Experimental Program for a Super Tau-Charm Factory

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University of Chinese Academy Sciences

the 62nd ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2018), 24-27 September 2018, Hong Kong, China
Disclaimer

only highlights, not comprehensive
Check the below links:

**Workshop on Physics at Future High Intensity Collider @ 2-7GeV in China**
13-16 January 2015
USTC
Asia/Shanghai timezone

http://cicpi.ustc.edu.cn/indico/conferenceDisplay.py?confId=87

**2nd international workshop on High Intensity Electron-Positron Accelerator (HIEPA) at China (HIEPA2018)**
18-21 March 2018
1st floor in the ICC hall
Asia/Shanghai timezone

http://cicpi.ustc.edu.cn/indico/conferenceDisplay.py?confId=1009

**The SCTF CDR**

https://ctd.inp.nsk.su/c-tau/
Dedicated Tau-Charm Factories

ADONE, FRASCATI
’69-’93

SPEAR, SLAC, ’72-’90
6x10^{29} cm^{-2}.s^{-1}

BEPC, IHEP, ’90-’04
5x10^{30} cm^{-2}.s^{-1}

CESRc, Cornell, ’04-’08
7x10^{31} cm^{-2}.s^{-1}

VEPP-4M, Novosibisk, ’02-’12
1x10^{30} cm^{-2}.s^{-1}

BEPCII, IHEP, ’08-’18(?)
1x10^{33} cm^{-2}.s^{-1}
Fruitful BEPCII/BESIII Results

Z_{c}(3900)

Most precise measurement for D leptonic decay

Abrupt structure X(1835)

Large Isospin Violation

Precise Measurement on Cross section e^+e^-\rightarrow\pi^+\pi^-

First Λc at BESIII

≥210 publications

http://english.ihep.cas.cn/chnl/245/index.html

Xiao-Rui LYU

eefACT2018, Hong Kong
Broad Physics at $\tau$-charm Energy Region

- Hadron form factors
- $Y(2175)$ resonance
- Multiquark states with $s$ quark, $Z_s$
- MLLA/LPHD and QCD sum rule predictions
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with $\tau$ lepton
- XYZ particles
- Physics with $D(s)$ mesons
- $f_D$ and $f_{Ds}$
- $D_0$-$D_0$ mixing
- Charm baryons

$R = \frac{e^+e^- \rightarrow \text{hadron}}{s(e^+e^- \rightarrow \mu^+\mu^-)}$

**R scan**

- Precision $\Delta\alpha_{\text{QED}}$, $a_\mu$, charm quark mass extraction.
- Hadron form factor (nucleon, hyperon, $c$-ed baryon).

Blank at 5-7GeV to date
τ-c facility in China

Features and limits of BEPCII/BESIII

- Threshold production
- Clean Signal, low background
- High efficiency and resolution
- ..........

- limited energy range : 2-4.6 GeV
- Luminosity : $10^{33}$ cm$^{-2}$ s$^{-1}$
- No major upgrade proposal to date

BEPCII/BESIII will end her mission in 8-10 years

A STCF far beyond BEPCII, is nature extension

and a viable option for a post-BEPCII HEP project
Proposals of the Super Tau-Charm Factory (STCF)

HIEPA in China

Super-CT Project in Russia

Total number of accelerating structures: 104
Klystron number: 52
Total length of the linacs: ~440 m
energy of 1.5 – 2.5 (3) GeV
Physics @ STCF

- **Precise test of SM**
  - R Scan, Hadron form factor (nucleon, Λ, π), Δα_{QED}, a_u
  - tau lepton decays, lepton universality test
  - CKM matrix, Decay constants (f_D/f_{D^*}), form factors
  - Neutral D mixing and strong phase

- **New physics (tiny/forbidden in SM)**
  - Rare charmonium decays: LFV, LNV, BNV...
  - Rare charm decay: FCNC, LFV, LNV, invisible
  - Rare tau decay: FCNC, LFV, LNV
  - Rare light meson decay: η/η'/ω/φ

- **CP Violation**
  - Unexpected large CPV in tau or charm: tiny in SM
  - CP violation in hyperon and c-ed hadrons

- **hadron physics**
  - hadron spectroscopy
  - hadron-pair threshold effects
  - Glueball: direct test of QCD at low energy
  - Multiquark, exotics, hybrids.....
  - Charmonium(-like) spectroscopy
  - Charmed baryon decays

- **Exotic physics**
  - Light dark matter: light Higgs boson(a_0), U boson
  - New interactions

 rich of physics program, unique for physics with c quark and τ leptons, important playground for study of QCD, exotic hadrons and search for new physics.
Integral Luminosity of STCF

- No Synchrotron radiation mode, assume running time 9 months/year
- Assume data taking efficiency 90%

\[10^{35}\text{cm}^{-2}\text{s}^{-1} \times 86400\text{s} \times 270\text{days} \times 90\% \approx 2.0\text{ab}^{-1}/\text{year}\]

10 years data taking, total 20 ab\(^{-1}\) conservatively

Excellent opportunities for the \(\tau\)-charm physics

Native question: competition between STCF and BELLE-II?
Data samples

Data samples with 1 ab⁻¹ integral luminosity

<table>
<thead>
<tr>
<th>Data Set</th>
<th>process</th>
<th>$\sigma$/nb</th>
<th>$N$</th>
<th>ST eff./%</th>
<th>ST N</th>
<th>$\sigma$/nb</th>
<th>N</th>
<th>Tag N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>-</td>
<td>-</td>
<td>$1.0 \times 10^{12}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>-</td>
<td>-</td>
<td>$3.0 \times 10^{11}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$D^0 \bar{D}^0(3.77)$</td>
<td>$\sim 3.6$</td>
<td>$3.6 \times 10^9$</td>
<td>10.8</td>
<td>$0.78 \times 10^9$</td>
<td>-</td>
<td>$1.4 \times 10^9$</td>
<td>-</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$D^+ D^-(3.77)$</td>
<td>$\sim 2.8$</td>
<td>$2.8 \times 10^9$</td>
<td>9.4</td>
<td>$0.53 \times 10^9$</td>
<td>-</td>
<td>$7.7 \times 10^8$</td>
<td>-</td>
</tr>
<tr>
<td>$D_s$</td>
<td>$D_s D_s^*(4.18)$</td>
<td>$\sim 0.9$</td>
<td>$0.9 \times 10^9$</td>
<td>6.0</td>
<td>$0.11 \times 10^9$</td>
<td>-</td>
<td>$2.5 \times 10^8$</td>
<td>-</td>
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<tr>
<td>$\tau^+$</td>
<td>$\tau^+ \tau^-(3.68)$</td>
<td>$\sim 2.4$</td>
<td>$2.4 \times 10^9$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
<td>$0.9 \times 10^9$</td>
</tr>
<tr>
<td>$\tau^+$</td>
<td>$\tau^+ \tau^-(4.25)$</td>
<td>$\sim 3.6$</td>
<td>$3.5 \times 10^9$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Lambda_c$</td>
<td>$\Lambda_c \Lambda_c^*(4.64)$</td>
<td>$\sim 0.6$</td>
<td>$5.5 \times 10^8$</td>
<td>5.0</td>
<td>$0.55 \times 10^8$</td>
<td>-</td>
<td>$1.6 \times 10^8$</td>
<td>$3.6 \times 10^4$</td>
</tr>
</tbody>
</table>

The luminosity is 1.0 ab⁻¹. * process $e^+e^- \rightarrow D(*)-\bar{p}\pi^+\Lambda_c^+$.

- **Belle-II** (50/ab) has 50~100 times more statistics
- **STCF** is expected to have higher detection efficiency
- **STCF** has low backgrounds for productions at threshold
Charmonium-(like) spectroscopy

Key Science question: Is there any exotic hadron exist

- States below charm threshold are all well observed
- Many missing states above charm threshold
- Many new observations in the last decade

X(3872)  Y(3940)  Z(3900)  Z(3950)
X(3940)  Y(4008)  Z(4020)  Z(4050)
X(4160)  Y(4260)  Z(4200)  Z(4250)
X(4350)  Y(4360)  Z(4350)  Z(4430)
Y(4660)

Nature unclear
- Charmonium?
- Hybrid?
- Tetraquark?
- Molecule?
- Non-resonance?

A better understanding on charmonium spectrum may help to understand their natures

Godfrey & Isgur, PRD 32, 189 (1985)
Charmonium(-like) states @ STCF

• $\psi/Y$/hybrid$(ccg)\ (1^{--})$ produced in the $e^+e^-$ collision
  – To determine the resonance parameters for the excited $\psi$ or $Y$ state
  – Precisely measure the x-sec of inclusive/exclusive final states at different energy points
• Charge parity $c=+1$ states produced via radiative transition from vector $\psi/Y$
  – The decay rate $\psi(nS/nD)\rightarrow\gamma X(3872), X(3940)$…
  – Search for $\chi_{cJ}(2P), \chi_{cJ}(3P), \eta_c(3S), \eta_c(4S), \ldots$
    $B(\psi(3S)\rightarrow\gamma\chi'_{cJ}) = (7, 3, 1) \times 10^{-4}$ for $J=2,1,0$
    [Rev. Mod. Phys. 80, 1161 (2008) ]
• Search for new states from hadronic transition
  – To search for $Z_c, Z_{cs}, hc(2P) \ldots$
An example: search for $\eta_c(1^1D_2)$ and $\chi_{c1}(2^3P_1)$

**Naïve estimations @ STCF**

$L_{\text{peak}} = 10^{35}\text{cm}^{-1}\text{s}^{-1}$, 1 year running $= 10^6\text{pb}^{-1} = 1\text{ab}^{-1}$

a BESIII-like detector

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### $\eta_c(1^1D_2)$

- $\sigma(e^+e^-\rightarrow\pi^+\pi^-h_c(2P)) \sim 20\text{ pb @ Ecm=??GeV}$
- $B(h_c(2P)\rightarrow\gamma\eta_{c2}) \sim 3\times10^{-4}$ [E1 trans., Barnes’ 05]
- $B(\eta_{c2}\rightarrow\gamma h_c) \sim (44-54)\%$ [E1 trans., Fan’ 09]
- $B(h_c\rightarrow\gamma\eta_c) \sim 54\%$ [E1 trans., BESIII’10]
- $\varepsilon B(\eta_c\rightarrow\text{hadrons}) \sim 1.5\%$ at BESIII
- $N_{\text{obs}}=2 \times 10^{-5} \times L$ (L is int. lumi. in pb$^{-1}$)
- $N_{\text{obs}}=20$ events /year,
- Bkg is low for narrow $h_c$ and $\eta_c$

### $\chi_{c1}(2^3P_1)$

- $\sigma(e^+e^-\rightarrow\psi(nS)/\psi(mD)) \sim (3-7)\text{ nb}$ @ for n>1, m>2
- $B(\psi \rightarrow\gamma\chi'_{c1}) \sim 3\times10^{-4}$ [E1 trans., Barnes’ 05]
- $B(\chi'_{c1}\rightarrow\gamma\psi') \sim 1 \times 10^{-3}$ [E1 trans., Barnes’ 05]
- $B(\chi'_{c1}\rightarrow\gamma J/\psi) \sim 1 \times 10^{-4}$ [E1 trans., Barnes’ 05]
- $\varepsilon B \sim (1-5)\%$ at BESIII
- $N_{\text{obs}}=(1-10) \times 10^{-5} \times L$ (L is int. lumi. in pb$^{-1}$)
- $N_{\text{obs}}=(10-100)$ events /year,
- Bkg is low for narrow $\psi'$ and $J/\psi$
The XYZ states at BESIII

Different decay channels of the same observed states?  Other decay modes?  Now BESIII has very statistics-limited data to further probe the nature of these states?

Xiao-Rui LYU

eeFACT2018, Hong Kong
Multi-quark exotic states

- **STCF**: $e^+e^- \rightarrow Y/\psi \rightarrow Z_c + X$

- **B Factor**: ISR, B decay

**B factory**: Total integrate effective luminosity between 4-5 GeV is 0.23 ab$^{-1}$ for 50 ab$^{-1}$ data

- **STCF**: scan in region 4-5 GeV, 10 MeV/step, every point have 20 fb$^{-1}$/year, 10 time of Belle II for 50 ab$^{-1}$ data

- **STCF** have much higher efficiency than B Factory

**Belle with ISR**: PRL110, 252002, 967 fb$^{-1}$ in 10 years running time

**BESIII at 4.260 GeV**: PRL110, 252001, 0.525 fb$^{-1}$ in one month running time
Search for $1^- \text{ hybrid } H_{ccg} \rightarrow \gamma \eta_c & \gamma \chi_{c0}$

- $1^- \text{ Hybrid}$ may produce directly in $e^+e^-$ collision, and radiative decay to spin-zero charmonium states [in Hybrid, $cc$ in spin-singlet, LQCD by Dudek’09]
  - Assume $\sigma(e^+e^-\rightarrow H_{ccg}) \sim O(10^-100) \text{ pb}$ [???]
  - $B(H_{ccg}\rightarrow \gamma \eta_c)\sim 2\times B(\eta_{c2}\rightarrow \gamma \chi_{c0}) \sim 4\times 10^{-4}$

- Scan between 4-5 GeV for 1 year ($2\text{ab}^{-1}$), search for exotic structure in process $e^+e^-\rightarrow \gamma \eta_c$ and $\gamma \chi_{c0}$
  - Assume $\varepsilon B \sim 10\%$ for $\gamma \eta_c$ and $\gamma \chi_{c0}$ decay to $\gamma$+hadrons

- With 100 energy points between 4-5 GeV
  - $N_{\text{obs}}(\gamma \eta_c) = O(8-80) \text{ events/point/year at peak}$
  - $N_{\text{obs}}(\gamma \chi_{c0}) = O(4-40) \text{ events/point/year at peak}$
Opportunities on $\tau$ Physics

• X sec grows from 0.1nb near threshold to 3.5nb at 4.25GeV
  – $10^8$ tau pairs per year at threshold ($x$-sec = 0.1nb)
  – $3.5 \times 10^9$ tau pairs/year at 4.25GeV ($x$-sec = 3.5nb)
  – $10^{10}$ tau pairs per year for Belle II ($x$-sec = 1nb)

• Physics highlighted physics program
  – Precision measurements of $\alpha_s$, $m_s$, $V_{us}$
  – Lepton Universality: $m_\tau$, $\tau \rightarrow \pi^+\nu_\tau$ and $\tau \rightarrow K^+\nu_\tau$
  – Lorentz structure of the amplitude for $\tau \rightarrow \ell\nu_\ell\nu_\tau$
  – Search for LFV processes: $\tau \rightarrow \ell\gamma$, $\ell\ell\ell$, $\ell h$
  – Search for CPV
  – V-A Structure of the weak current in leptonic decays
  – Rare hadronic decays

• Competition to Belle II
  – Threshold effect is important for controlling and understanding background
  – Longitudinal polarization of the initial beams will significantly increase sensitivity in searches for CPV in lepton decays.
Charged LFV search in $\tau$

Backgrounds are much smaller @STCF than at Belle-II. Even with less data more stringent limits can be achieved!!

($\tau \rightarrow \mu \gamma$ with $e^+e^- \rightarrow \tau \tau \gamma$)

Also LNV & BNV will be searched for.
cLFV Decay $\tau \to \ell \gamma$

- No evidence of new physics been found at high energy frontier.
- Important and complementary to search for new physics in the precision frontier.

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>RVV2</th>
<th>AKM</th>
<th>sLL</th>
<th>FBMSM</th>
<th>LHT</th>
<th>RS</th>
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</thead>
<tbody>
<tr>
<td>$D^0 \to D^0$</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$\epsilon_K$</td>
<td>★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$S_{\psi\psi}$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>??</td>
</tr>
<tr>
<td>$S_{4\psi\bar{\psi}}$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{CP}(B \to X\gamma)$</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{FB}(B \to K^\mu^\mu^-)$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$A_{(B \to K^\mu^\mu^-)}$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$B \to K^{0}\bar{\nu}\nu$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$B_s \to \mu^\pm\mu^\mp$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\nu\bar{\nu}$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$K_L \to \pi^+\nu\bar{\nu}$</td>
<td>★★★</td>
<td>★★</td>
<td>★★★</td>
<td>★</td>
<td>★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$\mu \to e\gamma$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$\tau \to \mu\gamma$</td>
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<td>★★★</td>
<td>★★★</td>
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<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
<tr>
<td>$\mu + N \to e + N$</td>
<td>★★★</td>
<td>★★★</td>
<td>★★★</td>
<td>★</td>
<td>★★★</td>
<td>★</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 3: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.


- $\mu/\tau$ anomalous decays
- $\mu \rightarrow e$ conversion
- Anomalous magnetic moment

In $\tau$-charm factory, $\tau \rightarrow \mu\gamma$ decay is a golden mode to search for NP.
cLFV Decay $\tau \rightarrow \mu \gamma$ @ B Factory

From A. Bondar, Charm2010

- **Current limit**: $\sim 4 \times 10^{-8}$ ($5 \times 10^8 \tau$-pairs)
  - BABAR: 516 fb$^{-1}$ [PRL, 104, 021802]
  - BELLE: 545 fb$^{-1}$
- **At $Y(4S)$**:
  - ISR background $e^+e^- \rightarrow \tau^+\tau^-\gamma$
  - Upper Limit $\propto 1/\sqrt{L}$
  - Expected limit: $3 \times 10^{-9}@50$ ab$^{-1}$ ($7 \times 10^{10}$ $\tau$-pairs)
- **Belle-II with $L=50$ ab$^{-1}$**
  - $10^{10}$ tau pairs per year (x-sec=1 nb)
- **STCF with $L=10^{35}$ cm$^{-2}$s$^{-1}$**
  - $10^8$ tau pairs per year at threshold (xsec=0.1 nb)
  - $3.5 \times 10^9$ tau pairs/year at 4.25 GeV (xsec = 3.5 nb)

What can STCF have with $3 \times 10^9 \tau\tau$ pairs / year?
STCF vs. Belle-II: $\tau \rightarrow \mu \gamma$ background

Background $e^+e^- \rightarrow \tau^+\tau^-\gamma$

Dominant BKG @ B Factory
- Dominant source at Y(4S): $e^+e^- \rightarrow \tau^+\tau^-\gamma$
- Does not contribute below $\sqrt{s} \approx 4m_\tau/\sqrt{3} \approx 4.1$ GeV.

Dominant BKG @ STCF
- $\tau$ decays: [arXiv:1206.1909]
  - direct ($\tau^+ \rightarrow \pi^+\pi^0\nu_\tau$) and combinatorial
  - QED processes:
    - $e^+e^- \rightarrow \mu^+\mu^-\gamma\gamma$, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-\gamma$
  - Continuum hadron production $e^+e^- \rightarrow qq$
  - $\psi(2S)$ and $D$-meson decays

Polarized beam may further suppress background and increase the sensitivity for the new physics significantly
Expected $\tau \rightarrow \mu \gamma$ BF upper limit @ STCF

<table>
<thead>
<tr>
<th>$E$(GeV)</th>
<th>$\sigma$(nb)</th>
<th>$L$(ab$^{-1}$)</th>
<th>$N_{\tau\tau}(10^{10})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.686</td>
<td>5.0</td>
<td>1.5</td>
<td>0.75</td>
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<tr>
<td>3.77</td>
<td>2.9</td>
<td>3.5</td>
<td>1.03</td>
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<td>4.17</td>
<td>3.6</td>
<td>2.0</td>
<td>0.71</td>
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<tr>
<td>Total</td>
<td></td>
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<td>7.0</td>
</tr>
</tbody>
</table>

Results from Vladimir Druzhinin, (BINP, Novosibirsk) at Workshop on Tau Charm at High Luminosity 26-31 May, 2013, La Biodola, Italy

Fast simulation for NP sensitivity and detector optimization is ongoing

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{E}/E=1.5%$</th>
<th>$\sigma_{E}/E=2.5%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal (BF=10$^{-9}$)</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Muon background</td>
<td>7</td>
<td>11</td>
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<tr>
<td>Pion background</td>
<td>83</td>
<td>271</td>
</tr>
<tr>
<td>Expected 90% CL upper limit for BF</td>
<td>$1.1 \times 10^{-9}$</td>
<td>$3.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>Expected 90% CL upper limit for BF with pion suppression by a factor of 30</td>
<td>$3.3 \times 10^{-10}$</td>
<td>$5.1 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Belle-II predicted limit: $3 \times 10^{-9}$@50ab$^{-1}$ ($7 \times 10^{10}$ $\tau$-pairs)
CP Violation in $\tau$ Decay

- CP violation is observed in B and K sectors, but not observed in lepton sector yet.
- Strongly suppressed in the SM ($A_{CP} \leq 10^{-12}$)
- A discovery of CPV in the tau sector would be a clean signature of NP
- One of the most promising CPV channels is $\tau^- \rightarrow K_S \pi^- \nu$

$$A_{\tau} = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K^0 \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K^0 \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K^0 \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K^0 \nu_\tau)}$$

- SM CP asymmetry from $K_S$-$K_L$ mixing is expected to be:
  
  \[ A_{SM}^{SM} \simeq 2\text{Re}(\epsilon) \simeq (0.36 \pm 0.01)\% \]

- BaBar measurement [PRD 85, 099904]: $2.8\sigma$ from SM!

$$A_{\tau} = (-0.36 \pm 0.23 \pm 0.11)\%$$

- Belle measurement [PRL 107, 131801]: does not see any asymmetry at the 0.2 - 0.3% level

$$A_{cp} = (1.8 \pm 2.1 \pm 1.4) \times 10^{-3} @ W \sim [0.89-1.11] \text{ GeV}$$

$$|\text{Im}(\eta_S)| < 0.026 \text{ or better.}$$
τ CPV in angular distribution

- Measurement on the angular CPV asymmetry is desirable
- Use T-odd rotationally invariant products in >=2 hadrons, such as $\tau^-\rightarrow\pi^-\pi^0\nu_\tau/k^-\pi^0\nu_\tau$, $\tau^-\rightarrow\pi^-\pi^+\pi^-\nu_\tau/K^-\pi^+\pi^-\nu_\tau$: $P_2^\tau \cdot (\vec{P}_{\pi^+} \times \vec{P}_{\pi^0})$
- Polarized of $\tau$ and beam are necessary
- Figure of Merits

$$\text{merit} = \text{luminosity} \times \bar{w}_Z \times \text{total cross section}$$
$$\propto \text{luminosity} \times (w_1 + w_2) \times \sqrt{1 - a^2a^2(1 + 2a)} ,$$

Y. S. TSAI, PRD 51 (1995) 3172

- BESIII @ 4.25 (10^{33}\text{cm}^{-2}\text{s}^{-1}) FOM=1
- STCF @ 4.25 (10^{35}\text{cm}^{-2}\text{s}^{-1}) FOM=100
- Belle-II@ (8x10^{35}\text{cm}^{-2}\text{s}^{-1}) FOM=52
Charm Physics

• $4 \times 10^9$ pairs of $D^{\pm,0}$ and $10^7 \sim 10^8 D_s$ pairs per year
  – $10^{10}$ charm from Belle II/year
• Competition to Belle II
  – The multiplicity of final state is lower by a factor of 2
  – Threshold effect, clear, double tagging
  – Produce in QM coherent state, $J^{PC}=1-$ for DD, $J^{PC}=0^{++}$ for $\gamma DD$
• Highlighted Physics programs
  – Precise measurement of leptonic, semi-leptonic decay ($f_D$, $f_{Ds}$, CKM matrix…)
  – $D^0$-$D^0$ bar mixing, CPV
  – Rear decay (FCNC, LFV, LNV….)
  – Excite charm meson states $D_J$, $D_{sJ}$ (mass, width, $J^{PC}$, decay modes)
  – Charmed baryons ($J^{PC}$, Decay modes, absolute BF)
## Features in studying charm hadron decays

<table>
<thead>
<tr>
<th></th>
<th>STCF</th>
<th>Belle(-II)</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production yields</strong></td>
<td>★★</td>
<td>★★★★★</td>
<td>★★★★★★★</td>
</tr>
<tr>
<td><strong>Background level</strong></td>
<td>★★★★★</td>
<td>★★</td>
<td>★★</td>
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<tr>
<td><strong>Systematic error</strong></td>
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<td>★★</td>
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<td><strong>Completeness</strong></td>
<td>★★★★★</td>
<td>★★★</td>
<td>★</td>
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<tr>
<td><strong>(Semi)-Leptonic mode</strong></td>
<td>★★★★★</td>
<td>★★★</td>
<td>★</td>
</tr>
<tr>
<td><strong>Neutron/K_L mode</strong></td>
<td>★★★★★</td>
<td>★★</td>
<td>★☆</td>
</tr>
<tr>
<td><strong>Photon-involved</strong></td>
<td>★★★★★</td>
<td>★★★★★☆☆</td>
<td>★☆</td>
</tr>
<tr>
<td><strong>Absolute measurement</strong></td>
<td>★★★★★</td>
<td>★★</td>
<td>★☆</td>
</tr>
</tbody>
</table>

- Most are precision measurements, which are mostly dominant by the systematic uncertainty
- STCF has overall advantage
Determination of $\gamma/\phi_3$ angle in CMK

- The cleanest way to extract $\gamma$ is from $B \to DK$ decays:
  - current uncertainty $\sigma(\gamma) \sim 5^0$
  - however, theoretical error: $10^{-6}$ (!)
  - over-constrain the Unitarity Triangle

- Information of \textit{D decay strong phase} is needed
  - Only can be accessed through quantum coherence of DD production at threshold

- ADS method: use \textit{D} doubly Cabibbo-suppressed decays, e.g. $D^0 \to K^+\pi^-$
  - With $1 \text{ ab}^{-1}$ @ STCF: $\sigma(\cos\delta_{K\pi}) \sim 0.007$; $\sigma(\delta_{K\pi}) \sim 2^0 \Rightarrow \sigma(\gamma) < 0.5^0$
  - BELLE-II expects $\sigma(\gamma) \sim 1.5^0$; upgraded LHCb: $\sigma(\gamma) \sim 1^0$

- GGSZ method: use Dalitz plot analysis of 3-body $D^0$ decays, e.g. $K_S \pi^+\pi^-$
  - high statistics; need precise Dalitz model
  - Belle results from GSSZ method in 2012: $\gamma = (77 \pm 15 \pm 4 \pm 4)^0$
  - STCF would reduce the contribution of $D$ Dalitz model to a level of $\sim 0.1^0$, since expected precision from future HL-LHCb projects would be $< 0.5^0$. 

Xiao-Rui LYU eeFACT2018, Hong Kong
Charm rare Decays

- FCNC suppressed by GIM mechanism in SM:
  - Short distance: interested, computable by pQCD, directly test SM
    \[ \mathcal{B}_{D^0 \to X_{u}^{0} e^+ e^-} \simeq 8 \cdot 10^{-9} \]
    \[ \mathcal{B}_{D^+ \to X_{u}^{+} e^+ e^-} \simeq 2 \cdot 10^{-8} \]
  - Long distance effect can enhance the rate to \(10^{-6} \sim 10^{-7}\), dominantly.
  - Allow with sizeable decay rate in NP
    - \(1\text{ab}^{-1}\) @ STCF can achieve the sensitivity to \(10^{-8} \sim 10^{-9}\), tested SM strictly
    - Can discriminate NP from SM by measuring:
      - \(D \to V l^+ l^-\): AFB asymmetry
      - \(D \to P l^+ l^-\): line shape of dilepton mass, to reveal the interference effect between long-distance and FCNC weak amplitude (NP amplitude);

- LFV, LNV and BNV decays are forbidden in the SM. However, NP models can allow at sizable levels.
  - STCF: \(10^{-8} \sim 10^{-9}\) \(\Rightarrow\) stringent constrains to NP models

More detail MC simulation are necessary!
Charmed Baryons

Charmed baryons are produced via $e^+e^- \rightarrow B_{1c}B_{2c}$ with $B_{ic} = n_1n_2c$

- Systematic measurement of absolute decay BFs with well controlled systematics and low backgrounds
- Thorough studies on the charmed baryon spectroscopy
R and QCD Physics

- Detailed study of exclusive processes $e^+ e^- \rightarrow (2-10)h$, $h=\pi, K, \eta, p…$
  - Scan between 2-7GeV and ISR $\sqrt{s} < 2$GeV
  - Meson Spectroscopy
  - Intermediate dynamics
  - Search for exotic states (tetraquarks, hybrids, glueballs)
  - Form factors
- High precision determination of $R = \frac{\sigma(e^+ e^- \rightarrow \text{hadrons})}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)}$ at low energies and fundamental quantities
  - $(g_\mu - 2)/2$, 92% from $< 2$GeV, 7% from 2-5GeV
  - $\alpha(M_Z)$, 19.0% from $< 2$GeV, 18.1% from 2-5GeV
  - QCD parameters (charm quark masses)
- Inclusive cross section $e^+ e^- \rightarrow h + X$
  - QCD parameters ($\alpha_s$, quark and gluon condensates)
  - Fragmentation functions; MLLA/LPHP prediction
  - Spin alignment of vector
- Two photon Physics
  - Measurement of $\Gamma_{\gamma\gamma}$ for $J^{PC} = 0^+, 0^{++}, 2^-, 2^{++}$ states
  - Study of $\gamma\gamma^* \rightarrow R$, $R = 1^{++}$
  - Transition Form Factors in $\gamma^*\gamma^* \rightarrow R$
  - Cross section of $\gamma\gamma \rightarrow \text{hadrons}$
Impact on \((g_\mu - 2)/2\)

At present, the anomalous magnetic moment of the muon \(a_\mu = (g - 2)\mu/2\) are known with an uncertainty of about one half per million!

\[
a_{\mu}^{\text{SM}} = (11 659 180.2 \pm 4.9) \cdot 10^{-10},
\]

\[
a_{\mu}^{\text{exp}} = (11 659 208.9 \pm 6.3) \cdot 10^{-10}.
\]

Data-driven approach:
reduce model uncertainty to 10-20%

SM-Exp: 3.5\(\sigma\) difference
Sensitive to probe new physics.

High Luminosity of STCF will largely improve the SM precisions
The threshold production of baryon pair

The Born cross section of the reaction $e^+ e^- \rightarrow \gamma^* \rightarrow B \bar{B}$ can be parameterized in terms of electromagnetic form factors:

$$\sigma_{B \bar{B}}(q) = \frac{4\pi \alpha^2 C \beta}{3q^2} \left[ |G_M(q)|^2 + \frac{1}{2\tau} |G_E(q)|^2 \right]$$

- Baryon velocity $\beta = \sqrt{1 - 4m_B^2 c^4 / q^2}$, $\tau = q^2 / (4m_B^2 c^4)$
- For charged $B$, the Coulomb factor $C$ will result in a non-zero cross section at threshold

Form factor reflects spatial distributions of electric charge and current inside the nucleon

100x more statistics at STCF will much enhance the understandings of these 'unexpected' threshold enhancement!
Summary

• **STCF is one of the crucial precision frontier**
• **Important playground for studying non-perturbative QCD and search for new physics**
  ✓ Charmonium(-like) states and exotic hadrons (luminosity and CME)
  ✓ Charmed meson (luminosity)
  ✓ Charmed baryon (CME)
  ✓ Tau CP and rare decay (polarized beam)
  ✓ New physics search (luminosity)
  ✓ ........
• **Complementary to Belle-II and LHCb in understanding the QCD/EW models and searching for new physics**
Thank you!

谢谢！
Nucleon Electromagnetic Form Factors (NEFFs)

Spatial distributions of electric charge and current inside the nucleon

Space-like: FF real

Time-like: FF complex

Complete picture of nucleon structure requires space-like and time-like FF

Space-Like FF
1% Precision
<table>
<thead>
<tr>
<th></th>
<th>BES-III 10^{33} cm^{-2} s^{-1}</th>
<th>STCF 10^{35} cm^{-2} s^{-1} (1 ab^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ</td>
<td>10 \times 10^9</td>
<td>10 \times 10^{11}</td>
</tr>
<tr>
<td>ψ(2S)</td>
<td>3 \times 10^9</td>
<td>3 \times 10^{11}</td>
</tr>
<tr>
<td>D(3.773 GeV)</td>
<td>6 \times 10^7</td>
<td>6 \times 10^9</td>
</tr>
<tr>
<td>Ds (4.17 GeV)</td>
<td>1 \times 10^7</td>
<td>1 \times 10^9</td>
</tr>
<tr>
<td>τ^+τ^- (3.68 GeV)</td>
<td>3 \times 10^7</td>
<td>2.4 \times 10^9</td>
</tr>
<tr>
<td>τ^+τ^- (4.25 GeV)</td>
<td>3 \times 10^7</td>
<td>3.5 \times 10^9</td>
</tr>
<tr>
<td>Λ_c^+Λ_c^- (4.64 GeV)</td>
<td>3 \times 10^6</td>
<td>6 \times 10^8</td>
</tr>
</tbody>
</table>