Physics Program for the Super Tau-Charm Facility (STCF)

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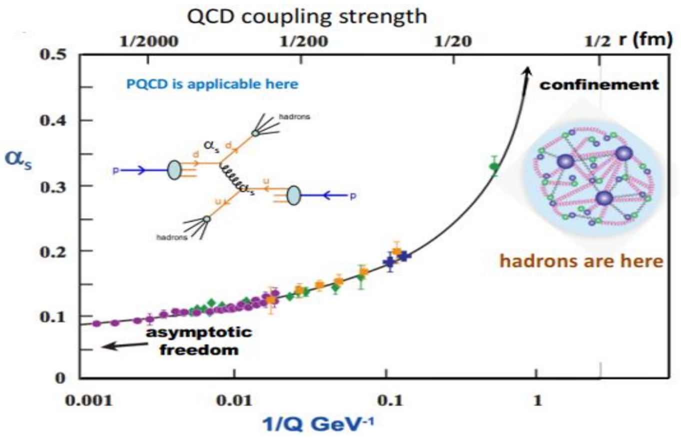
On behalf of STCF working group

超级陶粲装置
Super Tau-Charm Facility

Challenges of the SM

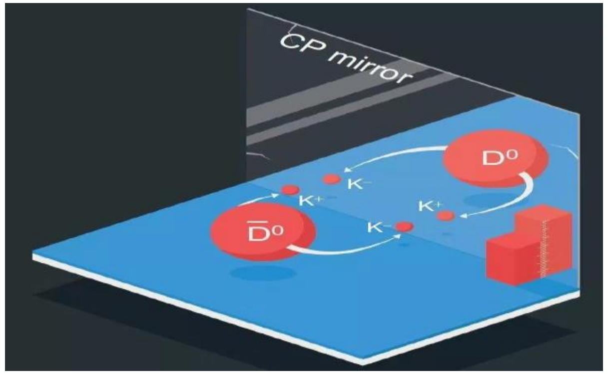
The SM is well-tested, however, reminds several fundamental questions :

- Color confinement : structure of nuclear, formation of colorless hadrons…
- CP Violation : matter-antimatter asymmetry of universe
- Mass hierarchy, Dark matter, Number of flavors, …

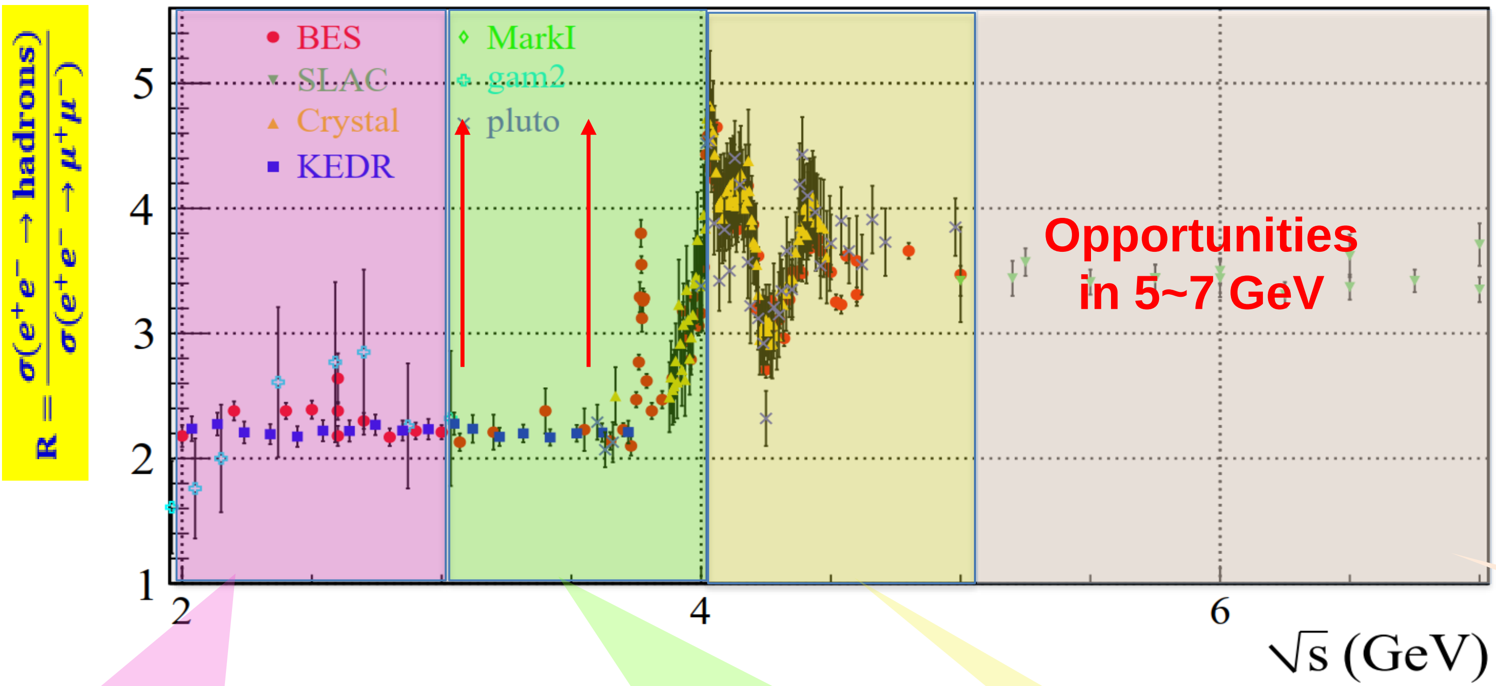


HEP science drives (Snowmass 2021) :

- Use Higgs boson as a tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of Dark Matter
- Understand cosmic acceleration :Dark Energy and inflation
- Explore the unknown : new particles, interactions and physical principles
- Flavor physics as a tool for discovery



Physics at the Tau-Charm Energy Region



Unique Features τ-c facilities:

- Transition region between perturbative and non-perturbative QCD
- Threshold effects of pair production of hadrons and τ leptons
- Rich resonance structures, large production X-sec for charmonium(-like) states and exotics

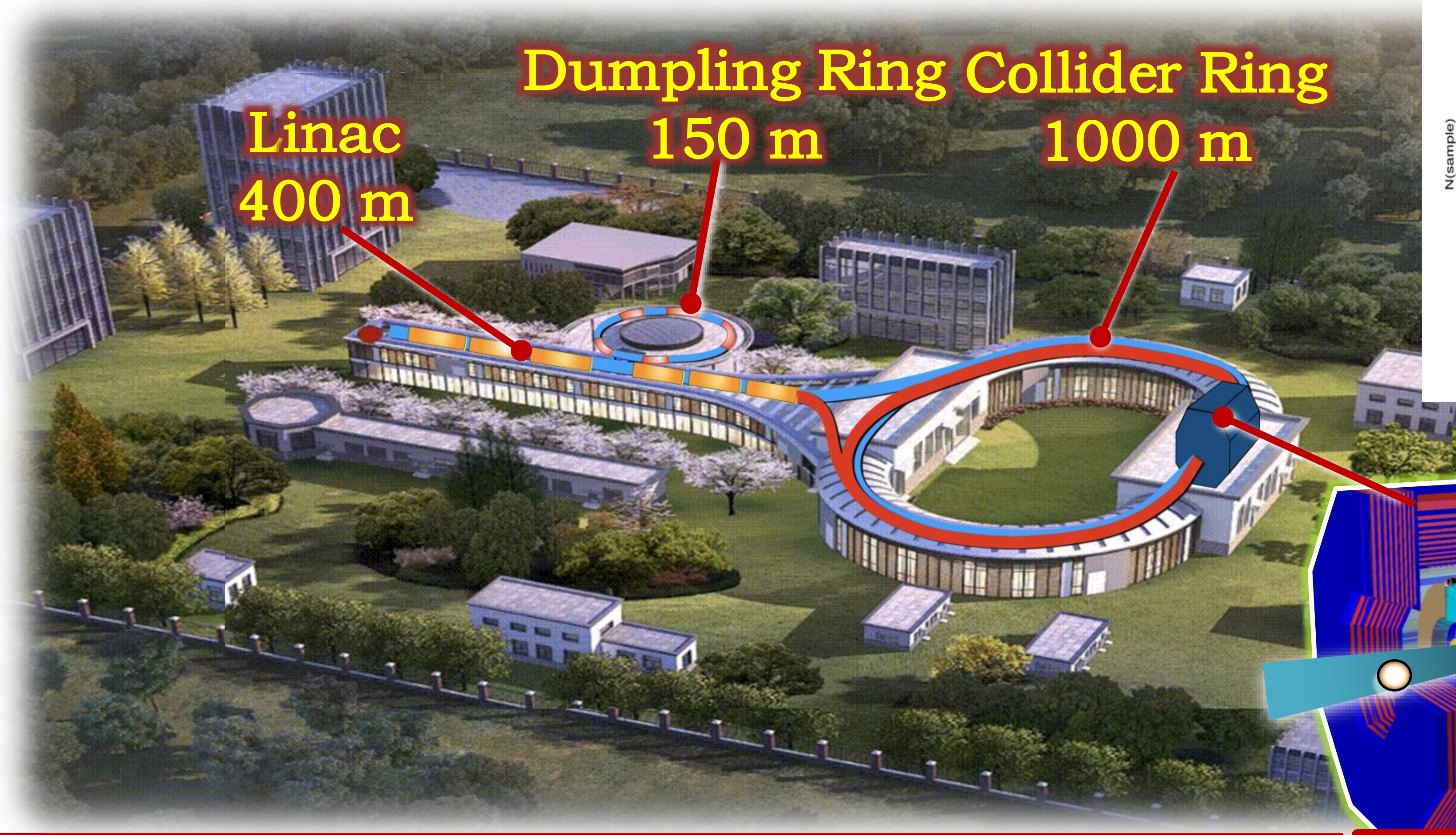
- Hadron form factors
- $Y(2170)$ resonance
- Mutltiquark states with s quark
- R value / g-2 related

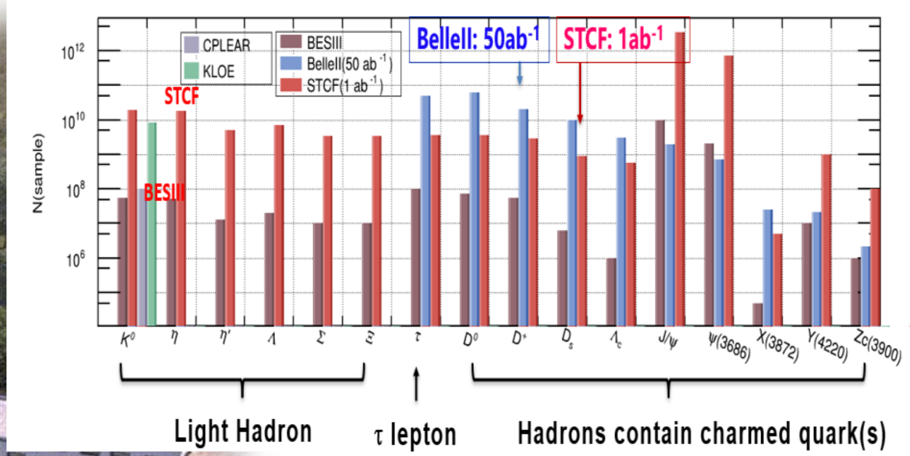
- Light hadron spectroscopy
- Gluonic and exotic states
- Processes of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

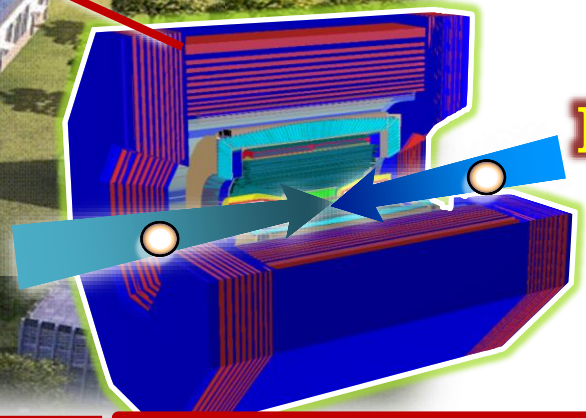
- *XYZ* particles
- Physics with D mesons
- f_D and f_{D_s}
- $D^0 - \bar{D}^0$ mixing
- Charm baryons

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

The Super Tau-Charm Facility (STCF)





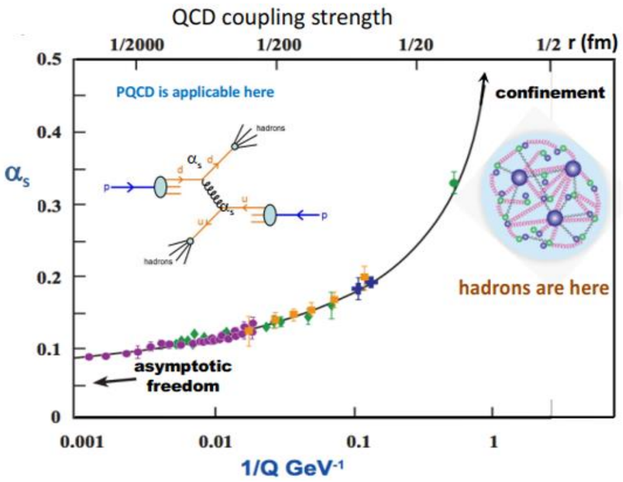


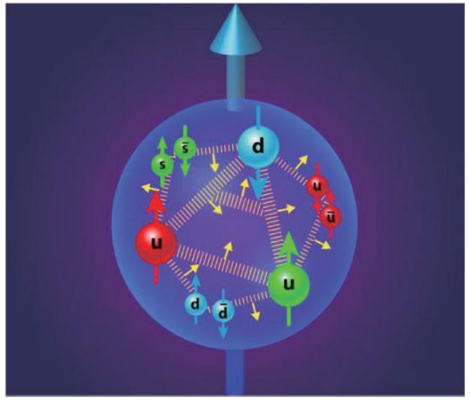
- Center-of-Mass energy coverage : 2-7GeV;
- Peak Luminosity > 0.5×10^{35} cm^{-2} s^{-1} @ 4GeV
- Potential to increase lumi. & realize beam polarization

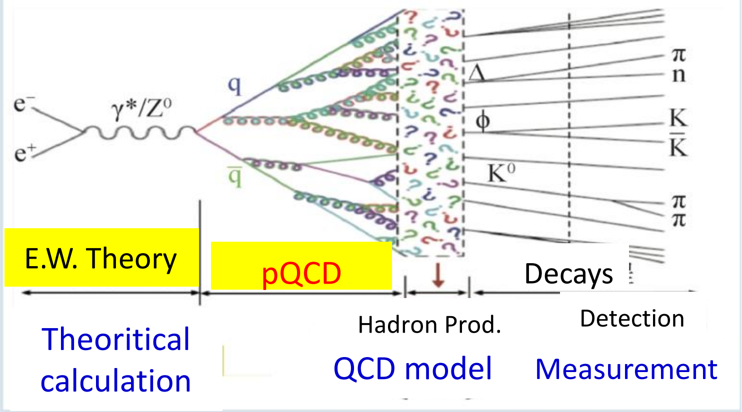
A factory produced massive tau lepton and hadrons, to unravel the mystery of how quarks form matter and the symmetries of fundamental interactions

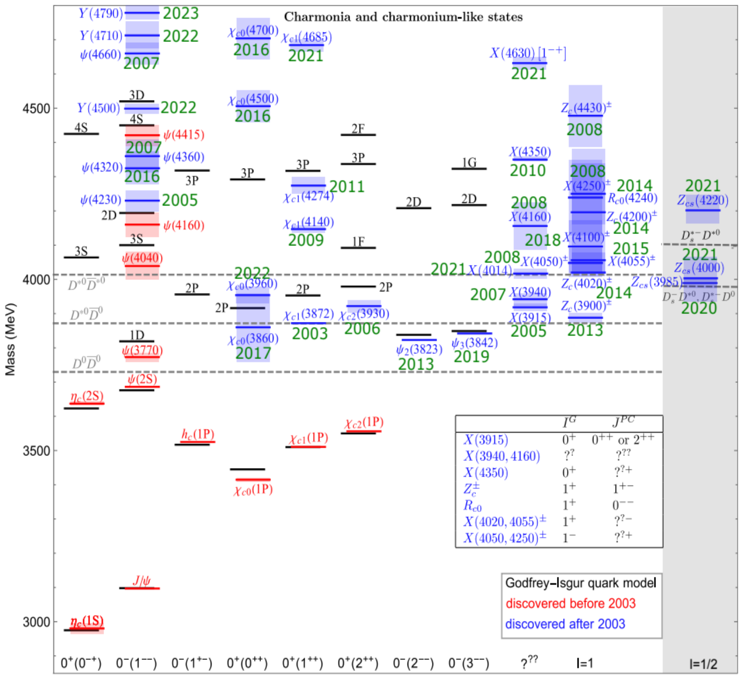
Physics Opportunity : QCD Confinement

- QCD confinement in low-energy region and its non-perturbative feature are the remaining challenge
- The effects are 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 nature studying platforms







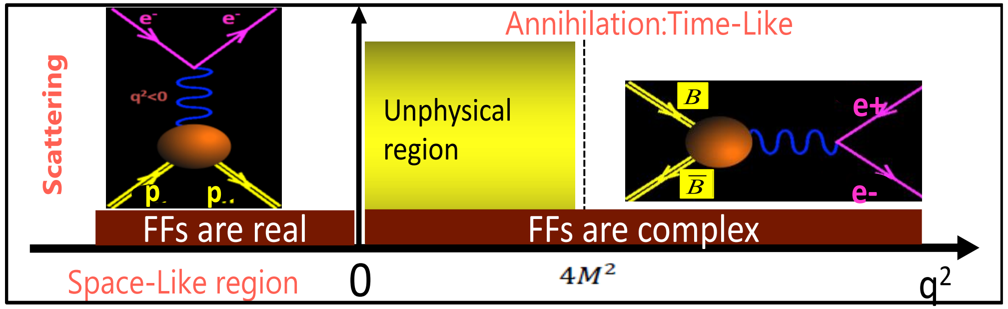


STCF Unique Advantages :

- Perturbative and non-Perturbative transition energy region
- Threshold production of baryon, hyperon
- Large cross section for charmmonium

Electromagnetic form factors (EMFFs)

EMFFs are fundamental properties, directly connected to charge and current distributions of the nucleon

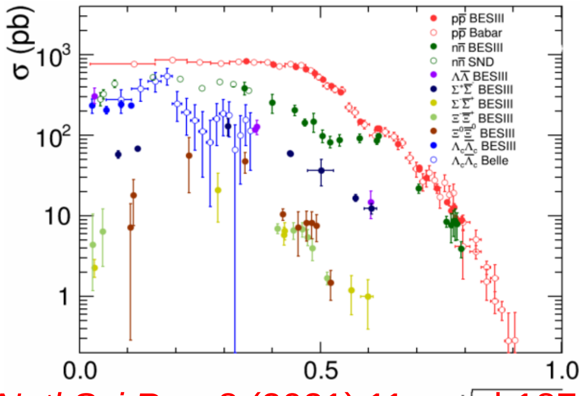


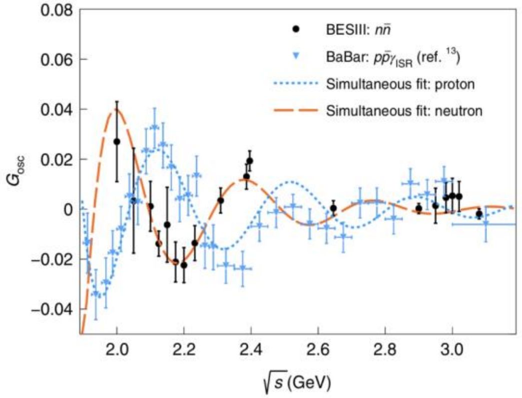
Eic/EicC ⟷ STCF

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

Current status





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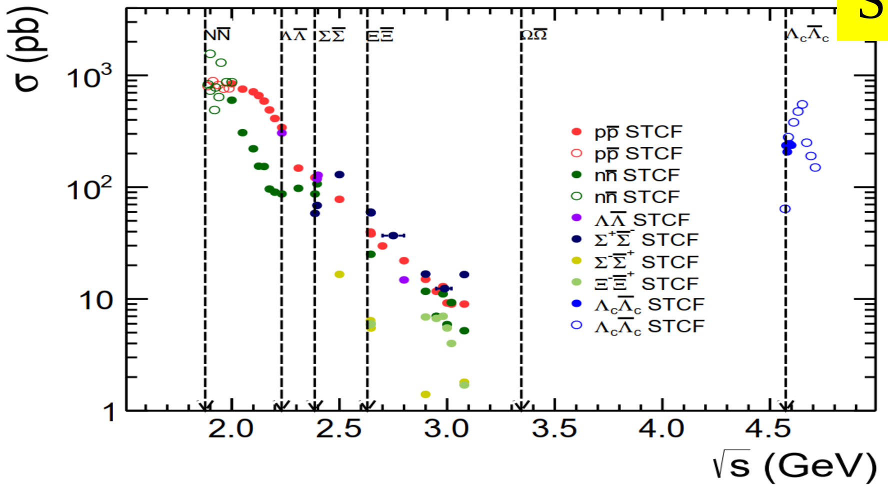
STCF Prospect

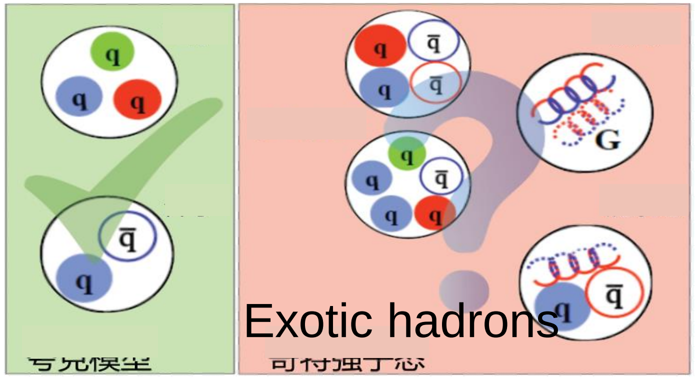


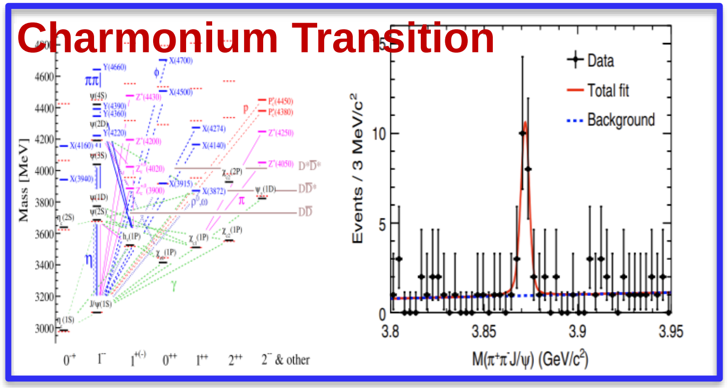
STCF prospect for TL-EMFFs:

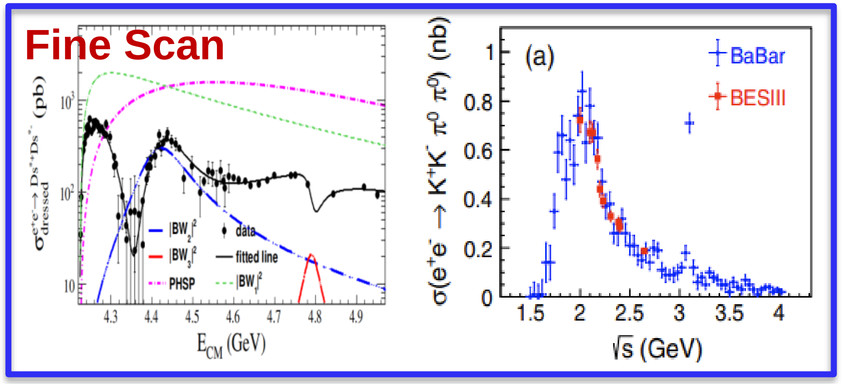
- Improve cross section measurement with 1-2 order
- Reveal the near-threshold cross section singularity and mystery of G_E and G_M

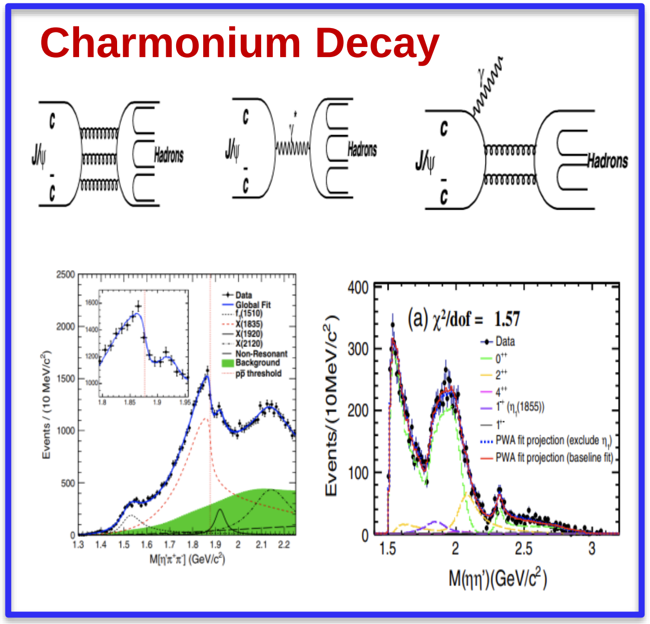
Hadron Spectroscopy and Exotic

A unique territory for the QCD confinement









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

- 3T J/ψ, 0.6T $\psi(3686)$, 1B Y(4230), 100M $Z_c(3900)$ and 5M X(3872)

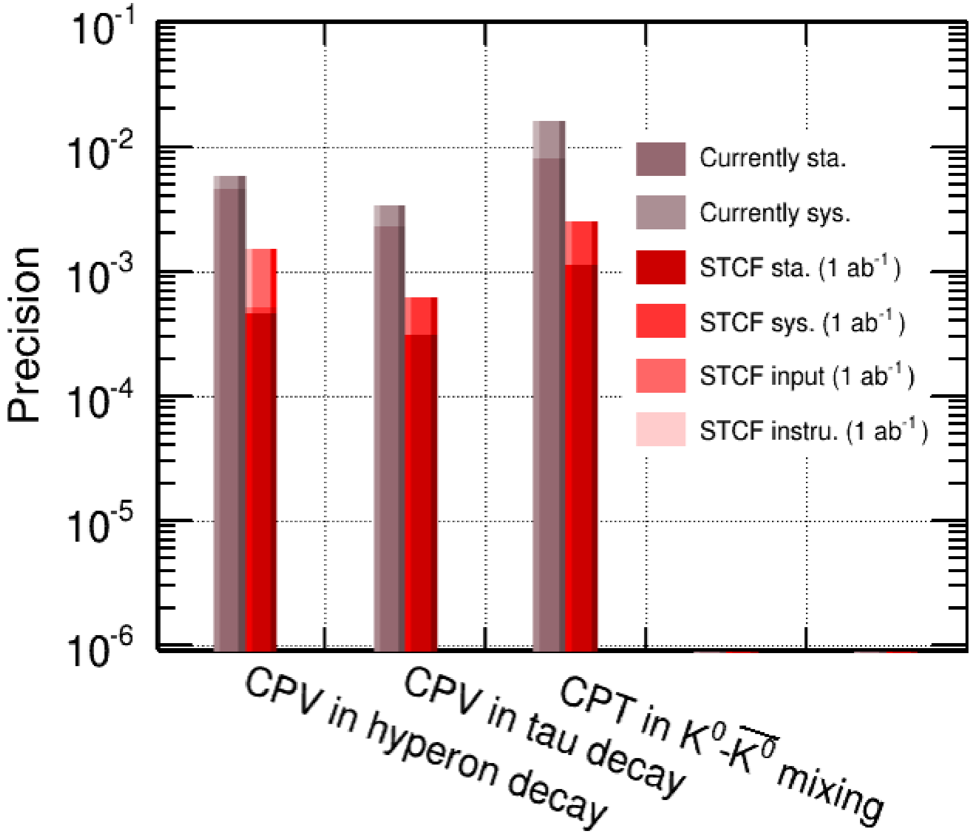
Physics opportunities :

- 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

Physics Opportunity : 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



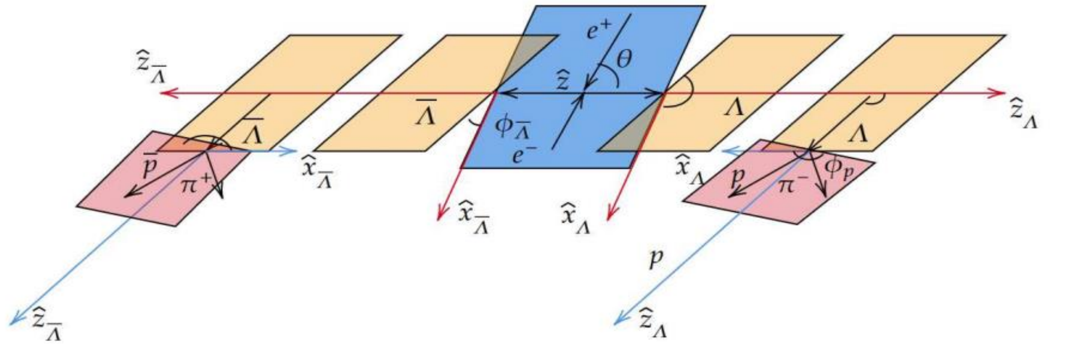
Unique advantages :

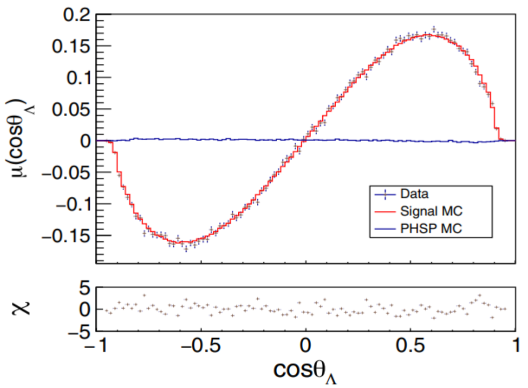
- Quantum correlated, large statistics, clear background

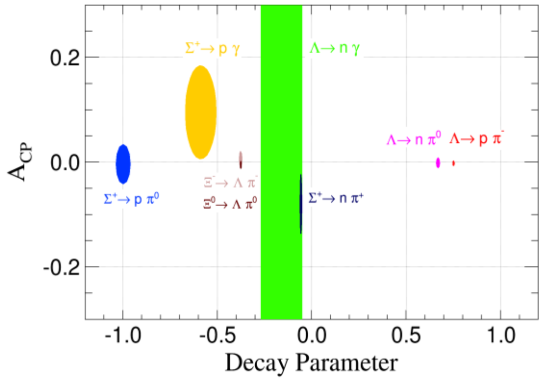
CPV in Hyperon Decay

- 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

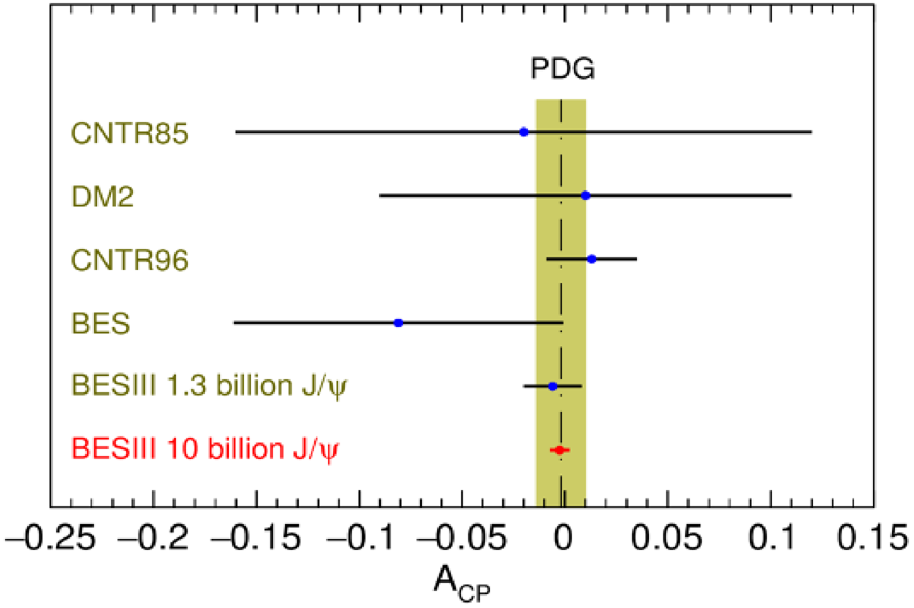
CP test $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$







PRL 129, 131801 (2022)



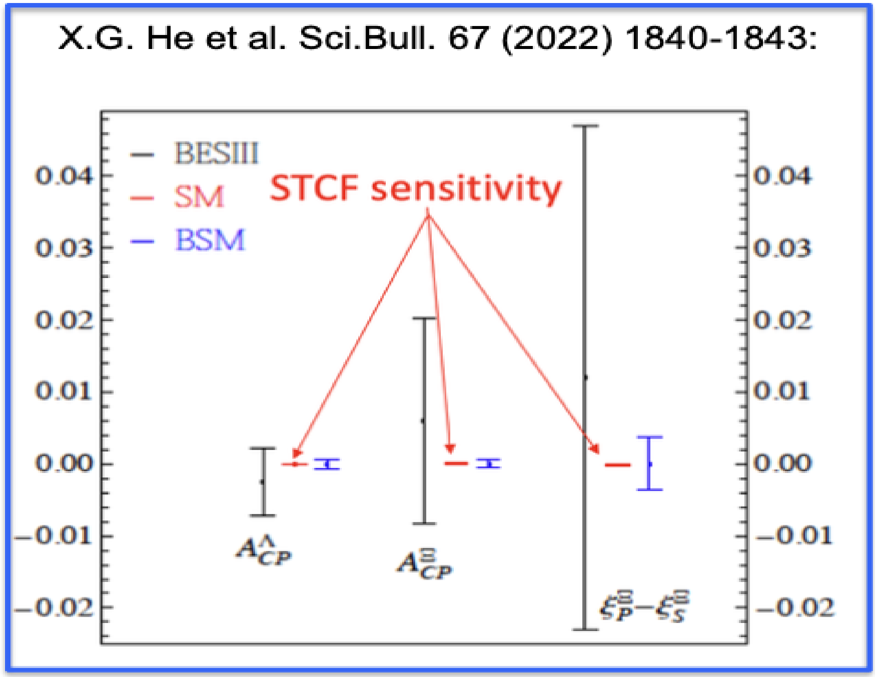
0.5% level sensitivity for CPV test

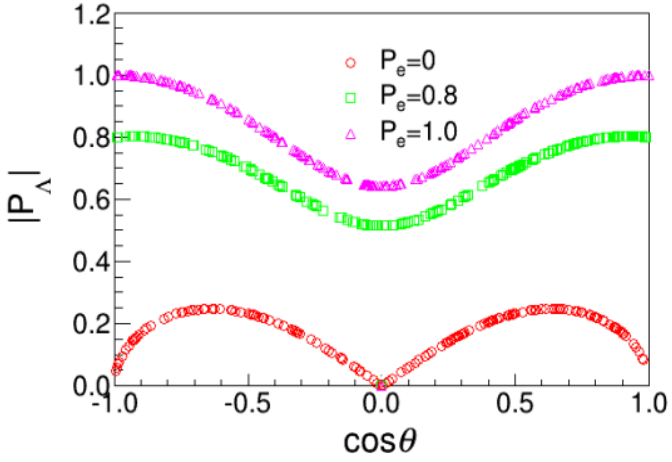
SM prediction: 10^{-4}~10^{-5}

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

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



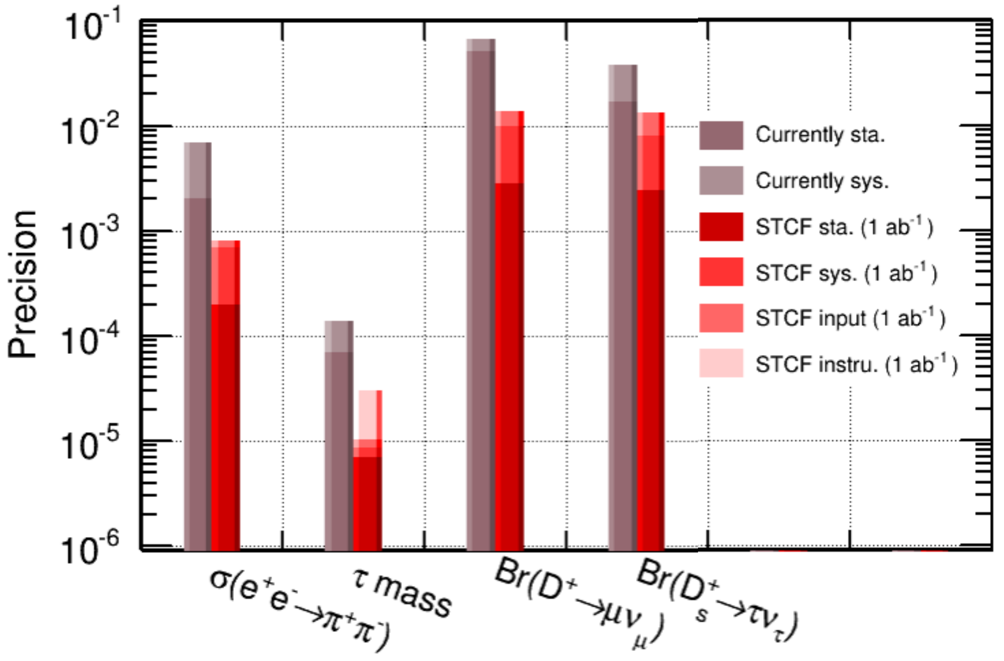


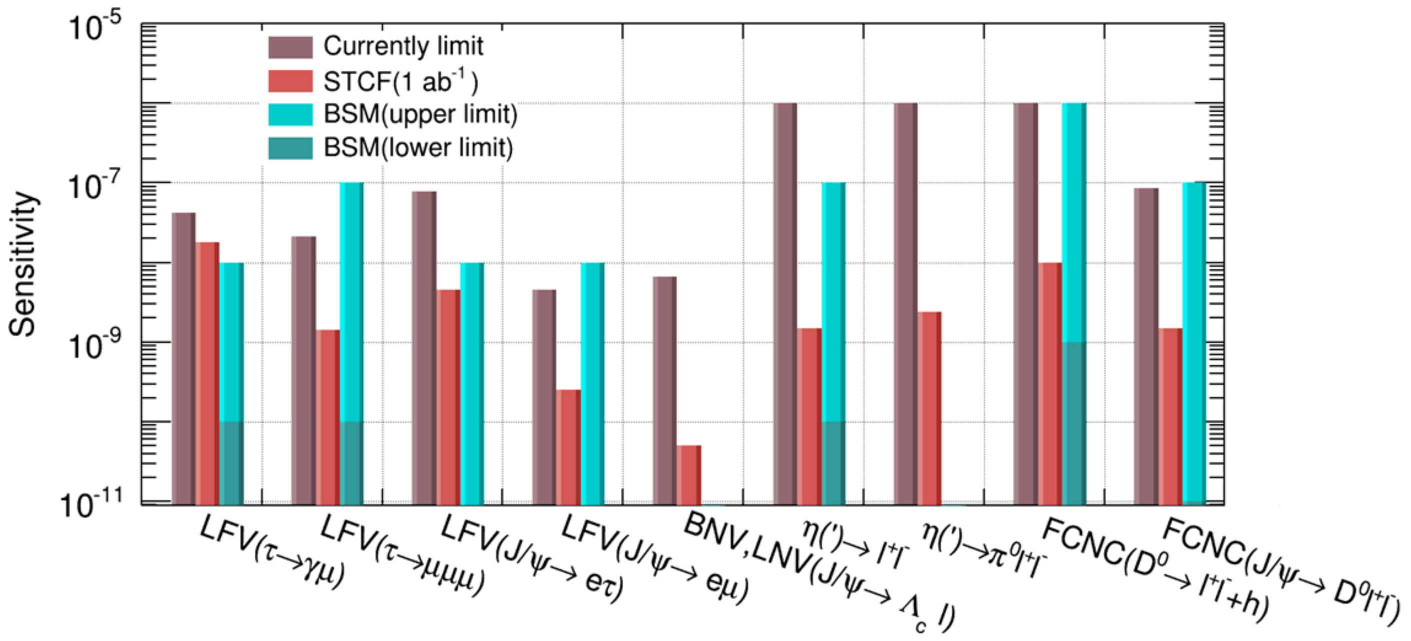
$$\sigma_{A_{CP}} \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha_1 \sqrt{N_{sig}} \sqrt{\langle P_B^2 \rangle}}.$$

$$\xrightarrow{1\times 10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.1} \sigma_{A_{CP}} \sim 1.4\times 10^{-4}$$

$$\xrightarrow{1\times 10^9\ \Lambda\bar{\Lambda},\quad \langle P_B^2\rangle=0.8} \sigma_{A_{CP}} \sim 5\times 10^{-5}$$

Precision Measurements and Rare Decays

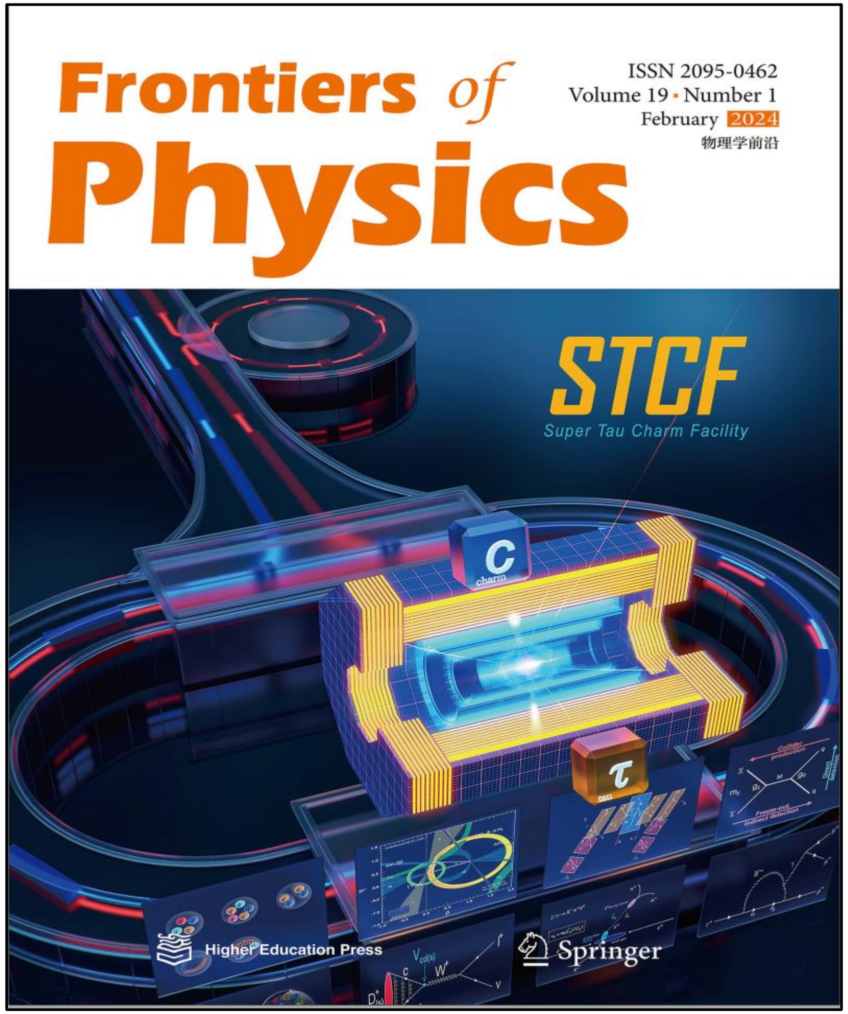




STCF physics opportunities :

- 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

Beyond What I can cover



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

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

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

- 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

2022.4

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

Anhui Province endorse the key technology R&D project, and offer funds 364M 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)	STCF: 15th-five-year plan

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)

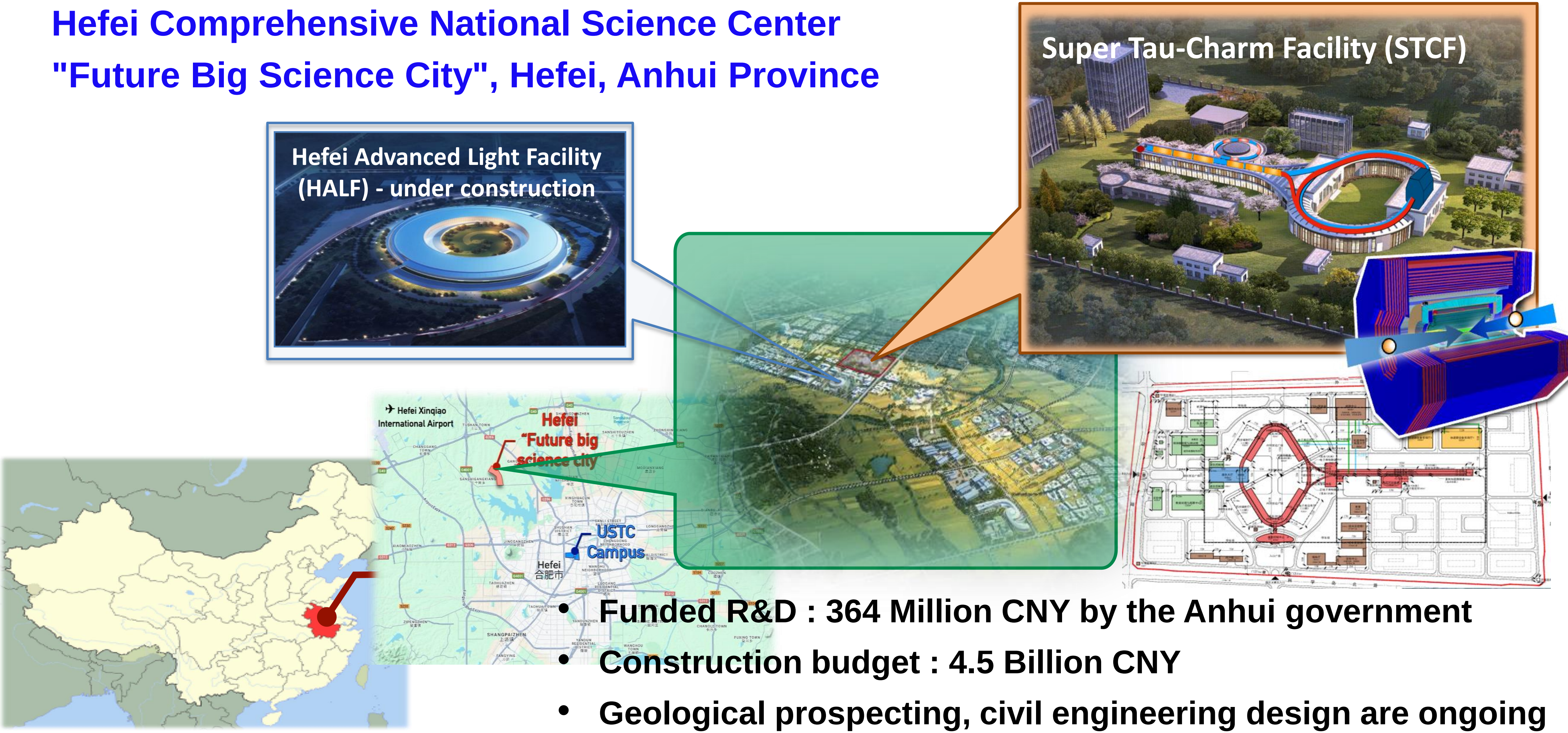
International Future Tau-Charm Facility Workshops

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	1^{st} FTCF (Joint International Workshop)
2019.08	Moscow, Russia	2^{nd} FTCF
2020.11	Online, China	3^{rd} FTCF
2021.11	Online, Russia	4^{th} FTCF
2024.01	Hefei, China	5^{th} FTCF
2024.11	Guangzhou, China	6^{th} FTCF

Site : Hefei, Anhui Province

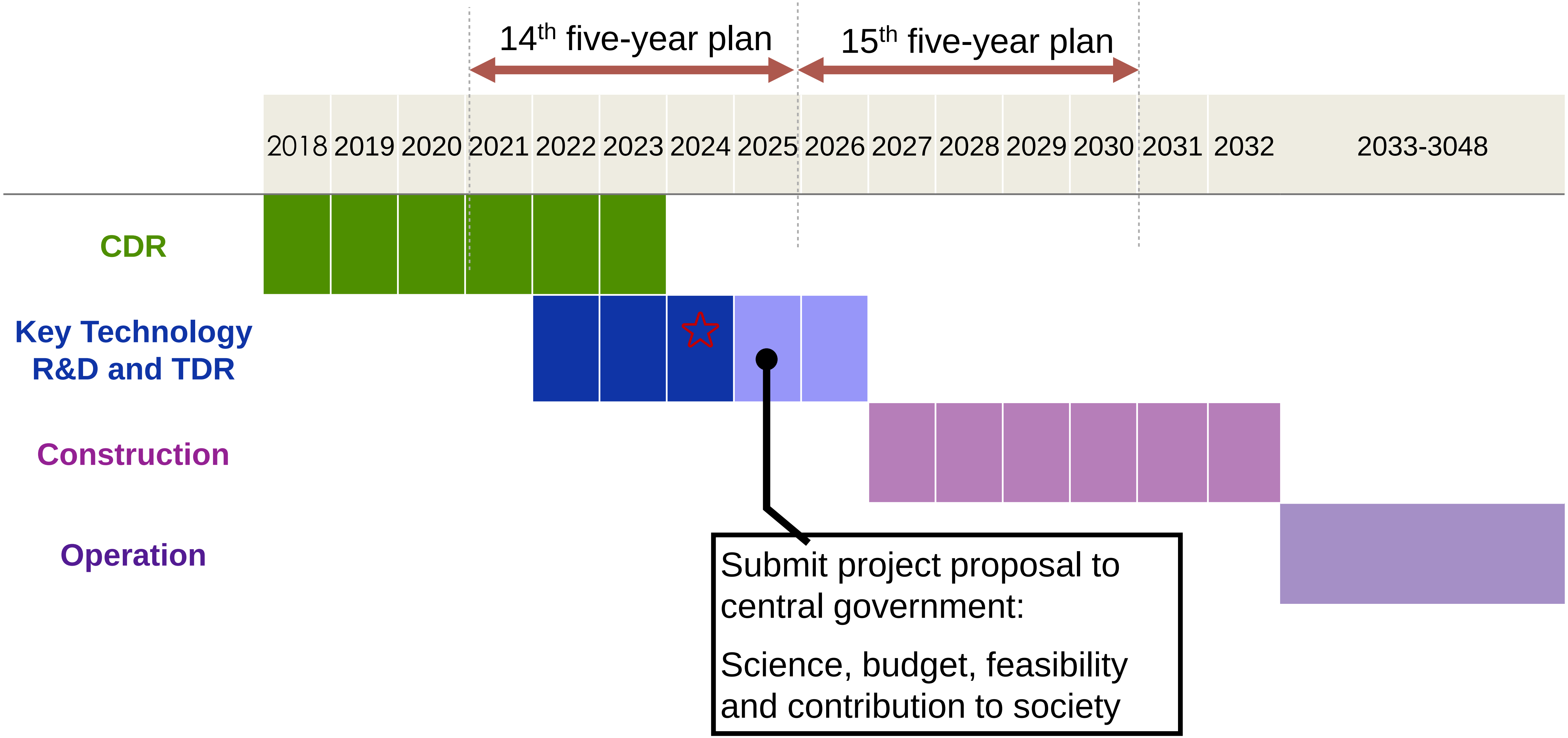
Hefei Comprehensive National Science Center

"Future Big Science City", Hefei, Anhui Province



- **Funded R&D : 364 Million CNY by the Anhui government**
- **Construction budget : 4.5 Billion CNY**
- **Geological prospecting, civil engineering design are ongoing**

Tentative Project Schedule

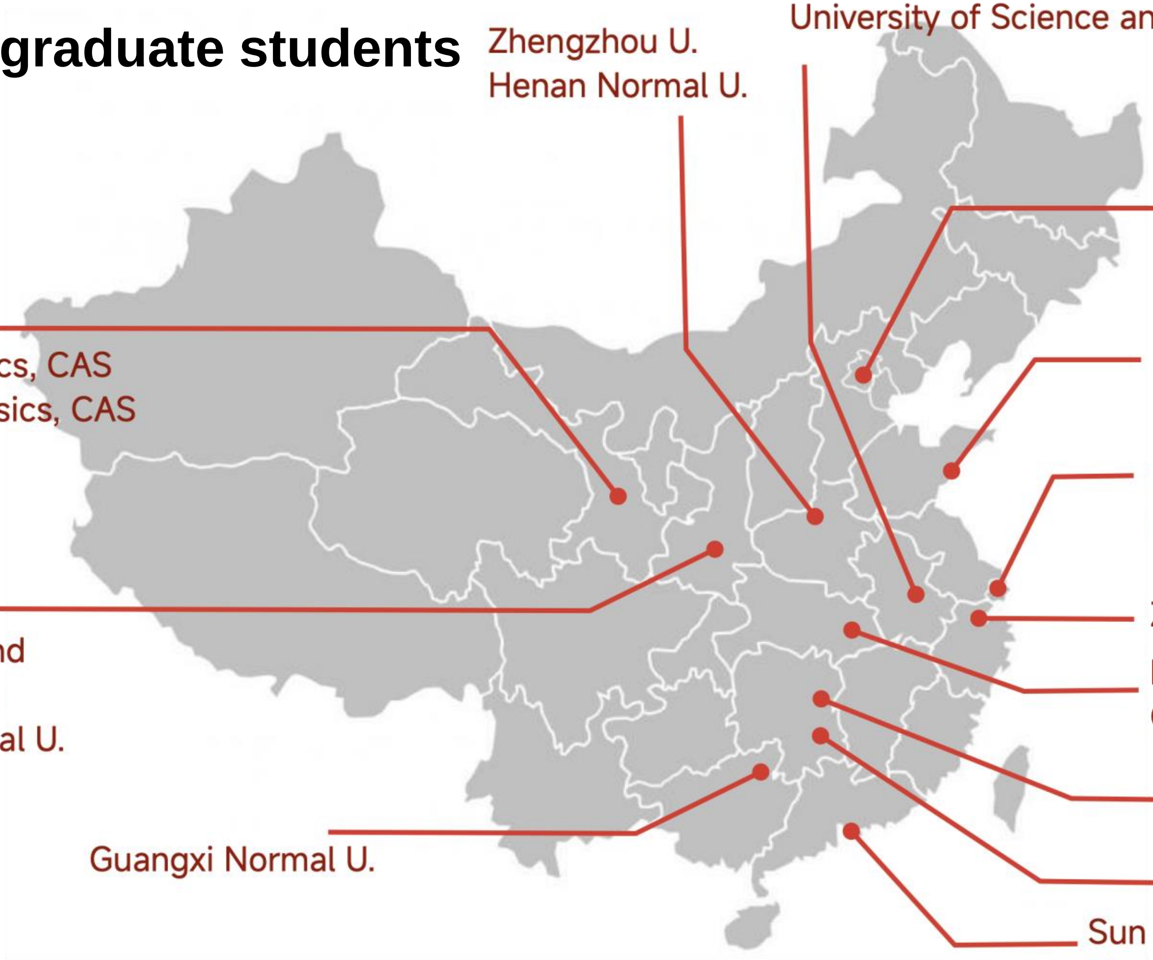


Key Technology R&D – Research team

Began from year 2023

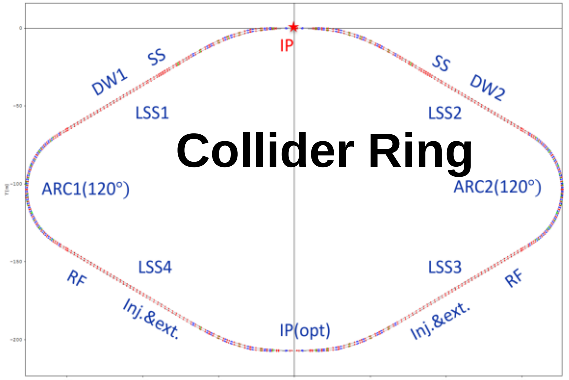
More than 20 universities/Institutes:

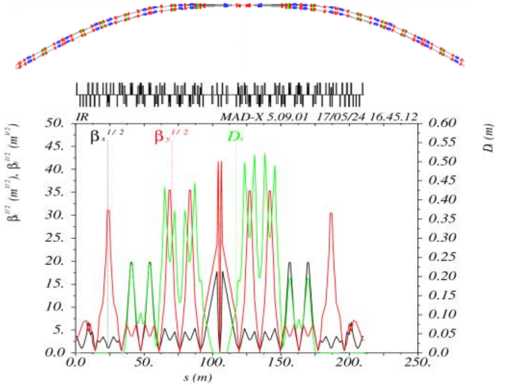
170 faculties and 140 graduate students



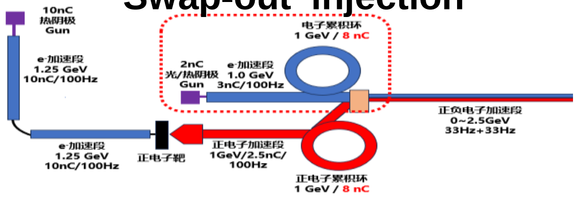
Key Technology R&D Progress

Accelerator Design

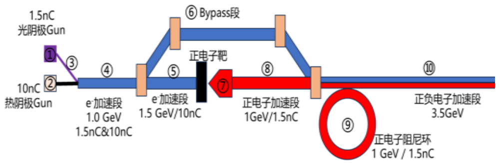




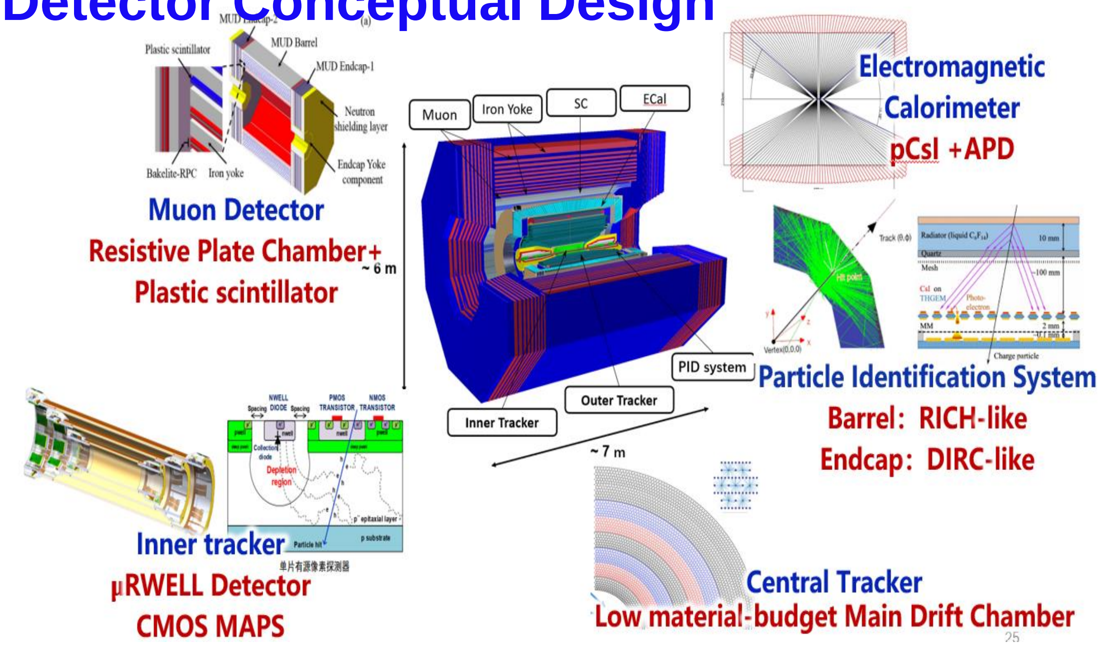
Swap-out injection



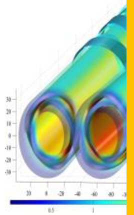
Off-axis injection



Detector Conceptual Design

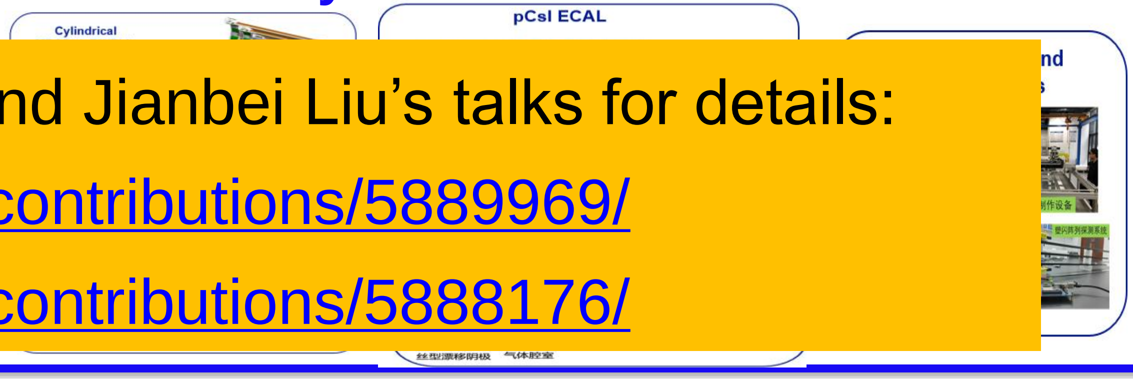


Accelerator Key Technology R&D



Dual ap... supercondu...

Detector Key Technology R&D



Great Progresses, see Jingyu Tang and Jianbei Liu's talks for details:

https://indico.cern.ch/event/1291157/contributions/5889969/

https://indico.cern.ch/event/1291157/contributions/5888176/

Summary

- The STCF has unique features, making it a viable medium-term HEP project in China with excellent value-to-cost ratio and great physics potential for breakthroughs
- The STCF faces challenges in key technologies of accelerator, detector, electronics etc, the R&D project is ongoing with strong backing from local governments. All the key technologies will be overcame through various ways within 2-3 years
- Aiming to submit a proposal to the central government in 2025 for inclusion in the 15th five-year plan (2026-2030)
- Expanding international collaboration and exploring synergies with other projects are crucial. All forms of collaboration are opened.

Thank you

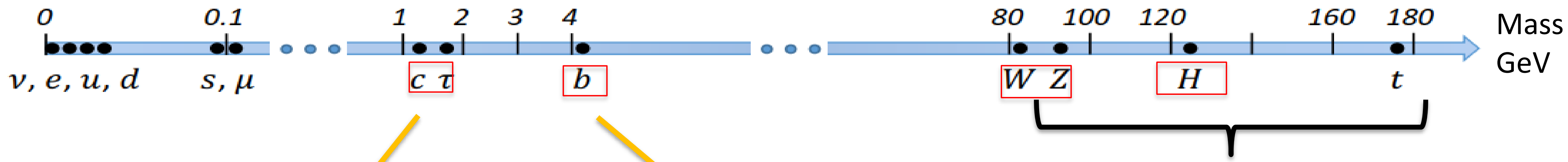
The 6th International Workshop on Future Tau Charm Facilities (FTCF2024-Guangzhou)

- 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/

Future e^+e^- Collider Factory

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



τc-factory

BEPC-II (China)

Super τc Factory

STCF (China), SCTF (Russia)

×100 gain in luminosity

B-factory

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

Super KEKB (Japan)

LHCb (CERN)

Z- and H- factory

LEP, LEP-2 (CERN)

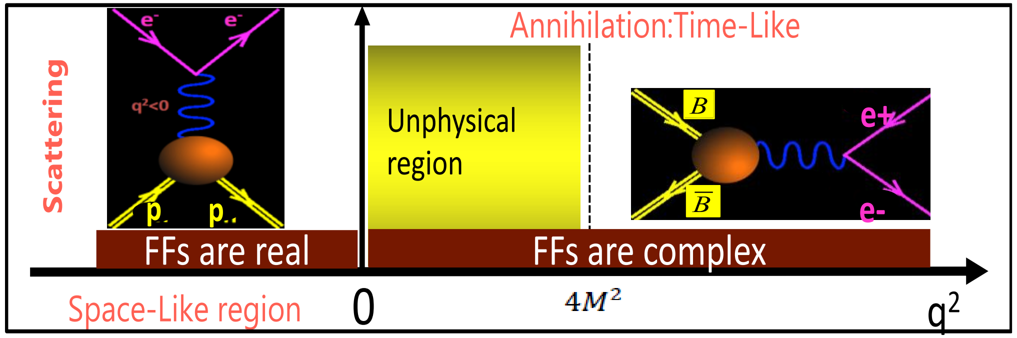
FCC-ee (CERN)

CEPC (China)

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

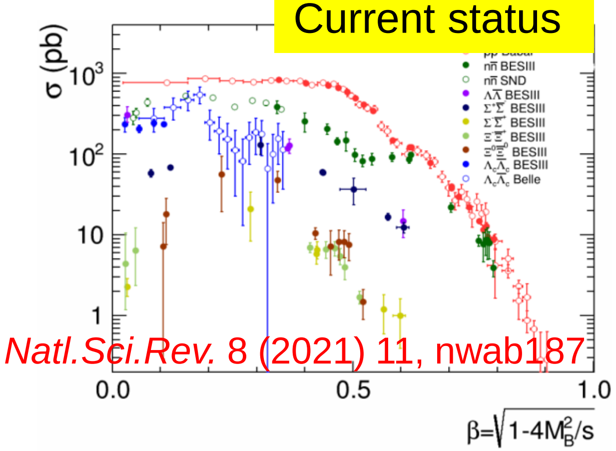
Electromagnetic form factors (EMFFs)

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



Eic/EicC ⟷ STCF

Current status



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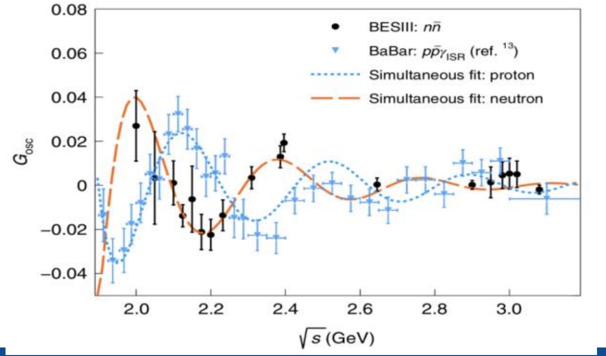

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- Damped oscillation distribution of $|G_E/G_M|$ ratio.
- Evolution of the phase between G_E and G_M.
- The asymptotic behavior of TL-EMFFs

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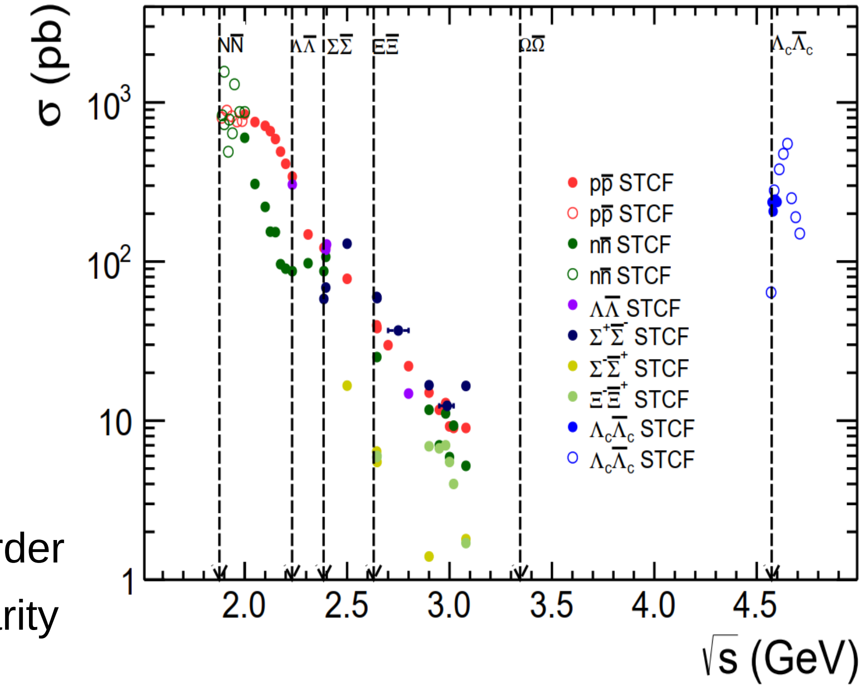
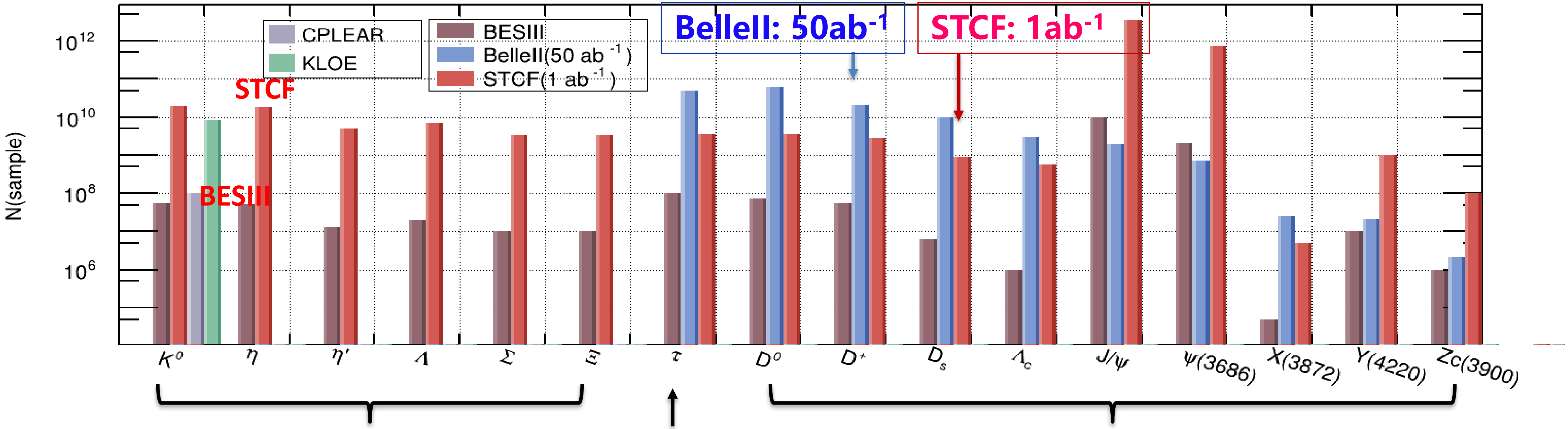
- Reveal the near-threshold cross section singularity and mystery of G_E and G_M.

STCF Prospect



Unique data sample



Light Hadron **τ lepton** **Hadrons contain charmed quark(s)**

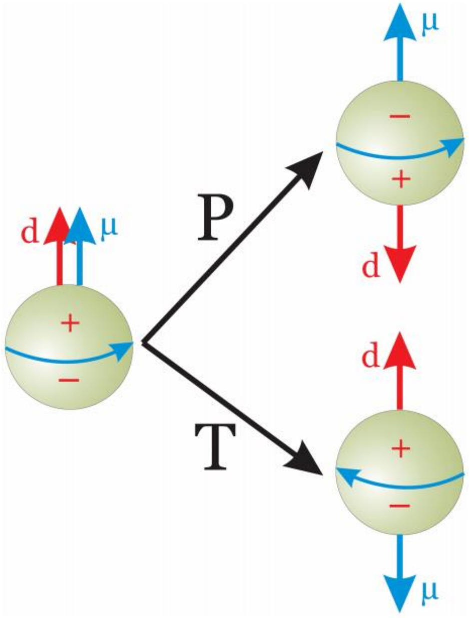
not only a τ-charm factory, but also a factory for XYZ exotics, hyperons, light hadrons

Huge statistics + High resolution + Low background

High precision measurement ➜ Discovery

EDM in Hyperon

μ: magnetic dipole moment
d: electric dipole moment

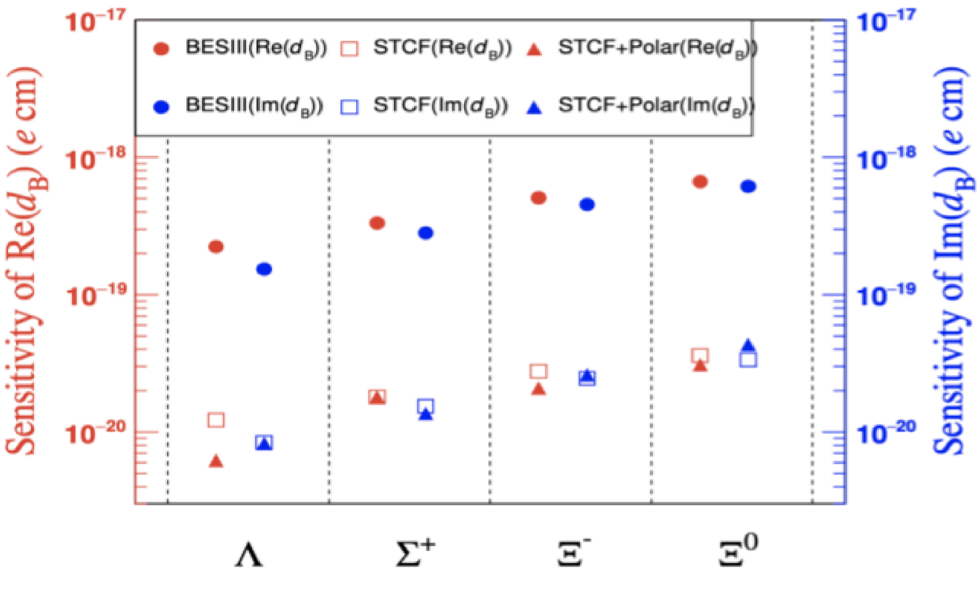


Non-zero EDM will violate P and T symmetry: T violation ↔ CP violation, if CPT holds

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

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

Systematic measurement of the EDMs of the hyperon family!



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

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

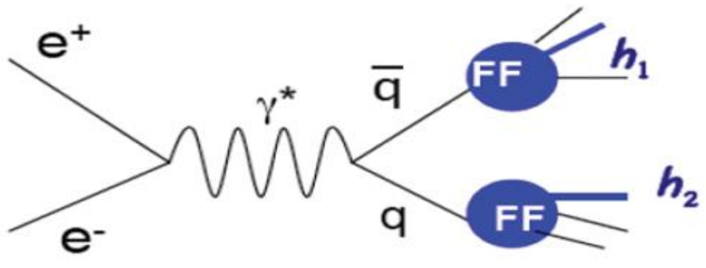
BESIII: milestone for hyperon EDM measurement
Λ 10^{-19}e cm (FermiLab 10^{-16} e cm)
first achievement for Σ^+,Ξ^- and Ξ^0 at level of 10^{-19}e cm
a litmus test for new physics

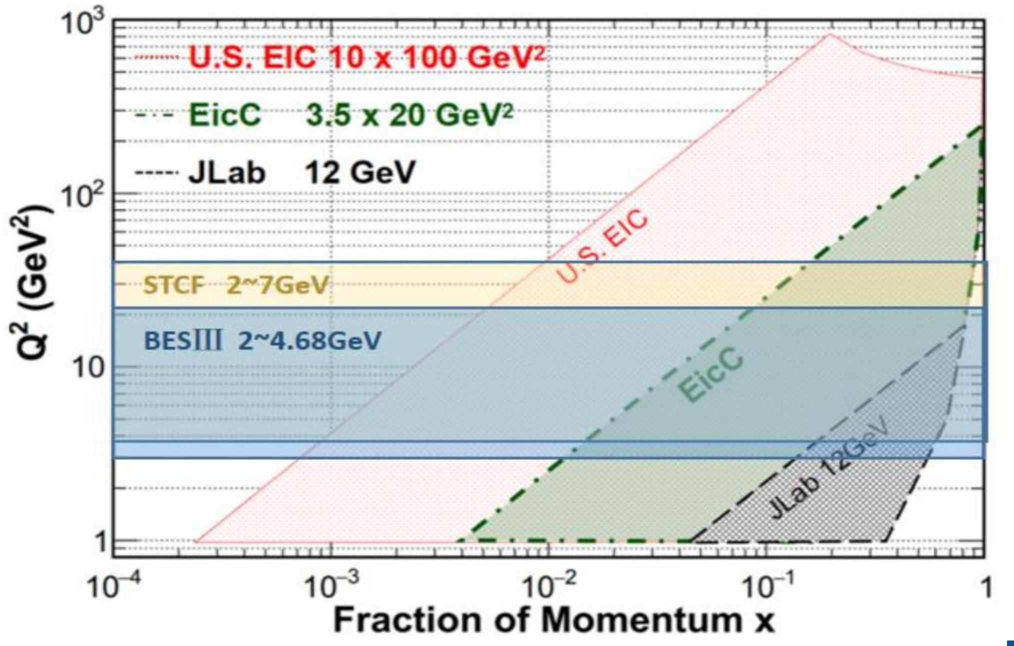
STCF: improved by 2 order of magnitude

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

Fragmentation Function (FF)

- FFs describes the processes of quarks/gluon hadronization, is non-perturbative process, can not be calculated theoretically
- To accurately extract proton Parton Distribution Functions (PDFs), more precise FFs are required
- e^+e^- collider experiment provides the cleanest input for FFs fitting. With polarized electron beam, more FFs can be studied





STCF prospects :

- will provide the most precise FFs in q^2 range 4-50 GeV^2 with multi-dimensional binning
- Precise test the universality of FFs in the different processes, and its evolution with q^2
- Provide important inputs for EIC, EicC, JLab experiments