The Future of High Energy Physics and China’s Role

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RAL, Oct.5, 2018
A Very Active Field

- Hadron physics & QCD
- Neutrinos
- CP violation
- Antimatter
- Dark matter
- Axions
- Hadron physics & QCD

High Energy

- LHC: ATLAS/CMS
- ILC, FCC, CEPC/SPPC

Extra-dimensions

- Supersymmetry
- Compositeness

Precision tests

- Standard Model
- Rare decays

High precision

- BESIII, LHCb, BELLE II
- LUX, Xenon, LZ
- COMET, mu2e, g-2, K-decays
- ADMX

Higgs

- Daya Bay, JUNO, T2K, Nova,
- SuperK, HyperK, LBNF/DUNE,
- Icecube/PINGU, KM3net/ORKA,
- SNO+, EXO/nEXO, KamLAND-Zen,
- Gerda, Katrin
- LUX, Xenon, LZ, PandaX, CDEX,
- Darkside, ...

Others

- LHC: ATLAS/CMS
- ILC, FCC, CEPC/SPPC
- China-based
- China-participated

Others

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- ILC, FCC, CEPC/SPPC

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Standard Model of Cosmology

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- Fermi, DAMPE, AMS,
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- Fermi, DAMPE, AMS,
- LHC: ATLAS/CMS
- ILC, FCC, CEPC/SPPC

Others
Roadmaps of HEP in the World

• Japan (2012)
  – If new particles (e.g. Higgs) are discovered, build **ILC**
  – If $\theta_{13}$ is big enough, build **HyperK** and T2HK

• EU (2013)
  – Continue **LHC**, upgrade its luminosity, until 2035
  – Study future circular collider (**FCC-hh** or **FCC-ee**)

• US (2014)
  – Build long baseline neutrino facility **LBNF/DUNE**
  – Study future colliders

A new round of roadmap study is starting
Where Are We Going ?

• ILC is a machine we planned for ~30 years, way before the Higgs boson was discovered. Is it still the only machine for our future ?
• Shall we wait for results from LHC/HL-LHC to decide our next step ?
• What if ILC could not be approved ?
• What is the future of High Energy Physics ?
• A new route:
  – Thanks to the low mass Higgs, there is a possibility to build a circular e+e- collider (Higgs factory) followed by a proton machine in the same tunnel
  – This idea was reported for the first time at the “Higgs Factory workshop (HF2012)” in Oct. 2012 at Fermilab
Since 80’s, IHEP were working on e+e- colliders: BEPC/BEPICII
Since 2005, IHEP was discussing the next machine after BEPCII
The idea of a Circular e+e- Collider(CEPC) followed by a Super proton-proton collider(SPPC) quickly gained the momentum in IHEP and in the world
Science of CEPC-SPPC

• Electron-positron collider (90, 250 GeV)
  – Higgs Factory \( (10^6 \text{ Higgs}) \):
    • Precision study of Higgs\((m_h, J^{PC}, \text{couplings})\), Similar & complementary to ILC
    • Looking for hints of new physics
  – Z & W factory \( (10^{10} \text{ Z}^0) \):
    • precision test of SM
    • Rare decays ?
  – Flavor factory: b, c, \(\tau\) and QCD studies

• Proton-proton collider (~100 TeV)
  – Directly search for new physics beyond SM
  – Precision test of SM
    • e.g., \(h^3\) & \(h^4\) couplings

Precision measurement + searches: Complementary with each other!
Higgs: the Window to New Physics

• A very special particle:
  – The only elementary particle with spin 0
    • Really elementary?
    • Similar to $p$, Cooper pair?
  – The only elementary particle with non-gauge interactions
    • Self-coupling and Yukawa coupling: anything new?

• Directly related to physics beyond SM & Cosmology
  – May interact with dark matter particles
  – Origin of the mass of Higgs?
  – Self-coupling may affect the evolution of the universe
  – Understand the vacuum: why meta-stable?

• Goal: By detailed and precise measurement of Higgs properties to understand these issues

<table>
<thead>
<tr>
<th>particle</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark: $u$, $d$,...</td>
<td>$1/2$</td>
</tr>
<tr>
<td>lepton: $e$,...</td>
<td>$1/2$</td>
</tr>
<tr>
<td>photon</td>
<td>1</td>
</tr>
<tr>
<td>$W,Z$</td>
<td>1</td>
</tr>
<tr>
<td>gluon</td>
<td>1</td>
</tr>
<tr>
<td>Higgs</td>
<td>0</td>
</tr>
</tbody>
</table>

Detailed study of Higgs can not be skipped.
Precision Higgs Physics by CEPC

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2} \mathcal{O}_{6,i} \]
\[ \delta \sim c_i \frac{v^2}{M^2} \]

At LHC:
- Direct searches: \( M \sim 1 \) TeV
- 10% precision: \( M \sim 1 \) TeV

At CEPC:
- 1% precision ⇒ \( M \sim 10 \) TeV

Higgs factory is our first choice if no new physics at LHC
Higgs factory is also a great choice if new physics found at LHC
Nature of EW Phase Transition?

- 1\textsuperscript{st} or 2\textsuperscript{nd} order ⇒ Huge implications
  - O(1) deviations in $h^3$ coupling
  - O(1\%) shift in $h$-$Z$ coupling

- CEPC can determine it:
  - $h^3$ coupling at CEPC: 20-30\%
  - $h$-$Z$ coupling at CEPC: $< 0.2\%$

M. McCullough, PRD 90(2014)015001

[Graph showing precision of measurements at different facilities]

arXiv:1608.06619
Improvement in Electroweak Precision

• A total of $10^{11} Z$
• A detailed study of $Z$ & $W$ to look for deviations from the Standard Model
• Can probe new physics up to $\sim$ TeV, better than HL-LHC by a factor of 3
## Comparison with Other Machines

<table>
<thead>
<tr>
<th></th>
<th>Science</th>
<th>Upgrade</th>
<th>Technology</th>
<th>Cost</th>
<th>Schedule</th>
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<tbody>
<tr>
<td>CEPC</td>
<td>****</td>
<td>****</td>
<td>****</td>
<td>*****</td>
<td>*****</td>
</tr>
<tr>
<td>SppC</td>
<td>*****</td>
<td>*</td>
<td>**</td>
<td>***</td>
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<tr>
<td>ILC</td>
<td>****</td>
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<tr>
<td>FCC-ee</td>
<td>****</td>
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<td>?</td>
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<tr>
<td>FCC-pp</td>
<td>*****</td>
<td>*</td>
<td>**</td>
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<td>VLHC</td>
<td>*****</td>
<td>***</td>
<td>****</td>
<td>**</td>
<td>?</td>
</tr>
<tr>
<td>Muon collider</td>
<td>*****</td>
<td>****</td>
<td>*</td>
<td>*</td>
<td>?</td>
</tr>
</tbody>
</table>

CEPC+SPPC is the best combination
CEPC is also a great light source

- From dipole magnet, the photon energy can reach 628keV.
- From Wiggler or undulator, the photon energy can reach 100MeV.
- Incredible application on nuclear physics, material science, micro-processing, etc.
CEPC Accelerator Design

3 Machines in a tunnel:
- CEPC & booster
- SppC

Compatibility is the key

6~10 GeV

Electron

Positron

Booster

Energy Ramp 10 -> 45/120 GeV

LINAC

Storage Ring

45/120 GeV
Baseline: 100 km, 30 MW; Upgradable to 50 MW, High Lumi Z
Try all means to cut cost down
An alternative based on Plasma Wakefield Accelerator: 45 GeV

- HTR PWFA with good stability (single stage $TR=3-4$, Cascaded stage 6-12, high efficiency)
- Positron generation and acceleration in an electron beam driven PWFA using hollow plasma channel ($TR=1$)
For the same cost, CEPC may obtain $\times 6$ more Higgs (+ a tunnel for proton machine)
## Main Parameters

<table>
<thead>
<tr>
<th></th>
<th>Higgs</th>
<th>W</th>
<th>Z (3T)</th>
<th>Z (2T)</th>
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<tbody>
<tr>
<td>Number of IPs</td>
<td>2</td>
<td></td>
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<td>Beam energy (GeV)</td>
<td>120</td>
<td>80</td>
<td>45.5</td>
<td></td>
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<tr>
<td>Circumference (km)</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synchrotron radiation loss/turn (GeV)</td>
<td>1.73</td>
<td>0.34</td>
<td>0.036</td>
<td></td>
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<tr>
<td>Crossing angle at IP (mrad)</td>
<td>16.5×2</td>
<td></td>
<td></td>
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<tr>
<td>Piwinski angle</td>
<td>2.58</td>
<td>7.0</td>
<td>23.8</td>
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<tr>
<td>Number of particles/bunch $N_e (10^{10})$</td>
<td>15.0</td>
<td>12.0</td>
<td>8.0</td>
<td></td>
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<tr>
<td>Bunch number (bunch spacing)</td>
<td>242 (0.68µs)</td>
<td>1524 (0.21µs)</td>
<td>12000 (25ns+10%gap)</td>
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<tr>
<td>Beam current (mA)</td>
<td>17.4</td>
<td>87.9</td>
<td>461.0</td>
<td></td>
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<tr>
<td>Synchrotron radiation power /beam (MW)</td>
<td>30</td>
<td>30</td>
<td>16.5</td>
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<tr>
<td>Bending radius (km)</td>
<td></td>
<td>10.7</td>
<td></td>
<td></td>
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<tr>
<td>Momentum compact (10⁻⁵)</td>
<td>1.11</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\beta$ function at IP $\beta _x / \beta _y$ (m)</td>
<td>0.36/0.0015</td>
<td>0.36/0.0015</td>
<td>0.2/0.0015</td>
<td>0.2/0.001</td>
</tr>
<tr>
<td>Emittance $\varepsilon _x / \varepsilon _y$ (nm)</td>
<td>1.21/0.0031</td>
<td>0.54/0.0016</td>
<td>0.18/0.004</td>
<td>0.18/0.0016</td>
</tr>
<tr>
<td>Beam size at IP $\sigma _x / \sigma _y$ (µm)</td>
<td>20.9/0.068</td>
<td>13.9/0.049</td>
<td>6.0/0.078</td>
<td>6.0/0.04</td>
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<tr>
<td>Beam-beam parameters $\xi / \xi _y$</td>
<td>0.031/0.109</td>
<td>0.013/0.106</td>
<td>0.0041/0.056</td>
<td>0.0041/0.072</td>
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<td>RF voltage $V_{RF}$ (GV)</td>
<td>2.17</td>
<td>0.47</td>
<td>0.10</td>
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<tr>
<td>RF frequency $f_{RF}$ (MHz) (harmonic)</td>
<td>650 (216816)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Natural bunch length $\sigma _x$ (mm)</td>
<td>2.72</td>
<td>2.98</td>
<td>2.42</td>
<td></td>
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<tr>
<td>Bunch length $\sigma _y$ (mm)</td>
<td>3.26</td>
<td>5.9</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Betatron tune $\nu _x / \nu _y$</td>
<td></td>
<td></td>
<td>363.10 / 365.22</td>
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<tr>
<td>Synchrotron tune $\nu _x$</td>
<td>0.065</td>
<td>0.0395</td>
<td>0.028</td>
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<tr>
<td>HOM power/cavity (2 cell) (kw)</td>
<td>0.54</td>
<td>0.75</td>
<td>1.94</td>
<td></td>
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<tr>
<td>Natural energy spread (%)</td>
<td>0.1</td>
<td>0.066</td>
<td>0.038</td>
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<tr>
<td>Energy acceptance requirement (%)</td>
<td>1.35</td>
<td>0.4</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>Energy acceptance by RF (%)</td>
<td>2.06</td>
<td>1.47</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Photon number due to beamstrahlung</td>
<td>0.29</td>
<td>0.35</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Lifetime _simulation (min)</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime (hour)</td>
<td>0.67</td>
<td>1.4</td>
<td>4.0</td>
<td>2.1</td>
</tr>
<tr>
<td>$F$ (hour glass)</td>
<td>0.89</td>
<td>0.94</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Luminosity/IP $L (10^{34}cm^{-2}s^{-1})$</td>
<td>2.93</td>
<td>10.1</td>
<td>16.6</td>
<td>32.1</td>
</tr>
</tbody>
</table>
CEPC Funding in China

HEP seed money
11 M RMB/3 years (2015-2017)

Funding from NSFC strain
from 2015: ~ 2 M/yr

<table>
<thead>
<tr>
<th>CEPC相关基金名称（2015-2016）</th>
<th>基金类型</th>
<th>负责人</th>
<th>承担单位</th>
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<tbody>
<tr>
<td>额精度气体探测器及激光校正的研究(2015)</td>
<td>重点基金</td>
<td>李玉兰/陈元培</td>
<td>清华大学/高能物理研究所</td>
</tr>
<tr>
<td>成像型电磁量能器关键技术研究(2016)</td>
<td>重点基金</td>
<td>刘福彬</td>
<td>中国科学技术大学</td>
</tr>
<tr>
<td>CEPC局部双环对撞区挡板系统设计及磁极笼场补偿(2016)</td>
<td>面上基金</td>
<td>白文</td>
<td>高能物理研究所</td>
</tr>
<tr>
<td>用于顶点探测器的高分辨、低功耗SOI像素芯片的若干关键技术的研究(2015)</td>
<td>面上基金</td>
<td>卢云鹏</td>
<td>高能物理研究所</td>
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<tr>
<td>基于粒子流算法的电磁量能器性能研究(2016)</td>
<td>面上基金</td>
<td>王志刚</td>
<td>高能物理研究所</td>
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<tr>
<td>基于THGEM探测器的数字量能器的研究(2015)</td>
<td>面上基金</td>
<td>俞伯祥</td>
<td>高能物理研究所</td>
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<td>高精度量能器上的通用粒子流算法开发(2016)</td>
<td>面上基金</td>
<td>何曼奇</td>
<td>高能物理研究所</td>
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<tr>
<td>正电子/反电子连续抑制型气体探测器的实验研究(2016)</td>
<td>面上基金</td>
<td>祁辉</td>
<td>高能物理研究所</td>
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<tr>
<td>CEPC对撞区聚焦系统的最新研究(2015)</td>
<td>青年基金</td>
<td>王亮</td>
<td>高能物理研究所</td>
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<tr>
<td>利用透镜型CPS提高顶点探测器空间分辨精度的研究(2016)</td>
<td>青年基金</td>
<td>周扬</td>
<td>高能物理研究所</td>
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<tr>
<td>关于CEPC动力学孔径研究(2016)</td>
<td>青年基金</td>
<td>王毅伟</td>
<td>高能物理研究所</td>
</tr>
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</table>

Funding from NCDR
Failed

Funding from the MOST
36 M/5yr in 2016
31 M/5yr in 2018

Funding from CAS
40 M/5yr talent program
6 M/5r international collaboration
360 M/5y HTc materials and magnet

Funding Beijing city
300 M/3yr for accelerator(light source)
6 M/5yr for RF cavities

Funding needed for CEPC design and R&D are mostly satisfied
R&D and Prototypes

Superconducting RF Cavities

High precision, low field dipole magnet

Collaborating on Klystrons

6m long vacuum pipes (Al & Cu)
SRF Cavities

- Key components for CEPC and other accelerators
- A new SRF testing facility is under construction, thanks to Beijing city government
- Shanghai city government decided to build Shanghai Coherent Light Facility (SCLF).
  - 432 1.3 GHz cavities
  - 54 Cryomodules
- IHEP plans to provide > 1/3 of cavities and cryomodules, an excellent exercise for us.
CEPC/SPPC and FCC

- It would be great if we can have one of them
- We are happy to collaborate with FCC and even join the FCC if it is approved
- We believe that it is better to start e+e- first and in the meantime to develop the next generation magnet technology
  - Current technology based on NbSn$_3$ is already 60 years old: difficult, expensive and not so high the field
  - Next generation high Tc Superconducting cable should be our goal, in particular Fe-based HTC
    - Advantages: metal, easy to process; isotropic; cheap in principle
- ~ 20 years development time needed for HTC cable is just about right for us to work on the e+e- collider
High Field Magnet based on HTC Cable?

- Future FCC_hh/SPPC should based on future technologies
- HTC has a huge impact beyond HEP if we can improve the performance/cost ratio by a factor 100
- Fe-based HTC cable at CAS
  - World highest Tc Fe-based materials
  - World first ~ 115 m Fe-based SC cables: $12000 \text{ A/cm}^2$ @ 10 T
- A collaboration on “HTC SC materials” established
  - IOP, USTC, IOEE, SC cable companies
  - Two approaches:
    - Fe-based HTC cables
    - ReBCO & Bi-2212
  - Funding from CAS 360M RMB/5yrs
- A workshop in Hong Kong this Jan. Next one in KEK
International Collaboration

- Limited international participation for the CDR
  - Not in any roadmap
  - No funding support
- Hopefully it will be included in the roadmap of Europe, Japan and the US
- International advisory board: A lot of suggestions
- MOUs signed with many institutions
- Welcome recommendation/suggestions
Other Activities in China

- Standard Model
- Hadron physics & QCD
- Neutrinos
- CP violation
- Antimatter
- Axions
- Compositeness
- Extra-dimensions
- Supersymmetry
- Precision tests
- Rare decays
- Dark matter
- Neutrinos
- Dark matter

- Accelerator based experiments
- Cosmic-ray physics at high altitude
- Space experiments
- Underground experiments

High Energy

Cosmology

Standard Model of Cosmology

> 30 years of experience on e⁺e⁻ collider!
BESIII Collaboration

64 institutions
~ 400 collaborators

US (5)
- Univ. of Hawaii
- Carnegie Mellon Univ.
- Univ. of Minnesota
- Univ. of Rochester
- Univ. of Indiana

EUROPE (16)
- Germany: Univ. of Bochum, Munster, Giessen, GSI, Mainz, HIM
- Russia: JINR, Dubna; BINS, Novosibirsk
- Italy: Univ. of Torino, Frascati Lab, Ferrara Univ.
- Netherlands: KVI/Univ. of Groningen
- Sweden: Uppsala Univ.
- Turkey: Turkey Accelerator Center
- UK: Manchester, Oxford

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

India (1)
- Univ. of Punjab
- COMSAT CIIT

China (37)
- IHEP, CCAST, 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.
- Zhongshan Univ., Nankai Univ.
- Shanxi Univ., Sichuan Univ., Fudan
- Suzhou Univ., Hangzhou Normal Univ.
- Hunan Univ., Liaoning Univ.
- BIPCT
- Henan Univ. of Sci. & Tech., Neihang Univ.
- Nanjing Univ., Nanjing Normal Univ.
- Guangxi Normal Univ., Guangxi Univ.
- Hong Univ., Hong Kong Chinese Univ.

Mongolia (1)
- Inst. of Phys. and tech.

Korea (1)
- Souel Nat. Univ.

Japan (1)
- Tokyo Univ.
Main Highlights:
- Discovery of $Z_{c}^{\pm}(3900)$: a four-quark states
- Discovery of accompany states: $Z_{c}^{0}(3900)$, $Z_{c}(4025)/Z_{c}(4020)$, ...
- Discovery of structures in $Y(4260)$
- Exotic light hadrons: $X(1835)$, $X(1870)$, $X(2120)$, ...
- New decay channels
- Charm physics, tau, QCD, etc.

> 20 papers/year, ~ 200 papers in total so far

BESIII will continue to operate for another ~8 years.
**Future Plan of BEPCII/BESIII**

- Up to now, ~ 20-30 papers/year, ~ 200 papers in total
- Minor upgrades completed, more under study
- BEPCII/BESIII will continue to operate for another ~8 years.

<table>
<thead>
<tr>
<th></th>
<th>Previous data</th>
<th>BESIII present</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>J/ψ</strong></td>
<td>BESII 58M</td>
<td>4.2 B</td>
<td>10 B</td>
</tr>
<tr>
<td><strong>ψ’</strong></td>
<td>CLEO: 28 M</td>
<td>0.5 B</td>
<td>3 B</td>
</tr>
<tr>
<td><strong>ψ”</strong></td>
<td>CLEO: 0.8/fb</td>
<td>2.9/fb</td>
<td>20 /fb</td>
</tr>
<tr>
<td><strong>Above open charm</strong></td>
<td>CLEO: 0.6/fb</td>
<td>0.5/fb @ ψ(4040) 2.3/fb @ ~4260, 0.5/fb @ 4360 0.5/fb @ 4600, 1/fb @ 4420</td>
<td>5-10 /fb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scan from 4.19 – 4.28, 10 MeV step, 500 pb⁻¹/point, 7 points</td>
<td></td>
</tr>
<tr>
<td><strong>R scan &amp; Tau</strong></td>
<td>BESII</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><strong>Y(2175)</strong></td>
<td></td>
<td>100 pb⁻¹</td>
<td></td>
</tr>
<tr>
<td><strong>ψ(4160)</strong></td>
<td></td>
<td>3 fb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>
Astrophysics in China Since 50’s

Yunnan, 3200m, 60’s

Tibet, 5500m, 70’s

Cloud Chamber, 60’s

Tibet, 4200m, 90’s
A large air shower array for cosmic rays and $\gamma$-astronomy
- Construction just started, data taking at ~ 2020
- Complementary to CTA:
  - All the time, all the sky
  - Time-variant and extended sources
  - Fast indication for CTA

Main Array:
- 5195 scintillator detectors every 15 m
- 1146 $\mu$-detectors every 30 m

Sichuan, 4300 m a.s.l.
Cosmic-Ray in Space

- 3D crystal calorimeter for dark matter searches and cosmic-ray physics
- Acceptance & energy range $\times 10$
- Collaboration with Italy, Sweden, Switzerland, …
- To be launched in 2025

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$X_0(\lambda)$</th>
<th>$\Delta E/E$ for e</th>
<th>e/p sep</th>
<th>GF m$^2$sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERD (2020)</td>
<td>55(3)</td>
<td>1%</td>
<td>$10^{-6}$</td>
<td>3.1</td>
</tr>
<tr>
<td>Fermi (2008)</td>
<td>10</td>
<td>12%</td>
<td>$10^{-3}$</td>
<td>0.9</td>
</tr>
<tr>
<td>AMS02 (2011)</td>
<td>17</td>
<td>2%</td>
<td>$10^{-6}$</td>
<td>0.12</td>
</tr>
<tr>
<td>DAMPE (2015)</td>
<td>31</td>
<td>1%</td>
<td>$10^{-4}$</td>
<td>0.3</td>
</tr>
<tr>
<td>CREAM (2015)</td>
<td>20(1.5)</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
JinPin Underground Laboratory

- The deepest underground laboratory in the world: 2400 m
- Current experiments: dark matter searches
  - Xe-based PandaX
  - Ge-based CDEX

Latest PandaX results

PRL 117, 121303 (2016)
New Jinpin Underground Laboratory

- Continue dark matter searches
- Start double beta-decay experiment

**PandaX-III**: 0.2-1 t high pressure gaseous $^{136}$Xe TPC for $\beta\beta$ decays
Daya Bay Experiment

**Solar ν Oscillation**
\[ \sin^2 2\theta_{12} \sim 0.9 \]

**Atm. ν Oscillation**
\[ \sin^2 2\theta_{23} \sim 1 \]

\[ \nu_1 \]
\[ \nu_2 \]
\[ \nu_3 \]

\[ \theta_{13} ? \]
Results and Prospects

- $\sin^2 2\theta_{13}$ is determined to be non-zero
- Precision improved from $\sim 20\%$ to $\sim 4\%$
- Daya Bay will operate until 2020, precision expected: $< 3\%$
- Combined with T2K & Nova, CP Phase is estimated to be $\sim -90^\circ$
The JUNO Experiment

<table>
<thead>
<tr>
<th>NPP</th>
<th>Daya Bay</th>
<th>Huizhou</th>
<th>Lufeng</th>
<th>Yangjiang</th>
<th>Taishan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Operational</td>
<td>Planned</td>
<td>Planned</td>
<td>Under construction</td>
<td>Under construction</td>
</tr>
<tr>
<td>Power</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>17.4 GW</td>
<td>18.4 GW</td>
</tr>
</tbody>
</table>

Overburden ~ 700 m

Kalping, Jiang Men city, Guangdong Province

by 2020: 26.6 GW
JUNO Detector and Challenges

- Largest LS detector $\Rightarrow \times 20$ KamLAND, $\times 40$ Borexino
- Highest light yield $\Rightarrow \times 2$ Borexino, $\times 5$ KamLAND

- Hugh cavern:
  - $\approx 48 \times 70$m
- Largest Acrylic tank:
  - $\Phi 35.4$m (13m@SNO)
- 20 kt LS
  - Best attenuation length: 25m (15m @ Daya Bay)
- 20000 20” PMT
  - Highest photon detection efficiency: $30\% \times 100\% = 30\%$ ($25\% \times 60\% = 15\% @ $SuperK$)

- Mass Hierarchy
- Oscillation parameters
- Supernova neutrinos
- Geo-neutrinos
- Solar neutrinos
- Double beta decays
Detector R&D and Construction

- A huge acrylic tank:
  - R&D and design completed, procedures of manufacturing understood
  - Prototypes underway
  - Contract signed

- A SS structure to hold the acrylic tank and to mount PMTs
  - Design completed, contract signed
  - Issues like tem. change, earth quake, Assembly & installation understood

- 20 kt liquid scintillator
  - Completed the optimization of LS for the best light yield and attenuation length
  - Completed the 20t test of purification: attenuation length > 20 m.
  - Radio-purity under testing
Photomultipliers

- Large, High QE PMT’s is the key to obtain sufficient photons
- Efforts started in 2009 to develop MCP-PMT, with a goal of QE > 35%
- Partnered with companies and research institutes: NNVC, XIOPM, etc.
- Successful development:
  - NNVC: QE(30%)*DE(100%) > 27%
  - Hamamatsu: QE(30%)*DE(90%) > 27%
- Contract signed (based on quality, availability, cost, risk et al.)
  - 15000 from NNVC, 5000 from Hamamatsu
- More than 6000 MCP-PMT from NNVT and 4000 PMT from Hamamatsu
  - Most of them met our spec.
  - New tubes from NNVT now has DE > 30%

Hamamatsu:
PDE ~ 28%
P/V ~ 5

New NNVT:
PDE ~ 30%
P/V ~ 6
~ 600m vertical shaft, ~1300m sloped tunnel
Underground cavern with 50 m diameter, 70 m height
JUNO Collaboration

Europe (28)
Belgium (1)
ULB
Czech (1)
Charles U
Latvia (1)
IECS
Finland (1)
U.Oulu
France (5)
APC Paris
CPPM Marseille
IPHC Strasbourg
Subatech Nantes
CENBG-IN2P3

Italy (8)
INFN-Catania
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Mi-Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma 3

Germany (7)
FZ Jülich
RWTH Aachen
TUM
U.Hamburg
IKP FZI Jülich
U.Mainz
U.Tuebingen

Russia (3)
INR Moscow
JINR
MSU

Slovakia (1)
FMPICU

America (6)
US (2)
UMD
UMD-Geo
Chile (2)
PCUC
UTFSM
Brazil (2)
PUC-Rio
UEL

China (33)
BJ Nor. U.
CAGS
Chongqing U.
Shanghai JT U.
DGUT
ECUST
Guangxi U.
HIT
IHEP
U. Of South China
Ninan U.
Nanjing U.
Nat. Chiao-Tung U.
Nat. Taiwan U.
Nat. United U.

Armenia (1)
Yerevan Phys. Inst.

Thailand (3)
SUT
PPRLCU
NARIT
Parkistan (1)
PINSTECH

Asia (38)
Nankai U.
NCEPU
Pekin U.
SDU
Sichuan U.
CIAE
SYSU
Tsinghua U.
UCAS
USTC
Jilin U.
Wuhan U.
Wuyi U.
Xi'an JT U.
Xiamen U.
NUU.

17 countries/regions, 72 institutions, 550 members
Other Neutrino Projects

- There are tens of neutrino projects under operation, construction and planning.
- In ten years from now, oscillation will be completely understood:
  - Nova+JUNO+ORCA/PINGU+DUNE will determine the mass hierarchy, while DUNE+T2HK will determine the CP phase.
- $0^\nu \beta\beta$ decay will be the next breakthrough.

- Hints from cosmology: $< \sim 1 \text{ eV}$
- Guess from Oscillation: $\sim 1 \text{ meV}$
- Katrin will probe to $\sim 0.2 \text{ eV}$

\[
(m_{\nu_e})^{\text{eff}} = |\Sigma_i |U_{ei}|^2 m^2_{\nu_i}|^{1/2}
\]

- $0^\nu \beta\beta$ decay should target for $\sim 1 \text{ meV}$

\[
<M_{ee}> = |\Sigma_i (U_{ei})^2 m_{\nu_i}|
\]
**JUNO-ββ**

- Insert a balloon filled with $^{136}$Xe-loaded LS (or $^{130}$Te) into the JUNO detector
- Cosmic-induced backgrounds are removed by cutting a volume around the muon track
- Yes, sensitivity scales with the mass

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Mass (t)</th>
<th>$&lt;m_{ββ}&gt;$, meV</th>
</tr>
</thead>
<tbody>
<tr>
<td>nEXO</td>
<td>$^{136}$Xe</td>
<td>5</td>
</tr>
<tr>
<td>GERDA</td>
<td>$^{76}$Ge</td>
<td>1</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>1</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{130}$Te</td>
<td>8</td>
</tr>
<tr>
<td>KamLAND -Zen</td>
<td>$^{136}$Xe</td>
<td>1</td>
</tr>
<tr>
<td>JUNO-ββ</td>
<td>$^{136}$Xe</td>
<td>50</td>
</tr>
</tbody>
</table>

Zhao et al., arXiv: 1610.07143, CPC 41 (2017) 5
Summary

• Particle Physics is a great field
  – Incredible success in the past
  – More to come in the future

• We are now at a critical point: which accelerator is the next one?
  – CEPC + SPPC (or FCC$_{ee}$+FCC$_{hh}$) is the best choice

• China may play a very important role:
  – Great success in the past and a number of new initiatives
  – Good opportunities: economics, political support, ...

• Looking forward a closer collaboration