Introduction to Belle II Physics

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what do we mean by "physics"?

(in particle physics)

- Fundamental laws of particles and interactions
  - Standard model {quarks, leptons, bosons, Higgs + ??
  - coupling constants, interaction vertices, (masses)…

- discovery: extraction of couplings, vertices, masses,… through phenomena involving particles & interactions
  - hadron/lepton/boson: production/scattering/decay …

what is produced in SuperKEKB?

$\beta_{CMS} \approx 0.27$

CMS

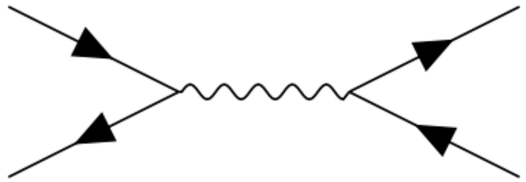
7.0 GeV e^- → ← 4.0 GeV e^+

$$\sqrt{s} = 10.579 \text{ GeV}$$

- Event rate $w = \mathcal{L} \times \boldsymbol{\sigma}$
  - Instantaneous Luminosity $\mathcal{L}$, now ≈ 5 x 10^{34} $cm^{-2}s^{-1}$ @ SuperKEKB
  - $\boldsymbol{\sigma}$ cross section depends on process type

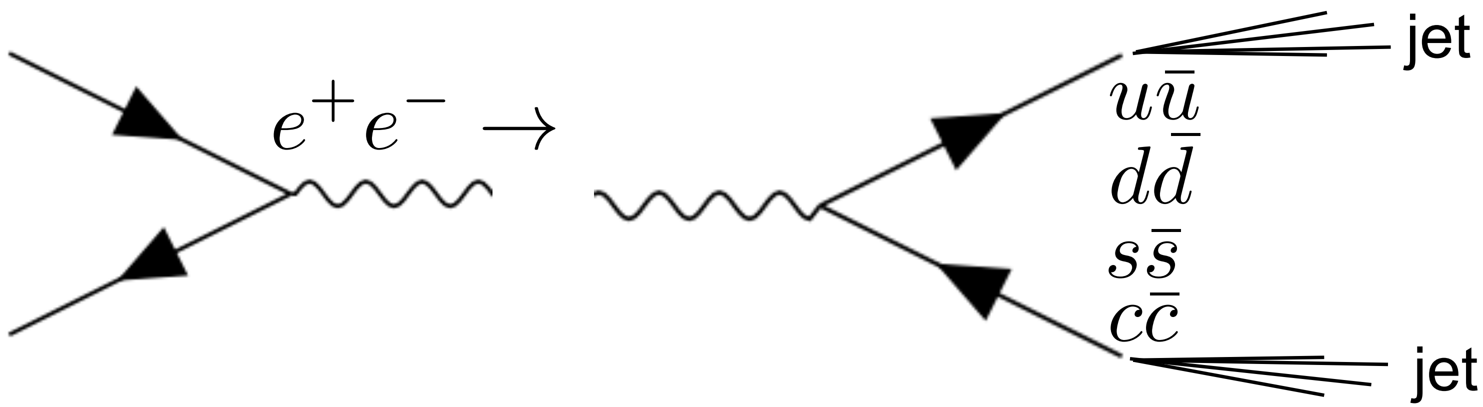
Unit: barn = 10^{-24} cm^2
➔ nb = 10^{-33} cm^2

- e.g. lepton pair production at ≈10 GeV (QED) $\mu^+\mu^-$, $\tau^+\tau^-$
  - each type $\sigma \approx 1$ nb ➔ w ≈ 5 x 10^{34} x 10^{-33} = 50 Hz



what is produced in SuperKEKB?

- quark pair production (QED) ➔ hadron jets (QCD)
  - σ ≈ 1 nb x (charge) q^2 x 3(color) x (1+QCD corrections)
    - u+d+s: σ ≈ 2 nb ➔ w ≈ 100 Hz
    - c: σ ≈ 1.3 nb ➔ w ≈ 73 Hz

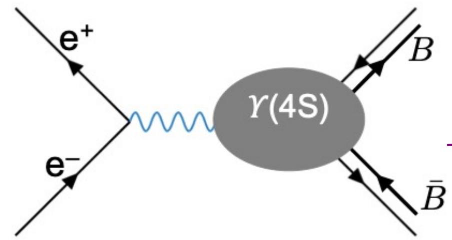


  - continuum: σ ∝ 1/s [s=(CME)^2]
- $b\bar{b}$ quark pairs: ≈mass threshold; σ complex structure vs s
  - resonances, phase space, hadronic effects

These appear as hadronic events (multiparticle, vs pair)

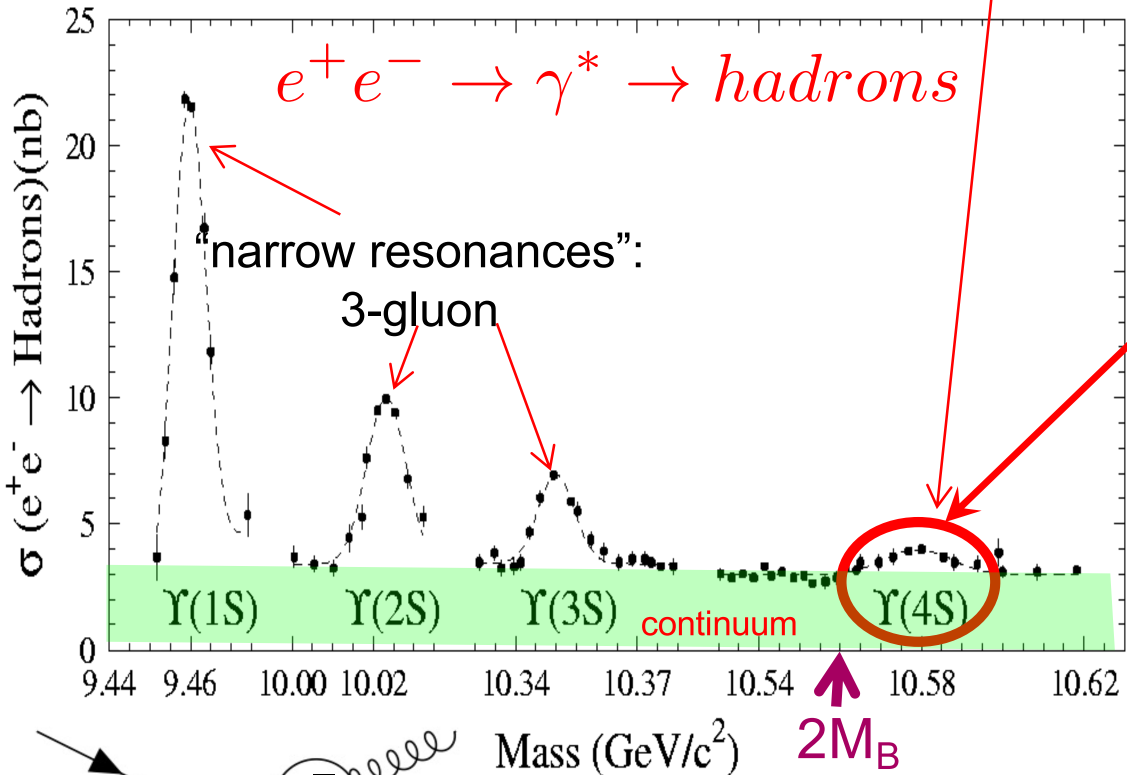
what is produced in SuperKEKB?

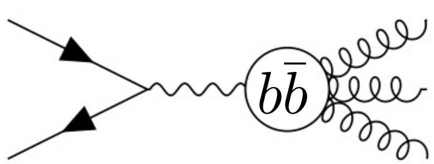
Upsilon (Υ) $b\bar{b}$ resonances

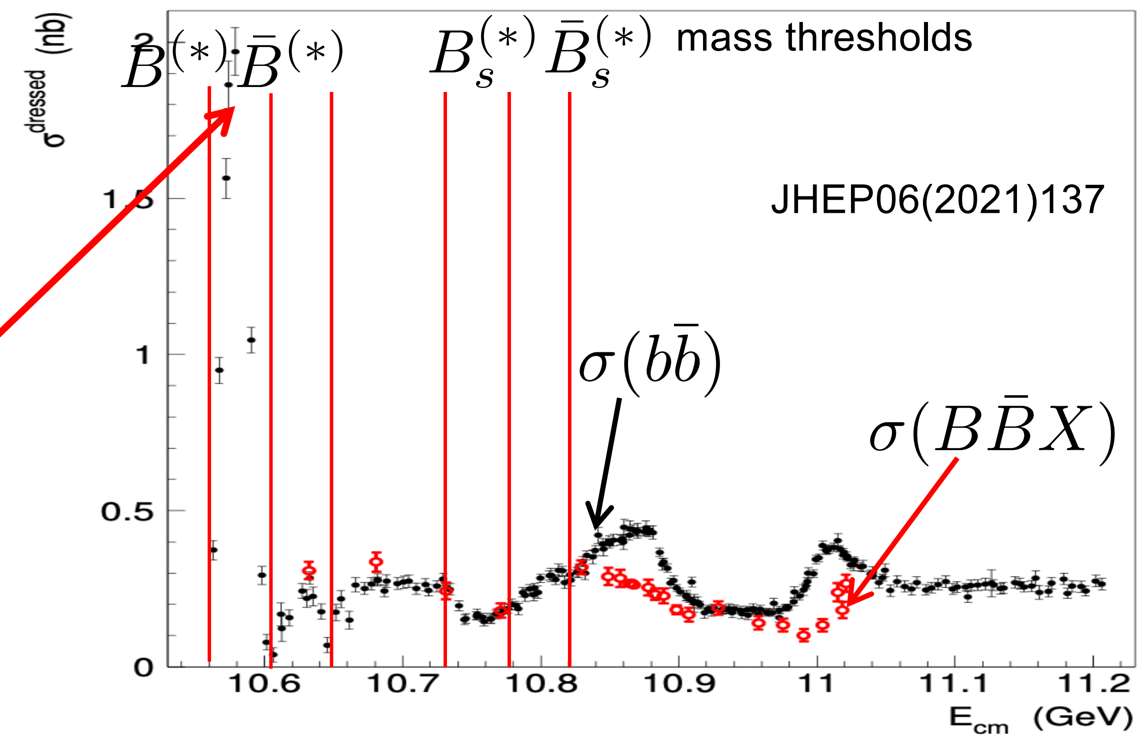


$B_q = \{B_d^0, B_u^+\}$

$\Upsilon(4S) \to B_q \bar{B}_q$







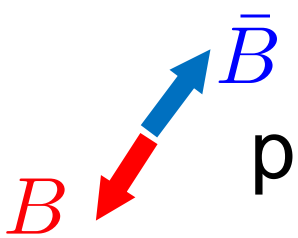
above Υ(4S), udsc subtracted

Uniqueness of Υ(4S) for B meson studies

- $\Upsilon(4S) \to B^+B^-, B^0\bar{B}^0$ (mostly)
  - $B^+ + B^0$: $\sigma \approx 1$ nb ➔ w ≈ 50 Hz

    ➔ events/year ≈ 50 Hz x 3 x 10^7sec x efficiency (≈0.6) ≈ 10^9

    (1 Belle dataset; SuperKEKB aiming for 5X over 10 yrs)
- exclusive B pairs (no additional particles) ➔
  - clean events
  - kinematic constraints
    - in CMS



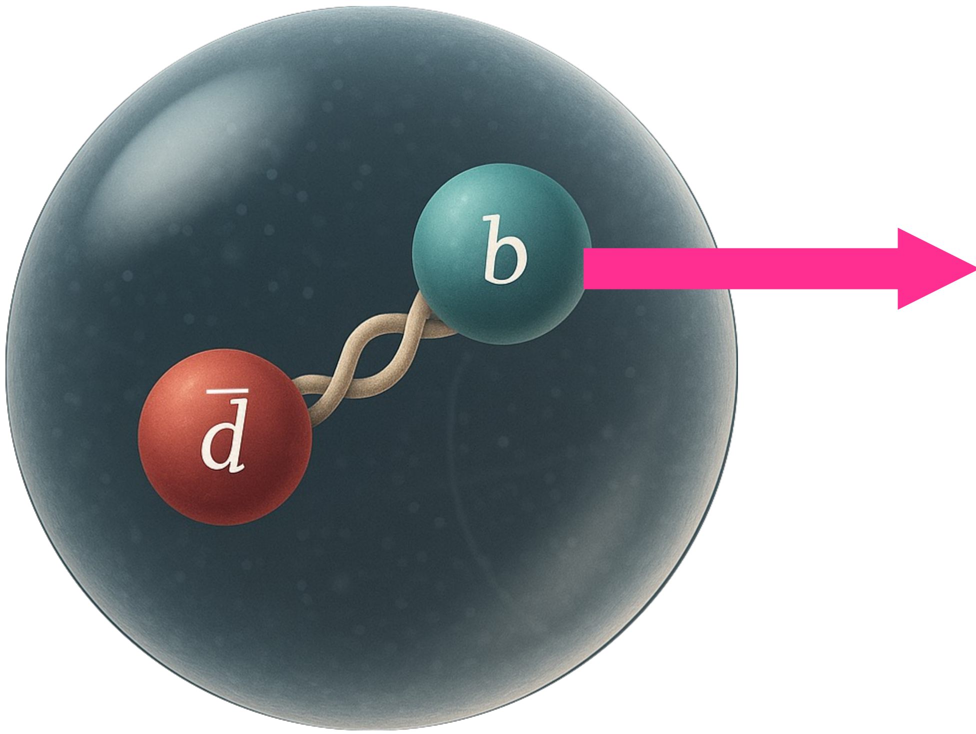
pc~0.33 GeV non-relativistic

Features of SuperKEKB/Belle II data

- e^+e^-: event cleanliness, high luminosity
  - O(10^9) events/year (each,several types) .. and rising!
- of high current interest
  - B mesons
  - charm hadrons
  - τ pairs
  - $\{\bar{b}b\}$ resonances
  - missing energy (dark matter) in the above events

How do B's decay? some basics

- B meson: $\{\bar{b}q\}$ where q is u or d
  - pseudoscalar; S=0, L=0
  - "stable" ➔ b-quark decays by weak force to <u>lighter</u> quarks

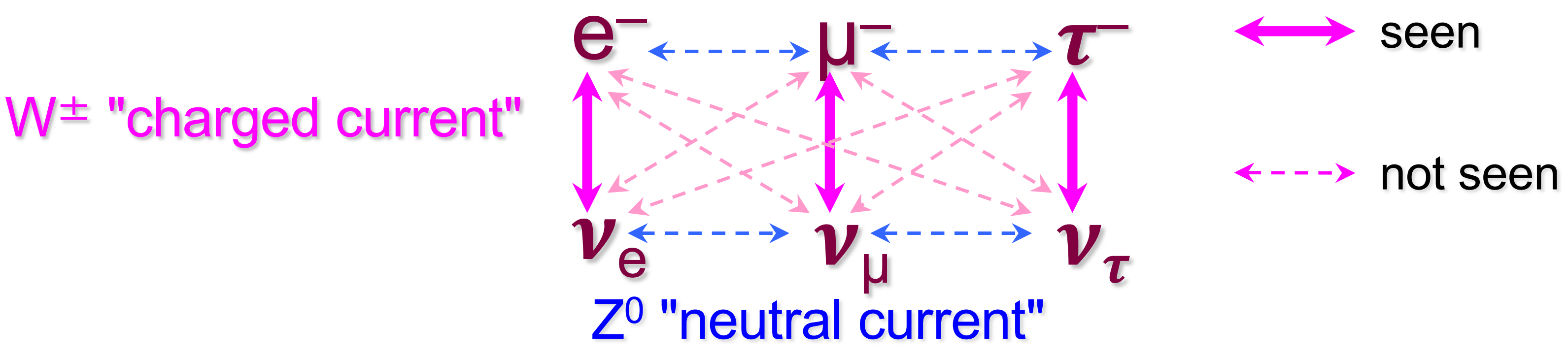


  - rate of transitions depend on weak couplings, phase space

weak flavor couplings of quarks

fermion flavors are mediated by $W^{\pm}$, Z^0

- leptons: ~universal weak coupling g_F, no generation x-ing



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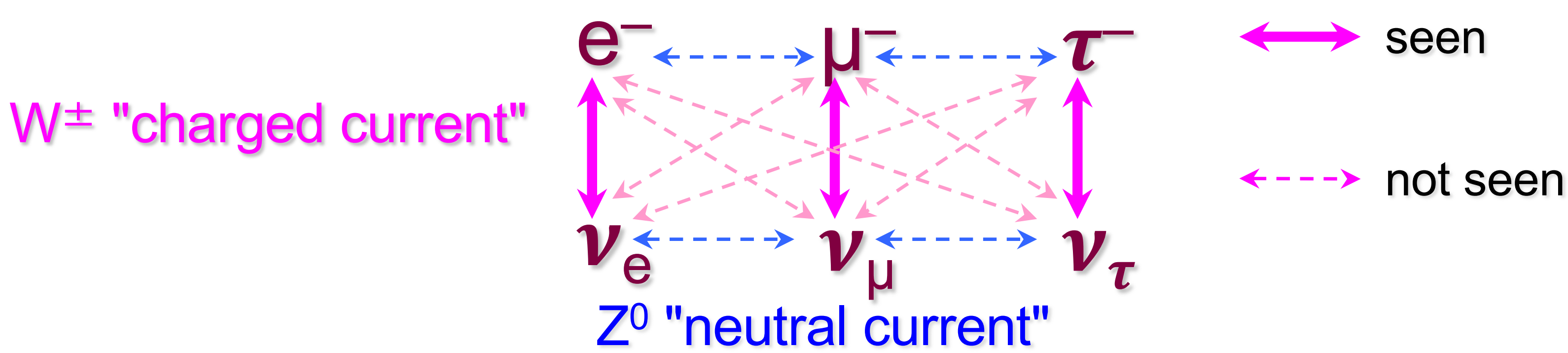
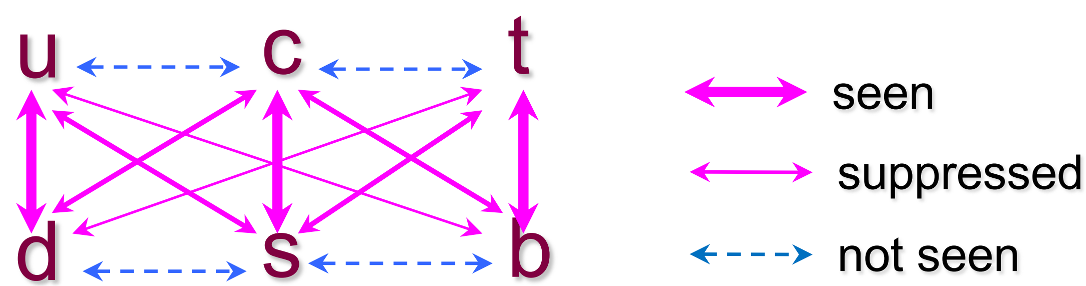


- quarks:
  - generations conserved in neutral but not charged current



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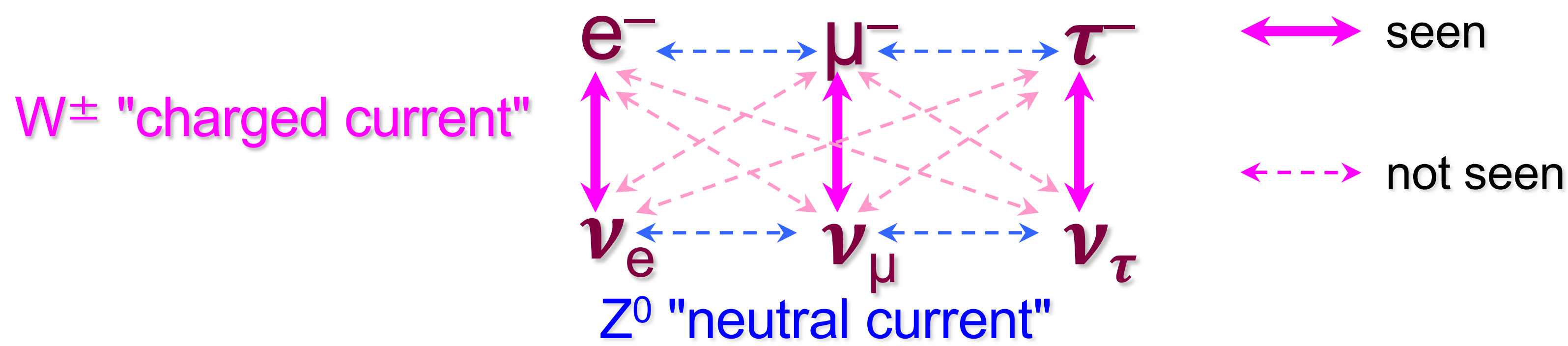

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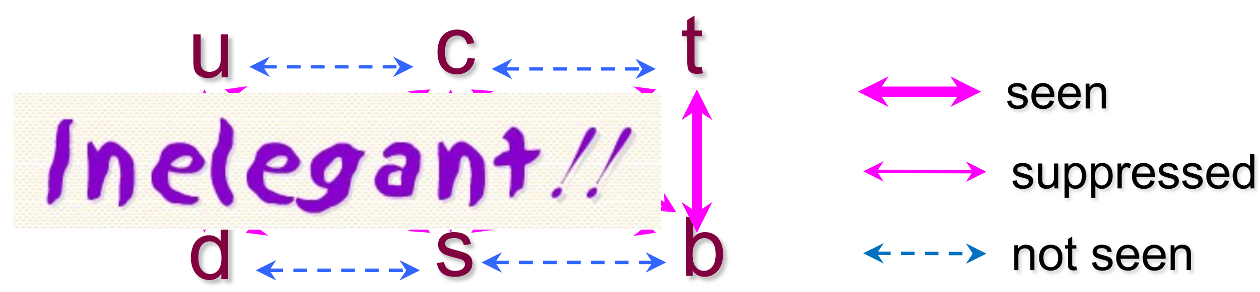


Elegance restored

GIM (Glashow-Iliopoulos-Maiani) picture:

"weak eigenstates" ≠ mass eigenstates {d, s, b}

-> linear transformation between 2 bases: matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$\mathcal{M}$: Cabibbo-Kobayashi-Maskawa (CKM) matrix

complex
preserves metric
" orthogonality

} ≡ unitary

in this picture, the charged-current couplings look universal:

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} d' \quad\ s' \quad\ b' \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

- generation conservation
- suppression of FCNC
- multiplicity of charged couplings
- CP violation for ≥3 generations

A mini-History of flavor physics

- GIM mechanism ➔ prediction of 4th (charm) flavor (1970)
  - discovery of J/ψ (1974) ➔ B. Richter, S. Ting

- GIM+CP violation in K_L ➔ prediction of 3rd generation (1973)
  - discovery of τ (1975) ➔ M. Perl

  - Υ (1977)
  - CP violation in B decay (Belle, Babar 2002)
    ➔ M. Kobayashi, T. Maskawa

Unitarity of CKM is central to the 3-generation Standard Model

How does CP violation show up?

- CKM: 3x3, complex ➔ 9 real + 9 imaginary parameters

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} =$$

How does CP violation show up?

- CKM: 3x3, complex ➔ 9 real + 9 imaginary parameters
  - unitarity constraints ➔ 3 real + 1 irreducibly complex parameters

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{matrix} \\ u \\ c \\ t \end{matrix} \begin{matrix} d & s & b \\ \end{matrix}\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix}$$

Wolfenstein parametrization (unitary to $O(\lambda^4)$)

unitarity condition $$\sum_k V_{ik} V^*_{jk} = \delta_{ij}$$

Focus on generations 1 & 3

- Applying the unitarity condition $$\sum_k V_{ik}V_{jk}^* = \delta_{ij}$$
- for i=1, j=3

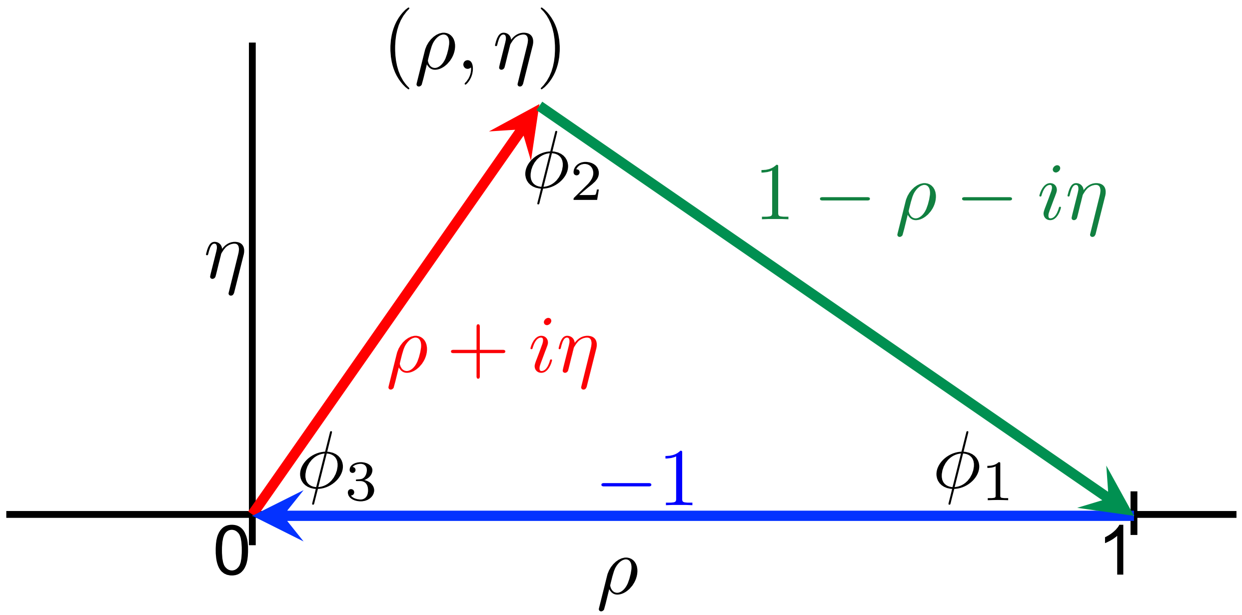
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix} \end{array}$$

$$= \lambda^3 A[\underbrace{(\rho + i\eta) - 1 + (1 - \rho - i\eta)}]$$

3 terms form a "Unitarity triangle" in the ρ-η complex plane

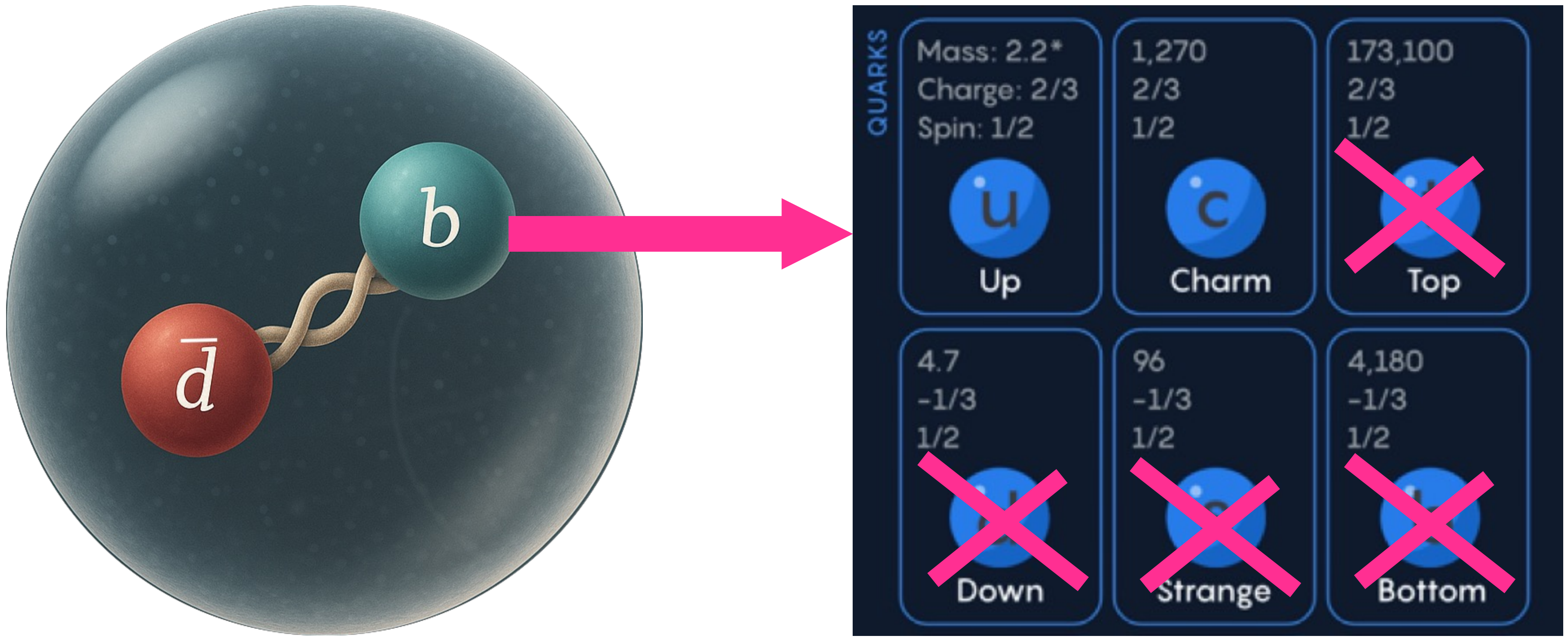
Unitarity Triangle



$$= \lambda^3 A[(\rho + i\eta) - 1 + (1 - \rho - i\eta)]$$

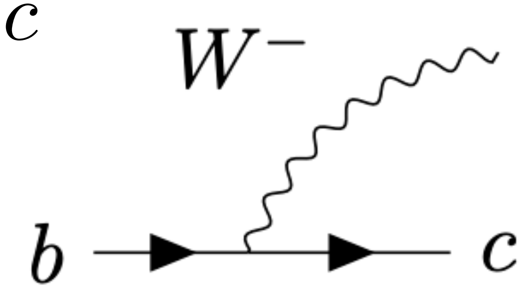
3 terms form a "Unitarity triangle" in the ρ-η complex plane

return to B decay

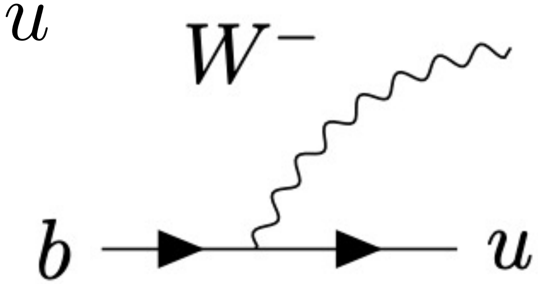


Allowed direct couplings are

$b \to c$

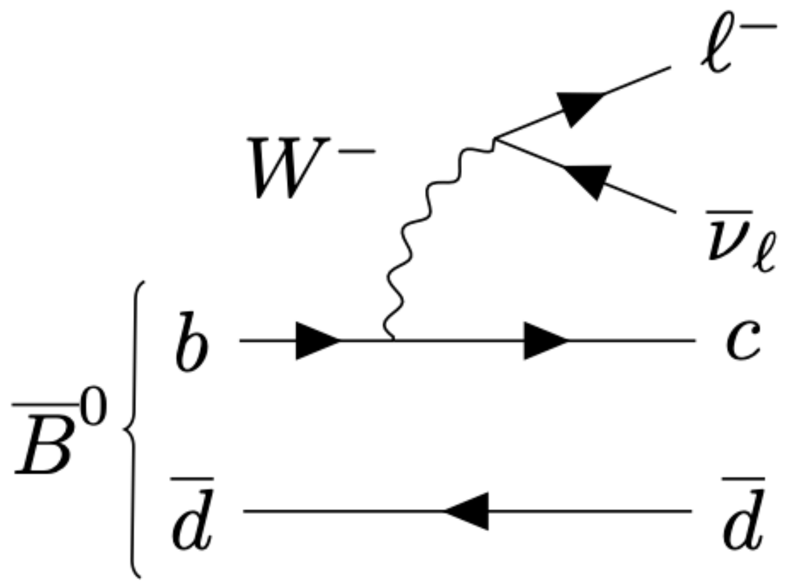


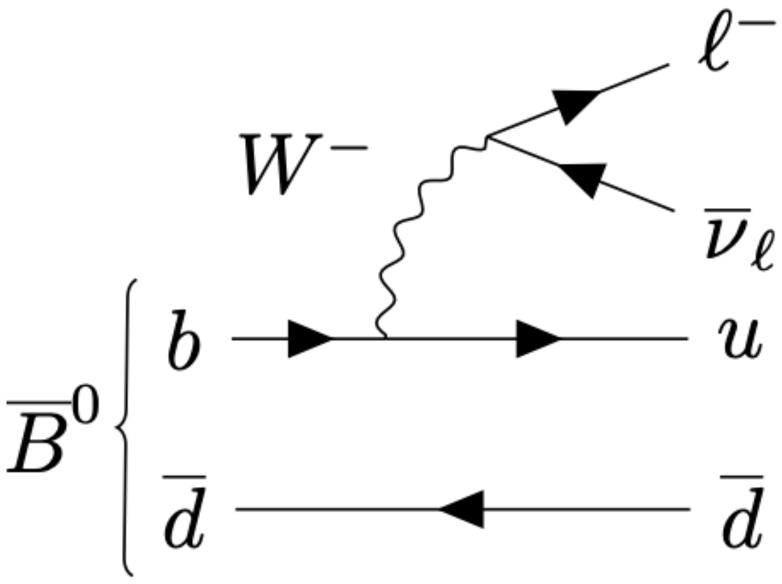
$b \to u$



dominant path: spectator

Example: semileptonic





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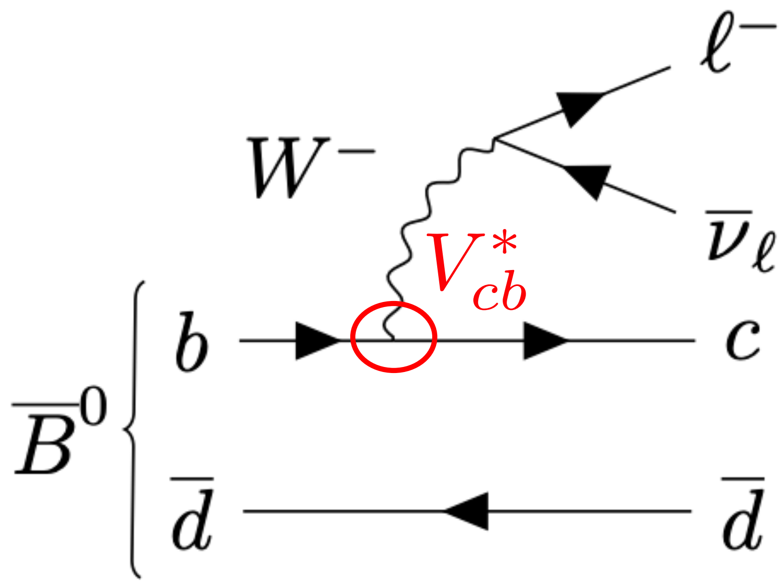

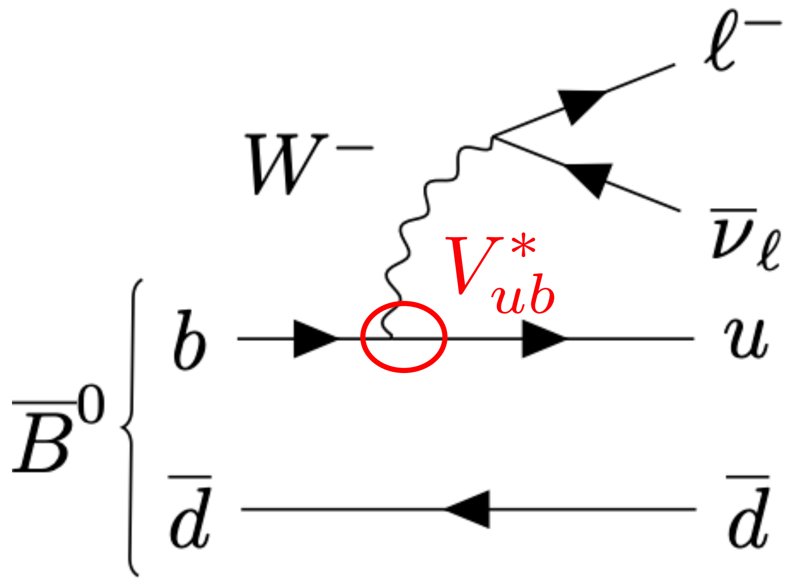

rate (partial width) depends on

- $|V_{ij}|^2$
- hadronic final states (phase space, wavefunctions)

dominant path: spectator

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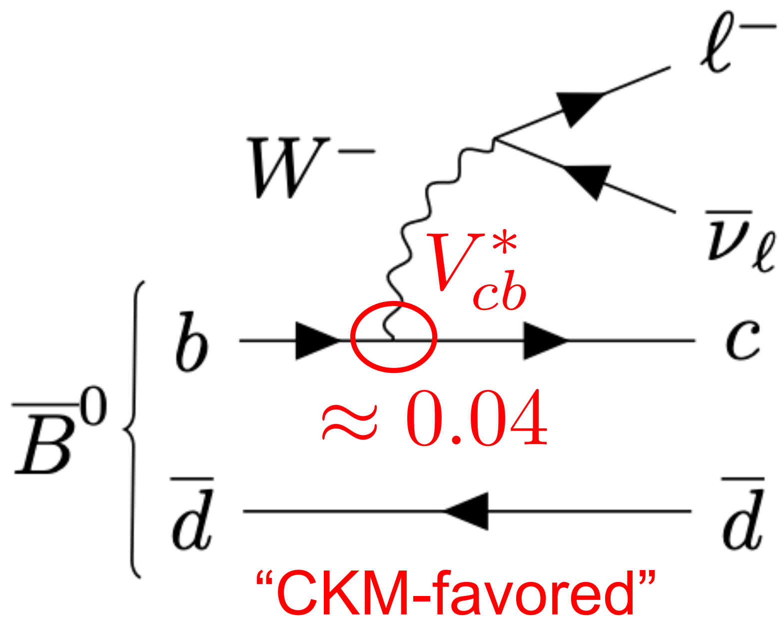

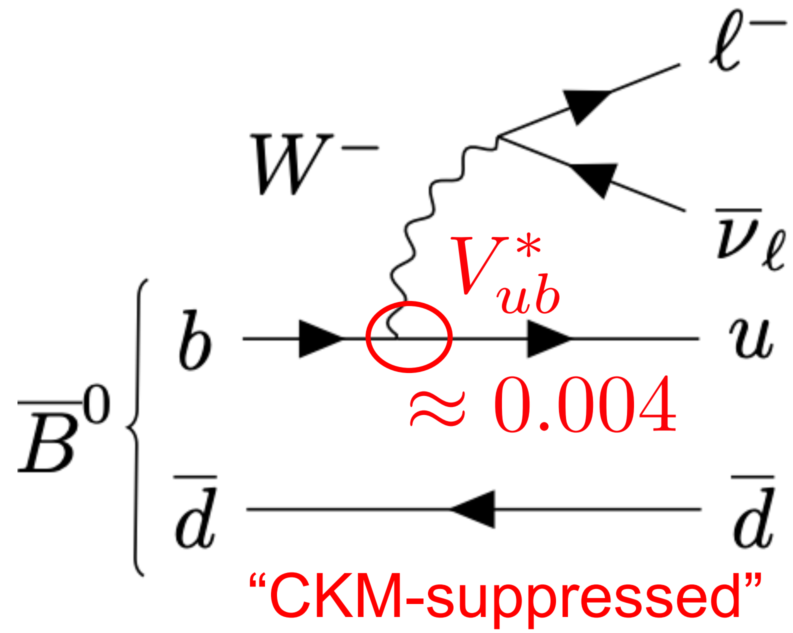

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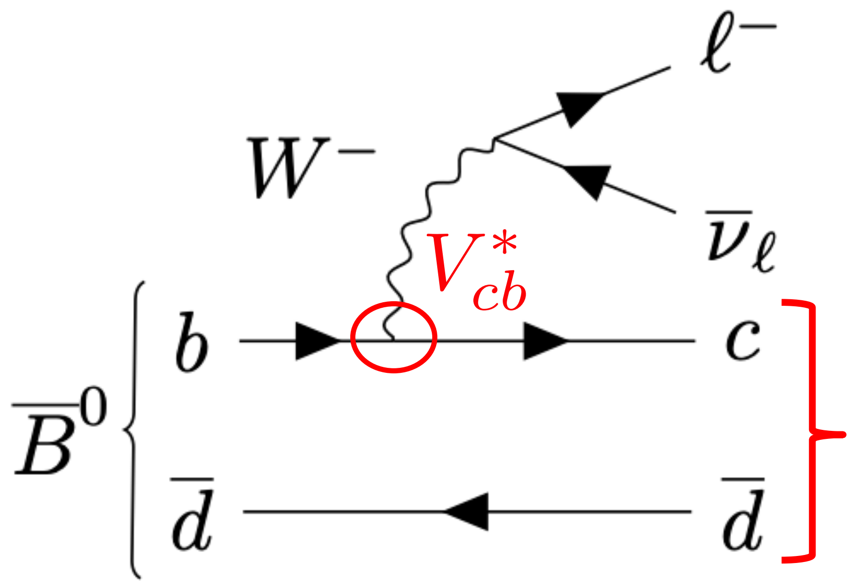
Measured & theoretical rates ➔ V_{ij}

precision is limited by pesky hadronic uncertainties

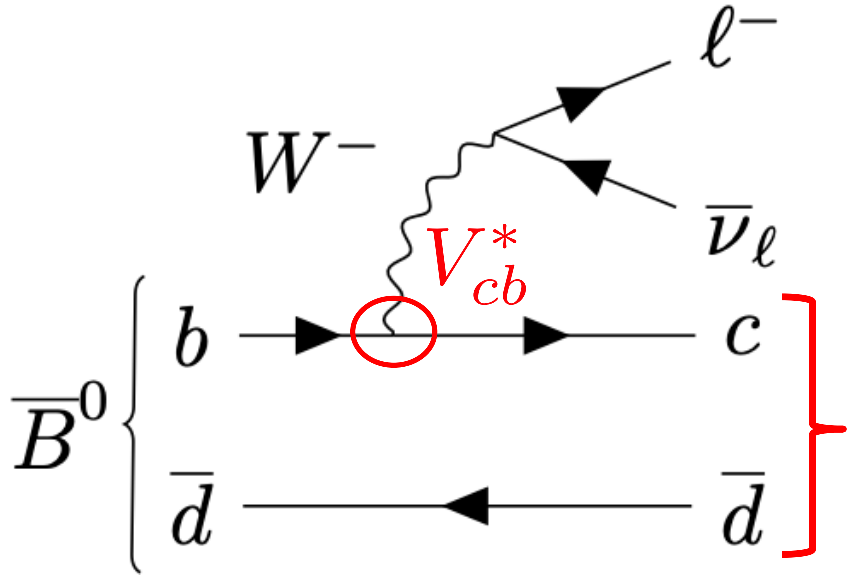


meson (e.g., D, D^*);
multihadron ($D^{(*)}+\pi(\pi)$; D_sK, …
hard to model, measure

rate (partial width) depends on

- $|V_{ij}|^2$
- hadronic final states (phase space, wavefunctions)

V_{ij} strategy



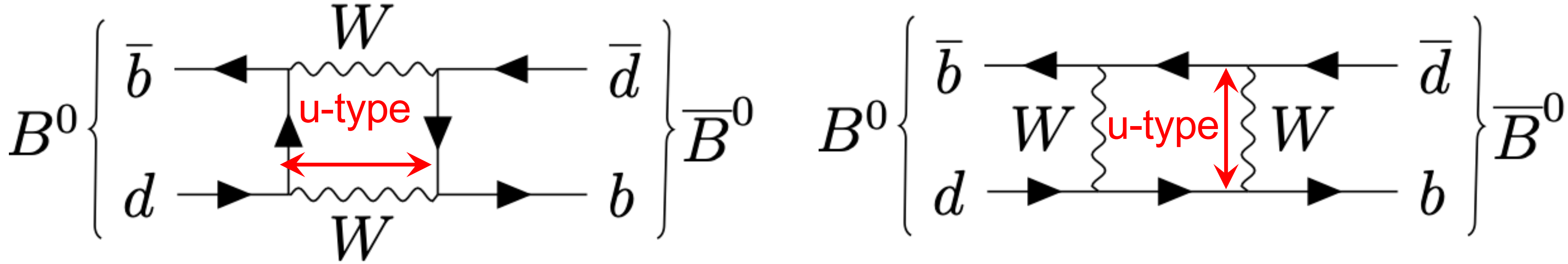
Measure in multiple ways, iterate w development of models until they converge

- mesons separately (exclusive)
- all together (inclusive)

rate (partial width) depends on

- $|V_{ij}|^2$
- hadronic final states (phase space, wavefunctions)

Meson-antimeson mixing



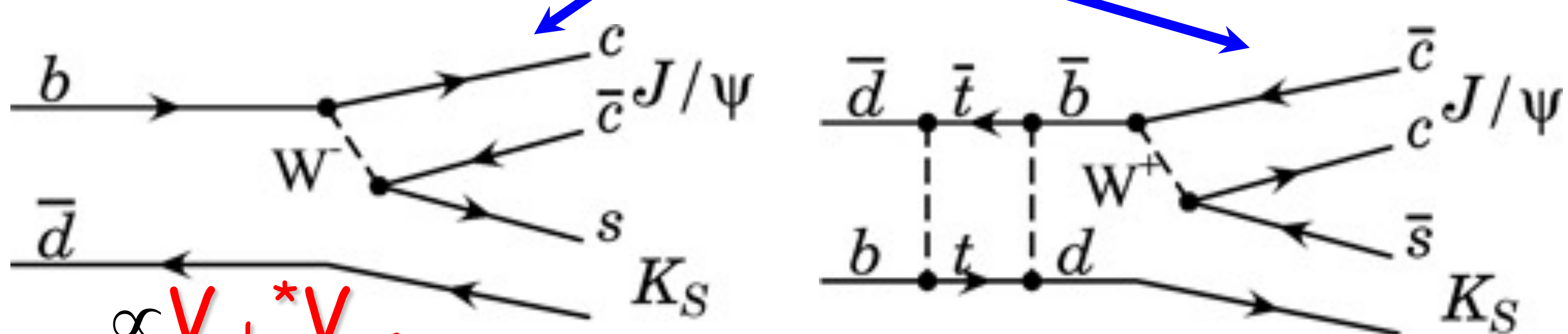
- largest contribution where internal quarks are *t*
- decay with time oscillation
  - observable in Belle II due to moving CMS

each B travels <$\beta\gamma c\tau$>≈130 μm before decaying

Time-dependent CP violation

- single final state accessible w/wo mixing
- first measured mode $B^0 \to J/\psi K_S^0$

identical hadronic processes → same |Amplitude|, no hadronic uncertainty



$\propto V_{cb}{}^{*} V_{cs}$

$\propto \underline{V_{tb}{}^{*2} V_{td}{}^{2}}\, V_{cb} V_{cs}{}^{*}$

difference

Time-dependent CP violation

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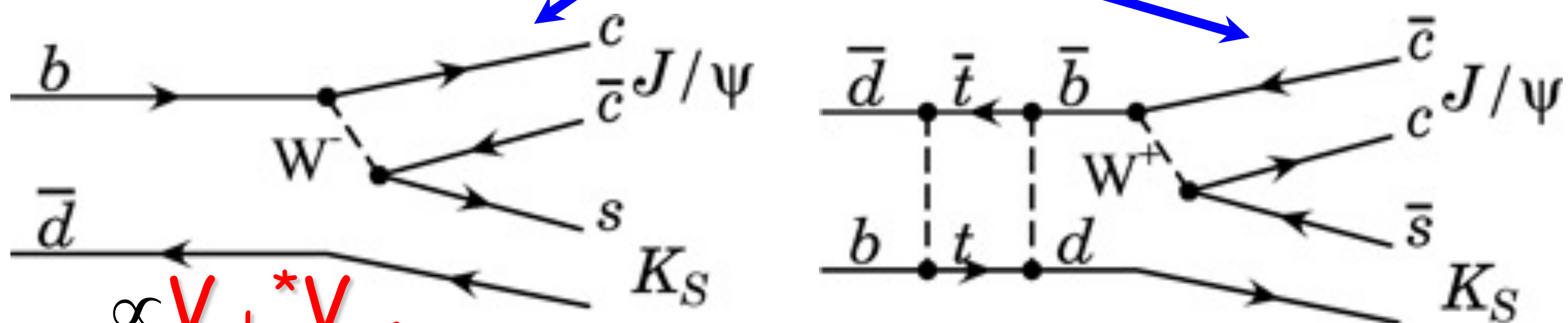

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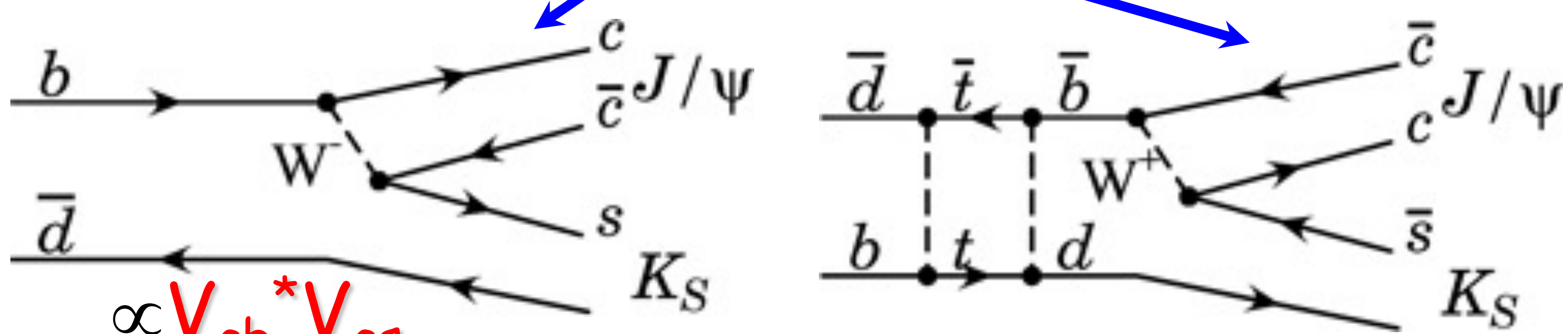

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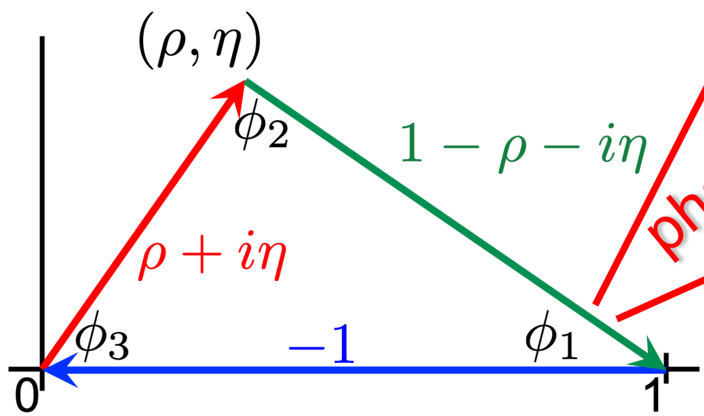
phase difference =2φ₁



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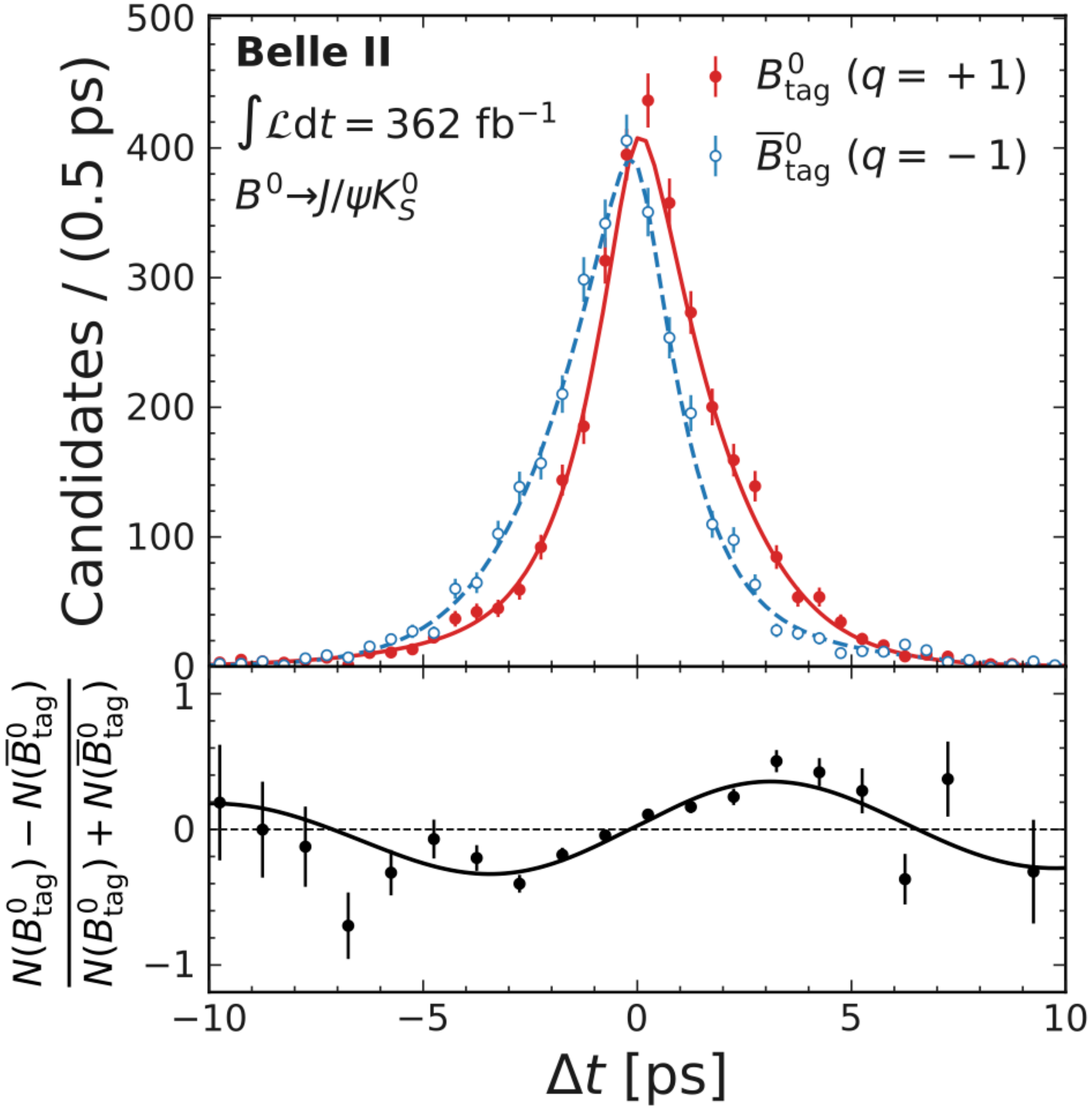
$B^0 \to J/\psi K_S^0$

- yields sin $2\boldsymbol{\varphi}_1$ with smallest theory uncertainty



PRD 110, 012001 (2024)

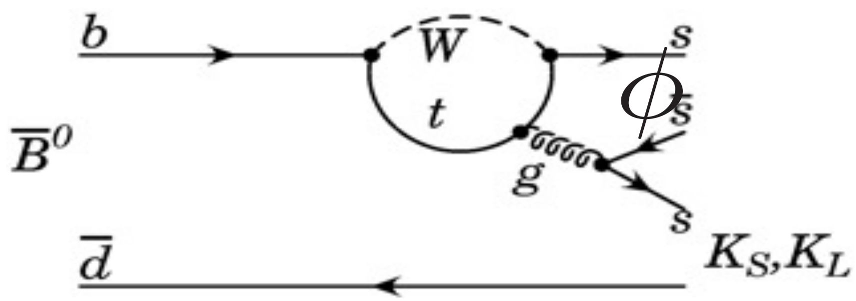
$\boldsymbol{\varphi}_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$

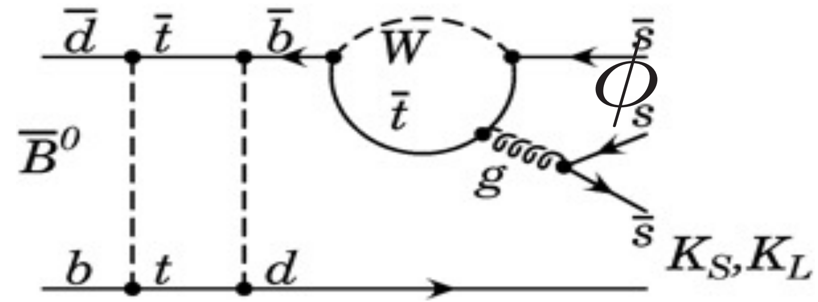
Similar (but different) paths to sin2φ_1

- Example $B^0 \rightarrow \phi K^0$

"penguin" (real V_{ij}) $\propto V_{tb}^{*} V_{ts}$

mixing+penguin $\propto V_{tb}^{*2} V_{td}^{2} V_{tb} V_{ts}^{*}$





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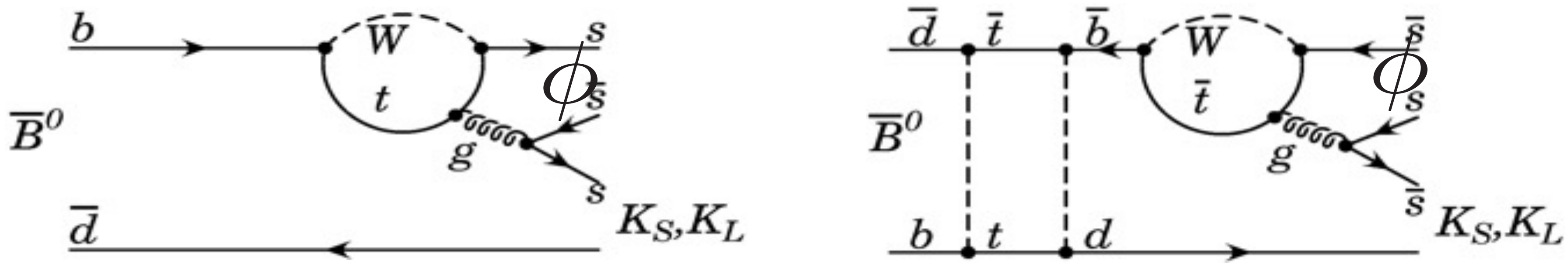

larger theoretical uncertainties: why bother measuring this?

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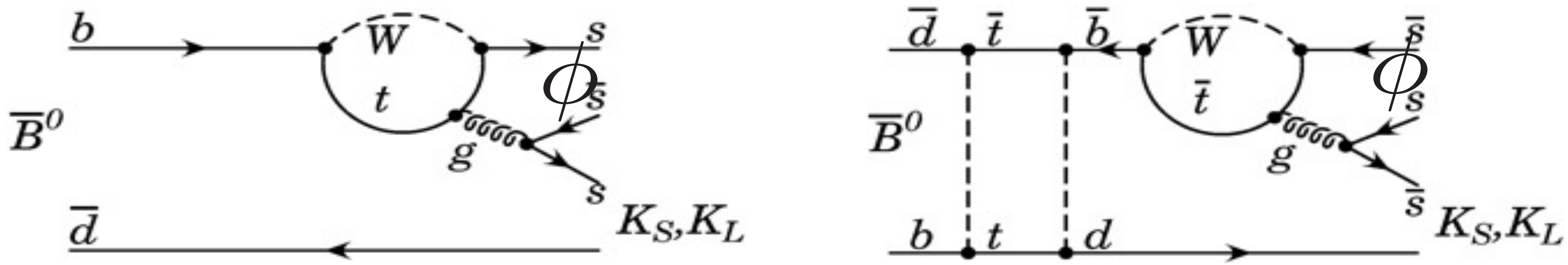
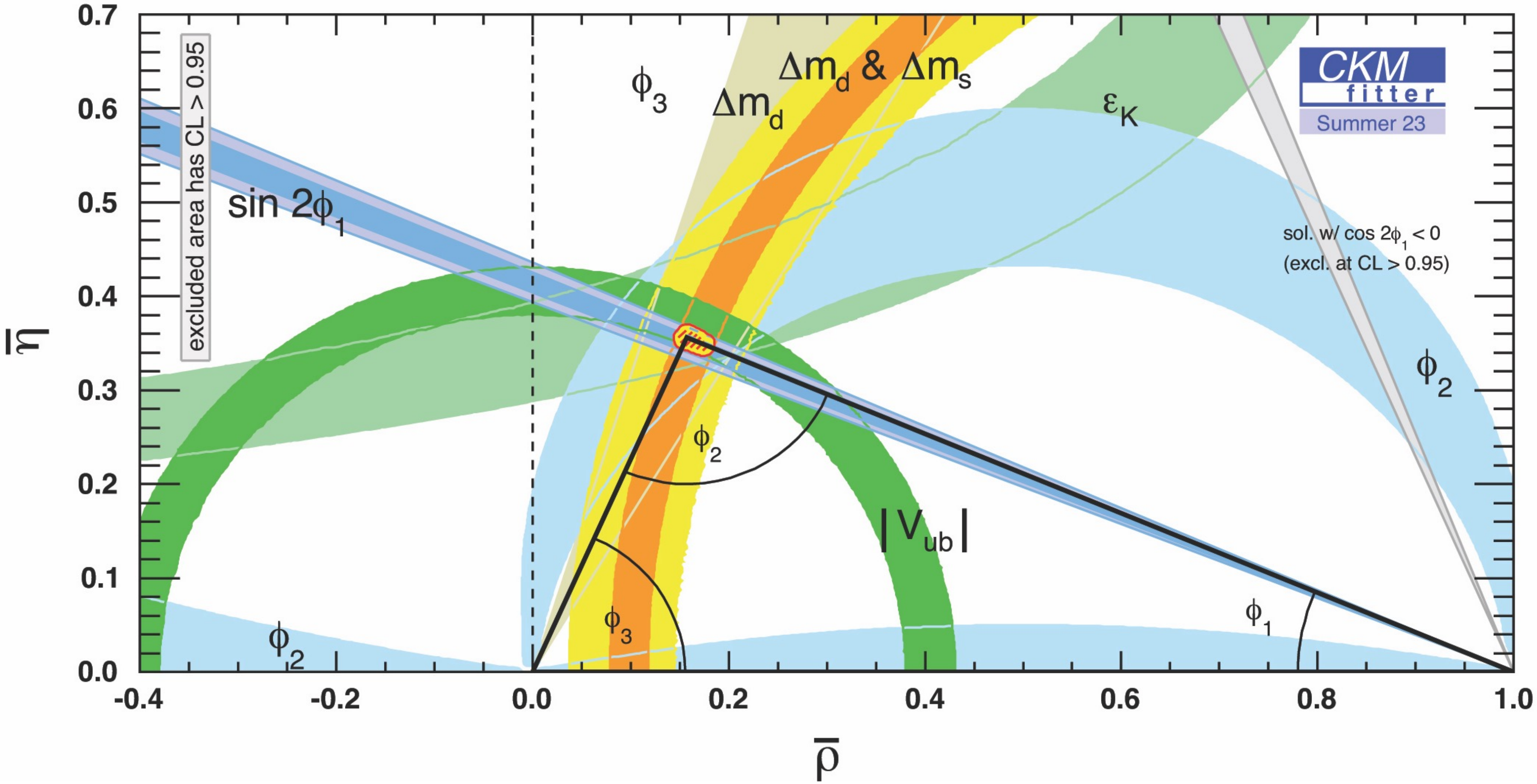


larger theoretical uncertainties: why bother measuring this?

- a different "sin 2φ_1" could indicate New Physics
- different paths compared for consistency (or not) w Standard Model

CKM tests

allowed regions filled



- “best” evaluation of ($\boldsymbol{\rho},\boldsymbol{\eta}$) … assuming no New Physics
- New Physics may appear as inconsistency or poor fit

Looking forward: improve statistics & resolution…

… and hope for fun surprises!

Summary

- Belle II/SuperKEKB: e^+e^- at ≈10 GeV
- Core: precision to test CKM unitarity, probe beyond Standard Model at high mass scales in
  - B mesons
  - charm hadrons
  - τ leptons
- More to come this week: enjoy!
  - plenary
    - semileptonic decays, CP violation, τ, dark matter
  - many ECR talks!

- backup

Belle II: rich Physics program (not only NP)