Belle II prospects for the measurements of $|V_{us}|$, $|V_{cd}|$ and $|V_{cs}|$

Jitendra Kumar
On behalf of the Belle II collaboration

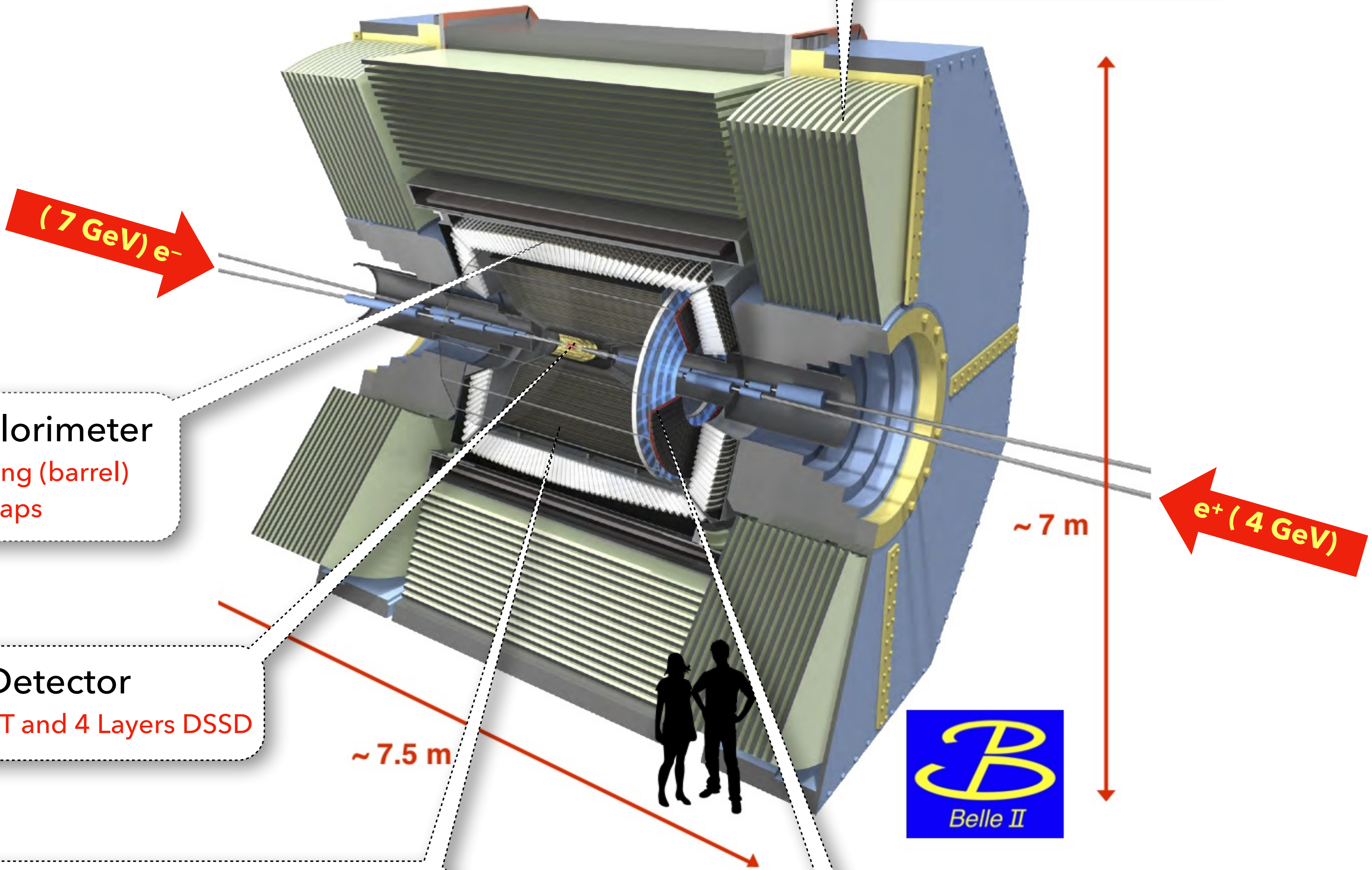
Carnegie Mellon University

Outline

Overview of measurements, studies and future prospects

- Belle II detector and data taking status
- Charm/τ potential and performance at Belle II
- Belle II prospects on $|V_{us}|$, $|V_{cd}|$ and $|V_{cs}|$
- Summary

Belle II overview



KL and muon Detector
Resistive Plate Chamber
Scintillator + WLSF + MPPC

Electromagnetic Calorimeter
CsI(Ti), waveform Sampling (barrel)
Pure CsI for end caps

Vertex Detector
2 Layers PXD DEPFET and 4 Layers DSSD

Central Drift Chamber
Smaller cells, long lever arm, fast electronics

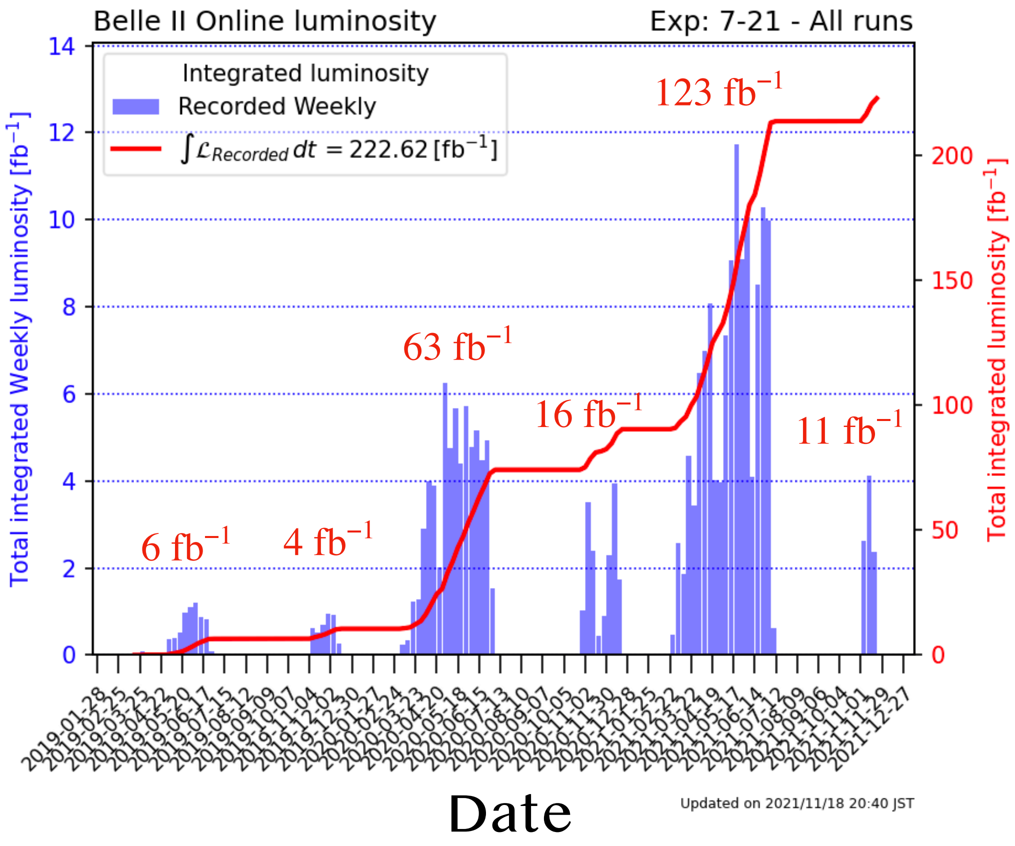
Particle Identification
Time of Propagation in barrel region
and ARICH in forward region

Ref: Belle2 TDR: arXiv: 1011.0352

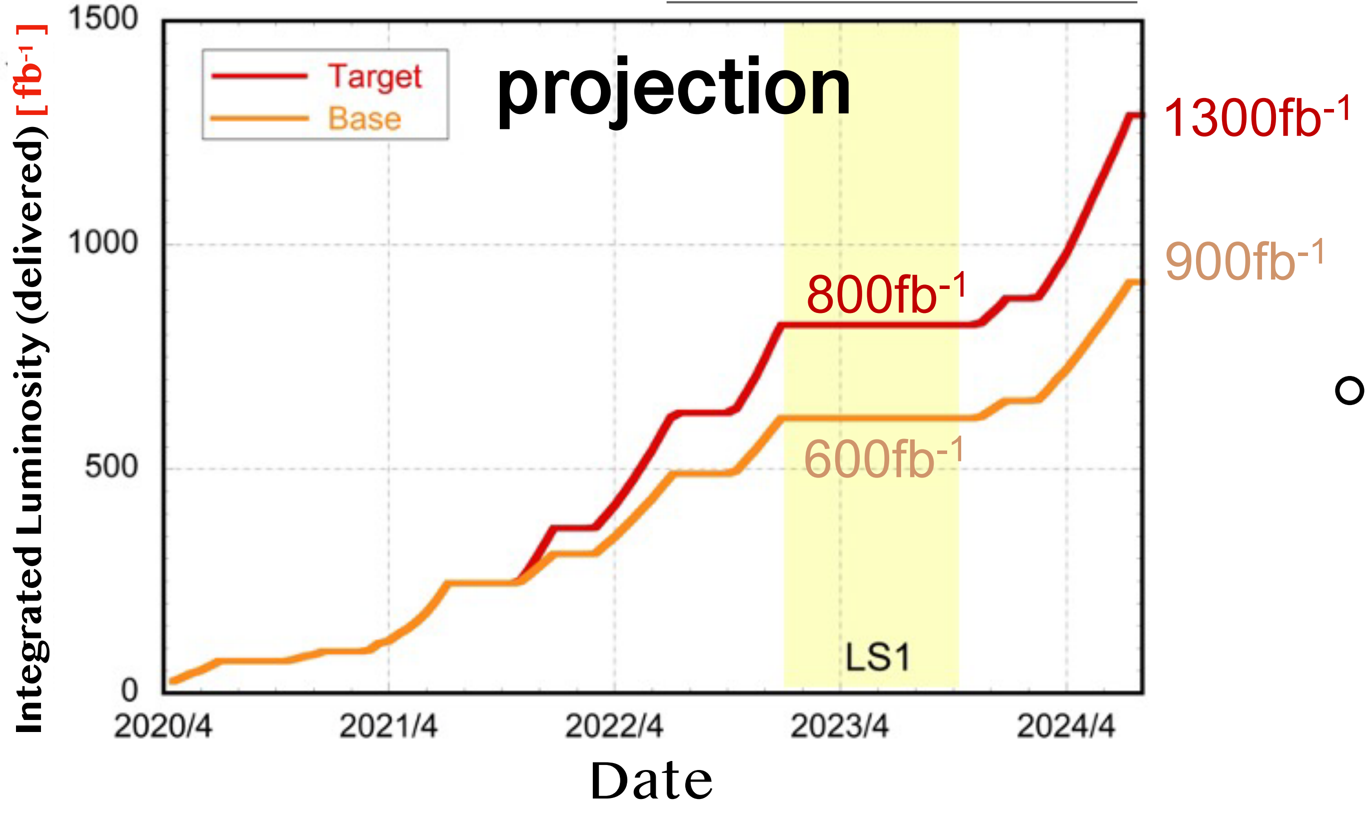
Belle II data status

as of now

- Continued data-taking through Covid-19 pandemic
- Integrated luminosity $\mathcal{L}_{\text{int}}$ ~223 fb^{-1} (Nov 18, 2021)
- Highest instantaneous luminosity ~3.1 × 10^{34} cm^{-2}s^{-1}
  - **New world record archived** in June 2021 🥇 ☀
  - SuperKEKB design luminosity: 6.5 × 10^{35} cm^{-2}s^{-1}



see Alessandro Gaz' talk



- **so far..**

  BelleII charm/τ studies focused on detector/reconstruction performance, resolutions, and systematic effects..

☀Belle highest in June'09 : 2.1 × 10^{34} cm^{-2}s^{-1}

Ref: https://confluence.desy.de/display/BI/Belle+II+Luminosity

charm/τ opportunities at Belle II

Powerful SuperKEKB

- 50 ab^{-1} = ~50 x Belle
- e^+e^- collisions (asymmetric beam energies)
  - offer stringent kinematic constraints for reconstruction of final states with neutrinos
  - acceptance and trigger criteria that introduce much less bias on flight length and kinematic properties
  - ..more in Physics Book

Impact

- **Charm Physics**
  - B-factory ▶ "charm-factory" (60×10^9 pairs of c with 50 ab^{-1})
    - excellent Dalitz plot analysis (uniform efficiency and non-biasing trigger)
    - better reconstruction of neutrinos
- **τ Physics**
  - B-factory ▶ "τ-factory" (~50×10^9 events with 50 ab^{-1})
    - measure wide range of observables (CP asymmetries, invariant mass spectra, lepton universality etc.)
    - precision measurements or indirect search of BSM (beyond SM) physics
    - direct search of forbidden decays

Ref: Belle2 Physics Book arxiv1808.10567

charm/τ opportunities at Belle II

highlights of **Belle II**

- New silicon vertex detector provides better vertex resolution
- Good PID even with higher beam background environment
- More tracking volume♉ ⇝ higher K_s efficiency (w.r.t. LHCb)
- .. more in TDR and Physics Book

Impact

- **Charm/τ Physics**
  - Facilitate measurement of mixing parameters, and CP violations with neutrals in the final state
  - Belle II performance is expected to improve w.r.t. to Belle;
    - improved IP resolution (e.g. x2 better D^0 proper time resolution)
    - reduced statistical uncertainties
    - ..and if systematic uncertainties are reduced

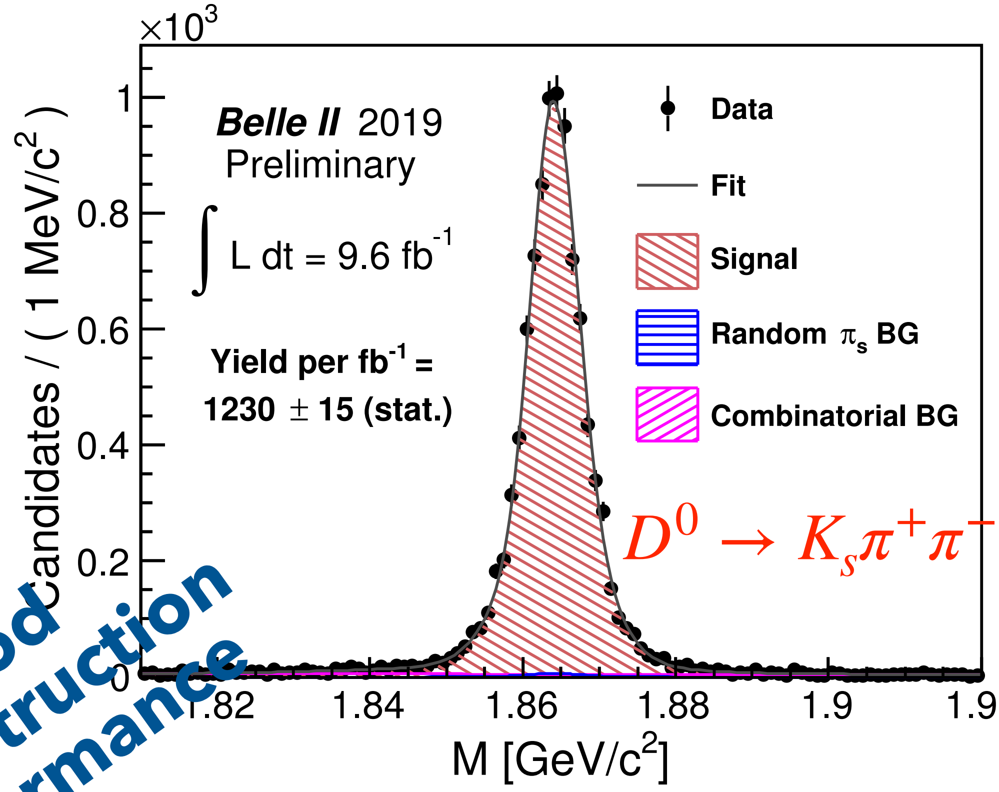
♉from Central Drift Chamber (CDC) and Silicon Vertex Detector(SVD)

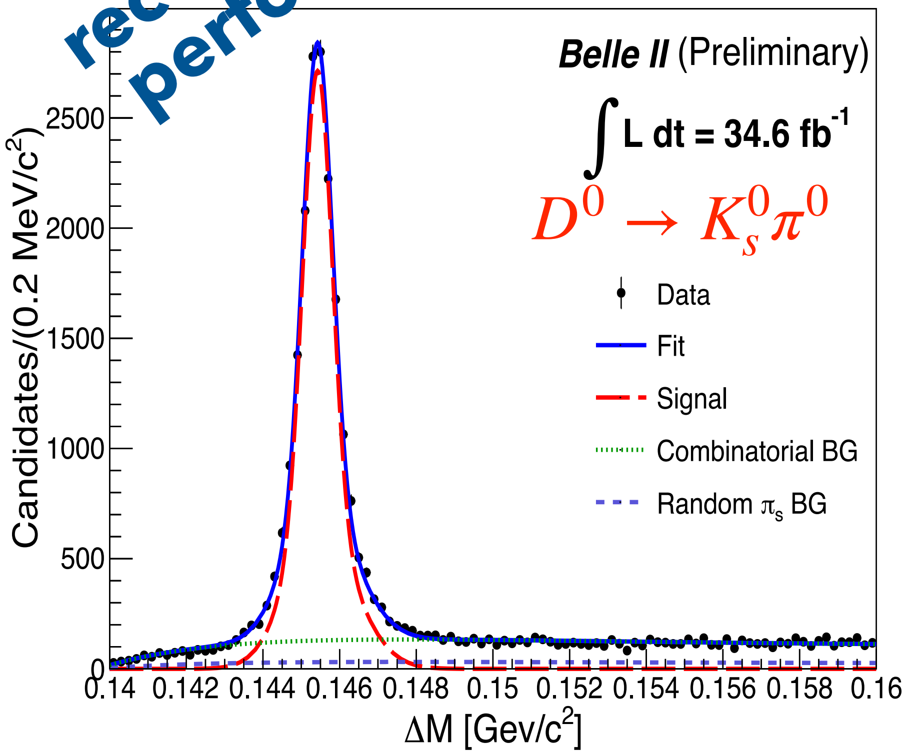
Ref: Belle2 Physics Book arxiv1808.10567

Current Belle II performance

charm results

Good reconstruction performance

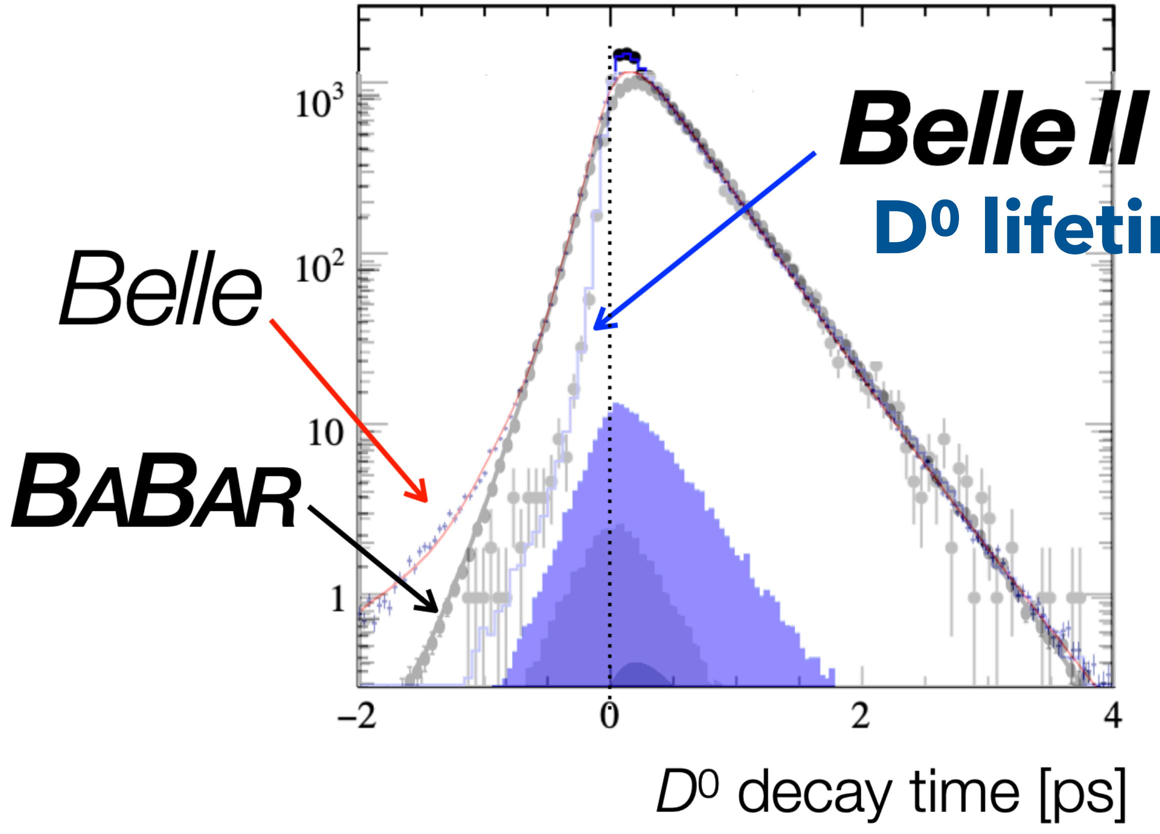




Phys. Rev. Lett. 127, 211801 (2021)

World's Best

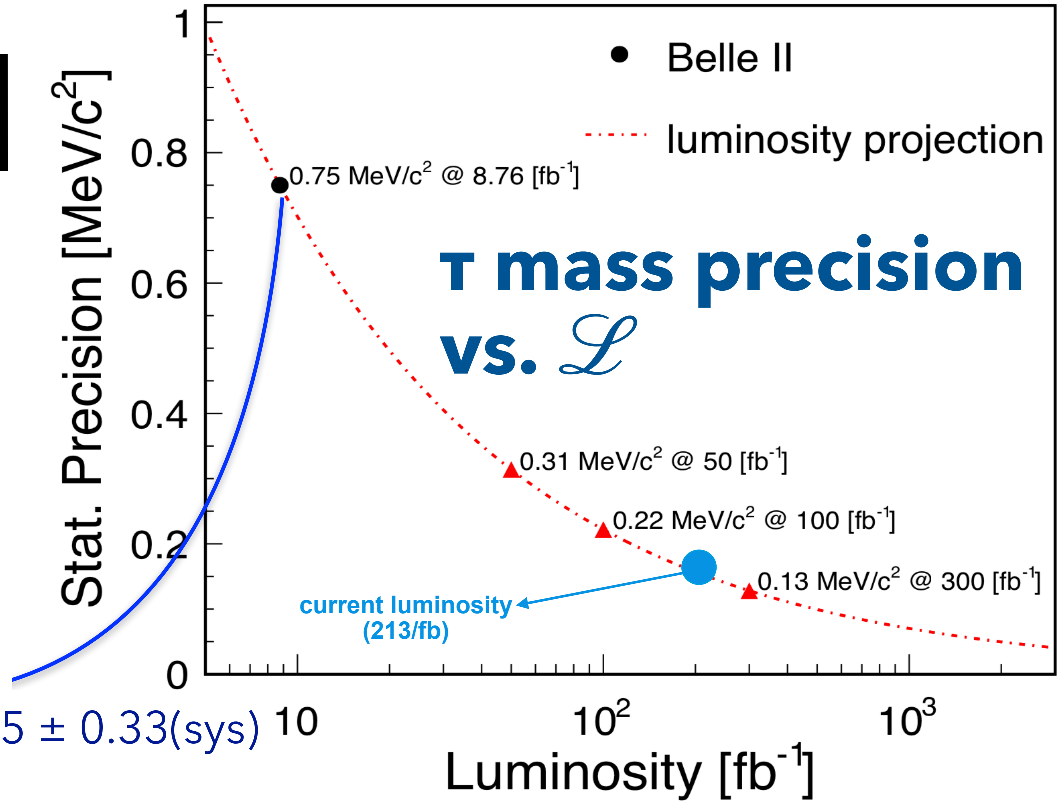
x2 better w.r.t. Belle



τ results

arXiv:2008.04665

Belle II 2020



τ mass precision vs. $\mathscr{L}$

- m_τ 1777.28 ± 0.75 ± 0.33(sys)

1 | V_{us} | status and Belle II prospects

- s ↔ u transition
- Experimental measurements
  - kaon decays
    - traditional (also for form factor) and most accurate among all
    - but precision is limited from theory (LCQD) uncertainties (on form factor $f_+(0)$ & f_k/f_π)
  - hyperon decays
  - τ decays with strangeness in the final state (today's focus)

$|V_{us}|$ from τ decays (methods)

Exclusive method

1. Compare BR ratio: $\tau^- \to K^-\nu_\tau$ and $\tau^- \to \pi^-\nu_\tau$

$$\frac{\Gamma_{\tau^-\to K^-\nu_\tau}}{\Gamma_{\tau^-\to\pi^-\nu_\tau}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{(1-m_K^2/m_\tau^2)^2}{(1-m_\pi^2/m_\tau^2)^2}(1-\delta_{LD})$$

long-distance
radiative
corrections

- ▶ $|V_{us}| = 0.2234 \pm 0.0015$ (HFLAV 2021 preliminary)
  - ⦿ -2.1σ from CKM unitarity
  - ⦿ but large uncertainties as compared to kaons
    - ▶ $|V_{us}|(K \to l3)$: 0.2231 ± 0.0006

2. via branching fraction: $\tau^- \to K^-\nu_\tau$

electroweak
corrections

$$\mathcal{B}(\tau^-\to K^-\nu_\tau) = \frac{G_F^2 f_K^2 |V_{us}|^2 m_\tau^3 \tau_\tau}{16\pi\hbar}\left(1-\frac{m_K^2}{m_\tau^2}\right)^2 S_{EW}$$

- ▶ $|V_{us}| = 0.2226 \pm 0.0015$ (HFLAV 2021 preliminary)
  - ⦿ -2.6σ from CKM unitarity
  - ⦿ but large uncertainties as compared to kaons
    - ▶ $|V_{us}|(K \to l3)$: 0.2231 ± 0.0006

Inclusive method

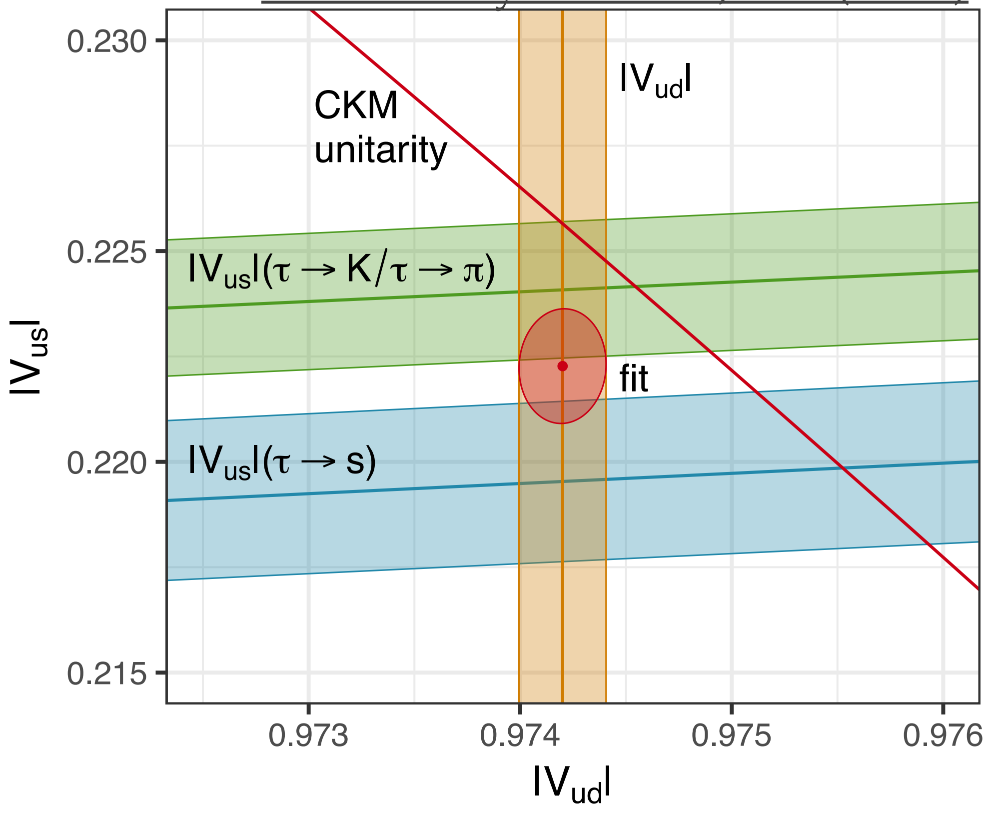
1. via spectral moments : $\tau \to s$ decays

$$|V_{us}| = \sqrt{\frac{R_s}{\frac{R_{ns}}{|V_{ud}|^2}-\delta_\tau}}$$

S (hadron with S = 0)
NS (hadron with S ≠ 0)

- ▶ $|V_{us}| = 0.2192 \pm 0.0019$ (HFLAV 2021 preliminary)
  - ⦿ -3.6σ lower from CKM unitarity

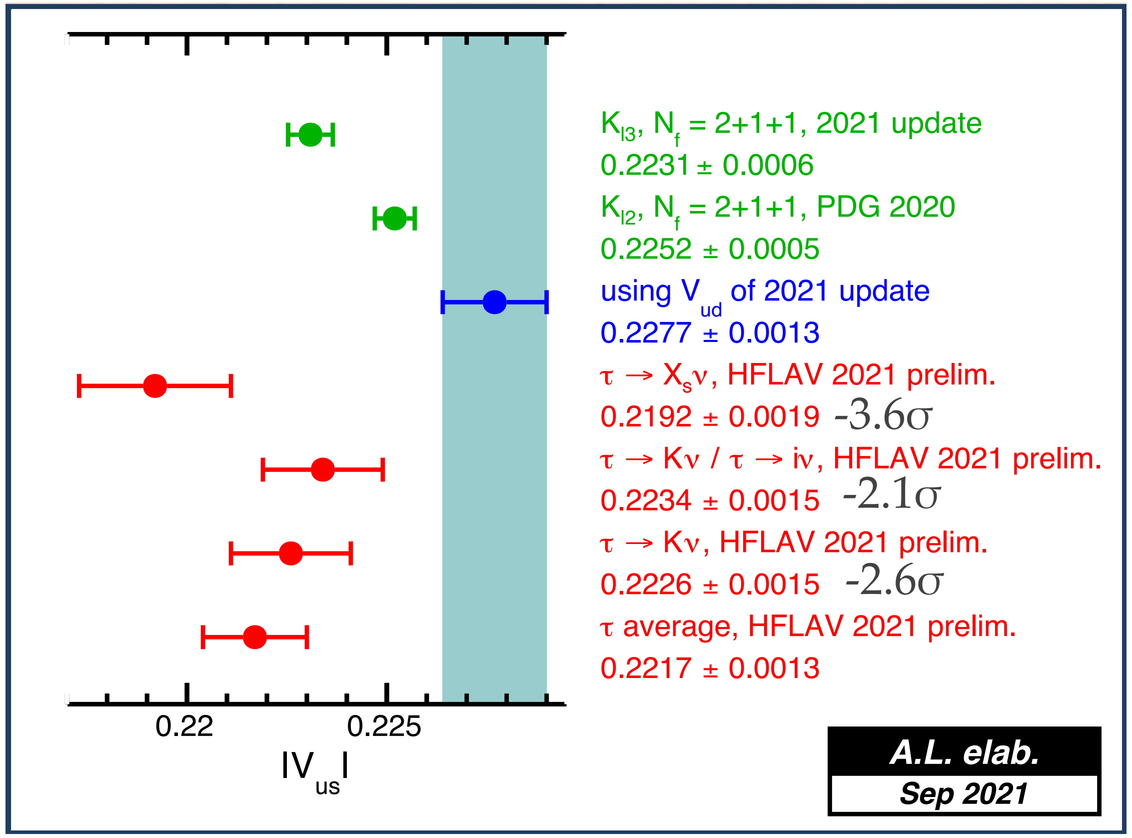
SciPost Phys. Proc. 1, 001 (2019)



⦿ alternate methods [1], [2]: consistent with K and CKM unitarity

$|V_{us}|$ from τ decays (status)

By Alberto Lusiani in Tau 2021 **NEW**



Current status

- **Kaon decays** (HFLAV 2021 preliminary)
  - $|V_{us}|$: see latest numbers on plot for → $l3$ & $l2$
    - $|V_{ud}| - |V_{us}|_K$ anomaly ~3σ
      - ~5σ without increased |Vud| systematics
- τ decays **(average** HFLAV 2021 preliminary**)**
  - $|V_{us}| = 0.2217 \pm 0.0013$
    - $\tau \to s$: -3.6σ lower from CKM unitarity

Belle II prospects

— will perform LFU like analysis (use 3x1 and 1x1 topologies)

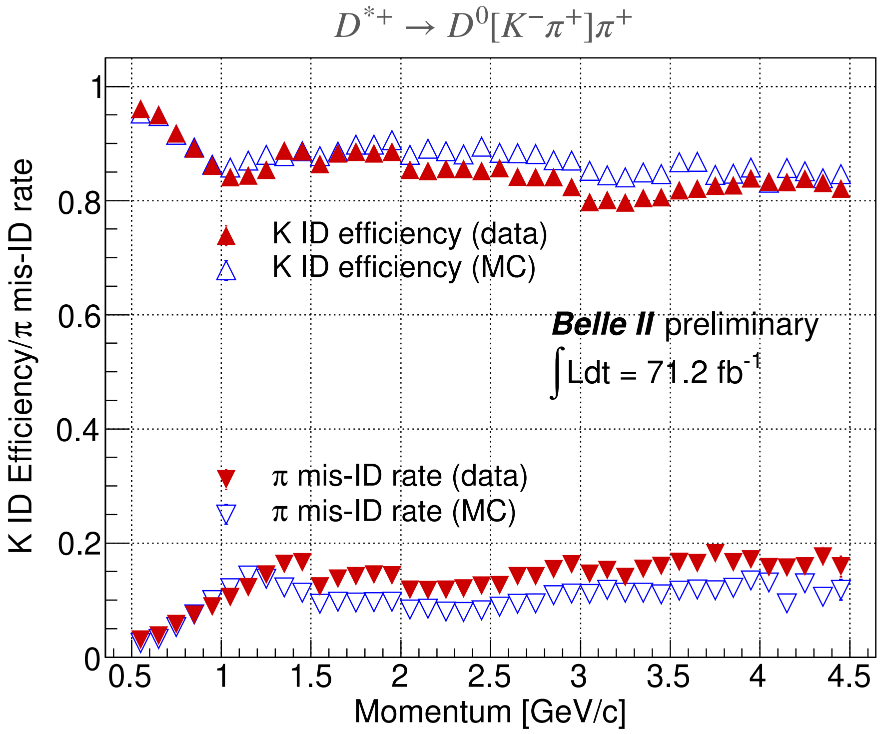
— statistical uncertainties will be improved with larger data-set

— also improved systematics from

  — PID[1], trigger efficiency from detector upgrades

  — MC inputs (background estimation, modeling of decays[2])

Belle II PID performance (efficiency/fake rates)



1. PID (scale factor uncertainty will scale inverse to the statistics of the data sets)
2. Modeling of decays in the generator (KKMC, Tauola)

2 | V_{cs} | status and Belle II prospects

- Cabibbo-favoured (c → s transition)
- Experimental measurements
  - with D and D_s meson decays (today's focus)
    - Leptonic ($D_s \to \ell\nu$) decay ⇝ simplest and theoretically cleanest processes

      Decay constants f_D is required from Lattice QCD
    - Semi-leptonic decay ($D \to K\ell\nu$)

      Form factor $f(q^2)$ is required from Lattice QCD
  - charm baryon and $W^{\pm}$ decays

$|V_{cs}|$ via leptonic decay: $D_s \to \ell\nu$

$$\Gamma(D^+_{(s)} \to \ell^+\nu) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} |V_{cd(s)}|^2 M_{D^+_{(s)}} M^2_{\ell^+} \left(1 - \frac{M^2_{\ell^+}}{M^2_{D^+_{(s)}}}\right)^2$$

Overview

- decay modes: $\to \mu\nu$, $\to e\nu$ & $\to \tau\nu$
- decay suppressed by helicity conservation hence decay rates $\propto m_l^2$
  - → $e\nu$ branching fraction is very small ~ 10^{-7}
  - → $\tau\nu$ is favored over $\mu\nu$

analysis method (Belle)

$$e^+e^- \to c\bar{c} \to D_{tag} X_{frag} K_{frag} D_s^{*-} (\to D_s^- \gamma)$$

D_{tag}: D^+, D^0, Λ_c^+ & D^{*+}, D^{*0}

X_{frag}: $\pi, K(even), p$

Tag: Tagged decays
Frag: Fragmented particles

Step1: reconstruct tag side D_{tag}, build X_{frag} and then extract D_s^- via missing mass analysis

→ missing mass peak at ~ D_s^- mass

Step2: used signal from step 1 and search/extract D_s^- yield for $\to \mu\nu$, $\to e\nu$ & $\to \tau\nu$

→ **measure branching fraction** ▶ $\mathcal{B}(D_s^+ \to f) = \dfrac{N(D_s^+ \to f)}{N^{\rm inc}_{D_s} \cdot f_{\rm bias} \cdot \varepsilon(D_s^+ \to f | \text{incl. } D_s^+)}.$

Step3: calculate $f_{D_s} V_{us}$ from step 2, then two approach

1. take f_{D_s} from Lattice QCD
→ extract V_{us} and compare w/ CKM unitarity

2. take V_{us} from CKM unitarity
→ extract f_{D_s} and compare w/ Lattice QCD

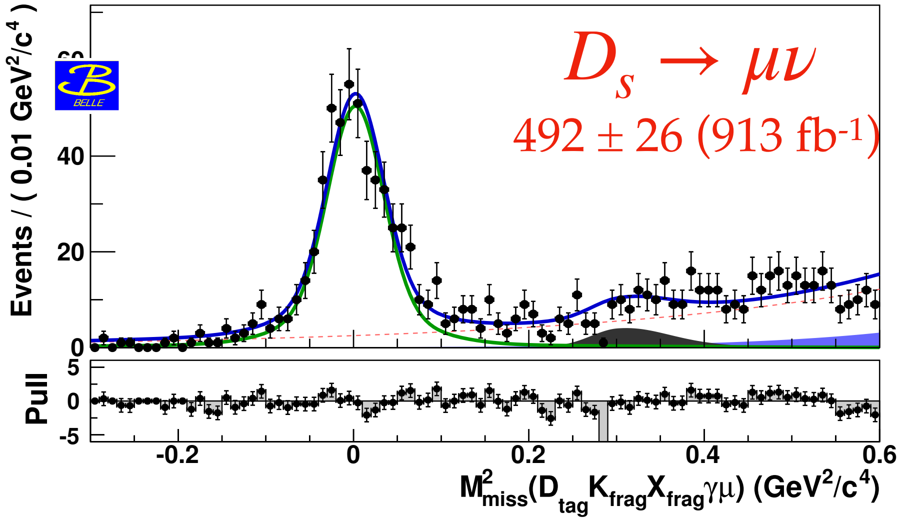
$|V_{cs}|$ via leptonic decay: $D_s \to \ell\nu$

$$\Gamma(D_{(s)}^+ \to \ell^+\nu) = \frac{G_F^2}{8\pi} f_{D_{(s)}^+}^2 |V_{cd(s)}|^2 M_{D_{(s)}^+} M_{\ell^+}^2 \left(1 - \frac{M_{\ell^+}^2}{M_{D_{(s)}^+}^2}\right)^2$$

Current status

▶ $D_s \to \mu\nu$

- several results in past years by BaBar, Belle, BESIII[1] [2][latest] and CLEO-c
- the most precise result from BESIII (2021) with 6.2 fb-1
- Belle performed analysis with 913 fb-1



HFLAV 2021

- **$|V_{cs}| = 0.9839 \pm 0.0115(\text{exp.}) \pm 0.0020(\text{LQCD})$**
  - average with $D_s \to \tau\nu$
  - $f_{D_s} = 249.9 \pm 0.5$ MeV (LQCD) $= 0.2\%$ precision
- **$f_{D_s} = 252.6 \pm 3.0$ MeV**
  - global fit: $|V_{cs}| = 0.973394^{+0.000074}_{-0.000096}$

Belle II prospects 50 ab-1

- ⇝ improved stats. uncertainty
  - $\delta(|V_{cs}|) = \pm 0.004$ (stat.)
  - $\delta(|f_{D_s}|) = \pm 0.9$ (stat.) MeV
- ⇝ systematics uncertainty (possible improvements)
  - with precision measurement of peaking backgrounds
  - in normalization (err. scaled with luminosity and are reducible with clean X_{tag})

inclusive	Yield per luminosity
B-factory (Belle)	$100\cdot10^3$ per ab^{-1}
Charm-factory (CLEO-c) $\sqrt{s} = 4.17$ GeV	$73\cdot10^3$ per fb^{-1}
Charm-factory (BESIII) $\sqrt{s} = 4.01$ GeV	$22\cdot10^3$ per fb^{-1}

$D_s \to \mu\nu$ *Yield*

Source	$\mu\nu$ [%]
Statistical	±5.32
Normalization	±1.95
Tag bias	±1.37
Tracking	±0.35
Efficiency	±1.78
PID	±1.96
D_s background	±0.82
Comb. bkg. PDF	±0.02
Signal PDF	–
τ cross-feed	–
$\mathcal{B}(\tau \to X)$	–
PDF stat.	–
Total syst.	±3.67
Stat. + Syst.	±6.46

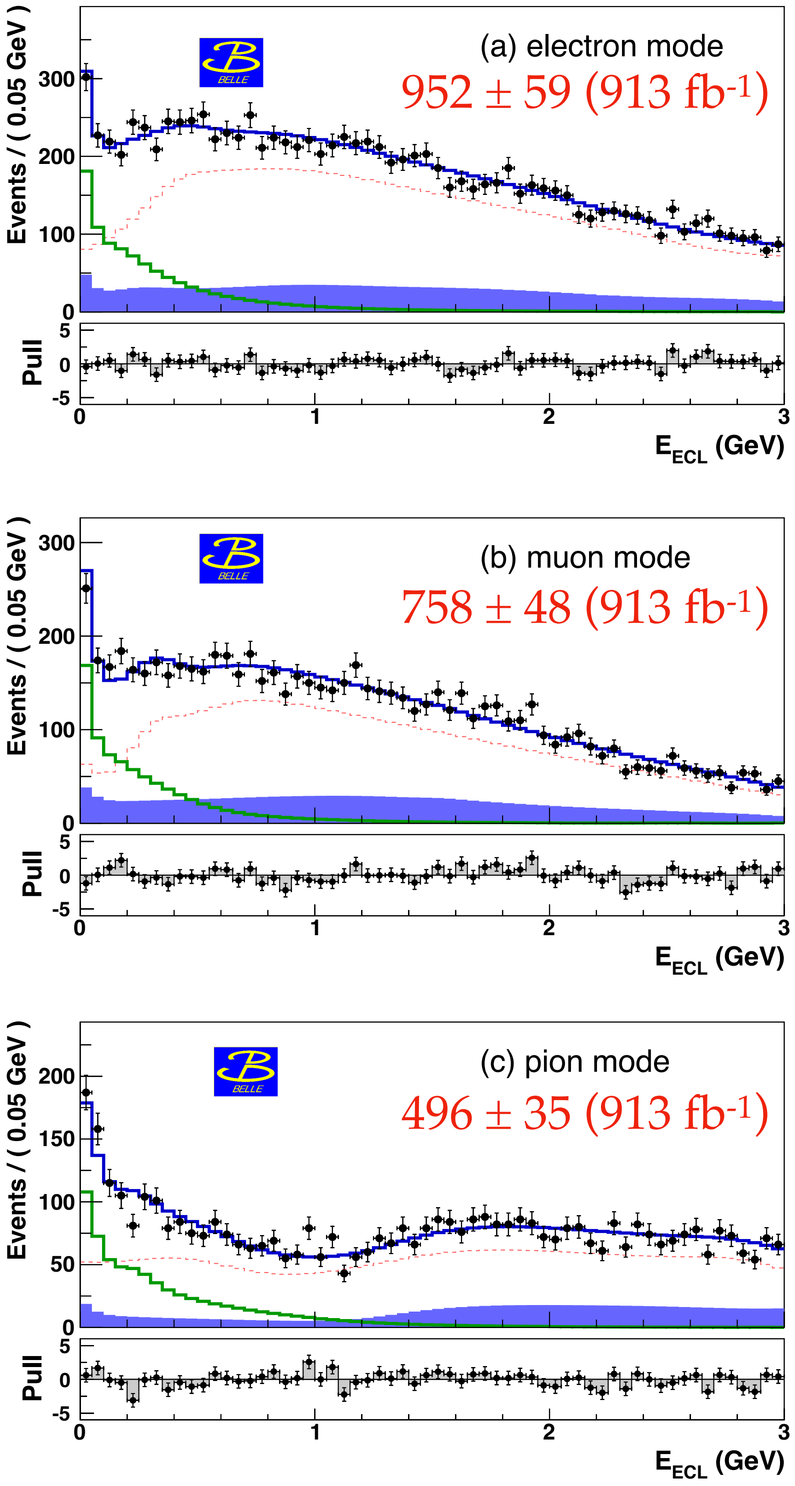
$|V_{cs}|$ via leptonic decay: $D_s \to \ell\nu$

$$\Gamma(D^+_{(s)} \to \ell^+\nu) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} |V_{cd(s)}|^2 M_{D^+_{(s)}} M^2_{\ell^+} \left(1 - \frac{M^2_{\ell^+}}{M^2_{D^+_{(s)}}}\right)^2$$

Current status

▶ $D_s \to \tau\nu$

- several results in past years by BaBar, Belle, BESIII[1] (new: [2][3]) and CLEO-c
- Belle modes; $\to e^+\nu\nu$, $\to \mu^+\nu\nu$, $\to \pi^+\nu$
    - signal D_s extraction via fit to excess E_{ECL}



HFLAV 2021

- ◉ $|V_{cs}|$ = 0.9839 ± 0.0115(exp.) ± 0.0020(LQCD)
    - average with $D_s \to \mu\nu$
    - $f_{D_s} = 249.9 \pm 0.5$ MeV (LQCD)
- ◉ f_{D_s} = 252.6 ± 3.0 MeV
    - global fit: $|V_{cs}| = 0.973394^{+0.000074}_{-0.000096}$

$D_s \to \tau\nu$ *Yield*

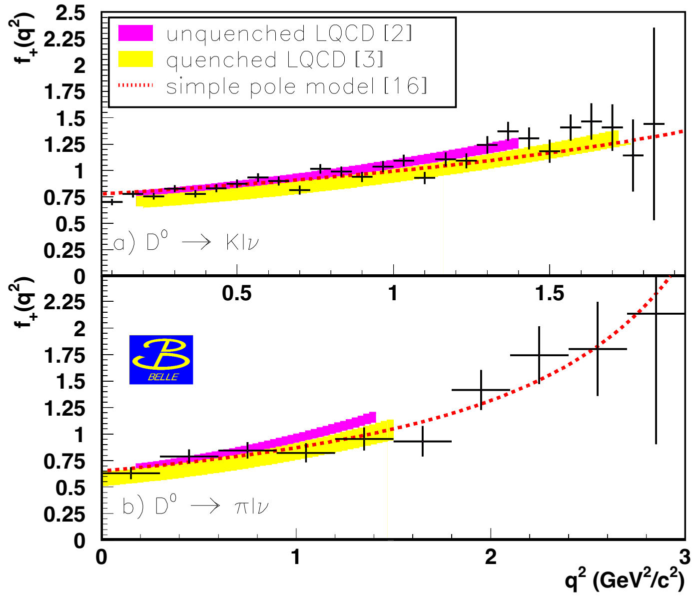
Source	$\tau\nu$ [%]
Statistical	±3.75
Normalization	±1.95
Tag bias	±1.37
Tracking	±0.35
Efficiency	±0.84
PID	±1.70
D_s background	**±2.84**
Comb. bkg. PDF	**-2.54**
Signal PDF	**$+2.95$**
τ cross-feed	±0.94
$\mathcal{B}(\tau \to X)$	±0.19
PDF stat.	±1.44
Total syst.	$^{+5.40}_{-5.19}$
Stat. + Syst.	$^{+6.57}_{-6.40}$

Belle II prospects 50 ab^{-1}

- ⇝ improved stats. uncertainty
    - $\delta(|V_{cs}|) = \pm 0.003$ (stat.) ⇝ comparable to theory err.
    - $\delta(|f_{D_s}|) = \pm 0.6$ (stat.) MeV ⇝ comparable to theory err.
- ⇝ systematics uncertainty (possible improvements)
    - with precision measurement of peaking backgrounds
    - in normalization (err. scaled with luminosity and are reducible with clean X_{tag})

$|V_{cs}|$ via semi-leptonic decay: $D \to K\ell\nu$

- **Belle results** @ 282 fb^{-1}
  ~2567 $D \to K\ell\nu$



Current status

▶ $D \to K\ell\nu$

- several results in past years by <u>BaBar</u>, <u>Belle</u>, <u>BESIII</u> and <u>CLEO-c</u>

<u>HFLAV 2021</u>

~0.4% precision

◉ Form factors $f_+^{DK}(0)$ **= 0.765 ± 0.0031 (ETM 17D, 18)**

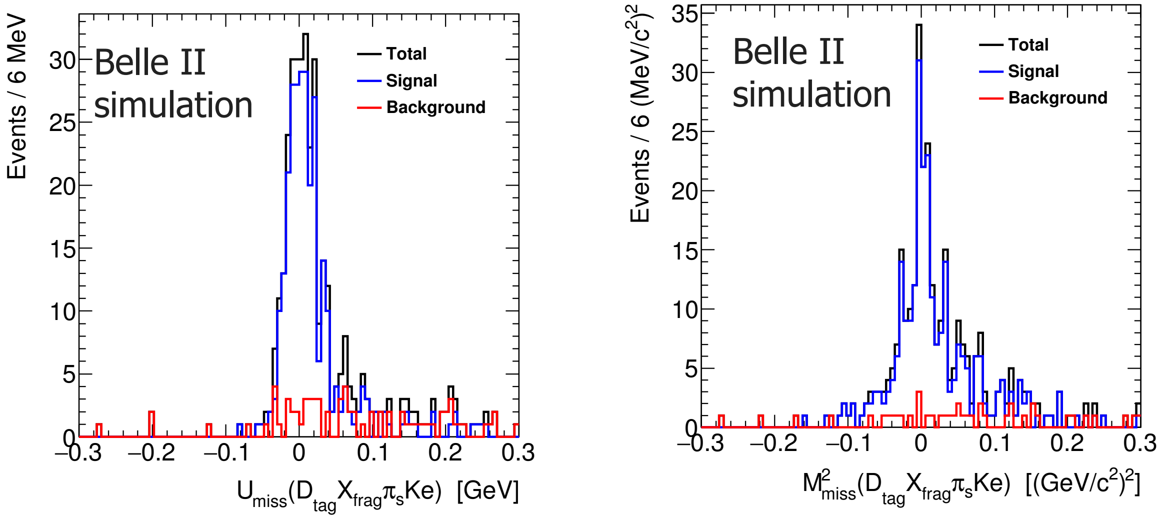
◉ $|\mathbf{V_{cs}}|$ **= 0.9447 ± 0.0043(exp.) ± 0.0137(LQCD)**

Tag side:	D^0	D^+
Final state:	$K^-\pi^+$	$K^-\pi^+\pi^+$
	$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$
	$K^-\pi^+\pi^+\pi^-$	$K_S^0\pi^+$
	$K^-\pi^+\pi^+\pi^-\pi^0$	$K_S^0\pi^+\pi^0$
	$K_S^0\pi^+\pi^-$	$K_S^0\pi^+\pi^+\pi^-$
	$K_S^0\pi^+\pi^-\pi^0$	$K^+K^-\pi^+$
X_{frag} :	π^+	none
	$\pi^+\pi^0$	π^0
	$\pi^+\pi^+\pi^-$	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$

Belle II prospects

$$e^+e^- \to c\bar{c} \to D_{tag}^{(*)} X_{frag} D_{sig}^{*-} (\to \bar{D}^0_{sig}\pi_s^-)$$

- MC studies with 1 ab^{-1}
  - based on $M^2_{miss} = P^2_{miss}$ & $U_{miss} = E_{miss} - P_{miss}$
  - missing mass resolution is comparable with Belle
  - small continuum background contribution
  - with 50 ab^{-1} data
    — larger data (~4.55 x 10^5 $D \to K\ell\nu$)
    ⇝ reduced stat. uncertainties
- scenario with charm factory experiments (e.g. BESIII)
  - challenging to compete with BESIII (with 20 fb^{-1} data plans)
  - but Belle II will add important confirmation/constraints



$$P_{\text{miss}} = P_{e^+} + P_{e^-} - P_{D_{\text{tag}}} - P_{X_{\text{frag}}} - P_h - P_l$$

3 $|V_{cd}|$ status and prospects

- Cabibbo-suppressed (c → d transition)
- Experimental measurements
  - Early study via neutrino production of charm (νN)
  - More precise results using D meson decays (today's focus)
    - Leptonic ($D^+ \to \ell^+ \nu$) decay

      Decay constant f_D is required from (e.g. Lattice QCD)
    - Semi-leptonic decay ($D \to \pi \ell \nu$)

      Form factor $f(q^2)$ is required from theory (e.g. Lattice QCD)

$|V_{cd}|$ via leptonic decay: $D^+ \to \ell^+\nu$

$$\Gamma(D^+_{(s)} \to \ell^+\nu) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} |V_{cd(s)}|^2 M_{D^+_{(s)}} M^2_{\ell^+} \left(1 - \frac{M^2_{\ell^+}}{M^2_{D^+_{(s)}}}\right)^2$$

Overview

- decay modes: $\to \mu\nu$, $\to e\nu$ & $\to \tau\nu$
- Belle II analysis method will be similar to $D_s \to \ell\nu$ analysis

Current status

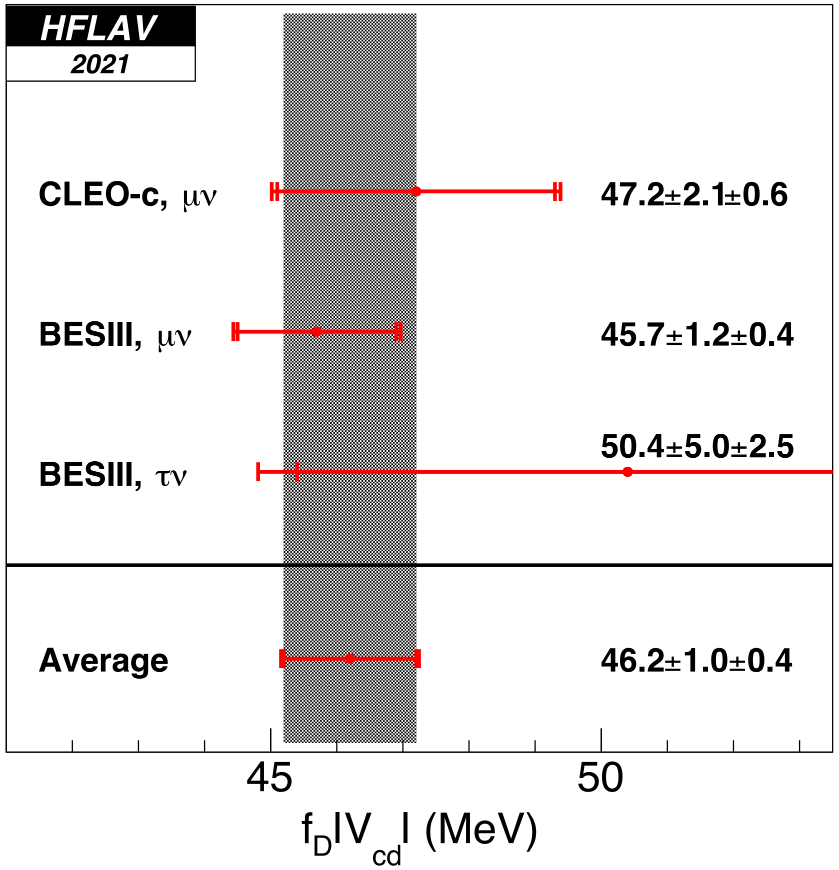
- **$f_D \cdot |V_{cd}|$: so far from charm factories only**
  - $\mu^+\nu_\mu$ ‣ CLEO-c(2008) and BESIII (2014)
  - $\tau^+\nu_\tau$ ‣ CLEO-c(2008) for upper limit on BR and BESIII (2019)
  - $e^+\nu_e$ ‣ CLEO-c(2008) for upper limit on BR

  ⦿ world average $f_D \cdot |V_{cd}| = 46.1 \pm 1.0 \pm 0.3 \pm 0.2$ (from $\mu^+\nu_\mu$)

  ⦿ ratio of $BR(\mu^+\nu_\mu)/BR(\tau^+\nu_\tau)$ is compatible with SM prediction

- **decay constants f_{D^+} from LQCD**
  - f_{D^+} ‣ $= 212.7 \pm 0.7$ MeV

  ⦿ average from FNAL/MILC 17 and ETM 14E



- **$|V_{cd}|_{D\to l\nu}$ HFLAV (June 2021)**

  ⦿ $V_{cd} = 0.2181 \pm 0.0049(\text{exp.}) \pm 0.0007(\text{LQCD})$

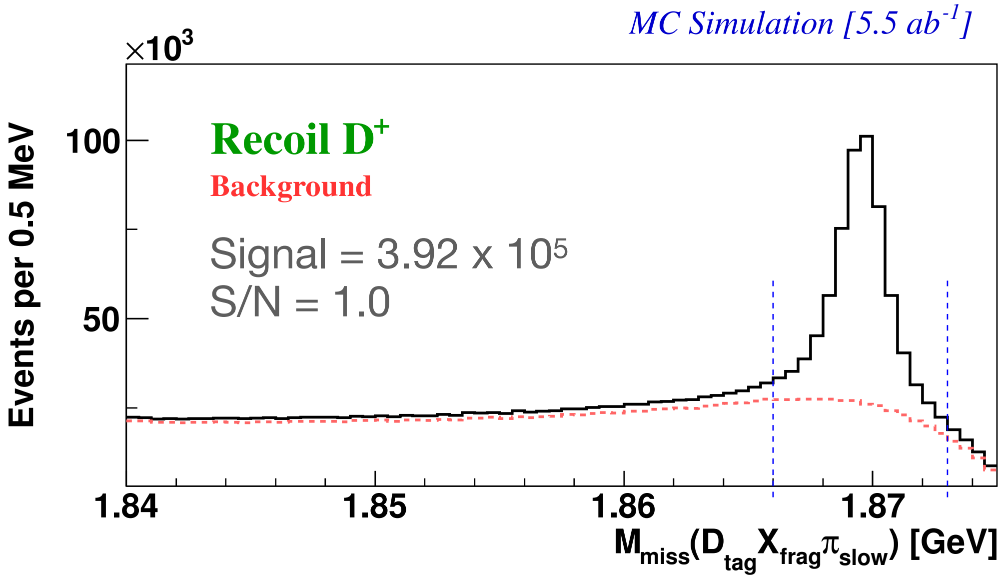
  ⦿ also consistent with semi-leptonic measurement $D \to \pi l\nu$ decays (in slide #18)

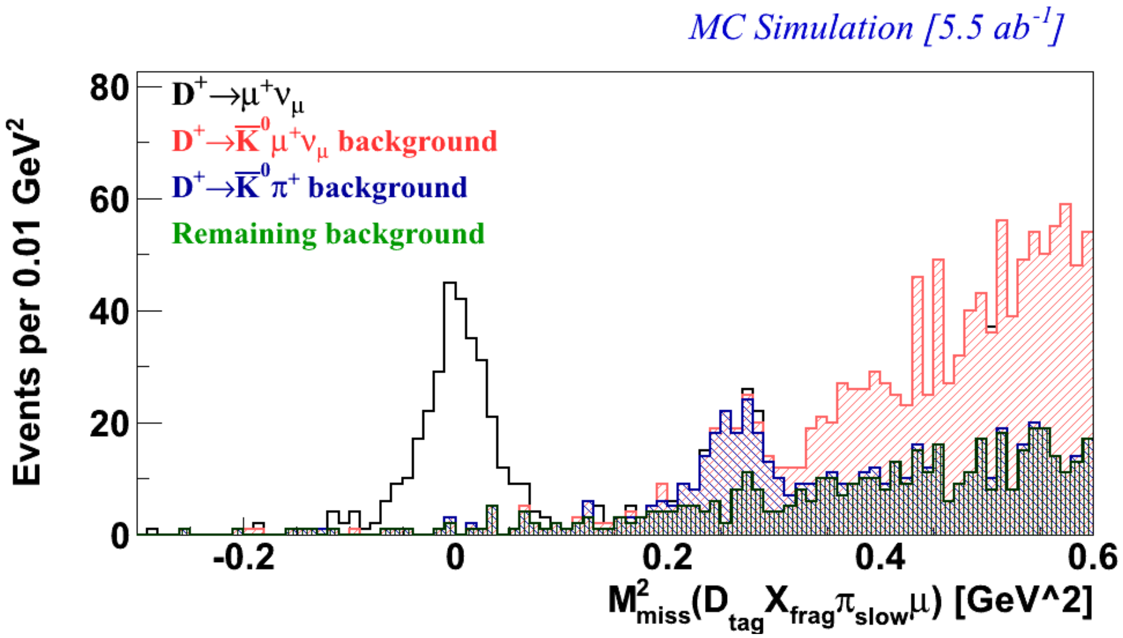
$|V_{cd}|$ via leptonic decay $D^+ \to \ell^+\nu$

$$\Gamma(D^+_{(s)} \to \ell^+\nu) = \frac{G_F^2}{8\pi} f^2_{D^+_{(s)}} |V_{cd(s)}|^2 M_{D^+_{(s)}} M^2_{\ell^+}\left(1-\frac{M^2_{\ell^+}}{M^2_{D^+_{(s)}}}\right)^2$$

Belle II prospects ▸ $D^+ \to \mu^+\nu$

- **MC studies** ▸ Belle II MC: 5.5 ab^{-1}
- **Method** $e^+e^- \to c\bar{c} \to \bar{D}X_{frag}D^{*+}\left(\to D^+\pi^0_{slow}\right)\ \mu^+\nu_\mu$
  - Fit to missing mass $\bar{D}X_{frag}\mu\pi^0_{slow}$
  - Require 1 charged track from IP and with μ-ID requirement





- **Belle II (50 ab^{-1})**
  - $D^+ \to \mu^+\nu_\mu$: inclusive (exclusive) decays ~ 3.5 x 10^6 (1250)
  - Statistical error on $\delta(f_D \cdot |V_{cd}|) = 0.65$ MeV (which currently dominates in WA)
    - ~ improved by factor of 2 w.r.t. to current measurement from CLEOc (1.9) and BESIII (1.2)
    - ~ also compititive to BESIII plans with 20 fb-1 (~current x7) planned over next two years

$|V_{cd}|$ via semi-leptonic decay: $D^0 \to \pi^- \ell^+ \nu$

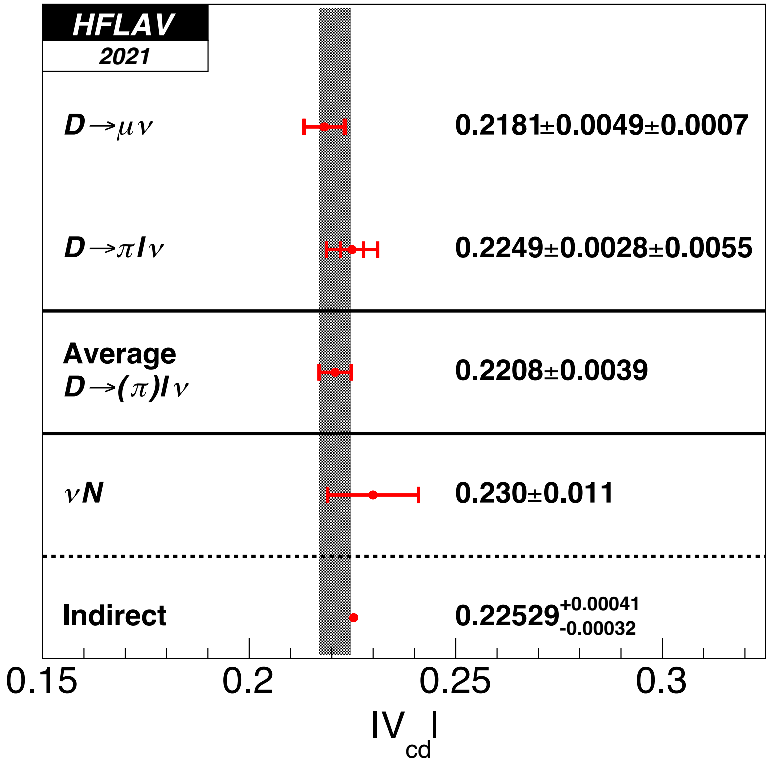
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 p_h^3}{24\pi^3} |V_{cd}|^2 \, |f_+(q^2)|^2$$

- decay modes: $\pi e \nu$ & $\pi \mu \nu$

Current status

- Several results in past years by BaBar, Belle, BESIII and CLEO-c
  - Form factors $f_+^{\pi K}(0)$ = **0.612 ± 0.035 (ETM 17D, 18)**
  - **$|V_{cd}|$ = 0.2249 ± 0.0028(exp.) ± 0.0055(LQCD)**

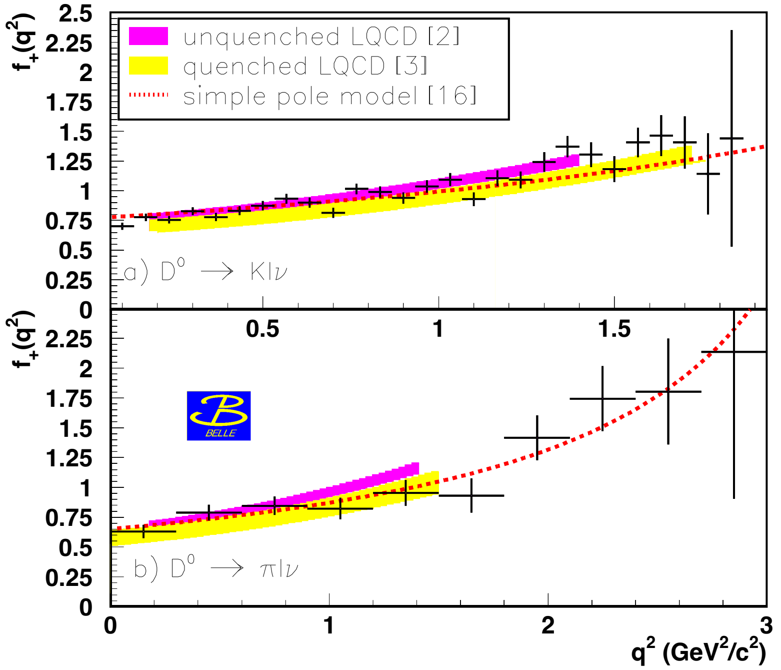
    less precision > 2%



Belle II prospects

- Belle II MC studies with 1 ab^{-1} (method discussed at slide: #11)
  — missing mass resolution is comparable with Belle
- with 50 ab^{-1} data-set
  — larger sample ~7 x 10^5 (projected w/ BaBar analysis) of $D_s \to \pi \ell \nu$
  ⇝ reduced stat. error

- **Belle results** @ 282 fb^{-1}



— Belle has higher purity (79% but ~21K signal @ 50ab^{-1}) as compare to BaBaR (53% purity)
— But Belle measurement have larger systematic err.

Summary

- SuperKEKB and Belle II provide an excellent platform for charm/τ measurements
  - – a good start ..

    ▶ $\tau(D^0) = 410.5 \pm 1.1\,(\text{stat}) \pm 0.8\,(\text{syst})$ fs Phys. Rev. Lett. 127, 211801 (2021)
    - World's best: D^0 decay time resolution (x2 better than that of Belle/BaBar)
  - – more exciting results to come soon with larger luminosity in coming years.

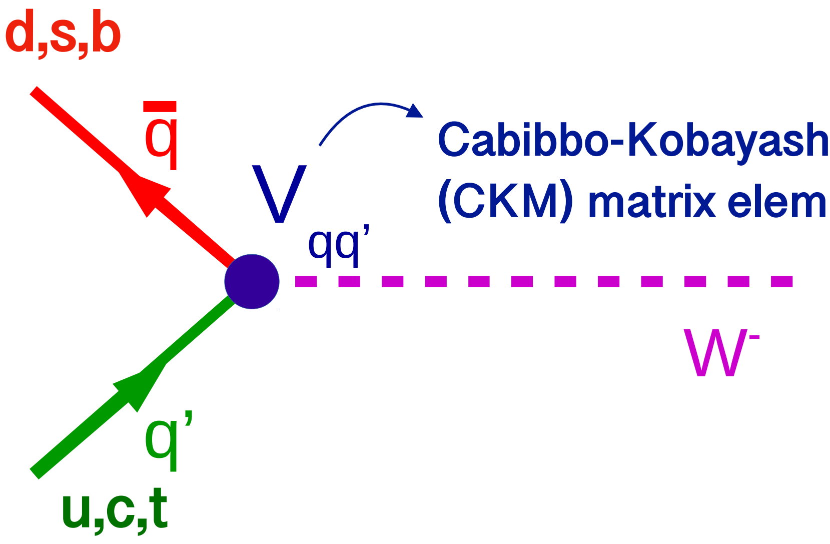
- **CKM parameters with full 50 ab^{-1}**
  - **|Vus| (from τ)**
    - Belle II will provide an important insight to the current discrepancy of $|V_{us}|$ from kaon decays and τ decays (also inclusive vs exclusive)
    - also will add important input to the current 3σ $|V_{ud}| - |V_{us}|_K$ anomaly
  - **|Vcs| and |Vcd| (from charm)**
    - Statistically improved results from leptonic and semi-leptonic D/D_s decays
    - Belle II will also measure |Vcd| from $D^+ \to \mu^+\nu$ decays (first attempt in B-factory)

Thank you

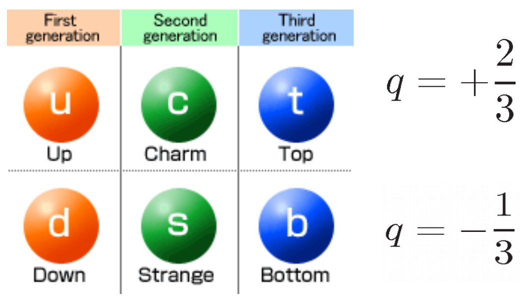
CKM Matrix

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

- In SM: the coupling of the quarks via the charged weak current is described by CKM matrix

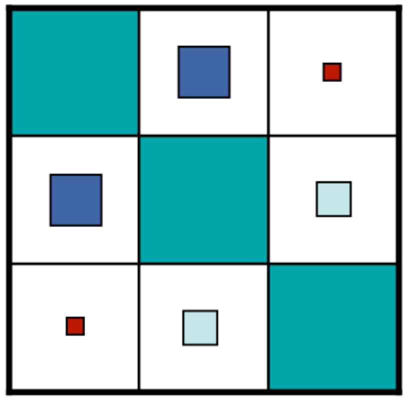


Cabibbo-Kobayashi-Maskawa (CKM) matrix elements



$q = +\frac{2}{3}$

$q = -\frac{1}{3}$



○ 3x3 unitarity complex matrix

- Unitarity constraints + freedom to redefine the complex phase (~ 4 parameters == 3 mixing angle and 1 phase ⇒ CPV)

○ with Wolfenstein parameterization

- $\lambda = \sin(\theta_c) = 0.22$

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

○ unitarity triangles

- $V_{qq'}V^{\dagger}_{qq'} = V^{\dagger}_{qq'}V_{qq'} = 1$
- q≠q': 6 triangle relations (∑3 complex number = 0)

$$V_{ud}V^*_{us} + V_{cd}V^*_{cs} + V_{td}V^*_{ts} = 0$$