QCD Physics in the Future Super Tau-Charm Facility (STCF)

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(On behalf of the STCF working group)

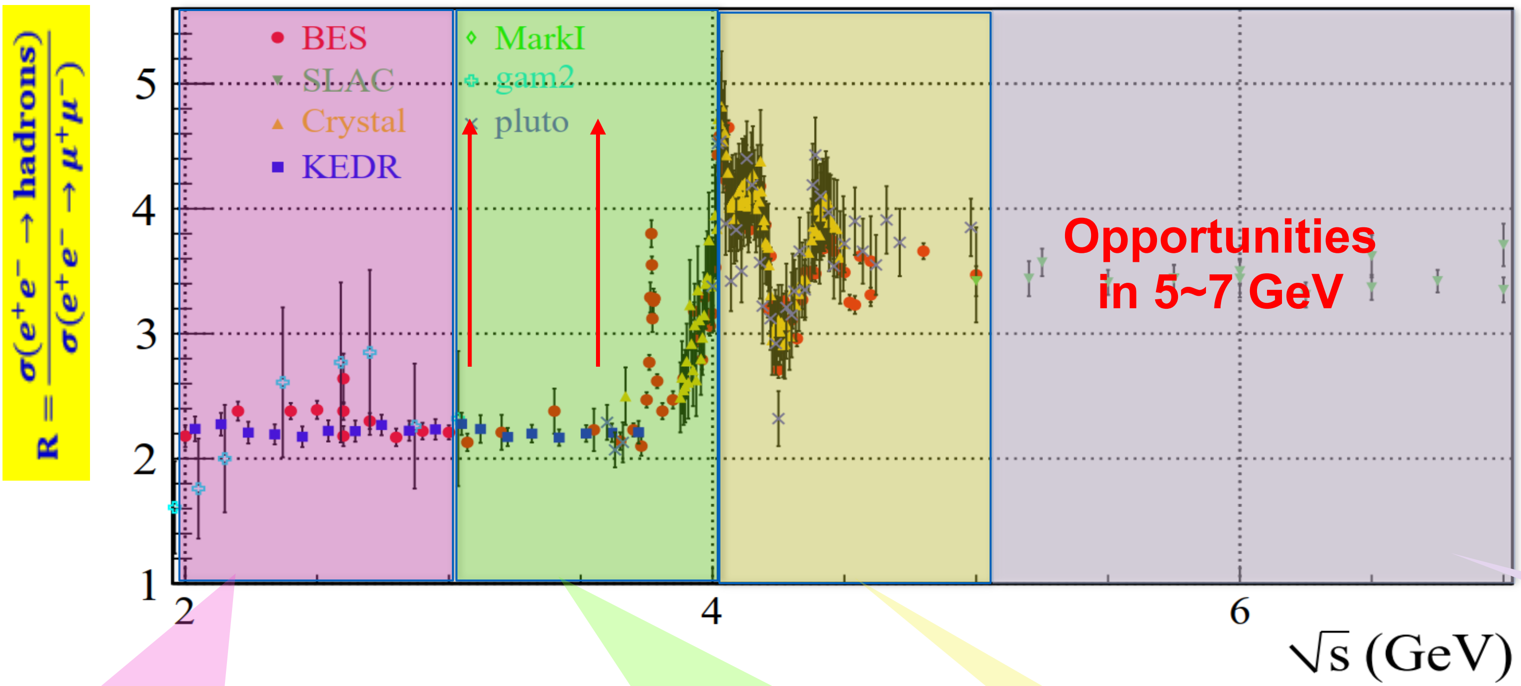
超级陶粲装置

Super Tau-Charm Facility

Outline

- Introduction
- Physics Opportunities
- Project Promotion and progress
- Summary and Outlook

Physics at the Tau-Charm Energy Region



Unique Features at 2-7GeV:

- Transition region between perturbative and non-perturbative QCD
- Threshold effects of pair production of hadrons and τ lepton
- Rich resonant structures, large production cross sections for charmonium(-like) states and exotics

- Hadron form factors
- $Y(2175)$ resonance
- Mutltiquark states with s quark
- R value / g-2 related

- Light hadron spectroscopy
- Gluonic and exotic states
- Processes of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

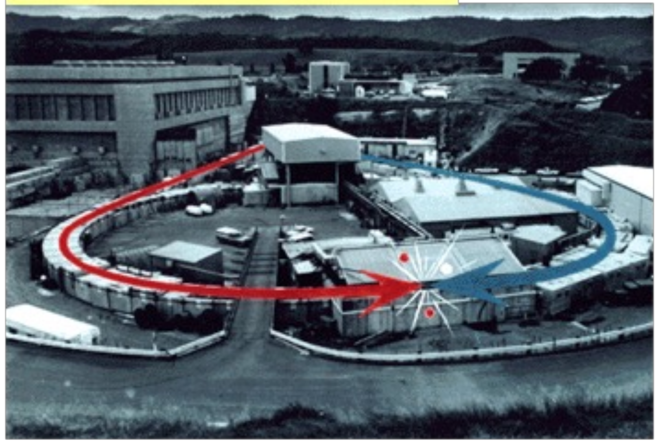
- *XYZ* particles
- Physics with D mesons
- f_D and f_{D_s}
- $D^0 - \bar{D}^0$ mixing
- Charm baryons

- Complete *XYZ* family
- Hidden-charm pentaquarks
- Search for di-charmonium states
- More charmed baryons
- Hadron fragmentation

Dedicated Tau-Charm Factories

ADONE, FRASCATI
'69-'93

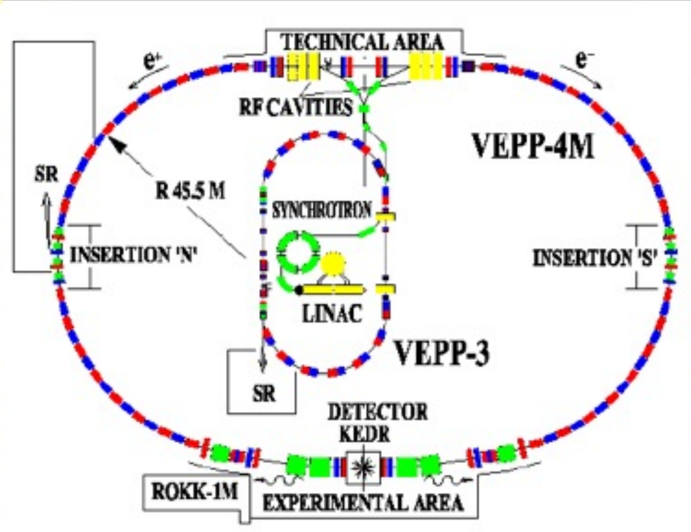
SPEAR, SLAC, '72-'90
6×10^{29} cm^{-2}.s^{-1}



BEPC, IHEP, '90-'04
5×10^{30} cm^{-2}.s^{-1}

CESRc, Cornell, '04-'08
7×10^{31} cm^{-2}.s^{-1}

VEPP-4M, Novosibisk, '02-'12
1×10^{30} cm^{-2}.s^{-1}



BEPCII, IHEP, '08-'30(?))
1×10^{33} cm^{-2}.s^{-1}

Future e^+e^- Collider Factory

Energy ranges of high luminosity e^+e^- colliders (factories) correspond to **production thresholds** of known particles

τ-c factory

BEPCII (China)

×100 gain in luminosity

Super τ-c Factory

STCF (China), SCTF (Russia)

B-factory

PEP-II (USA), KEK-B (Japan)

Super KEKB (Japan)

LHCb (CERN)

Z- and H- factory

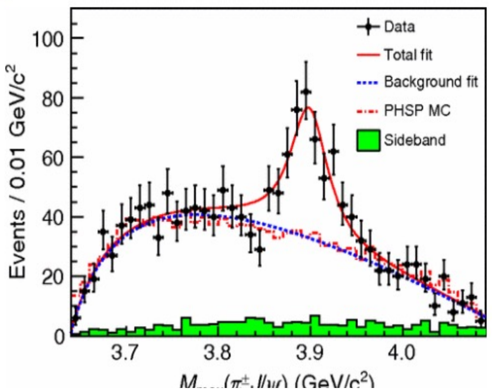
LEP, LEP-2 (CERN)

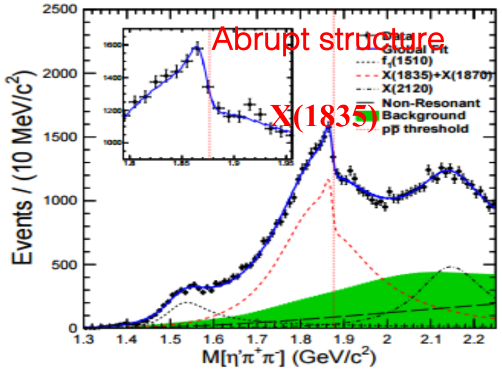
FCC-ee (CERN)

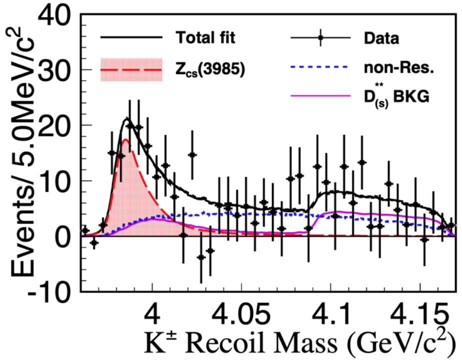
CEPC (China)

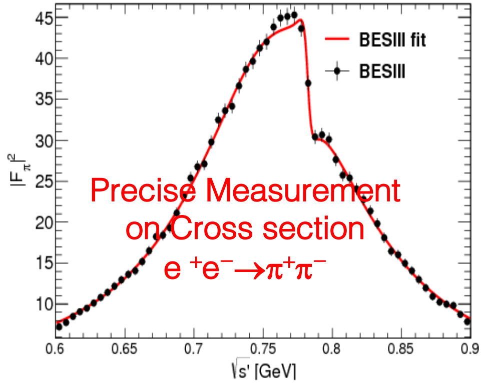
Ultimate performance (precision) is determined by luminosity and detector quality

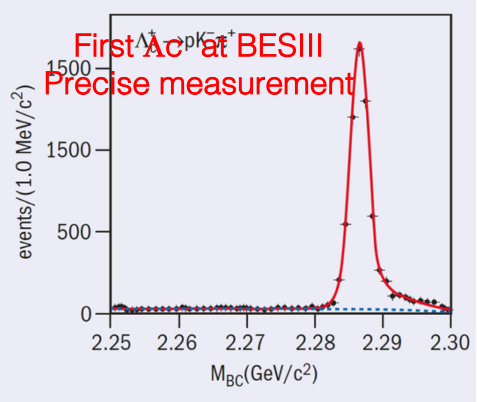
Fruitful BEPCII/BESIII Results

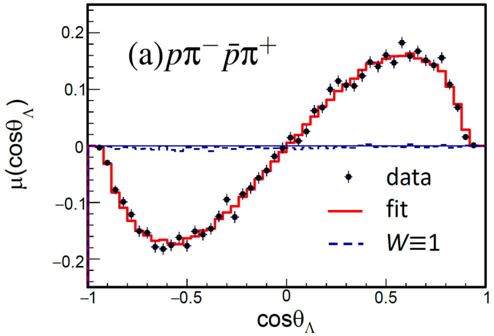


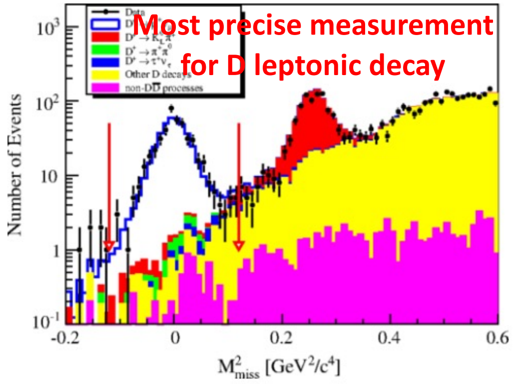


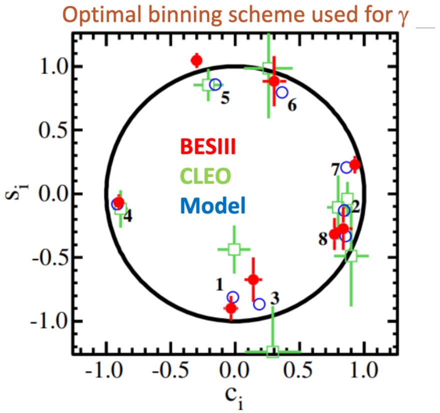




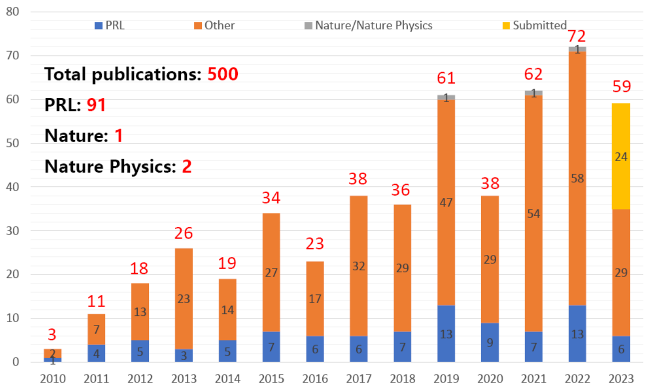








BESIII publications (May 9, 2023) **>500**

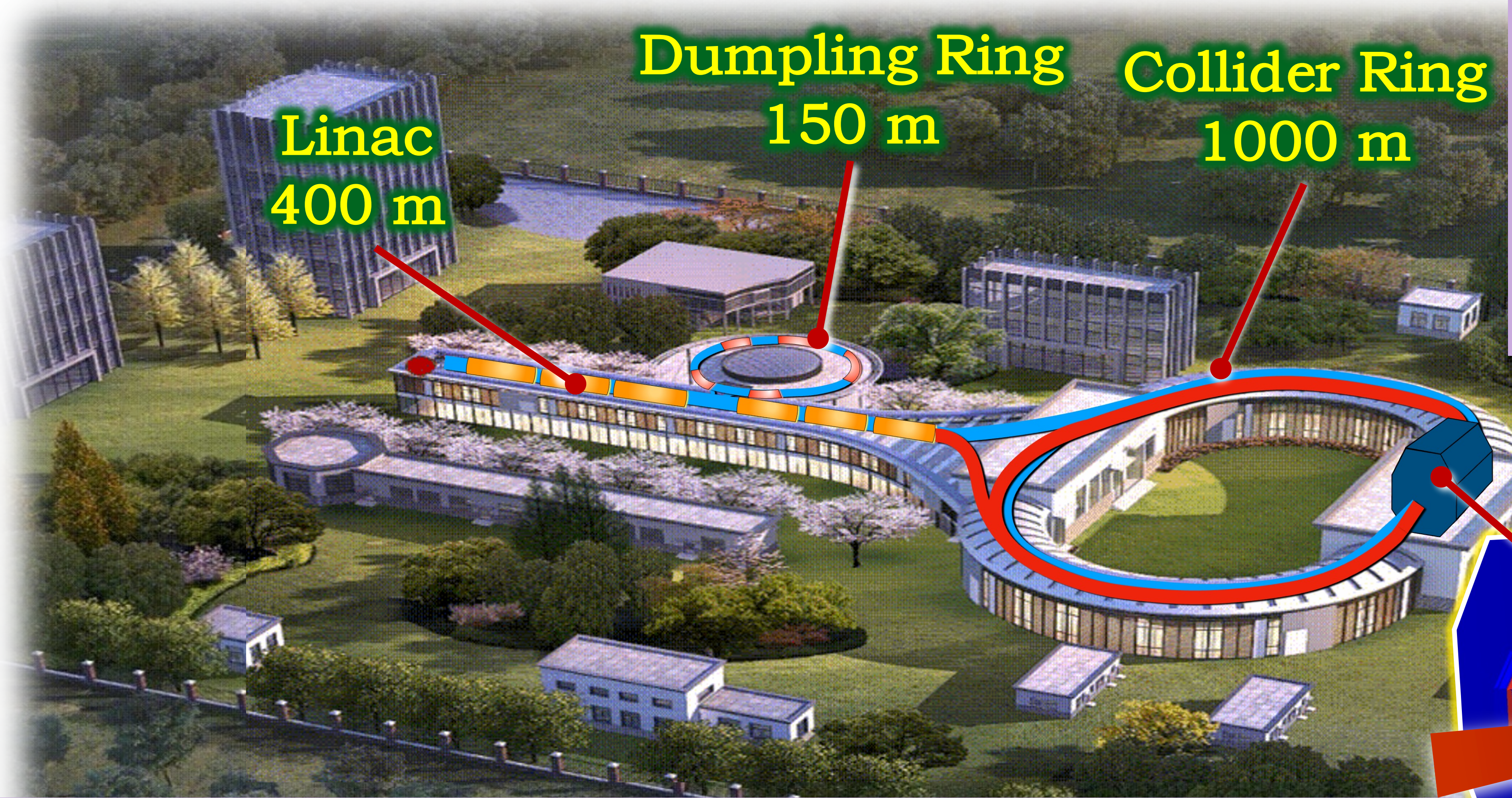


Tau-Charm Facility in China

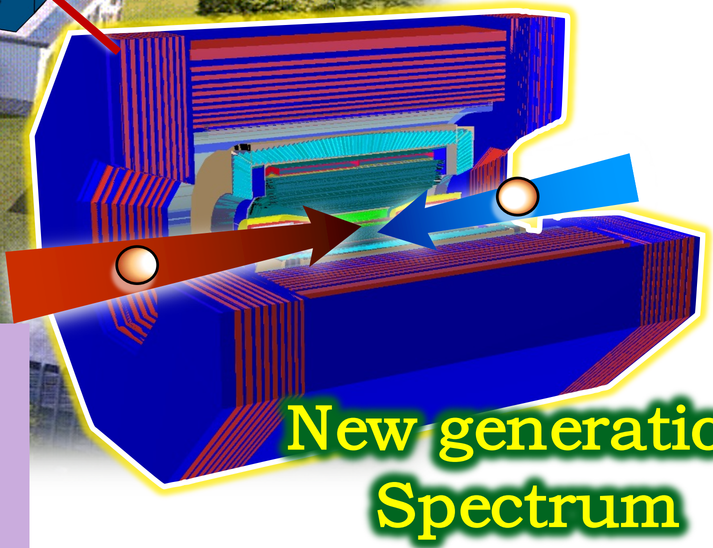
- BEPCII/BESIII have run 10 years, and are playing a leading role in tau-charm physics area.
- Limited by length of storage ring, no space and potential for major upgrade.
- Physics study limited by the Statistics (luminosity), collision energy up to 4.9 (**5.6**) GeV ……
- Many of the physics can be covered by ISR at Belle II
- BEPCII/BESIII will end her mission in 5 - 8(?) years

A Super Tau-Charm Facility (STCF) is the nature extension and a viable option for a post-BEPCII HEP project in China

The Super Tau-Charm Facility (STCF)



A factory produces massive **tau lepton** and **charmed hadrons**, to relieve the mystery of **how quarks form matter** and the symmetry of **fundamental interactions**

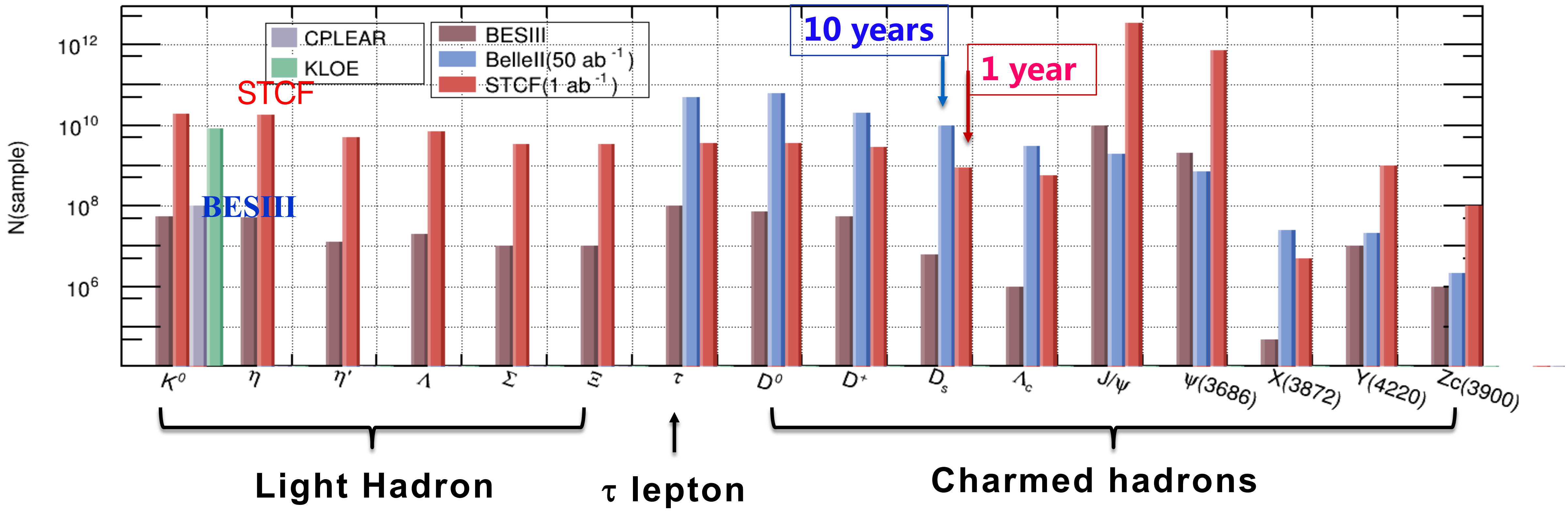


- Center-of-Mass energy coverage : 2-7GeV;
- Peaking Luminosity >$0.5\sim1\times10^{35}$ cm^{-2} s^{-1} @ 4GeV
- Potential to increase luminosity & realize beam polarization

Unique Data Sample

Huge statistics data sample + High Resolution + Low background

High precision measurement → Discovery



not only a τ-charm factory, but also a factory for XYZ exotics, hyperons, light hadrons

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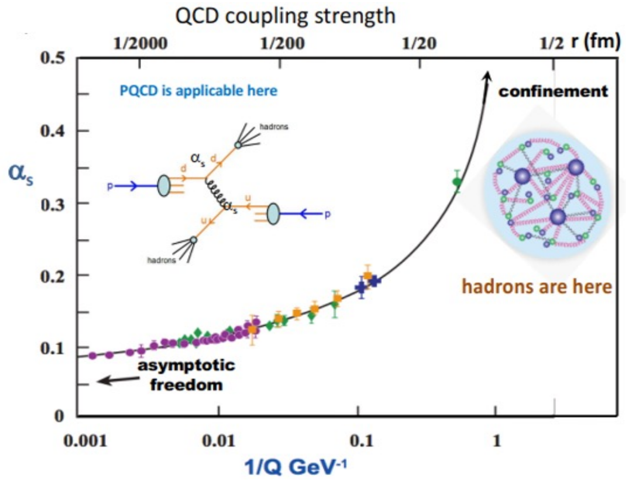
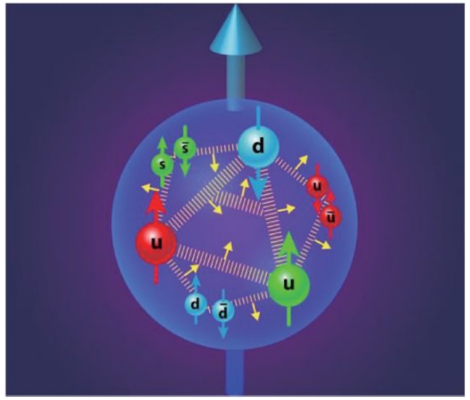
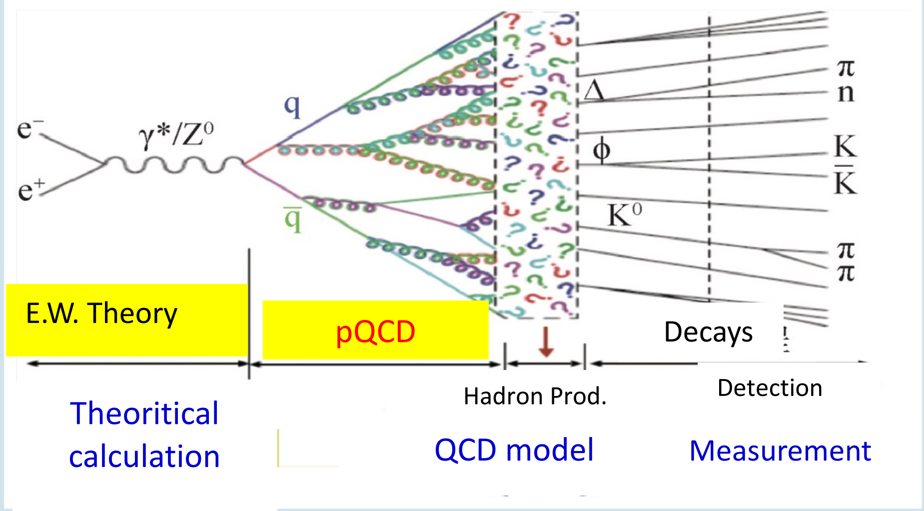
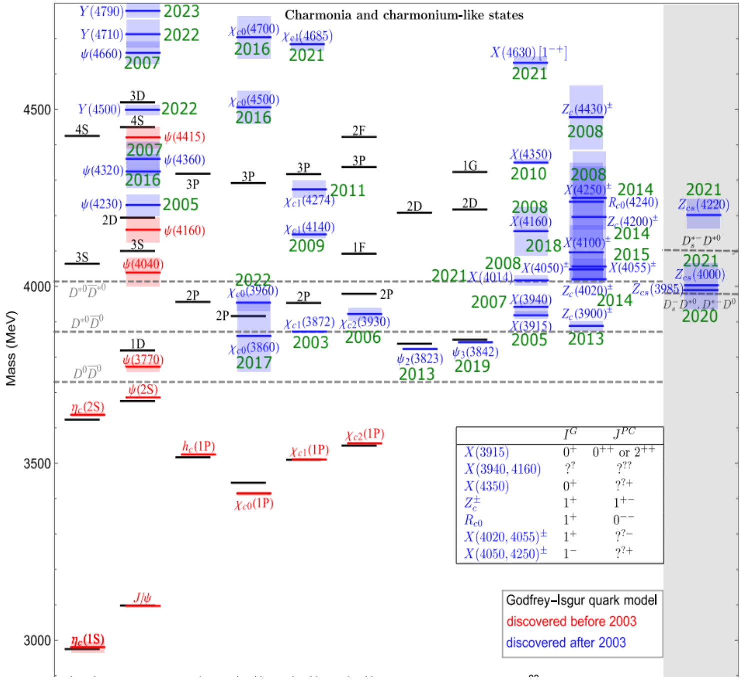
Non-Perturbative QCD and Confinement

- Quark confinement and non-perturbative feature in low-energy QCD region are the remaining challenge
- The effects is becoming the bottleneck in the precision measurement and new physics searching
- The inner structure of nucleon, the spectroscopy of hadron and exotic, fragmentation function are the experimental objectives









STCF unique advantage :

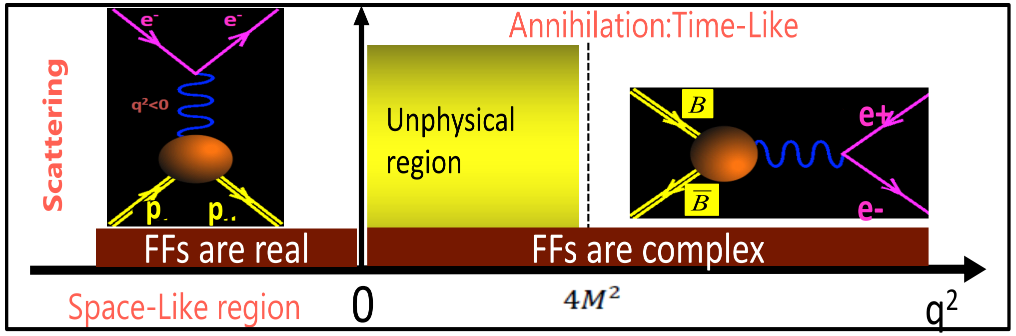
- Perturbative and non-perturbative transition energy region
- Threshold production of nucleon, hyperon and charmed baryons
- Large cross section for charmmonium

R value and QCD Physics

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

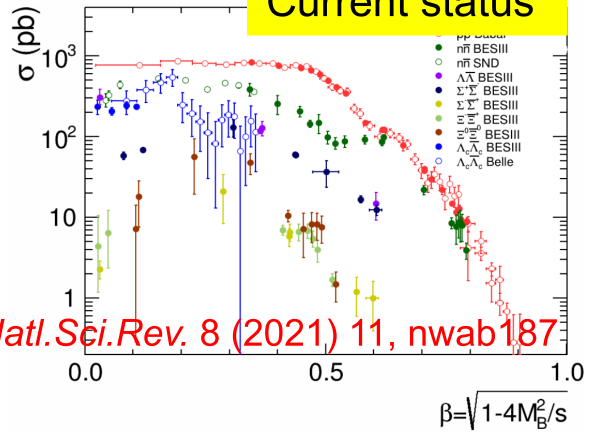
Electromagnetic Form Factors (EMFFs)

- EMFFs are fundamental properties, directly connected to charge and current distributions of the nucleon
- Various models describe time-like FF in non-perturbative region: ChEFT, VMD, relativistic CQM, parton model, pQCD etc.
- Dispersion analysis provide a coherent framework for the joint interpretation of space-like and time-like EMFFs over the entire q^2 regions

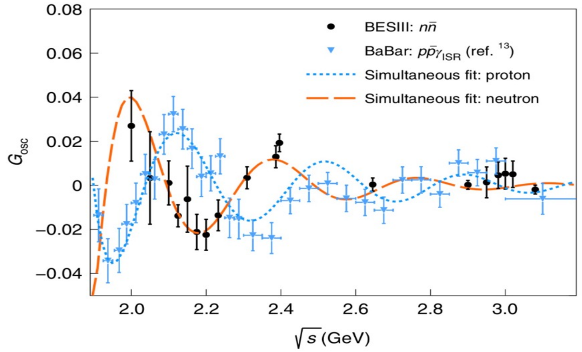


SIDIS ⟷ STCF

Current status



Natl.Sci.Rev. 8 (2021) 11, nwab187



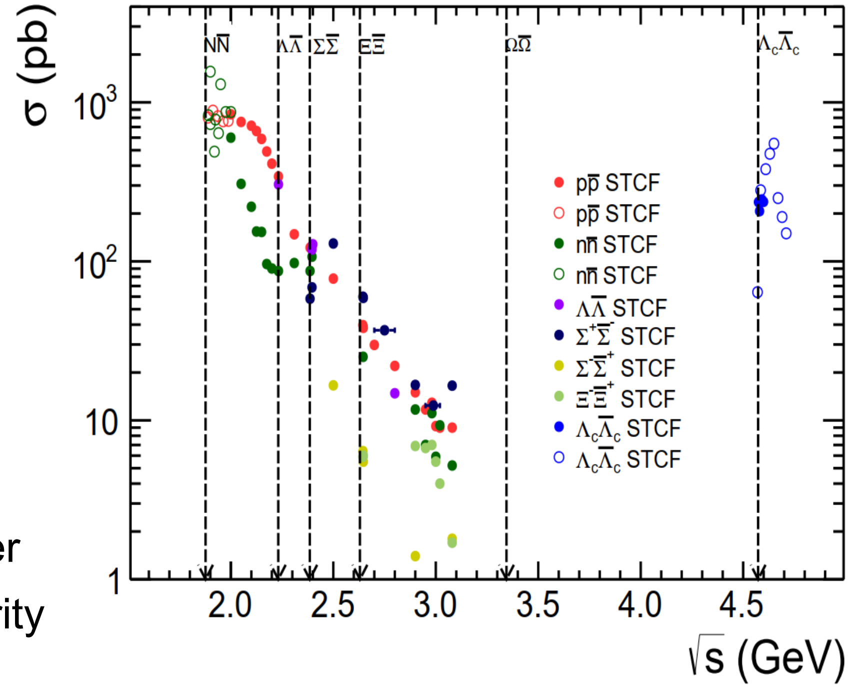
Remaining questions of TL-EMFFs:

- Step-like behavior of production cross section, indication of near-threshold singularity.
- Damped oscillation distribution after subtracting modified dipole in effective FF.
- Damped oscillation distribution of $|G_E/G_M|$ ratio.
- Evolution of the phase between G_E and G_M.
- The asymptotic behavior of TL-EMFFs

STCF prospect for time-like EMFFs:

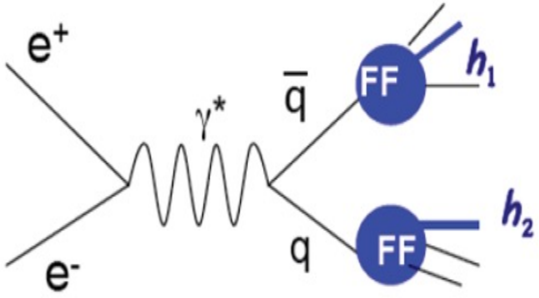
- Improve cross section measurement by 1-2 order
- Reveal the near-threshold cross section singularity and mystery of G_E and G_M.

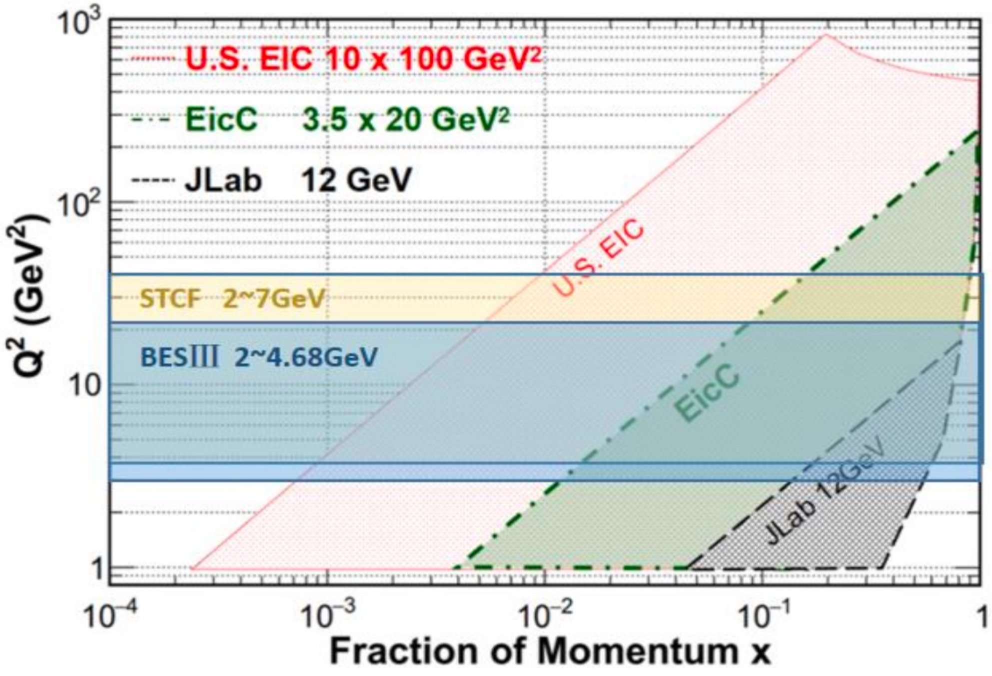
STCF Prospect



Fragmentation Function

- Fragmentation function, describing the processes of quarks/gluon hadronization, is non-perturbative process and challenging in theoretical calculation.
- To accurately extract Parton Distribution Functions (PDFs), precise knowledge FFs are required.
- e^+e^- collider experiment provides the cleanest input for extracting FFs. With polarized electron beam, polarized FFs can be studied.



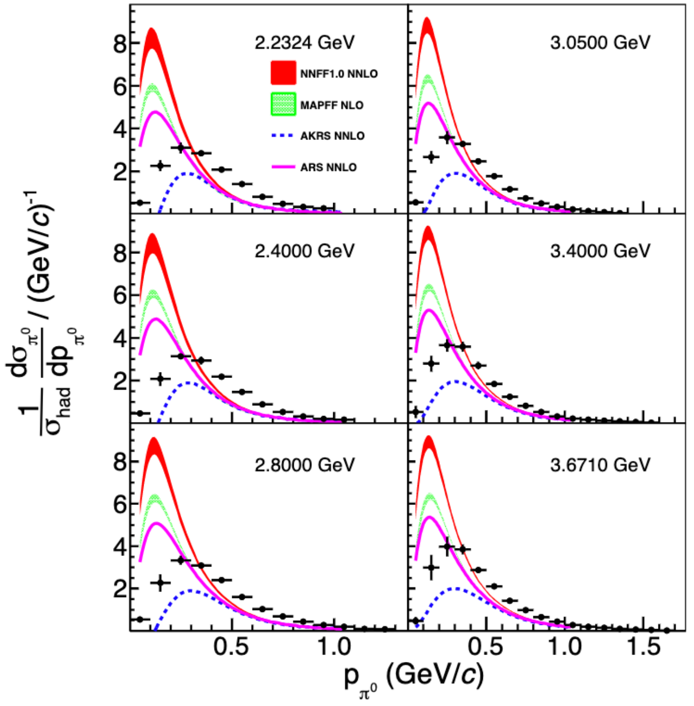


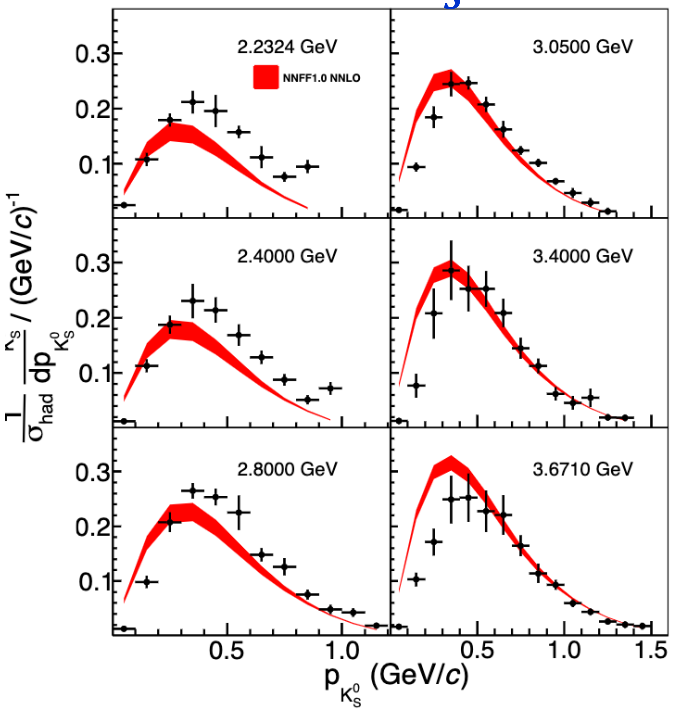
STCF prospects :

- The most precise fragmentation function in q^2 range 4-50 GeV^2 with dependences on multi-dimensional kinematics
- Precision test of the universality of fragmentation function in the different processes, and its evolution with q^2
- Provide important input for EIC, EicC and JLab experiments

Inclusive hadron production in e^+e^- annihilations at BESIII

π^0 PRL130, 231901 (2023) K_S





arXiv:2401.17873

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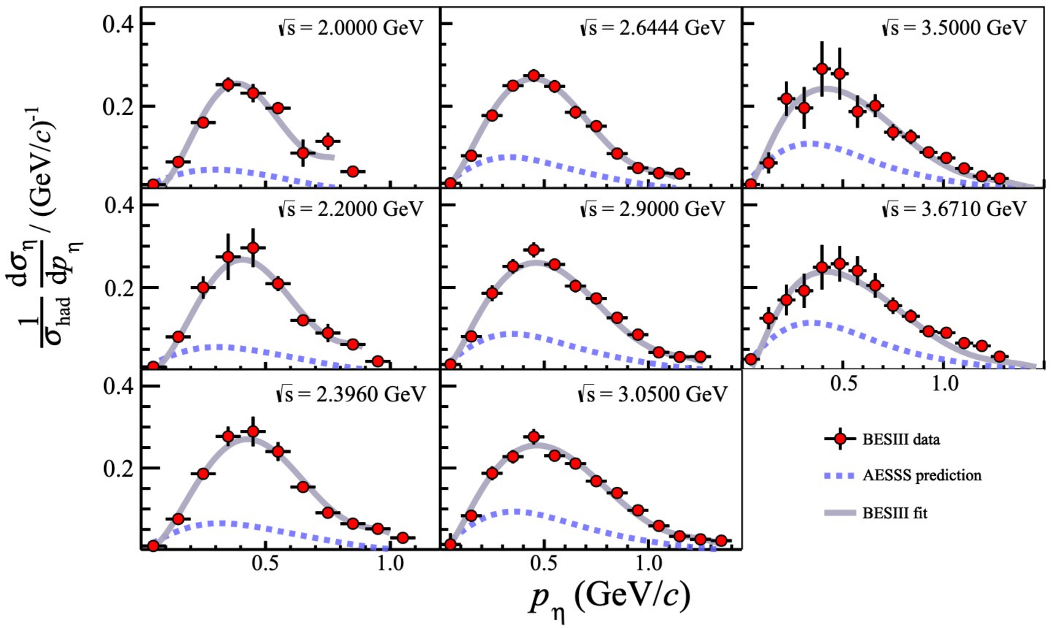
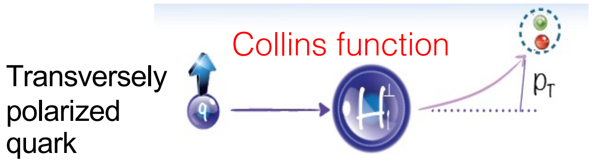


- broad z_h coverage from 0.1 to 0.9
- the agreement between data and theoretical calculations degenerates as the c.m. energies decrease
- provide brand new inputs in low-energy region to global fits of fragmentation function

Collins Fragmentation Function



J. C. Collins, Nucl. Phys. B396, 161 (1993)

$$D_{hq^\uparrow}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{zM_h},$$

H_1: Collins FF

→ describes the fragmentation of a transversely polarized quark into a spin-less hadron *h*.

→ leads to an azimuthal modulation of hadrons around the quark momentum.

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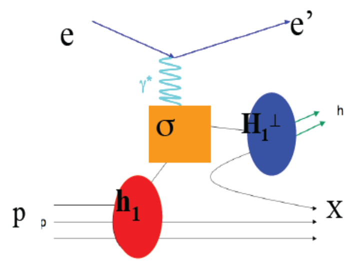
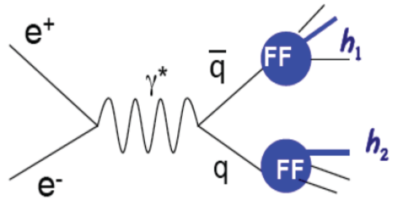
Transversity ⊗ Collins FF

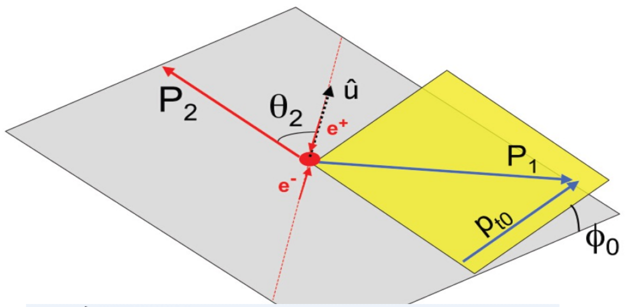


e+ e-

Collins FF ⊗ Collins FF

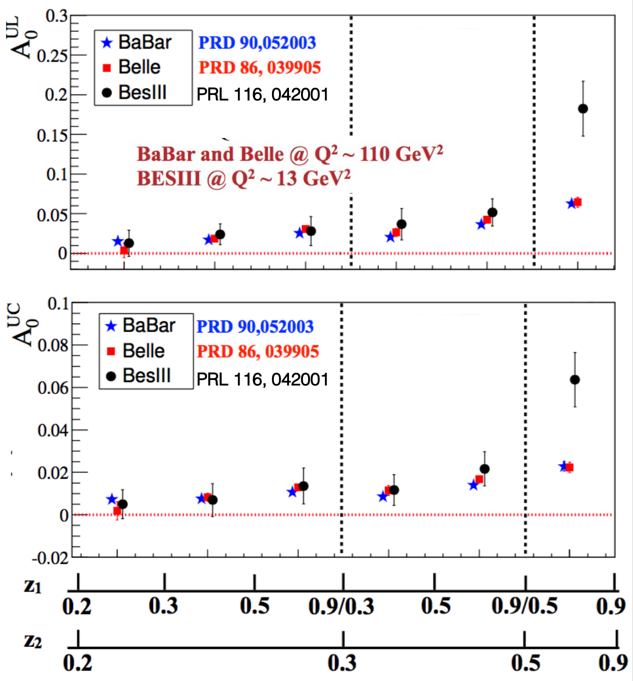


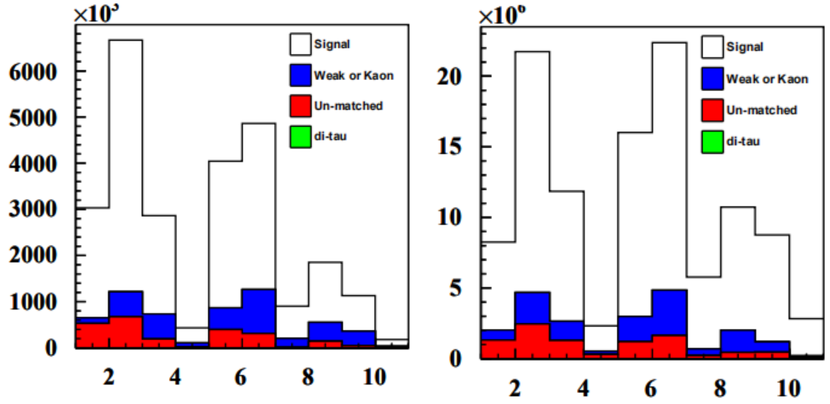
D. Boer, NPB 806, 23 (2009)



$$e^+e^- \to q\,\bar{q} \to h_1\,h_2\,X$$

$$\sigma \sim 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$



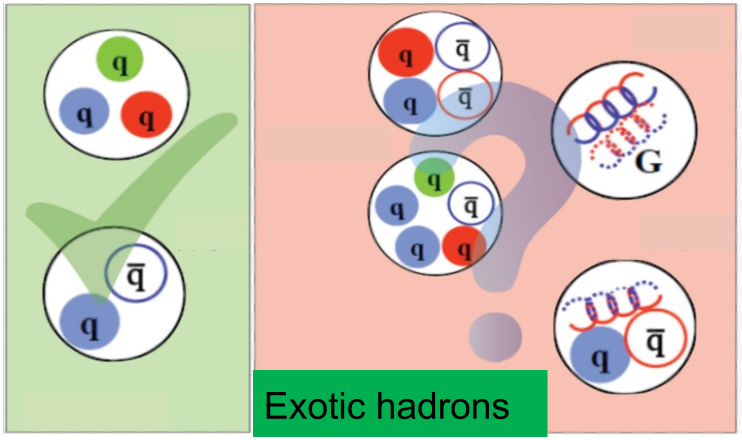


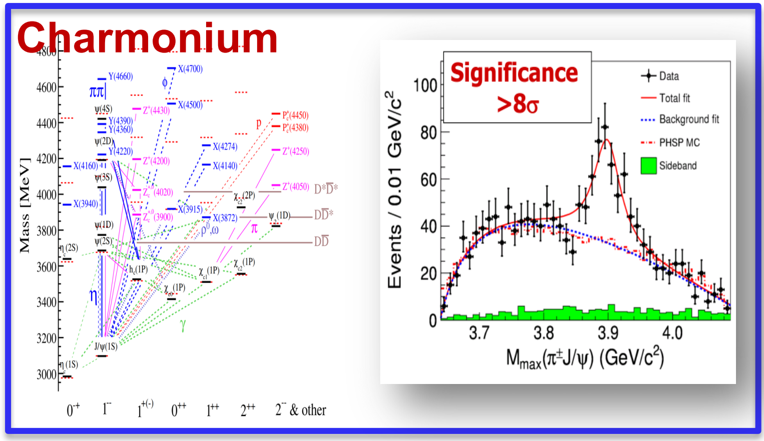
- The statistical uncertainty asymmetry A^{UL} with $1ab^{-1}$ at 7 GeV[1]:
  - $(1.4\sim4.2)\times10^{-4}$ for $\pi\pi X$
  - $(3.5\sim20)\times10^{-3}$ for KKX
- 2% precision required by EicC

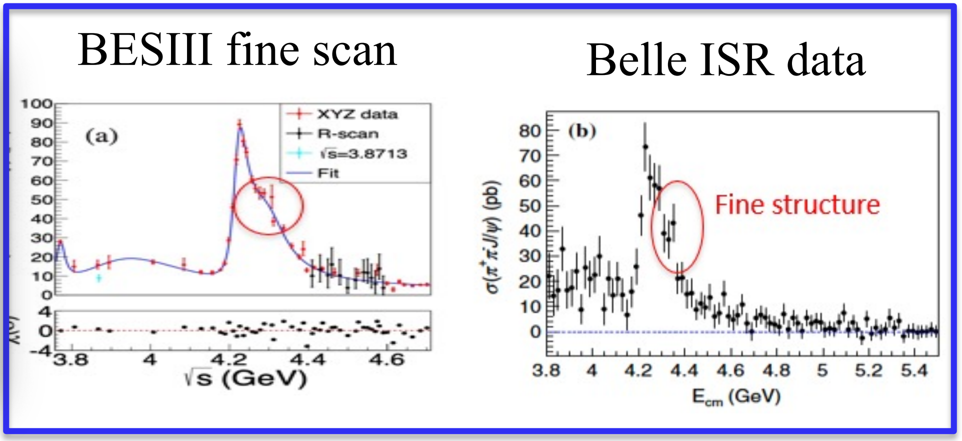
[1] B. L. Wang et al., Journal of UCAS 38 (2021) 433

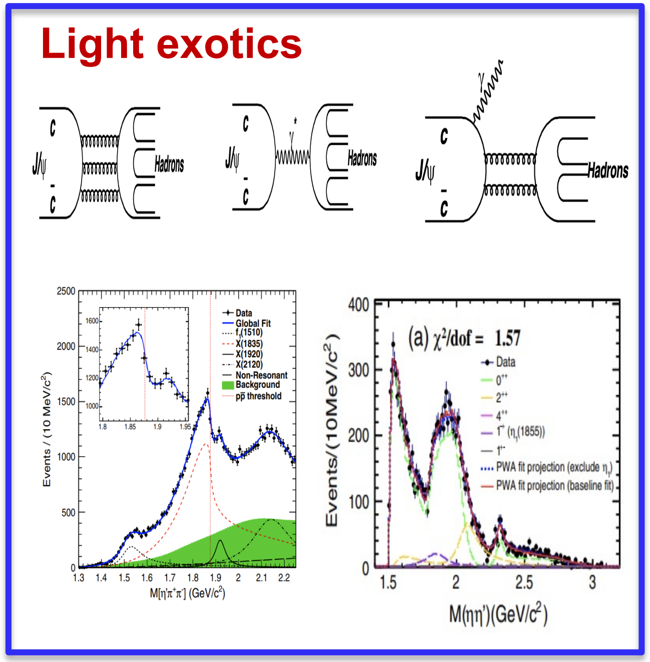
Hadron Spectroscopy and Exotics

A unique territory for studying QCD









A Charmonium(-like) factory (per year):

- 3T J/ψ, 0.1T $\psi(3686)$, 1B Y(4230), 100M $Z_c(3900)$ and 5M X(3872)

Physics opportunities :

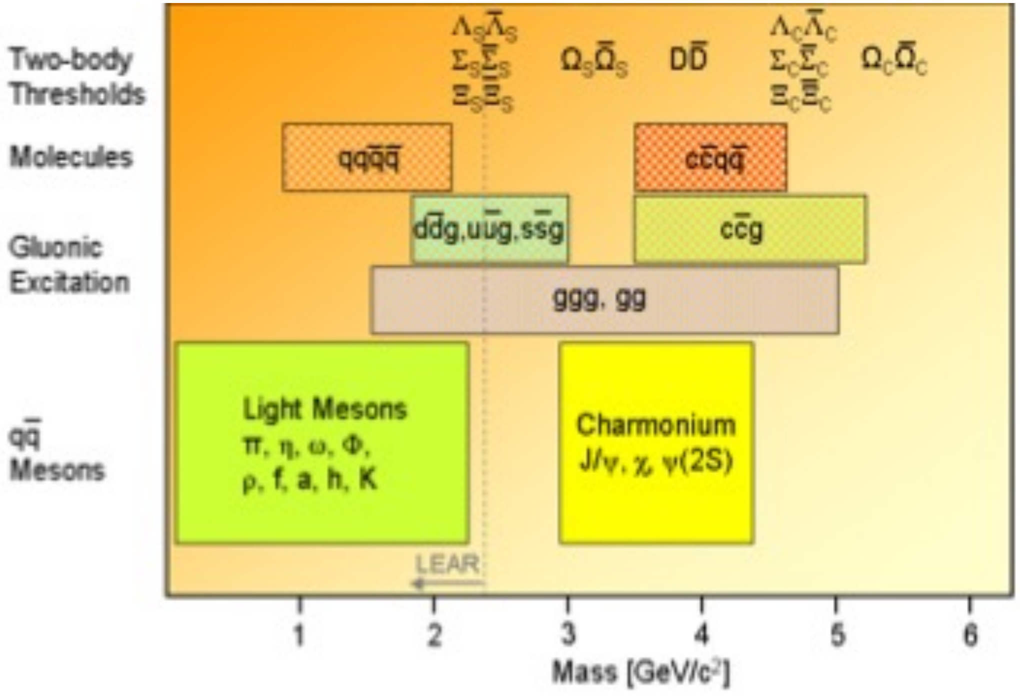
- Energy dependent structures of $Z_{c(s)}$
- More XYZ states → Spectroscopy
- Missing charmonium states and their transitions
- Traces of glueballs and Hybrid states

STCF has an absolute advantage in studying hadron spectroscopy and exotic states, and is expected to achieve significant breakthroughs.

Study of Hadron Spectroscopy

At STCF, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

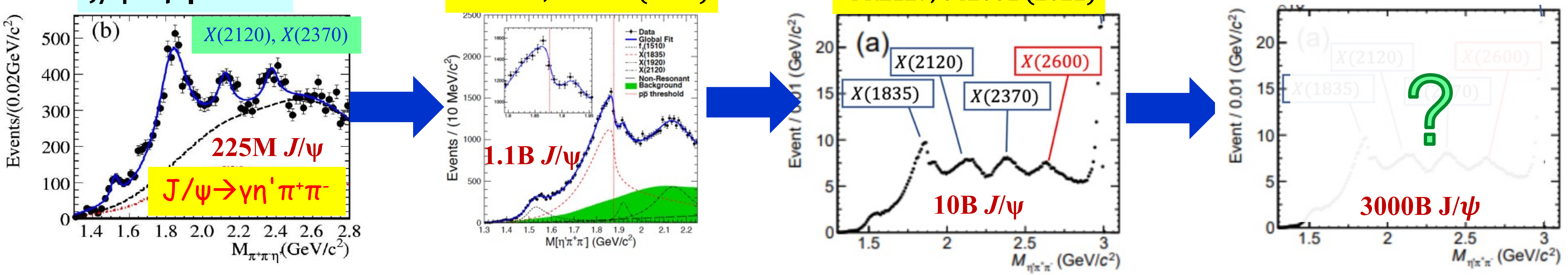
- Light hadrons: charmonium radiative decays (act as spin filter) for example **3T J/ψ** and **100B $\psi(2S)$**
- Heavy hadrons: direct production, radiative and hadronic transitions (**data between 3.8~7 GeV**)



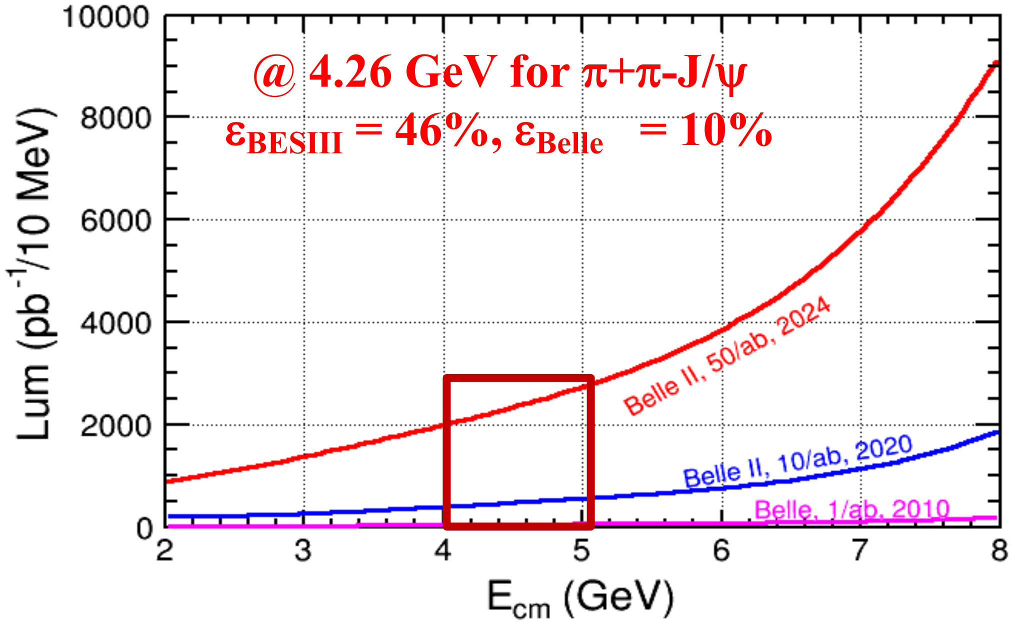
$J/\psi\to\gamma\eta'\pi^+\pi^-$

PRL117, 042002 (2016)

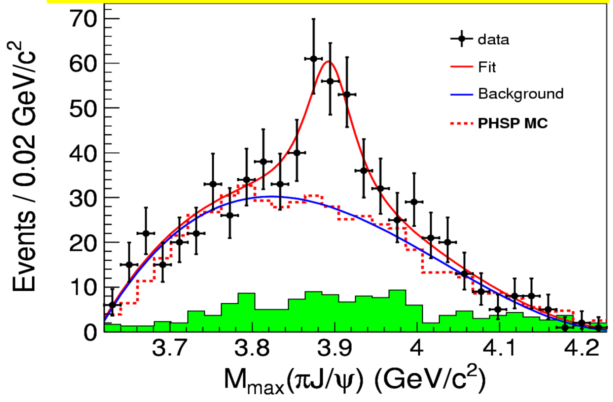
PRL129, 042001 (2022)



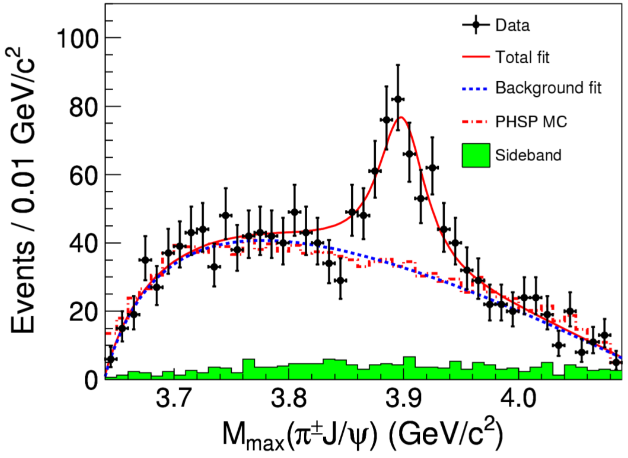
Charmonium(like) Spectroscopy at STCF



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



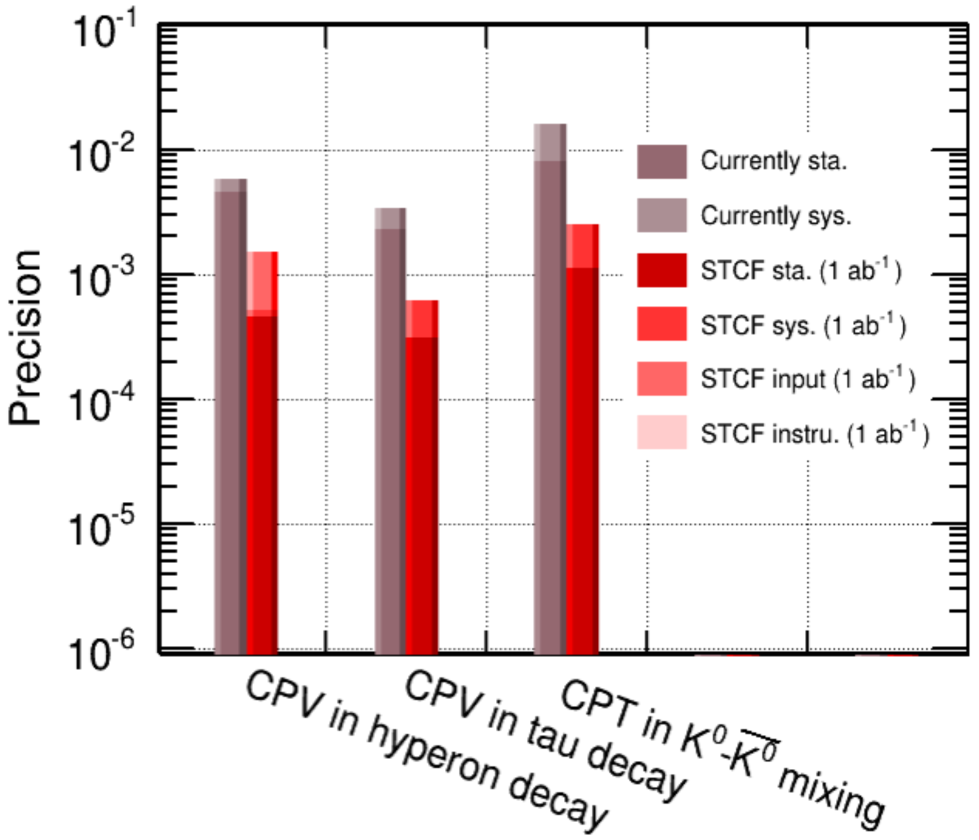
BESIII at 4.260 GeV: PRL110, 252001
0.525 fb^{-1} in one month running time



- B factory : Total integrate effective luminosity between 4-5 GeV is 0.23 ab^{-1} for 50 ab^{-1} data
- τ-C factory : scan in 4-5 GeV, 10 MeV/step, every point have 10 fb^{-1}/year, 5 time of Belle II for 50 ab^{-1} data
- τ-C factory have much higher efficiency and low background than B Factory

CP Violation

- CPV observed in K, B, D mesons, all **consistent with** CKM theory in SM
- **Baryon asymmetry** of the universe indicates the existence of **non-SM CPV sources**
- STCF is capable of searching for **CPV in hyperon and τ lepton**, as well as **CPT violation in Kaon** with high sensitivity



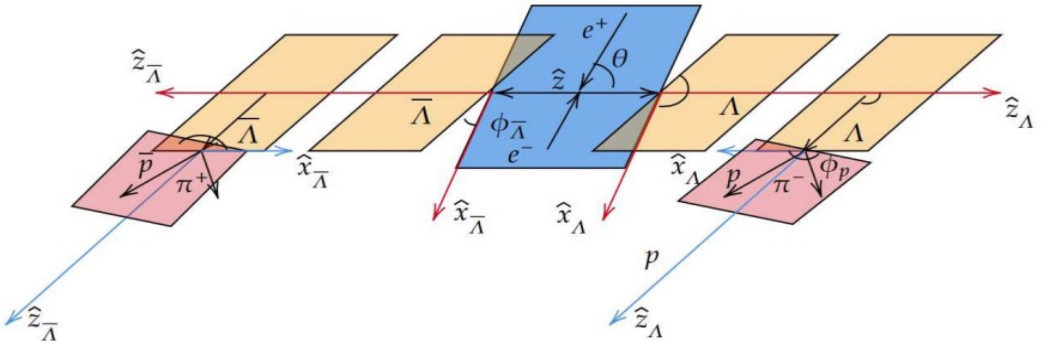
Unique advantages :

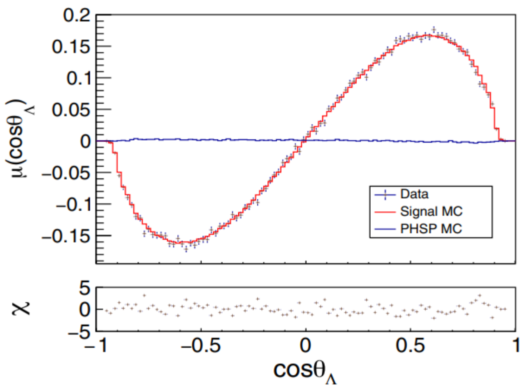
- quantum correlation, huge statistics, clean background

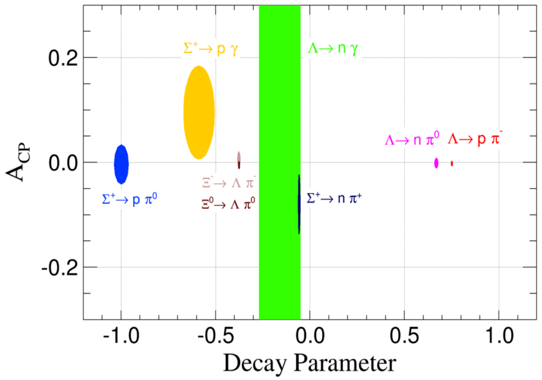
CPV in Hyperon Decay

- BESIII has observed the polarization of hyperon in the J/ψ decay, and carried out CPV measurement by performing the jointly angle distribution analysis.
- The sensitivity to test CPV in the J/ψ decay is found to be much improved due to the quantum correlation between hyperon pair, and the polarization of hyperon

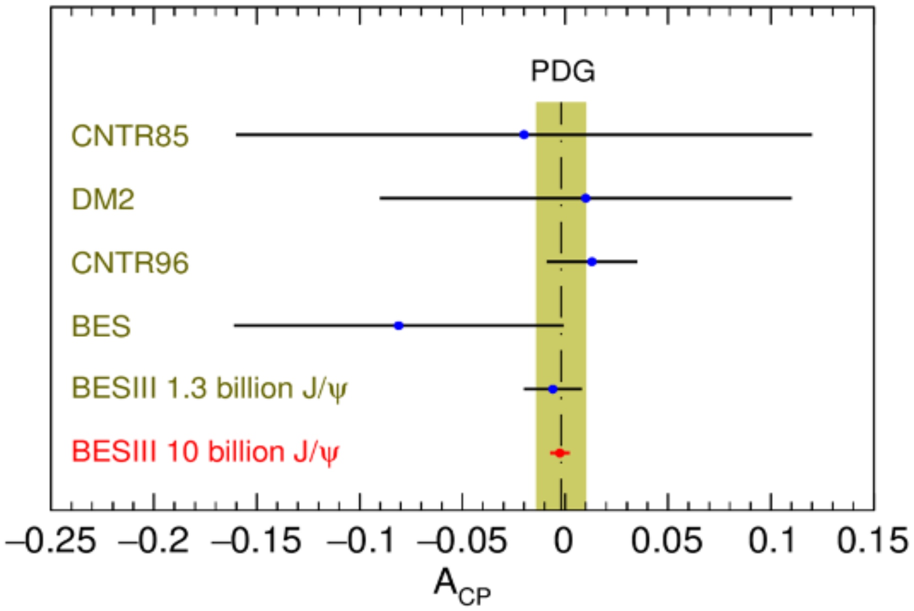
CP test $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$







PRL 129, 131801 (2022)



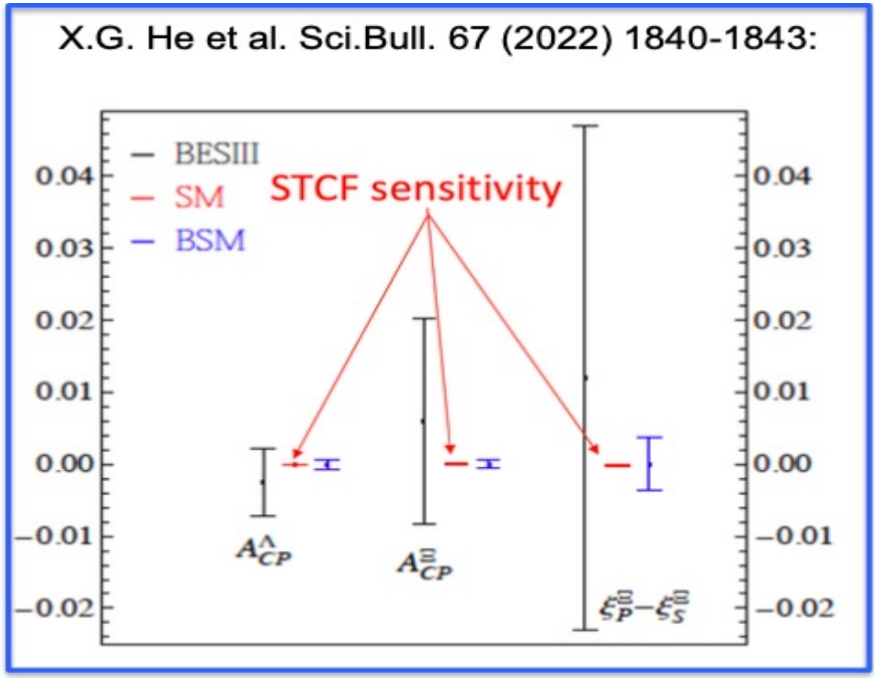
0.5% level sensitivity for CPV test

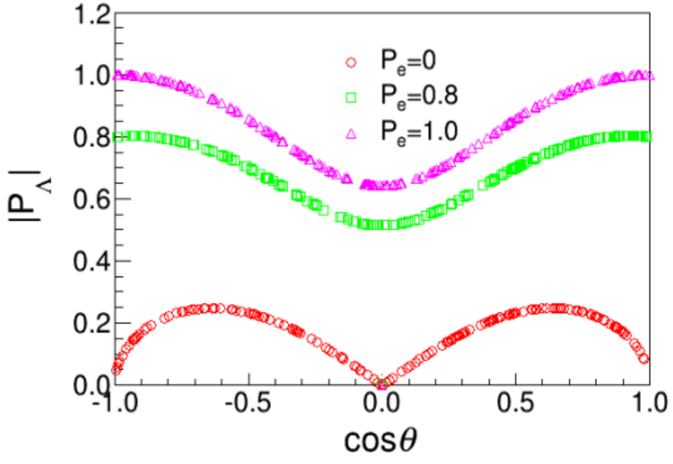
SM prediction: 10^{-4}~10^{-5}

CPV in Hyperon Decay

- STCF has 10^{12} J/ψ per year, corresponding 10^9 hyperon pair, the CPV test sensitivity challenge SM prediction 10^{-4}~10^{-5}
- Polarized electron can significant improve the test sensitivity

$$P_\Lambda = \frac{\gamma_\psi P_e \sin\theta \hat{x}_1 - \beta_\psi \sin\theta\cos\theta \hat{y}_1 - (1+\alpha_\psi) P_e \cos\theta \hat{z}_1}{1+\alpha_\psi \cos^2\theta}.$$





$$\sigma_{A_{CP}} \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha_1 \sqrt{N_{sig}} \sqrt{\langle P_B^2 \rangle}}.$$

$$\xrightarrow{1\times10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.1} \sigma_{A_{CP}} \sim 1.4\times10^{-4}$$

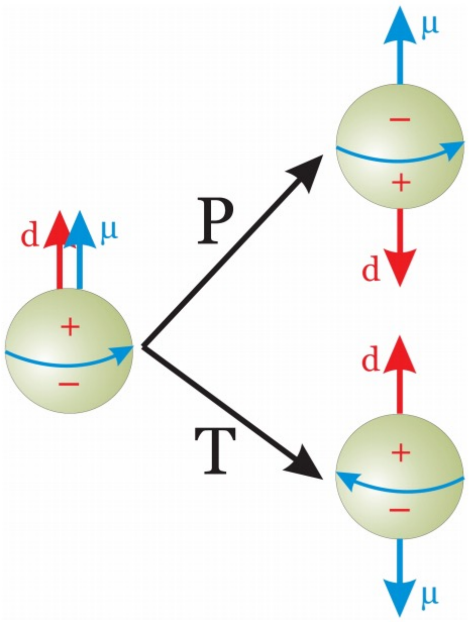
$$\xrightarrow{1\times10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.8} \sigma_{A_{CP}} \sim 0.5\times10^{-4}$$

EDM in Hyperon

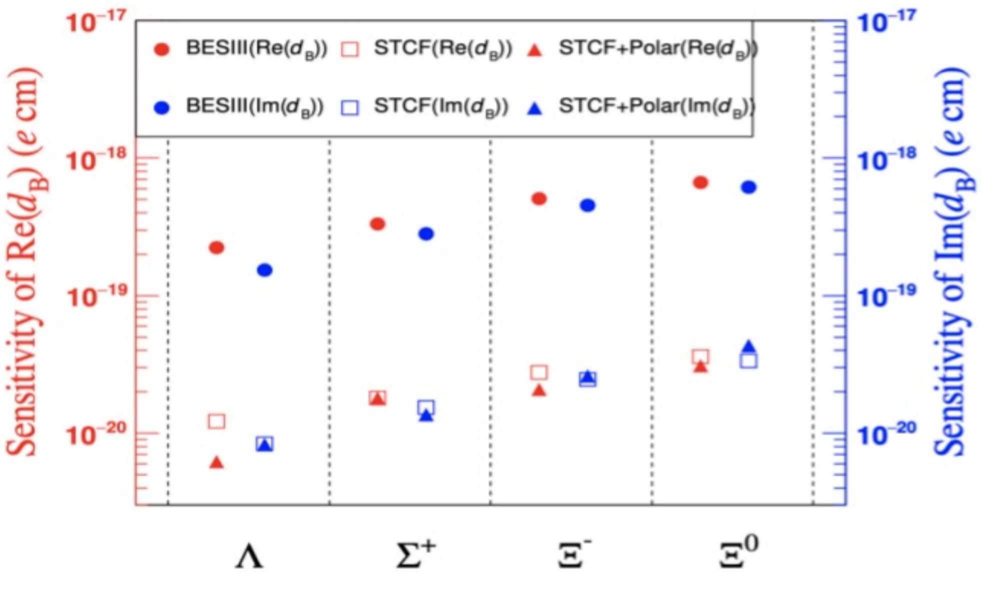
Detailed dynamics in J/ψ decay to hyperon pair have been studied:

$$\mathcal{A} = \epsilon_\mu(\lambda)\bar{u}(\lambda_1)\left(F_V\gamma^\mu + \frac{i}{2M_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T\right)v(\lambda_2)$$

μ: magnetic dipole moment
d: electric dipole moment



Systematic measurement of the EDMs of the hyperon family!



(a)Sensitivity of $Re(d_B)$ and $Im(d_B)$

X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

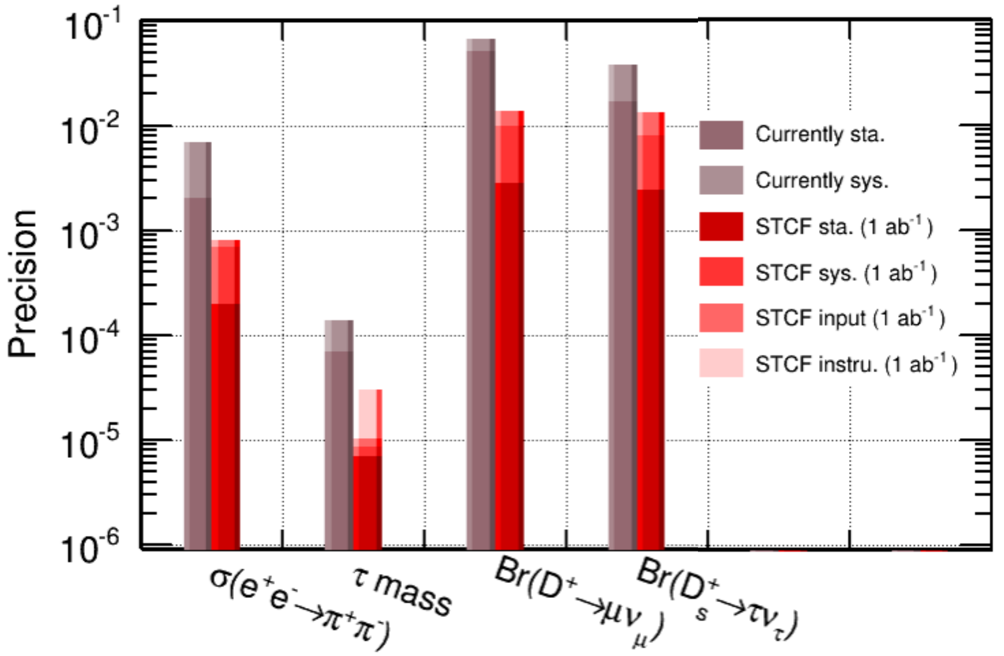
SM: $\sim 10^{-26}$ e cm

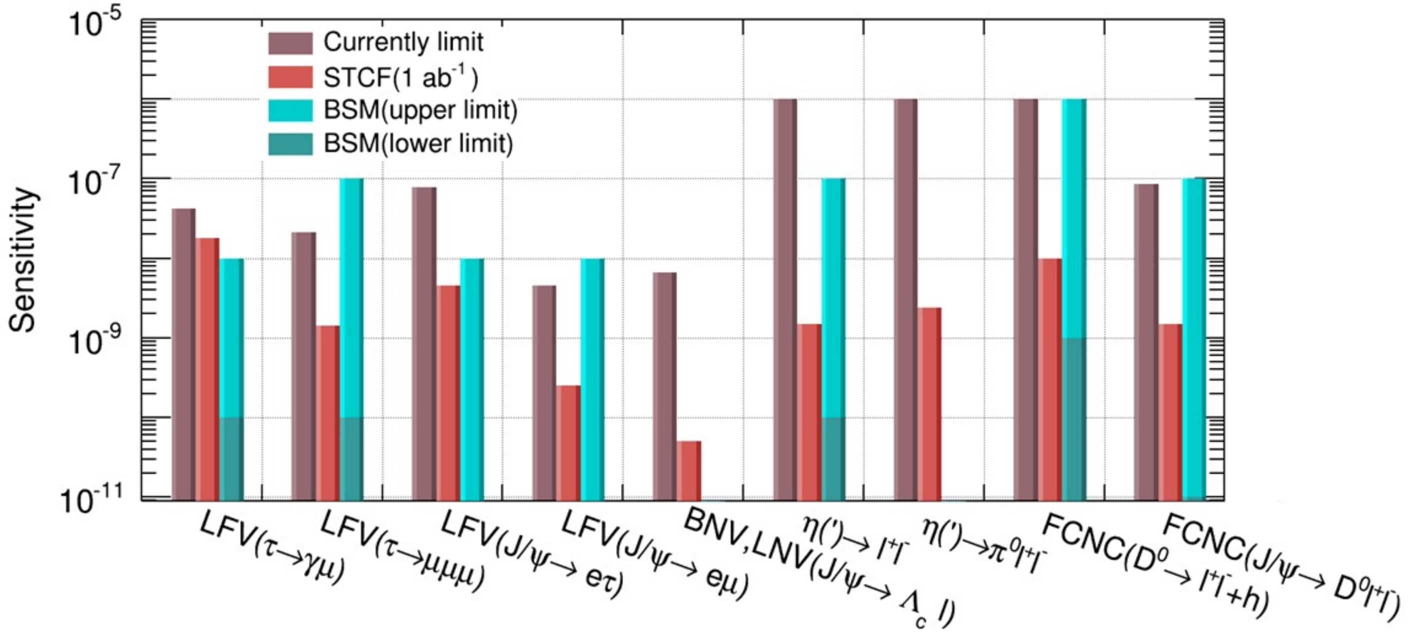
BESIII: milestone for hyperon EDM measurement
Λ $10^{-19}e$ cm (FermiLab 10^{-16} e cm)
first achievement for Σ^+,Ξ^- and Ξ^0 at level of $10^{-19}e$ cm
a litmus test for new physics

STCF: improved by 2 order of magnitude

Non-zero EDM will violate P and T symmetry: T violation ↔ CP violation, if CPT holds.

Precision Measurements and Rare Decays





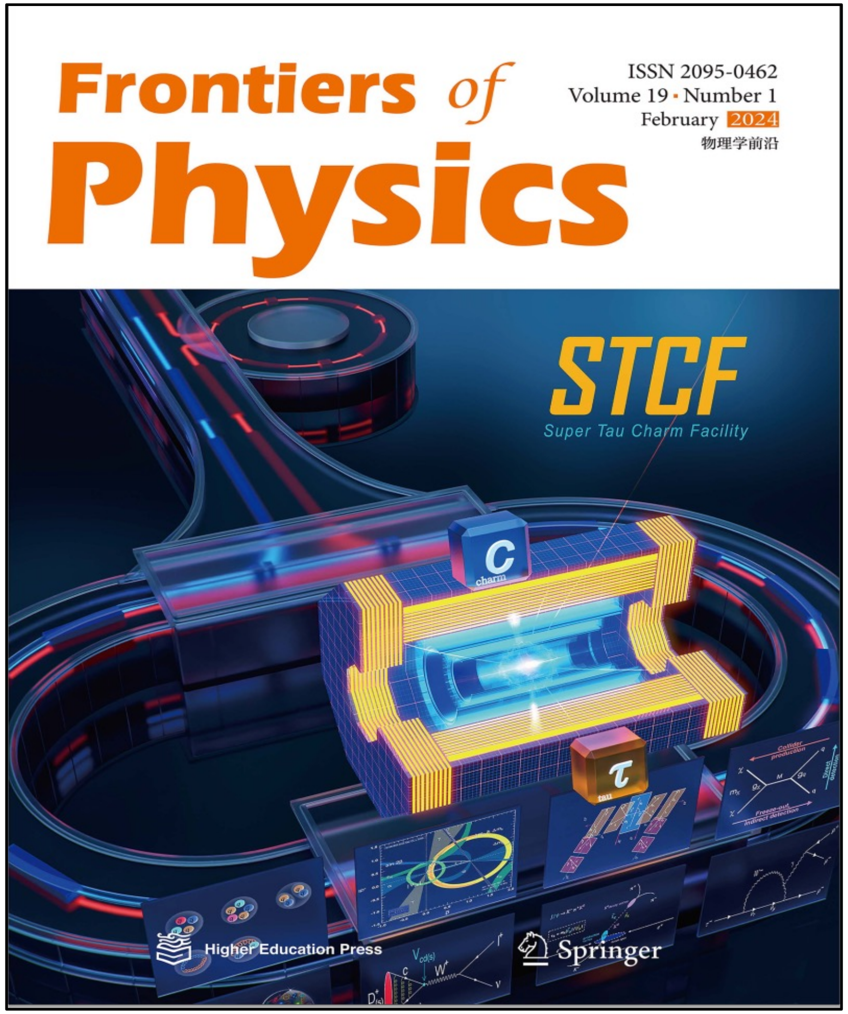
STCF physics opportunities :

- improve the current precisions of many important measurements by ~1 order of magnitude
- enhance sensitivities to various rare or forbidden decays by ~2 orders of magnitude.

More Physics Beyond

Key words / main topics of STCF physics CDR citations

CP in charmed baryon
Near-threshold resonance
EMFFs
Triangle singularity
Tau EDM
D_s^* radiative decay
Hyperon-Nucleus Scattering
FCNC
Light-cone distribution amplitudes
Millicharged particles
K0-K0bar
Neutral meson mixing
Spin 3/2 polarization
QCD sum rules
Muon g-2 and $\alpha(M_Z^2)$
$\Lambda-\bar{\Lambda}$ oscillation
Axion-like particle
cLFV
Fully charm tetraquarks
$SU(2)_L$-singlet vector-like fermion partners
$\Delta S=2$ Nonleptonic hyperon decay
Hyperon EDM
X(4014)
Proton charge radius
Coupled-channel effect
$a_0(1710)$
Invisible decay of J/psi



M. Achasov, et al., STCF conceptual design report (Volume 1): Physics & detector, Front. Phys. 19(1), 14701 (2024)

Outline

- ☐ Introduction
- ☐ Physics Opportunities
- ☐ **Project Promotion and progress**
- ☐ Summary and Outlook

Project Promotion

2011

Super Charm-tau Factory

Proposed at "Workshop for acc. based high energy physics development strategy"

2015

Fragrant Hills Science Forum
Demonstrated its importance and necessity, Urging to lauch fesibility study and R&D

2017

Hefei Comprehensive National Science and Technology center,
STCF listed as a big science facility to be promoted

2018

USTC "double first-class" key project
Launch the conceptual design study and feasibility study

2021

Conceptual Design report
Publish the CDR for the physics and Detector, formulate the preliminary CDR for accelerator

2022.4

Governments of Anhui Province and Hefei City
Launch the STCF Key Technology R&D project

- **Chinese Academy of Sciences**, 2021-2026, International Partnership program, 5.0 M RMB
- **Ministry of Science and Technology**, 2022-2027, National Key R&D Program of China, 17.5 M RMB
- **National Natural Science Foundation** of China, 2024-2027, Group of Key Projects, 14.0 M RMB

Conferences/Workshops

(Domestic) STCF Workshops

Time	Place	Content
2018.10	Hengyang (USC)	STCF
2019.03	Beijing (UCAS)	STCF: Physics
2019.07	Hefei (USTC)	STCF: Accelerator
2019.08	Hefei (USTC)	STCF: Phys. & simulations
2019.11	Beijing (UCAS)	STCF: CDR
2020.08	Hefei (USTC)	STCF: From CDR to TDR
2022.12	Guangzhou (SYSU)	STCF: R&D kick-off
2023.07	Zhengzhou (ZZU)	STCF: Collaboration
2024.07	Lanzhou (LZU)	(scheduled)

STCF workshop 2022, online

STCF workshop 2023, Zhengzhou

STCF Key Technology R&D Project Kick-off Meeting, Hefei, 2023

STCF Project Development Meetings

Time	Place	Meetings
2022.04	Hefei (USTC)	STCF Key Technology R&D Project Demonstration Meeting
2023.08	Hefei (USTC)	STCF Key Technology R&D Project Kick-off Meeting
2023.12	Hefei (USTC)	STCF Key Technology R&D Project Budget Review Meeting
2024.01	Hefei (USTC)	STCF 1st International Advisory Committee Meeting
2024.05	Hefei (USTC)	STCF 1st National Consultative Committee Meeting

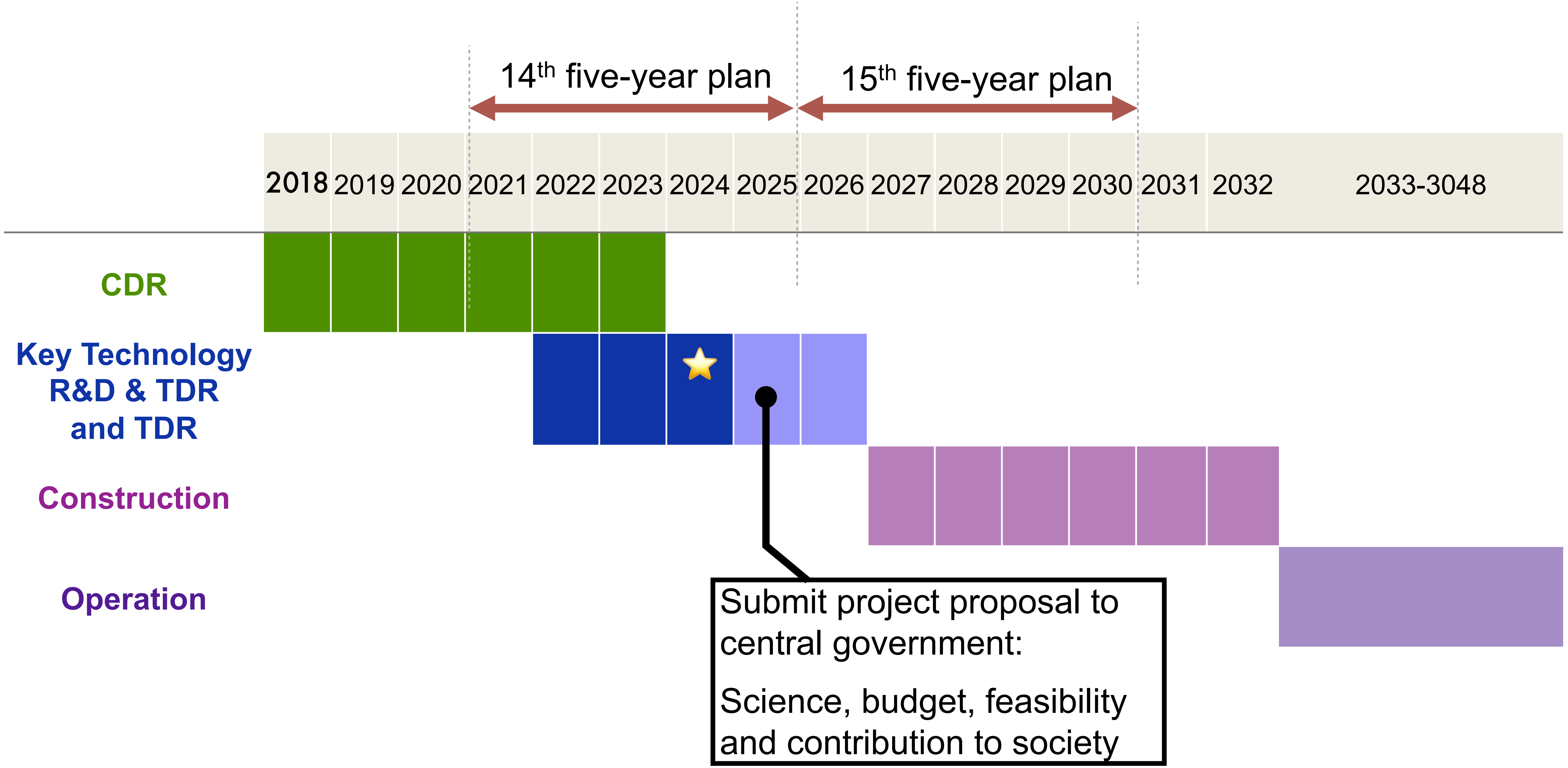
STCF 1st IAC meeting (Hefei, 2024)

STCF 1st NCC meeting (Hefei, 2024)

International Collaborations

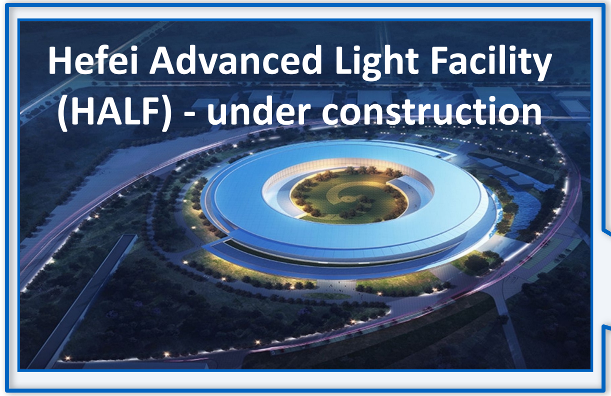
Time	Place	Content
2015.01	Hefei, China	International Workshop focused on Super tau-Charm Facility in China
2018.03	Beijing, China	International Workshop focused on Super tau-Charm Facility in China
2018.05	Novosibirsk, Russia	International Workshop focused on Super tau-Charm Facility in Russia
2018.12	Paris, France	1st FTCF (Joint International Workshop)
2019.08	Moscow, Russia	2nd FTCF
2020.11	Online, China	3rd FTCF
2021.11	Online, Russia	4th FTCF
2024.01	Hefei, China	5th FTCF
2024.11	Guangzhou, China	6th FTCF

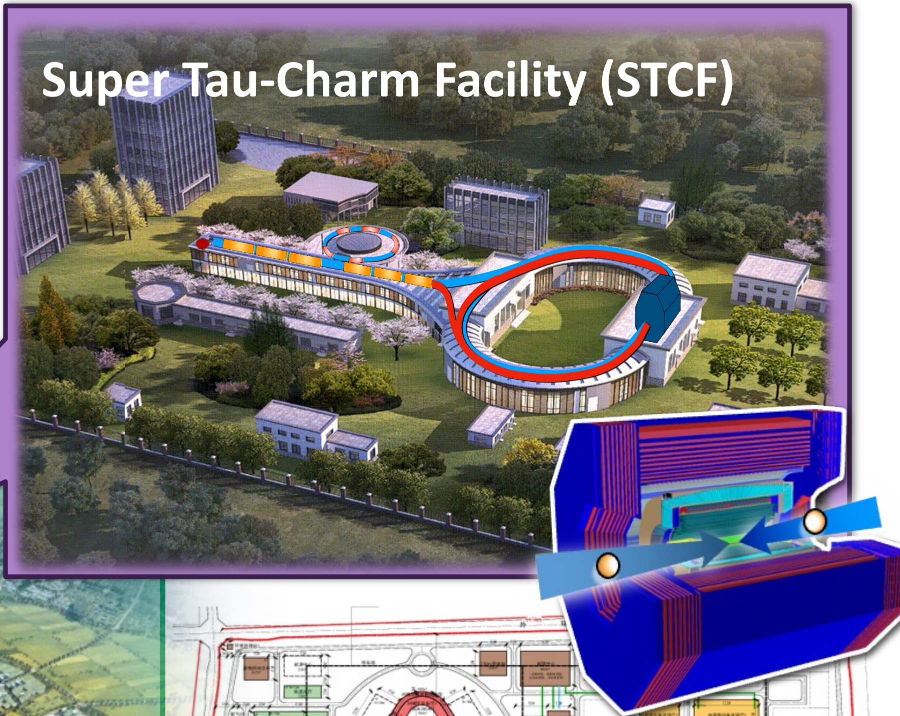
Tentative Project Schedule

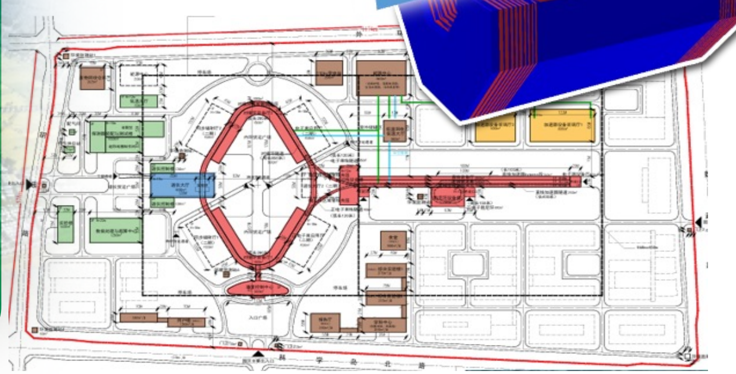


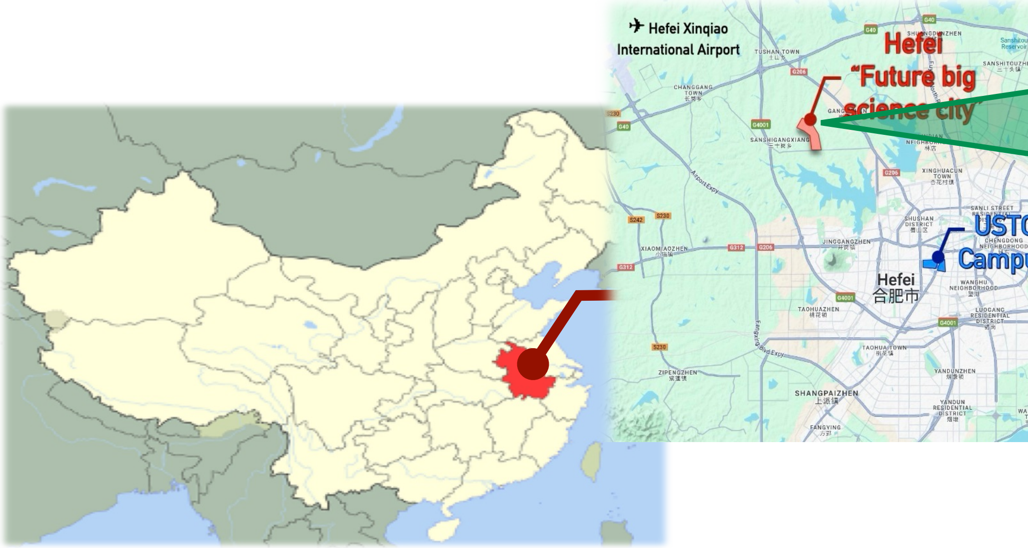
Site : Hefei in Anhui Province

Hefei Comprehensive National Science Center
“Future Big Science City” , Hefei, Anhui Province









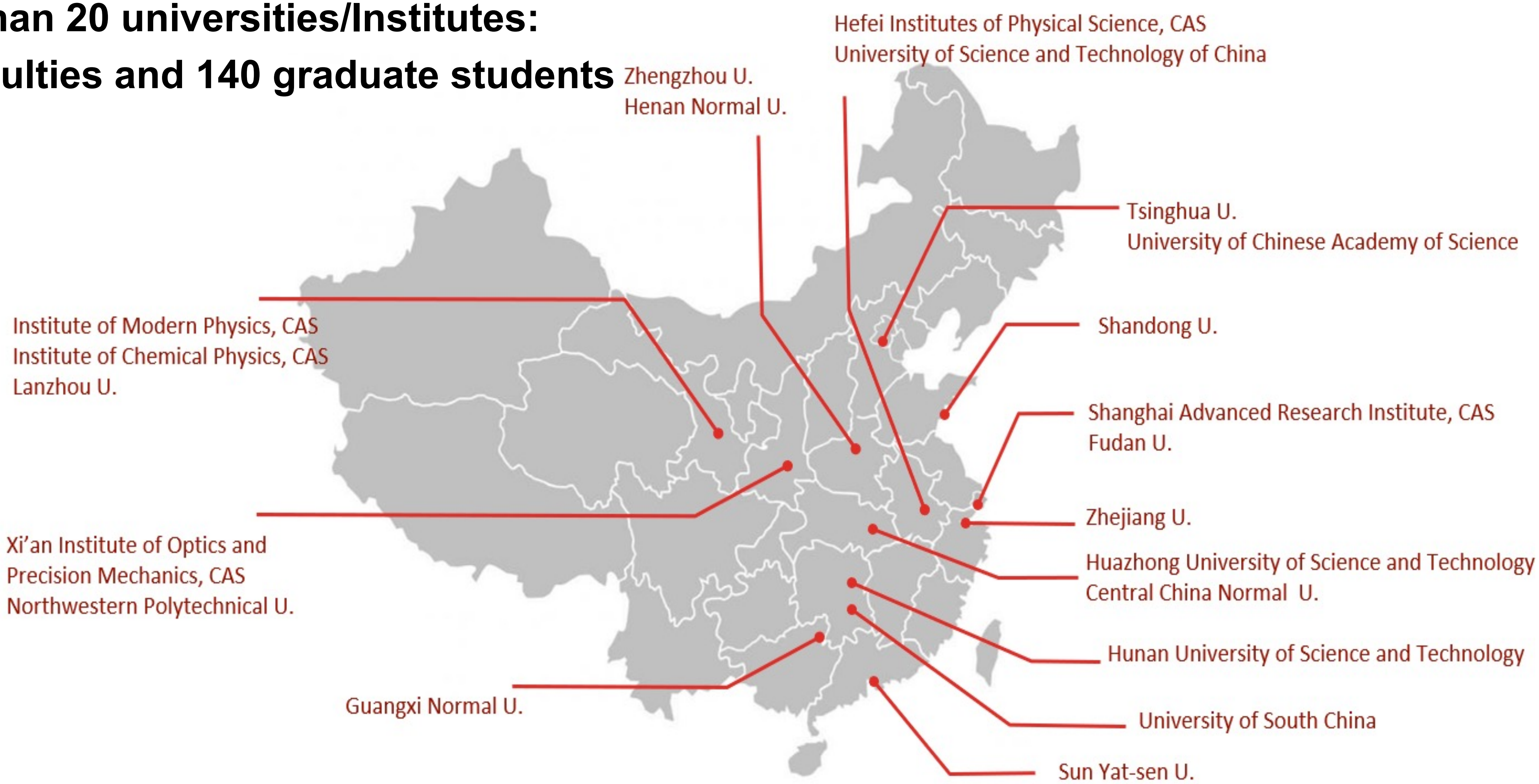
- **Funded R&D : 0.4 Billion CNY by the Anhui government**
- **Construction budget : 4.5 Billion CNY**

Key Technology R&D – Research team

Began from year 2023

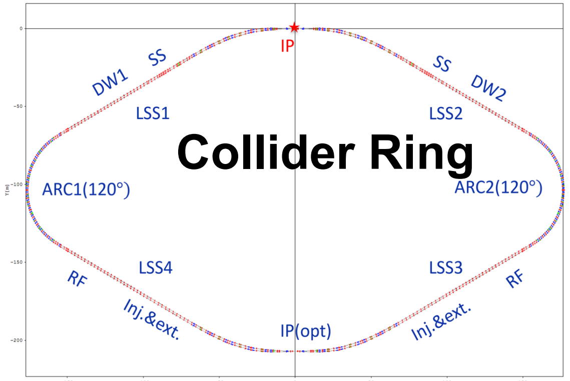
More than 20 universities/Institutes:

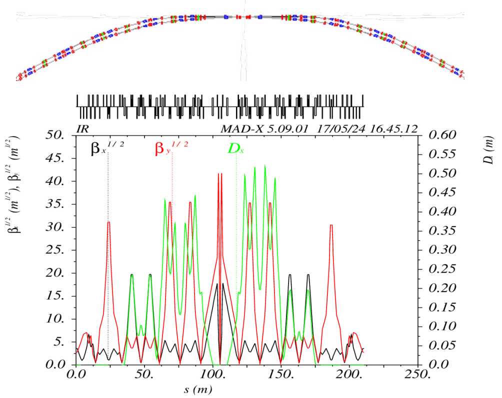
170 faculties and 140 graduate students



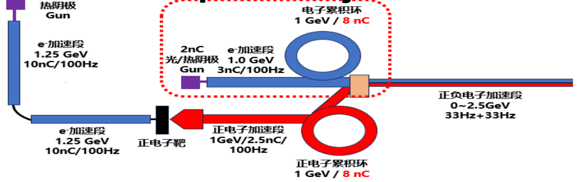
Progress of Key Technology R&D

Accelerator Design

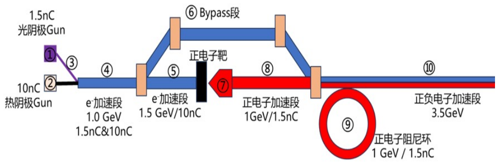




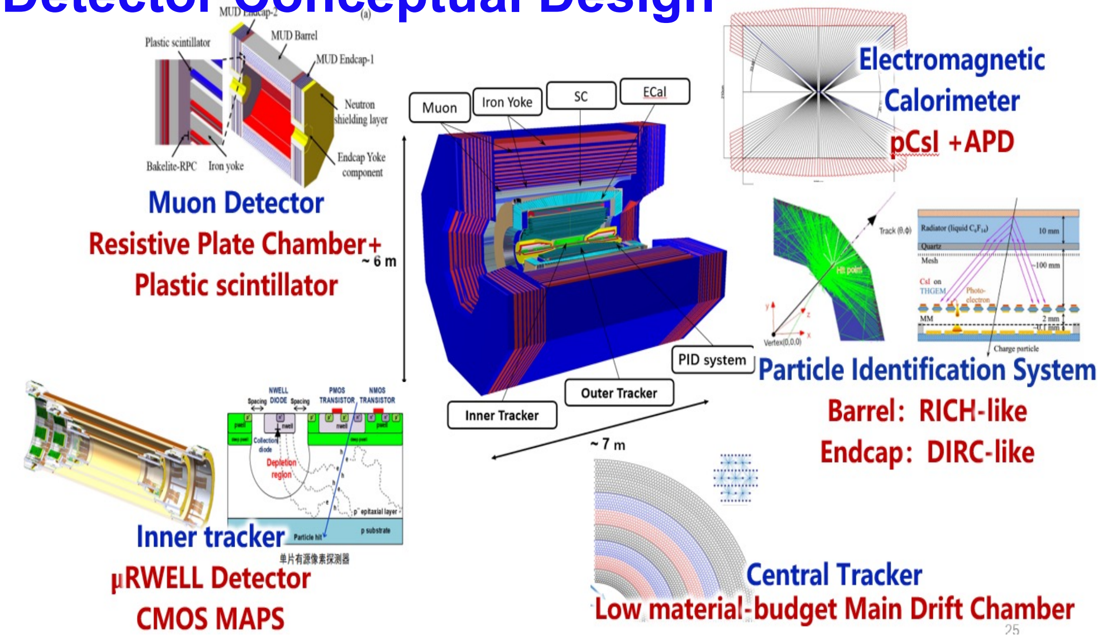
Swap-out injection



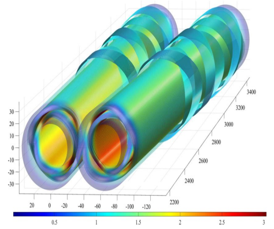
Off-axis injection



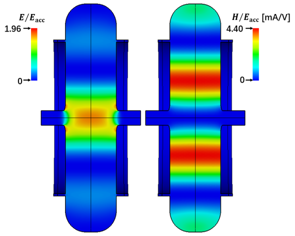
Detector Conceptual Design



Accelerator Key Technology R&D

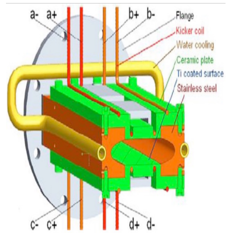


Dual aperture superconduct



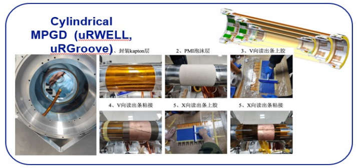
RF Cavity (TM020)

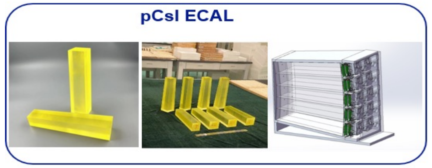
Photocathode Electron Gun

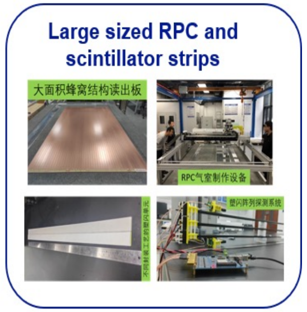


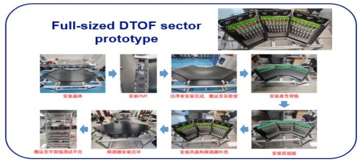
Multi-wire nonlinear kicker

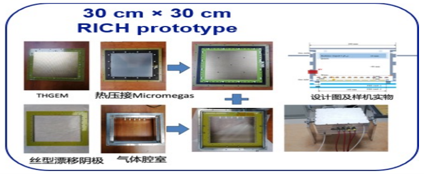
Detector Key Technology R&D











Summary

- STCF is an unique facility in precision frontier
  - Ecm = 2-7GeV, peaking $\mathcal{L} > 0.5\times10^{35}$ $cm^{-2}s^{-1}$, polarized beam (Phase II)
  - Symmetric, double ring with circumference around 600~1000 m
- STCF has rich physics program, and has potential for breakthrough to the understanding of strong interaction, and to the new physics searches, but it also challenge in both accelerator and spectrometer
- Project R&D is ongoing with strong support from local government and key technologies will be developed in 2-3 years.
- Aiming to submit a proposal to the central government in 2025 for inclusion in the 15th five-year plan (2026-2030)
- More international collaboration and synergies with other projects are always welcome.

The 6th International Workshop on Future Tau Charm Facilities (FTCF2024-Guangzhou)

- **The 6th International Workshop on Future Tau Charm Facilities (FTCF2024-Guangzhou)**
- **will be hosted by Sun Yat-Sen University (SYSU), in Guangzhou, China, Nov. 17 - 21, 2024**

https://indico.pnp.ustc.edu.cn/event/1948/

The 12th Circum-Pan-Pacific Symposium on High Energy Spin Physics

November 9-12, 2024 at Hefei, China

Topics of the symposium include:

- Transverse and longitudinal spin structure of the nucleon
- Polarized parton distribution functions and fragmentation functions
- Transverse momentum dependent distributions
- Generalized parton distributions and form factors
- Spin physics in future electron-ion colliders (EICs)
- Spin polarization in heavy ion collisions
- Spin structure of the nucleon in Lattice QCD and effective QCD models
- New ideas, methods and future facilities

Registration and more details:

https://indico.pnp.ustc.edu.cn/event/1119/overview

Previous versions:
Miyazaki(2019), Taipei(2015), Ji'nan(2013), Cairns(2011), Yamagata(2009), Vancouver(2007), Tokyo(2005), Washington(2003), Beijing(2001), Wako(1999), Kobe (1996).


Thanks for your attention!
Welcome to join!

Backup