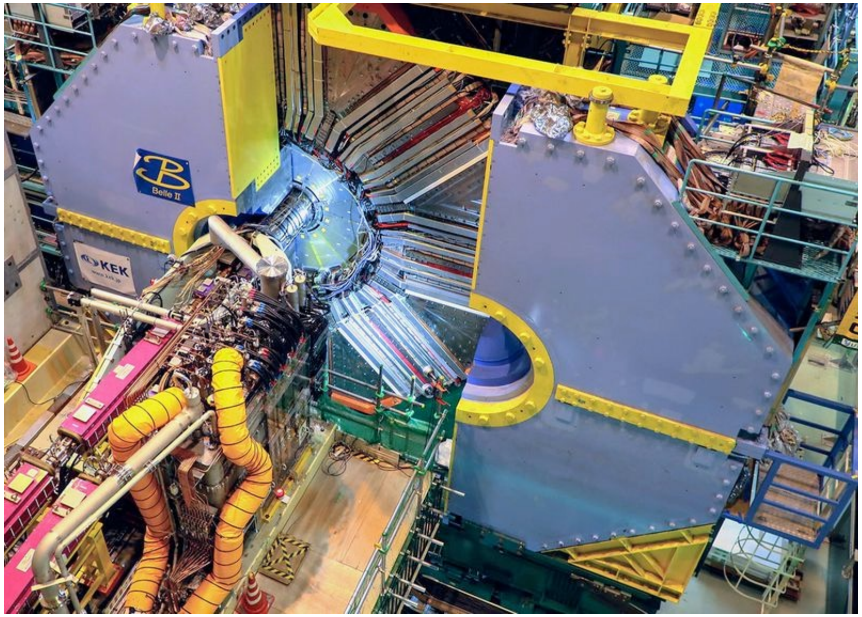
Introduction to B Physics, Belle II@SuperKEKB

Tom Browder, University of Hawai'i at Manoa



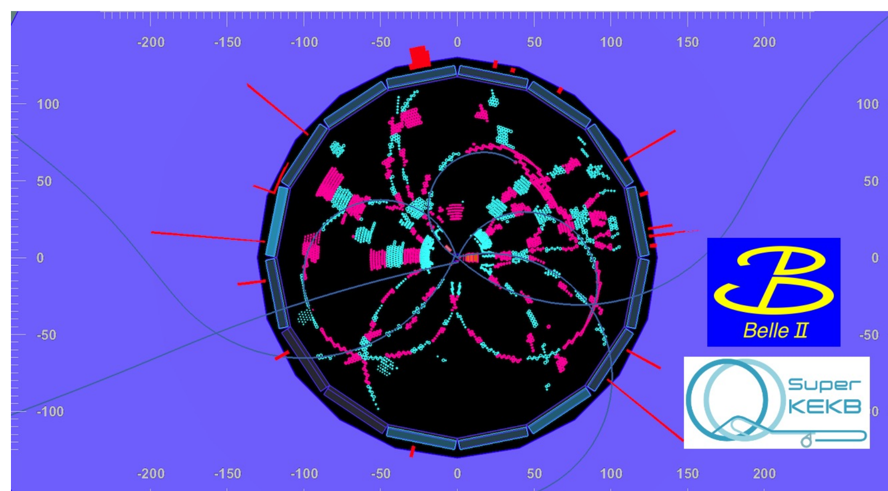
The complex superconducting final focus is partially visible here (before closing the endcap).

Inside the SuperKEKB tunnel

Learning Goal: Understand some of the core B physics, *Time Dependent CP violation, QM, and Penguins if time permits). Follow-up and review of Prof Libby's and Prof. Datta's talks.*

CKM couplings, semileptonic B decays will be covered by Dr. Raynette Tonder

$$e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$$



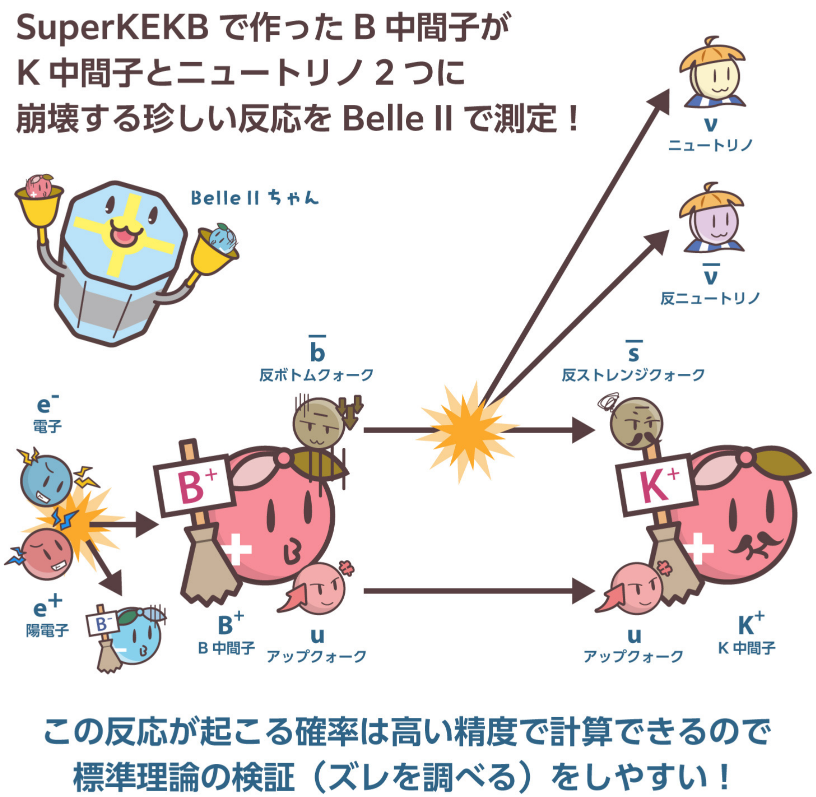
One learning goal for this summer workshop:

Why is the first evidence for the weak decay $B \to K \nu \bar{\nu}$ at Belle II significant?

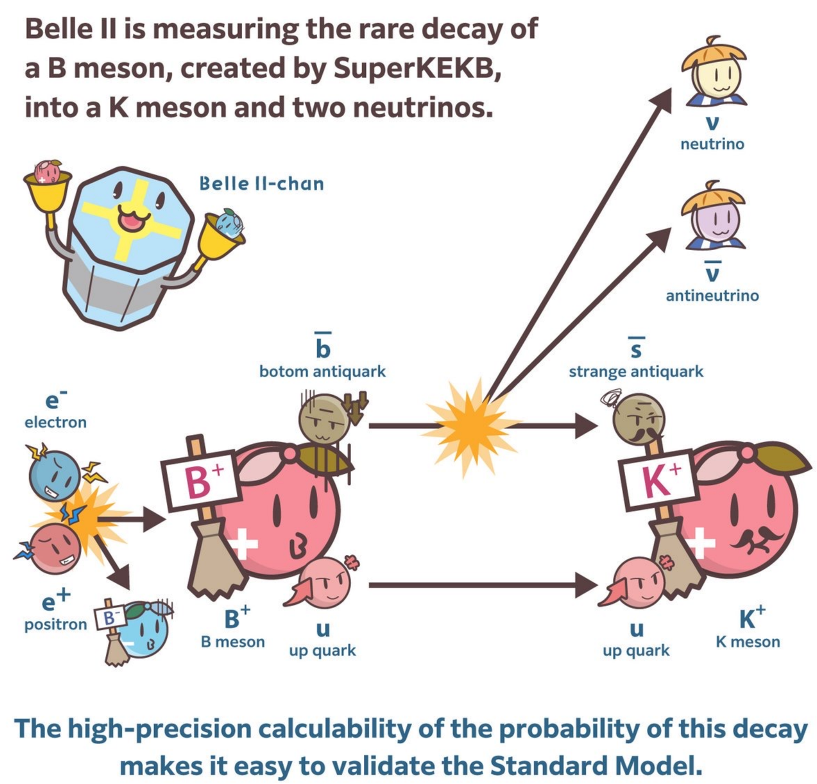
Discussed in talks by Karim Trabelsi and Jim Libby

Why is there a manga about this topic ?

How could this lead to a discovery of BSM physics ?



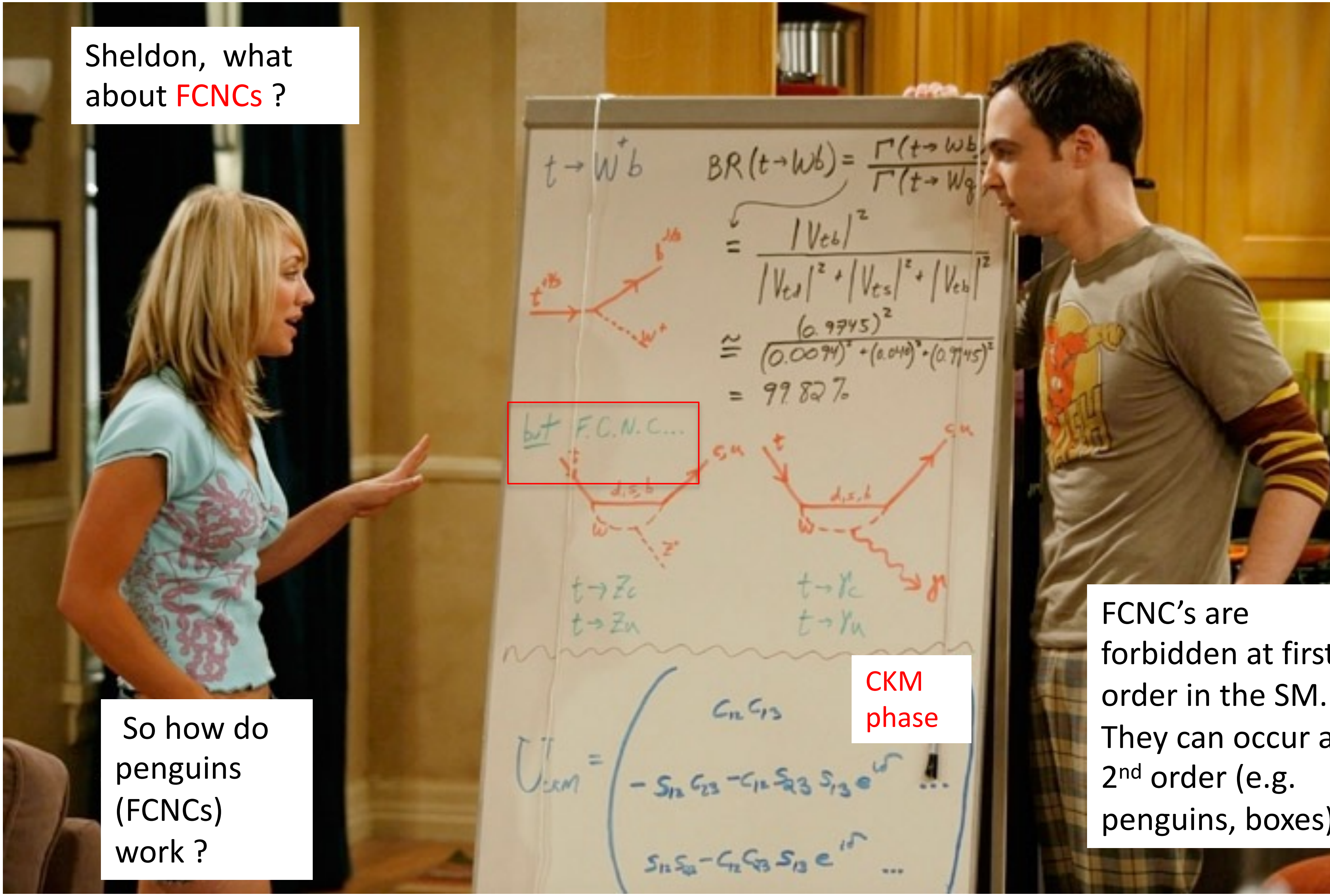
Japanese Original



English Translation

A b quark has charge -1/3, an s quark has charge -1/3 so this decay is a flavor changing neutral current (FCNC).

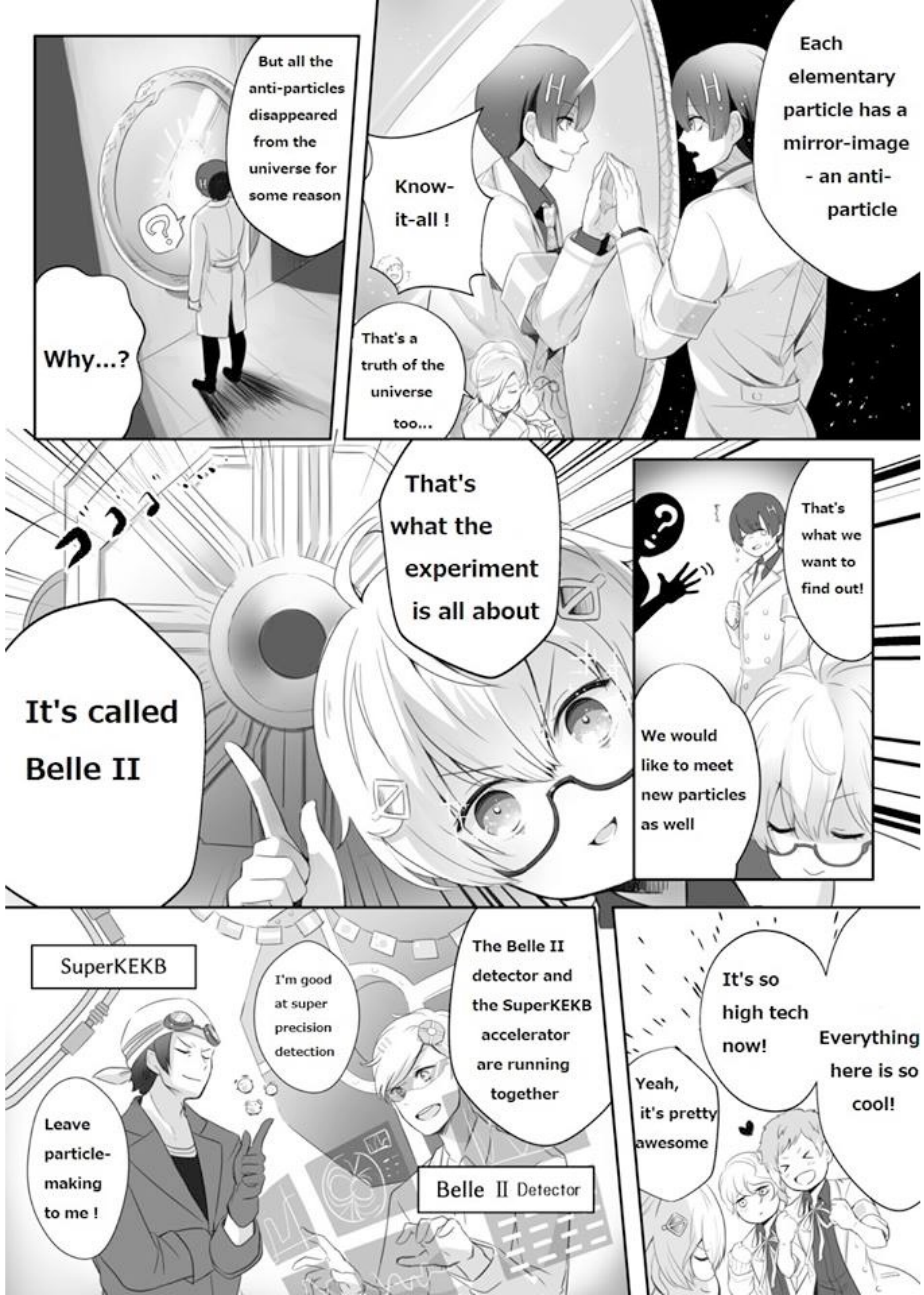
Old US TV Show, Big Bang Theory Episode (FCNCs)



Whiteboards by Prof. David Saltzberg (UCLA)

CP Violation is now included in most of the undergraduate particle physics textbooks.
(see backup material on P and CP) and intro talks by Dr Hulya Atmacan, talk by Jim Libby

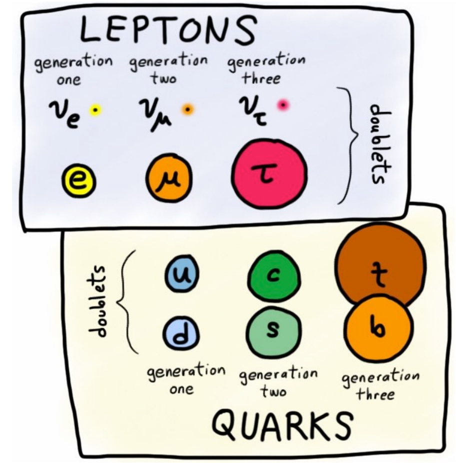
There is even a comic book or ***manga*** *explanation of CP violation.*



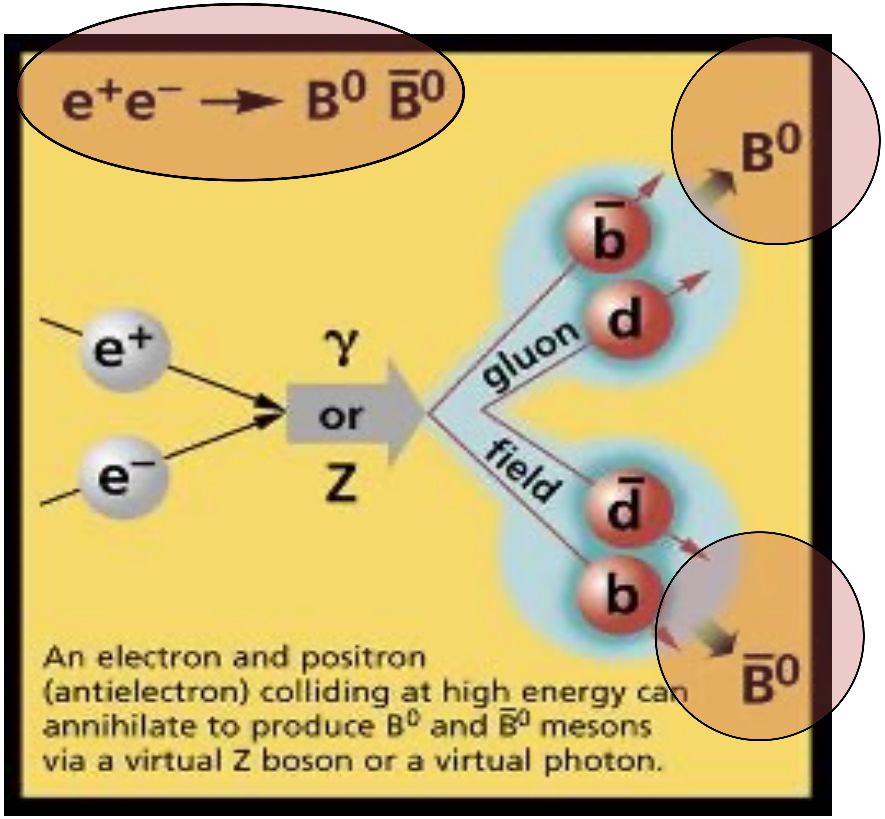
Particle Physics Review question:
What are the three types of CP violation ?

B mesons:
"Laboratory rats of the weak interaction"

"Breed large numbers and watch them die"



At the ϒ(4S), B Bbar pairs are produced with NO additional particles.



Exotic bound state of matter and antimatter (hydrogen-like) b quark mass ~ 5 x proton mass

Lifetime ~ 1.5ps

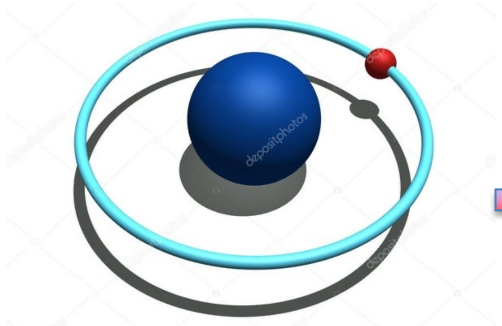
c

$$\begin{pmatrix} t \\ b \end{pmatrix}$$

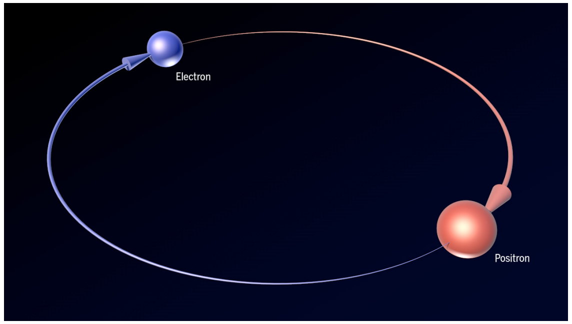
s

More on this in a moment

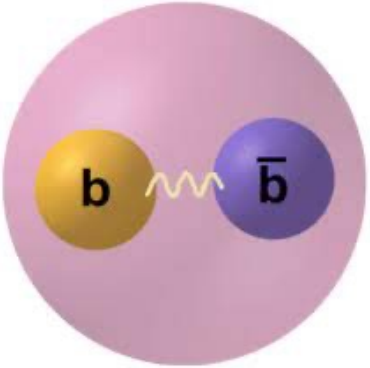
1987: ARGUS@DESY found that the neutral B meson can transform into its *anti-particle*, "B-Bbar mixing"



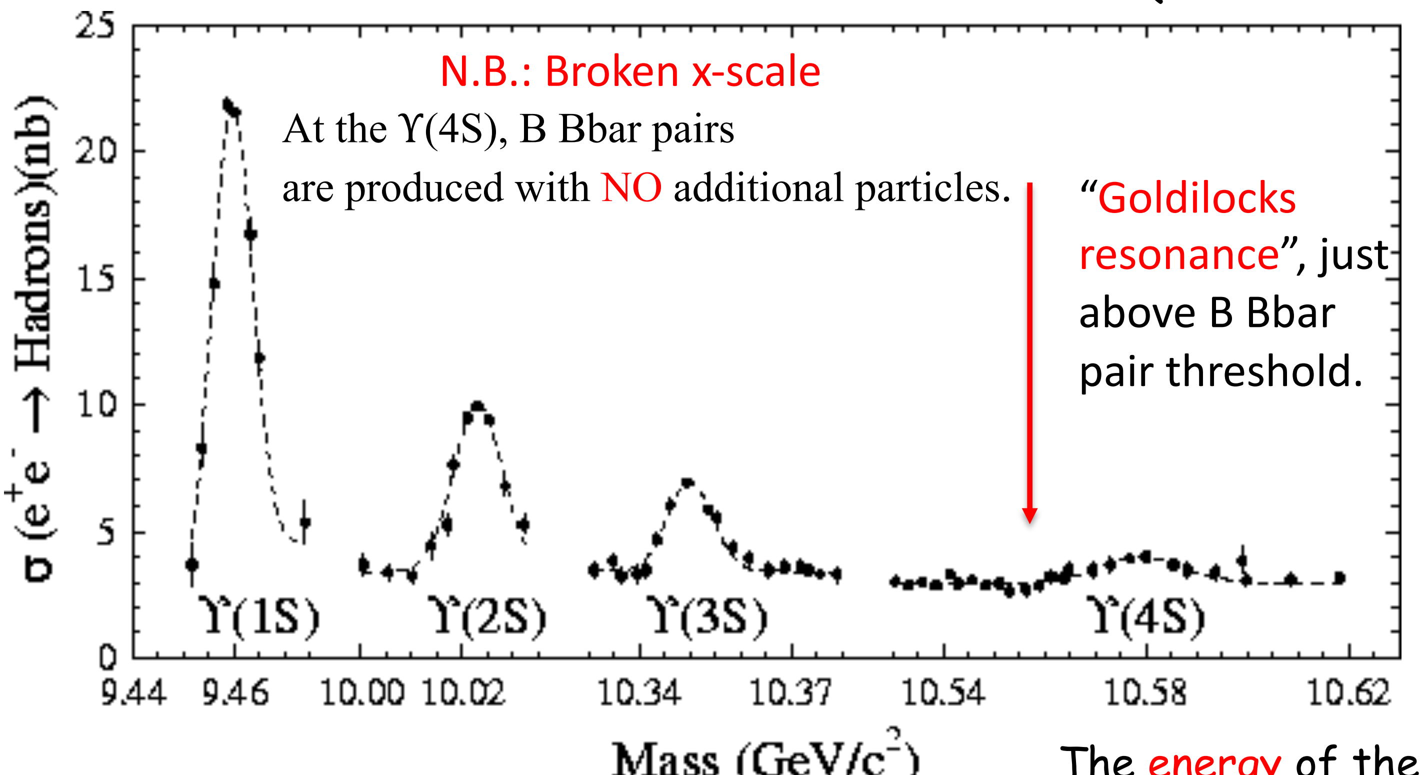
Hydrogen (proton and electron bound state)



Positronium (e+e- bound state)



Bottomonium (b bar bound state), QCD instead of QED.



Ole Miss Q: Why are the Upsilon(nS) states (n=1,2,3) so narrow (10's of keV) ?

The energy of the e+e- machine is tuned to the Υ(4S) resonance

Particle-Antiparticle Mixing

Start with a B^0 (wait a while, a few x 10^{-12} sec)

There is a large probability it will turn into its anti-particle, an anti-B^0 i.e.

$$B^0 \to \bar{B}^0$$

$$\begin{cases} x_d = 0.769 \pm 0.004 & (B_d^0\text{–}\overline{B}_d^0 \text{ system}) \\ x_s = 26.89 \pm 0.07 & (B_s^0\text{–}\overline{B}_s^0 \text{ system}) \end{cases},$$

This also happens with K^0 (strange quarks) and D^0 (charm quark) mesons.

x (%)	$0.50^{+0.13}_{-0.14}$
y (%)	0.62 ± 0.07

Particle-Antiparticle Mixing

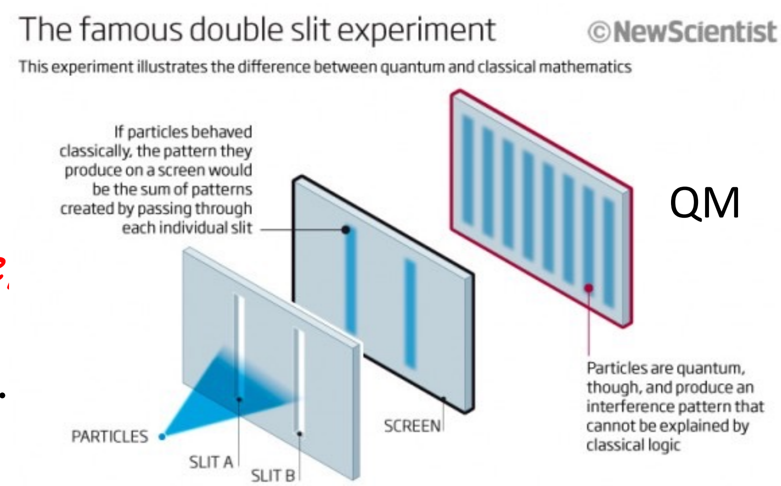
There is a large probability it will turn into its anti-particle, an anti-B^0 (or vice versa) i.e.

$$B^0 \rightarrow \bar{B}^0$$

Let's add in Quantum Mechanical Interference

"We choose to examine a phenomenon which is impossible, absolutely *impossible*, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery."

--Richard P. Feynman

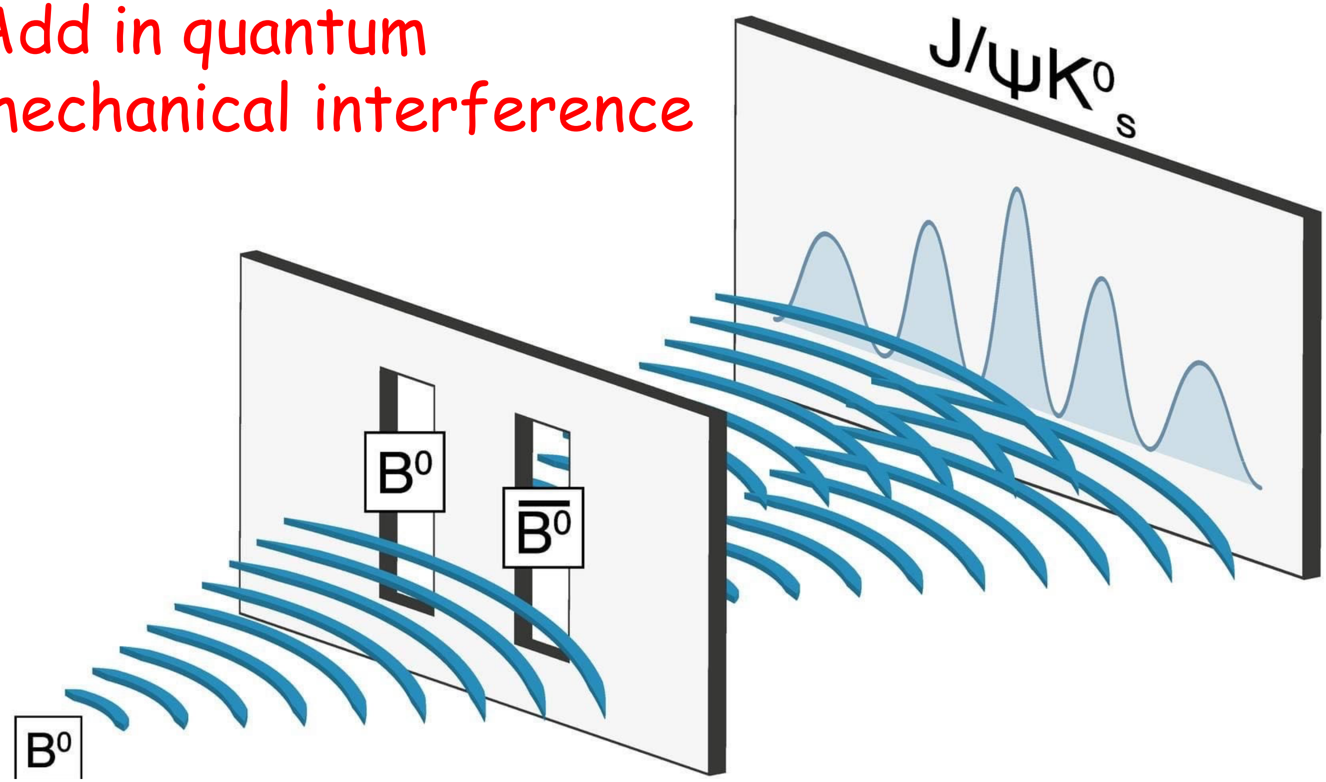


QM

Even for single electrons

Figure from CERN LHCb outreach (also see Hazumi 2001)

Add in quantum mechanical interference



Q: But how can we generate a phase difference between the two paths (so that there is an interference pattern on the screen) ?

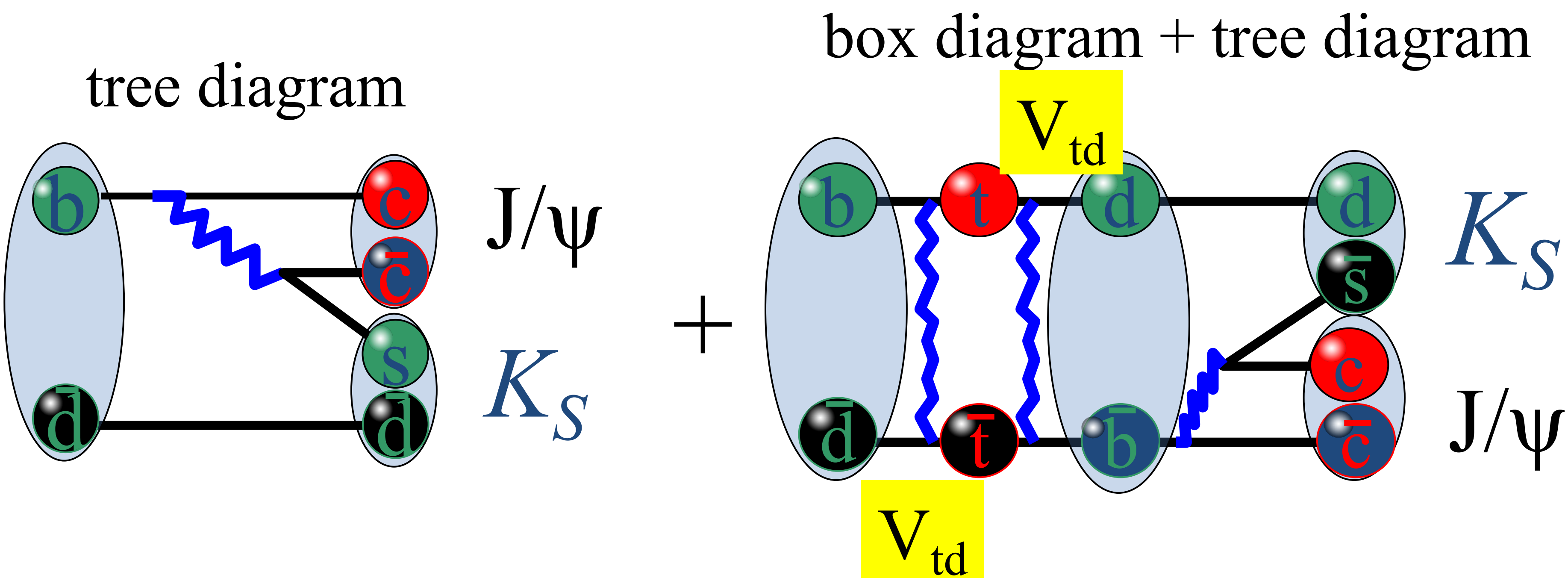
Ans: $B^0 \rightarrow J/\psi$ Ks *and*

$B^0 \rightarrow \bar{B}^0 \rightarrow J/\psi$ Ks (via particle-anti particle mixing). These two paths have different weak interaction phases.

So we conclude:
Time-dependent *CP* violation is

"*A Double-Slit experiment*" with particles and antiparticles

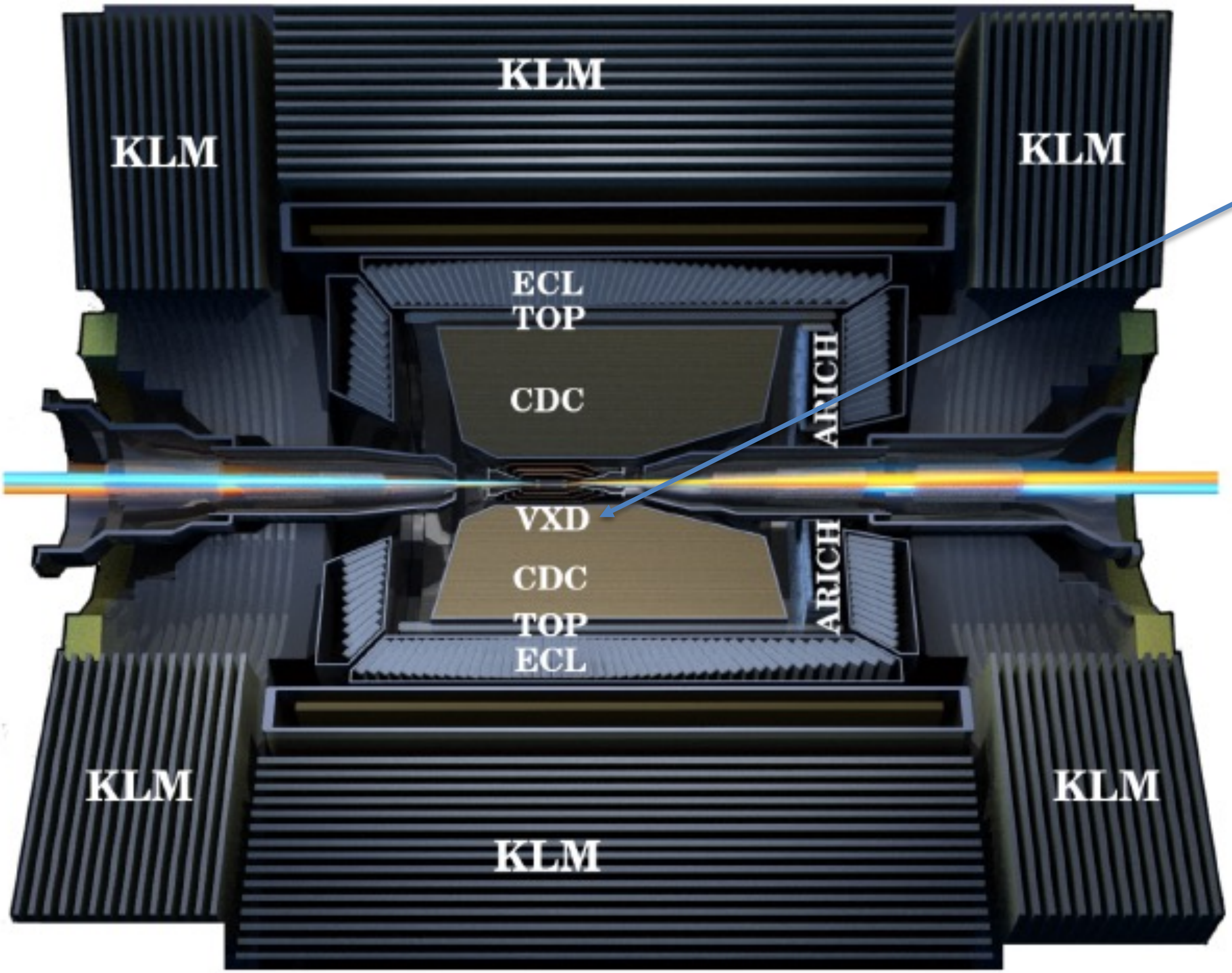
QM interference between two diagrams



Measures the phase of V_{td} or equivalently the phase of $B^0 \to \bar{B}^0$ mixing.

Reminder: Cross-section of "Belle II in Black"

See intro talks by Dr Seema Choudury, Prof. Leo Piilonen

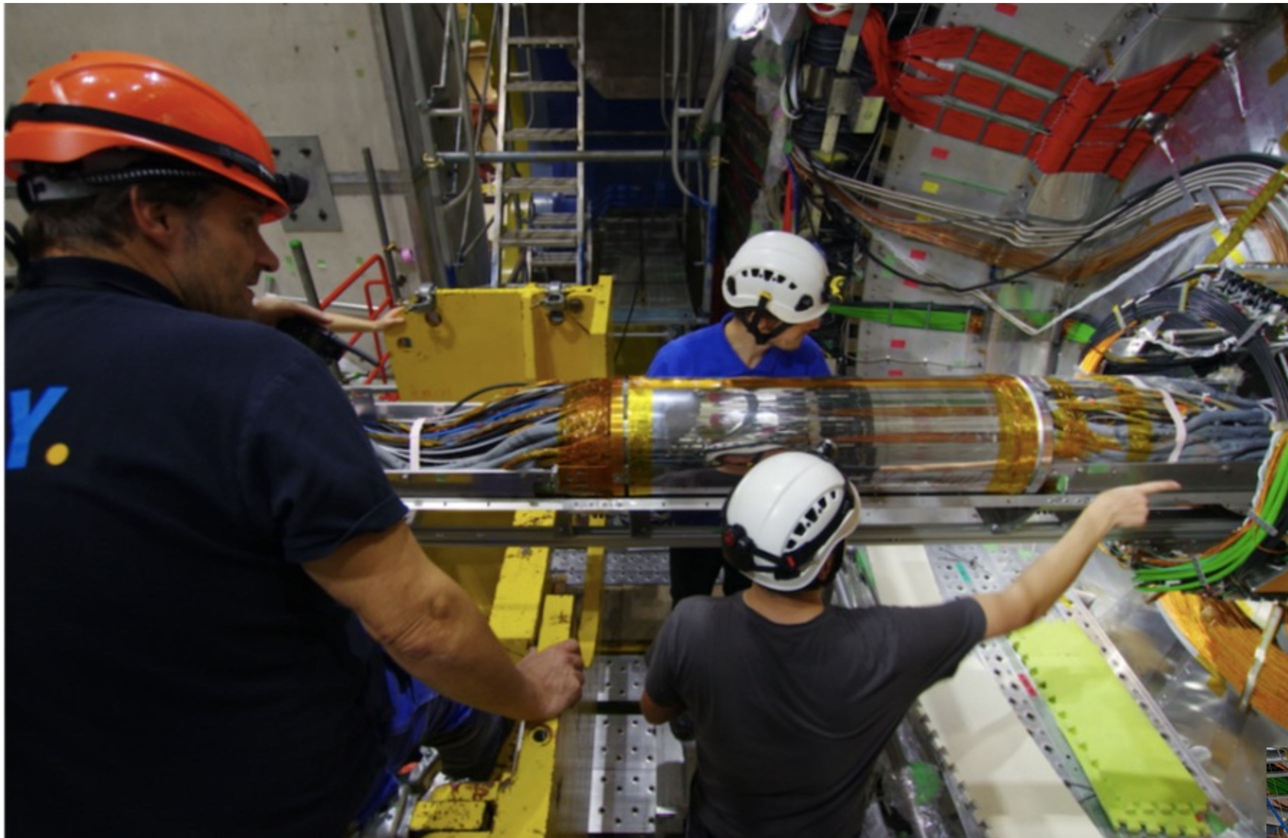


This is the core component of Belle II for time-dependent CPV measurements.

Time Dependent Measurements at Belle II

"Pain et beurre" (i.e .bread and butter) for the B factories.

"misoshiro to gohan" ?



Belle II

Belle II VXD installed on Nov 21, 2018. (PXD L1 and two ladders of L2. and the SVD (4 layers))

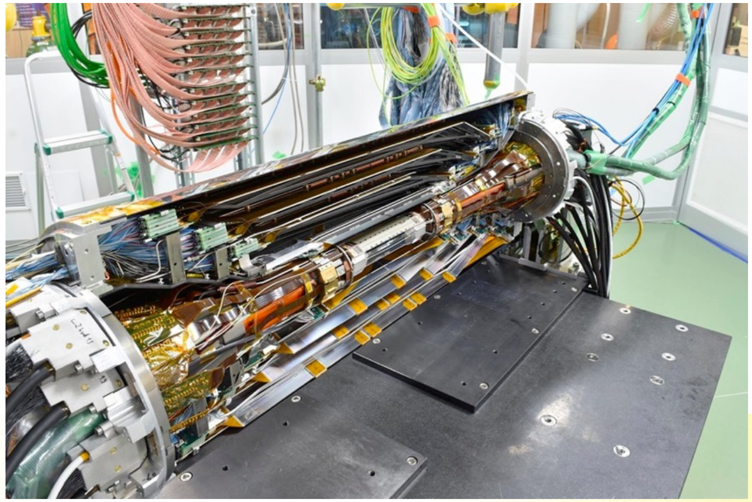
See talk by Karim Trabelsi.

LS1: VXD upgrade,
Now up to PXD2 (2024)

B→J/ψ K_S and the measurement of CPV

We use a "Golden" CP Eigenstate

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



$$\Delta t \approx \frac{\Delta z}{\beta\gamma}$$

Only 0.28 at SuperKEKB

$$B^0 \to f \; ; B^0 \to \overline{B^0} \to f$$

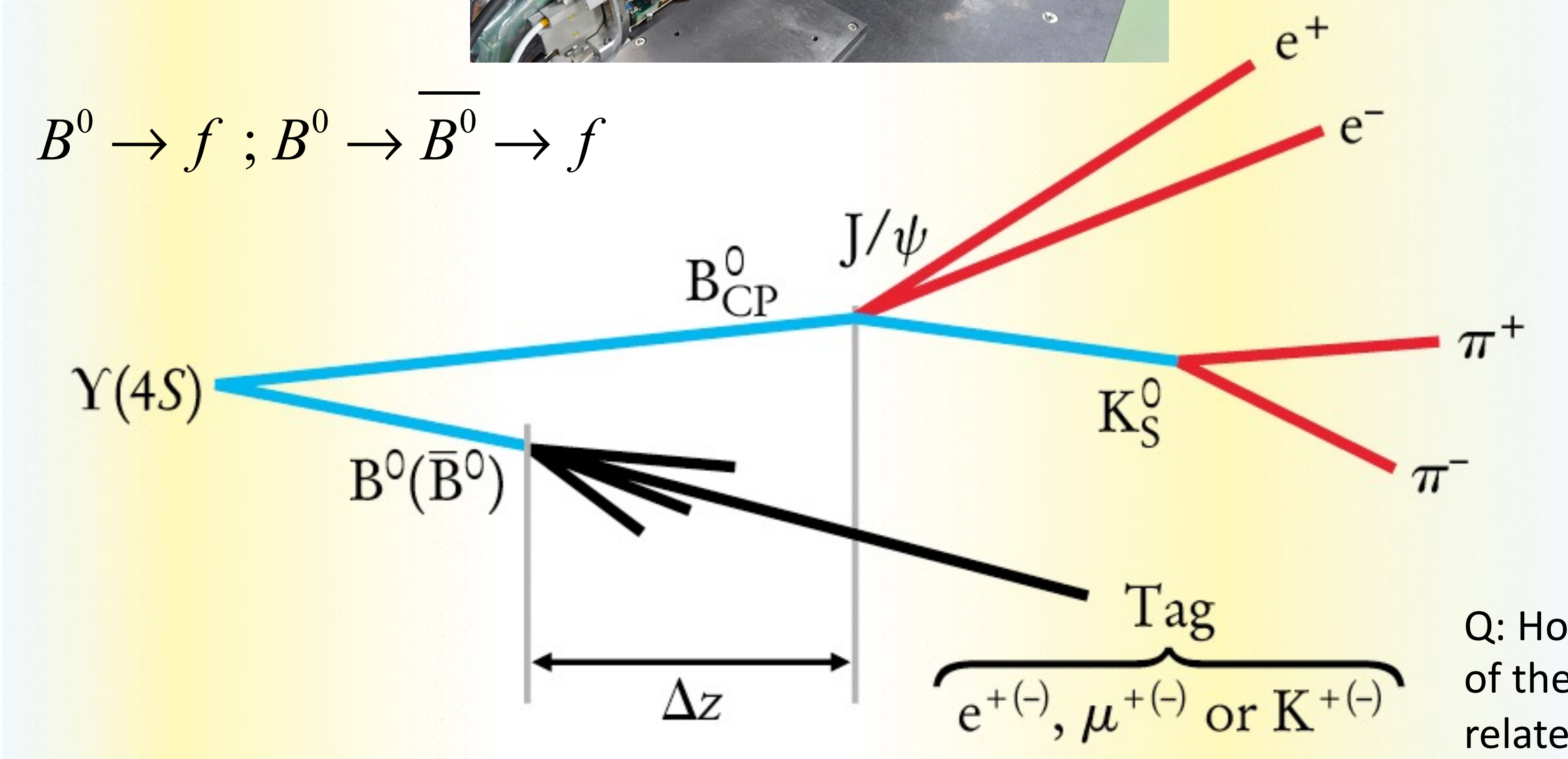
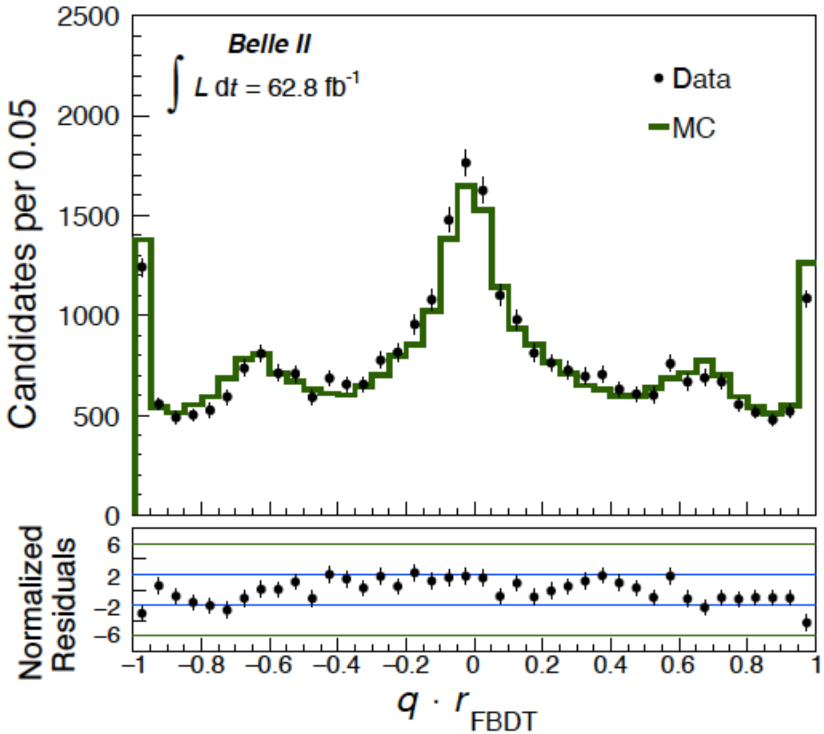


Figure credit: Physics Today

Q: How is the sign of the lepton related to the b flavor ?

Flavor Tagging (b quark or anti-b quark ?)



Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	l^-
Intermediate Kinetic Lepton	l^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum P*	l^-, π^-
Fast-Slow-Correlated (FSC)	l^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \to D^{*+}\ \overline{\nu}_\ell\ \ell^-$
$\hookrightarrow D^0\ \pi^+$
$\hookrightarrow X\ K^-$

$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$
$\hookrightarrow K^0\ \nu_\ell\ \ell^+$

$\overline{B}^0 \to \Lambda_c^+\ X^-$
$\hookrightarrow \Lambda\ \pi^+$
$\hookrightarrow p\ \pi^-$

Time-independent method with 62.8 fb^{-1}

	$\varepsilon_{\mathrm{eff},i} \pm \delta\varepsilon_{\mathrm{eff},i}$		
r- Interval	FBDT	DNN	Belle
0.000 – 0.100	0.1 ± 0.1	0.0 ± 0.1	0.0
0.100 – 0.250	0.5 ± 0.2	0.3 ± 0.1	0.4 ± 0.1
0.250 – 0.500	3.3 ± 0.5	2.3 ± 0.4	2.3 ± 0.1
0.500 – 0.625	3.3 ± 0.5	4.2 ± 0.5	3.5 ± 0.1
0.625 – 0.750	6.1 ± 0.6	3.8 ± 0.5	4.6 ± 0.2
0.750 – 0.875	5.4 ± 0.5	5.9 ± 0.6	5.5 ± 0.1
0.875 – 1.000	11.3 ± 0.6	12.3 ± 0.7	13.8 ± 0.3
Total	30.0 ± 1.3	28.8 ± 1.3	30.1 ± 0.4

So far, the fast BDT does better than deep learning neural net.

We obtain ε_*eff* = ε(1-2 w)^2 = 30.0+-1.2+-0.4 %, which is similar to the Belle result of 30.1+-0.4%

https://arxiv.org/abs/2008.02707, Published in EPJC

Last year, we had a breakthrough with GNNs (Graphical Neural Networks) → ε_eff = 37% (GFlat)

Flavor (mixing) asymmetry (for self-tagged decays) =

$$\frac{N(OF) - N(SF)}{N(OF) + N(SF)}$$

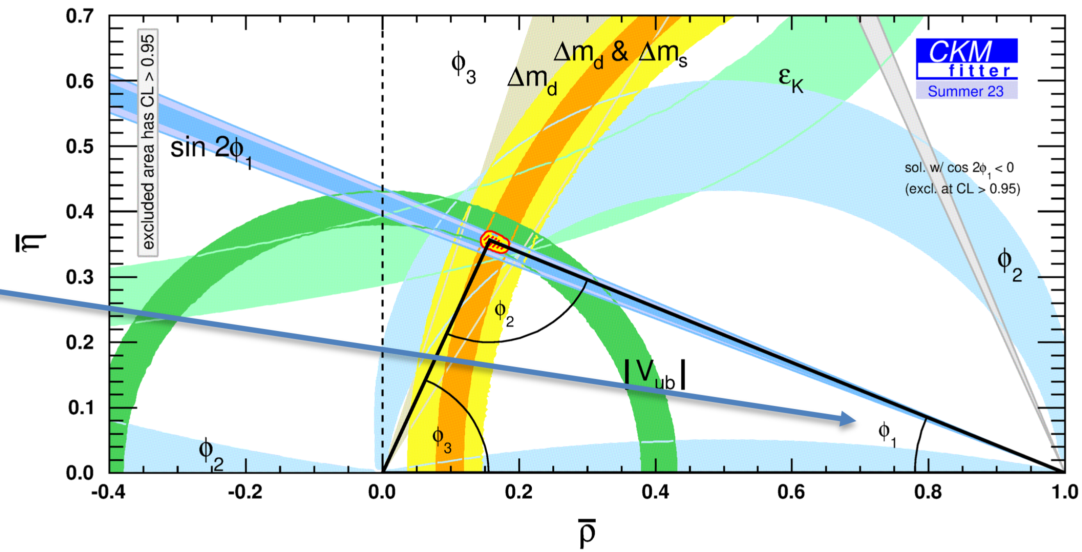
N(OF) = Number of opposite flavor pairs e.g B→D+ pi-, l+ tag

N(SF) = Number of opposite flavor pairs e.g B→D+ pi-, l- tag

CP Asymmetry (for CP eigenstates such as J/ψ K_S)

$$\frac{N(\bar{B}^0) - N(B^0)}{N(\bar{B}^0) + N(B^0)}$$

Measure interior angles of the unitarity triangle.

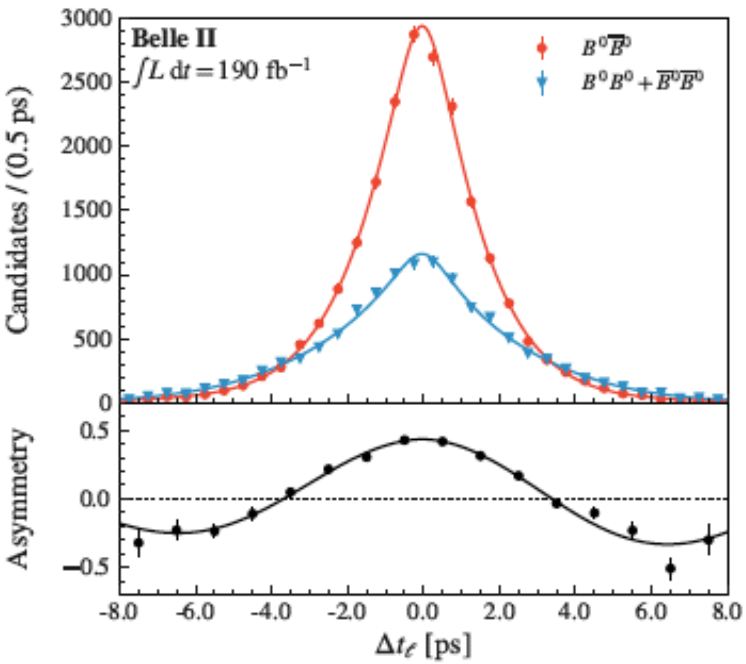


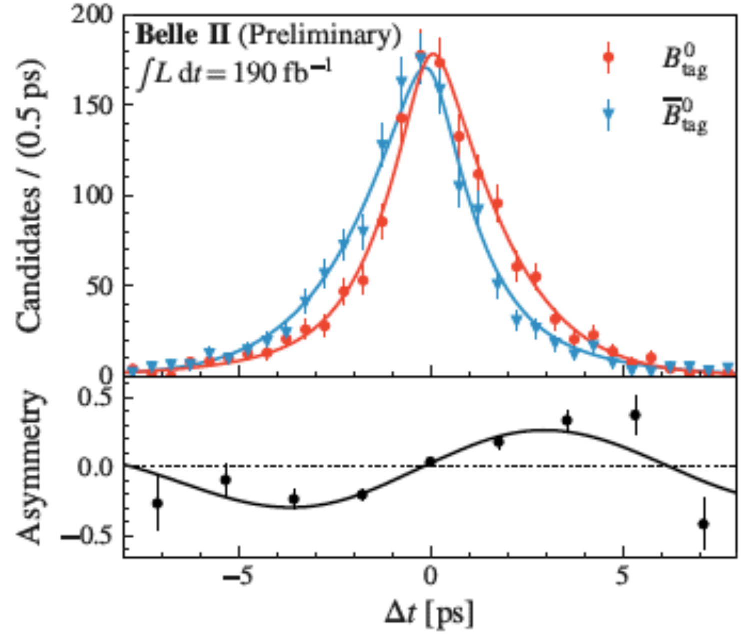
Verification of B-Bbar mixing (particle-anti particle mixing) in Belle II data (*not CPV*)

Verification of mixing induced CP Violation in *early* Belle II data using CP eigenstate

$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\mathrm{ps}^{-1}$$

Flavor specific states for mixing





https://arxiv.org/abs/2302.12791

https://arxiv.org/abs/2302.12898

Figure 1 – Projections of the Δt fit on the $B^0 \to D^{(*)-}\pi^+$ (left) and $B^0 \to J/\psi K^0_S$ (right) samples.

$$N_{SF/OF} \sim \frac{\exp(-|\Delta t|/\tau)}{4\tau}[1 \pm (1-2w)\cos(\Delta m_d \Delta t)] \otimes R(\Delta t)$$

$$N_{+/-} \sim \frac{\exp(-|\Delta t|/\tau)}{4\tau}\{1 \pm (1-2w)\sin(2\phi_1)\sin(\Delta m_d \Delta t)\} \otimes R(\Delta t)$$

$$\boxed{\sin(2\phi_1)[\sin(2\beta] = 0.720 \pm 0.062(stat) \pm 0.016(sys)}$$

Belle II TDCPV result with the GFlat Flavor Tagger using GNNs

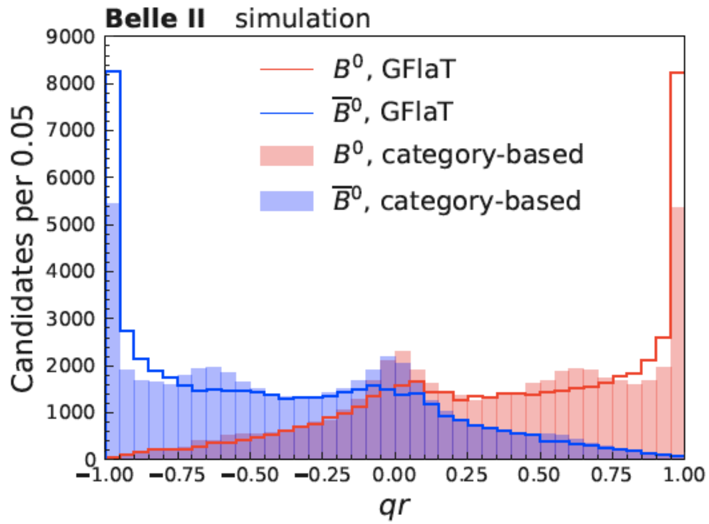
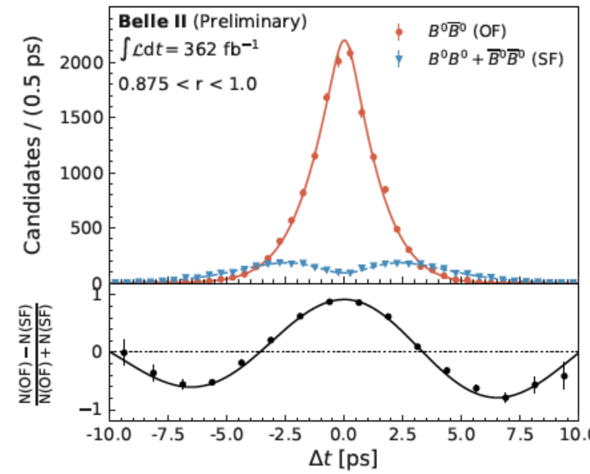
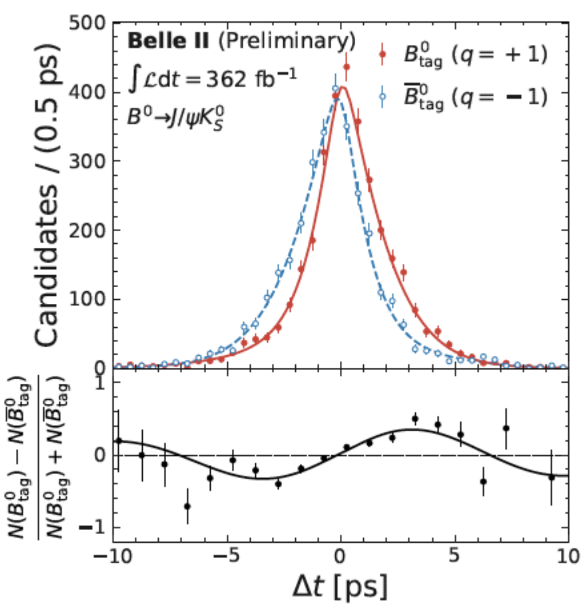


Figure 1. Distributions of qr for true B^0 and $\overline{B}^0$ from GFlaT

er in simulated data.





We demonstrate GFlaT by measuring S and C for $B^0 \to J/\psi K^0_{\mathrm{S}}$,

$$S = \quad 0.724 \pm 0.035 \pm 0.014, \tag{9}$$

$$C = -0.035 \pm 0.026 \pm 0.013, \tag{10}$$

This result with the full Run1 Belle II dataset (accepted for publication in Phys. Rev. D)

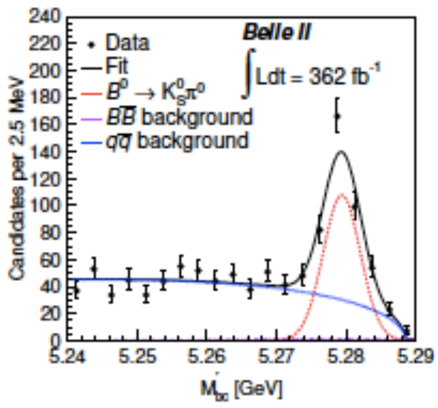
https://arxiv.org/abs/2402.17260

Belle II has results for $B \to K_S \pi^0$, ϕK_S, $\eta' K_S$, $K_S K_S K_S$ time-dependent CPV in $b \to s$ q qbar or penguin transitions (involving CKM element V_{ts}). These are statistics limited.

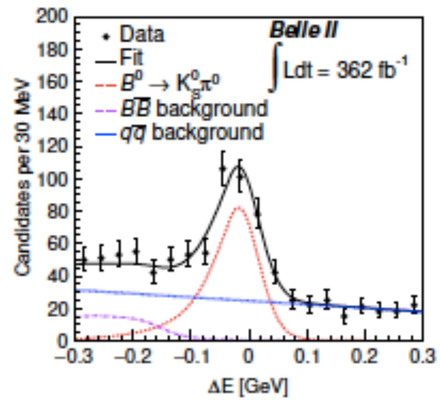
M_{bc} and ΔE (Jim Libby's talk)

Ole Miss Review question:

Does V_{ts} have a complex phase ?

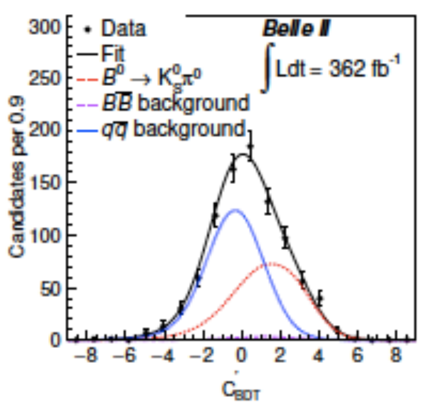


(a)

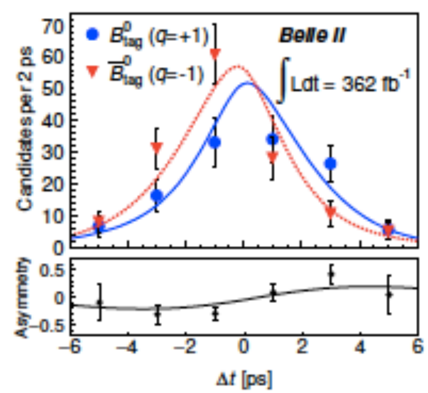


(b)

Here is one example from a recent PRL (Phys. Rev. Lett 131, 111803 (2023)



(c)

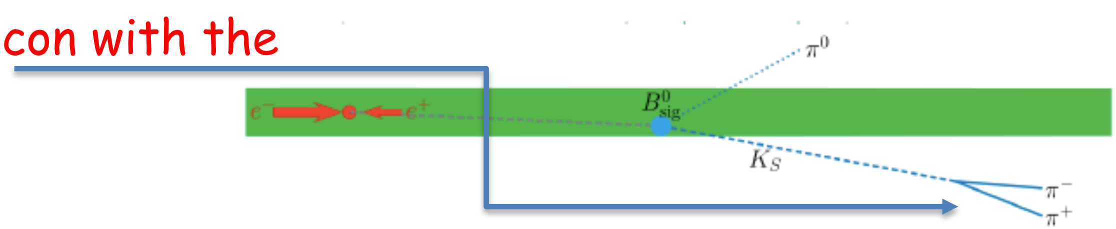


(d)

$$S = 0.75^{+0.20}_{-0.23} \pm 0.04$$

$$C = -0.04^{+0.14}_{-0.15} \pm 0.05$$

Idea: Ks vertexing in the silicon with the beam spot constraint.



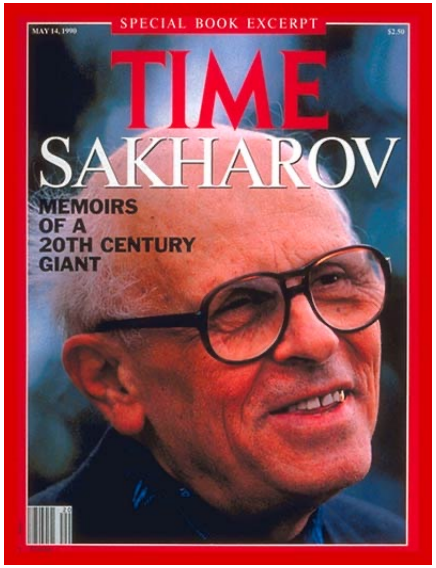
2008:

Critical Role of the B factories in Japan (KEK) and the US (SLAC) in the verification of the Kobayashi-Maskawa hypothesis was recognized and cited by the Nobel Foundation

A single irreducible complex phase accounts for all the matter-antimatter asymmetries in particle physics.

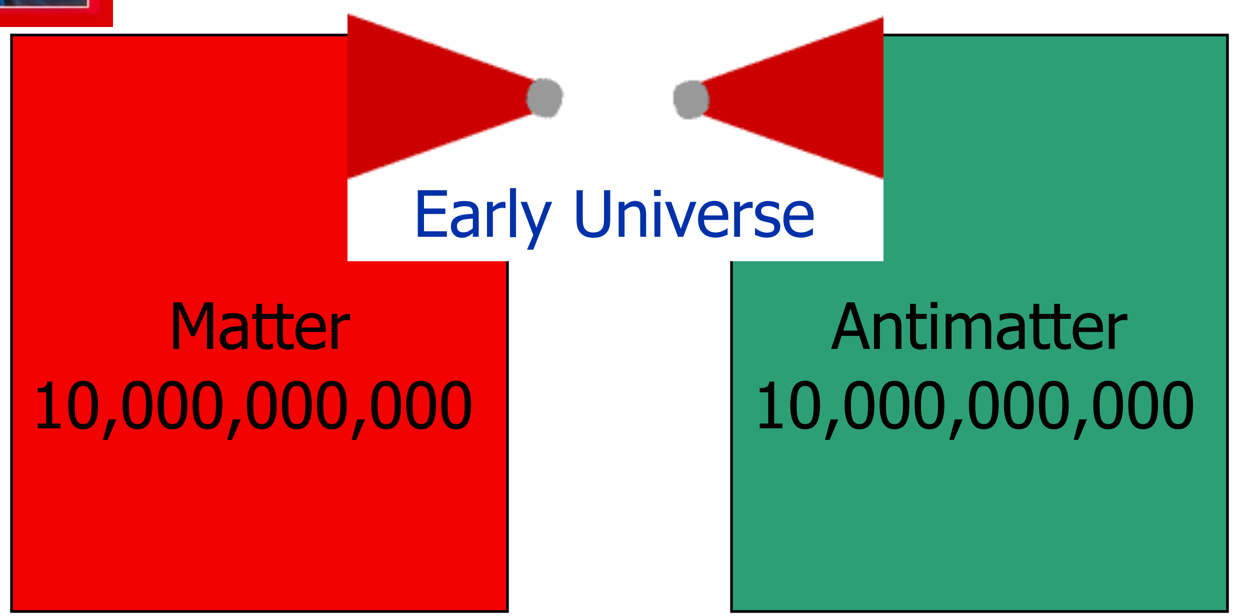
CP violating effects in the B sector are O(1) rather than O(10^{-3}) as in the kaon system.

Why is CP Violation Interesting ?



- *1967: Andrei Sakharov (brilliant Russian physicist and dissident): the cosmic connection linking particle physics with the existence of the Universe. CP violation (discovered in 1964 in neutral kaons) is the key.*

One of the three ingredients needed.



“Tsukuba, we have a Problem”

(with deep apologies to Tom Hanks and Apollo 13)

Former KEK DG Yamauchi

New KEK DG Asai

WMAP data

$$\boxed{\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}}$$

KM prediction

$$\left(\frac{n_b}{n_\gamma}\right)^{\mathrm{SM}} \propto \frac{J_{CP}}{T_c^{12}} \sim 10^{-20}$$

What does this mean ?

$$\left\{ \text{The CP Violation (matter-antimatter asymmetry) predicted by Kobayashi and Maskawa is too small, by} \sim\textit{10 orders of magnitude} \text{ in the Standard Model.} \right\}$$

Physics

Beyond the SM +

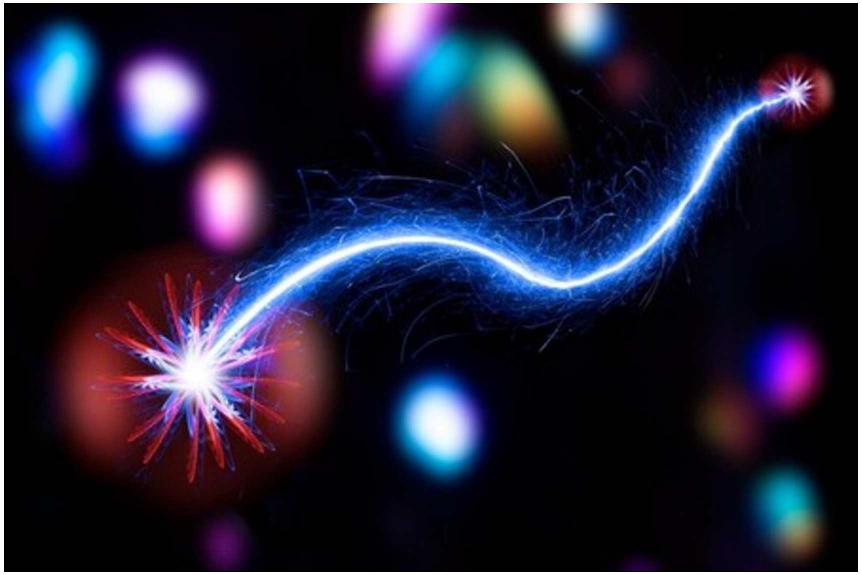
Discoveries ahead.

Let's briefly talk about quantum mechanics

Quantum mechanics is used everyday and in an essential way in particle physics along with special relativity.

Examples include Breit-Wigner resonances, the Heisenberg uncertainty principle, addition of angular momenta, symmetry operators and eigenstates, particle-antiparticle mixing etc….*but there are only a few examples of QM entanglement*

Einstein called QM entanglement, "spooky action at a distance".



Recently, ATLAS published a paper on QM entanglement for spins of top-anti top quark pairs produced at threshold. https://arxiv.org/abs/2311.07288

CMS followed up with their own paper https://arxiv.org/html/2406.03976v1

Sabine Hossenfelder Video on ATLAS result https://www.youtube.com/watch?v=lt7a3wjf3qY

The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state.**

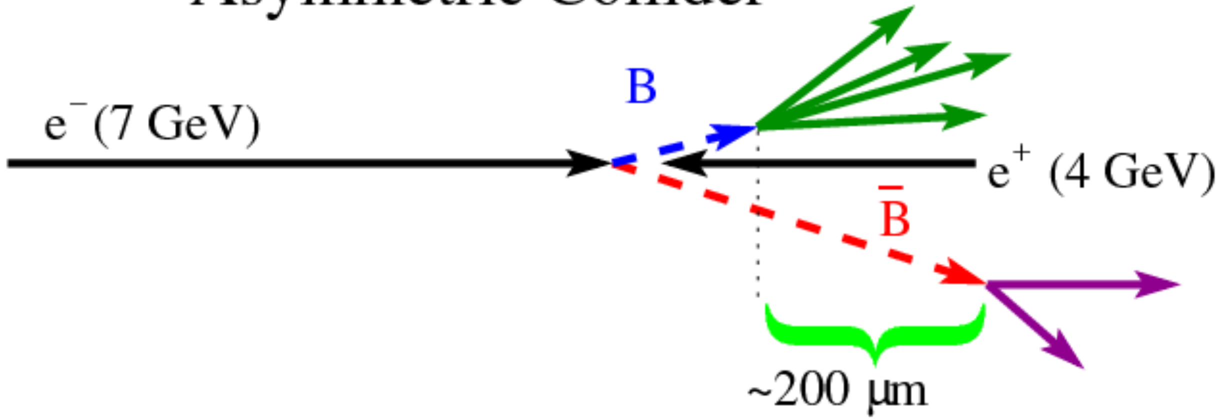
$$|\Psi>=|B^0(t_1,f_1)\overline{B^0}(t_2,f_2)>-|B^0(t_2,f_2)\overline{B^0}(t_1,f_1)>$$

(Why is there a minus sign ?)

Need to measure decay time differences to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (N.B. One B must decay before the other can mix) [*why ?*]

Asymmetric Collider



Not to scale

The beam energies are asymmetric (7 on 4 GeV)

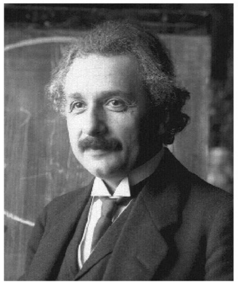
The decay distance is increased by around a factor ~7

Reminder: Quantum Mechanical Entanglement

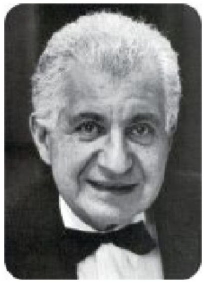
The wavefunction of the two-particle system is NOT the product of two independent wavefunctions.

Each B^0-anti B^0 pair is an Einstein-Podolsky-Rosen (EPR) experiment. Time dependence of mixing is determined by this feature.

You probably studied EPR in your QM course

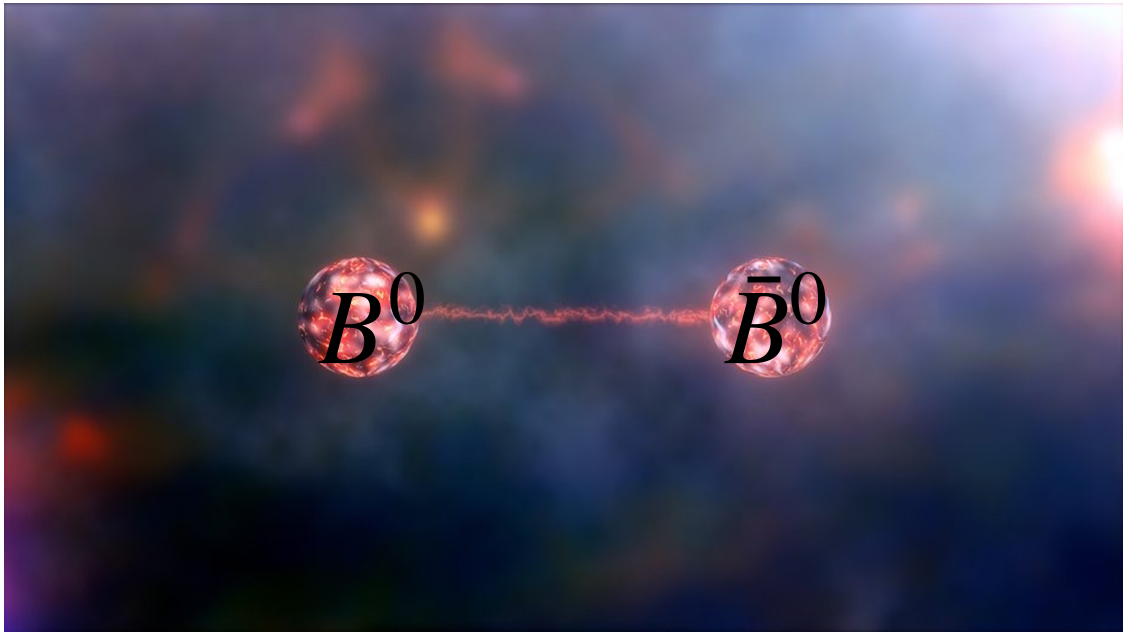


Albert Einstein



Boris Podolsky

Nathan Rosen



Original from Caltech outreach

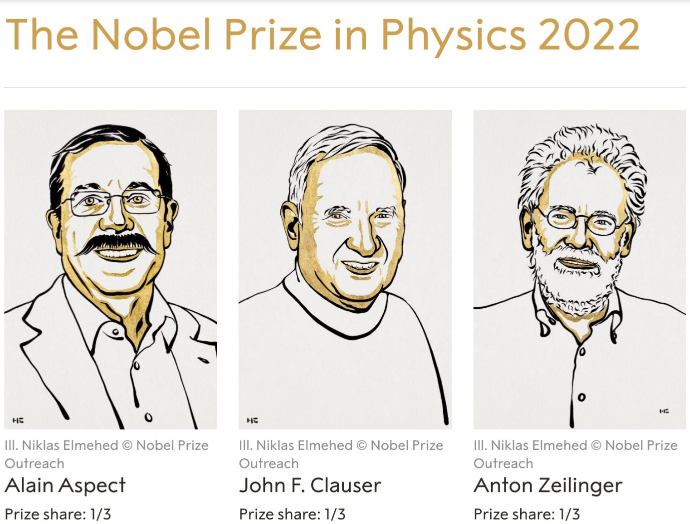
Figure credit: V. de Schwanberg/sciencesource.com

The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state.**

$$|\Psi\rangle = |B^0(t_1,f_1)\overline{B^0}(t_2,f_2)\rangle - |B^0(t_2,f_2)\overline{B^0}(t_1,f_1)\rangle$$ Ans: C=-1

Need to measure decay time differences to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (N.B. One B must decay before the other can mix) [Ans: otherwise the overall wavefunction is zero]



Nobel Prize for "QM Entanglement"

Each B^0-anti B^0 pair is an Einstein-Podolsky-Rosen (EPR) experiment.

Belle checked for the breakdown of QM in https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.131802 https://arxiv.org/abs/quant-ph/0702267

Q: Can Belle II do more on QM entanglement ? Ans: YES !

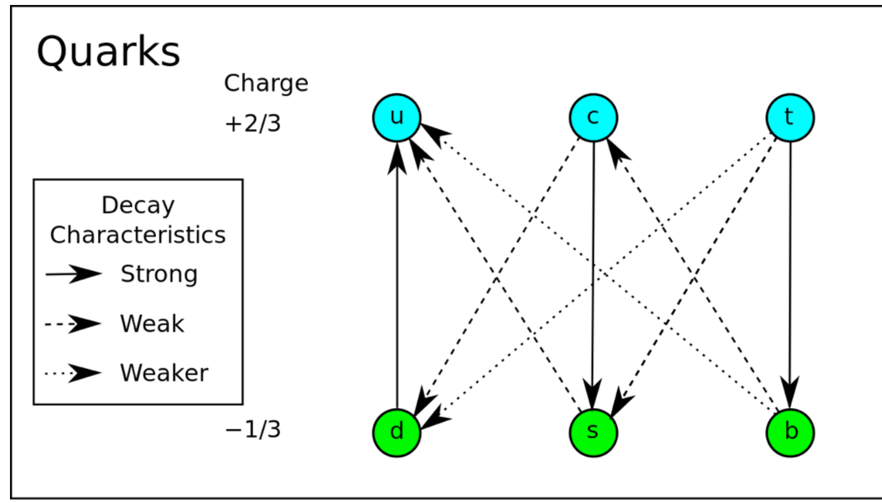
Let's review a few weak interaction fundamentals that are needed to understand rare decays and Belle II Physics.

Q: What is a rare decay of a B meson ?

Ans 1: A decay that is suppressed.

But compared to what ?

Ans: **Suppressed compared to a decay involving a b→c transition**, which is dominant (since b is a "down-type quark").



Q: So which transitions give rise to rare decays ?

Ans 1: *Decays that involve a jump in generations (extra CKM suppression)*

Ans 2: b→u decays

Q: But what about b→s or b→d transitions, why aren't they shown here ?

Spoiler Alert: They do not occur at 1st order in the weak interaction. Penguins or boxes.

Please remember strong decays do not change flavor.

Radiative Penguins in B decay

1975: Vainshtein, Zakharov and Shifman

Some examples:

$$B^0 \to K^{*0}\gamma \to K^+\pi^-\gamma$$

$$B^+ \to K^{*+}\gamma \to K^+\pi^0\gamma$$

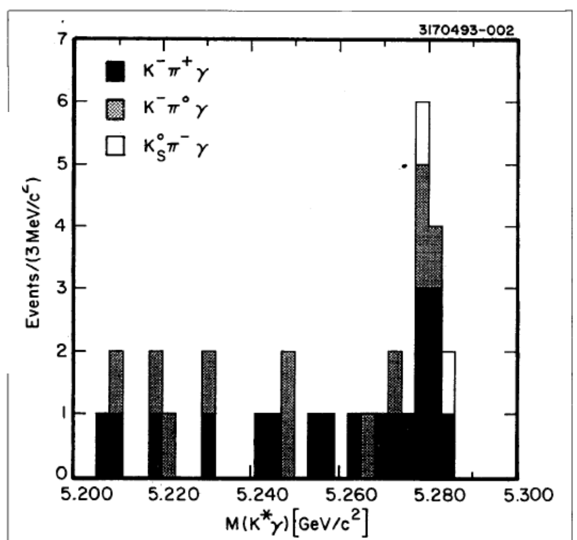
$$B^+ \to K^{*+}\gamma \to K_S^0\pi^+\gamma$$

John Ellis, the CERN theorist who coined the name "Penguin" (a type of FCNC).

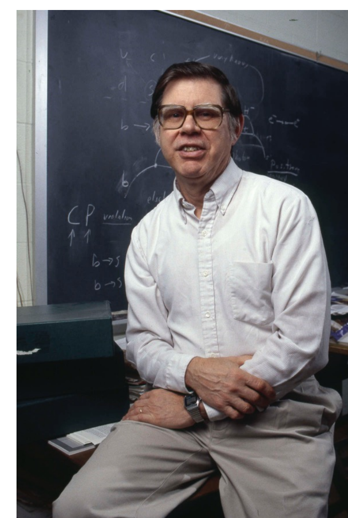
1993 CERN Courier:

CORNELL CLEO discovers B meson penguins

N.B. Using 1.5 x 10^6 B meson pairs (1.5 fb^{-1})/ less than Belle II/day



Ed Thorndike (1934-2023)



Belle II's CsI(Tl) calorimeter (~Belle with improved waveform sampling and timing). 8736 crystals covering 90% of the solid angle.

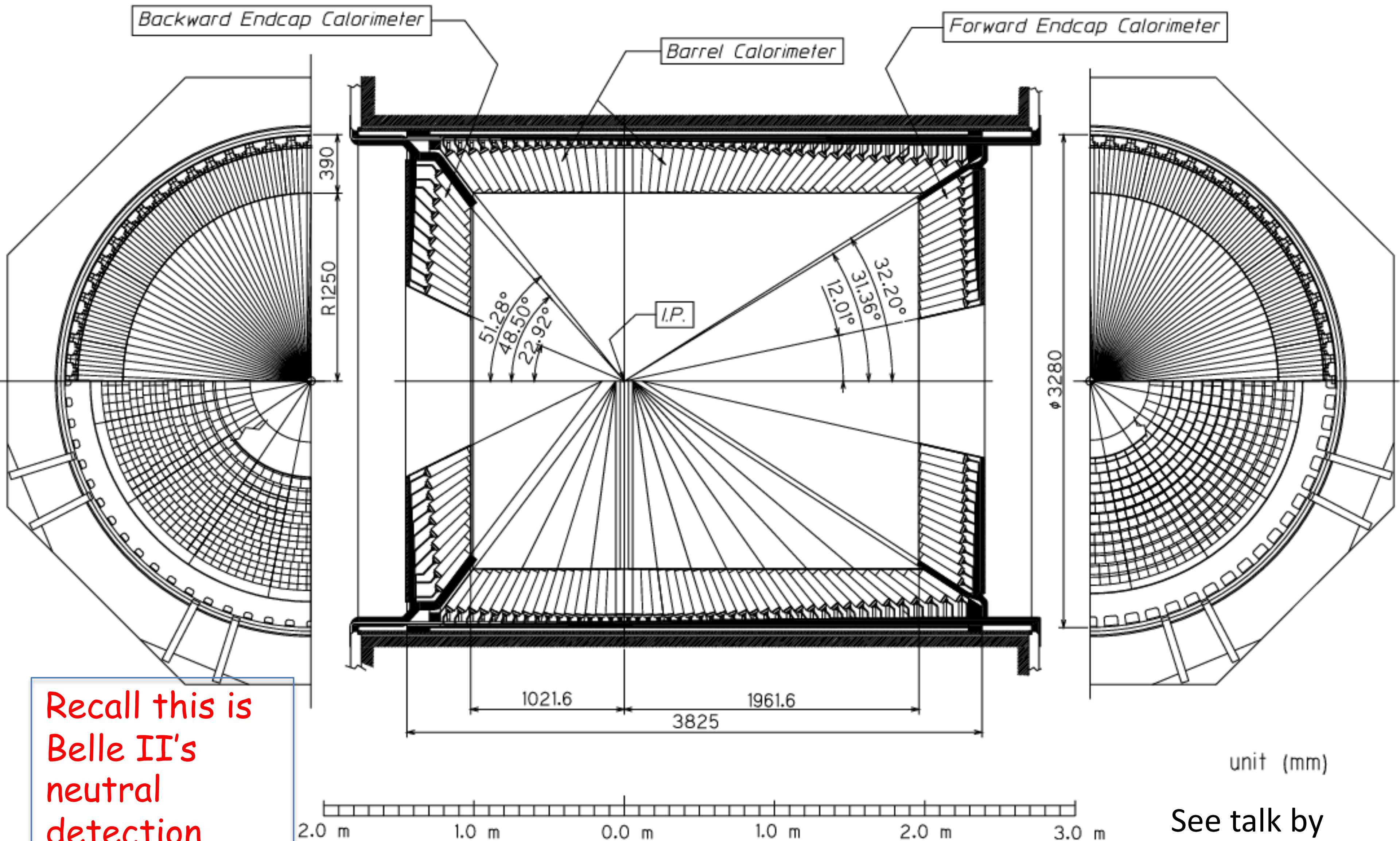


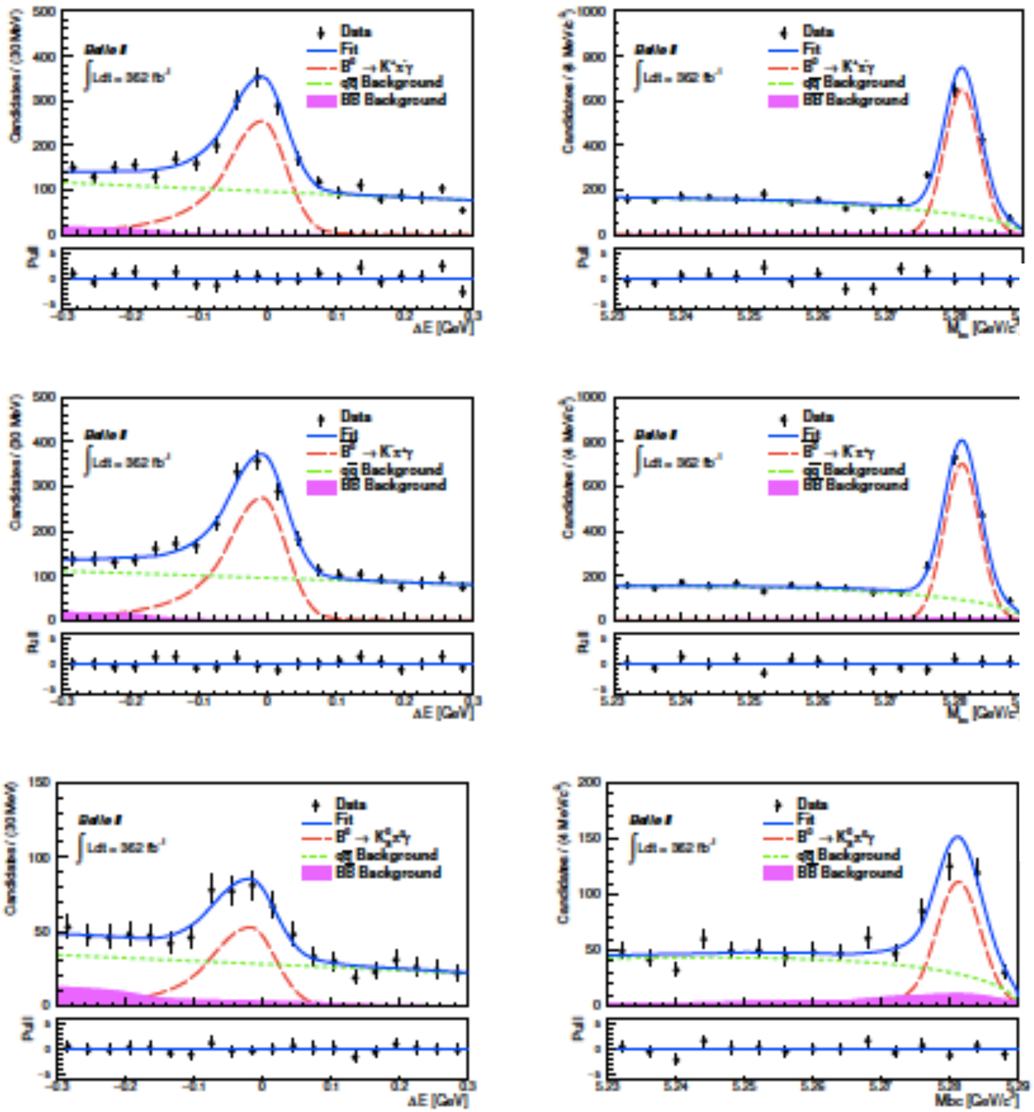
Fig. 69. Overall configuration of ECL.

Recall this is Belle II's neutral detection superpower

See talk by Leo Piilonen

Belle II, 2024

Some b→s radiative penguins at Belle II



Belle II publication in progress with 362 fb^{-1}, R. Tiwary et al.

Table 1. Number of signal, continuum and $B\overline{B}$ background events obtained from the fit.

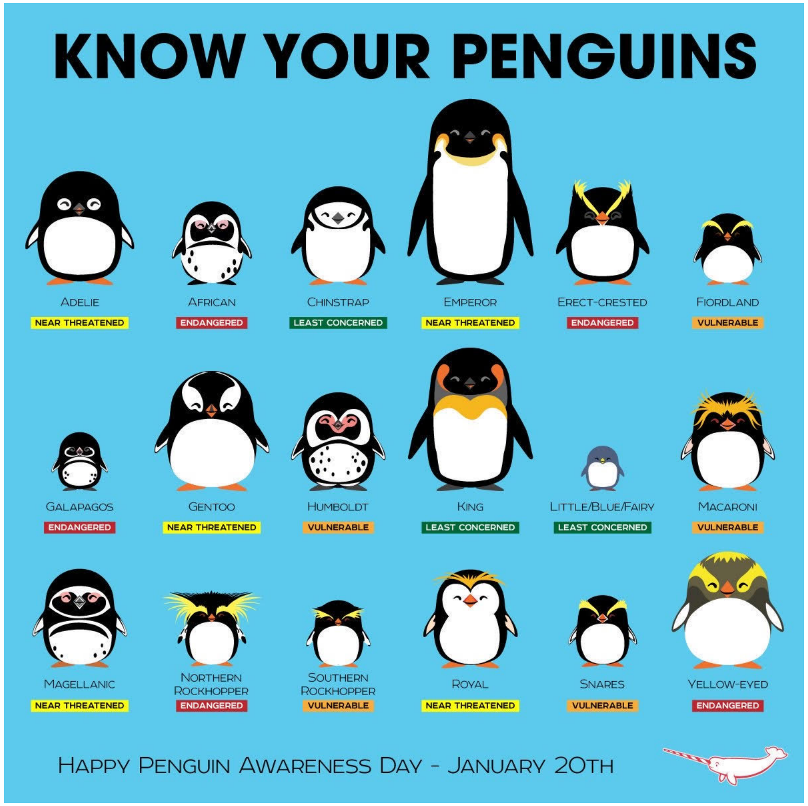
Channel	Signal	Continuum	$B\overline{B}$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	2198 ± 53	3830 ± 119	196 ± 80
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	233 ± 20	564 ± 49	93 ± 45
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	815 ± 35	2014 ± 115	259 ± 108
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	674 ± 29	1357 ± 78	113 ± 58

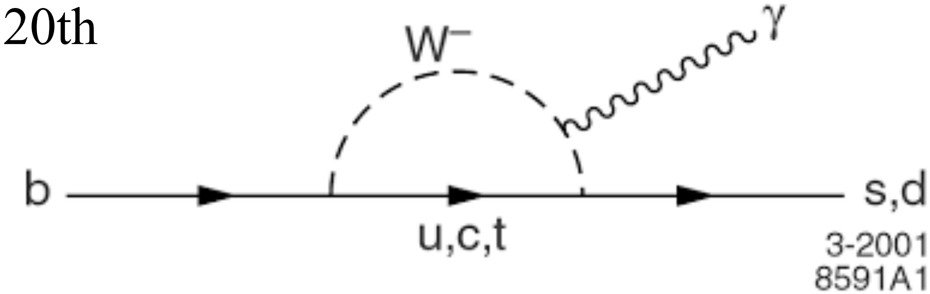
Table 2. Measured branching fractions, $\mathcal{A}_{CP}$, $\Delta\mathcal{A}_{CP}$, and Δ_{0+} for $B \to K^*\gamma$ channels. The first quoted uncertainties are statistical and the second are systematic.

Channel	$\mathcal{A}_{CP}$ (%)	$\mathcal{B}$ (10^{-5})
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$-3.2 \pm 2.4 \pm 0.4$	$4.15 \pm 0.10 \pm 0.11$
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	–	$4.24 \pm 0.37 \pm 0.23$
$B^0 \to K^{*0}\gamma$	$-3.2 \pm 2.4 \pm 0.4$	$4.16 \pm 0.10 \pm 0.11$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$1.5 \pm 4.2 \pm 0.9$	$3.91 \pm 0.18 \pm 0.19$
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$-3.5 \pm 4.3 \pm 0.7$	$4.13 \pm 0.19 \pm 0.13$
$B^+ \to K^{*+}\gamma$	$-1.0 \pm 3.0 \pm 0.6$	$4.04 \pm 0.13 \pm 0.13$
$B \to K^*\gamma$	$-2.3 \pm 1.9 \pm 0.3$	$4.12 \pm 0.08 \pm 0.11$
	$\Delta\mathcal{A}_{CP}$ (%)	Δ_{0+} (%)
$B \to K^*\gamma$	$2.2 \pm 3.8 \pm 0.7$	$5.1 \pm 2.0 \pm 1.5$

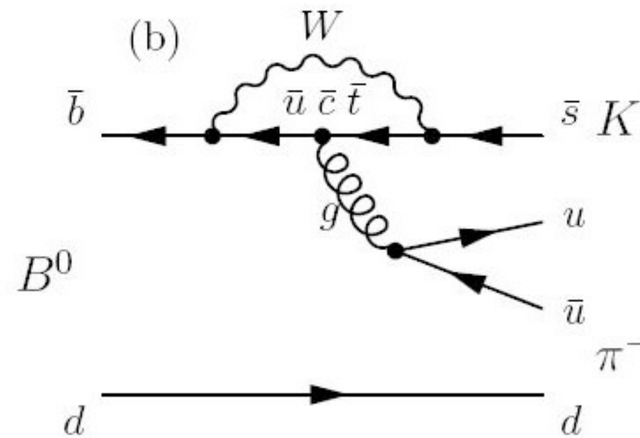
$$\Delta E = E_{recon} - E_{beam}$$

Recap for “Penguin Awareness Day”, Jan 20th

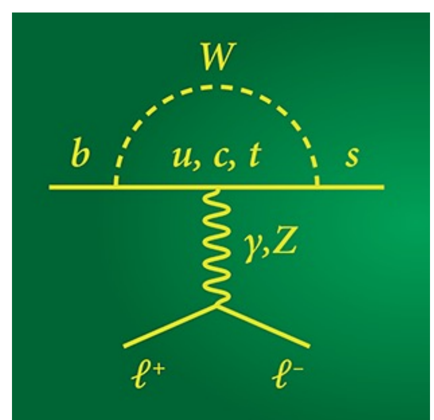




“Radiative Penguin”
(b→s γ)



“Gluonic Penguin”
(b→s gluon)



Q: But there is one more in our penguin taxonomy. Do you remember what it is?

Ans. Electroweak Penguins.
e.g. b→s [Z^*, γ^*]→s l+ l-

nature Vol 452|20 March 2008|doi:10.1038/nature06827

An old anomaly:

LETTERS

In 2008, “the K π puzzle” appeared in Nature.
Charged and neutral A(CP's) for B→Kπ penguins differ. Is this a sign of new physics ? *How do we tell ?*

Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

Also confirmed by BaBar and then LHCb

A_{CP}			
Mode	BaBar	Belle	LHCb
$K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
$K^+\pi^0$	$0.030 \pm 0.039 \pm 0.010$	$0.043 \pm 0.024 \pm 0.002$	0.025+-0.015+0.006
$K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$	$-0.011 \pm 0.021 \pm 0.006$	$-0.022 \pm 0.025 \pm 0.010$
$K^0\pi^0$	$-0.13 \pm 0.13 \pm 0.03$	$0.14 \pm 0.13 \pm 0.06$	

In summary, we have measured the CP asymmetries for $B \to K^\pm\pi^\mp$, $K^\pm\pi^0$ and $\pi^\pm\pi^0$ using 535 million $B\bar{B}$ pairs. Direct CP violation in $B^\pm \to K^\pm\pi^\mp$ is observed, accompanied by a large deviation between $\mathcal{A}_{K^\pm\pi^\mp}$ and $\mathcal{A}_{K^\pm\pi^0}$. Although this deviation could be due to our limited understanding of the strong interaction, the difference in direct CP asymmetries for charged versus neutral B decays may be an indication of new sources of CP violation beyond the standard model of particle physics.

How will we make progress ?

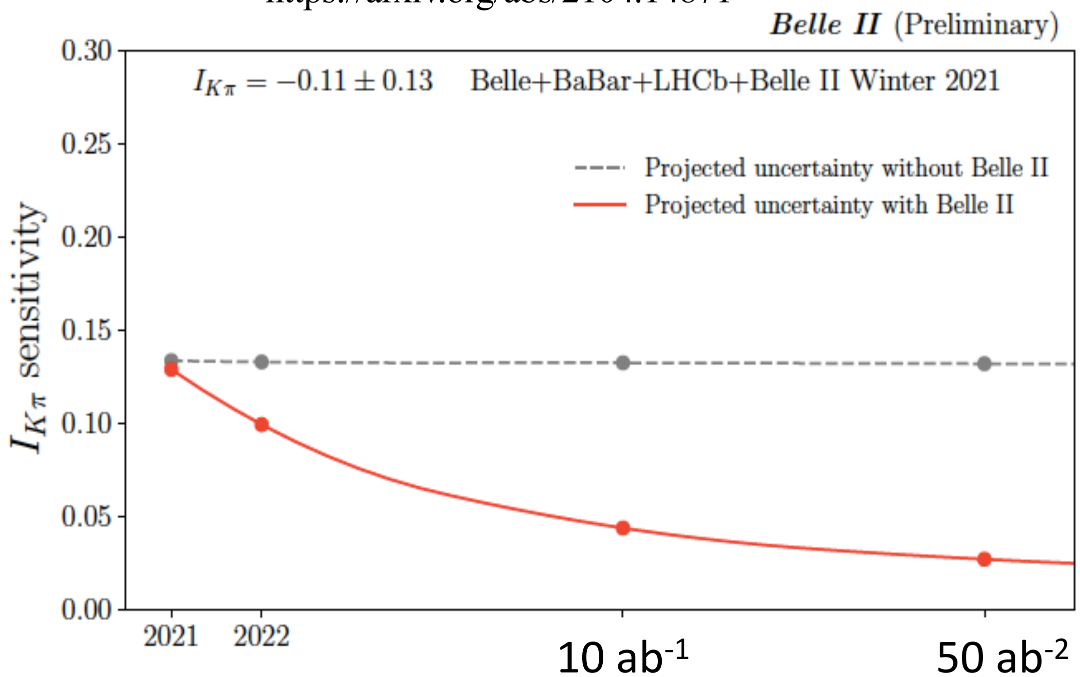
The isospin sum rule in the next decade.

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

https://arxiv.org/abs/2104.14871

Michael Gronau

The isospin sum rule detects enhanced NP electroweak penguins in B → $K\,\pi^-$



Requires neutrals *and* flavor tagging.

Without Belle II measurements of $A_{CP}(B^0 \rightarrow K^0\,\pi^0)$, we are stuck.

FIG. 4. The projected uncertainty on $I_{K\pi}$ with and without Belle II inputs. The inputs for $I_{K\pi}$ are averages of the estimated updates from ongoing LHCb and Belle II experiments with current world averages [10]. The red curve shows a projection when updates on the complete set of $K\pi$ measurements are considered, and the grey curve is the case if only $A_{K^+\pi^-}, A_{K^+\pi^0}, A_{K^0\pi^+}$ are updated by LHCb. The projection corresponds to the luminosity plans from LHCb and Belle II.

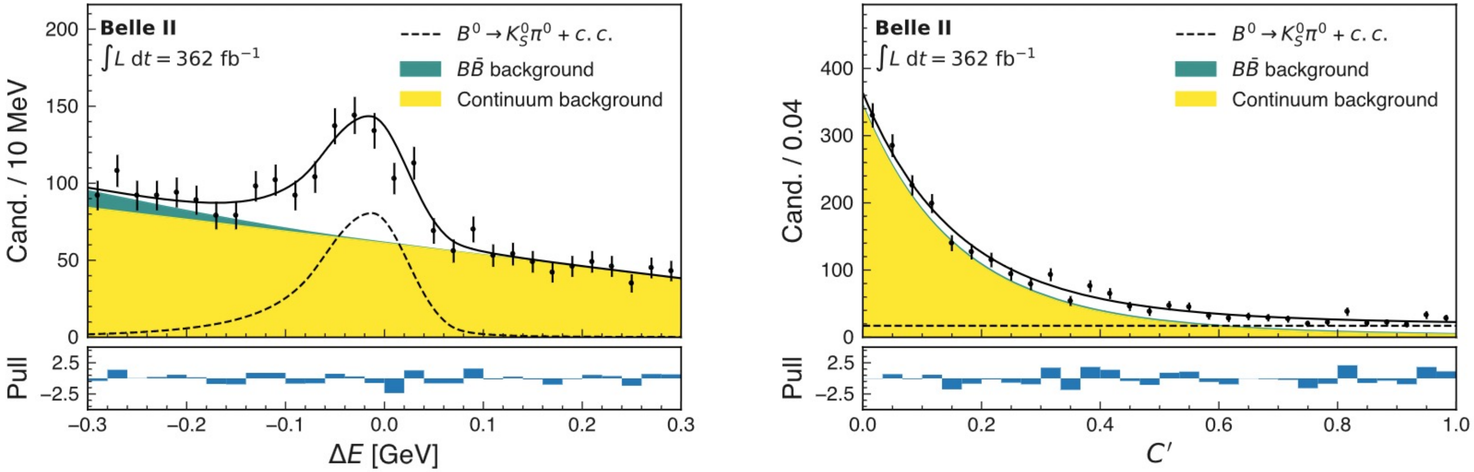
<u>Belle II recently *published* a new result on the B-->h h isospin sum rule.</u>

More on A_{CP} ($B \to K_S \pi^0$) and the isospin sum rule at Belle II

PHYSICAL REVIEW D **109**, 012001 (2024)

Also https://arxiv.org/abs/2310.06381

Measurement of branching fractions and direct *CP* asymmetries for $B \to K\pi$ and $B \to \pi\pi$ decays at Belle II



Signal yield = 502 ± 32

A_{CP} ($B \to K^0\ \pi^0$) = -0.06 $\pm 0.15(stat) \pm 0.05\ (syst)$

Time-independent method
(Requires flavor tagging i.e. discrimination of B^0 and anti-B^0).

Combine this with time-dependent result including overlaps and correlations

A_{CP} ($B \to K^0\ \pi^0$) = 0.04 $\pm 0.15(stat) \pm 0.05\ (syst)$

- Putting all together, we obtain an overall Belle II isospin test:

$$I_{K\pi} = -0.03 \pm 0.13(stat) \pm 0.05(syst)$$

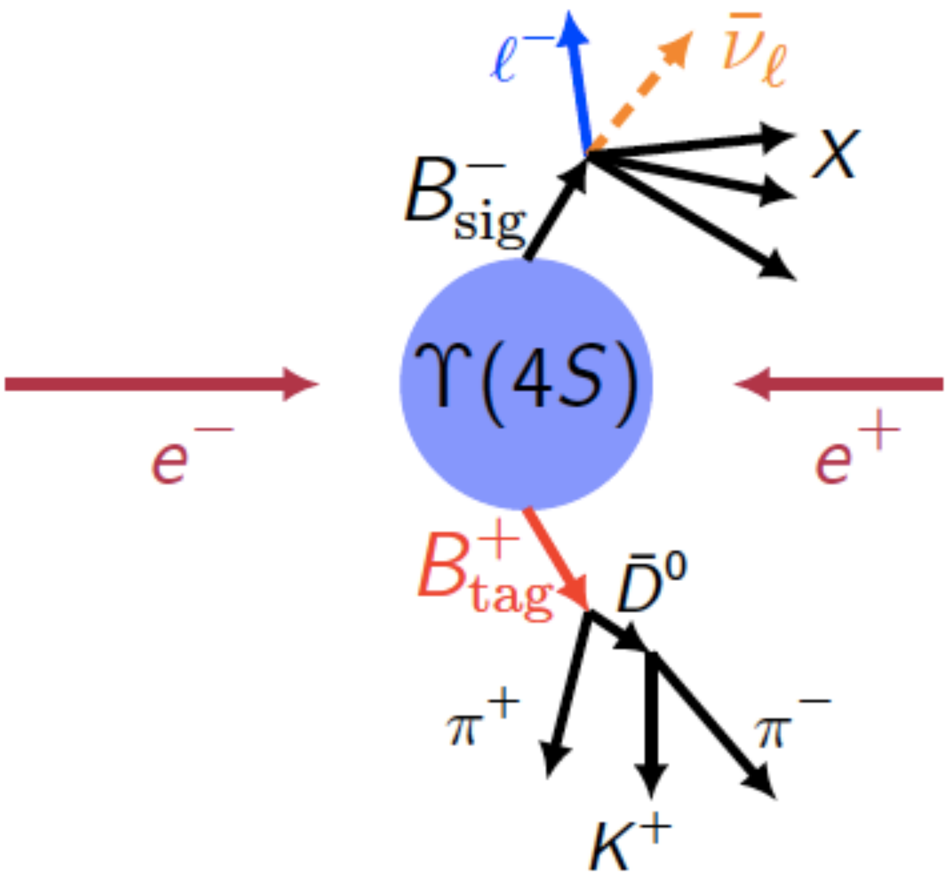
Which Belle II capabilities might be relevant for BSM physics ?

Full and equally strong capabilities for electrons and muons

See talk by Leo Piilonen

Photons, K_S's with excellent resolution and efficiency

Neutrinos via "missing energy" and missing momentum. Hermeticity.



Another Belle II "Superpower"

https://arxiv.org/abs/2008.06096

This is now called FEI "Full Event Interpretation" and uses large numbers of tag modes via a BDT (Boosted Decision Tree).

$Clean\ but\ effiency\ \varepsilon{\sim}0.5\%$

T. Keck et al., Comput. Softw. Big Sci. 3, 6 (2019), arXiv:1807.08680 [hep-ex].

Lepton Universality Tests in b→s l+ l- transitions

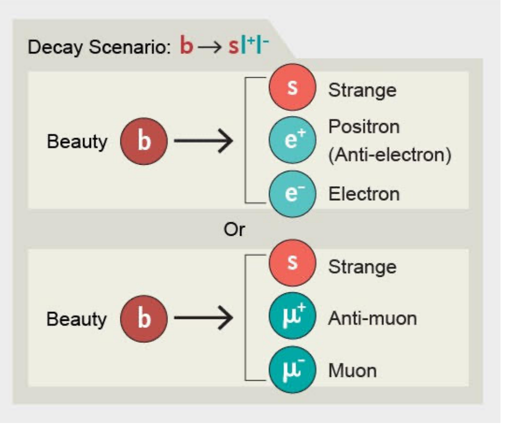
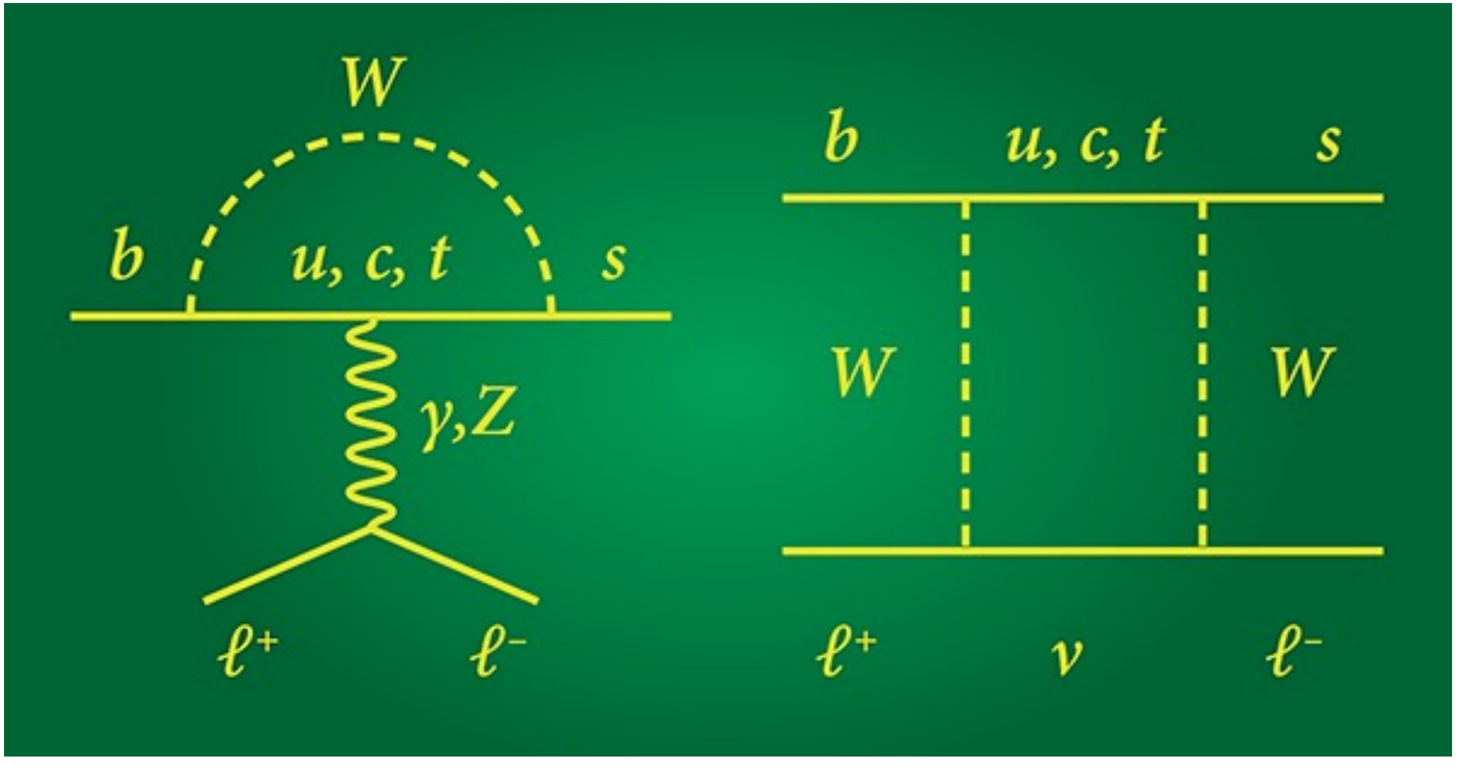


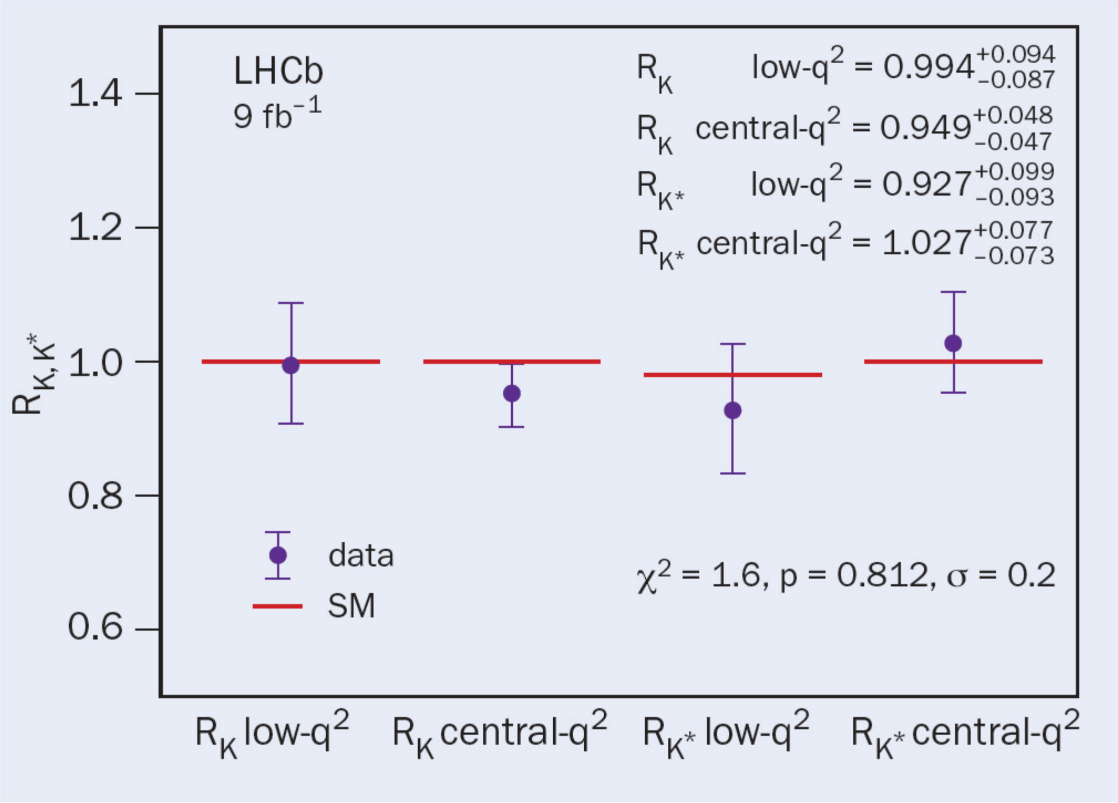
Figure credit: Scientific American



"Electroweak Penguin" "Box"

Possible breakdown of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, was reported in 2021.

https://arxiv.org/abs/2103.11769, and published in Nature



Alas, a mistake was found in the analysis.

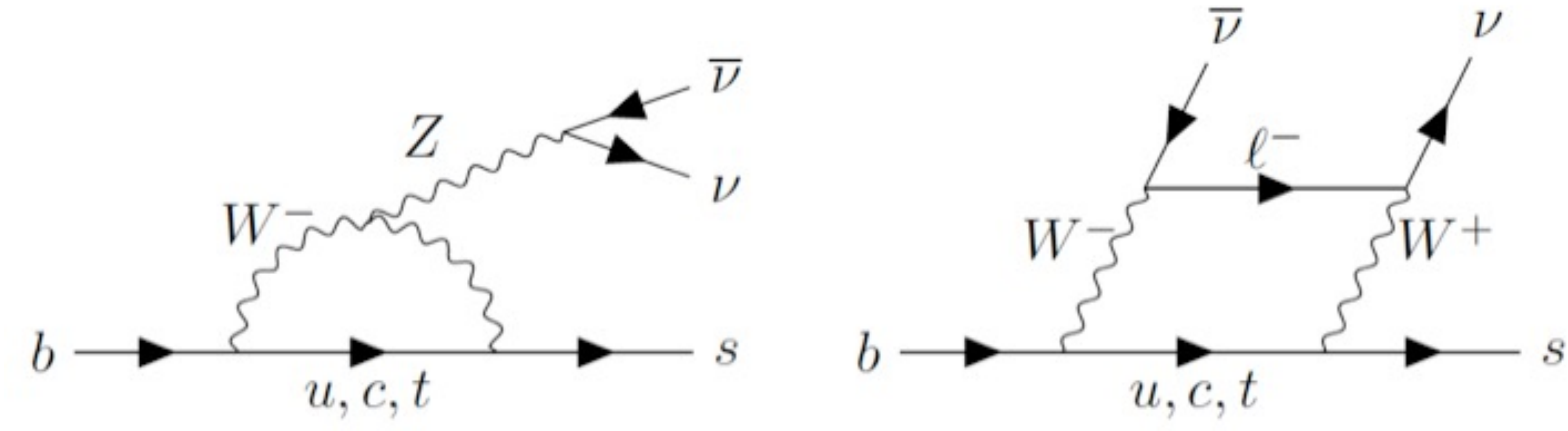
Details in https://arxiv.org/abs/2212.09153

Updated results for R_K *consistent with unity* published in PRL 131, 058013 (2023)

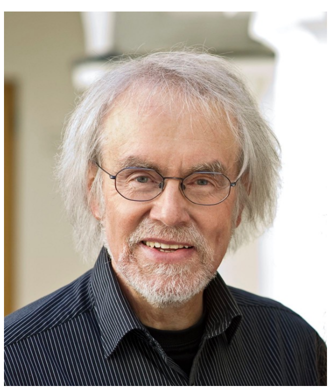
Still hints in angular asymmetries

"Although a component of this shift can be attributed to statistical effects, it is understood that this change is primarily due to systematic effects," explains LHCb spokesperson Chris Parkes of the University of Manchester. "The systematic shift in R(K) in the central q^2 region compared to the 2021 result stems from an *improved understanding of misidentified hadronic backgrounds to electrons*, due to an underestimation of such backgrounds and the description of the distribution of these components in the fit. New datasets will allow us to further research this interesting topic, along with other key measurements relevant to the flavour anomalies." –CERN Courier Dec 2022

$B \to K\nu\bar{\nu}$: BSM without hadronic uncertainties



(a) Penguin diagram (b) Box diagram



Andrezj Buras

Note that in contrast to $B \to K^{(*)}\, l^+ \, l^-$ angular asymmetries, there are NO "dirty" long distance (charm annihilation) $b \to c$ cbar s contributions from $B \to J/\psi\, K^{(*)}$ and $B \to \psi(2S)\, K^{(*)}$

For example, https://arxiv.org/abs/1409.4557

The $B \to K^{(*)}$ ν *vbar* missing energy modes are accessible to Belle II (and Belle), but might be difficult at a hadron experiment.

Signal: B→K ν ν

[Belle II reports a 3.5σ excess or "evidence"]

http://arxiv.org/abs/2311.14647 (published in PRD)

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging. (X 10-20 ε compared to FEI, but large bkgs).

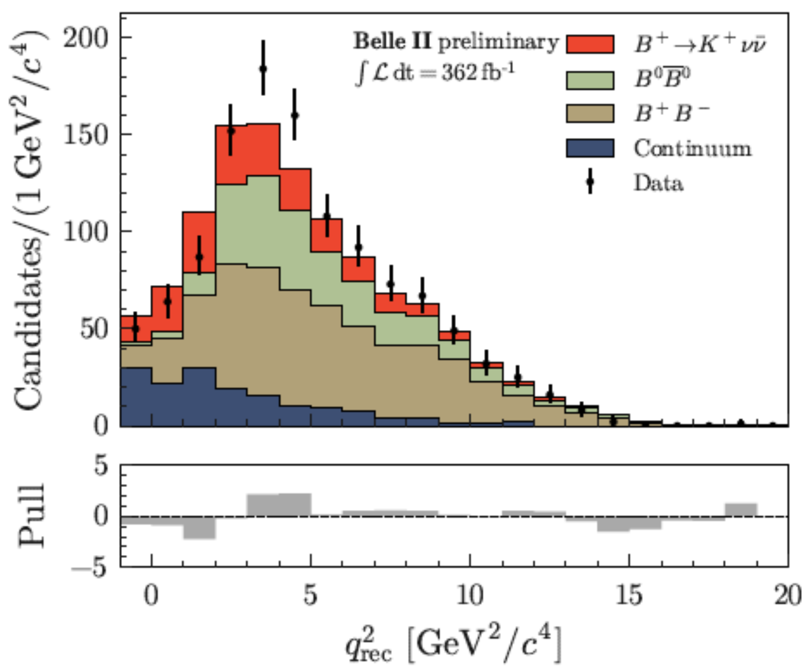
Now add on some ML/AI (boosted decision trees or BDTs) to help us tame the large backgrounds.

Fits in bins of BDT2 and q^2

- **Signal candidate:**
  - an identified charged kaon that gives the minimal mass of the neutrino pair q^2_{rec} (computed as K^+ recoil)

Event (pre-selection):	BDT$_1$ (first filter):	BDT$_2$ (final selection):
• $4 \le N_{track} \le 10$ • $E_{total} > 4$ GeV • $17^o < \vartheta_{miss} < 160^o$	• 12 event-shape based kinematic variables	• *35 input variables*: using signal, event, and their correlations

Distributions for the signal-enhanced region in the ITA (Inclusive tagged analysis)



B→K ν νbar: BSM without hadronic uncertainties

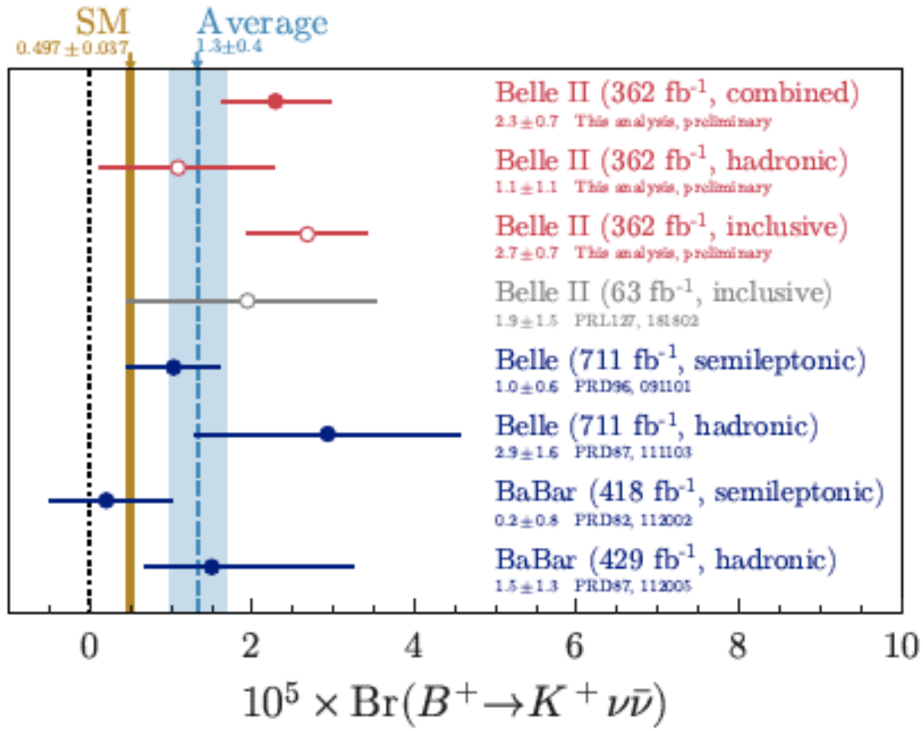
A new anomaly is emerging (now ~2.7σ from the SM)

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

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.

Phys. Rev. Lett. 127, 181802, (2021) and a consistency check with hadronic FEI.

Can now apply to old Belle data too.



It is quite possible that NP shows up in b→s nu nubar and not b→s l+ l- or vice-versa.
Perhaps third generation couplings b->s $\tau^+\tau^-$ are enhanced ?

Dark matter could also play a major role.

>>>This is one way that Belle II could discover BSM Physics soon <<<

B Physics with Belle II@SuperKEKB/ "Take home" message

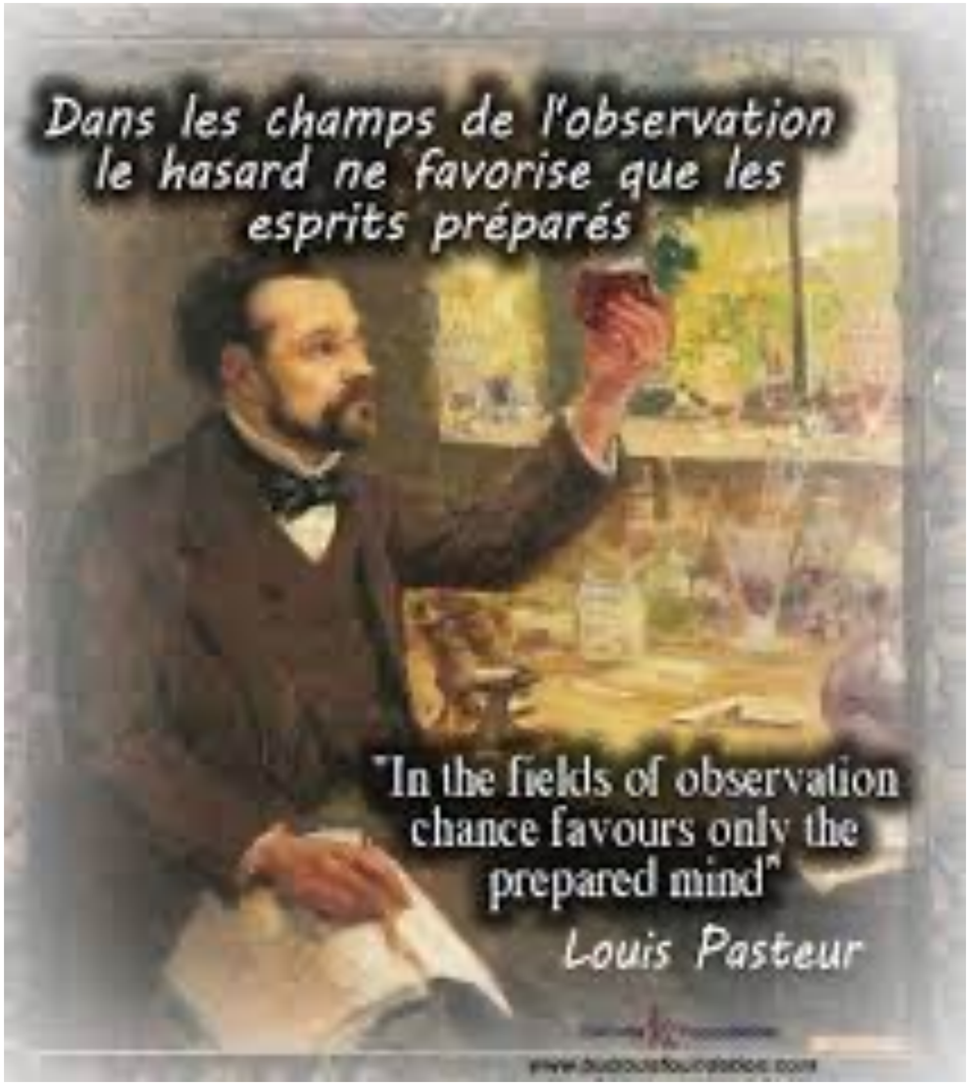
Quantum mechanics, entanglement, symmetry and *symmetry breaking* are at the heart of the particle physics in Belle II

Two core parts of the Belle II physics program were discussed today:
Time-Dependent CP Violation
Rare Decays

Early career researchers need to understand these results and measurements to prepare for their own discoveries.
Try the exercises.

Dr Raynette Tonder will discuss CKM measurements and semileptonic decays next.

Review questions and Backup slides



Review questions

What are the three types of CP violation ?

Ans: I *CP violation in mixing* i.e. violation in the wavefunction ($\Delta S=2$), "epsilon" in the kaon system.

Ans: II *CP violation in the decay amplitude* a.k.a. "direct CP violation", "epsilon-prime' ($\Delta S=1$ or $\Delta B=1$)

Ans: III CP violation due to the interference between decays with and without mixing. ($\Delta B=2$)

Weak Interaction Review question:

Find the valence quark composition, dependence on CKM matrix elements and relative rates of the following processes (order them by strength).

$$1)\ B^0 \rightarrow D^- \pi^+$$

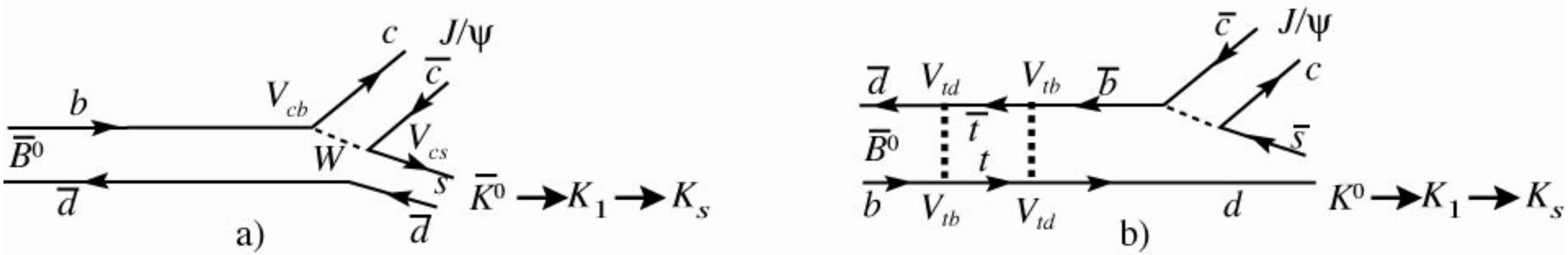
$$2)\ B^0 \rightarrow \pi^- \pi^+$$

$$3)\ B^0 \rightarrow \pi^- K^+$$

$$4)\ B^0 \rightarrow D^- K^+$$

Hint: B^0 = bbar d or anti-B^0= b dbar

Diagrams for $B \rightarrow J/\psi\ K_S$



Review Question: Why is this process CP violating ?

Ans: The element V_{td} is complex and the amplitudes interfere.

Meson mixing and CP violation in the B_d and B_s systems.

Bd-anti Bd mixing 2023

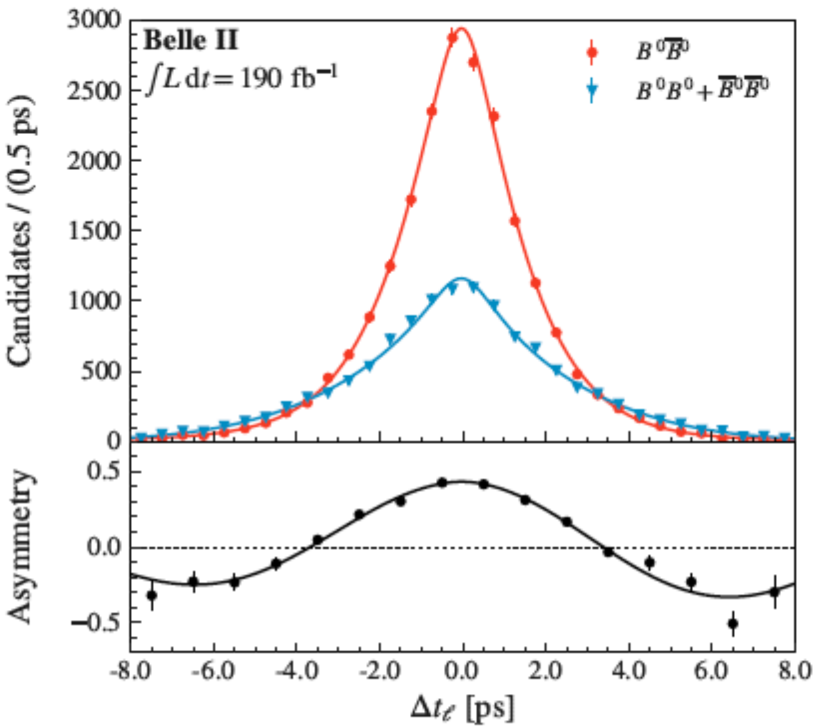
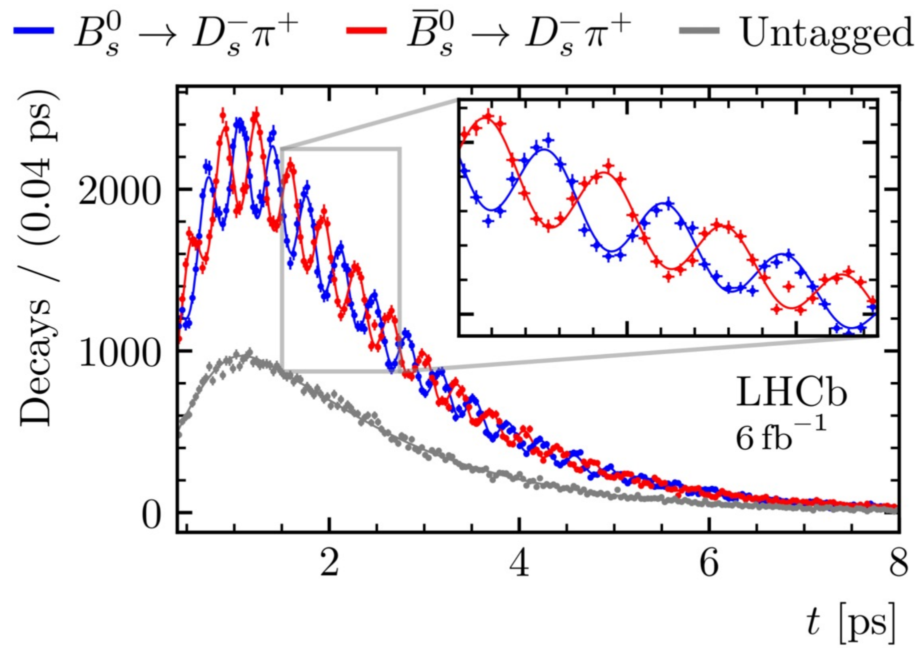


FIG. 3. Distribution of Δt_ℓ in data (points) and the fit model (lines) for opposite-flavor candidate pairs (red) and same-flavor pairs (blue) and their asymmetry (black).

Bs-anti Bs mixing 2022



Ole Miss Review question: Do we expect large CPV in Bs mixing ? Explain.

Exercise:
Draw the Feynman diagrams for
1) $B \rightarrow K^* \gamma$
2) $B \rightarrow \rho \gamma$

How is the ratio of 2) to 1) related to a ratio of CKM matrix elements ?

Can this CKM ratio be obtained from another method ?

Exercise:
What decay modes and final states are used for

$\phi 1, \quad \phi 2, \quad \phi 3$

determinations ?

Draw the appropriate Feynman diagrams.

Which ones involve loops (boxes) ?
Which ones involve tree diagrams ?

Strong interaction eigenstates:

$K^0, \overline{K^0}$

Weak interaction eigenstates:

K_S, K_L

Table 8.1. Lifetimes, total widths and mass differences of the pseudoscalar neutral flavoured mesons

	τ (ps)	$c\tau$ (μm)	Γ (ps^{-1})	Γ (meV)	Δm (ps^{-1})	Δm (meV)
K_L	$51.16 \pm 0.21 \times 10^3$	15.3×10^6	2.0×10^{-5}	1.3×10^{-5}	$0.005\,292 \pm 0.000\,009$	$0.003\,483 \pm 0.000\,006$
K_S	89.54 ± 0.05	2.67×10^4	0.011	7.4×10^{-3}		
D_H	0.4101 ± 0.0015	123	2.4	1.61	0.0145 ± 0.0056	0.0096 ± 0.0037
D_L	0.4101 ± 0.0015					
B_H	1.519 ± 0.007	459	0.65	0.43	0.507 ± 0.005	0.3337 ± 0.0033
B_L	1.519 ± 0.007					
B_{sH}	1.497 ± 0.015	439	0.86	0.57	17.69 ± 0.08	11.5 ± 0.5
B_{sL}	1.497 ± 0.015					

Question: How much do the K_S and K_L lifetimes differ ?
What is the mass difference in milli-electron volts ?

More Backup Slides

“You cannot swim for new horizons until you have courage to lose sight of the shore.”
— William Faulkner

Yet Parity is Violated

Particles w/ Strange quarks

- Same mass, same lifetime, BUT

$\theta \rightarrow \pi^+ \pi^0$ (21%) $P(\theta) = +1$

$\tau \rightarrow \pi^+ \pi^- \pi^+$ (6%) $P(\tau) = -1$

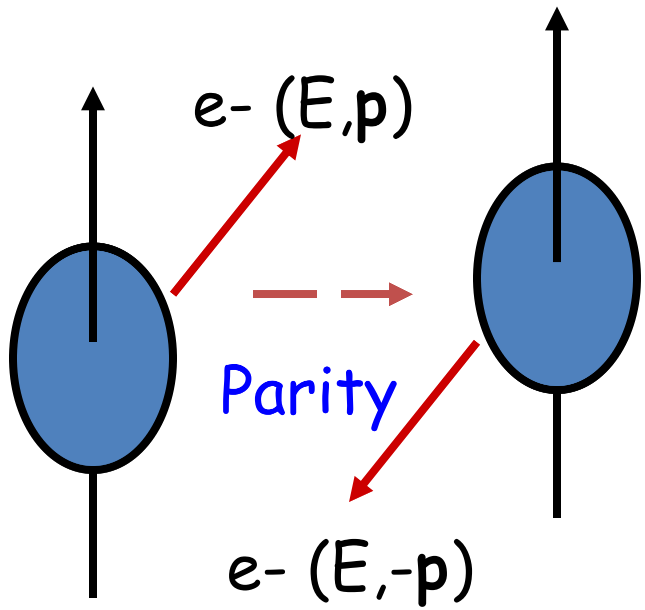
Actually both K^+

C.N Yang & T.D. Lee, 1956

Experimental discovery

B field

Co^{60}Nuclei spin aligned Beta decay to Ni^{*60}



Pauli: "I do not believe that the Lord is a weak left-hander"

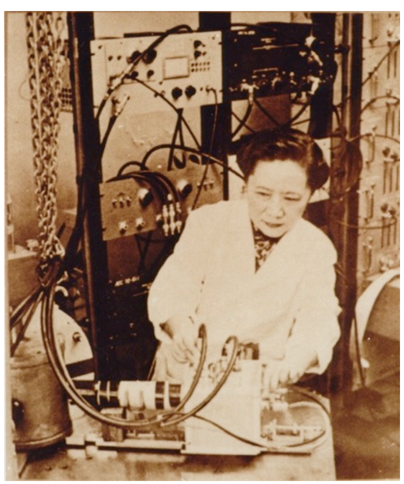
Initial conclusion from Madame Wu's experiment and from theorists Lee and Yang

Parity (P) is violated in the weak interaction

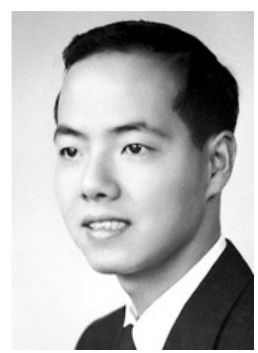
But expect CP should be preserved (or "conserved") in the weak interaction.

C.S. Wu

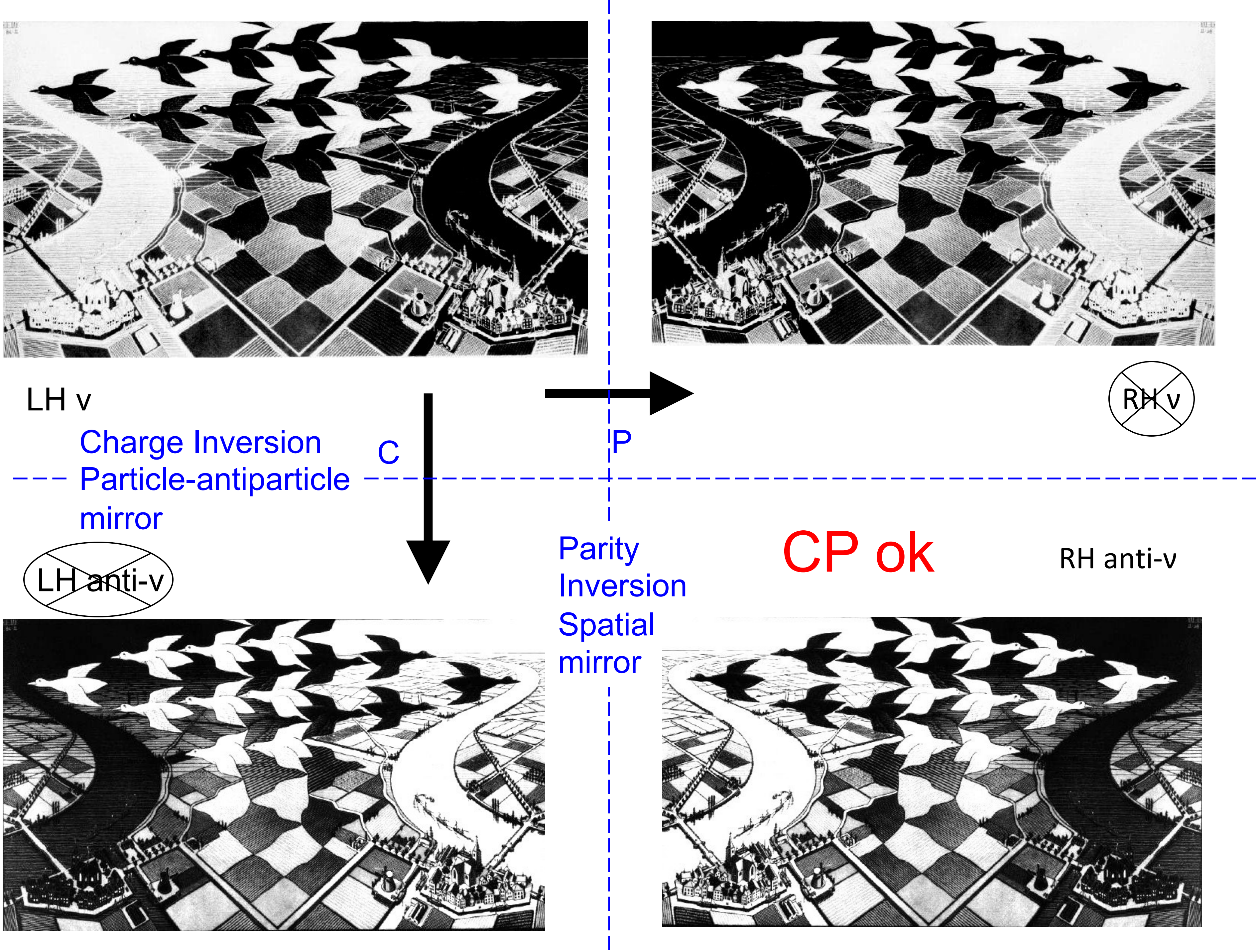
Did not receive the Nobel Prize



T.D. Lee



C.N. Yang

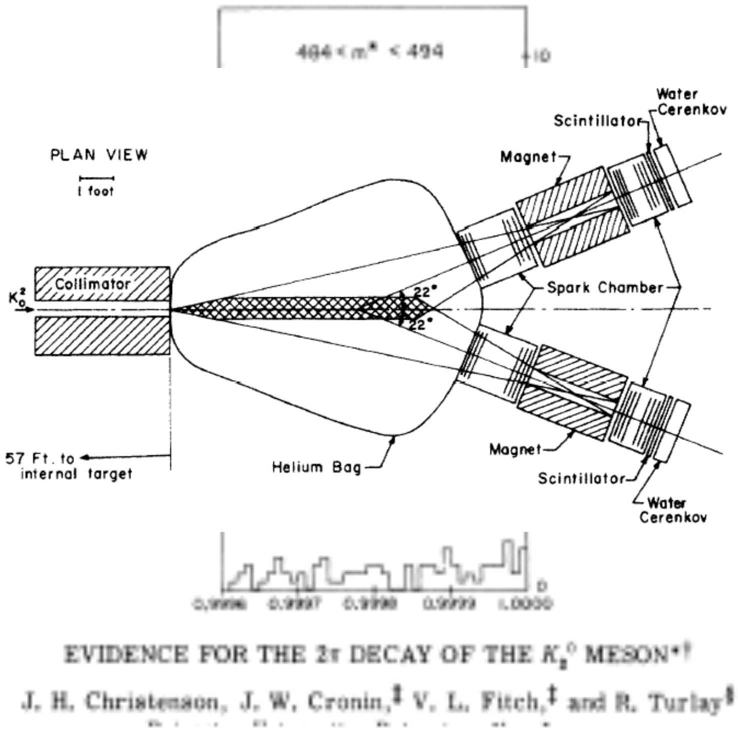


LH ν
~~RH ν~~
C
P
Charge Inversion
Particle-antiparticle
mirror
~~LH anti-ν~~
Parity
Inversion
Spatial
mirror
CP ok
RH anti-ν

1964: CP symmetry is violated

CP=-1 CP=+1

$$B(K_L \to \pi^+\pi^-) = (2.0 \pm 0.4) \times 10^{-3}$$



Phys. Rev. Lett. 13, 138 (1964)

Shocking but <u>Alternative interpretations ruled out</u>

- A new particle X: $K_L \rightarrow K_S + X$
- A new long-range force
- Extra nonlinear terms in the Schrödinger equation (beyond quantum mechanics !)
- *Regeneration of K_S on an unfortunate fly trapped in the helium bag.*

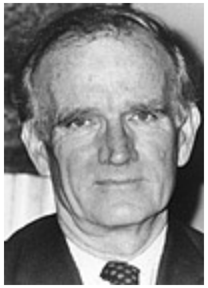
➔ *There is a small difference between matter & antimatter*

CP Violation

- *There are small* **differences** *between matter and anti-matter observed in the weak interaction.*

- *The small effect is seen only in particles containing strange quarks called "K-longs"*

Jim Cronin, University of Chicago



Val Fitch, Princeton University

Two young Japanese punks figured it out:

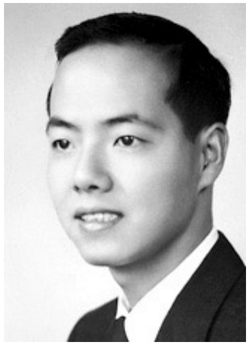
KM shown in 1973 (Kyoto)

Makoto Kobayashi

Toshihide Maskawa

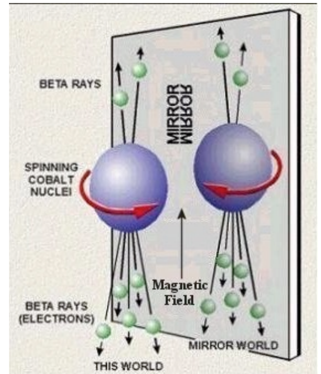
Need 3 generations of quarks ! (only two were known at the time)

Nobel Prizes from Surprising Discoveries about
Weak Interactions of Quarks



T.D. Lee

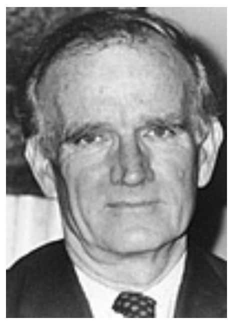
C.N. Yang



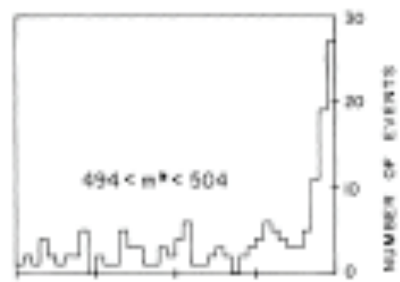
Maximal P violation

1957

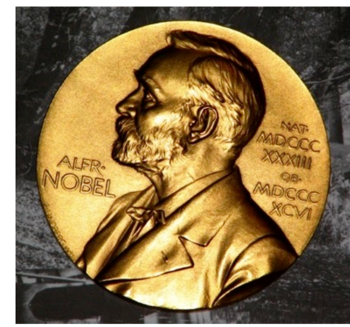
J. Cronin



V. Fitch



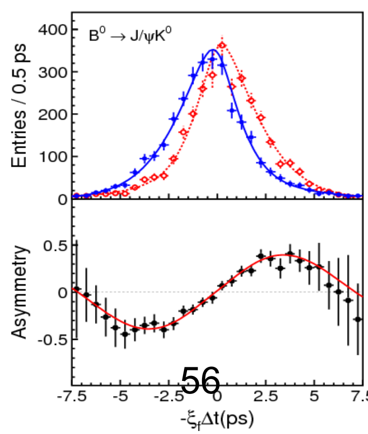
Small CP violation



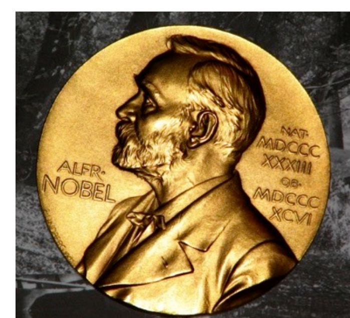
1980

M. Kobayashi

T. Maskawa



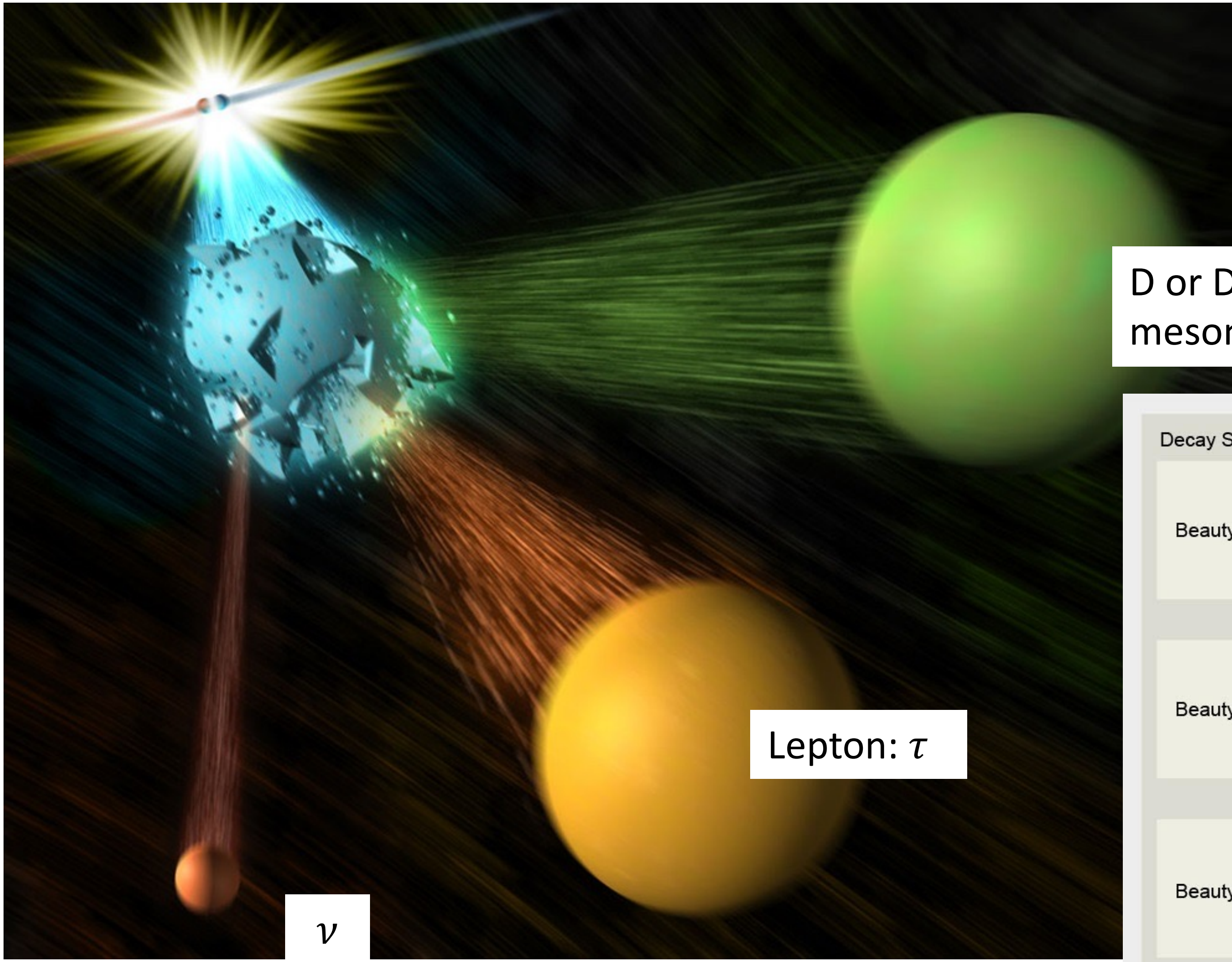
O(1) CP violation and 3 generations



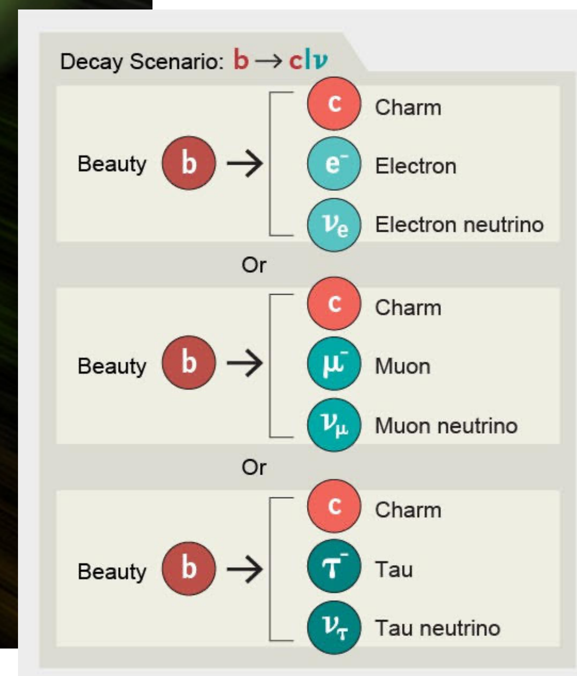
2008

SLAC
Outreach

Possible breakdown of lepton universality in B→D$^{(*)}$ τ υ



Lepton Universality

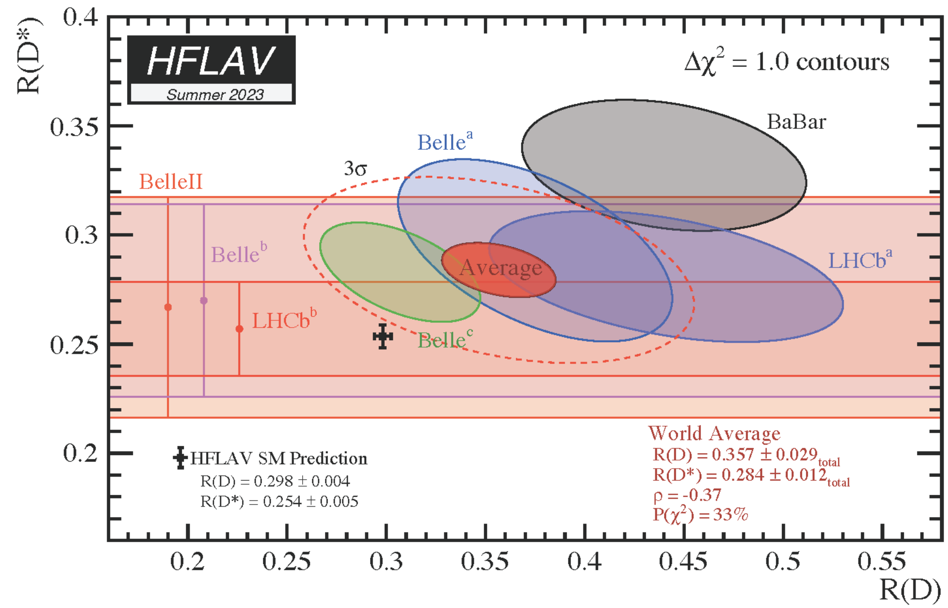


Note this picture has a production process (EM) and a weak decay

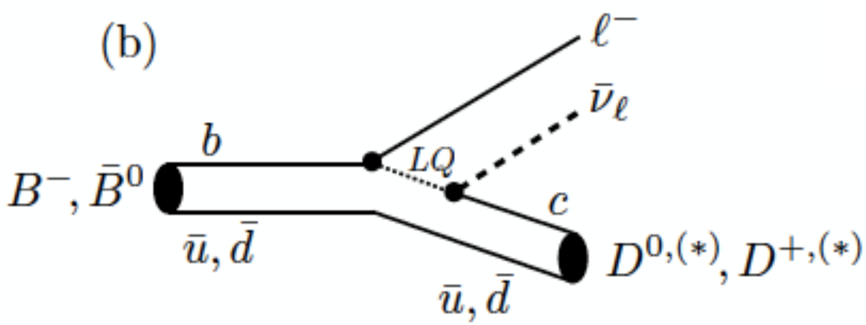
B→D$^{(*)}$ τ υ, possible breakdown of lepton universality

$$R_D^{(*)} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

This might be BSM in the weak b→c charged current



Normally mediated by virtual W charged current.
Some BSM physics possibilities (leptoquarks (LQ), charged Higgs type 3 etc..):

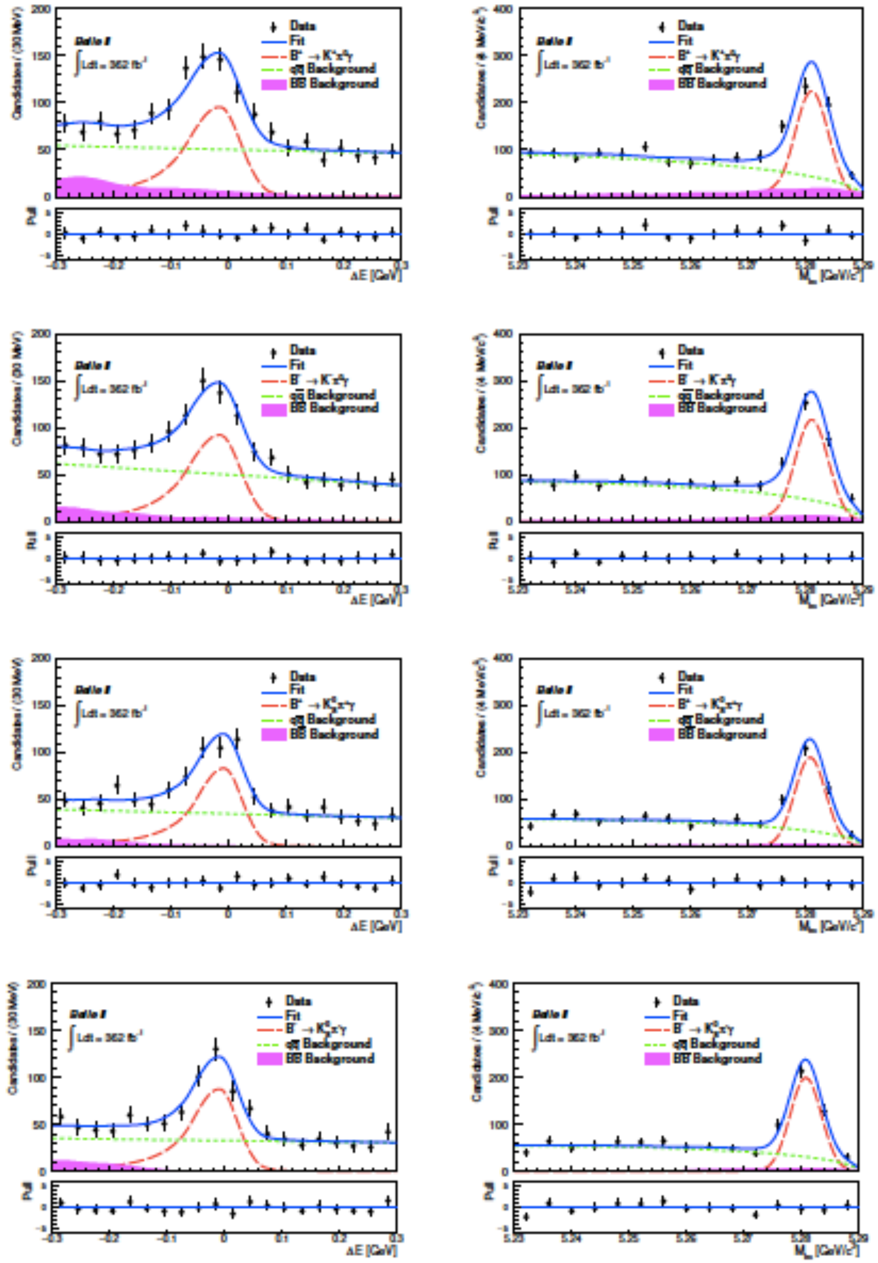


Belle, Belle II, BaBar, LHCb combined: Some evidence of lepton universality breakdown in semileptonic B decays with τ leptons.

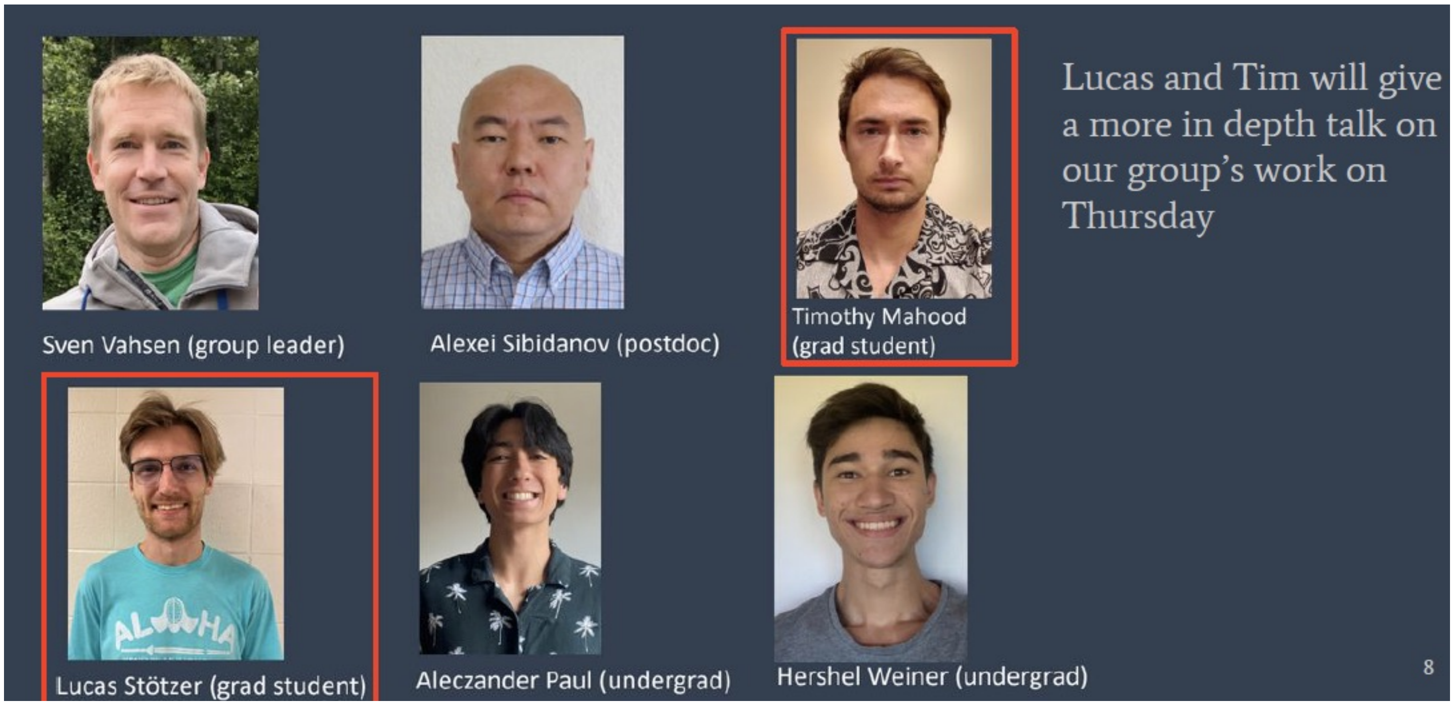
With the first Belle II result , the combined deviation is 3.3σ from the SM. (see https://arxiv.org/abs/2401.02840, submitted to PRD.)

Future: Look at q^2, angular distributions to detect BSM physics.

More radiative penguins:



US Belle II QM
Entanglement/Decoherence team



Talks by Tim, Luca and Hershel at this workshop