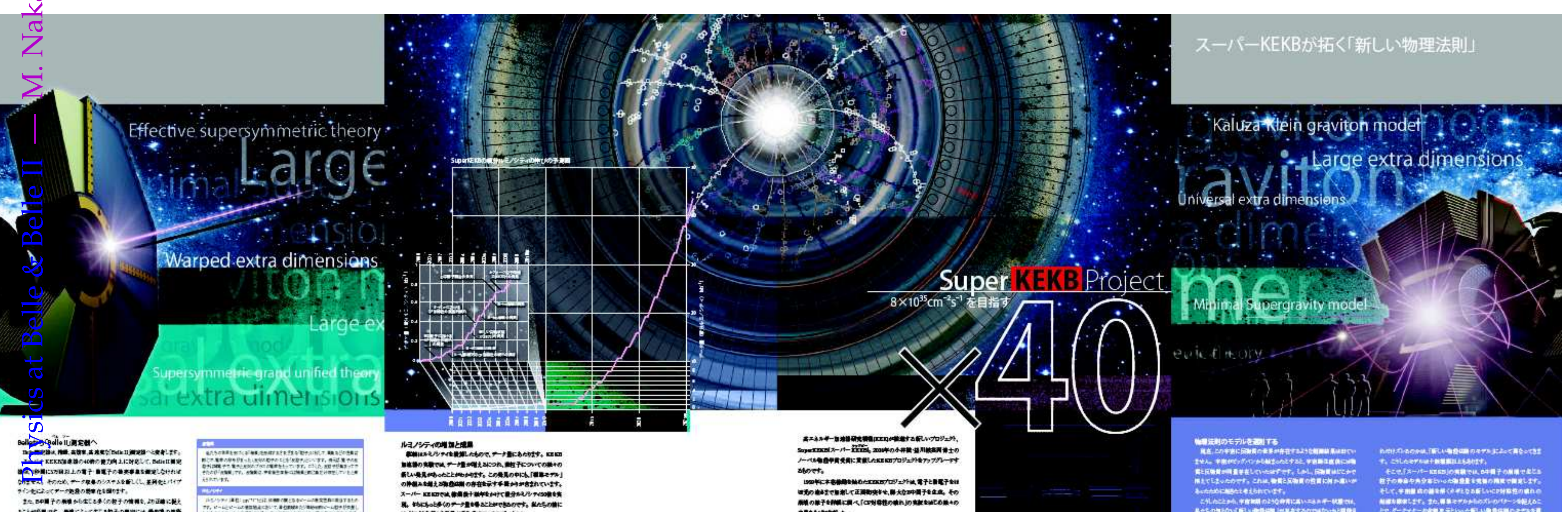
Physics at Belle & Belle II

Mikihiko Nakao (KEK-IPNS)

DESY-KEK collaboration meeting

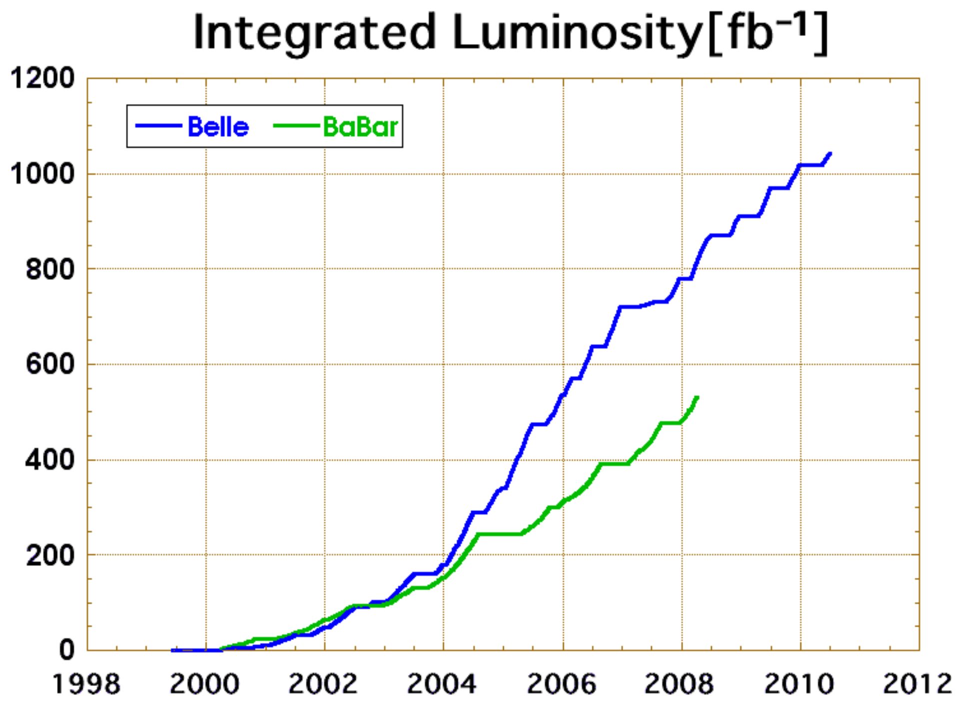
March 20, 2012 at DESY



Outline

- **Status of Belle activity**
- **Unitarity triangle from B decays**
- **Bottomonia** (shooting like bamboo after rain)
- τ **physics** (after discussion with Carsten Niebuhr)
- **A few words on Belle II physics**
- **Short summary**

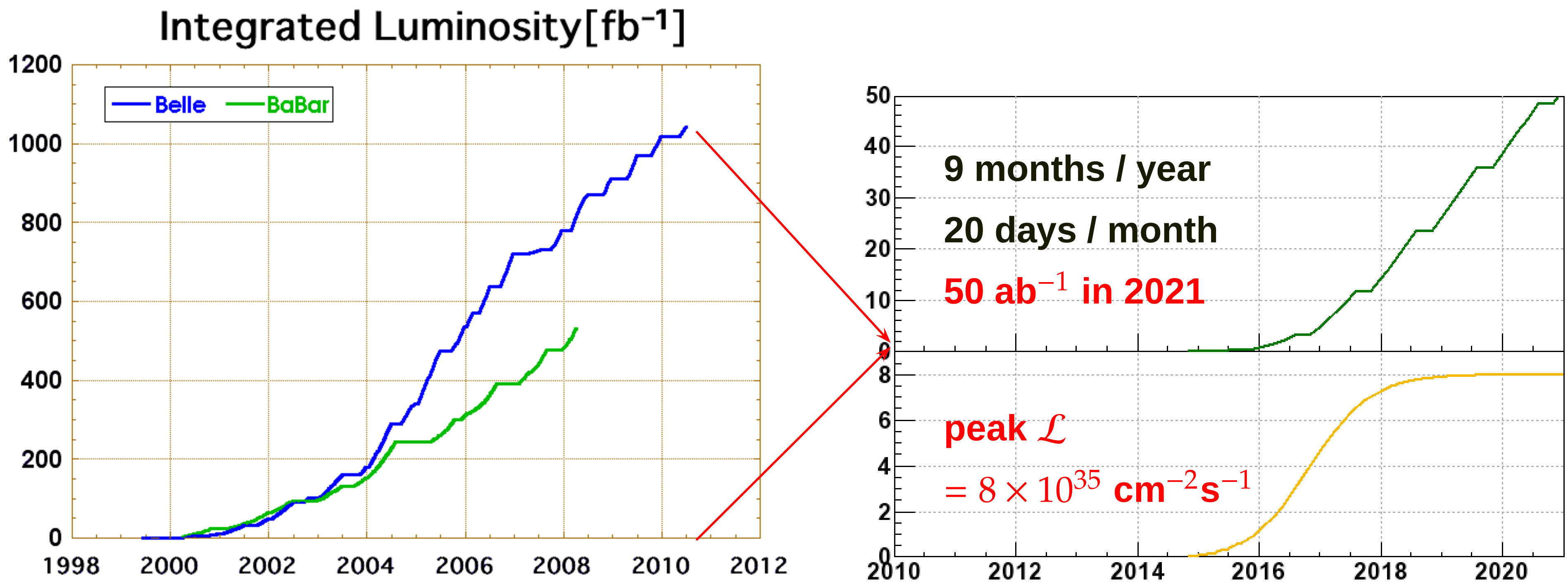
World largest data samples



- $\Upsilon(4S)$ **711 (+90 off) fb^{-1} (772M $B\overline{B}$)**
- $\Upsilon(5S)$ **121 fb^{-1} (7.1M B_s pairs)**
- $\Upsilon(2S)$ **24.1 (+1.7 off) fb^{-1} (158M 2S)**
- $\Upsilon(1S)$ **5.7 (+1.8 off) fb^{-1} (100M 1S)**
- second largest sample $\Upsilon(3S)$ 2.95 (+0.25) fb^{-1}

total 1.041 ab^{-1}

World largest data samples ×50 at Belle II



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Citation statistics for Belle publications

Compiled by S. Eidelman

Frequently Cited Papers

Year	50–99	100–199	200–300	> 300	Total
2010	48	24	6	4	82
2011	59	29	8	4	100

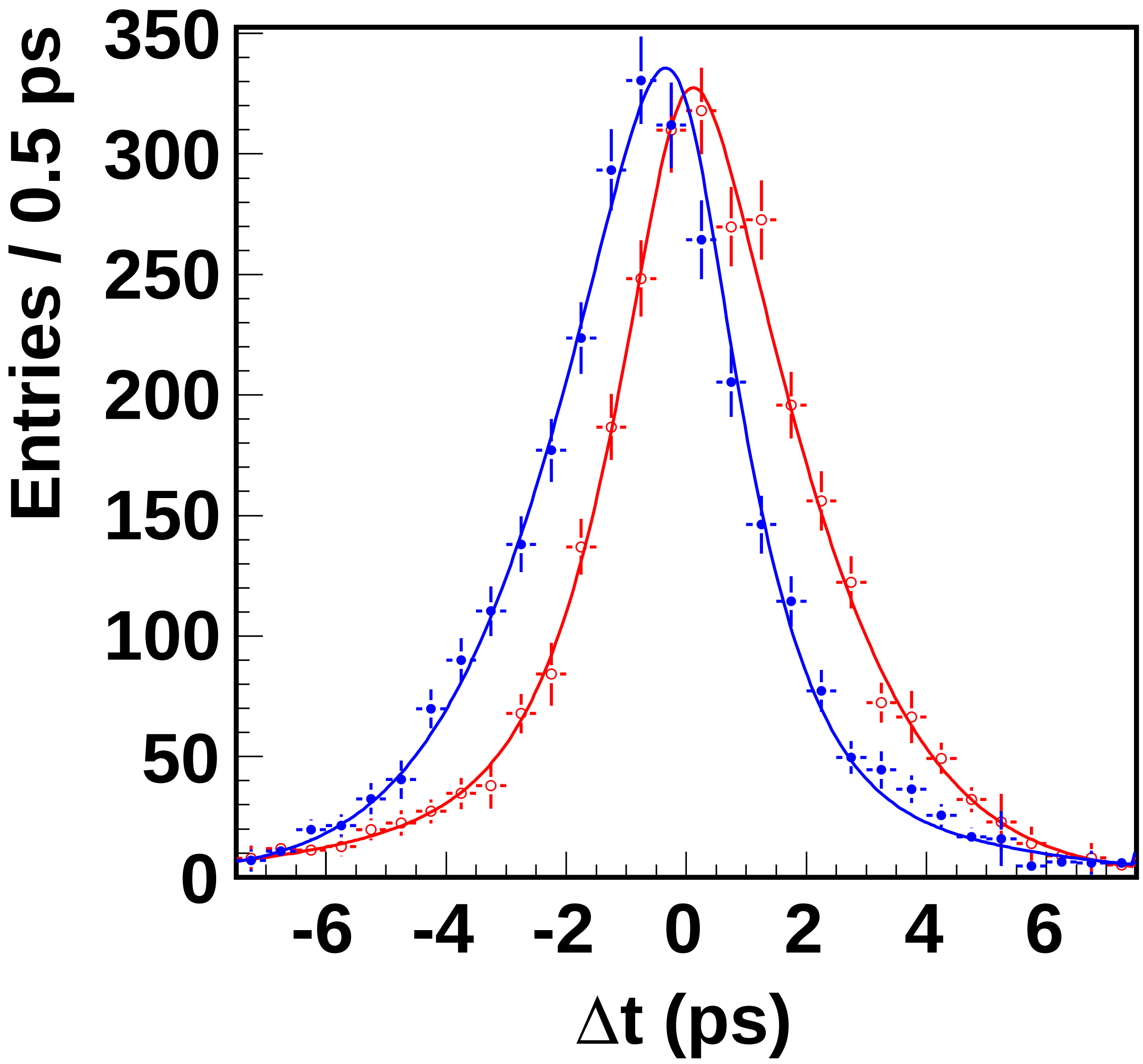
Number of Cites for 10 Most Cited Belle Papers

N	Title	Year	2008	2009	2010	2011
1	X(3872)	2003	392	480	548	638
2	Large CPV	2001	461	487	522	551
3	CP in $B^0\bar{B}^0$	2002	349	358	373	386
4	$B \to X_s\gamma$	2001	318	335	357	363
5	$b \to s\gamma$	2004	196	219	238	254
6	$Y(3945)$	2005	–	183	212	250
7	D mixing	2007	–	–	–	248
8	$D^*_{s0}(2317)$, $D_{s1}(2460)$	2003	204	218	229	239
9	$B \to \tau\nu$	2006	–	–	209	239
10	$2c\bar{c}$	2002	188	212	225	238
11	D^{**}	2004	191	204	216	226

D Mixing paper is now frequently cited

- **Wide range of Belle program:**
  - B, B_s, $D^{(*(*))}_{(s)}$, τ, $c\bar{c}$-like, $b\bar{b}$-like, 2γ-process, ISR, exotic objects, . . .
  - CP and other asymmetries, decay rates, masses, widths, J^{PC}, . . .
- **357 publication as of today** (a few were just submitted)
  - ~10 always in pipeline (collaboration review and authorship confirmation)

Final $\sin 2\phi_1$



772M $B\overline{B}$

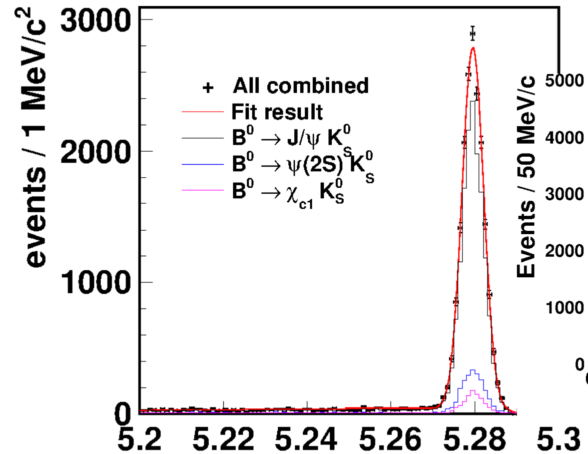
arXiv:1201.4643

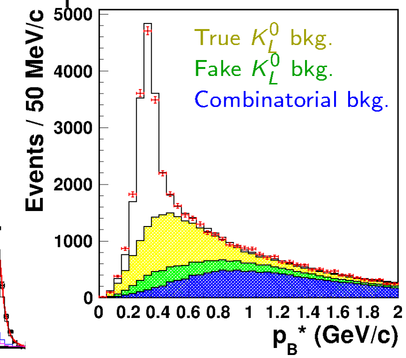
to appear in PRL

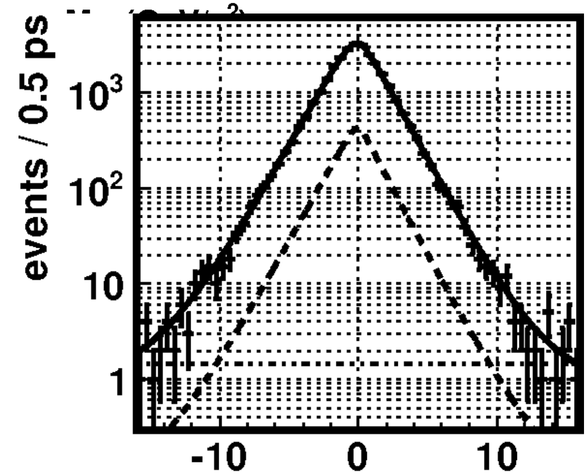
$$\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$$

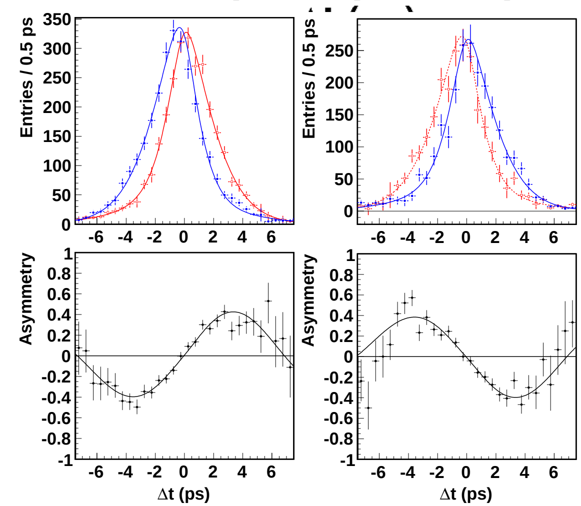
Behind final $\sin 2\phi_1$

- **Final addition of data**
  44% more than previous publication
- **Improved reconstruction**
  18% gain in average
  Flavor tag is also improved
- **More modes** $\psi(2S)K^0_S$ and $\chi_{c1}K^0_S$ added
  total 2.1x gain for CP odd
- **Improved vertexing**
  a better estimator for the vertex quality
  reduced systematic error (but still dominant)
- **Subtle physics effects**
  tag-side interference taken into account



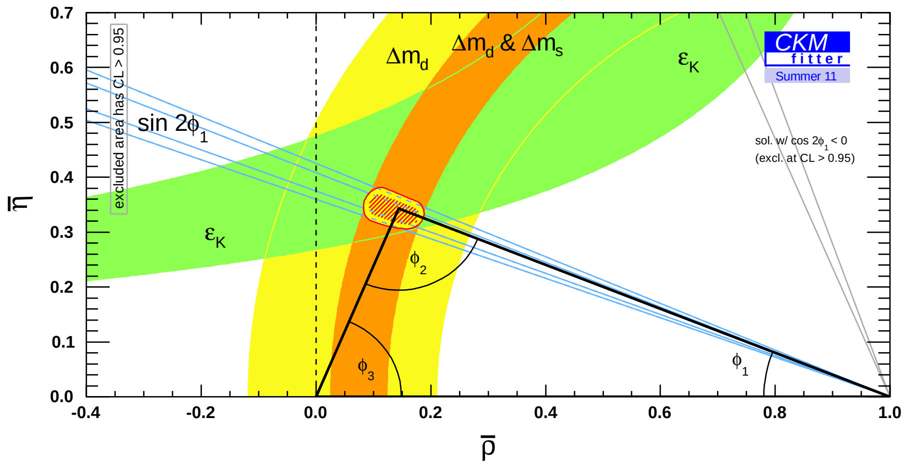




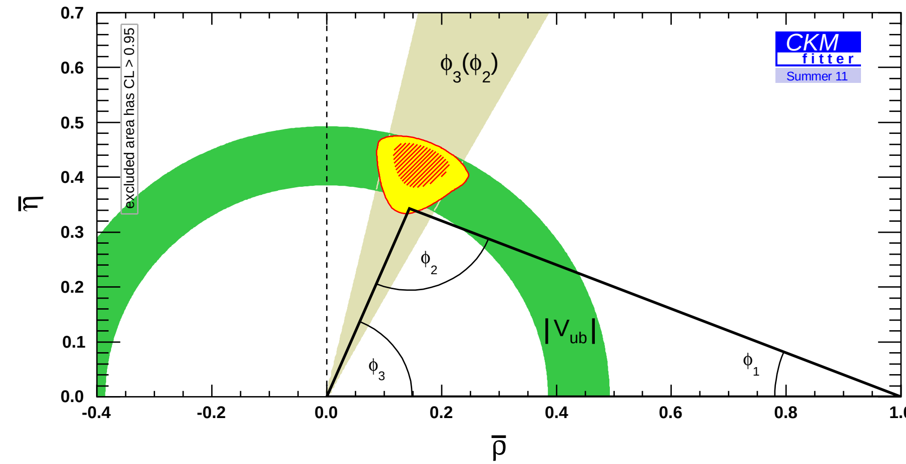


the world-best single measurement, but still room to improve by factor ~2 at Belle II (DEPFET vertexing helps!)

ϕ_1 as reference

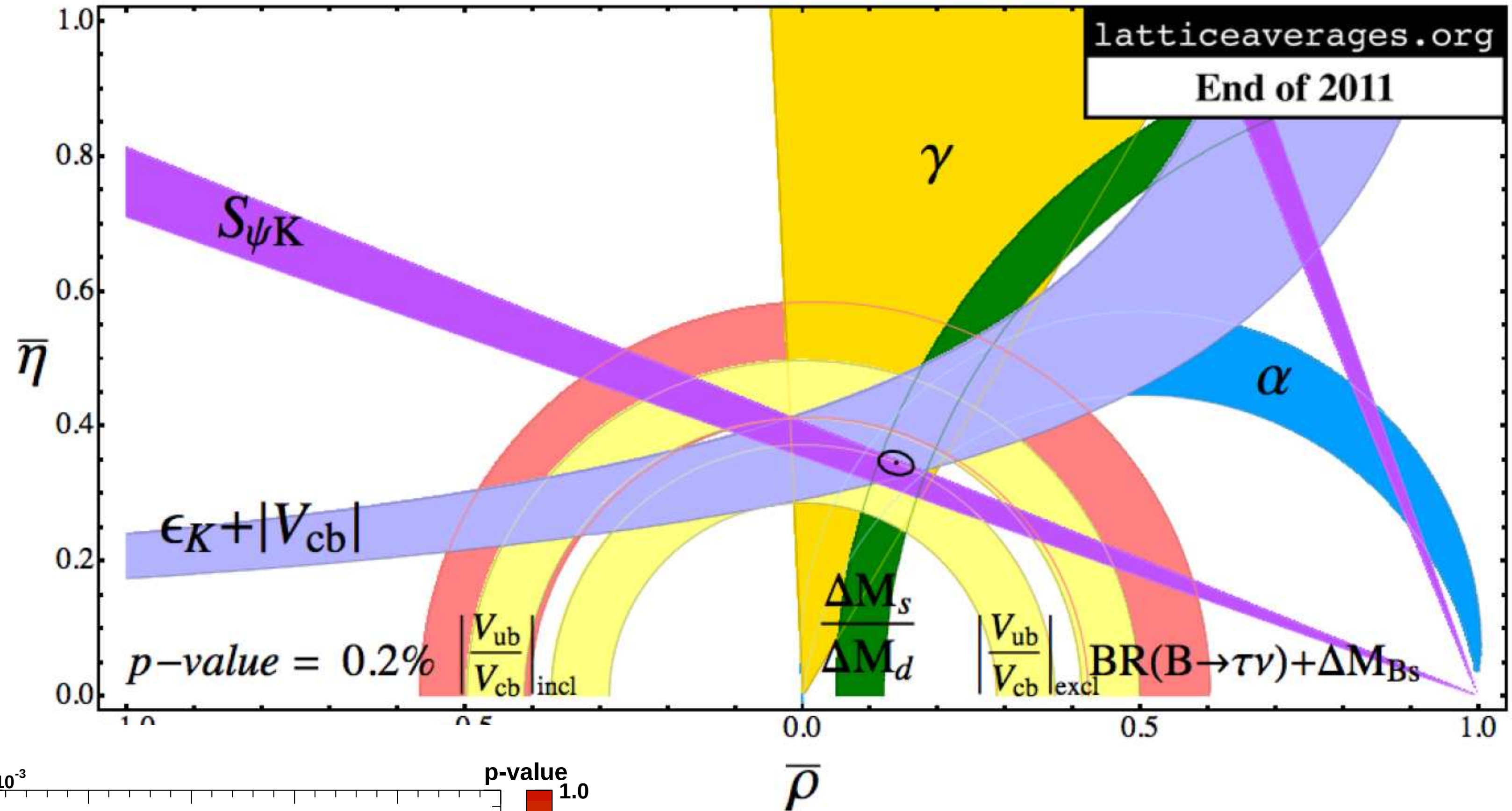


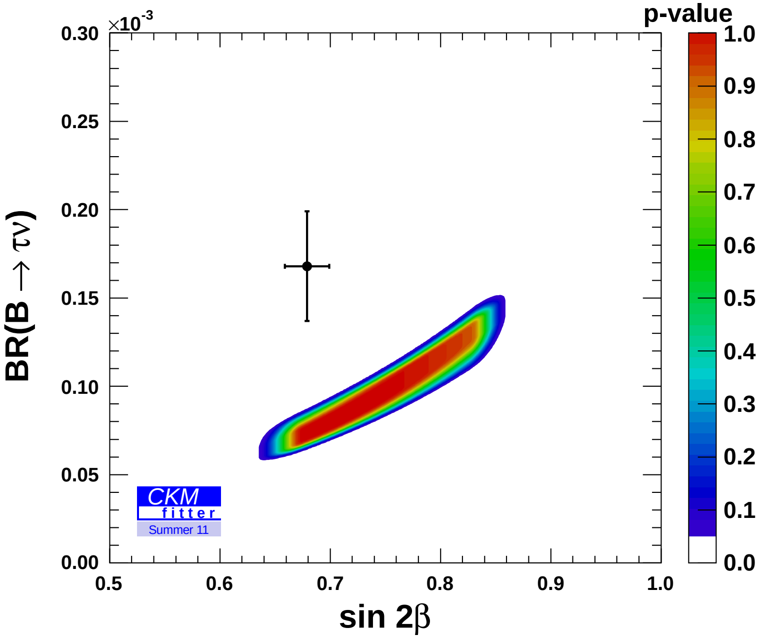
Loop measurements
(SM: phase and size of V_{td})



Tree measurements
(SM: phase and size of V_{ub})

- **ϕ_1 is the best UT measurement, but not a SM reference**
- **Most likely NP in the loop measurements only (ϕ_1 and $|V_{td}|$) and may differ from the tree measurements (ϕ_3 and $|V_{ub}|$)**
- **Experimental precision:** $\phi_1 \gg \phi_2 \gg \phi_3$, $|V_{cb}| \gg |V_{td}|, |V_{ub}|$
  Theoretical cleanness: $\phi_1, \phi_3 \gg \phi_2 \gg |V_{cb}| \gg |V_{ub}|, |V_{td}|$





- **2.7σ tension: ϕ_1 and $B^+ \to \tau^+ \nu$**
- **Disagreement between exclusive and inclusive $b \to u \ell^- \overline{\nu}$**
- **Theory problem?** (mostly lattice. . .)
- **New physics?**

UT_d : taking V_{ub} seriously

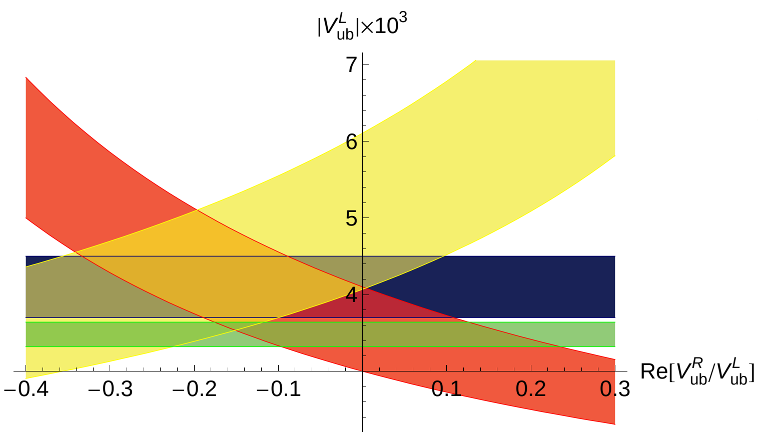
Enrico Lunghi

- The 3.3 discrepancy between inclusive and exclusive V_{ub} could be a hint for new physics in right-handed currents:
  [Chen, Nam; Crivellin; Buras, Gemmler, Isidori; EL, Soni (in preparation), see Tanaka's talk]

$$V_{ub} u_L \not{W} b_L \implies V_{ub}(u_L \not{W} b_L + \xi^R_{ub}\, u_R \not{W} b_R)$$

- Impact on semileptonic decays:

$$|V_{ub}|_{\rm incl} \implies \sqrt{1+|\xi^R_{ub}|^2}|V_{ub}|_{\rm incl}$$
$$|V_{ub}|_{\rm excl} \implies |1+\xi^R_{ub}|\;|V_{ub}|_{\rm excl}$$
$$\mathrm{BR}(B\to\tau\nu) \implies |1-\xi^R_{ub}|^2 \mathrm{BR}(B\to\tau\nu)$$



$B^+ \to \tau^+\nu$

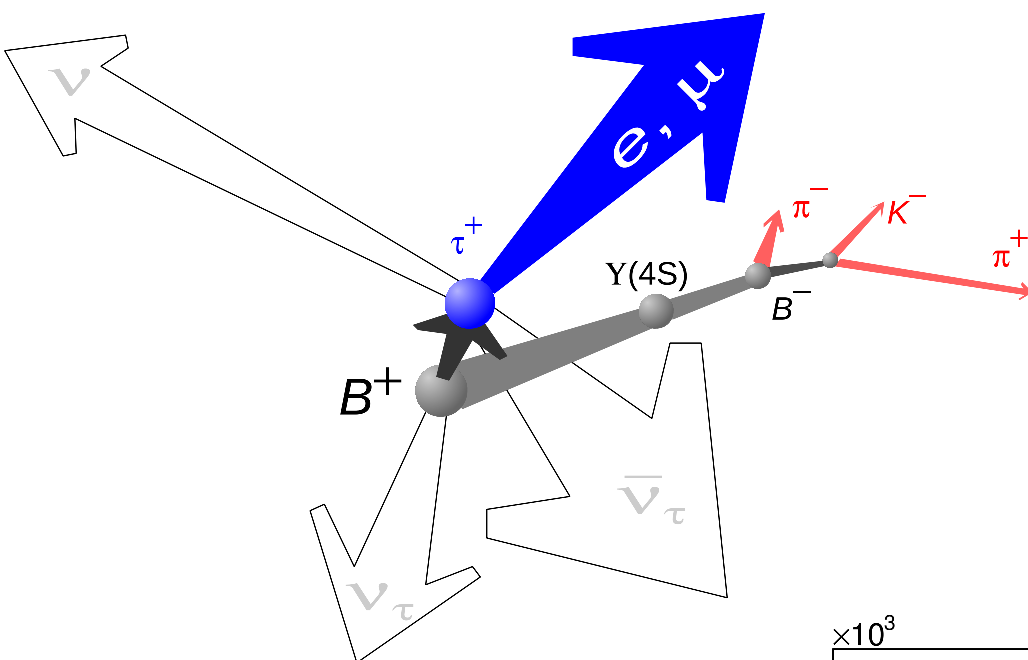
inclusive $b\to u\ell^-\bar{\nu}$

CKM fit

exclusive $b\to u\ell^-\bar{\nu}$

- **Urgent: finalize $B\to\tau\nu$** (summer 2012 plan)
- **Inclusive & exclusive $b\to u\ell^-\bar{\nu}$, theory bound also severe**

Full reconstruction tag



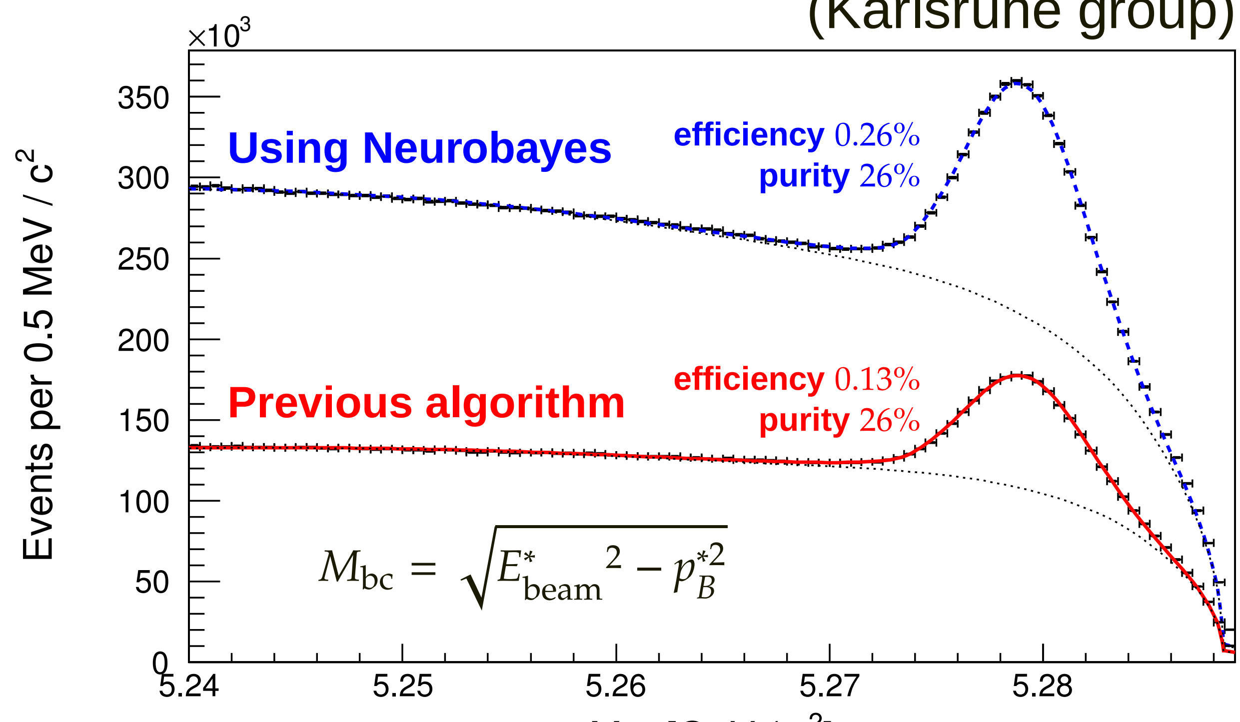
- Tag the other B for the modes with ≥ 2 neutrinos
- Also useful for inclusive and exclusive $b \to u\ell^-\overline{\nu}$ (Bonn group)

For $B^+ \to \tau^+\nu$**,**

- Tag improvement (×2)
- Final dataset (×1.7)
- Analysis improvement
- ⇒ **stat. error~1/2**

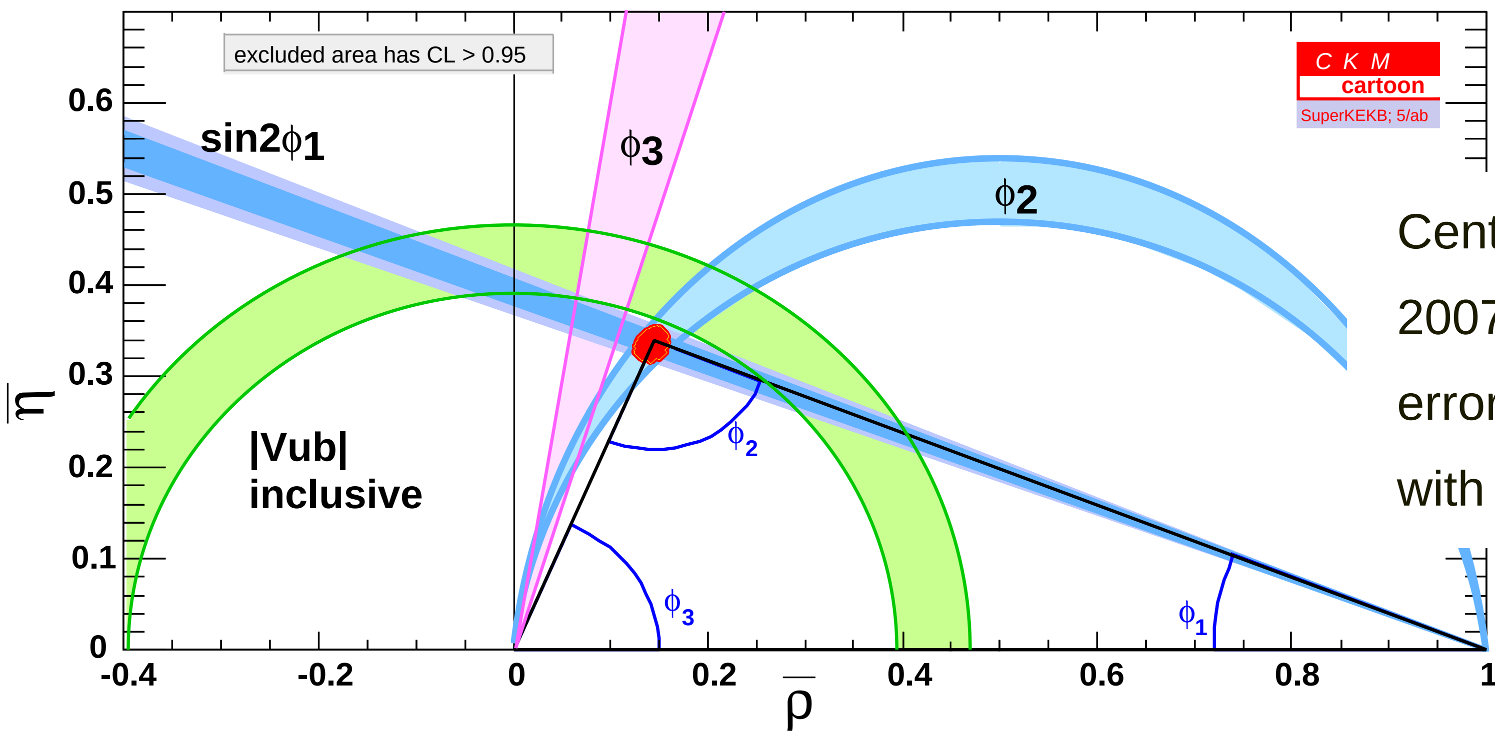
(to appear soon)

(Karlsruhe group)



ϕ_2

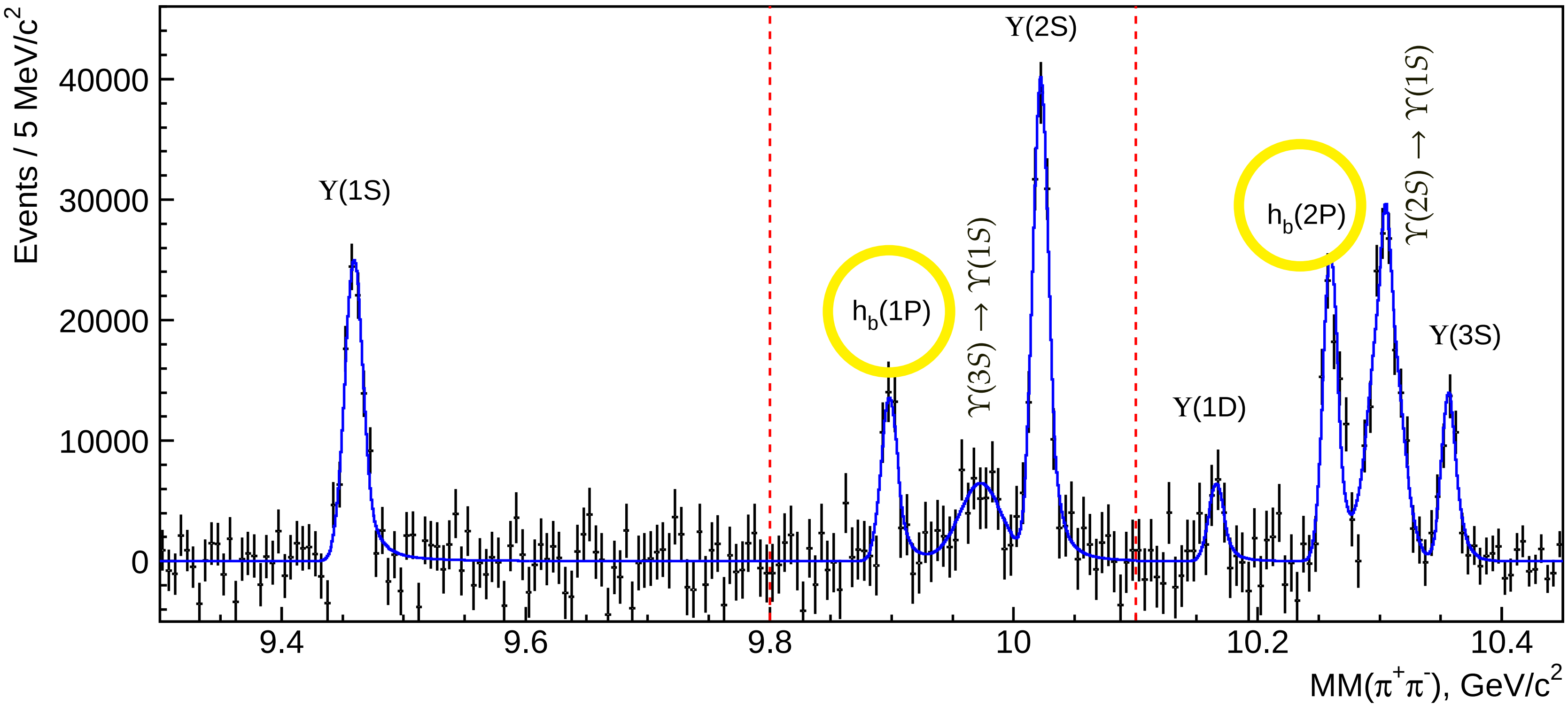
- **Isospin analysis of** $B \to \pi\pi$ **modes (**$\pi^+\pi^-$**,** $\pi^+\pi^0$ **and** $\pi^0\pi^0$**), results in preparation for summer 2012** (MPI group)
- **Similar modes** $B \to \rho\pi$ (more involved due to Dalitz) **or** $B \to \rho\rho$ (and polarization) **have good sensitivity** (last result 449M/535M)
- ϕ_2 **makes the reference angle** ϕ_1 **to a reference point (**ρ**,** η**) at Belle II**



Central values from 2007 averages and errors for 50 ab^{-1} with no Lattice info

Bottomonia boom

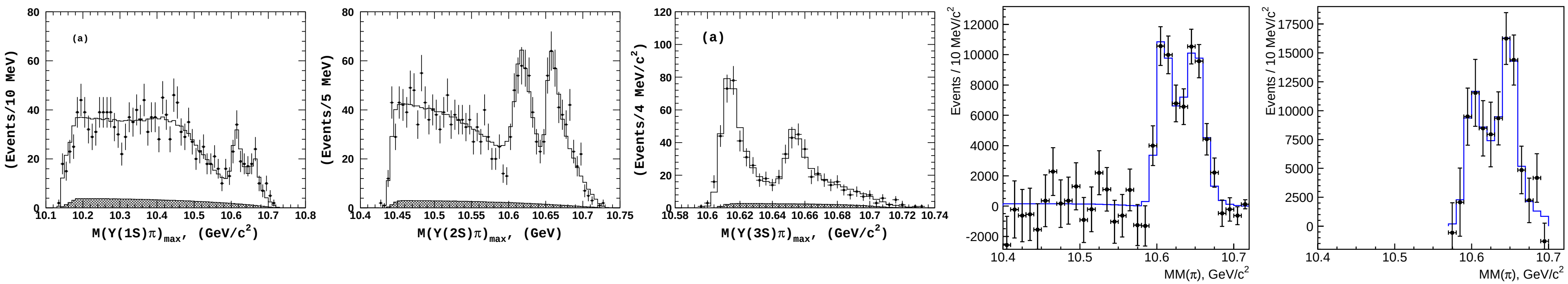
We took data at $\Upsilon(1S, 2S, 3S)$ to study bottomonia, but $\Upsilon(5S)$ turned out to be an excellent bottomonia factory (R. Mussa)

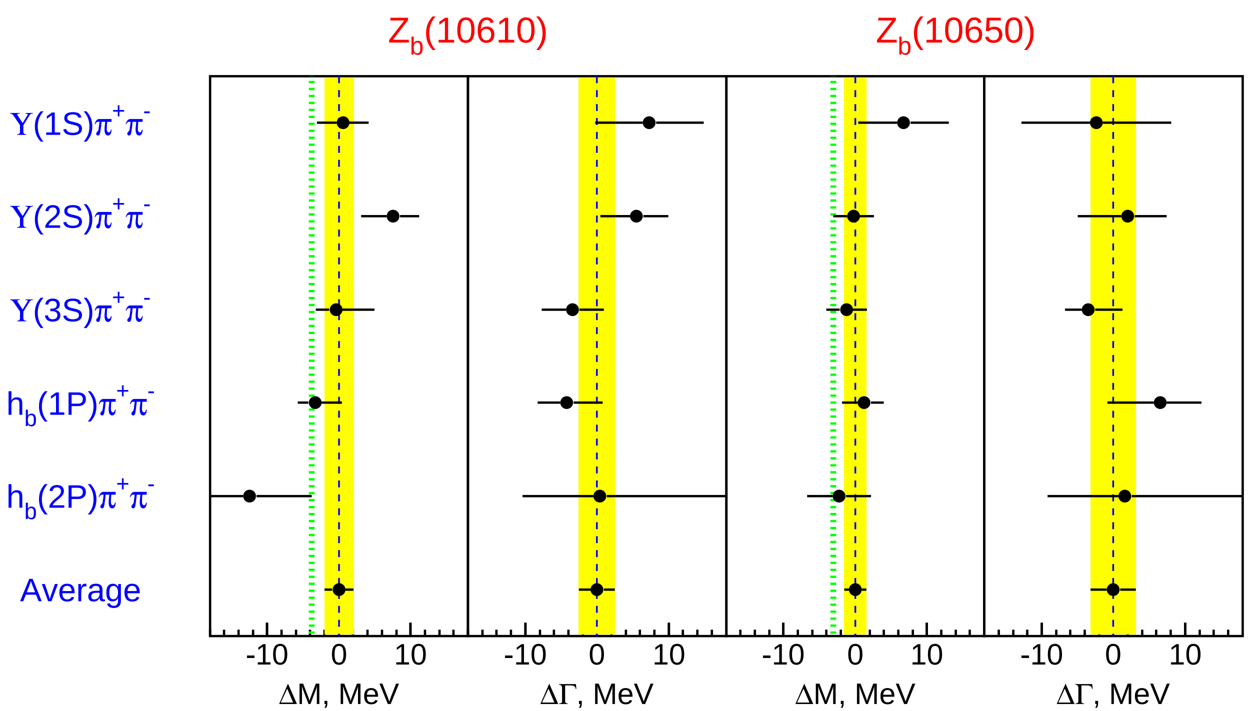


- **Large spin-singlet state $h_b(1P)$ and $h_b(2P)$ found in $\Upsilon(5S)$ data**
  - Found in $\pi^+\pi^-$ recoil mass
  - Source for other bottomonium(-like) states: Z^+_{b1}, Z^+_{b2}, $\eta_b(1S)$, ...
- **$\Upsilon(1D)$ is also separately confirmed**

Charged bottomonia

$\Upsilon(1S)\pi^+$ $\Upsilon(2S)\pi^+$ $\Upsilon(3S)\pi^+$ $h_b(1P)\pi^+$ $h_b(2P)\pi^+$



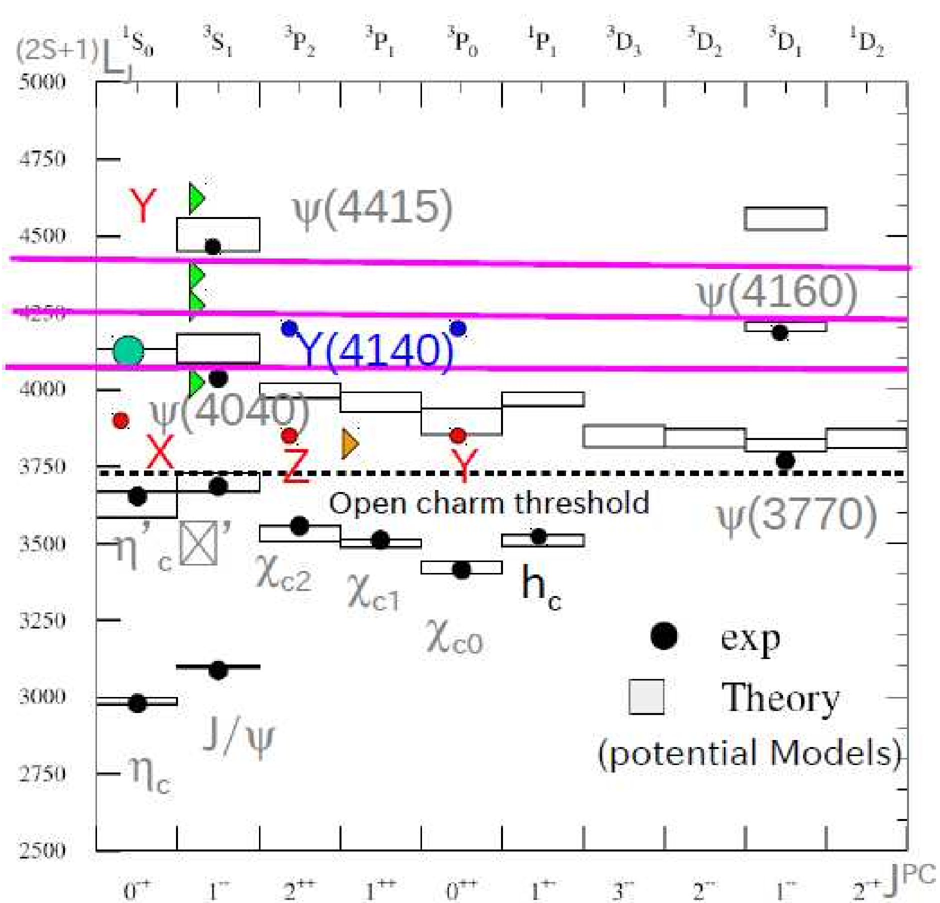


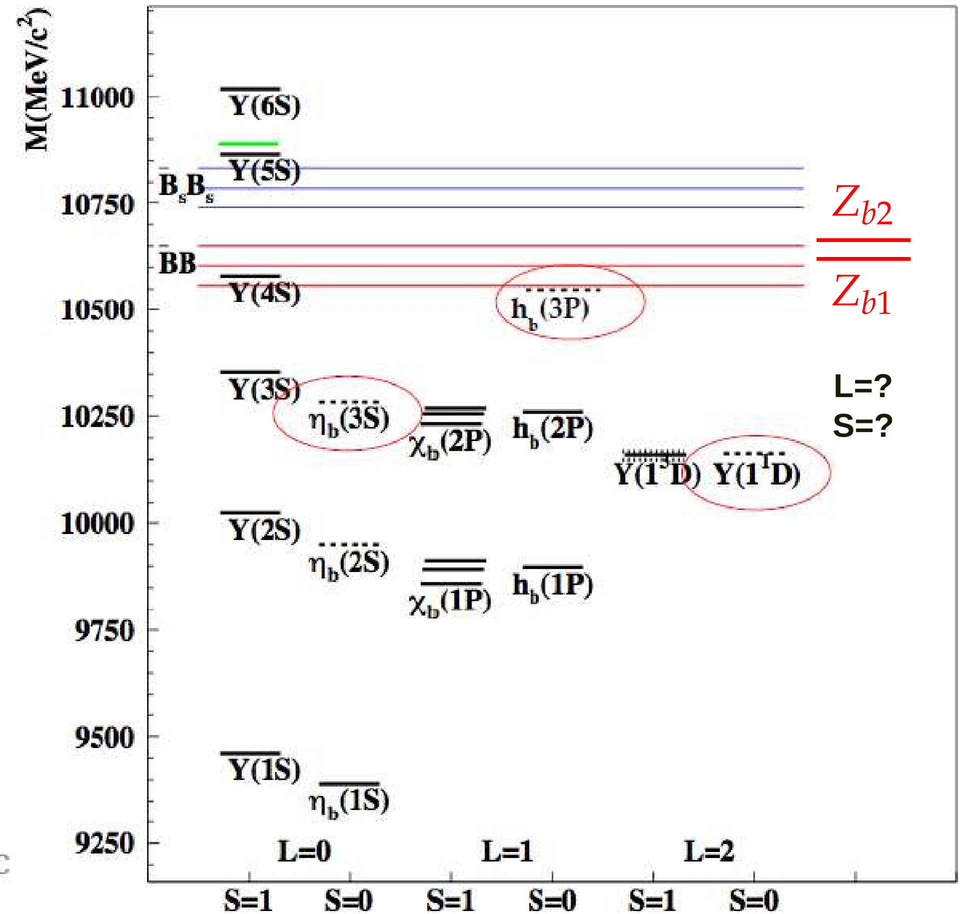
$M = 10608.4 \pm 2.0$ **MeV** $M = 10653.2 \pm 1.5$ **MeV**

$\Gamma = 15.6 \pm 2.5$ **MeV** $\Gamma = 14.4 \pm 3.2$ **MeV**

- Charged bottomonia Z_b found in 5 decay channels
- Just above BB^* and B^*B^* threshold
- Similar to charged charmonia $Z(4430)$, Z_1, Z_2

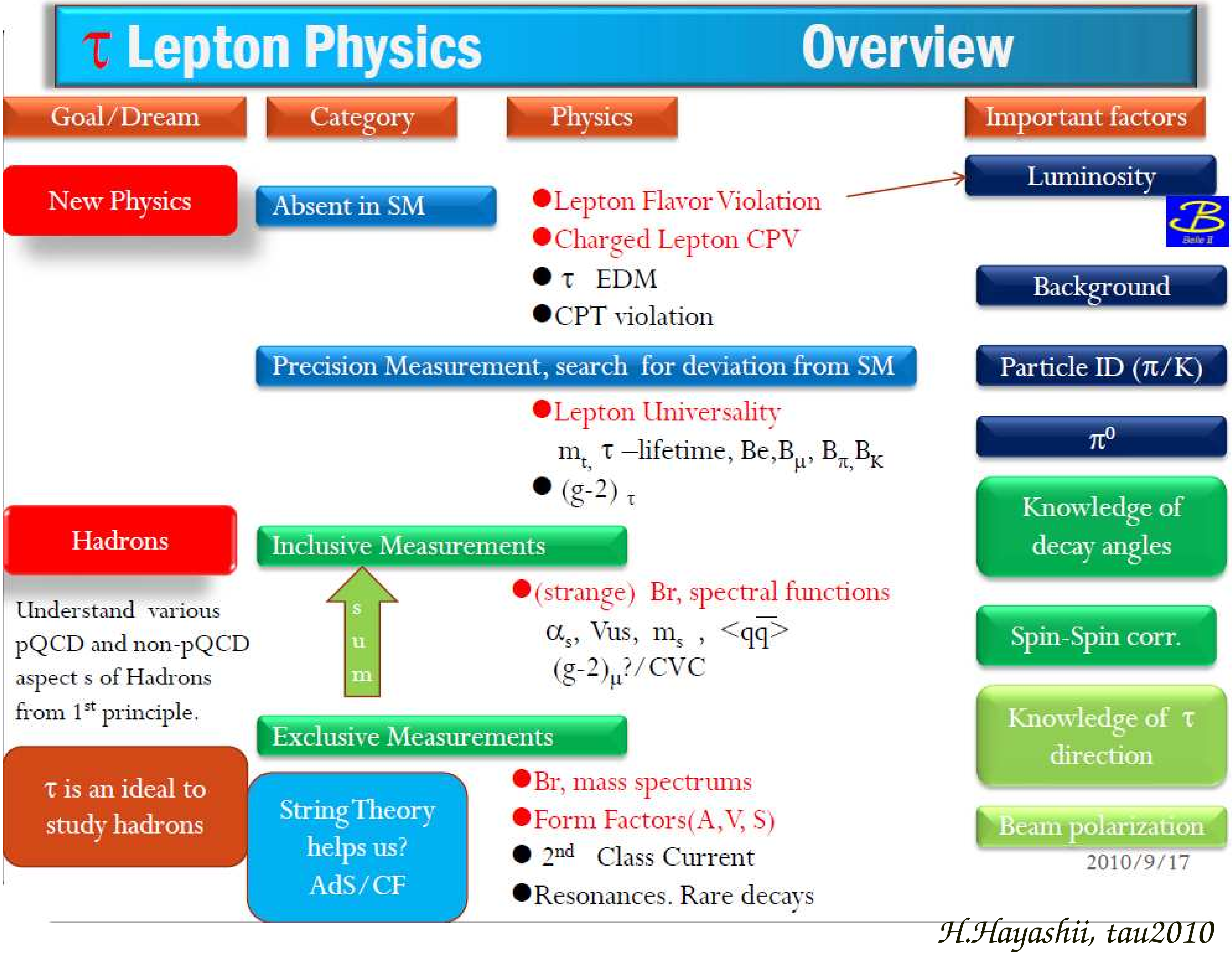
Onia landscape





- **Charmonia:** **still many mysteries including $X(3872)$**
- **Bottomonia:** **charged Z_b states but no other "unexpected"?**

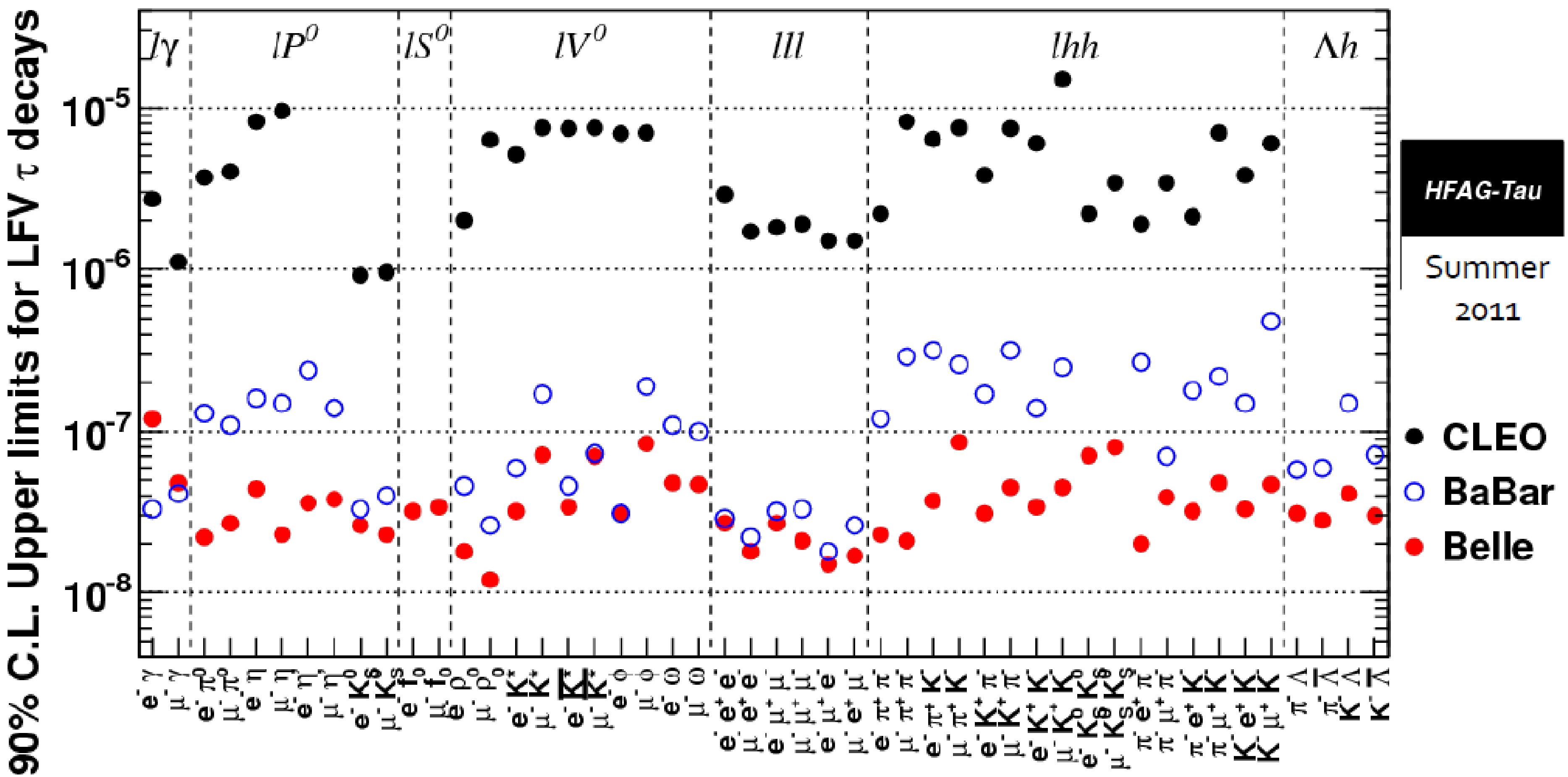
Let me skip also interesting charmonia(-like) and charm physics…


τ Lepton Physics Overview
Goal/Dream
Category
Physics
Important factors
New Physics
Absent in SM
Lepton Flavor Violation
Charged Lepton CPV
τ EDM
CPT violation
Luminosity
Belle II
Background
Precision Measurement, search for deviation from SM
Particle ID (π/K)
Lepton Universality
m_τ, τ –lifetime, B_e,B_μ, B_π,B_K
$(g-2)_\tau$
π^0
Hadrons
Inclusive Measurements
Knowledge of decay angles
sum
(strange) Br, spectral functions
α_s, Vus, m_s , <$q\bar{q}$>
$(g-2)_\mu$?/CVC
Understand various pQCD and non-pQCD aspect s of Hadrons from 1st principle.
Spin-Spin corr.
Exclusive Measurements
Knowledge of τ direction
τ is an ideal to study hadrons
String Theory helps us? AdS/CF
Br, mass spectrums
Form Factors(A,V, S)
2nd Class Current
Resonances. Rare decays
Beam polarization
2010/9/17
H.Hayashii, tau2010

τ lepton flavor violation

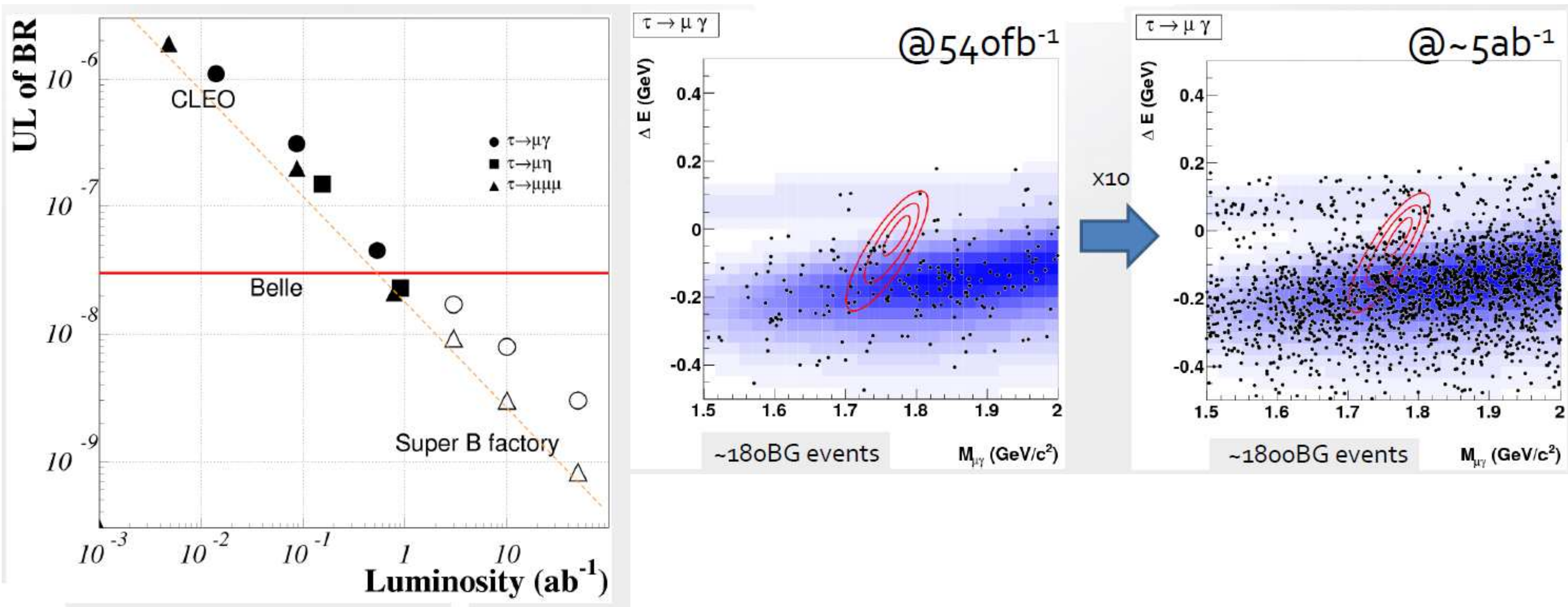
- **"No LFV" in the SM, LFV is an unmistakable sign of NP**
- **LFV naturally shows up in many extensions to the SM**
  - MSSM + seesaw, Higgs mediated, Little Higgs, heavy majorana ν_R
  - Branching fraction can be as large as $O(10^{-7})$ or $O(10^{-8})$
- **Many possible decay modes:**
  - $\tau \to \mu\gamma$, $\tau \to \ell\ell\ell$, $\tau \to \mu\eta$, $\tau \to \ell$ + any hadrons
  - Different modes have different sensitivity to different NP models
  - Already excluding some predictions, still large room to explore
- **Synergy with $\mu \to e\gamma$ measurement**

LFV search status



- Belle reported the best upper limits in most of the modes
- All upper limits below 10^{-7}, almost reaching 10^{-8}
- Belle's $\tau \to e\gamma$ and $\tau \to \mu\gamma$: work in progress

τ LFV prospects

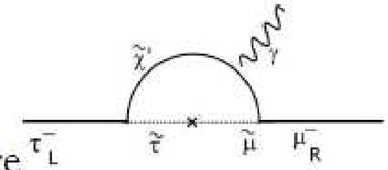


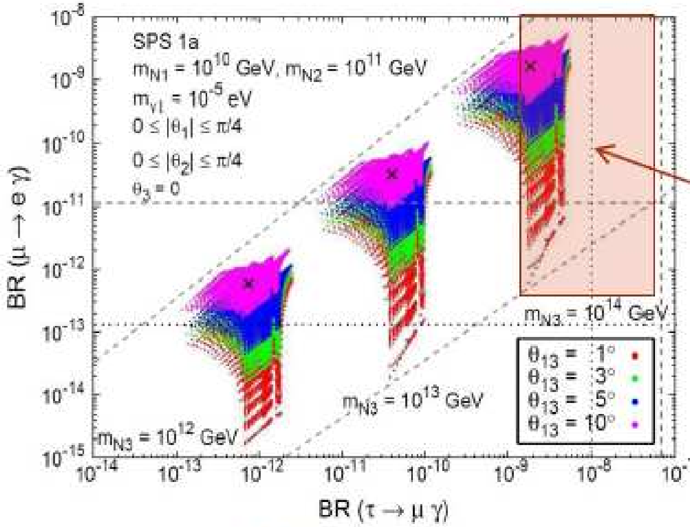
- **Expected upper limits updated thanks to recent analysis improvements**
- **Can reach $\mathcal{B} \sim 8\times10^{-10}$ for $\tau\to\mu\mu\mu$, $\mathcal{B}\sim 3\times10^{-9}$ for $\tau\to\mu\gamma$**
- **Keeping beam background low is the top priority**

Belle II Sensitivity for some models

$\tau \to \mu\gamma$ vs. $\mu \to e\gamma$

MSSM+seesaw, dipole diagrams are dominated.

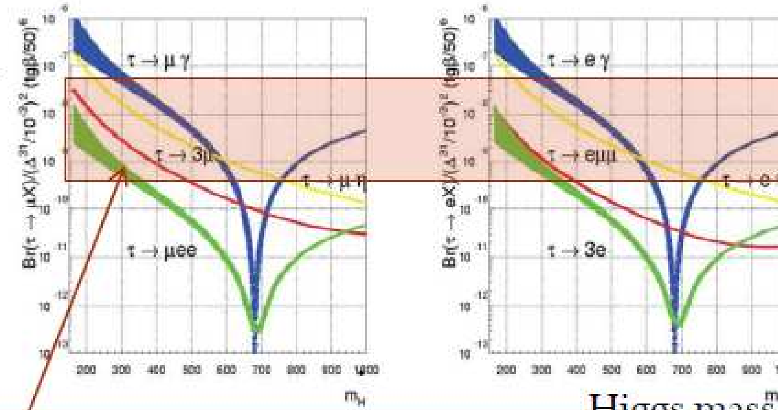




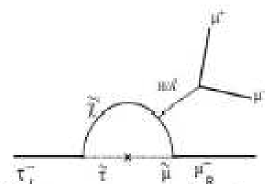
S. Antusch et al., JHEP 11, 090 (2006).

$\tau \to 3\mu$ $\tau \to \mu\eta$ Higgs madiated

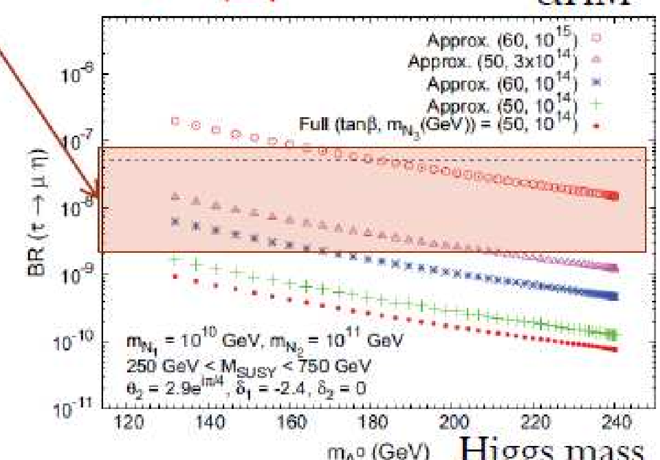
Paradisi., 0602 (2006) 050



Region covered by Belle II experiments



$\tau \to \mu\eta$ UHM



MSSM + seesaw + light Higgs

M. Herrero et al. arxiv:0903.5151

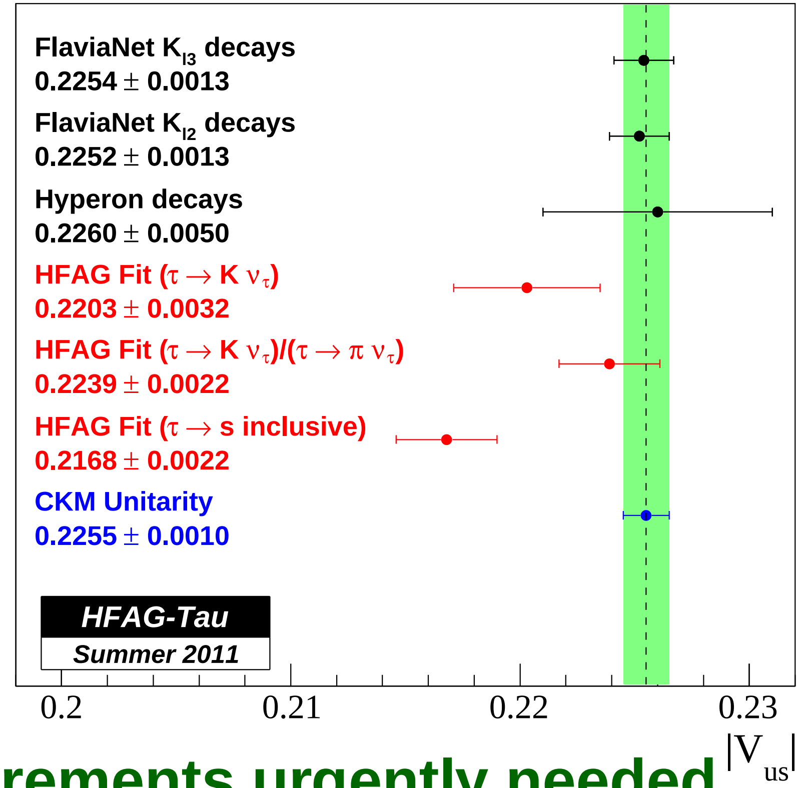
If Higgs is light (130–400 GeV), Higgs-mediated diagram plays an important role.

Belle II has a good sensitivity for such a scenario.

H.Hayashii, tau2010

$|V_{us}|$ from τ decays

- $|V_{us}|$ **determined in multiple ways**
  - From CKM unitarity
  - From semileptonic K decays
  - From the ratio $(\tau \to K\nu)/(\tau \to \pi\nu)$
  - Something wrong in the ratio $(\tau \to$ strange$)/(\tau \to$ non-strange$)$?

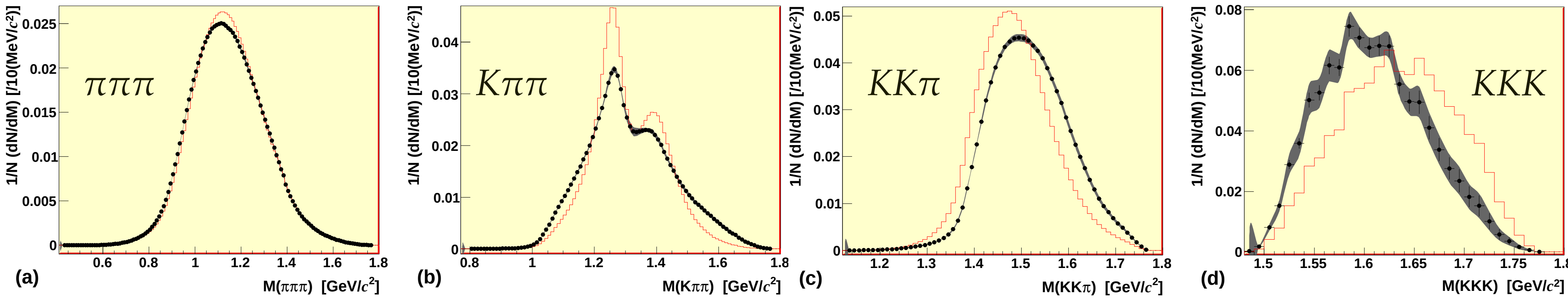


- τ **is competitive, improved measurements urgently needed**
  - Belle results on $(\tau \to K\nu)/(\tau \to \pi\nu)$ is missing (but will be limited by the form factor uncertainties)
  - Inclusive measurement needs to measure "all" exclusives one-by-one
  - Systematic shift may be due to detector bias? Belle detector systematics (esp. for K_S^0 and π^0) are now known better

Initial discussion started with C. Niebuhr and H. Hayashii

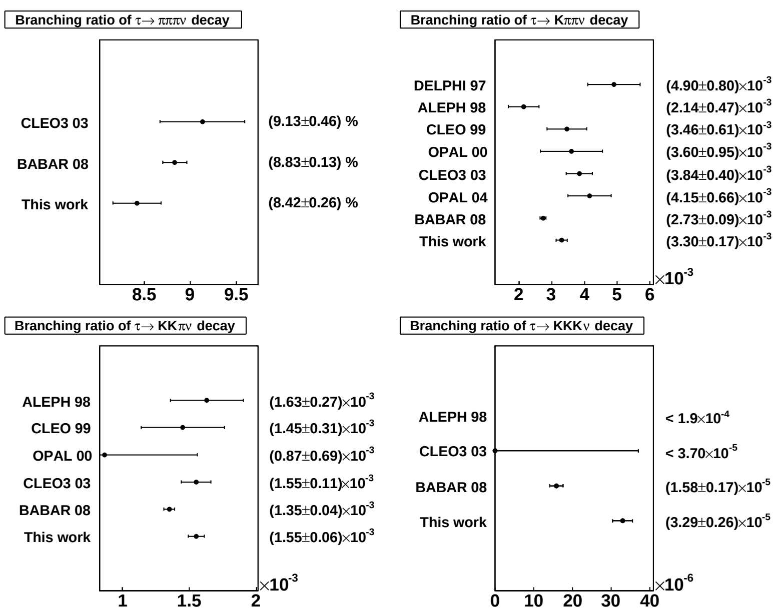
An example

$\tau \to h^+ h^- h^+ \nu_\tau \ (h = \pi, K)$ [Belle 666 fb^{-1}]



- 1-3 prong events are selected
- Cross-feeds between 4 modes unfolded
- Mass spectrum iteratively unfolded

  TAUOLA MC (in red) does not model well
- Normalized to well-known $\tau \to \ell\nu\nu$
- Systematic error dominant (except KKK)
- Discrepancy between Belle/BaBar?



- And this will be a very nice sample to search for CPV in τ decays

Belle II physics in a nutshell

$o(10^2)$ higher luminosity

complementarity to other experiments (LHCb, K-factory, BES...)

→ theory uncertainty matches the expected exp. precision

→ theory uncertainty will match the expected exp. precision with expected progress in LQCD

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	input	$0.5\% \to 0.1\%_{\rm Latt}$	0.2246 ± 0.0012	0.1%	K factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$\|V_{ub}\|$ $[B \to \pi \ell \nu]$	input	$10\% \to 5\%_{\rm Latt}$	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \to \psi \phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \to \phi \phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \to K^* \gamma}$	few $\times$ 0.01	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \to \phi \gamma}$	few $\times$ 0.01	0.01	—	0.05	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \to s \gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \to \tau \nu)$	1×10^{-4}	$20\% \to 5\%_{\rm Latt}$	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu \nu)$	4×10^{-7}	$20\% \to 5\%_{\rm Latt}$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu^+ \mu^-)$	3×10^{-9}	$20\% \to 5\%_{\rm Latt}$	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \to \mu^+ \mu^-)$	1×10^{-10}	$20\% \to 5\%_{\rm Latt}$	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{\rm FB}(B \to K^* \mu^+ \mu^-)_{q_0^2}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \to K \nu \bar{\nu}$	4×10^{-6}	$20\% \to 10\%_{\rm Latt}$	$< 1.4 \times 10^{-5}$	20%	Super-B
$\|q/p\|_{D-\rm mixing}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	10%	K factory
$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory
$R^{(e/\mu)}(K \to \pi \ell \nu)$	2.477×10^{-5}	0.04%	$(2.498 \pm 0.014) \times 10^{-5}$	0.1%	K factory
$\mathcal{B}(t \to c Z, \gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-13})$	$< 0.6 \times 10^{-2}$	$\mathcal{O}(10^{-5})$	LHC (100 fb^{-1})

Isidori, Nir, Perez, 1002.0900

DNA matching — synergy in BSM chase

[A.Buras, arXiv:1012.1447]

	AC	RVV2	AKM	δLL	FBMSSM	$SSU(5)_{\rm RN}$
$D^0-\bar{D}^0$	★★★	★	★	★	★	★
ϵ_K	★	★★★	★★★	★	★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★★
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★
$A_{7,8}(K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★★★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★★★
d_e	★★★	★★★	★★	★	★★★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★★★

SUSY models

	LHT	RSc	4G	2HDM	RHMFV
$D^0-\bar{D}^0$ (CPV)	★★★	★★★	★★	★★	
ϵ_K	★★	★★★	★★	★★	★★
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	★★★
$S_{\phi K_S}$	★	★	★★		
$A_{\rm CP}(B\to X_s\gamma)$	★		★		
$A_{7,8}(K^*\mu^+\mu^-)$	★★	★	★★		
$B_s\to\mu^+\mu^-$	★	★	★★★	★★★	★★
$K^+\to\pi^+\nu\bar{\nu}$	★★★	★★★	★★★		★★
$K_L\to\pi^0\nu\bar{\nu}$	★★★	★★★	★★★		★★
$\mu\to e\gamma$	★★★	★★★	★★★		
$\tau\to\mu\gamma$	★★★	★★★	★★★		
$\mu+N\to e+N$	★★★	★★★	★★★		
d_n	★	★★★	★	★★★	
d_e	★	★★★	★	★★★	
$(g-2)_\mu$	★	★★	★		

non SUSY models

Short summary

- **Belle has been producing (way too) many exciting results, surpassing the original expectation, and Belle II will follow (**sorry for omissions, but impossible to cover all by a single speaker)
- **Still many uncovered Belle physics waiting for contributions**
- **There are interesting tensions, Belle II will fully uncover**
- **DESY contribution to Belle and Belle II physics will beautifully blossom**