Charm Physics at BESIII/BEPCII Experiment

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(on behalf of BESIII Collaboration)

50 Years with the GIM Mechanism
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Outline

• Introduction on charm physics
  • Why is charm charming? Why is charm challenging?
  • Charm samples

• Introduction on BESIII/BEPCII

• Selected charm physics results at BESIII/BEPCII
  • Pure and semi-leptonic decays
  • Hadronic decays
  • Charm baryon decays
\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

- 3x3 unitary complex matrix
- 4 parameters
- 3 mixing angles and 1 phase

Precision \~ 5-10% before BESIII

Precision: \( |V_{ub}|_{\text{exc}} \sim 4\% \), \( |V_{cb}| \sim 2\% \)

CKM matrix
Charm is charming

- Unique to test QCD in low energy
- Over-constrain the SM, probe for new physics
  - Precision CKM physics in B sector needs input from charm
- CPV and mixing
  - The only up-type quark to form weakly decaying hadrons, complementary to K and B systems

Charm is challenging

- Intermediate mass, compared to $\Lambda_{\text{QCD}}$ -- not heavy, not light
- Do methods like Heavy Quark Expansion and Factorization work?  
- CKM and GIM suppression can be strong – low rates  

→ Theory

→ Large data sample
What can we learn from charm decays?
Charm Leptonic Decays $D_{(s)} \rightarrow \ell \nu$

- Charm leptonic decays involve both weak and strong interactions.
- The weak part is easy to be described as the annihilation of the quark-antiquark pair via the standard model $W^+$ boson.
- The strong interactions arise due to gluon exchanges between the charm quark and the light quark. These are parameterized in terms of the ‘decay constant’.

\[
\Gamma(D_{(s)} \rightarrow \ell \nu) = |V_{cd(s)}|^2 \times \frac{f_{D_{(s)}}^2}{8\pi} \times \frac{G_F^2 m_{D_{(s)}}^3}{m_{\ell}^2 m_{D_{(s)}} (1 - m_{\ell}^2 / m_{D_{(s)}}^2)^2}
\]

- Exp. decay rate + $|V_{cs(d)}|^{\text{CKMfitter}}$ → calibrate LQCD @charm & extrapolate to Beauty
- Exp. decay rate + LQCD → CKM matrix elements
Charm semi-leptonic decays $D_{(s)} \rightarrow \pi (K) \ell \nu$

- The effects of the strong and weak interactions can be separated in semi-leptonic decays
- Good place to measure CKM matrix elements and study the weak decay mechanism of charm mesons; calibrate LQCD

At zero positron mass limit:

\[
\frac{d\Gamma(D_{(s)} \rightarrow K(\pi) \ell \nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2 P_{K(\pi)}^3}{24 \pi^3} f_+(q^2)^2
\]

- Analyze exp. partial decay rates $\rightarrow$ $q^2$ dependence of $f_+^{K(\pi)}(q^2)$, extract $f_+^{K(\pi)}(0)$ with $|V_{cs(d)}|^{\text{CKMfitter}}$ as input – calibrate QCD
- Exp. + LQCD calculation of $f_+^{K(0)}$ and $f_+^{\pi(0)} \rightarrow V_{cs(d)}$ – constrain CKM
Test of lepton universality (LU)

BaBar, LHCb and Belle found evidence of lepton universality violation in semi-leptonic B decays, either via the Cabibbo-suppressed (CS) transition $b \rightarrow c$ or flavor-changing-neutral-current (FCNC) transitions.

- **LHCb $R(D^*)$ measurements**

  \[
  R(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}
  \]

  $3.7 \sigma$ tension with SM

- **$R(K)$ measurements**

  LHCb measured $R(K)$ in the di-lepton invariant mass squared from 1-6 GeV$^2$/c$^4$, $\sim 10\%$ precision (PRL 113, 151602 (2014))

  \[
  R_K = \frac{\Gamma(B \rightarrow K\mu^+\mu^-)}{\Gamma(B \rightarrow Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036
  \]

  Compatible with SM prediction of 1 within $2.6 \sigma$. 

M. Smith at FPCP 2018
Test of lepton universality (LU)

• Study the analogous decays in charm quark sector is important.


\[
R \equiv \frac{\Gamma(D_{(s)}^+ \to \tau^+\nu)}{\Gamma(D_{(s)}^+ \to \mu^+\nu)} = \frac{m_{\tau}^2 \left(1 - \frac{m_{\tau}^2}{M_{D_{(s)}^+}^2}\right)^2}{m_{\mu}^2 \left(1 - \frac{m_{\mu}^2}{M_{D_{(s)}^+}^2}\right)^2} = 2.67 \pm 0.01 (9.75 \pm 0.01)
\]

\[
R^{0(+)} = \frac{B(D^{0(+)} \to \pi^{-}(0)\mu^+\nu)}{B(D^{0(+)} \to \pi^{-}(0)e^+\nu)} \sim 0.97
\]

\[
R^{0(+)} = \frac{B(D^{0(+) \to K^{-}(0)\mu^+\nu})}{B(D^{0(+) \to K^{-}(0)e^+\nu})} \sim 0.97
\]

Hadronic decays of charm mesons

- Probe non-perturbative QCD
  - Help to understand hadron spectroscopy
  - Study SU(3) flavor symmetry
  - Study short and long distance effects

- Strong phase measurement with quantum correlated $\psi(3770) \rightarrow D^0 \bar{D}^0$ is crucial in the model-independent determinations of $\gamma$ and charm mixing/direct CPV.
Measurement of $|V_{ub}|/|V_{cb}|$ from B decays

The dominant error comes from the big uncertainty of $B(\Lambda_c^+ \rightarrow pK^+\pi^-)$

**$\Lambda_c$ Measurements [PDG2015]**

- Total BFs < 65%
- Large uncertainties, most larger than 20%
- Most BFs are measured relative to $\Lambda_c \rightarrow pK\pi$
Charm physics contributors

B physics experiments are well suited for charm physics

- **LHCb/hadron machine:** huge production X-section, excellent lifetime resolution due to the boost; large combinatorial BG, difficult with neutral and missing particles
- **B factories:** clean environment, good to detect neutral particles; lower boost, poorer lifetime resolution
BESIII @ Beijing Electron Positron Collider (BEPC) – charm facility

beam energy: 1.0 – 2.3 GeV

2004: started BEPCII upgrade, BESIII construction
2009 - now: BESIII physics run

- 1989-2004 (BEPC): 
  \[ L_{\text{peak}} = 1.0 \times 10^{31} \text{cm}^2\text{s} \]
- 2009-now (BEPCII):
  \[ L_{\text{peak}} = 1.0 \times 10^{33}/\text{cm}^2(4/5/2016) \]

MDC: spatial reso. 115\(\mu\)m 
dE/dx reso: 5% 
EMC: energy reso.: 2.4% 
BTOF: time reso.: 70 ps 
ETOF: time reso.: 60 ps 

\(\tau\)-charm Physics
Physics at τ - charm Energy Region

- Hadron form factors
- Y(2175)
- Zs states?
- QCD test

- Light hadron spectroscopy
- Glueballs, hybrids, multi-quark states
- Rare decays
- Tau physics

- XYZ
- charm physics (QCD, CKM, mixing, CPV)
- Charmed baryons

- Rich of resonances: charmonia, charmed mesons, charmed baryons
- Threshold characteristics (pairs of τ, D, D_s, ...) -- low BG at threshold, high X-section
- Transition between pQCD and non-pQCD
- Energy location of the new forms of hadrons
Unique data sets at open charm thresholds

- $D^{+(0)}$
  - $\sigma(e^+e^- \rightarrow D^{0}\overline{D}^{0}) \sim 3.6 \text{ nb} \Rightarrow 21\text{M} D^0 \text{ produced}$
  - $\sigma(e^+e^- \rightarrow D^+D^-) \sim 2.9 \text{ nb} \Rightarrow 17\text{M} D^+ \text{ produced}$

- $D_s^+$
  - $\sigma(e^+e^- \rightarrow D_s^+D_s^-) \sim 0.3 \text{ nb} \Rightarrow 0.3\text{M} D_s \text{ produced}$
  - $\sigma(e^+e^- \rightarrow D_s^{*+}D_s^-) \sim 1 \text{ nb} \Rightarrow 6\text{M} D_s \text{ produced}$

- $\Lambda_c^+$
  - $\sigma(e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-) \sim 0.2 \text{ nb} \Rightarrow 0.2\text{M} \Lambda_c \text{ produced}$

- No boost, no lifetime measurement
- Almost free of background
- $\psi(3770) \rightarrow D\overline{D}$, quantum correlation $\rightarrow$ strong phase measurement
Double tag method (DT)

Signal side: $\mu^+$ is reconstructed, $\nu$ is reconstructed by $\text{MM}^2$

$$E_{\text{miss}} = E_{\text{beam}} - E_{\mu^+}, \quad \vec{p}_{\text{miss}} = -\vec{p}_{D^-} - \vec{p}_{\mu^+}$$

$$M^2_{\text{miss}} = E^2_{\text{miss}} - |\vec{p}_{\text{miss}}|^2, \quad U_{\text{miss}} = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$

Tag side: $K^+K^-\pi^- +...$, very clean decay modes

Non-$D^*_s+D^-_s$ events can be suppressed by beam-constrained mass cut

$$M_{BC} = \sqrt{\left(\frac{E_{\text{CM}}}{2}\right)^2 - |\vec{p}_{D^-}|^2}$$

ST yield:

$$N_{\text{ST}}^i = 2 \times N_{DD} \times B_{\text{ST}}^i \times \varepsilon_{\text{ST}}^i$$

DT yield:

$$N_{\text{DT}}^i = 2 \times N_{DD} \times B_{\text{ST}}^i \times B_{\text{sig}} \times \varepsilon_{\text{ST vs. sig}}^i$$

Average eff.:

$$\bar{\varepsilon}_{\text{sig}} = \frac{\sum_{i=1}^{N} (N_{\text{ST}}^i \times \varepsilon_{\text{ST vs. sig}}^i / \varepsilon_{\text{ST}}^i) / \sum_{i=1}^{N} N_{\text{ST}}^i}{N_{\text{ST}}^i \times \varepsilon_{\text{sig}}}$$

Absolute Br.:

$$B_{\text{sig}} = \frac{N_{\text{DT}}^{\text{tot}}}{N_{\text{ST}}^{\text{tot}} \times \bar{\varepsilon}_{\text{sig}}}$$

Advantages: almost background free, absolute Brs.
Charm (Semi)-leptonic decays
$3.19 \text{ fb}^{-1} @ E_{cm} = 4.178 \text{ GeV, } e^+ e^- \rightarrow D_s^\pm D_s^{*\mp} \rightarrow \gamma/\pi^0 D_s^+ D_s^-$

$\sigma(e^+ e^- \rightarrow D_s^\pm D_s^{*\mp}) \sim 6 \text{ nb, } \sim 6 \text{ M } D_s^\pm$ produced.

**Signal side: fit missing mass square**

$B(D_s^+ \rightarrow \mu^+ \nu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$

$f_{D_s^+} |V_{cs}| = 246.2 \pm 3.6_{\text{stat.}} \pm 3.5_{\text{syst.}} \text{ MeV}$

$B_{PDG}(D_s^+ \rightarrow \tau^+ \nu) = (5.48 \pm 0.23) \times 10^{-2}$

$\frac{B(D_s^+ \rightarrow \tau^+ \nu)}{B(D_s^+ \rightarrow \mu^+ \nu)} = (9.98 \pm 0.52) \text{ (SM: 9.74)}$

**Tag side: 14 $D_s^-$ decay modes**

Most precise to date
Take $|V_{cs}|^{\text{CKMfitter}}$ as input:

$$f_{D_s^+} = (252.9 \pm 3.7 \pm 3.6) \text{ MeV (}\mu^+\nu\text{ mode})$$

Take $f_{D_s}^{\text{LQCD}}$ as input:

$$|V_{cs}| = (0.985 \pm 0.014 \pm 0.014) (\mu^+\nu\text{ mode})$$
$D^+ \rightarrow \tau^+ (\rightarrow \pi^+ \bar{\nu}_\tau) \nu_\tau$ : first evidence (4$\sigma$)

$2.93 \text{ fb}^{-1} @ E_{cm} = 3.773 \text{ GeV}$

$e^+ e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$

Split data into two:
- $\mu$-like: $E_{EMC} \leq 300 \text{ MeV}$ (mixture of $D^+ \rightarrow \tau^+ (\rightarrow \pi^+ \bar{\nu}_\tau) \nu_\tau$ and $D^+ \rightarrow \mu^+ \nu_\mu$)
- $\pi$-like: $E_{EMC} > 300 \text{ MeV}$ (mostly $D^+ \rightarrow \tau^+ (\rightarrow \pi^+ \bar{\nu}_\tau) \nu_\tau$).

Consistent with SM prediction, $R = 2.65 \pm 0.01$, within $\sim 0.9\sigma$
Take $|V_{cd}|^{\text{CKMfitter}}$ as input:

$$f_D^+ = (203.2 \pm 5.3 \pm 1.8) \text{ MeV (}\mu^+\nu\text{ mode)}$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNAL/MILC</td>
<td>PRD98,074512</td>
<td>212.7 ± 0.6</td>
</tr>
<tr>
<td>RBC/UKQCD</td>
<td>JHEP1712,008</td>
<td>208.7 ± 2.8</td>
</tr>
<tr>
<td>ETM</td>
<td>PRD91,054507</td>
<td>207.4 ± 3.8</td>
</tr>
<tr>
<td>FNAL/MILC</td>
<td>PRD90,074509</td>
<td>212.6 ± 0.4</td>
</tr>
<tr>
<td>HPQCD</td>
<td>PRD86,054510</td>
<td>208.3 ± 3.4</td>
</tr>
<tr>
<td>FNAL/MILC</td>
<td>PRD85,114506</td>
<td>218.9 ± 11.3</td>
</tr>
<tr>
<td>CLEO</td>
<td>PRD78,052003, $\mu\nu, \tau_\nu$</td>
<td>206.8 ± 0.7 ± 2.5</td>
</tr>
<tr>
<td>BESIII</td>
<td>arXiv:1908.08877, $\tau\nu$</td>
<td>224.5 ± 22.8 ± 11.3</td>
</tr>
<tr>
<td>BESIII</td>
<td>PRD89,051104, $\mu\nu$</td>
<td>203.2 ± 5.3 ± 1.8</td>
</tr>
<tr>
<td>BESIII</td>
<td>Expected (20 fb⁻¹), $\mu\nu$</td>
<td>203.2 ± 2.0 ± 1.5</td>
</tr>
</tbody>
</table>

Take $f_D^{\text{LQCD}}$ as input:

$$|V_{cd}| = (0.2210 \pm 0.0058 \pm 0.0047) \text{ (}\mu^+\nu\text{ mode)}$$

- SM fit: PDG18, $0.22438 \pm 0.00044$
- PDG, $D^{0(+) \rightarrow \pi^{-0})\nu}$: $0.214 \pm 0.003 \pm 0.009$
- CLEO, $D^+ \rightarrow \mu\nu, \tau_{\nu}$: $0.218 \pm 0.009 \pm 0.003$
- BESIII, $D^+ \rightarrow \tau\nu$: $0.237 \pm 0.024 \pm 0.012$
- BESIII, $D^+ \rightarrow \mu\nu$: $0.2210 \pm 0.0058 \pm 0.0047$
- BESIII, Expected (20 fb⁻¹), $D^+ \rightarrow \mu\nu$: $0.2210 \pm 0.002 \pm 0.0017$
Form factor in $D^0 \to K^- \mu^+ \nu_\mu$

$D^0 \to K^- \mu^+ \nu_\mu$ is studied in the recoiling system of three tag modes:

- Signal shape: MC simulated shape convoluted with Gaussian.
- BG shape in tag side: ARGUS func.
- BG in signal side:
  - $D^0 \to K^- \pi^+ \pi^0$ MC simulated shape convoluted with Gaussian
  - Continuum background shape: MC simulated shape

$2.93 \text{ fb}^{-1} \@ E_{cm} = 3.770 \text{ GeV}$

$\mathcal{B}_{D^0 \to K^- \mu^+ \nu_\mu} = (3.429 \pm 0.019_{\text{stat.}} \pm 0.035_{\text{syst.}})\%$
D^0 → K^-μ^+ν_μ: Fit to partial decay rates

Series expansion parameterization for form factor (2nd order):

\[ f_+^K(t) = \frac{1}{P(t)\Phi(t, t_0)} \frac{f_+^K(0)P(0)\Phi(0, t_0)}{1 + r_1(t_0)\phi(0, t_0)}(1 + r_1(t_0)[\phi(t, t_0)]) \]

\[ \chi^2 = \sum_{i,j=1}^{N_{\text{intervals}}} (\Delta \Gamma_{i,\text{msr}}^i - \Delta \Gamma_{i,\text{exp}}^i) G_{i,j}^{-1} (\Delta \Gamma_{j,\text{msr}}^j - \Delta \Gamma_{j,\text{exp}}^j) \]

In full q^2 interval: \( R_{\mu/e} = 0.974 \pm 0.007 \pm 0.012 \)

SM prediction: 0.97

No deviation larger than 2σ from 1 is observed in q^2 interval of (0.2, 1.5) GeV^2/c^4.
$f^D_+ \rightarrow K(0)$ and $f^D_+ \rightarrow \pi$

**BESIII:**

- $20 \text{ fb}^{-1} @ 3770 \text{ MeV}$

---

**ETM**
- PRD96,054514
- $0.765 \pm 0.031$

**HPQCD**
- PRD82,114506
- $0.747 \pm 0.011 \pm 0.015$

**Belle**
- PRL97,061804, $D^0 \rightarrow K\ell^+\nu$
- $0.695 \pm 0.007 \pm 0.022$

**BaBar**
- PRD76,052005, $D^0 \rightarrow K e^+\nu$
- $0.727 \pm 0.007 \pm 0.009$

**CLEO**
- PRD80,032005, $D \rightarrow K e^+\nu$
- $0.739 \pm 0.007 \pm 0.005$

**BESIII**
- PRD92,112008, $D^* \rightarrow K^0 e^+\nu$
- $0.748 \pm 0.007 \pm 0.012$
- PRD96,012002, $D^+ \rightarrow K^0 e^+\nu$
- $0.7246 \pm 0.004 \pm 0.0115$
- PRL122,011804, $D^0 \rightarrow K \mu^+\nu$
- $0.7327 \pm 0.0039 \pm 0.0030$
- PRD92,072012, $D^0 \rightarrow K e^+\nu$
- $0.7366 \pm 0.0026 \pm 0.0036$
- Expected (20 fb$^{-1}$), $D^0 \rightarrow K e^+\nu$
- $0.7366 \pm 0.0009 \pm 0.0036$

**BESIII**

**Inputs from 2018 PDG CKMFitter**

| Inputs: | $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$ |
| Inputs: | $|V_{cd}| = 0.22438 \pm 0.00044$ |
First extractions of FFs of $D_s^+ \rightarrow \eta^{(')} e^+\nu$

BESIII: $3.19 \text{ fb}^{-1} @ 4180 \text{ MeV}$

\[
f_{+}^{D_s \rightarrow \eta (0)} = 0.446 \pm 0.005 \pm 0.004
\]

\[
f_{+}^{D_s \rightarrow \eta^{(')} (0)} = 0.477 \pm 0.049 \pm 0.011
\]

Statistical errors dominate
Charm hadronic decays
About $\gamma$

- $\gamma$ is the least well known CKM constraint

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

- Theory uncertainty on $\gamma$ is very small: $\delta \gamma / \gamma \sim O(10^{-7})$ (arXiv: 1308.5663)

- Status of $\gamma$:
  - Direct: $\gamma = (73.5^{+4.3}_{-5.0})^\circ$
  - Pre-LHCb: $\gamma = (73^{+22}_{-25})^\circ$

- Goal
  - Belle II: $1.5^0$ with 50 ab$^{-1}$ arXiv:1808.10567
  - LHCb: arXiv:1808.08865v2

<table>
<thead>
<tr>
<th>Runs</th>
<th>Collected / Expected luminosity</th>
<th>Year attained</th>
<th>$\gamma / \phi_3$ sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb Run-1 [7, 8 TeV]</td>
<td>3 fb$^{-1}$</td>
<td>2012</td>
<td>8$^\circ$</td>
</tr>
<tr>
<td>LHCb Run-2 [13 TeV]</td>
<td>5 fb$^{-1}$</td>
<td>2018</td>
<td>4$^\circ$</td>
</tr>
<tr>
<td>Belle-II Run</td>
<td>50 ab$^{-1}$</td>
<td>2025</td>
<td>1.5$^\circ$</td>
</tr>
<tr>
<td>LHCb phase-1 upgrade [14 TeV]</td>
<td>50 fb$^{-1}$</td>
<td>2030</td>
<td>&lt; 1$^\circ$</td>
</tr>
<tr>
<td>LHCb phase-2 upgrade [14 TeV]</td>
<td>300 fb$^{-1}$</td>
<td>(&gt;2035)</td>
<td>&lt; 0.4$^\circ$</td>
</tr>
</tbody>
</table>
\[ \gamma / \phi_3 \] extraction

- Sensitivity through interference between \( b \to u \) and \( b \to c \) transitions

- Require \( D^0 \) and \( \bar{D}^0 \) decay to a common final state, \( f(D) \): 
  Interference occurs when \( D^0 \) and \( \bar{D}^0 \) decay to the same final state \( f \)

\[ K_S^0 \text{hh} ; K_{\pi\pi} ; K_{\pi\pi\pi} ; K_{\pi\pi\pi^0} \]

- Comparison of \( B^- \) and \( B^+ \) rates allow \( \gamma \) to be extracted
- But other parameters to be considered
  - In particular, \( \delta_D \) – accessed in quantum-correlated D-decays

\[ \frac{\langle B^- \to \bar{D}^0 K^- \rangle}{\langle B^- \to D^0 K^- \rangle} = r_B e^{i(\delta_{B^-} - \gamma)} \]
The correlated state

For a physical process producing $D^0 \bar{D}^0$ such as

$$e^+e^- \rightarrow \psi'' \rightarrow D^0 \bar{D}^0$$

The $D^0 \bar{D}^0$ pair will be a quantum-correlated state

For a correlated state with $C = -$

$$\psi_- = \frac{1}{\sqrt{2}} \left( |D^0\rangle |\bar{D}^0\rangle - |\bar{D}^0\rangle |D^0\rangle \right)$$

$$\hat{C}|D^0\rangle = |\bar{D}^0\rangle$$

$$\hat{C}|\bar{D}^0\rangle = |D^0\rangle$$

$$\langle K^-\pi^+ |D^0\rangle^{DCS}_{K\pi} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

$$\langle K^-\pi^+ |D^0\rangle^{CF}_{K\pi}$$

$$\sqrt{2} A(D_{CP}^+ \rightarrow K^-\pi^+) = A(D^0 \rightarrow K^-\pi^+) \pm A(\bar{D}^0 \rightarrow K^-\pi^+)$$
<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Quantity of interest</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \to K_S^0\pi^+\pi^-$</td>
<td>$c_i$ and $s_i$</td>
<td>Binning schemes as those used in the CLEO-c analysis. With 20 fb$^{-1}$ of data at 3.773 GeV, it might be worthwhile to explore alternative binning.</td>
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</tr>
<tr>
<td>$D \to K^{\pm}\pi^+\pi^+\pi^-$</td>
<td>$R$, $\delta$</td>
<td>In bins guided by amplitude models, currently under development by LHCb.</td>
</tr>
<tr>
<td>$D \to K^{+}K^{-}\pi^+\pi^-$</td>
<td>$c_i$ and $s_i$</td>
<td>Binning scheme guided by the CLEO-c model [69] or potentially an improved model in the future.</td>
</tr>
<tr>
<td>$D \to \pi^+\pi^-\pi^+\pi^-$</td>
<td>$F_+$ or $c_i$ and $s_i$</td>
<td>Unbinned measurement of $F_+$. Measurements of $F_+$ in bins or $c_i$ and $s_i$ in bins could be explored.</td>
</tr>
<tr>
<td>$D \to K^{\pm}\pi^+\pi^0$</td>
<td>$R$, $\delta$</td>
<td>Simple 2-3 bin scheme could be considered.</td>
</tr>
<tr>
<td>$D \to K_S^0K^{\pm}\pi^+$</td>
<td>$R$, $\delta$</td>
<td>Simple 2 bin scheme where one bin encloses the $K^*$ resonance.</td>
</tr>
<tr>
<td>$D \to \pi^+\pi^-\pi^0$</td>
<td>$F_+$</td>
<td>No binning required as $F_+ \sim 1$.</td>
</tr>
<tr>
<td>$D \to K_S^0\pi^+\pi^-\pi^0$</td>
<td>$F_+$ or $c_i$ and $s_i$</td>
<td>Unbinned measurement of $F_+$ required. Additional measurements of $F_+$ or $c_i$ and $s_i$ in bins could be explored.</td>
</tr>
<tr>
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<td>$F_+$</td>
<td>Unbinned measurement required. Extensions to binned measurements of either $F_+$ or $c_i$ and $s_i$.</td>
</tr>
<tr>
<td>$D \to K^{\pm}\pi^+$</td>
<td>$\delta$</td>
<td>Of low priority due to good precision available through charm-mixing analyses.</td>
</tr>
</tbody>
</table>
Quantum Correlated measurements with 2.93 fb$^{-1}$ data

- Strong phase of $D \rightarrow K^- \pi^+$  
  
- Strong phase of $D \rightarrow K_s \pi^+ \pi^-$, to be submitted this December

- CP+ fractions of $D \rightarrow \pi^+ \pi^- \pi^0$ and $K^+ K^- \pi^0$  
  
- Strong phase of $D \rightarrow K_s K^+ K^-$  
  
- Strong phase of $D \rightarrow K^- \pi^+ \pi^0$ and $K^- \pi^+ \pi^+ \pi^-$  
  
- Analysis of $D \rightarrow 2(\pi^+ \pi^-)$  
  
- Analysis of $D \rightarrow K_s \pi^+ \pi^- \pi^0$  
  
- Analysis of $D \rightarrow K_s K^+ \pi^-$ and $K_s K^- \pi^+$  

PLB734(2014)227

Preliminary
The only kinematic allowed baryonic charm decay mode
At short-distance level, Br. expected to be $\sim 10^{-6}$ (chiral suppression by the factor $(\frac{m_{\pi}}{m_{D_s}})^4$)
Long distance effect may enhance Br: $\sim 10^{-3}$
First evidence by CLEO-c: $(1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$ (PRL 100, 181802(2008))

$Br(D_s^+ \rightarrow p\bar{n}) = (1.21 \pm 0.10 \pm 0.05) \times 10^{-3}$

- Weak annihilation process is not the driving mechanism
- The hadronization process driven by non-perturbative dynamics determines underlying physics
$D_s^+ \to \omega \pi^+$ and $\omega K^+$

- $D_s^+ \to \omega \pi^+$: pure W-annihilation process, first evidence by CLEO: $(2.1 \pm 0.9 \pm 0.1) \times 10^{-3}$ with $6.0 \pm 2.4$ events

- Q. Qin et al. [PRD 89, 054006] predicts, with $\text{Br}(D_s^+ \to \omega \pi^+)$ as one input:
  \[ B(D_s^+ \to \omega K^+) = 0.6 \times 10^{-3}, \quad A_{CP}(D_s^+ \to \omega K^+) = -0.6 \times 10^{-3} \]  
  (without $\rho - \omega$ mixing)
  \[ B(D_s^+ \to \omega K^+) = 0.07 \times 10^{-3}, \quad A_{CP}(D_s^+ \to \omega K^+) = -2.3 \times 10^{-3} \]  
  (with $\rho - \omega$ mixing)

- $D_s^+ \to \omega K^+$ (SCS): CLEO set UL: $< 2.4 \times 10^{-3}$@90% C. L.

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**BRs**

$Br(D_s^+ \to \omega \pi^+)$
\[ = (1.77 \pm 0.32 \pm 0.13) \times 10^{-3} \]

$Br(D_s^+ \to \omega K^+)$
\[ = (0.87 \pm 0.24 \pm 0.08) \times 10^{-3} \]
Charm baryon decays
□ BESIII: 567pb\(^{-1}\) at 4.599GeV, 12 MeV above \(\Lambda_c^+\bar{\Lambda}_c^-\) threshold in \(e^+ e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-\)
□ Double tag method to measure absolute \(B_{\text{rs}}\).

<table>
<thead>
<tr>
<th>Mode</th>
<th>This work (%)</th>
<th>PDG (%)</th>
<th>BELLE (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pK^0_S)</td>
<td>1.52 ± 0.08 ± 0.03</td>
<td>1.15 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>(pK^-\pi^+)</td>
<td>5.84 ± 0.27 ± 0.23</td>
<td>5.0 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>(pK^0\pi^0)</td>
<td>1.87 ± 0.13 ± 0.05</td>
<td>1.65 ± 0.50</td>
<td></td>
</tr>
<tr>
<td>(pK^0_S\pi^+\pi^-)</td>
<td>1.53 ± 0.11 ± 0.09</td>
<td>1.30 ± 0.35</td>
<td></td>
</tr>
<tr>
<td>(pK^-\pi^+\pi^0)</td>
<td>4.53 ± 0.23 ± 0.30</td>
<td>3.4 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>(\Lambda\pi^+)</td>
<td>1.24 ± 0.07 ± 0.03</td>
<td>1.07 ± 0.28</td>
<td></td>
</tr>
<tr>
<td>(\Lambda\pi^+\pi^0)</td>
<td>7.01 ± 0.37 ± 0.19</td>
<td>3.6 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>(\Lambda\pi^+\pi^-\pi^+)</td>
<td>3.81 ± 0.24 ± 0.18</td>
<td>2.6 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>(\Sigma^0\pi^+)</td>
<td>1.27 ± 0.08 ± 0.03</td>
<td>1.05 ± 0.28</td>
<td></td>
</tr>
<tr>
<td>(\Sigma^+\pi^0)</td>
<td>1.18 ± 0.10 ± 0.03</td>
<td>1.00 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>(\Sigma^+\pi^+\pi^-)</td>
<td>4.25 ± 0.24 ± 0.20</td>
<td>3.6 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>(\Sigma^+\omega)</td>
<td>1.56 ± 0.20 ± 0.07</td>
<td>2.7 ± 1.0</td>
<td></td>
</tr>
</tbody>
</table>

□ \(B(\Lambda_c^+ \rightarrow pK^−\pi^+)\): BESIII precision comparable with Belle’s
□ BESIII \(B(\Lambda_c^+ \rightarrow pK^-\pi^+)\) is compatible with BELLE’s within 2\(\sigma\)
□ Improved precisions in other modes significantly
Evidence of $\Lambda_c^+ \rightarrow p\eta$, and search for $\Lambda_c^+ \rightarrow p\pi^0$

**Measurement of $B[\Lambda_c^+ \rightarrow \Lambda X]$**

PRL121(2018)062003

PDG: $B[\Lambda_c^+ \rightarrow \Lambda X] = (35 \pm 11)\%$

Measurement of $B[\Lambda_c^+ \rightarrow eX]$

PRL 121 251801(2018)

PDG: $B[\Lambda_c^+ \rightarrow \Lambda X] = (4.5 \pm 1.7)\%$

Measurement of $B[\Lambda_c^+ \rightarrow \Lambda X]$

Important to calibrate the CF amplitude in charmed baryon sector, and guide experimental searches.

$$B(\Lambda_c^+ \rightarrow \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%.$$ 

This implies 1/3 $\Lambda_c^+ \rightarrow \Lambda X$ decay BFs are still to be unmeasured

$$A_{CP} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%.$$ 

Test effective quark model calculation, and guide experimental searches.

$$B(\Lambda_c^+ \rightarrow Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09)\%.$$
Prospects of $\Lambda_c$ measurements

<table>
<thead>
<tr>
<th>Leading hadronic decays</th>
<th>Typical two-body decays</th>
<th>Semi-leptonic decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$B(K\pi^+)$ = (3.89 ± 0.04)% (1.0%)</td>
<td>$B(K_s\pi^0)$ = (1.19 ± 0.04)% (3.4%)</td>
</tr>
<tr>
<td>$D^+, B(K\pi^+\pi^+)$ = (8.98 ± 0.28)% (3.1%)</td>
<td>$B(K_s\pi^+)$ = (1.47 ± 0.08)% (5.4%)</td>
<td>$B(K_s\nu)$ = (4.41 ± 0.07)% (1.5%)</td>
</tr>
<tr>
<td>$D_s, B(K^+K^+\pi^+)$ = (5.45 ± 0.17)% (3.8%)</td>
<td>$B(K_sK^+)$ = (1.40 ± 0.05)% (3.6%)</td>
<td>$B(\phi\nu)$ = (2.39 ± 0.23)% (9.6%)</td>
</tr>
<tr>
<td>$\Lambda_c, B(K\pi^+\pi^+)$</td>
<td>$B(K_p\pi^+)$ = PDG2014: (5.0 ± 1.3)% (26%)</td>
<td>$B(K\pi\nu)$ = PDG2014: (2.1 ± 0.6)% (29%)</td>
</tr>
<tr>
<td>PDG2017(w/ BESIII): (6.35 ± 0.33)% (5.2%)</td>
<td>PDG2017: (1.52 ± 0.08)% (5.6%)</td>
<td>BESIII: (3.63 ± 0.43)% (12%)</td>
</tr>
<tr>
<td>$5/fb @4.64\text{GeV}$ $\rightarrow$ (&lt;2%) (Systematic error dominant)</td>
<td>$5/fb @4.64\text{GeV}$ $\rightarrow$ (&lt;2%) (Systematic error dominant)</td>
<td>$5/fb @4.64\text{GeV}$ $\rightarrow$ (3.3%) (Statistical error dominant)</td>
</tr>
</tbody>
</table>

With $5/fb @4.64\text{GeV}$, more $\Lambda_c$ semi-leptonic decays can be expected.
Summary

• Charm (semi-)leptonic decays provide precision calibration of LQCD; precision measurements of CKM matrix elements

• Charm hadronic decays are key labs to understand non-perturbative QCD; provide important inputs to model-independent determination of $\gamma$ and charm mixing/CPV

• Precision flavor physics still needs high precision charm data

Thank you!
Categorise decays sensitive to $\gamma$ depending on the $\overline{D}^0 \rightarrow f$ final state

- GLW (Gronau, London, Wyler) [1991]
  - CP eigenstates e.g. $D \rightarrow KK, D \rightarrow \pi\pi$
- ADS (Atwood, Dunietz, Soni) [1997, 2001]
  - CF or DCS decays e.g. $D \rightarrow K\pi$
- GGSZ (Giri, Grossman, Soffer, Zupan) [2003]
  - 3-body final states e.g. $D \rightarrow K_S^0\pi\pi$
- TD (Time-dependent)
  - Interference between mixing and decay e.g. $B_s^0 \rightarrow D_s^- K^+$ [phase is $(\gamma - 2\beta_s)$]
  - Penguin free measurement of $\phi_s$?
- Dalitz
  - Look at 3-body $B$ decays with $D^0$ or $\overline{D}^0$ in the final state, e.g. $B^0 \rightarrow D^0 K^+\pi^-$