Charm and Charmonium physics at BES-III

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Location
Upgrade of BEPC (started 2004, first collisions July 2008)
Beam energy \(1 \ldots 2.3\) GeV
Optimum energy 1.89 GeV
Single beam current 0.91 A
Crossing angle: \(\pm 11\) mrad

Design luminosity: \(10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
Achieved: \(6.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)

Beam energy measurement:
Laser compton backscattering
\(\Delta E / E \approx 5 \times 10^{-5}\)
\((\approx 50\text{ keV at } \tau \text{ threshold})\)
BEPC-II storage rings: a $\tau$-charm factory

\[ \sqrt{s} [\text{GeV}] \]

\[ \sigma [\text{mb}] \]
Physics requirements on detector

- \( \tau \)-charm region, \( \sqrt{s} = 2 \cdots 4.3 \) GeV
- \( e^+ e^- \) CMS almost at rest in lab frame, crossing angle of \( \pm 11 \) mrad creates small boost
- Running on \( J/\psi, \psi(3686) \) resonances: very large cross section
  need fast detector and fast DAQ
- Typical hadronic final states:
  - rather low multiplicity (compared to \( B \) factories)
  - most probable momentum \( \approx 0.3 \) GeV/\( c \), almost no tracks above 1 GeV/\( c \)
  - most probable photon energy \( \approx 100 \) MeV

- Need tracking . . . for rather low energetic particles:
  minimise multiple scattering
- typical \( \beta\gamma c\tau \) for \( D \) mesons \( \sim 40 \) \( \mu \)m:
  no vertex detector to minimise material
BES-III detector

Magnet yoke

SC magnet, 1T

RPC

TOF, 90ps

Be beam pipe

MDC, 120 mm
0.5% at 1 GeV/c

CsI(Tl) calorimeter, 2.5% @ 1 GeV

Total weight 730 ton,
~40,000 readout chnls,
Data rate: 5kHz, 50Mb/s

Comparable performance to CLEO-c, + muon ID
BES-III detector
The BES-III Collaboration

>300 physicists
49 institutions from 10 countries
Data samples

$J/\psi$  225 M + 1,000 M  
(Jul. 2009 + 2012) 

$\psi(3686)$  106 M + 400 M  
(Apr. 2009 + 2012) 

$\psi(3770)$  2.9 fb$^{-1}$  
(2010–2011) ($\sim 3.5 \times$ CLEO-c) 

- 470 pb$^{-1}$ near 4010 MeV  
  (2011) 
- Mass scan near $\tau\tau$ threshold 
- Scan for $R$, 2.0 ··· 3.65 GeV 
- 2013: 500 pb$^{-1}$ each near 4260, 4360 MeV for ”XYZ” studies

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as of 2011:

![Graph showing data samples](image)
Physics programme

**Light hadron physics**
- meson and baryon spectroscopy
- multiquark states
- threshold effects
- glueballs & hybrids
- two-photon physics
- form-factors

**Charmonium physics**
- precision spectroscopy
- transitions and decays

**QCD and \( \tau \)**
- precision \( R \) measurement
- \( \tau \) decays

**Charm physics**
- semi-leptonic form factors
- decay constants \( f_D \) and \( f_{D_s} \)
- CKM matrix: \( |V_{cd}|, |V_{cs}| \)
- \( D^0 - \bar{D}^0 \) mixing, CPV
- strong phases

**Precision mass measurements**
- \( \tau \) mass
- \( D \) mass

**XYZ meson physics**
- \( Y(4260), Y(4360) \) properties
- \( Y(4260) \to \pi\pi h_c \) decays

\( \ldots \)
Light hadron spectroscopy
Charm as a tool for light hadron spectroscopy

We know

- mesons and baryons

QCD also allows

- molecules/multi-quarks
- hybrids
- glueballs

Totalitarian principle: Everything not forbidden is compulsory

‘...while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc.’

Gell-Mann, Phys. Lett. 8, 214 (1964)
Light hadron spectroscopy

Questions to constituent quark model:

Why so many states in meson spectrum?

- Too many isoscalar $0^{++}$ states:
  $f_0(600)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, $f_0(1810)$
- Same for isoscalar $1^{++}$ states:
  $f_1(1285)$, $f_1(1420)$, $f_1(1510)$, only 2 predicted
- Nature of $a_0(980)$, $f_0(980)$?

Do any of non-$q\bar{q}$ or non-$qqq$ states exist?

- multi-quark states, glueballs, hybrids . . .
- Allowed by QCD, but no (few?!) candidates yet?
... using charmonium decays

- Large production cross section: enormous statistics, favourable background conditions

- All quantum numbers accessible in \( J/\psi \) and \( \psi(3686) \) decays

- Initial state well defined \( (J^{PC} = 1^{--}) \)

- Radiative decays: high probability provide access to \( C = +1 \) states

- 3-gluon annihilation is flavour-blind nice source of excited strange baryons

⇒ Need a copious source of charmonium and a good detector: BES-III
Some highlights

- Anomalous $f_0(980)$ lineshape in $J/\psi \rightarrow \gamma f_0(980)\pi^0$

  ![Graphs](image)

  \[
  M = 989.9 \pm 0.4\text{MeV}/c^2, \quad \Gamma = 9.5 \pm 1.1\text{MeV}/c^2 \quad \text{and} \quad M = 987.0 \pm 1.4\text{MeV}/c^2, \quad \Gamma = 4.6 \pm 5.1\text{MeV}/c^2
  \]

- Large isospin breaking width $\eta(1405) \rightarrow \pi f_0(980)$

  \[
  \frac{\mathcal{B}(\eta(1405) \rightarrow f_0(980)\pi^0)}{\mathcal{B}(\eta(1405) \rightarrow a_0(980)\pi^0)} \approx 25\%
  \]

- Triangle anomaly and $f_0 - a_0$ mixing?

  ![Diagram](image)

W. Gradl — BES-III 16 11 Jan 2013

PRL 108, 182001

Wu et al., PRL 108, 081803 (2012)
Some highlights (II)

- Resonances in $J/\psi \rightarrow \gamma \eta' \pi \pi$
  
  $X(1835)$ [seen by BES-II before], $X(2120)$, $X(2370)$

  ![Graph](image1)

  What are these? excited $\eta/\eta'$? Pseudoscalar glueball?
  Quantum numbers? Other decay channels?

- $X(1870)$ in $J/\psi \rightarrow \omega X$, $X \rightarrow a_0(980)^\pm \pi^\mp$

  ![Graph](image2)

  same state?

PRL 106, 072002

PRL 107, 182001
Charmonium states
Below threshold charmonium spectrum

... all states established, but spin singlet states least well known:

$\eta_c(1S)$ mass, width measurements inconsistent
$\eta_c(2S), h_c(1P)$ properties not well known
Mass and width of $\eta_c(1S)$

Ground state charmonium ($c\bar{c}$), but mass and width not well known:
Tension between radiative $J/\psi$ transitions and production in $\gamma\gamma$, $p\bar{p}$, $B$ decays

CLEO-c found distortion in $\eta_c(1S)$ line shape

$c\bar{c}$ hyperfine splitting: $\Delta m_{hf}(1S) \equiv m(J/\psi) - m(\eta_c)$
important experimental input for Lattice QCD, dominated by $\Delta m(\eta_c)$

Phys. Rev. Lett. 102,011801
\( \psi(3686) \rightarrow \gamma \eta_c(1S), \eta_c \) exclusive decays

Interference with non-resonant decay important! All decay channels show same relative phase within 3\( \sigma \) \( \Rightarrow \) fix to common value in fit

\[
m(\eta_c) = 2984.3 \pm 0.6 \pm 0.6 \text{ MeV}/c^2
\]

\[
\Gamma(\eta_c) = 32.0 \pm 1.2 \pm 1.0 \text{ MeV}
\]

\[
\phi = 2.40 \pm 0.07 \pm 0.08 \text{ rad} \quad \text{or} \quad 4.19 \pm 0.03 \pm 0.09 \text{ rad}
\]
$\eta_c(1S)$ mass and width

Hyperfine splitting $\Delta m(1S) = 112.6 \pm 0.8$ MeV/$c^2$

Consistent with results from $B$ factories in other production mechanisms.
Line shape, interference with non-resonant decays important

HFS in better agreement with LQCD and quark model predictions:
Observation of $\psi(3686) \rightarrow \gamma \eta_c(2S)$
Observation of $\psi(3686) \rightarrow \gamma \eta_c(2S)$

First seen in Crystal Ball at SLAC in recoil spectrum of $\psi(3686) \rightarrow \gamma X$, using $1.8M \psi(3686)$, with $m = 3495 \pm 5$ MeV/$c^2$ Phys. Rev. Lett. **48**, 70 (1982)

Observed by Belle in $B^\pm \rightarrow K^\pm \eta_c(2S)$, $\eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$, also seen by BABAR and CLEO in $\gamma \gamma$ production

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process</th>
<th>$m$ [MeV/$c^2$]</th>
<th>$\Gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>$B^\pm \rightarrow K^\pm \eta_c(2S) \rightarrow K^\pm K_S^0 K^\pm \pi^\mp$</td>
<td>3654 ± 6 ± 8</td>
<td>—</td>
</tr>
<tr>
<td>CLEO</td>
<td>$\gamma \gamma \rightarrow \eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$</td>
<td>3642.9 ± 3.1 ± 1.5</td>
<td>6.3 ± 12.4 ± 4.0</td>
</tr>
<tr>
<td>BABAR</td>
<td>$\gamma \gamma \rightarrow \eta_c(2S) \rightarrow K_S^0 K^\pm \pi^\mp$</td>
<td>3630.8 ± 3.4 ± 1.0</td>
<td>17.0 ± 8.3 ± 2.5</td>
</tr>
<tr>
<td>BABAR</td>
<td>$e^+ e^- \rightarrow J/\psi c \bar{c}$</td>
<td>3645.0 ± 5.5$^{+4.9}_{-7.8}$</td>
<td>—</td>
</tr>
<tr>
<td>PDG '12</td>
<td></td>
<td>3638.9 ± 1.3</td>
<td>10 ± 4</td>
</tr>
</tbody>
</table>

M1 transition $\psi(3686) \rightarrow \gamma \eta_c(2S)$ with exclusive reconstruction of $\eta_c(2S)$ not yet observed. Exploit factor 60 in statistics: 108 M $\psi(3686)$

Experimentally challenging: $E_\gamma \sim 50$ MeV
\( \psi(3686) \rightarrow \gamma \eta_c(2S) \) with \( \eta_c(2S) \rightarrow K^0_S K \pi, KK \pi^0 \)

**Mass and width**

Simultaneous fit yields:

\[
\begin{align*}
m(\eta_c(2S)) &= 3637.6 \pm 2.9 \pm 1.6 \text{ MeV/}c^2 \\
\Gamma(\eta_c(2S)) &= 16.9 \pm 6.4 \pm 4.8 \text{ MeV}
\end{align*}
\]

**Branching fraction**

Using BABAR’s

\[
\mathcal{B}(\eta_c(2S) \rightarrow KK \pi) = (1.9 \pm 0.4 \pm 1.1)\%
\]

\[
\mathcal{B}(\psi(3686) \rightarrow \gamma \eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}
\]

cf. CLEO-c: < 7.4 \times 10^{-4}
$h_c(1^1P_1)$

Spin singlet $P$ wave ($S = 0$, $L = 1$)

Potential model:
$P$ wave hyperfine splitting non-zero if $P$-wave spin-spin interaction non-zero:

$$\Delta m_{hf}(1P) = m(1^1P_1) - \langle m(1^3P_J) \rangle \neq 0$$

with $\langle m(1^3P_J) \rangle = \frac{1}{9} (m(\chi_{c0}) + 3m(\chi_{c1}) + 5m(\chi_{c2}))$

First observation by CLEO-c in $e^+e^- \rightarrow \psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma\eta_c$

$\Delta m_{hf}(1P) = 0.08 \pm 0.18 \pm 0.12 \text{ MeV}/c^2$, consistent with zero HFS
$h_c$: Spin-singlet $^1P_1$ state

only detect $\pi^0$: "inclusive"
compute $m_{h_c}$ from kinematics

\[ \text{Rate} \propto B(\psi(3686) \rightarrow \pi^0 h_c) \]
$h_c$: Spin-singlet $^1P_1$ state

only detect $\pi^0$: "inclusive"
compute $m_{h_c}$ from kinematics
\[ \text{Rate } \propto B(\psi(3686) \rightarrow \pi^0 h_c) \]

detect $\pi^0$ and $\gamma$: "E1 tagged"
compute $m_{h_c}$ from kinematics
\[ \text{Rate } \propto B(\psi(3686) \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c) \]
$h_c$: Spin-singlet $^1P_1$ state

only detect $\pi^0$: "inclusive"
compute $m_{h_c}$ from kinematics
Rate $\propto B(\psi(3686) \rightarrow \pi^0 h_c)$

detect $\pi^0$ and $\gamma$: "E1 tagged"
compute $m_{h_c}$ from kinematics
Rate $\propto B(\psi(3686) \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c)$

detect $\pi^0$, $\gamma$ and $\eta_c \rightarrow X$ decay products: "exclusive"
m$_{h_c}$ from 4C kin. fit
Rate $\propto B(\psi' \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c) \times B(\eta_c \rightarrow X)$
\[ \psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c \]


\[ m(h_c) = 3525.40 \pm 0.13 \pm 0.18 \text{ MeV/}c^2 \]
\[ \Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28 \text{ MeV} \]
\[ < 1.44 \text{ MeV} \quad @90\% C.L. \]

1P Hyperfine mass splitting:

BES-III: \[ 0.10 \pm 0.13 \pm 0.18 \text{ MeV/}c^2 \]
CLEO-c: \[ 0.02 \pm 0.19 \pm 0.13 \text{ MeV/}c^2 \]
$\psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c, \eta_c$ exclusive decays

16 different $\eta_c$ decay channels

Simultaneous fit to $\pi^0$ recoil mass; results consistent with E1-tagged

\[ m = 3525.31 \pm 0.11 \pm 0.15 \text{ MeV}/c^2 \]
\[ \Gamma = 0.70 \pm 0.28 \pm 0.25 \text{ MeV} \]
Use $\psi(3686) \rightarrow \pi^0 h_c \rightarrow \pi^0 \gamma \eta_c$ as source for $\eta_c$.

$\eta_c$ lineshape in these decays not as distorted as in $\psi(3686) \rightarrow \gamma \eta_c$; smaller (non-existent?) non-resonant interfering contributions.

Best channel to determine $\eta_c$ resonance parameters (with enough statistics . . .)
yesterday’s search $\rightarrow$ today’s discovery $\rightarrow$ tomorrow’s calibration
Open charm
Advantage of open charm at threshold

\( e^+ e^- \) collider near threshold:

\[
e^+ e^- \to \psi(3770) \to D^0 \bar{D}^0 \quad [C = -1]
\]
\[
e^+ e^- \to \gamma^* \to D^0 \bar{D}^0 \gamma \quad [C = +1]
\]

Good for charm flavour physics:

- Threshold production in \( e^+ e^- \) environment: very clean
- Know initial energy and quantum numbers of \( D \bar{D} \) system
- Fully reconstruct \( D \) and \( \bar{D} \) (double tag)
- Absolute measurements
Leptonic decays

\[ \Gamma(D^+ \rightarrow \ell^+ \nu) = f_D^2 |V_{cd}|^2 \frac{G_F^2}{8 \pi} m_D m_{\ell}^2 \left(1 - \frac{m_{\ell}^2}{m_D^2}\right)^2 \]

Decay constant \( f_D \) incorporates strong interaction effects (wave function at origin)

Use charm leptonic decays to validate theory (LQCD) apply to \( B \) physics, which requires \( f_B \)

Multiple tests with charm: \( f_D, f_{Ds} \)

Sensitivity to new physics (cf. BABAR’s \( B^+ \rightarrow \tau^+ \nu \))
Semi-leptonic decays

\[ \frac{d\Gamma(D \to K(\pi)\ell\nu)}{dq^2} = \frac{G_F^2 |V_{cs(d)}|^2}{24\pi^3} \mathcal{K}(q^2) |f_+(q^2)|^2 \]

Use strong interaction theory (LQCD) for form factor \( f_+(q^2) \), extract CKM matrix element

Use \( |V_{cs(d)}| \) as input, test form factors

Validate FF calculations with charm: help reduce theoretical uncertainties in measurements of \( |V_{ub}| \)

Semileptonic \( D \) decays to pseudoscalar mesons cleanest tests
Impact on CKM

- Knowledge of form factors limited by form factors, decay constants
- Use LQCD as input
- Widths of bands from mixing and $|V_{ub}|$ will be reduced as charm validates LQCD
- Long-term goal: over-constrain CKM, find new physics
$D$ Tagging

From $\psi(3770)$, open charm production is $D^0\bar{D}^0$ and $D^+D^-$

Fully reconstruct one $D$ using $\sim 20$ decay modes about 15% of the total $D$ width (compare to $B$ tagging at $B$ Factory!)

Kinematic variables to select tag side:

$$m_{BC} = \sqrt{E_{\text{beam}}^2 - \vec{p}^2}$$
$$\Delta E = E_D^* - E_{\text{beam}}^*$$

Hadronic tag on one side gives clean "beam" of $D^0$ or $D^+$ on the other side for leptonic/semi-leptonic studies.
Neutrino can be reconstructed from missing energy and momentum.
Leptonic decay $D^+ \rightarrow \mu^+ \nu$ — Tag selection

9 different hadronic tag modes

\[ \ln 2.9 \text{ fb}^{-1} : N_{D^-}^{\text{tag}} = (1.566 \pm 0.002) \times 10^6 \]
Leptonic decay $D \rightarrow \mu \nu$ — signal selection

- Require exactly one track in addition to tag, with the right charge
- Positive muon ID
- No extra photon
- Consistent with leptonic decay:
  \[ M_{\text{miss}}^2 = (E_{\text{beam}} - E_{\mu})^2 - (\vec{p}_{\text{tag}} - \vec{p}_{\mu})^2 \approx 0 \]

- Select 425 signal candidates
  small background
  momentum spectrum consistent with leptonic $D$ decay
Leptonic decay $D^+ \rightarrow \mu^+ \nu$ — Results

BES-III preliminary

\[ N(D^+ \rightarrow \mu^+ \nu) = 377.3 \pm 20.6 \]
\[ \mathcal{B}(D^+ \rightarrow \mu^+ \nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4} \]
\[ f_{D^+} = (203.9 \pm 5.7 \pm 2.0) \text{ MeV} \]

Consistent with CLEO-c
Still limited by statistics — need more data!
Rare decay $D^0 \rightarrow \gamma\gamma$

- FCNC transition $c \rightarrow u\gamma$, forbidden in SM at tree level

- $u$ needs to annihilate with $\bar{u}$ to produce the other photon

- Short-distance contribution extremely suppressed: GIM cancellation between $d$ and $s$ in loops

- Possibly large long-distance contributions

- SM: $\mathcal{B}(D^0 \rightarrow \gamma\gamma) \sim 10^{-8}$ or less Fajfer et al., Phys. Rev. D 64, 074008 (2001)

- Could receive large enhancement by physics beyond SM (e.g. MSSM)
$D^0 \rightarrow \gamma\gamma$ experimental status

- **CLEO2**, using $13.8 \text{ fb}^{-1}$ around $\Upsilon(4S)$:  
  \[ B(D^0 \rightarrow \gamma\gamma) < 2.9 \times 10^{-5} \quad @90\%C.L. \]
  \[ \text{Phys. Rev. Lett. 90, 101801 (2003)} \]

- **CLEO-c**: $818 \text{ pb}^{-1}$ at $\psi(3770)$ ($6 \text{ M } D^0$ produced)  
  \[ B(D^0 \rightarrow \gamma\gamma) < 8.63 \times 10^{-6} \quad @90\%C.L. \]
  \[ \text{Charm 2010} \]

- **BABAR**: $470.5 \text{ fb}^{-1}$ around $\Upsilon(4S)$ ($201 \text{ M } D^0$ produced)  
  \[ \text{Phys. Rev. D 85, 091107 (2012)} \]
  \[ B(D^0 \rightarrow \gamma\gamma) < 2.2 \times 10^{-6} \quad @90\%C.L. \]

- **BES-III**: $2.9 \text{ fb}^{-1}$ at $\psi(3770)$ ($20 \text{ M } D^0$ produced)  
  \[ \text{Charm 2012} \]
$D^0 \to \gamma \gamma$ at BES-III

- First attempt: maximise statistics, use single tags only
- Hard selection against continuum, Bhabha backgrounds
- Normalise branching fraction to $D^0 \to \pi^0 \pi^0$
  (major background, fixed in fit)
- Fit to data:
  $N(D^0 \to \gamma \gamma) = -2.9 \pm 7.1$ events
- Dominating systematics from background rejection
$D^0 \to \gamma\gamma$ at BES-III

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  $N(D^0 \to \gamma\gamma) = -2.9 \pm 7.1$ events
- Dominating systematics from background rejection

\[ \mathcal{B}(D^0 \to \gamma\gamma) / \mathcal{B}(D^0 \to \pi^0\pi^0) < 5.8 \times 10^{-3} \ @90\% C.L. \]
\[ \mathcal{B}(D^0 \to \gamma\gamma) < 4.6 \times 10^{-6} \ @90\% C.L. \]

Compare $D^0 \rightarrow \gamma\gamma$ at BES-III and BABAR

BES-III: $N_{\text{sig}} = -2.9 \pm 7.1$ events
BABAR: $N_{\text{sig}} = -6 \pm 15$ events

$B_{\text{BES-III}} / B_{\text{BABAR}} \sim 0.5$
$\varepsilon_{\text{BES-III}} / \varepsilon_{\text{BABAR}} \sim 2$

But
$N(D^0)_{\text{BES-III}} / N(D^0)_{\text{BABAR}} \sim 0.1$

Preliminary

Contamination from $D^0 \rightarrow \pi^0\pi^0$
Prospects for $D^0 \rightarrow \gamma \gamma$ and other rare $D$ decays

Prospects:
study advantage of double tag to remove backgrounds?

... and other radiative and rare decays:
$D^0 \rightarrow \nu \bar{\nu}, \nu \bar{\nu} \gamma, \nu \bar{\nu} \pi^0,$
$D^0 \rightarrow X_{u} \ell^+ \ell^-, D^0 \rightarrow \mu e$ (LFV)

With $5 \div 10 \text{fb}^{-1}$ at $\psi(3770)$,
BES-III will provide
$10^{-6} - 10^{-7}$ sensitivity

still above most SM predictions, but reach into BSM parameter space

remove all background from continuum, Bhabha, . . .
remaining: $D^0 \rightarrow \pi^0 \pi$, which we measure
Summary

- BES-III successfully taking data since 2008
  - world’s largest data samples at $J/\psi$, $\psi(3686)$, $\psi(3770)$, $\psi(4040)$
  - more data coming soon

- **Light hadron spectroscopy**
  - New structures, old ones confirmed
  - interesting, puzzling isospin breaking branching ratios
  - (and much more)

- **Charmonium transitions**
  - precision measurements of $\eta_c(1S)$ and $h_c$ properties
  - first observation of $\psi(3686) \rightarrow \gamma \eta_c(2S)$

- **Charm decays**
  - precision $D$ physics coming soon; tools in preparation

- Interesting times ahead
谢谢！