Particle Physics in China
Present & Future

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Outline

• Introduction

• Physics program @ BESIII
  – modern exotic mesons (XYZ) @ BESIII
  – Charm physics, $\Lambda_c$, light hadron $X(1835)$

• UH contribution:
  – $\tau$ – mass
  – old-fashion exotic mesons $\pi_1(1400)$, $\pi_1(1600)$ …

• BESIII future … and beyond
# Story of Stuff (SM)

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Gauge Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>u/c/t</td>
<td>e/μ/τ</td>
<td>W</td>
</tr>
<tr>
<td>g</td>
<td>ν_e/ν_μ/ν_τ</td>
<td>Z</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Quarks**
  - u (up) mass ≈ 2.3 MeV/c^2
  - c (charm) charge = 2/3, spin = 1/2
  - t (top) charge = 2/3, spin = 1/2
  - d (down) mass ≈ 4.8 MeV/c^2
  - s (strange) charge = -1/3, spin = 1/2
  - b (bottom) charge = -1/3, spin = 1/2

- **Leptons**
  - e (electron) mass = 0.511 MeV/c^2
  - μ (muon) mass = 105.7 MeV/c^2
  - τ (tau) mass = 1.777 GeV/c^2

- **Gauge Bosons**
  - Photon γ
  - W
  - Z
  - Higgs boson

- **Masses**
  - Higgs boson mass = 126 GeV/c^2
  - W mass = 80.4 GeV/c^2
  - Z mass = 91.2 GeV/c^2
All ‘ordinary’ hadrons are made of 2 or 3 quarks!

More precisely (QM): $q\bar{q}$ or $qqq$

What we observe:

- nucleons $\rightarrow$ $p = uud$, $n = udd$
- light mesons $\rightarrow$ $\pi^+ = u\bar{d}$, $\pi^- = \bar{u}d$
- charm meson $\rightarrow$ $D^+ = c\bar{d}$, $D^- = \bar{c}d$
- charmonium $\rightarrow$ $J/\psi = c\bar{c}$
Extraordinary QCD

QCD allowed but unusual == exotic:

- multi-quark states
- glueballs
- hybrids ...
- any meson with $J^{PC} = 0^{--}, 0^{-+}, 1^{+-}, 2^{++} \ldots$

We learn from hadron spectroscopy!
Heavy Flavor QCD: exotics popping out!

Why do we care?

N. Brambilla, et. al.: .... understanding QCD background was instrumental to the Higgs discovery ...!

Understanding QCD excitations in low-energy region might be instrumental for discovering NP in precision frontier?
**Z_c(4430) in B→ψ'π^+(-)K**

**Belle 2008**

- **PRL 100, 142001 (2008)**
  - Z(4430)^+

**Rapid phase transition at the peak of the amplitude:**
- Points to resonance!

**PRL 112, 222002 (2014)**
- Z(4430)^-
  - J^P = 1^+

---

M. Kornicer
22 Oct. 2015 :: University of Hawaii
Pentaquark @ LHCb

Two $P_c$, one exhibits phase transition consistent with resonance!
Experiments
BESIII Collaboration

- Pakistan (2)
  - Univ. of Punjab
  - COMSAT CIIT

- Korea (1)
  - Seoul Nat. Univ.

- Japan (1)
  - Tokyo Univ.

- China (30)
  - IHEP, CCAST, GUCAS, Shandong Univ.,
    - Univ. of Sci. and Tech. of China
    - Zhejiang Univ., Huangshan Coll.
    - Huazhong Normal Univ., Wuhan Univ.
    - Zhengzhou Univ., Henan Normal Univ.
    - Peking Univ., Tsinghua Univ.,
    - Zhengshan Univ., Nankai Univ.
    - Shanxi Univ., Sichuan Univ., Univ. of South China
    - Hunan Univ., Liaoning Univ.
    - Nanjing Univ., Nanjing Normal Univ.
    - Guangxi Normal Univ., Guangxi Univ.
    - Suzhou Univ., Hangzhou Normal Univ.
    - Lanzhou Univ., Henan Sci. and Tech. Univ.
    - Hong Kong Univ., Hong Kong Chinese Univ.

- US (6)
  - Univ. of Hawaii
  - Univ. of Washington
  - Carnegie Mellon Univ.
  - Univ. of Minnesota
  - Univ. of Rochester
  - Univ. of Indiana

- Europe (13)
  - Germany: Univ. of Bochum,
    - Univ. of Giessen, GSI
    - Univ. of Johannes Gutenberg
    - Helmholtz Ins. in Mainz
  - Russia: JINR Dubna; BINF Novosibirsk
  - Italy: Univ. of Torino,
    - Frascati Lab, Univ. of Ferrara
  - Netherlands: KVI/Univ. of Groningen
  - Sweden: Uppsala Univ.
  - Turkey: Turkey Accelerator Center

~350 members
53 institutions
11 countries
Beijing Electron Positron Collider II

BESIII

BEMS

Linac
BEPCII

Beam energy: 1-2.3 GeV
Crossing angle: 22 mrad
Design Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
Optimum energy: 1.89 GeV
Energy spread: $5.16 \times 10^{-4}$
No. of bunches: 93
Bunch length: 1.5 cm
Total current: 0.91 A
SR mode: 0.25 A @ 2.5 GeV

BEMS
Compton back-scattering for high precision beam energy measurement

BESIII is here
BESIII detector

Magnet Yoke

TOF:
80 ps - barrel

Be beam pipe

1 T SC magnet

RPC
9 layers

MDC: $\delta p/p = 0.58\%$, $dE/dx \sim 6\%$ at 1 GeV

CsI(Tl) calorimeter:
$\delta E = 2.5\%$ at 1 GeV

NIM A614, 345 (2010)
Energy range @ BEPCII

**2 ~ 4.6 GeV**

Transition between perturbative and non-perturbative QCD

Resonance rich: charmonia and charmed mesons

Interesting thresholds: \( \tau\tau, DD, D^*D^*, \Lambda_c\Lambda_c \ldots \)

Multi-quark states found, possible gluonic excitations...
Data collected by BESIII

World largest: $J/\psi$, $\psi(2S)$, $\psi(3770)$, $\Upsilon(4260)$ ... from direct $e^+e^-$ collisions!
BESIII: “τ-charm” factory

Charmonium physics:
- Spectroscopy
- transitions and decays

Light hadron physics:
- meson & baryon spectroscopy
- glueball & hybrid
- two-photon physics
- e.m. form factors of nucleon

Charm physics:
- (semi)leptonic + hadronic decays
- decay constant, from factors
- CKM matrix: $V_{cd}, V_{cs}$
- $D^0$-$D^0$bar mixing and CP violation
- rare/forbidden decays

Tau physics:
- Tau decays near threshold
- tau mass scan

...and many more.

- $X(3780), Y(4260), Z(3900), \Lambda_c$ ...
- $X(1835), X(2120), X(2370), Y(2175), Zs?$, $\pi_1(1600), f_0(980)-a_0(980)$...
- matrix elements for $\eta, \eta'$
- $f_D, f_{Ds}, EM$ FFs nucleon, hyperon, pion FF ...
- precision $\tau$-mass
- $\psi(2S) \rightarrow \tau\tau$ ...
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Charm physics:
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- decay constant, from factors
- CKM matrix: Vcd, Vcs
- D^0-D^0bar mixing and CP violation
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Tau physics:
- Tau decays near threshold
- tau mass scan

...and many more.
What do we see in the detector?

\[ e^+e^- \rightarrow J/\psi \rightarrow \mu^+\mu^- \]

\[ e^+e^- \rightarrow J/\psi \rightarrow e^+e^- \]

Signal purity 90%
Charged charmonium-like structure: $e^+e^- \rightarrow \pi^\mp (\pi^\pm J/\psi)$

- manifestly exotic:
  - couples to $c\bar{c}$
  - has charge
  - at least 4 quarks
  - what is it?

$Z_c(3900) \rightarrow \pi^\pm J/\psi$

- Significance $> 8\sigma$

M: $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c$^2$
Γ: $(46 \pm 10 \pm 20)$ MeV
R: $(21.5 \pm 3.3 \pm 7.8)\%$

PRL 110, 252001 (2013)
The first $Z_c$ confirmed by data from three experiments!
**Neutral partner!**

Studying $e^+e^-$ → $\pi^0\pi^0 J/\psi$ at different $\sqrt{s}$

**Isospin triplet established!**

\[ M: (3894.8 \pm 2.3 \pm 2.7) \text{ MeV/c}^2 \]

\[ \Gamma: (29.6 \pm 8.2 \pm 8.2) \text{ MeV} \]

Significance = $10\sigma$
$\sqrt{s} = 4.26$ GeV

Single D-tag: reconstruct $\pi^+$ and $D^0 \rightarrow K^-\pi^+$ and require that missing mass is consistent with $D^*$; (do the same for $\pi^+D^-D^{*0}$)

**Z_c(3900): close to D*D threshold**

\[ e^+e^- \rightarrow \pi^+ D^0 D^{*-} + c.c. \]
\[ e^+e^- \rightarrow \pi^+ D^- D^{*0} + c.c. \]
\[ \rightarrow K^-\pi^+ \pi^+ \]

Mass [MeV/c^2]:
\[ 3883.9 \pm 1.5 \pm 4.2 \]

Width [MeV]:
\[ 24.9 \pm 3.3 \pm 11.0 \]

Enhancement in both $D\overline{D}^*$ modes, labeled $Z_c(3883)$

PRL 112, 022001 (2014)
Reconstruct $\pi^+$ and $D^0$, $D^-$, in 4 or 6 decay modes, plus require $\pi$ in missing $D^*$ mass:

Mass [MeV/c$^2$]: $3884.3 \pm 1.2 \pm 1.5$
Width [MeV]: $23.8 \pm 2.1 \pm 2.6$

Angular analysis: $J^{PC} = 1^+$ from ST & DT!
$e^+ e^- \rightarrow \pi^+ \pi^- \omega @ 4.23-4.26 \text{ GeV}$

\[ \omega \rightarrow \pi^+ \pi^- \pi^0 \]

No significant $Z_c(3900) \rightarrow \pi \omega$ signal!

$\Gamma(Z_c(3900) \rightarrow \pi \omega) < 0.2 \% \ \Gamma_{\text{tot}}(Z_c(3900))$

Indicates that $c \bar{c}$ annihilation is suppressed!
$e^+e^- \rightarrow \pi\pi h_c(1P)$

$h_c \rightarrow \gamma \eta_c; \eta_c$ in 16 decay channels @ 13 different energies!

$\pi^\pm h_c$ structure observed: $Z_c(4020)$

$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}/c^2$

$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$

$e^-e^+ \rightarrow \pi^0\pi^0 h_c(1P)$:

$M = 4023.9 \pm 2.2 \pm 3.8 \text{ MeV}/c^2$

$\Gamma$ – fixed

Another isospin triplet established!
$Z_c(4020)$ close to $D^*D^*$ threshold

$e^+e^- \rightarrow \pi^- (D^*\bar{D}^*)^+ + c.c. \text{ at } \sqrt{s} = 4.26 \text{ GeV}$

Tag a $D^*$ and `bachelor` $\pi^-$:
look for recoil mass against $\pi^-$
after reconstructing $\pi^0$ to suppress
the background.

$D^*\bar{D}^*$ structure observed $Z_c(4025)$:
$M = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV/c}^2$
$\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$

If $Z_c(4020)$ and $Z_c(4025)$ are the same, coupling to $D^*\bar{D}^*$ much stronger compared to $\pi h_c$:

$$\sigma[e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp] = 137 \pm 9 \pm 15 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \rightarrow \pi^\pm Z_c(4025)^\mp \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp]}{\sigma[e^+e^- \rightarrow (D^*\bar{D}^*)^\pm\pi^\mp]} = 0.65 \pm 0.09 \pm 0.06$$
**Z_c(4020) close to D^*D^* threshold**

If Z_c(4020) and Z_c(4025) are the same, coupling to D^*D^* much stronger compared to πh_c:

\[
\sigma [e^+e^- \rightarrow (D^*\overline{D}^*)^\pm \pi^\mp] = 137 \pm 9 \pm 15 \text{ pb at 4.26 GeV}
\]

\[
\frac{\sigma [e^+e^- \rightarrow \pi^\pm Z_c(4025)\overline{\pi} \rightarrow (D^*\overline{D}^*)^\pm \pi^\mp]}{\sigma [e^+e^- \rightarrow (D^*\overline{D}^*)^\pm \pi^\mp]} = 0.65 \pm 0.09 \pm 0.06
\]
What we know so far!

\[ e^+ e^- \rightarrow \pi^- \pi^+ J/\psi \]

\[ e^+ e^- \rightarrow \pi^0 \pi^0 J/\psi \]

\[ e^+ e^- \rightarrow \pi^- \pi^+ h_c \]

\[ e^+ e^- \rightarrow \pi^0 \pi^0 h_c \]

\[ e^+ e^- \rightarrow \pi^- (D \bar{D}^*)^+ \]

\[ e^+ e^- \rightarrow \pi^0 (D \bar{D}^*)^0 \]

\[ e^+ e^- \rightarrow \pi^- (D^* \bar{D}^*)^+ \]

\[ e^+ e^- \rightarrow \pi^0 (D^* \bar{D}^*)^0 \]

\[ Z_c(3900)^+? \]

\[ Z_c(3900)^0? \]

\[ Z_c(4020)^+? \]

\[ Z_c(4020)^0? \]
**X(3872) @ BESIII**

**Strong evidence for**

\[ X(3872) \rightarrow \pi\pi J/\psi \]

\[ M = 3871.9 \pm 0.7 \pm 0.2 \text{ MeV/c}^2 \]

**Suggestive of**

\[ Y(4260) \rightarrow \gamma X(3872) \]

**PRL 112, 092001 (2014)**

**New mode of production of X(3872) and Y(4260) decay?**

If we take

\[ \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi) \sim 5\%, \ (\ > 2.6\% \ \text{in PDG}) \]

\[ \frac{\sigma(e^+e^-\rightarrow \gamma X(3872))}{\sigma(e^+e^-\rightarrow \pi^+\pi^- J/\psi)} \sim : 10\% \quad \text{Large transition ratio!} \]
Cross section measurements completed or ongoing (not a comprehensive list):

- $e^-e^+ \rightarrow \omega \chi_0$
  - no $\omega \chi_1$ or $\omega \chi_2$
- $e^-e^+ \rightarrow \eta J/\psi$ & $\eta' J/\psi$
- $e^-e^+ \rightarrow \eta \pi^0 J/\psi$
- $e^-e^+ \rightarrow \gamma \phi J/\psi$
- $e^-e^+ \rightarrow \gamma \chi_c J$
- …
What is the nature of multi-$q$ objects?

$\bar{Q}Q$  
Loop Corrections

$\bar{Q}Qg$  
Instantons

chiral doublers

hadrocharmonium

diquarks
cusps

Modern Exotic Hadrons” INT workshop starts in a couple of weeks!

E. Swanson: HADRON 2015
LH charmonium decays - hunting ground for light glueballs and hybrids

- "Gluon-rich" process
- Clean high statistics data samples from e+e- production
- I(J^PC) filter in strong decays of charmonium

\[
\begin{align*}
\Gamma(J/\psi \to \gamma G) & \sim O(\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha_s^3), \\
\Gamma(J/\psi \to \gamma M) & \sim O(\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha_s^4)
\end{align*}
\]
Light-hadrons: $X(???)$ $J^P=??$

This just an example, a lot of important analyses ongoing ...
Charm physics @ BESIII

Leptonic and semi-leptonic D decays are ideal window to probe for weak and strong effects

\[ \Gamma(D^{+}_{(s)} \to \ell^{+}\nu_{\ell}) = \frac{G_F^2 f^{2}_{D^{+}_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_{\ell}^2 m_{D^{+}_{(s)}}^2 \left(1 - \frac{m_{\ell}^2}{m_{D^{+}_{(s)}}^2}\right)^2 \]

\[ \frac{d\Gamma}{dq^2} = X \frac{G_F^2 |V_{cd(s)}|^2}{24\pi^3} \rho^3 |f_+(q^2)|^2 \]

- Precision measurements of decay constants \(f_{D^+}, f_{Ds^+}\), form factors \(f_+^{D \to K(\pi)}(q^2)\) of semi-leptonic decays of \(D_{(s)}\) mesons will calibrate LQCD calculations at higher accuracy.

- Recently improved LQCD calculations on \(f_{D(s)}^{[0.5(0.5)\%]}, f_+^{D \to K(\pi)}(0) [2.4(4.4)\%]\) provide good chance to precisely measure the CKM matrix element \(|V_{cs(d)}|\), which are important for the unitarity test of the CKM matrix and search for NP beyond the SM.
Improved form factor $f_+ \rightarrow D^{K(\pi)}(0) @ BESIII$
Improved $|V_{cs(d)}|$ @ BESIII

- **Method 1**: $B[D^{(s)^+ \rightarrow l^+\nu}]$
  - Input $t_{D^{s+}}, m_{D^{s+}}, m_\mu$, on PDG and LQCD calculated $f_{D^{s+}}$
  - $|V_{cd(s)}|$ Hussein

- **Method 2**: $f_{D^{+} \rightarrow K(\pi)(0)}|V_{cs(d)}|$
  - Input $f_{D^{+} \rightarrow K(\pi)(0)}$ of LQCD
  - $|V_{cs(d)}|$ Hussein

**Measurements**:
- Method: $D^{+} \rightarrow \mu^+\nu$
  - 1.009±0.040±0.020 (CLEO-c)
  - 0.978±0.026±0.022 (BaBar)
  - 1.041±0.033±0.032 (Belle)

- Method: $D^{0} \rightarrow \tau^+\tau^-$
  - 1.015±0.030±0.018 (CLEO-c)
  - 0.960±0.034±0.049 (BaBar)
  - 1.025±0.019±0.031 (Belle)

- Average ($D^{+} \rightarrow l^+\nu$)

**Data Sources**:
- PDG2014 $(\nu\bar{\nu})$
- CDHS, CCFR, CHARMII, CHORUS
- HPQCD Calculation
  - PRD56(2002)054510, CLEO-c ($D^{+} \rightarrow \mu^+\nu$)
  - PRD84(2011)114505, CLEO-c ($D^{+} \rightarrow \pi^+\nu$)
  - PRD90(2014)051104 (CHARM2012)
  - BESIII Preliminary ($D^{+} \rightarrow \mu^+\nu$)
  - Babar Preliminary ($D^{0} \rightarrow \pi^{-}\nu$)

**BESIII** will take 3 fb$^{-1}$ data at 4.17 GeV in 2016, improved measurement of $f_{D^{s+}}$ and $|V_{cs}|$ by $D^{+} \rightarrow l^+\nu$ is expected in the near future.
$\Lambda_c \to \Lambda e^+ \nu_e$ is $c \to s l \nu$ dominated, provides important info for:

- testing theoretical predictions for $B(\Lambda_c^+ \to \Lambda e^+ \nu_e)$
- LQCD calibration
- additional information for determining CKM elements
$\Lambda_c$ @ BESIII

Single Tag (ST)

![Diagrams showing distributions of various decay modes and their corresponding numbers of events.]

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_j^{ST}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pK_S^0$</td>
<td>1243 ± 37</td>
</tr>
<tr>
<td>$pK^-\pi^+$</td>
<td>6308 ± 88</td>
</tr>
<tr>
<td>$pK_S^0\pi^0$</td>
<td>558 ± 33</td>
</tr>
<tr>
<td>$pK_S^0\pi^+\pi^-$</td>
<td>485 ± 29</td>
</tr>
<tr>
<td>$pK^-\pi^+\pi^0$</td>
<td>1849 ± 71</td>
</tr>
<tr>
<td>$\Lambda\pi^+$</td>
<td>706 ± 27</td>
</tr>
<tr>
<td>$\Lambda\pi^+\pi^0$</td>
<td>1497 ± 52</td>
</tr>
<tr>
<td>$\Lambda\pi^+\pi^-\pi^+$</td>
<td>609 ± 31</td>
</tr>
<tr>
<td>$\Sigma^0\pi^+$</td>
<td>522 ± 27</td>
</tr>
<tr>
<td>$\Sigma^+\pi^0$</td>
<td>309 ± 24</td>
</tr>
<tr>
<td>$\Sigma^+\pi^+\pi^-$</td>
<td>1156 ± 49</td>
</tr>
<tr>
<td>$\Sigma^+\omega$</td>
<td>157 ± 22</td>
</tr>
</tbody>
</table>

ST sum: ~1.5K
$\Lambda_c$ @ BESIII

**Single Tag (ST)**

- $pK^0_S$
- $pK^-$ and $\pi^+$
- $\Lambda\pi^+$
- $\Lambda\pi^+\pi^0$
- $pK^0_S\pi^0$
- $\Lambda\pi^+\pi^-\pi^+$
- $pK^0_S\pi^+\pi^-$
- $\Sigma^+\pi^0$

**Double Tag (DT)**

- $pK^0_S$
- $pK^-$ and $\pi^+$
- $pK^-\pi^+\pi^0$
- $\Lambda\pi^+$
- $\Lambda\pi^+\pi^0$
- $\Sigma^+\pi^+\pi^-$
- $pK^0_S\pi^0$
- $\Lambda\pi^+\pi^-\pi^+$
- $\Sigma^0\pi^+$
- $pK^0_S\pi^+\pi^-$
- $\Sigma^+\pi^0$
- $\Sigma^+\omega$

**ST sum:** $\sim 1.5K$
We perform a simultaneous fit to all tag modes, taking into account the correlations.

<table>
<thead>
<tr>
<th>Decay modes</th>
<th>global fit $\mathcal{B}$</th>
<th>PDG $\mathcal{B}$ [1]</th>
<th>Belle $\mathcal{B}$ [6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pK_S$</td>
<td>$1.52 \pm 0.08 \pm 0.03$</td>
<td>$1.15 \pm 0.30$</td>
<td></td>
</tr>
<tr>
<td>$pK^-\pi^+$</td>
<td>$5.84 \pm 0.27 \pm 0.23$</td>
<td>$5.0 \pm 1.3$</td>
<td></td>
</tr>
<tr>
<td>$pK_S\pi^0$</td>
<td>$1.87 \pm 0.13 \pm 0.05$</td>
<td>$1.65 \pm 0.50$</td>
<td></td>
</tr>
<tr>
<td>$pK_S\pi^+\pi^-$</td>
<td>$1.53 \pm 0.11 \pm 0.09$</td>
<td>$1.30 \pm 0.35$</td>
<td></td>
</tr>
<tr>
<td>$pK^-\pi^+\pi^0$</td>
<td>$4.53 \pm 0.23 \pm 0.30$</td>
<td>$3.4 \pm 1.0$</td>
<td>$6.84 \pm 0.24^{+0.21}_{-0.27}$</td>
</tr>
<tr>
<td>$\Lambda\pi^+$</td>
<td>$1.24 \pm 0.07 \pm 0.03$</td>
<td>$1.07 \pm 0.28$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda\pi^+\pi^0$</td>
<td>$7.01 \pm 0.37 \pm 0.19$</td>
<td>$3.6 \pm 1.3$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda\pi^+\pi^-\pi^+$</td>
<td>$3.81 \pm 0.24 \pm 0.18$</td>
<td>$2.6 \pm 0.7$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^0\pi^+$</td>
<td>$1.27 \pm 0.08 \pm 0.03$</td>
<td>$1.05 \pm 0.28$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+\pi^0$</td>
<td>$1.18 \pm 0.10 \pm 0.03$</td>
<td>$1.00 \pm 0.34$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+\pi^+\pi^-$</td>
<td>$4.25 \pm 0.24 \pm 0.20$</td>
<td>$3.6 \pm 1.0$</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+\omega$</td>
<td>$1.56 \pm 0.20 \pm 0.07$</td>
<td>$2.7 \pm 1.0$</td>
<td></td>
</tr>
</tbody>
</table>

- $\mathcal{B}(pK^-\pi^+)$: BESIII precision comparable with Belle’s result
- BESIII rate $\mathcal{B}(pK^-\pi^+)$ is smaller
- Improved precision of the other 11 modes significantly
Search for a light CP-odd Higgs boson in the radiative decays of J/ψ

The BESIII Collaboration, M. Ablikim

(Submitted on 6 Oct 2015 (v1), last revised 10 Oct 2015 (this version, v2))

We search for a light Higgs boson $A^0$ in the fully reconstructed decay chain of $J/\psi \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+ \mu^-$ using $(225.0 \pm 2.8) \times 10^6 J/\psi$ events collected by the BESIII experiment. The $A^0$ is a hypothetical CP-odd light Higgs boson predicted by many extensions of the Standard Model including the Next-to-Minimal Supersymmetric Standard Model. We find no evidence for $A^0$ production and set 90\% confidence-level upper limits on the product branching fraction $B(J/\psi \rightarrow \gamma A^0) \times B(A^0 \rightarrow \mu^+ \mu^-)$ in the range of $(2.8 - 471.4) \times 10^{-8}$ for $0.212 \leq m_{A^0} \leq 3.0$ GeV/c$^2$. The new limits are an order of magnitude below our previous results and can exclude a large portion of the parameter space of the new physics models.
What else can we do @ BESIII?

UH contribution!

Fred Harris

Gary Varner

Tao Luo (left)

Xiaoling Li (visiting)
Leptonic world: $\tau$-mass

$m_\tau$ is a fundamental parameter in SM:

$$B(\tau \rightarrow e\nu\bar{\nu}) \frac{\tau_\tau}{g_\tau} = \frac{g_\tau^2 m_\tau^5}{192\pi^3}$$

$$Q = \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} \approx \frac{2}{3}$$

Test lepton universality: $g_e = g_\mu = g_\tau$

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau} \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \rightarrow e\nu\bar{\nu})}{B(\mu \rightarrow e\nu\bar{\nu})} (1 + F_W)(1 + F_\gamma)$$

Heaviest lepton, known with least precision:

- $M_e = 0.510998910 \pm 0.000000013 \ (2.6 \times 10^{-8})$
- $M_\mu = 105.658367 \pm 0.000004 \ (3.8 \times 10^{-8})$
- $M_\tau = 1776.82 \pm 0.16 \ (9.0 \times 10^{-5})$
Measure Compton scattered photon energy with high precision!

\[ E_e = \frac{E_\gamma}{2} \left[ 1 + \sqrt{1 + \frac{m_e^2}{E_\gamma E_\gamma}} \right] \]

\[ \delta m_{\psi}/m_\psi = 2 \times 10^{-5} \]

\[ \delta \Delta / \Delta = 6\% \]

*NIM A659, 21 (2011)*
Ingredients:

- **Luminosity** from $\gamma\gamma$ and Bhabha events (Fred)

- **Hadronic cross-section**: energy scale and energy spread from resonance line shapes (Mihajlo)

- **$\tau$ cross-section**: 13 two-prong decay modes, $ee$, $e\mu$, $e\pi$, $eK$, $\mu\mu$, $\mu K$, $\pi K$, $KK$, $e\rho$, $\mu\rho$ and $\pi\rho$ (with accompanying neutrinos implied) (Tao)

Analysis: 18 scan points

- $7 @ J/\psi$
- $4 @ \tau$
- $7 @ \psi(2S)$

using only 1/5 of proposed data = 24pb$^{-1}$
Hadronic cross section

Extrapolate mass correction, $\Delta M$ and energy spread $\delta \omega$ to $\tau$ region:

$\Delta M = 54 \pm 32$ KeV/c$^2$

$\delta w = 1.469 \pm 85$ MeV/c$^2$
The most precise measurement so far, tests lepton universality @ 0.4 σ level:

\[
(g_\tau / g_\mu)^2 = 1.0016 \pm 0.0042
\]
\[ \chi_{c1} \rightarrow hhh \ (0^--0^-0^-) \]

Assume two-body processes: \( 1^{++} \rightarrow (0^--0^-0^-) (\eta \pi \pi) \)

\( l=0: \chi_{c1} \rightarrow R_j \eta; \ R_j \rightarrow \pi \pi \)

\( l=1: \chi_{c1} \rightarrow R_j \pi; \ R_j \rightarrow \eta \pi \)

S-wave: the lowest orbital two-body excitation, manifestly exotic

<table>
<thead>
<tr>
<th>( J^{PC} )</th>
<th>( L )</th>
<th>Decay sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^{++}</td>
<td>P</td>
<td>( f_0(980) \eta, \ a_0(980) \pi )</td>
</tr>
<tr>
<td>1^{--}</td>
<td>S, D</td>
<td>( \pi_1(1600) \pi )</td>
</tr>
<tr>
<td>2^{++}</td>
<td>P, F</td>
<td>( f_2(1270) \eta, \ a_2(1320) \pi )</td>
</tr>
<tr>
<td>4^{++}</td>
<td>F, H</td>
<td>( f_4(2020) \eta, \ a_4(2040) \pi )</td>
</tr>
</tbody>
</table>

\( \pi_1(1400) \rightarrow \eta \pi : \) GAMS, KEK, C. Barrel, E852

\( \pi_1(1600) \rightarrow f_1 \pi; \ \eta' \pi; \ b_1 \pi: \) VES, E852, COMPASS, CLEO-c

Old 4q candidates: \( a_0(980) \rightarrow \eta \pi, \ f_0(980) \rightarrow \pi \pi: \)
$450M \ \psi(2S) \rightarrow \gamma \chi_{c1} ; \ \chi_{c1} \rightarrow \eta \pi \pi$

$N(\chi_{c1}) \sim 35000$

Purity after background subtraction: $98.5 \pm 0.3 \%$
$450 M \ \psi(2S) \rightarrow \gamma \chi_{c1} ; \ \chi_{c1} \rightarrow \eta \pi \pi$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\mathcal{B}(\chi_{c1} \rightarrow \eta \pi^+ \pi^-) \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \pi^+ \pi^-$</td>
<td>$4.819 \pm 0.031 \pm 0.088 \pm 0.210$</td>
</tr>
<tr>
<td>$a_0(980)^\pm \pi^\mp$</td>
<td>$3.506 \pm 0.034 \pm 0.182 \pm 0.153$</td>
</tr>
<tr>
<td>$a_2(1320)^\pm \pi^\mp$</td>
<td>$0.185 \pm 0.009 \pm 0.038 \pm 0.008$</td>
</tr>
<tr>
<td>$a_2(1700)^\pm \pi^\mp$</td>
<td>$0.048 \pm 0.005 \pm 0.014 \pm 0.002$</td>
</tr>
<tr>
<td>$S_{kk}\eta$</td>
<td>$0.123 \pm 0.007 \pm 0.018 \pm 0.005$</td>
</tr>
<tr>
<td>$S_{pp}\eta$</td>
<td>$0.791 \pm 0.019 \pm 0.037 \pm 0.035$</td>
</tr>
<tr>
<td>$\pi \pi S\eta$</td>
<td>$0.859 \pm 0.021 \pm 0.031 \pm 0.037$</td>
</tr>
<tr>
<td>$f_2(1270)\eta$</td>
<td>$0.371 \pm 0.012 \pm 0.054 \pm 0.016$</td>
</tr>
<tr>
<td>$f_4(2050)\eta$</td>
<td>$0.027 \pm 0.004 \pm 0.009 \pm 0.001$</td>
</tr>
</tbody>
</table>

**Clear evidence for $a_2(1700)$ in $\chi_{c1}$ decays.**

**First measurement of $g'_{\eta \pi} \neq 0$ using $a_0(980) \rightarrow \eta \pi$ line shape.**

**Measured upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c^2 region.**
Very rich and fruitful program:

- $3 \text{fb}^{-1} @ 4.17 \text{ GeV}$ expected in 2016
- Lots of proposals, including high precision $\tau$-mass
- Plans to continue next 6-8 years, partially in XYZ

<table>
<thead>
<tr>
<th></th>
<th>BESIII</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>$1.3 \times 10^9$ 21x BESII</td>
<td>$10 \times 10^9$</td>
</tr>
<tr>
<td>$\psi'$</td>
<td>$0.6 \times 10^9$ 24x CLEO-c</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>$\psi(3770)$</td>
<td>2.9 fb$^{-1}$ 21x CLEO-c</td>
<td>20 fb$^{-1}$</td>
</tr>
<tr>
<td>Above open charm threshold</td>
<td>0.5 fb$^{-1}$ @ $\psi(4040)$, 1.9 fb$^{-1}$ @~4260, 0.5 fb$^{-1}$ @4360, 1.0 fb$^{-1}$ @4420, 0.5 fb$^{-1}$ @4600</td>
<td>5-10 fb$^{-1}$</td>
</tr>
<tr>
<td>$R$ scan and tau</td>
<td>3.8-4.6 GeV at 105 energy points 2.0-3.1 GeV at 20 energy points</td>
<td></td>
</tr>
<tr>
<td>$\Upsilon(2175)$</td>
<td>100 pb$^{-1}$ (2015)</td>
<td></td>
</tr>
<tr>
<td>$\psi(4170)$</td>
<td>3 fb$^{-1}$ (next run)</td>
<td></td>
</tr>
</tbody>
</table>
What’s next
High Intensity Electron Positron Accelerator (HIEPA)

Collaborative Innovation Center for Particle Physics and Interaction

- University of Science and Technology of China
- Institute of High Energy Physics, CAS
- Institute of Theoretical Physics, CAS
- Tsinghua University
- University of Chinese Academy of Sciences
- Shangdong University
- Shanghai Jiaotong University
- Peking University
- Nanjing University
- Nankai University
- Wuhan University
- Hua Zhong Normal University
HIEPA: super $\tau$-charm factory!

- provide unique opportunities in the energy region that bridges the perturbative and non-perturbative QCD
- search for new forms of hadrons and explore the structure of hadrons
- search for possible NP at high intensity and high precision frontier.

Key features:
- HIEPA covers the CM energy of 2-7 GeV
- peak luminosity $L = 10^{35}$ cm$^{-2}$s$^{-1}$
- possible polarized beam
- serve as a 3rd/4th generation SRF
- do FEL studies..
HIEPA location

Center for Big Science of CAS
(USTC + CAS Hefei Branch)

National Research Center

Airport

College of Advanced Technology, USTC

USTC
CEPC & SppC

CEPC is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider SppC, to study the new physics beyond the Standard Model.
CEPC & SppC

Phase 1: \(e^+e^-\) Higgs (Z) factory  
Two detectors, 1M ZH events in 10yrs  
\(E_{cm} \approx 240\text{GeV}, \text{luminosity} \sim 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}\), can also run at the Z-pole  
Precision measurement of the Higgs boson (and the Z boson)

Phase 2: a discovery machine; pp collision with \(E_{cm} \approx 50\text{-}100\ \text{TeV}\); ep,HI options  
Discovery machine for BSM

QingHuangDao site  
300km from Beijing
CEPC & SppC: preCDR review

“The committee considers the CEPC-SPPC to be well aligned with the future of China’s HEP program, and in fact the future of the global HEP program.”

“The committee strongly endorses the physics case of the CEPC, as outlined in the preCDR, recognizing it as an essential step in the understanding of Nature”

“The Committee has been very impressed with the progress during such a short period of time, as well as the work and presentations shown, mostly done by the young generation, who are the ones that can devote their careers to this project through the coming decades”

• Physics goals and precision reachable (preliminary)
• No technological obstacles that cannot be overcome
• Specification of R&D items
• Initial cost estimate
• Complete preCDR (implement reviewers comments),
CEPC & SppC: Pre. R&D and funding

1. IHEP internal investment ~10M RMB
   organize teams, initialize preliminary R&D

2. Seek funding from Chinese Ministry of Sci. & Tech.
   kick-off R&D

In May 2015, the CEPC Study Group decided to begin the CDR process, with a preliminary target date of completion: end of 2016

An International Advisory Committee has been formed to advise the CEPC SG on int’l collaboration, organizational structures, governance, Science & Technology issues, etc.
Future in China seems bright!

Thank you
R&D plan of the 20 T accelerator magnets

(Very Preliminary)

- **2015-2020**: Development of a 12 T operational field Nb$_3$Sn twin-aperture dipole with common coil configuration and 10$^{-4}$ field quality; Fabrication and test of 2~3 T HTS (Bi-2212 or YBCO) coils in a 12 T background field and basic research on tape superconductors for accelerator magnets (field quality, fabrication method, quench protection).

- **2020-2025**: Development of a 15 T Nb$_3$Sn twin-aperture dipole and quadrupole with 10$^{-4}$ field uniformity; Fabrication and test of 4~5 T HTS (Bi-2212 or YBCO) coils in a 15 T background field.

- **2025-2030**: 15 T Nb$_3$Sn coils + HTS coils (or all-HTS) to realize the 20 T dipole and quadrupole with 10$^{-4}$ field uniformity; Development of the prototype SppC dipoles and quadrupoles and infrastructure build-up.

A long term plan for SC 20T magnets is being developed will be a world wide effort
Multi-quark objects

\[
\begin{align*}
\pi\pi J/\psi & \quad \pi D\bar{D}^* \\
Z_c(3900) & \\
\pi\pi h_c & \quad \pi D^*\bar{D}^* \\
Z_c(4025) & \\
K\pi\chi_{cJ} & \\
Z_1(4050) & \quad Z_2(4250) \\
K\pi J/\psi & \quad Z_c(4200)
\end{align*}
\]

No fundamental distinction between “tetraquarks” and “meson-meson bound states”.

\[
\begin{align*}
\pi K\psi' & \\
Z_c(4475) & \\
\pi\pi h_b(nS) & \quad \pi\pi h_b(nP) \\
\pi B\bar{B}^* & \quad Z_b(10610) \quad Z_b(10650) \\
\pi J/\psi & \quad P_c(4380) \quad P_c(4450)
\end{align*}
\]
$Z_c(3883)$: angular analysis

$0^-, \pi$ in P-wave: \( \frac{dN}{dcos\theta_\pi} \propto 1 - cos^2\theta_\pi \)

$1^-, \pi$ in P-wave: \( \frac{dN}{dcos\theta_\pi} \propto 1 - cos^2\theta_\pi \)

$1^+, \pi$ in S-wave: \( \frac{dN}{dcos\theta_\pi} \propto \text{flat} \)

(assuming D-wave small near threshold)

$0^+$: excluded by parity conservation

**Data clearly favor** \( J^{PC} = 1^+ \)

If \( Z_c(3900) \) and \( Z_c(3883) \) are the same:

\[
\frac{\mathcal{B}(Z_c \rightarrow D^* \bar{D})}{\mathcal{B}(Z_c \rightarrow J/\psi \pi)} = 6.2 \pm 1.1 \pm 2.7
\]

Compare to:

\[
\frac{\mathcal{B}(\psi(4040) \rightarrow D^{(*)} D^{(*)})}{\mathcal{B}(\psi(4040) \rightarrow J/\psi \eta)} = 192 \pm 27
\]

Open charm decays clearly suppressed: different dynamics in \( Y(4260) - Z_c(3900) \) system!
## What do we know so far!

<table>
<thead>
<tr>
<th>State</th>
<th>Mass(MeV)</th>
<th>Width(MeV)</th>
<th>Decay mode</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(3900)^\pm$</td>
<td>$3899.0 \pm 3.6 \pm 4.9$</td>
<td>$46 \pm 10 \pm 20$</td>
<td>$\pi^\pm J/\psi$</td>
<td>$e^+e^- \rightarrow \pi^+\pi^- J/\psi$</td>
</tr>
<tr>
<td>$Z_c(3900)^0$</td>
<td>$3894.8 \pm 2.3 \pm 2.7$</td>
<td>$29.6 \pm 8.2 \pm 8.2$</td>
<td>$\pi^0 J/\psi$</td>
<td>$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$</td>
</tr>
<tr>
<td>$Z_c(3885)^\pm$</td>
<td>$3883.9 \pm 1.5 \pm 4.2$</td>
<td>$24.8 \pm 3.3 \pm 11.0$</td>
<td>$D^0D^*-$</td>
<td>$e^+e^- \rightarrow \pi^+D^0D^*-$</td>
</tr>
<tr>
<td></td>
<td>[single D tag]</td>
<td>[single D tag]</td>
<td>$D^-D^*0$</td>
<td>$e^+e^- \rightarrow \pi^+D^-D^*0$</td>
</tr>
<tr>
<td></td>
<td>$3884.3 \pm 1.2 \pm 1.5$</td>
<td>$23.8 \pm 2.1 \pm 2.6$</td>
<td>$D^-D^*0$</td>
<td></td>
</tr>
<tr>
<td>$Z_c(3885)^0$</td>
<td>$3885.7^{+4.3}_{-5.7} \pm 8.4$</td>
<td>$35.0^{+11}_{-12} \pm 15$</td>
<td>$(DD^*)0$</td>
<td>$e^+e^- \rightarrow \pi^0(D^0D^*0)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow \pi^0(D^0D^*0)$</td>
<td></td>
</tr>
<tr>
<td>$Z_c(4020)^\pm$</td>
<td>$4022.9 \pm 0.8 \pm 2.7$</td>
<td>$7.9 \pm 2.7 \pm 2.6$</td>
<td>$\pi^\pm h_c$</td>
<td>$e^+e^- \rightarrow \pi^+\pi^- h_c$</td>
</tr>
<tr>
<td>$Z_c(4020)^0$</td>
<td>$4023.9 \pm 2.2 \pm 3.8$</td>
<td>fixed</td>
<td>$\pi^0 h_c$</td>
<td>$e^+e^- \rightarrow \pi^0\pi^0 h_c$</td>
</tr>
<tr>
<td>$Z_c(4025)^\pm$</td>
<td>$4026.3 \pm 2.6 \pm 3.7$</td>
<td>$24.8\pm5.6\pm7.7$</td>
<td>$D^*0D^-$</td>
<td>$e^+e^- \rightarrow \pi^+(D^* \bar{D}^*)-$</td>
</tr>
<tr>
<td>$Z_c(4025)^0$</td>
<td>$4025.5^{+2.0}_{-4.7} \pm 3.1$</td>
<td>$23.0 \pm 6.0 \pm 1.0$</td>
<td>$(D^<em>D^</em>)0$</td>
<td>$e^+e^- \rightarrow \pi^0(D^<em>D^</em>)0$</td>
</tr>
</tbody>
</table>
Reconstruct $\chi_c \rightarrow \gamma J/\psi \rightarrow \gamma \ell^+\ell^-$

look for $\pi\pi$ recoil

$e^+e^- \rightarrow \gamma \pi^+\pi^- \chi_c$ at 4.2-4.6 GeV

X(3823) candidate consistent with $\psi(1^3D_2) \rightarrow \gamma \chi_c$

$e^+e^- \rightarrow \pi^+\pi^- X(3823) \rightarrow \pi^+\pi^- \gamma \chi_c$

Cross-section v.s. energy

Line shape consistent with both Y(4260) & Y4360

$M = 3821.7 \pm 1.3 \pm 0.7$ MeV,  significance 6.7$\sigma$

$\Gamma < 16$ MeV at 90% C.L.
In the SM:

\[
\Gamma(D_{(s)}^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_\ell m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2
\]

Bridge to precisely measure

- Decay constant \(f_{D(s)^+}\) with input \(|V_{cd(s)}|^{\text{CKMfitter}}\)
- CKM matrix element \(|V_{cd(s)}|\) with input \(f_{LQCD}^{D(s)^+}\)
Comparing existing $D \to K(\pi)^-e^+\nu$ differential rates:

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

Bridge to precisely measure:

- Form factors $f_+^{D\to K(\pi)^-}(0)$ with input $|V_{cd(s)}|^{CKM fitter}$
  - Single pole form
    $$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}}$$
  - ISGW2 model
    $$f_+(q^2) = f_+^{(0)} \left(1 + \frac{q^2}{M_{pole}^2} \right) - 2$$
  - Modified pole model
    $$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right) (1 - \alpha \frac{q^2}{M_{pole}^2})}$$
  - Series expansion model
    $$f_+(t) = \frac{1}{P(t)\Phi(t, t_0)a_0(t_0)} \left(1 + \sum_{k=1}^{\infty} r_k(t_0) [z(t, t_0)]^k \right)$$

- CKM matrix element $|V_{cs(d)}|$ with input $f_+^{LQCD, D\to K(\pi)^-}(0)$
Comparing existing \( f_{D^+} \), \( f_{Ds^+} \)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Averaged</td>
<td>Expected</td>
<td>Δ</td>
</tr>
<tr>
<td>( f_{D^+} ) (MeV)</td>
<td>203.9±4.7</td>
<td>1.8σ</td>
</tr>
<tr>
<td>( f_{Ds^+} ) (MeV)</td>
<td>256.9±4.4</td>
<td>1.7σ</td>
</tr>
<tr>
<td>( f_{D^+:f_{Ds^+}} )</td>
<td>1.260±0.036</td>
<td>2.5σ</td>
</tr>
</tbody>
</table>

- Improving measurement with larger data sample is necessary!
The most precise measurement so far, tests lepton universality @ 0.4 σ level:

$$\left( \frac{g_\tau}{g_\mu} \right)^2 = 1.0016 \pm 0.0042$$
MC normalized by the luminosity and ratio of efficiencies for $\tau$-pair identification in data and MC

<table>
<thead>
<tr>
<th>Final state</th>
<th>1 Data</th>
<th>1 MC</th>
<th>2 Data</th>
<th>2 MC</th>
<th>3 Data</th>
<th>3 MC</th>
<th>4 Data</th>
<th>4 MC</th>
<th>Total Data</th>
<th>Total MC</th>
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<tbody>
<tr>
<td>$e_e$</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>3.7</td>
<td>13</td>
<td>12.2</td>
<td>84</td>
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<td>101</td>
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<td>$e_\mu$</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>9.1</td>
<td>35</td>
<td>31.4</td>
<td>168</td>
<td>192.6</td>
<td>211</td>
<td>233.1</td>
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<tr>
<td>$e_\pi$</td>
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<td>$\mu_\mu$</td>
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<td>2.9</td>
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<td>$\mu_\pi$</td>
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<td>0.8</td>
<td>7</td>
<td>9.0</td>
<td>10</td>
<td>10.1</td>
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<tr>
<td>$\pi_\pi$</td>
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<td>63.8</td>
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<td>0.3</td>
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<td>11</td>
<td>9.3</td>
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<td>0.4</td>
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<td>974</td>
<td>975.7</td>
<td>1171</td>
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</table>

Agree well
\( \tau - \text{mass: systematic uncertainties} \)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \Delta m_{\tau} ) (MeV/c(^2))</th>
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<tr>
<td>Theoretical accuracy</td>
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<td>Cut on number of good photons</td>
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<td>Cuts on PTEM and acoplanarity angle</td>
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<td>mis-ID efficiency</td>
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</table>
Adapted by A. Szczepaniak from

1. $S_{KK}$: for $KK \rightarrow \pi\pi$

2. $S_{\pi\pi}$: for $\pi\pi \rightarrow \pi\pi$, expanded using $z_{th}(s)$

$$S(s)_{\pi\pi} = c_0 S^0_{\pi\pi} + c_1 z_{KK} S^0_{\pi\pi} + c'_1 z_{st} S^0_{\pi\pi} + c_2 z^2_{st} S^0_{\pi\pi}$$

$$z_{KK}(s) = \frac{\sqrt{s + s_0} - \sqrt{4m_K^2 - s}}{\sqrt{s + s_0} + \sqrt{4m_K^2 - s}}$$

$$z_{st}(s) = \frac{\sqrt{s + s_0} - \sqrt{s' + s}}{\sqrt{s + s_0} + \sqrt{s' + s}}$$
Using dispersion relation; instead of Flatte parametrization, based on PRD 78 74023 (2008)

\[
D_\alpha(s) = m_0^2 - s - \sum \Pi_c(s) \quad \quad \quad \quad Im \Pi_c(s) = g_c^2 \rho_c(s) \quad \quad \quad \quad Re \Pi_c(s) = \frac{1}{\pi} P \int_{s_{th}}^{inf} \frac{Im \Pi_c(s') ds'}{(s' - s)}
\]

\[
D_\alpha(s) = m_0^2 - s - \left[ \sum_c Re \Pi_c(s) - Re \Pi_c(m_0) \right] - i \sum_c Im \Pi_c.
\]
From the last non-measured to Mostly precisely measured neutrino Mixing angle in a few years!

\[
\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}
\]