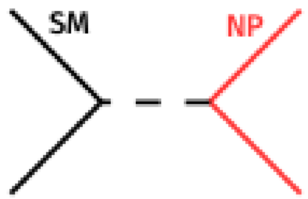


Future Flavours: Prospects for Beauty, Charm and Tau Physics , May 2022

Rare B decays

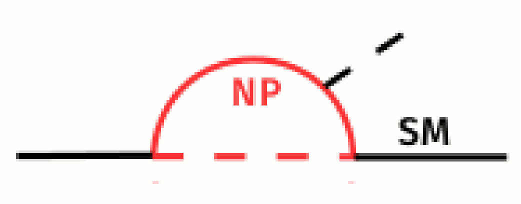
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



limited by beam energy

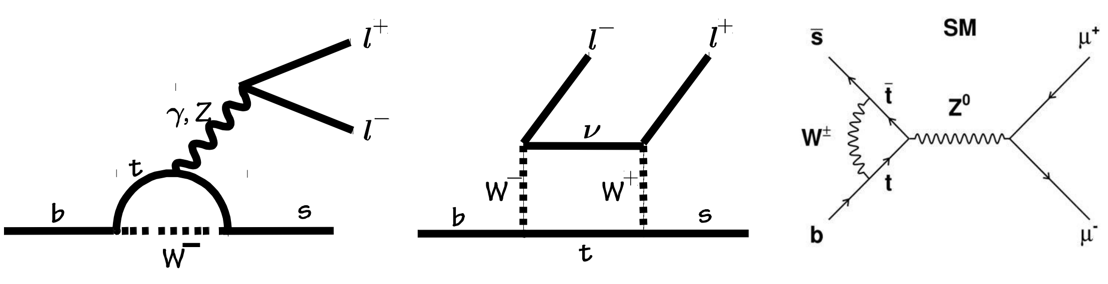
intensity frontier

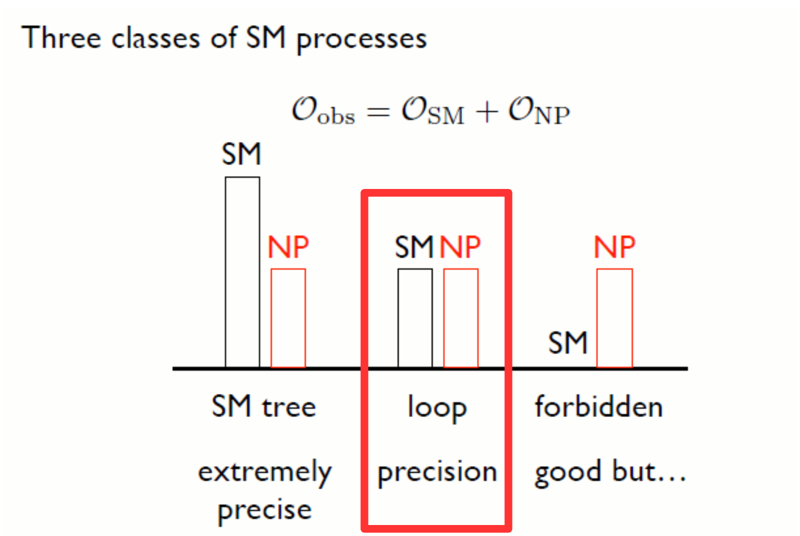


limited by statistics

→ **NP beyond the <u>direct</u> reach of the LHC**

New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**





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

Model candidates

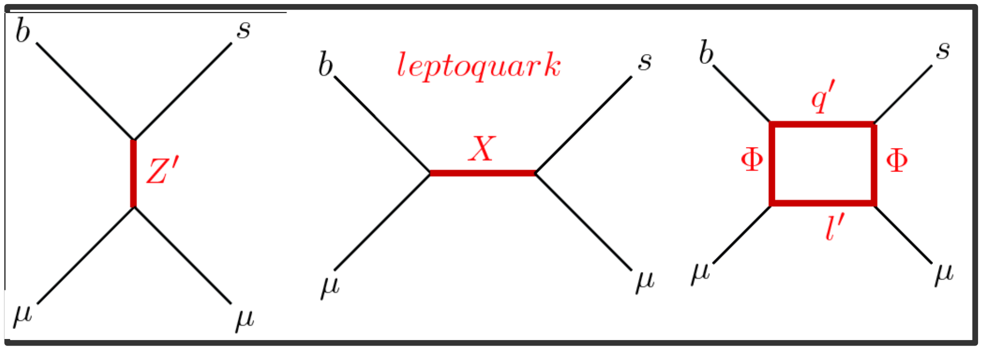
- ✓ Effective operator from Z' exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ **Models with leptoquarks**

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

✧ **Models with loop induced effective operator**

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



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

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

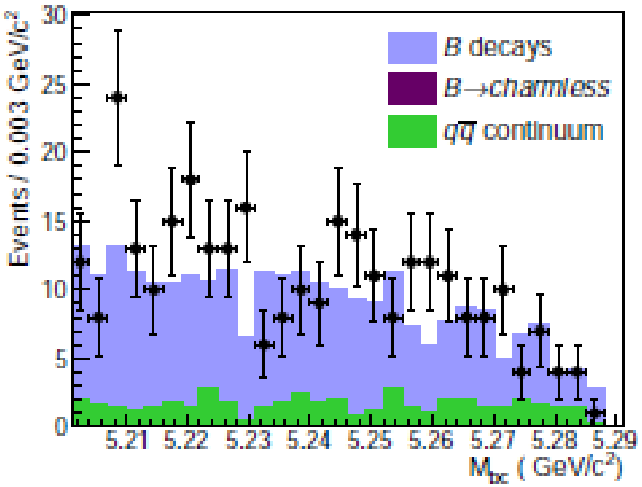
G.Isidori, FPCP 2020: correlations among b→s(d)ll' within the U(2)-based EFT

	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}	$B \to \pi \mu e$???

Panjab Univ. (Sunil Bansal)
IMSc Chennai (Rahul Sinha)
IIT Guwahati (Bipul Bhuyan)
MNIT Jaipur (Kavita Lalwani)
IISER Mohali (Vishal Bhardwaj)
IIT Bhubaneswar (Seema Bahinipati)
TIFR (Gagan Mohanty)
IIT Hyderabad (Anjan Giri)
IIT Madras (Jim Libby)

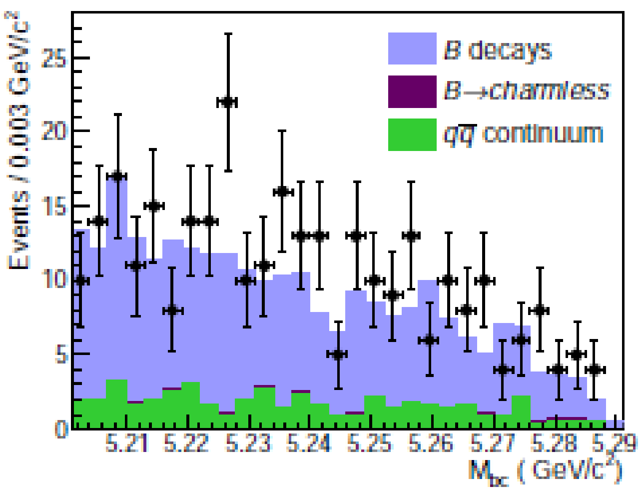
LFV $B \to K^* l l'$ decays

Saurabh Sandilya (UC) et al (Belle collaboration)
[arXiv:1807.03267, Phys. Rev. D 98, 071101 (2018)]



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

$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 1.2\times10^{-7}$ at 90%CL



$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 1.6\times10^{-7}$ at 90%CL

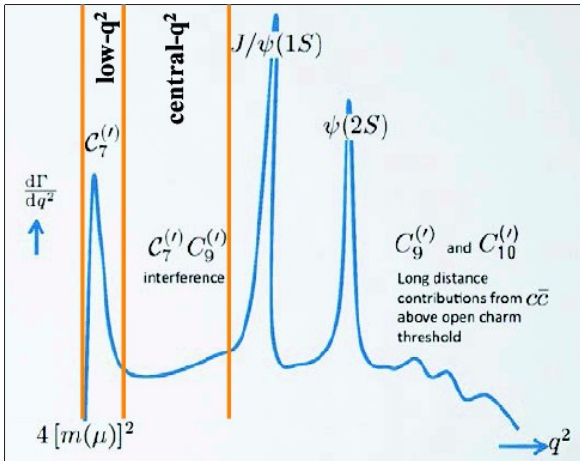
Belle II can get 90% UL at 10^{-8} level with 50 ab^{-1}

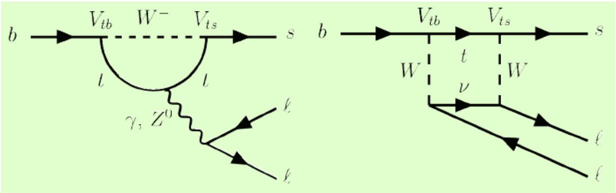
Search for charged lepton flavor violating decays of $\Upsilon(1S)$
Sourav Patra (IISER Mohali) et al (Belle collaboration)
[arXiv:2201.09620, to appear in JHEP]

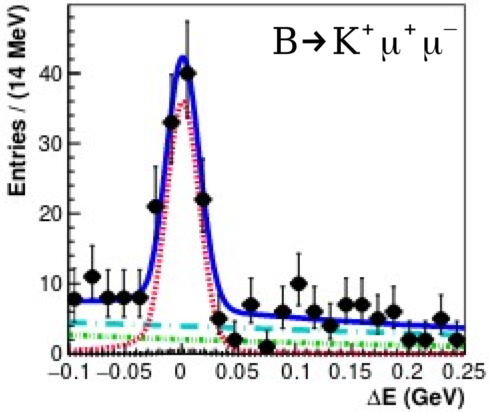
Test of lepton universality using $B^+ \to K l^+ l^-$ decays

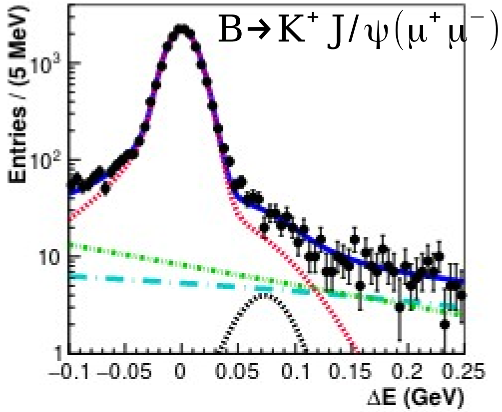
Seema Choudhury (IIT Hyderabad) et al (Belle collaboration)

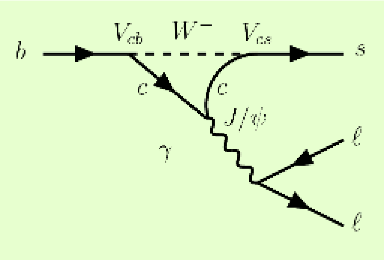
[**arXiv:1908.01848, JHEP 03 (2021) 105**]

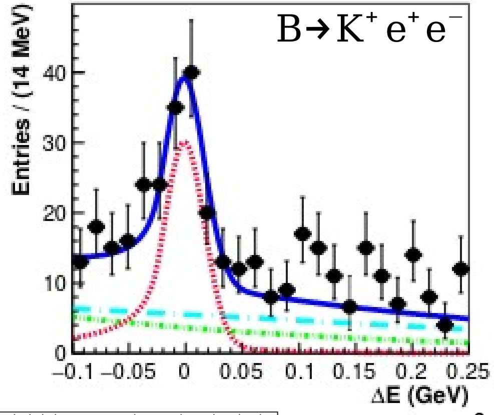


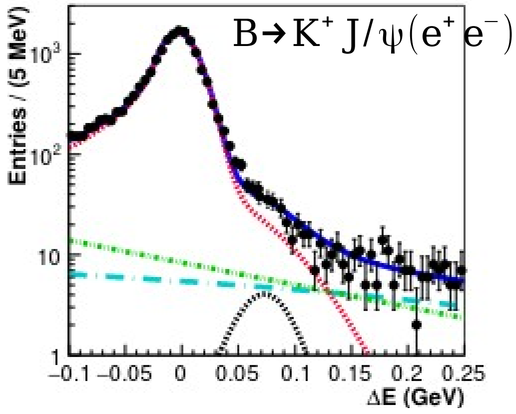


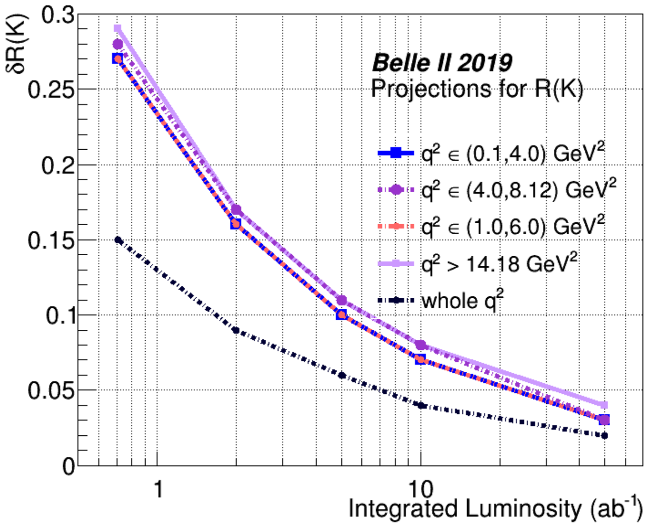


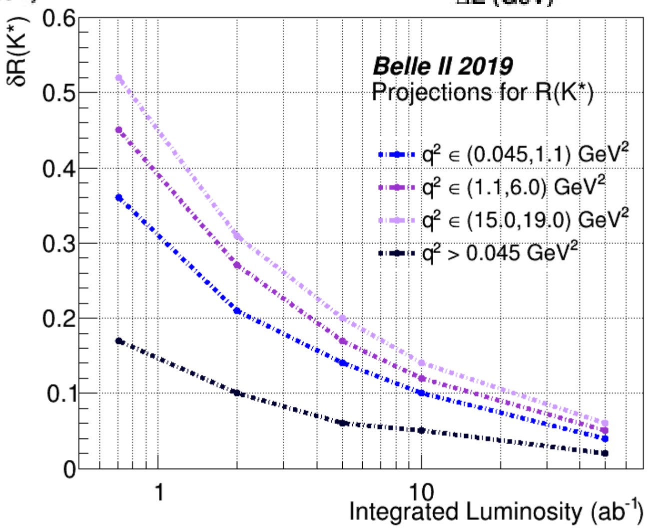




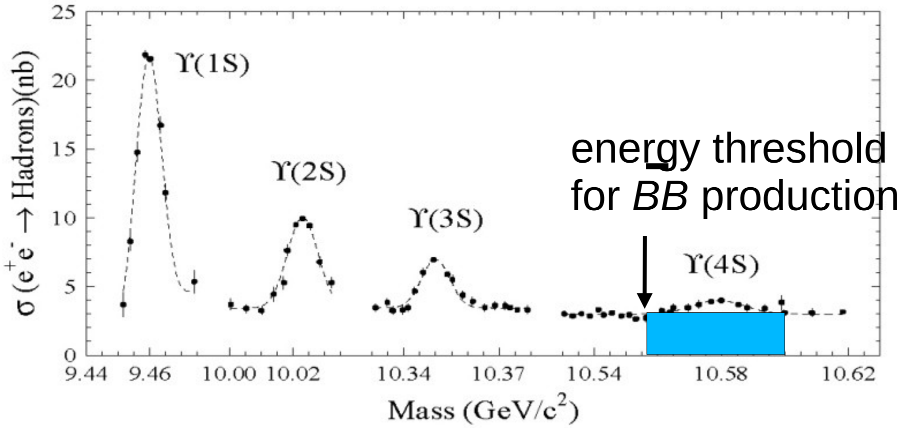


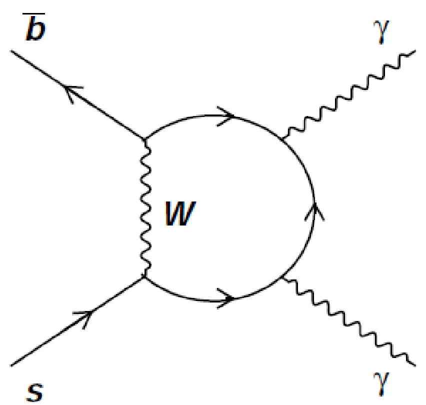


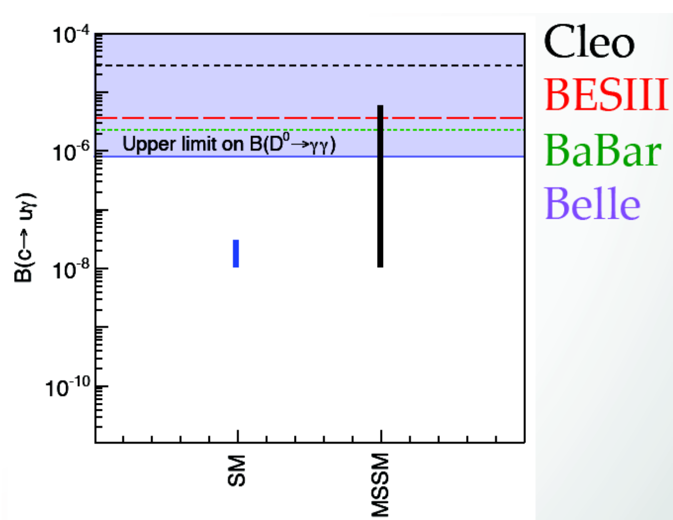




Who says we can't study B_s ?

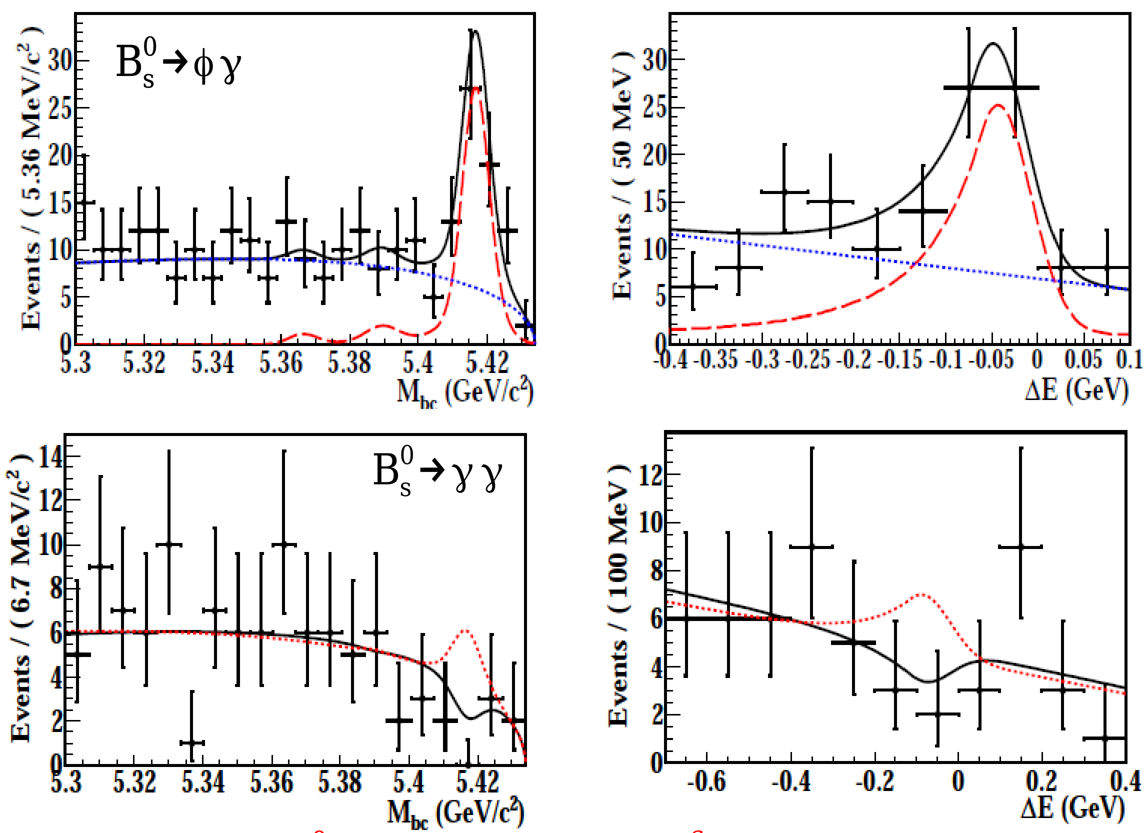






Deepanwita Dutta (IIT Guwahita) et al (Belle collaboration)
[**arXiv:1411.7771, Phys. Rev. D 91, 011101 (2015)**]

at Υ(5S), Υ(10860)



$B(B_s^0 \to \gamma\gamma) < 3.1 \times 10^{-6}$ at 90% CL

Search for the rare decay $D \to \gamma\gamma$ at Belle
Nisar NK (TIFR) et al (Belle collaboration)
[**arXiv:1512.02992, Phys. Rev. D 93, 051102 (2016)**]

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

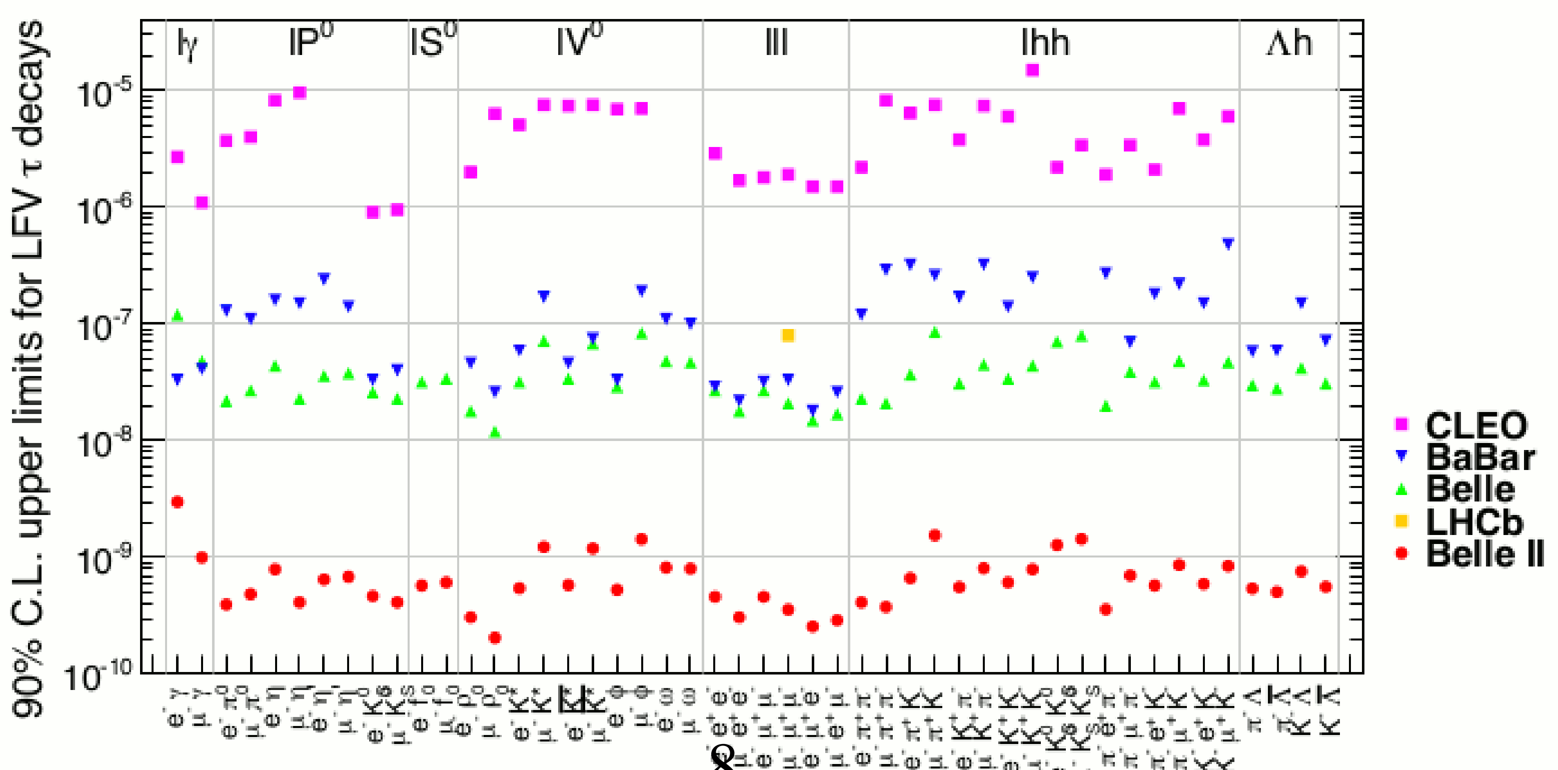
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left| U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \right|^2 < 10^{-40}$$

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

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}

	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	$O_{G\tilde{G}}$	–	–	–	–	–	✓

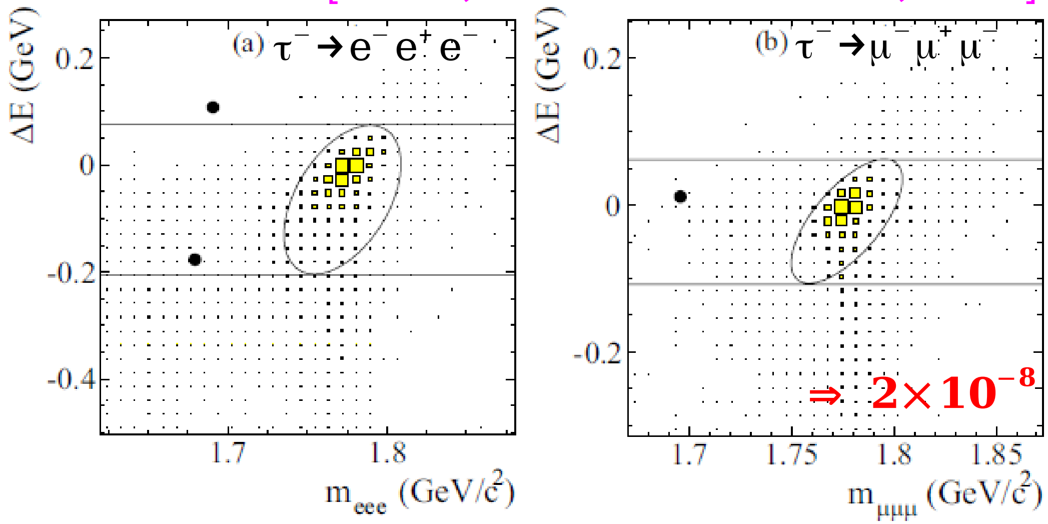
Celis, Cirigliano, Passemar (2014)



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]



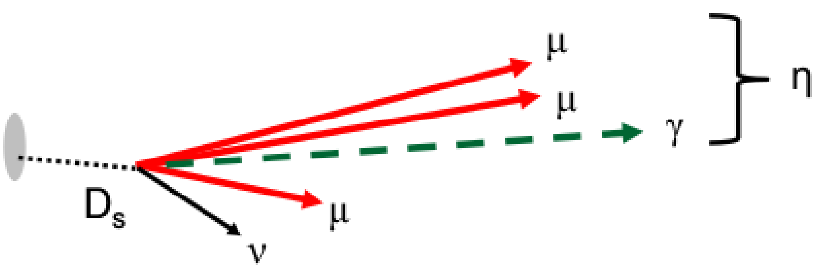
⇒ 2×10^{-8} at 90%CL

how to improve further ?

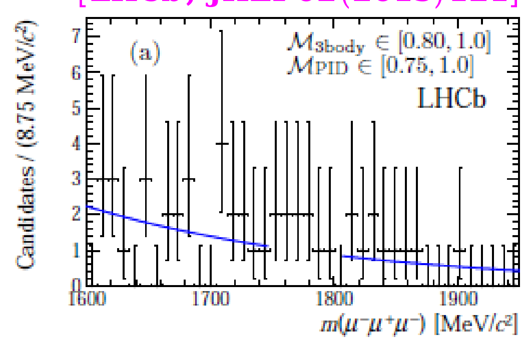
…considering $\tau\to\mu/e\,h^+h^-$ in function of one prong tag categories

…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

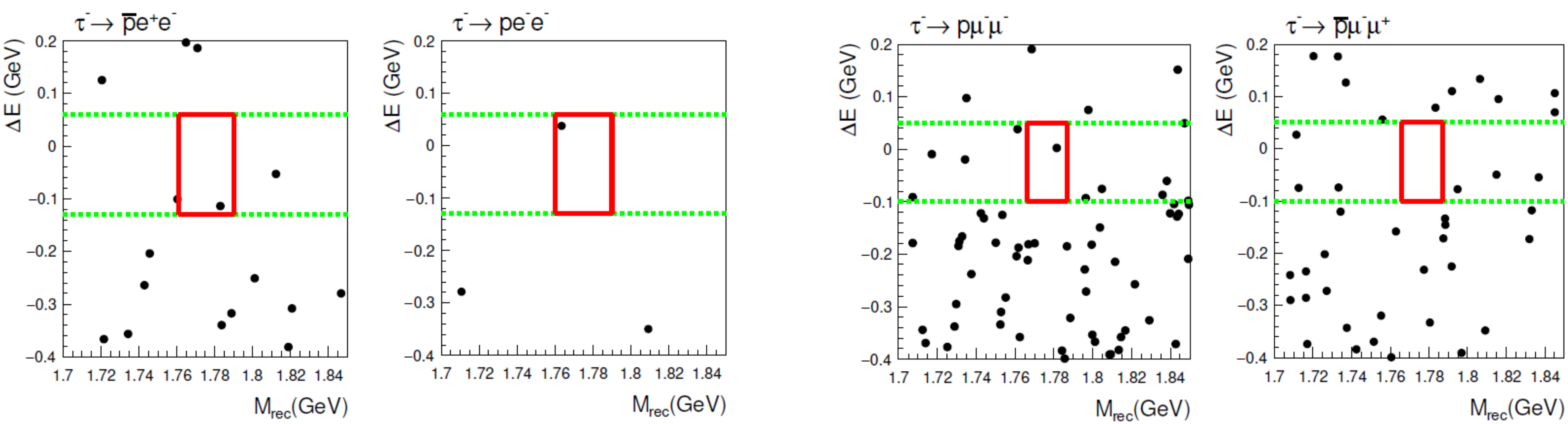
Most improvement in coming decade is expected from Belle II, which can reach 1×10^{-9} [arXiv:1011.0352] and will do even better if can achieve ~ zero bckgd

τ LFV decays

Debashis Sahoo (TIFR) et al (Belle collaboration)
[**arXiv:2010.15361, Phys. Rev. D 91, 011101 (2015)**]

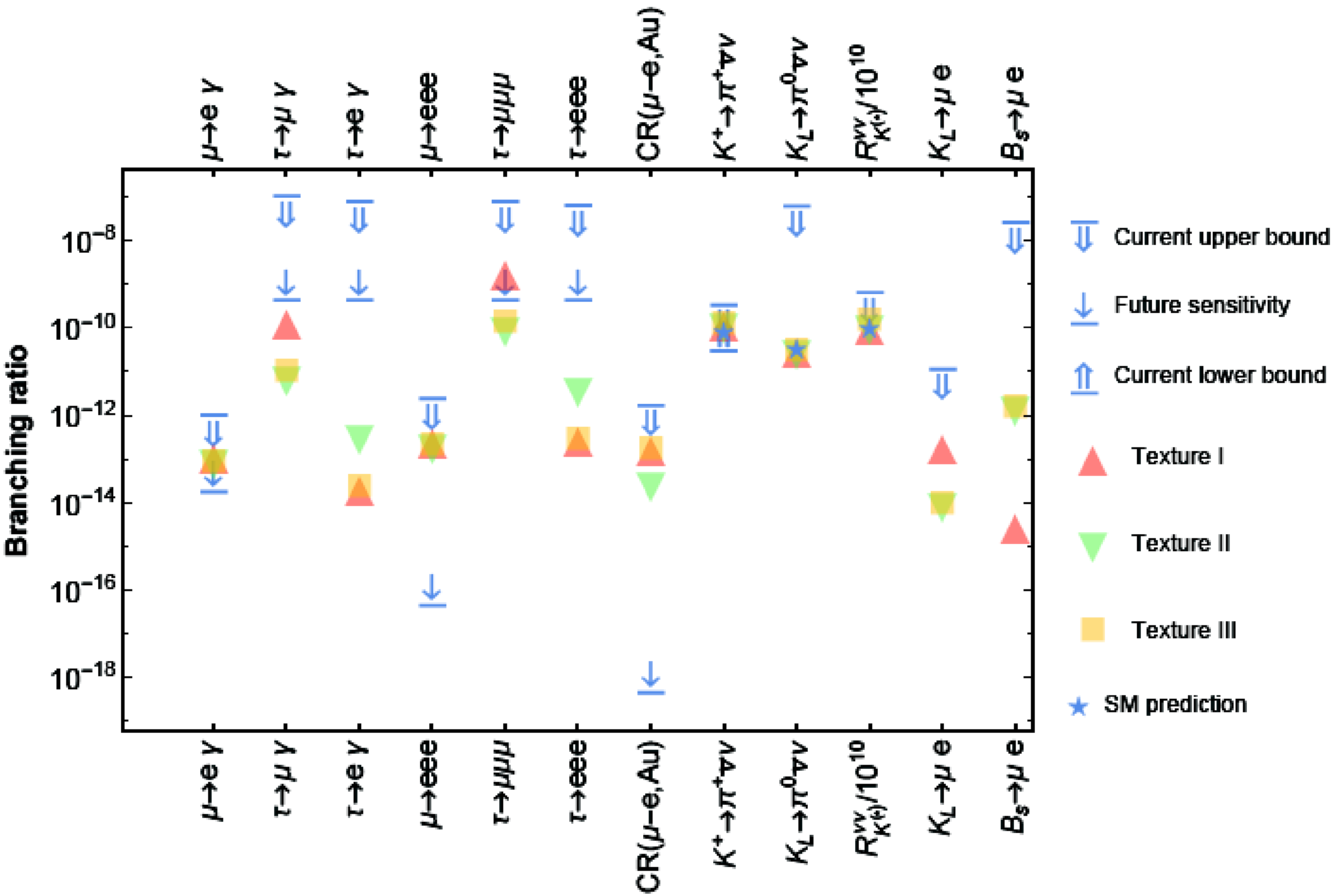
LHCb: UL for $\tau \to p\mu\mu$ at $3-4 \times 10^{-7}$ (90%CL)

We search for lepton-number- and baryon-number-violating decays $\tau^- \to \overline{p}e^+e^-$, pe^-e^-, $\overline{p}e^+\mu^-$, $\overline{p}e^-\mu^+$, $\overline{p}\mu^+\mu^-$, and $p\mu^-\mu^-$ using 921 fb^{-1} of data, equivalent to $(841 \pm 12) \times 10^6$ $\tau^+\tau^-$ events, recorded with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. In the absence of a signal, 90% confidence-level upper limits are set on the branching fractions of these decays in the range $(1.8–4.0) \times 10^{-8}$. We set the world's first limits on the first four channels and improve the existing limits by an order of magnitude for the last two channels.



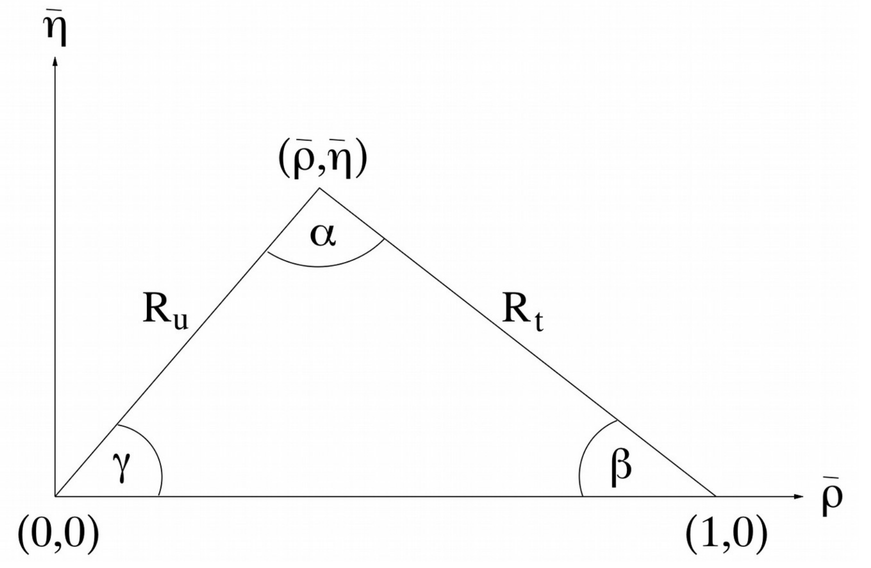
more observables...

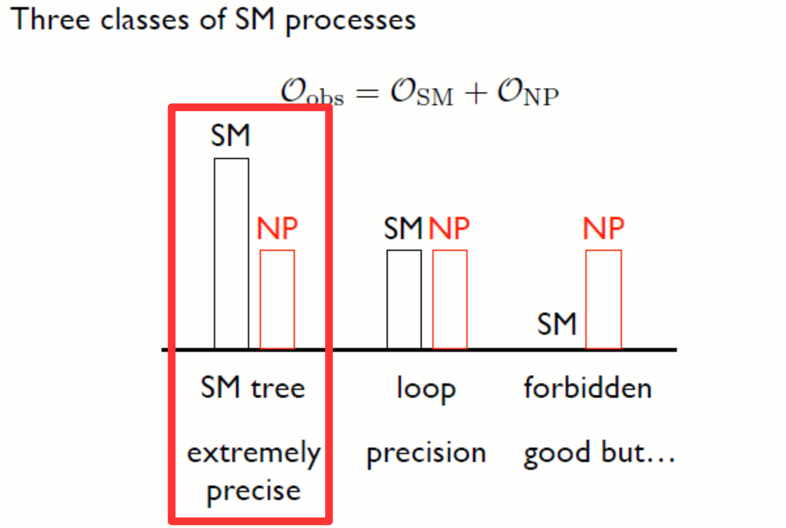
C.Hati et al, arXiv:1806.10146



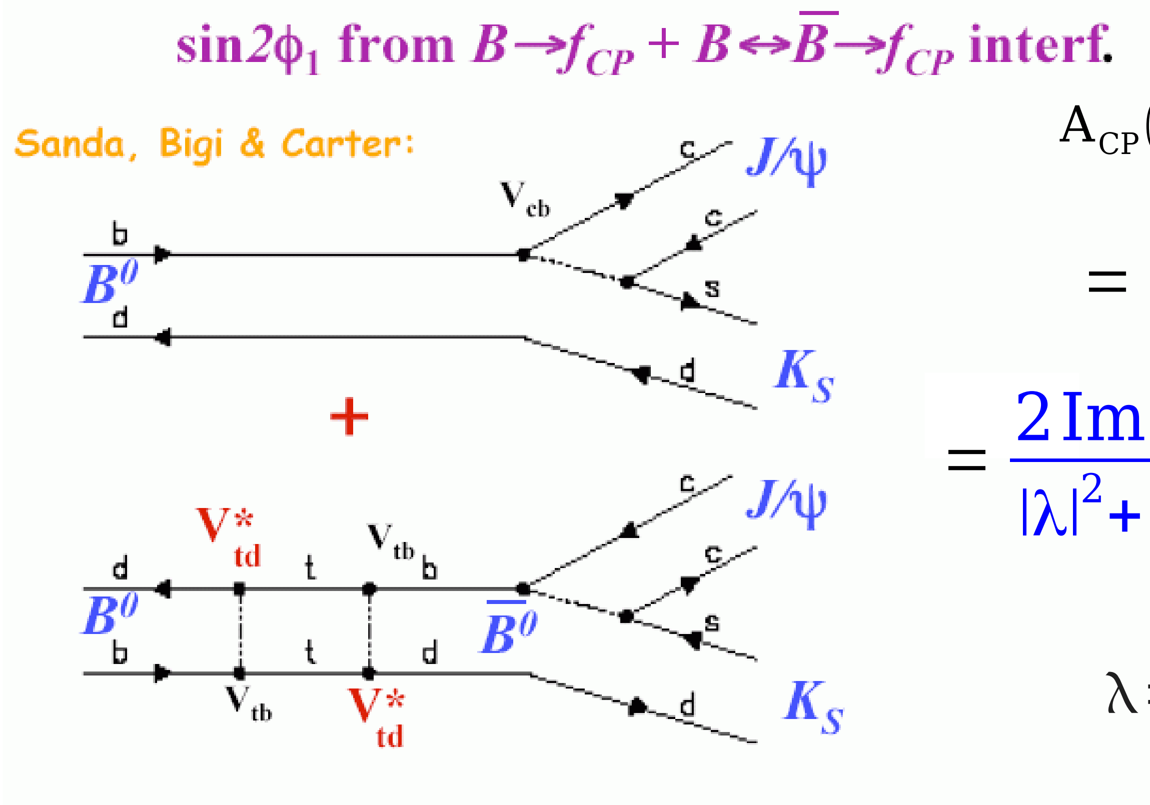
A.Datta et al, arXiv:1609.09078: interesting modes are $\tau\to 3\mu$, and $\Upsilon(3S)\to\mu\tau$

Precision measurements





Time−dependent CP asymmetries in decays to CP eigenstates



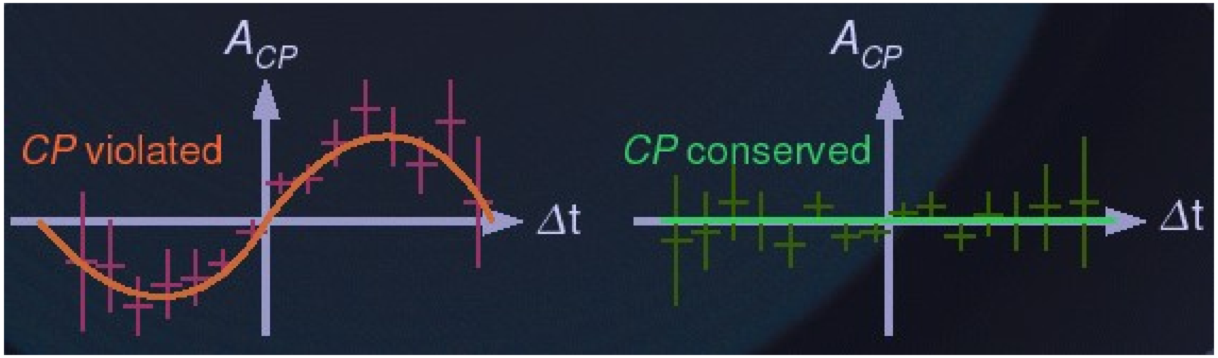
$$A_{CP}(f;t)=\frac{N(\overline{B}^0(t)\to f)-N(B^0(t)\to f)}{N(\overline{B}^0(t)\to f)+N(B^0(t)\to f)}$$

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

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

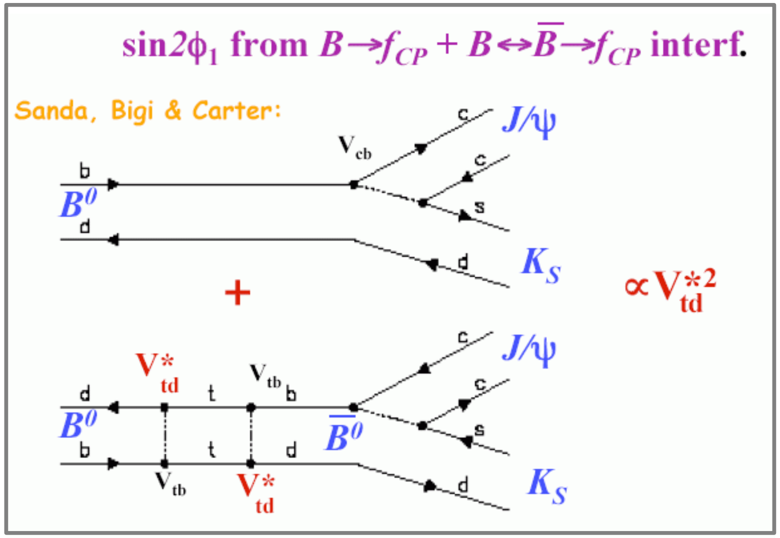
$$\lambda=\frac{q}{p}\,\frac{A(\overline{B}^0\to f)}{A(B^0\to f)}=e^{-i2\phi_i}\frac{\overline{A}_f}{A_f}$$

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

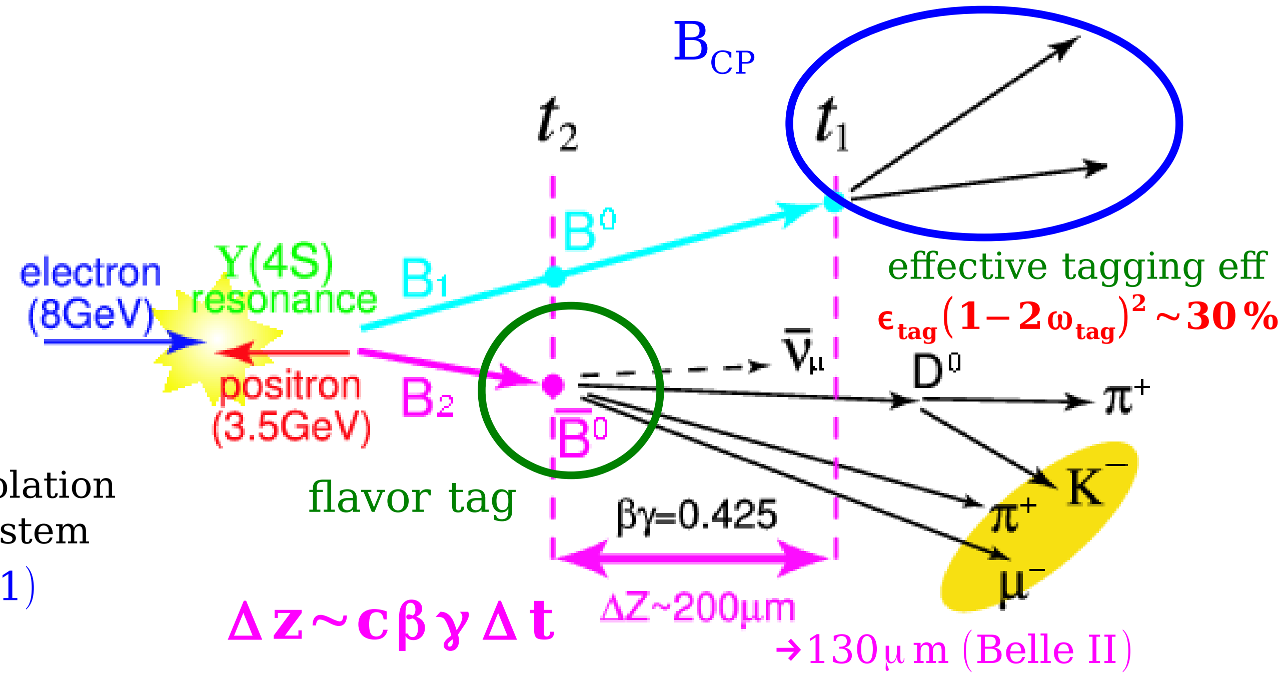


C = −A

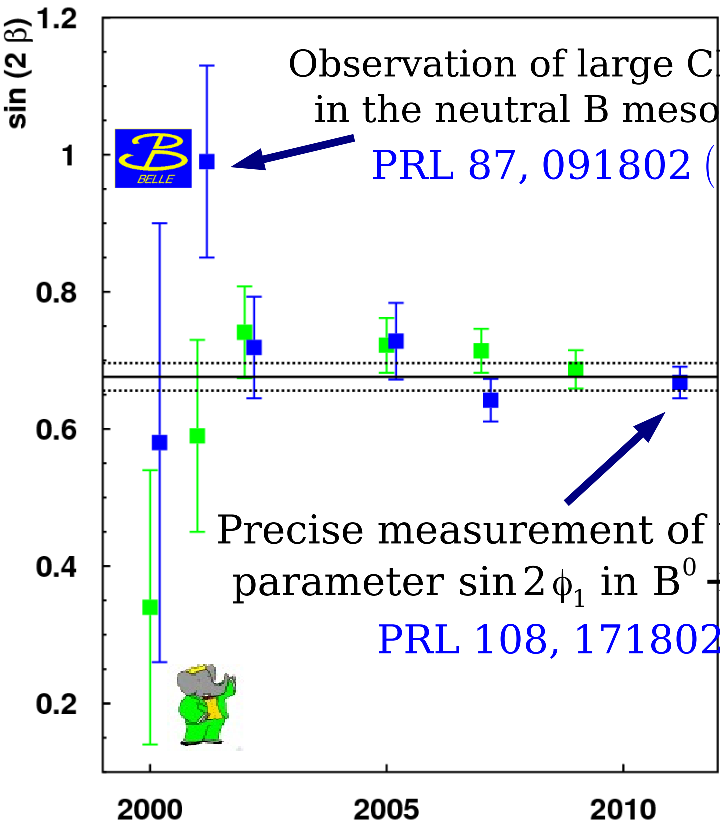
Time−dependent CP asymmetries in decays to CP eigenstates



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



Effective tagging efficiency
$\epsilon_{tag}(1-2\omega_{tag})^2\% \sim 30\%$



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)

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

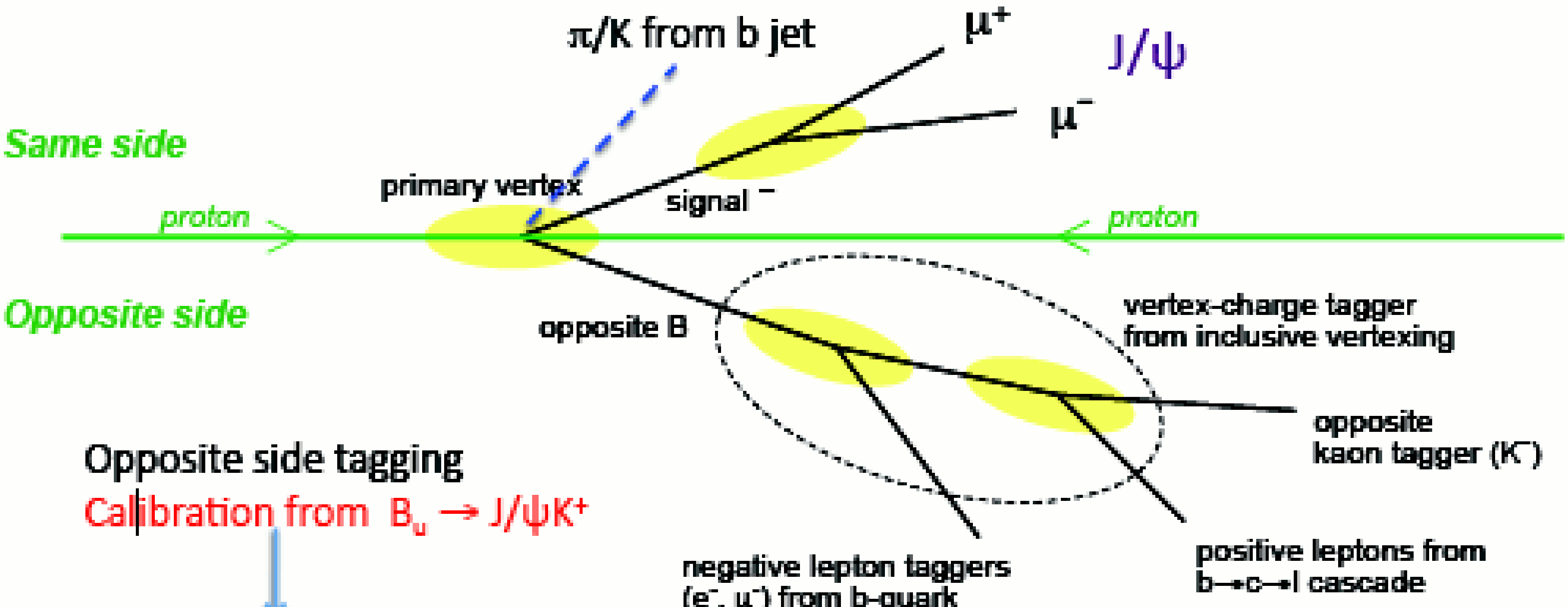
A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's

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

Flavour-Tagging at LHCb

tagging efficiency ε_{tag} ~ 50%
effective mistag ω_{tag} ~ 39%
effective tagging power $\varepsilon_{tag}(1-2\omega_{tag})^2$ ~ 2.4%

Same side Kaon tagging
Calibration from $B_s \to D_s\pi$



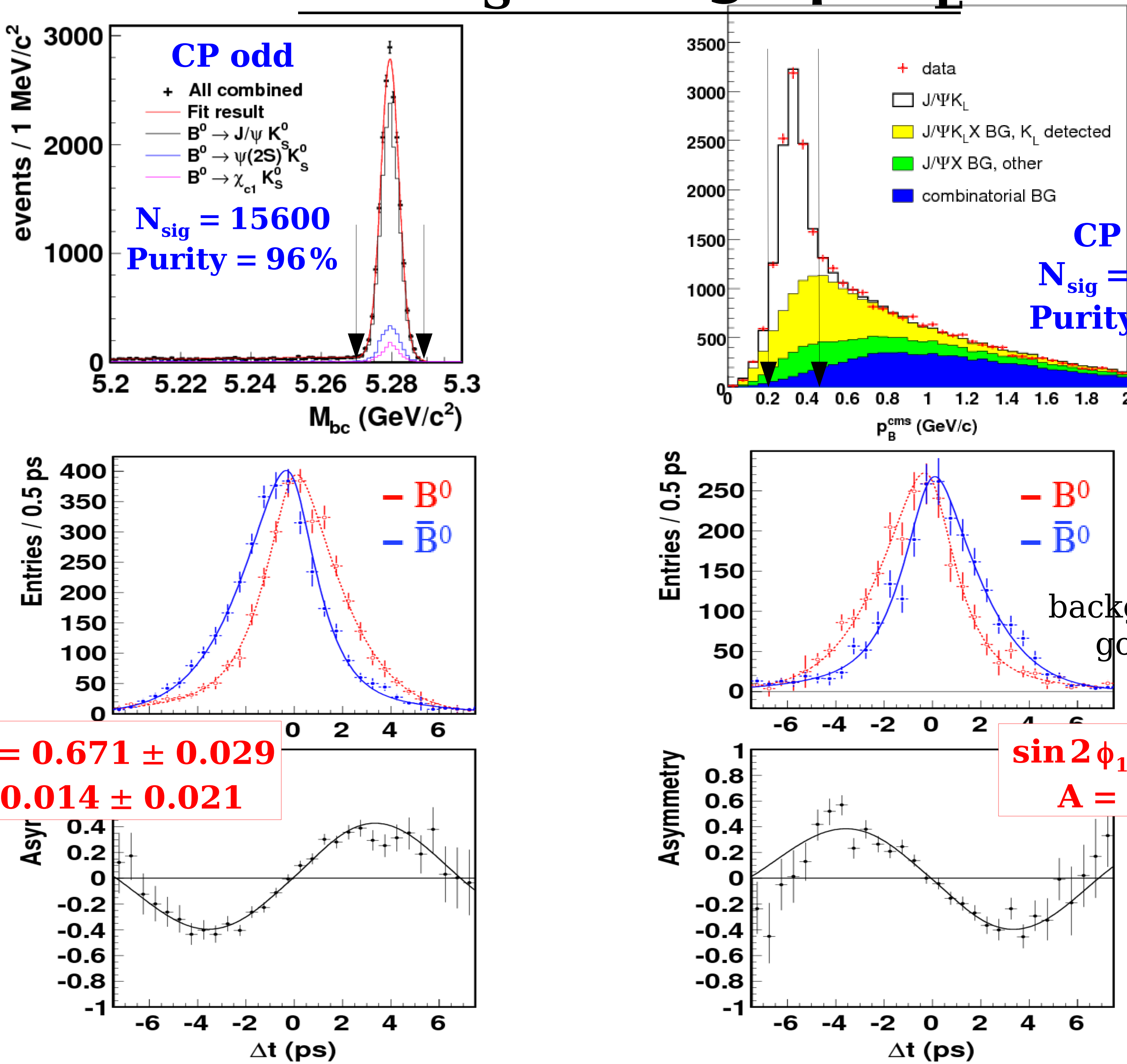
Opposite side tagging
Calibration from $B_u \to J/\psi K^+$

tagging efficiency ε_{tag} ~ 65%
effective mistag ω_{tag} ~ 39%
effective tagging power $\varepsilon_{tag}(1-2\omega_{tag})^2$ ~ 3.0%

Analyses can either use average
or per event tagging information

$c\bar{c}\,K_S$ and $J/\psi\,K_L$

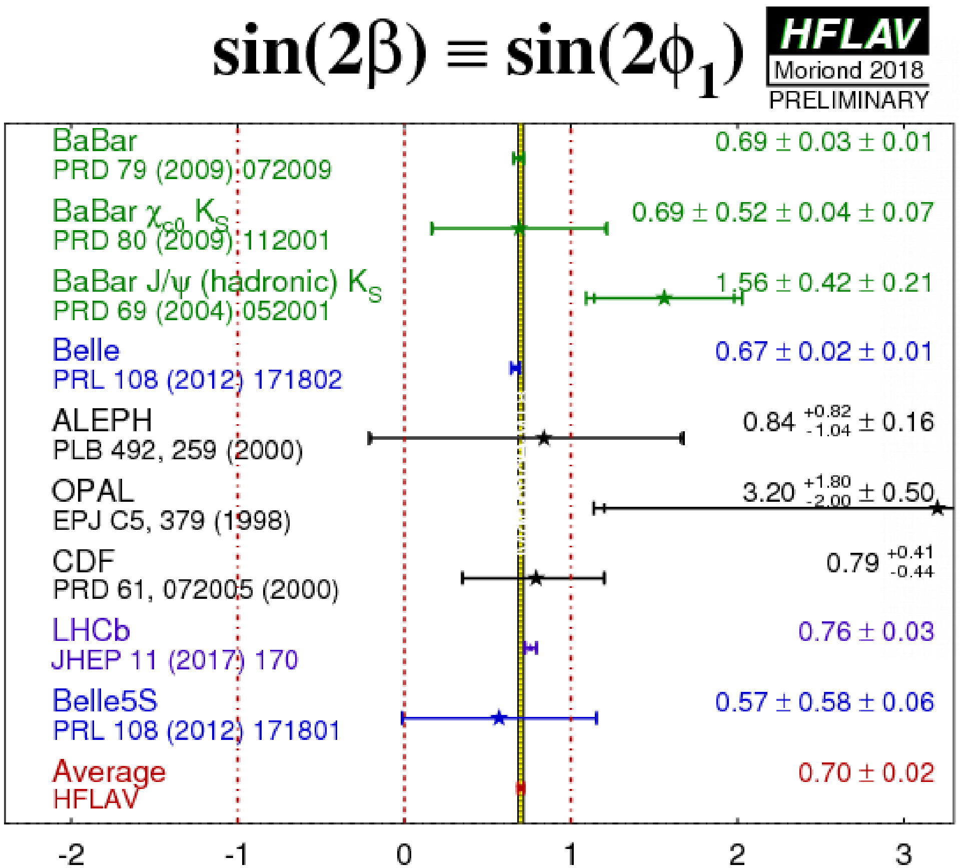
772×10^6 $B\bar{B}$ pairs

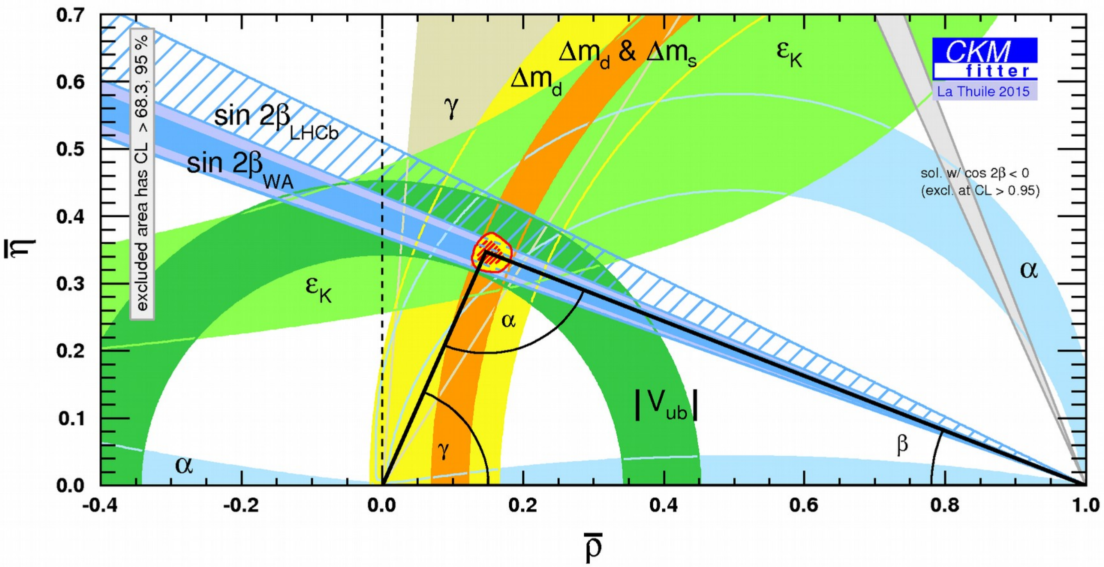


$\sin 2\phi_1 = 0.671 \pm 0.029$
$A = -0.014 \pm 0.021$

$\sin 2\phi_1 = 0.641 \pm 0.047$
$A = 0.019 \pm 0.026$

Measurement of $\sin 2\beta$





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

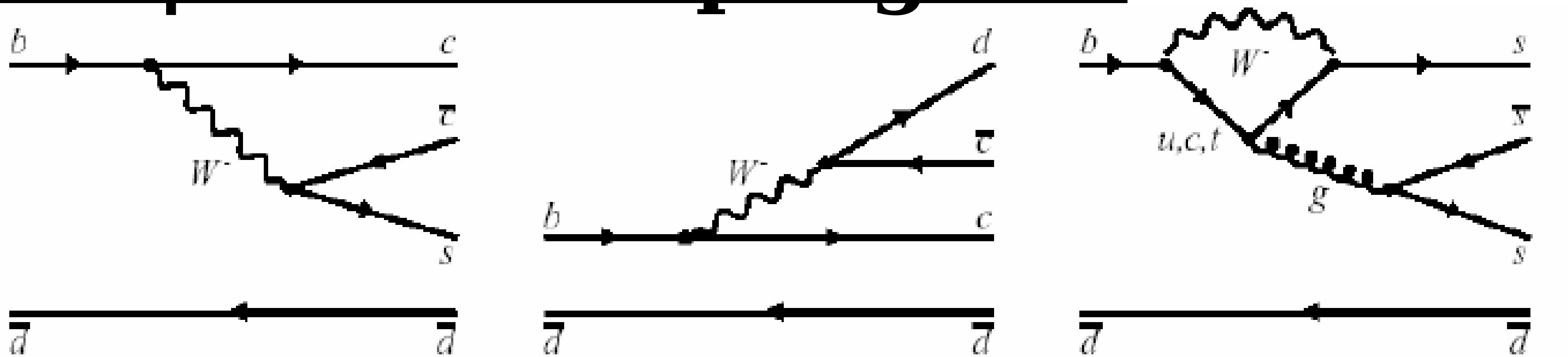
$\sin 2\beta$ at Belle II

	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 ←

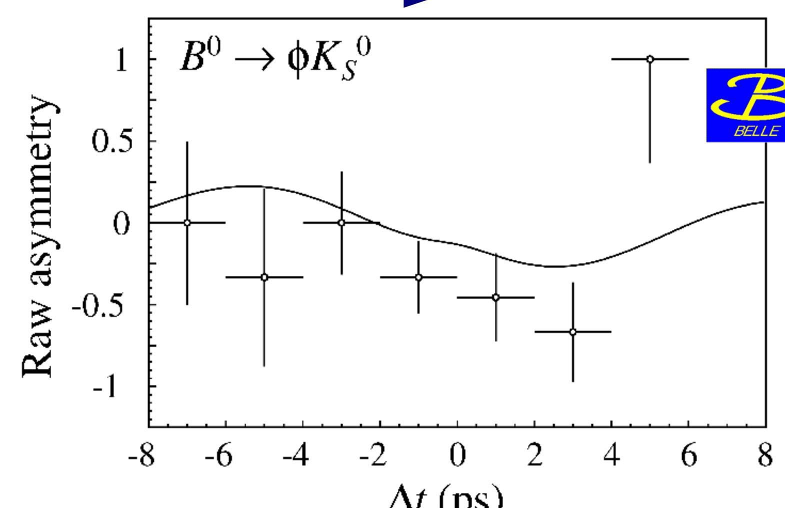
increasing sensitivity to new physics →

EX−ANOMALY !

first reported in Moriond EW 2002

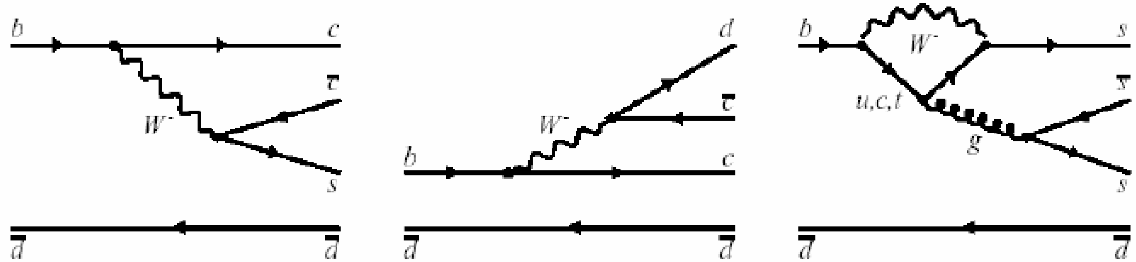
"$\sin 2\beta$" $= -0.73 \pm 0.64 \pm 0.22$

[PRD 67, 031102 (2003)]



sin 2β with b→s penguins

dominated by B-factories

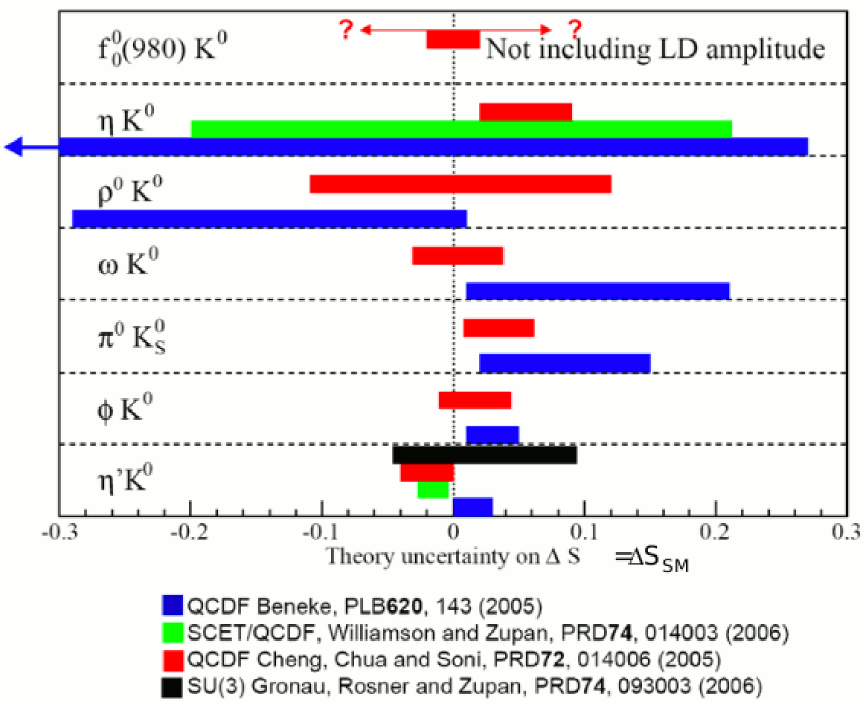


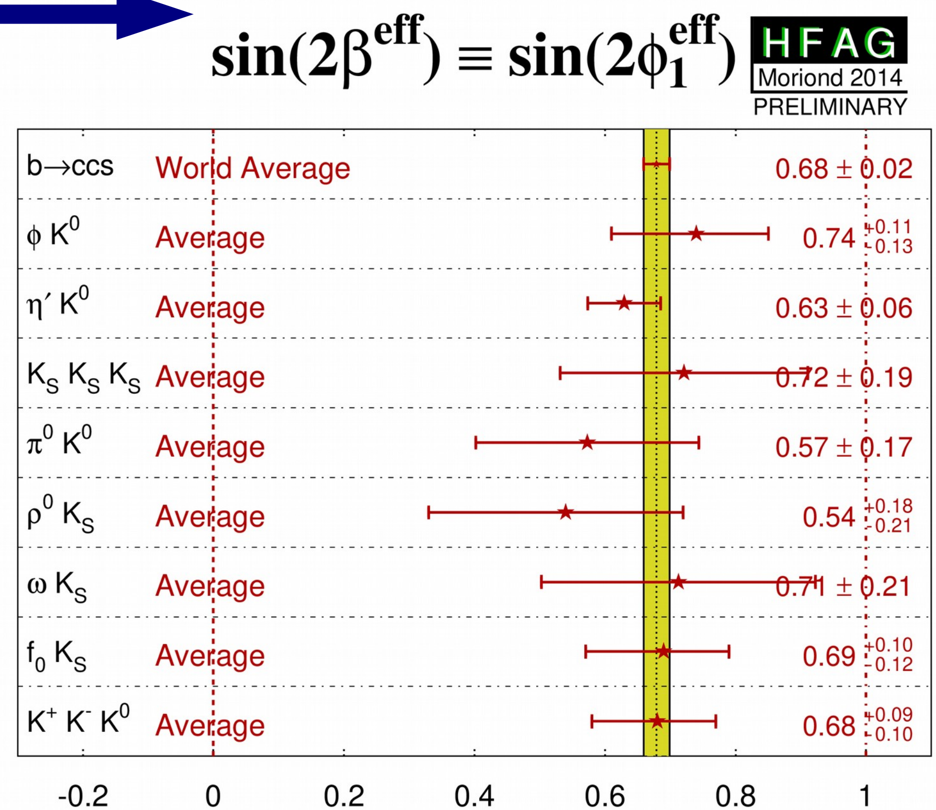
$J/\psi K^0_S, \psi(2S)K^0_S, \chi_{c1}K^0_S,$ $\eta_c K^0_S, J/\psi K^0_L,$ $J/\psi K^{*0}(K^{*0} \to K^0_S \pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K^0_S,$ $K^0_S K^0_S K^0_S, \eta' K^0, K^0_S\pi^0,$ $\omega K^0_S, f_0(980)K^0_S$

increasing tree diagram amplitude ←

increasing sensitivity to new physics →

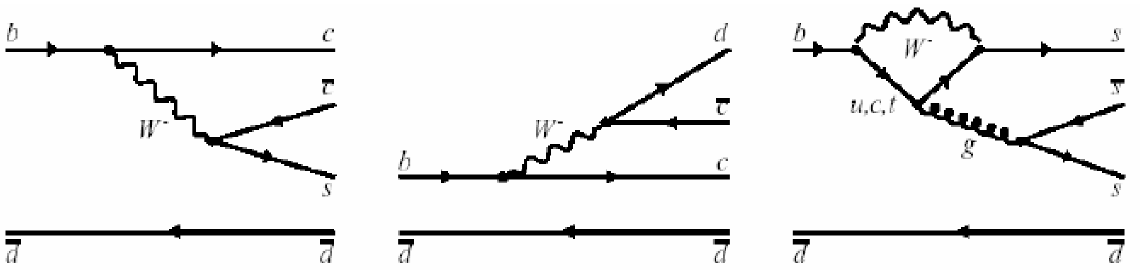
More statistics crucial for mode-by-mode studies





sin 2β with b→s penguins

dominated by B-factories

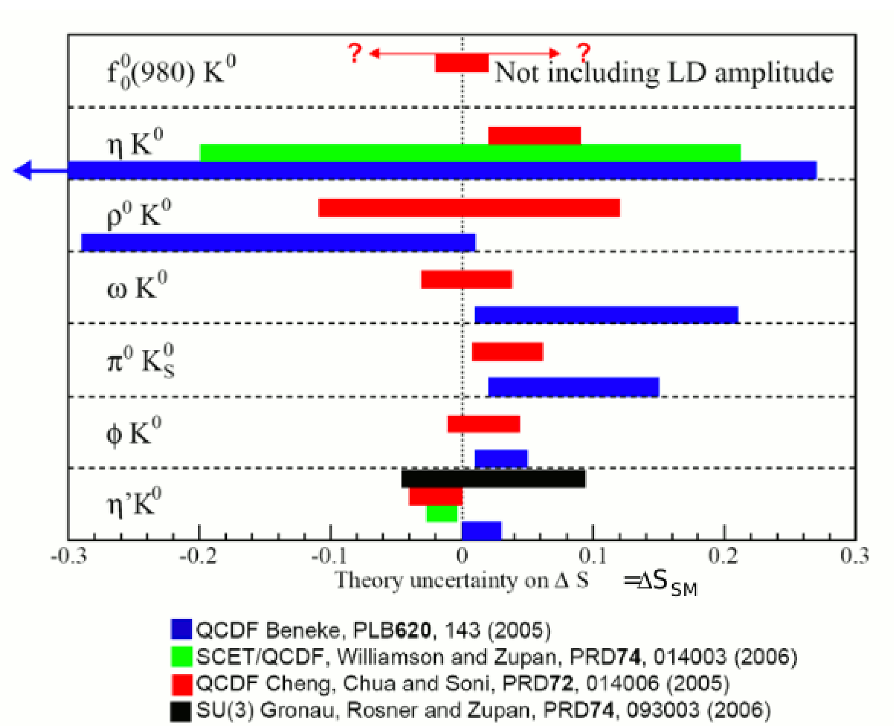


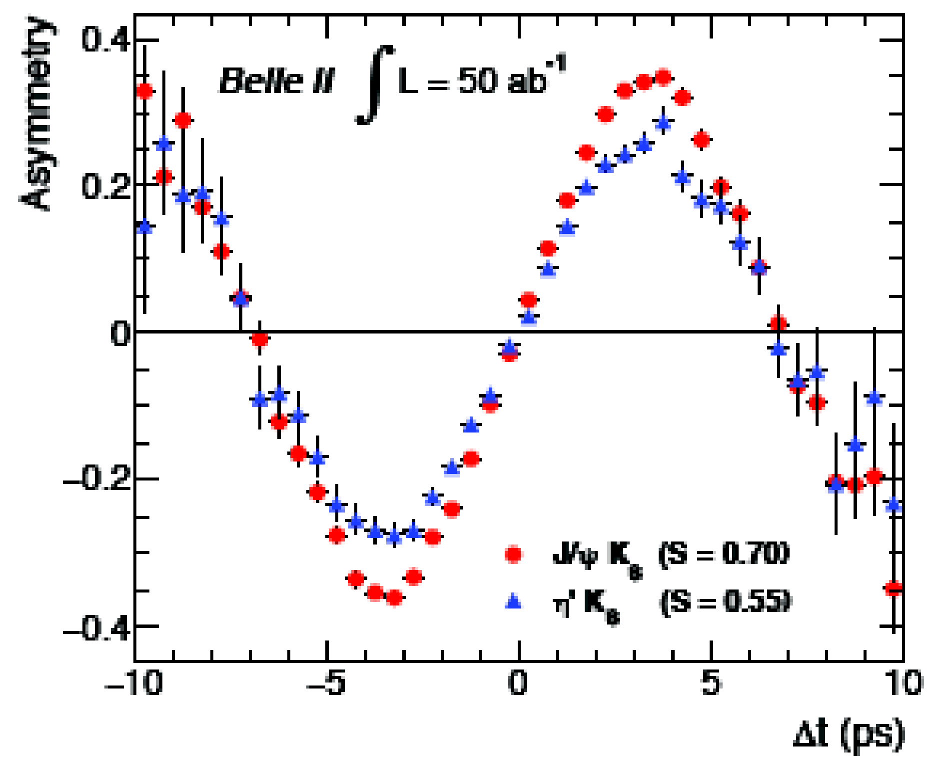
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \to K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0,$ $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$

← increasing tree diagram amplitude

increasing sensitivity to new physics →

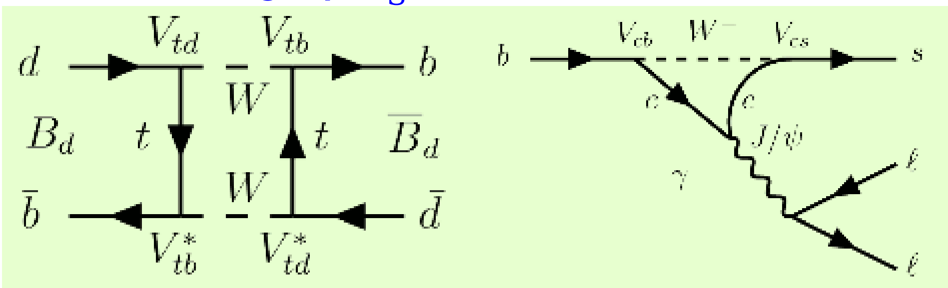
Channel	$\int \mathcal{L}$	Event yield	$\sigma(S)$	$\sigma(A)$
ϕK^0	5 ab^{-1}	5590	0.048	0.035
$\eta' K^0$	5 ab^{-1}	27200	0.027	0.020
ωK_S^0	5 ab^{-1}	1670	0.08	0.06
$K_S\pi^0\gamma$	5 ab^{-1}	1400	0.10	0.12
$K_S\pi^0$	5 ab^{-1}	5699	0.09	0.10



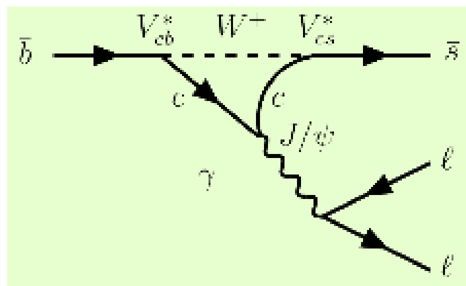


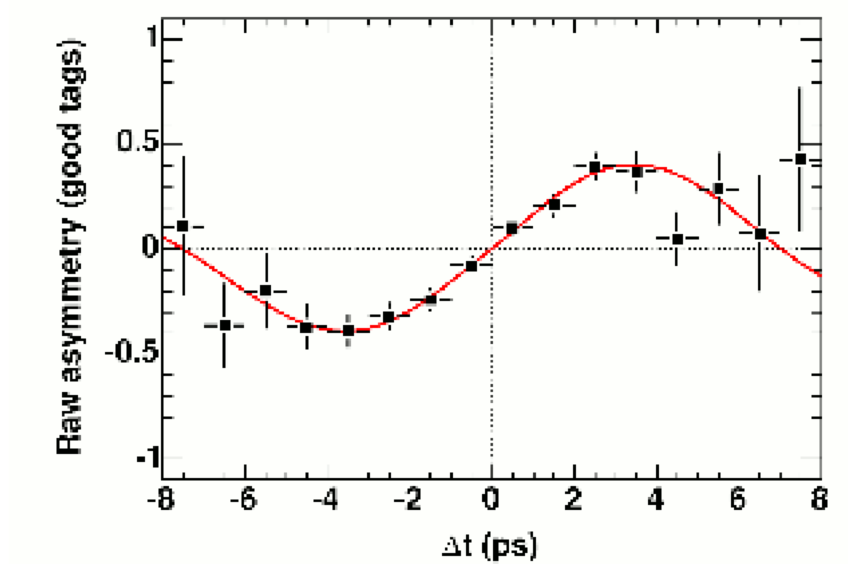
Mixing-induced CP violation

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

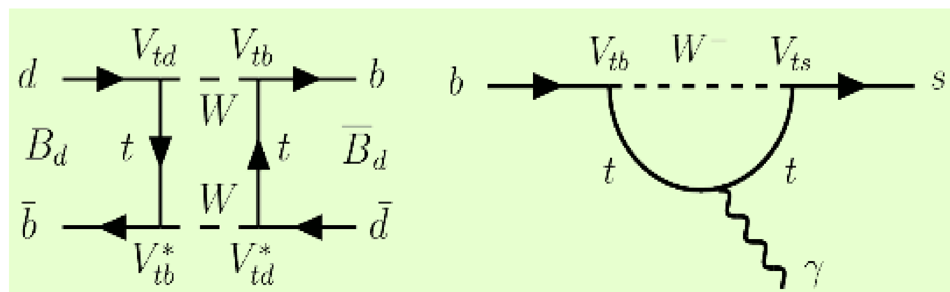


interferes with

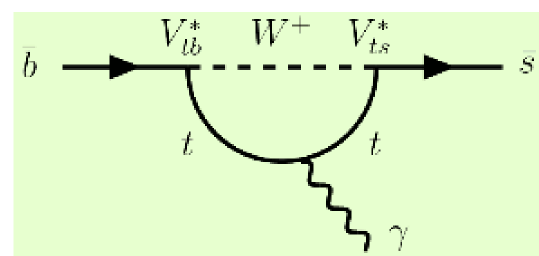




What about $B^0 \to \gamma K^0_S \pi^0$?



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 $S \sim -2(m_s/m_b)\sin(2\phi_1)$

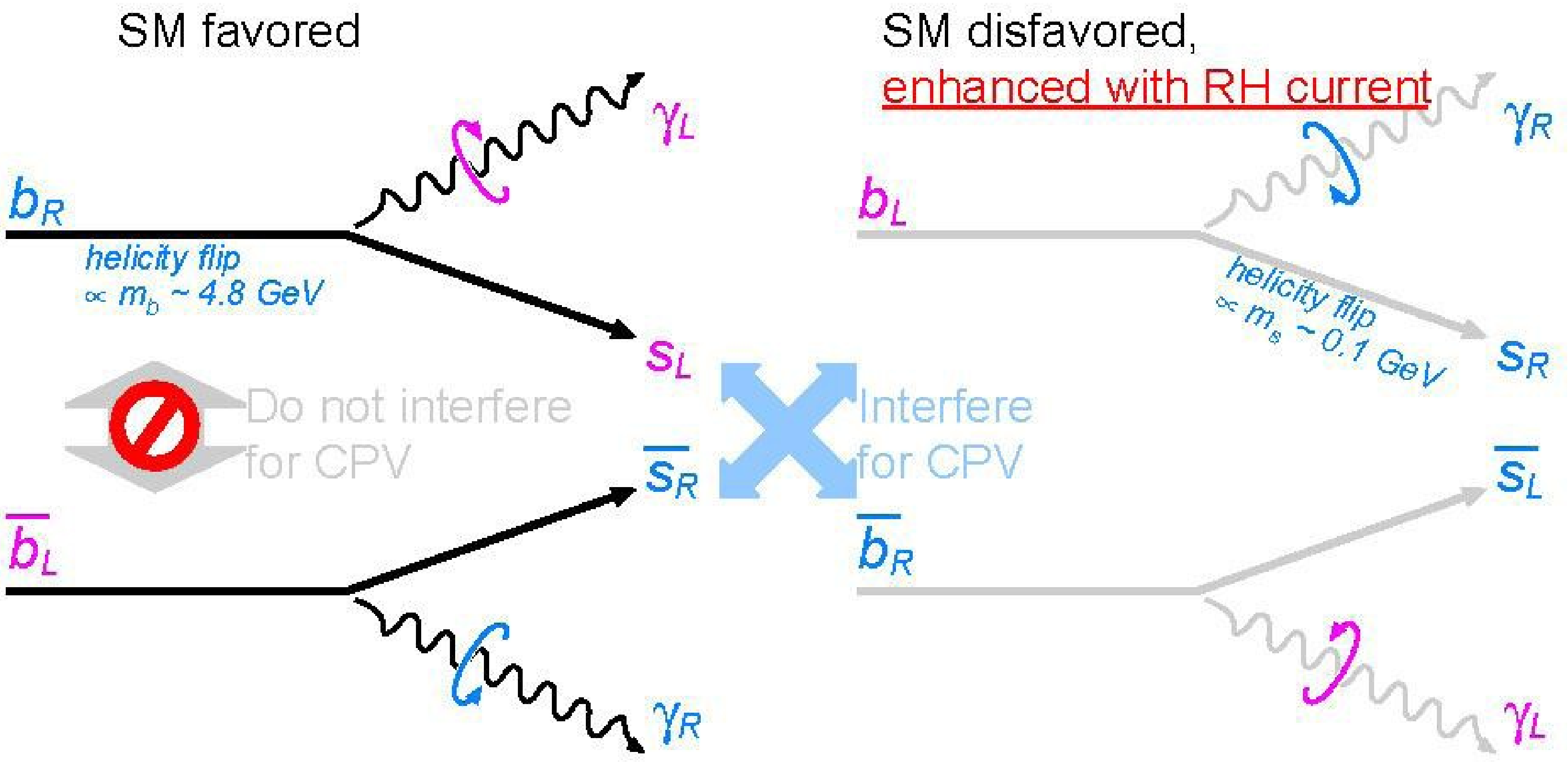
$B \to K^*(K^0_S \pi^0)\gamma$

time−dependent 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).

$\Rightarrow$ 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 $K^0_S \pi^0 \gamma$

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

  ⇒ 30% more K_S with vertex hits available, effective tagging eff. 13% better

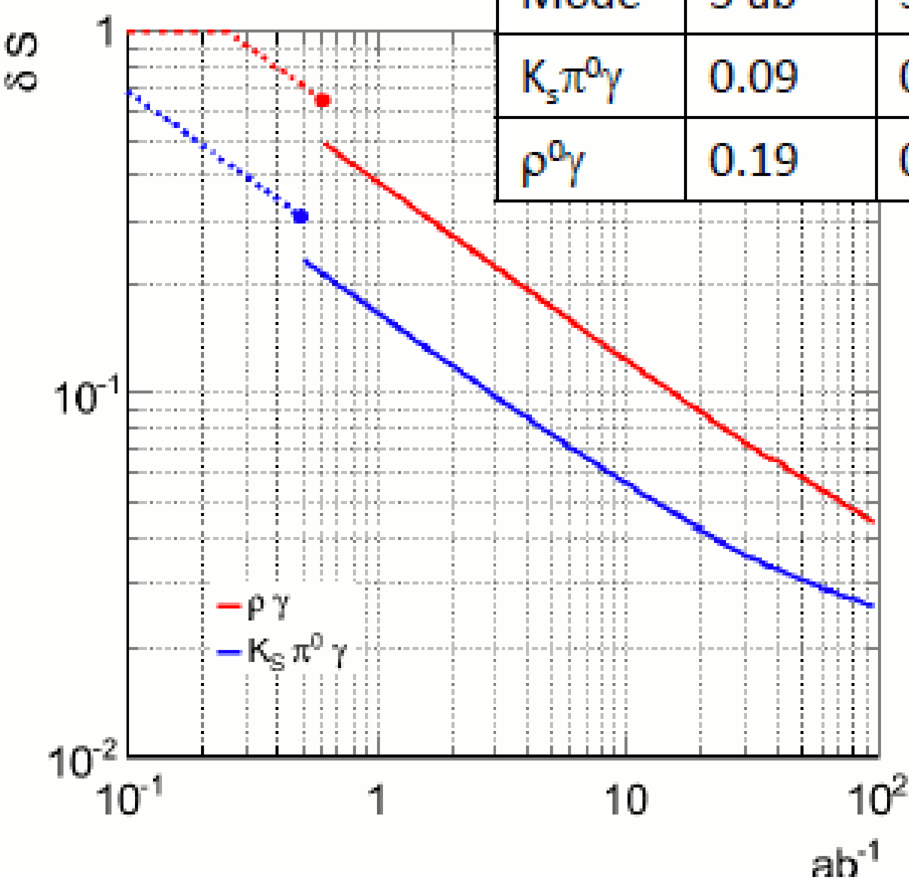
HFLAV

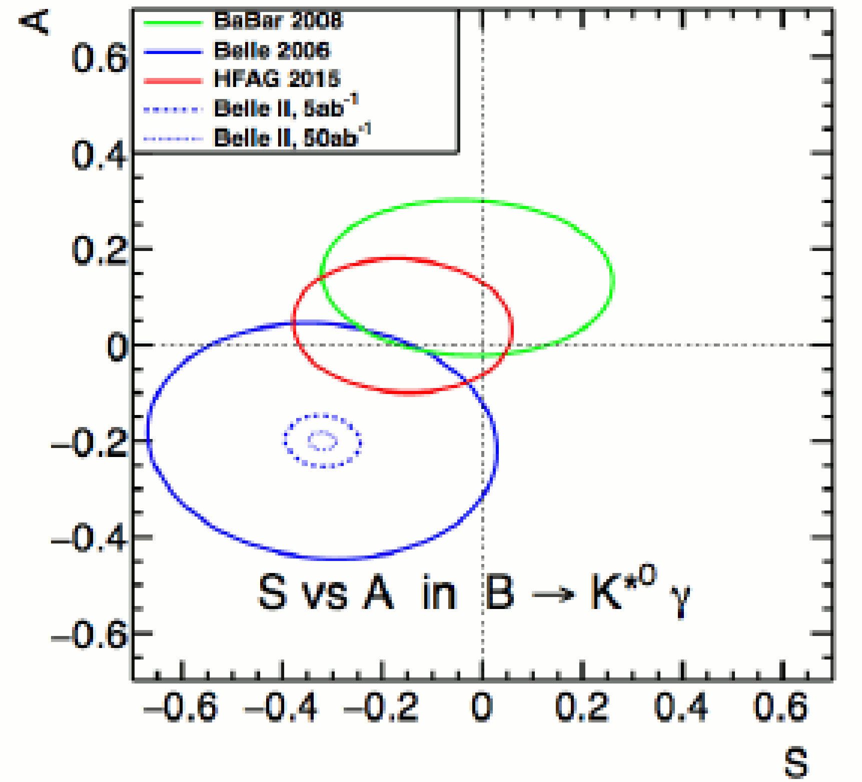
$S_{CP}^{K^{*0}\gamma} = -0.16 \pm 0.22$

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

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

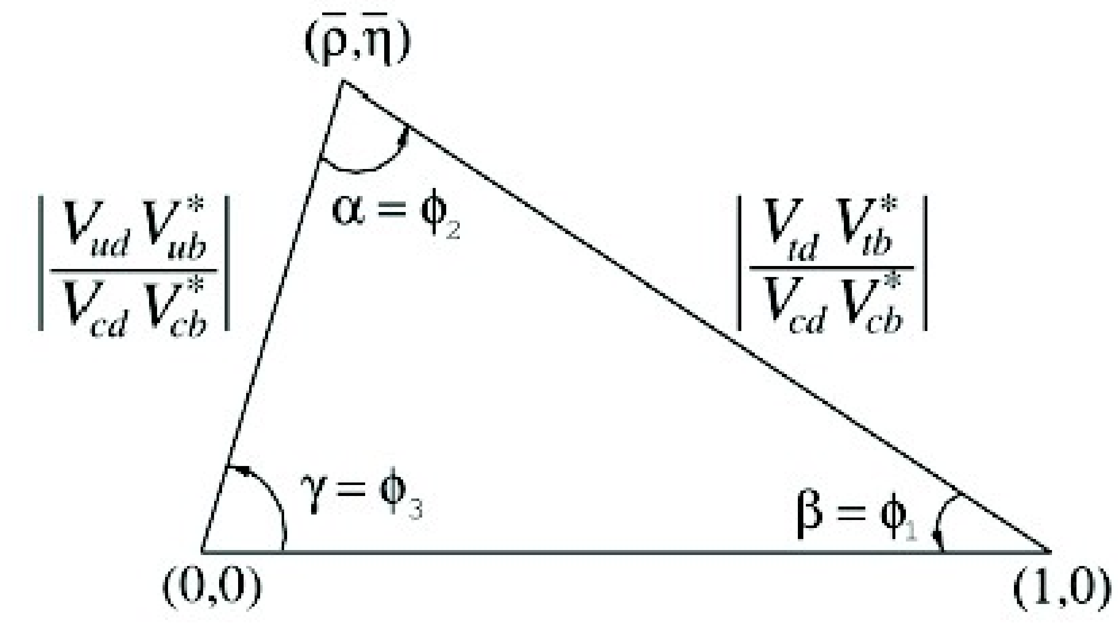
Mode	5 ab^{-1}	50 ab^{-1}
$K_s\pi^0\gamma$	0.09	0.030
$\rho^0\gamma$	0.19	0.064





16σ deviation with 50 ab^{-1}.

Motivation



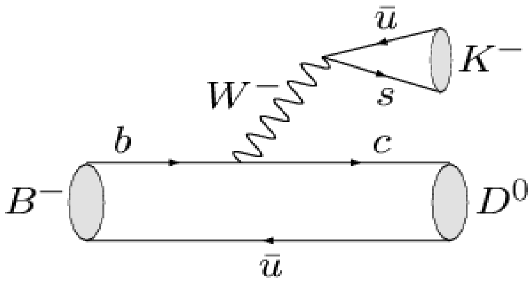
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),\ \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),\ \boldsymbol{\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)}$$

In Wolfensteing parameterisation, up to order λ^4, all the CKM elements involved are real except V_{ub}^* and V_{td}:

$$\alpha \approx \arg\left(-\frac{V_{td}}{V_{ub}^*}\right),\ \beta \approx \arg\left(-V_{td}^*\right),\ \boldsymbol{\gamma \approx \arg\left(-V_{ub}^*\right)}$$

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

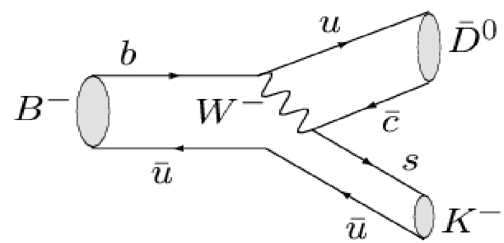
- Theoretically pristine $B \to DK$ approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



color allowed

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

$\sim A\lambda^3$



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

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

relative weak phase is γ

relative strong phase is δ_B

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

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

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

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

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

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

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

$B \to \ldots$

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

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

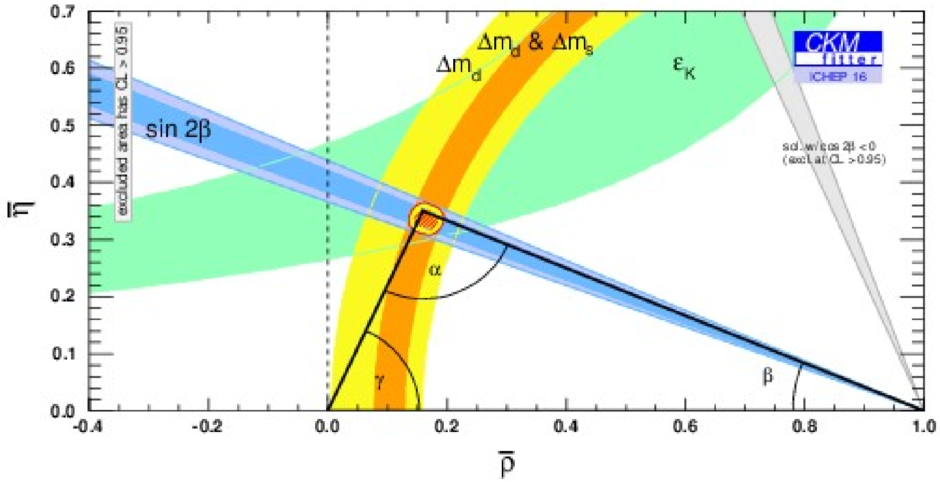
$D \to KK\pi^0,\ \pi\pi\pi^0 \ldots$

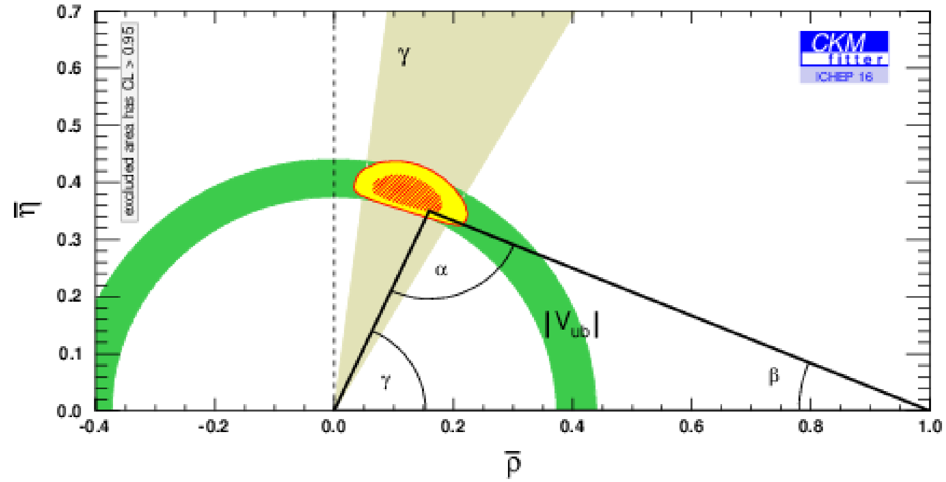
$D \to K_S \pi\pi, K_S KK$

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

$D \to \ldots$

Motivation





Loop processes more easily altered by presence of NP

Loop vs Tree

constraints on the apex of UT currently more stringents from loop measurements

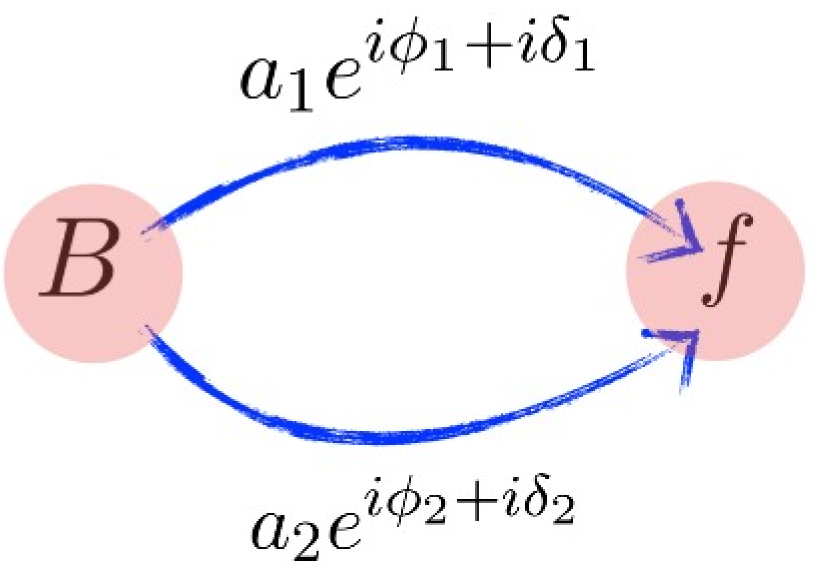
Why γ is a key goal ?

γ is least well measured parameter of UT
Theoretically pristine
with LHCb and Belle II the ideal degree level precision is possible

Direct CPV (CPV in decay)

$$Asym_f \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{1 - |A_f/\bar{A}_f|^2}{1 + |A_f/\bar{A}_f|^2}$$

In order to have non-vanishing CP asymmetry, $Asym \neq 0$, the $B \to f$ decay amplitude needs to receive contributions from (at least) two different terms with differing weak, $\phi_{1,2}$, and strong phases, $\delta_{1,2}$



$$A_f = a_1 e^{i\phi_1 + i\delta_1} + a_2 e^{i\phi_2 + i\delta_2},$$

$$\bar{A}_f = a_1 e^{-i\phi_1 + i\delta_1} + a_2 e^{-i\phi_2 + i\delta_2}.$$

Direct CPV (CPV in decay)

$$A_f = a_1 e^{i\phi_1 + i\delta_1} + a_2 e^{i\phi_2 + i\delta_2},$$
$$\bar{A}_f = a_1 e^{-i\phi_1 + i\delta_1} + a_2 e^{-i\phi_2 + i\delta_2}.$$

The weak phases are due to CKM phase in the SM Lagrangian and change the sign under CP transformation, while the strong phases are due to on-shell rescattering of particles (pions, etc) and are thus CP even, the same as QCD interactions. The CP asymmetry is, in simplifying limit $a_2/a_1 \ll 1$,

$$\mathcal{A}_f = \frac{a_2}{a_1}\sin(\phi_2 - \phi_1)\sin(\delta_2 - \delta_1) + \mathcal{O}(a_2^2/a_1^2).$$

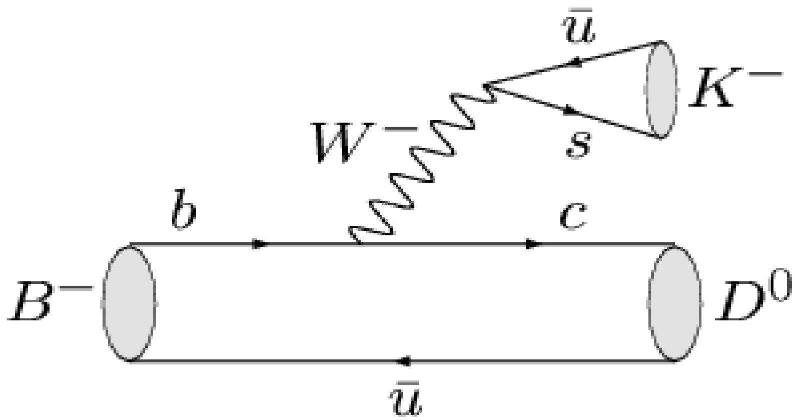
The CP asymmetry vanishes in the limit where either

(i) there is only one contribution to the amplitude $a_2 \to 0$
(ii) if the weak phase difference vanishes, $\phi_2 - \phi_1 \to 0$
(iii) if the strong phase difference vanishes, $\delta_2 - \delta_1 \to 0$

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

- Theoretically pristine $B \to DK$ approach

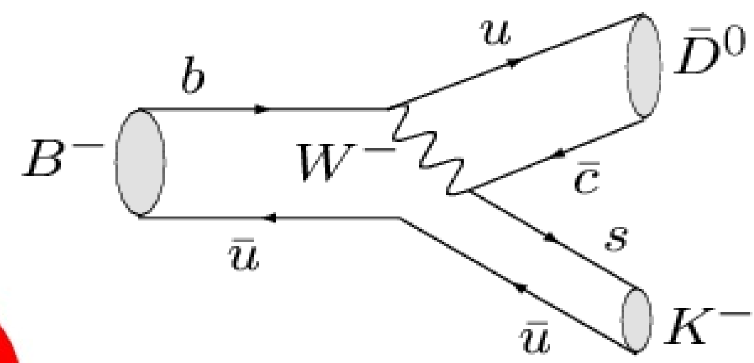
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$



color allowed

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

$\sim A\lambda^3$



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

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

CKM elements involved are $\frac{V_{cs} V_{ub}^*}{V_{us} V_{cb}^*}$ while $\gamma \equiv \arg\left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)$

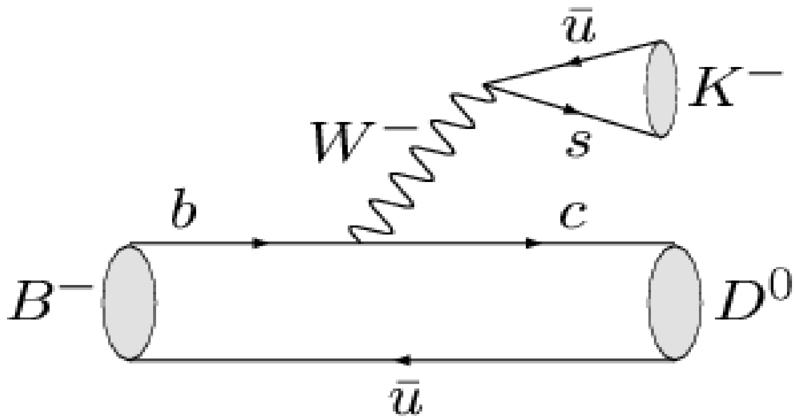
$$\Rightarrow \frac{V_{cd} V_{cs}}{V_{ud} V_{us}} = -1 + \frac{A\lambda^4}{2} - A^2\lambda^5\left(\rho + i\eta - \frac{1}{2}\right) + O(\lambda^6)$$

$\Rightarrow$ leading order correction on γ is of the order $\lambda^5 \sim 10^{-4}$ (negligible)

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

- Theoretically pristine $B \to DK$ approach

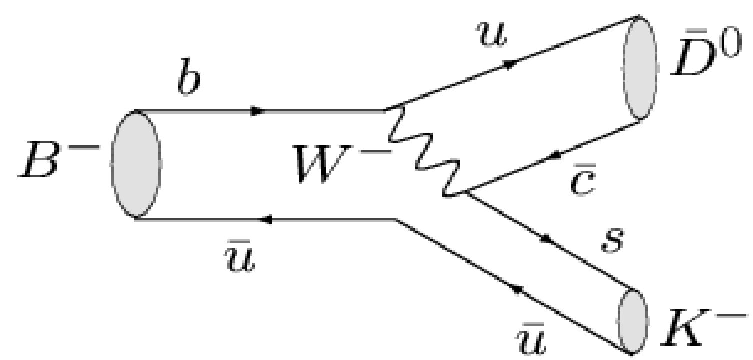
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



color allowed

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

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



color suppressed

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

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

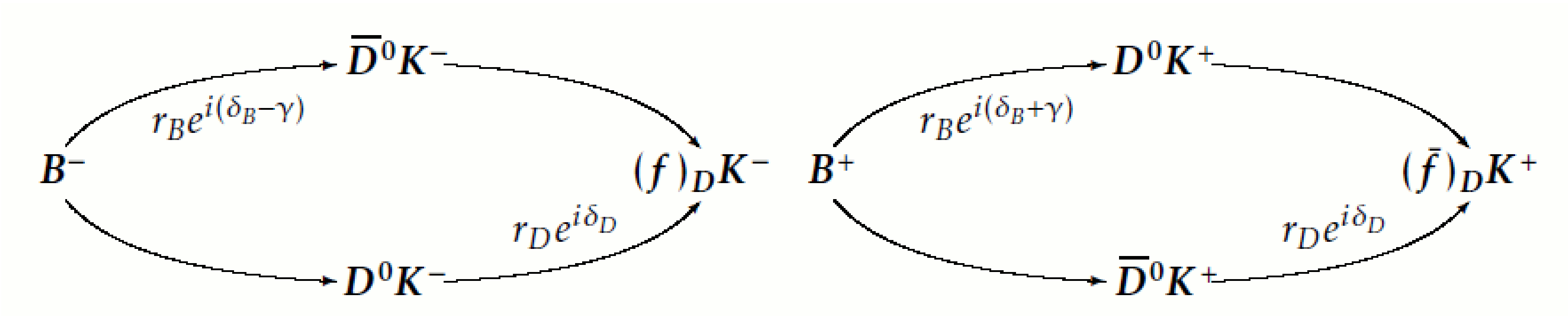
relative magnitude of suppressed amplitude is r_B

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

relative weak phase is γ, relative strong phase is δ_B

$\Rightarrow$ for $D\pi$: same dependence to γ, but different $r_B \sim 0.01$ $(V_{us} \to V_{ud},\ V_{cs} \to V_{cd})$

γ, first principles…



$$A(B^-\to D^0K^-) = A_B \text{ and } A(B^-\to \overline{D}^0K^-) = A_B r_B e^{i(\delta_B-\gamma)}$$

$$A(B^+\to \overline{D}^0K^+) = A_B \text{ and } A(B^+\to D^0K^+) = A_B r_B e^{i(\delta_B+\gamma)}$$

amplitudes of the subsequent D^0 and $\overline{D}^0$ decays to a common final state f

$$A(\overline{D}^0\to f) = A_D \text{ and } A(D^0\to f) = A_D r_D e^{i\delta_D}$$

assuming direct CPV in D decays negligibly small: $A(D^0\to f) \equiv A(\overline{D}^0\to \bar{f})$ and $A(\overline{D}^0\to f) \equiv A(D^0\to \bar{f})$

$$A(B^-\to D(\to f)K^-) \equiv A(B^-\to D^0K^-)A(D^0\to f) + A(B^-\to \overline{D}^0K^-)A(\overline{D}^0\to f)$$
$$= A_BA_Dr_De^{i\delta_D} + A_Br_Be^{i(\delta_B-\gamma)}A_D,$$
$$A(B^+\to D(\to \bar{f})K^+) \equiv A(B^+\to \overline{D}^0K^+)A(\overline{D}^0\to \bar{f}) + A(B^+\to D^0K^+)A(D^0\to \bar{f})$$
$$= A_BA_D + A_Br_Be^{i(\delta_B+\gamma)}A_Dr_De^{i\delta_D}.$$

γ, first principles…

rates of $B^- \to D K^-$ and $B^+ \to D K^+$

$$\left|A(B^- \to D(\to f)K^-)\right|^2 = |A_B|^2|A_D|^2\left[r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B - \gamma - \delta_D)\right],$$

$$\left|A(B^+ \to D(\to \bar{f})K^+)\right|^2 = |A_B|^2|A_D|^2\left[r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B + \gamma - \delta_D)\right].$$

if D final state f is CP eigenstates (GLW method):
$r_D = 1$, and $\delta_D = 0\ (\pi)$ for CP-even (odd) eigenstate

$$A_{CP} = \frac{\Gamma(B^- \to D(\to f)K^-) - \Gamma(B^+ \to D(\to \bar{f})K^+)}{\Gamma(B^- \to D(\to f)K^-) + \Gamma(B^+ \to D(\to \bar{f})K^+)},$$

$$A_{CP+} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma} \qquad A_{CP-} = \frac{-2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 - 2r_B\cos\delta_B\cos\gamma}$$

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

- Reconstruct D in final states accessible to both D^0 and $\overline{D}^0$
  - $D = D_{CP}$, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$

    GLW method (Gronau-London-Wyler)
  - $D = D_{sup}$, Doubly-Cabbibo suppressed decays as $K\pi$

    ADS method (Atwood-Dunietz-Soni)
  - Three-body decays as $D \to K_S\pi^+\pi^-$, $K_SK^+K^-$

    GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

- Largest effects due to
  - charm mixing
  - charm CP violation

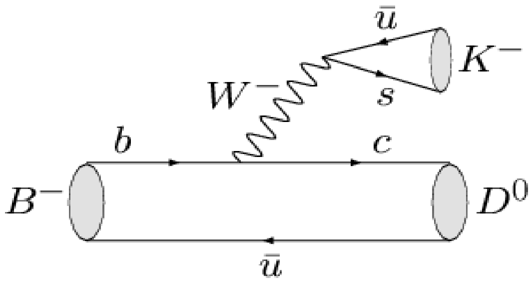
  } negligible

  Y.Grossman, A.Soffer, J.Zupan [PRD 72, 031501 (2005)]

- Different B decays (DK, D^*K, DK^*)
  - different hadronic factors (r_B, δ_B) for each

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

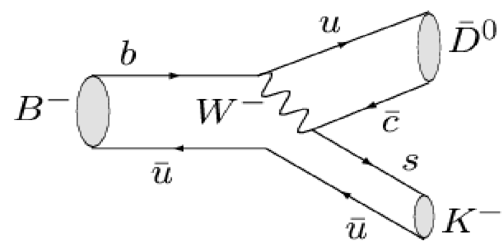
- Theoretically pristine B→DK approach
- Access γ via interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



color allowed

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

$\sim A\lambda^3$



color suppressed

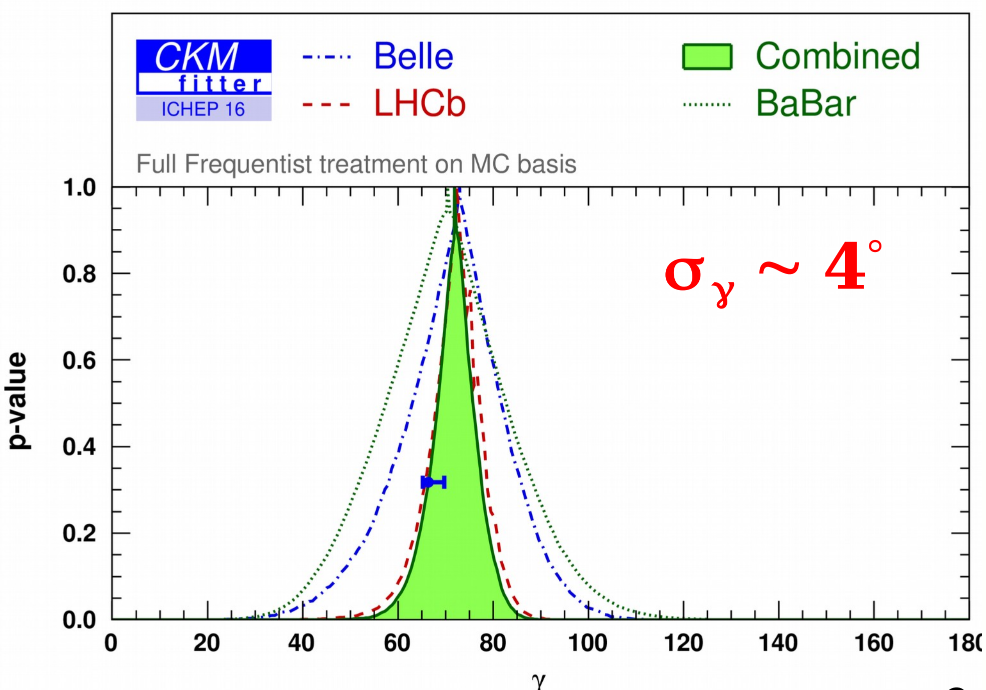
$B^- \to \overline{D}^0 K^- \sim V_{ub} V_{cs}^*$

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

relative weak phase is γ

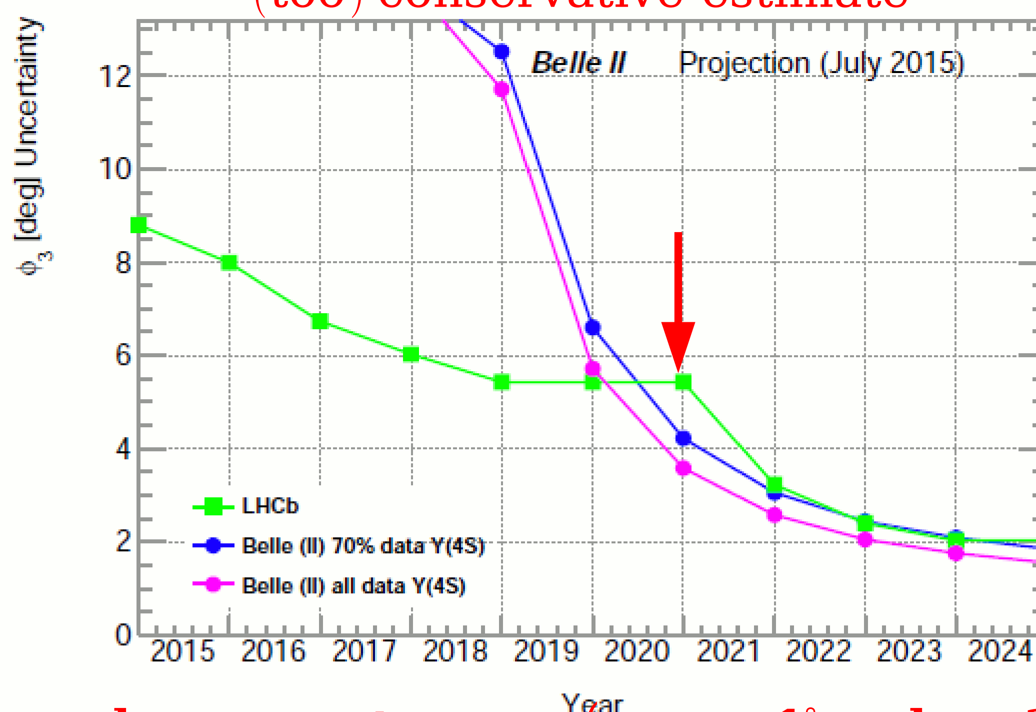
relative strong phase is δ_B

$r_B \simeq 0.1$



$\sigma_\gamma \sim 4^\circ$

(too) conservative estimate



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

BPGGSZ study $B \to D(K_S^0 h^+ h^-) h^-$

Niharika Rout (Madras) et al (Belle/Belle II collaboration)
[**arXiv:2110.12125, JHEP (2022) 63**]

BPGGSZ Method Study of $B^- \to D(\to K_S^0 h^+ h^-) h^-$ $h = \pi, K$

First Belle + Belle II analysis

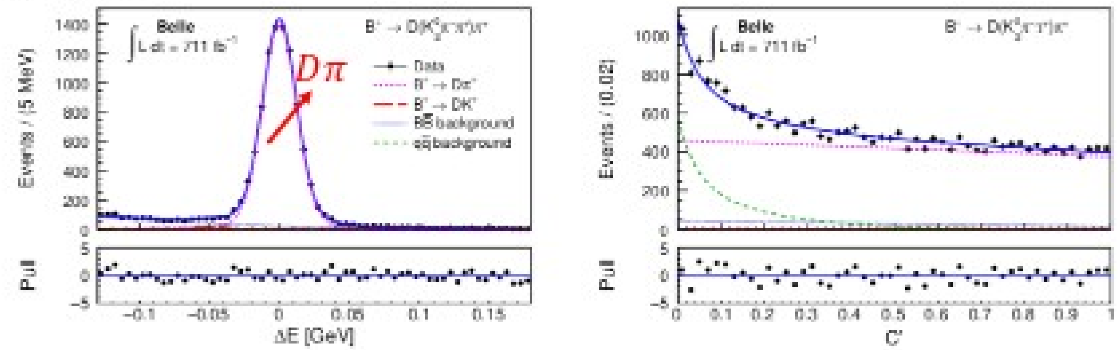
- Analysis with $711 fb^{-1}$ Belle data and $128 fb^{-1}$ Belle II data
- Unbinned 2D simultaneous fit of ΔE versus C' (right plot) for $B^- \to D^0(K_S^0\pi^+\pi^-)K^-$.

Component	PDF (ΔE)	PDF ($\text{FBDT}_{\text{trans}}$)
Signal	DG + Bifur-Gaus	poly (1st)
$B\overline{B}$ bkg	expo +(poly)	Chebychev poly-1st(2nd)
$q\overline{q}$ bkg	Chebychev poly (1st)	2 expo
DK ($D\pi$) component	DG + Bifur-Gaus	Chebychev poly (1st)

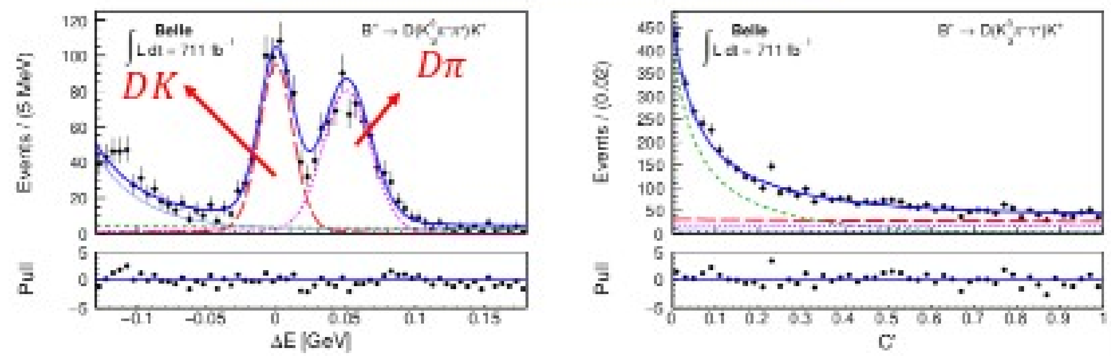
- Performed simultaneous fit in 160 categories; 80(16×4 + 4×4) of Belle and 80 of Belle II
- Signal region :
  - $|\Delta E| < 0.05\ GeV$
  - $0.65 < C' < 1.0$

$(x_\pm, y_\pm) = r_B(\cos(\phi_3 + \delta_B), \sin(\phi_3 \pm \delta_B))$ are common to all the bins and are extracted from the fit

pion enhanced $\mathcal{L}(K/\pi) < 0.6$



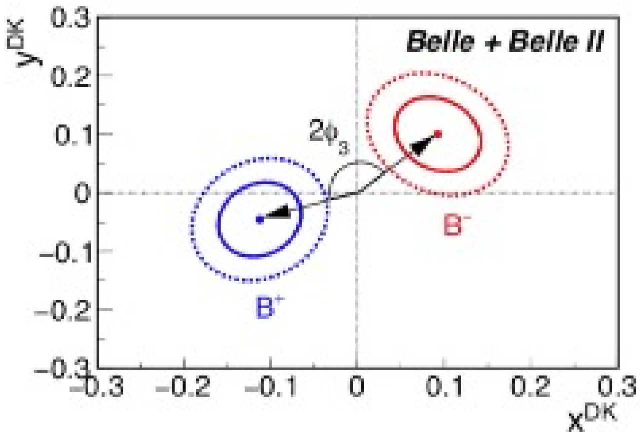
kaon enhanced $\mathcal{L}(K/\pi) > 0.6$



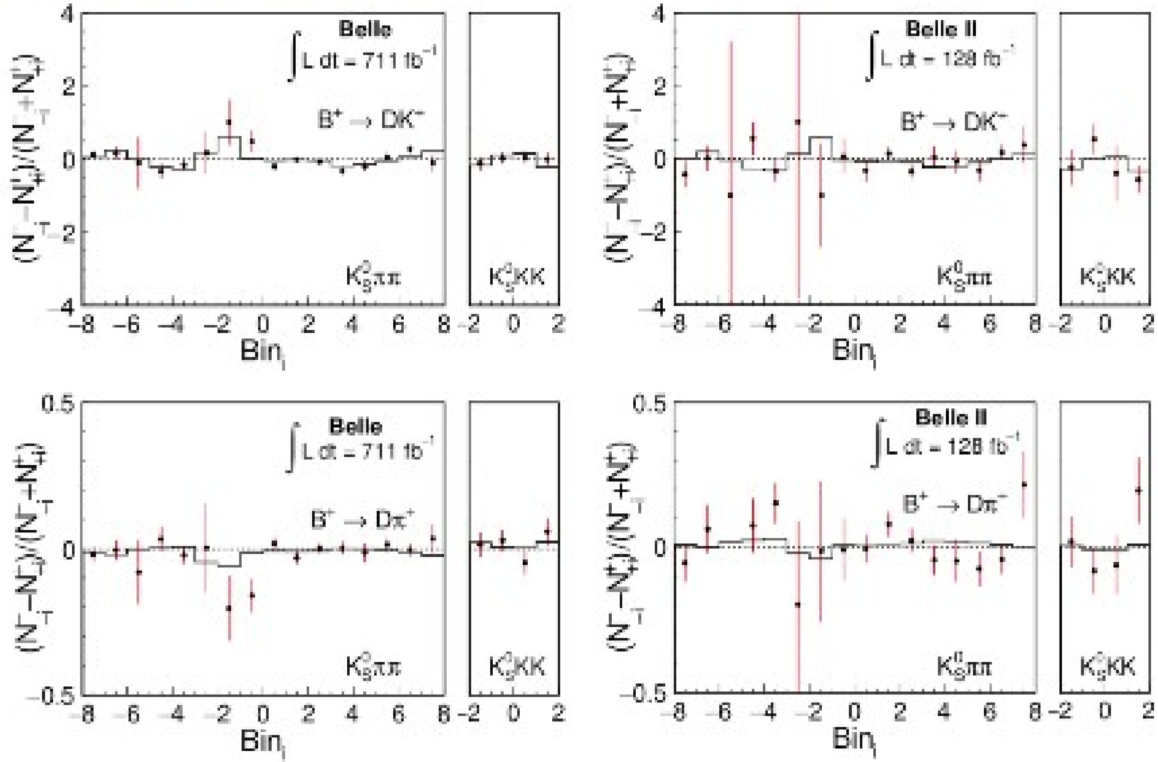
BPGGSZ study $B \to D(K^0_S h^+ h^-) h^-$

Niharika Rout (Madras) et al (Belle/Belle II collaboration)
[arXiv:2110.12125, JHEP (2022) 63]

First Belle + Belle II analysis



Uncertainty ~14° in earlier Belle measurement
PhysRevD.85.112014

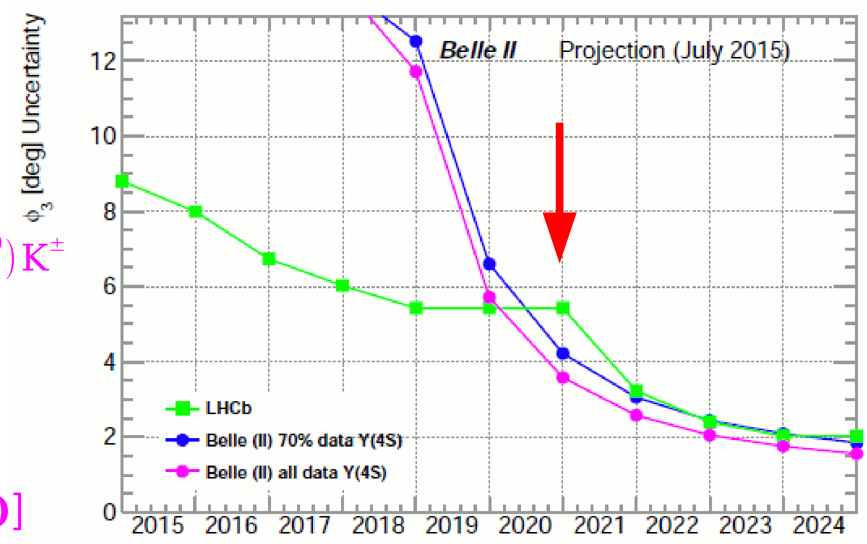


- ☐ Preliminary result :

$\delta_B(^\circ) = 124.8 \pm 12.9\ (\text{stat.}) \pm 0.5\ (\text{syst.}) \pm 1.7\ (\text{ext. input})$
$r_B^{DK} = 0.129 \pm 0.024\ (\text{stat.}) \pm 0.001\ (\text{syst.}) \pm 0.002\ (\text{ext. input})$
$\phi_3(^\circ) = 78.4 \pm 11.4\ (\text{stat.}) \pm 0.5\ (\text{syst.}) \pm 1.0\ (\text{ext. input})$

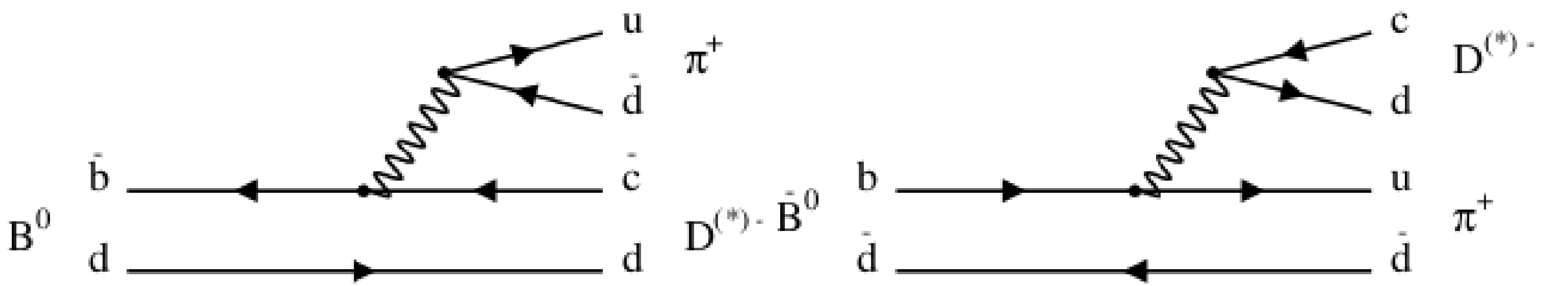
First measurement of the CKM angle β with $B^\pm \to D(K^0_S \pi^+ \pi^- \pi^0) K^\pm$
Resmi PK (Madras) et al (Belle collaboration)
[arXiv:1908.09499, JHEP 1910, 178 (2019)]

Evidence for the suppressed decay $B^- \to D(K^+ \pi^- \pi^0) K^-$
Minakshi Nayak (Madras) et al (Belle collaboration)
[arXiv:1310.1741, Phys. Rev. D 88, 091104(R) (2013)]



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

$\sin 2\beta + \gamma$ [method]



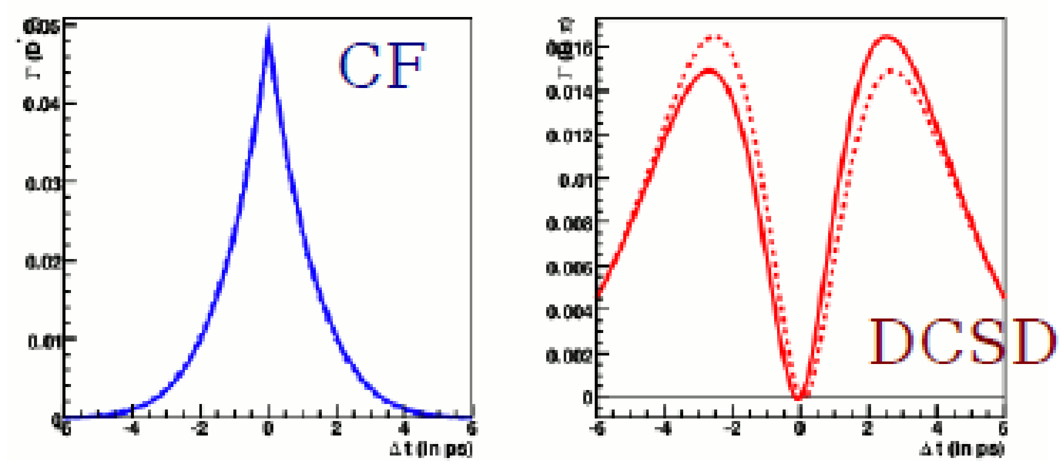
$$\Gamma(B^0 \to D^{*+}\pi^-) = \alpha[1 - C\cos(\Delta m\Delta t) - S^+\sin(\Delta m\Delta t)],$$
$$\Gamma(B^0 \to D^{*-}\pi^+) = \alpha[1 + C\cos(\Delta m\Delta t) - S^-\sin(\Delta m\Delta t)],$$
$$\Gamma(\bar{B}^0 \to D^{*+}\pi^-) = \alpha[1 + C\cos(\Delta m\Delta t) + S^+\sin(\Delta m\Delta t)],$$
$$\Gamma(\bar{B}^0 \to D^{*-}\pi^+) = \alpha[1 - C\cos(\Delta m\Delta t) + S^-\sin(\Delta m\Delta t)].$$

$$\alpha = e^{-|\Delta t|/\tau_{B^0}}/8\,\tau_{B^0}$$

$S^{\pm} = -(2R/(1+R^2))\sin(2\beta + \gamma \pm \delta)$

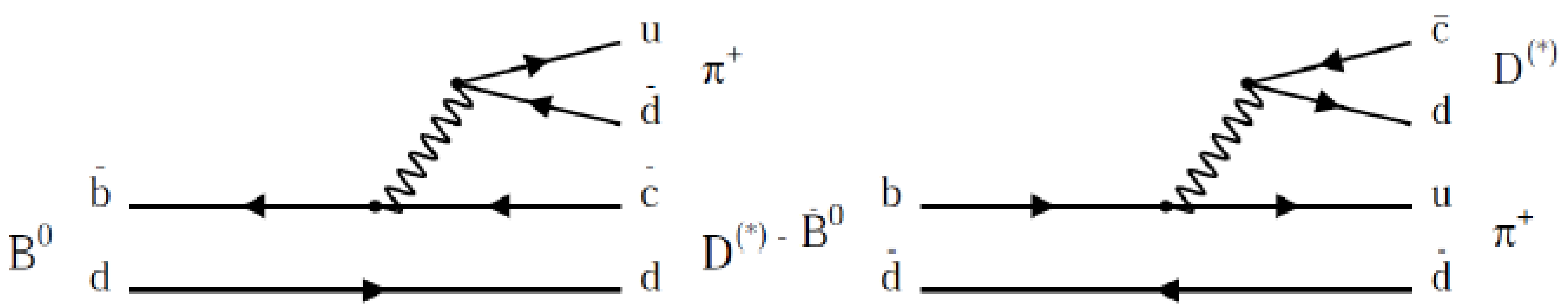
$C = (1-R^2)/(1+R^2) = 1$

though large samples, R values expected to be small ($\simeq 0.02$)



Time - dependent measurements

- All of the measurements presented so far were time-independent
- Time-dependent measurements (mixing induced CPV) also possible:
  - $B^0 \to D^{(*)}\pi$, $B^0 \to D^{(*)}\rho$
- In order to extract γ from $B \to SS/SV$ decays, must supply $r = |A_{DCS}/A_{CF}|$ externally (expected to be ~ 1-2%), usually assuming SU(3) symmetry



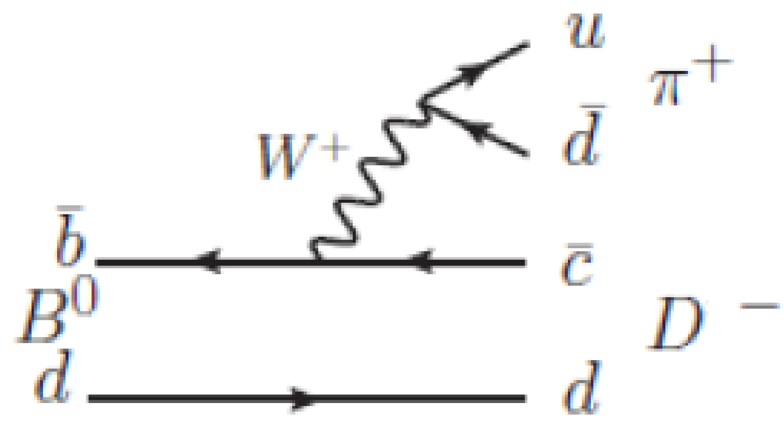
- In $B \to VV$ decays, one can extract all physics parameters from data
- Belle study: ~ 100 k evts per ab^{-1},
  3 helicity configurations: $A = \sum_\lambda A_\lambda$
  we use Cartesian coordinates $\{r_\lambda, \delta_\lambda, \phi_w\} \to \{x_\lambda, y_\lambda, \bar{x}_\lambda, \bar{y}_\lambda\}$
  $\sigma(2\beta+\gamma) \simeq 11^\circ$ for Belle II with 50 ab^{-1}

$D^{\pm}\pi^{\mp}$ time-dep analysis and $\sin 2\beta+\gamma$ extraction

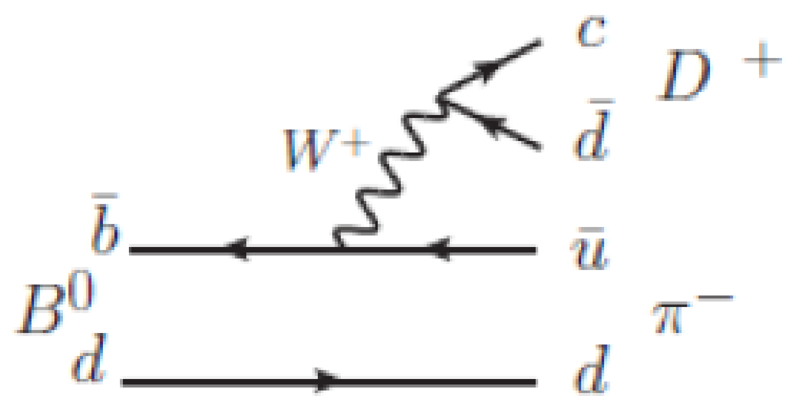
Seema Bahinipati (UC) et al (Belle collaboration)
[**arXiv:1102.0888, Phys.Rev.D84:021101, 2011**]

$$S^{\pm} = \frac{2 r_{D\pi} \sin(\delta \pm (2\beta+\gamma))}{1+R^2}$$

$$r_{D\pi} = \frac{|A(B^0 \to D^+\pi^-)|}{|A(B^0 \to D^-\pi^+)|}$$



CF decay



DCS decay

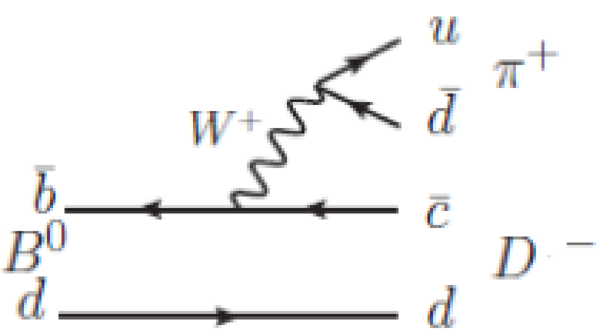
⇒ expected to be around 2%

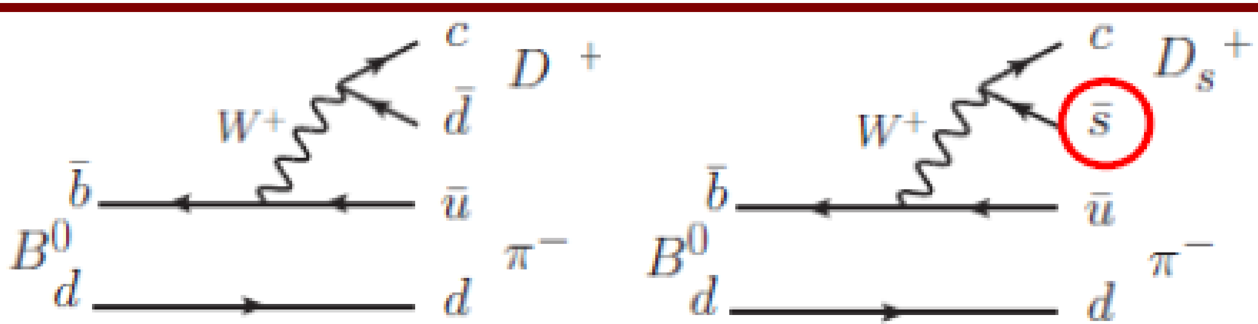
⇒ can't be measured directly from $D\pi$ analysis, need other inputs...

$B \to D_s^{(*)}\pi$

Nikhil Joshi (TIFR) et al (Belle collaboration)
[**arXiv:0912.2594, Phys.Rev.D 81 (2010) 031101**]

Abinash Das (TIFR) et al (Belle collaboration)
[**arXiv:1007.4619, Phys.Rev.D 82 (2010) 051103**]





$$r_{D\pi} \simeq \tan\theta_c \frac{f_D}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+ \pi^-)}{\mathcal{B}(B^0 \to D^- \pi^+)}}$$

$\mathcal{B}(\times 10^{-6})$	Exp.	Ref.
$25 \pm 4 \pm 2$	BaBar	arXiv:0803.4296
$19.9 \pm 2.6 \pm 1.8$	Belle	arXiv:1007.4619
$26.7 \pm 2.0 \pm 2.2$	LHCb	LHCb-ANA-2015-037

$\Rightarrow$ **following arXiv:1208.6463:** $r_{D\pi} = (1.70 \pm 0.08 \pm 0.25(\text{theo.}))\%$

Observation of CP violation in charm

[Phys. Rev. Lett. 122 (2019) 211803]

full Run 2 data 5.9 fb^{-1}

count how many D^0 and anti-D^0 decay into $\pi^+\pi^-$ and K^+K^- should be equal if matter = antimatter

experimentally: easier to measure (time integrated) difference in CP asymmetry:

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$

- many systematics cancel at first order
- initial flavour of D meson tagged by charge of π in prompt decays ($D^{*+} \to D^0\pi^+$), and by the muon charge in secondary production ($B^0 \to D^0\mu^- X$)

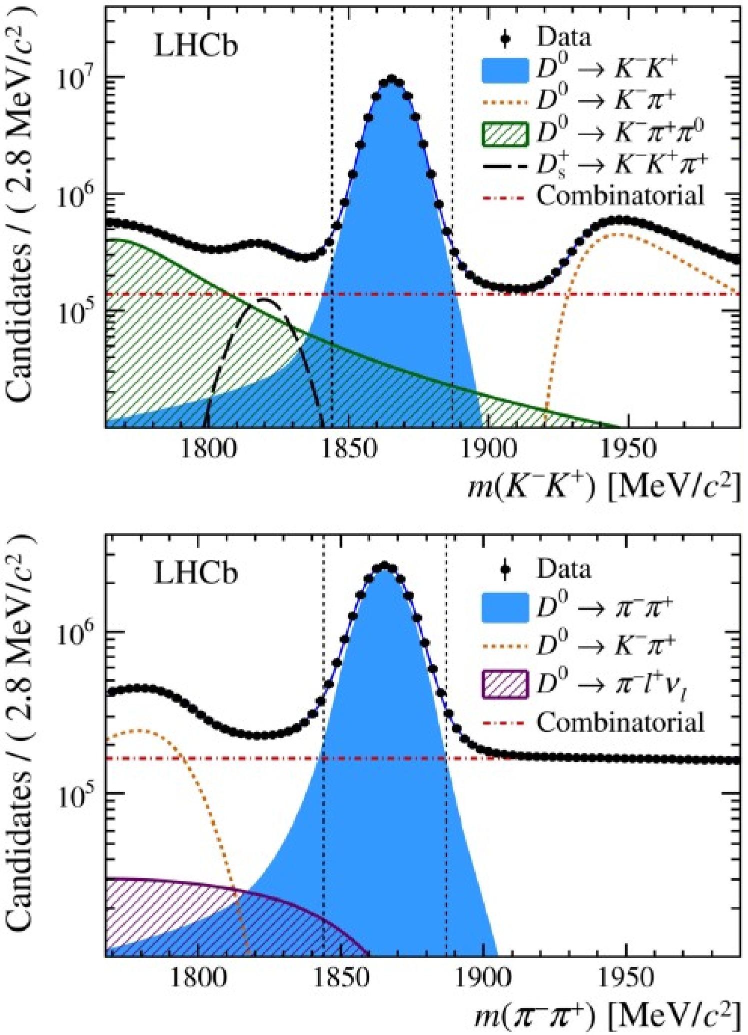
combination with Run 1 result

$\Delta A_{CP} = (-15.4 \pm 2.9)10^{-4}$

→ 5.3 σ difference from 0

→ roughly compatible with SM predictions
WA dominated by LHCb

uncertainties of SM predictions larger than data



Further CPV studies in charm

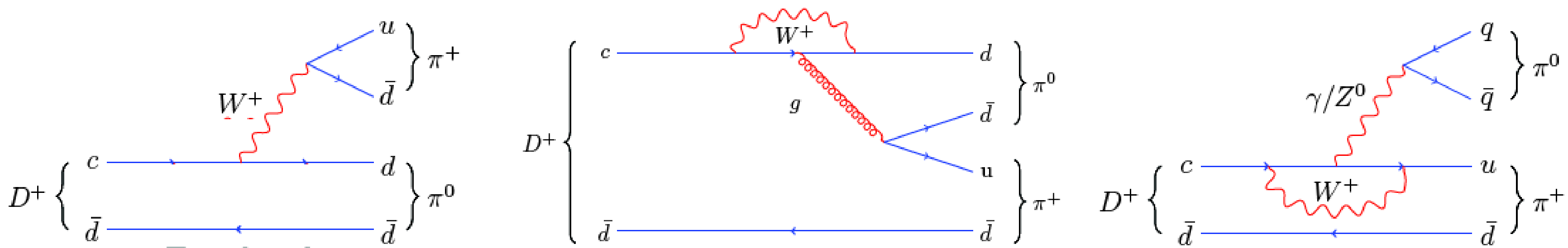
$D^+ \to \pi^+ \pi^0$, $D \to \pi^0 \pi^0$

Varghese Babu (TIFR) et al (Belle collaboration)
[arXiv:1712.00619, Phys. Rev. D 97, 011101 (2018)]
NK Nisar (TIFR) et al (Belle collaboration)
[arXiv:1404.1266, Phys. Rev. Lett. 112, 211601 (2014)]

$A_{CP}(D^+ \to \pi^+\pi^0) < 10^{-5}$
in the SM due to isospin symmetry

Would be smoking gun for NP

PLB 302 (1993) 319, PRD 85 (2012) 114036



Tree level

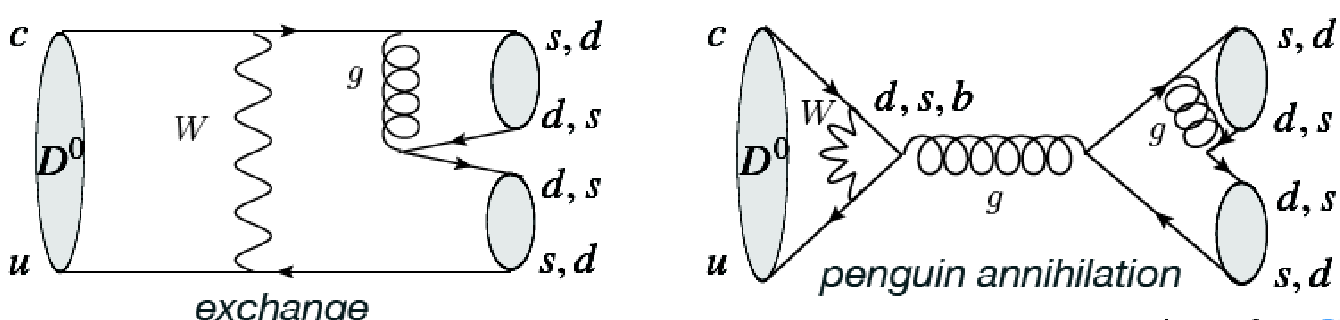
Forbidden QCD loop
$\Delta I = \frac{3}{2}$ transition prohibited for gluon
…but not for NP

EW loop
suppressed by α

$D^0 \to K^0_S K^0_S$

Nibedita Das (IIT Bhubaneswar) et al (Belle collaboration)
[arXiv:1705.05966, Phys. Rev. Lett. 119, 171801 (2017)]

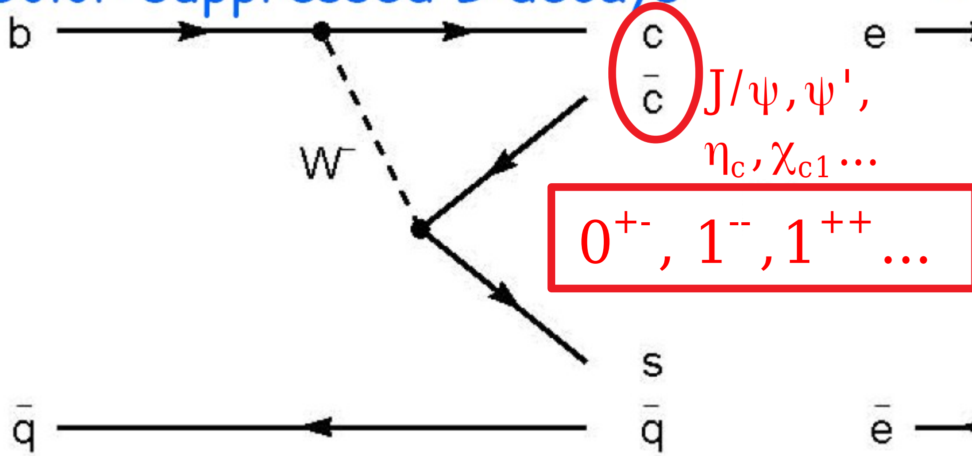
- ***CPV* could be enhanced up to the percent level**
  Nierste & Schacht 2015



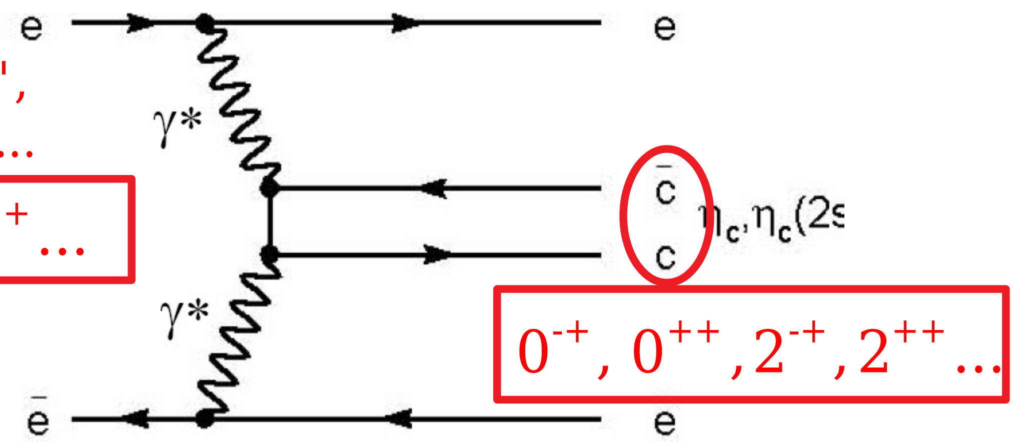
Figures from Cheng & Chiang 2012

B-factories produce lots of $c\bar{c}$-like pairs

Color-suppressed B decays

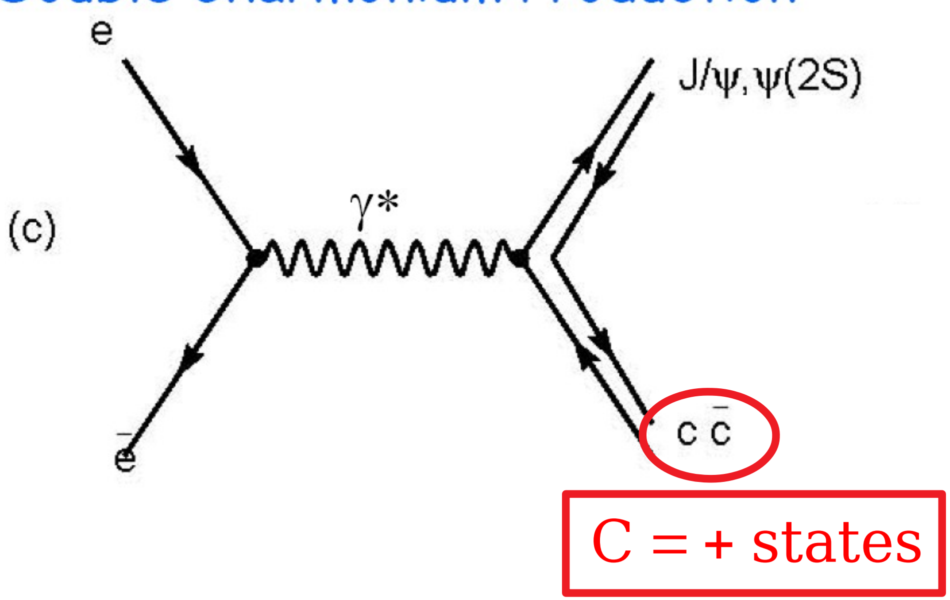


Two photon Production

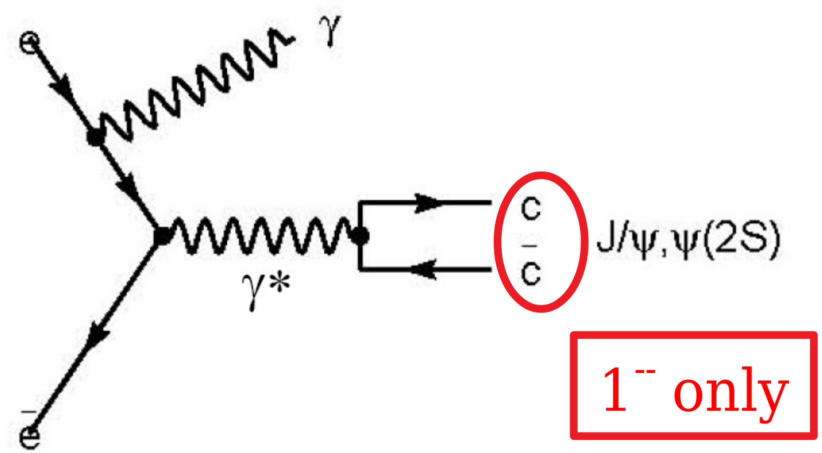


$Brs \sim 10^{-2}$ (inclusive)

Double Charmonium Production



Initial State Radiation



Spectroscopy in one slide…

Observation of X(3872) → $J/\psi\gamma$ and Search for X(3872) → $\psi'\gamma$ in B decays
Vishal Bhardwaj (Panjab) et al (Belle collaboration)
[**arXiv:1105.0177, Phys.Rev.Lett. 107, 9 (2011)**]

Evidence of a New Narrow Resonance Decaying to $\chi_{c1}\gamma$ in $B\to\chi_{c1}\gamma K$
Vishal Bhardwaj (Nara U) et al (Belle collaboration)
[**arXiv:1304.3975, Phys. Rev. Lett. 111, 032001 (2013)**]

Observation of X(3872) in $B\to X(3872)K\pi$ decays
Anu Bala (Panjab) et al (Belle collaboration)
[**arXiv:1501.06867, Phys. Rev. D 91, 051101 (R)**]

Inclusive and exclusive measurements of B decays to χ_{c1} and χ_{c2} at Belle
Vishal Bhardwaj (Nara U) et al (Belle collaboration)
[**arXiv:1512.02672, Phys. Rev. D 93, 052016 (2016)**]

Search for the $B\to Y(4260)K$, $Y(4260)\to J/\psi\pi^+\pi^-$ decays
Renu Gargh (Panjab) et al (Belle collaboration)
[**arXiv:1901.06470, Phys. Rev. D 99, 071102 (2019)**]

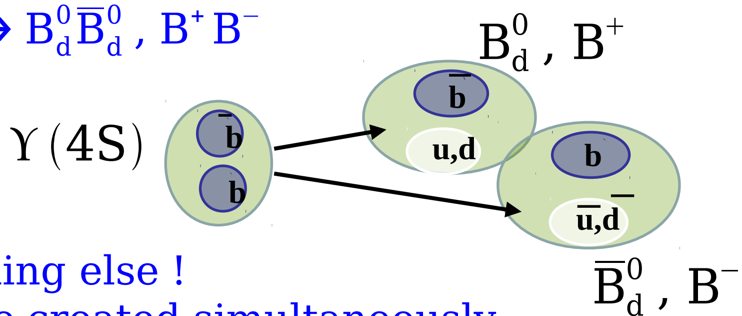
Search for X(3872) and X(3915) decay into $\chi_{c1}\pi^0$ in B decays at Belle
Vishal Bhardwaj (Panjab) et al (Belle collaboration)
[**arXiv:1904.07015, Phys. Rev. D 99, 111101 (2019)**]

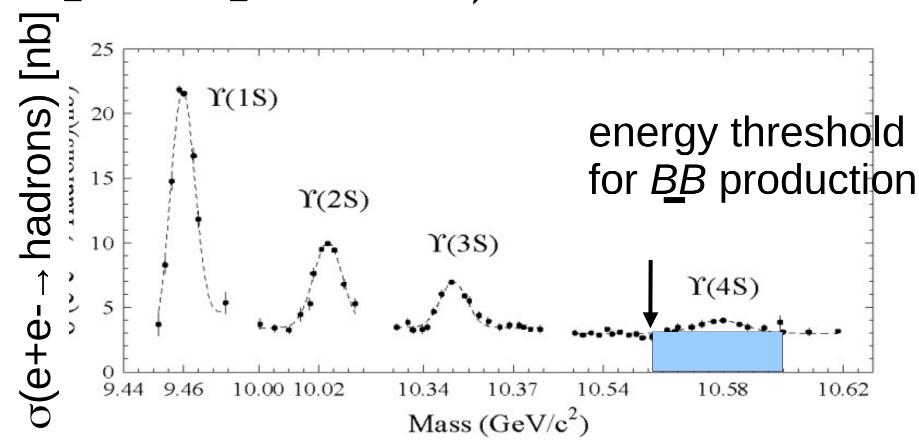
Belle II, a flavour-factory,
a rich physics program...

◦ 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:

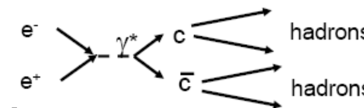
– **a (Super) B-factory (~1.1×10^9 $B\overline{B}$ pairs per ab^{-1})**

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





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



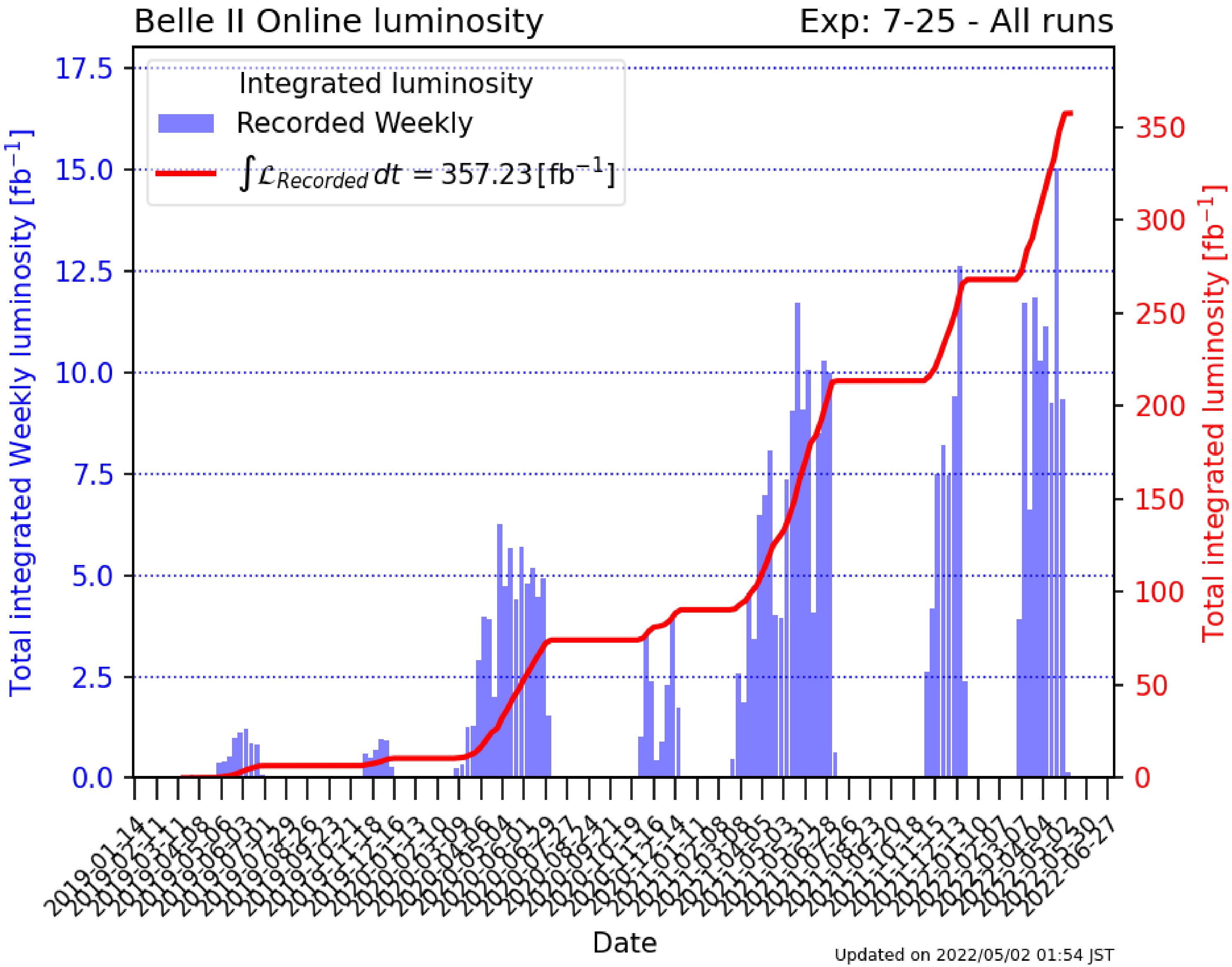
– **a (Super) charm factory (~1.3×10^9 $c\overline{c}$ pairs per ab^{-1})**

– **a (Super) τ factory (~1.3×10^9 $\tau^+\tau^-$ pairs per ab^{-1})**

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

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

Belle II's first steps ...



long way to go for 50 ab^{-1}...