Recent experimental results in B physics

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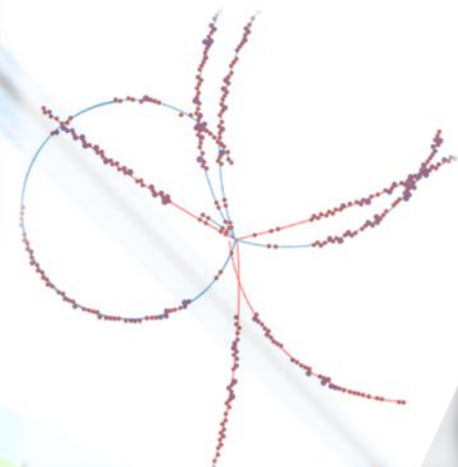


ICPPA-2020

MEPhI, Moscow

SM: successes and failures

The SM successes:

All particles have been observed

All symmetries have been confirmed and

The mechanism of symmetry breaking is established

All parameters have been measured

Essentially all experimental measurements are consistent with the SM predictions

BUT in the same time a lot of intrinsic problems

Inconsistencies at high energies (rad. corrections , UV divergences , Landau pole)

Still no unification of strong and electroweak interactions

Large number of free parameters

CP-violation is not completely understood

Flavor mixing and the number of generations is arbitrary

The origin of the mass spectrum in unclear

Most of open questions are addressed to the flavor sector

Flavor physics in the SM …

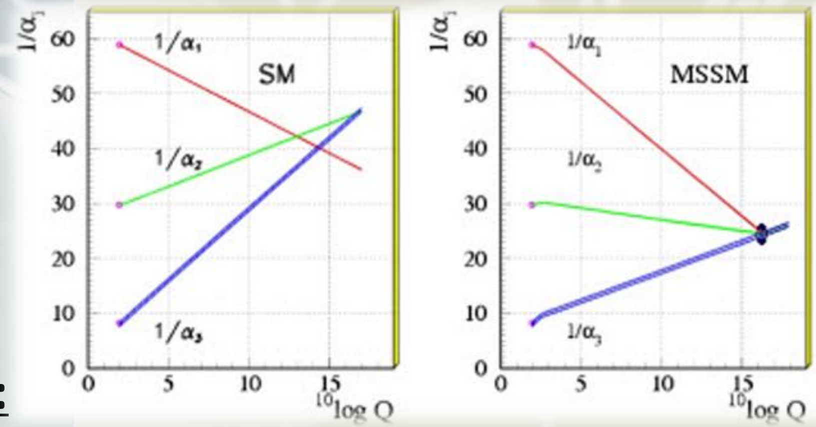
bosonic sector of the SM:

$@1\text{GeV}: g' \sim 0.3, \quad g \sim 0.6, \; g_s \sim 0.6, \; \lambda \sim 1$

5 free parameters:

one defines the scale

+ 4 dimensionless coupling constants



Ideally, we have to accept one scale parameter, and expect that dimensionless parameters are some geometrical constants; there is a hint that gauge constants are related to each other...

fermionic (flavor) sector (without neutrino):

3 Yukawa constants for charged leptons:

6 Yukawa constants for quarks

4 quark-mixing parameters

$$Y_t \sim 10^0, \quad Y_b \sim 10^{-2}, Y_c \sim 10^{-2},$$

$$Y_s \sim 10^{-3}, Y_u \sim 10^{-5}, Y_d \sim 10^{-5},$$

$$Y_\tau \sim 10^{-2}, Y_\mu \sim 10^{-3}, Y_e \sim 10^{-6},$$

$$|V_{ud}| \sim 1, |V_{us}| \sim 0.2, |V_{cb}| \sim 0.04,$$

$$|V_{ub}| \sim 0.004, \delta_{KM} \sim 1$$

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?**

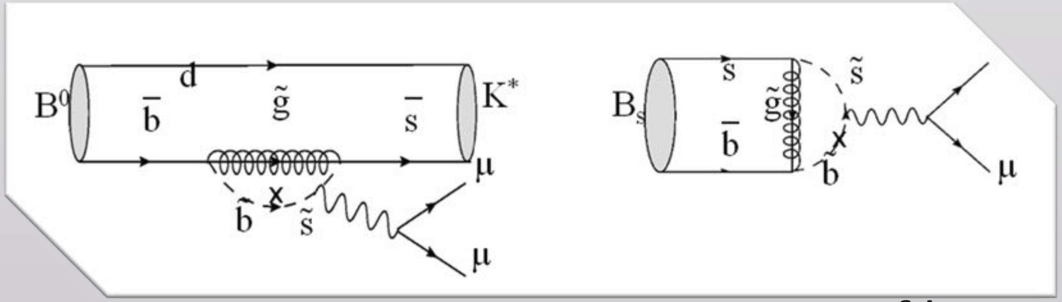
All these "W*hys?*": The SM flavor puzzle

CP violation: enigmatic phenomenon & effective tool for New Physics searches

…is not only touching the most miraculous phenomenon

It is also a powerful tool to search for New Physics:

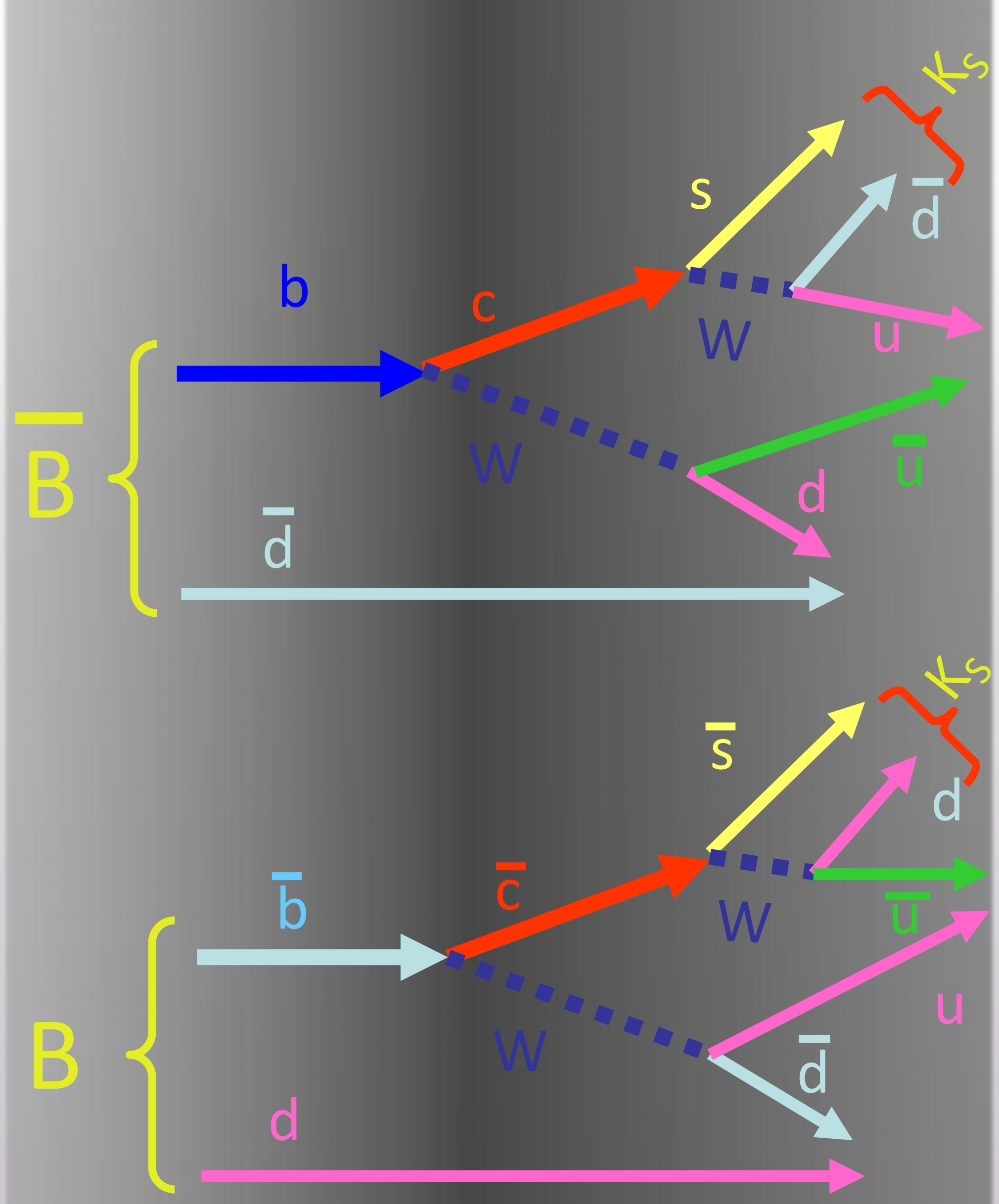
- predictions for CP violation pattern is very often more theoretically clean than predictions for branching fractions (cancelation of QCD uncertainties)
- CP violation is often related to box/loop diagrams: new particles can run over similar loops and compete with the SM contribution. Measuring CP we compare amplitudes of SM and NP, rather than probabilities (amplitudes squared).



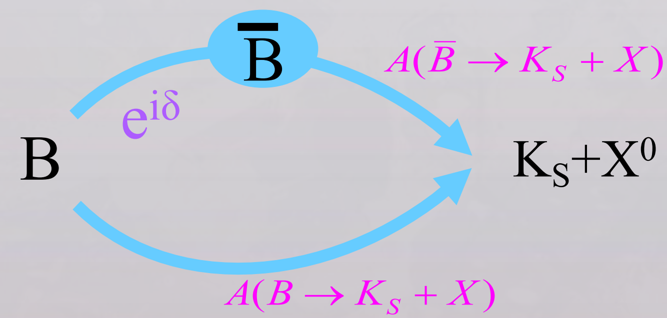
B-mesons are of key importance for precision flavor test

- The SM contribution is suppressed by small CKM elements, more chances for NP to compete with the SM.
- Large b-quark mass enhance loop contribution with new particles.

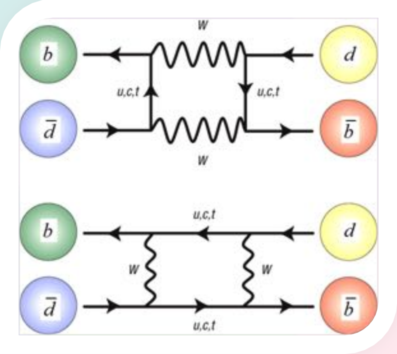
Carter-Sanda idea



In 1980 nobody could think of golden mode ($J/\psi\ K^0_S$). But Carter & Sanda realized that two succeeding CKM-favored W emitions may result in (almost, up to s-d replacement) same quark configuration. s-d difference is hidden in K^0_S. Thus, both B^0 and B^0-bar decay into the indistinguishable final state (even if intermediate states D^0/D^0-bar are different). They estimated the CP violation effect may be as large as 10% (obviously, they pulled the effect up), but the Nature is very generous: in reality the effect is ~100%.



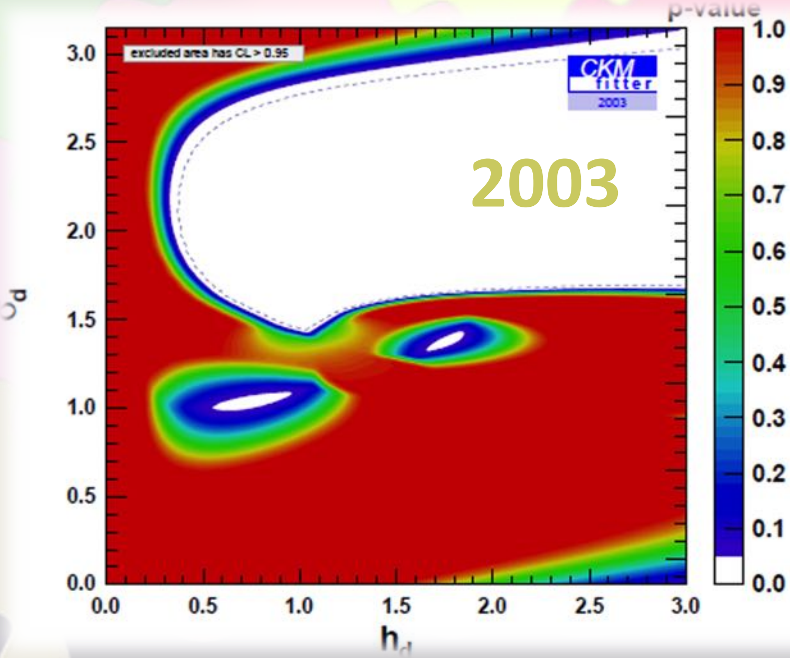
CP violation: enigmatic phenomenon & effective tool for New Physics searches

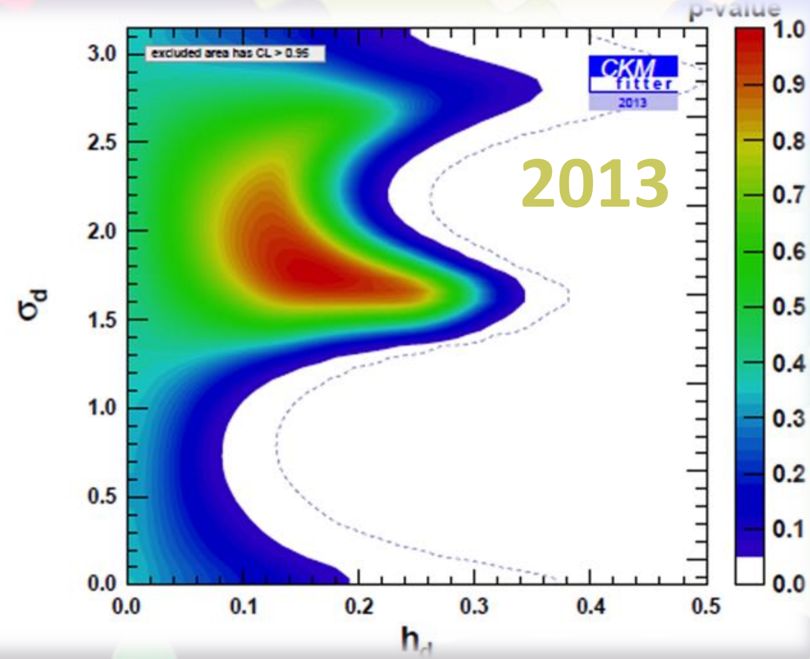


Before CP-studies at B-factories it was not known, if the SM is the main contributor to the B^0B^0-mixing

NP

$$\Delta m_d = \Delta m_d^{SM} \times (1 + h_d e^{2i\sigma})$$





To continue study, SUPER B FACTORY NEEDED

When you are searching for New Physics

there is no limit to what you need

- you should insist on 10 times more than you think you need

***- if you see no effect** with 100 times more than you thought you need,*

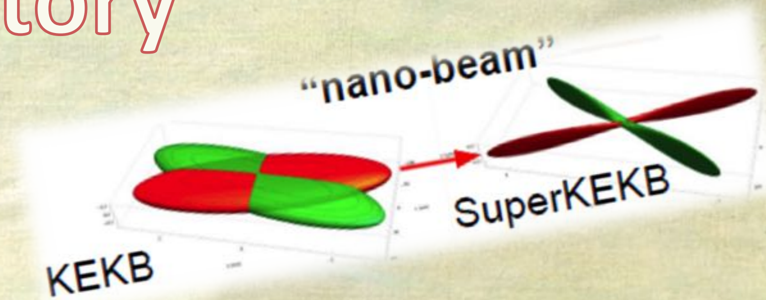
require 100 times more!

- remember $\varepsilon_K = 2 \times 10^{-3}$

модействия в предположении, что CP сохраняется. А в лекциях в Дубне [33] и в книге [34] я настаивал на том, что экспериментальная проверка CP-инвариантности является одним из высших приоритетов. Группа Оконова в Дубне искала CP-запрещенные распады $K_2^0 \to \pi^+\pi^-$ и установила верхний предел для их относительной вероятности, примерно 2×10^{-3} [35]. (Они не обнаружили ни одного двухчастичного распада, зарегистрировав 600 трехчастичных.) К сожалению, на этом их эксперимент был прекращен решением директора лаборатории. Группе не повезло. Два года спустя несколько десятков двухчастичных событий с относительной вероятностью, почти достигнутой в [35], было открыто принстонской группой [36].

- remember neutrino mass

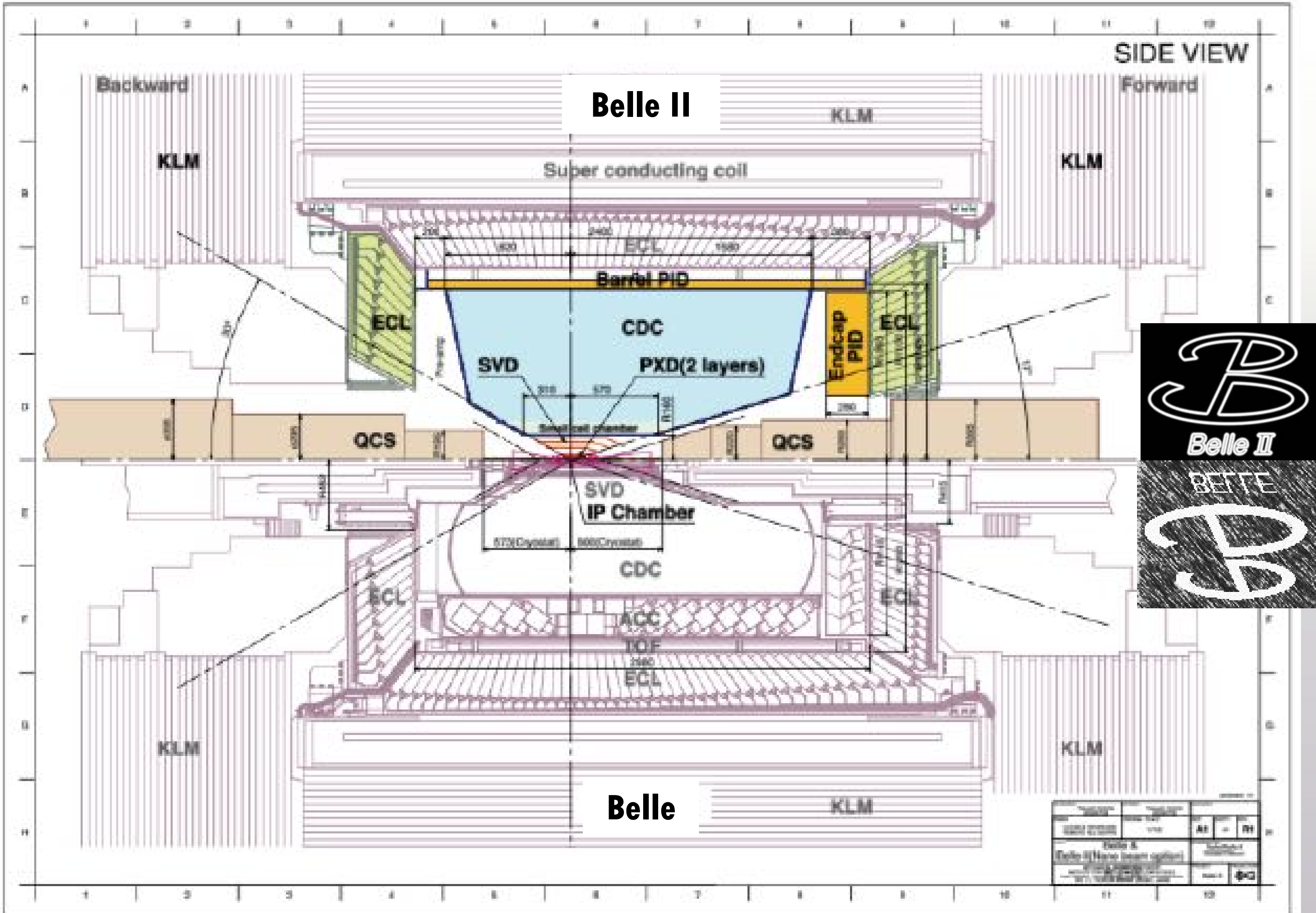
Super B-factory



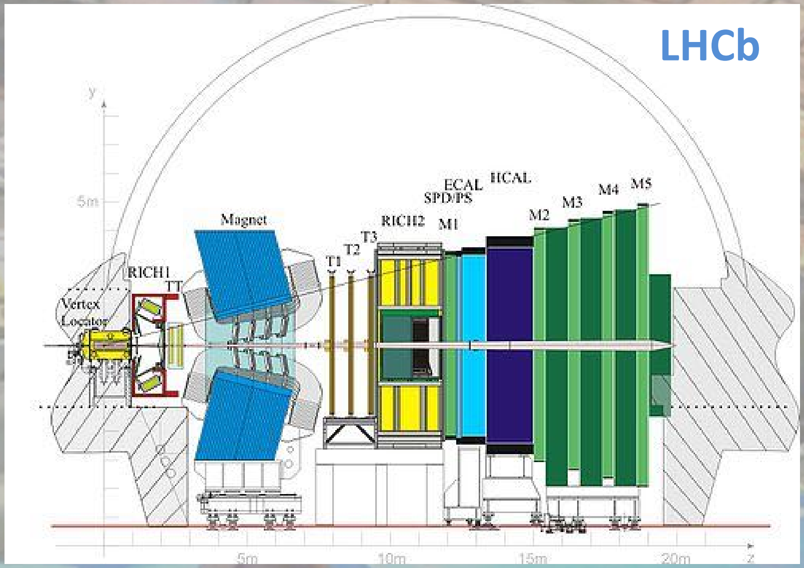
$B\text{-}\bar{B}$ $B\text{-}\bar{B}$ $B\text{-}\bar{B}$

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

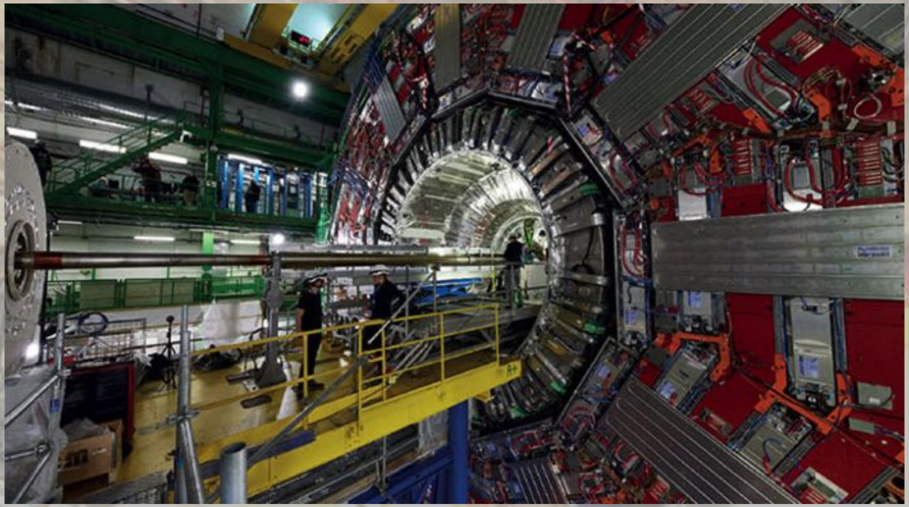
Parameter	KEKB Design	KEKB Achieved	SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	1	0.85/0.64	0.27/0.24
σ_y (μm)	1.9	0.94 → 1/20 →	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6/7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19 → x2 →	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 → x40 →	80


SIDE VIEW
Backward
Forward
Belle II
KLM
KLM
KLM
Super conducting coil
ECL
Barrel PID
CDC
ECL
ECL
Endcap PID
SVD
PXD(2 layers)
QCS
QCS
SVD
IP Chamber
CDC
ECL
ECL
ACC
TOF
ECL
KLM
KLM
Belle
KLM

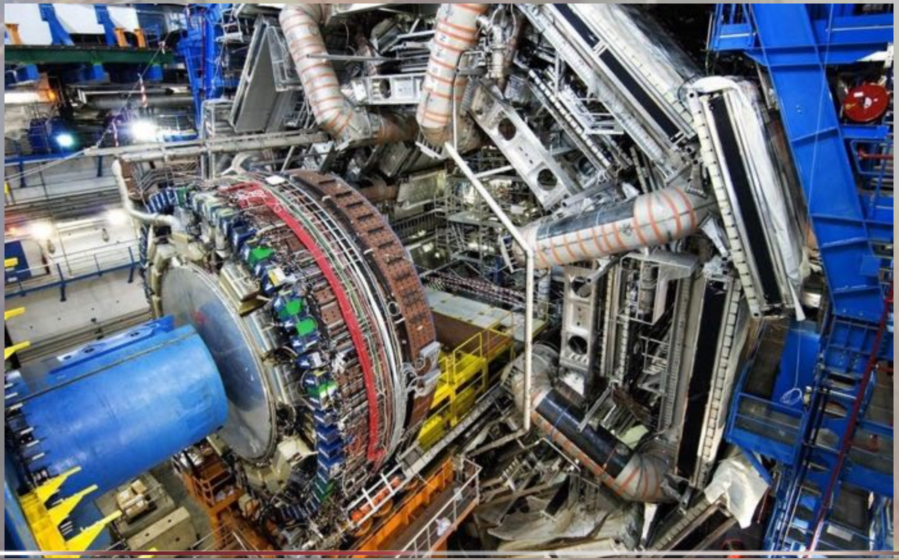
B-physics at LHC



Forward detector designed for B-physics



B-physics is important part of central detector program

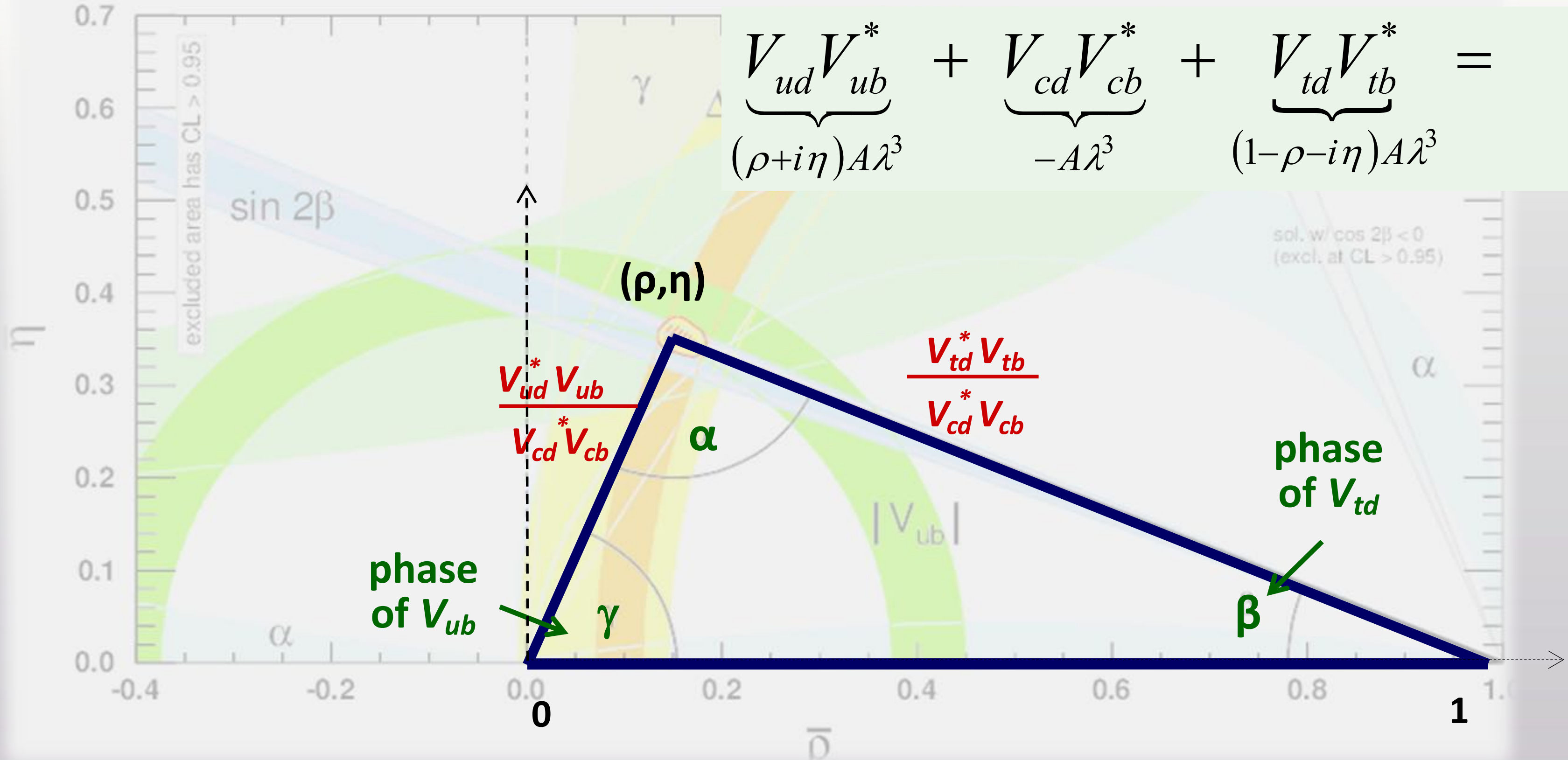


Search for New Physics in CP violation

$$V_{CKM}=\begin{pmatrix}1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta)\\ -\lambda & 1-\lambda^2/2 & A\lambda^2\\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1\end{pmatrix}+O(\lambda^4)$$

$$V^{\dagger}_{\mathrm{CKM}}\cdot V_{CKM}=V_{CKM}\cdot V^{\dagger}_{\mathrm{CKM}}=1$$

$$\underbrace{V_{ud}V^*_{ub}}_{(\rho+i\eta)A\lambda^3}+\underbrace{V_{cd}V^*_{cb}}_{-A\lambda^3}+\underbrace{V_{td}V^*_{tb}}_{(1-\rho-i\eta)A\lambda^3}=0$$

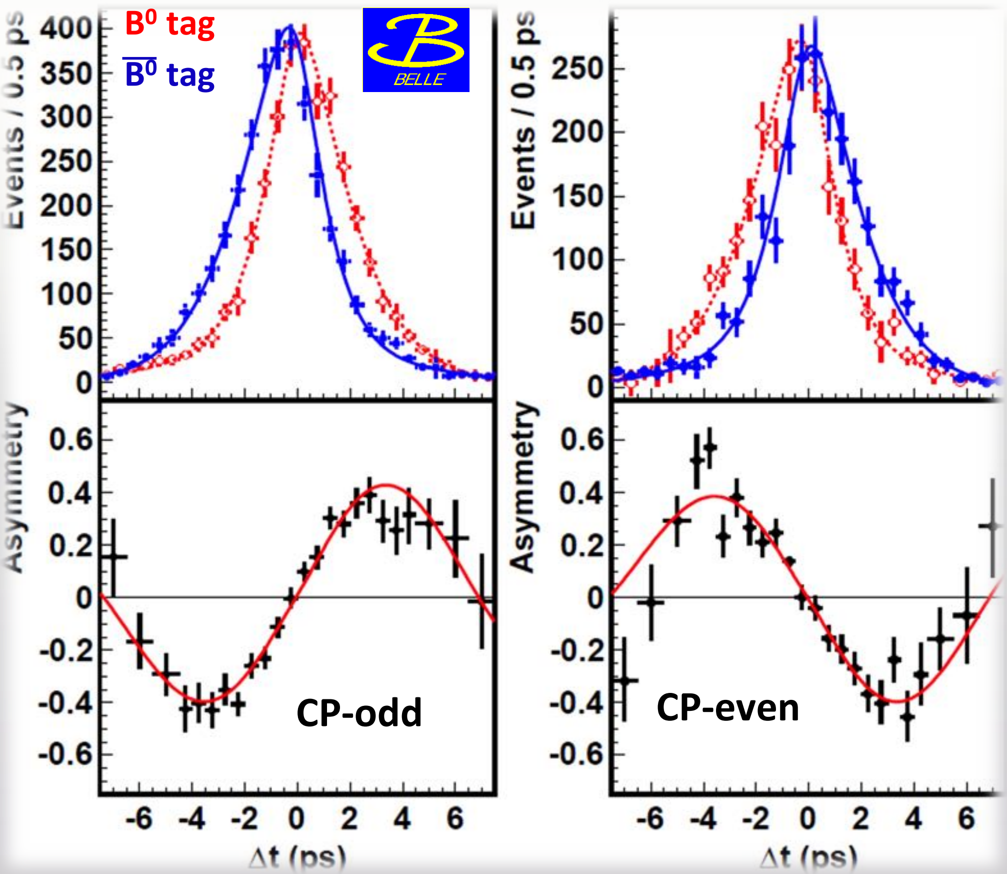


Consistency of Unitarity triangle = probe for NP at *O*(1TeV)

- UT Sides from Br's
- UT angles from CP violation

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

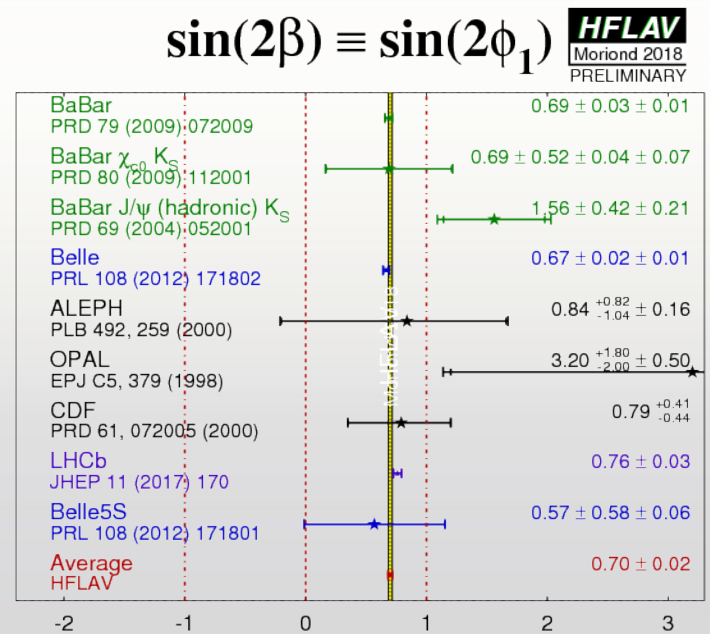
Belle 2012 (0.8 ab^{-1}): $B \to ccK^0_S$ & $B \to J/\psi K^0_L$

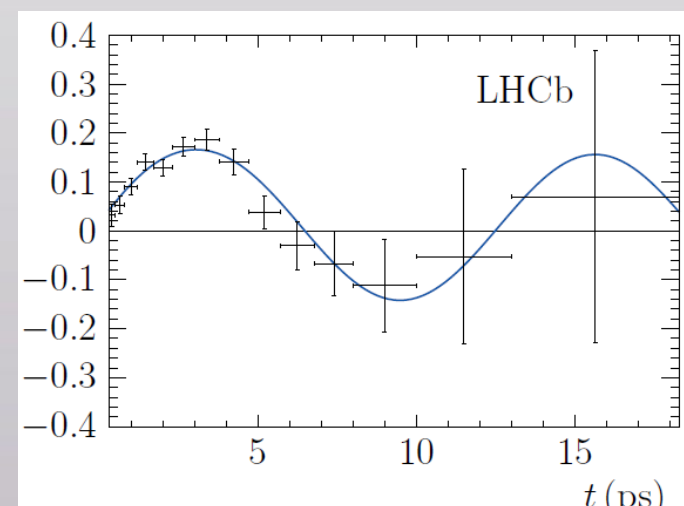


PRL 108 171208 (2012)

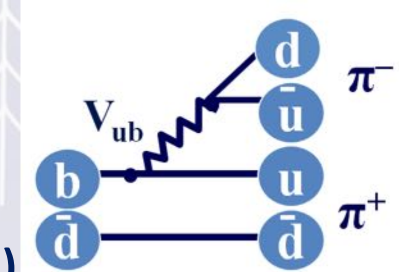
sin(2β) = 0.667 ± 0.023 ± 0.012 (0.9°)

A_f = 0.006 ± 0.016 ± 0.012

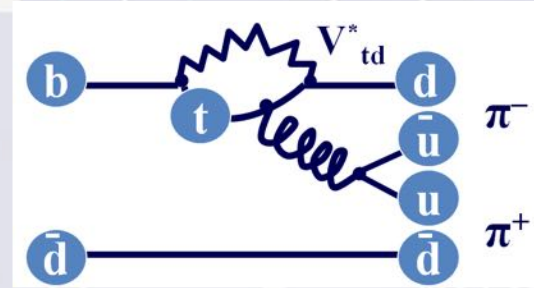




α measurements



$B^0 \to \pi\pi$
$B^0 \to \rho\rho$
$B^0 \to \rho\pi$



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

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

Parameter S of indirect CPV related to effective $\alpha(\alpha_{eff})$ shifted by extra angle

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

δ – the relative strong phase between T and P amplitudes

$r < 1$ – ratio of P to T amplitude

To extract α additional inputs required

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

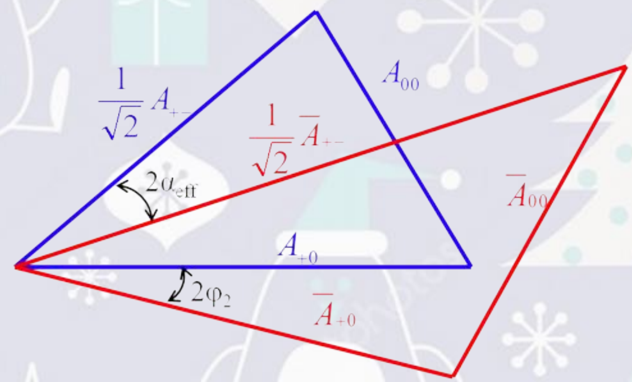
The cleanest method is isospin analysis (Gronau and London)

We need to measure all 6 BR's of B^0 and B^+ to $\pi\pi$ decays: $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^+\pi^0$

Need neutral modes!

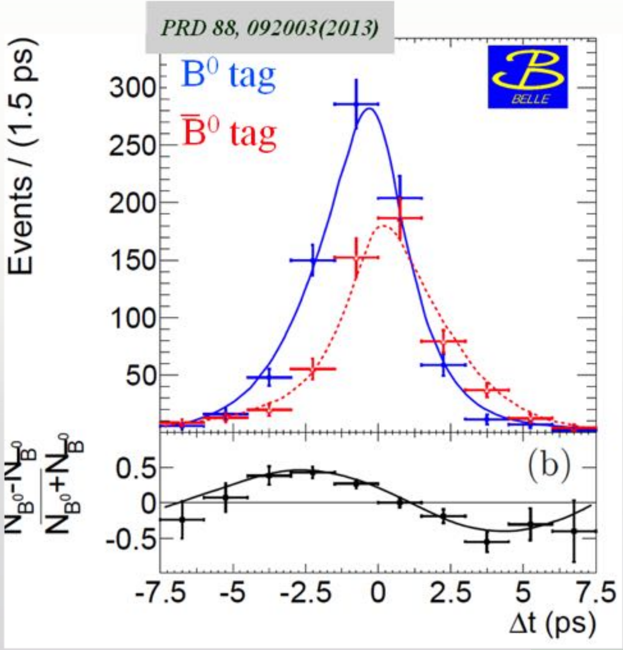
$$A_{+-} + \sqrt{2}\,A_{00} = \sqrt{2}\,A_{+0}$$
$$\overline{A}_{+-} + \sqrt{2}\,\overline{A}_{00} = \sqrt{2}\,\overline{A}_{+0}$$

$$A_{+-} = A(B^0 \to \pi^+\pi^-) = e^{-i\alpha}\,T^{+-} + P$$
$$\sqrt{2}\,A_{00} = \sqrt{2}\,A(B^0 \to \pi^0\pi^0) = e^{-i\alpha}\,T^{00} + P$$
$$\sqrt{2}\,A_{+0} = \sqrt{2}\,A(B^+ \to \pi^+\pi^0) = e^{-i\alpha}\,(T^{00} + T^{+-})$$



Isospin triangles

α: experimental results

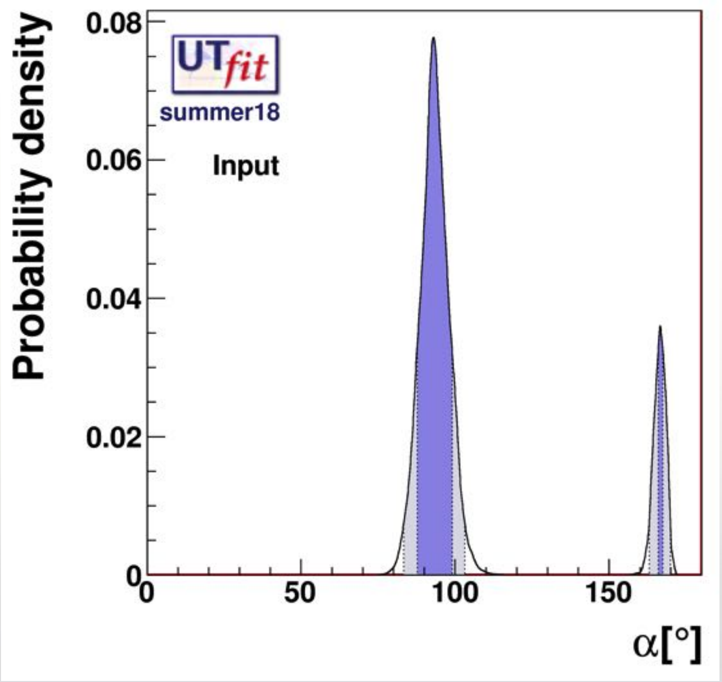


$B^0 \to \rho^0\rho^0$

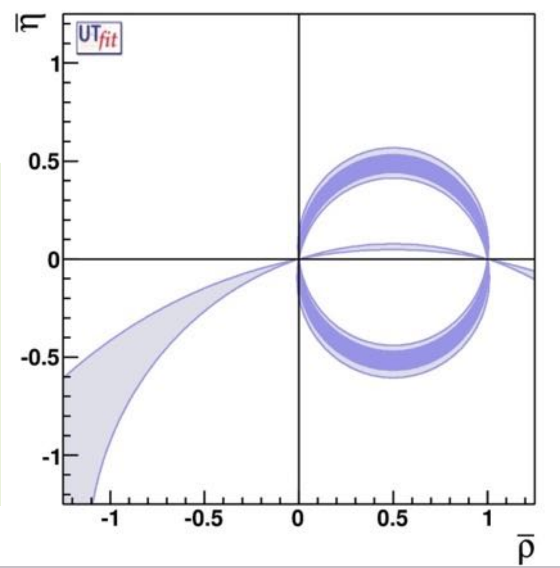
- angular analysis
- purely CP=+1 final state
- small Br, small penguin contribution

$B^0 \to \rho^\pm\pi^\pm$

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



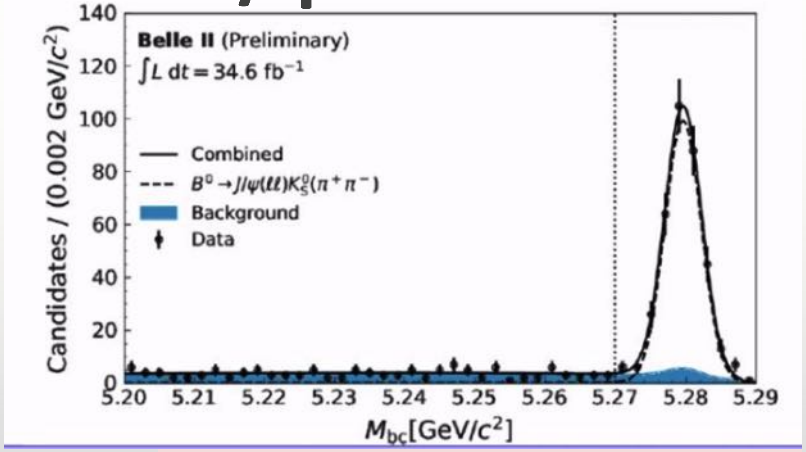
$$\alpha_{WA} = (88.8^{+2.3}_{-2.3})^\circ \bigcup (177.8^{+3.7}_{-4.9})^\circ$$



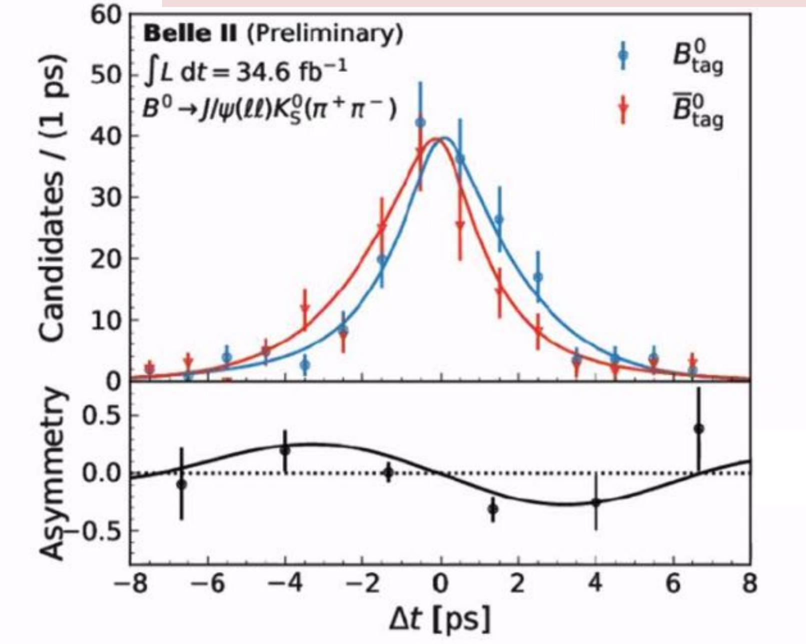
- Complicated analysis (especially for $\rho^0\rho^0$)
  - method was checked many times by Belle & BaBar
  - Belle & BaBar consistent results
- Statistics limited (not systematic)
- B factories only (a lot of neutrals in the final states)

Belle-II started to produce first physics results

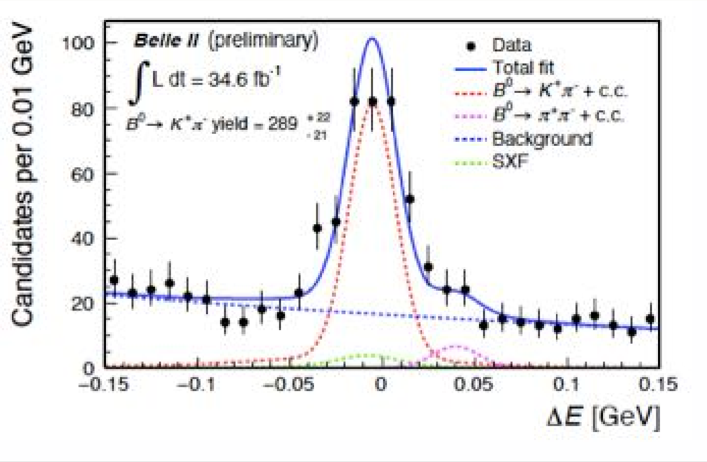
$B^0 \to J/\psi$ K0

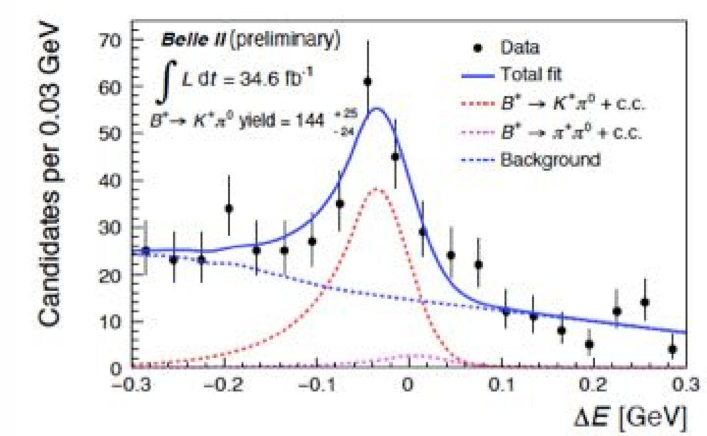


$\sin(2\beta) = 0.55 \pm 0.21 \pm 0.04$

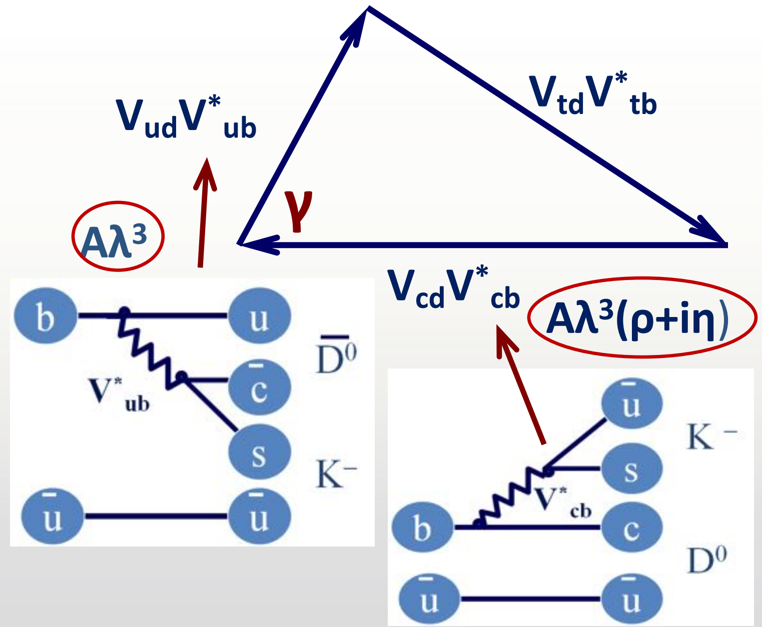


$B \to \pi\pi$





Direct CPV and angle γ

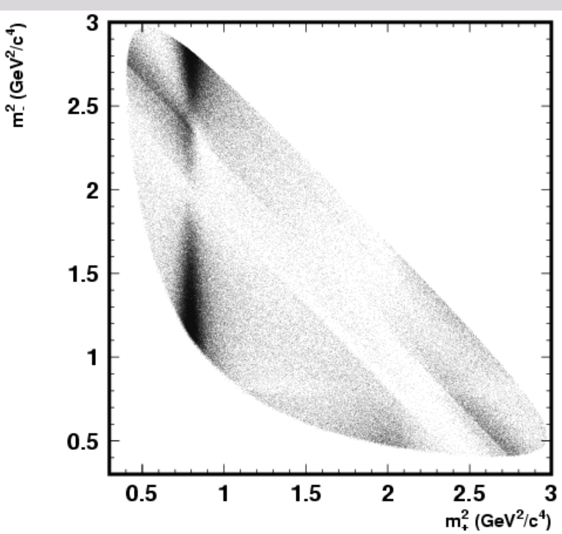


B→DK: the angle between two amplitudes is really γ, but the final states are different $D^0 \neq \overline{D^0}$

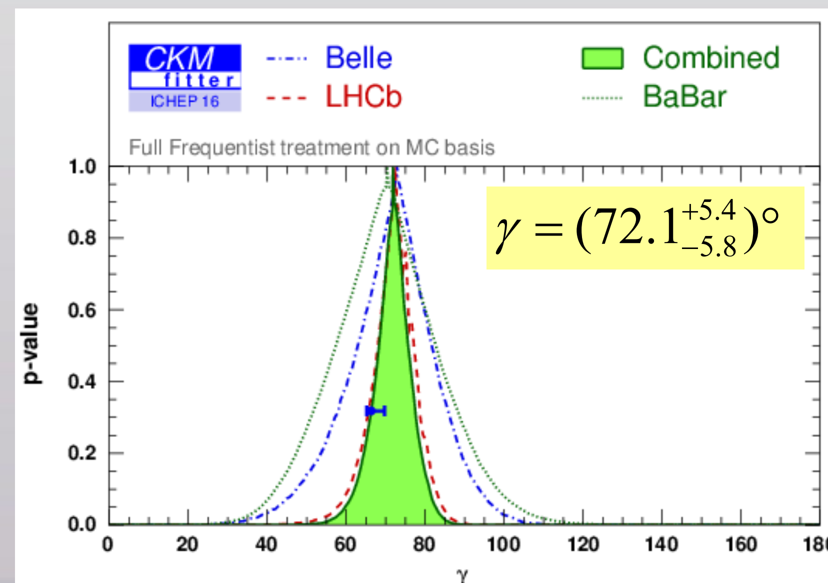
- **GLW method: use D^0 decays into two-body CP eigenstates, *e.g.* $D^0 \to K^+ K^-$**
- **GGSZ/Belle method: Dalitz analysis of 3-body final state, *e.g.* $D^0 \to K_S^0 \pi^+ \pi^-$**

Measure B^+/B^- asymmetry across Dalitz plot

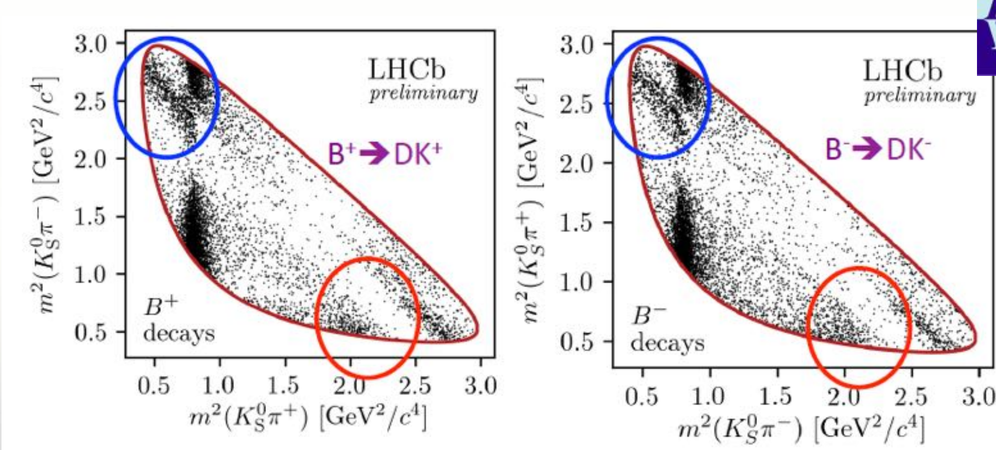
$$A_\pm = f\left(m_+^2, m_-^2\right) + r_B e^{\pm i\gamma} e^{i\delta} f\left(m_-^2, m_+^2\right)$$

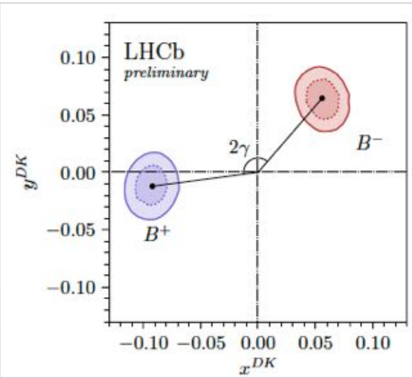


The accuracy of present measurements is limited by statistics. The systematic and model uncertainties are much smaller.



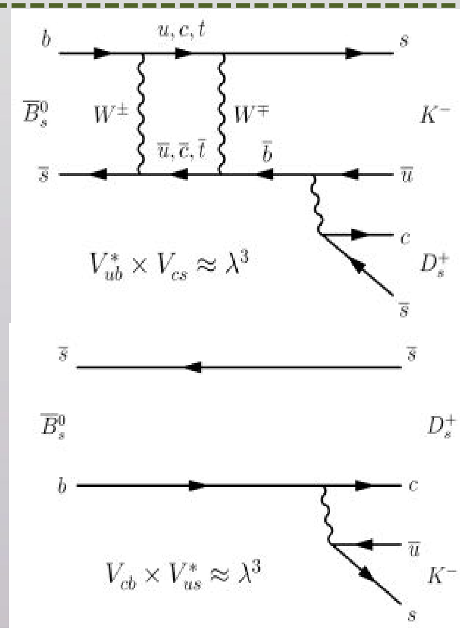
Recent LHCb results on γ



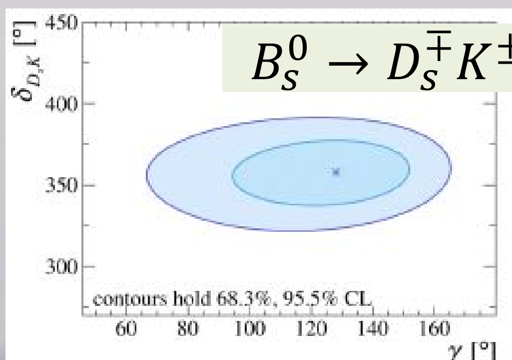


$B^\pm \to D^0 K^\pm$

$\gamma = (69 \pm 5)^\circ$

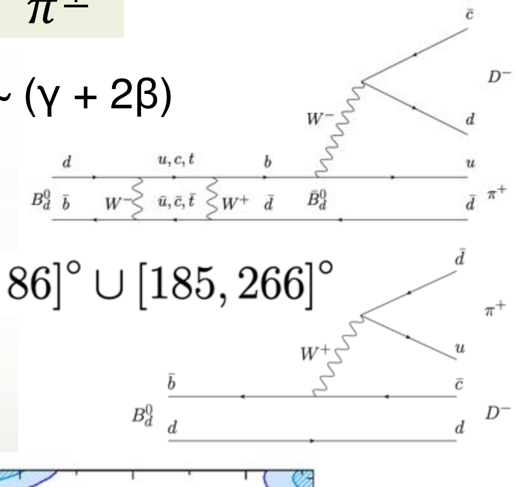


$B_s^0 \to D_s^\mp K^\pm$

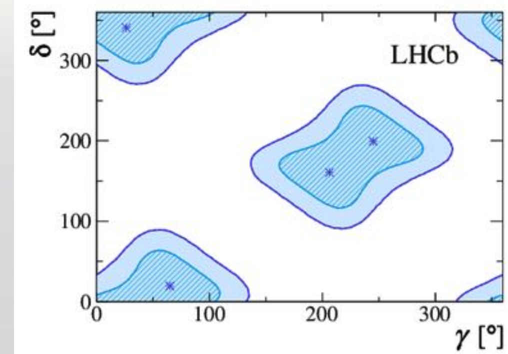


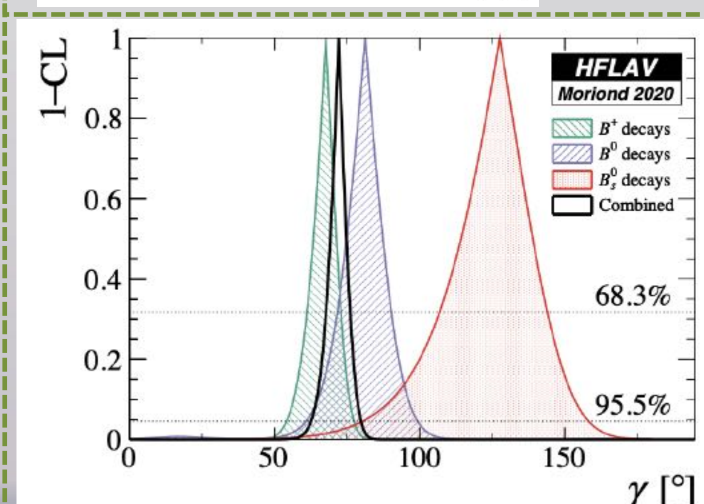
$B_d^0 \to D^\mp \pi^\pm$

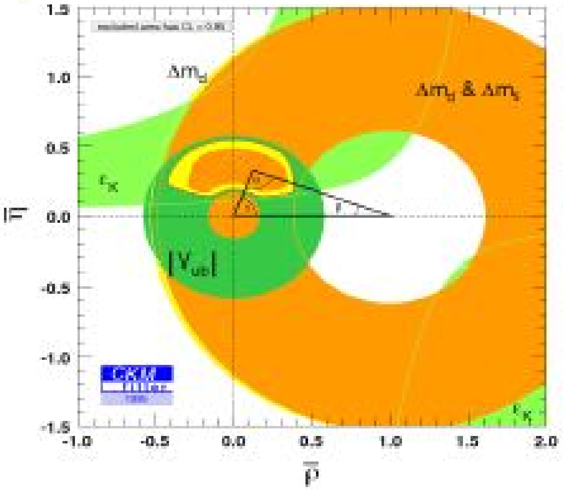
CP~ (γ + 2β)



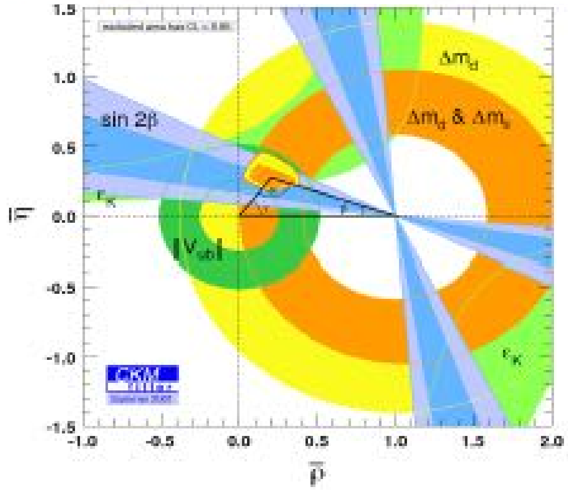
$\gamma \in [5, 86]^\circ \cup [185, 266]^\circ$



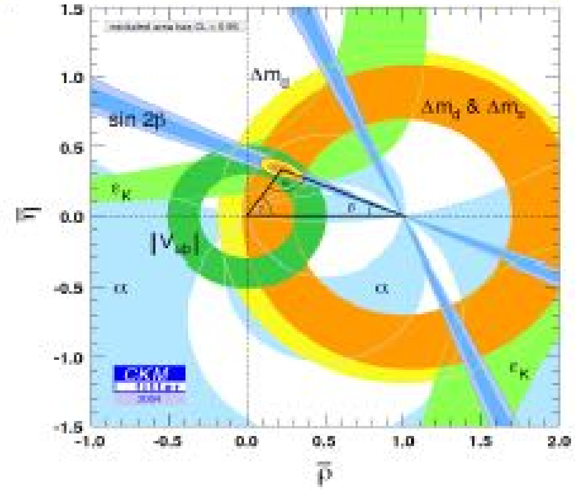




1995

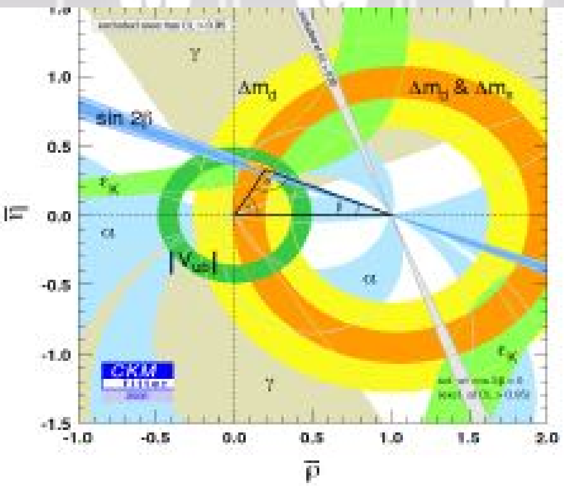


2001

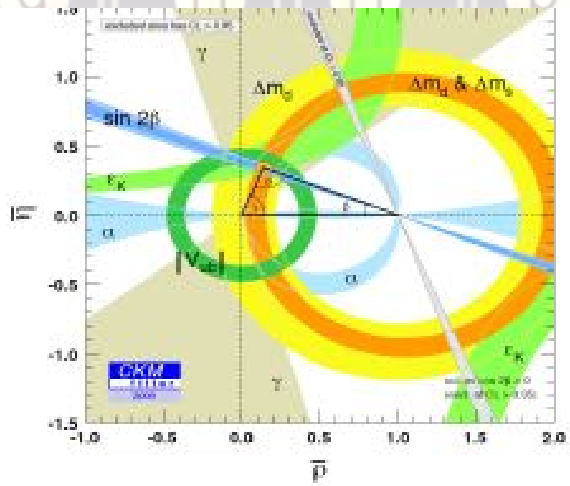


2004

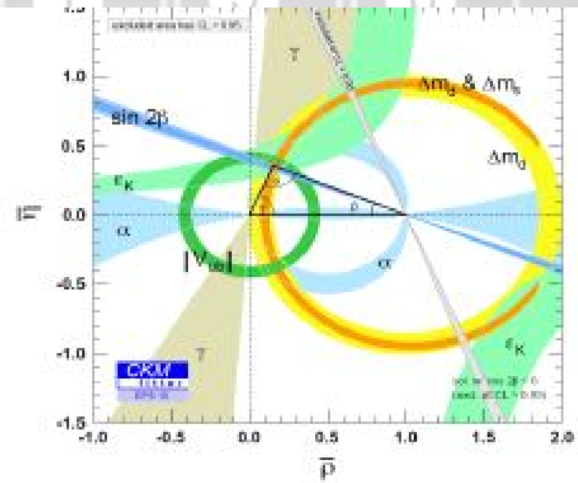
Unitarity triangle: two decades history



2006



2009

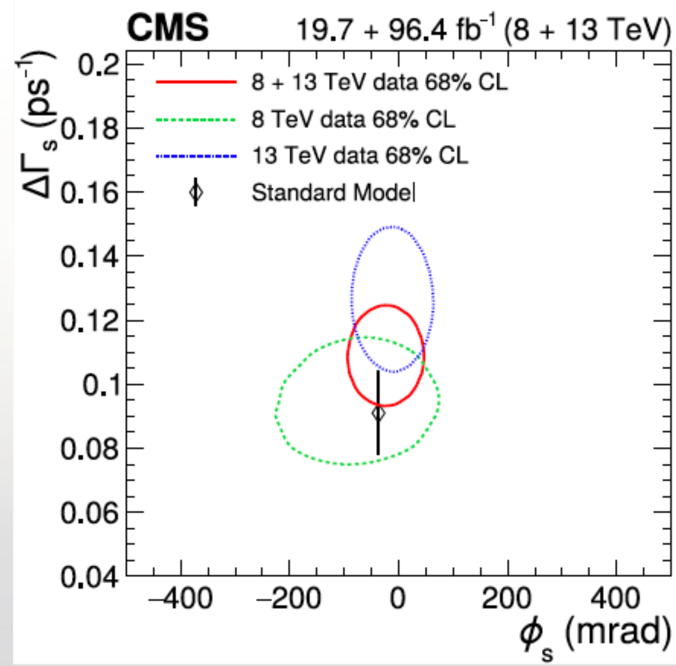


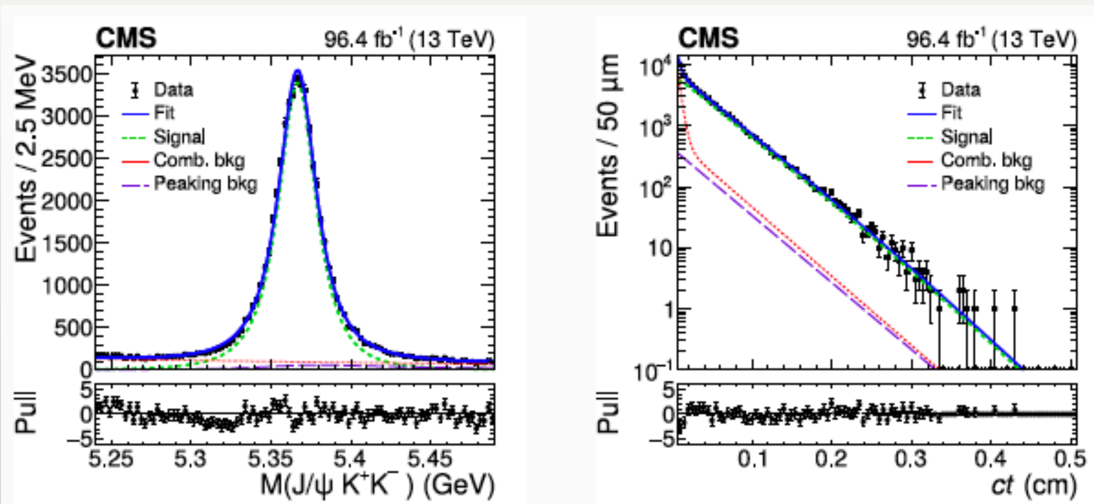
2015

CP violation in B_s

Search for indirect CPV in $B_s^0 \to J/\psi\phi(1020)$

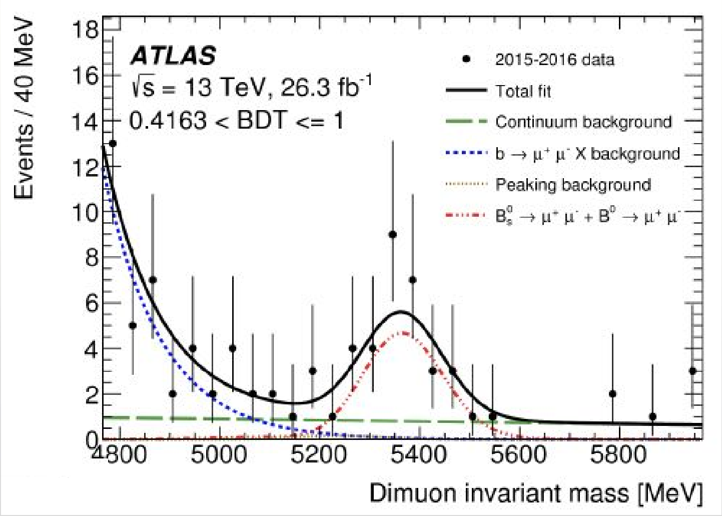
SM prediction: $\phi_s = -2\beta_s = -36.96^{+0.72}_{-0.84}$

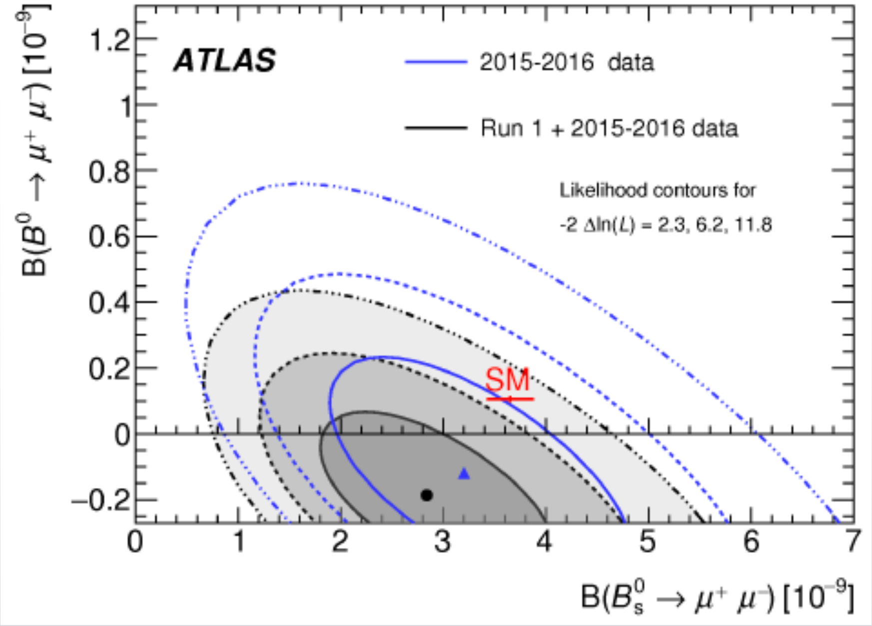




	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Reference
CMS	−21 ± 45	0.1073 ± 0.0097	CMS-BPH-20-001
ATLAS	−87 ± 41	0.0641 ± 0.0049	CERN-EP-2019-218
LHCb	−81 ± 32	0.0777 ± 0.0062	EUR.PHYS.J.C79(2019)706
SM	$-36.96^{+0.72}_{-0.84}$	0.091 ± 0.013	CKMfitter, arXiv:1912.07621

$B_s^0 \to \mu^-\mu^+$

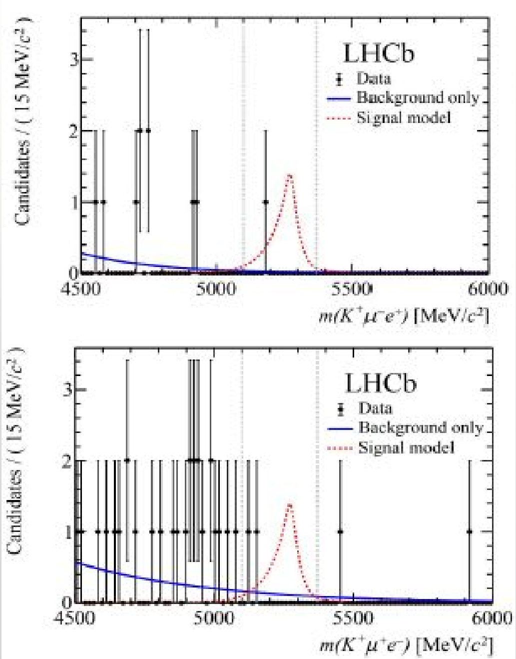


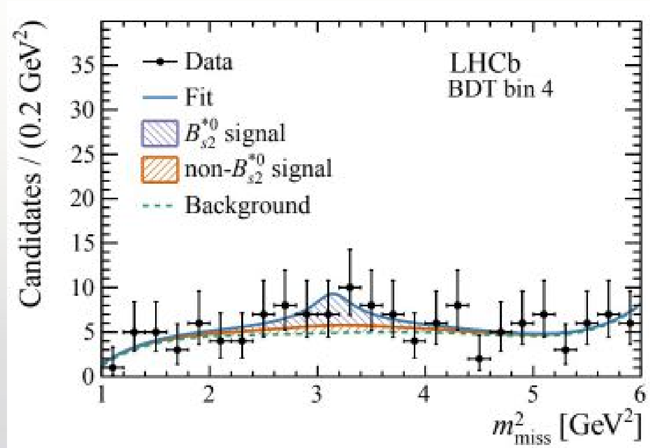


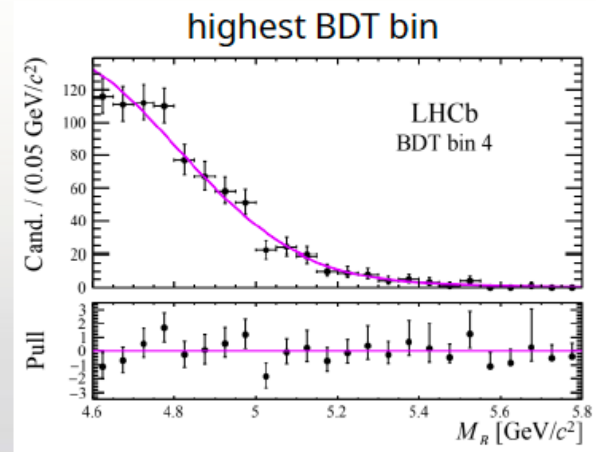
	SM	LHCb	CMS	Atlas
$B(B_s^0 \to \mu^+\mu^-)\times 10^{-9}$	3.6 ± 0.14	$3.0 \pm 0.6^{+0.3}_{-0.2}$	$3.0^{+1.0}_{-0.9}$	$2.8^{+0.8}_{-0.7}$
$B(B_d^0 \to \mu^+\mu^-)\times 10^{-9}$	0.10 ± 0.01	$0.15^{+0.12}_{-0.10}$	$0.35^{+0.21}_{-0.18}$	< 0.21

Search for lepton flavor violation in B-decays

$B^+ \to K^+\mu^\pm e^\mp$ | $B^+ \to K^+\mu^\pm\tau^\mp$ | $B^+_{(s)} \to \mu^\pm\tau^\mp$



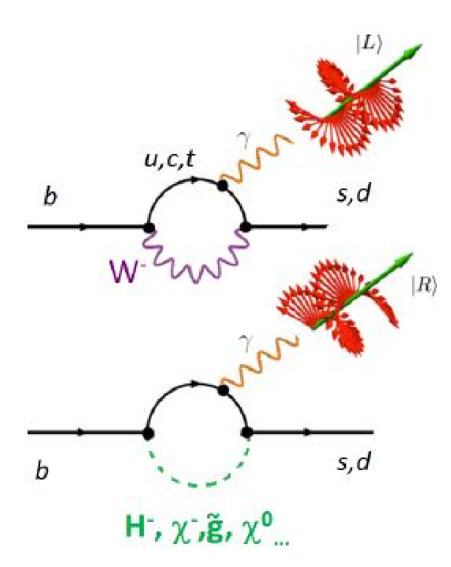


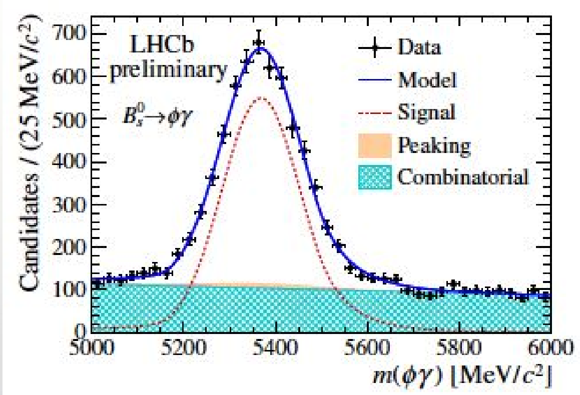


	$B^+ \to K^+\mu^\pm e^\mp$	$B^+ \to K^+\mu^\pm\tau^\mp$	$B^0_{(s)} \to \mu^\pm\tau^\mp$
Model expectation		$O(10^{-5}) - O(10^{-9})$	$O(10^{-5}) - O(10^{-9})$
LHCb UL 90%CL	$6.4(7.0)\times10^{-9}$	3.9×10^{-5}	$1.4(4.2)\times10^{-5}$
Previous UL (BaBar)	9.1×10^{-8}	4.5×10^{-5}	$2.2(-)\times10^{-5}$

With sensitivity reached one can already critically test beyond SM

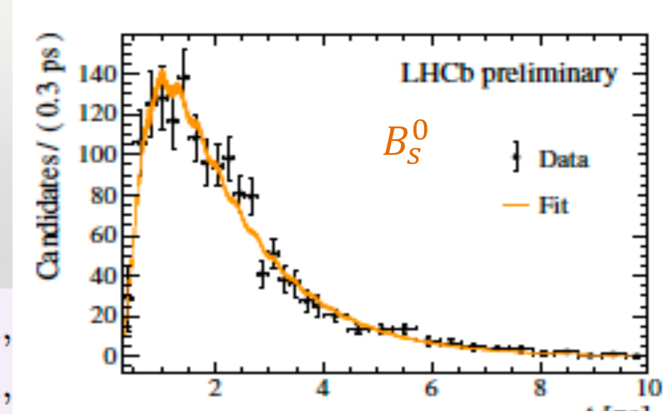
Search for wrong photon polarization in penguin decays

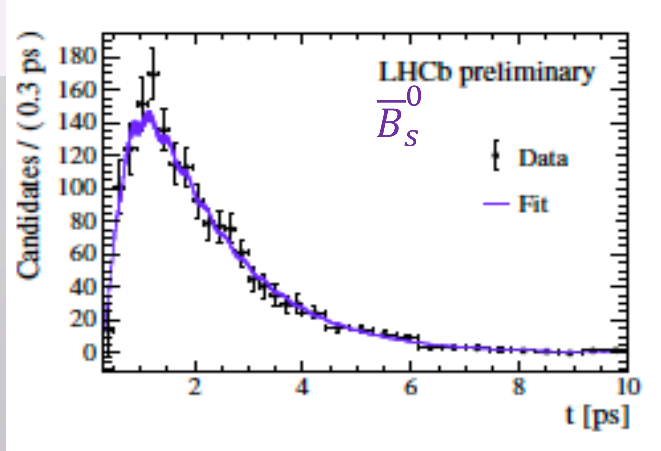




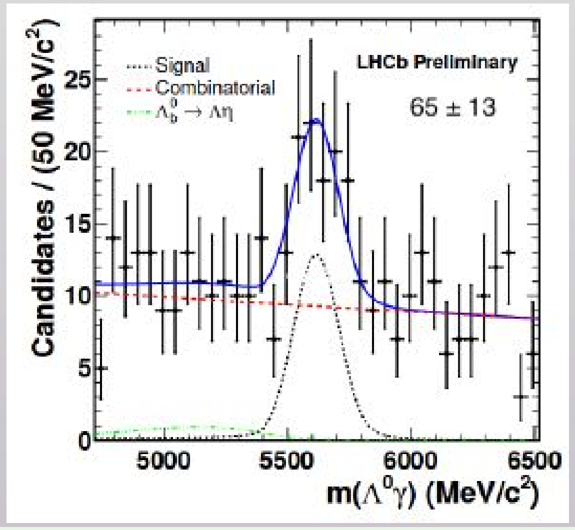
$$\Gamma(t) \propto e^{-\Gamma t}\left[ch\left(\frac{\Delta\Gamma t}{2}\right) - A^{\Delta} sh\left(\frac{\Delta\Gamma t}{2}\right) \pm C cos(\Delta m_s t) \mp S sin\,(\Delta m_s t)\right]$$

$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$





First observation of $\Lambda_b \to \Lambda\gamma$



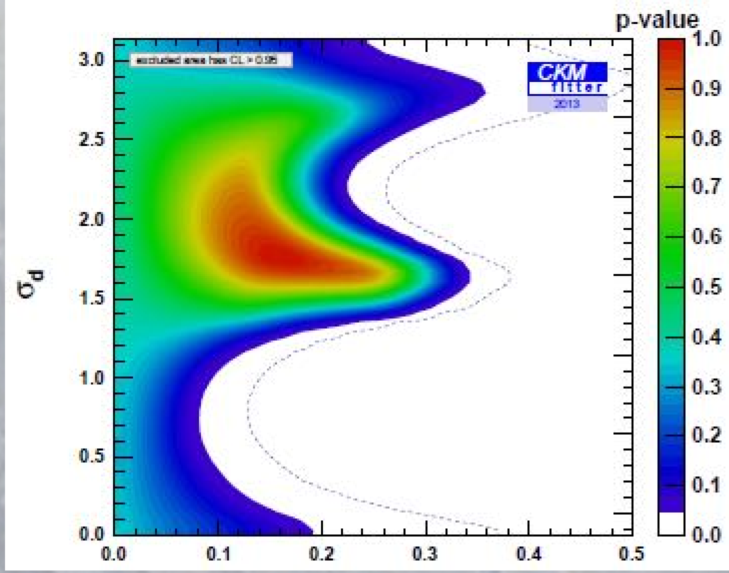
$$B(\Lambda_b \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.7 \pm 0.6)\times 10^{-6}$$

Summary I

$$\Delta m_d = \Delta m_d^{SM} \times (1 + h_d e^{2i\sigma})$$

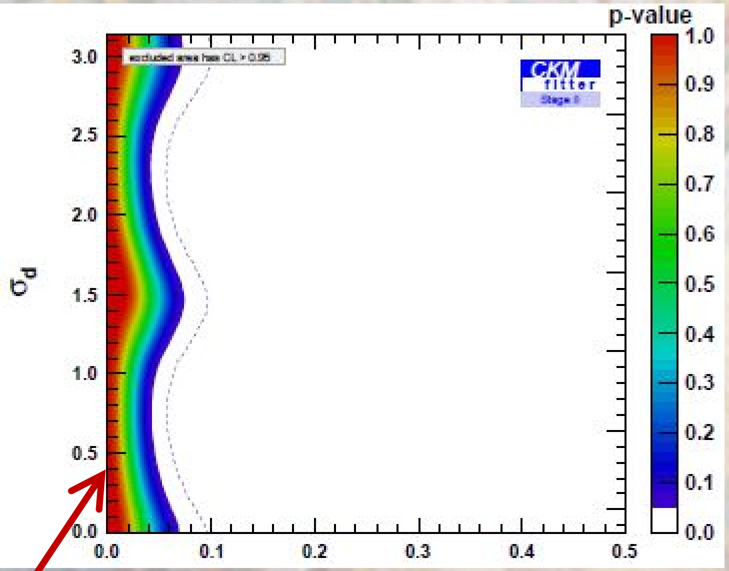
NP

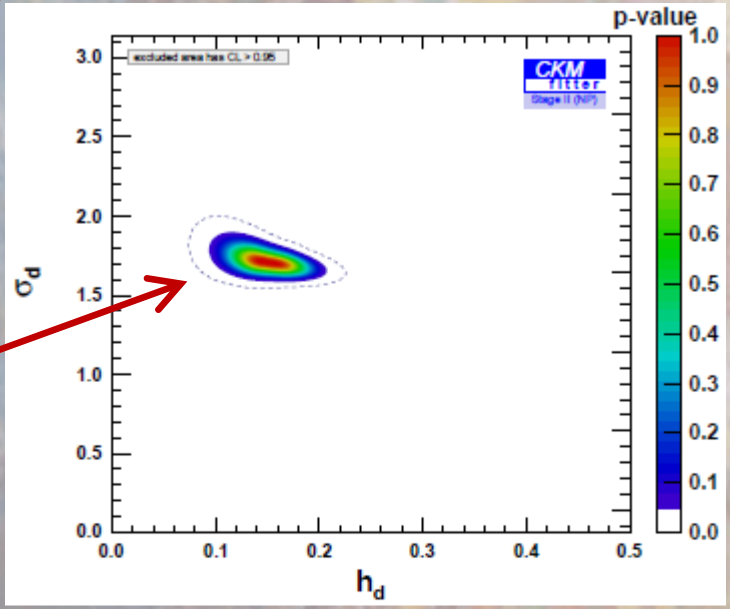
Now we are here:



In 5-10 years two scenarios:

- Improve UL by a factor of 5-10
- or observe something new!



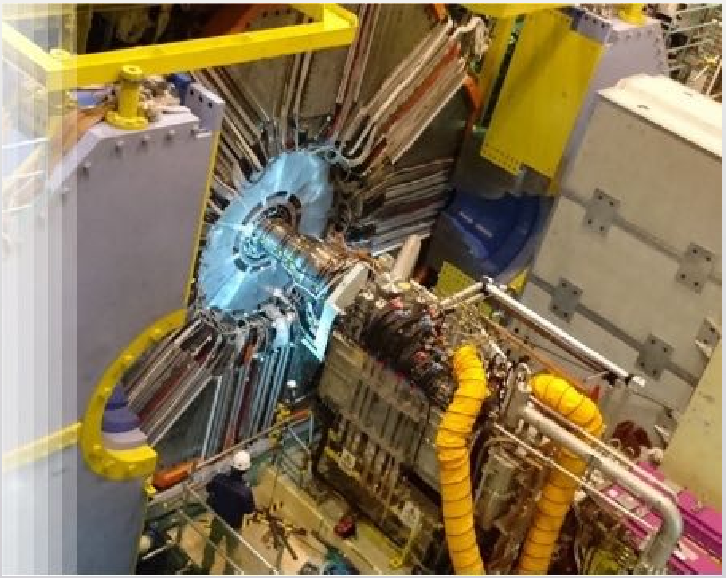


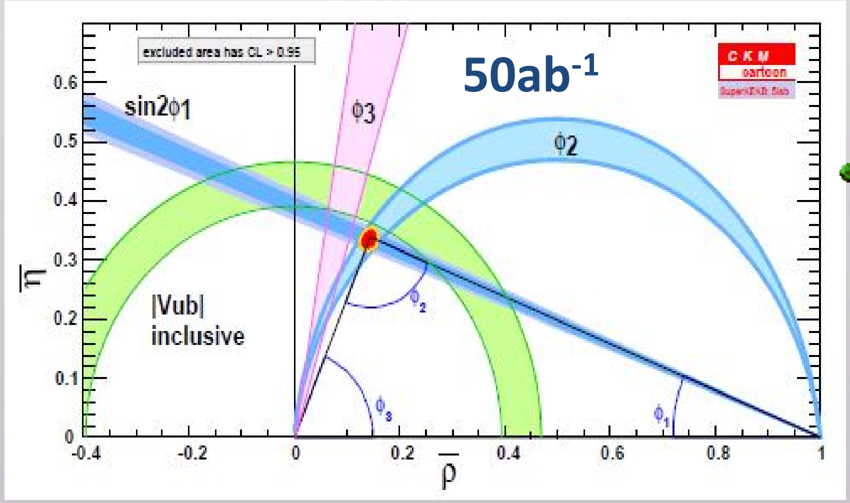
Summary II

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

Up to now the sensitivity of Flavor experiments to New Physics amplitude was ~10% of those from the SM; in 5-10 years it will be improved by an order of magnitude.

- **Rich physics program for Belle II**
- **Belle II is healthy and started data taking in 2018**
- **Belle II goal of 50/ab will provide great sensitivity and complimentarity to LHCb information in many areas of flavor, CPV and related fields**

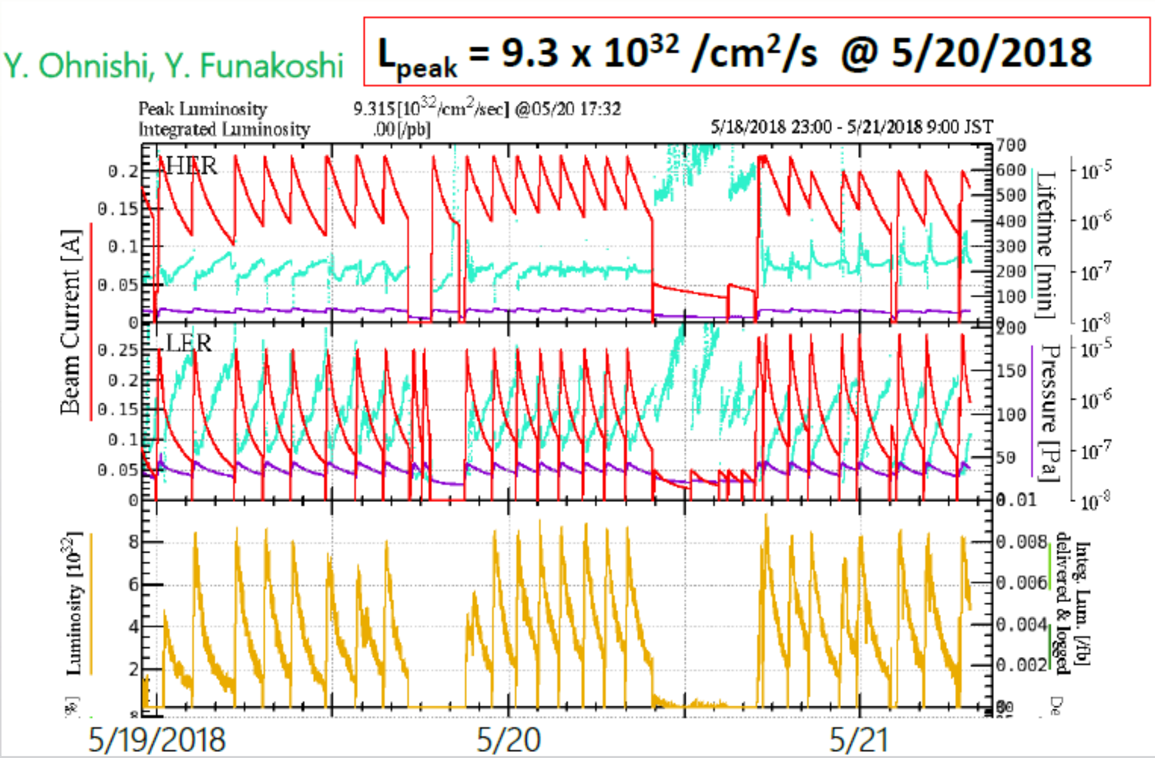




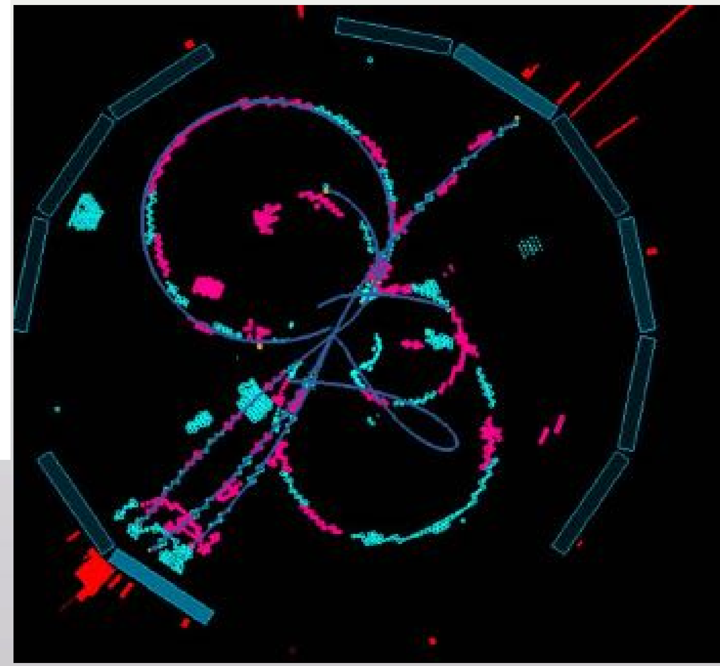
- **We hope to observe something like THIS in 5-7 years**

UT 2014		Belle II
α	4° (WA)	1°
β	0.8° (WA)	0.2°
γ	8.5° (WA) 14°(Belle)	1-1.5°

Summary III



Belle II + SuperKEKB have successfully started operation



... the first hadronic event recorded at Belle II!

From January 2019 -- phase III:
add vertex detector (Belle II full set) and perform long run for CP violation studies

T H A N K   Y O U !