HEP Lecture: Flavour Physics

DESY Summer Student Lectures, 23.08.2022

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https://indico.desy.de/event/35182/

PART 1: What does flavour physics explore?

PART 2: OK... then, how to measure?

PART 1: What does flavour physics explore?

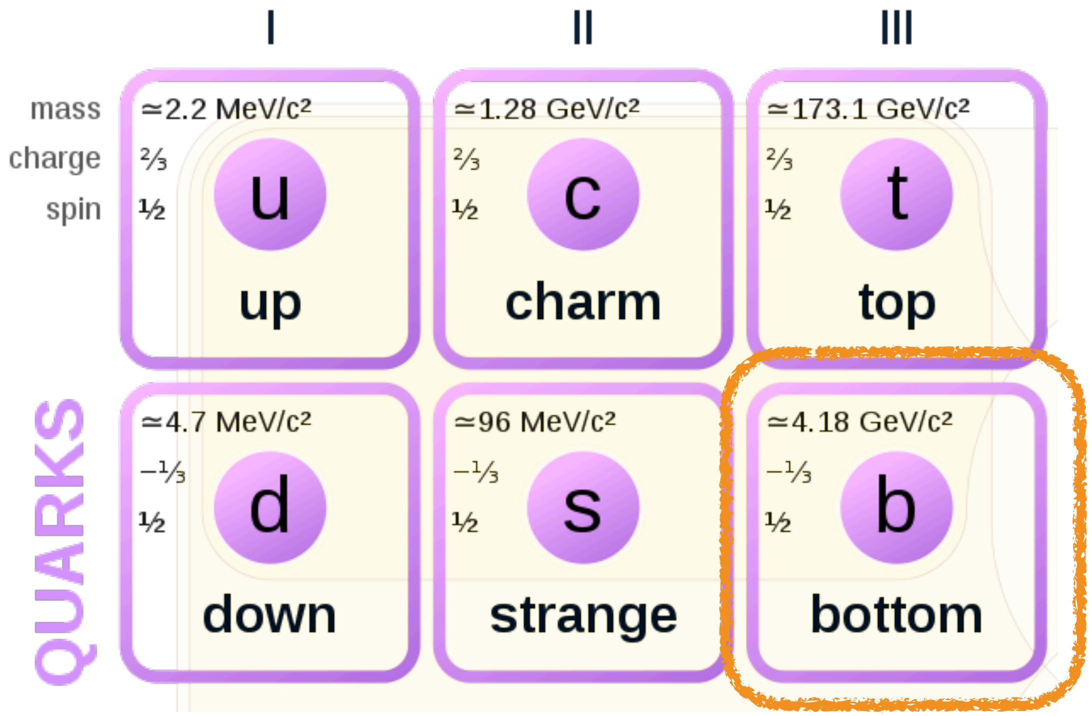
PART 2: OK... then, how to measure?

A few examples in B physics

B Physics

- Large mass of b quark allows many interesting decays for mesons containing a b quark.

$$B^0(d\bar{b}), B^+(u\bar{b}), B_s(s\bar{b}), B_c(c\bar{b})$$

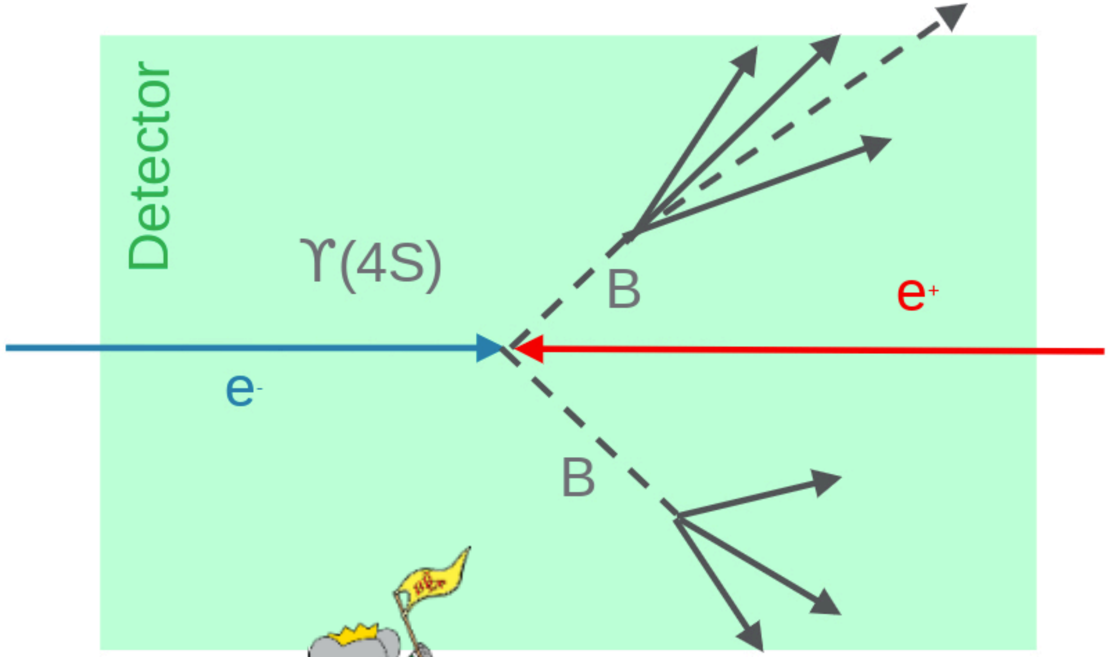


- With a **large** sample of B mesons can:
  - ➡ Measure the CKM Matrix elements.
  - ➡ Test CKM matrix unitarity.
  - ➡ Matter/anti-matter asymmetries.
  - ➡ Search for rare decays.
  - ➡ Search for new particles in decays.

B Physics Experiments

B Factories: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

- Minimal collision pile-up, well-known collision energy.
- Good at final states with neutrals and missing-energy.



LHC: $pp \rightarrow bb + X$

- Very high production rate.
- Collision energy not well known.

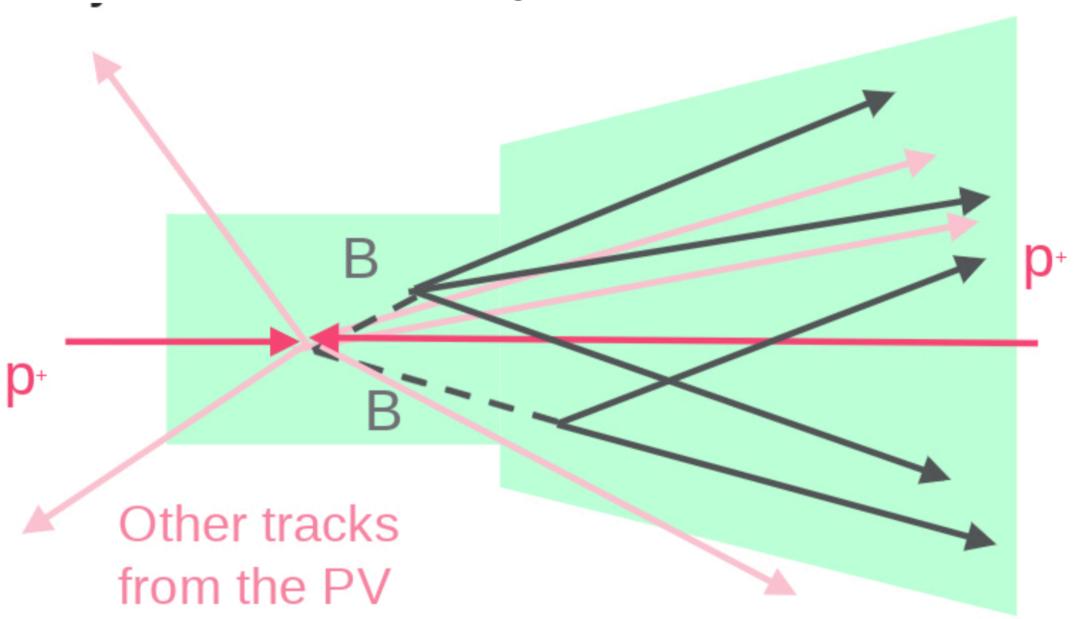


Image: S. Cunliffe

Belle II is maybe (?) the only experiment that explains how it works via its logo:

Plenty of Puns

1) Belle collides electrons and their anti-particle positrons
2) B breaks the symmetry between el - le
   (i.e. between matter and antimatter)
3) Belle investigates beauty quarks, which are of course "belle"

Belle II is maybe (?) the only experiment that explains how it works via its logo:

BEAST

(**B**eam **E**xorcism for **A** **ST**able BELLE Experiment)

The BEAST experiment: a background detector for the commissioning of the BELLE experiment

Plenty of Puns

1) Belle collides electrons and their anti-particle positrons
2) B breaks the symmetry between el - le
   (i.e. between matter and antimatter)
3) Belle investigates beauty quarks, which are of course "belle"

Picture: movies.disney.com

$e^+e^- \rightarrow hadrons$ **Cross-section**

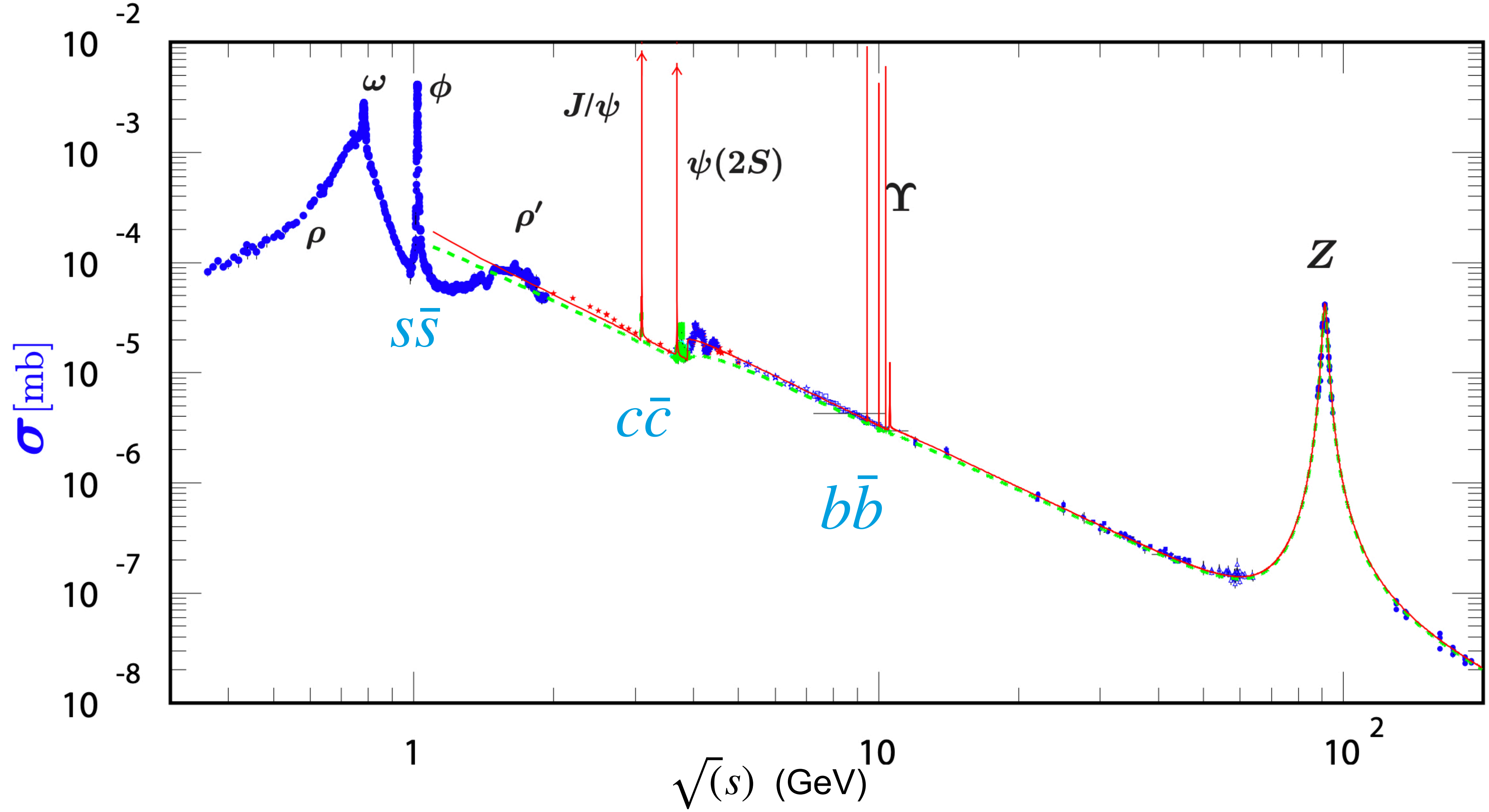


Figure: Particle Data Group https://pdg.lbl.gov/2014/hadronic-xsections/rpp2014-sigma_R_ee_plots.pdf

$e^+e^- \rightarrow hadrons$ Cross-section

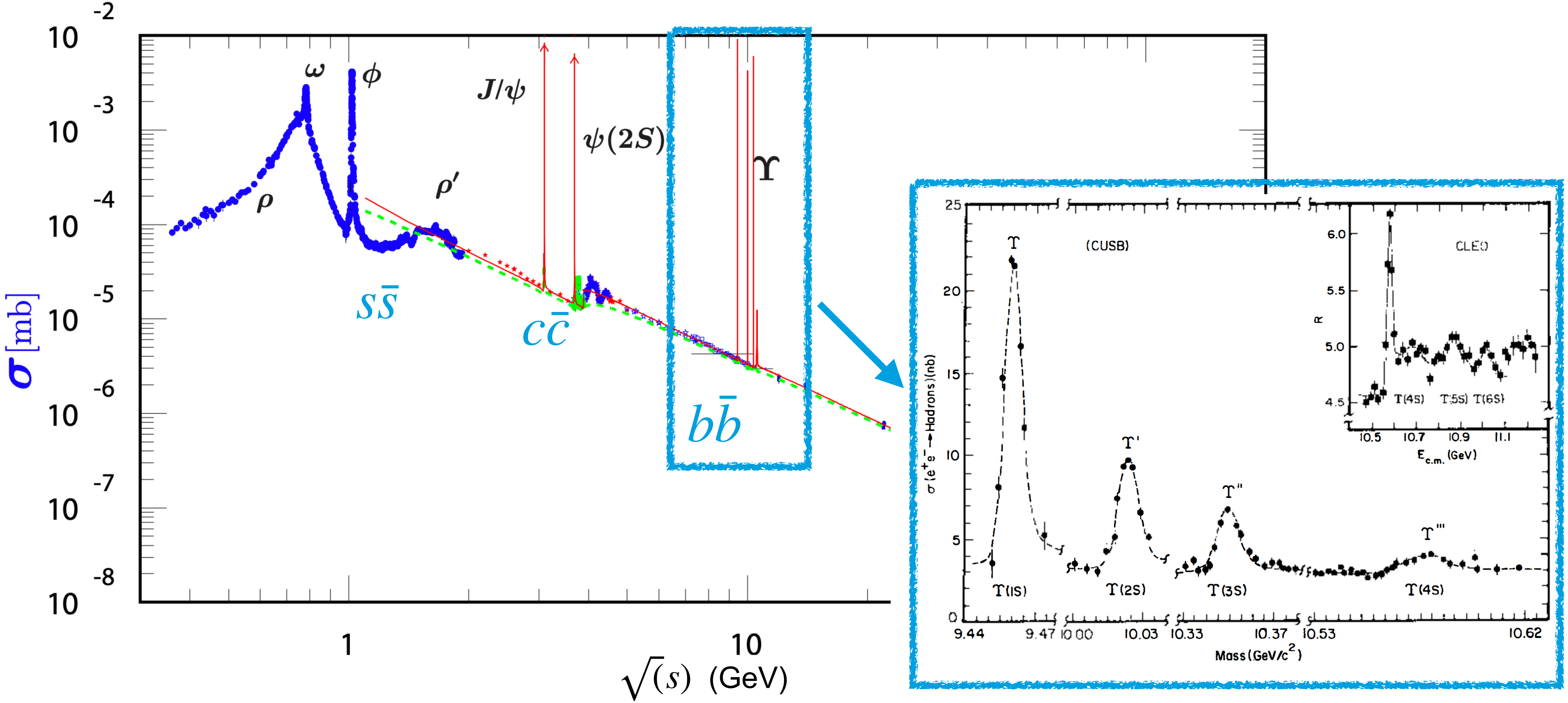
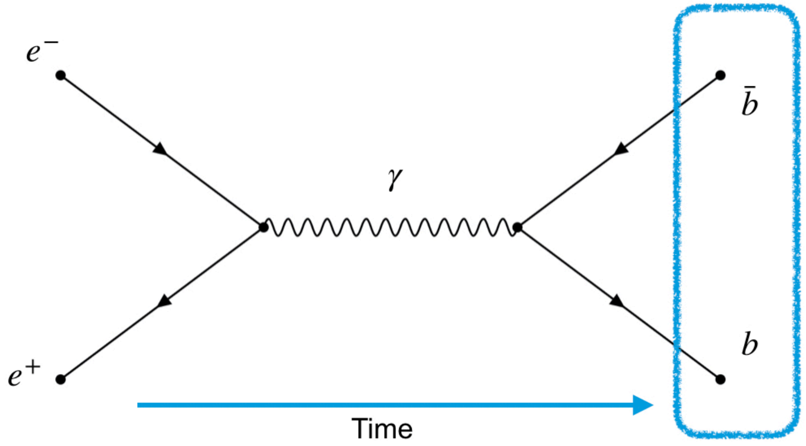
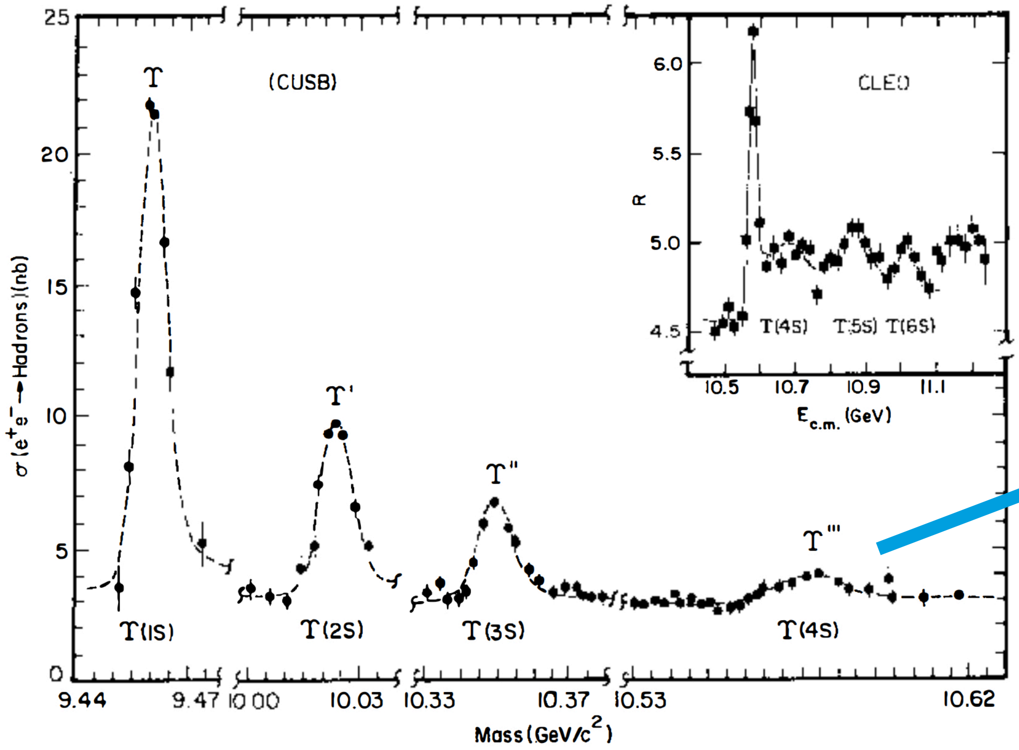


Figure: D. Besson and T. Skwarnicki Annu. Rev. Nucl. Part. Sci. 1993.43:333-78
https://www.annualreviews.org/doi/pdf/10.1146/annurev.ns.43.120193.002001

$\Upsilon(4S)$ Resonance

- $\Upsilon(4S)$ correspond to bound $b\bar{b}$.
- Maximize production by tuning e^+e^- collider at $\Upsilon(4S)$ mass (10.58 GeV, about 2 x B meson mass).
- >96% of $\Upsilon(4S)$ decays are to B mesons!





$\Upsilon(4S)$

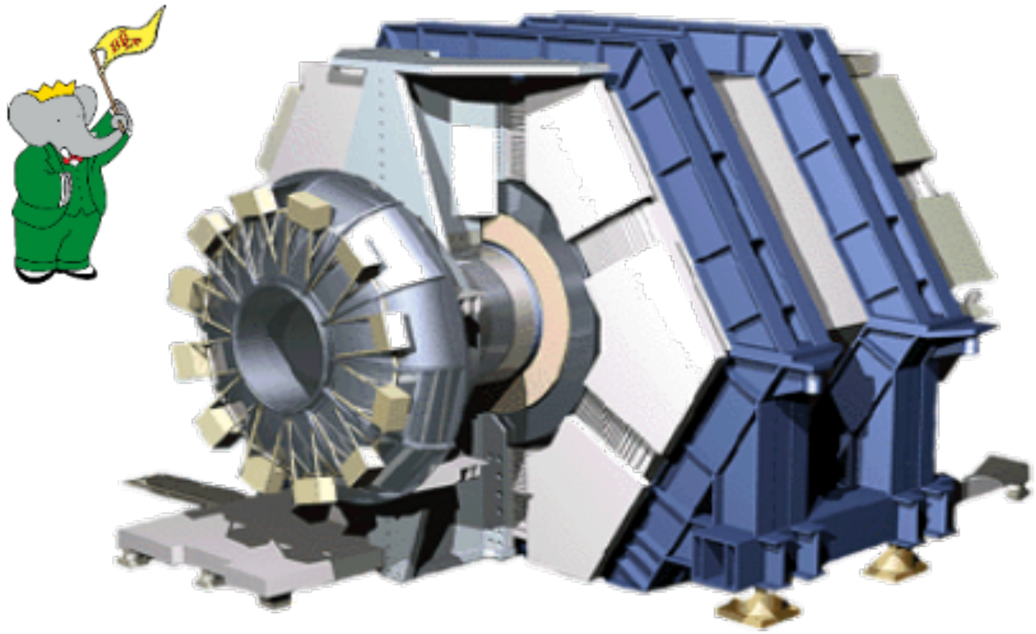
Γ_1	$B\overline{B}$	> 96%
Γ_2	B^+B^-	$(51.4 \pm 0.6)\%$
Γ_3	D_s^+ anything + c.c.	$(17.8 \pm 2.6)\%$
Γ_4	$B^0\overline{B}^0$	$(48.6 \pm 0.6)\%$
Γ_5	$J/\psi K_S^0 + (J/\psi, \eta_c) K_S^0$	$< 4 \times 10^{-7}$
Γ_6	non-$B\overline{B}$	< 4%

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

B-Factories in the 2000's

- e^+e^- collision energy is turned to $\Upsilon(4S)$ resonance.
- **BaBar Experiment** (at SLAC in USA) ~ **over 500 million** $B\bar{B}$ recorded!
- **BELLE Experiment** (at KEK in Japan) ~ **over 770 million** $B\bar{B}$ recorded!

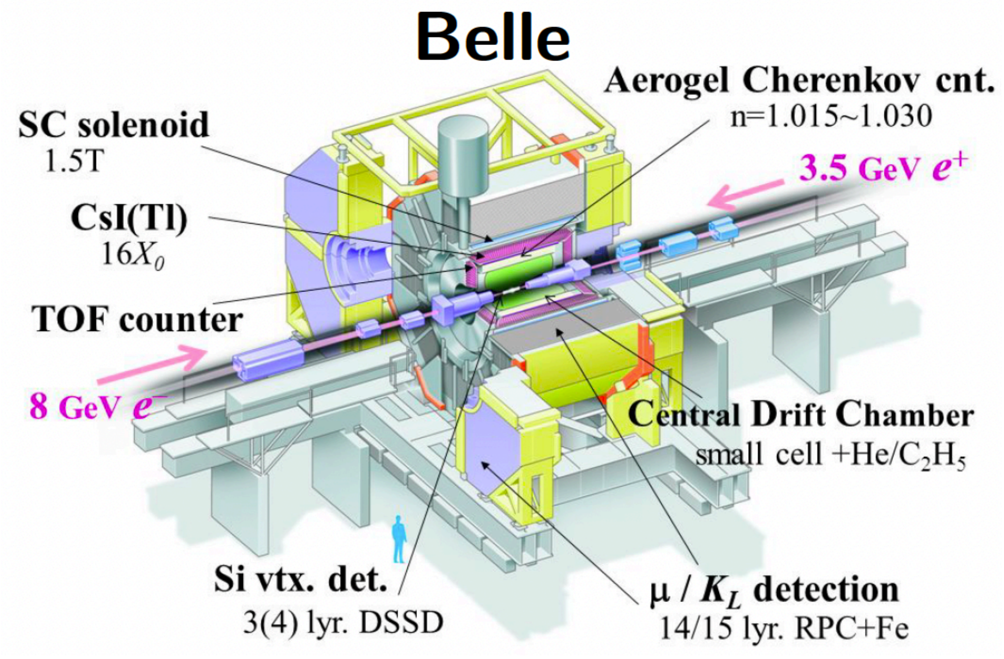
BaBar



BELLE

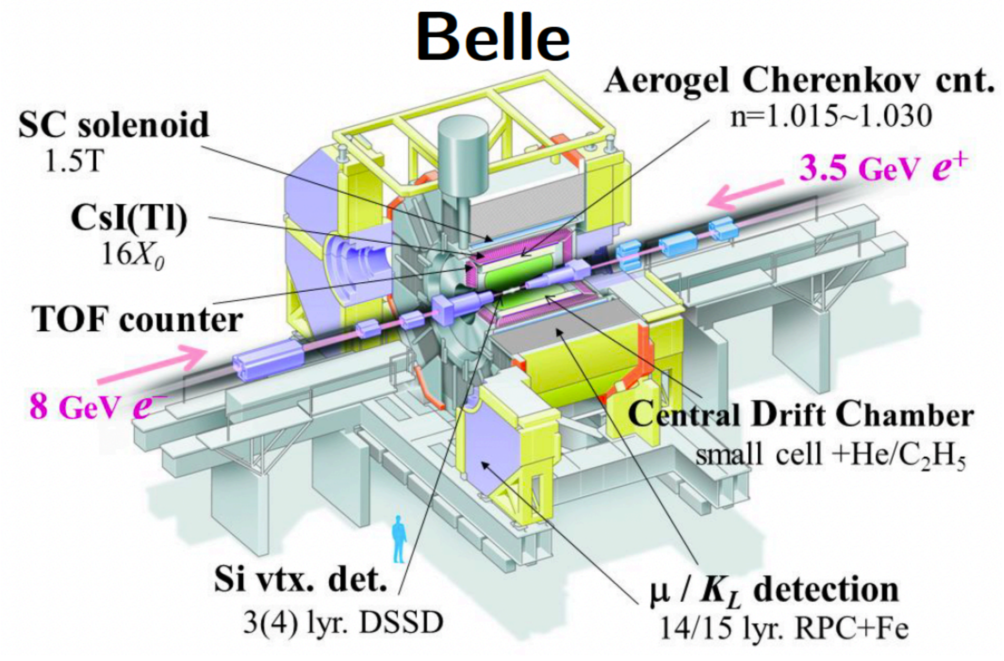
BELLE

Belle Detector



KEKB:
Max. instantaneous luminosity $2.1 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Belle Detector



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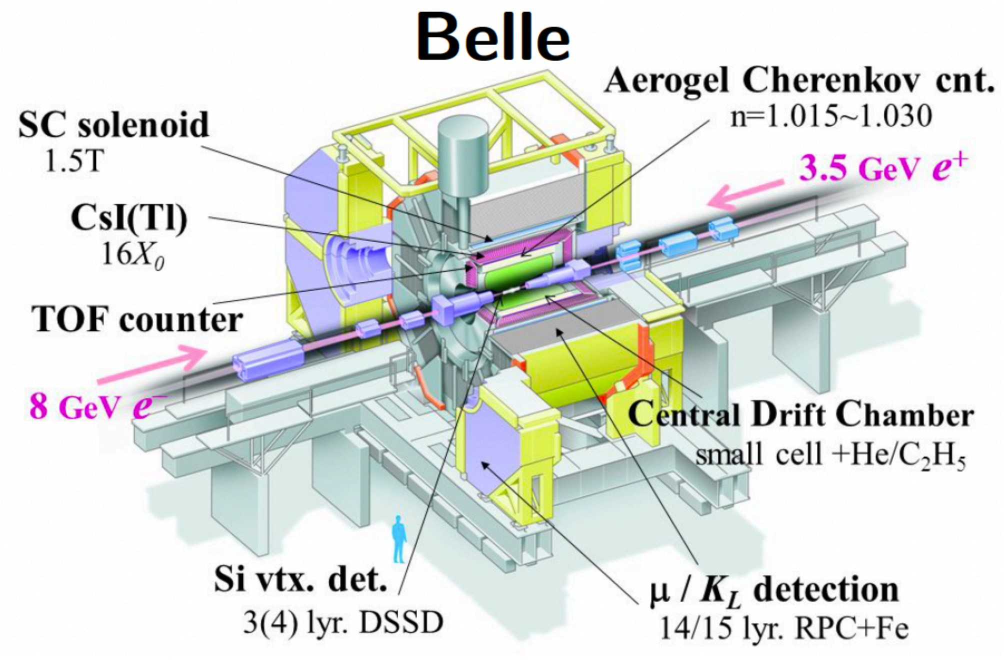
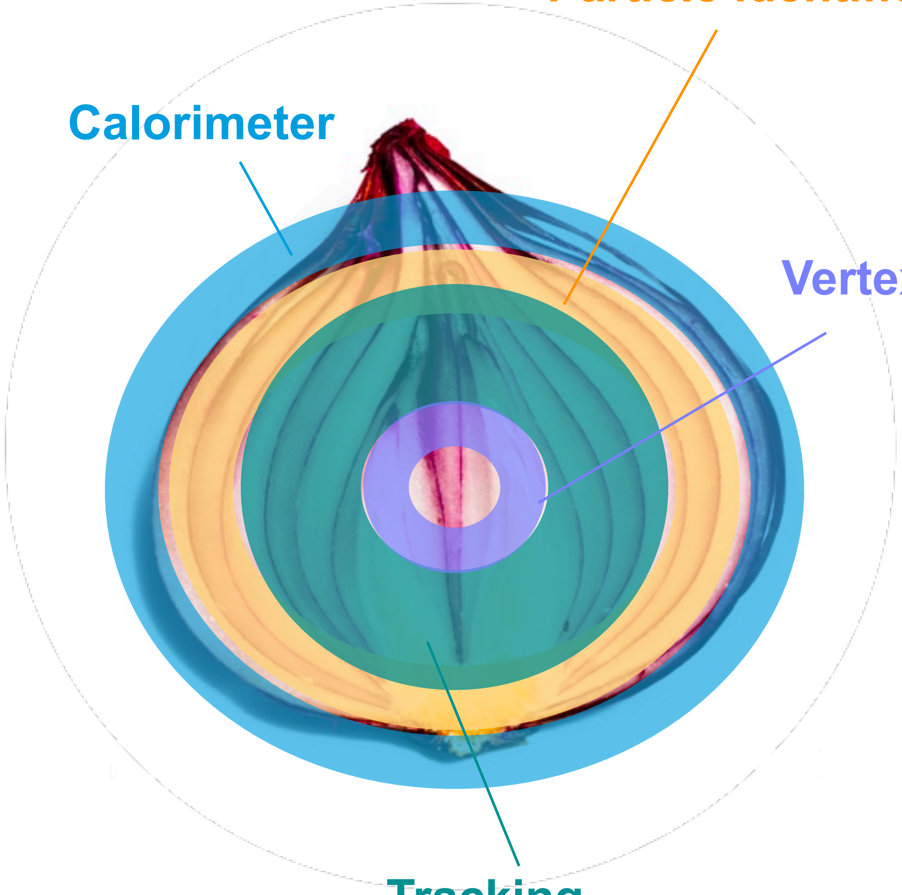
Belle Detector





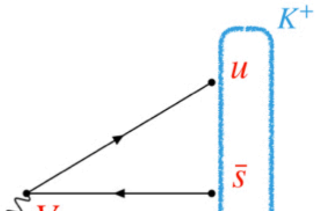
KEKB:

Max. instantaneous luminosity $2.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

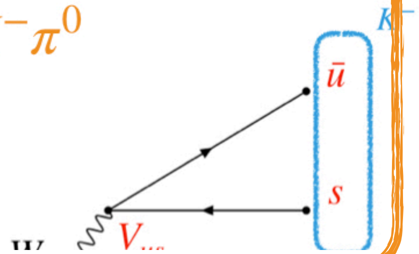
Observing Direct Charge-Parity Violation

Q2: Do you expect these decays to have the same rate?

a) $B^+ \to K^+\pi^0$



b) $B^- \to K^-\pi^0$



- Requires **interference** between two diagrams.

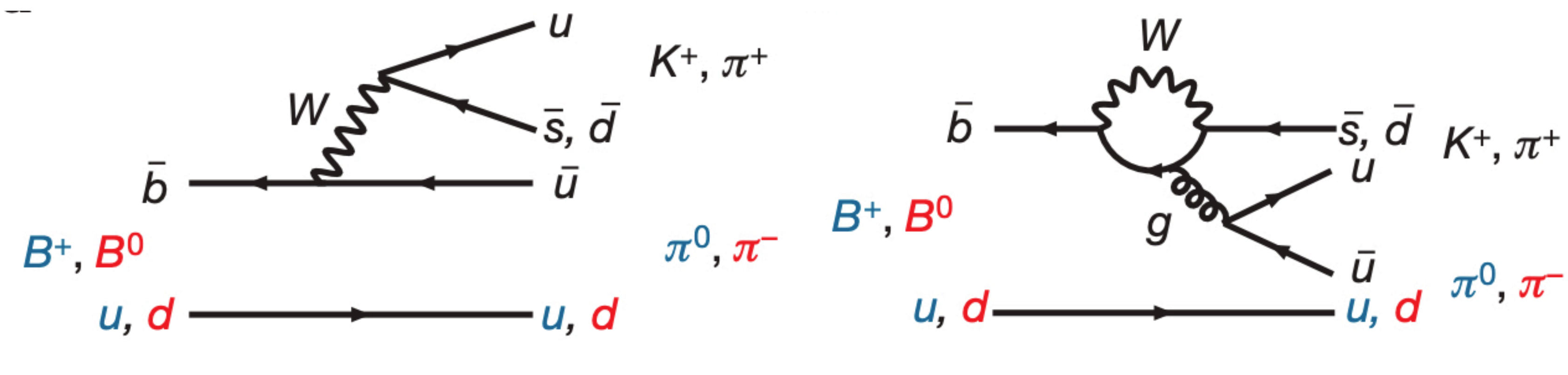


Figure 17.4.4. The dominant Tree-level (a) and Penguin-loop (b) Feynman diagrams in the two-body decays $B \to K\pi$ and $B \to \pi\pi$ (Lin, 2008).

Figure: A. J. Bevan et al. The Physics of the B Factories Eur. Phys. J. C74 (2014) 3026

Direct Charge-Parity Violation at BELLE

- Signal component corresponds to red peak.
- Signal yield seen by-eye to be different for matter vs. anti-matter!
- Result is an example of **Direct CP Violation**.

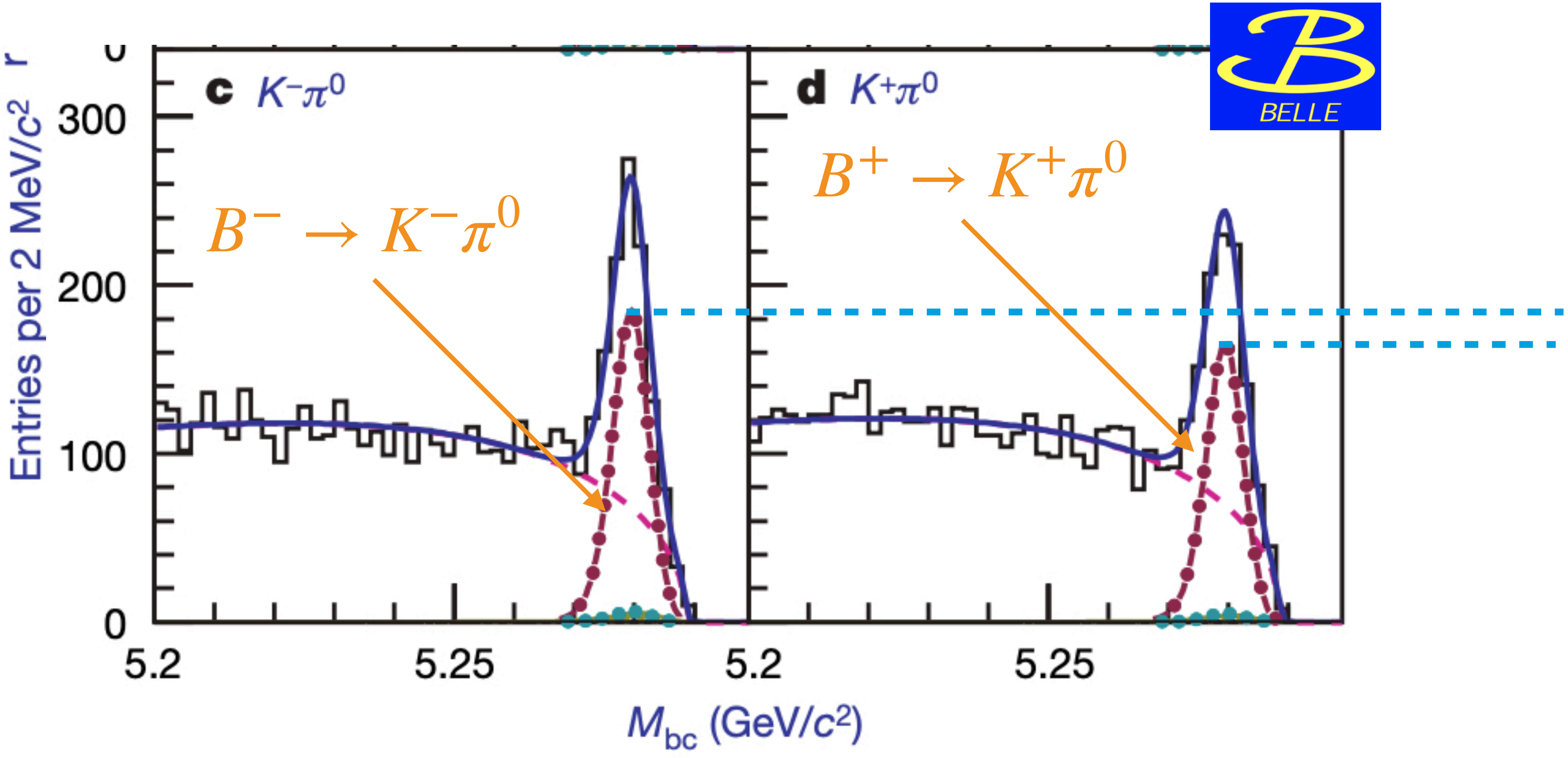
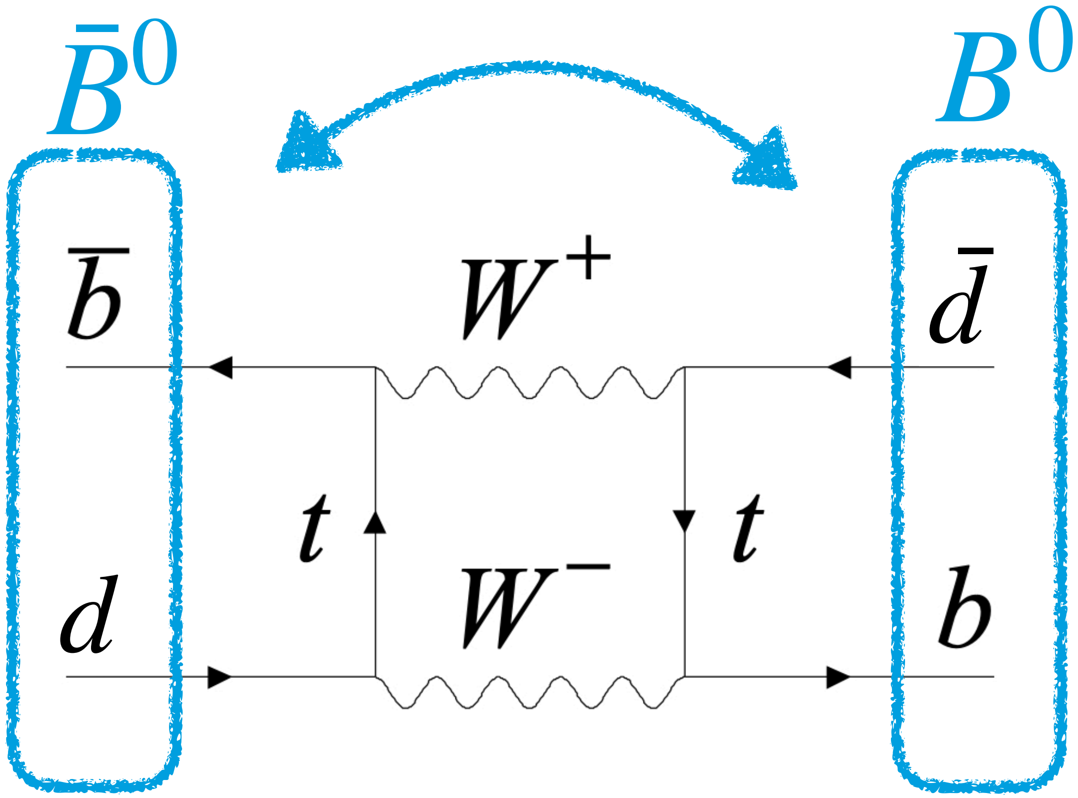


Figure: A. J. Bevan et al. The Physics of the B Factories Eur. Phys. J. C74 (2014) 3026

$B^0 - \bar{B}^0$ Mixing

- Neutral B mesons undergo $B^0 - \bar{B}^0$ mixing.

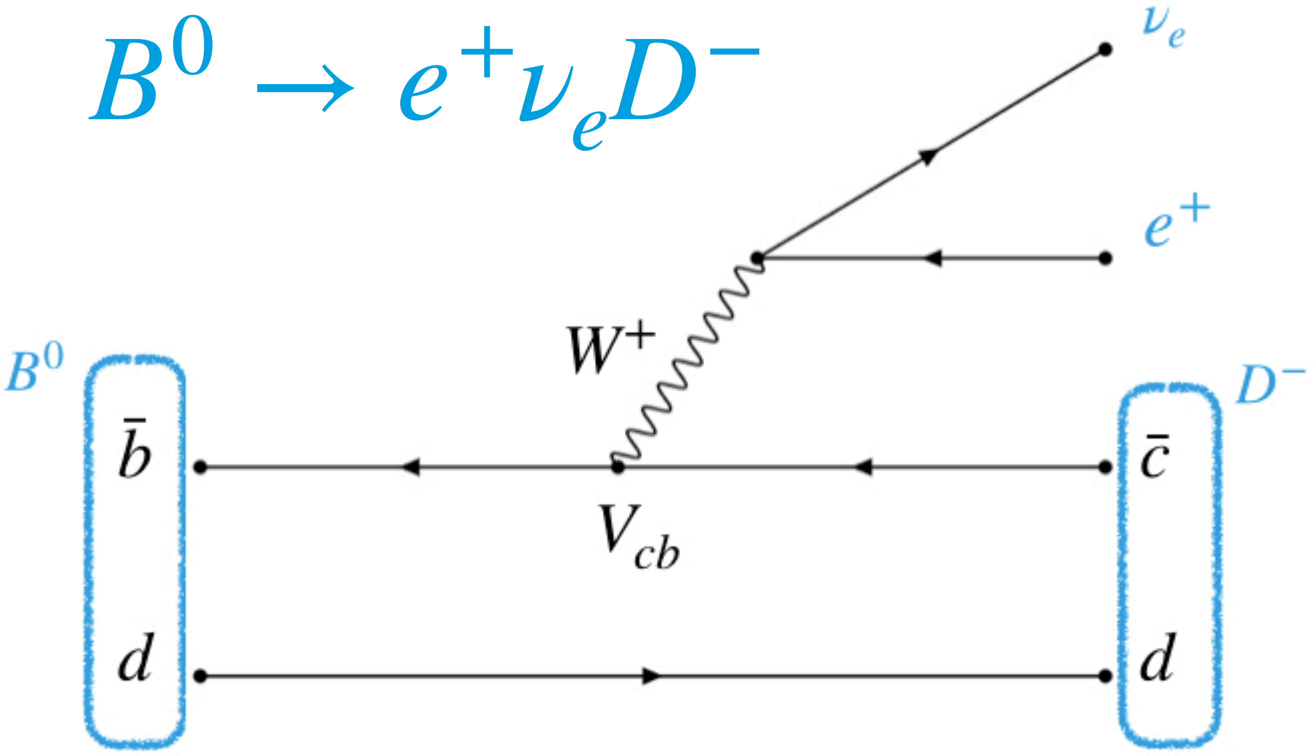


- In the decay $\Upsilon(4S) \to B^0\bar{B}^0$, the B's are in an entangled state.

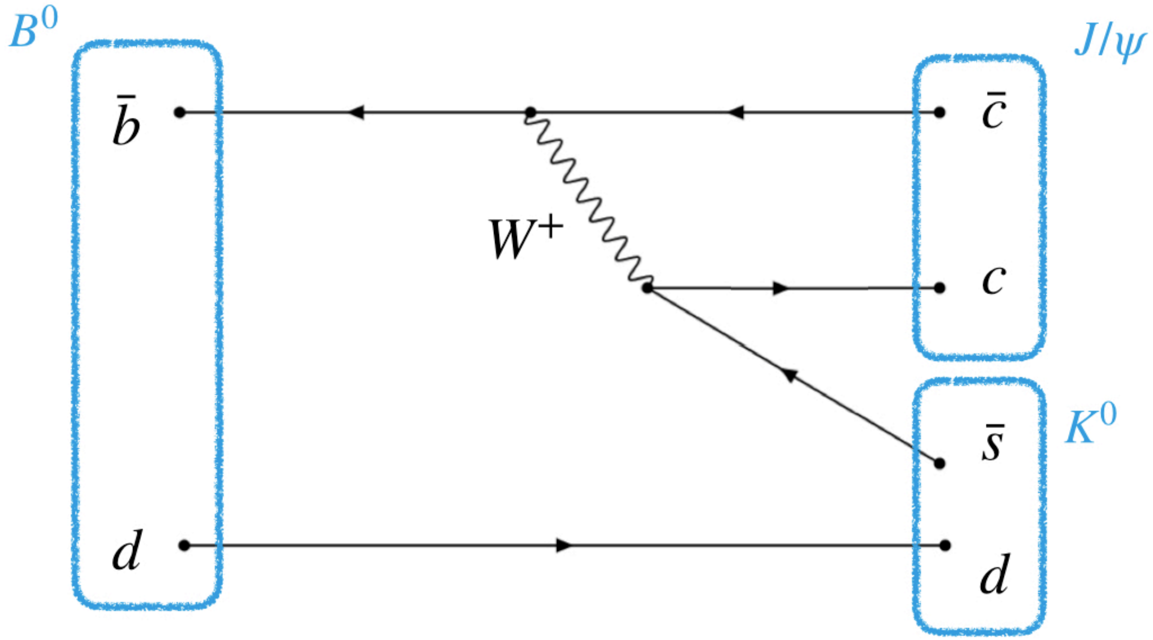
$$\Upsilon(4S) \longrightarrow \begin{matrix} B^0 \\ \bar{B}^0 \end{matrix} \rightarrow \begin{matrix} \bar{B}^0 \\ B^0 \end{matrix} \rightarrow \begin{matrix} B^0 \\ \bar{B}^0 \end{matrix}$$

Semi-leptonic and Hadronic Decays

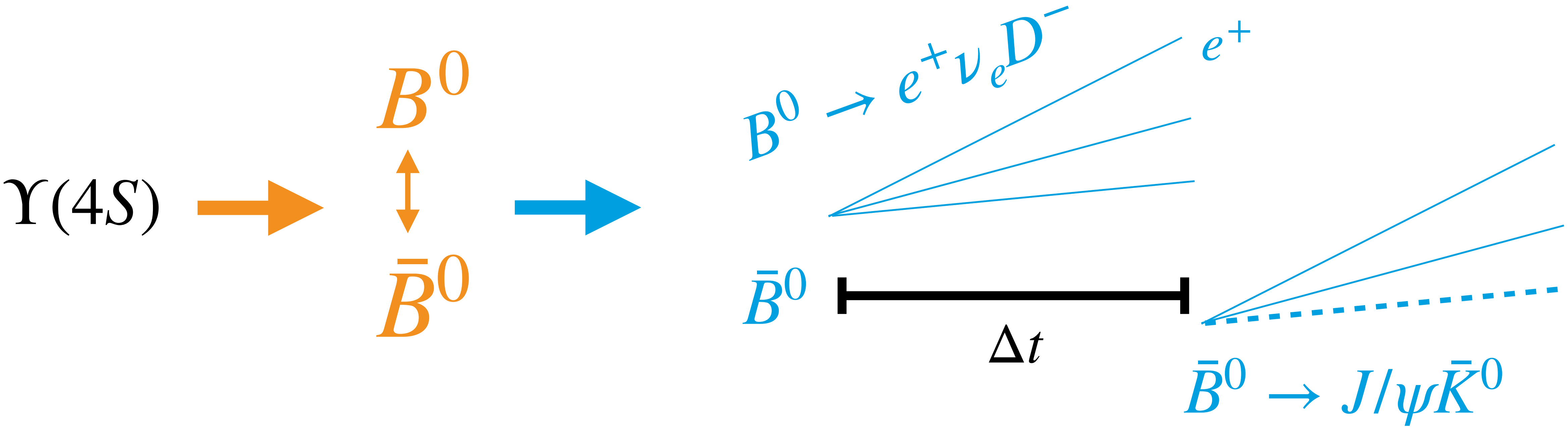
$$B^0 \rightarrow e^+ \nu_e D^-$$



$$B^0 \rightarrow J/\psi K^0$$

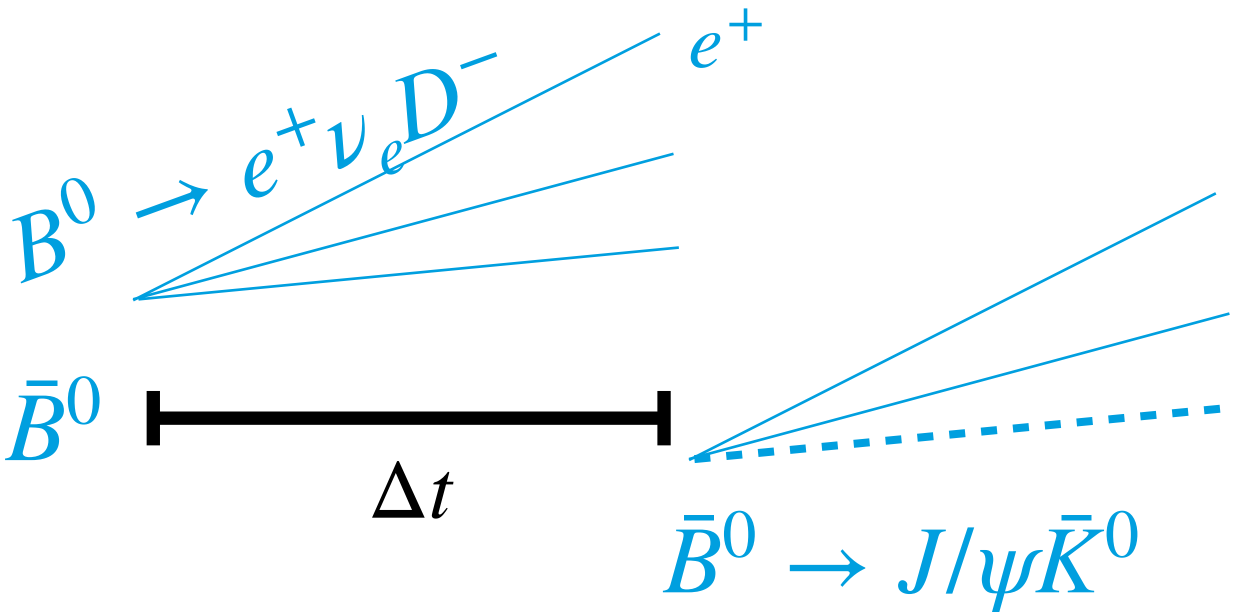


Time Dependent CP-Violation Measurement



Time Dependent CP-Violation Measurement

$\Upsilon(4S) \rightarrow B^0 \leftrightarrow \bar{B}^0 \rightarrow$



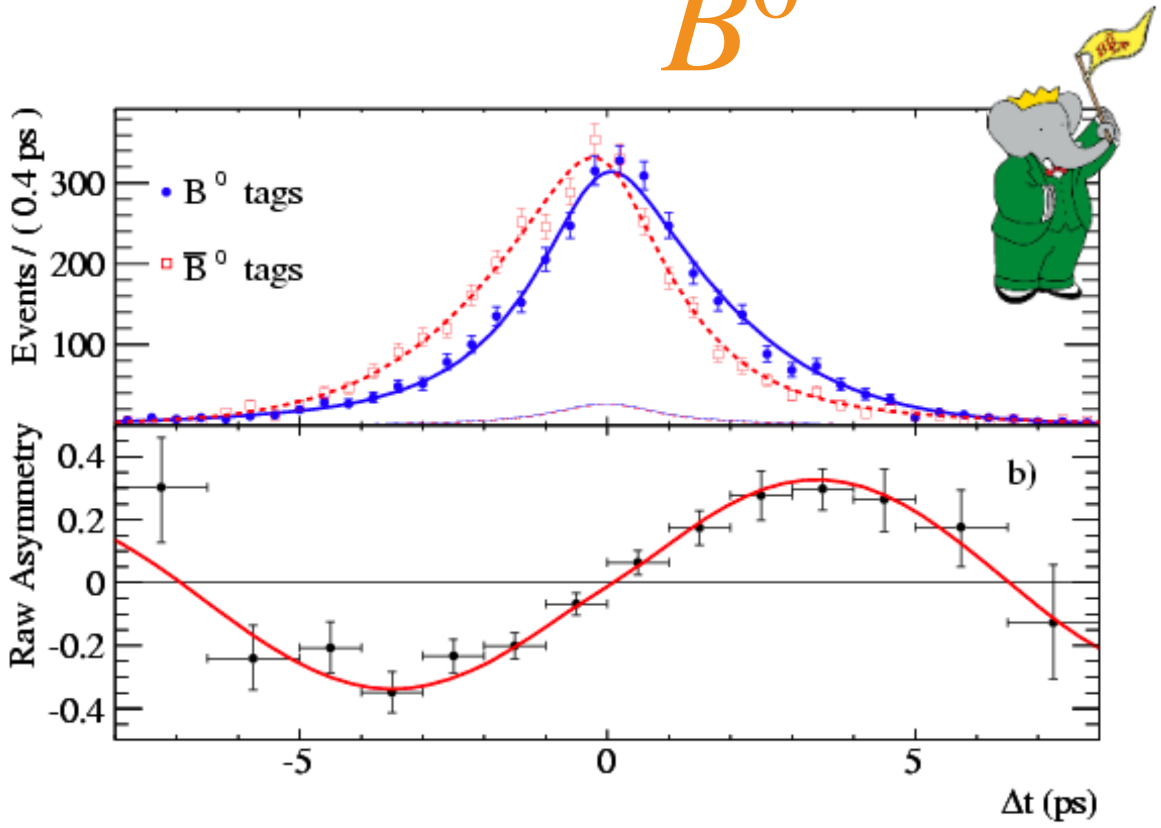
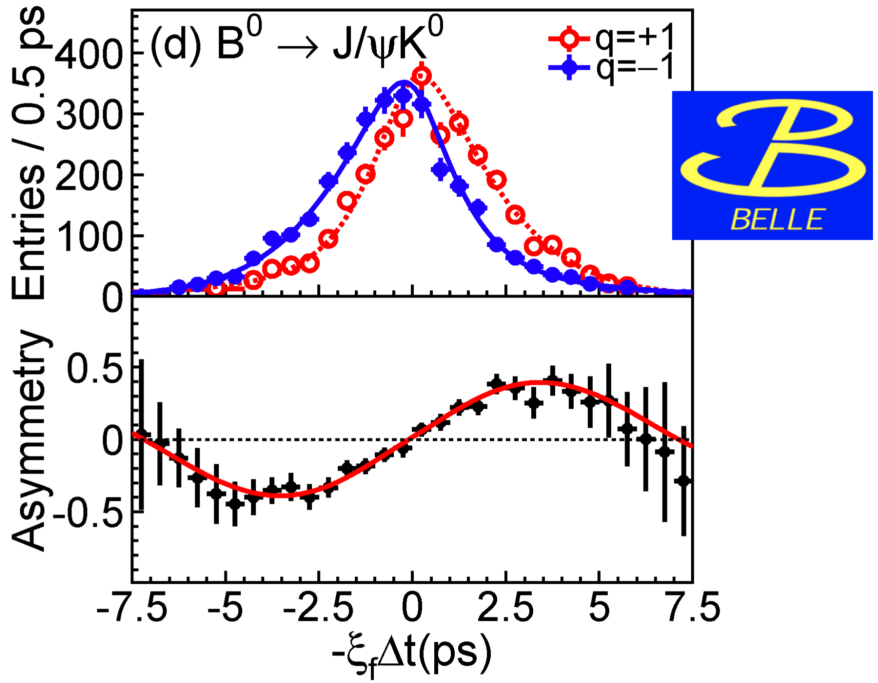


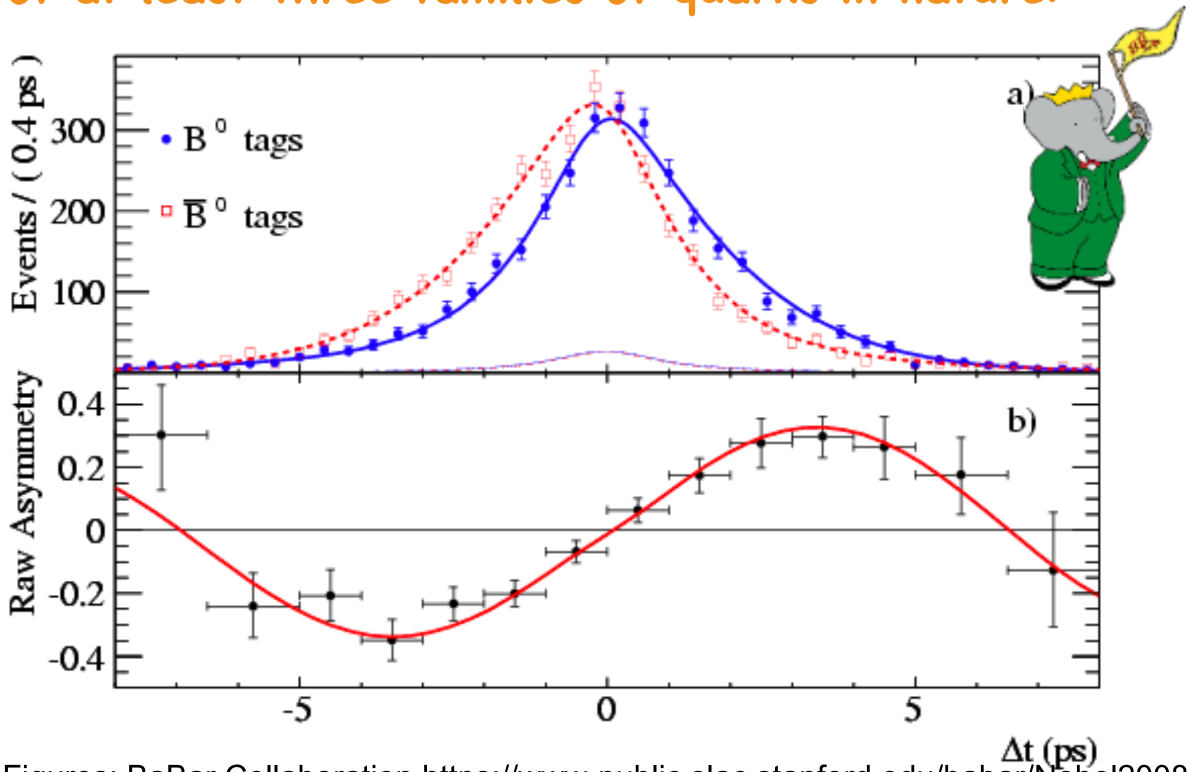
Figure: BaBar Collaboration https://www-public.slac.stanford.edu/babar/Nobel2008.aspx

2008 Nobel Prize in Physics

Experimental confirmation of large matter/anti-matter asymmetries in B mesons provided by Belle and BaBar lead to 2008 Nobel Prize in Physics:

- Yoichiro Nambu (1/2) - "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"
- **Makoto Kobayashi and Toshihide Masukawa (1/2) - "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature."**

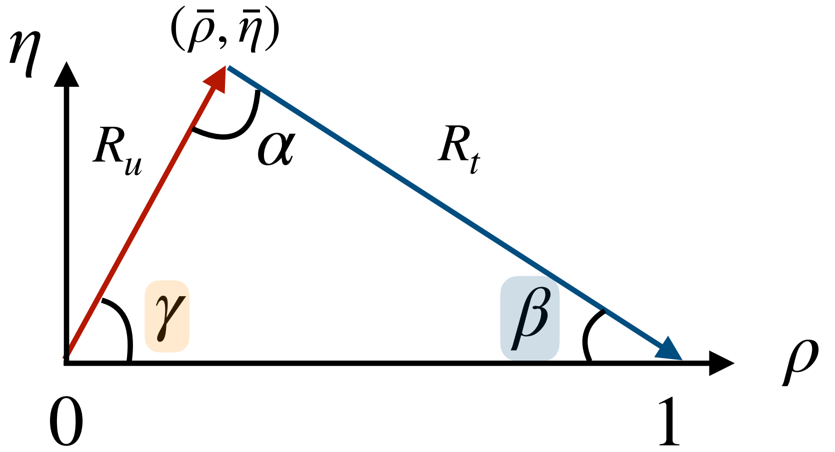




Figures: BaBar Collaboration https://www-public.slac.stanford.edu/babar/Nobel2008.aspx
Bellle Collaboration https://belle.kek.jp/belle/km_nobel/index.html

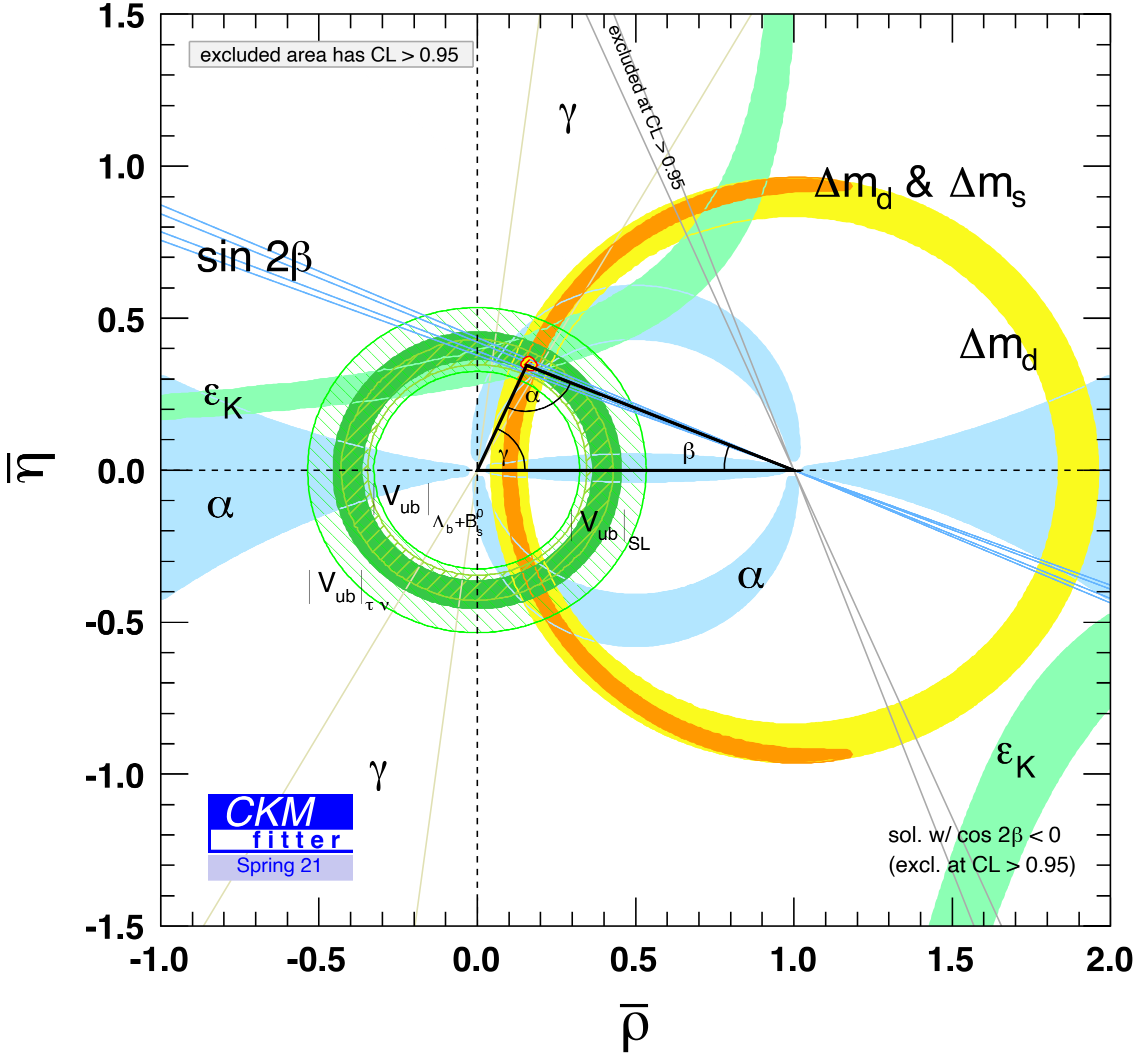
Global CKM Fit

Recap:



$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{\rho^2 + \eta^2} \qquad R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{(1-\rho)^2 + \eta^2}\ .$$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \beta = \arg\left(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

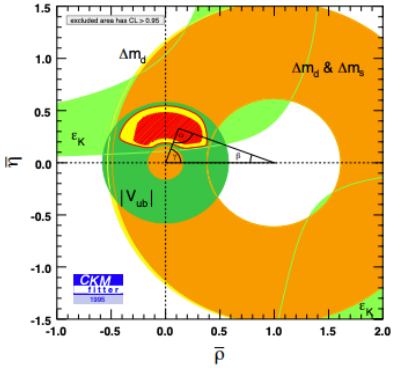


http://ckmfitter.in2p3.fr/www/results/plots_spring21/ckm_res_spring21.html

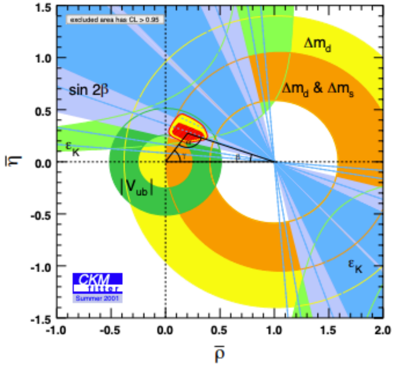
Global CKM Fit

😄 Precision is getting better and better

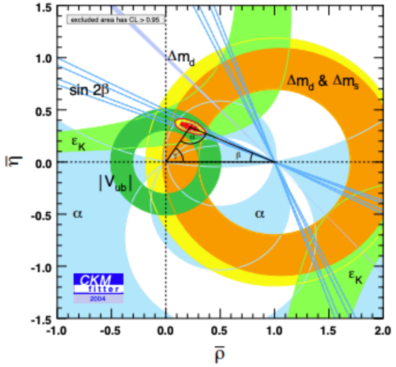
🤔 But…the green circle stays similar as 15 years ago



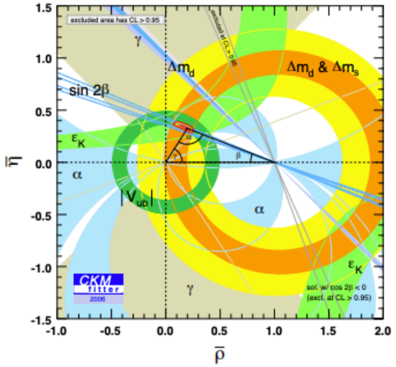
1995



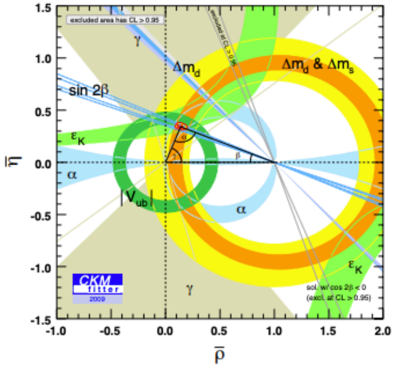
2001



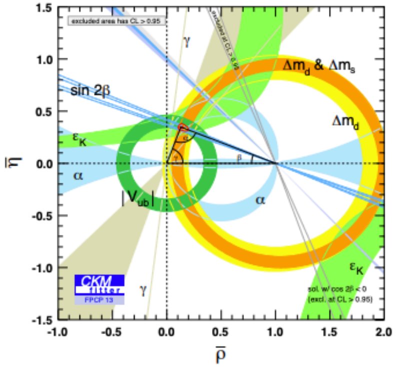
2004



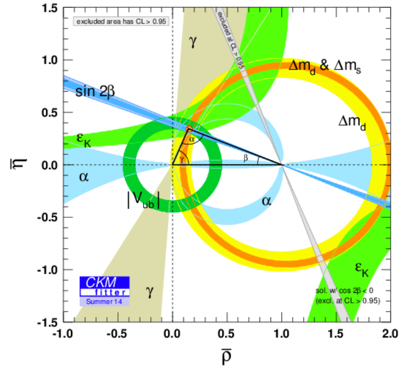
2006



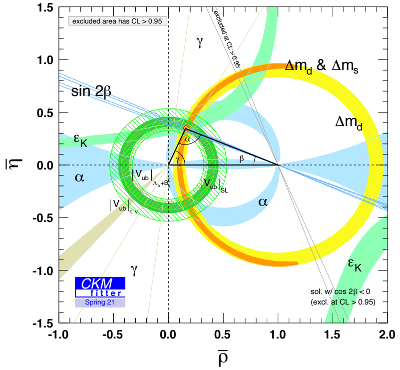
2009



2013



2014

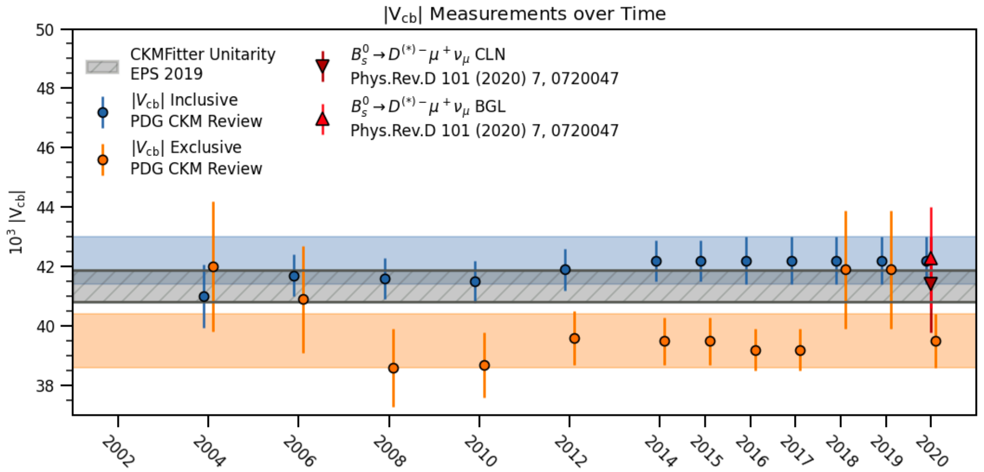


2021

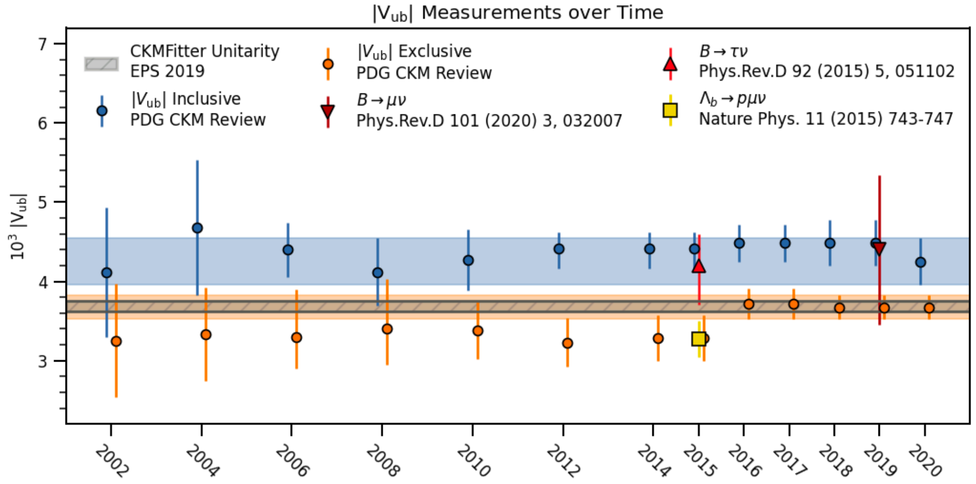
V_{xb} Puzzle

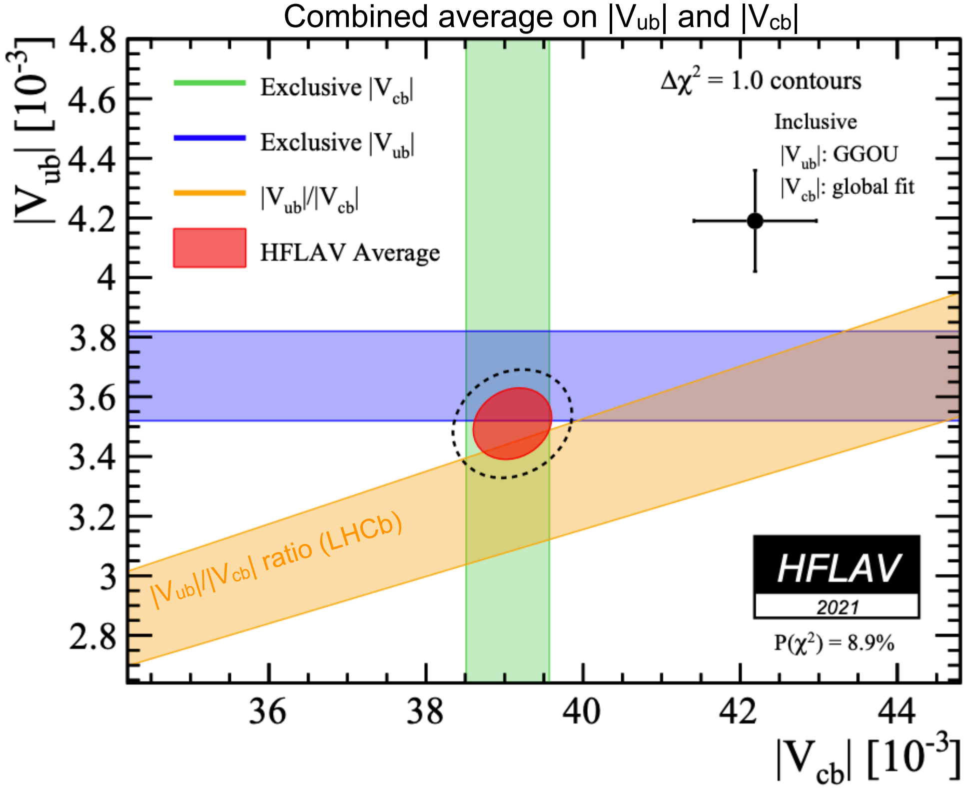
Long-standing discrepancy of **inclusive** & **exclusive** determinations

$|V_{cb}|$



$|V_{ub}|$





$$|V_{ub}| = (3.51 \pm 0.12) \times 10^{-3}$$
$$|V_{cb}| = (39.10 \pm 0.50) \times 10^{-3}$$

$$|V_{ub}|^{incl.} = (4.19 \pm 0.17) \times 10^{-3}$$
$$|V_{cb}|^{incl.} = (42.19 \pm 0.78) \times 10^{-3}$$

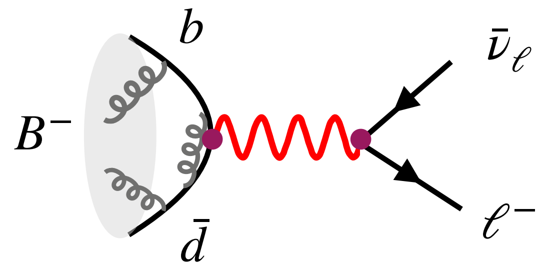
arXiv:2206.07501 [hep-ex]

How do we measure $|V_{xb}|$?

1) Hadronic decays → theory very hard, experimentally easy

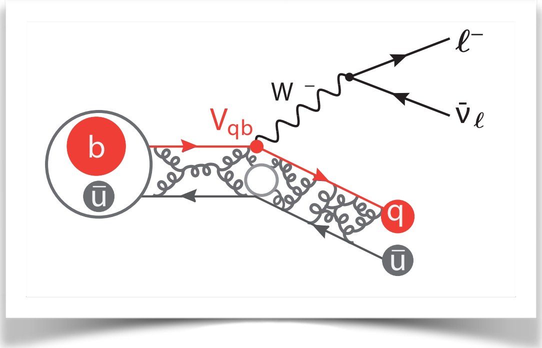
2) Leptonic decays → theory “easy” experimentally very hard

$$\mathcal{B}(B \to \mu\bar{\nu}_\mu) \sim 10^{-7}$$
$$\mathcal{B}(B \to \tau\bar{\nu}_\tau) \sim 10^{-4}$$



3) Semileptonic decays → **theory doable, experimentally doable**

How do we measure $|V_{xb}|$ in semileptonic decays ?



Inclusive $|V_{ub}|$

$$\bar{B} \to X_u \, \ell \, \bar{\nu}_\ell$$

+ Fermi Motion / Shape Function

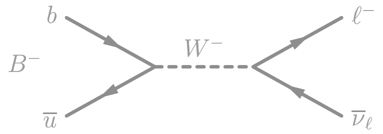
Inclusive $|V_{cb}|$

$$\bar{B} \to X_c \, \ell \, \bar{\nu}_\ell$$

Operator Product Expansion

$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q \, \ell \, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]$$

'Leptonic' $|V_{ub}|$



$$\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2$$

B-Meson decay constant

Exclusive $|V_{ub}|$

$$\bar{B} \to \pi \, \ell \, \bar{\nu}_\ell, \Lambda_b \to p \, \mu \, \bar{\nu}_\mu$$

Exclusive $|V_{cb}|$

$$\bar{B} \to D \, \ell \, \bar{\nu}_\ell, \bar{B} \to D^* \, \ell \, \bar{\nu}_\ell$$

$$\mathcal{B} \propto |V_{cb}|^2 \, f^2$$

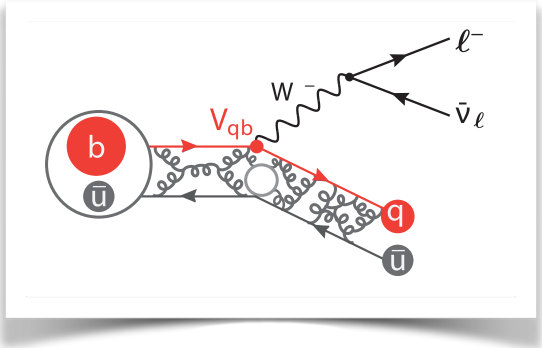
Form Factors

$$\langle B | H_\mu | P \rangle = (p + p')_\mu \, f_+$$

How do we measure $|V_{xb}|$ in semileptonic decays ?

Inclusive $|V_{ub}|$ | Inclusive $|V_{cb}|$

+ Ferm ... pansion



Measured
Branching Fraction

$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(\bar{B} \to X_q \, \ell \, \bar{\nu}_\ell)}{\tau \, \Gamma(\bar{B} \to X_q \, \ell \, \bar{\nu}_\ell)}}$$

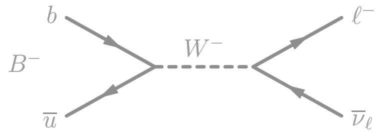
Prediction from
Theory but often also constrained
from **measured differential distributions**

Theory from non-perturbative Methods:

- Lattice QCD (high q^2)
- QCD Sum rules (low q^2)

$$q^2 = (p - p')^2$$

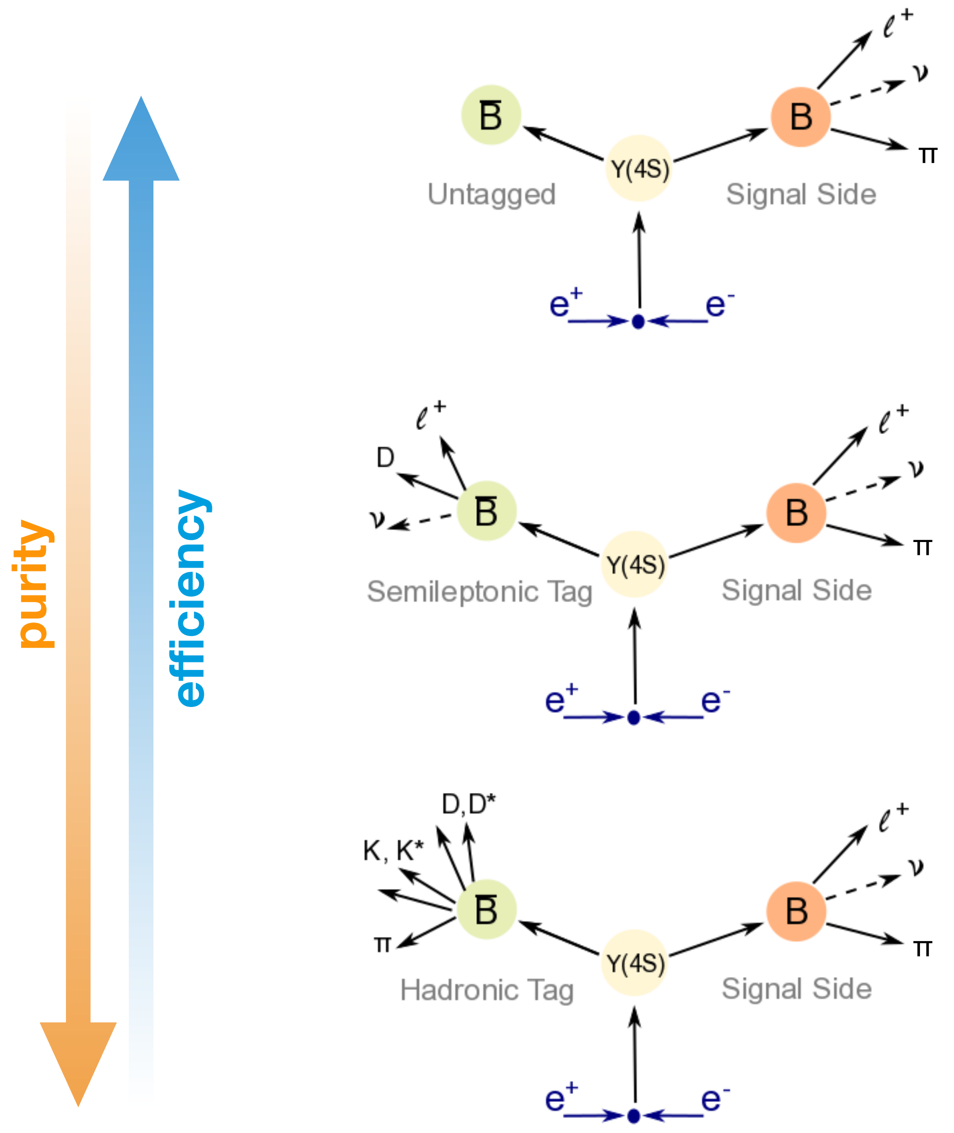
‘Leptonic’ $|V_{ub}|$



$$\mathcal{B} \propto |V_{ub}|^2 \, f_B^2 \, m_\ell^2$$

B-Meson decay constant

Event Reconstruction with Tagging Techniques

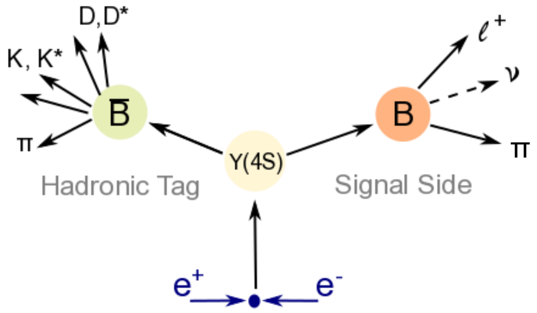


- Untagged / inclusive tag
  - Loose constraints on signal
  - Very large statistics, but also very large background
  - Efficiency $\epsilon \approx \mathcal{O}(100\%)$
- Semileptonic tag
  - Mid-range reconstruction efficiency $\epsilon \approx \mathcal{O}(1\%)$
  - Due to multiple neutrinos, less information about B_{tag}
- Hadronic tag
  - Cleaner sample
  - Knowledge of $p(B_{sig})$
  - Low tag-side efficiency $\epsilon \approx \mathcal{O}(0.1\%)$

Inclusive $|V_{ub}|$ Measured on Belle

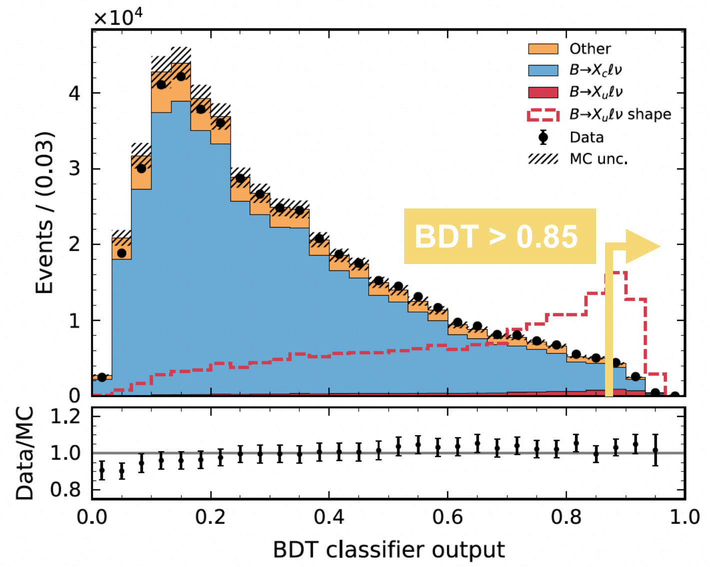
PRD 104 , 012008 (2021), arXiv:2102.00020

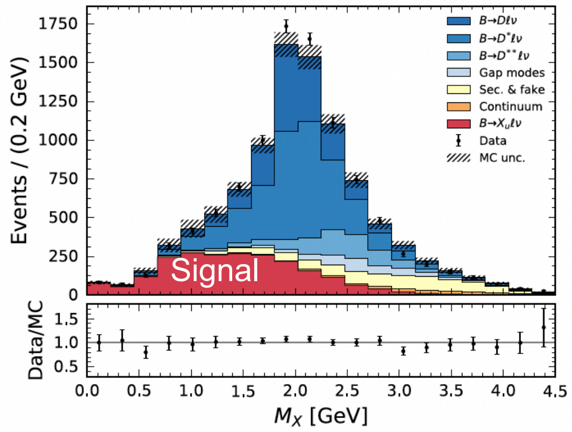
- Using **full Belle** dataset of **711 fb^{-1}**
- **Hadronic tagging** with Neural Networks (0.2-0.3% efficiency)
- Use **machine learning (BDT)** to suppress backgrounds with 11 training features, e.g. MM^2,#$K^{\pm}$, #K_S, etc.

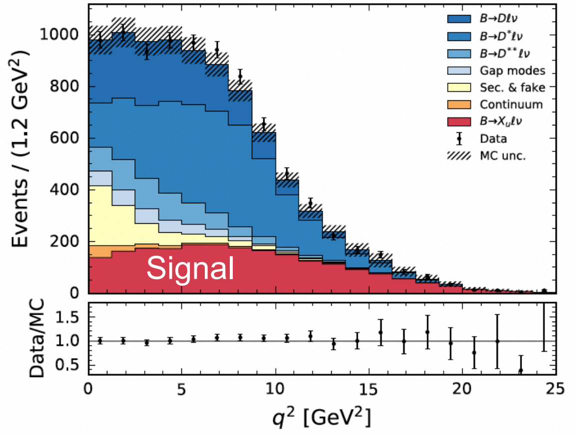


Can fully assign each final state particle to either the tag or signal side

→ Allows to reconstruct X_u







Reconstructed kinematic variables

- Hadronic system X:

$$p_X = \sum_i \left(\sqrt{m_\pi^2 + |\mathbf{p_i}|^2}, \mathbf{p_i}\right) + \sum_i (E_i, \mathbf{k_i})$$

- Missing mass squared:

$$MM^2 = (P_{\Upsilon(4S)} - P_{\text{tag}} - P_X - P_\ell)^2$$

- Leptonic system:

$$q^2 = (P_B - P_X)^2 = (P_l + P_\nu)^2$$

Inclusive $|V_{ub}|$ Measured on Belle

PRD 104 , 012008 (2021), arXiv:2102.00020

- Extract signal using binned likelihood in **3 phase space (PS) regions:**
  - $E_\ell^B > 1$ GeV **(covers 86% of available signal PS)**
  - $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV **(56%)**
  - $E_\ell^B > 1$ GeV, $M_X < 1.7$ GeV, $q^2 > 8$ GeV^2 **(31%)**
- Signal yields further corrected for efficiency & acceptance in 3 PS regions
- Convert partial BF in $E_\ell^B > 1$ GeV of 2D fit result to $|V_{ub}|$
- Based on **four** calculations of the **decay rate**

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell^+ \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u \ell^+ \nu_\ell)}}$$

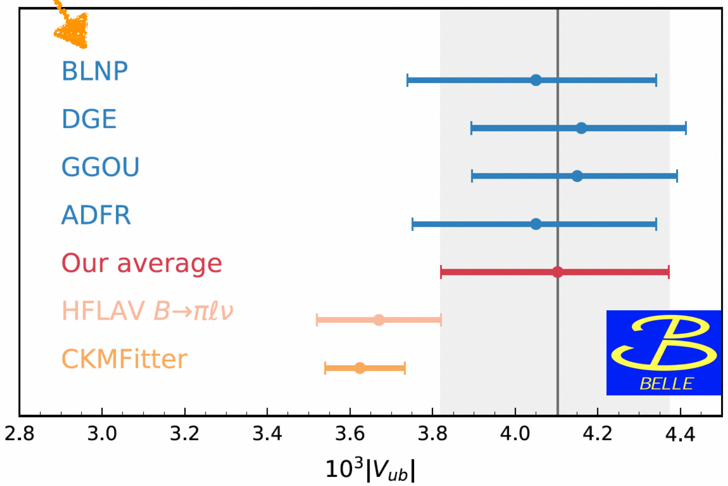
$\Delta\mathcal{B}(E_\ell^B > 1$ GeV$) =$

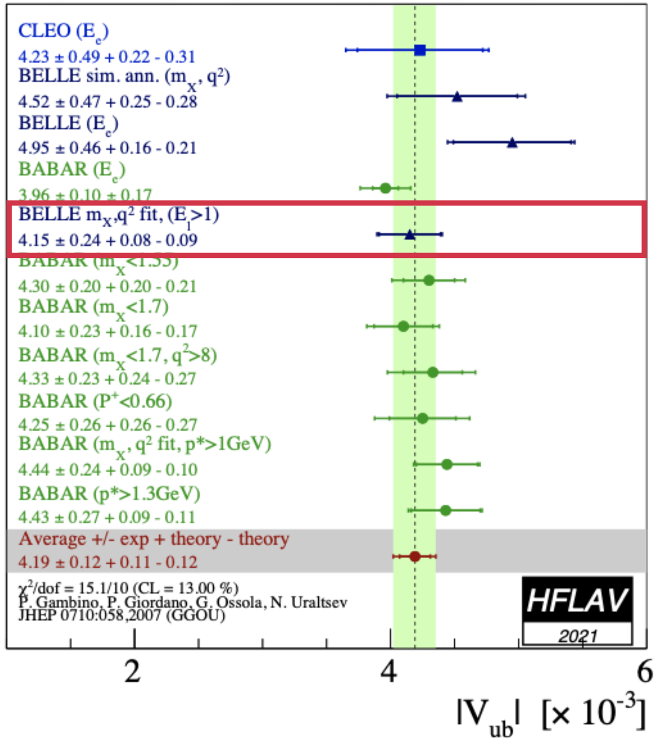
$(1.59 \pm 0.07_{stat} \pm 0.16_{sys}) \times 10^{-3}$

Our average:

$|V_{ub}| = (4.10 \pm 0.09_{stat} \pm 0.22_{sys} \pm 0.15_{theo}) \times 10^{-3}$

compatible with excl. and CKM expectation within 1.3σ and 1.6σ respectively

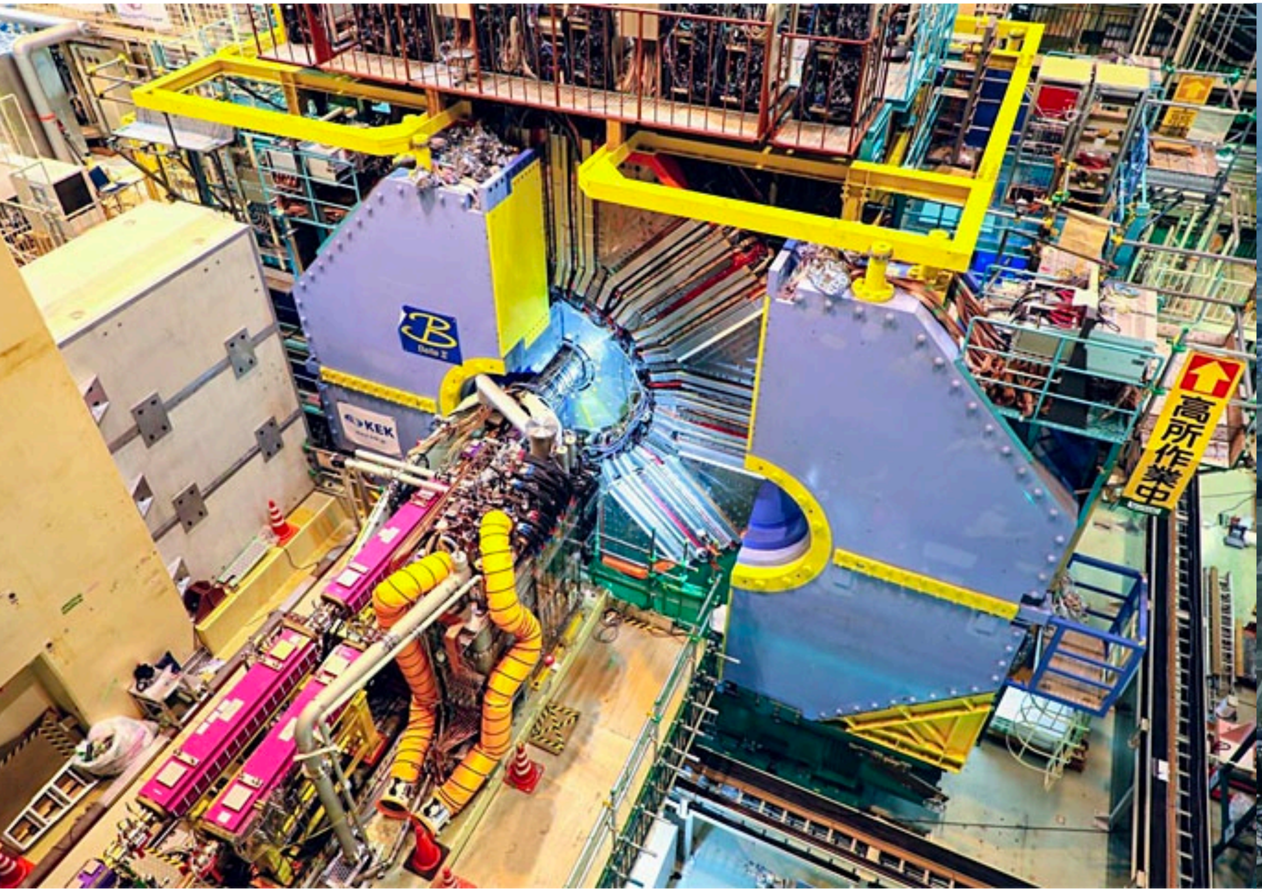


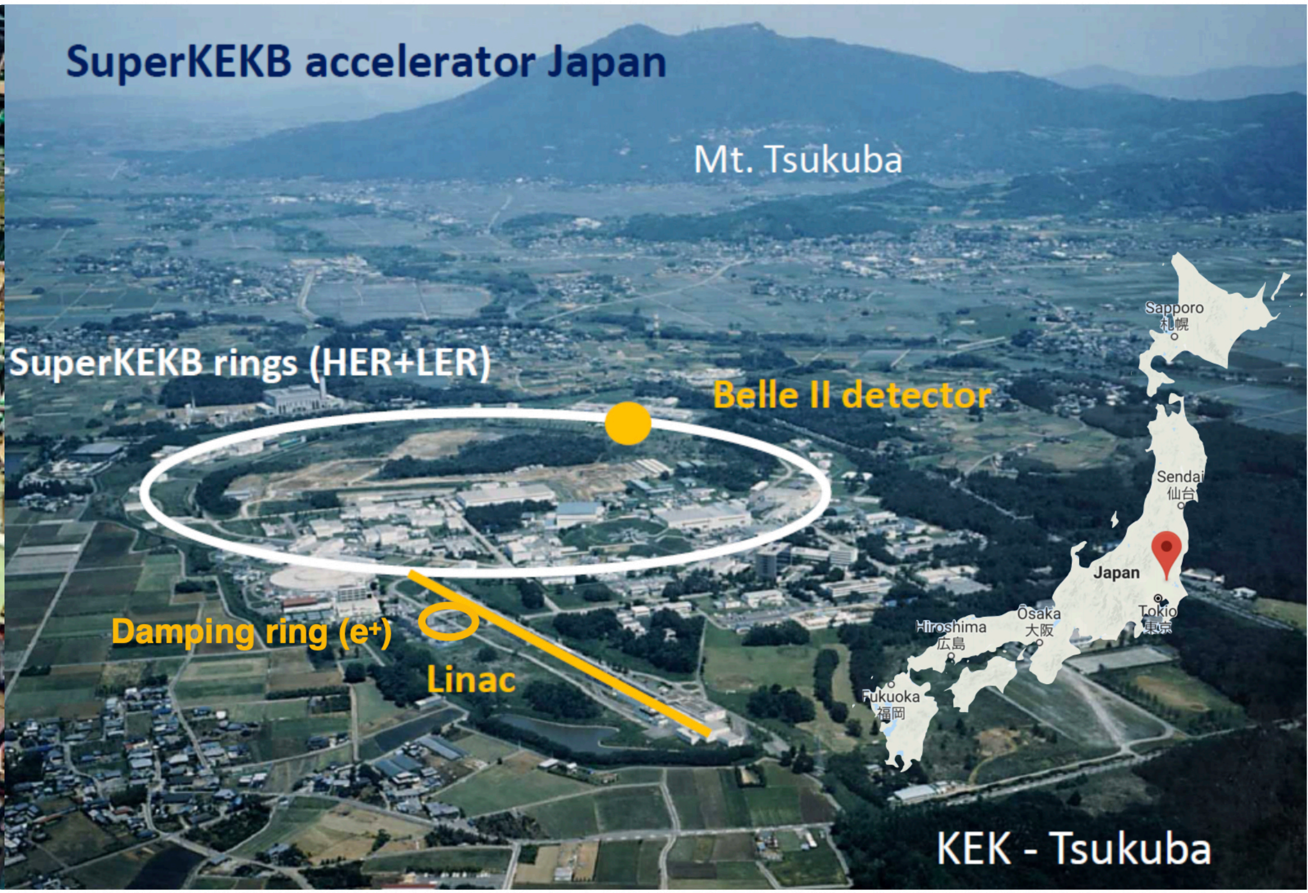


arXiv:2206.07501 [hep-ex]

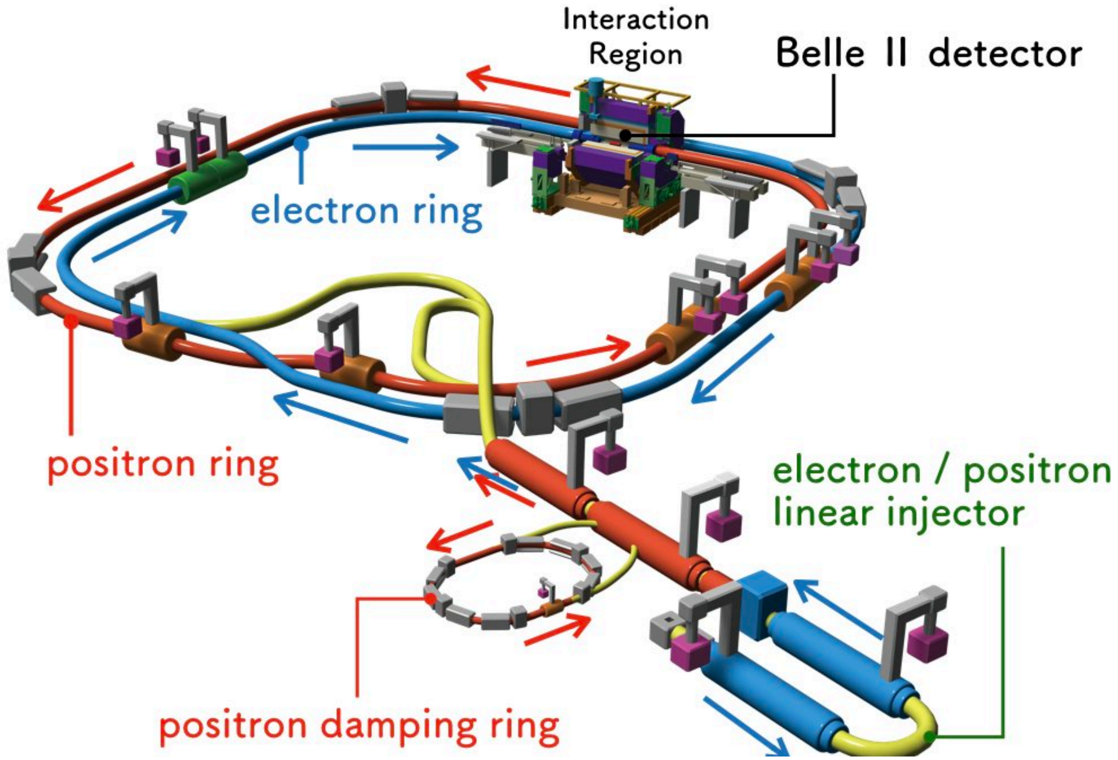
Belle II: A Super B-Factory

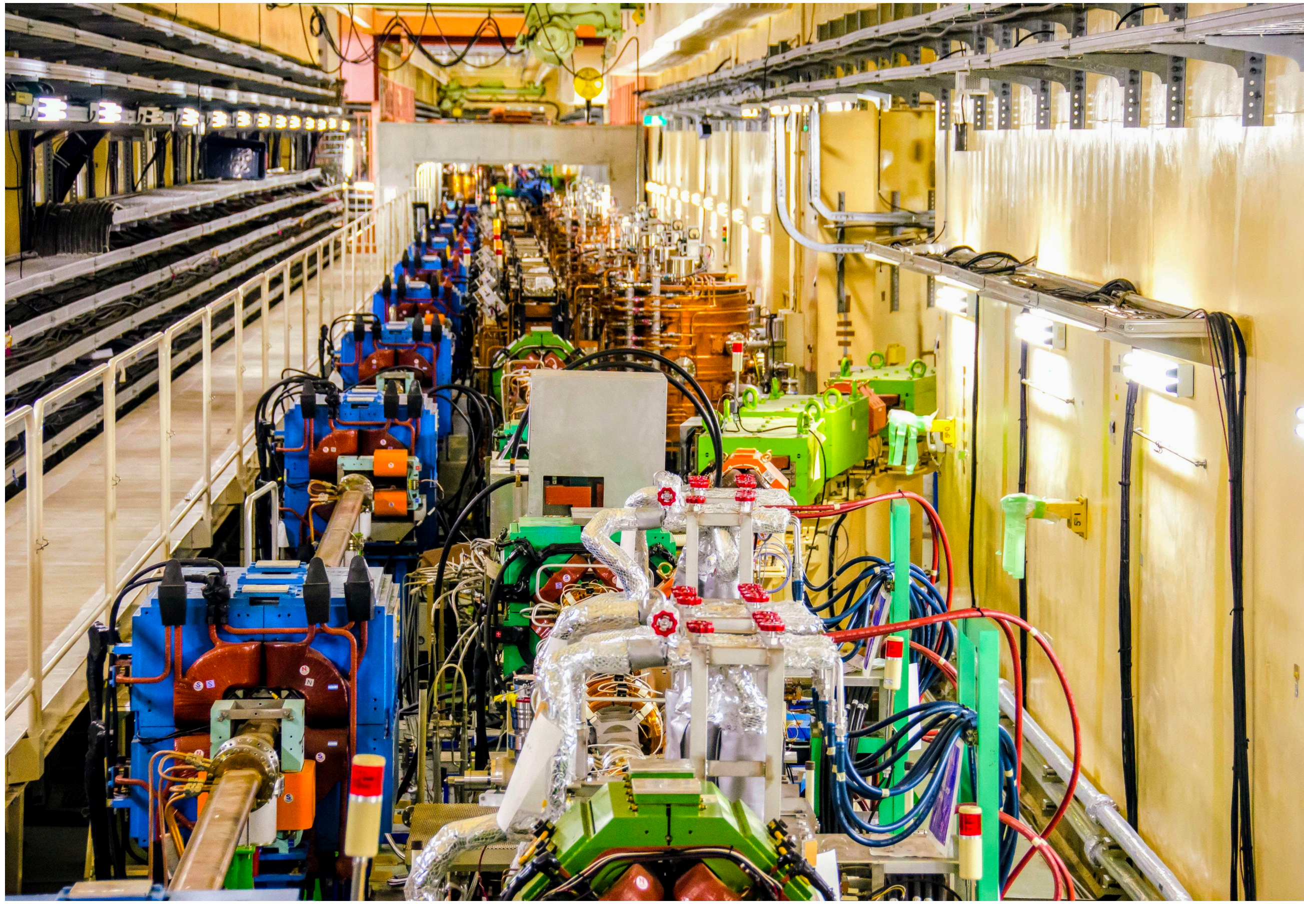
- Belle II is the next generation B Factory at KEK in Japan.
- Goal is to collect **50 billion** $B\bar{B}$ **pairs!**



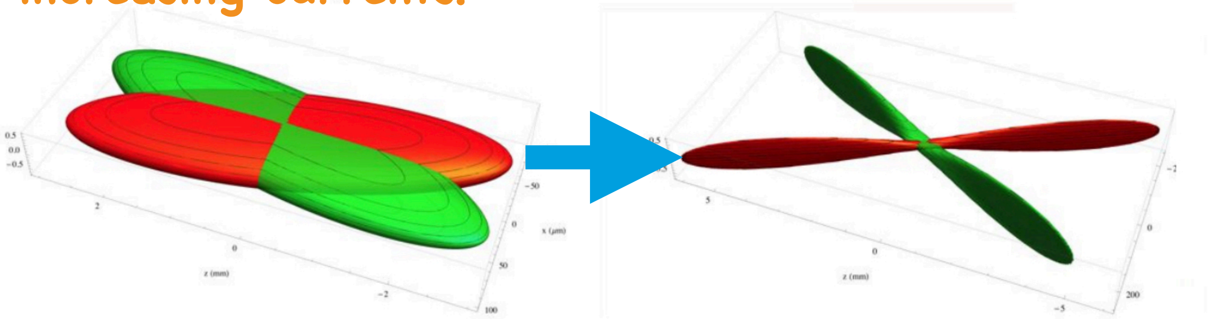


The SuperKEKB Collider



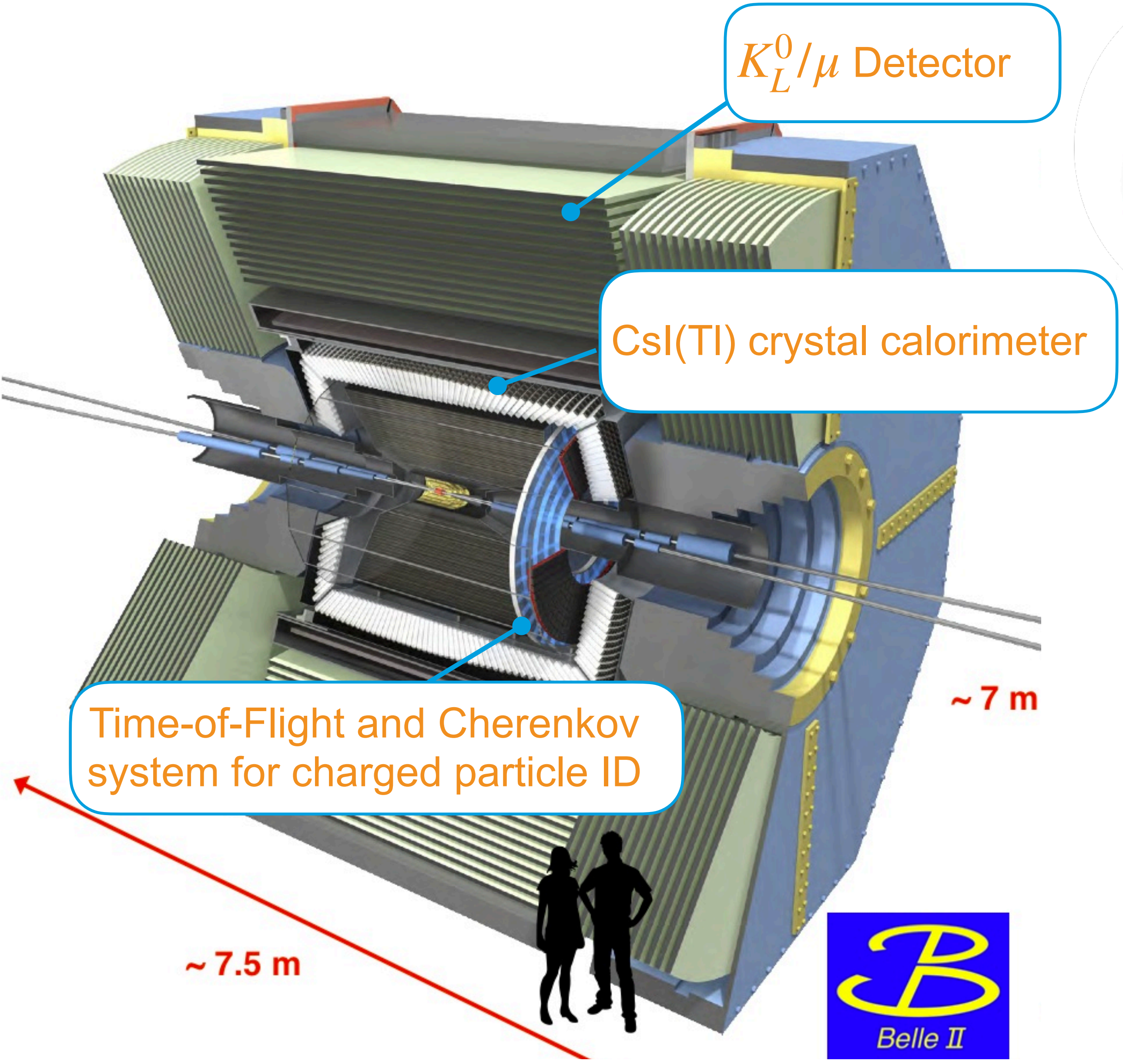


40x increase in luminosity by squeezing beams and increasing currents!

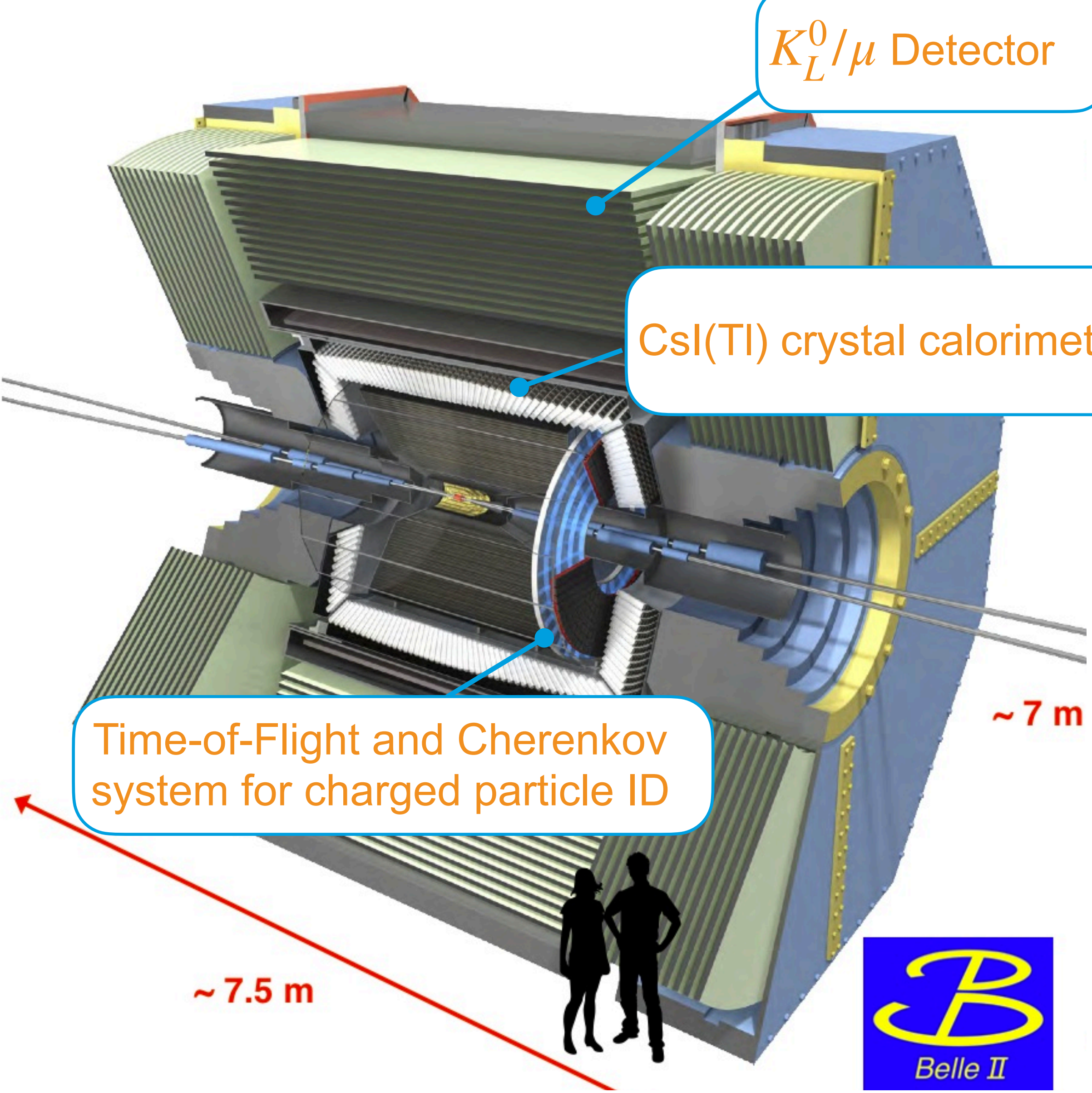


Current holds the world record for instantaneous luminosity!

Belle II Detector

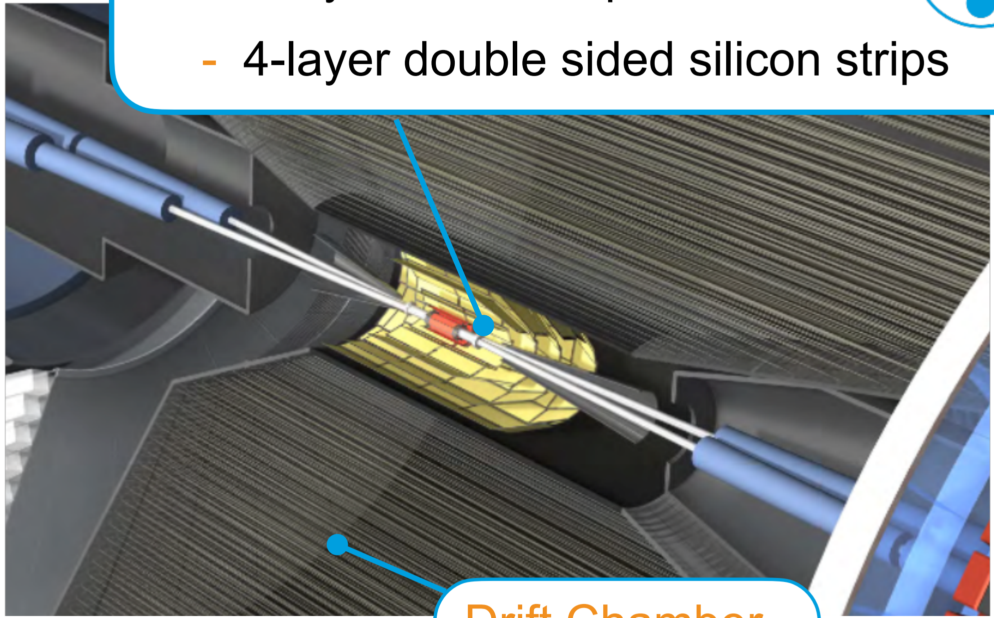


Belle II Detector

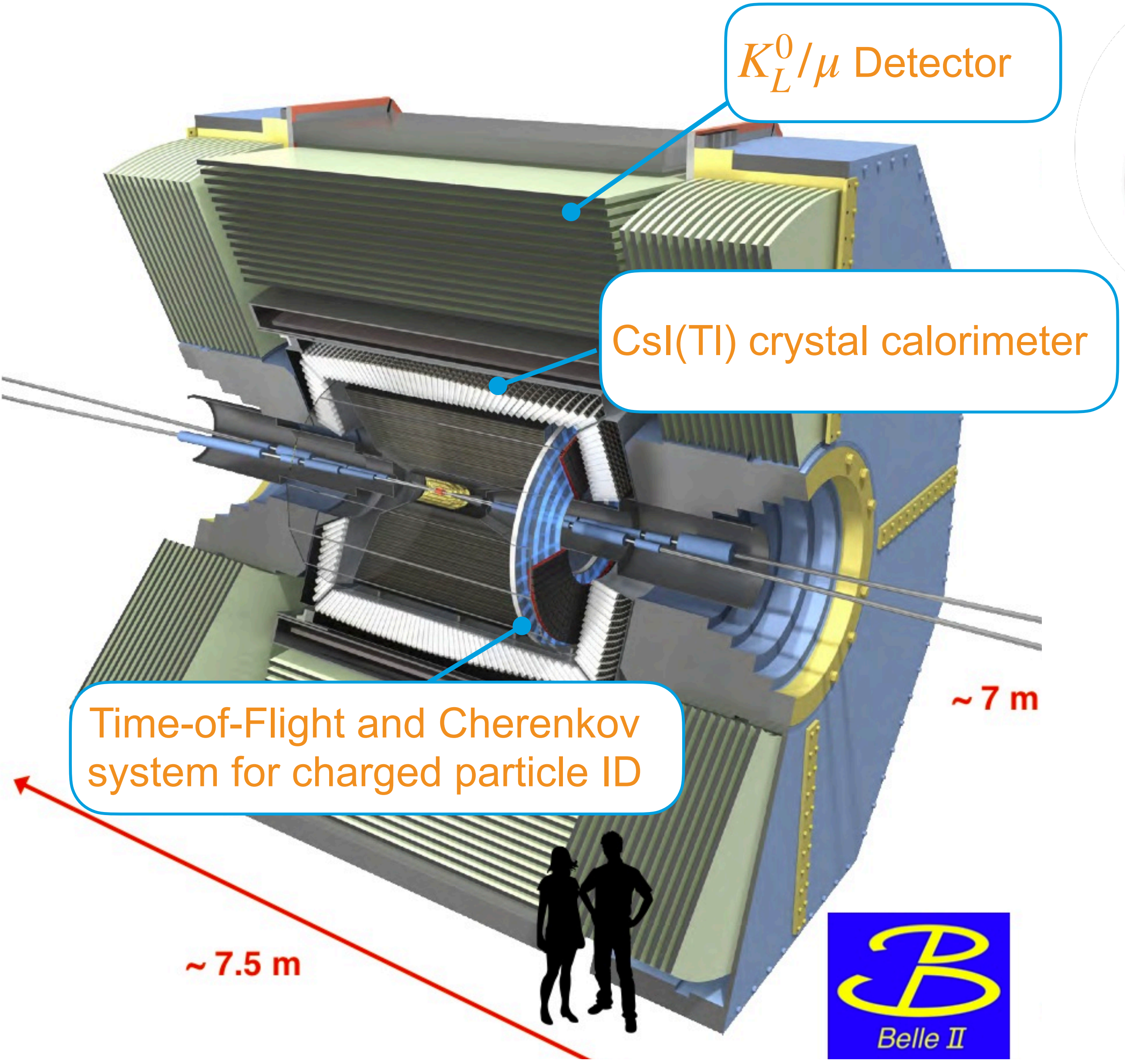


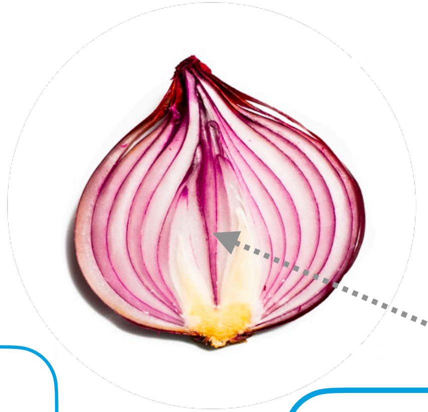
Vertexing:

- 2-layer DEPFET pixel detector
- 4-layer double sided silicon strips



Belle II Detector





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- 2-layer DEPFET pixel detector
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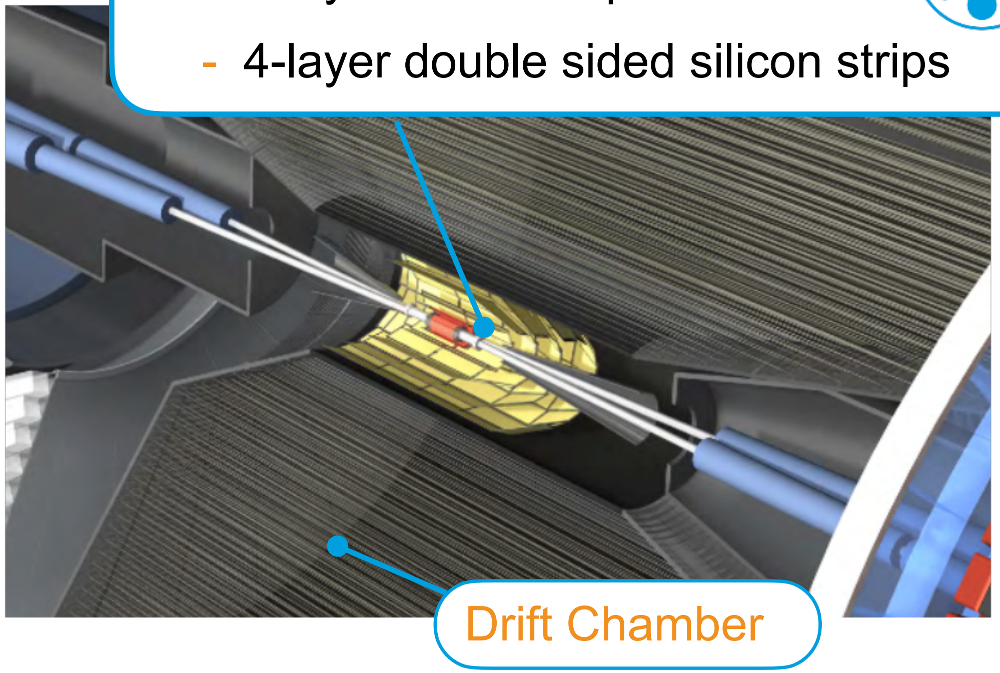
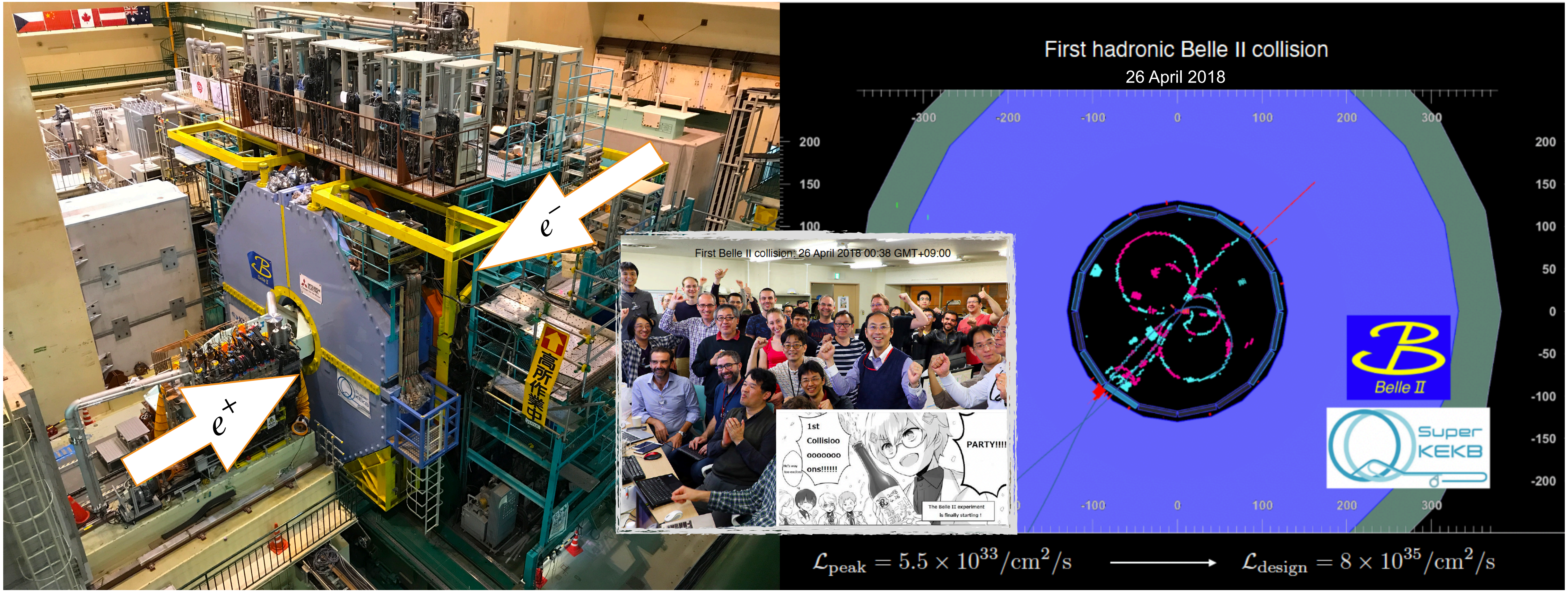


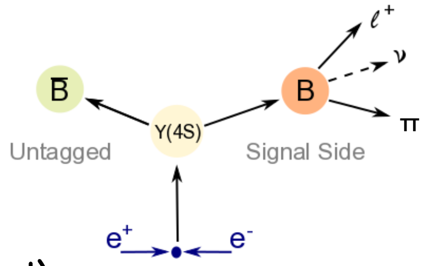
Belle II Collisions



Untagged $B \to \pi \ell \nu$ and Exclusive $|V_{ub}|$

Preliminary result shown in ICHEP 2022

- Using **early Belle II** dataset of **189 fb^{-1}**
- Signal lepton with high momenta
- Pion with good tracking quality
- No reconstruction of tag-side B meson (untagged)



- Fit differential spectra of q² with LQCD constraints on the decay form factor

$$\mathcal{B}_{B^0\to\pi^-\ell^+\nu_\ell} = (1.421 \pm 0.056 \pm 0.126) \times 10^{-4},$$
$$|V_{ub}|_{B^0\to\pi^-\ell^+\nu_\ell} = (3.54 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.16_{\text{theo}}) \times 10^{-3}.$$

Consistent with HFLAV world average;
uncertainty about 60% higher

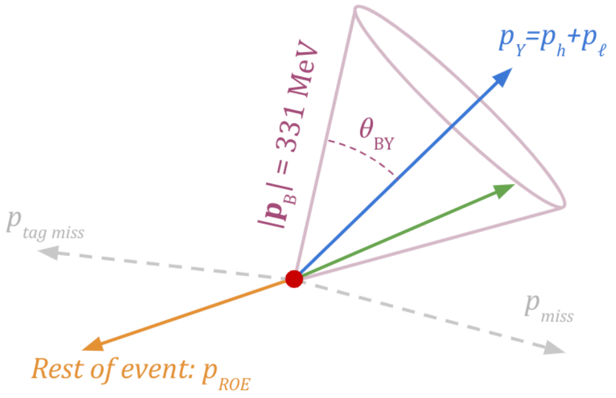
q^2 estimation

- $q^2 = (p_B - p_\pi)^2$
- p_B is **not known** (untagged); estimated with new method and errors in q^2 corrected

Background reduction

Boosted Decision Trees trained on kinematic variables, independently in each channel and q^2 bin:

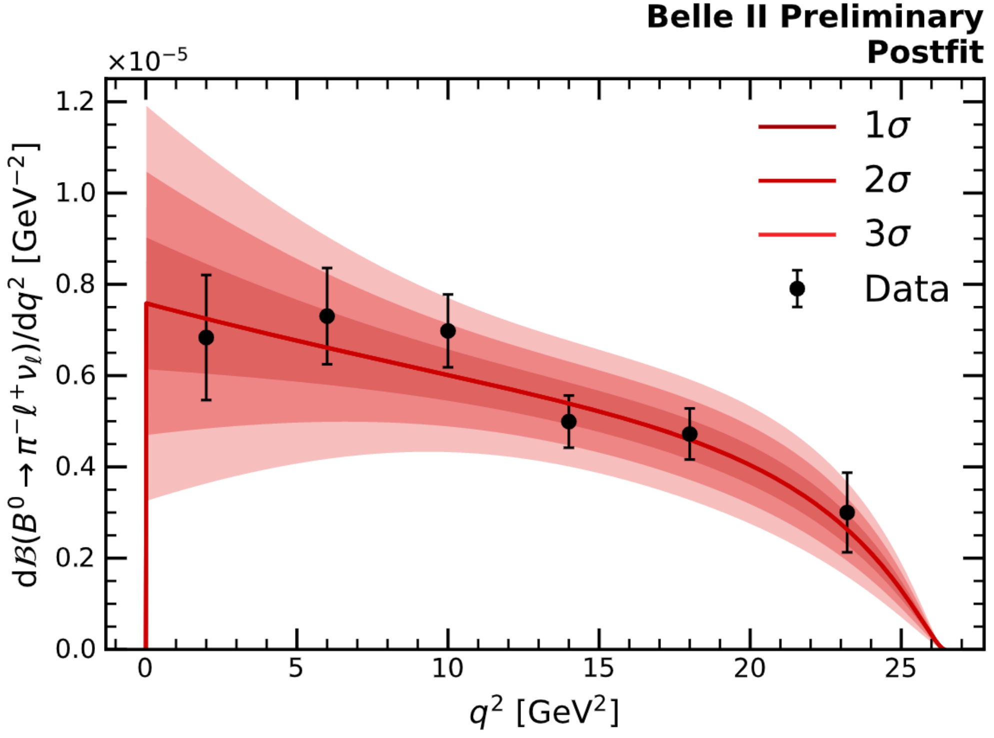
- Other *BB* events
- Continuum
- Two-photon processes [$ee\tau\tau$]



Choose p_B as **weighted mean** with weights:

$$\frac{1}{2}\left(1 - \hat{p}_{\text{ROE}} \cdot \hat{p}_B\right) \sin\theta_B$$

Credit: Peter Lewis

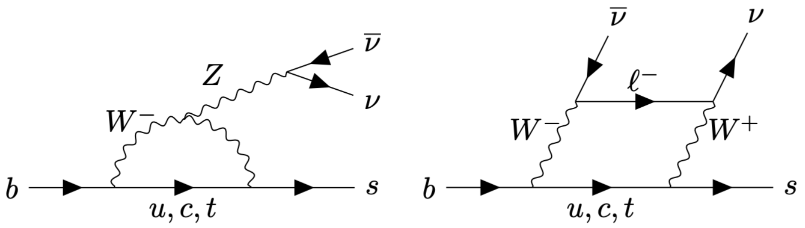


$B^+ \to K^+\nu\nu$ with Inclusive Tagging

PRL 127 , 181802 (2021), arXiv:2104.12624

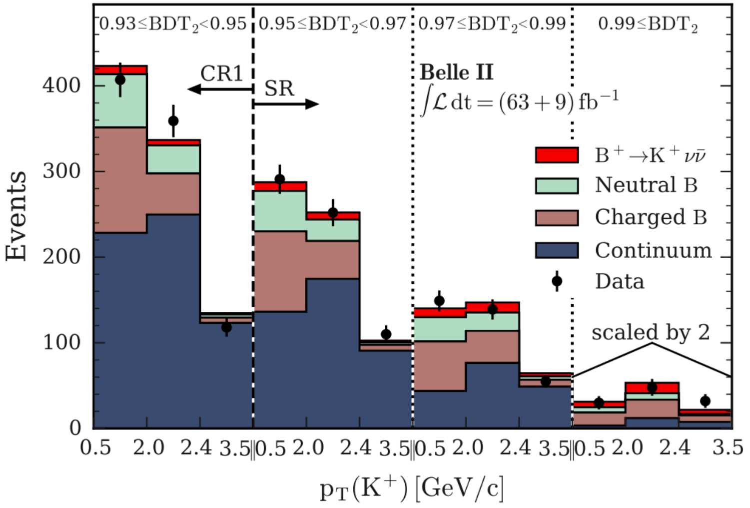
- $b \to s$, flavour-changing neutral current involved
- Rare decay offers a complementary probe for BSM
- Single highest-p_T K^+ is selected as signal candidate
- All the rest particles of the event are used to reconstruct the tag-side B meson (inclusive tagging)
- Two sequential BDTs are trained that combine event topology, signal kaon and rest-of-event properties, etc. to remove backgrounds

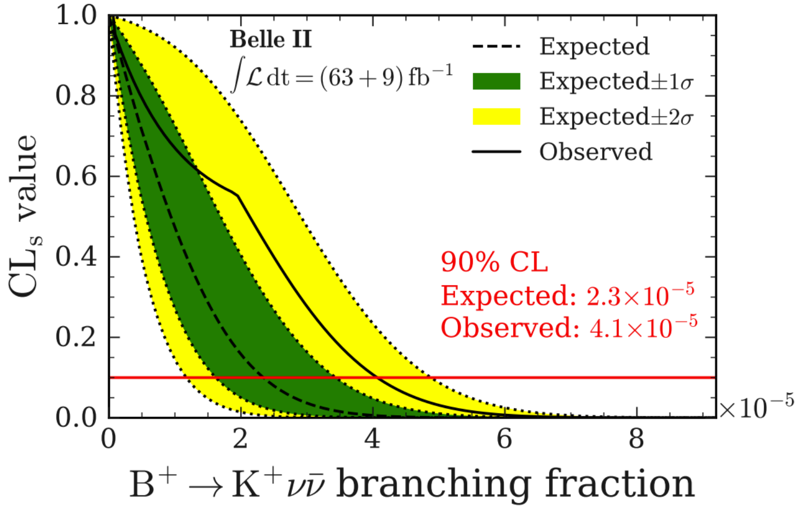
The lowest-order in SM:

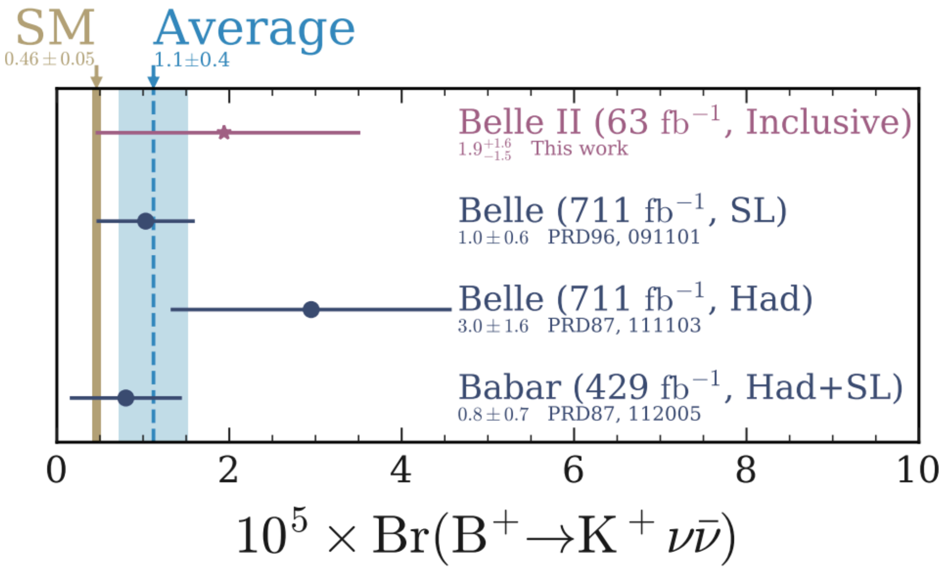


(a) Penguin diagram (b) Box diagram

Predicted BF:
~ 5 x 10^{-6}



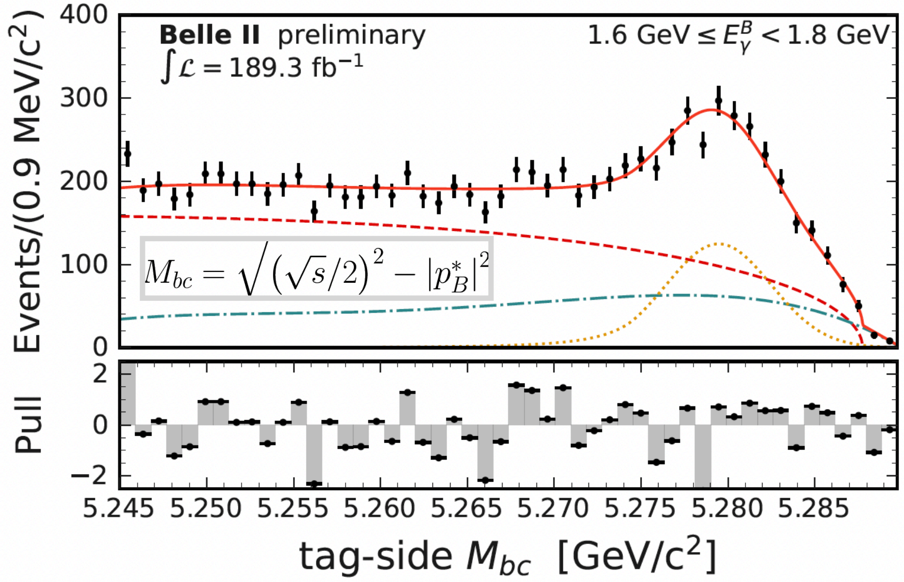


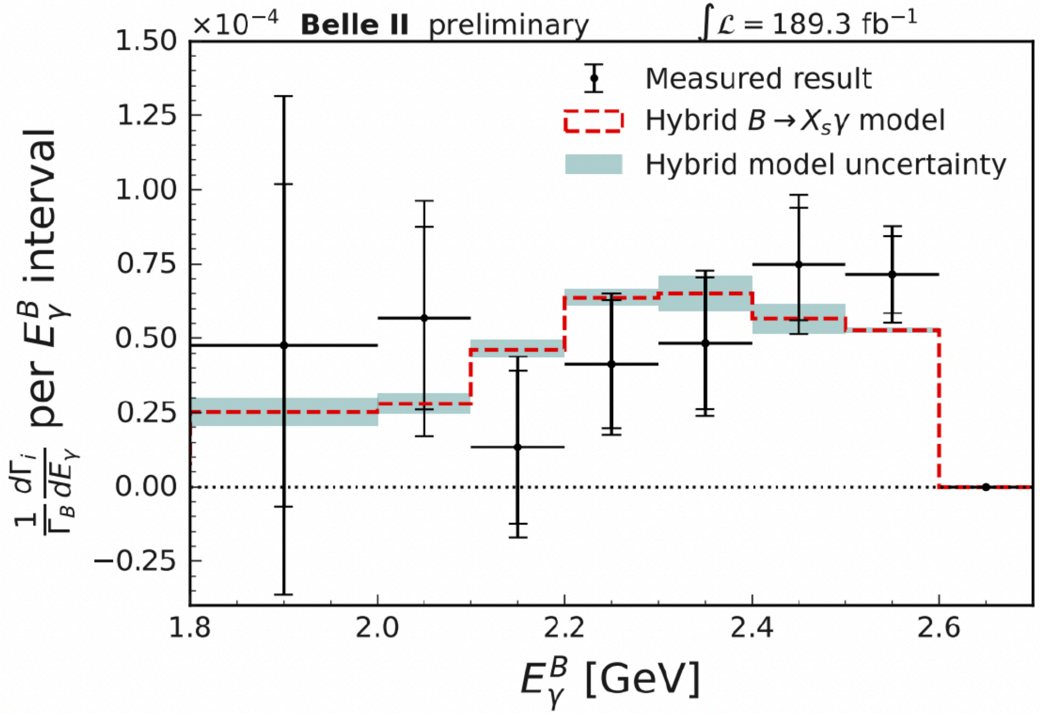


$B \to X_s\gamma$ with Hadronic Tagging

Preliminary result shown in ICHEP 2022

- Radiative penguins $b \to s\gamma$
- Photon energy spectra involves the Fermi motion of b-quark in B
- Hadronic decays of tag-side B are reconstructed (hadronic tagging)
- Challenged by large photon background from other processes
  - High energy threshold of signal photon
  - Suppress background of light-quark continuum and other B decays



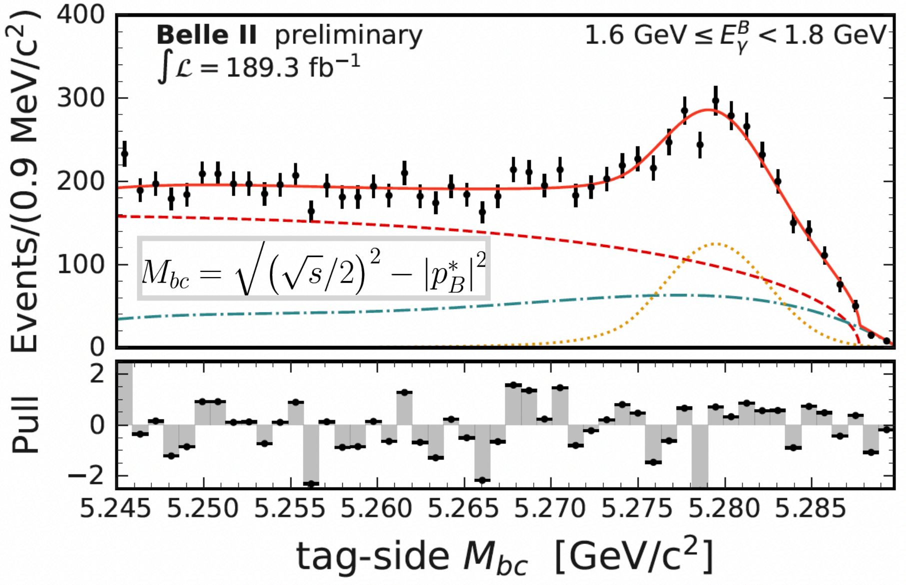


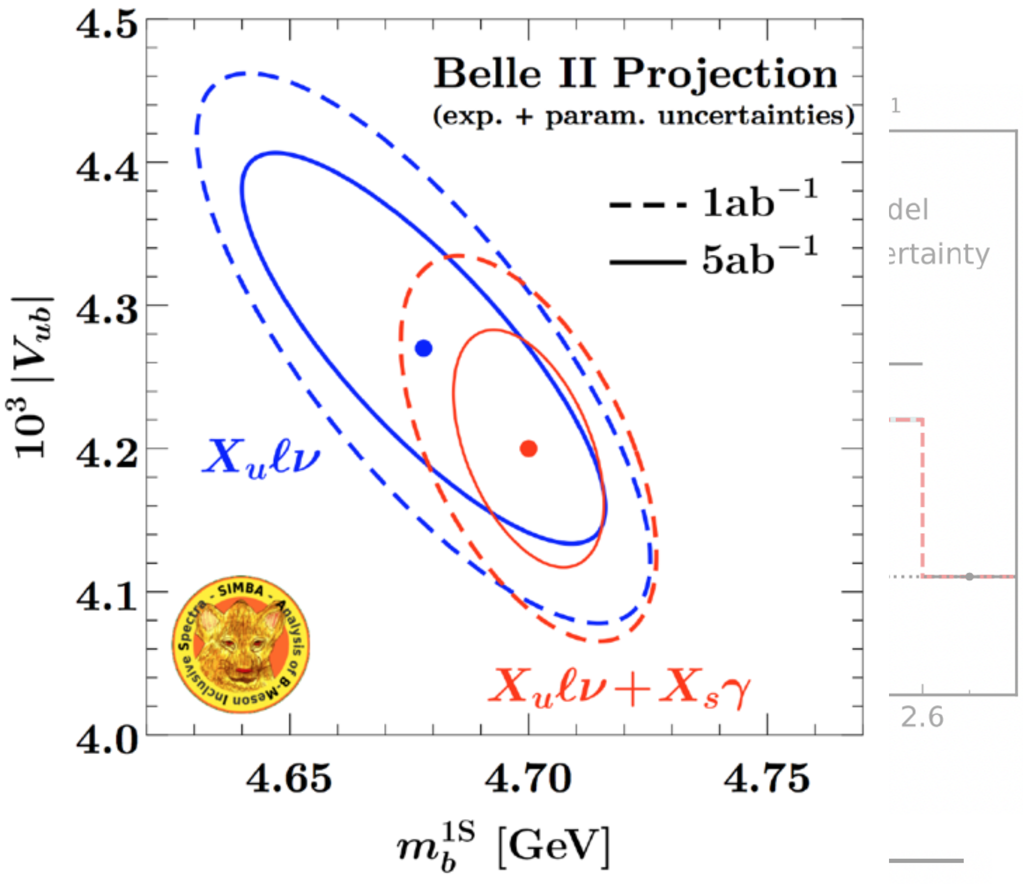
E_γ^B threshold, GeV	Branching fraction (10^{-4})
1.8	3.54 ± 0.78 (stat.) $\pm$ 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) $\pm$ 0.47 (syst.)

$B \to X_s \gamma$ with Hadronic Tagging

Preliminary result shown in ICHEP 2022

- Radiative penguins $b \to s\gamma$
- Photon energy spectra involves the Fermi motion of b-quark in B meson (non-perturbative shape functions)
- Hadronic decays of tag-side B are reconstructed (hadronic tagging)
- Challenged by large photon background from other processes
    - High energy threshold of signal photon
    - Suppress background of light-quark continuum and other B decays



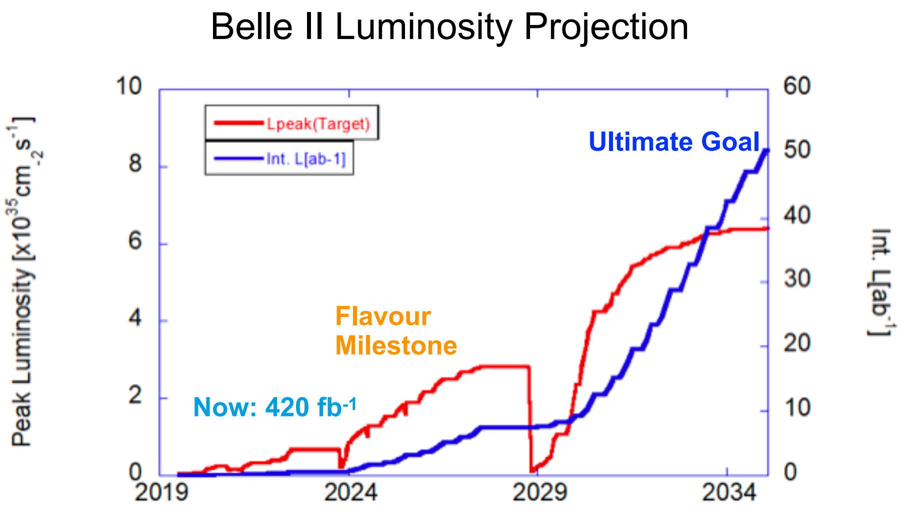


Theo+Exp: direct extract coefficients of shape functions in a global fit and obtain $|V_{ub}|$!!

Golden Channels @ Belle II

Flavour Milestone (5-10 ab^{-1})

Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	New Physics
$B \to \pi l \nu$	$\|V_{ub}\|$	★★★	10-20	★★★	★★★	★★	★
$B \to X_u l \nu$	$\|V_{ub}\|$	★★	2-10	★★★	★★	★★★	★
$B \to \tau \nu$	$\mathcal{B}$	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu \nu$	$\mathcal{B}$	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)} l \nu$	$\|V_{cb}\|$	★★★	1-10	★★★	★★	★★	★
$B \to X_c l \nu$	$\|V_{cb}\|$	★★★	1-5	★★★	★★	★★	★★
$B \to D^{(*)} \tau \nu$	$R(D^{(*)})$	★★★	5-10	★★	★★★	★★★	★★★
$B \to D^{(*)} \tau \nu$	P_τ	★★★	15-20	★★★	★★★	★★	★★★
$B \to D^{**} l \nu$	$\mathcal{B}$	★	-	★★	★★★	★★	-
$B \to l \nu \gamma$	λ_B	★★	-	★★★	★★★	★	★★
$B \to K^{(*)} \nu \nu$	$\mathcal{B}$, F_L	★★★	>50	★★★	★★★	★	★★

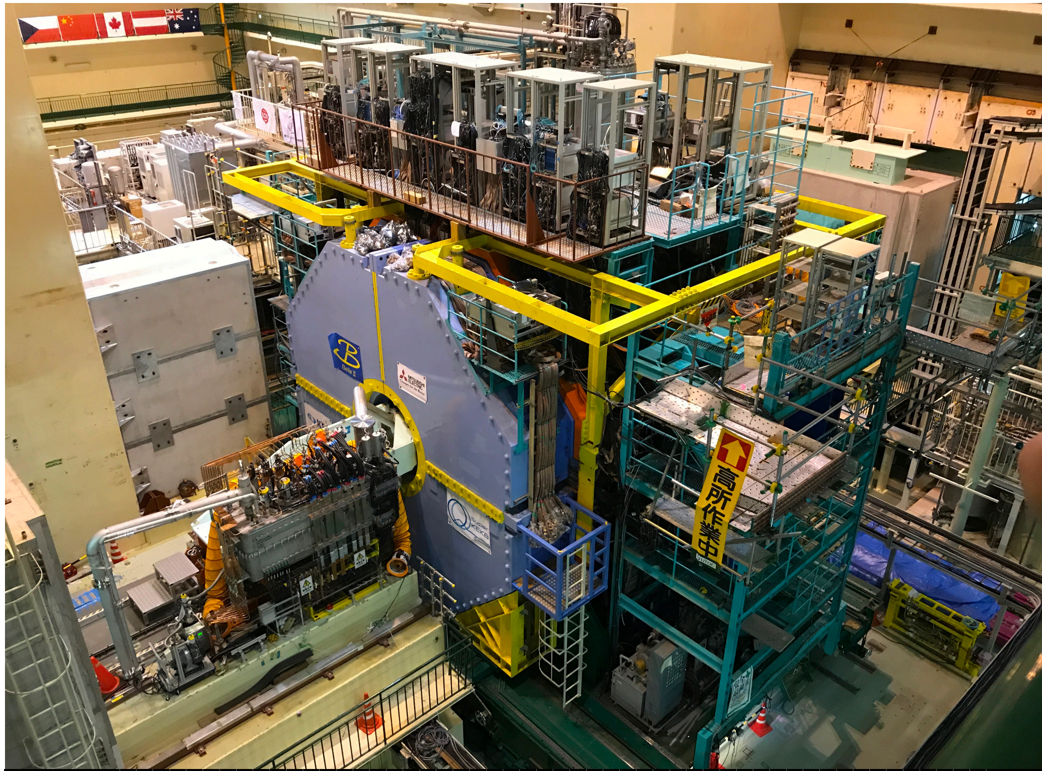


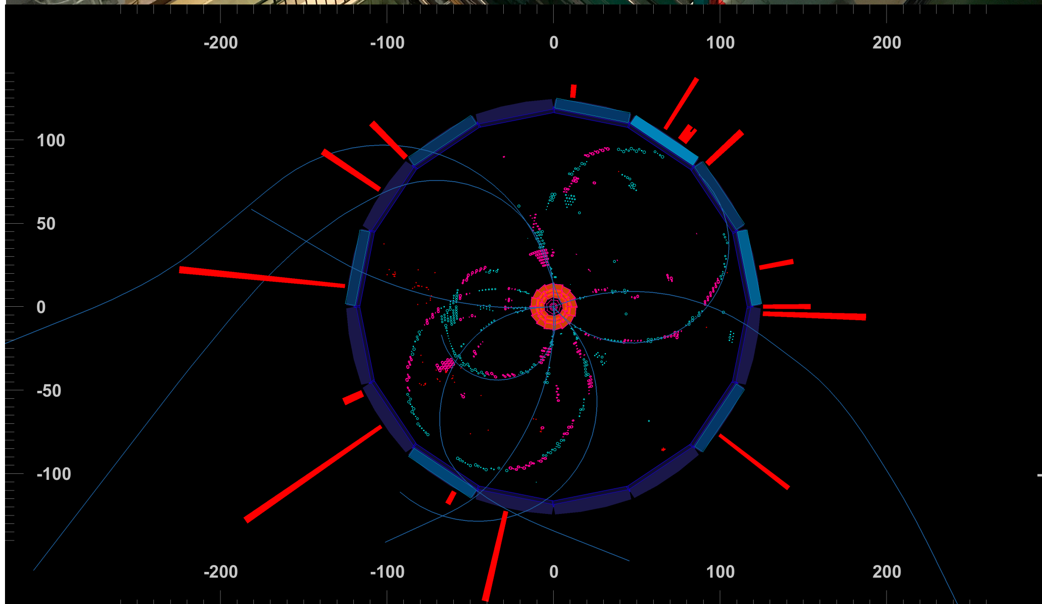
The Belle II Physics Book, *Progress of Theoretical and Experimental Physics*, Volume 2019, Issue 12, December 2019, 123C01,
https://doi.org/10.1093/ptep/ptz106
arXiv: 1808.10567 [hep-ex]

Summary

- Many new opportunities in flavour physics and Belle II!
  - ➡ Precision measurements of CKM matrix elements!
  - ➡ Precision measurements with rare B decays!
  - ➡ Searches for new sources of CP violation!
  - ➡ Searches for rare decays!
  - ➡ Searches for new particles in decays!
  - ➡ Dark Matter searches!
  - ➡ also possible in Charm sector…

- Detailed references for physics at Belle II:
  - ➡ **Belle II Physics Book** (arXiv: 1808.10567)
  - ➡ **Snowmass White Paper**: Belle II physics reach and plans for the next decade and beyond (arXiv:2207.06307)





Belle II Collaboration

>1100 physicists and engineers from 126 institutions in 26 countries

You are warmly welcome to join us!

see Belle II positions (developing) and inspire-HEP

Thank you very much for your attention!

Acknowledgments

Some of this material was adapted with permission from the flavour physics lectures by Prof. Dr. Florian Bernlochner and the previous years HEP lectures by Dr. Savino Longo and Dr. Sam Cunliffe.