Aspen Winter Conference
New Methods and Ideas at the Frontiers of Particle Physics
March 2022

Belle II: Recent Results, Status, and Prospects

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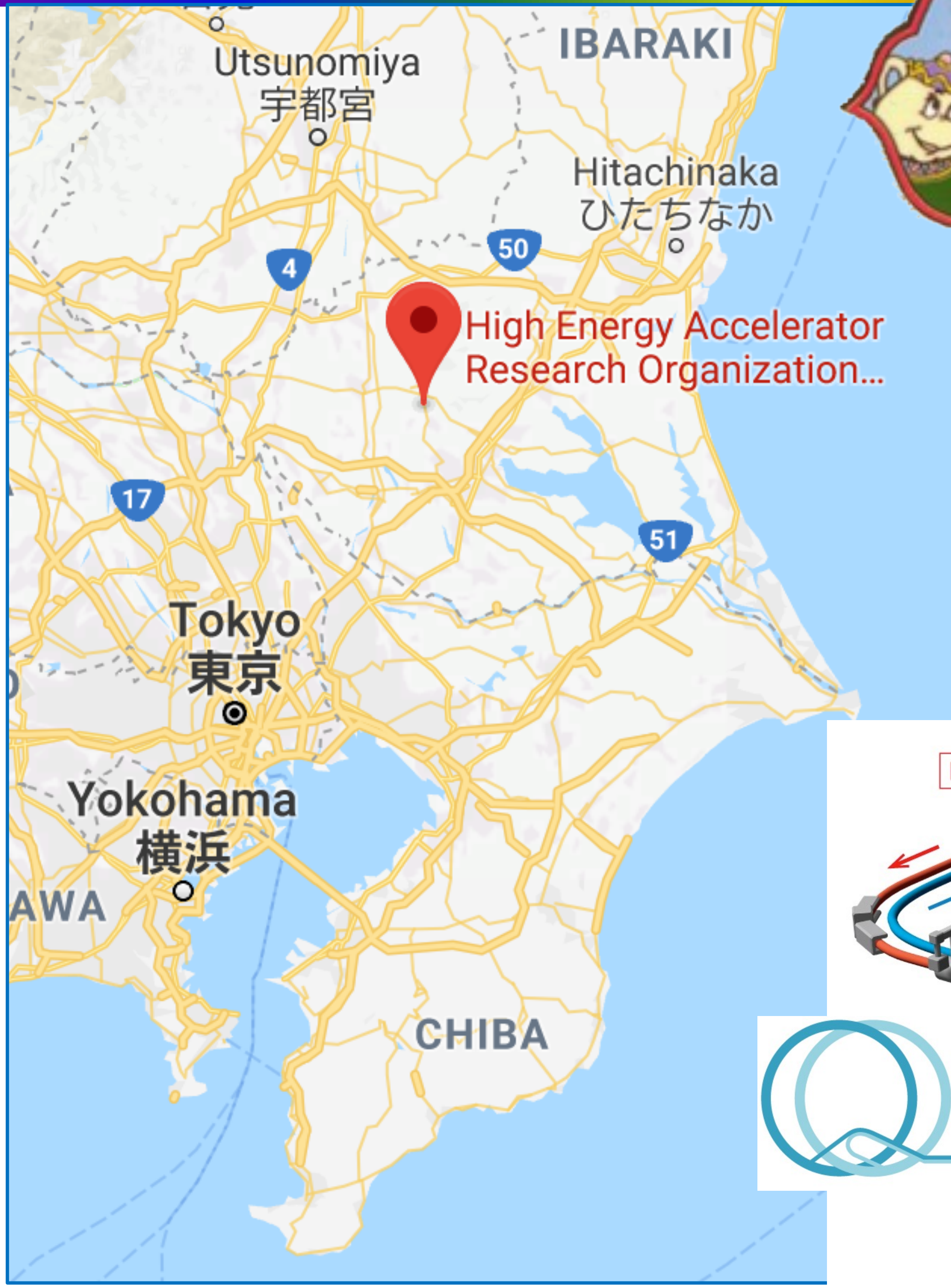
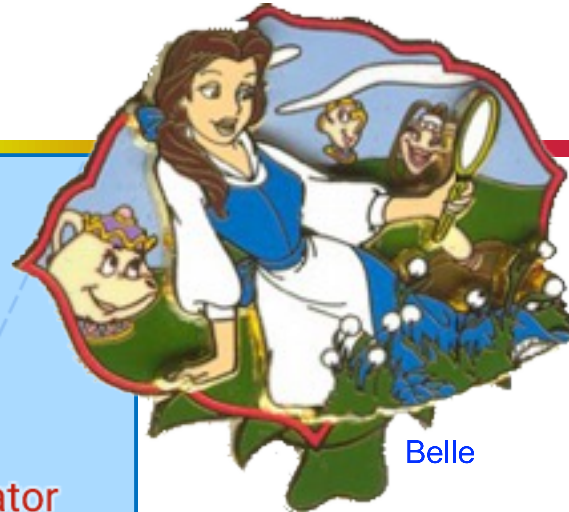
Belle II/SuperKEKB





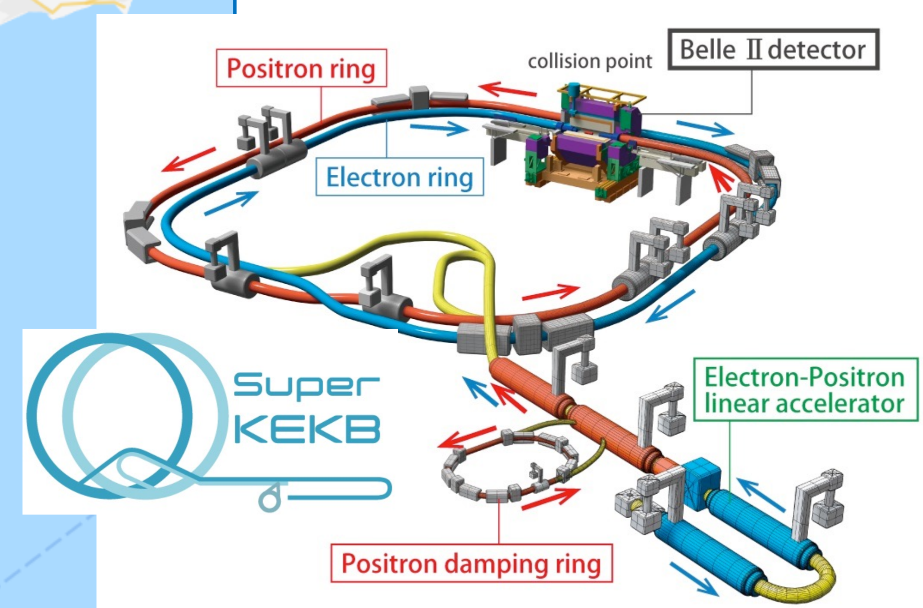
Belle

Belle II Collaboration

≈1100 researchers

>123 institutions

≈26 nations



Motivation

Big **Q**uestions

- Origin of generations & role of flavor
- CP violation & baryon asymmetry

Not addressed by Standard Model; need "New Physics" (NP)

Both **Q**uestions necessarily involve 3 generations → heavy quarks

Where to look for NP?

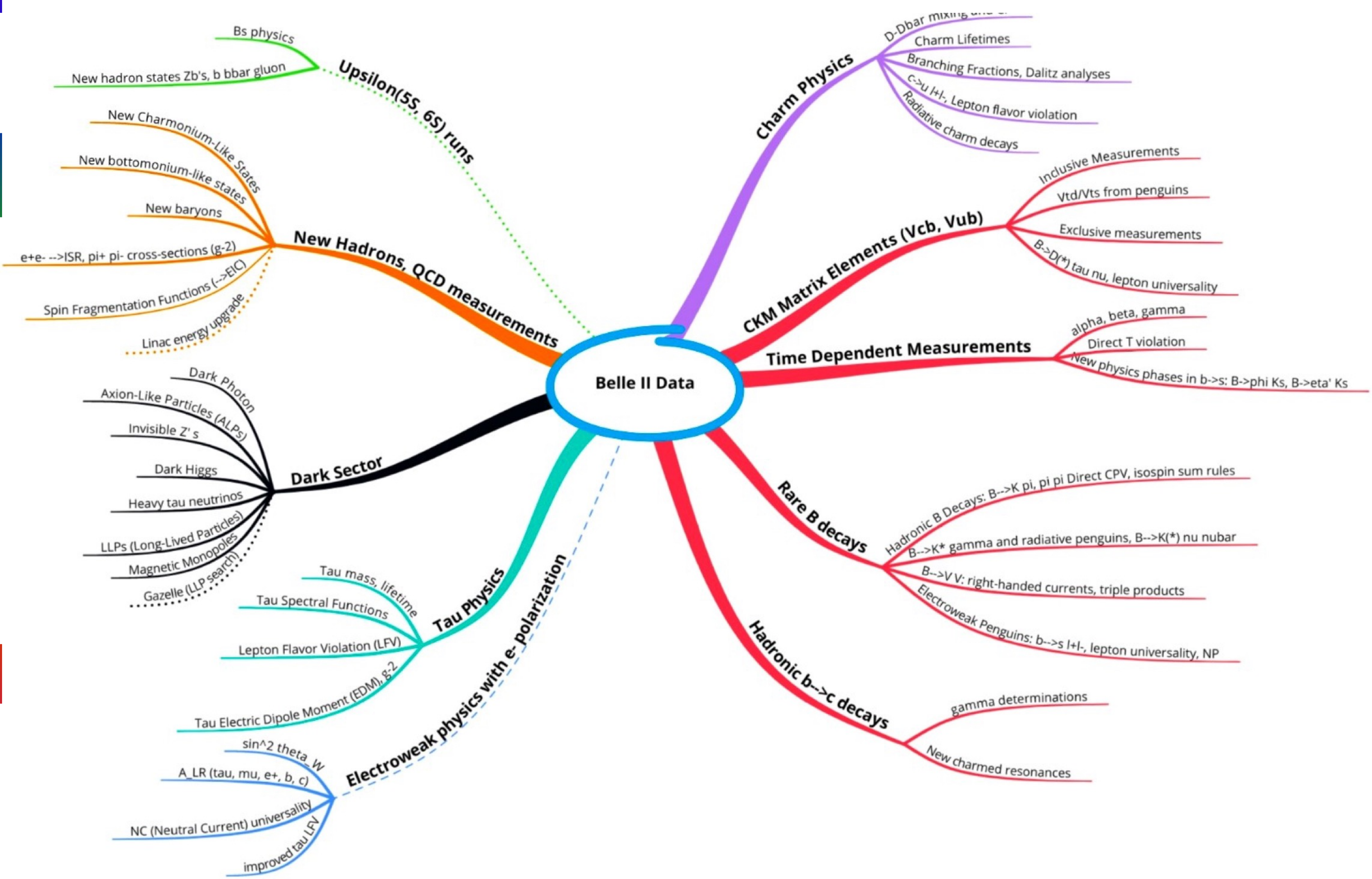
- Direct searches at Energy Frontier ➔ stringent limits
- Indirect: SM anomalies, *hints* in B decay
  - e.g. lepton universality: tension

$$\mathcal{R}(D^{(*)}) \equiv \frac{(B \to \bar{D}^{(*)}\tau^+\nu)}{(B \to \bar{D}^{(*)}\ell^+\nu)} \text{ (≈3.9 } \sigma\text{); } R(K^{(*)}) \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \text{ (1.5-3.1 } \sigma\text{)}$$

Belle II will probe New Physics (NP) at the multi-TeV scale: B, c, τ

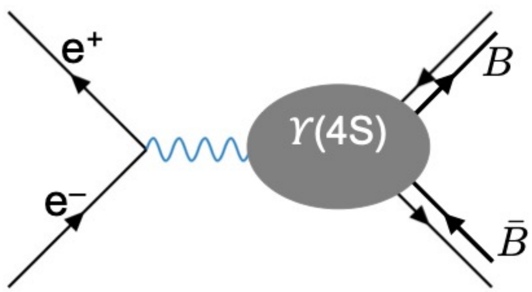
- Precision Standard Model measurements & challenges (multiprong)
  - Unitarity of CKM matrix → CP asymmetries, rare decays
  - lepton universality
- dark particles via missing energy

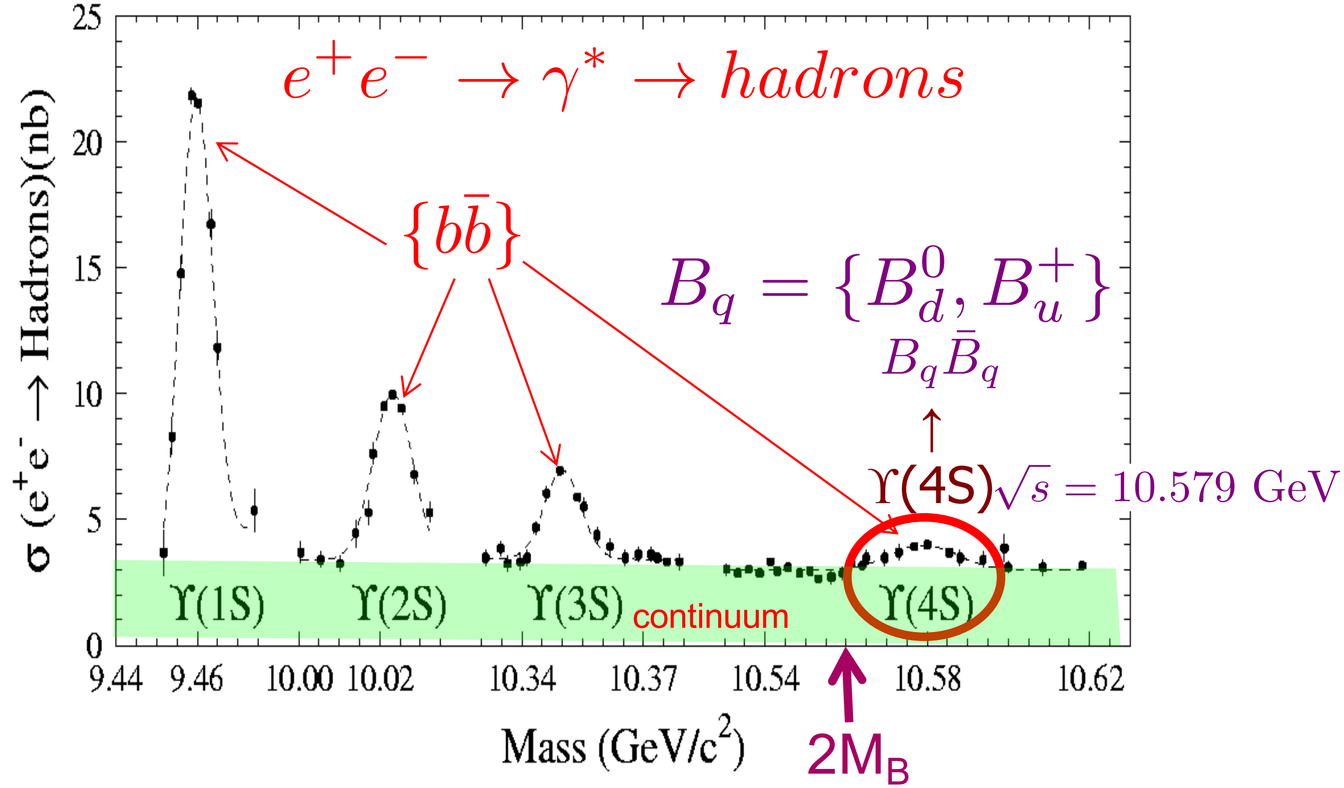
Belle II: rich Physics program (not only NP)



Belle II @ SuperKEKB: $e^+e^- \to \Upsilon(4S)$ (primarily)

Upsilon region
9-12 GeV





- Complete annihilation ⇒ event CMS = e^+e^- CMS
- Near-threshold @ ϒ(4S): exclusive B-pair events
- "Hermetic" detector captures (almost) every detectable particle

  => "neutrals reconstruction" {K_L, n, ν, dark matter}
- Average multiplicity (chg+neutral) ~15-20

Event environment

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

SuperKEKB beams are asymmetric (7 Gev e^-/4 GeV e^+):
produces Υ(4S) ≈1 nb

v ≈ 0.27 c

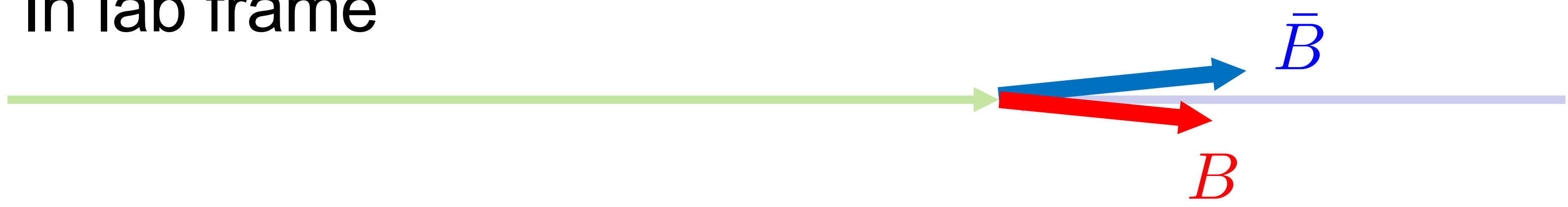
Event environment

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

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

Slow: $p_B \approx 0.33$ GeV/c in CMS

In lab frame



In lab frame each B travels $\langle\beta\gamma c\tau\rangle \approx 130\ \mu m$ in direction of CMS

Event environment

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

➔ many channels

B^+ modes	B^0 modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	

D^+, D^{*+}, D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	

➔ light "stable" particles

$\to \pi^\pm/K^\pm/p/\bar{p}$

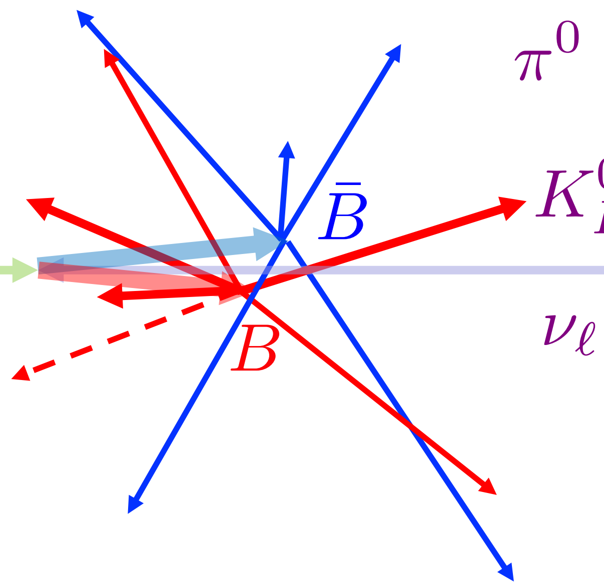
$e^\pm/\mu^\pm$

$K_S^0 \to \pi^+\pi^-$

$\pi^0 \to \gamma\gamma$

$K_L^0/n/\bar{n}$

$\nu_\ell/\bar{\nu}_\ell$



B reconstruction

Full reconstruction (>1000 modes)

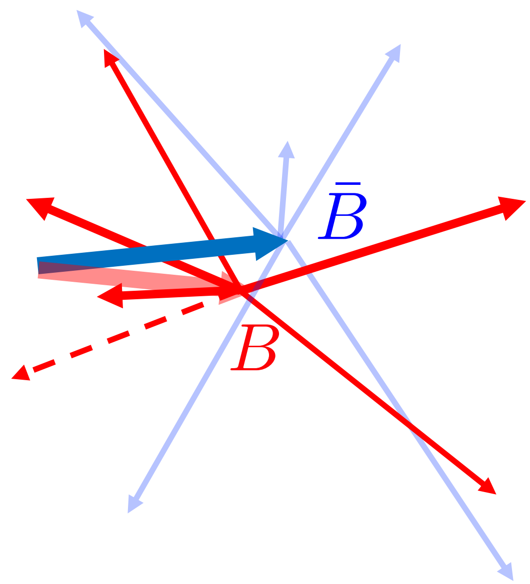
$$E_{\rm tag} = \sum_{i,{\rm tag}} E_i = E_{\rm beam} \quad \text{(CMS frame)}$$

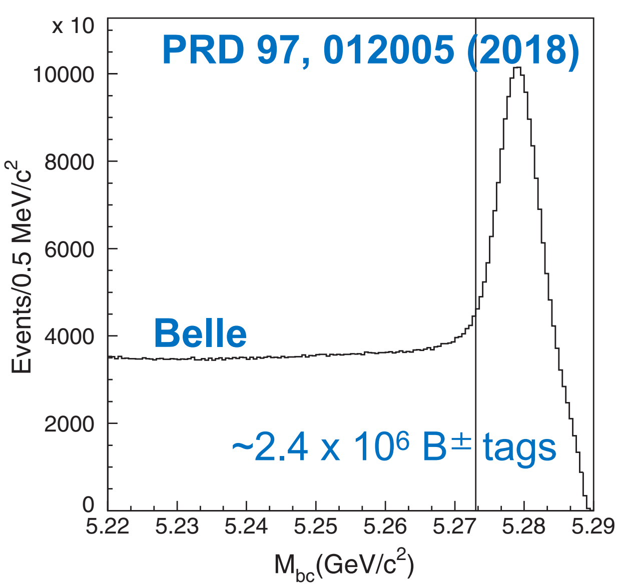
$$\vec{p}_{\rm tag} = \sum_{i,{\rm tag}} \vec{p}_i$$

→ Beam-constrained mass

$$M_{\rm bc} = \sqrt{E_{\rm beam}^2 - \vec{p}_{\rm tag}^{\,2}}$$

Remainder
(detected & undetected)
= other B





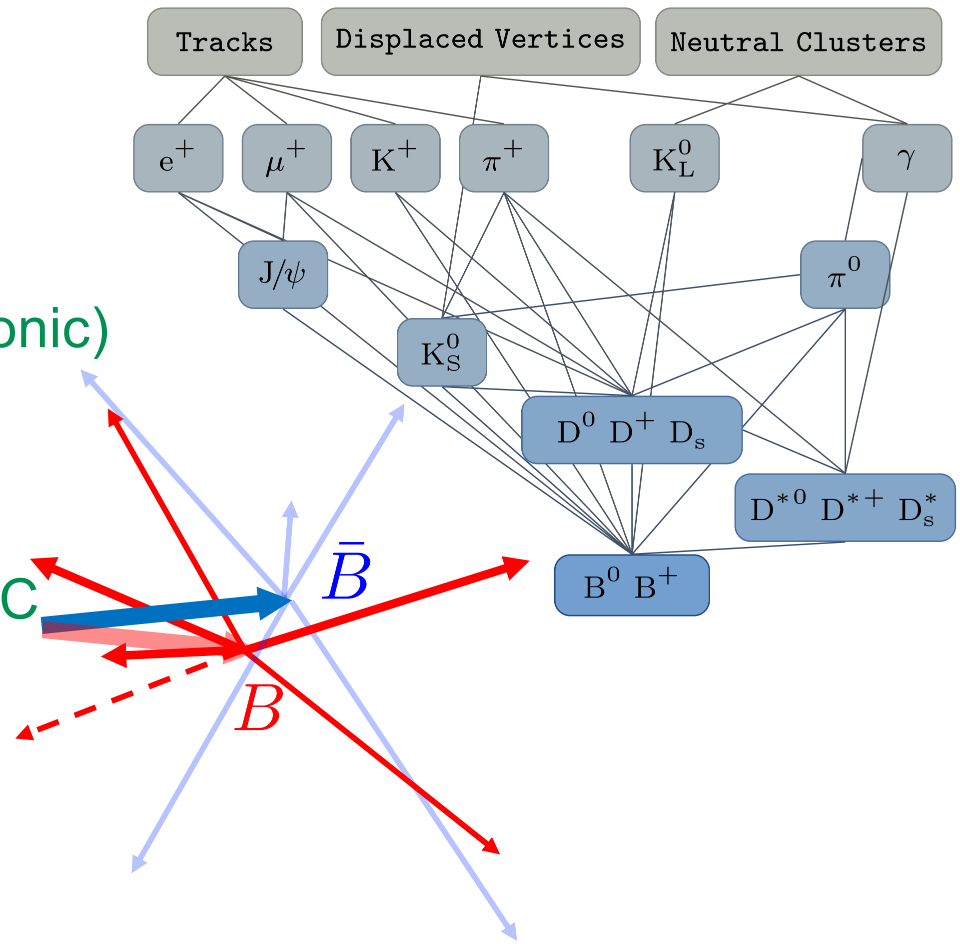
- absolute branching fractions
- inclusive rates
- detailed angular, kinematic distributions
- invisible particles (neutrinos, dark matter)
- low systematics

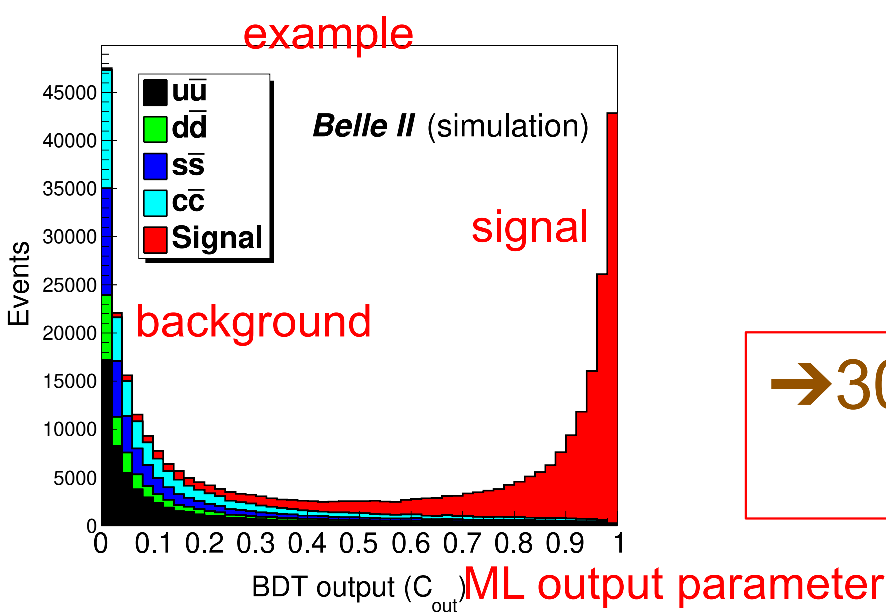
Belle II: Full Event Interpretation

Machine Learning

To differentiate "signal," background events

- Input information
  - Tags: full, partial (e.g. semileptonic)
  - rest-of-event
  - event shape
  - vertexing
- ML Training: signal / background MC





➔30%-50% efficiency improvement vs Belle full reconstruction

Belle II: improve through resolution, (much) better statistics

Brief history & status

e^+e^- B-factories (≈equal #'s $B\bar{B},\ c\bar{c},\ \tau^+\tau^-$)

- Belle (1999-2010) 772M events, each; ≈600 papers published
- Babar (1999-2008) 465M; ≈600 published
- Belle II (2019-)
  - 189.3 fb^{-1} ≈190M: results reported here
  - to date: ≈290 M collected; ultimate goal = 50G (>100X)
  - published /submitted physics results so far
    - Integrated luminosity [Chinese Physics C 44, 021001 (2020)]
    - search for invisible Z' [PRL 124, 141801 (2020)]
    - search for Axion-like [PRL 125, 161806 (2020)]
    - search for $K\nu\bar{\nu}$ [PRL 127, 181802 (2021)]
    - D^0 and D^+ lifetimes [PRL 127, 211801 (2021)]
    - Belle+Belle II, CKM angle φ_3 [JHEP 02 2022, 063 (2022)]

Belle II NEW results

charm lifetimes

experimental: partial widths require full; $\Gamma_{partial} = \mathcal{B} \times \Gamma = \mathcal{B}/\tau$

Belle II 72 fb^{-1}:
PRL 127, 211801 (2021)
BEST

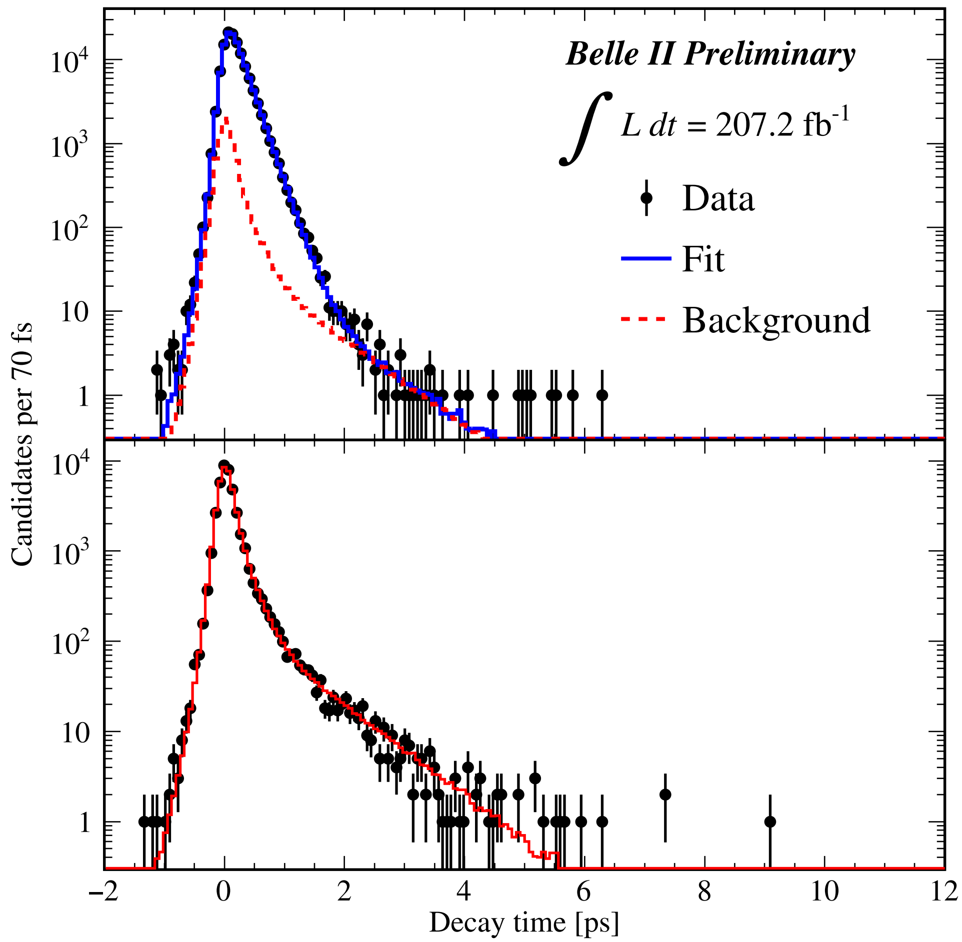
$$\tau(D^0) = (410.5 \pm 1.1_{stat} \pm 0.8_{sys})\ \mathrm{fs}$$
$$\tau(D^+) = (1030.4 \pm 4.7_{stat} \pm 3.1_{sys})\ \mathrm{fs}$$

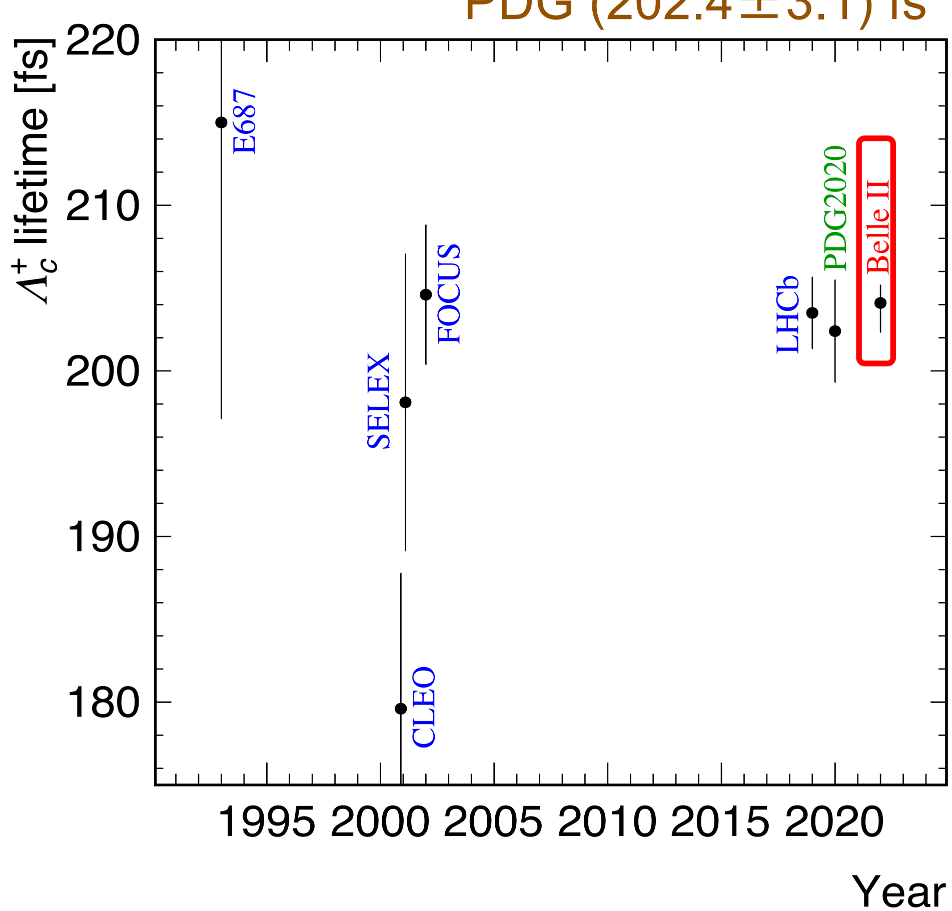
PDG
(410.1±1.5) fs
(1040±7) fs

NEW Λ_c 207 fb^{-1}

$$\tau(\Lambda_c) = (204.12 \pm 0.84_{stat} \pm 0.69_{sys})\ \mathrm{fs}$$

PDG (202.4±3.1) fs





Search for Darkhiggstrahlung

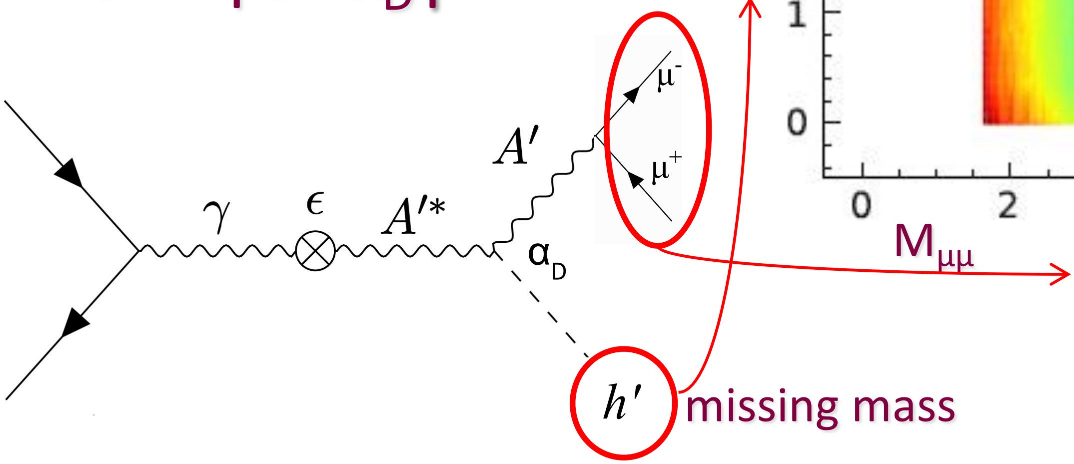
non-SM

2-track trigger: 8.34 fb^{-1}

dark Higgs+dark photon

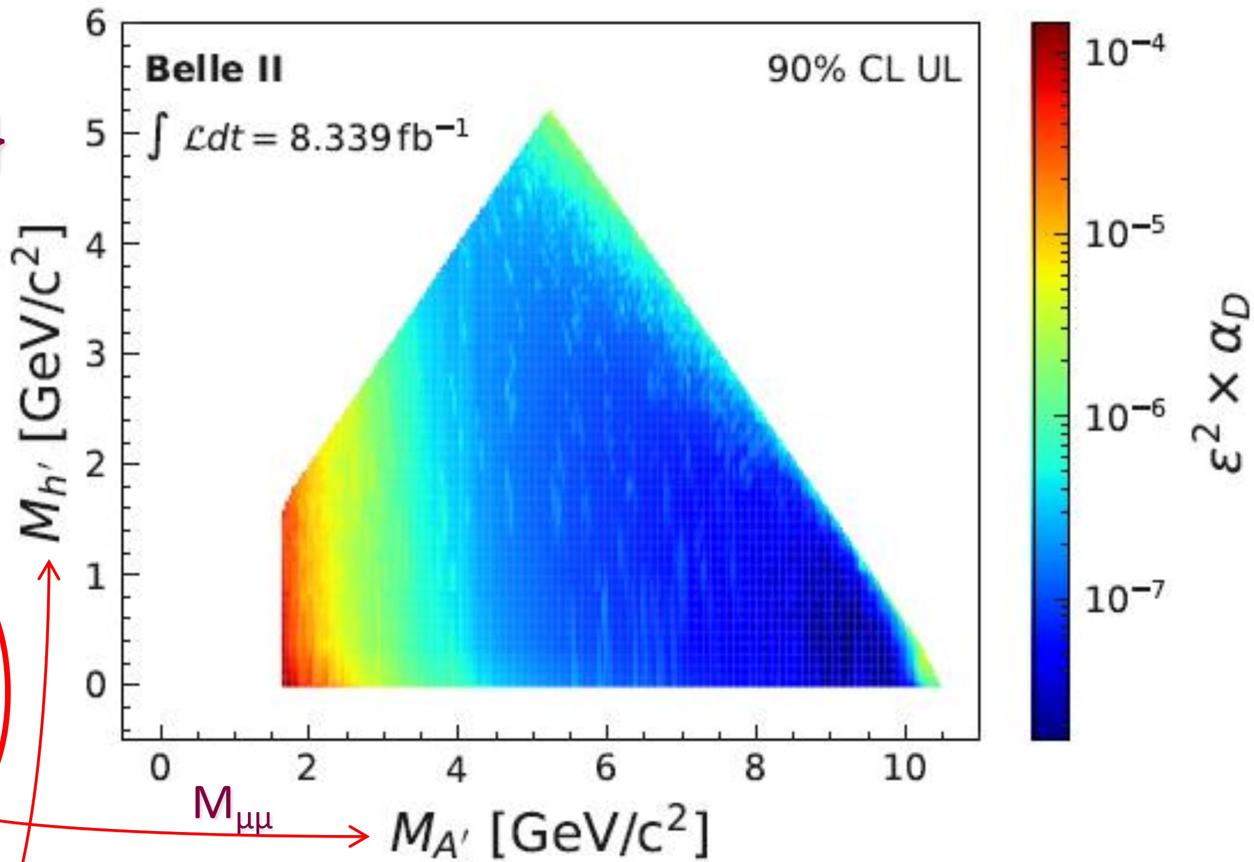
$e^+e^- \to h' A' \{\to \mu^+\mu^-\}$

$\sigma \propto |\varepsilon^2 \alpha_D|^2$

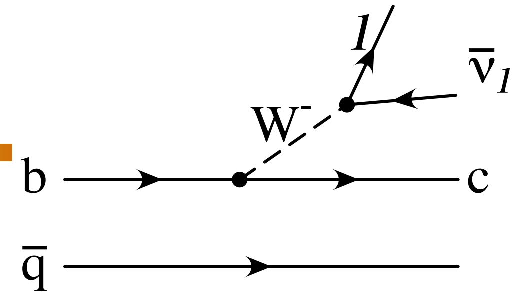


Belle II preliminary

90% CL upper limits on $\epsilon^2 \times \alpha_D$

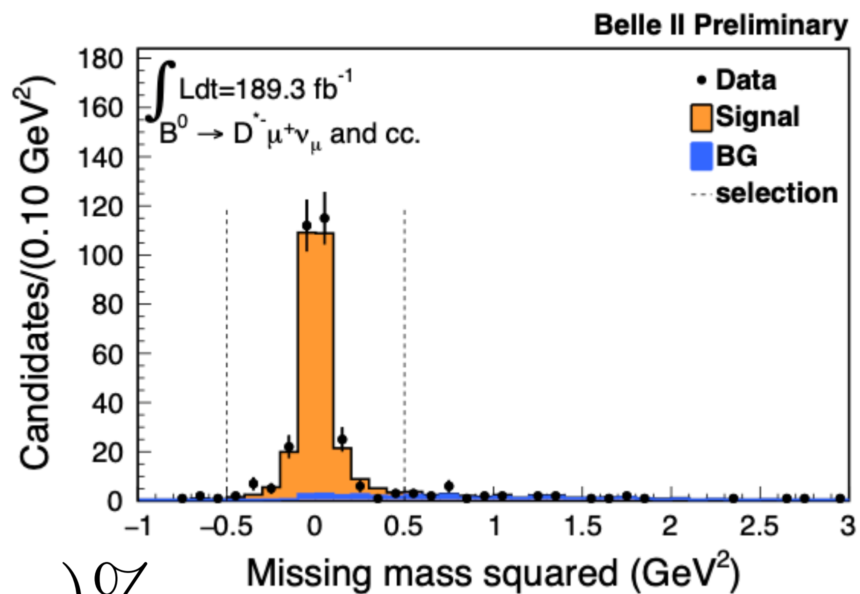


$B^0 \to D^{*-}\ell^+\nu$



SM: spectator ➔ $|V_{cb}|$

- experimental considerations
  - FEI, ν via missing mass
    ➔ clean exclusive reconstruction

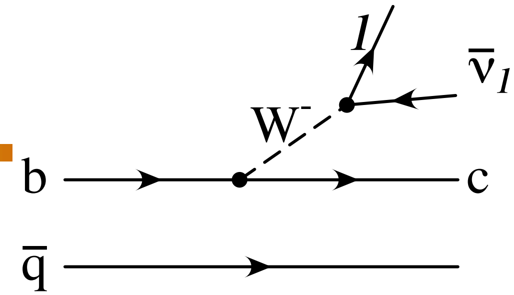


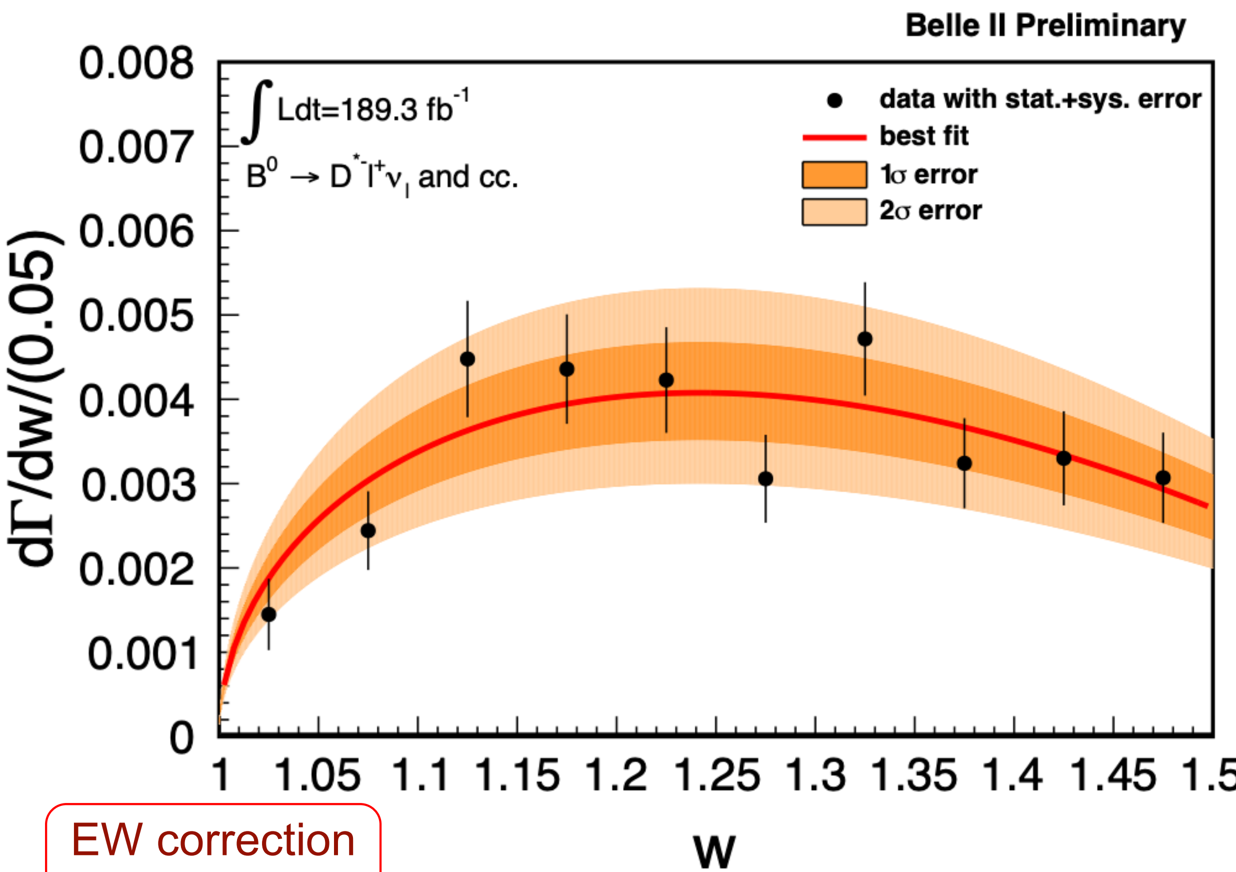
$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu)$$
$$= (5.27 \pm 0.22_{stat} \pm 0.38_{sys})\%$$

[PDG: (5.06±0.12)%]

- $\mathcal{B}$ to $|V_{cb}|$: Heavy Quark Effective Theory (HQET)
  ➔ q^2 distribution/form factor

$B^0 \to D^{*-}\ell^+\nu$





$$w = \frac{m_B^2 - m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

$=1$ at q^2_{max}

EW correction (theory)

phase space

form factor (theory)
Parametrized shape
lattice eval at w=1

$$\frac{d\Gamma}{dw} = \frac{\eta_{EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2$$

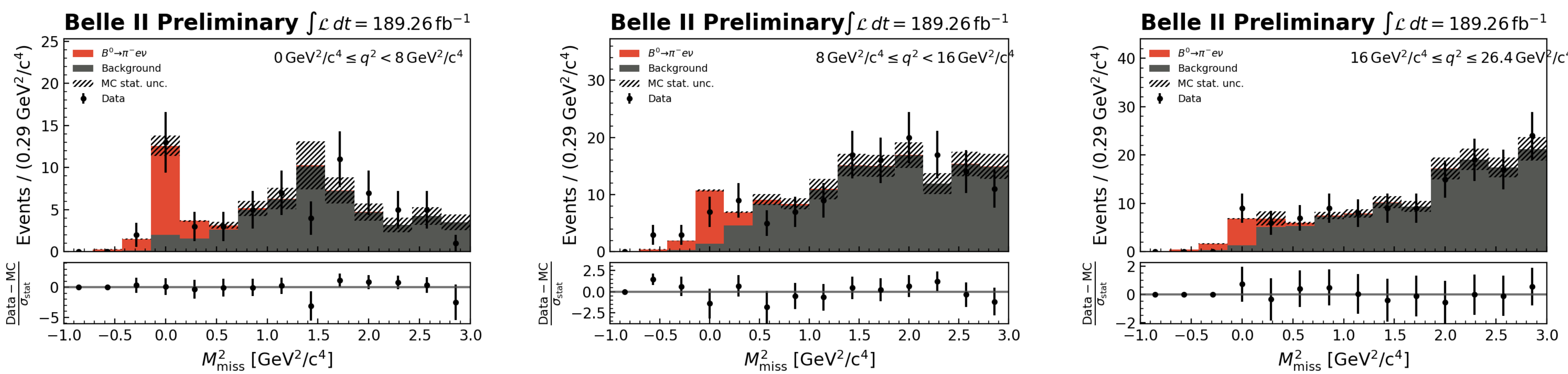
➜ $|V_{cb}| = 0.0379 \pm 0.0027$

$B \to \pi e^+ \nu$

SM: spectator ➔ $|V_{ub}|$

- experimental & theoretical (similar to $|V_{cb}|$)
  similar experimental/theoretical approach
  3 bins of q^2; fit for form factor; evaluate at w=1

$$B^0 \to \pi^- e^+ \nu$$



$|V_{ub}|$: q^2 distribution

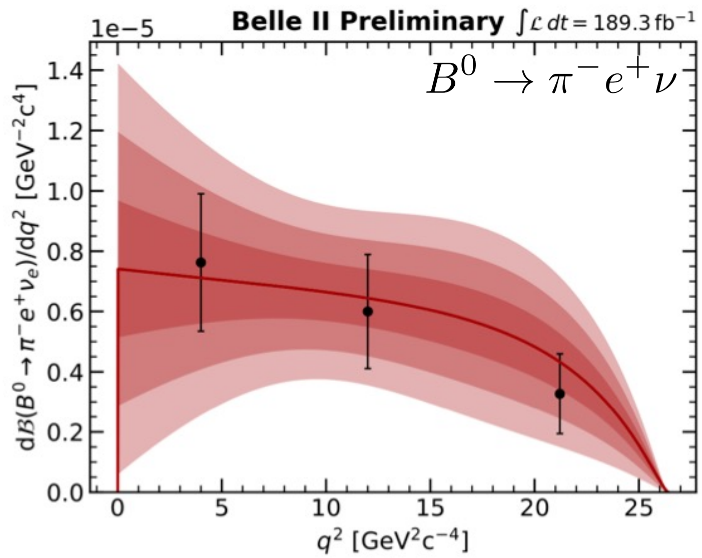
$$\frac{d\mathcal{B}}{dq^2}(B \to \pi \ell \nu) \propto |\mathcal{M}|^2 \propto |V_{ub}|^2 f_+^2(q^2)$$

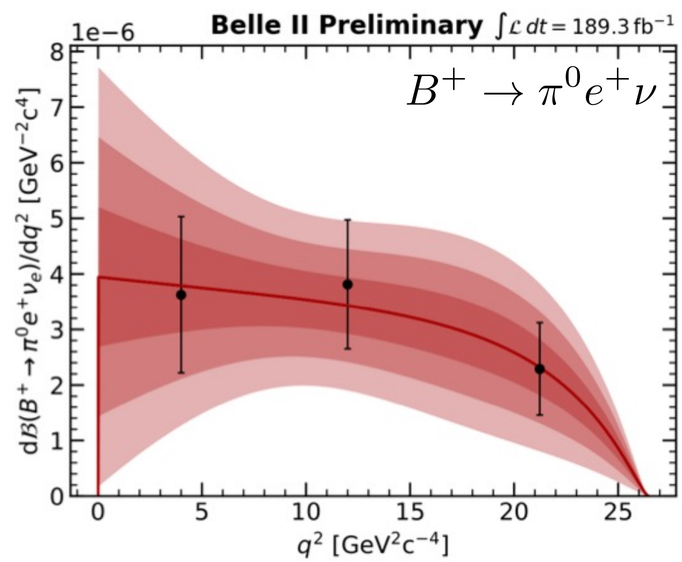
$B^0 \to \pi^- e^+ \nu$

$\mathcal{B}=(1.43 \pm 0.27_{stat} \pm 0.07_{sys})\text{x}10^{-4}$

$B^+ \to \pi^0 e^+ \nu$

$\mathcal{B}=(8.33 \pm 1.67_{stat} \pm 0.55_{sys})\text{x}10^{-5}$





Decay mode	Fitted $\|V_{ub}\|$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55) \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.21 \pm 0.63) \times 10^{-3}$
Combined fit	$(3.88 \pm 0.45) \times 10^{-3}$

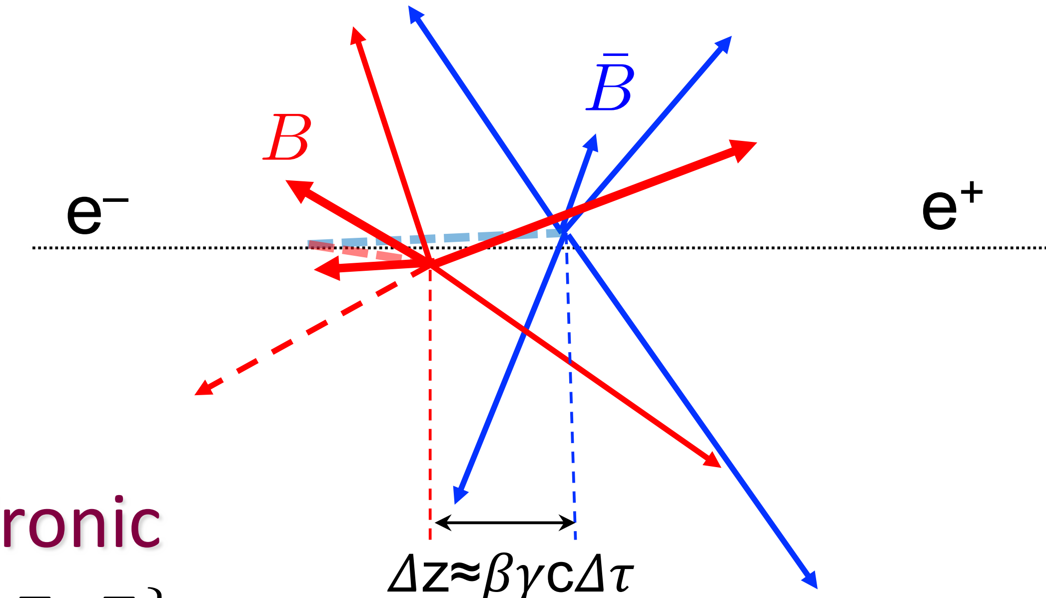
B^0 lifetime and mixing Δm_d

SM: benchmark for CP asymmetry measurements

CMS in lab frame: $\beta\gamma \approx 0.27$

➔ mean vertex separation

$\Delta z \approx 130\ \mu m$



Vertex reconstruction

- fully reconstructed hadronic

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

$$B^0 \to D^{(*)-}\pi^+\{D^{*-} \to \bar{D}^0\pi^-, \bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-\}$$

- + Belle flavor tag – 7 quality bins, dilution factors w_i

Time distributions: same/opposite flavor

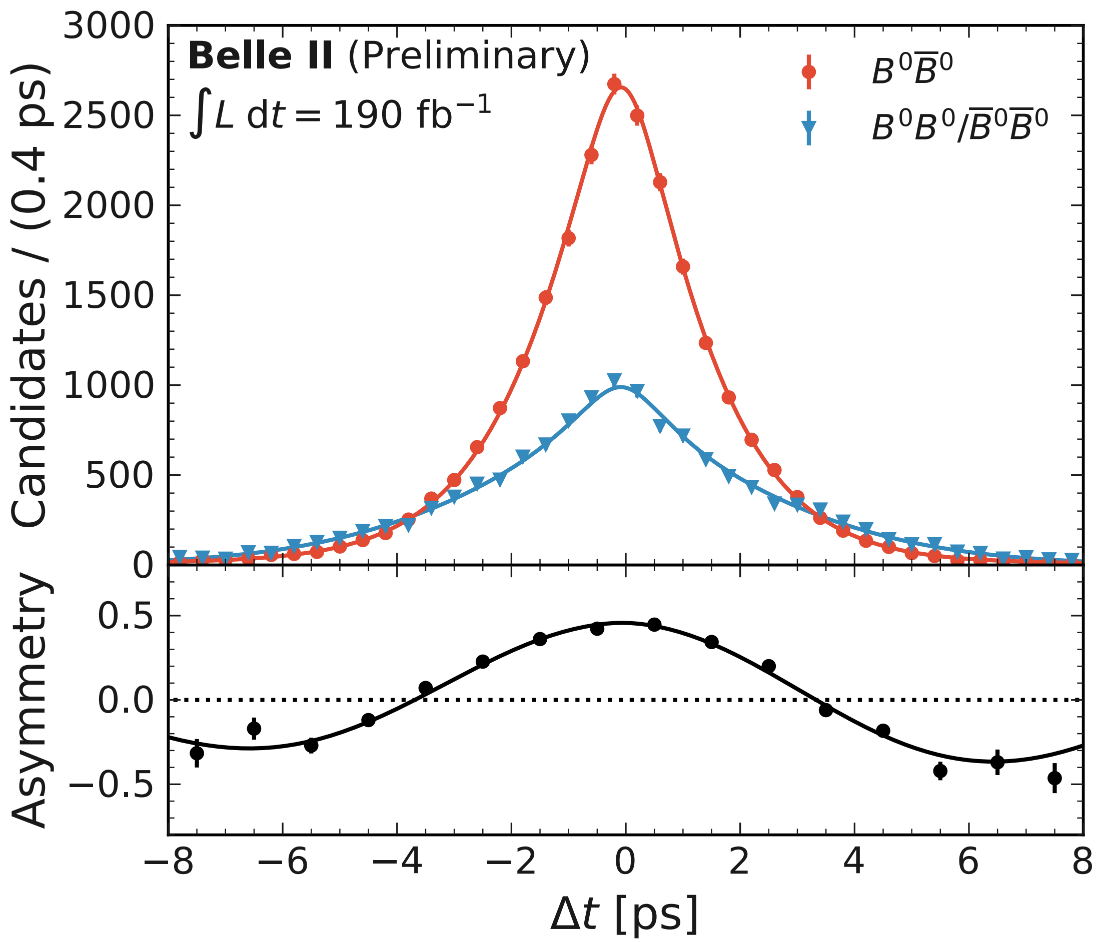
$$f(\Delta t') = \frac{e^{-|\Delta t'|/\tau_{B^0}}}{4\tau_{B^0}}(1 + q\mathcal{D}\cos\Delta m_d \Delta t')$$

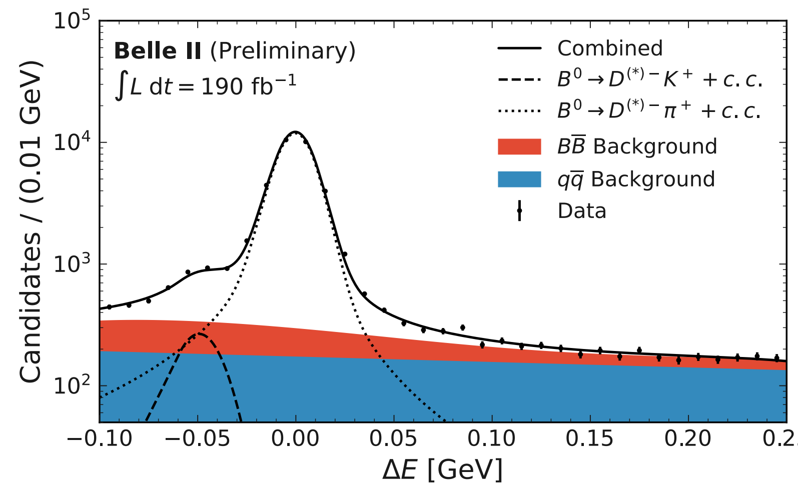
q = 1 opp flavor

q = –1 same flavor

$\mathcal{D}$ = 1–2w

B^0 lifetime and mixing Δm_d

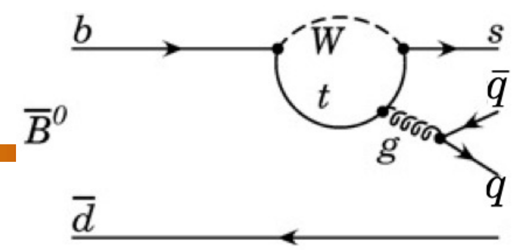




$$\tau_{B^0} = 1.499 \pm 0.013\,(\mathrm{stat.}) \pm 0.008\,(\mathrm{syst.})\ \mathrm{ps}$$

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

$B^0 \to K^0\pi^0$



SM: time-dependent CP asymmetry

sin2φ_1

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\}],$$

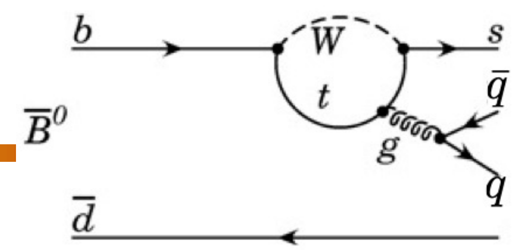
$\mathcal{A}_{CP}$: Kπ isospin sum rule

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

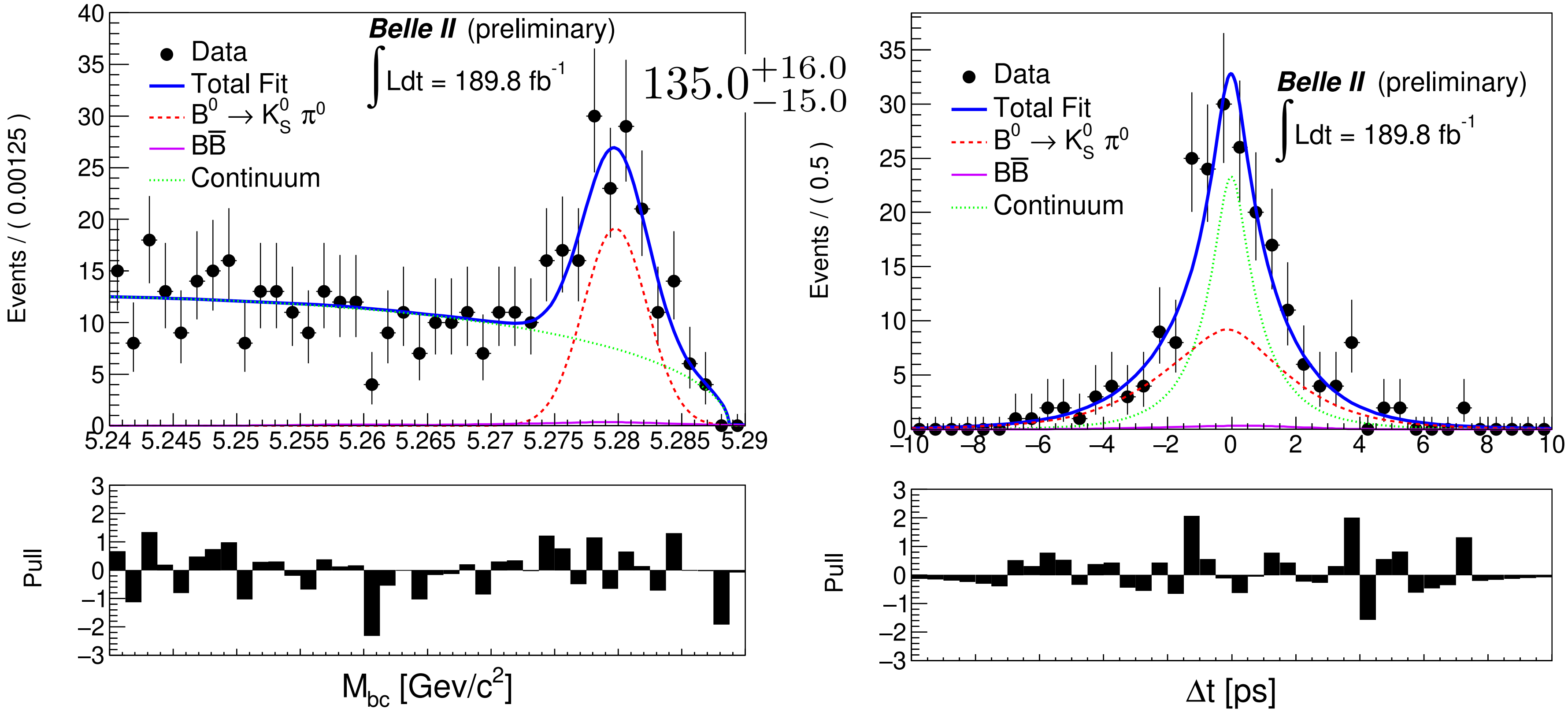
$K^0\pi^0$: only at e^+e^- B-factory, most challenging

NP: may appear as $\mathcal{A}_{CP} \neq 0$

$B^0 \to K^0\pi^0$



Branching fraction, $\mathcal{A}_{CP}$



Observable	Fitted value	WA[1] value
$\mathscr{B}(B^0 \to K^0\pi^0) \times 10^{-6}$	$11.0 \pm 1.2(stat) \pm 1.0(syst)$	9.9 ± 0.5
$\mathcal{A}_{CP}$	$-0.41^{+0.30}_{-0.32}(stat) \pm 0.09(syst)$	-0.01 ± 0.10

$B^0 \to K_S^0 \pi^0 \gamma$

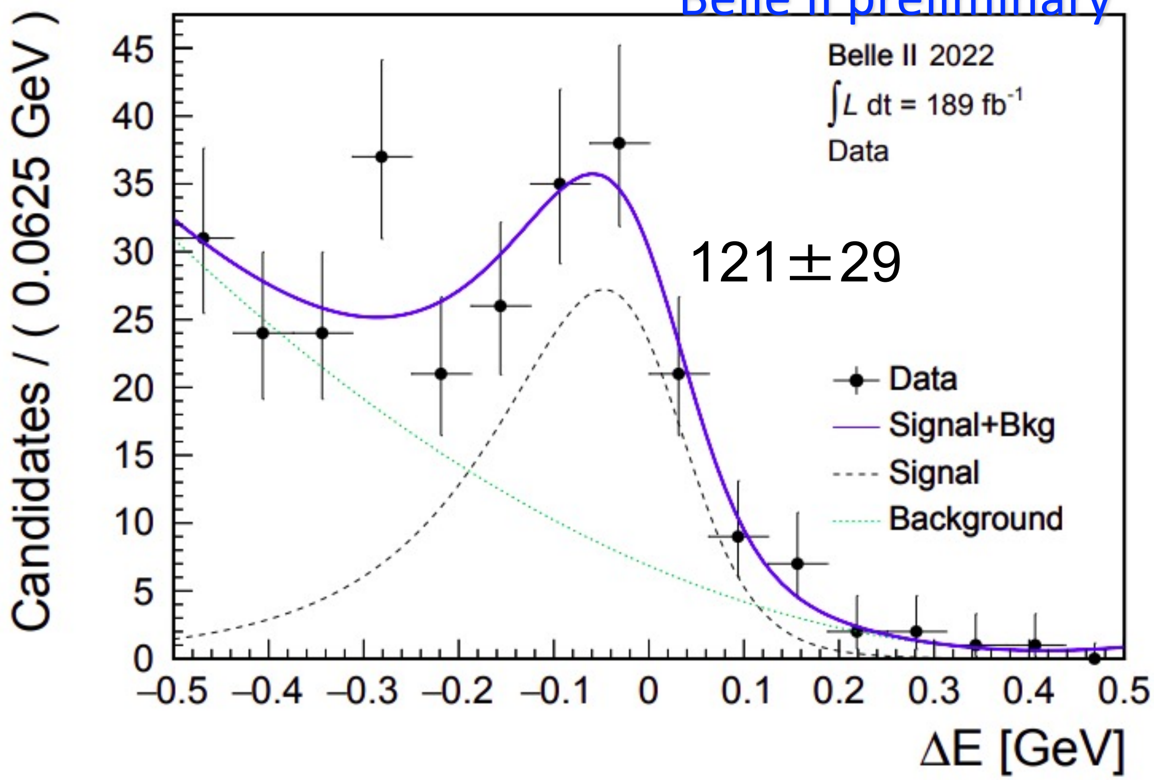
SM b→s γ: γ polarization is flavor-specific due to V-A

→ CP asymmetry suppressed

NP may appear as time-dependent CP asymmetry

Branching fraction

Belle II preliminary



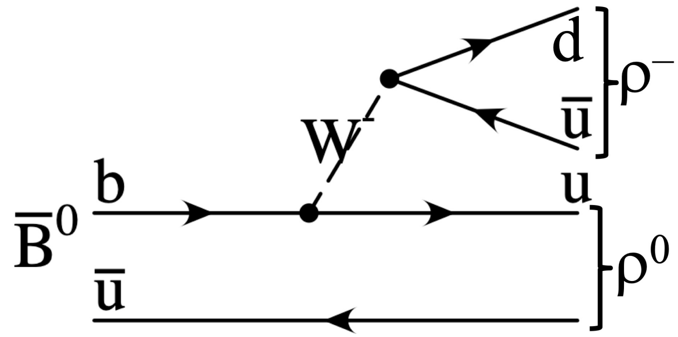
$$\mathcal{B}\left(B^0 \to K_S^0 \pi^0 \gamma\right) = (7.3 \pm 1.8\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})) \times 10^{-6}$$

$B^{\pm} \to \rho^{\pm}\rho^{0}$

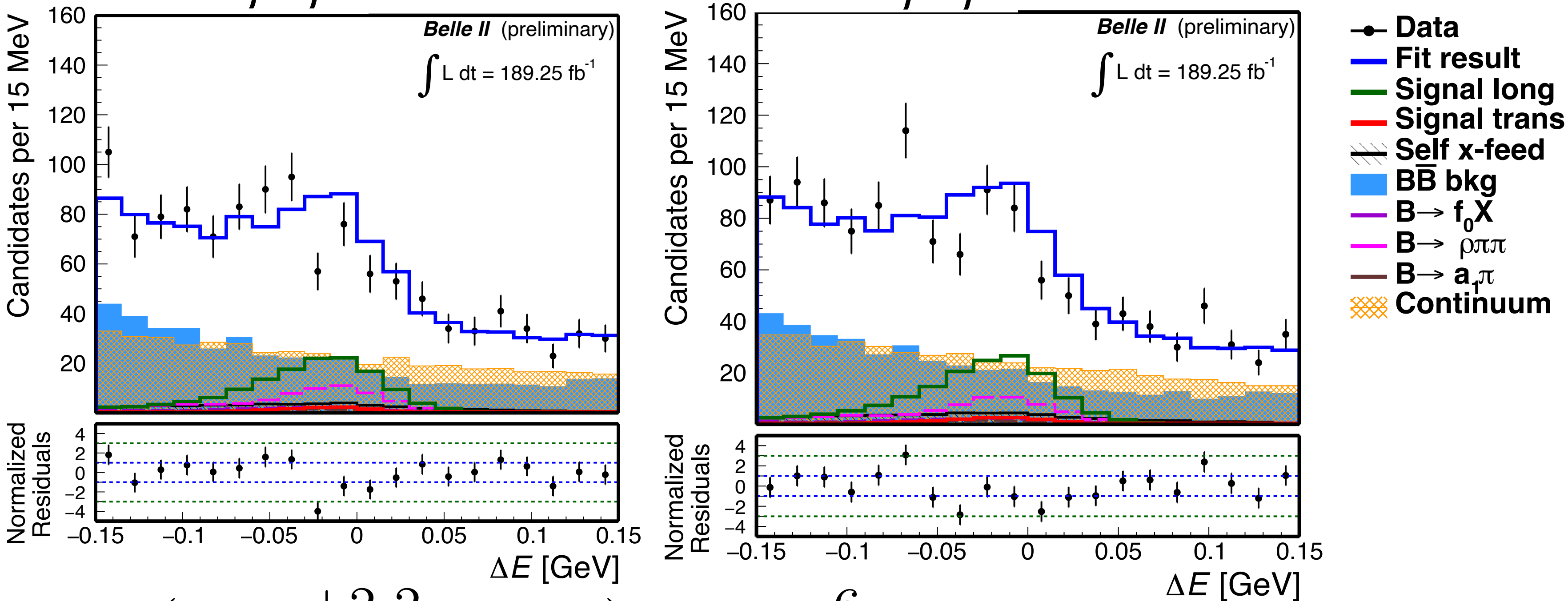
SM: b ➔ u

- φ_2 via BF/isospin relations
  - polarization-dependent

NP: Direct CP asymmetry $\mathcal{A}_{CP}$



$B^- \to \rho^-\rho^0$ $\quad$ $B^+ \to \rho^+\rho^0$



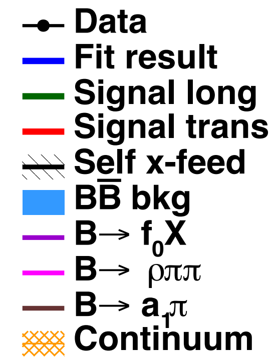
$$\mathcal{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

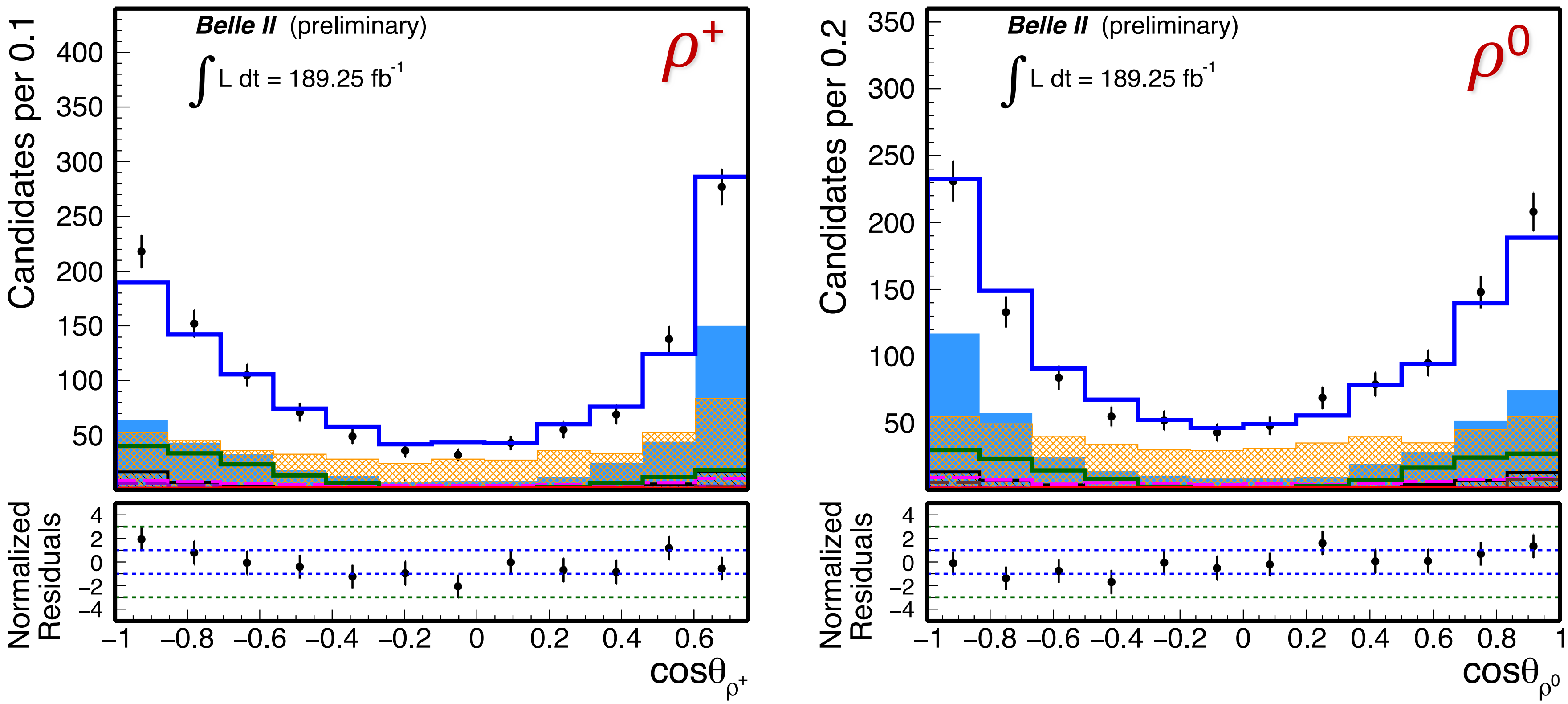
$$\mathcal{A}_{CP} \equiv \frac{\Gamma_{B^-} - \Gamma_{B^+}}{\Gamma_{B^-} + \Gamma_{B^+}} = -0.069 \pm 0.068 \pm 0.039$$

$B^{\pm} \to \rho^{\pm}\rho^{0}$

longitudinal polarization fraction f_{L}

cos(helicity angle)





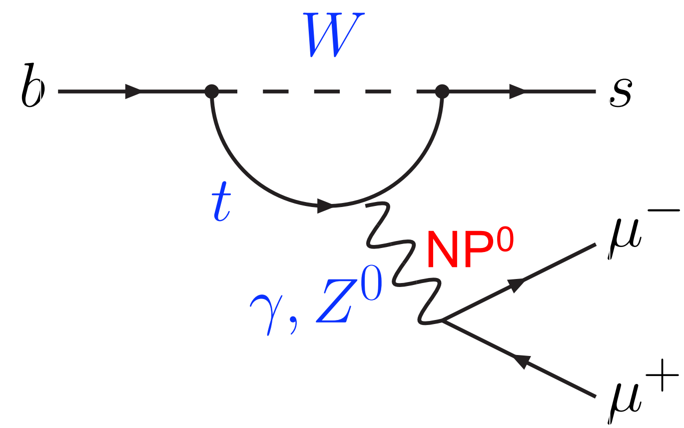
$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

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

SM: suppressed (CKM unitarity)

NP may appear in anomalies of

- branching fraction(s)
  - lepton universality μ/e



$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

$$= 1 \pm \mathcal{O}(10^{-2}])$$

1.5-3.1σ tension [LHCb]

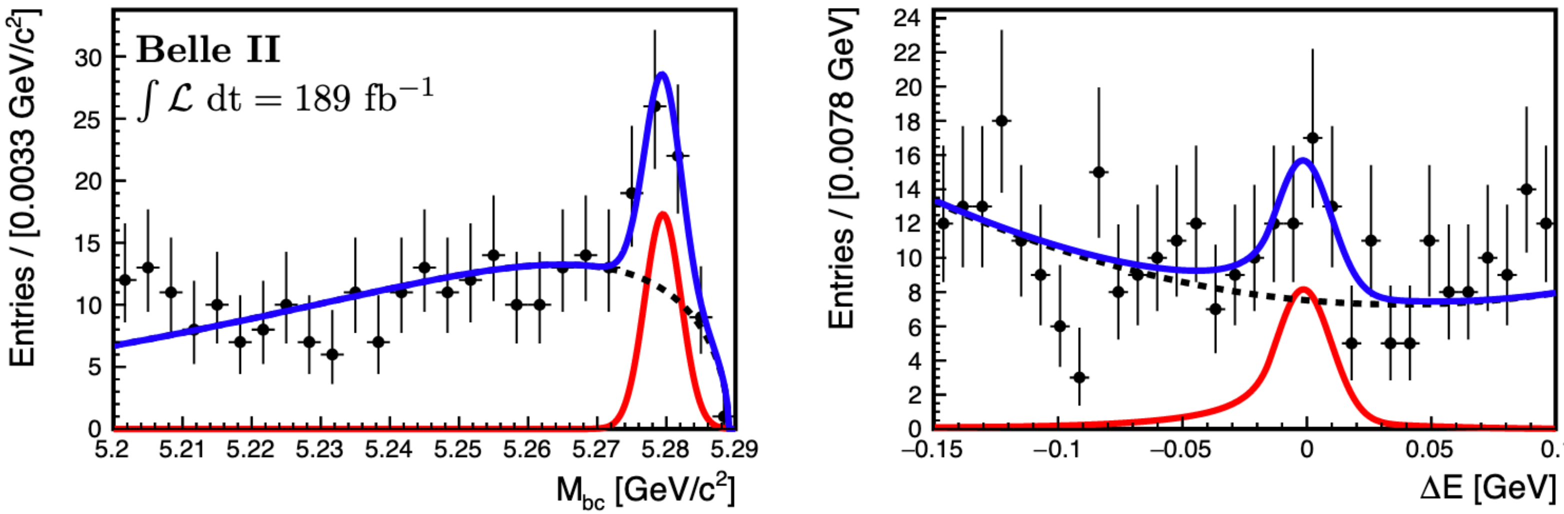
- Angular distributions

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

Belle II preliminary

B→K*ℓℓ fit projections

● data
signal PDF
background PDF
total PDF



PDG $\mathcal{B}$ x 10^6

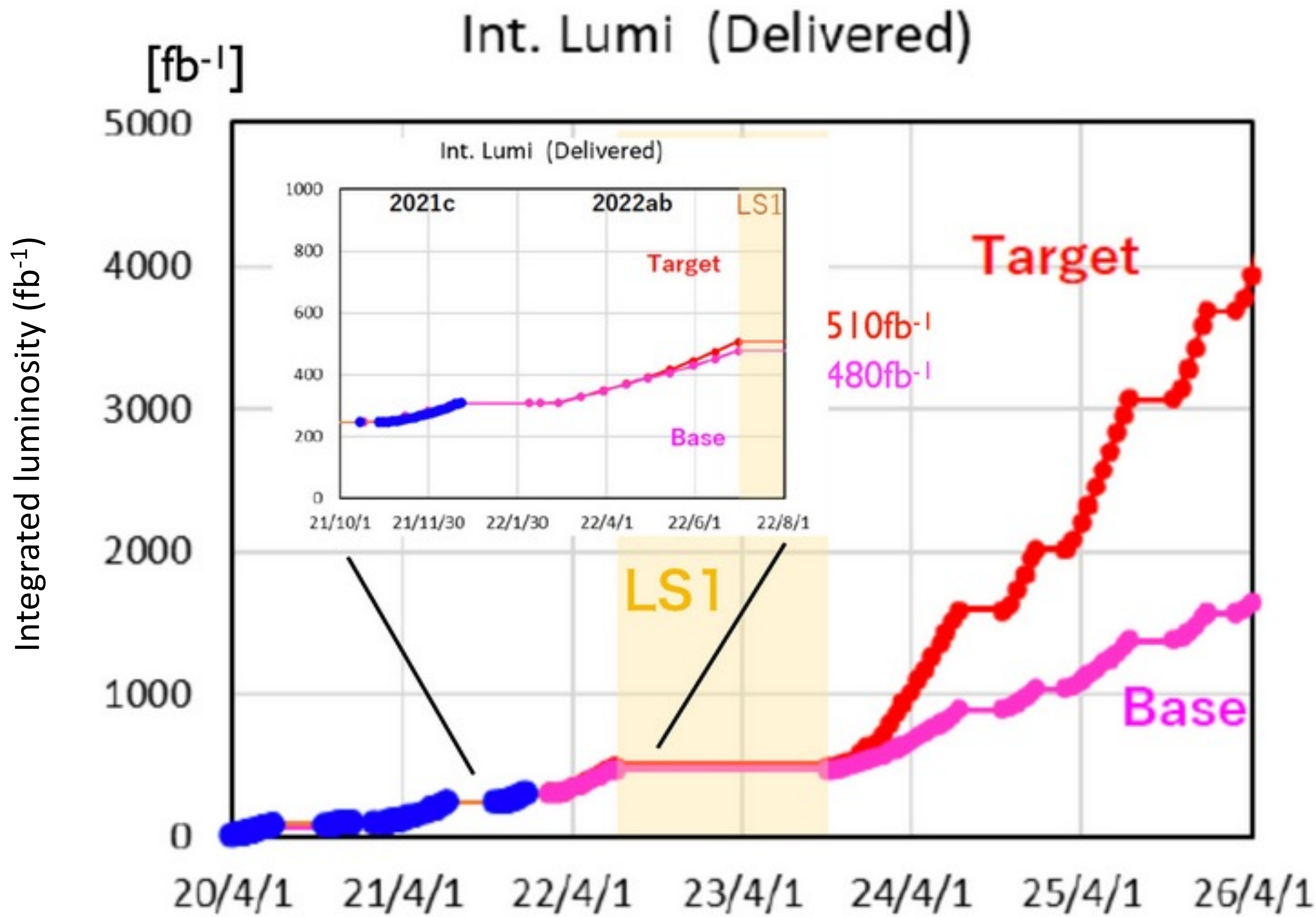
$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$$ 0.94±0.05

$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$$ 1.03±.19

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$$ 0.99±0.12

K*ee is dominated by B-factories

SuperKEKB/Belle II Luminosity Profile



Summary

$e^+e^-@\Upsilon$ region: powerful event environment, rich physics

- Belle II/SuperKEKB: hermetic detector, nano-beams
  - 189.3 fb^{-1} analyzed, new results
    - time-dependent measurements
      - world-leading charm lifetimes: D^0, D^+, Λ_c
      - B mixing, lifetime – ready for time-dependent CP
      - A_{CP} for $B^0 \to K^0\pi^0$ (single K_S vertex!)
    - time-independent
      - $|V_{xb}|$ via exclusive semileptonic/form factors
      - B decays: $\rho^\pm\rho^0,\ K_S^0\pi^0\gamma,\ K^*\ell^+\ell^-$
      - darkhiggsstrahlung search
- (Much) more to come – probe multi-TeV mass scale at the Intensity Frontier …

with better statistics & resolution…

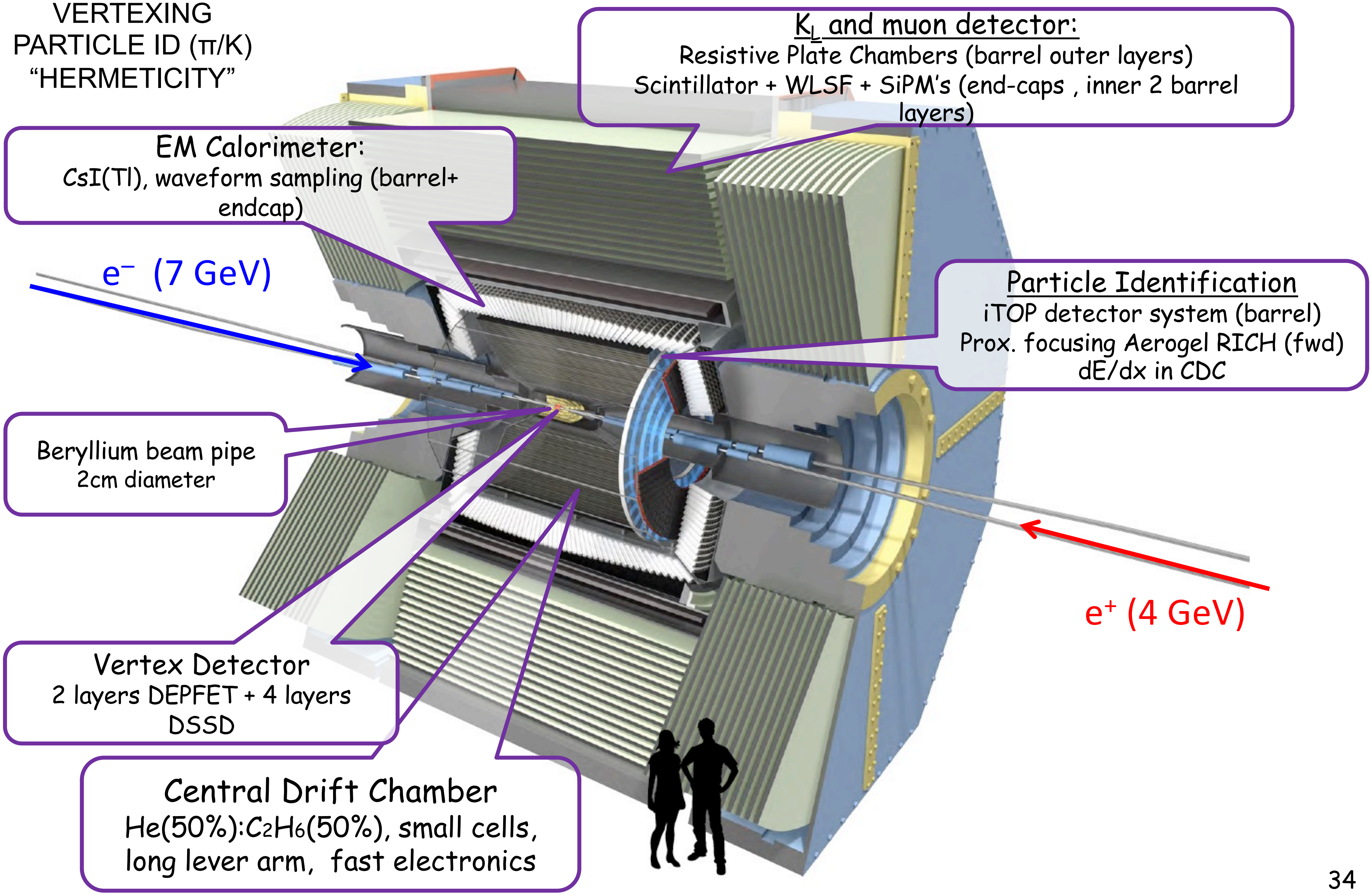
K. Kinoshita

… be prepared for surprises

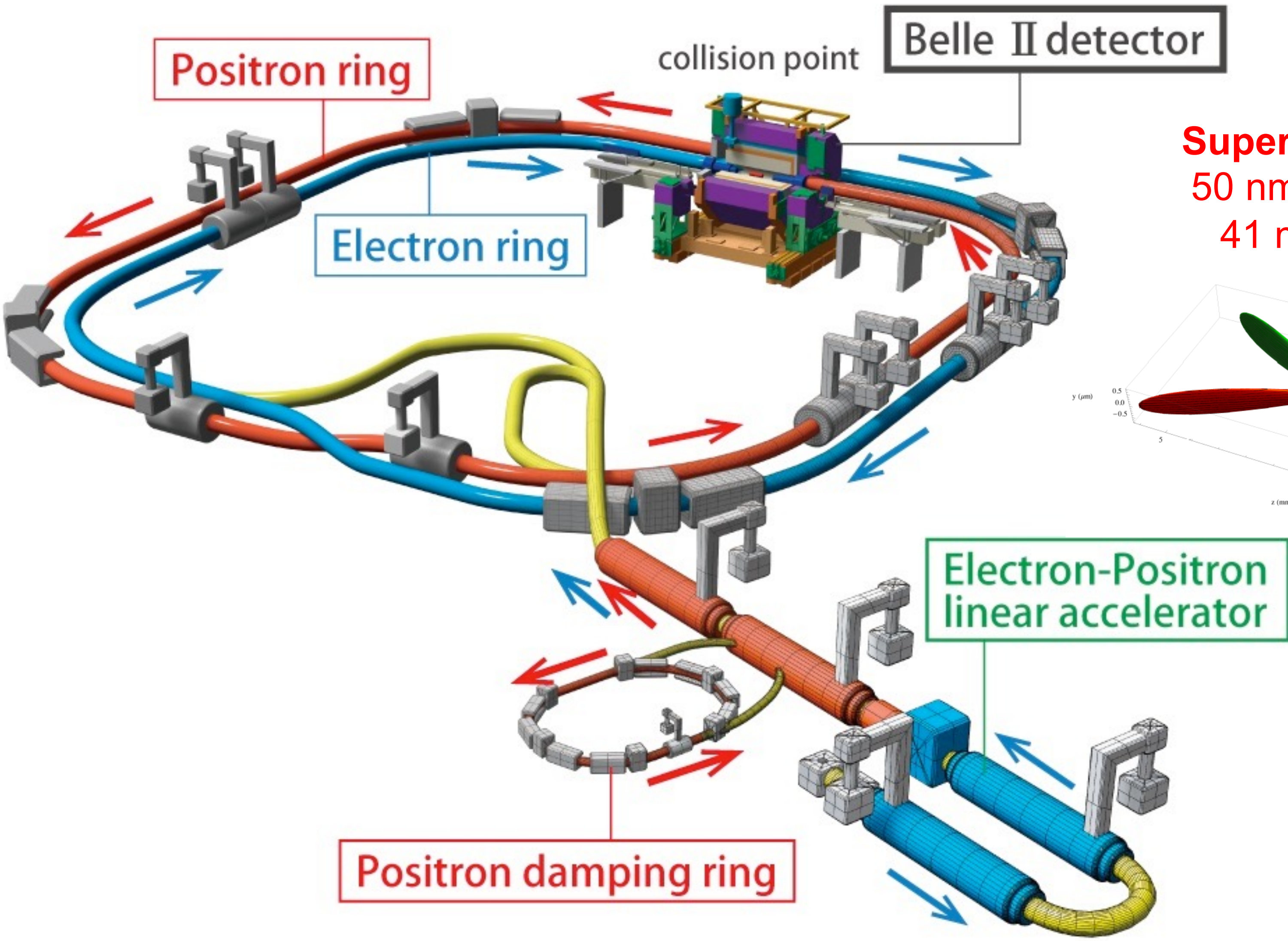
Backup Slides

Belle II Detector

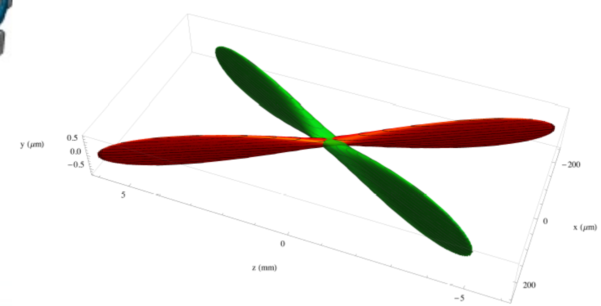
STATISTICS
VERTEXING
PARTICLE ID (π/K)
“HERMETICITY”



SuperKEKB



SuperKEKB nano-beam
50 nm x 10µm x 0.5 mm
41 mr crossing angle



CKM Matrix

Standard Model: 12 fermion flavors (+antifermion)

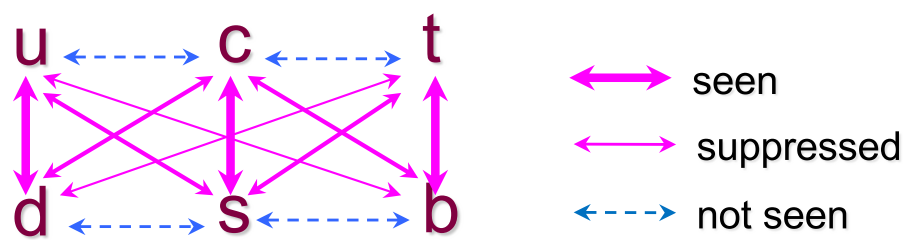
Flavors interact only via the Weak force, mediated by $W^{\pm}$, Z^0

quark couplings:

- neutral current – ≈universal, no generation x-ing
- charged current – all different, ≈ generation-conserving

$W^{\pm}$ "charged current"

Z^0 "neutral current"



All observations explained if matrix of couplings is unitary

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

9 complex couplings

→18 free parameters

GIM

(Glashow-Iliopoulos-Maiani)

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

unitary transforation

mass ↔ weak

eigenstates

Kobayashi-Maskawa

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

For 3 generations, 4 free parameters, including

1 irreducible **imaginary** part

Unitarity of CKM matrix

Decay rates ∝ |Amplitude|²

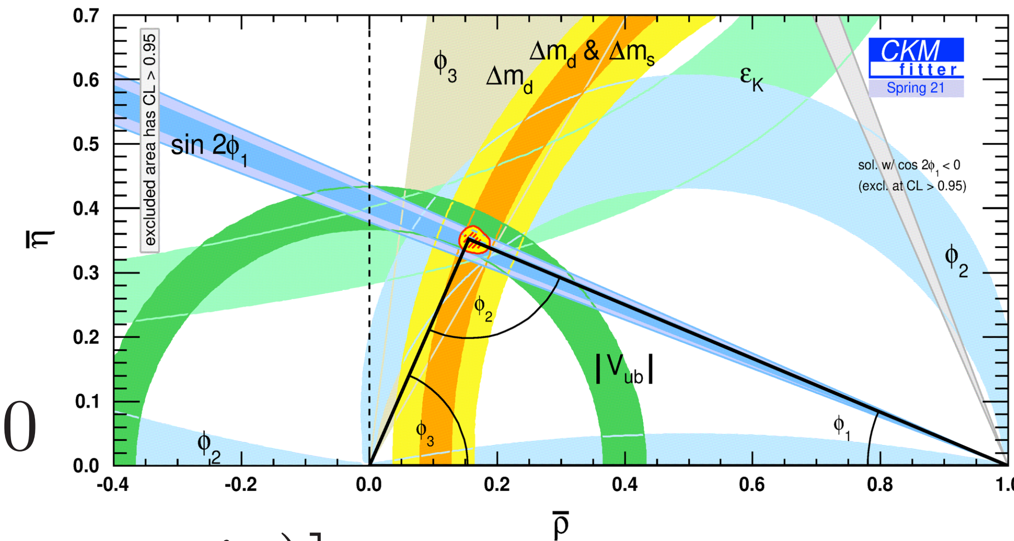
$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{bmatrix}$$

Unitarity: $\sum_k V_{ik} V_{jk}^* = \delta_{ij}$

Explicitly for i=1, j=3:

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

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



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