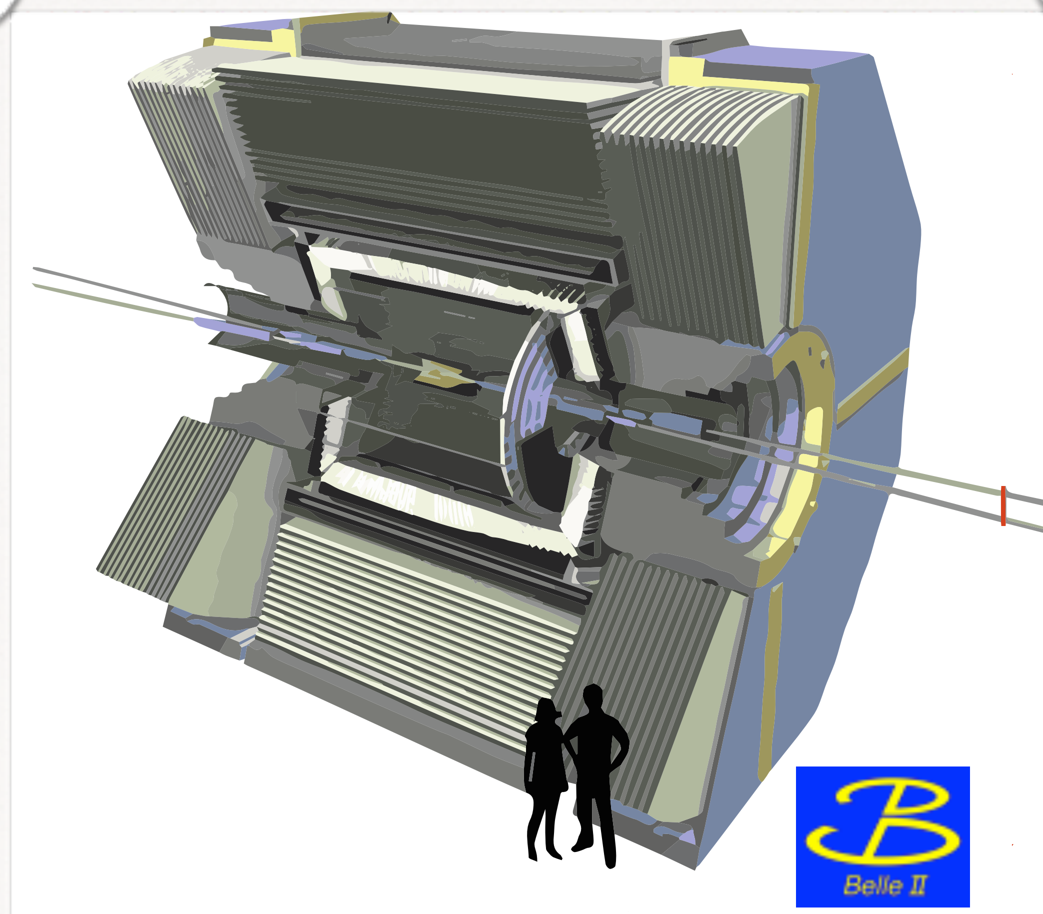
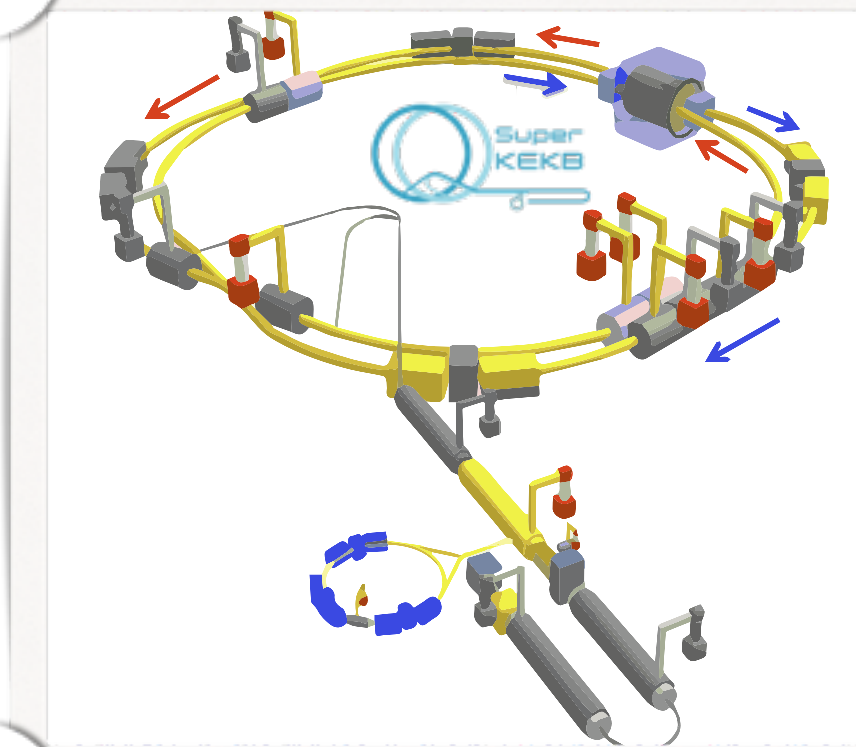
The *Belle II* Experiment





OUTLINE

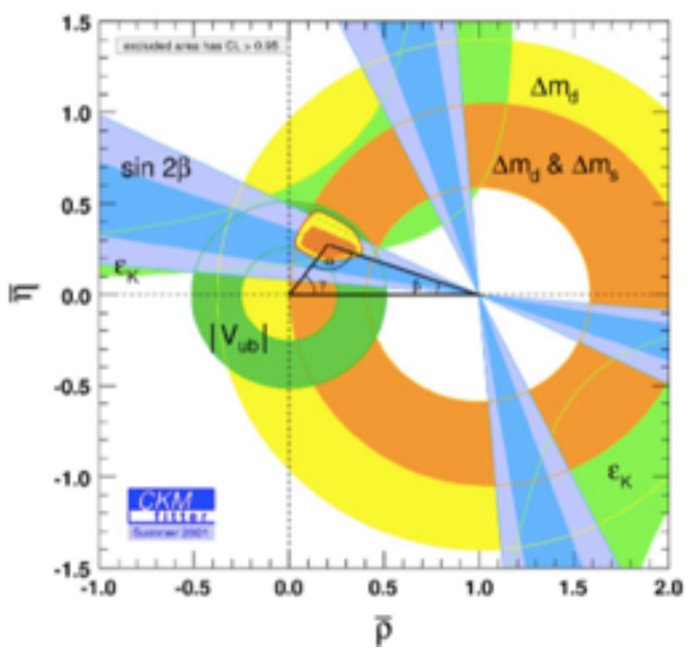
- ✓ Motivation
- ✓ SuperKEKB and the *Belle II* Detector
- ✓ B & Charm Physics Highlights
- ✓ Conclusions

Giulia Casarosa, INFN - Sezione di Pisa

on behalf of the *Belle II* Collaboration

Flavour Physics @ B Factories

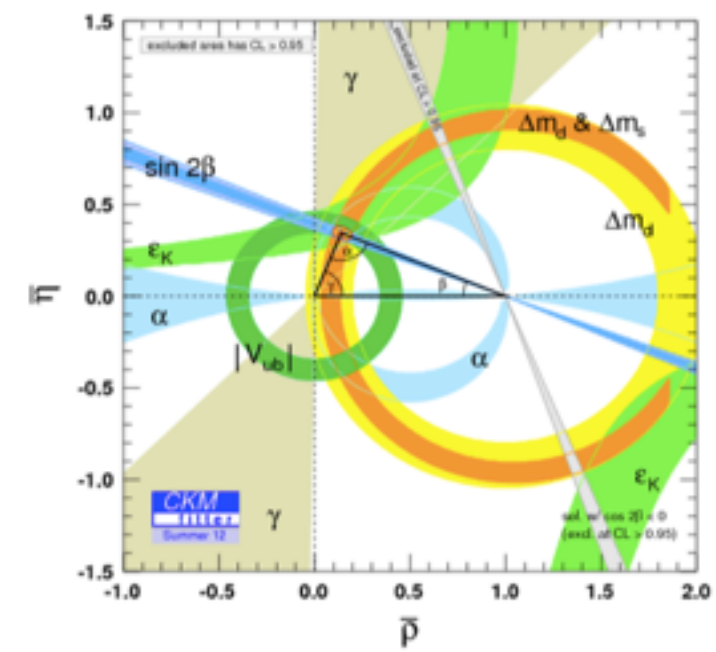
EPS 2001



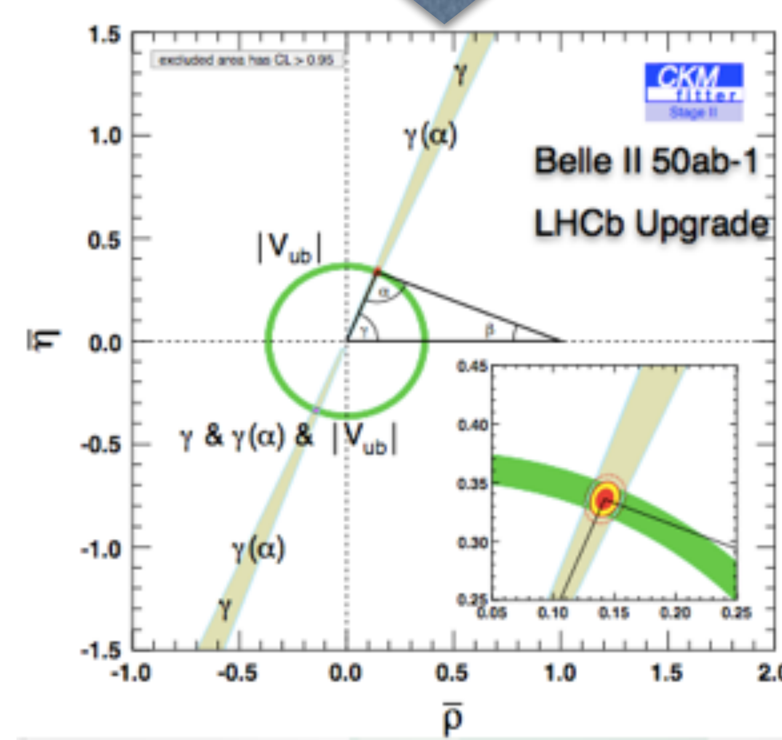
BELLE ⊕ BABAR

$\mathscr{L}$ =1.5 ab^{-1}

ICHEP 2012



LHCb upgrade ⊕ *Belle II*



- BELLE and BABAR collected 1.5 ab^{-1} of data together and
  - confirmed CKM mechanism as CPV source in Standard Model (SM)
  - observed new hadrons
  - searched for rare decays
  - investigated τ physics
  - …
- *Still a lot of observations are not accommodated in the SM (neutrino mass, dark matter, size of the observed CP violation, …)*
- Need a *significantly* larger data sample to open windows on New Physics (NP)
  - flavour physics provides a **beyond-TeV-scale** probe

High-Luminosity Asymmetric B Factory

- ➡ Target luminosity is $\mathscr{L}$ = 8x10^{35} cm^{-2}s^{-1} (x40 w.r.t. BELLE)
- ➡ Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

beam current

beam-beam parameter

geometrical reduction factors

beam aspect ratio at the IP

vertical beta-function at the IP

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	129	90	0.0881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathscr{L}$	2.1x10		**8x10^{35}**		cm^{-2}s^{-1}

High-Luminosity Asymmetric B Factory

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  - double beam currents
  - squeeze beams @

Lorentz factor

beam

beam-beam

$L = \frac{\gamma}{2e r_e} \ldots$

beam aspect … at the IP

vertical beta-function at the IP

reduced CM boost

- reduced vertex separation, Δt resolution
- increased detector hermeticity

squeezed beams @ IP

- greatly improved constraint for decay chain vertex fitting

parameters		LER		SuperKEKB LER	SuperKEKB HER	units
beam energy	E_b	3.5	8	4	7	GeV
CM boost	βγ	0.425		0.28		
h				41.5		mrad
ho			24	3.2	4.6	nm
			0.66	.37	0.40	%
b		5.9		32/0.27	25/0.30	mm
			1.19	3.6	2.6	A
bea			90	0.0881	0.0807	
		2		10/0.059		μm
		0		8x10^{35}		cm^{-2}s^{-1}

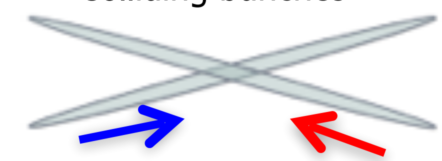
x40 luminosity

- higher background rates (~10-20x)
  - detectors occupancy, radiation damage, fake hits, pile-up noise in the calorimeter
- higher event rate
  - higher trigger rate, DAQ, computing
- x40 produced signal events

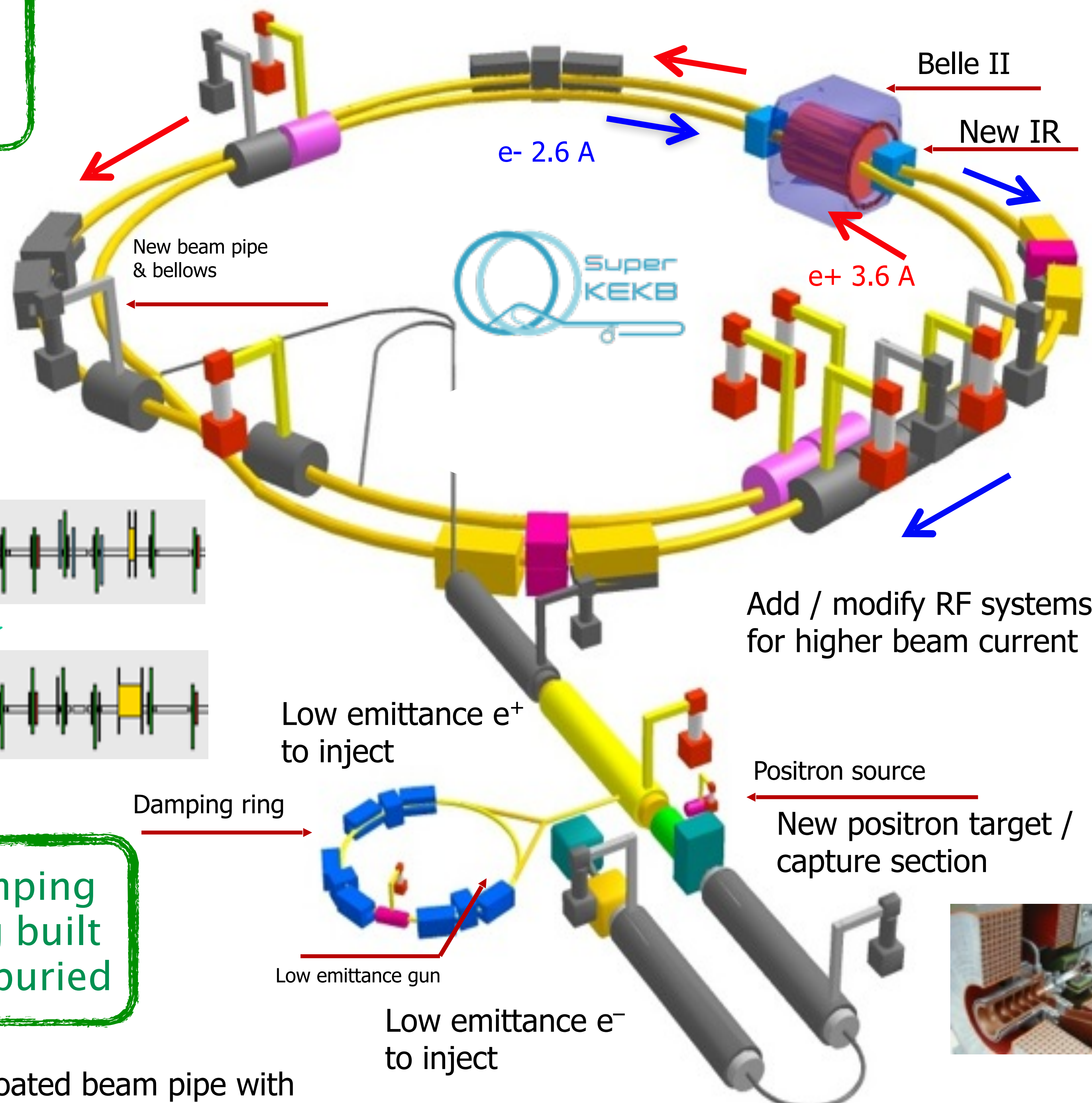
SuperKEKB Status

Longer LER dipoles magnets installed

increase wiggler cycles



New superconducting / permanent final focusing quads near the IP



Add / modify RF systems for higher beam current

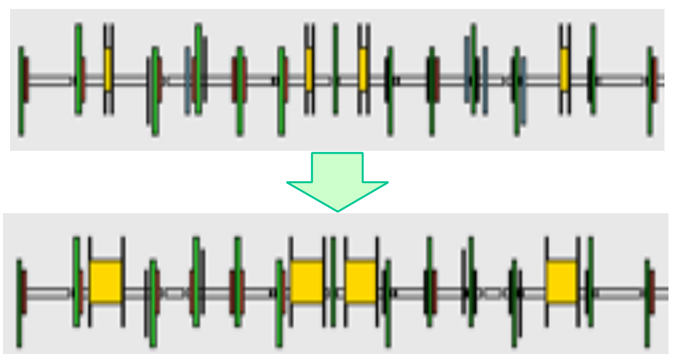
Low emittance e^+ to inject

New positron target / capture section

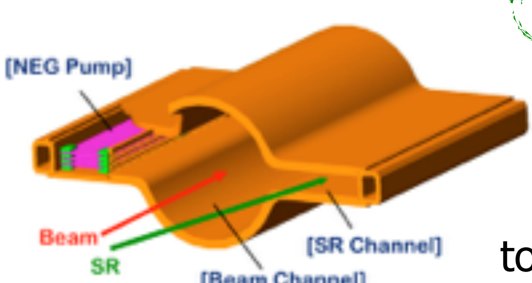
Low emittance e^- to inject

New LER & HER wiggler cavities installed

Redesign the lattices of HER & LER to squeeze the emittance



Damping Ring built and buried



TiN-coated beam pipe with antechambers

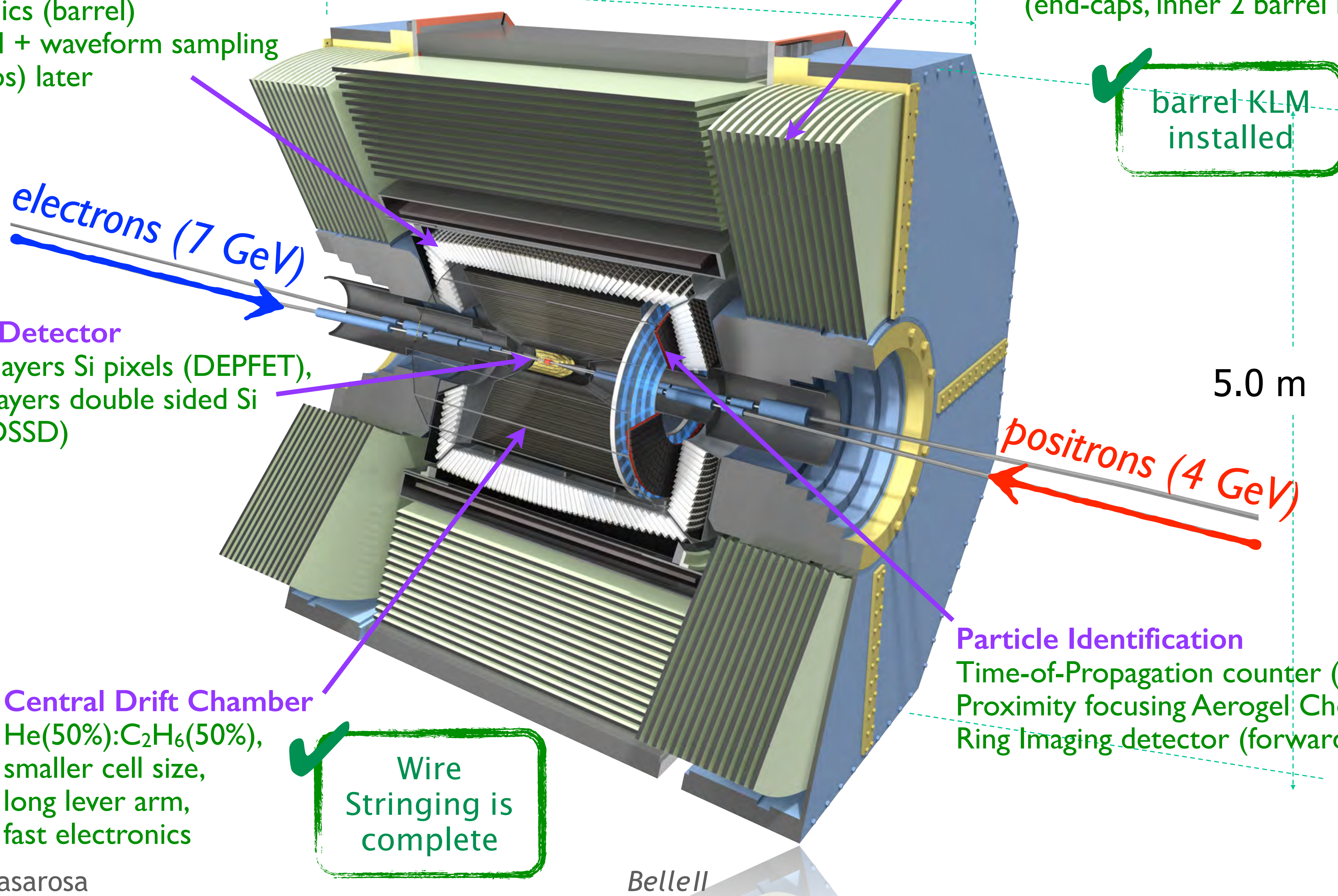
to reduce Synchrotron radiation

expected completion by the end 2014
(Japanese Fiscal Year)

The *Belle II* Detector

K_L & μ Detector
Resistive Plate Counter (barrel outer layers),
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM calorimeter
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later



Vertex Detector
PXD: 2 layers Si pixels (DEPFET),
SVD: 4 layers double sided Si strips (DSSD)

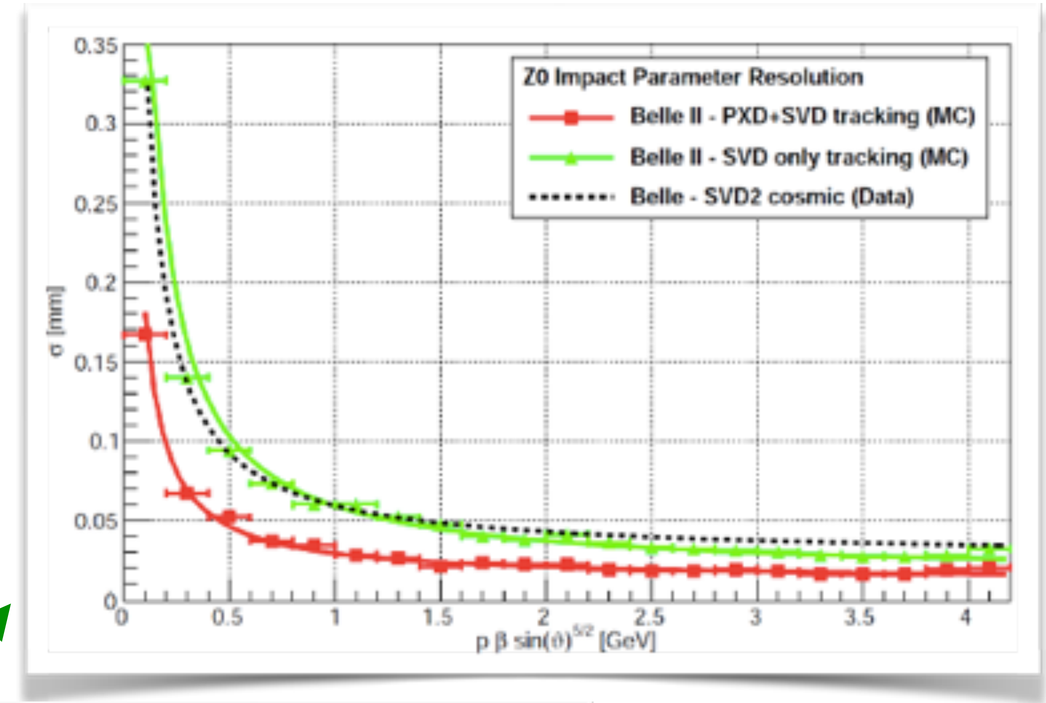
Central Drift Chamber
He(50%):C_2H_6(50%),
smaller cell size,
long lever arm,
fast electronics

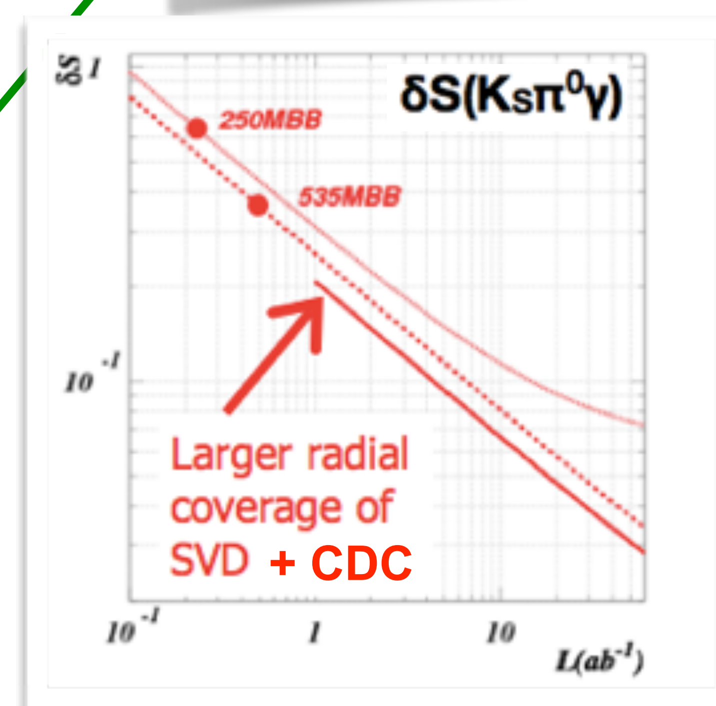
Particle Identification
Time-of-Propagation counter (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

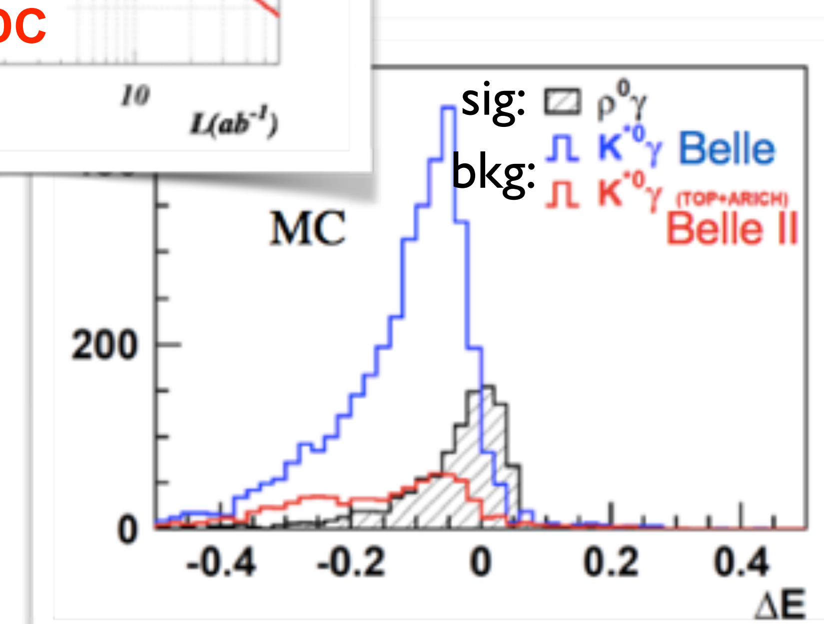
The B Factory *Belle II* & Improvements

➡ B Factory advantages over hadron collider detectors:

- ☆ clean event environment
- high trigger efficiency
- ☆ high-efficiency detection of neutrals (γ, π^0, η, η', …)
- many control samples to study systematics
- good kinematic resolution (Dalitz plots analysis)
- missing energy and missing mass analysis are straightforward



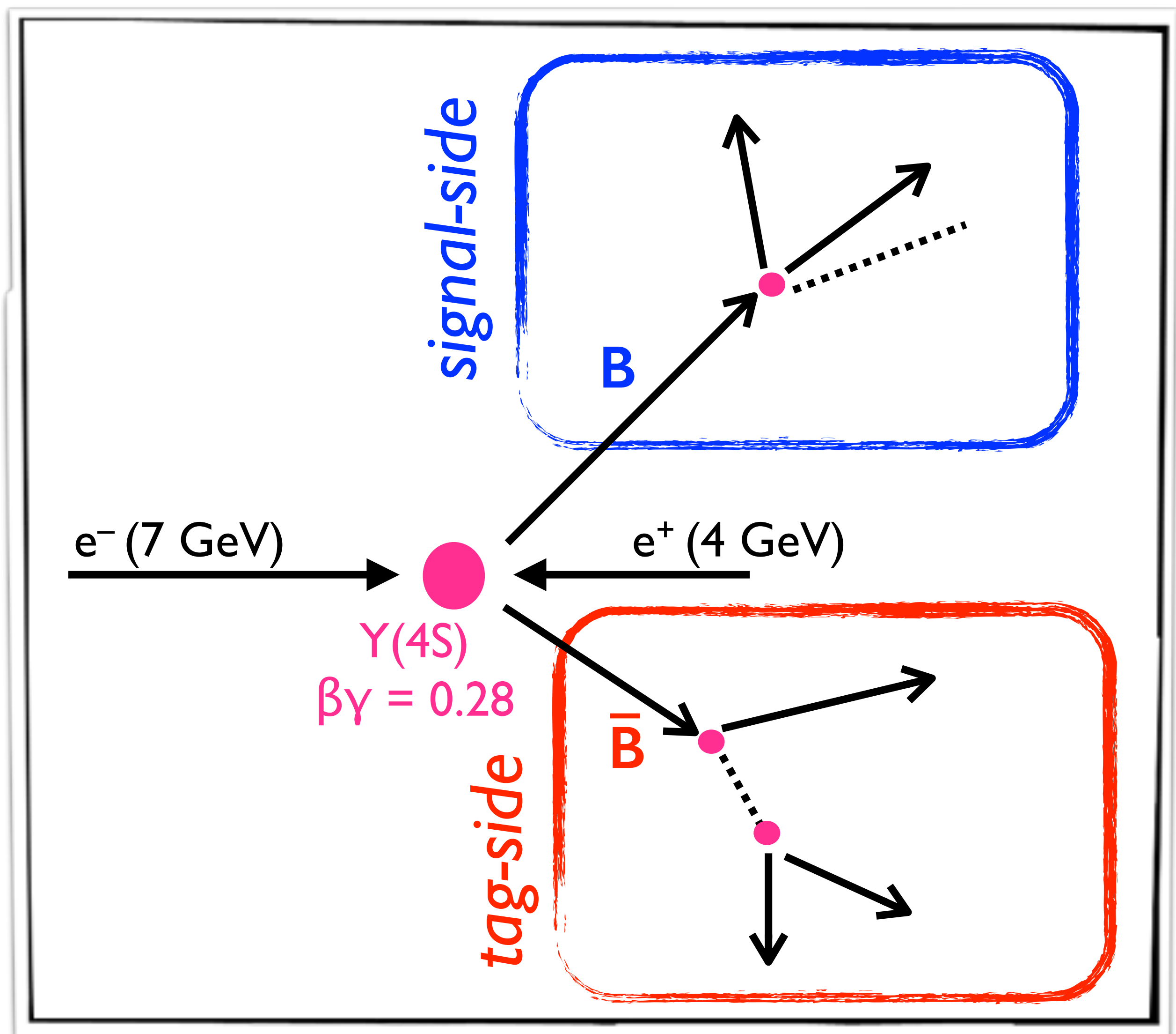




IMPROVEMENTS wrt BELLE

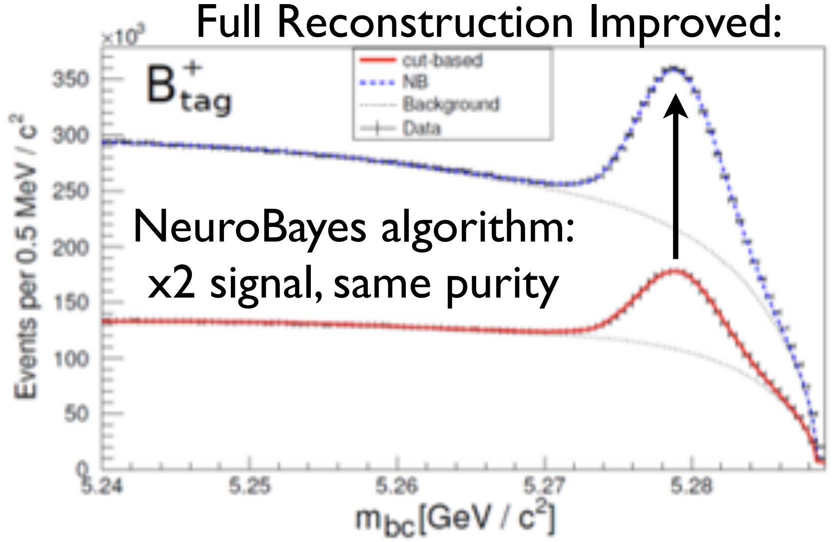
- IP and secondary vertex resolution
- K_S and π^0 reconstruction
- K/π separation
- PID and μ ID in the end caps

B Physics at a B Factory



- **Full Reconstruction** of the tag-side:
  - signal-side: weak signature e.g. $B^+ \to \tau^+\nu$
  - semileptonic tag: ε~1.5%, more bkg, no p_B reconstruction
  - hadronic tag: ε~0.2%, less bkg (purity ≈ 20%), p_B reconstruction
- **Inclusive Reconstruction** of the tag-side:
  - signal-side: strong signature e.g $B^+ \to \mu^+\nu$, apply PID and measure p_μ
  - ignore details, measure inclusive observables
  - higher efficiency but more bkg

Full Reconstruction Improved:



- effective offline B meson beam ✔
- high-efficiency flavour/charge tagging
- high performances in channels with missing energy (can exclude decay products of one B from further analysis)

Belle II ~ LHCb Physics Reach

NON-EXHAUSTIVE LIST

Observable	SM prediction	
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	input	
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	input	Belle II
$\lvert V_{ub}\rvert$ $[B \to \pi \ell \nu]$	input	Belle II
γ $[B \to DK]$	input	Belle II/LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	Belle II/LHCb
$S_{B_s \to \psi \phi}$	0.036	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	Belle II/LHCb
$S_{B_s \to \phi \phi}$	0.036	LHCb
$S_{B_d \to K^* \gamma}$	few $\times$ 0.01	Belle II
$S_{B_s \to \phi \gamma}$	few $\times$ 0.01	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	Belle II/LHCb
$A^s_{\rm SL}$	2×10^{-5}	LHCb
$A_{CP}(b \to s \gamma)$	< 0.01	Belle II
$\mathcal{B}(B \to \tau \nu)$	1×10^{-4}	Belle II
$\mathcal{B}(B \to \mu \nu)$	4×10^{-7}	Belle II
$\mathcal{B}(B_s \to \mu^+ \mu^-)$	3×10^{-9}	LHCb
$\mathcal{B}(B_d \to \mu^+ \mu^-)$	1×10^{-10}	LHCb
$A_{\rm FB}(B \to K^* \mu^+ \mu^-)_{q_0^2}$	0	LHCb
$B \to K \nu \bar{\nu}$	4×10^{-6}	Belle II
$\lvert q/p \rvert_{D-{\rm mixing}}$	1	Belle II
ϕ_D	0	Belle II
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	8.5×10^{-11}	
$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$	2.6×10^{-11}	
$R^{(e/\mu)}(K \to \pi \ell \nu)$	2.477×10^{-5}	
$\mathcal{B}(t \to c Z, \gamma)$	$\mathcal{O}(10^{-13})$	

✓ nice complementarity between LHCb and BelleII

✓ some channels with comparable precision

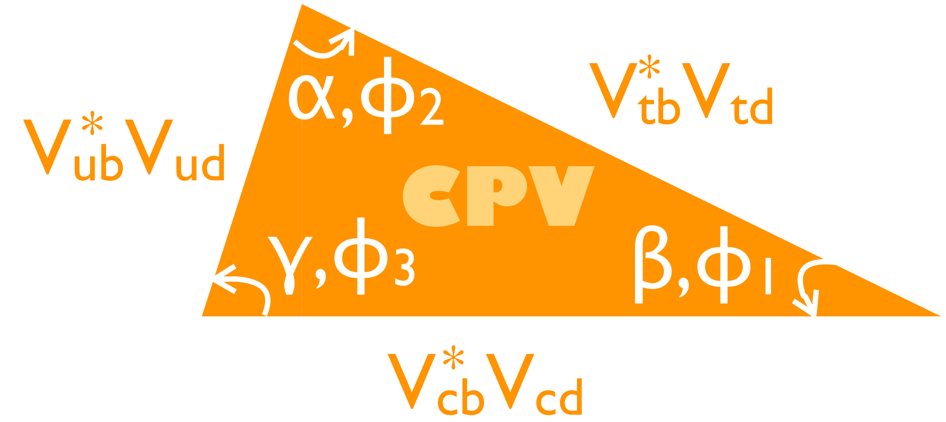
adapted from

1. **Flavor Physics Constraints for Physics Beyond the Standard Model**
Gino Isidori (Frascati & TUM-IAS, Munich), Yosef Nir, Gilad Perez (Weizmann Inst.). Feb 2010. 33 pp.
Published in **Ann.Rev.Nucl.Part.Sci. 60 (2010) 355**

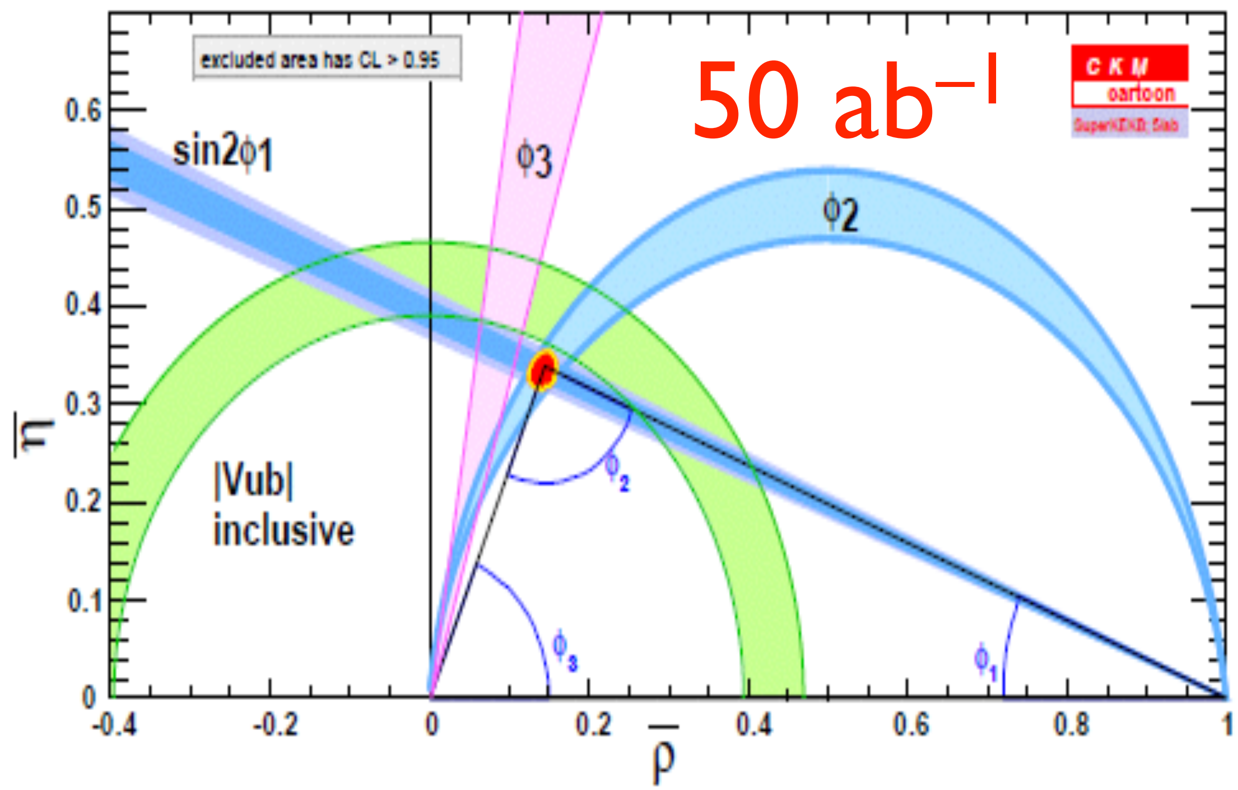
Y. Kwon@BEAUTY2014

The Unitary Triangle

➡ *Belle II* will continue improving the constraints of the CKM Unitary Triangle



ANGLES	BELLE/WA	*Belle*	Theory
β, ϕ_1	1.4° / 0.8°	0.4°	
α, ϕ_2	- / 4°	1°	
γ, ϕ_3	14° / 8.5°	1.5°	



SIDES	BELLE	*Belle*	Theory
$\lvert V_{cb}\rvert$ incl	1.7%	1.2%	
$\lvert V_{cb}\rvert$ excl	2.2%	1.4%	
$\lvert V_{ub}\rvert$ incl	7%	3.0%	
$\lvert V_{ub}\rvert$ excl	8%	2.4%	
$\lvert V_{ub}\rvert$ lept	14%	3.0%	

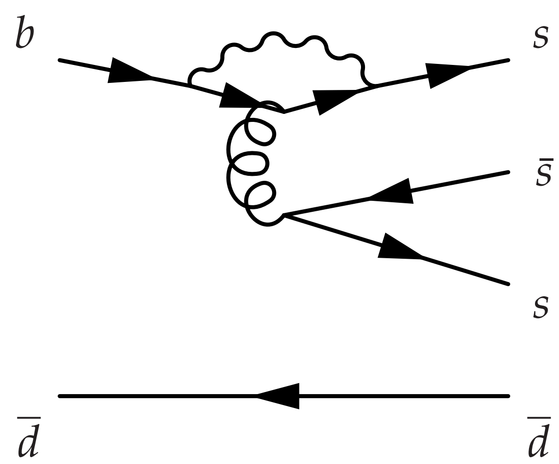
Experiment	Theory
very precise	clean
precise	clean/LQCD
moder. prec.	moder. prec.

Is there another CP Violating phase?

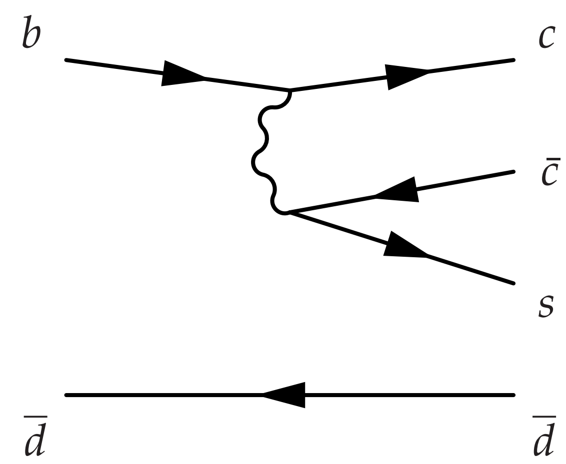
$B^0 \to \phi K^0$

$B^0 \to \eta' K^0$

$B^0 \to K^0 K^0 K^0$

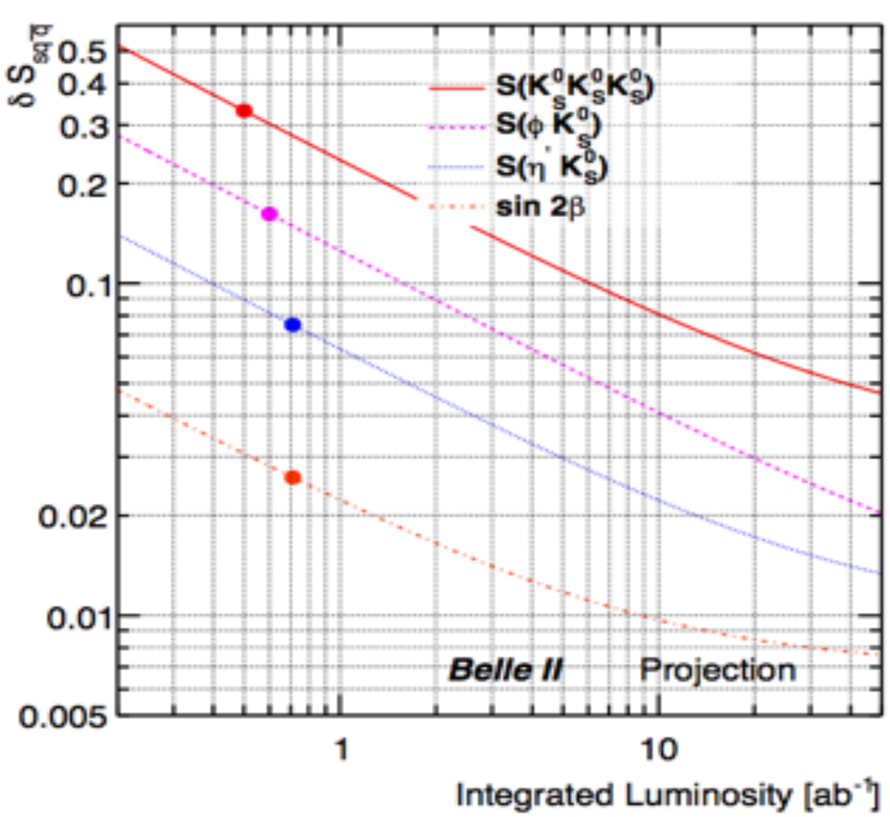


VS



$B^0 \to J/\psi K^0$

$$\frac{dN}{dt} = e^{-\Gamma t}[1 + q(A\cos(\Delta m t) + S\sin(\Delta m t))]$$

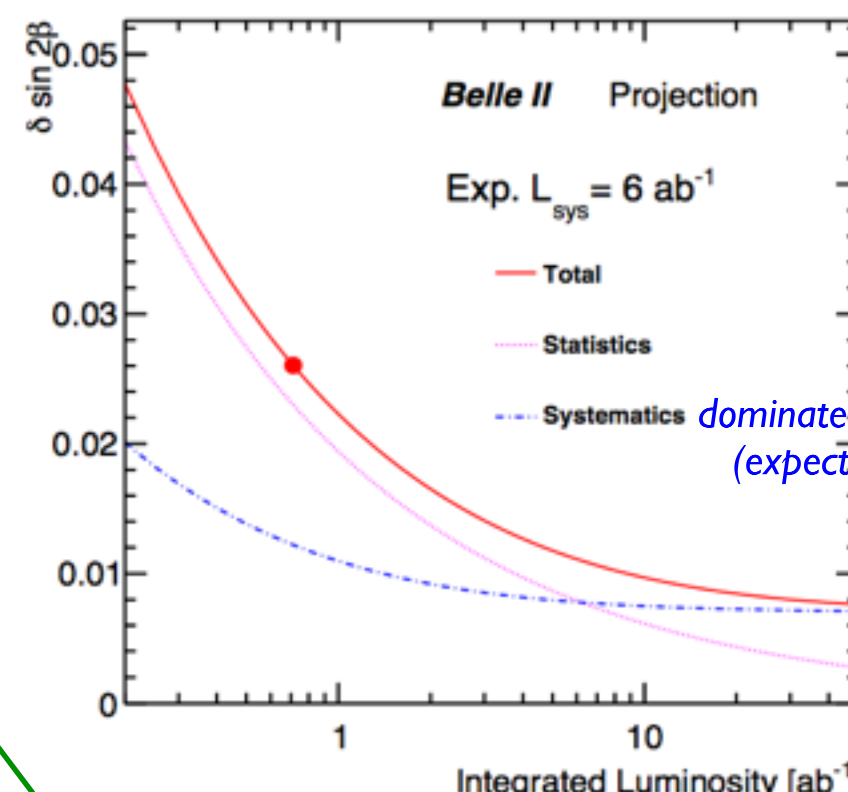


0.033 $S(K^0K^0K^0)$

0.018 $S(\phi K^0)$

0.011 $S(\eta' K^0)$

0.008 $S(J/\psi K^0)$



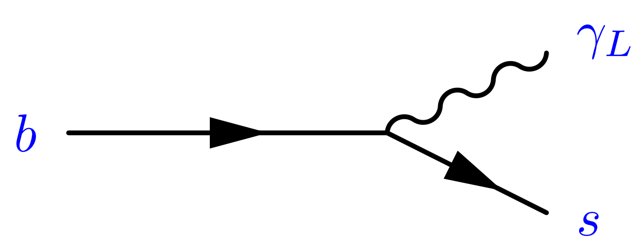
dominated by vertex resolution (expected improvement by factor 3)

0.008

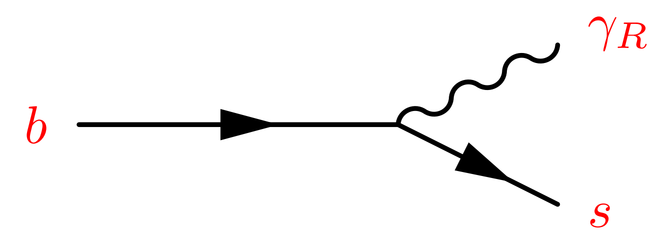
The expected precision is good enough to distinguish different theory models

Looking For Right-Handed Currents

➡ Particular NP scenario can be tested in b→sγ and b→dγ transitions

SM: 

and



dominant

helicity suppressed (m_s/m_b)

➡ In helicity-changing NP models there may be an enhancement of the helicity-suppressed amplitude.

$$\frac{dN}{dt} = e^{-\Gamma t}[1 + q(A\cos(\Delta m t) + S\sin(\Delta m t))]$$

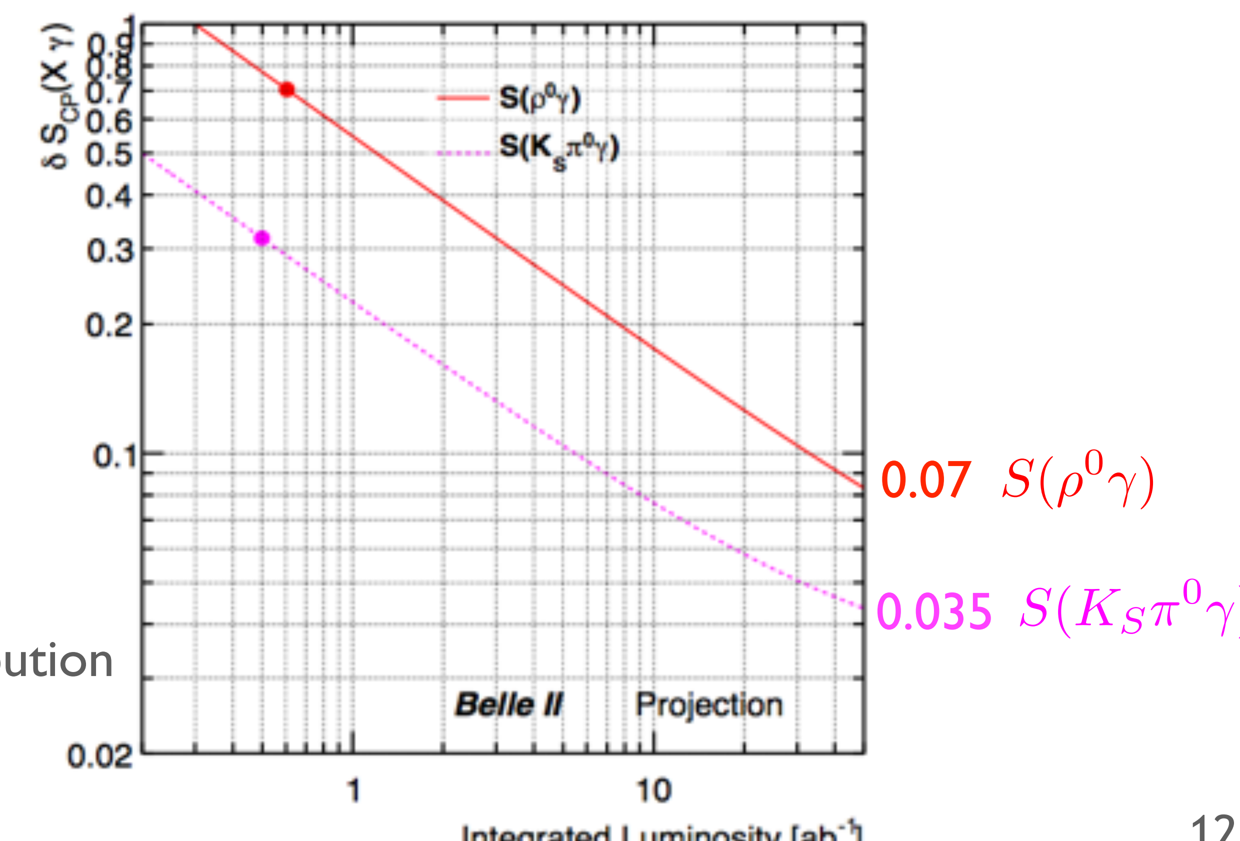
➡ For $B^0 \to K_S \pi^0 \gamma$ we expect:

- Standard Model

$$S^{SM}_{K_S\pi^0\gamma} = -2\frac{m_s}{m_b}\sin(2\beta) \sim -0.03$$

- Left-Right symmetric models:

$$S^{LR}_{K_S\pi^0\gamma} = 0.67\cos(2\beta) \sim 0.5$$



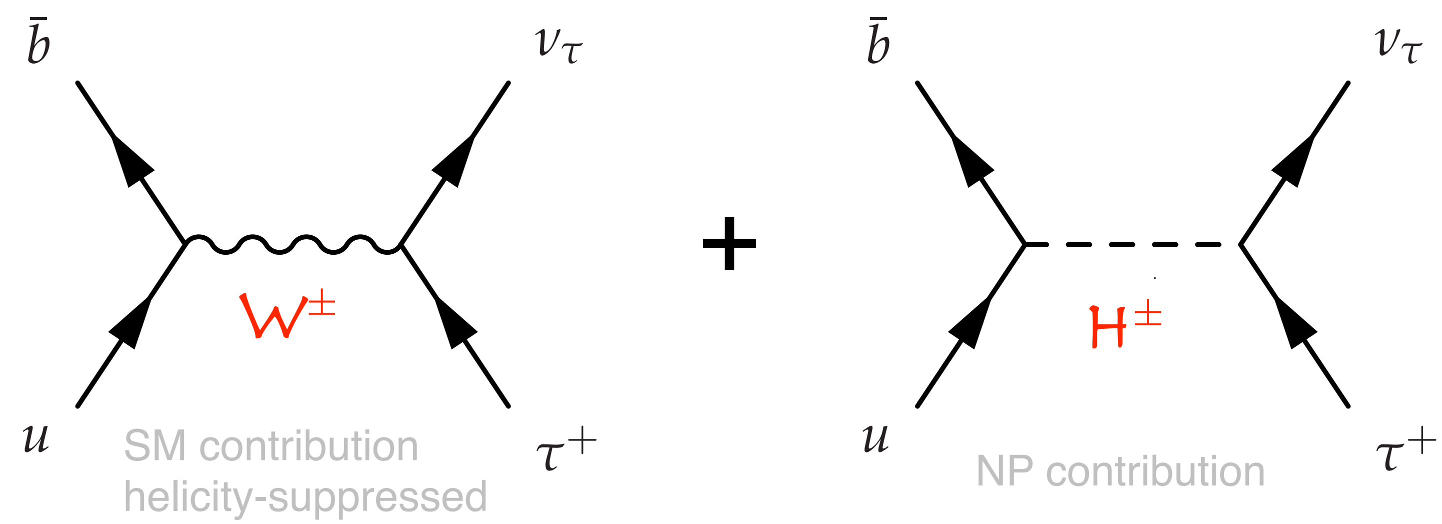
NOTE:

- the final state is different ($\gamma_L \neq \gamma_R$) → indirect CPV only contribution
- we do not measure the helicity of γ

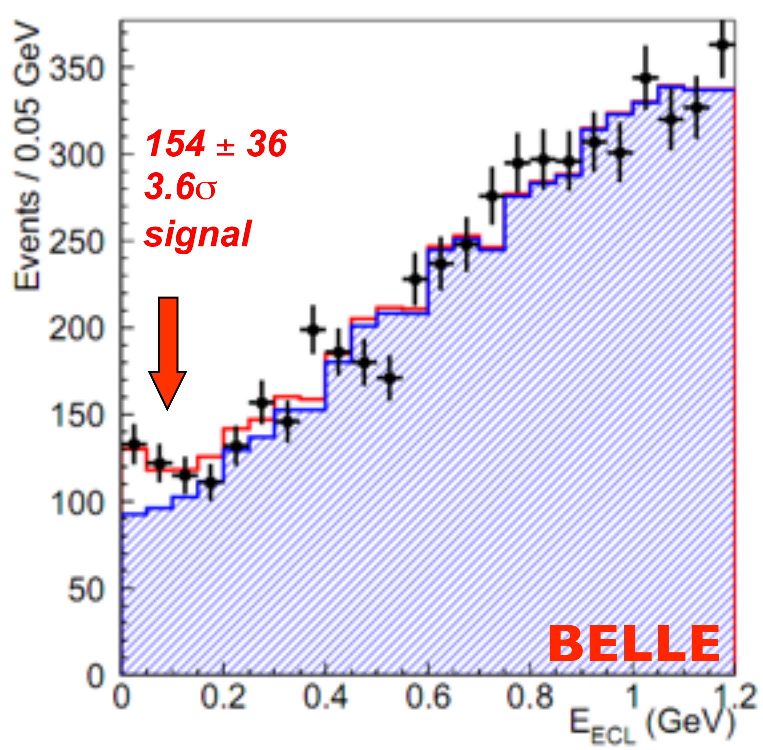
Looking for a Charged Higgs: $B^+ \to \tau^+ \nu$

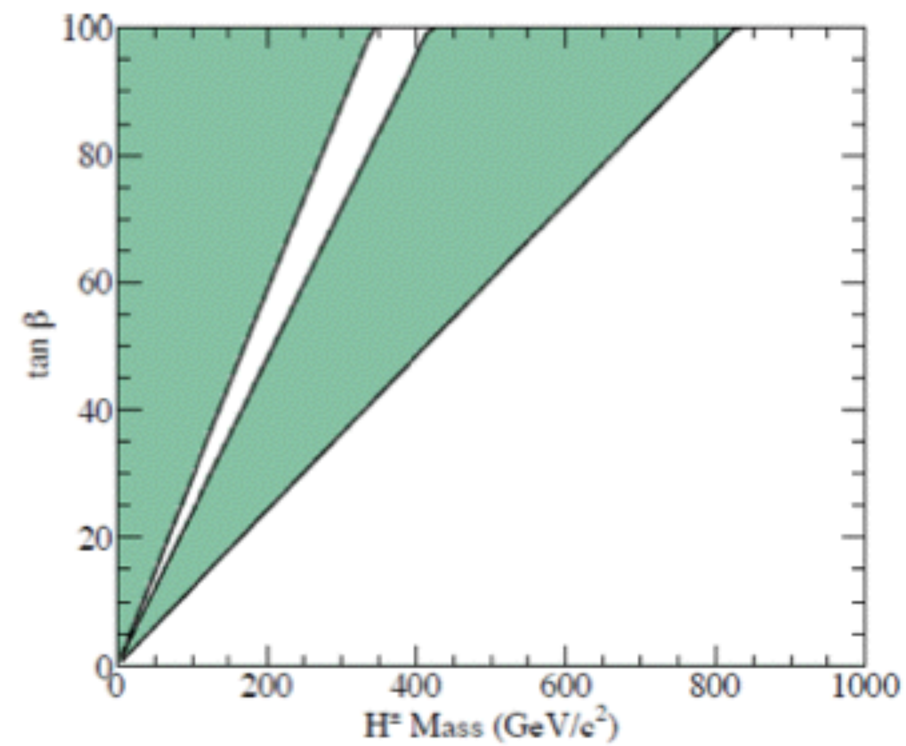
2-Higgs doublet model:

$$B = B_{SM} \times \left(1 - m_B^2 \frac{\tan^2\beta}{m_{H^\pm}^2}\right)$$



- ➡ tag-side: fully reconstructed B with both hadronic and semileptonic tags
- ➡ signal-side: one charged track (μ,e,π) + 2ν
- ➡ fit energy distribution in the calorimeter:





B-factories exclusion plot

B_{SM} = (1.11±0.28)x10^{-4} vs B_{HFAG} = (1.14±0.22)x10^{-4}

- f_B = (191±9) MeV (HPQCD, PDG12)
- $|V_{ub}|$ = (4.15±0.49) 10^{-3} (PDG12)

Looking for a Charged Higgs: $B^+ \to \tau^+ \nu$

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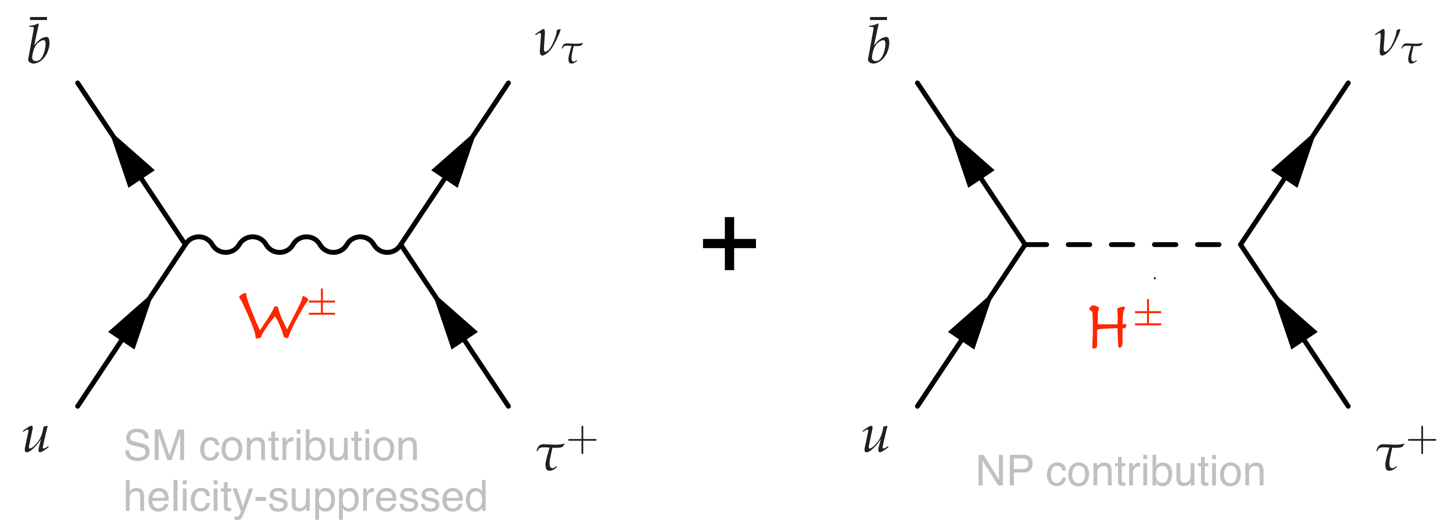
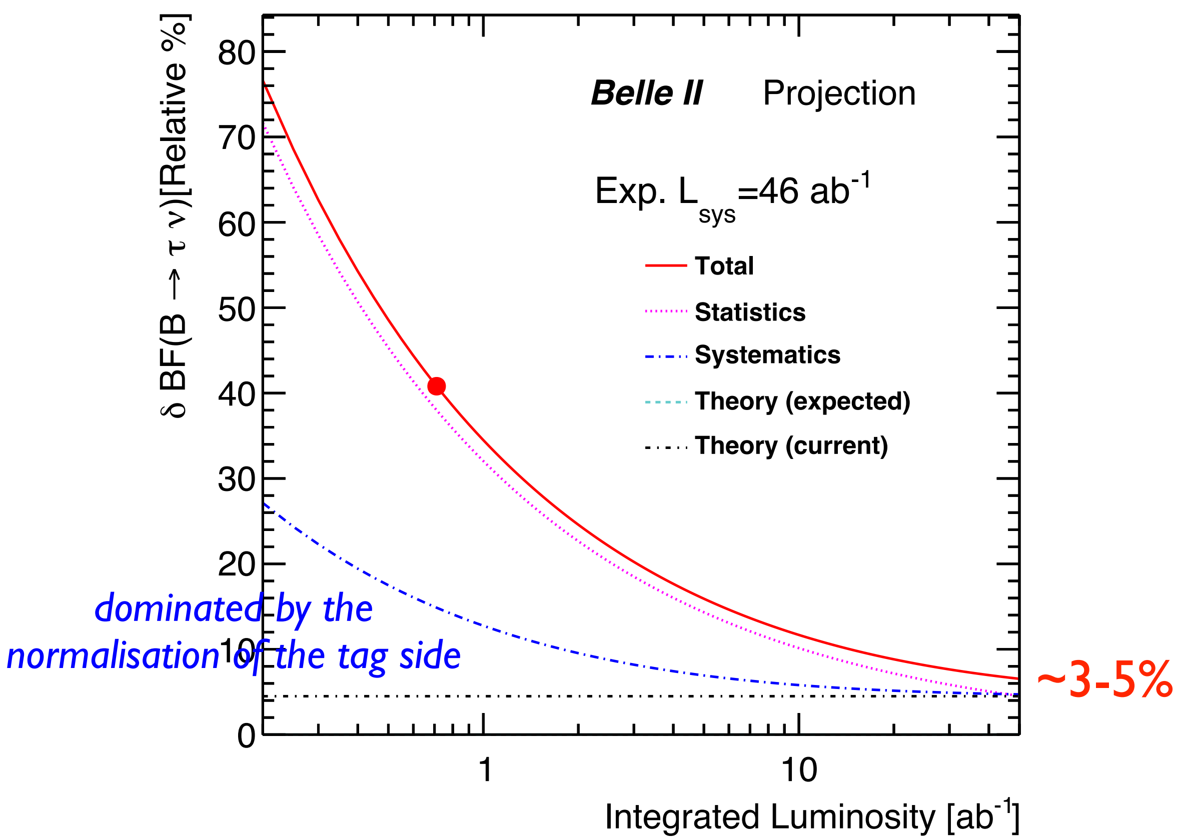
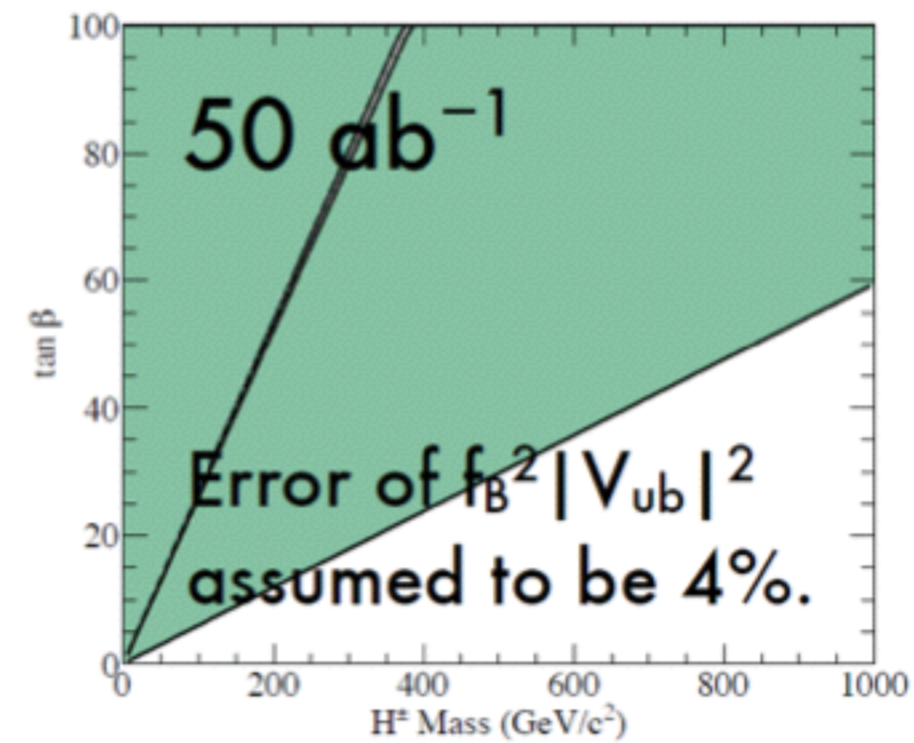
$$B = B_{SM} \times \left(1 - m_B^2 \frac{\tan^2 \beta}{m_{H^\pm}^2}\right)$$







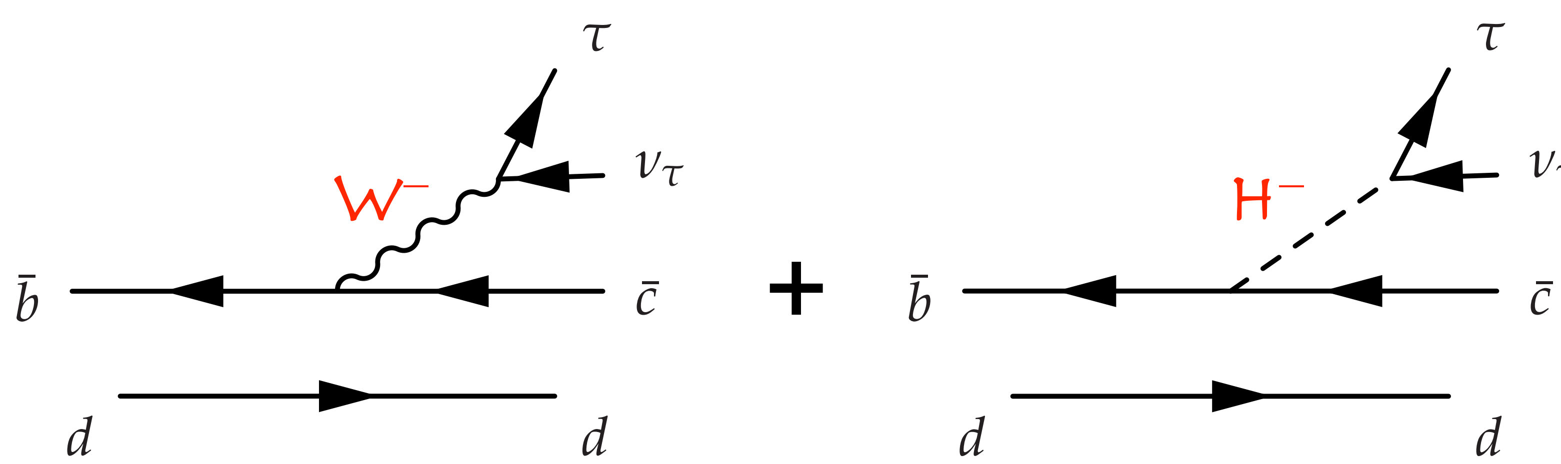
Super *B*-factory exclusion plot

➡ *Belle II* can also test lepton flavour universality: $R^{\tau\ell} = \frac{\Gamma(B \to \ell\nu)}{\Gamma(B \to \tau\nu)}, \quad \ell = e, \mu$

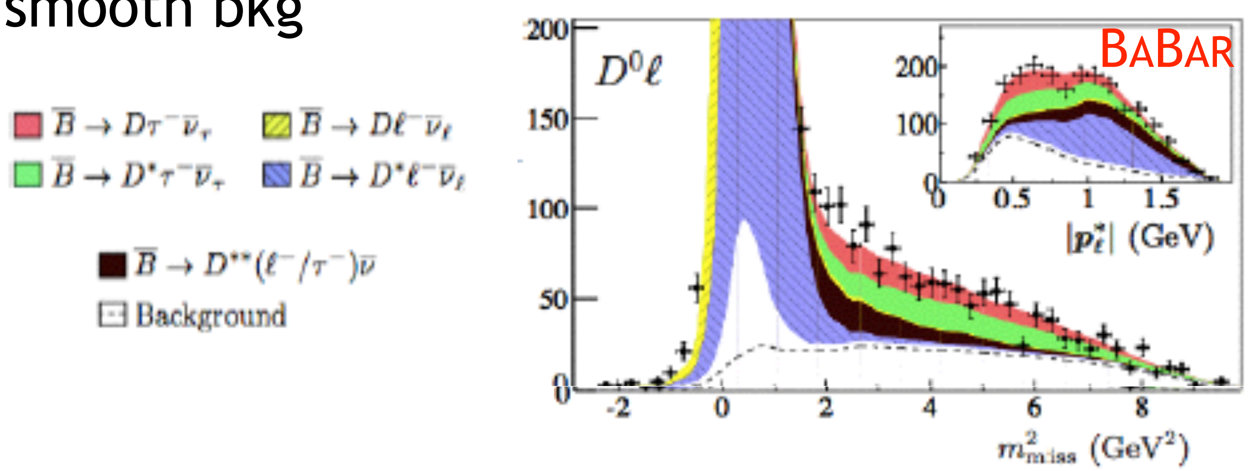
The Charged Higgs in $B \to D^{(*)}\tau\nu$

2-Higgs doublet model:

$$B = B_{SM} \times m_{W^\pm} \left(\frac{\tan\beta}{m_{H^\pm}} \right)$$



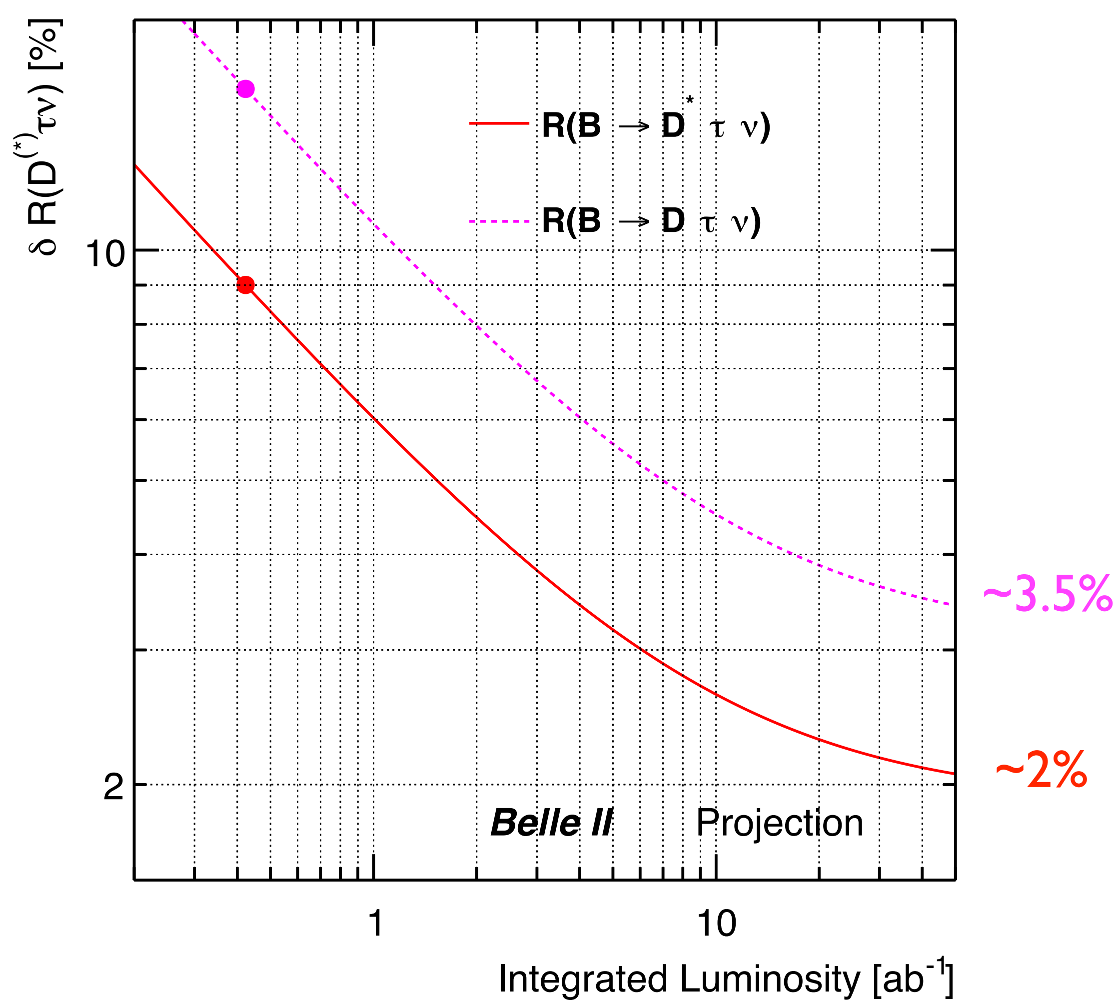
➡ Experimentally hard: signal is not a peak on a smooth bkg



➡ observable: $R = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)}$

➡ The most recent result (BABAR) shows an unexpected excess over the SM of ~3.4σ [R(D*) + R(D) combined]

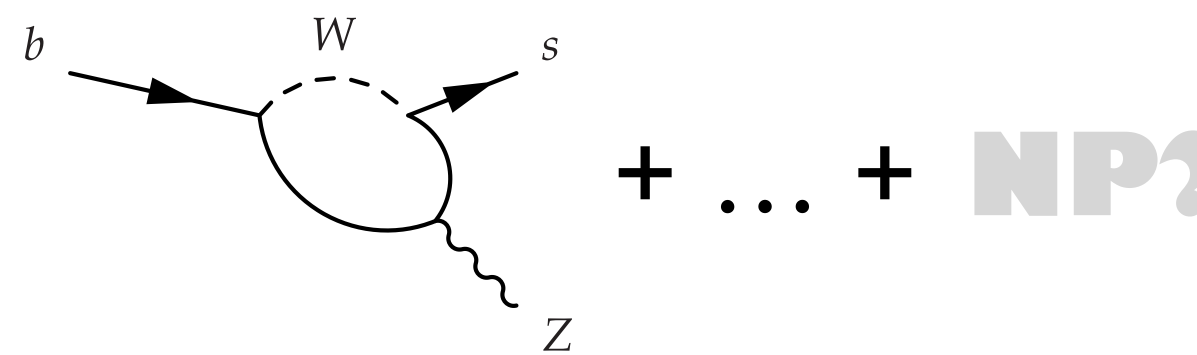
➡ *Belle II* will be able to confirm the excess already with 5 ab^{-1}

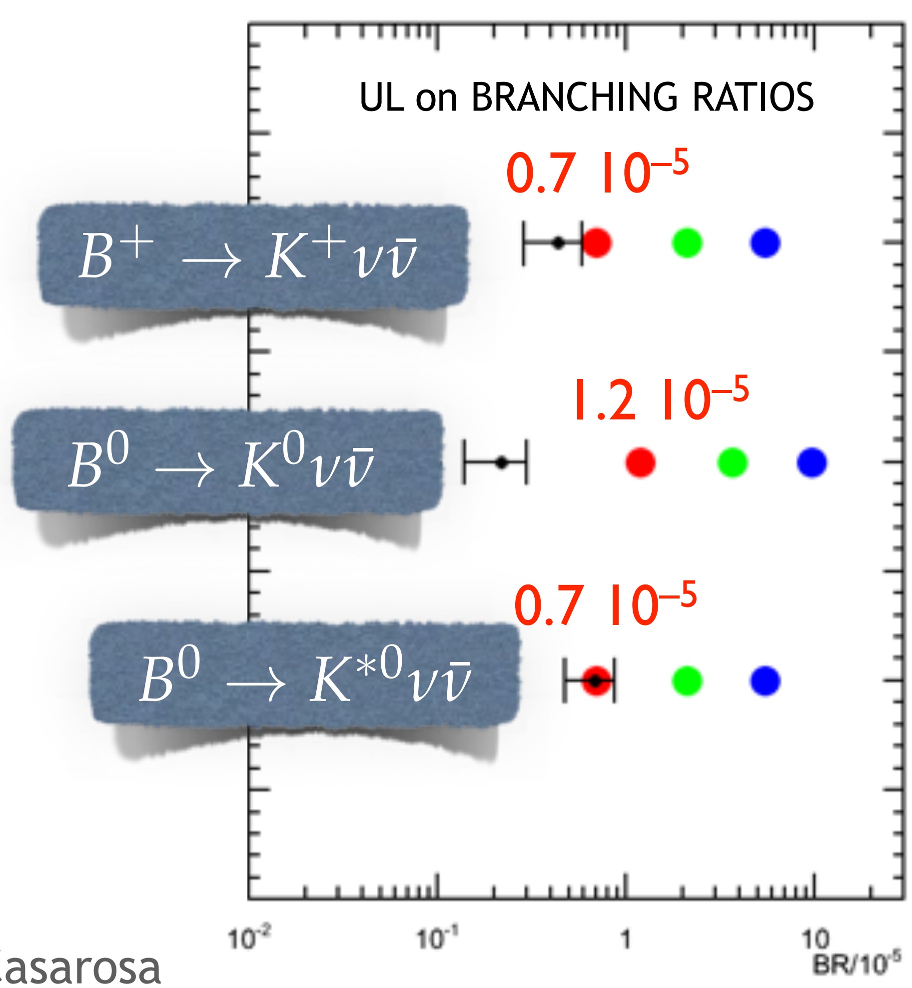


Rare Decays: $B \to h^{(*)}\nu\nu$

➡ Theoretically very clean since there are no long-distance contributions from vector resonances (no charged leptons in the final state)

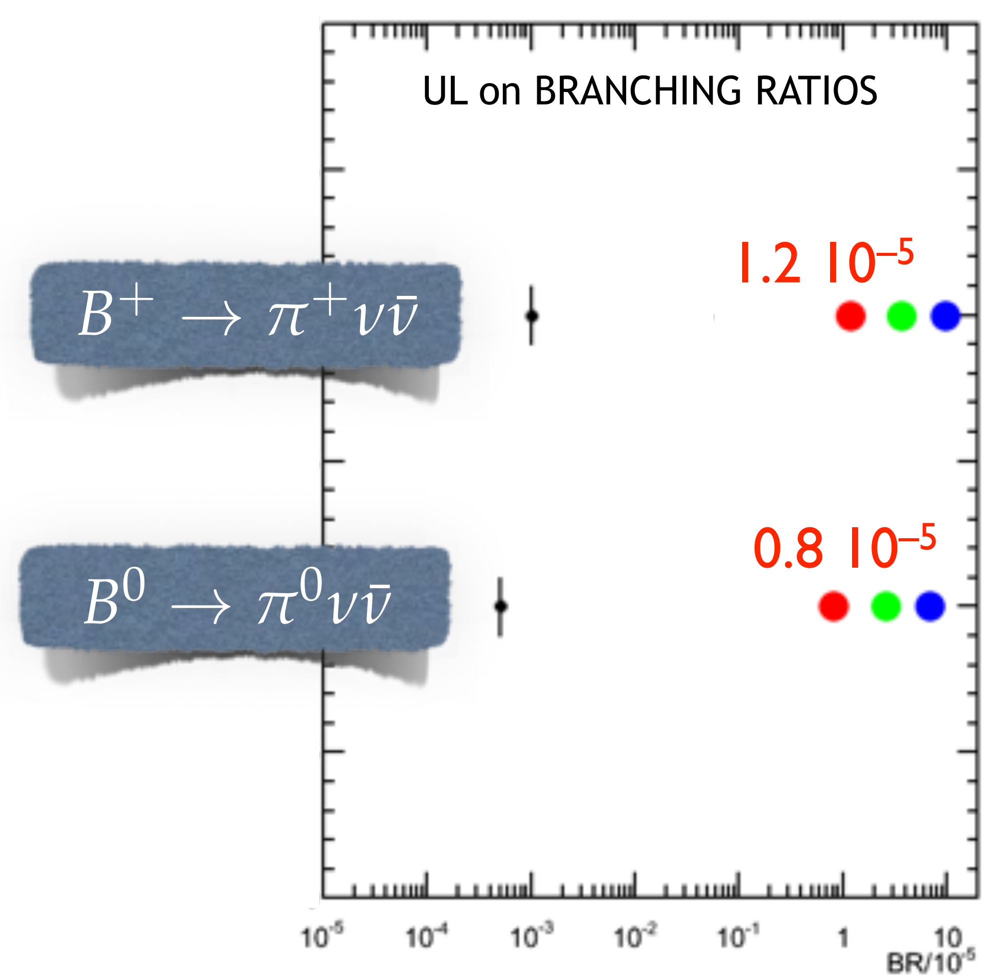
e.g.: $B \to K^{(*)}\nu\nu$ highly sensitive to Z penguin processes





● 50 ab⁻¹
● 5 ab⁻¹
● 0.7 ab⁻¹

SM BR



extrapolations based on hadronic tag reconstruction techniques

Charm Physics @ a B Factory

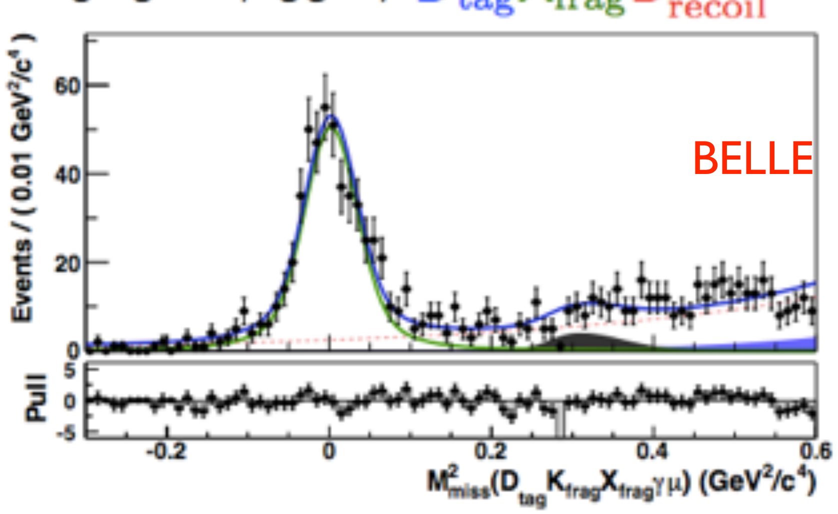
- No coherent production of the D^0 - $\bar{D}^0$ state:
  - no access to strong phases
  - D^0 flavour tagging with D^{*+} decays (lower efficiency, higher purity w.r.t. untagged D^0)

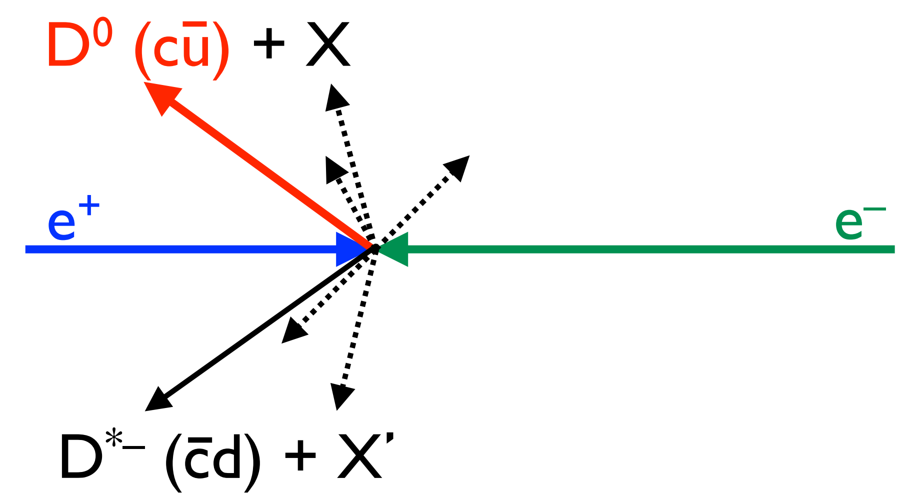
- Time-dependent analysis are possible assuming that D are produced at the interaction point

$$t = \ell/(\beta\gamma c)$$

- D full reconstruction for neutrinos and inclusive analyses (precise test of LQCD and NP searches in (semi)leptonic decays)

$$e^+e^- \to c\bar{c} \to \overline{D}_{\rm tag} X_{\rm frag} D^{(*)}_{\rm recoil}$$

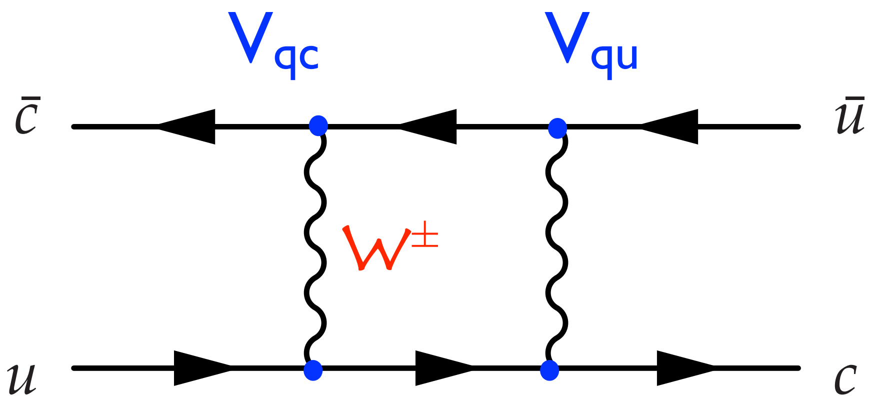




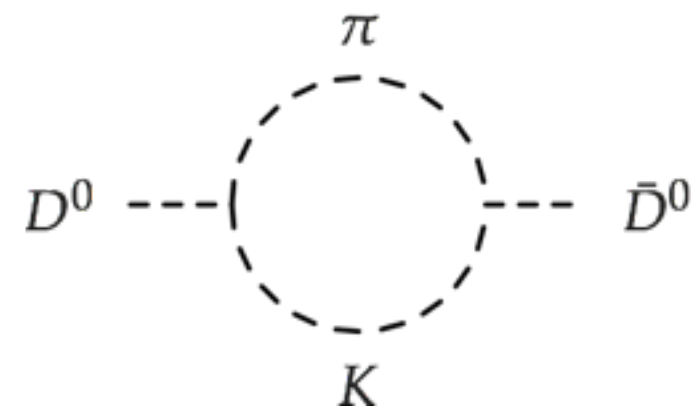
- average D^0 flight length $\ell \approx 200$ μm
- average proper time error ≈ 0.25 ps
- $p^*(D^0)$ > 2.5GeV/c removes 98% of D from B decays

Charm Mixing & Indirect CPV

SM:



+



virtual quarks are down-type!

short-distance + NP?

long-distance

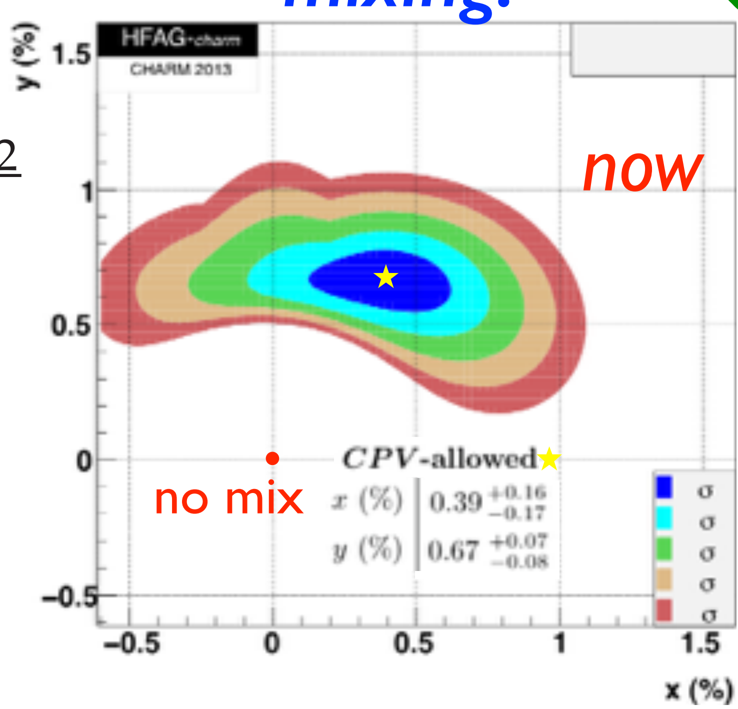
SM dominant, hard to compute

$$D^0 = p|D_1\rangle + q|D_2\rangle$$
$$\bar{D}^0 = p|D_1\rangle - q|D_2\rangle$$

$|D_{1,2}\rangle$ are the free-hamiltonian eigenstates of masses $m_{1,2}$ and widths $\Gamma_{1,2}$

mixing:

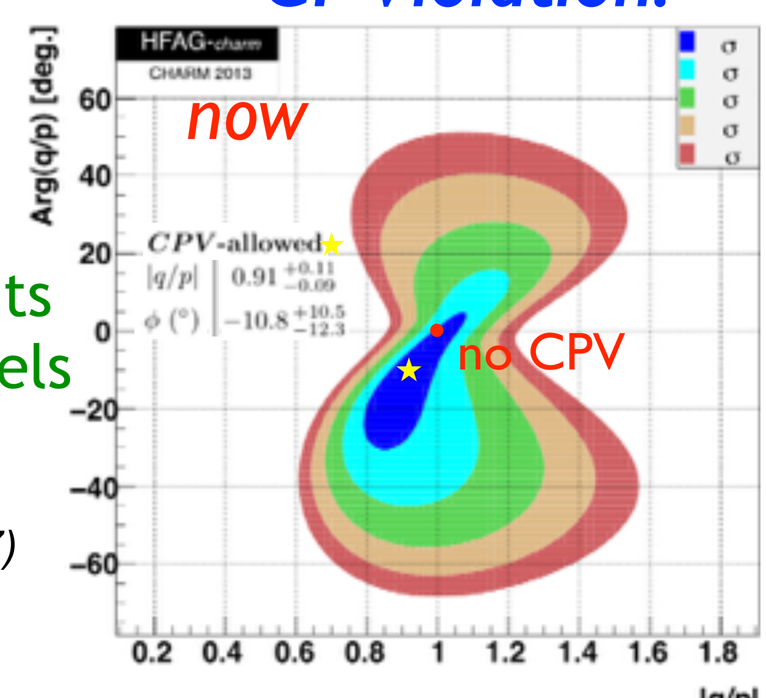
$$x = \frac{m_1 - m_2}{\Gamma}$$
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$



the measurements constrain NP Models

Golowich et al., PRD76, 095009 (2007)

CP Violation:



$\left|\frac{q}{p}\right|$ CPV in mixing

$$\phi = \arg\left(\frac{q}{p}\right)$$

CPV in the interference of decays with and without mixing

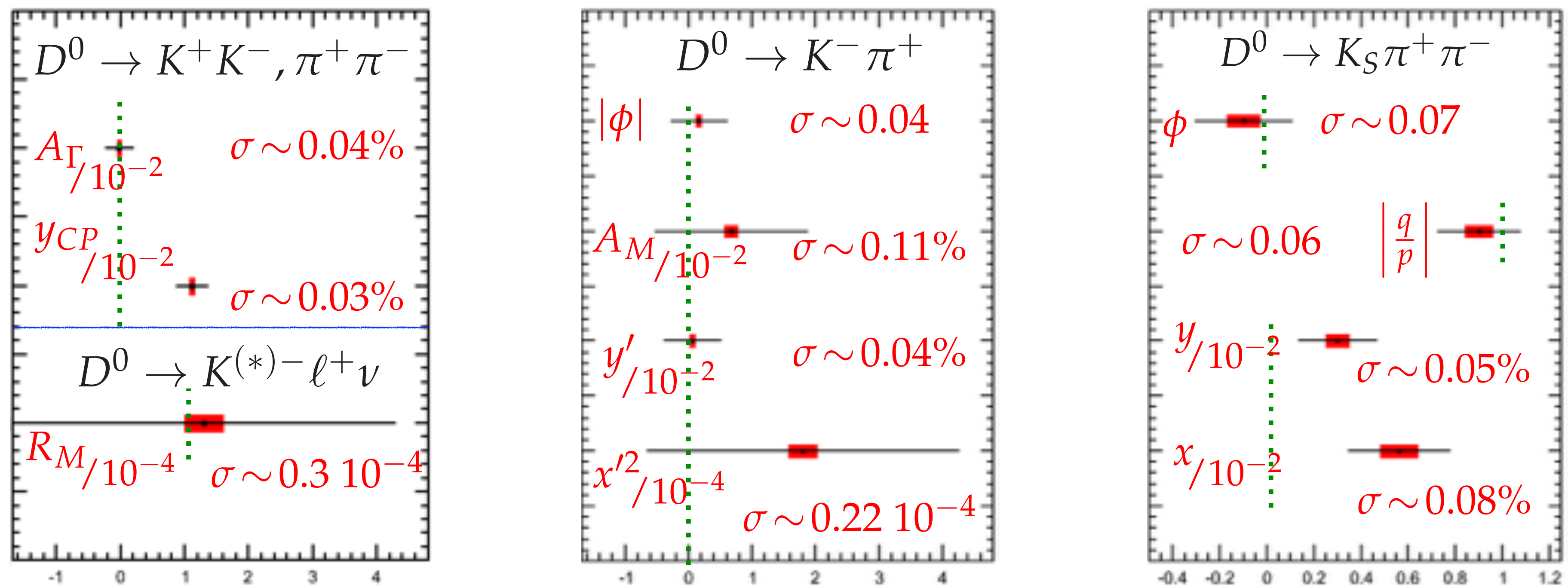
Charm Mixing & CPV @ *Belle II*

- All measurements will be essentially limited by the systematic error

Belle II projection
vs
BELLE measurement

⋮ = no mixing/CPV

NOTE: only the significant figures are reported in the plots



mixing:

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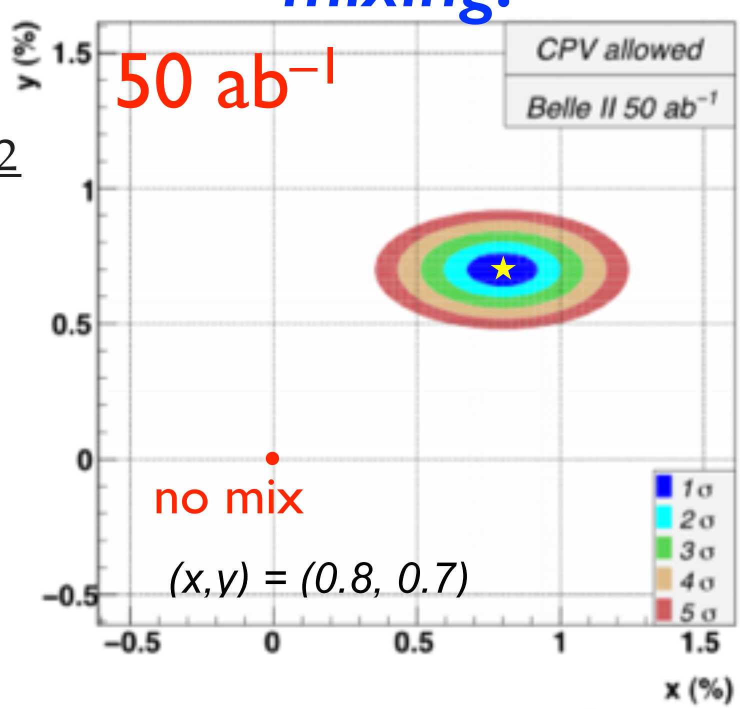
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

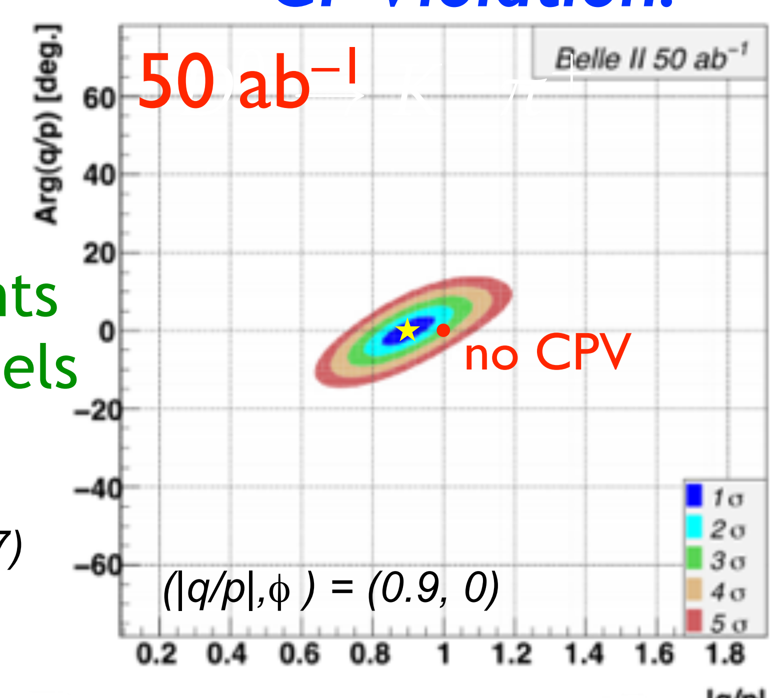
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$



the measurements constrain NP Models

Golowich et al., PRD76, 095009 (2007)

CP Violation:

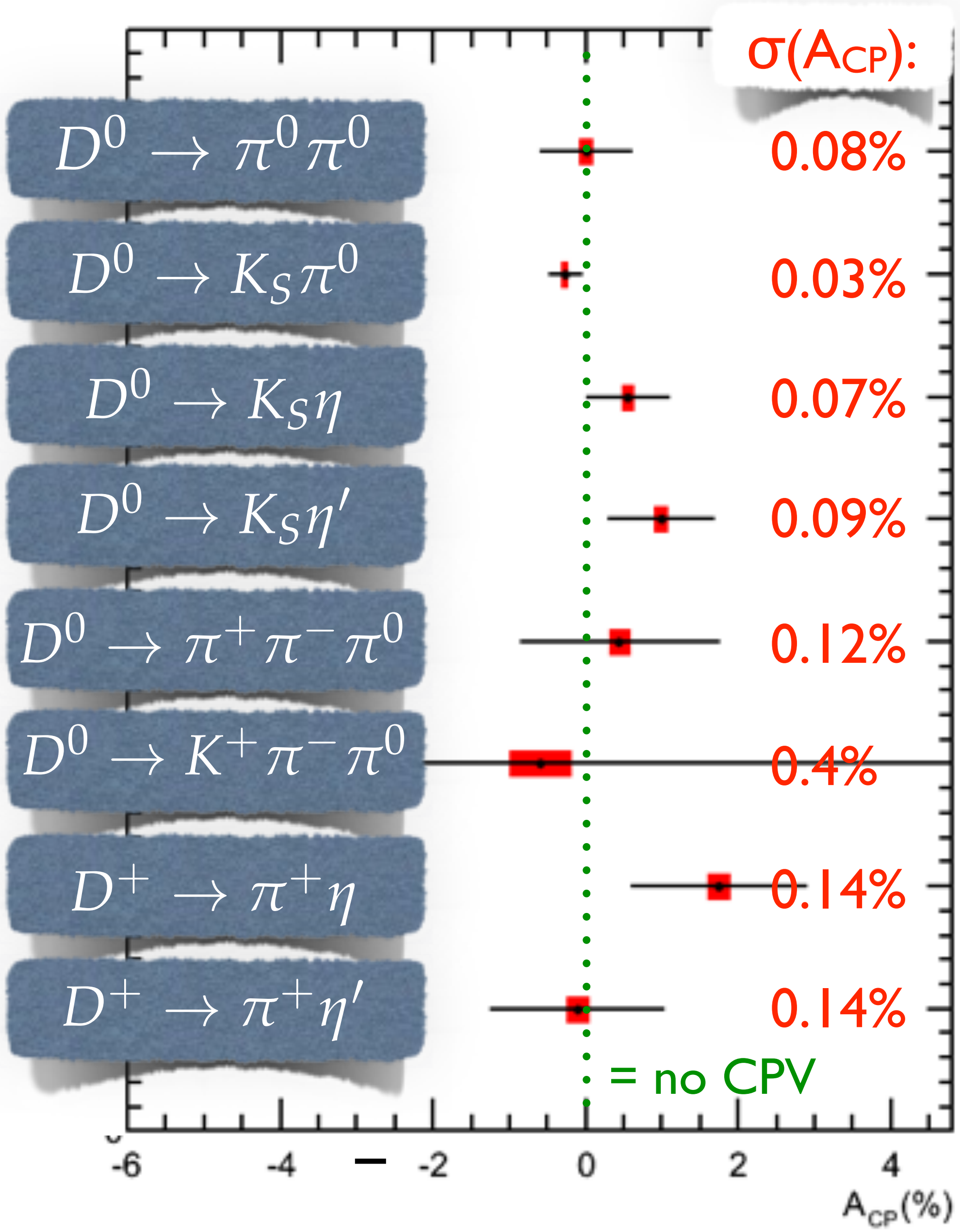


$\left|\frac{q}{p}\right|$ CPV in mixing

$\phi = \arg\left(\frac{q}{p}\right)$ CPV in the interference of decays with and without mixing

Time-Integrated CPV in Charm

Belle II projection vs BELLE measurement



other interesting channels:

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

➡ Experimental observable:

$$A_{CP} = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}$$

➡ *Belle II* initial state is symmetric under CP

➡ *Belle II* will give its major contribution in channels with neutrals in the final state

➡ Most measurements will be limited by the systematic error

- $K^0/\bar{K}^0$ different interaction with matter → 0.02% irreducible systematics in modes with K_S
- CPV in the K^0 system to be accounted for in the final asymmetry (true also for mixing analysis)

➡ Direct CPV sensitivity may reach a few in 10^{-5} in some cases!

- Direct CPV in radiative decays can be enhanced above 1%
  - $D^0 \to \phi\gamma$ A_{CP} up to 2 %
  - $D^0 \to \rho\gamma$ A_{CP} up to 10%

Belle II sensitivity at 50 ab^{-1} ≈ 1%

(Isidori, Kamenik PRL109 171801)

Conclusions

- Flavour Physics will continue to play a fundamental role in the process of understanding Nature in the next decade
- *Belle II* has a rich physics program, complementary to the one of LHCb. Both experiments are needed to shed light on the physics beyond the SM.
- SuperKEKB construction will be completed by ~ mid 2015. *Belle II* construction is ongoing, the first physics run is expected in 2017, 50 ab^{-1} expected by 2023.

NOTE: more on the physics program at Super B-factories in
arXiv: 1002.5012 (BelleII)
arXiv: 1008.1541 (SuperB)

march 2014

Thank You!