# Particle and AstroParticle physics in China.

## *Status and perspectives.*
## *Part I*

***Based on a talk of  Yifang Wang***
***at 20th Lomonosov Conf., Aug. 19, 2021***

By Oleg Fedin

# BEPCII - *Beijing Electron Positron Collider II*

An $e^+e^-$ collider at 2 – 4.6 GeV

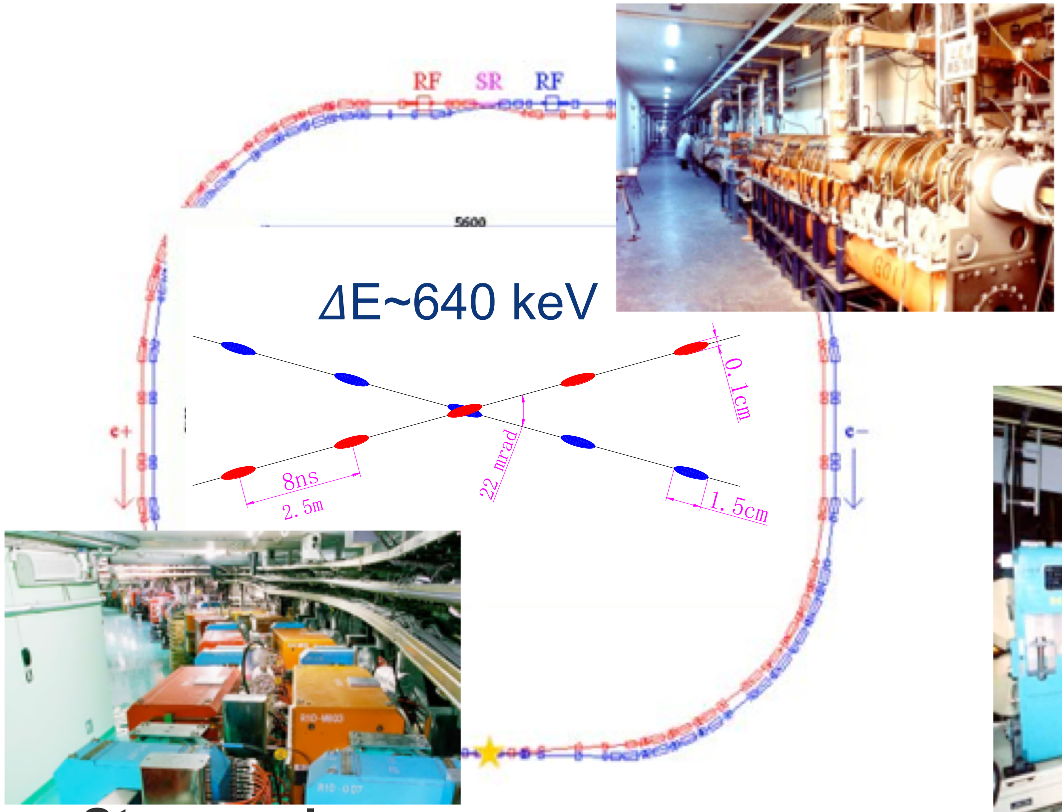
Design luminosity $10^{33}$ $cm^{-2}s^{-1}$ @1.89 GeV

Beam lifetime 2.7 hrs.

Operational from 2009

Highest peak and integral lumi recorded in 2020

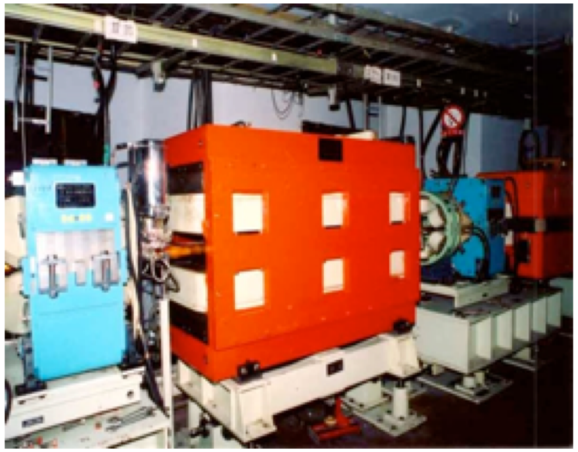
**Injector**



**Storage rings**

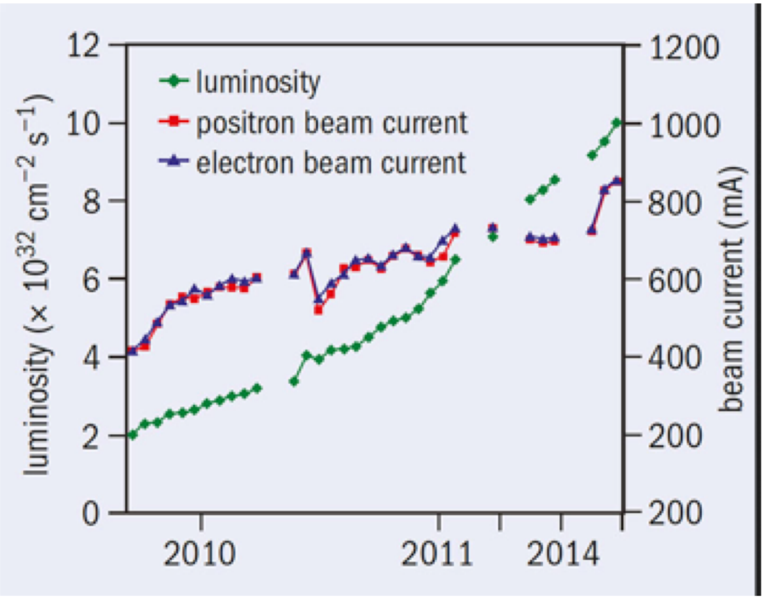
It is comparable with all the second-generation synchrotron radiation light sources running in the world.

**wiggler**



**SR front end region**

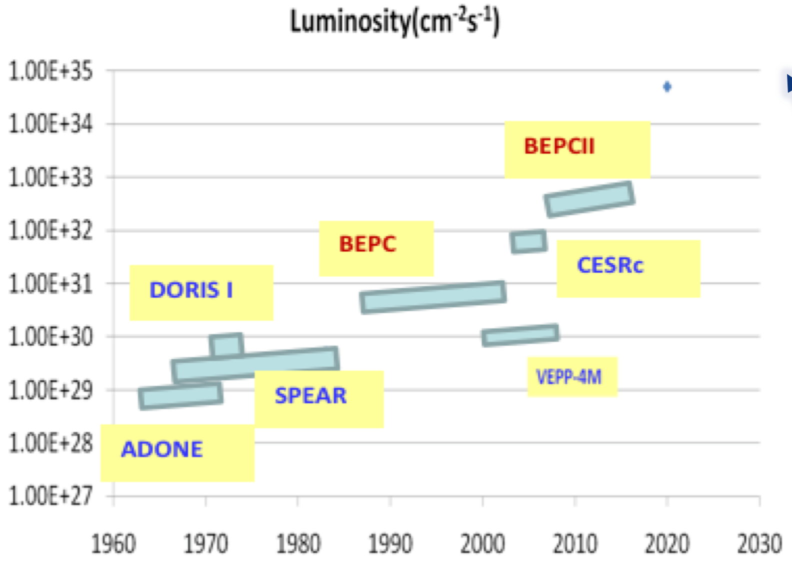
# BEPCII - *Beijing Electron Positron Collider II*



**arXiv:0911.4960**

**Expected data samples in a calendar year based on assumption that the total running time will be $10^7$ sec/year. Accordingly integrated lumi per year ~ 1 fb$^{-1}$**

| States | Energy (GeV) | Peak luminosity ($10^{33}$ cm$^{-2}$s$^{-1}$) | Physics cross-section (nb) | Events/year |
|---|---|---|---|---|
| $J/\psi$ | 3.097 | 0.6 | 3,400 | $1\times10^{10}$ |
| $\psi(2S)$ | 3.686 | 1.0 | 640 | $3\times10^{9}$ |
| $\tau^+\tau^-$ | 3.670 | 1.0 | 2.4 | $1.2\times10^{7}$ |
| $D^0\bar{D}^0$ | 3.770 | 1.0 | 3.6 | $1.8\times10^{6}$ |
| $D^+D^-$ | 3.770 | 1.0 | 2.8 | $1.4\times10^{6}$ |
| $D_sD_s$ | 4.030 | 0.6 | 0.32 | $1\times10^{6}$ |
| $D_sD_s$ | 4.170 | 0.6 | 1.0 | $2\times10^{6}$ |

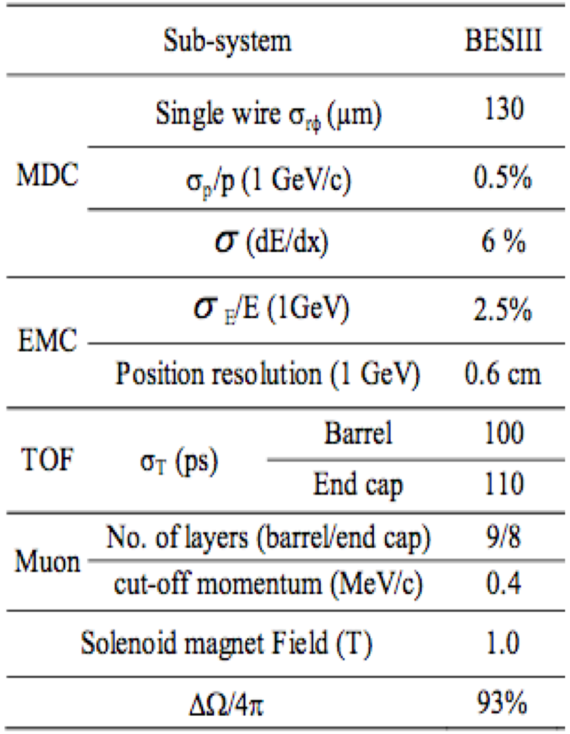


**cτ-factory @ Novosibirsk**

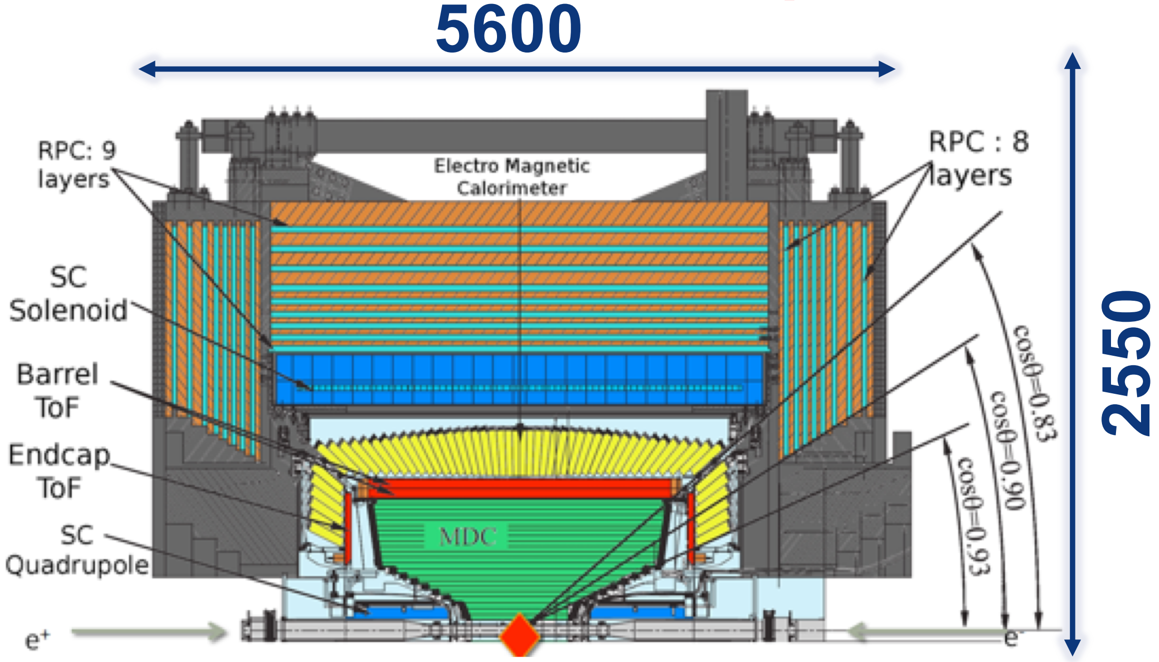
# BES III (*Beijing Spectrometer III*)

**02/2019: $10^{10}$ $J/\psi$**
**Collected around 30 $fb^{-1}$**

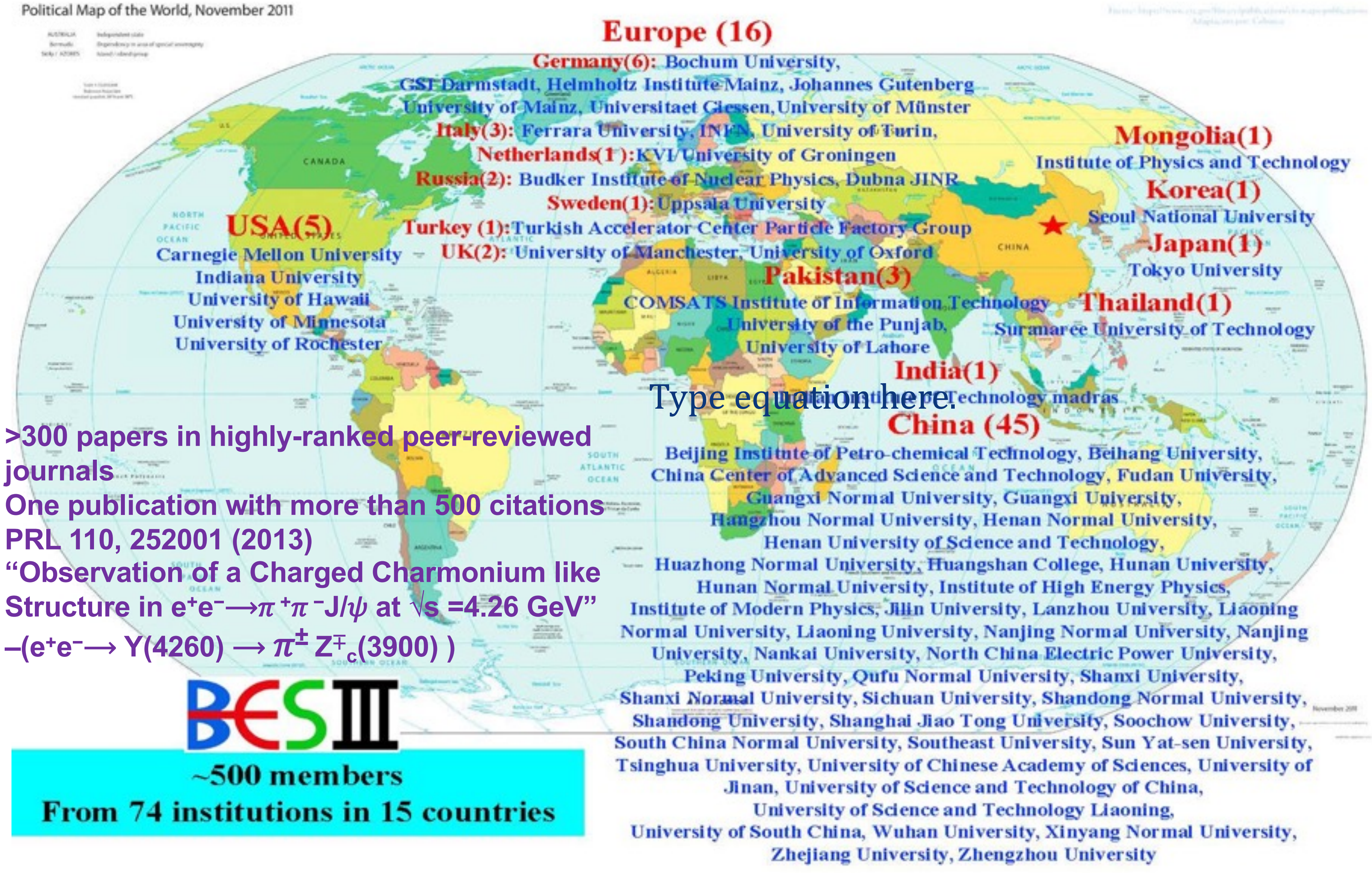
**arXiv:0911.4960**



| Sub-system | | | BESIII |
|---|---|---|---|
| MDC | Single wire $\sigma_{r\phi}$ (μm) | | 130 |
| | $\sigma_p/p$ (1 GeV/c) | | 0.5% |
| | $\sigma$ (dE/dx) | | 6 % |
| EMC | $\sigma_E/E$ (1GeV) | | 2.5% |
| | Position resolution (1 GeV) | | 0.6 cm |
| TOF | $\sigma_T$ (ps) | Barrel | 100 |
| | | End cap | 110 |
| Muon | No. of layers (barrel/end cap) | | 9/8 |
| | cut-off momentum (MeV/c) | | 0.4 |
| Solenoid magnet Field (T) | | | 1.0 |
| $\Delta\Omega/4\pi$ | | | 93% |



# The BES III Collaboration



**Europe (16)**

**Germany(6):** Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster

**Italy(3):** Ferrara University, INFN, University of Turin,

**Netherlands(1):** KVI/University of Groningen

**Russia(2):** Budker Institute of Nuclear Physics, Dubna JINR

**Sweden(1):** Uppsala University

**Turkey (1):** Turkish Accelerator Center Particle Factory Group

**UK(2):** University of Manchester, University of Oxford

**USA(5)**

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota
University of Rochester

**Pakistan(3)**

COMSATS Institute of Information Technology
University of the Punjab,
University of Lahore

**India(1)**

Indian Institute of Technology madras

Type equation here.

**Mongolia(1)**

Institute of Physics and Technology

**Korea(1)**

Seoul National University

**Japan(1)**

Tokyo University

**Thailand(1)**

Suranaree University of Technology

**China (45)**

Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Institute of High Energy Physics, Institute of Modern Physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu Normal University, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiao Tong University, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University

>300 papers in highly-ranked peer-reviewed journals
One publication with more than 500 citations
PRL 110, 252001 (2013)
"Observation of a Charged Charmonium like Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV"
–($e^+e^- \to Y(4260) \to \pi^{\pm} Z^{\mp}_c(3900)$ )

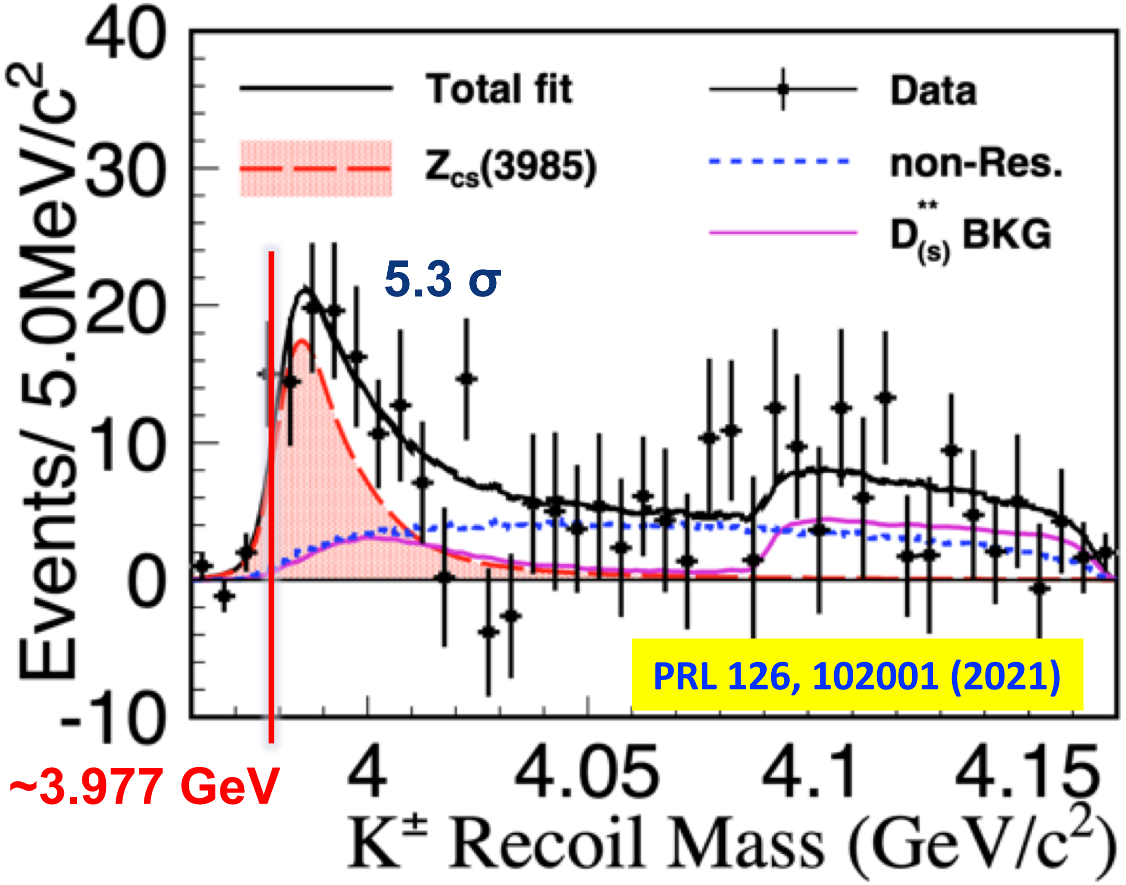
BESIII

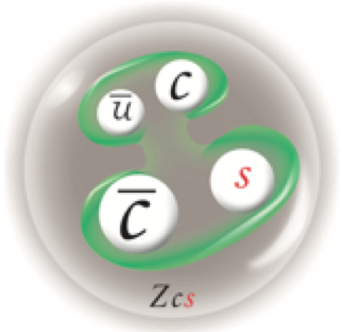
~500 members
From 74 institutions in 15 countries

$Y(4260)\ discovery:\ 2005\ BaBar\ \ B^- \to Y(4260)K^-$

# **BES III:** *Observation of strange four-quark meson $Z_{cs}(3985)$*

$e^+ e^- \to K^+ (D_s^- D^{*0} + D_s^{*-} D^0)$ @4.68 GeV





$e^+e^- \to K^+ Z^-_{cs}(3985)$

$M = 3982.5^{+1.8}_{-2.6} \pm 2.1$MeV

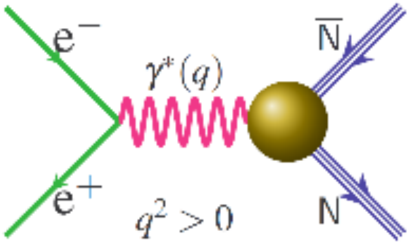
$\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

$J^P=1^-$

$D^-_s \to K^+K^-\pi^-$ & $D^-_s \to K^0_S K^-$

# BES III: Damped oscillatory behavior in neutron form-factor

$$\sigma_B = \frac{4\pi\alpha_{em}^2\beta C(q^2)}{3q^2}\left[|G_M(q^2)|^2 + |G_E(q^2)|^2\frac{1}{2\tau}\right] \qquad \tau = q^2/4m_N^2$$



$$|G| = \sqrt{\frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau + 1}}$$

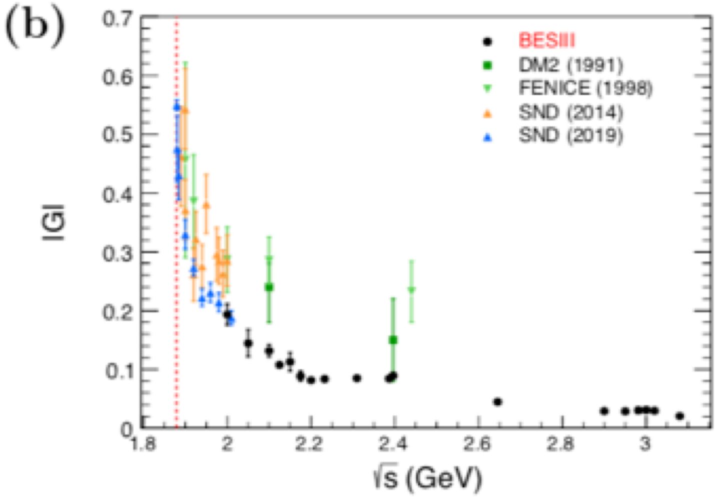
**Phys. Rev. Lett. 114, 232301 (2015)**

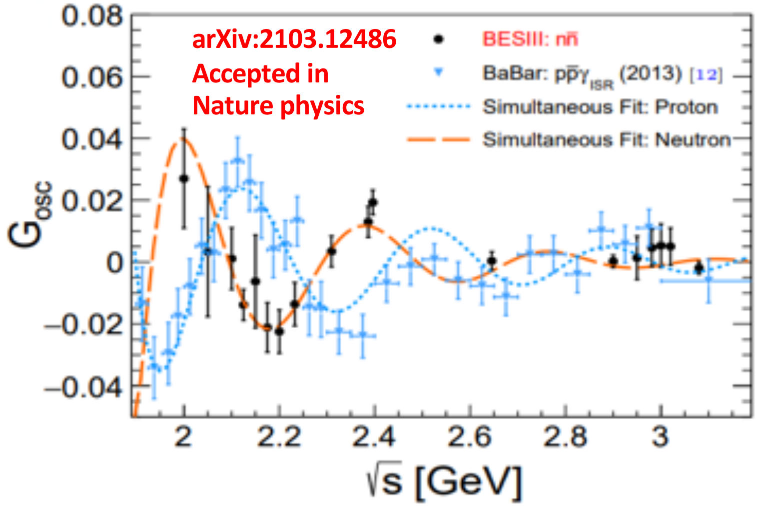
$$G(q^2) = G_0(q^2) + G(q^2)_{osc} \qquad \left|G_0^p\,(q^2)\right| = \frac{A_p}{(1+q^2/m_a^2)(1-q^2/0.71)}$$

regular background fit

oscillation fit

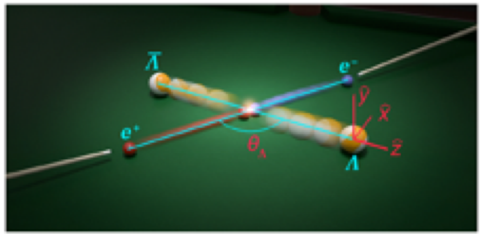
$$\left|G_p^n\,(q^2)\right| = \frac{A_n}{(1-q^2/0.71)^2} \qquad G(p)_{osc}^{n,p} = A^{n,p}e^{-B^{n,p}p}\cos(Cp + D^{n,p}) \quad p \equiv \sqrt{E^2 - m_{n,p}^2} \quad E = \frac{q^2}{2m_{n,p}} - m_{n,p}$$

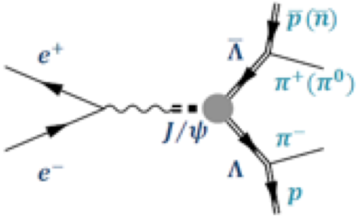



arXiv:2103.12486
Accepted in Nature physics

It suggests an interference effect involving rescattering processes at moderate kinetic energies of the outgoing hadrons. Such processes take place when the centres of mass of the produced hadrons are separated by ≃1 fm.

# BES III: *Polarization and entanglement in baryon–antibaryon pair production* $e^+e^-$ *annihilation*

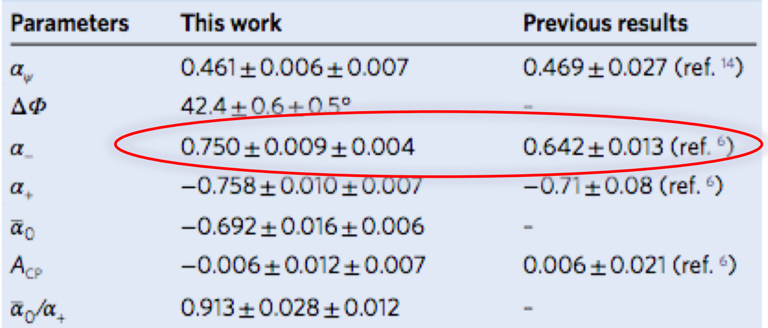




$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \overrightarrow{P_\Lambda}\vec{n}), \qquad |\alpha| < 1$$

$$J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$$

$$\mathcal{W}(\xi; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+)$$
$$= 1 + \alpha_\psi \cos^2\theta_\Lambda + \alpha_-\alpha_+ [\sin^2\theta_\Lambda (n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y})$$
$$+ (\cos^2\theta_\Lambda + \alpha_\psi) n_{1,z}n_{2,z}]$$
$$+ \alpha_-\alpha_+ \sqrt{1-\alpha_\psi^2} \cos(\Delta\Phi) \sin\theta_\Lambda \cos\theta_\Lambda (n_{1,x}n_{2,z} + n_{1,z}n_{2,x})$$
$$+ \sqrt{1-\alpha_\psi^2} \sin(\Delta\Phi) \sin\theta_\Lambda \cos\theta_\Lambda (\alpha_- n_{1,y} + \alpha_+ n_{2,y})$$

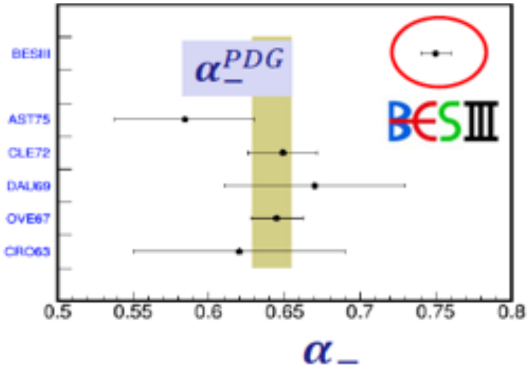


| Parameters | This work | Previous results |
|---|---|---|
| $\alpha_\psi$ | 0.461 ± 0.006 ± 0.007 | 0.469 ± 0.027 (ref. [14]) |
| $\Delta\Phi$ | 42.4 ± 0.6 ± 0.5° | - |
| $\alpha_-$ | 0.750 ± 0.009 ± 0.004 | 0.642 ± 0.013 (ref. [6]) |
| $\alpha_+$ | −0.758 ± 0.010 ± 0.007 | −0.71 ± 0.08 (ref. [6]) |
| $\bar{\alpha}_0$ | −0.692 ± 0.016 ± 0.006 | - |
| $A_{CP}$ | −0.006 ± 0.012 ± 0.007 | 0.006 ± 0.021 (ref. [6]) |
| $\bar{\alpha}_0/\alpha_+$ | 0.913 ± 0.028 ± 0.012 | - |

$\Lambda \to p\pi^-$: $\alpha_-=0.750\pm0.009\pm0.004$

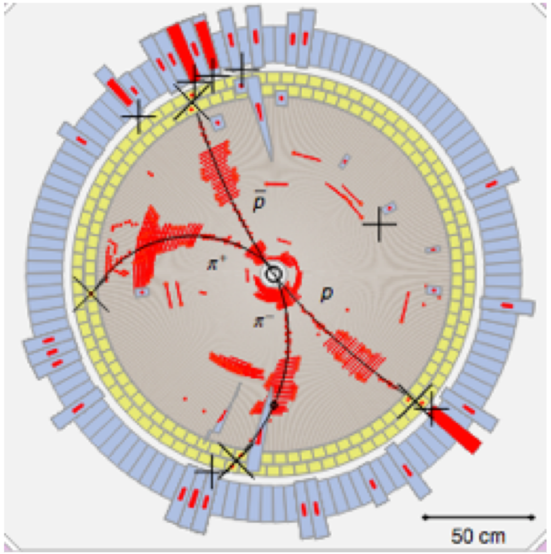
**Hyperon up-down parameter: 7σ upward shift from all previous measurements**

*Nature Physics* **15**, 631–634(2019)



**CP asymmetry SM predict ~$10^{-4}$**

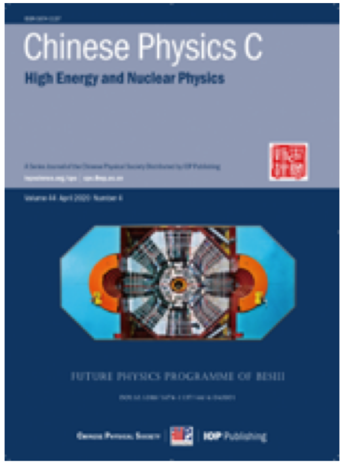
$$A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$$



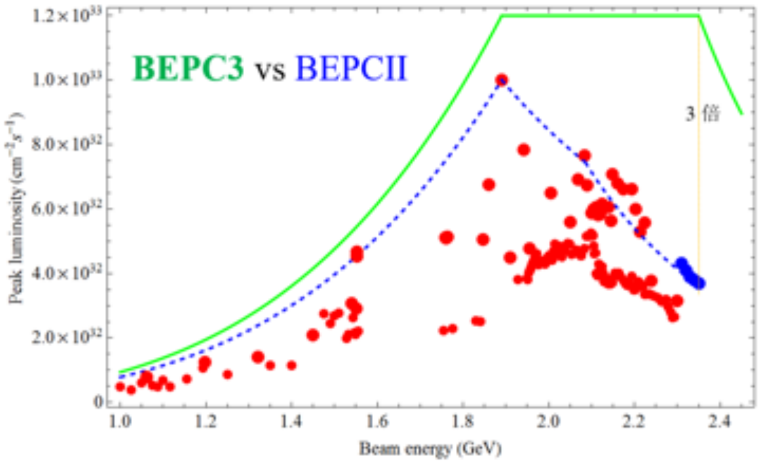
$J/\psi \to \Lambda\bar{\Lambda}$ : 400,000 events

# BES III: *Future Physics Program*

- Rich physics program requiring > 40 $fb^{-1}$, corresponding to 15 yrs of data taking at the present luminosity
- Detector upgrade:
  - end-cap TOF (110 ps) => multi-gap resistive plate chamber (MRPC) 68 ps
  - Inner MDC with a cylindrical GEM inner tracker
- Collider upgrade:
  - Luminosity × ~3 ➔ squeeze the beam size by adding a new RF cavity per beam
  - Replace the two SC quadrupole magnets near the IP to increase the beam energy from 2.45 up to 2.8 GeV for the interests of studying $\Xi_c$
  - slight decreasing energy down from 1 to 0.9 GeV, for the interests of studying nucleon productions
- Operation will continue until at least 2030

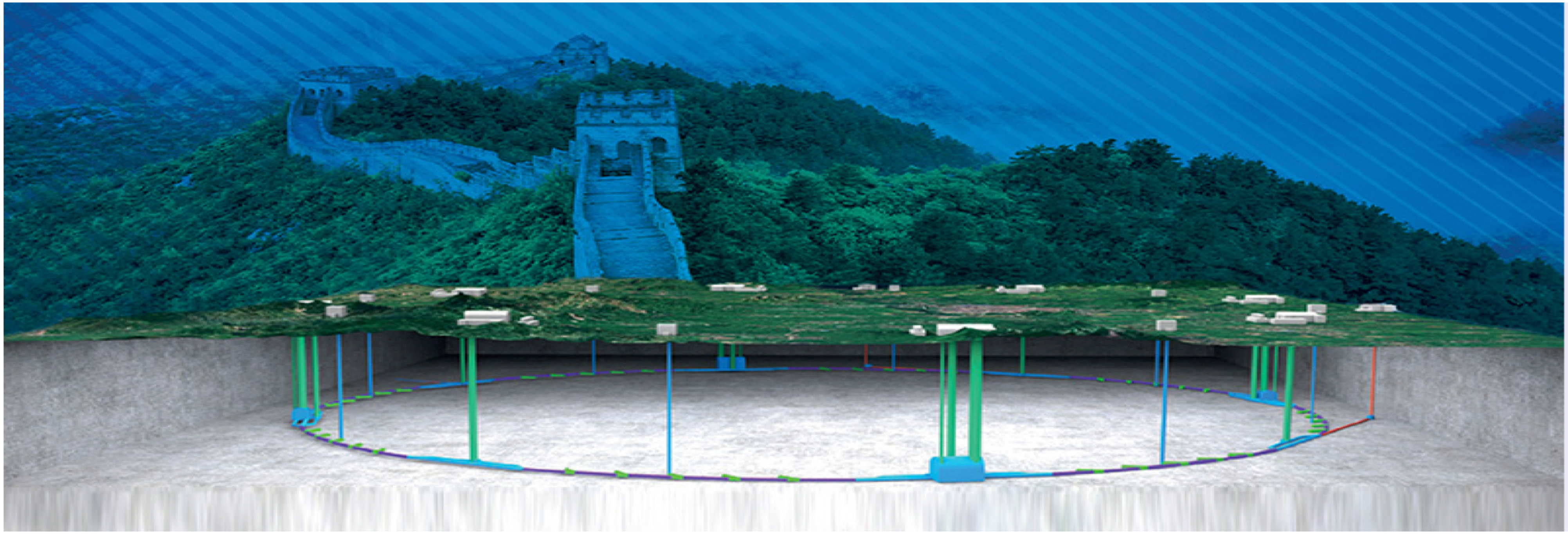


Chinese Physics C 44, 040001 (2020)
arXiv:1912.05983v3

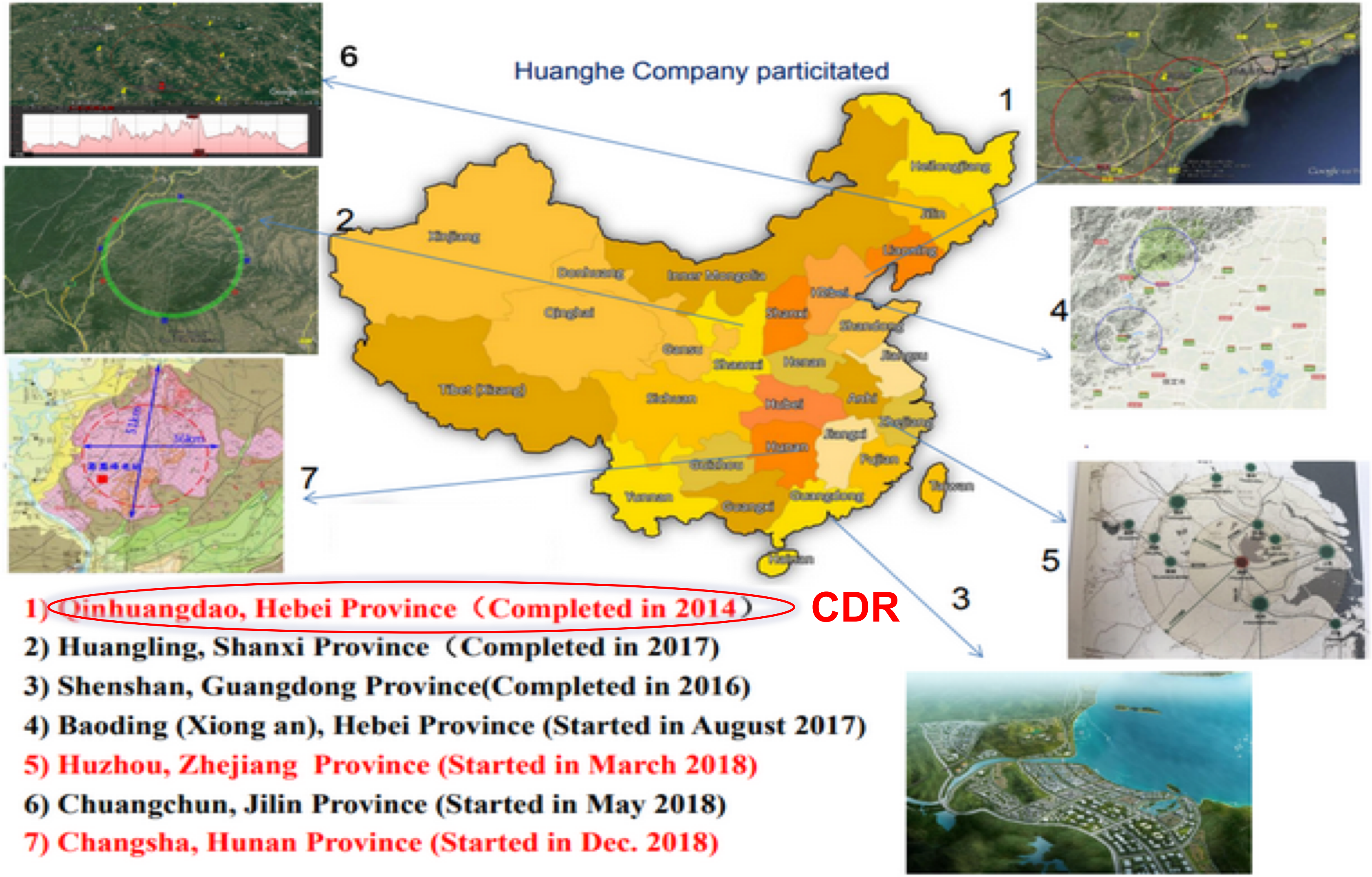


# CEPC - Circular Electron Positron Collider

- ❑ Since 2005, we were discussing the next machine after BEPCII
- ❑ The idea of a Circular e+e- Collider (CEPC) followed by a Super proton-proton collider (SPPC) was proposed in Sep. 2012, and quickly gained the momentum in IHEP and in the world
  - Looking for Hints@$e^+e^-$ Collider ➔ If yes, direct searches@PP collider
  - The tunnel can be re-used for pp, AA, ep colliders up to ~ 100 TeV ➔ compatibility study needed now



# CEPC Site selection



1) Qinhuangdao, Hebei Province（Completed in 2014）
2) Huangling, Shanxi Province（Completed in 2017)
3) Shenshan, Guangdong Province(Completed in 2016)
4) Baoding (Xiong an), Hebei Province (Started in August 2017)
5) Huzhou, Zhejiang Province (Started in March 2018)
6) Chuangchun, Jilin Province (Started in May 2018)
7) Changsha, Hunan Province (Started in Dec. 2018)

# CEPC Possible timeline

Pre-CDR & CDR (2013-2017)

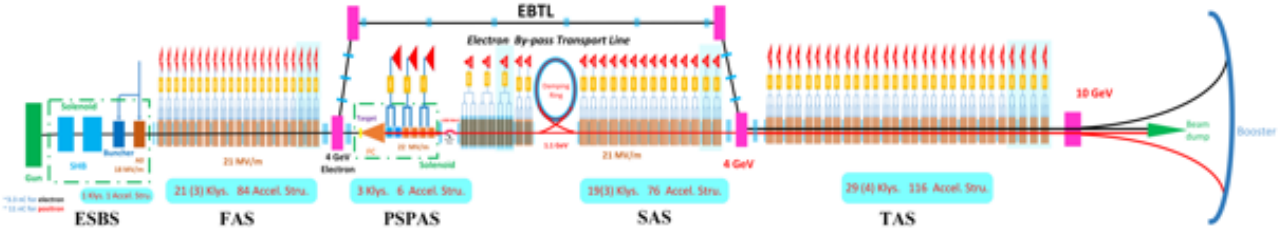
R&D and TDR (2018-2022)

Construction (2022-2030)

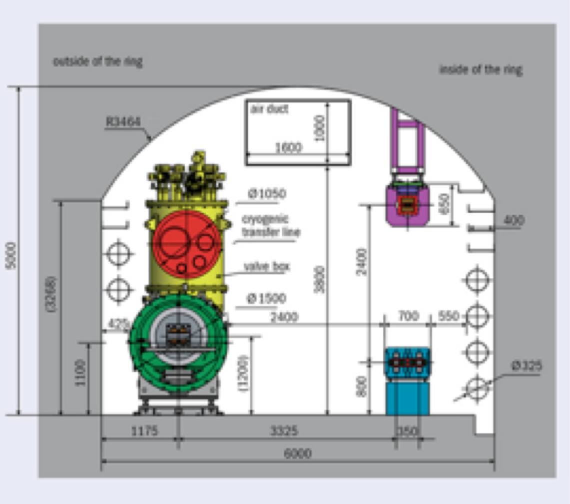
Data taking (2030-2040)

- The first stage is to complete a Preliminary Conceptual Design Report (PreCDR) in 2015 and a Conceptual Design Report (CDR) in 2018 (arXiv: 1809.00285 & arXiv:1811.10545). With the publication of this report, these goals have been achieved.
- The next stage is a 5-year period from 2018 to 2022 for R&D and for completion of a Technical Design Report (TDR)
- Construction will start in 2022 in the government’s 14th Five-Year Plan and continue in the 15th Five-Year Plan. Construction will be completed by 2030.
- Experiments can begin as early as 2030 when the 16th Five-Year Plan starts.
- The experiments will continue for about 10 years until 2040.
- After 2040, the superconducting magnets for the SPPC project are expected to be ready for installation, and the SPPC era will begin.

# CEPC Layout



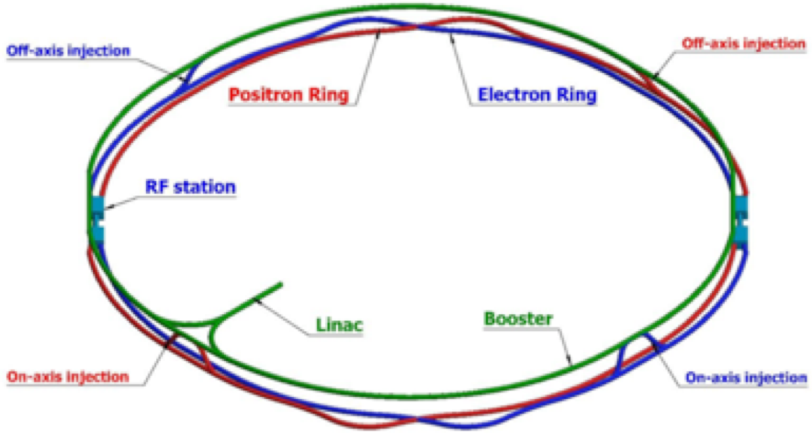
Linac injector (1.2km, 10GeV)

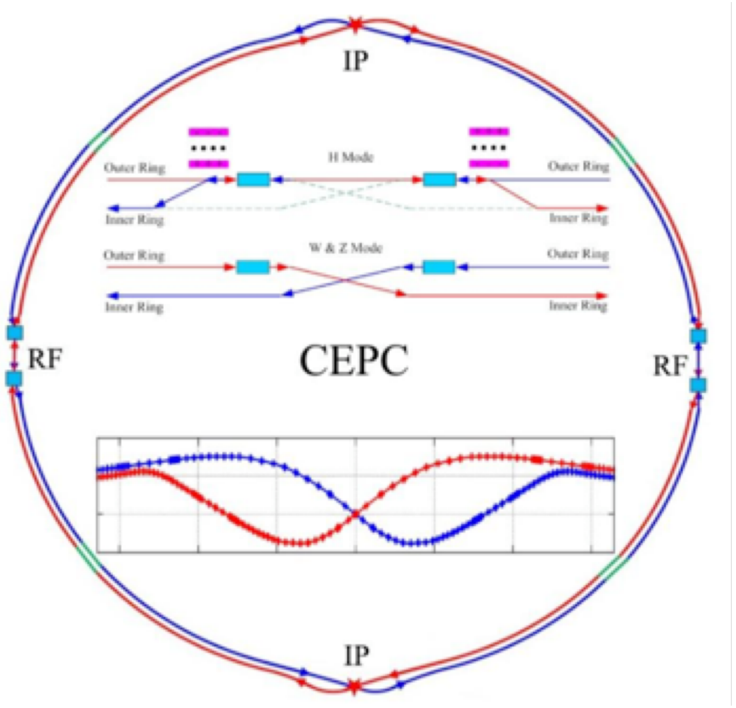


Collider ring (100km)

H ($e^+e^- \rightarrow ZH$)
Z ($e^+e^- \rightarrow Z$)
W ($e^+e^- \rightarrow W^+W^-$)

Booster ring (100km)





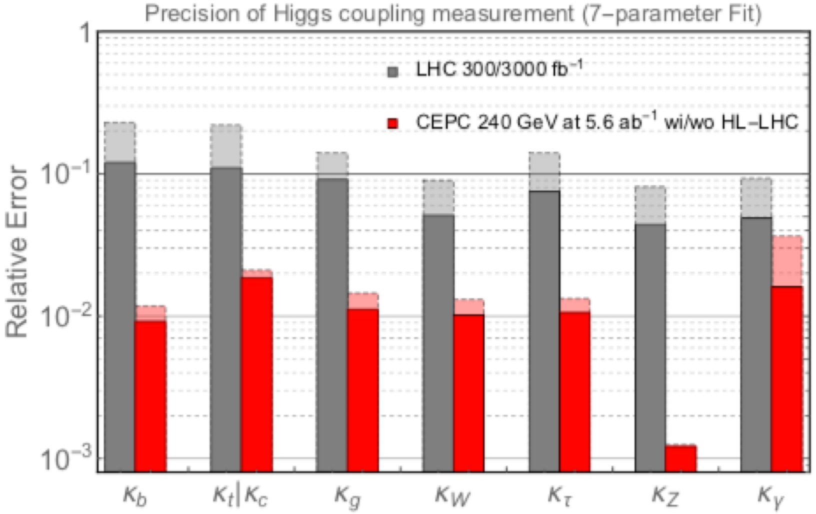
# CEPC 10 years operation plan 7-2-1

**1 атто = 10 $^{-18}$**

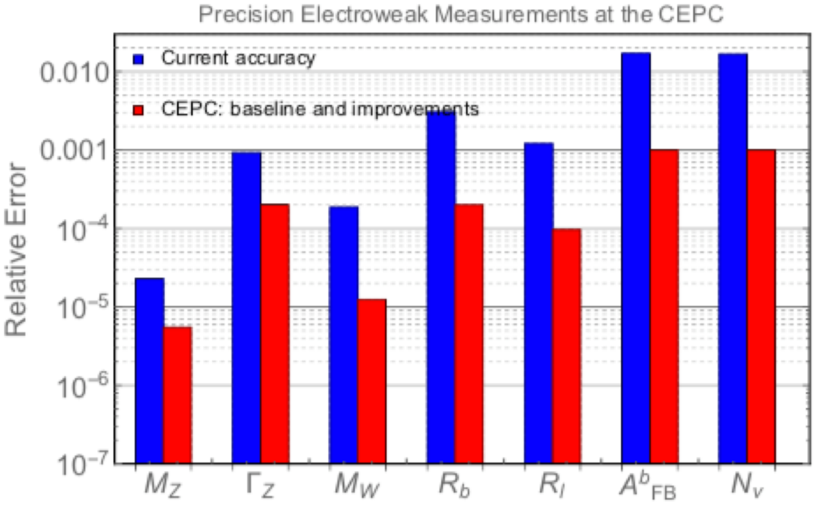
*arXiv: 1809.00285*

| Particle | $E_{\text{c.m.}}$ (GeV) | $L$ per IP ($10^{34}$ cm$^{-2}$s$^{-1}$) | Integrated $L$ per year (ab$^{-1}$, 2 IPs) | Years | Total Integrated $L$ (ab$^{-1}$, 2 IPs) | Total no. of particles |
|---|---|---|---|---|---|---|
| H | 240 | 3 | 0.8 | 7 | 5.6 | $1 \times 10^{6}$ |
| Z | 91 | 32 (*) | 8 | 2 | 16 | $7 \times 10^{11}$ |
| $W^{+}W^{-}$ | 160 | 10 | 2.6 | 1 | 2.6 | $1.5 \times 10^{7}$ |

(*) Assuming detector solenoid field of 2 Tesla during Z operation



(a)

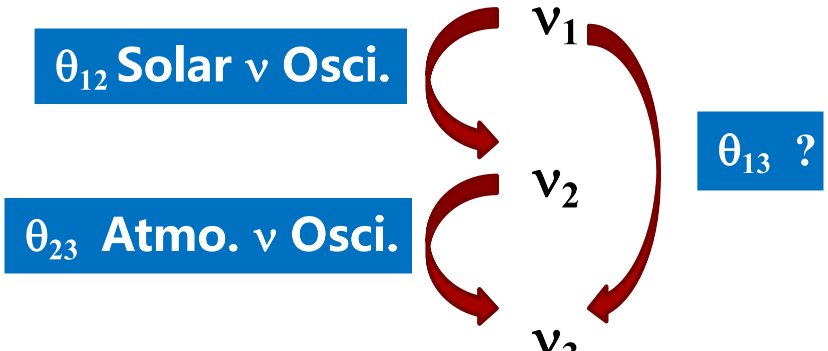


(b)

*arXiv:1811.10545*

# Daya Bay Experiment

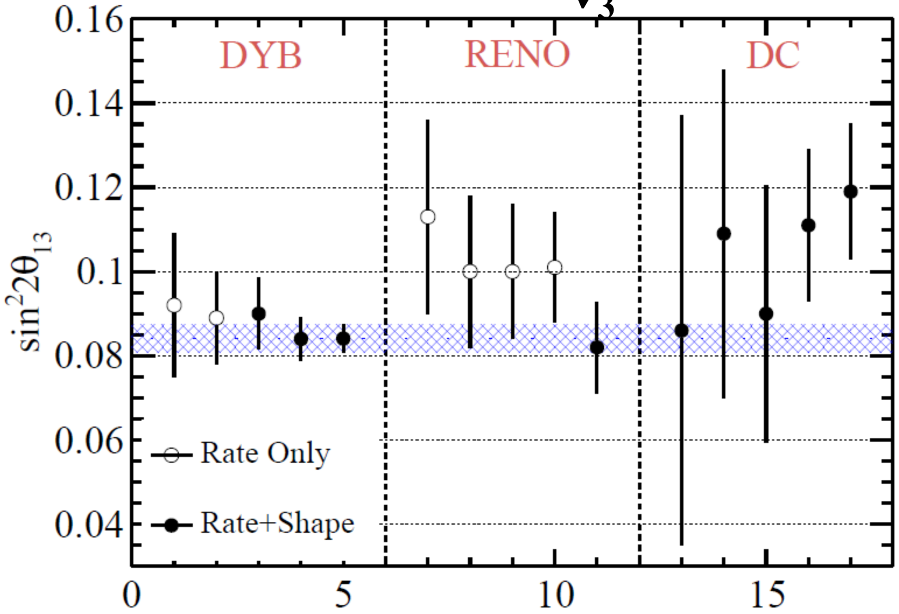
$$P = 1 - \sin^2(2\theta_{13})\,\sin^2\left(\frac{1.27\Delta m^2_{31} L}{E_\nu}\right)$$

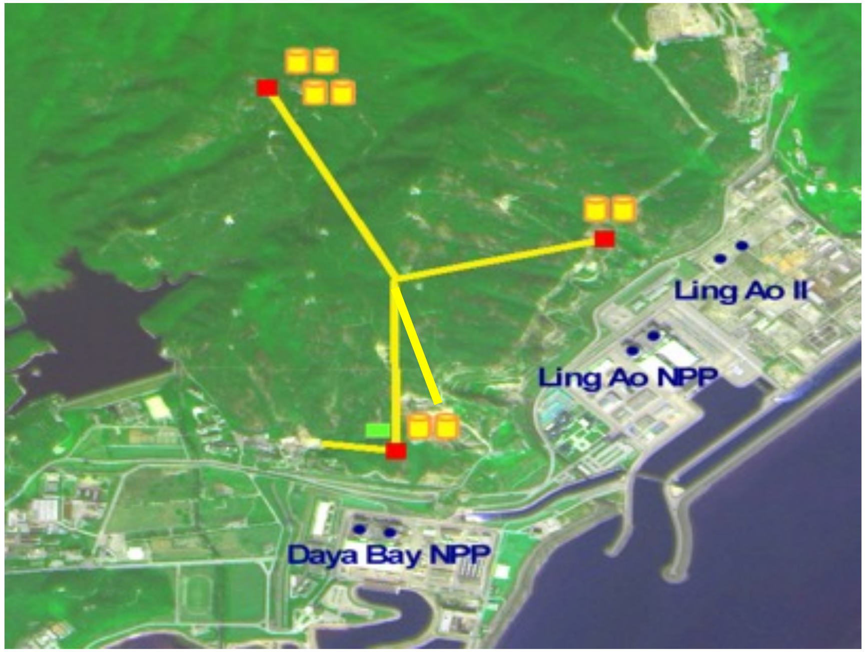


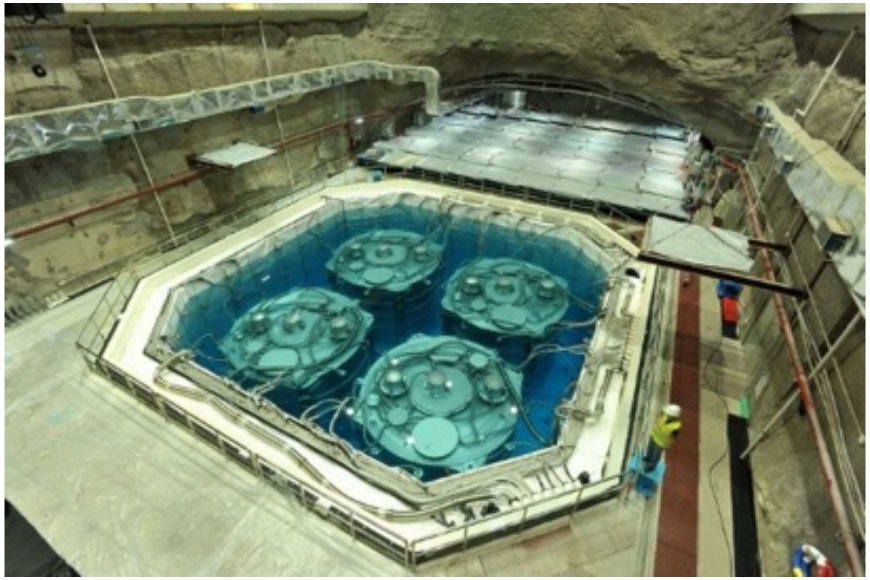
**$\theta_{12}$ Solar ν Osci.**

**$\theta_{23}$ Atmo. ν Osci.**

**$\theta_{13}$ ?**



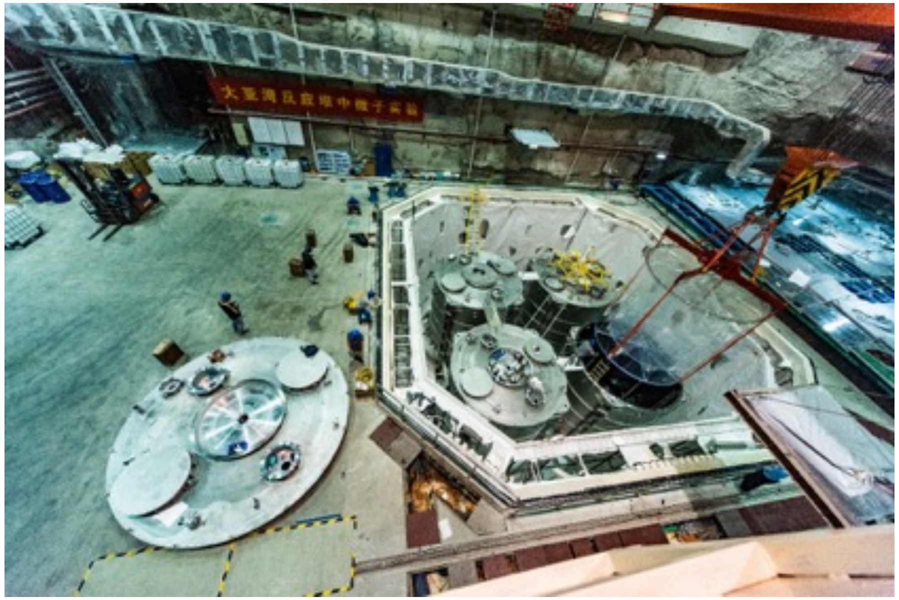




**2012:** $\sin^2(2\theta_{13}) = 0{,}092 \pm 0.016$ (стат.) $\pm\, 0{,}005$ (сист.)

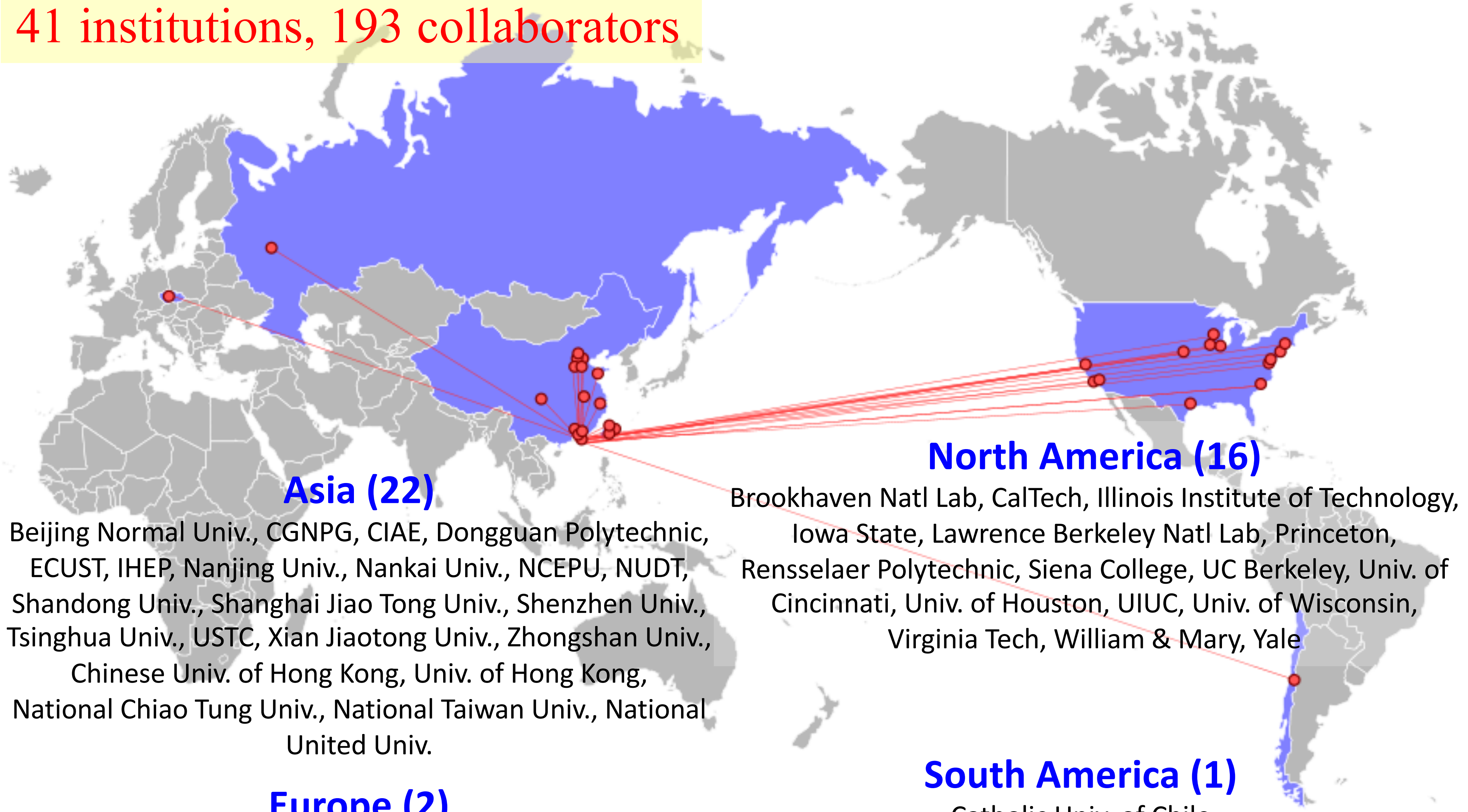
# Daya Bay decommissioning

- ☐ Data taking terminated on Dec. 12, 2020
  - ➢ Ceremony broadcasted online, 1.7 M viewers
- ☐ Data analysis will continue, expected $\sin^2 2\theta_{13}$ precision < 3%
- ☐ Detector decommissioning in process



# Daya Bay Collaboration

41 institutions, 193 collaborators



**Asia (22)**

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

**North America (16)**

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

**Europe (2)**

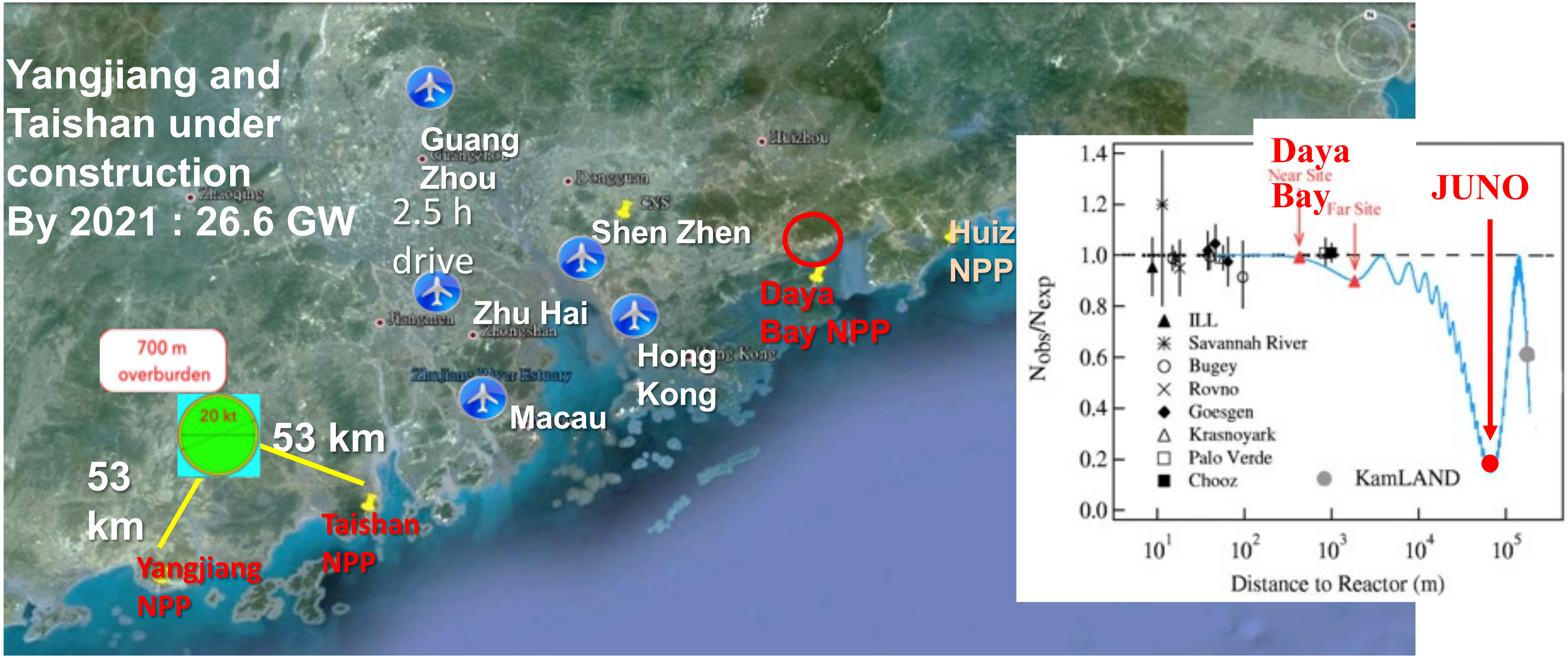
Charles University, JINR Dubna

**South America (1)**

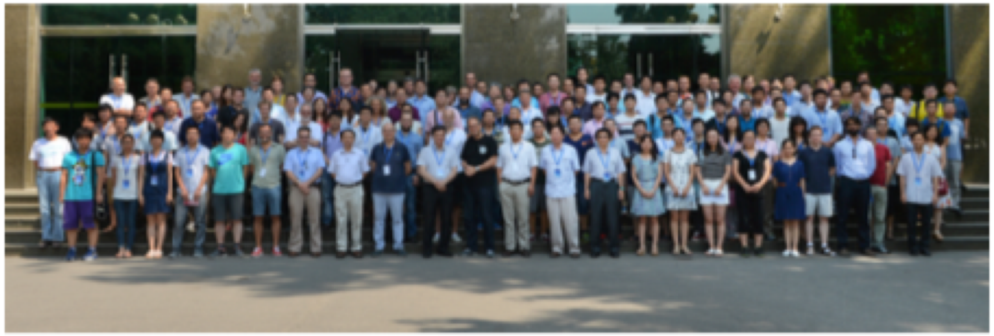
Catholic Univ. of Chile

# JUNO (*Jiangmen Underground Neutrino Observatory)* Experiment

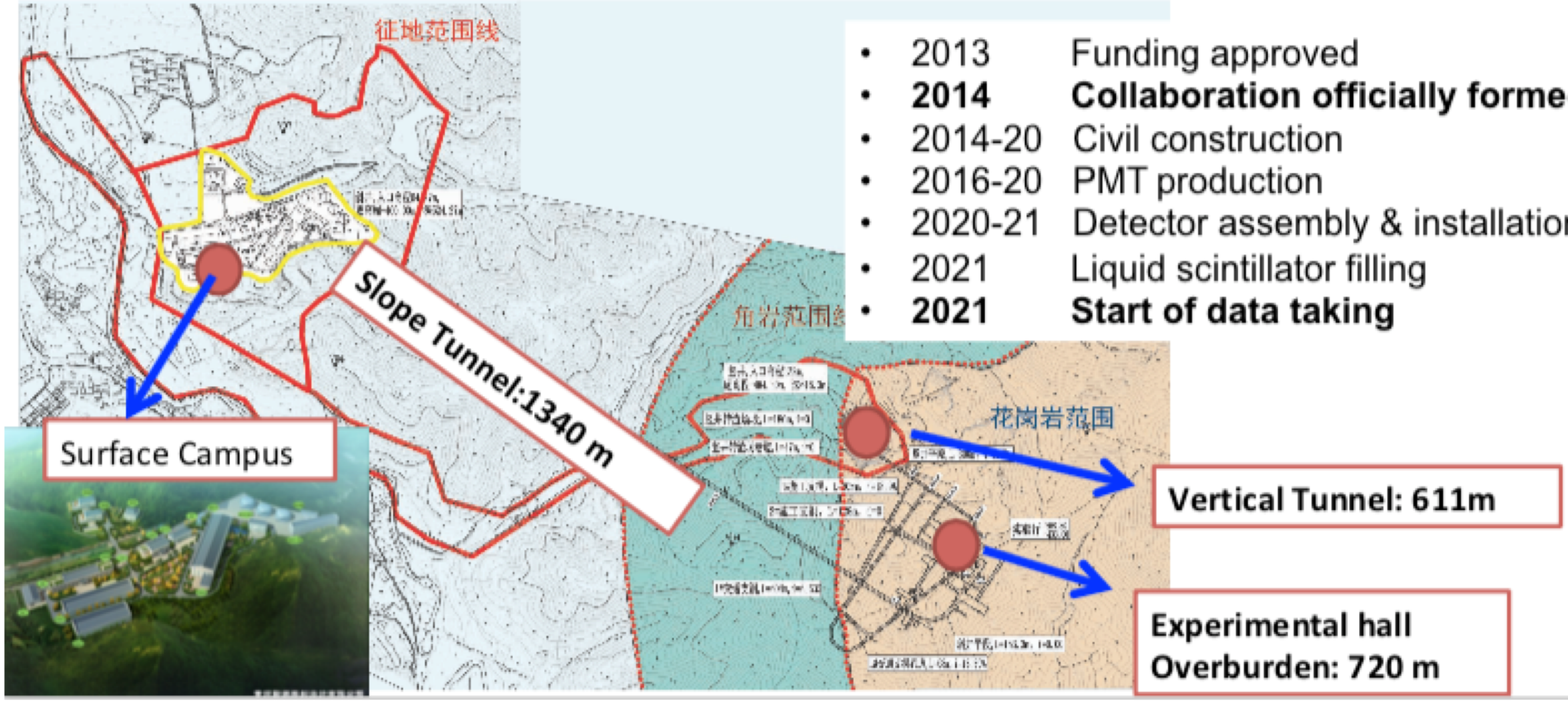
- JUNO is a “medium-baseline” (53km) reactor neutrino experiment (data taking foreseen in 2021)
- JUNO will be the largest Liquid Scintillator detector ever built **(20kt)**
- Goals : Measurement of the neutrino mass hierarchy (PNMH) and oscillation parameters + astroparticle and rare processes



# JUNO Collaboration



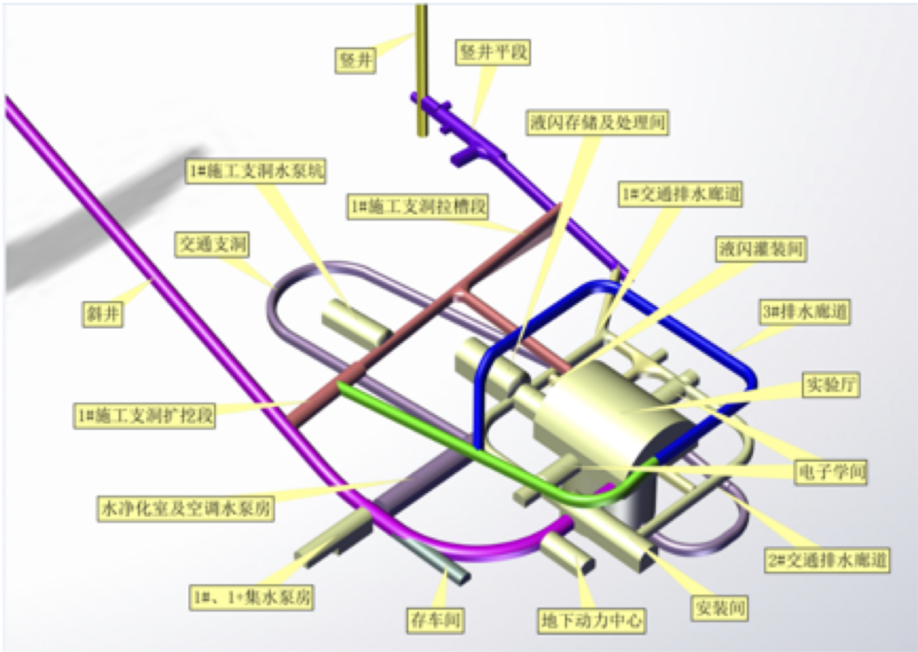
**77 institutions, from 17 countries, more than 600 scientists**



- 2013 Funding approved
- **2014 Collaboration officially formed**
- 2014-20 Civil construction
- 2016-20 PMT production
- 2020-21 Detector assembly & installation
- 2021 Liquid scintillator filling
- **2021 Start of data taking**

**~ 600m vertical shaft, ~1300m sloped tunnel**

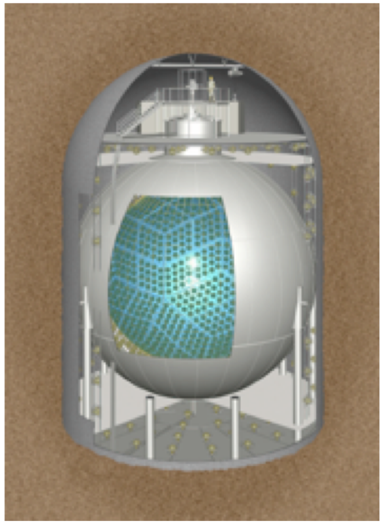
**All blasting completed on Dec. 30, 2020, water pool construction on the way**



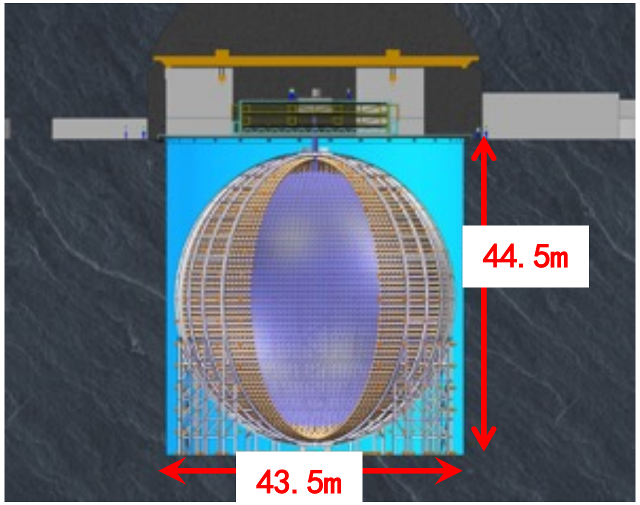
# The JUNO detector

**An unprecedented LS detector !**

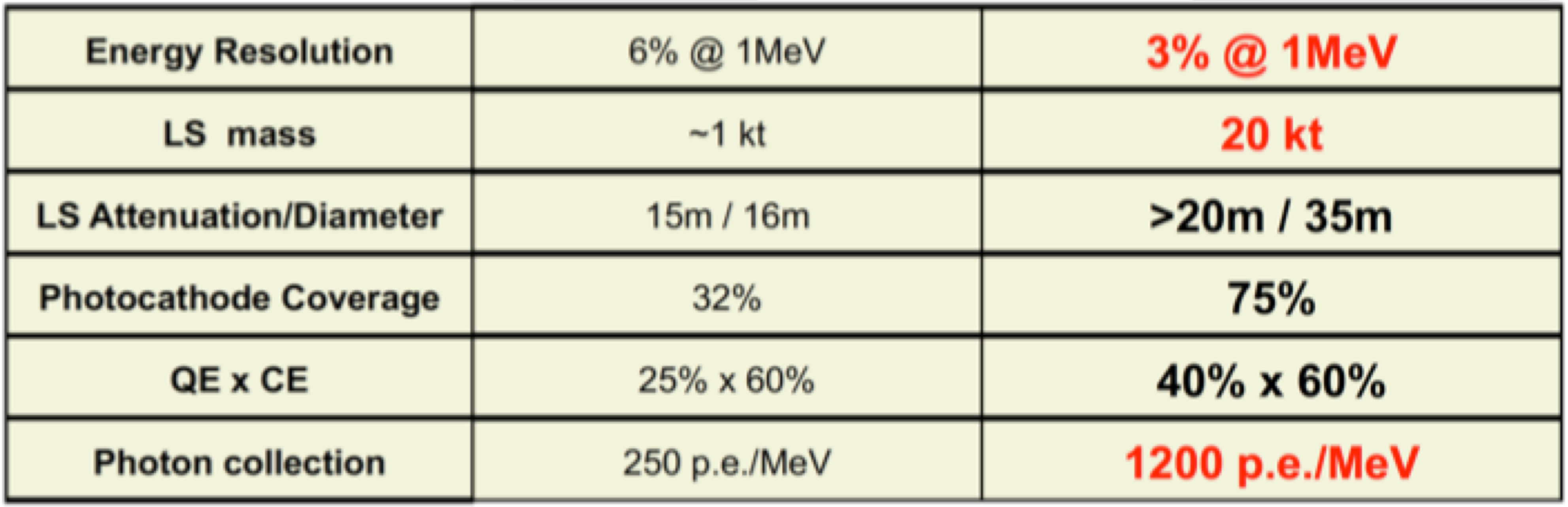
- ❑ **Largest LS detector**
  - ➔ × **20 KamLAND,**
  - × **40 Borexino**
- ❑ **Highest light yield**
  - ➔ × **2 Borexino,**
  - × **5 KamLAND**



**KAMLAND**

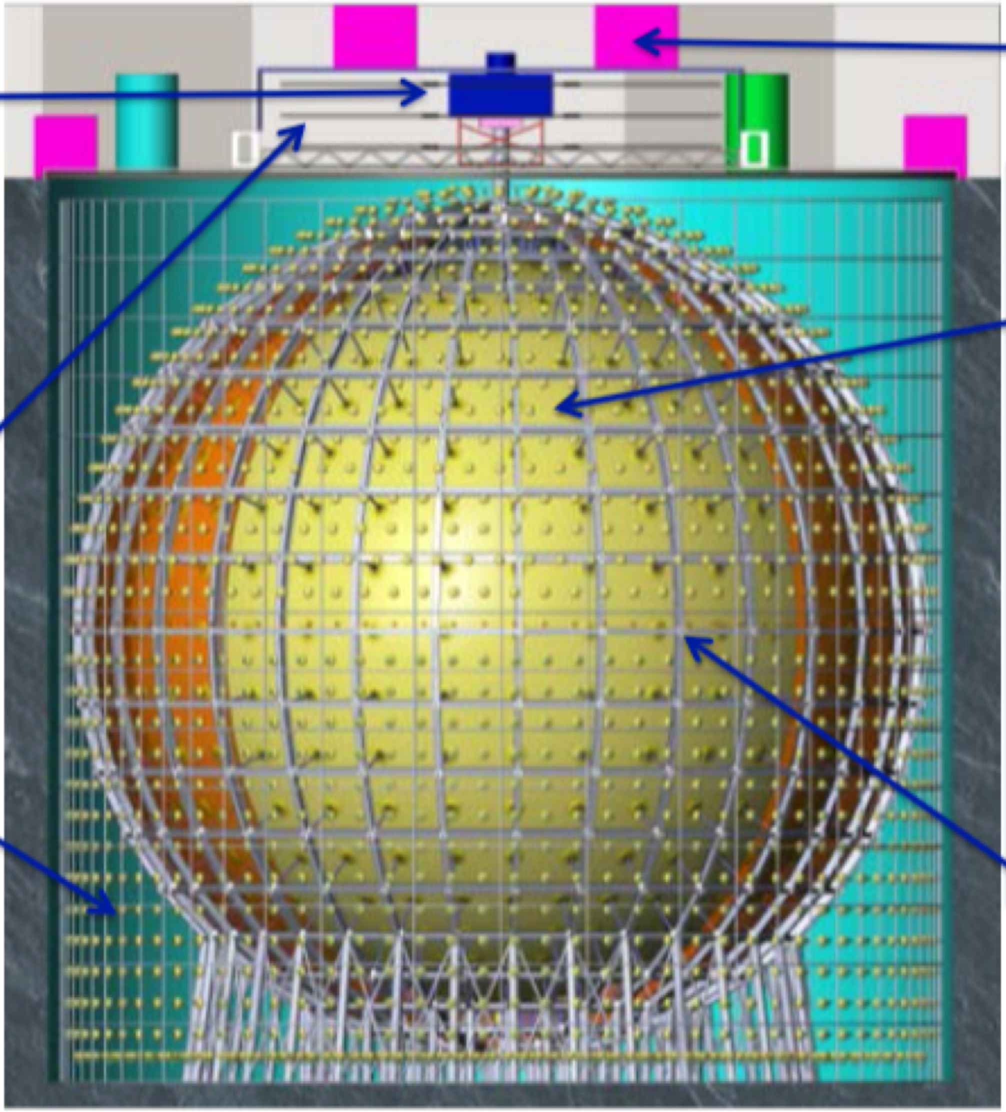


**JUNO**



| | | |
|---|---|---|
| Energy Resolution | 6% @ 1MeV | 3% @ 1MeV |
| LS mass | ~1 kt | 20 kt |
| LS Attenuation/Diameter | 15m / 16m | >20m / 35m |
| Photocathode Coverage | 32% | 75% |
| QE x CE | 25% x 60% | 40% x 60% |
| Photon collection | 250 p.e./MeV | 1200 p.e./MeV |

# JUNO detector main components



**Calibration**
4-complementary
Calibration
systems

Electronics

**Muon veto :**

Top Tracker

Water Cherenkov
Veto
20kt ultrapure
water and 2000
20'' PMTs

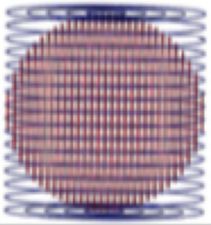
**Central detector :**

Acrylic sphere
(35.4 m diameter)

Filled with 20kt LAB
LS

18000 20'' PMTs and
25600 3'' PMTs

Stainless steel



Magnetic Field Compensating Coil

# Physics at JUNO

**JUNO Physics Book: arXiv: 1507.05613**

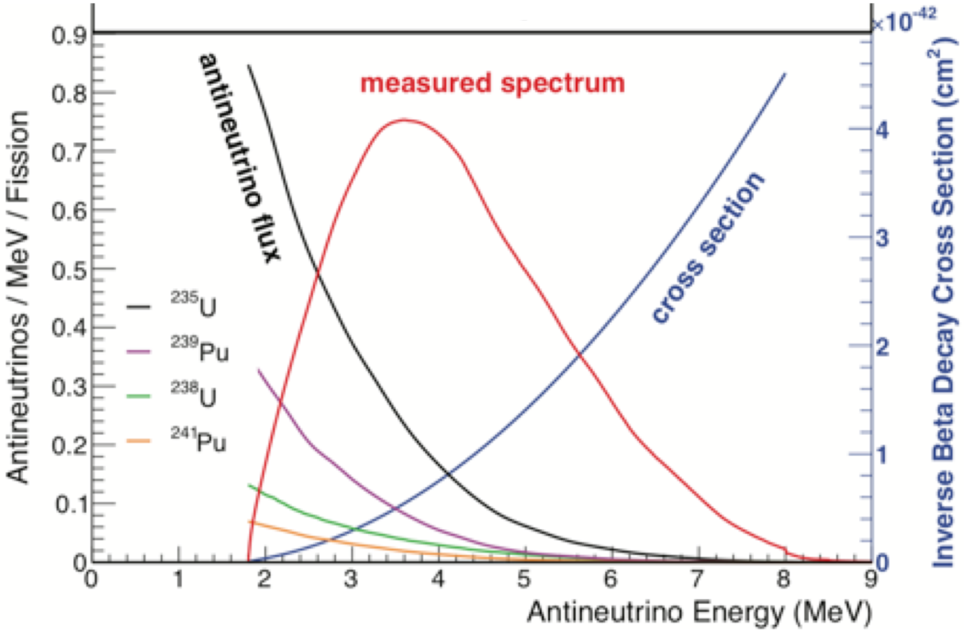
| ` | Current | JUNO |
|---|---|---|
| $\Delta m^2_{12}$ | 3% | 0.6% |
| $\Delta m^2_{23}$ | 3% | 0.6% |
| $\sin^2\theta_{12}$ | 4% | 0.7% |
| $\sin^2\theta_{23}$ | 10% | N/A |
| $\sin^2\theta_{13}$ | DYB | |

**Neutrinos are observed via inverse beta decay**

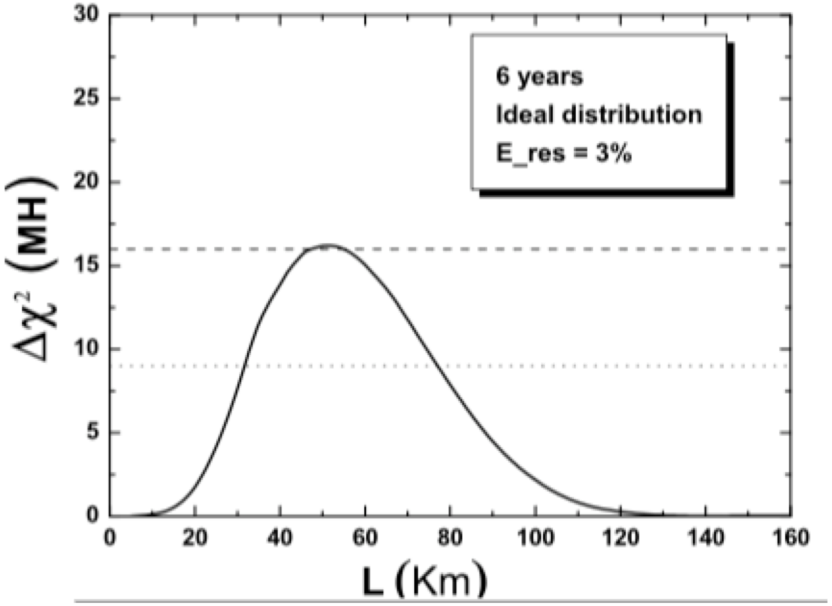
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\tau \approx 200\mu s \quad n + p \rightarrow d + \gamma$$

**Very clean signature**
**E range: 2 till 8 MeV**



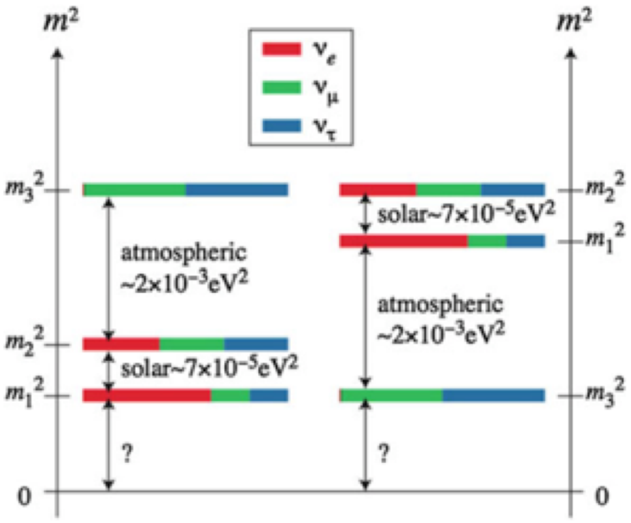
**Sensitivity for 100 k IBDs**
**(20 kton×35 GW×6 years).**



# JUNO Neutrino energy spectrum

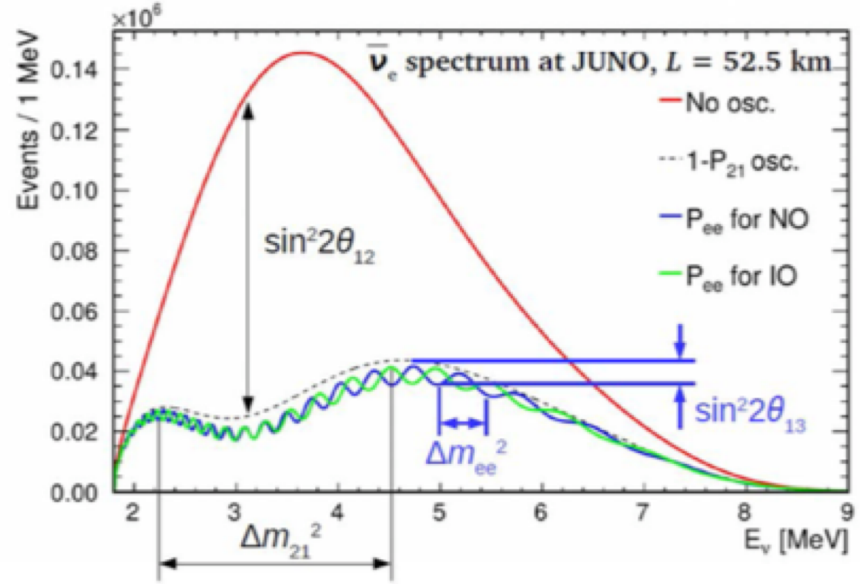
The Pee survival probability in vacuum

$$\begin{aligned}P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32}\\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})\\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})\\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})\end{aligned}$$



$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}, \qquad (\Delta m^2_{ij} \equiv m_i^2 - m_j^2)$$

$$\begin{aligned}\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21}\\ \mathrm{NH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}|\\ \mathrm{IH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|\end{aligned}$$



+ NH
- IH

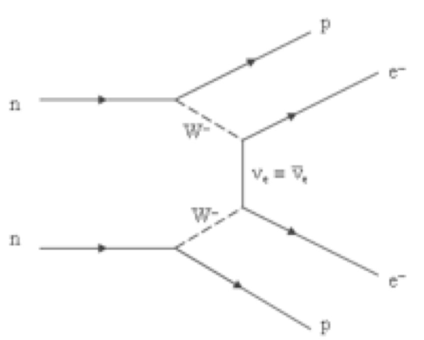
$$\pm\frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

# Physics at JUNO

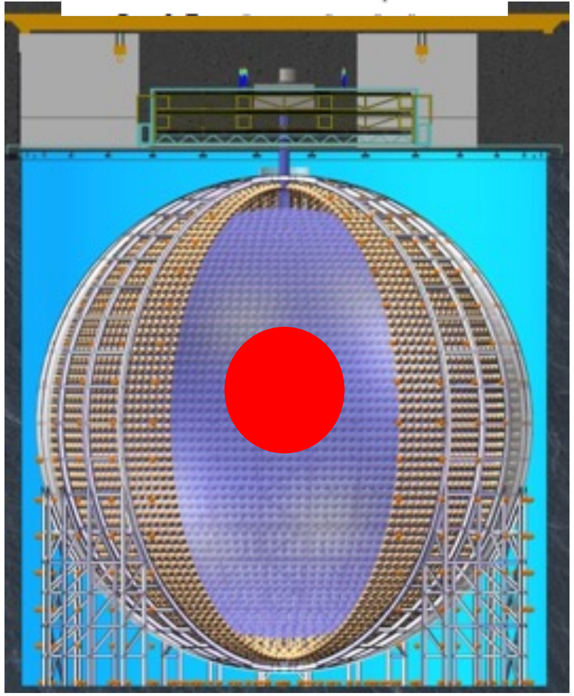
- Mass Hierarchy: 4σ in 6 yrs, independent of the CP phase
- Neutrino oscillation parameters： precision < 1%, and the test of unitarity of the mixing matrix
- Burst supernova neutrino: ~5000 events@10 kpc
- Discovery of diffused supernova neutrinos if ⟨E⟩ > 15 MeV
- Geoneutrinos: 400 evts/year determine U/Th ratio of the earth
- Solar neutrinos
- Proton decays: $p \to K^- + \overline{\nu}$

# JUNO - $0\nu\beta\beta$

- In ten years from now, oscillation will be mostly understood.
- 0nbb decay will be the next major breakthrough
- The best limits on the lifetime of $0\nu\beta\beta$ reach $10^{25}$ years ($m^{\nu}_{majorano} < 0.4$ eV)
- $0\nu\beta\beta$ : ${}_{54}^{136}Xe \rightarrow {}_{56}^{136}Ba$ $Q(M[{}^{136}Xe]-M[{}^{136}Ba]) = 2457.83(37)$ keV
- JUNO has the potential to reach a sensitivity (at 90% C. L.) to $T^{0\nu\beta\beta}_{1/2}$ of $1.8\times10^{28}$ yr ($5.6\times10^{27}$ yr) with ~50 tons (5 tons) of fiducial ${}^{136}Xe$ and 5 years exposure.



| | Nuclides | Mass (tons) | $<m_{\beta\beta}>$,meV |
|---|---|---|---|
| **KamLAND-Zen** | ${}^{136}Xe$ | 1 | 61-165 |
| **EXO** | ${}^{136}Xe$ | 0.2 | 93-286 |
| **nEXO** | ${}^{136}Xe$ | 5 | 7-22 |
| **GERDA/Majorana** | ${}^{76}Ge$ | 1 | 10-40 |
| **SNO+** | ${}^{130}Te$ | 8 | 19-46 |
| **JUNO-$\beta\beta$** | ${}^{136}Xe$ | 50 | 4-12 |
| | ${}^{130}Te$ | 100-200 | 2-6 |



**Insert a balloon filled with ${}^{136}Xe$-loaded LS(or ${}^{130}Te$) into the JUNO detector**

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

# JUNO TAO - Taishan Antineutrino Observatory

- ❑ TAO will measure the anti-neutrino spectrum at % level, to provide:
  - a model-independent reference spectrum for JUNO
  - a benchmark for investigation of the nuclear database
- ❑ Start to operate 2022 year.

arXiv:2005.08745v1

**Detector concept** :
2.8t Gd-loaded LS @-50$^0$C+ SiPM (10m$^2$ | $\varepsilon$>50% | 4500 e/MeV)
700k/year @ 30m from Taishan
20x JUNO 6-year data in 3 year
Energy resolution: 1.5%/√E

**Status:**
Design and R&D on the way:

- LS works in -50$^0$C
- SiPM & its readout electronics
- Mechanical design
- Measured onsite muon/neutron flux
- prototype a low temperature LS detector