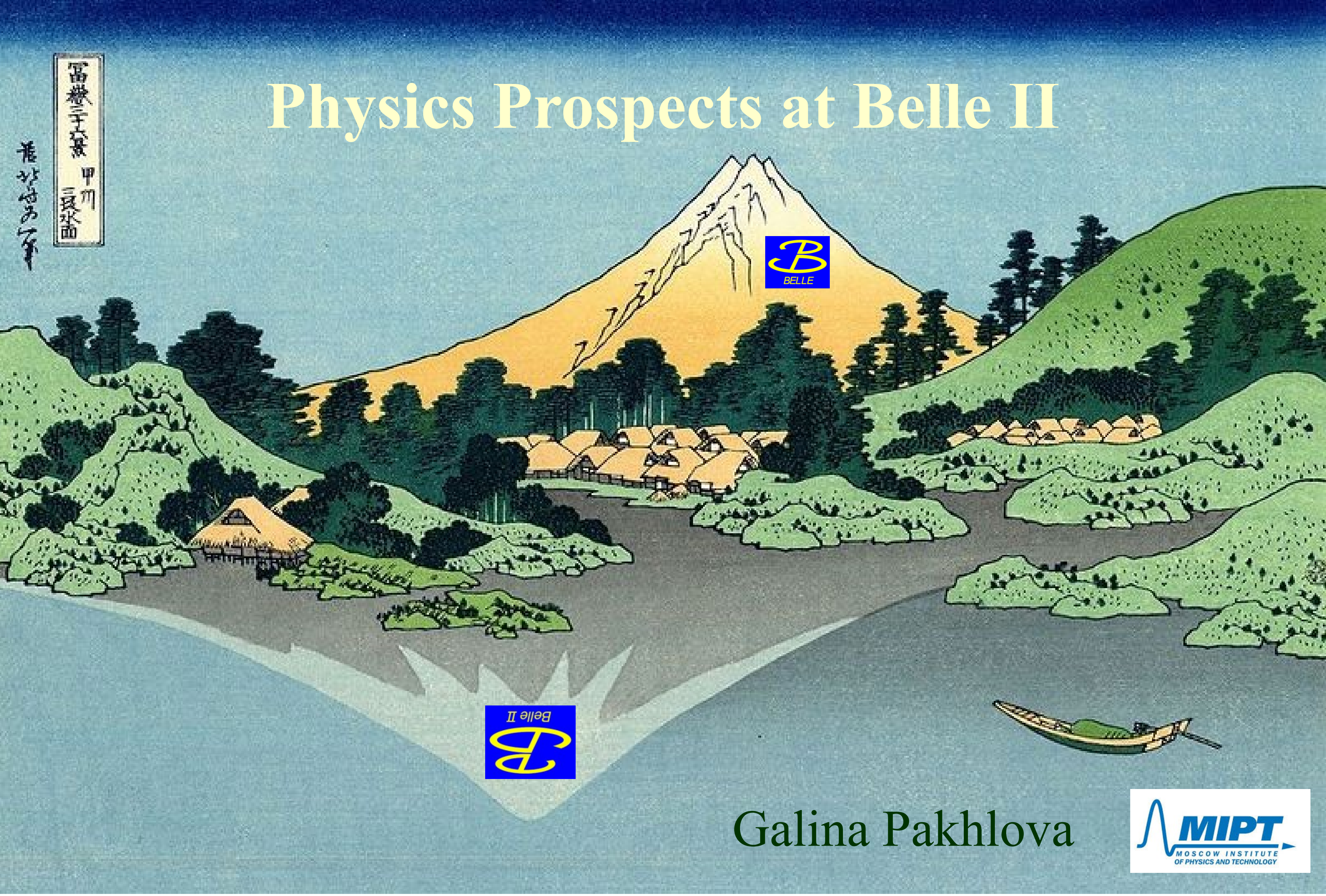


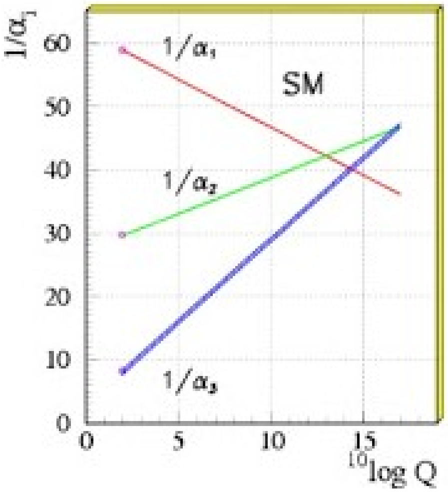
Physics Prospects at Belle II

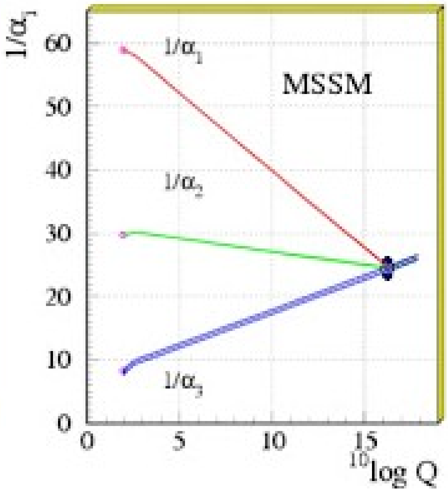
Galina Pakhlova

MIPT
MOSCOW INSTITUTE OF PHYSICS AND TECHNOLOGY

QFTHEP, June 29, 2015, Samara, Russia

Flavor physics in the SM





Bosonic sector of the SM

5 free parameters:

- ○ one defines the scale (vacuum expectation value)
- ○ 4 dimensionless coupling constants

Fermionic (flavor) sector

- ○ 3 Yukawa constants for charged leptons
- ○ 6 Yukawa constants for quarks
- ○ 4 quark-mixing parameters

This is a really miraculous part of the SM. There is no idea

- ○ why do we have many (3) generations?
- ○ why are these 13 constants such as they are?
- ○ why is there a hierarchy & smallness structure?
- ○ why is the mixing matrix almost unit, but not exactly?

All these Whys?:the SM flavor puzzle

Physics at (Super) B factories

New Physics beyond SM

- **B mesons** : CP Violation, Rare decays, CKM matrix elements
- **D mesons** : mixing, CP Violation, Rare decays
- **Tau leptons** : search for Lepton Flavor Violation

Access to (almost all, including complex phase) CKM matrix elements

New spectroscopy beyond standard quark model: tetraquarks, molecules etc

- **Hadron spectroscopy**: quarkonium (+like), charm and light mesons & baryons + exotics?
- **γγ physics**

Important input to QCD models

- Direct search for light sterile particles (sterile neutrino, dark photons etc)

Physics at (Super) B factories

Flavor Physics studies processes via loop diagram:

○ FCNC ($b \to s$, $b \to d$)
○ mixing (box diagram)
○ CP Violation (box, box+loop)

New Physics (e.g. SUSY) even at high mass scale can compete with SM

If New Physics will be found at LHC
its flavor and CP violating couplings should be studied at Flavor experiments
If New Physics will NOT be found at LHC
Flavor experiments give a chance to observe NP manifestation even for the mass scale > TeV

Benefits of (Super) B factories at e^+e^- colliders

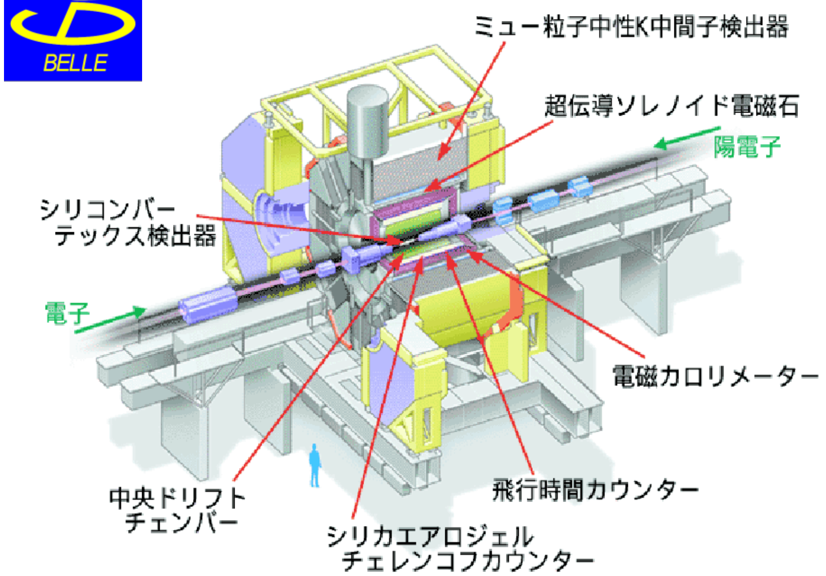
○ Low backgrounds, high trigger efficiency, high γ and π^0 reconstruction efficiency, high flavor tagging efficiency with low dilution
○ Negligible trigger bias and good kinematic resolution (due to low background)
○ Dalits analyses, absolute branchings, missing mass and missing energy measurements
○ Systematics differ from LHCb

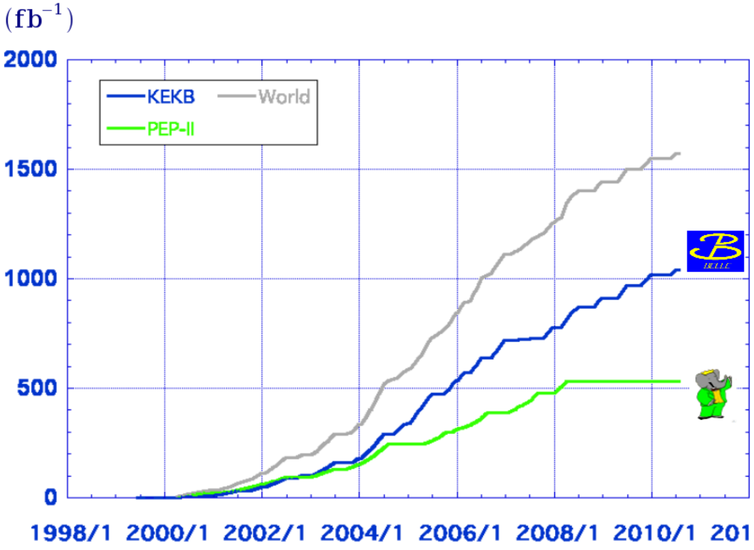
Belle experiment at KEKB

8 GeV (e^-) × 3.5 GeV (e^+)

designed luminosity: $10.0\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

achieved $21.2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (>2 times larger!)



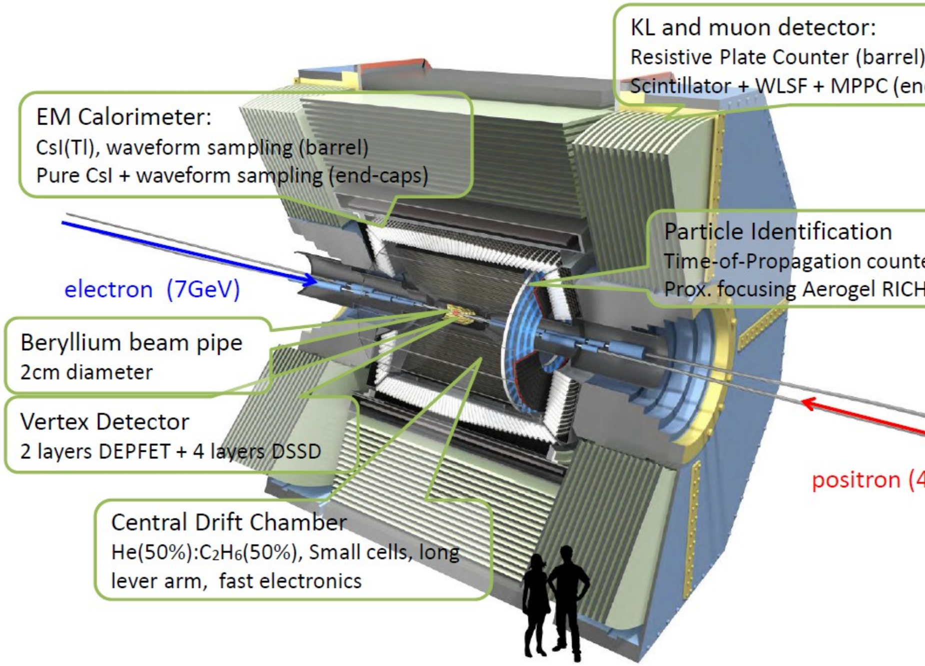


> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Completed data taking on June, 2010
to start SuperKEKB/Belle II upgrade

Belle II Detector



KL and muon detector:
Resistive Plate Counter (barrel)
Scintillator + WLSF + MPPC (end-caps)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

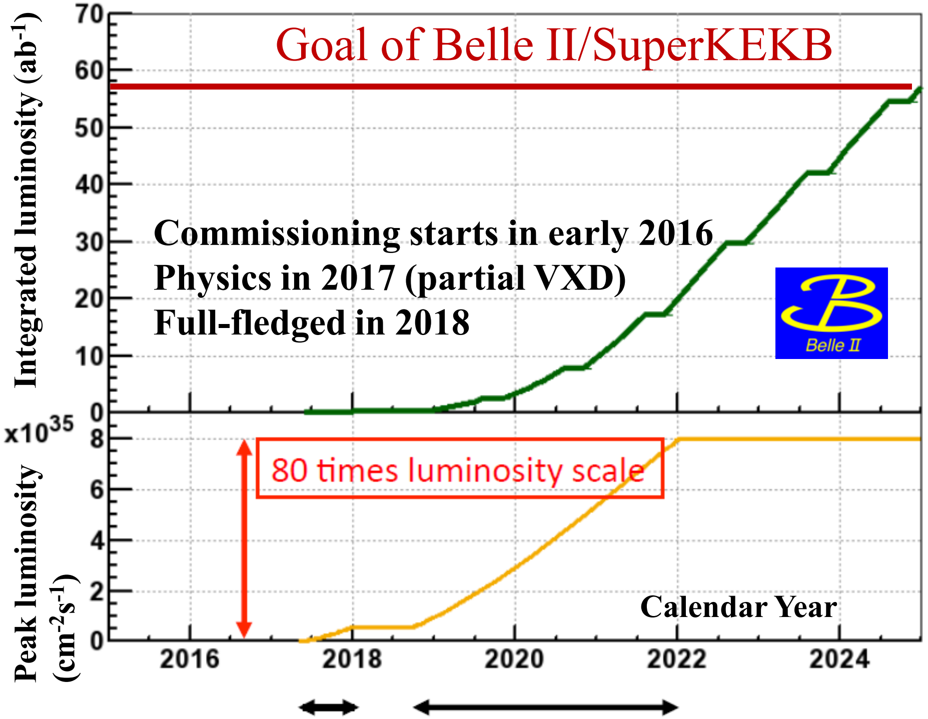
Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

SuperKEKB luminosity profile



3.85 years

The same time scale as KEKB

Belle/KEKB recorded ~1000 fb^{-1}
Now change units to ab^{-1}

Belle II with respect to Belle

Belle The energy asymmetry 8 GeV (e^-) × 3.5 GeV (e^+) ➔ $\beta\gamma=0.425$

- **sin(2β) the main goal of the experiment**
- **measurement of Δt between the two B mesons with high precision**

Belle II The energy asymmetry 7 GeV (e^-) × 4 GeV (e^+) ➔ $\beta\gamma= 0.28$

➔ better hermiticity

- **modes with neutrino in the final state (e.g. $B\to\tau\nu$)**

○ A smaller beam pipe radius (1.5 cm to 1.0 cm) allows for the innermost silicon detector layer to be positioned closer to the IP (2.0 cm to 1.3 cm)

- **significantly improve the resolution in the z direction**

○ Significantly increased outer radius of the SVD (from 8.8 to 14.0 cm)

- **more K^0_S for the time-dependent using K^0_S vertexing**

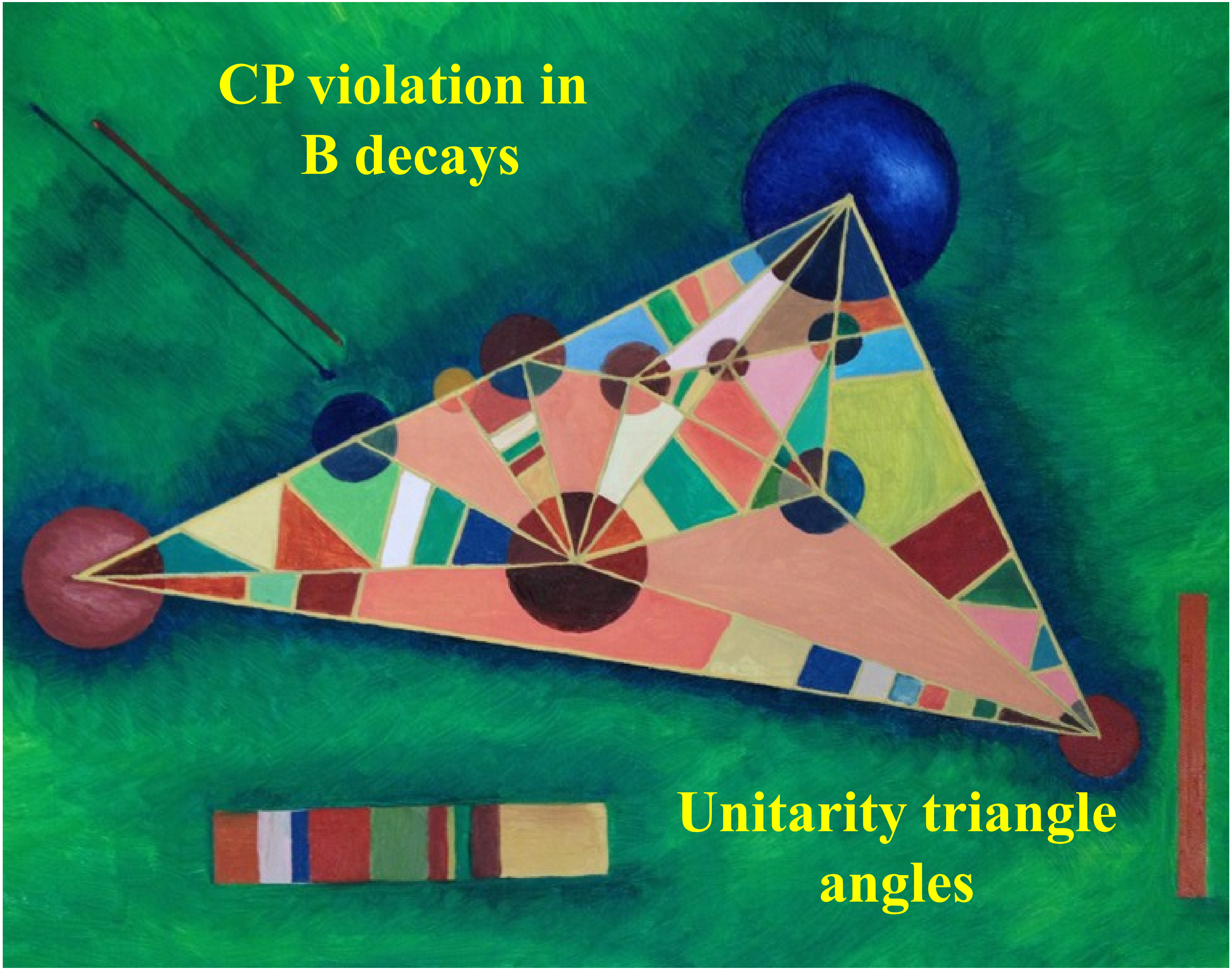
○ Higher reconstruction efficiency of D^* slow pions and better flavor tagging

○ PID improvements

- **improve K/π separation, flavor tagging, rare charmless decays or $b\to s\gamma$ efficiencies, background rejection**

○ Improvements to the KLM

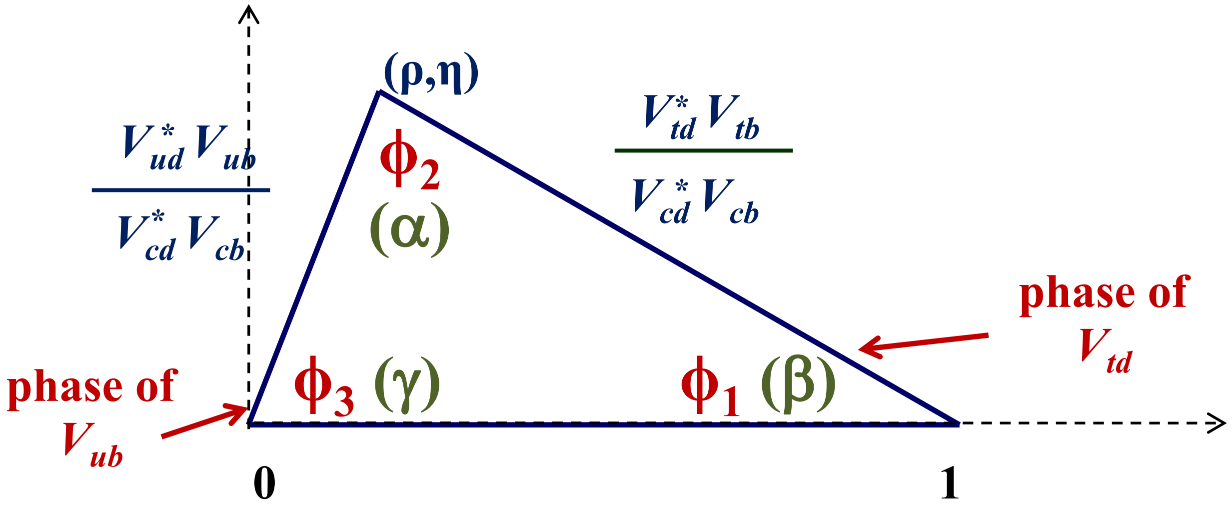
- **higher K_L veto efficiencies used in missing energy analyses ($B\to\tau\nu$)**



CP violation in B decays

Unitarity triangle angles

Unitarity Triangle for CP violation in B^0 mesons



(ρ,η)

$\frac{V_{ud}^* V_{ub}}{V_{cd}^* V_{cb}}$

$\frac{V_{td}^* V_{tb}}{V_{cd}^* V_{cb}}$

ϕ_2 (α)

ϕ_3 (γ)

ϕ_1 (β)

phase of V_{ub}

phase of V_{td}

0

1

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$

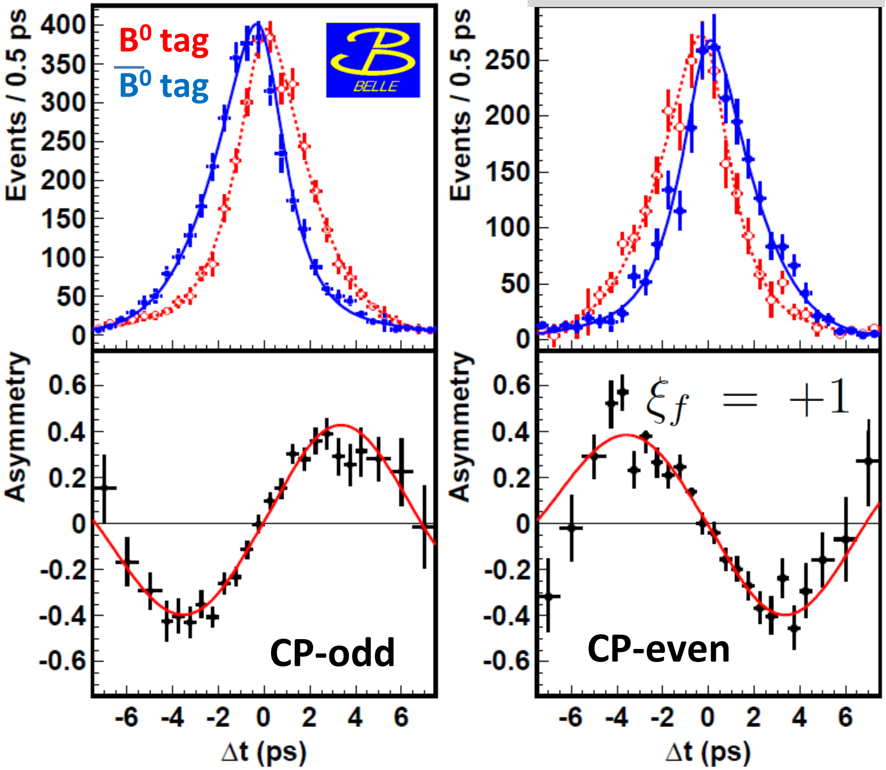
Belle II

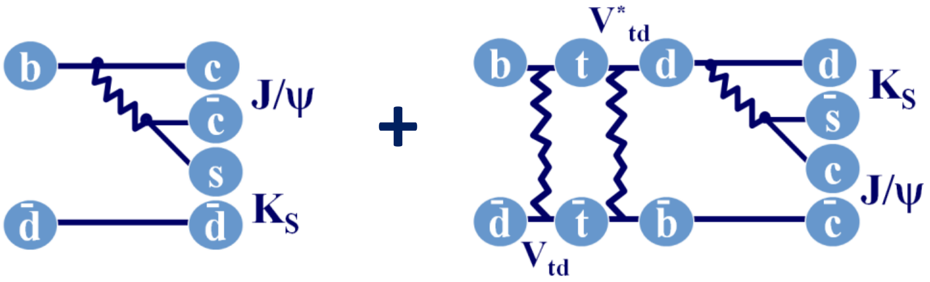
- ○ Precise measurements of UT angles
- ○ Tight constrained on CKM matrix elements
- ○ If inconsistency between angles or/and angles + sides ➔ indication for NP

Precise measurement of sin(2β) in $B^0 \to ccK^0$

$772 \times 10^6 \; B\bar{B}$ pairs

PRL 108 171208 (2012)





$$\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP} f_{tag}$$

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 + q \Big[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t) \Big] \Big\}$$

SM: $\mathcal{S}_f = -\xi_f \sin 2\phi_1$ and $\mathcal{A}_f = 0$

Belle 2012: $B \to J/\psi K^0_s$, $\psi(2S)K^0_s$, $\chi_{c1}K^0_s$ & $B \to J/\psi K^0_L$

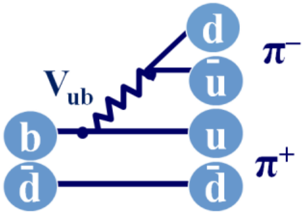
$\sin(2\phi_1) = 0.667 \pm 0.023 \pm 0.012$ (0.9°)

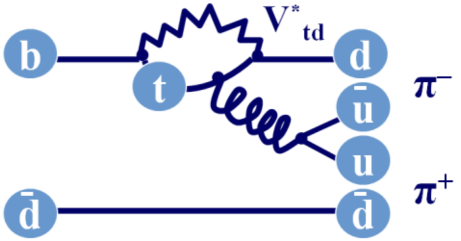
$A_f = 0.006 \pm 0.016 \pm 0.012$

(parameter of direct CPV)

Belle II		**sin(2β)** LHCb	
$5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$	$8\ \mathrm{fb}^{-1}$ (2018)	$50\ \mathrm{fb}^{-1}$
0.4°	0.3°	0.6°	0.3°

α measurements: $B^0 \to \pi\,\pi$





The decay amplitudes $B \to \pi^+\pi^-(\rho^+\rho^-)$ include:

- a tree term $T \sim V_{ub}^{*} V_{ud}$ (dominant)
- a penguin term $P \sim V_{tb}^{*} V_{td}$ (suppressed, but not small)

$$A_{CP}(\Delta t) = \frac{N(B^0 \to \pi^+\pi^-) - N(\overline{B}^0 \to \pi^+\pi^-)}{N(B^0 \to \pi^+\pi^-) + N(\overline{B}^0 \to \pi^+\pi^-)} = S \cdot \sin(\Delta m \Delta t) + \mathrm{A} \cdot \cos(\Delta m \Delta t)$$

Parameter S of indirect CPV:

$$S = \sin 2\alpha + 2r\cos\delta \sin(\beta+\alpha)\cos 2\alpha + O(r^2)$$

- δ – the relative strong phase between T and P amplitudes
- $r < 1$ – ratio of P to T amplitude

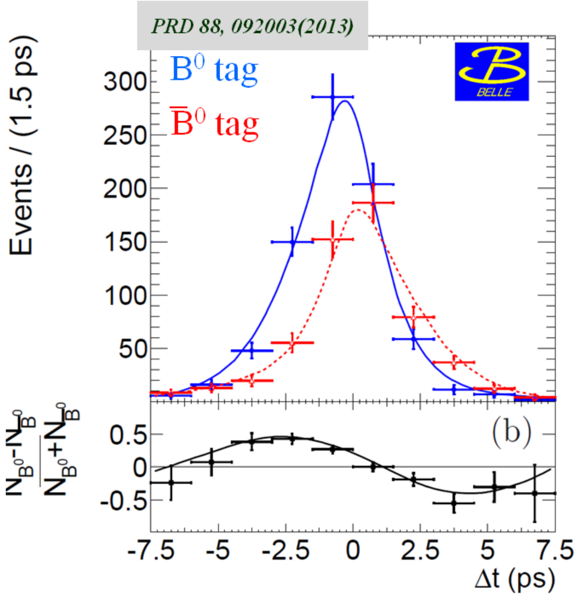
We can measure effective α (α_{eff}) shifted by extra angle

$$S = \sqrt{1-C^2}\,\sin(2\alpha_{eff}) \qquad \alpha_{eff} = \alpha + \theta$$

To measure α additional inputs are required

The cleanest method is the isospin analysis (Gronau and London)
We need to measure all 6 BR's of B^0 and B^+ to $\pi\pi$ decays: $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^+\pi^0$

α: experimental results



$B^0 \rightarrow \rho^0\rho^0$

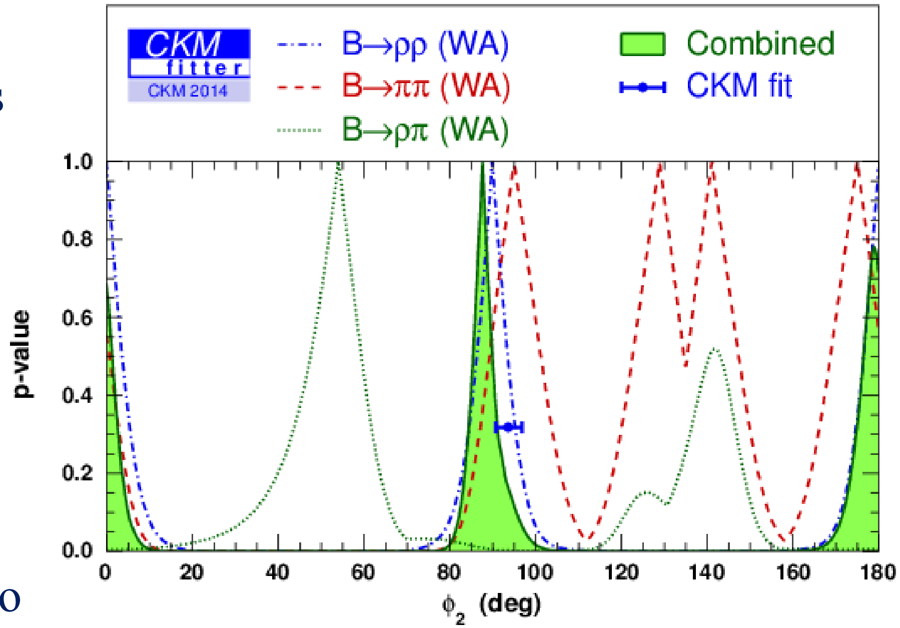
○ angular analysis

○ purely CP=+1 final state

○ small Br, small penguin contribution

$B^0 \rightarrow \rho^{\pm}\pi^{\pm}$

not CP eigenstate, but B^0 can decay to both $\rho^+\pi^-$ and $\rho^-\pi^+$

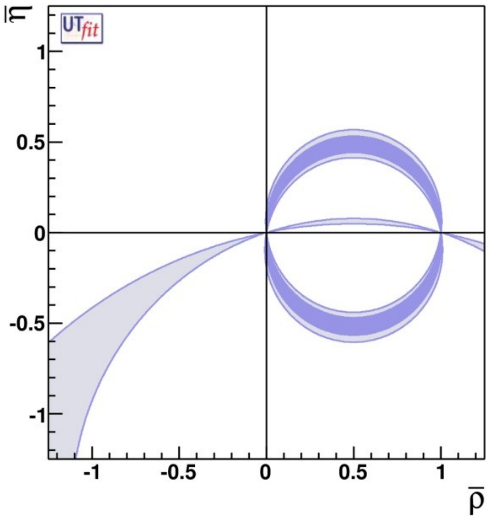


$B^0 \rightarrow \pi^+\pi^-$

$S_{CP} = -0.64 \pm 0.06 \pm 0.03$

$A_{CP} = +0.33 \pm 0.06 \pm 0.03$

$\alpha[\mathrm{WA,all}] = (87.7^{+3.5}_{-3.3})°$



○ Complicated analysis (especially for $\rho^0\rho^0$)

○ BUT method was checked many times by Belle & BaBar

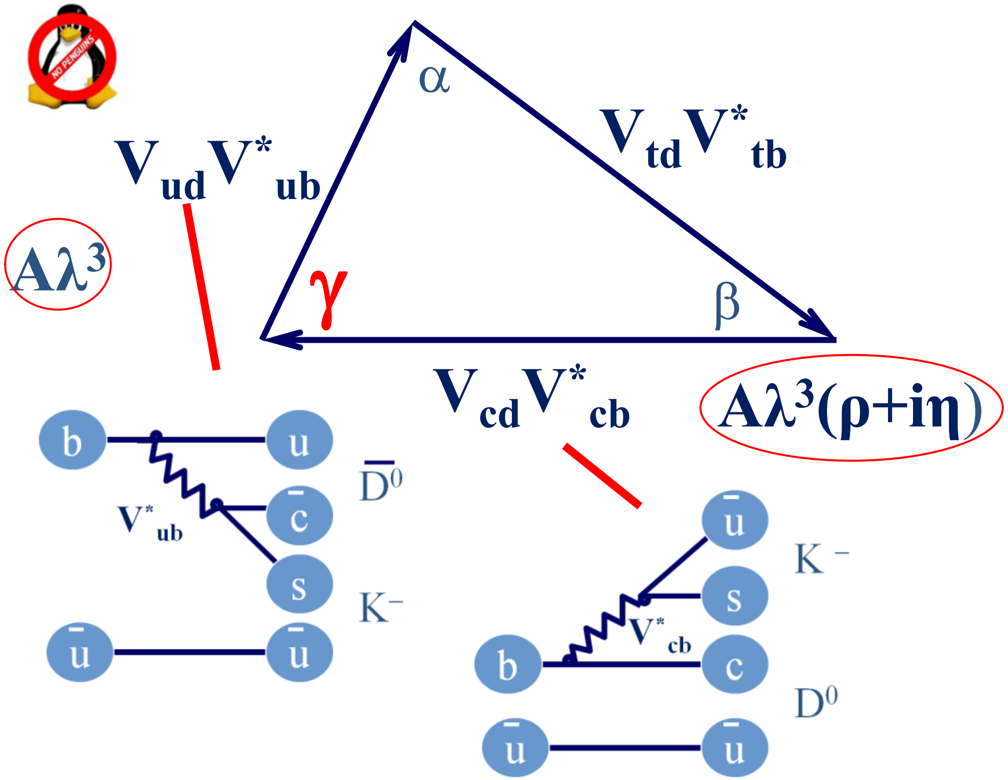
○ Belle & BaBar consistent results

○ Statistics limited (not systematic)

○ **B factories only** (a lot of neutrals in the final states)

○ **Expected errors : 5 ab^{-1} to be 2°, 50 ab^{-1} to be 1°**

Direct CPV and γ



$B \to DK$: the angle between two amplitudes is really γ, but the final states are different $D^0 \neq \bar{D}^0$

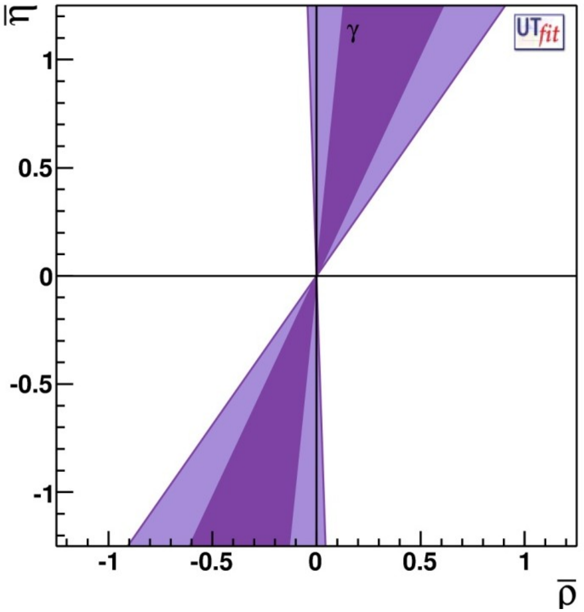
GLW method (Gronau, London, Wyler) ***PLB 253, 483 (1991)***
D^0 decays into CP eigenstate (rarely – Cabibbo suppressed modes, *e.g.* K^+K^-, $K_S\pi^0$)

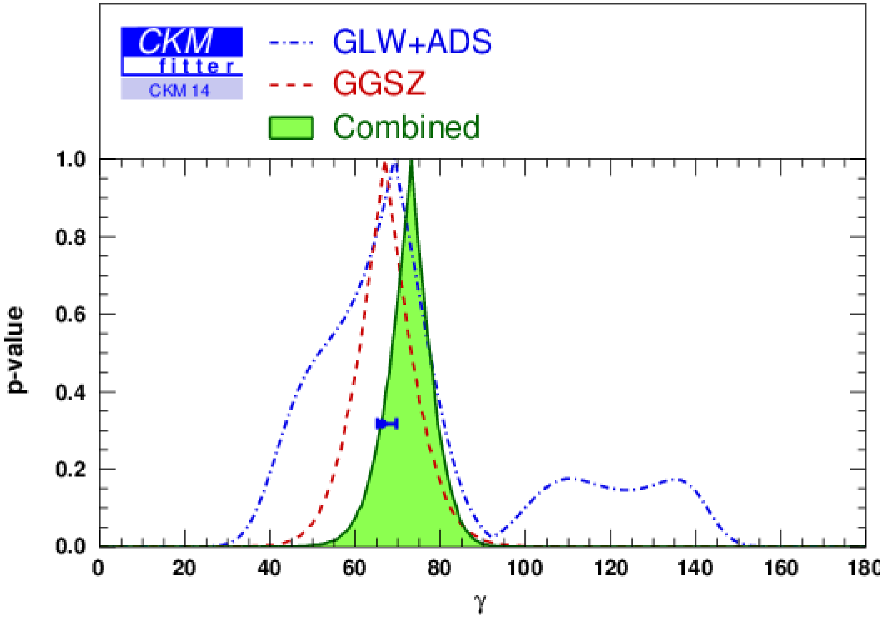
ADS method (Atwood, Dunietz, Soni) ***PRL 78, 3357 (1997)***
D^0 decays into final state typical for D^0 (very rarely – doubly Cabibbo suppressed modes, *e.g.* $K^+\pi^-$). Enhance CP asymmetry by suppression (in D-decay) of allowed (in B-decays)

GGSZ method (Giri, Grossman, Soffer, Zupan) ***PRD 68, 054018 (2003)***
*Used by experimentalists (**A.Bondar**) before suggested by theoreticians*
D^0 decays into three body state (*e.g.* $K_S\pi^+\pi^-$): mixture of opposite CP eigenvalues +1/–1 also contain doubly Cabibbo suppressed decays. Resolve by Dalitz analysis.

Fit to all measurements

$$\gamma(\text{combined} - 2014) = (73.2^{+6.3}_{-7.0})^\circ$$



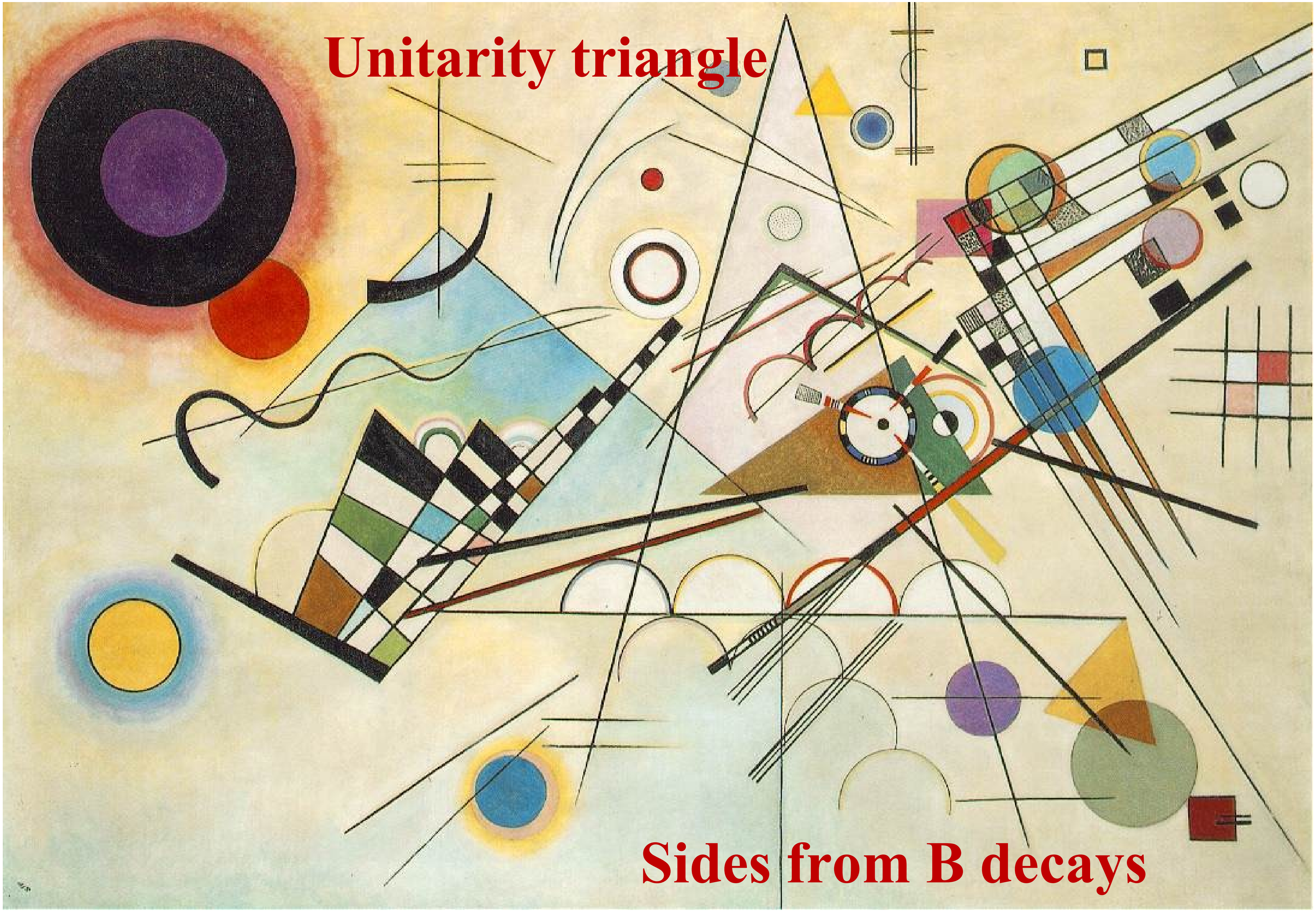


The accuracy of present measurements are limited by statistics (we really study VERY rare decay). The systematic and model uncertainties are much smaller.

Sensitivity of Belle II and LHCb upgrade

Decay mode	LHCb upgrade		Belle II
$B \to DK$ with $D \to hh'$, $D \to K\pi\pi\pi$	1.3°	[15]	2.0°
$B \to DK$ with $D \to K^0_S\pi\pi$	1.9°	[15]	2.0°
$B \to DK$ with $D \to 4\pi$	1.7°		–
$B \to DK\pi$ with $D \to hh'$, $D \to K^0_S\pi\pi$	1.5°	[16]	–
$B \to DK\pi\pi$ with $D \to hh'$	3.0°		–
Combined	1.1°		1.5°
Time-dependent $B^0_s \to D^{\mp}_s K^{\pm}$	2.4°	[15]	–

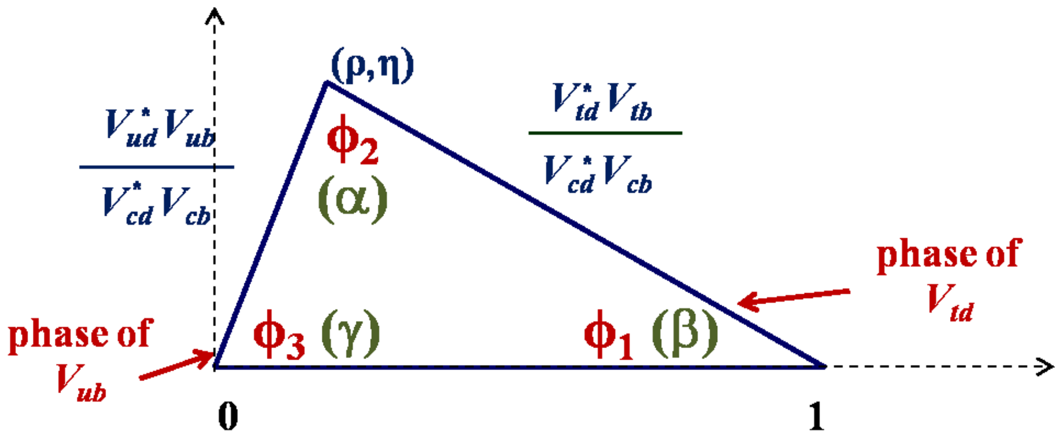
LHCb can measure this with better accuracy (charged modes) Belle-II provides important and independant cross check



Unitarity triangle

Sides from B decays

Sides of UT



~$|V_{ub}/V_{cb}|$

- ○ Inclusive semileptonic decays
  $|V_{cb}|$ $B \rightarrow X_c\, l\, \nu$
  $|V_{ub}|$ $B \rightarrow X_u\, l\, \nu$

- ○ Exclusive semileptonic decays
  $|V_{cb}|$ $B \rightarrow D^{(*)} l\, \nu$
  $|V_{ub}|$ $B \rightarrow \pi\, l\, \nu$

~$|V_{td}/V_{ts}|$

- ○ B_d and B_s mixing: $\Delta m_d/\Delta m_s$

Hadron colliders

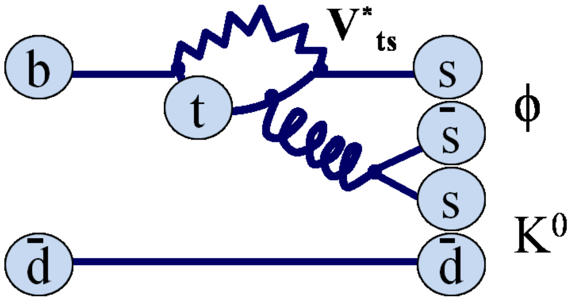
- ○ Radiative decays
  $b \rightarrow s\gamma$, $b \rightarrow d\gamma$

B factories

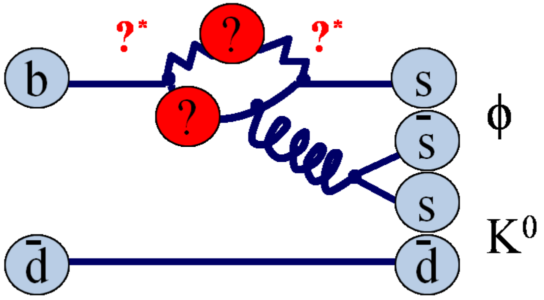
Observables	Belle (2014)	Belle II 5 ab^{-1}	50 ab^{-1}	$\mathcal{L}_s$ $[\text{ab}^{-1}]$
$\lvert V_{cb}\rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb}\rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub}\rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub}\rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub}\rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3

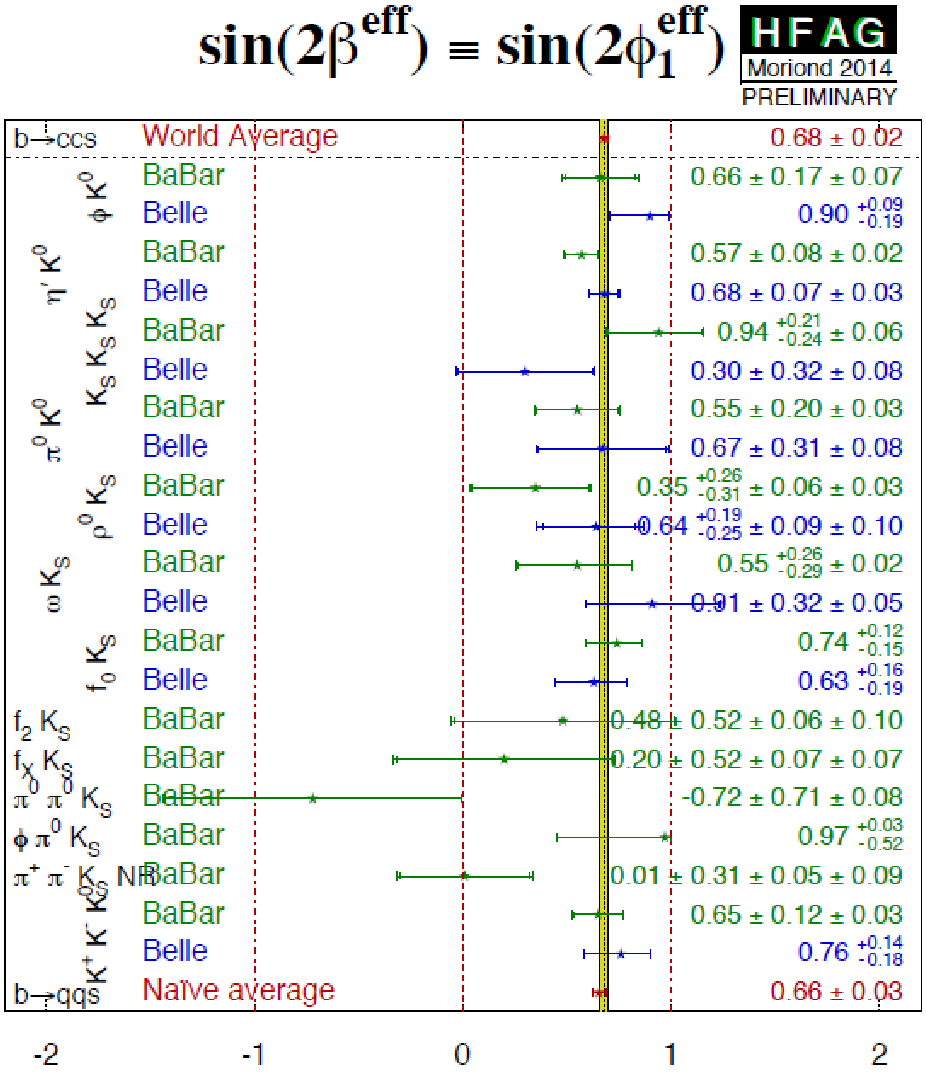
Search for New Physics

beyond UT



sin(2β) in b→sqq decays





Belle II measurement of sin(2β)

○ To check the consistency of Unitarity Triangle

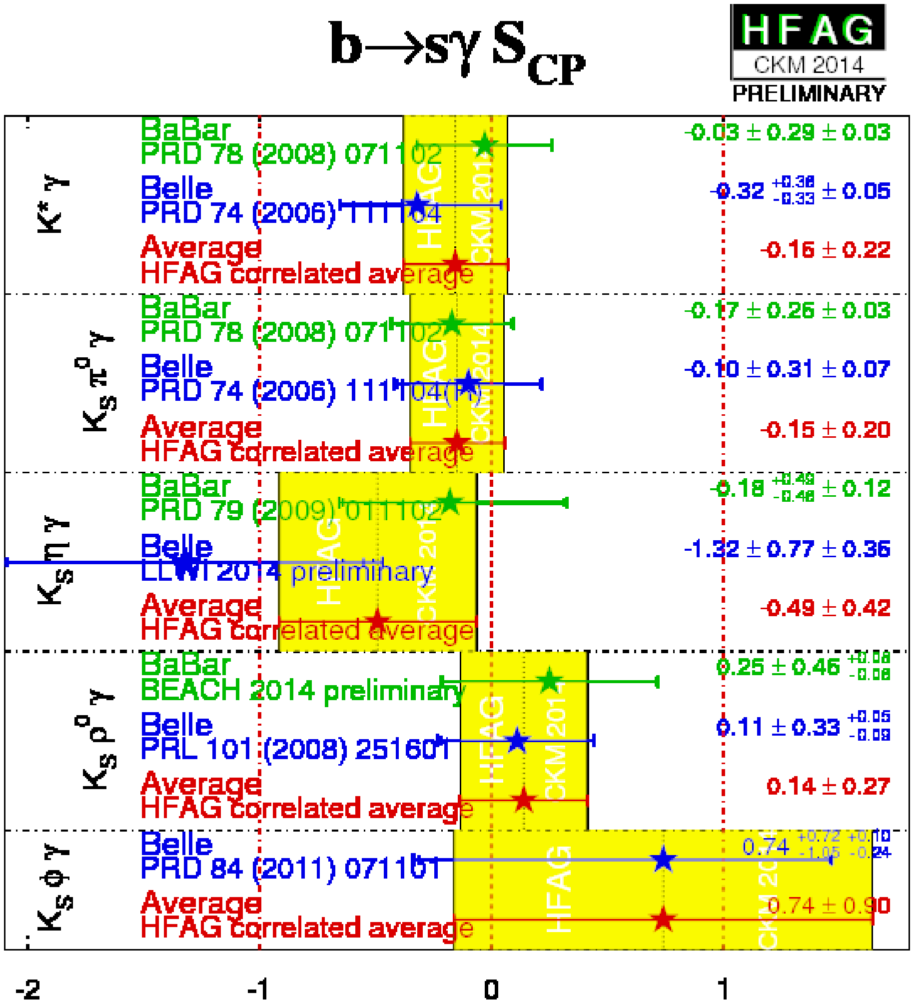
○ Search for new CP violating phases in b→s transitions by testing SM predictions

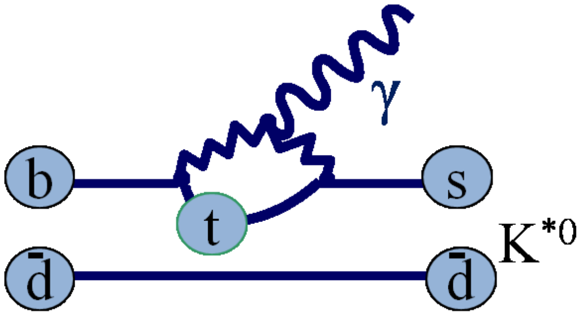
sin(2β) (b→s qq) = sin(2β) (J/ψ K^0)

Expected errors for the golden modes

Mode	5 ab^{-1}		50 ab^{-1}	
	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$
$\eta' K^0$	0.028	0.020	0.011	0.009
ϕK_S^0	0.053	0.070	0.018	0.023
$K_S K_S K_S$	0.101	0.064	0.033	0.021

Radiative penquin decays





Radiative penquin decays are the most sensitive probes for physics beyond SM:

○ occur at loop level and their rates can be accurately predicted in SM

○ loops could contain also new particles (e.g. SUSY)

○ Rate ≠ SM ➔ hint for NP

Time-dependent analyses of CPV in $B^0 \to K_S\pi^0\gamma$ probes the polarization of the photon:

○ in the SM for $b \to s\gamma$ the photon helicity is dominantly left-handed

○ mixing-induced CP violation in SM is expected to be small

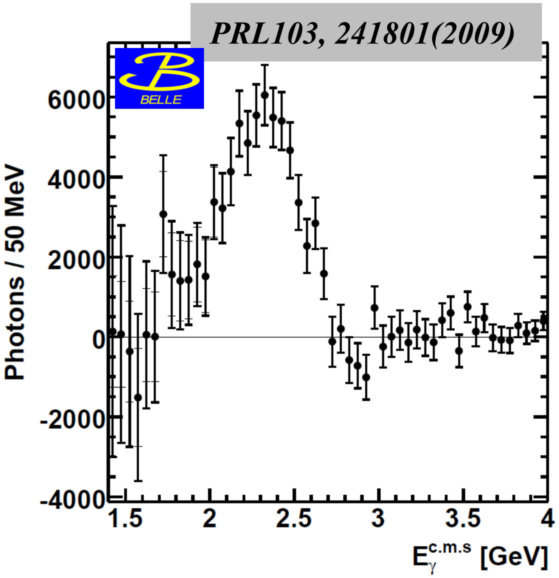
$$S \sim -2(m_s/m_b)\sin(2\beta) \equiv -2(m_s/m_b)\sin(2\varphi_1)$$

Belle II

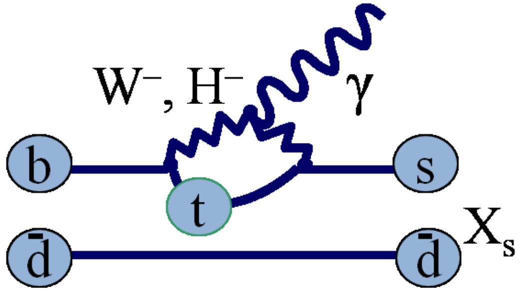
Expected errors for $\mathcal{S}$ measurements

Mode	5 ab^{-1}	50 ab^{-1}
$K_S\pi^0\gamma$	0.11	0.035
$\rho^0\gamma$	0.23	0.07

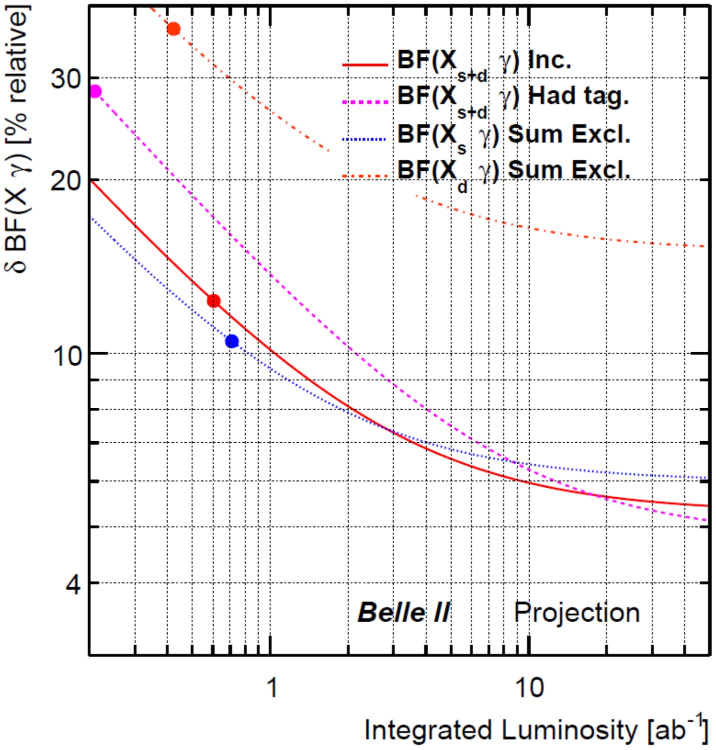
$B \rightarrow X_s\, \gamma$


PRL103, 241801(2009)

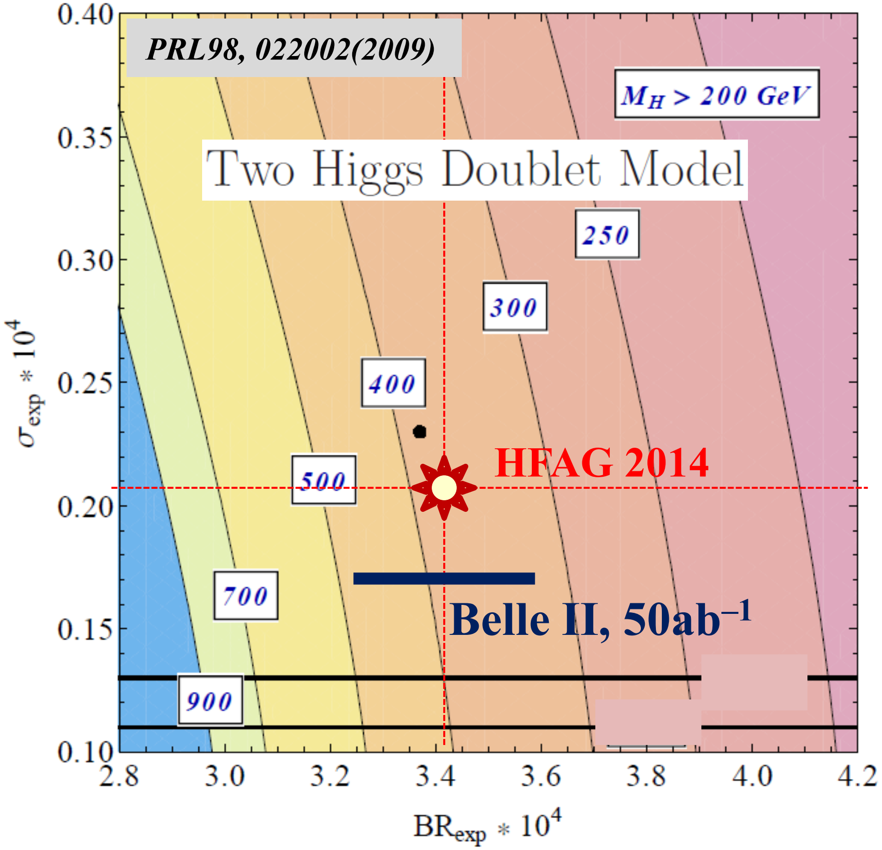
To reduce model uncertainty need to measure at as smaller E_γ as possible



WA: $Br(B \rightarrow X_s\, \gamma) = (3.43 \pm 0.21 \pm 0.007)10^{-4}$



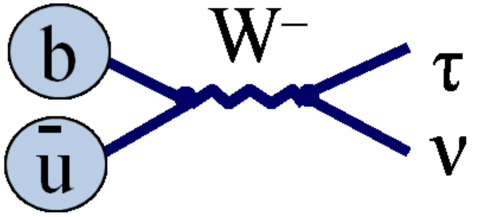
Lower limits on the charged Higgs


PRL98, 022002(2009)

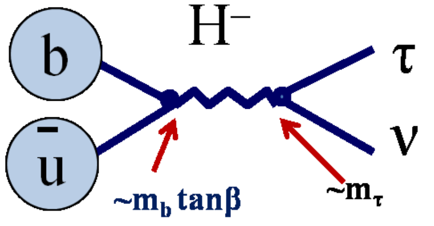
HFAG 2014

Belle II, $50ab^{-1}$

$B \to \tau\nu$



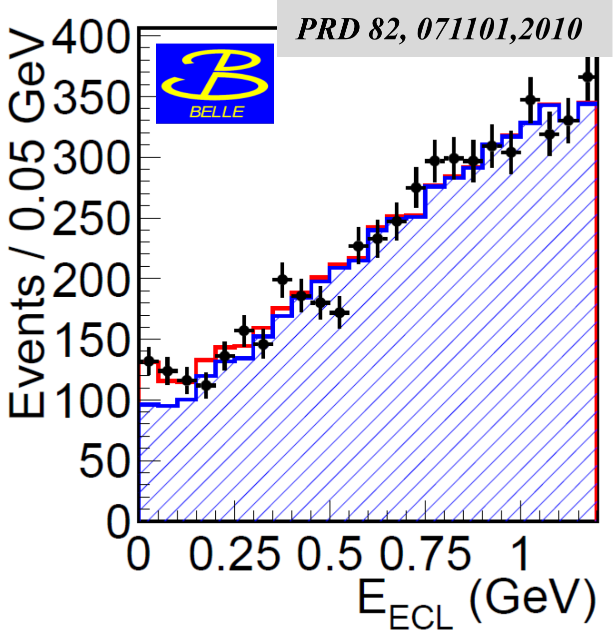
WA: $Br(B \to \tau\nu) = (1.14 \pm 0.22)\ 10^{-4}$

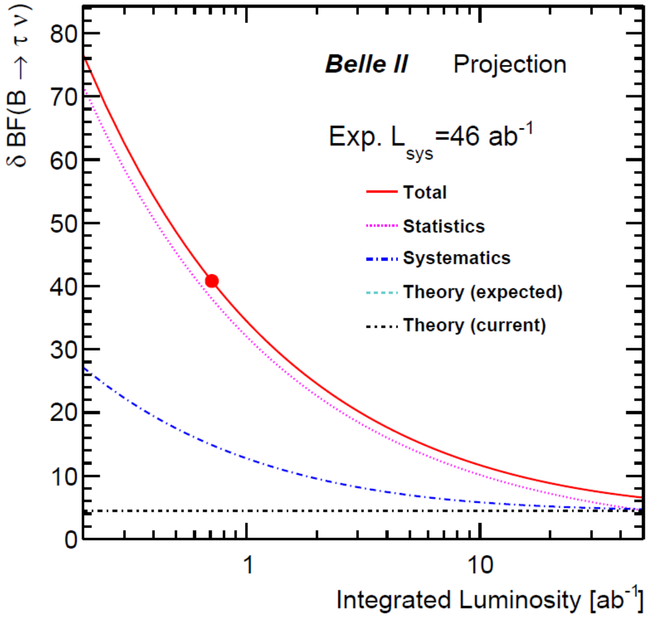


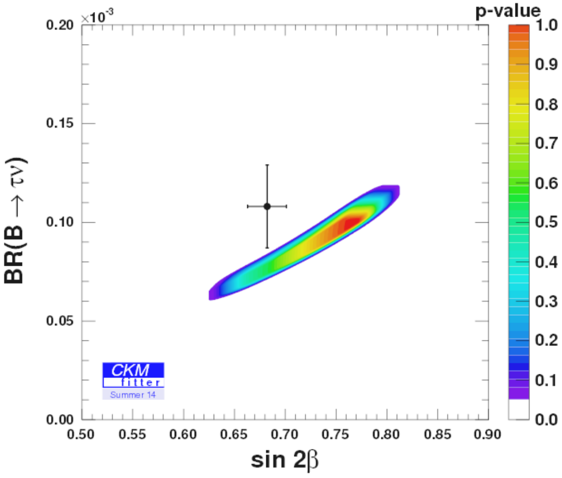
$$\boxed{\mathcal{B}(B^+ \to \tau^+\nu) = \frac{G_F^2\, m_B}{8\pi}\, m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2\, |V_{ub}|^2\, \tau_B}$$

Complicated analysis: purely leptonic decay

- ○ Signal: two neutrinos and one charged track
- ○ Tag: full reconstruction of leptonic or hadronic decays
- ○ Signal is seen as NO extra energy deposition in the ECL

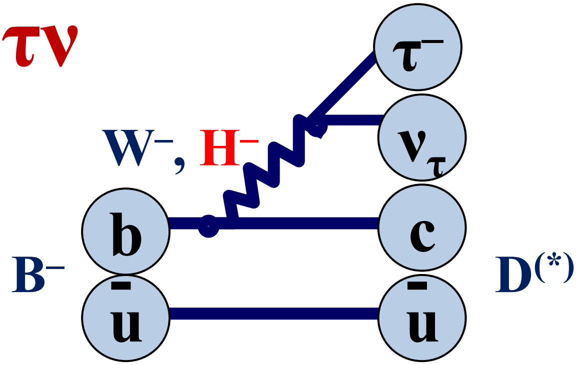






The discrepancy between SM prediction and measurement is 1.6 σ

Search for charged Higgs in $B \to D^{(*)}\tau\nu$



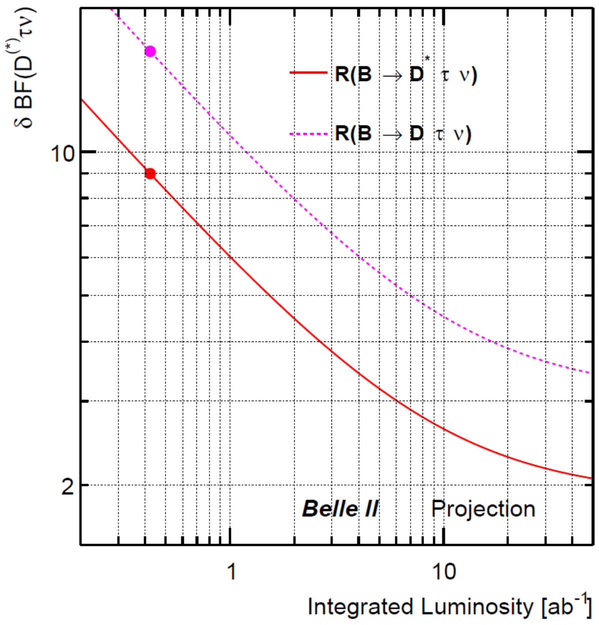
2-Higgs doublet model:

$$\mathcal{B}(B \to D^{(*)}\tau\nu) \;\propto\; \mathcal{B}_{SM} \cdot m_W \left(\frac{\tan\beta}{m_H}\right)$$

Charged Higgs

via branching fractions and the kinematic distributions of the final state

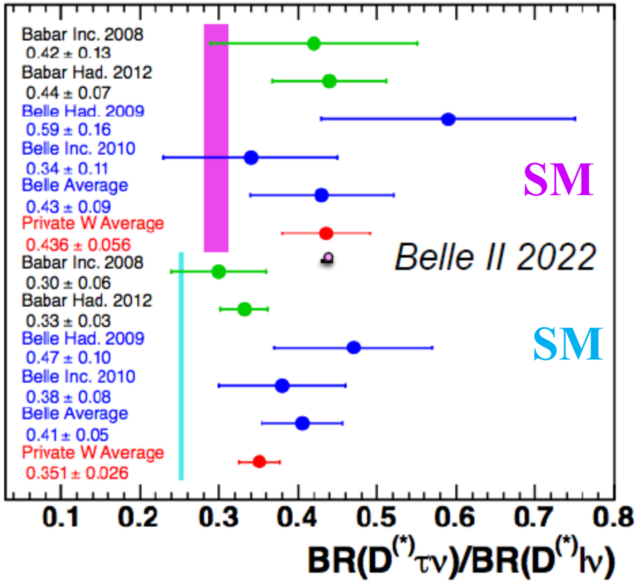
$$\mathcal{R}_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$



$R_{D(*)}$ measurements

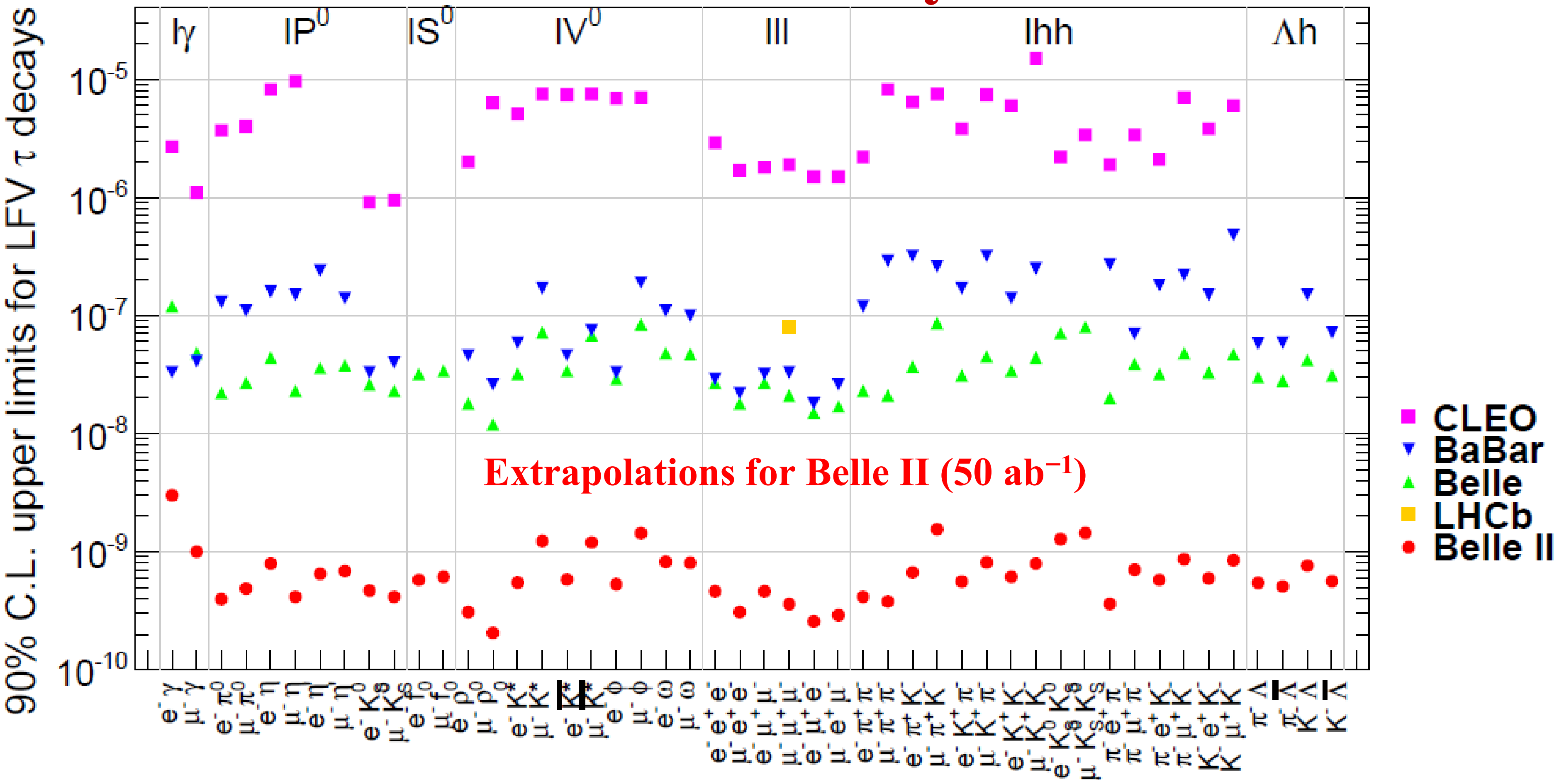
- ○ using two decay modes with very similar experimental signatures (with only the leptonic decay modes of the τ)
- ○ cancellation of form factor uncertainties & experimental systematic uncertainties

Hadron & inclusive lepton tagged



Belle II: resolve discrepancy with the SM

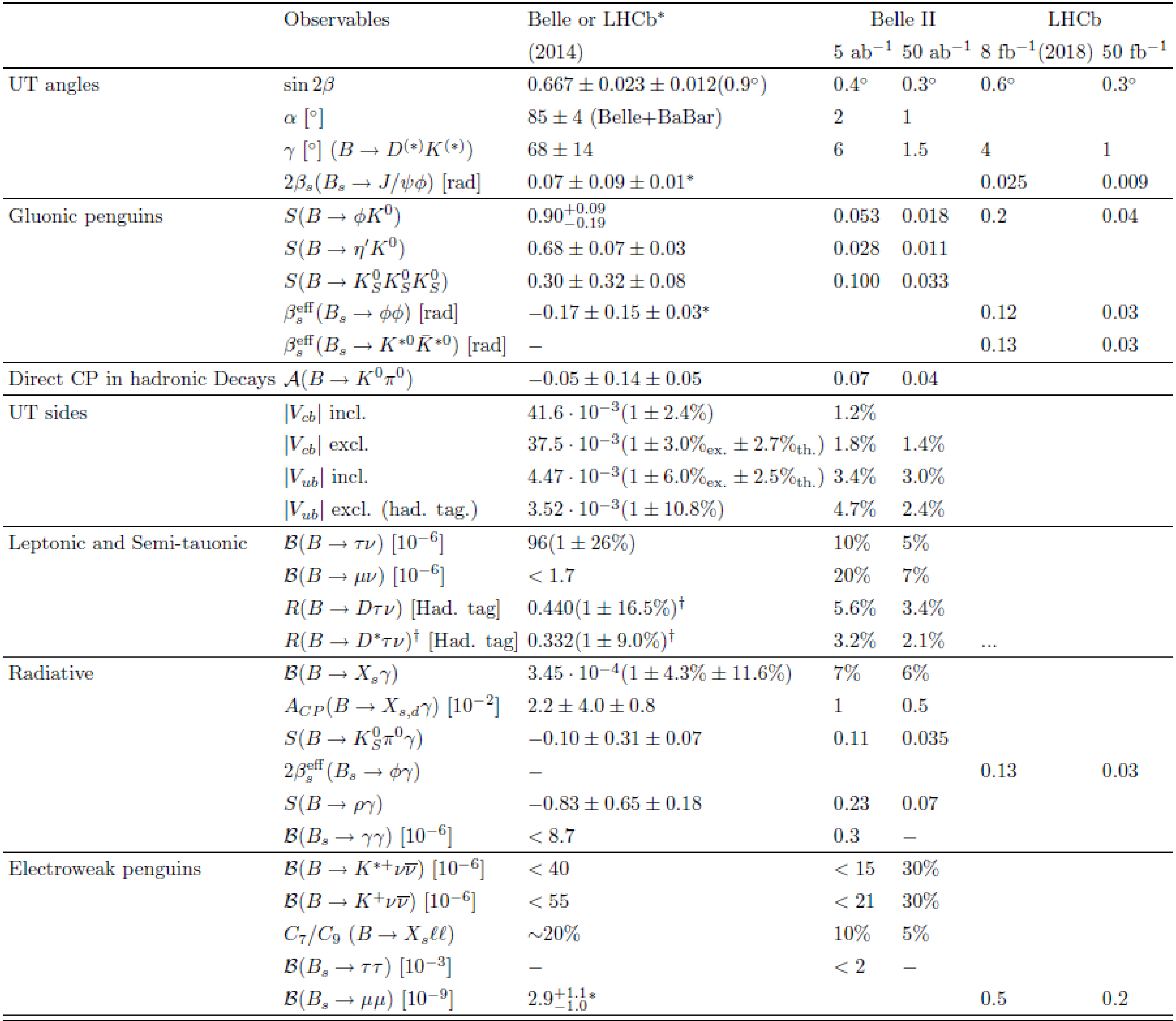
LFV τ decays



- ○ Lepton Flavor Violation is highly suppressed in the SM
- ○ LFV τ decays are clean and ambiguous probes for New Physics effects

Belle II : Sensitivity for LFV decay rates is over 100 times higher than Belle for the cleanest channels (τ→3l) and over 10 times higher for other modes, such as τ→lγ (due to irreducible background contributions)

Much more to be done at Belle II



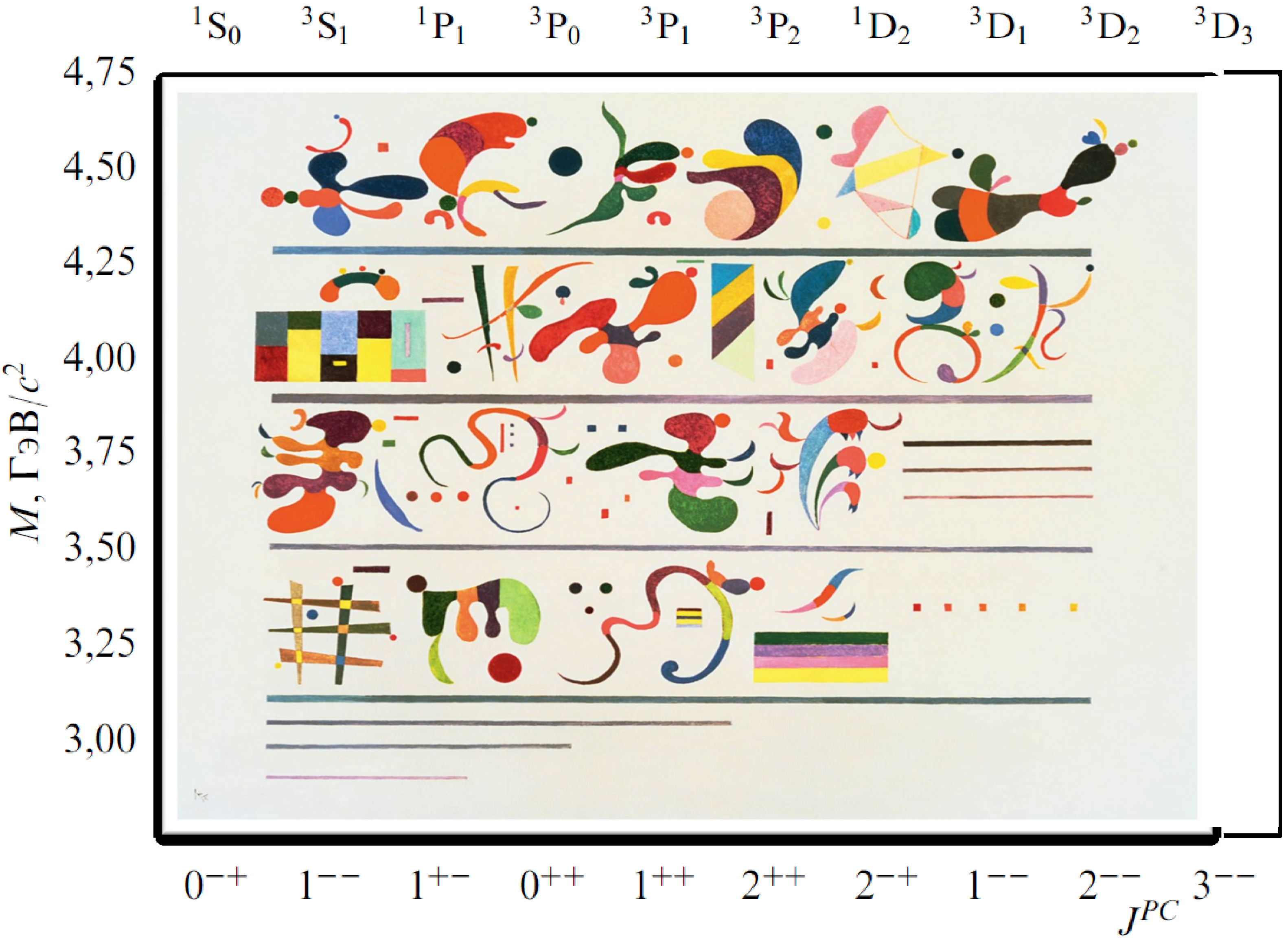
	Observables	Belle or LHCb*	Belle II		LHCb	
		(2014)	5 ab^{-1}	50 ab^{-1}	8 fb^{-1}(2018)	50 fb^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (0.9^\circ)$	0.4°	0.3°	0.6°	0.3°
	α [°]	85 ± 4 (Belle+BaBar)	2	1		
	γ [°] ($B \to D^{(*)} K^{(*)}$)	68 ± 14	6	1.5	4	1
	$2\beta_s (B_s \to J/\psi \phi)$ [rad]	$0.07 \pm 0.09 \pm 0.01^*$			0.025	0.009
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	0.053	0.018	0.2	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	0.028	0.011		
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	0.100	0.033		
	$\beta_s^{\mathrm{eff}} (B_s \to \phi\phi)$ [rad]	$-0.17 \pm 0.15 \pm 0.03^*$			0.12	0.03
	$\beta_s^{\mathrm{eff}} (B_s \to K^{*0} \bar{K}^{*0})$ [rad]	–			0.13	0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$	0.07	0.04		
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3} (1 \pm 2.4\%)$	1.2%			
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3} (1 \pm 3.0\%_{\mathrm{ex.}} \pm 2.7\%_{\mathrm{th.}})$	1.8%	1.4%		
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3} (1 \pm 6.0\%_{\mathrm{ex.}} \pm 2.5\%_{\mathrm{th.}})$	3.4%	3.0%		
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3} (1 \pm 10.8\%)$	4.7%	2.4%		
Leptonic and Semi-tauonic	$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	$96(1 \pm 26\%)$	10%	5%		
	$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	20%	7%		
	$R(B \to D\tau\nu)$ [Had. tag]	$0.440(1 \pm 16.5\%)^\dagger$	5.6%	3.4%		
	$R(B \to D^*\tau\nu)^\dagger$ [Had. tag]	$0.332(1 \pm 9.0\%)^\dagger$	3.2%	2.1%	...	
Radiative	$\mathcal{B}(B \to X_s \gamma)$	$3.45 \cdot 10^{-4} (1 \pm 4.3\% \pm 11.6\%)$	7%	6%		
	$A_{CP}(B \to X_{s,d} \gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$	1	0.5		
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035		
	$2\beta_s^{\mathrm{eff}} (B_s \to \phi\gamma)$	–			0.13	0.03
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07		
	$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	0.3	–		
Electroweak penguins	$\mathcal{B}(B \to K^{*+} \nu\bar{\nu})$ [10^{-6}]	< 40	< 15	30%		
	$\mathcal{B}(B \to K^+ \nu\bar{\nu})$ [10^{-6}]	< 55	< 21	30%		
	C_7/C_9 ($B \to X_s \ell\ell$)	~20%	10%	5%		
	$\mathcal{B}(B_s \to \tau\tau)$ [10^{-3}]	–	< 2	–		
	$\mathcal{B}(B_s \to \mu\mu)$ [10^{-9}]	$2.9^{+1.1}_{-1.0}{}^*$			0.5	0.2

To be done at Belle II else

	Observables	Belle or LHCb* (2014)	Belle II $5\ \mathrm{ab}^{-1}$	Belle II $50\ \mathrm{ab}^{-1}$	LHCb 2018	LHCb $50\ \mathrm{fb}^{-1}$
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$	2.9%	0.9%		
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$	3.5%	2.3%		
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	30%	25%		
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	$-32 \pm 21 \pm 9$	11	6		
	$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-3}]$	3.4*			0.5	0.1
	A_Γ $[10^{-2}]$	0.22	0.1	0.03	0.02	0.005
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	0.29	0.09		
	$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$	0.08	0.03		
Charm Mixing	$x(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	0.14	0.11		
	$y(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	0.08	0.05		
	$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	0.10	0.07		
	$\phi(D^0 \to K_S^0\pi^+\pi^-)$ $[^\circ]$	$-6 \pm 11 \pm {}^{4}_{5}$	6	4		
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7		
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12		
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3		

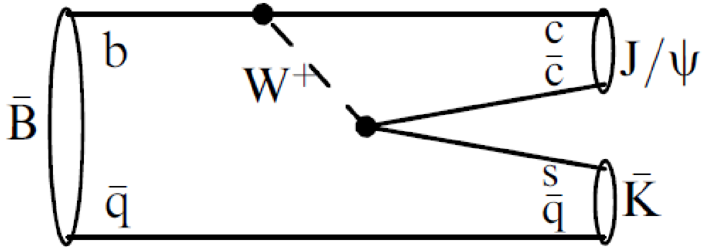
& charm spectroscopy, rare D decays, $\Upsilon(5S)$ physics, quarkonium(+like)

New quarkonium spectroscopy



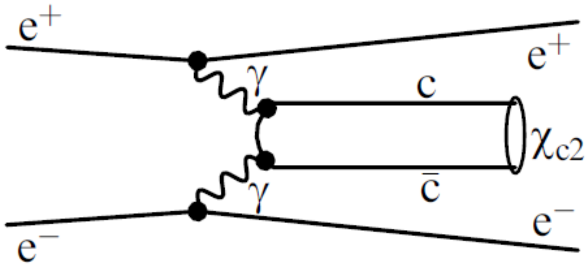
Charmonium(+like) production at (Super) B factories

B decays



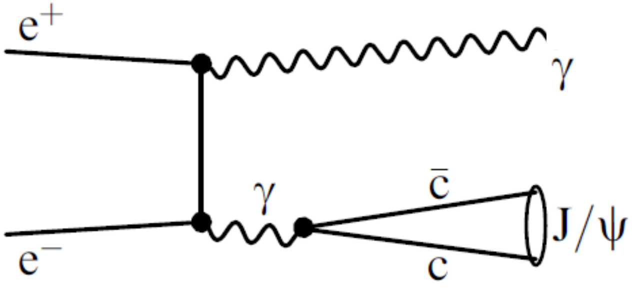
Any quantum numbers are possible, can be measured in angular analysis (Dalitz plot)

γγ fusion



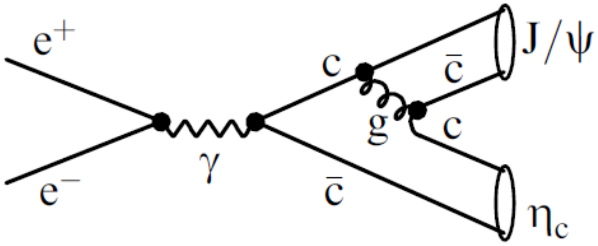
$J^{PC} = 0^{\pm+}, 2^{\pm+}$

e⁺e⁻ annihilation with ISR



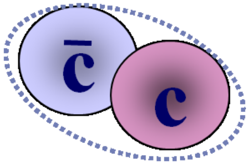
$J^{PC} = 1^{--}$

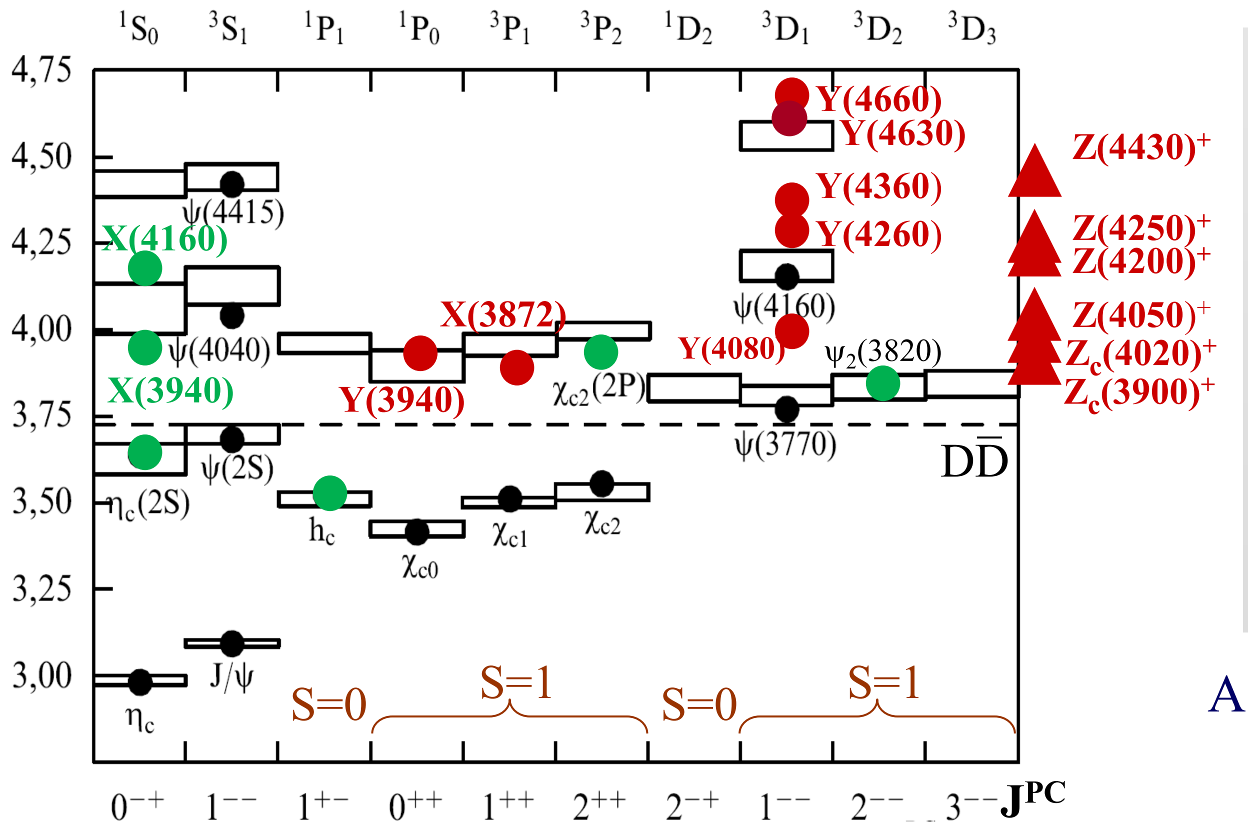
double charmonium production



in association with J/ψ only $J^{PC} = 0^{\pm+}$ seen

Charmonium(+like)



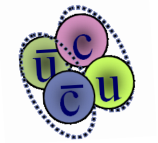


$(n+1)^{(2S+1)}L_J$

- n radial quantum number
- S total spin of quark-antiquark
- L relative orbital ang. mom.
  - L = 0, 1, 2 ... corresponds to S, P, D...
- J = S + L
- $P = (-1)^{L+1}$ parity
- $C = (-1)^{L+S}$ charge conj.

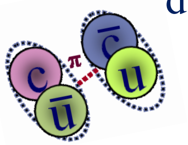
After 2002 **6 standard states** and **13(+4?) exotic**

Multiquark states



Tetraquark

tightly bound four-quark state

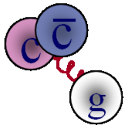


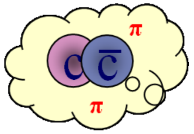
Molecular state

two loosely bound charm mesons

Charmonium hybrids

States with excited gluonic degrees of freedom

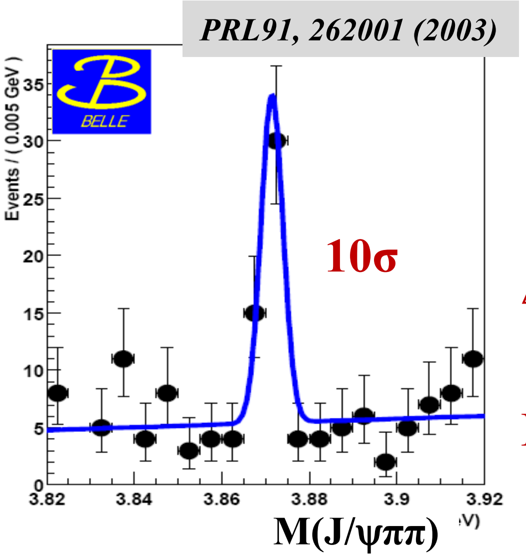




Hadro-charmonium

Specific charmonium state “coated” by excited light-hadron matter

X(3872)



M_X close to D^0D^{*0} threshold

M = 3871.68 ± 0.17 MeV

not clear below or above:

Δm = – 0.11 ± 0.22 MeV

surprisingly narrow:

Γ_{tot}< 1.2 MeV at 90% CL

$J^{PC} = 1^{++}$

finally established

Belle topcited: 1000+

First observed by Belle in $B \to K\, J/\psi \pi^+\pi^-$

Confirmed: BaBar, LHCb, CMS, ATLAS, CDF

Hadronic collisions: produced mostly promptly; only 0.263±0.023±0.016 from B-decays (CMS)

The most popular interpretation

Mixture of P-wave charmonium level χ_{c1}(2P) and S-wave DD^{*0} molecule

Known decays	BR relative to J/ψρ mode	Comments
J/ψρ	1	isospin violation
J/ψω	0.8 ± 0.3	isospin violation
J/ψγ	0.21 ± 0.06	Belle&Babar good agreement
ψ(2S)γ	0.50 ± 0.15	Belle&Babar disagreement LHCb confirms BaBar
D^0D^{*0}	~10	dominant mode

X(3872): tasks for Belle II

Search for X(3872) partners decays	Comments
$\chi_{c1}\,\gamma$ $\chi_{c2}\,\gamma$	Forbidden by C-parity conservation C-odd partners: tetraquark, molecule UL : $< 1/4$ from $J/\psi\,\pi^+\pi^-$
$J/\psi\,\eta$	C-odd partners: tetraquark UL : $< 1/2$ from $J/\psi\,\pi^+\pi^-$
$\eta_c\,\eta$ $\eta_c\,\pi^0$ $\eta_c\,\pi^+\pi^-$ $\eta_c\,\omega$	Search for other X-like molecular states UL : $\sim J/\psi\,\pi^+\pi$

○ Detailed pattern of X(3872) to charmonium transitions (radiative and hadronic) with significantly improved accuracy

○ Search for partners of X(3872)

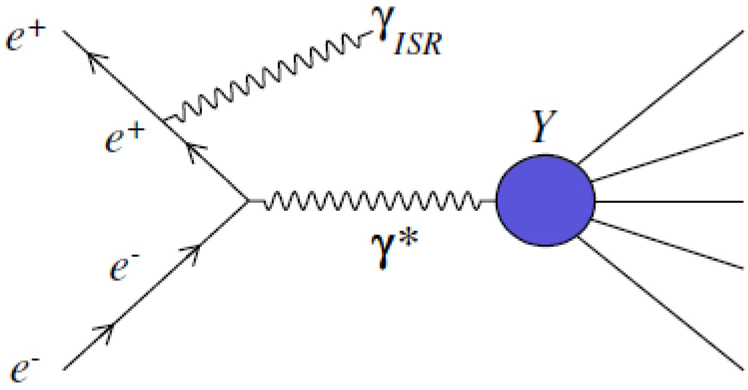
molecules with $J^{PC} = 0^{++}, 1^{+-}, 2^{++}\ldots$

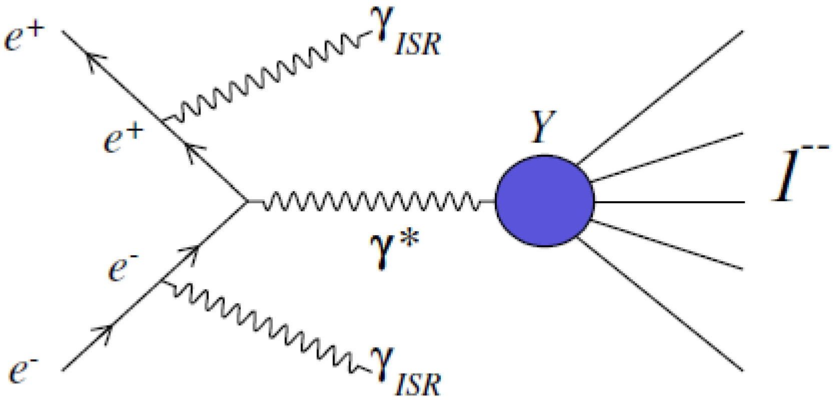
○ Measurements of absolute BR of $B \to KX(3872)$

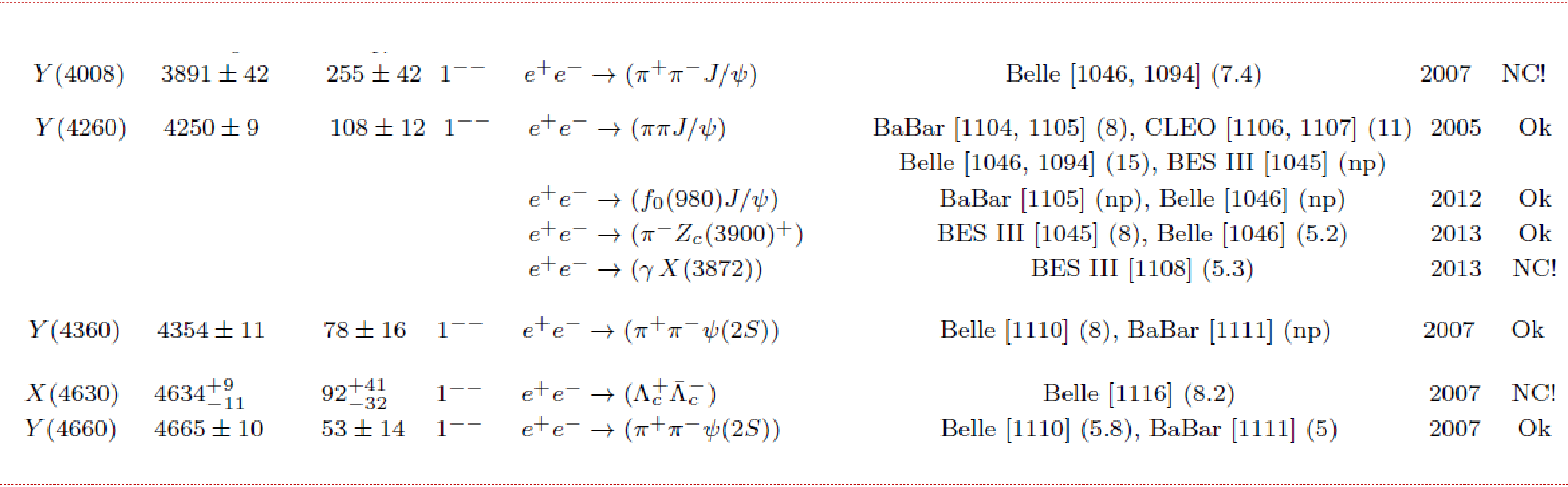
○ Measurements of line shape of X(3872) decaying to DD^* at threshold and to $J/\psi\pi^+\pi^-$ to clarify nature of X(3872): virtual or bound state ***Yu.S.Kalashnikova, A.V.Nefediev PRD80, 074004 (2009)***

○ Measurements of the total width of X(3872)

Vector states in e^+e^- annihilation with ISR

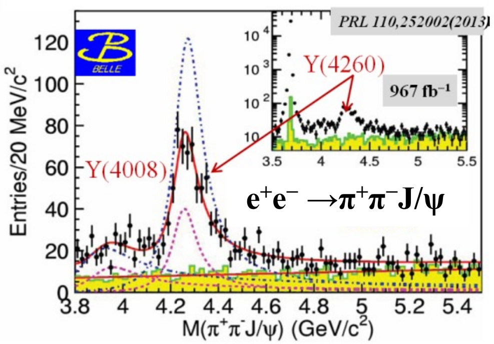


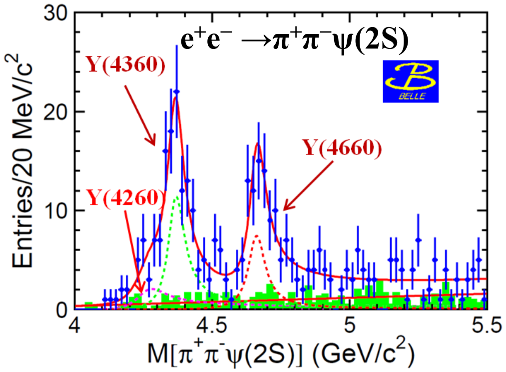


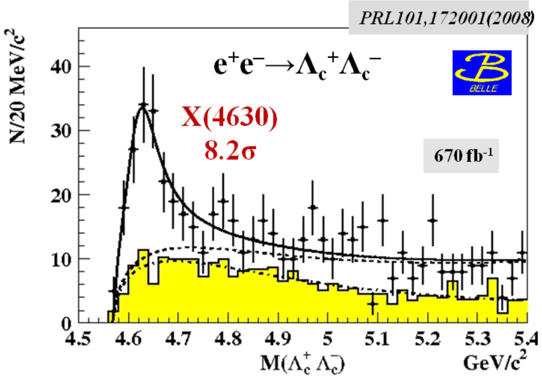


$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11) Belle [1046, 1094] (15), BES III [1045] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+ \bar{\Lambda}_c^-)$	Belle [1116] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle [1110] (5.8), BaBar [1111] (5)	2007	Ok

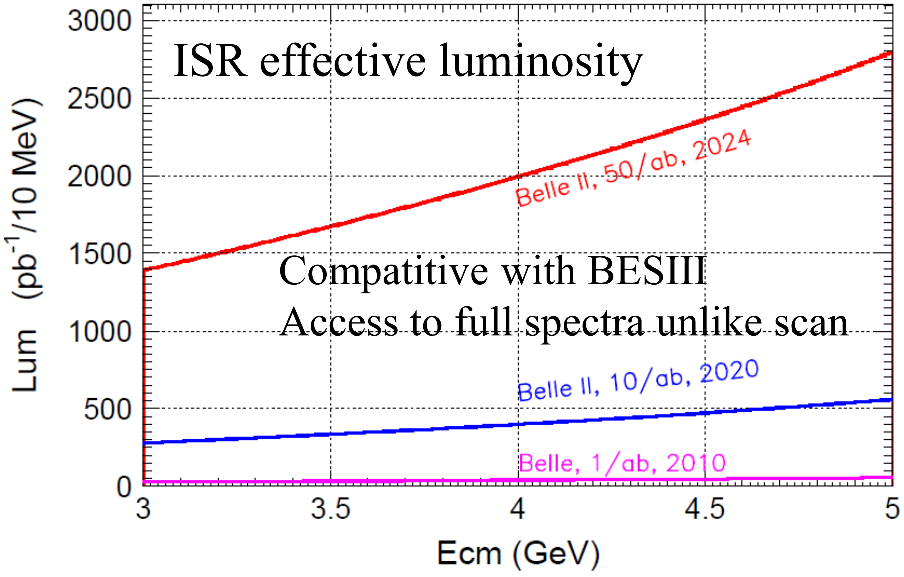
10th anniversary of Y family discovery







It seems that up to now we have not found an ISR state that has more than one decay mode. Hopefully Belle II will show that these states have multiple decay modes like the X(3872)



ISR effective luminosity

Compatitive with BESIII
Access to full spectra unlike scan

Open question: nature of Yfamily

Belle II tasks

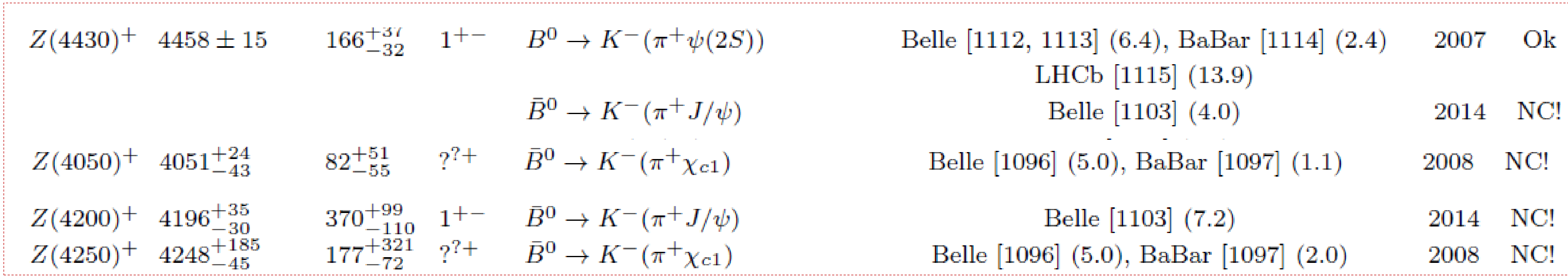
- Improve accuracy
- Confirmation of Y(4008)
- Confirm X(4630) found by Belle only
- Resolve X(4630) &Y(4660) puzzle
- Search for other final states: χ_{c1} , χ_{c2} ,η_c, X(3872) + and/or other light hadrons
  - Up to now only J/ψ, ψ(2S) + ππ, η

Charged charmonium-like states at Belle

Charged Z_c^+ states cannot be conventional charmonium or hybrid

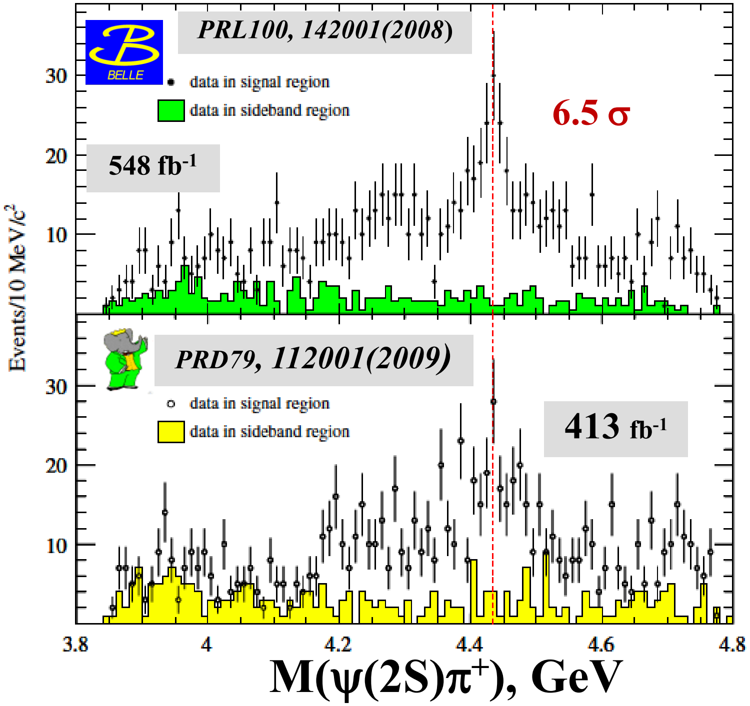
From four states found by Belle in B decays only Z(4430)$^+$ is confirmed (by LHCb)

Two states are found by Belle in e^+e^- annihilation + five more by BESIII



$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$B^0 \to K^-(\pi^+\psi(2S))$	Belle [1112, 1113] (6.4), BaBar [1114] (2.4) LHCb [1115] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+J/\psi)$	Belle [1103] (4.0)	2014	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$??^+$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$??^+$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!

$B \to Z^+_c K^-$



$Z(4430)^+$: three different analysis, $J^P = 1^+$

○ Fit to $M(\psi(2S)\pi^+)$ with $K^*(890)$&$K^*(1430)$ veto

○ Dalitz analysis

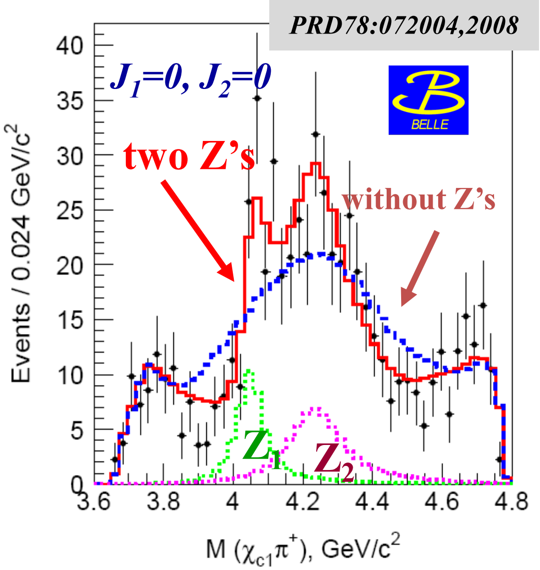
○ Full amplitude analysis to obtain spin-parity

Mass values are the same, width depends on method

$Z(4050)^+$ & $Z(4050)^+$

in $\chi_{c1}\pi^+$ final state

○ Daliz analysis



$Z_c(4200)^+$ in $J/\psi\ \pi^+$ final state, $J^P=1^+$

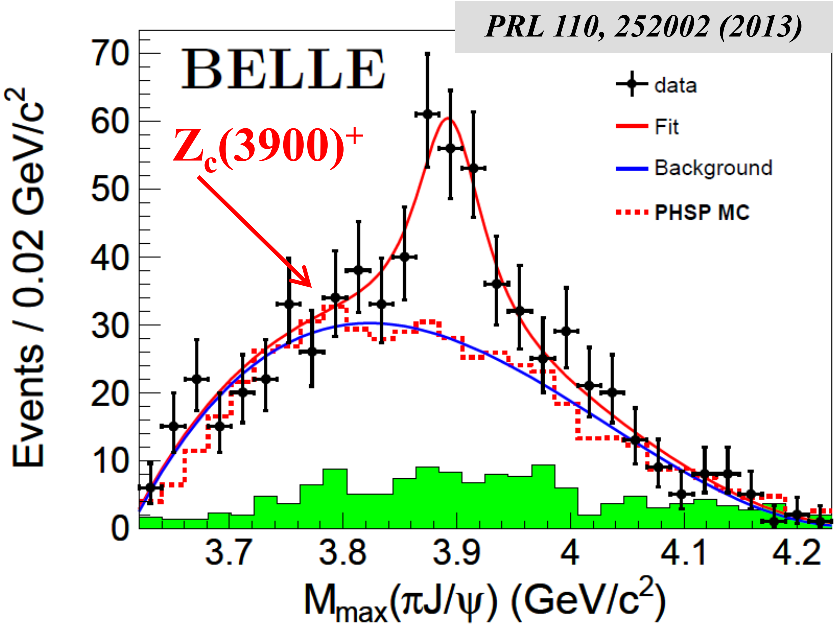
○ 4D-fit: Dalitz + angular variables

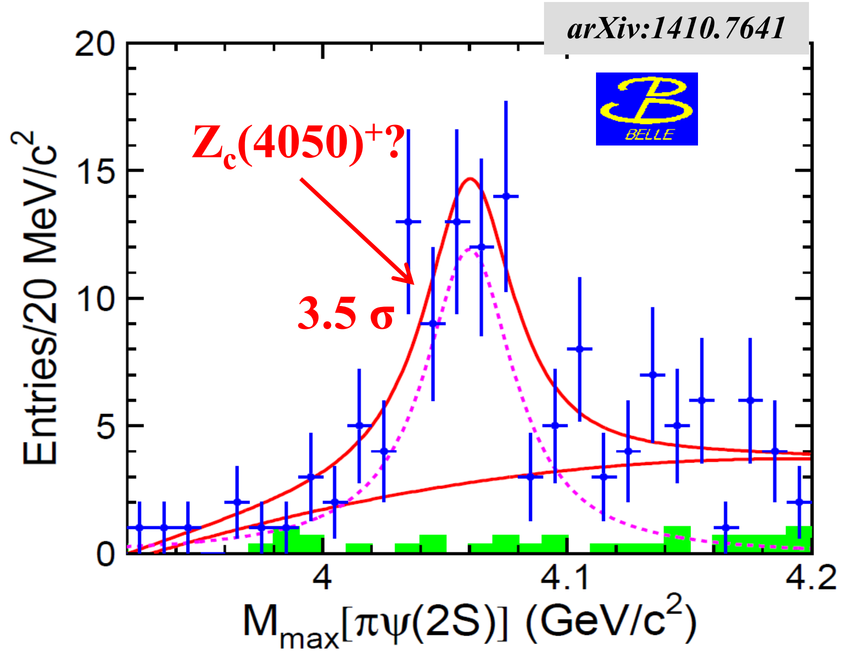
○ New decay mode $Z_c(4430)^+ \to J/\psi\ \pi$

  ○ order of magnitude suppressed (to $\psi(2S)\pi$) despite larger phase space

BaBar does not confirm Belle, but also does not rule it out!
Task for Belle II and LHCb (charged final states)

Z_c family in e^+e^- annihilation


PRL 110, 252002 (2013)


arXiv:1410.7641

J/ψπ mass from Y(4260) peaking at DD* threshold

New signal in Y(4360)→ π^- Z(4050)$^+$

Belle only

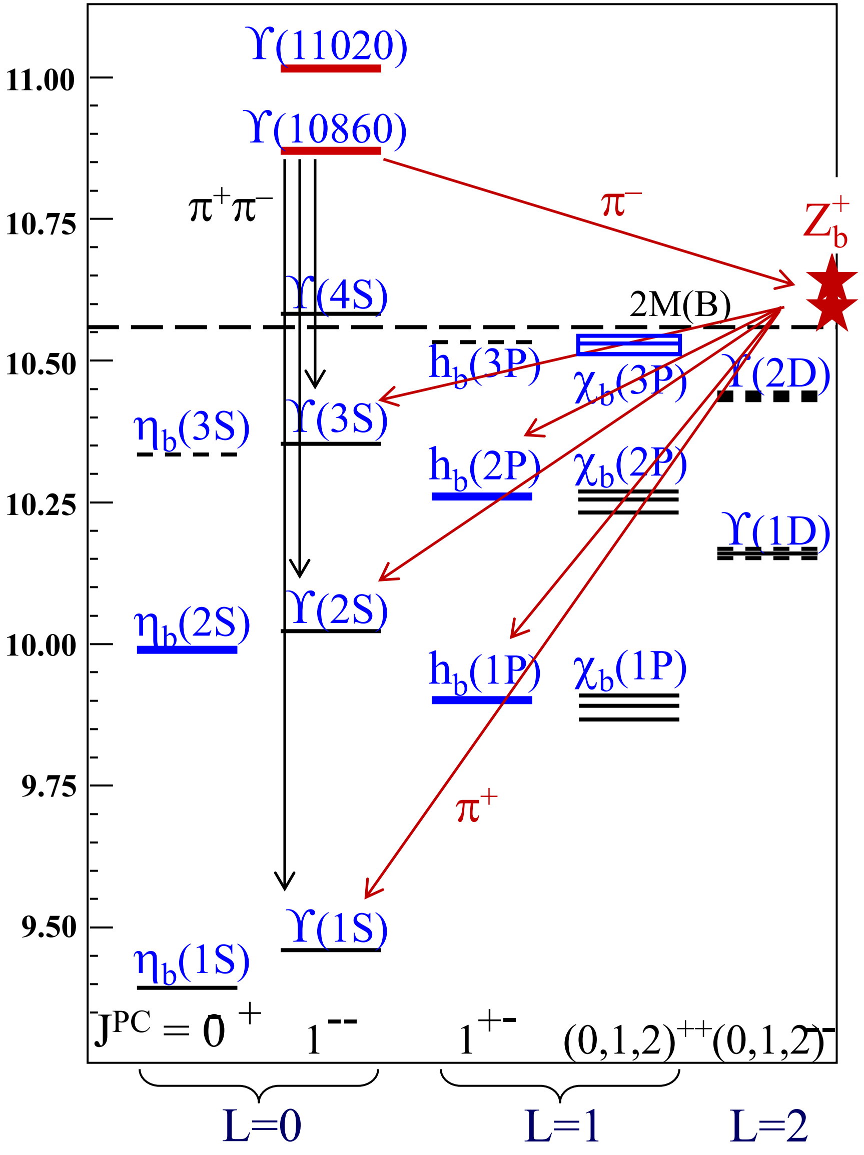
Only one charged state from the long BESIII list is confirmed by Belle (due to limited statistic)

$Z_c(3900)^+ \rightarrow J/\psi\pi^+$, $Z_c(3900)^0 \rightarrow J/\psi\pi^0$, $Z_c(3885)^+ \rightarrow DD^*$, $Z_c(4020)^+ \rightarrow \pi^+ h_c$, $Z_c(4020)^0 \rightarrow \pi^0 h_c$, $Z_c(4025)^+ \rightarrow D^*D^*$

Belle II

Confirm (or not) the BESIII & Belle charmonium-like states & to look for new structures in πψ(2S) et al using ISR

Charged bottomonium-like states



R.Mizuk

Anomalous production of Υ(nS) $\pi^+\pi^-$

$\Gamma(\Upsilon(5S)\to\Upsilon(1S)\pi^+\pi^-) = 260$ keV

$\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-) = 430$ keV

$\Gamma(\Upsilon(5S)\to\Upsilon(3S)\pi^+\pi^-) = 290$ keV

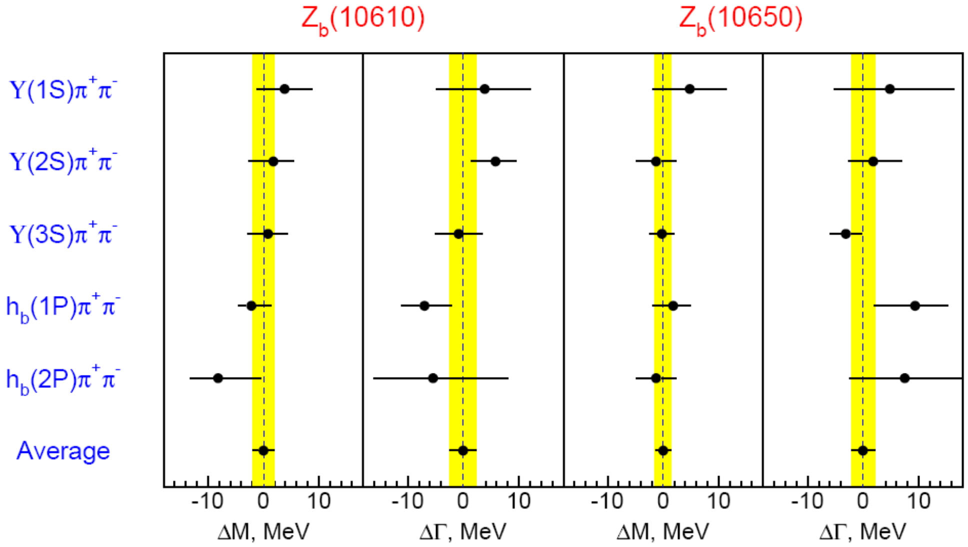
$\Gamma(\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-) = 6$ keV

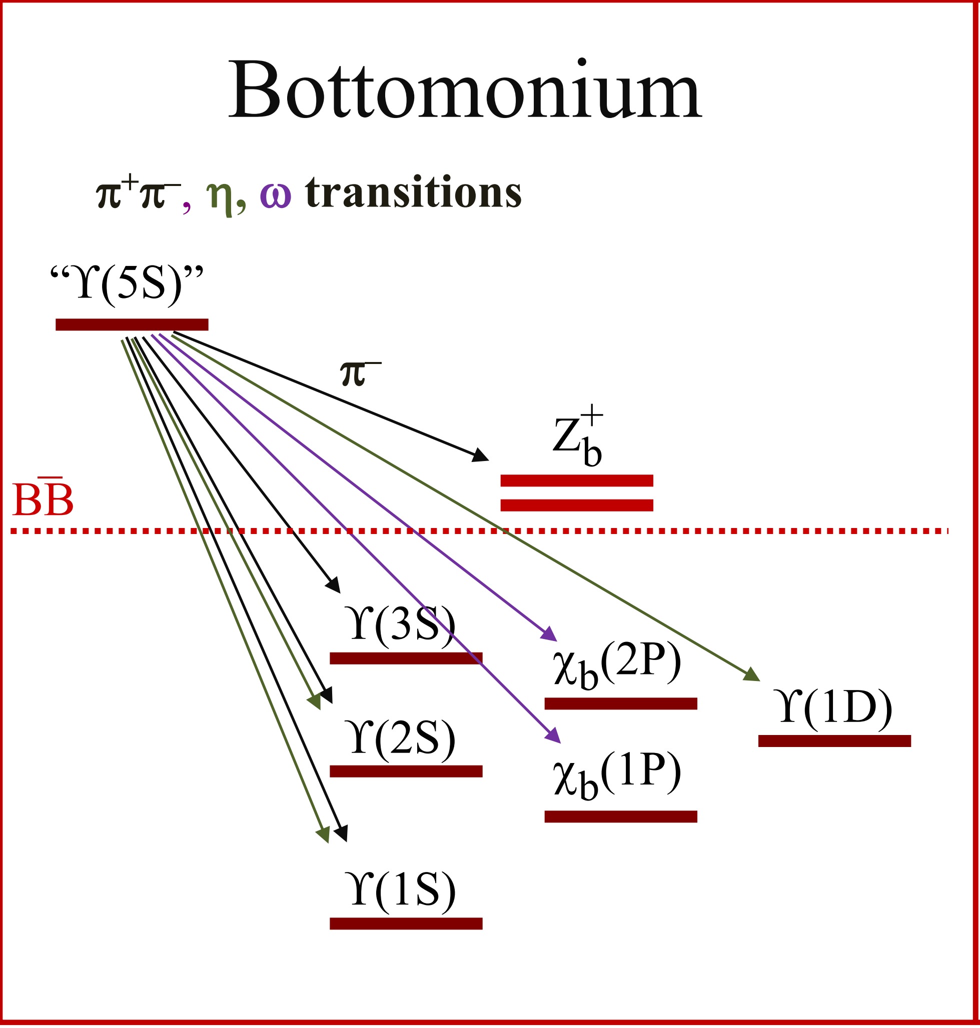
$\Upsilon(5S)\to Z_b(10610)^+\,\pi^-$, $Z_b(10650)^+\,\pi^-$

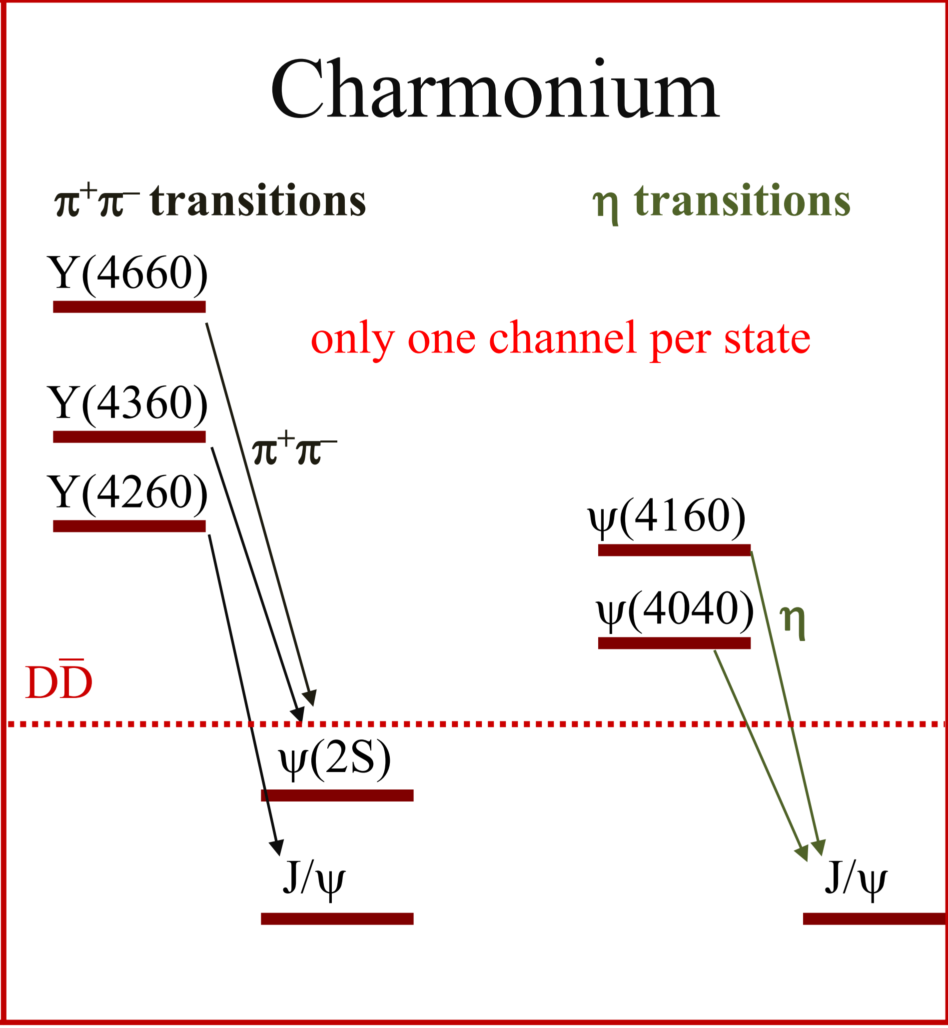
The most popular interpretation

BB^* and B^*B^* molecules

Masses near BB^* and B^*B^* thresholds







$\Gamma[\Upsilon(5S)\to\Upsilon(1S/2S)\eta] = 40/200$ keV

$\Gamma[\Upsilon(5S)\to\Upsilon(1D)(\pi^+\pi^-)/\eta] = 60/140$ keV

$\Gamma[\Upsilon(5S)\to\chi_{b1/2}(1P)\ \omega] = 80/30$ keV

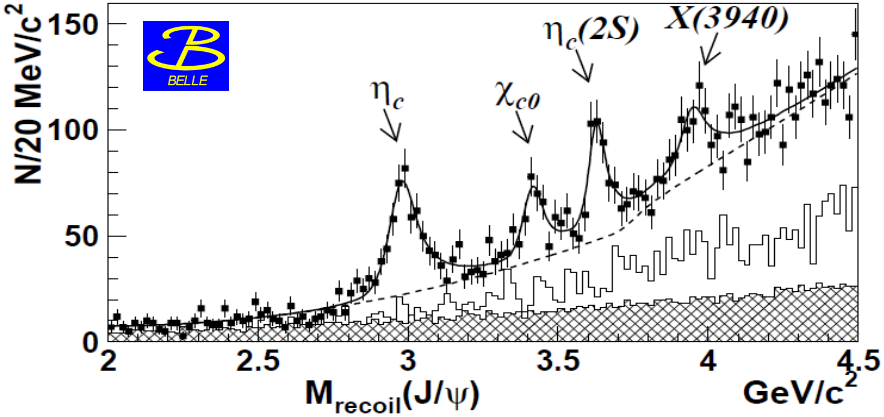
$\Gamma[\Upsilon(5S)\to\chi_{b1/2}(1P)\ (\pi^+\pi^-\pi^0)_{\text{non-res}}] = 30/30$ keV

$\Gamma[\ \Upsilon(5S)\to\Upsilon(1S)\ K^+K^-\ ] = 30$ keV

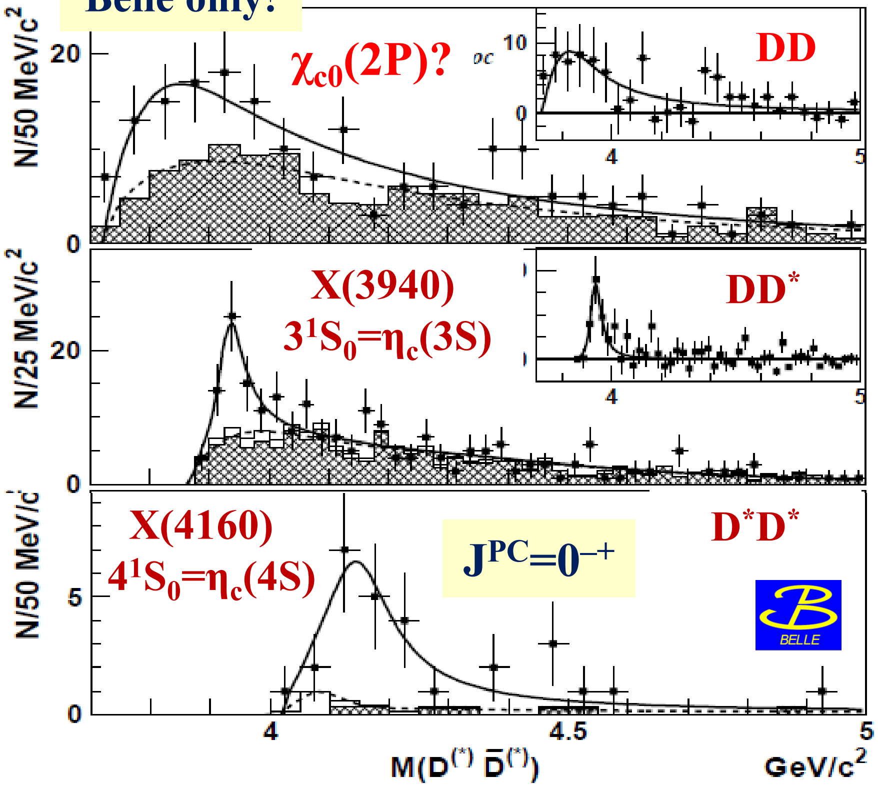
Molecule,
diquark-antidiquark,
hadrocharmonium…

R.Mizuk

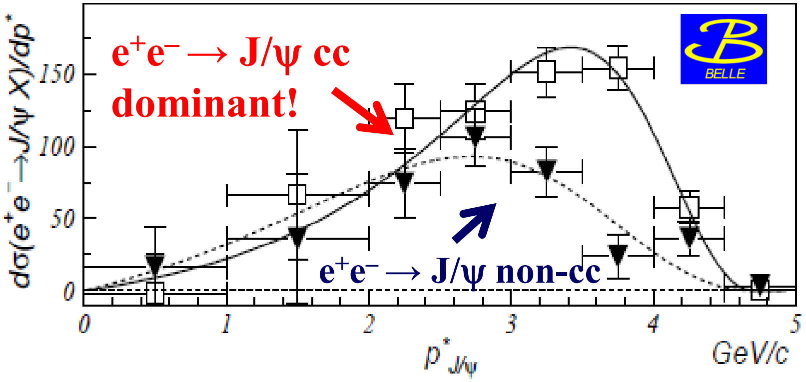
Charmonium double production



Belle only!



J/ψ production study with/without additional charm



$\sigma(e^+e^- \to J/\psi$ cc), pb	**$0.74 \pm 0.08^{+0.09}_{-0.08}$**
$\sigma(e^+e^- \to J/\psi$ non-cc), pb	**$0.43 \pm 0.09 \pm 0.09$**

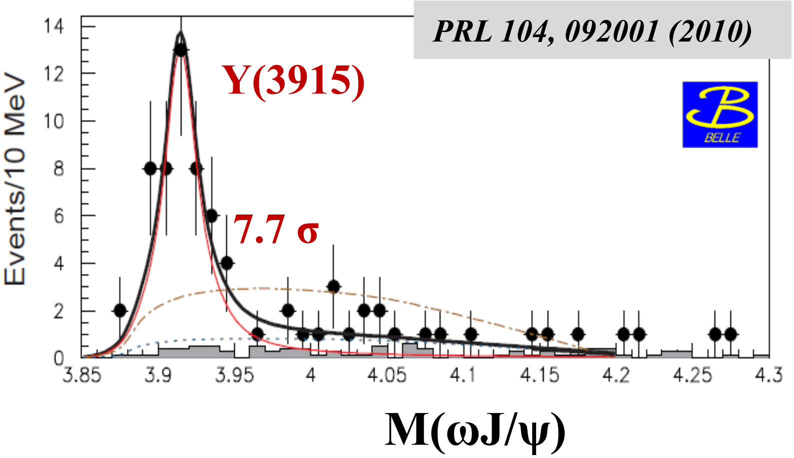
Belle II

○ Angular analysis for solid identification $\eta_c(3S)$, $\eta_c(4S)$, χ_{c0} . Search in B decays.

○ Search for new states in $e^+e^- \to J/\psi D^{(*)}D^{(*)}\pi$ and in $e^+e^- \to \chi_{c1} D^{(*)}D^{(*)}$

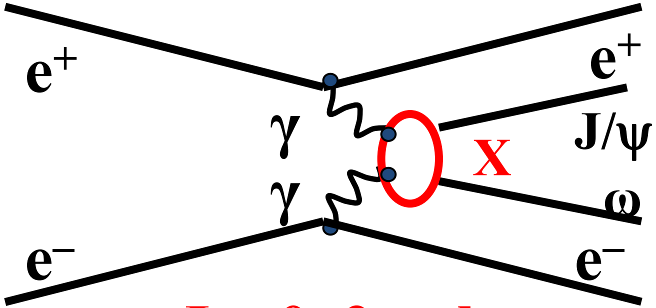
○ Production: reconstruction of the exclusive final states

○ Production studies with other charmonium states (e.g. $\psi(2S)$, χ_{c1})



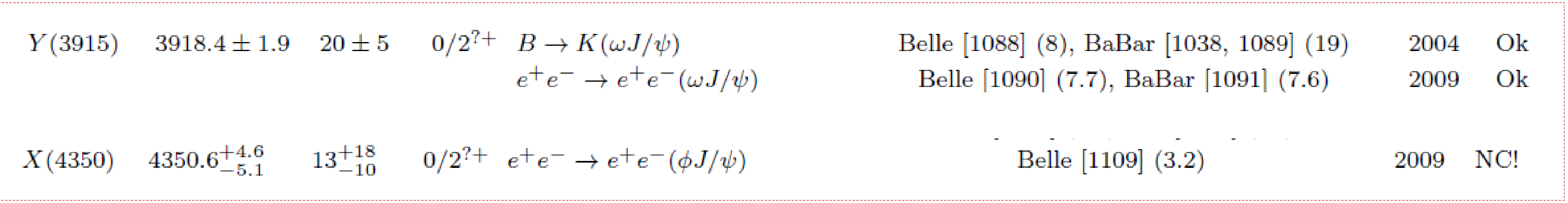
PRL 104, 092001 (2010)

Y(3940) & Y(3915)



J = 0, 2 only

Confirmed by BaBar, prefer $J^P=0^+$



$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!

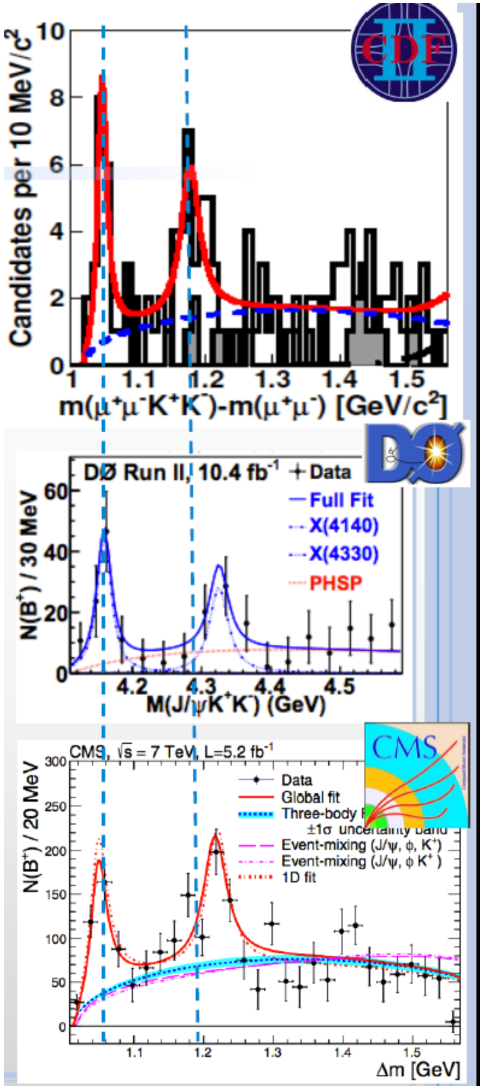
PDG: **Y(3940) = Y(3915)=χ_{c0}(2P)**

Theory ☹

- χ_{c0}(2P) production in two body B decays is suppressed
- $\chi_{c0}(2P) \to$ DD should be dominant, but not seen
- a better candidate for χ_{c0}(2P) seen in $e^+e^- \to$ J/ψDD

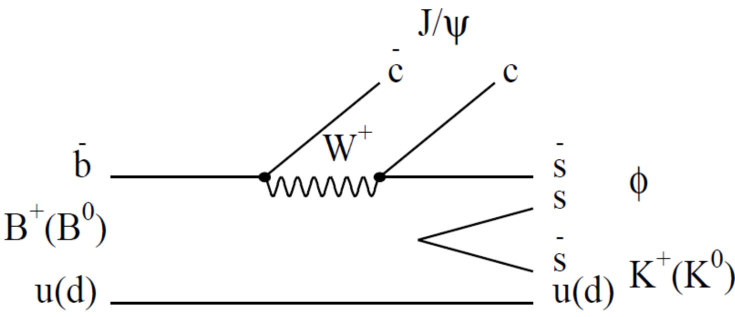
Tasks for Belle II

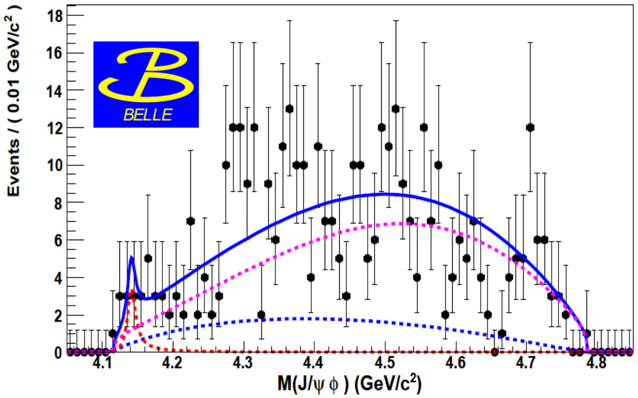
- (Not) confirm that Y(3940) = Y(3915) = χ_{c0}(2P)

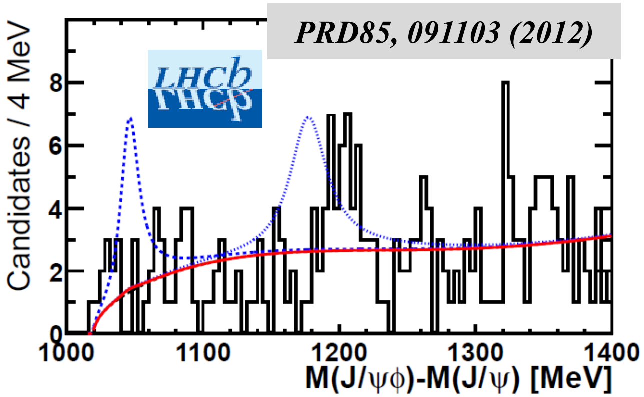


Seach for tetraquark

Y(4140) & Y(4274)
narrow peak at threshold
and one more nearby





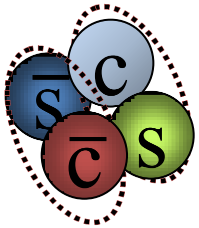


Belle: low momentum kaon detection efficiency is small. 50X more data should help

CDF, D0, CMS: **YES!**

Belle & LHCb: **NO!**

Task for Belle II



$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9), LHCb [1100] (1.4), CMS [1101] (>5) D0 [1102] (3.1)	2009	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0), CMS [1101] (>3), D0 [1102] (np)	2011	NC!

In conclusion

Physics beyond the Standard Model has successfully avoided detection up to now, but we are sure it is somewhere nearby

At Belle II we expect

- Measure UT (angles & sides) with much better precision. If new phases contribute to any measurable ➔ inconsistency of UT.
- CPV in b → sqq vs b → ccs: extra new phases in the penguin loop makes CPV parameters different
- Search for CPV in radiative decays $B \to K^{*0}(K_S^0 \pi^0) \gamma$ is a test of right-handed current in the penguin loop
- Rare decays, even Br's constrain mass of NP
- Electro-weak penguins $b \to s\mu\mu$, see, $s\nu\nu$: Br's, Q^2 -distribution, FB asymmetry are sensitive to NP
- Charm Physics
- Many new decay channels hardly/not seen with the present Belle statistics

About three dozens of quarkonium-like states was found recently and this list continues to increase

At Belle II we expect

- Precise measurements of known and search for new quarkonium and quarkonium-like states
- Many opportunities for analysis on exotic hadron physics
- A lot of surprises