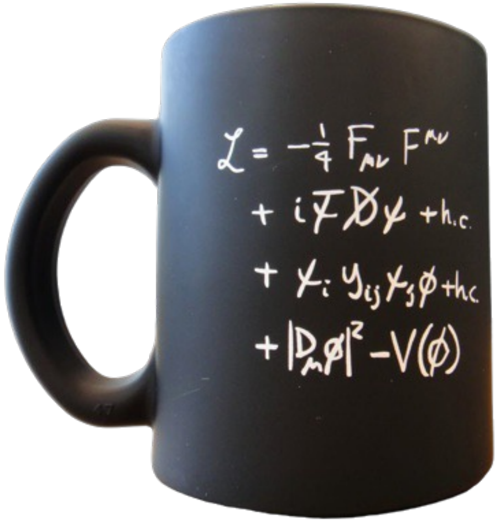
Recent Belle II results

P. Pakhlov,

HSE & LPI

SM: successes and failures



The SM successes:

- All particles have been observed
- All parameters have been measured
- All symmetries have been confirmed
  and the mechanism of symmetry breaking is established
- **All experimental measurements are essentially 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)
- More ingredients required from astrophysics and cosmology
- Still no unification of strong and electroweak interactions
- A 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 the open questions are addressed to the flavor sector

Flavor physics in the SM…

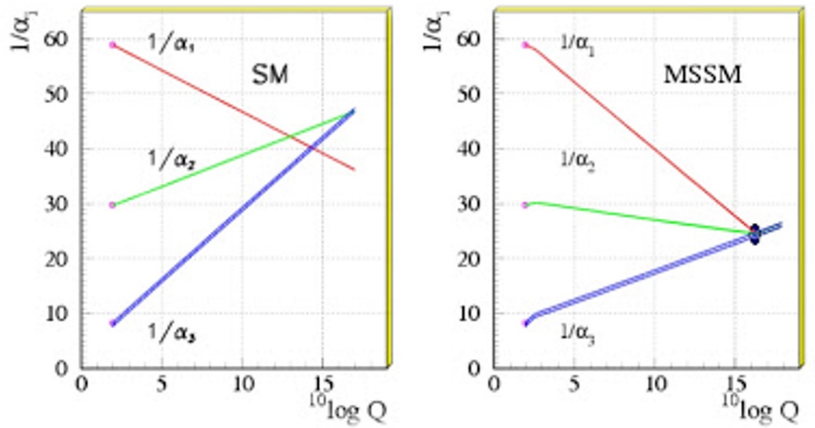
bosonic sector of the SM:

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...

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



fermionic (flavor) sector (without neutrino):

3 Yukawa constants for charged leptons:

6 Yukawa constants for quarks

4 quark-mixing parameters

There is no idea

- why we have many (exactly three) 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?

$$Y_t \sim 10^0, \quad Y_b \sim 10^{-2}, Y_c \sim 10^{-2},$$
$$Y_s \sim 10^{-3}, Y_u \sim 10^{-5}, Y_d \sim 10^{-5},$$
$$Y_\tau \sim 10^{-2}, Y_\mu \sim 10^{-3}, Y_e \sim 10^{-6},$$
$$|V_{ud}| \sim 1, |V_{us}| \sim 0.2, |V_{cb}| \sim 0.04,$$
$$|V_{ub}| \sim 0.004, \delta_{KM} \sim 1$$

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

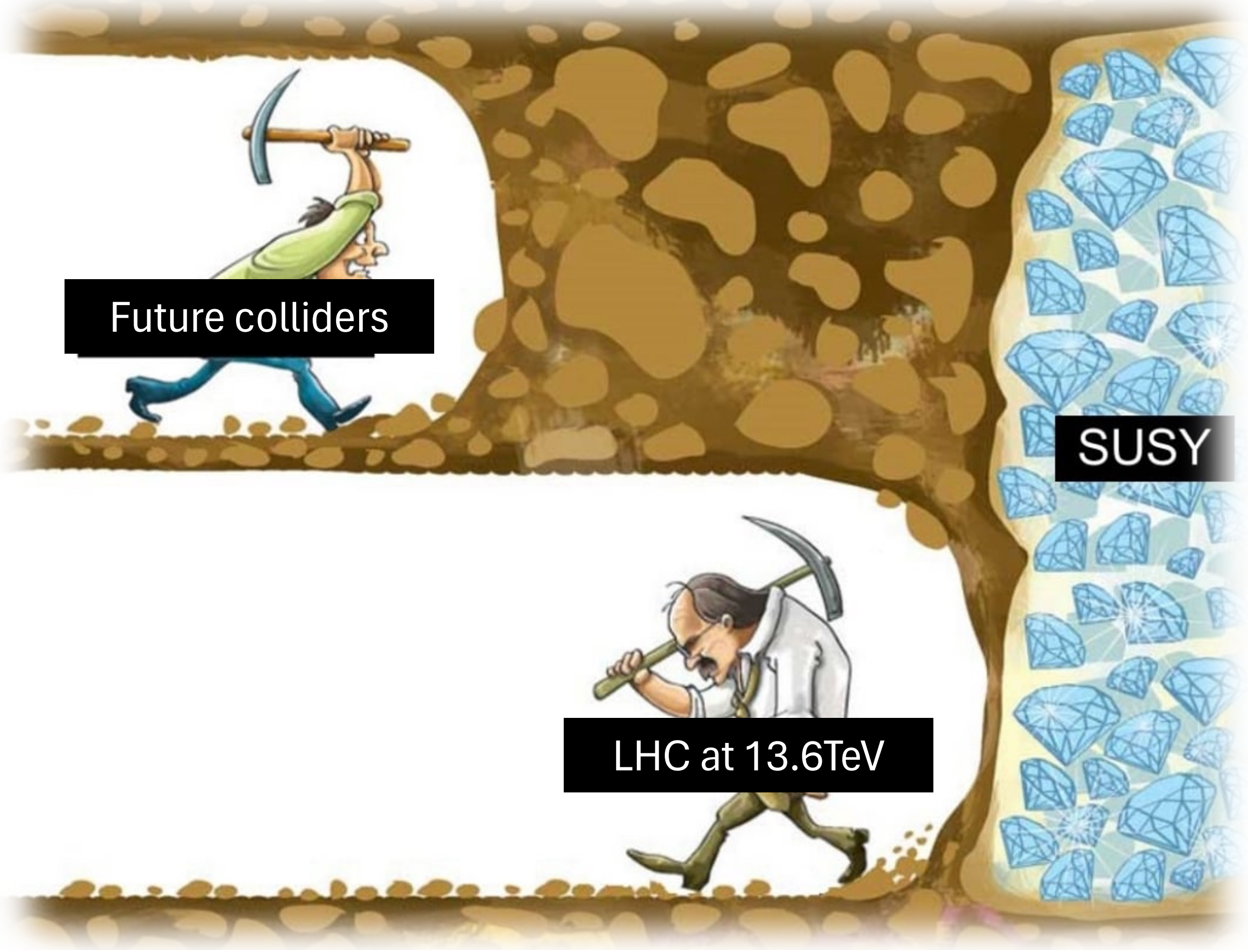
Beyond SM: successes and failures

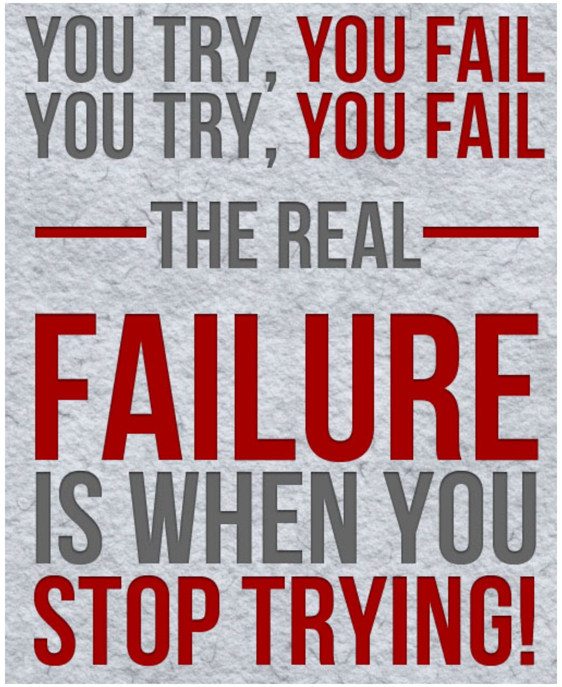
Beyond SM's success: we are sure that New Physics exists; moreover, we believe, it should reveal itself below the Plank scale

The ultimate aim of the LHC is to allow physicists to test the predictions of different theories of particle physics, including measuring the properties of the Higgs boson and searching for the large family of new particles predicted by supersymmetric theories, as well as other unsolved questions of physics

Beyond SM's failure: New Physics still not revealed after so many efforts

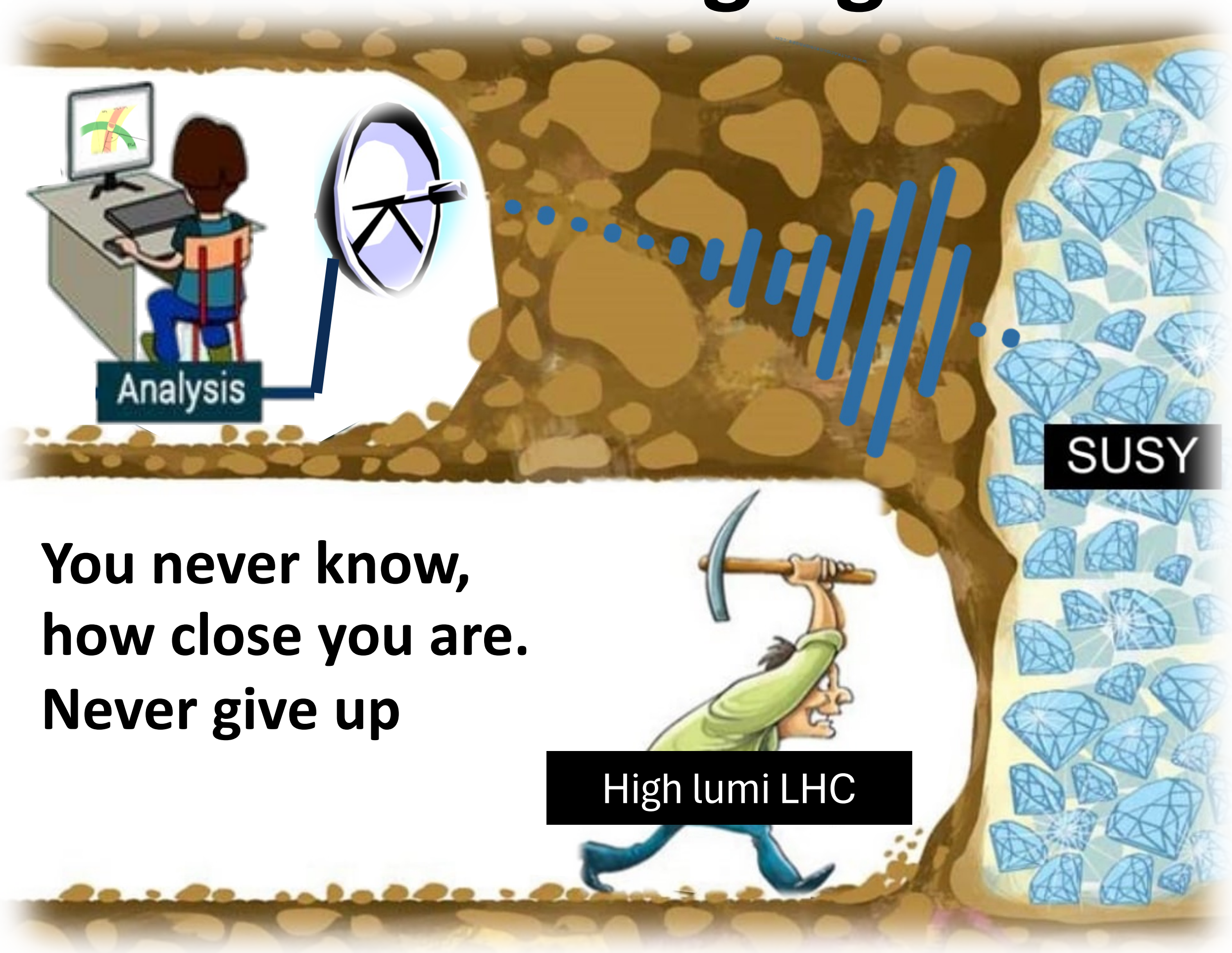
A pessimistic slide





Future colliders are too long-term projects, which are only at the discussion stage today.
They are expensive and do not guarantee success…

A more encouraging slide



You never know,
how close you are.
Never give up

Another opportunity is a remote sensing = sensitivity frontier experiment at medium/low energies

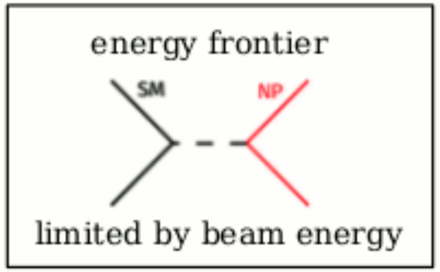
Flavor physics:

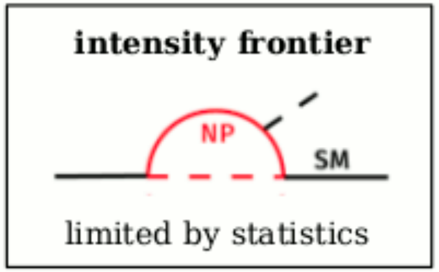
SM: the flavor puzzle(s)

Beyond SM: measurements are sensitive to NP

Cosmology: related to CP asymmetry

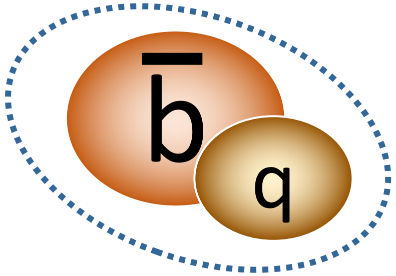
Produce NP directly: they are either seen in the detector or seen as missing energy



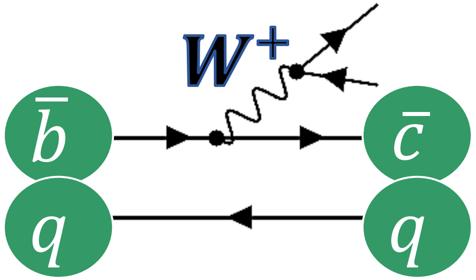


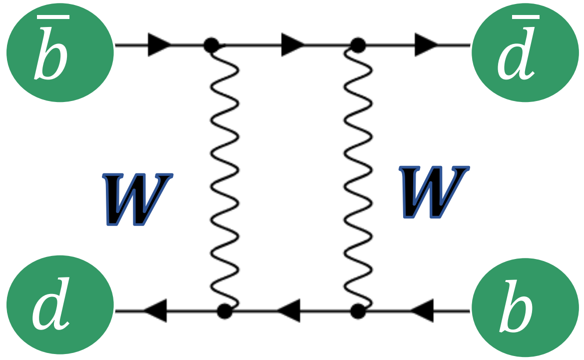
Produce NP in loop: SM particle are seen in the detector with kinematics biased wrt SM expectations

B-mesons

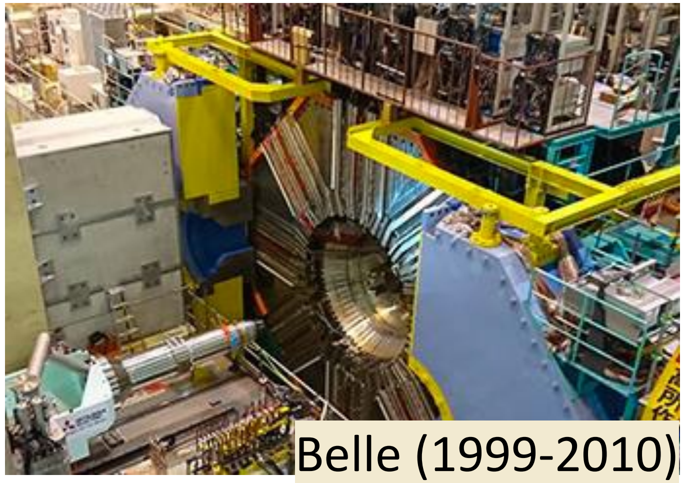


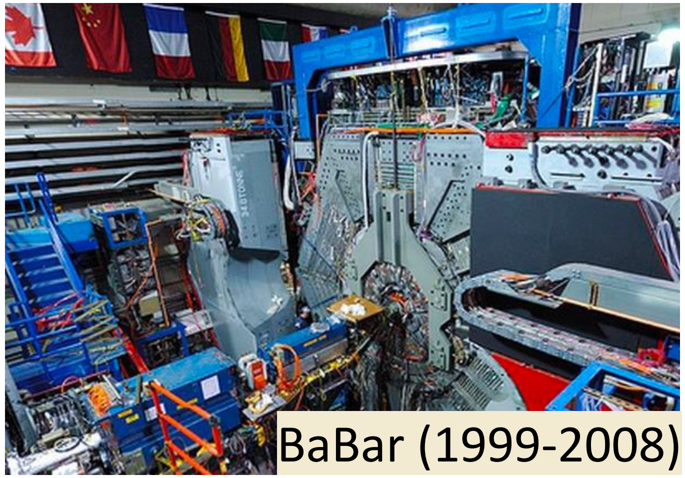
- The heaviest mesons decaying weakly; moreover, weak decays are CKM suppressed, thus even small NP amplitude can compete with the SM ones;
- Box/loop diagrams are big;
- All three quark generations are involved in B-decay diagrams: large CP violation





name	quarks	charge	Mass(GeV)	Lifetime (ps)
B_d^0	$\bar{b}d$	0	5.2796	1.519
B_u^+	$\bar{b}u$	+1	5.2793	1.641
B_s^0	$\bar{b}s$	0	5.3668	1.463
B_c^+	$\bar{b}c$	+1	6.277	0.45

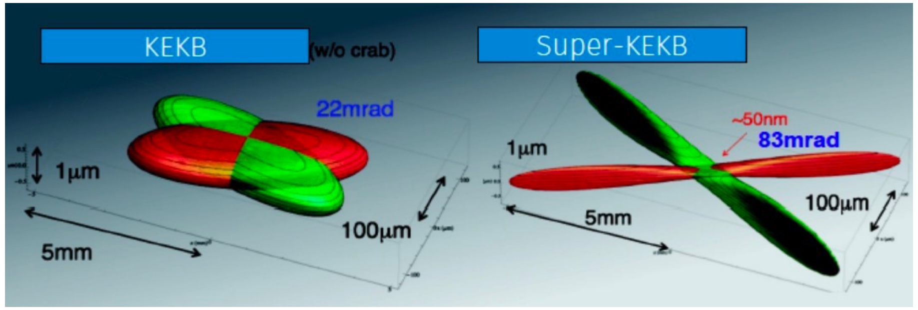




KEKB upgrade → SuperKEKB(nano-beam)

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

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



SuperKEKB is built in the tunnel of KEKB but is almost entirely new machine with all accelerator optics replaced with new ones.

× 20 smaller beam focus at interaction region; twice higher beam current

First beam in 2016 → first collision in April 2018

Run I: from March 2019 to June 2022; $L_{int} = 362/fb$

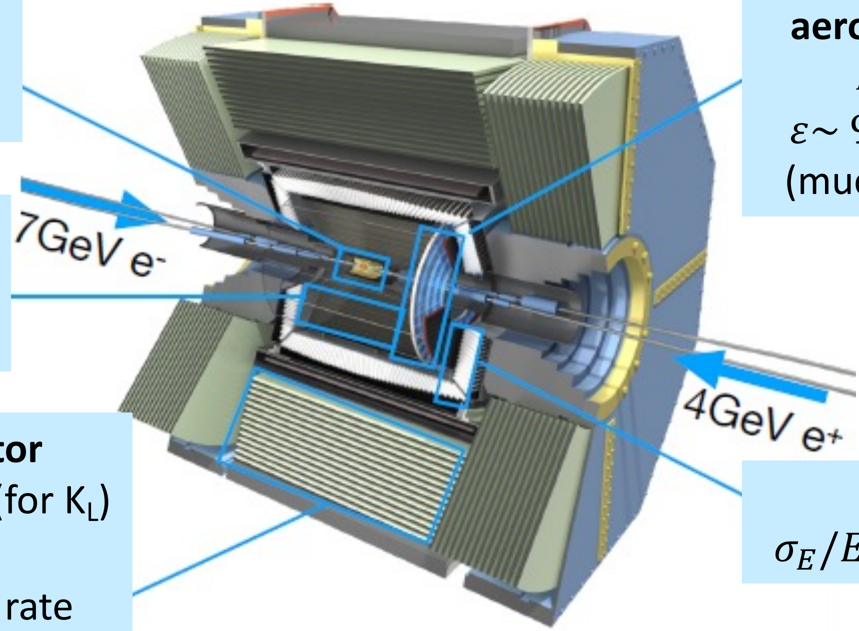
Run II: from February 2024; $L_{int} = 66/fb$

The Belle II detector

Vertex detector
$\sigma_z \sim 15\mu m$
(2× better than Belle)

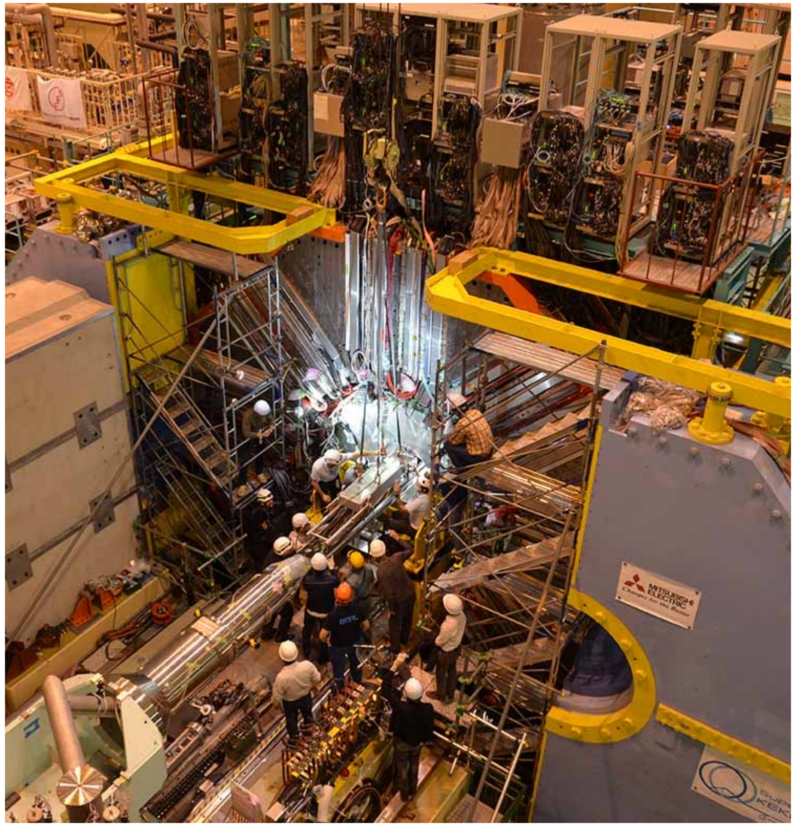
Drift chamber
$\sigma_{r\phi} \sim 100\mu m$
$\sigma_{dE/dx} \sim 5\%$

K_L and muon detector
$\sigma_\phi = \sigma_\theta \sim$10-20 mrad (for K_L)
μ/π separation:
$\varepsilon \sim 90\%$ @1.5% fake rate



Time of propagation & aerogel RICH detectors
K/π separation:
$\varepsilon \sim 96\%$ @1% fake rate
(much better than Belle)

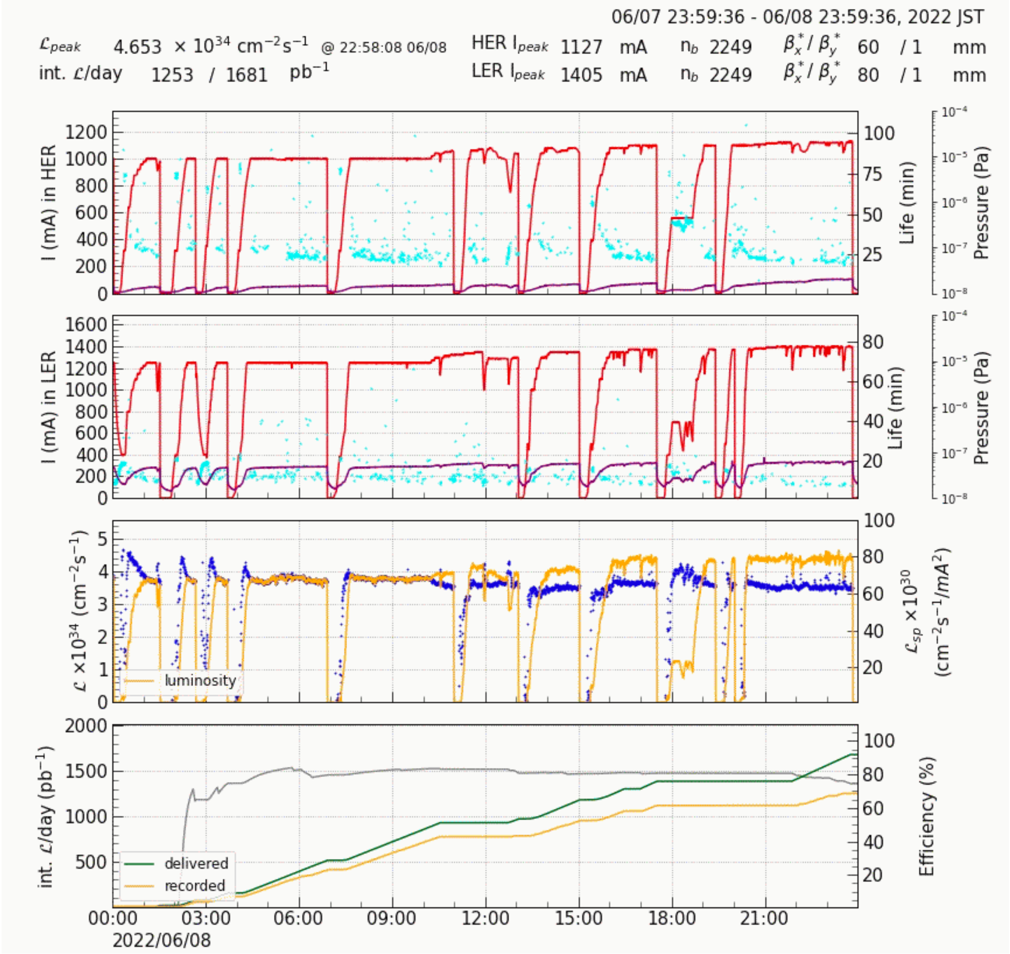
EM Calorimeter
$\sigma_E/E \sim 2\%\ @E = 1\ GeV$



Belle II is an upgrade of the Belle detector: capable of working at much higher background environment

Highlights: *Vertex:* 2 layers of pixels, 4 layers of DS Si strips with extended coverage, *Drift chamber:* smaller cell size + longer lever arm, *PID:* new TOP + ARICH

SuperKEKB performance

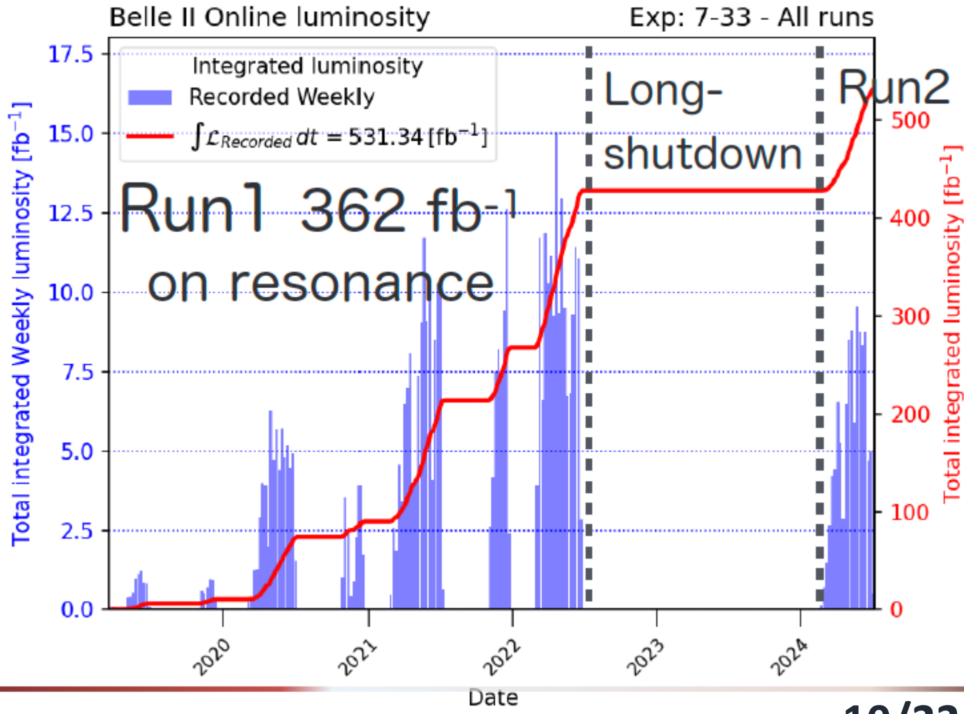


Run I achievements:

- Luminosity record (June, 2022): $\mathcal{L} = \mathbf{4.7{\times}10^{34}/cm^2/sec}$!
  - still ~20 times smaller than SuperKEKB design
  - > 2 times larger than Belle/KEK achieved
  - > 4 times larger BaBar/SLAC
- $\beta^*_y = 1$ mm; $I_{LER/HER} = 1.4/1.2$ A

Plans for Run II:

- Squeezing further $\beta^*_y \to 0.6$ mm
- Doubling (or more) the currents



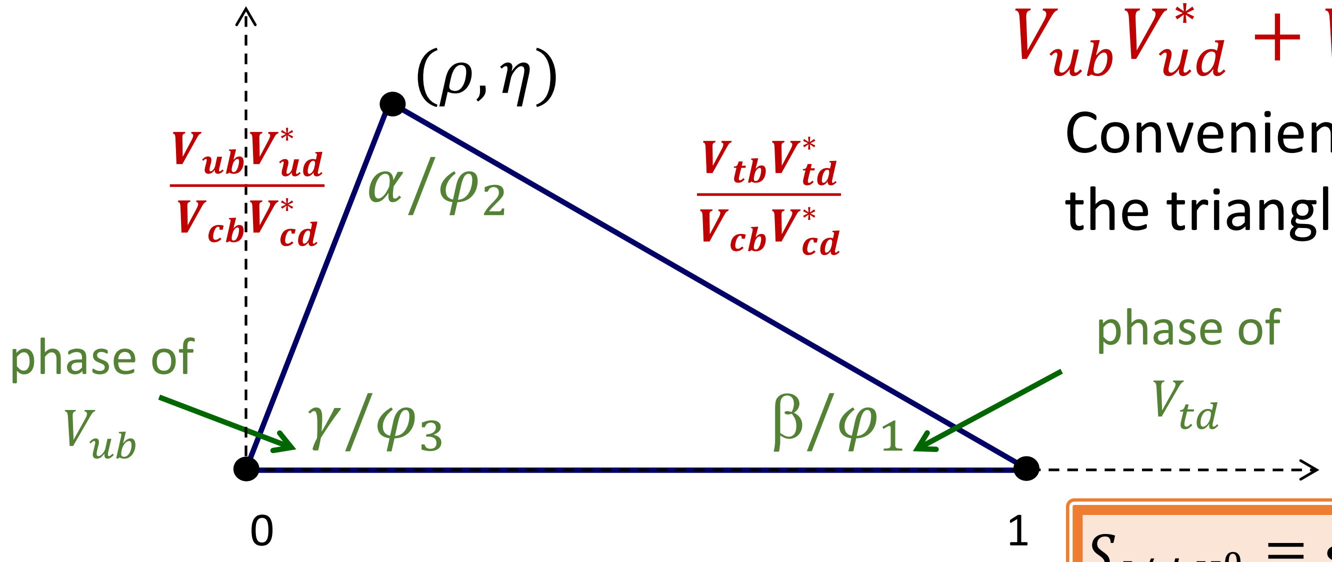
- Achieve $\mathcal{L} = \mathbf{10^{35}/cm^2/sec}$
- SuperKEKB resumed operation in October 2024 rafter summer shut down


UT angles
CP violation
selected results

CP violation in B-decays & Unitarity Triangle

Unitarity condition of CKM matrix $V_{CKM}^{\dagger}V_{CKM} = 1$ gives 9 constrains $V_{ij}V_{ik}^{*} = \delta_{jk}$:

- 3 ($j = k$) says that the probability for each quark to couple to W^{-} is summed up to 1;
- 6 ($j \neq k$) can be represented by triangles in the complex plane.
- 4 triangles are degenerate; 2 has comparable sides ($\propto \lambda^3$).
- One is the VIT (Very Important Triangle):



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

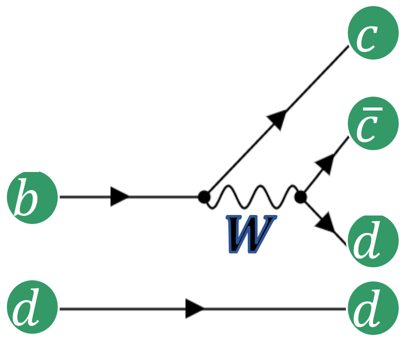
Convenient to normalize all sides to the base of the triangle ($V_{cd}V_{cb}^{*} = A\lambda^3$).

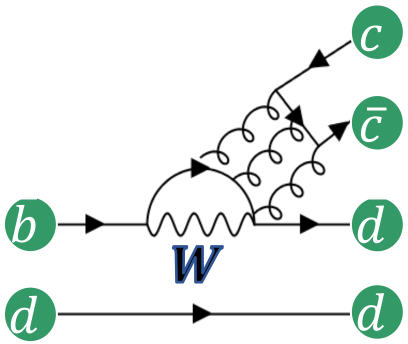
Then the coordinates of the upper apex are expressed through Wolfenstein parameters (ρ,η).

$$S_{J/\psi K^0} \equiv \sin 2\beta = 0.709 \pm 0.011$$

CP violation in $B^0 \to J/\psi\pi^0$

Mediated by $b \to c\bar{c}d$ transition, probe for loop contributions (unlike $J/\psi K^0$with different weak phase) for determination of $\phi_1(\beta)$

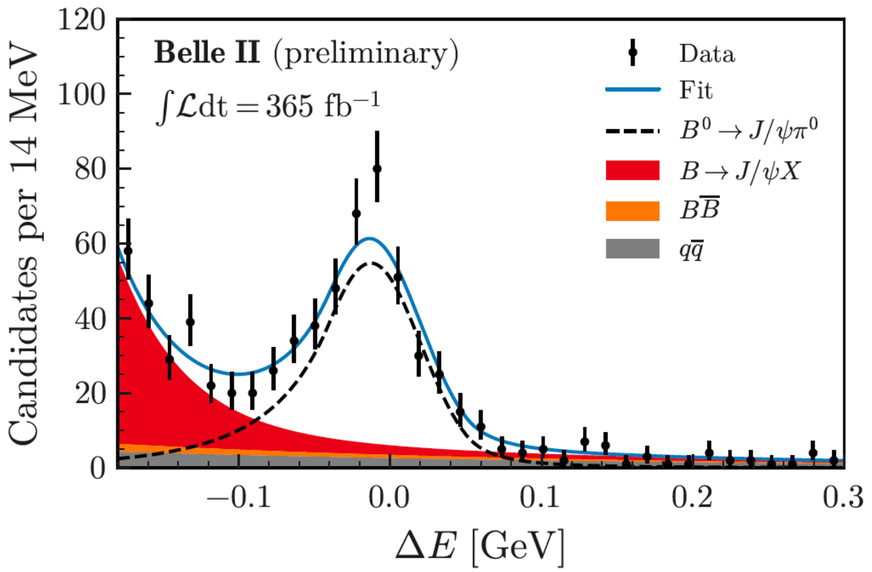


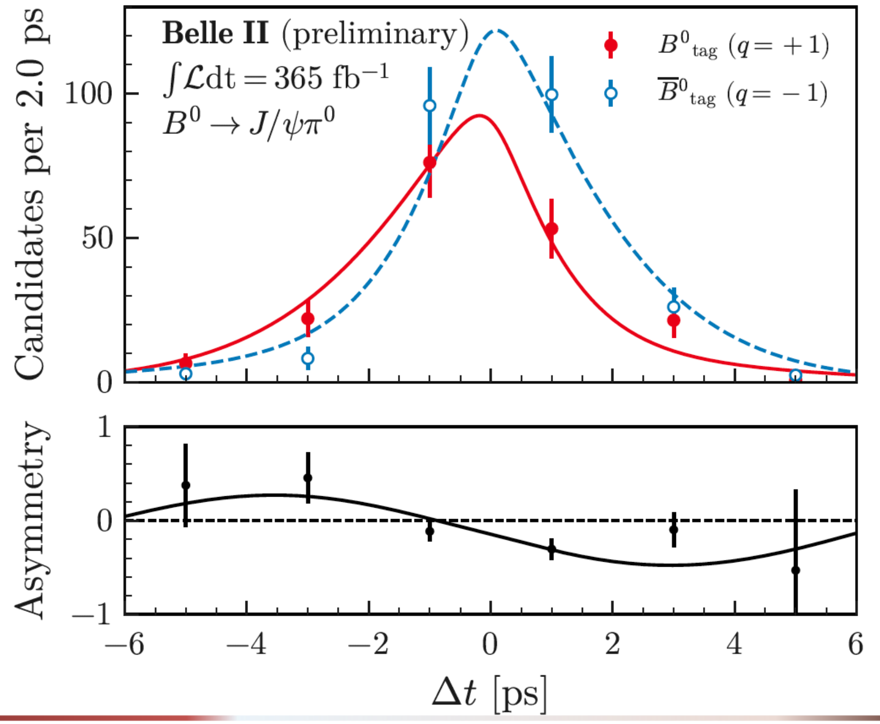


ArXiv:2410.08622
submitted to PRD

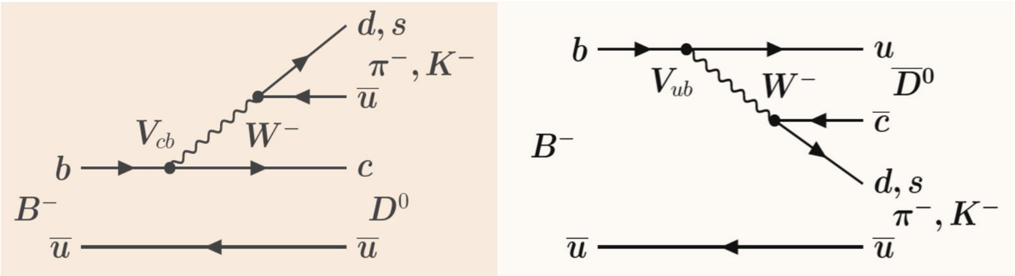
$$\mathrm{Br}(B^0 \to J/\psi\pi^0) = (2.02 \pm 0.12 \pm 0.10)\times 10^{-5}$$
$$S_{CP} = -0.88 \pm 0.17 \pm 0.03$$
$$C_{CP} = \ \ 0.13 \pm 0.12 \pm 0.03$$

First 5 sigma CP violation observation in this mode



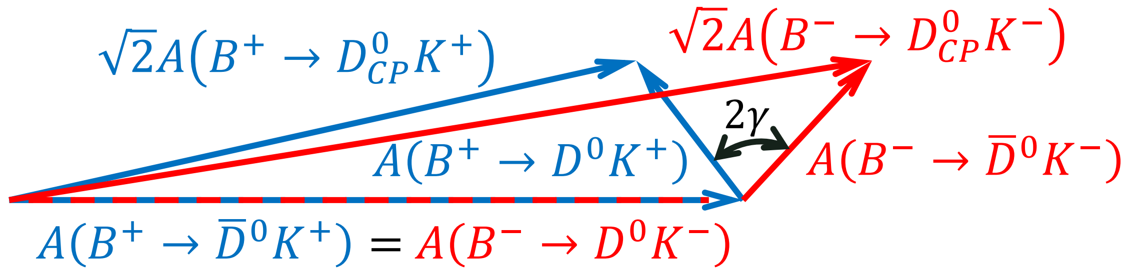


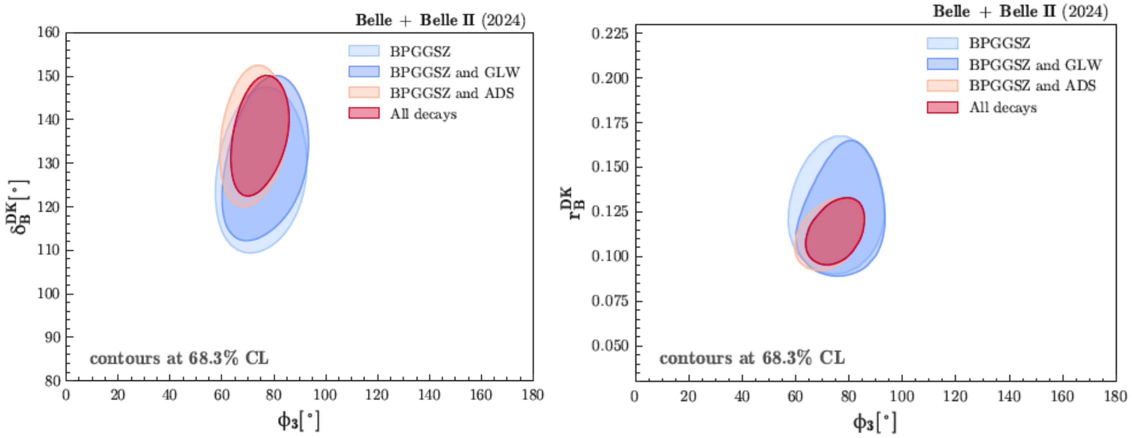
$\phi_3(\gamma)$ from combined Belle & Belle II data



Methods:

- *GLW:* D^0 decays into CP-eigenstate (CS modes, *e.g.* K^+K^-)
- *ADS*: D^0 decays into DCS mode
- *BPGGSZ:* D^0 Dalitz analysis (*e.g.* $K_S^0\pi^+\pi^-$)





ArXiv:2404.12817 accepted by JHEP

B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]	Ref.
$B^+ \to Dh^+$	$D \to K_S^0\pi^0, K^-K^+$	GLW	711 + 189	[23]
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	711 + 0	[15, 24]
$B^+ \to Dh^+$	$D \to K_S^0K^-\pi^+$	GLS	711 + 362	[25]
$B^+ \to Dh^+$	$D \to K_S^0h^-h^+$	BPGGSZ (m.i.)	711 + 128	[26]
$B^+ \to Dh^+$	$D \to K_S^0\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	711 + 0	[27]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0	[12]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K_S^0\pi^-\pi^+$	BPGGSZ (m.d.)	605 + 0	[28]

All Belle&Belle II measurements (59 inputs) in $B^- \to D^{(*)0}K^-(\pi^-)$ are fit to determine

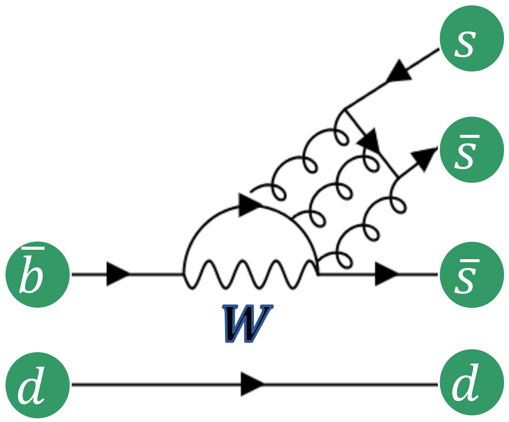
$\phi_3(\gamma) = (75.2 \pm 7.6)°$ in good agreement with global CKM fit $\gamma = (65.6^{+0.9}_{-2.7})°$

CP violation in $B^0 \to \eta' K_S^0$

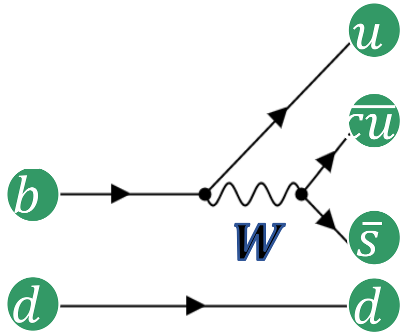
$\eta' \to \eta(\to \gamma\gamma)\pi\pi / \rho(\to \pi\pi)\gamma$

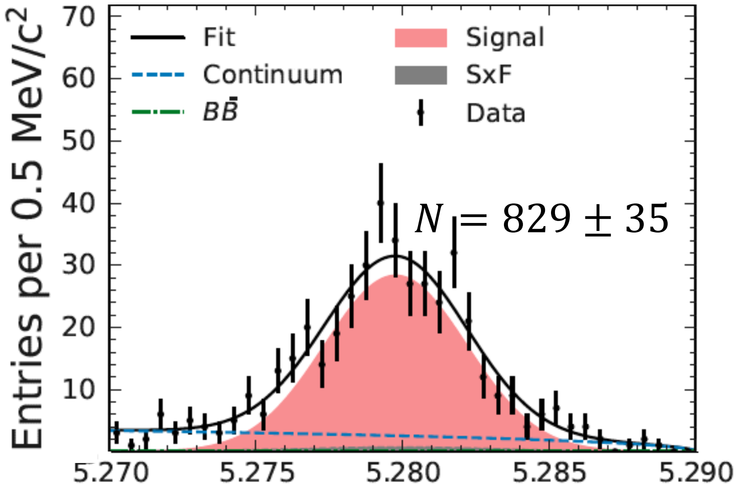
ArXiv:2402.03713
submitted to PRD

Mediated by $b \to s\bar{s}s$ transition = almost the golden penguin mode where CP violation parameters should coincide with those in $J/\psi K^0$ indirect CPV ($\sin 2\phi_1$ (2β))

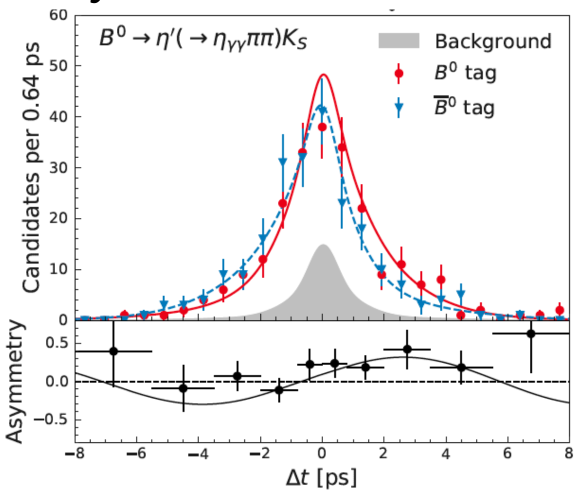


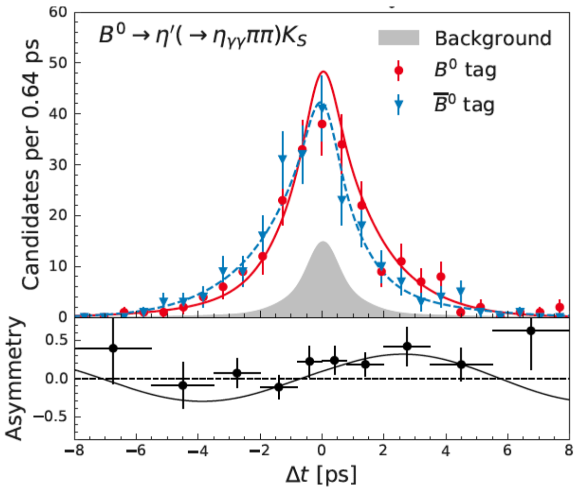
Penguin amplitude is dominant;
Tree one should be tiny (b $\to u$, CS, small $u\bar{u}$ in η')





$\int \mathcal{L}dt = 362 fb^{-1}$





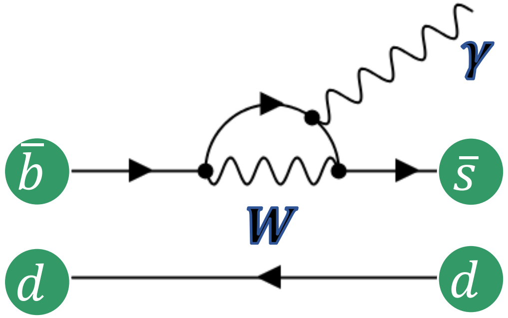
$$S_{CP} = 0.67 \pm 0.10 \pm 0.04$$
$$C_{CP} = -0.19 \pm 0.08 \pm 0.03$$

S_{CP} is consistent with $S_{CP}(J/\psi K^0)$;
C_{CP} is consistent with 0;
Sensitivity is better than at Belle and BaBar in spite of smaller data set

CP violation in $B^0 \to (K_S^0 \pi^0)\gamma$

ArXiv:2402.03713, submitted to PRL

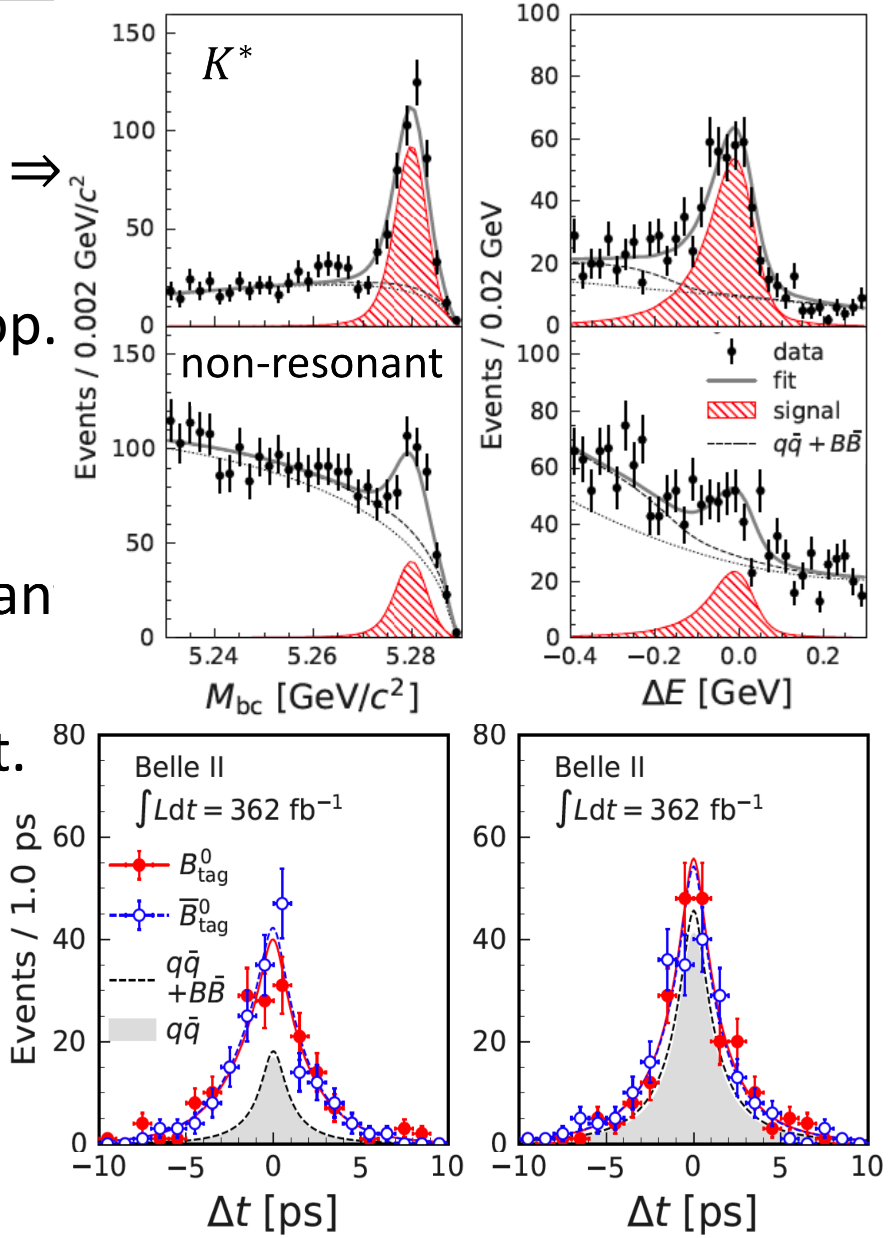
No indirect CP violation in SM due to almost 100% photon polarization (can distinguish B^0 and $\bar{B}^0$ by photon polarization ⇒ no interference ⇒ no CPV). Beyond SM: NP loop contributions can add wrong polarization due to quark chirality flip in the loop. Can happen in e.g. left-right symmetric model with heavy W_R



Divide into 2 samples: resonant (K^*: $0.8 < M_{K\pi} < 1$GeV) & non-resonan

Challenge: need B^0 decay vertex; only available detached K_S^0 and IP constraint.

Use BDT to suppress backgrounds.



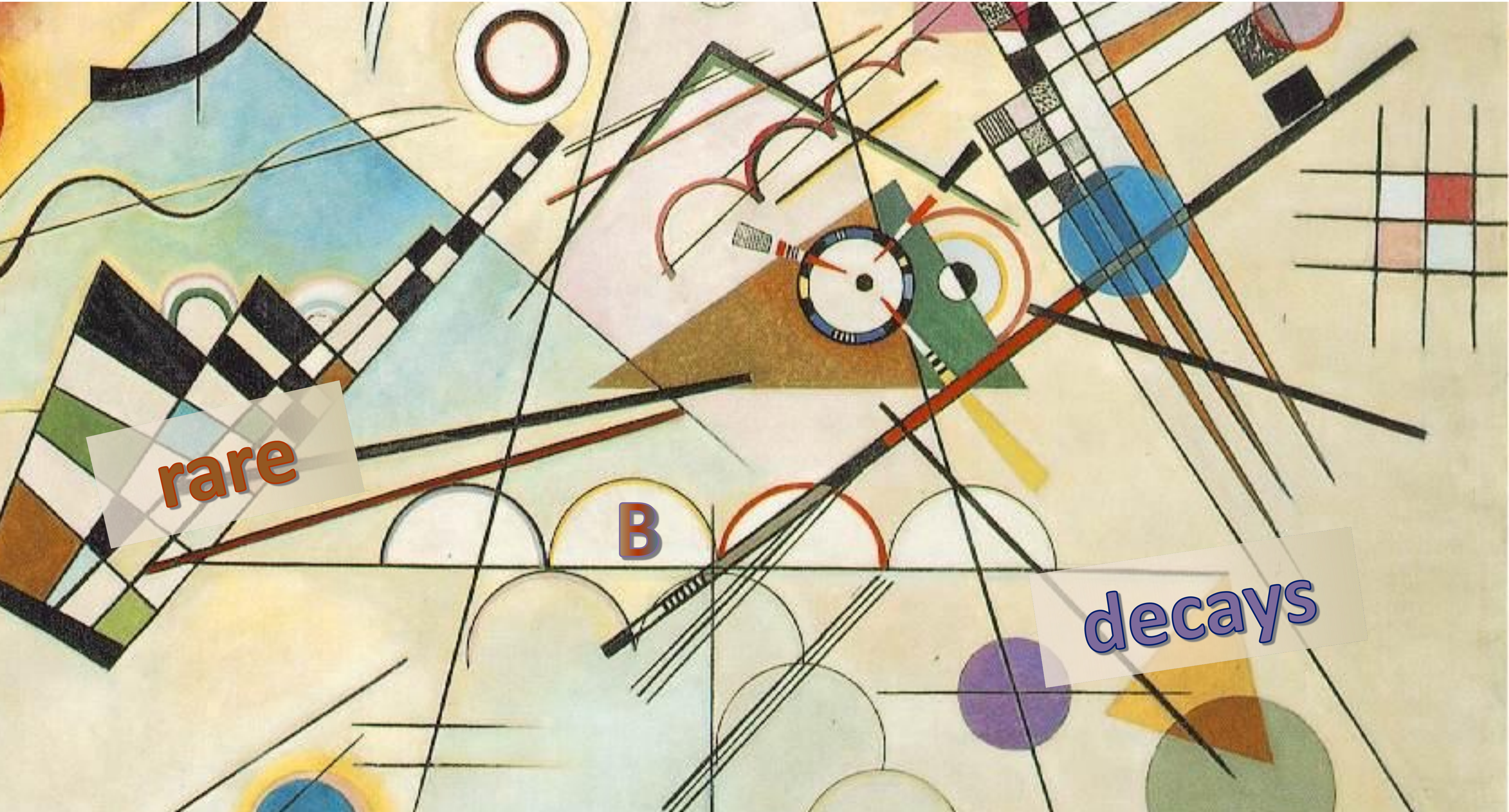
K^*:

$$S_{CP} = 0.00^{+0.27}_{-0.26}$$
$$C_{CP} = 0.10 \pm 0.13$$

non-resonant:

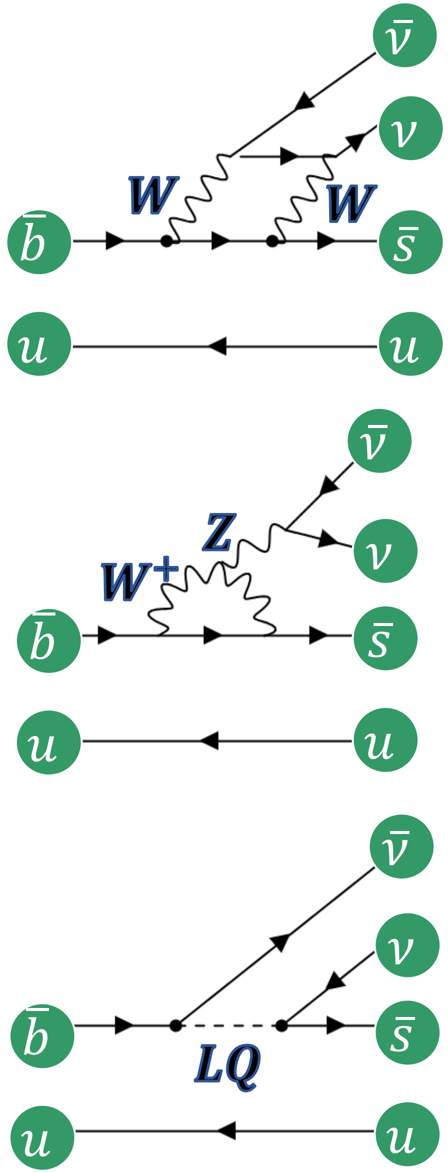
$$S_{CP} = 0.04^{+0.45}_{-0.44}$$
$$C_{CP} = -0.06 \pm 0.25$$

Consistent with the world average, and the most precise


rare
B
decays

$B^+ \to K^+\nu\bar{\nu}$

Electroweak penguin decays

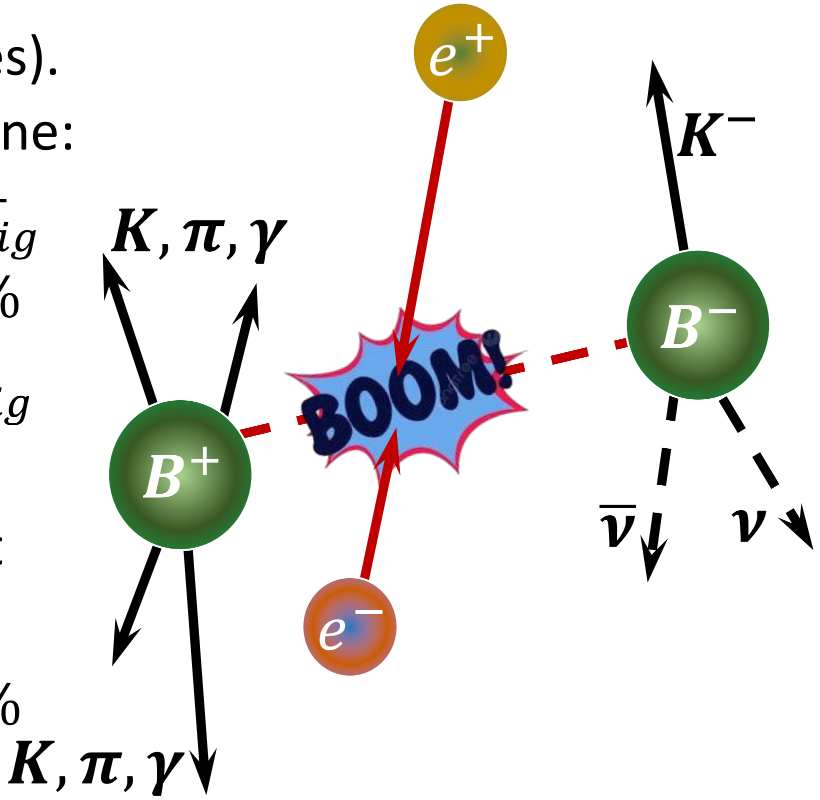


- Flavor Changing Neutral Currents occur at loop level in SM. Low BF's due to CKM and GIM suppression $B(b \to s\nu\bar{\nu}) \sim 10^{-5}$; $B(b \to s\tau\bar{\tau}) \sim 10^{-6}$
- Look for enhancements in FCNC (and LFV) due to NP contributions. Third generation coupling

Missing energy modes reconstruction

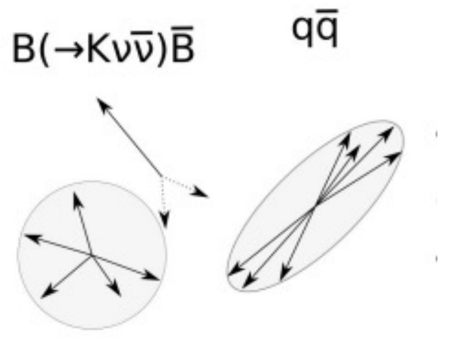
Initial kinematics is known (known beams' energies).
The second B-meson in the event tags the signal one:

- Hadronic tag, e.g. $B^+_{tag} \to \bar{D}^0\pi^+$. Very clean, B^-_{sig} kinematics fixed, but low efficiency, $\varepsilon \sim 0.1 - 0.5\%$
- Semileptonic tag, $B^+_{tag} \to \bar{D}^0\ell^+\nu$. Clean, but p_{sig} remains unconstrained, $\varepsilon \sim 2\%$
- Inclusive tag: add all reconstructed particles not from B^-_{sig} to B^+_{tag}. Large continuum background; optimize bg suppression at the expense of $\varepsilon \sim 10\%$



$B^+ \to K^+ \nu \bar{\nu}$

PRD 109, 112006 (2024)



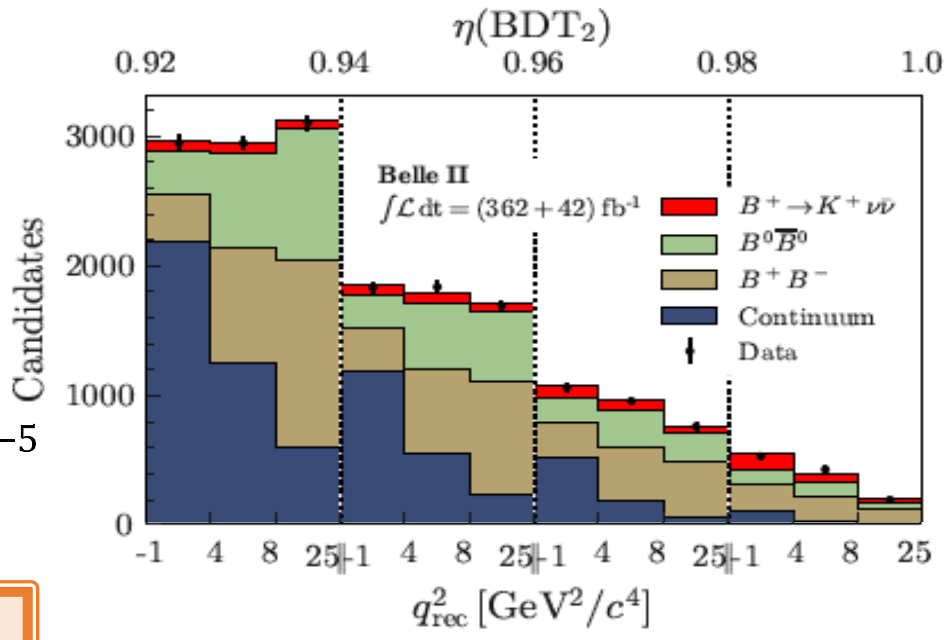
Use:

- *Inclusive Tag* use event topology and BDT and leads the final sensitivity (total eff. $\sim$8%, purity $\sim$0.8%)
- *Hadronic Tag* is used for consistency check and provides 10% increase in final combined result (total eff. $\sim$0.04%, purity $\sim$3.5%)

Fit: to q^2 (≡invariant mass of neutrinos) and BDT classifier to extract the signal yield

Check: all possible backgrounds

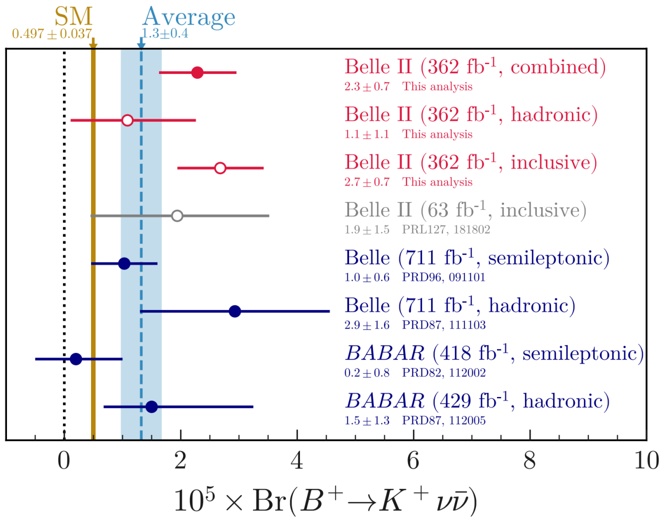
- Continuum (using 42/fb data)
- $B \to KD$ with D mimic missing (due to K_L) (using $B \to \pi D$)



$$Br_{Inclusive} = (2.7 \pm 0.5 \pm 0.5)\times 10^{-5}$$

$$Br_{Full} = (1.1^{+0.9+0.5}_{-0.8-0.5})\times 10^{-5}$$

$$Br = (2.3 \pm 0.5^{+0.5}_{-0.4})\times 10^{-5}$$



First evidence at 3.5 sigma;

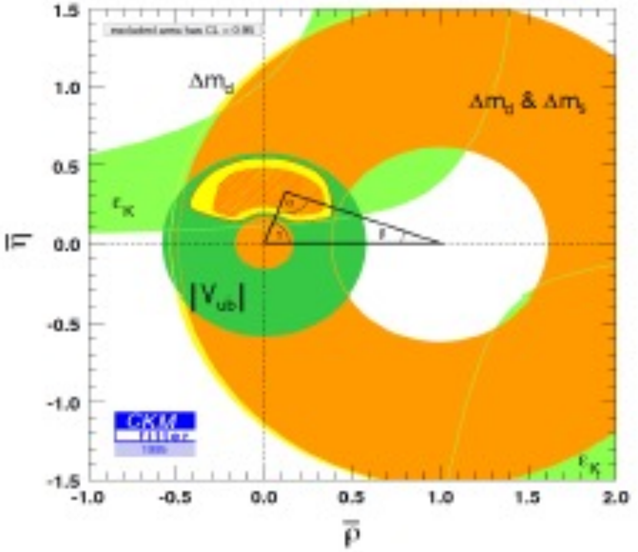
Tension with the SM ($\sim 0.6\times 10^{-5}$) at 2.7 sigma

Many other Belle II results in B physics

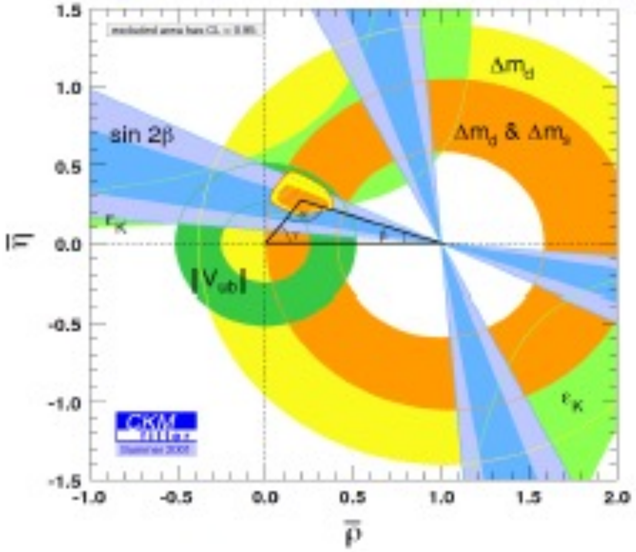
- Determination of $|V_{ub}|$ from simultaneous measurements of untagged $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^- \ell^+ \nu$ decays; *ArXiv: 2407.17403 (submitted to PRD)*
- Search for the decay $B^0 \to \gamma\gamma$; *PRD 110, L031106 (2024)*
- Measurement of branching fractions, CP asymmetry, and isospin asymmetry for $B \to \rho\gamma$ decays using Belle and Belle II data; *ArXiv: 2407.08984 (submitted to PRD)*
- Measurement of CP asymmetries in $B^0 \to K_S^0 K_S^0 K_S^0$ decays at Belle II; *PRD 109, 112020 (2024)*
- A test of lepton flavor universality with a measurement of $R(D^*)$ using hadronic B tagging at the Belle II experiment; *ArXiv: 2401.02840 (accepted by PRD)*

… and other fields (τ, charm, light hadrons, search for exotics)

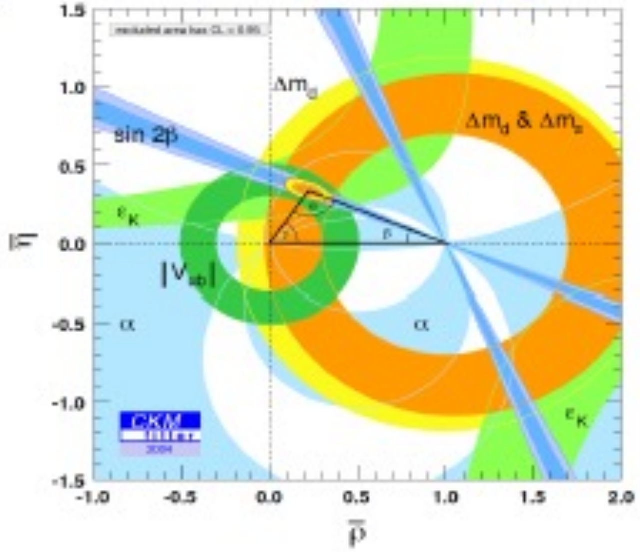
See talks of my Belle(II) colleagues at parallel session.



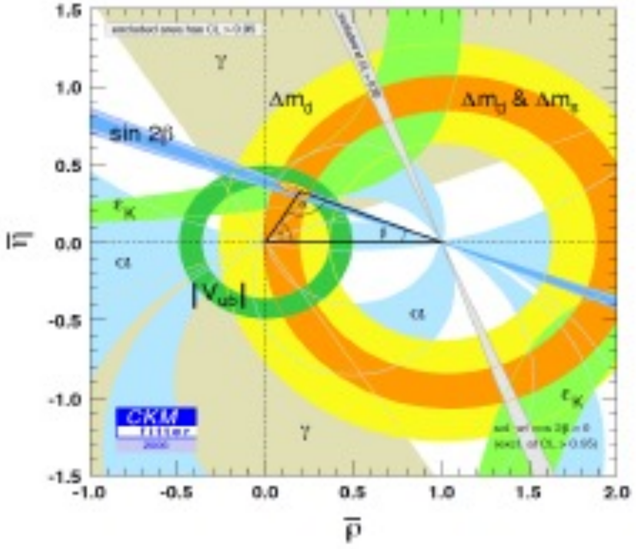
1995



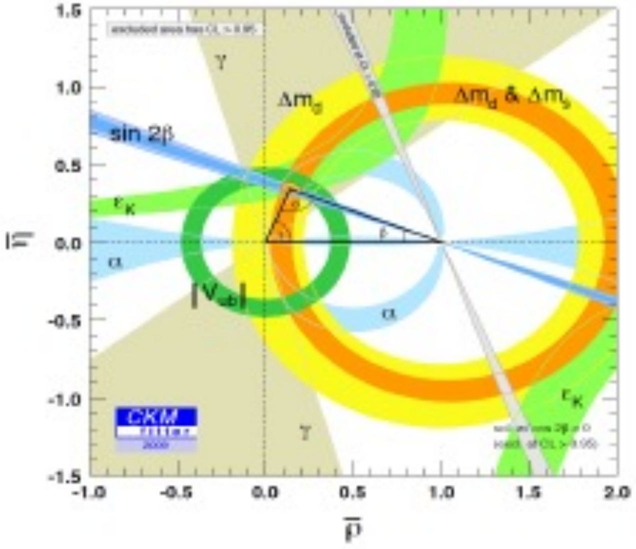
2001



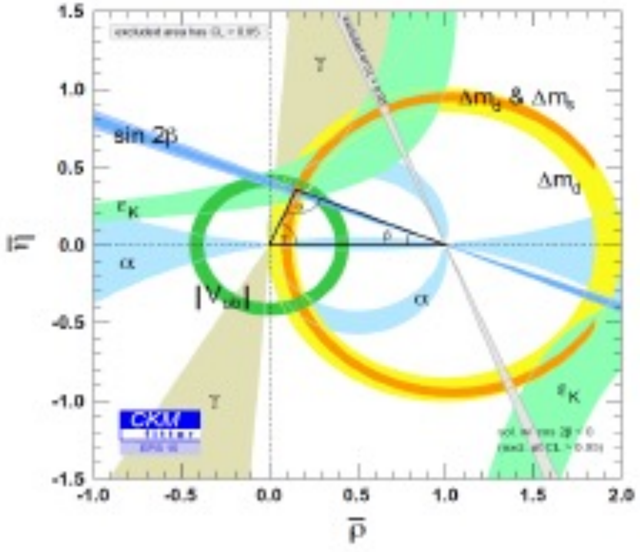
2004



2006



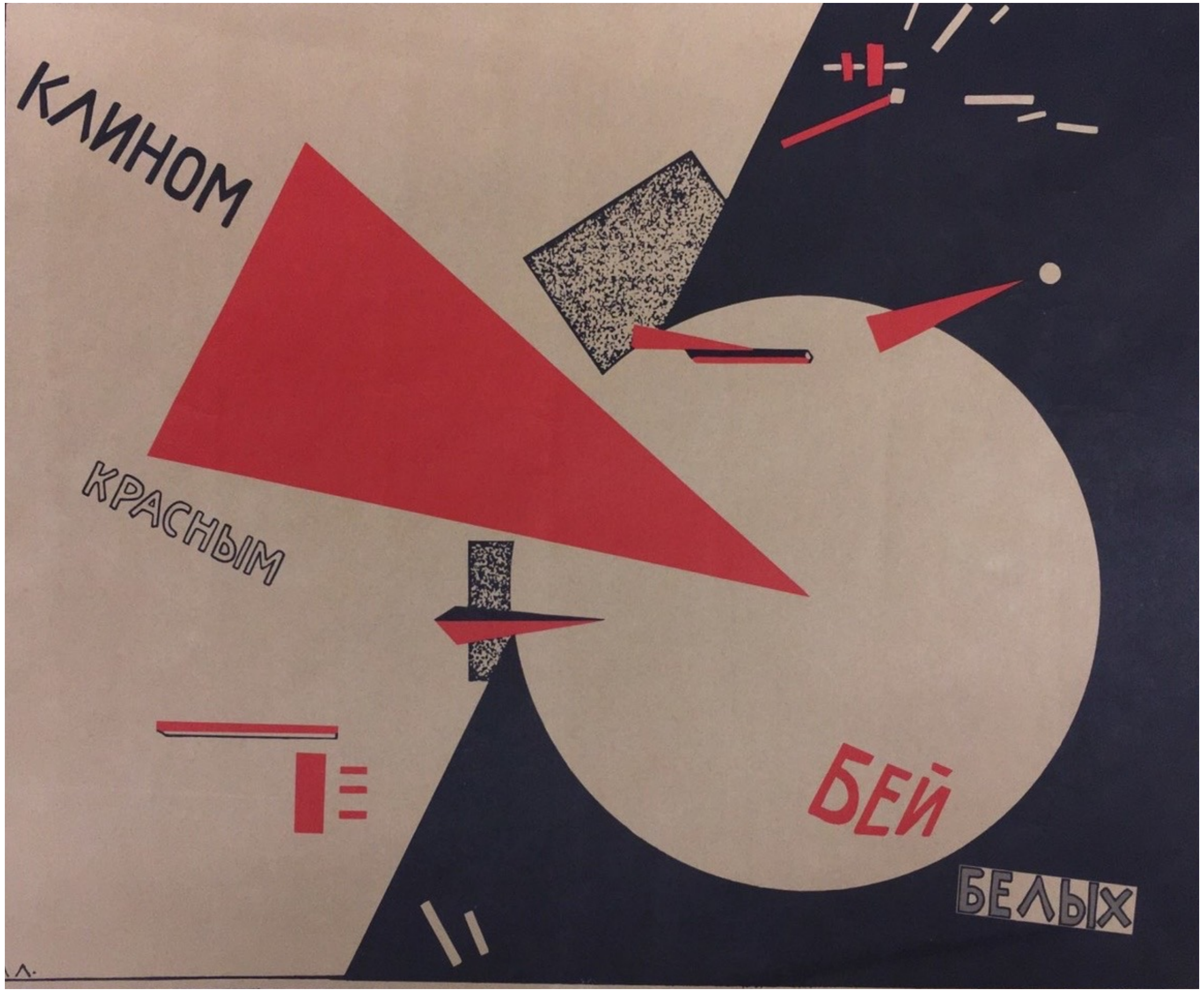
2009



2015

Summary

The flavor structure of the Standard Model is now established very well, but we still do not know where it came from. Even precisely measured parameters can not hint yet at a solution to the genesis of fermion generations and fermion-scalar couplings.



Physics beyond the Standard Model has successfully avoided detection up to now. But we are sure it is somewhere nearby. We should not be discouraged:

- New Physics definitely exists to solve the numerous SM problems;
- modern cosmology (as well as the Ministry of Education and Science) requires New Physics.