Experimental program for Super Tau-Charm Facility

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NSTAR2024

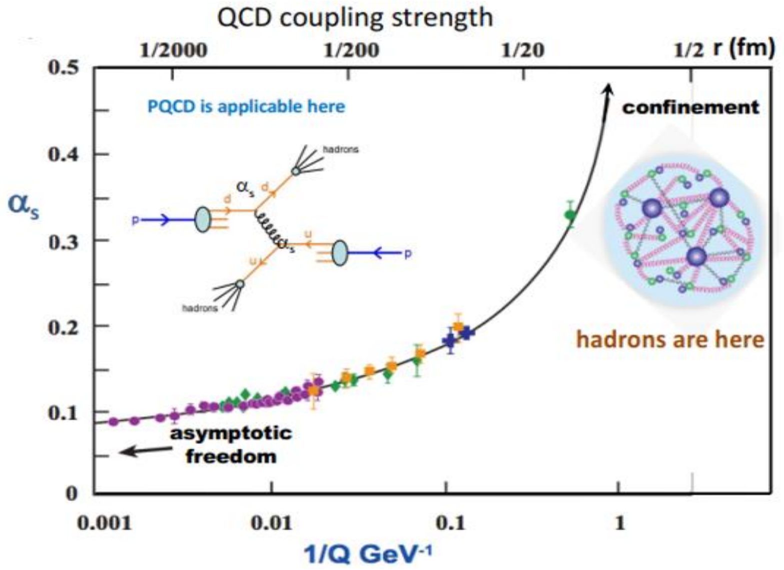
17/6/2024-21/6/2024, York

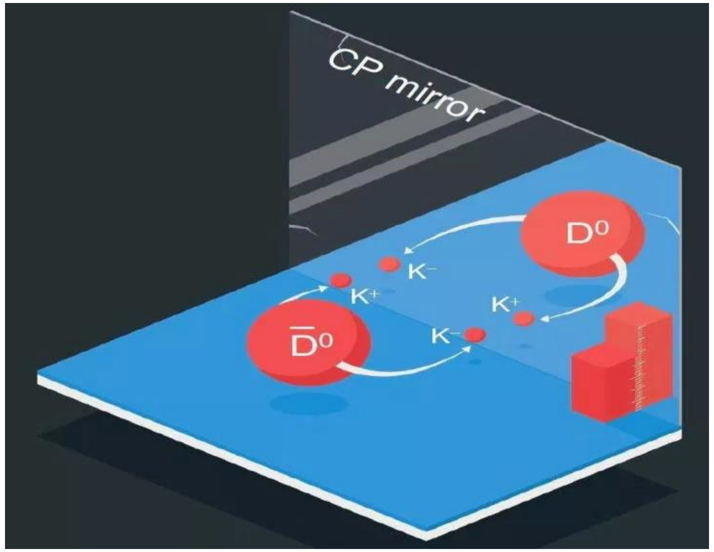
Challenges of the SM model

The SM of particle physics is a well-tested theoretical framework

However, the SM has a number of unresolved questions that require further investigations:

- **Confinement: formation of colorless bound states —— “hadrons”**
- **Matter-antimatter asymmetry of the Universe; dark matter, numbers of flavors, etc.**





Masses

Parameter	Value	Method
m_u	1.9 MeV	Lattice
m_d	4.4 MeV	Lattice
m_s	87 MeV	Lattice
m_c	1.3 MeV	Collider
m_b	4.24 MeV	Collider
m_t	173 GeV	Collider
m_e	511 keV	Non-collider
m_μ	106 MeV	Non-collider
m_τ	1.78 GeV	Collider
m_z	91.2 GeV	Collider
m_H	125 GeV	Collider

Couplings

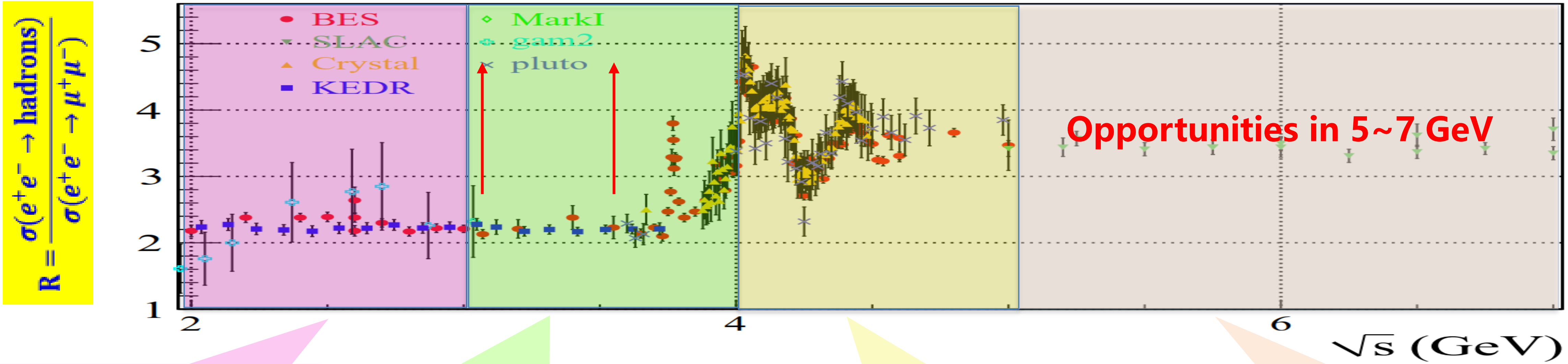
Parameter	Value	Method
α	0.0073	non-collider + collider
G_F	$1.17\text{x}10^{-5}$	Non-collider
α_s	0.12	Lattice + collider

Flavour and CP violation

Parameter	Value	Method
θ_{12} (CKM)	13.1°	Collider
θ_{23} (CKM)	2.4°	Collider
θ_{13} (CKM)	0.2°	Collider
δ (CKM-CPV)	0.995	Collider
θ (strong CP)	~0	Non-collider

Rich Physics in the Tau-Charm Energy Region

- **The tau-charm energy region covers a unique transition region between perturbative and non-perturbative QCD, with unique and rich physics programs**



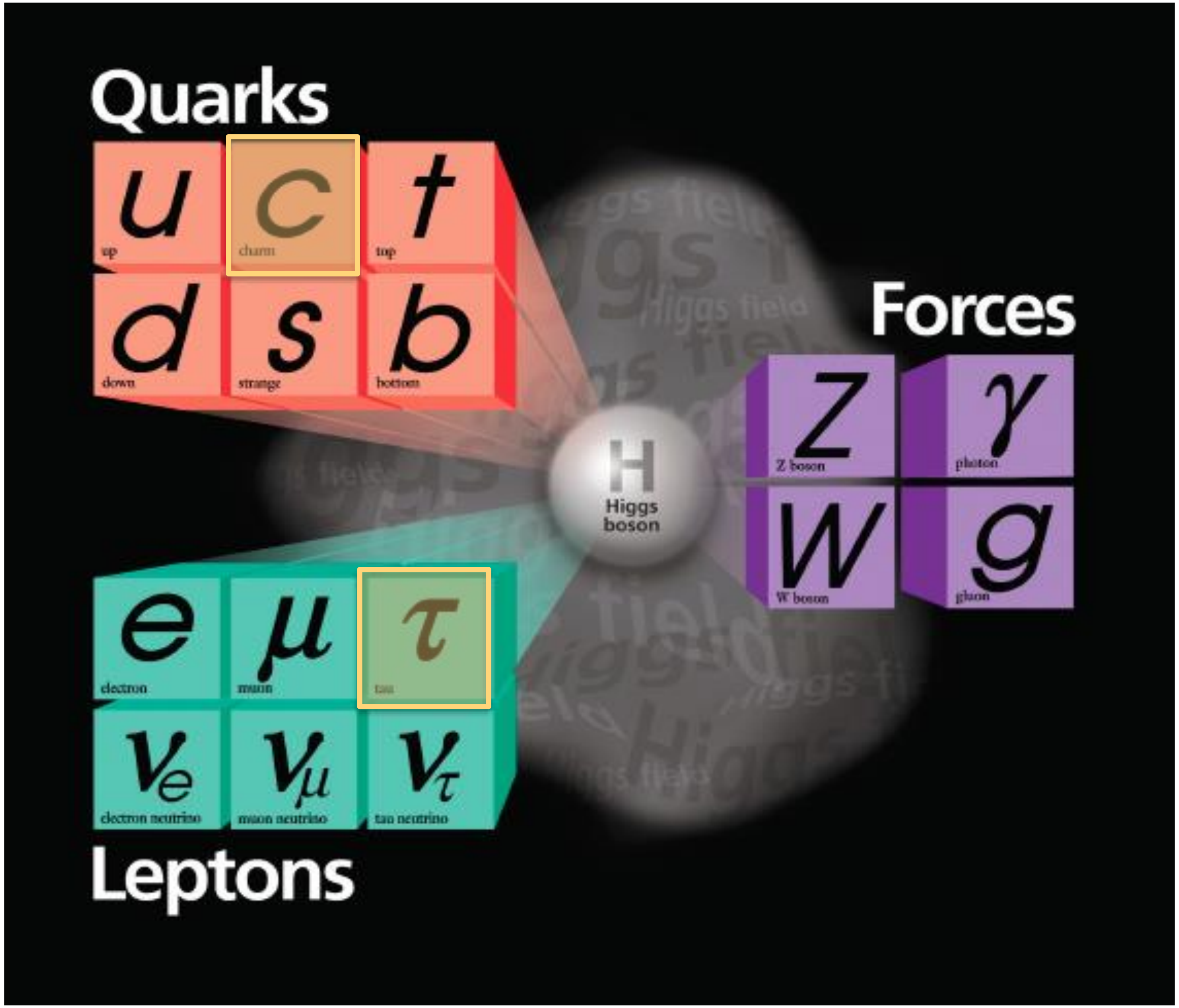
- Hadron form factors
- $Y(2175)$ resonance
- Mutltiquark states with s quark
- R value / g-2 related

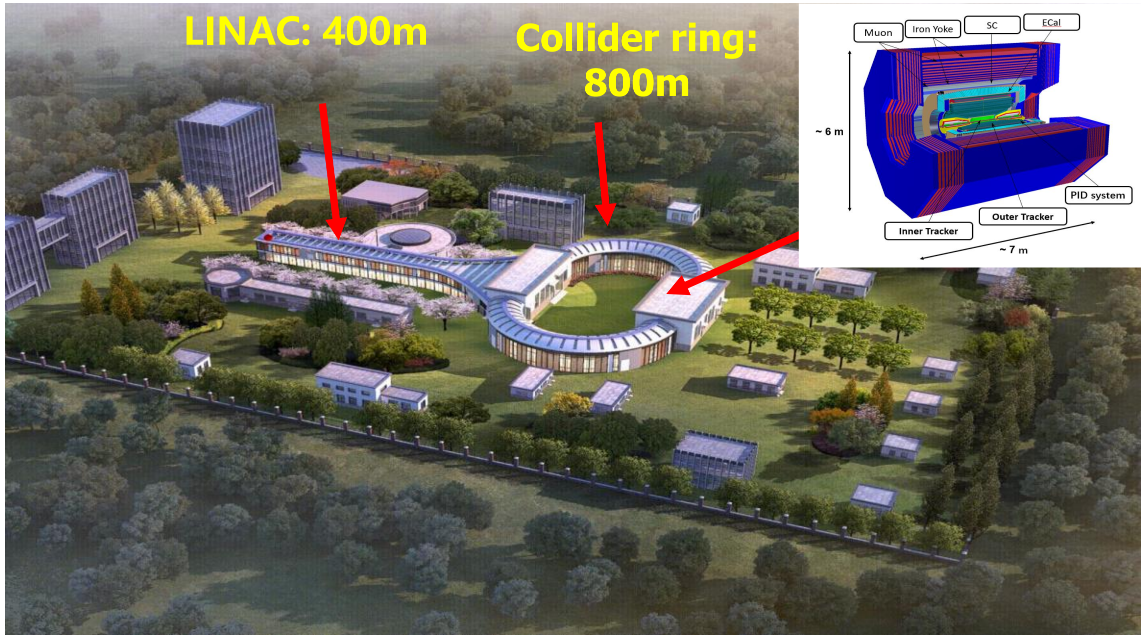
- Light hadron spectroscopy
- Gluonic and exotic states
- Processes of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- 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

The Super Tau Charm Facility





Energy range E_{cm} = 2-7 GeV

Peak luminosity >0.5×10^{35} $cm^{-2}s^{-1}$ at 4 GeV

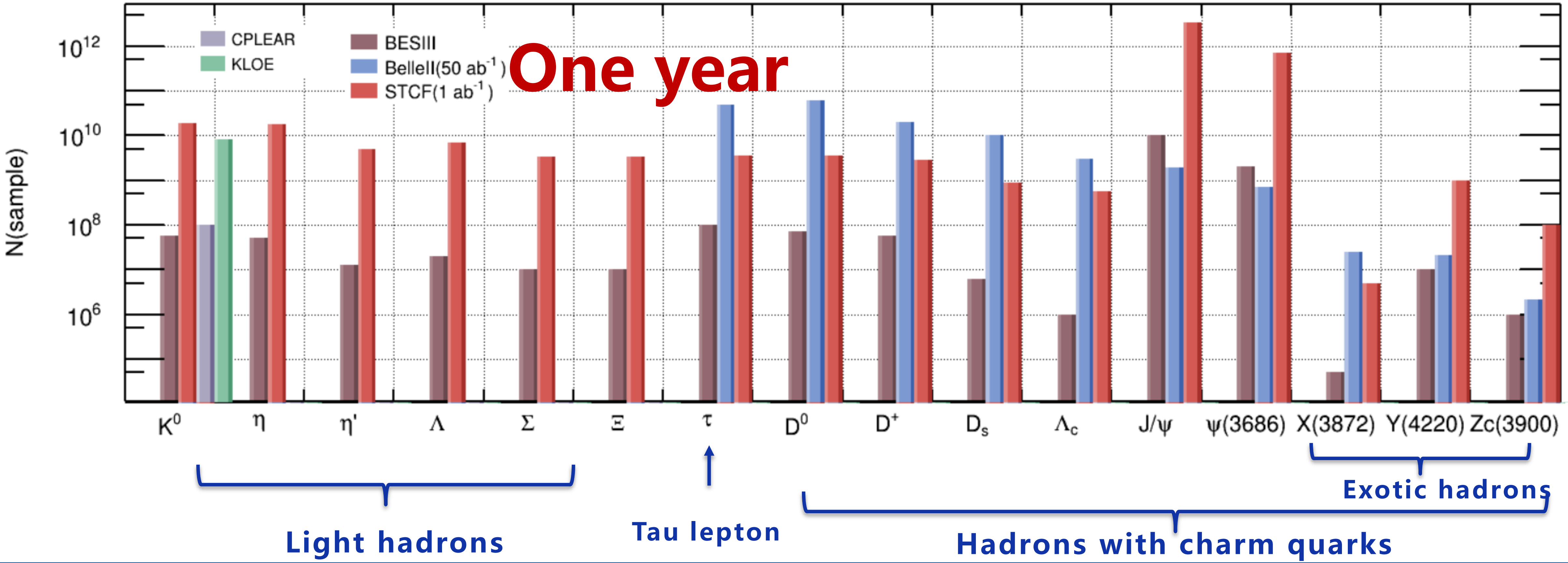
Potential to increase luminosity & realize beam polarization

Total cost: 4.5B RMB

1 ab^{-1} data expected per year

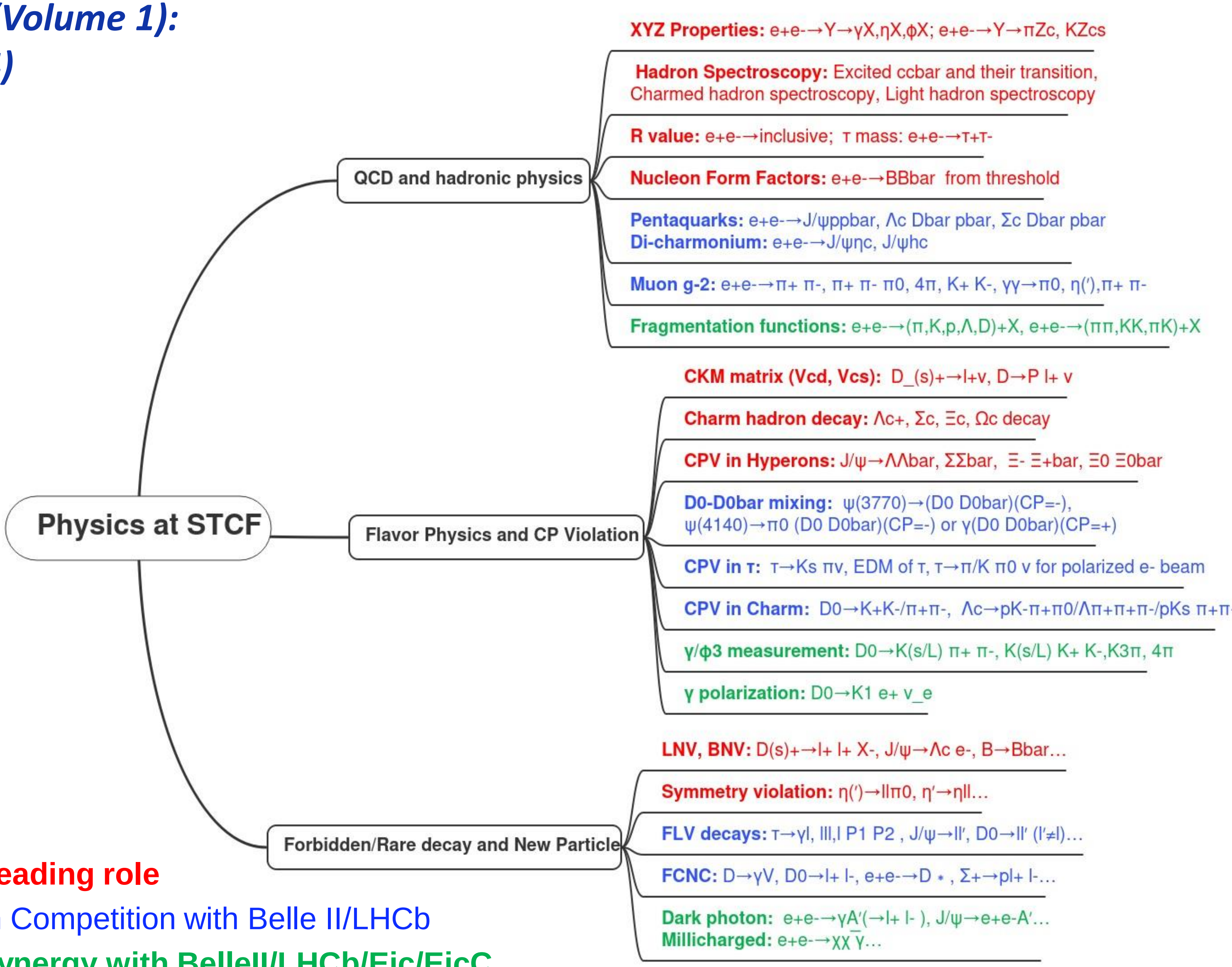
A Super Particle Factory

- Rich resonances, large production cross-sections of charmonium, threshold production of hadron and tau pairs
- Huge numbers of exotic hadrons, including multi-quarks & states with gluonic excitations



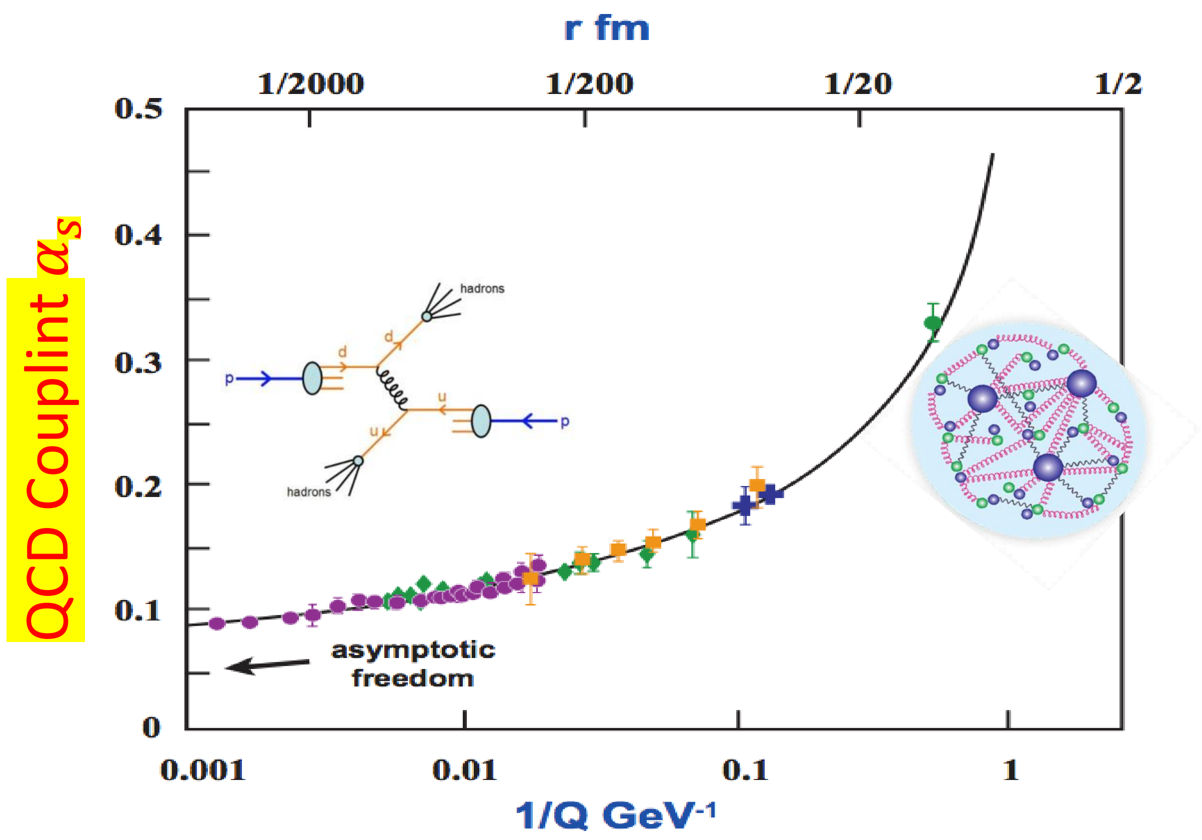
Physics Program at STCF

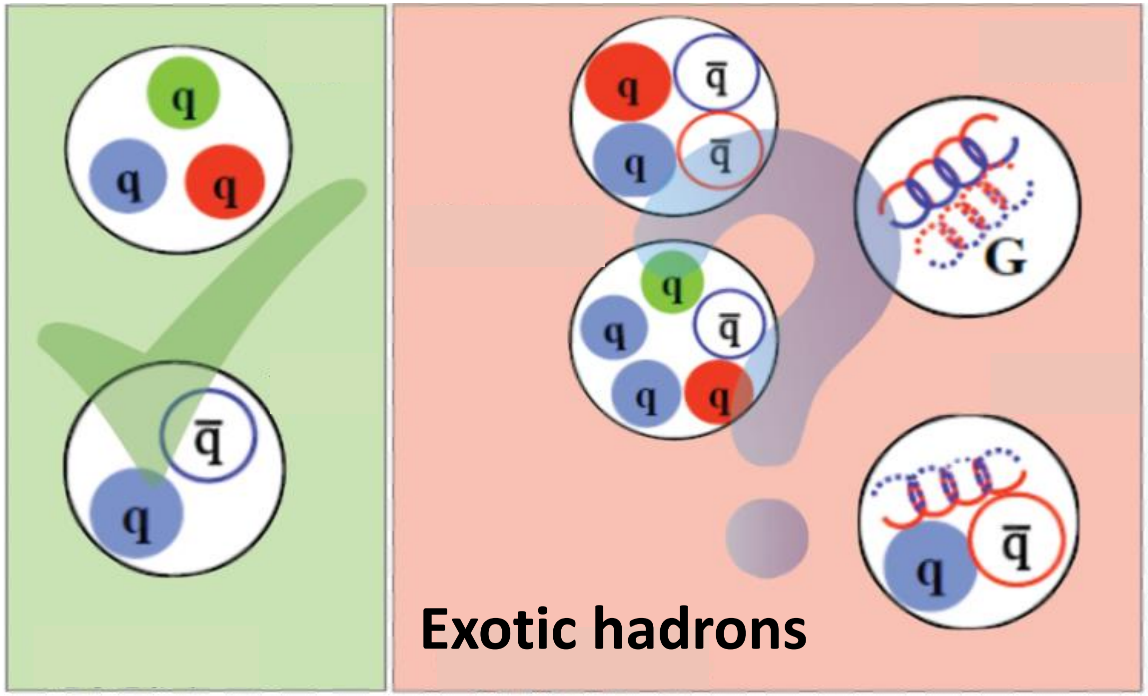
M. Achasov, et al., STCF conceptual design report (Volume 1): Physics & detector, Front. Phys. 19(1), 14701 (2024)



- Leading role
- In Competition with Belle II/LHCb
- Synergy with BelleII/LHCb/Eic/EicC

Key Question: Inner structure of hadrons

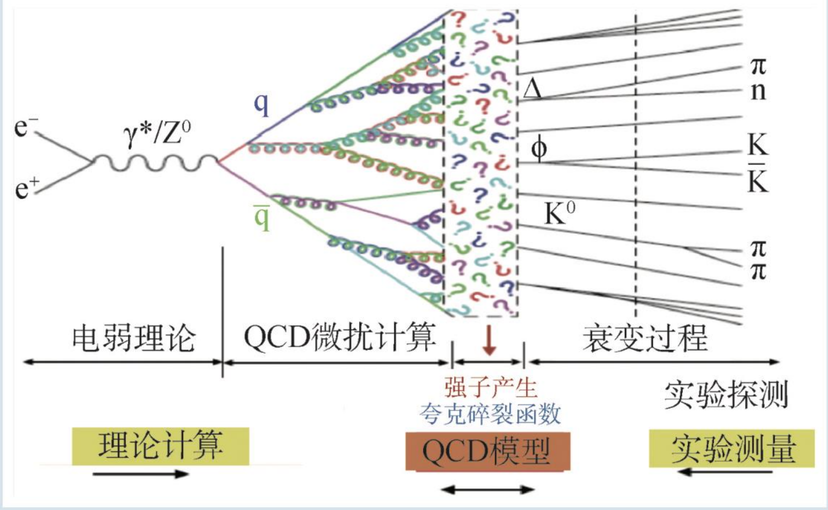


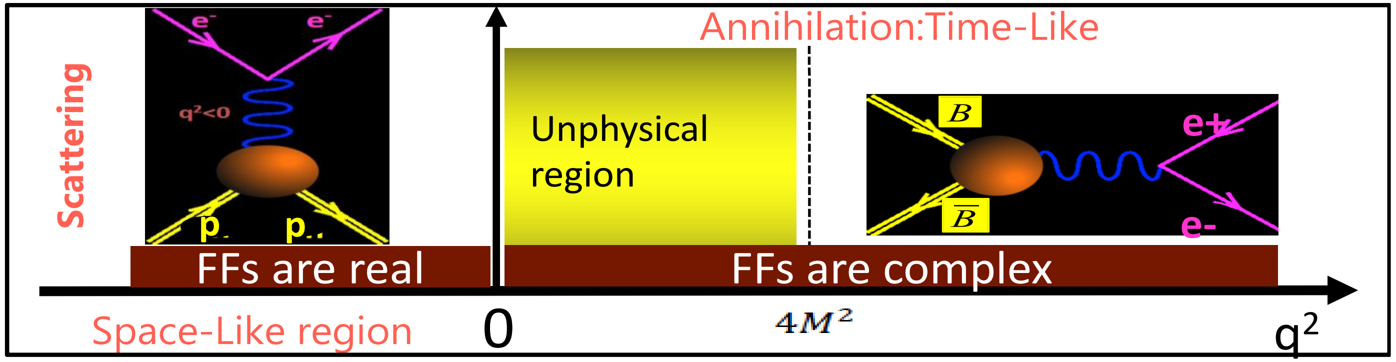


Hadron structure/spectroscopy is a crucial way to explore the QCD theory and confinement

QCD and hadron structure

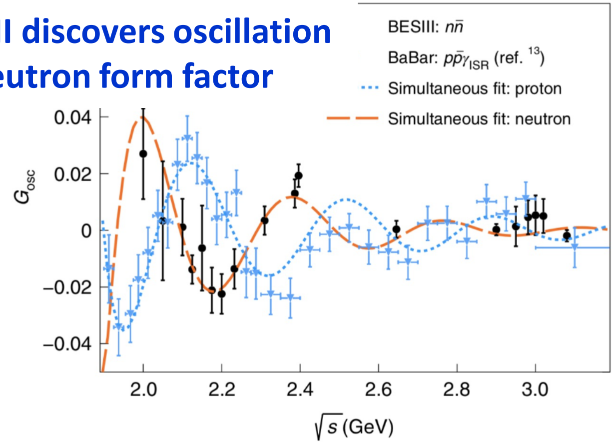
- Remaining big challenge in SM：non-perturbative effect in QCD theory
- The largest uncertainty is from the low-energy non-perturbative energy region
- STCF fine (ISR) scan from 0.6–7 GeV to study production of hadrons inclusively and exclusively



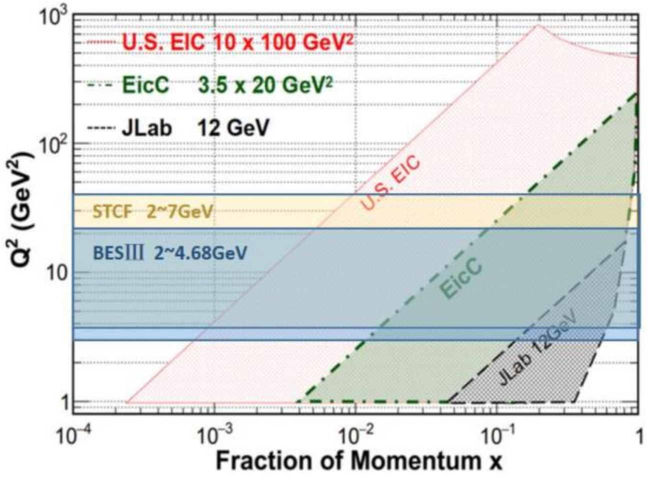


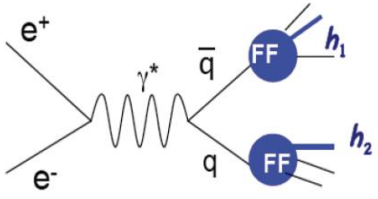
EicC **STCF**

BESIII discovers oscillation of neutron form factor

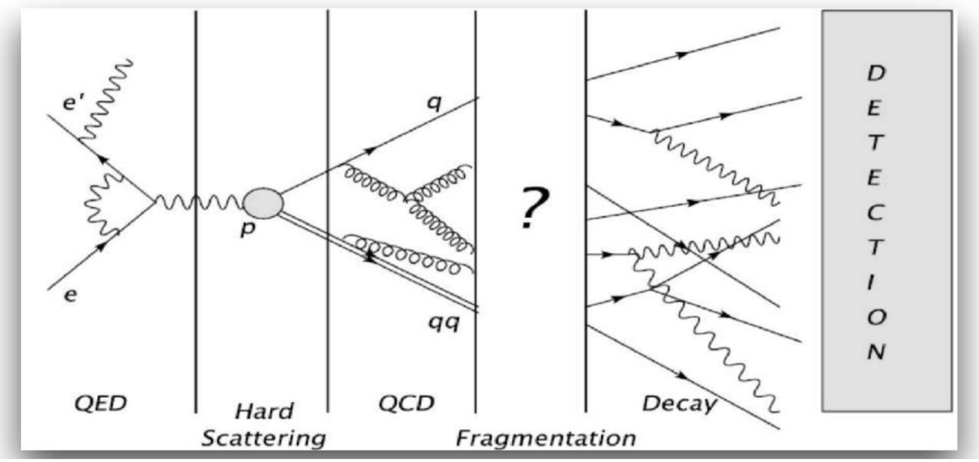


Hadron form factor and fragmentation function:
complementary measurements between deep inelastic experiments and STCF in similar Q^2 region



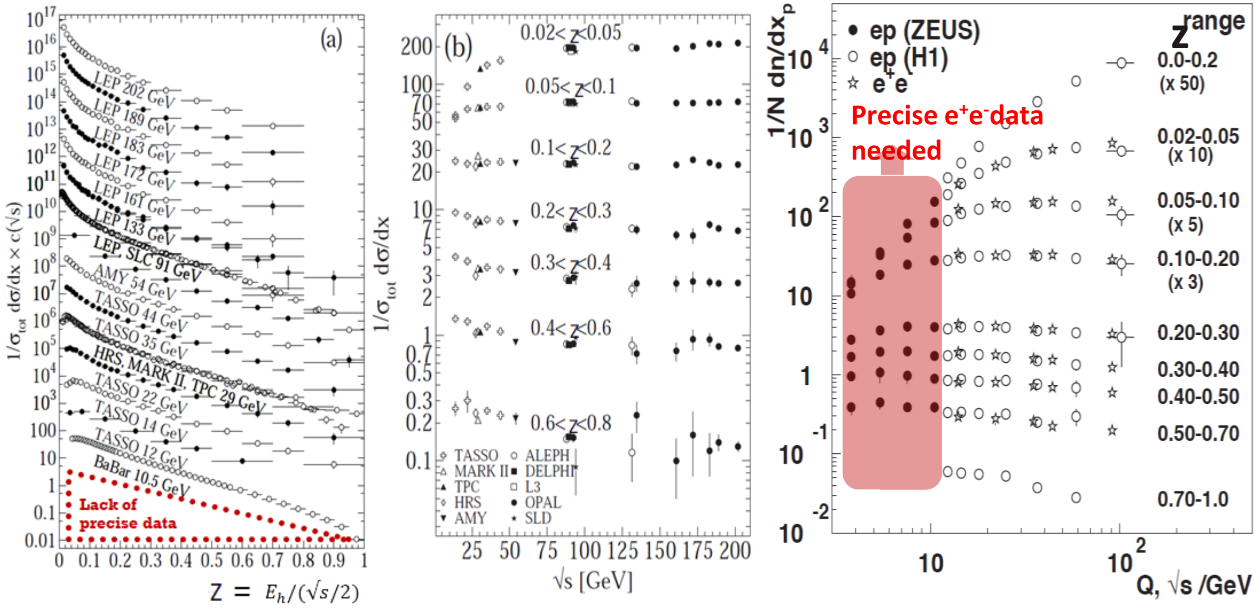


Fragmentation functions

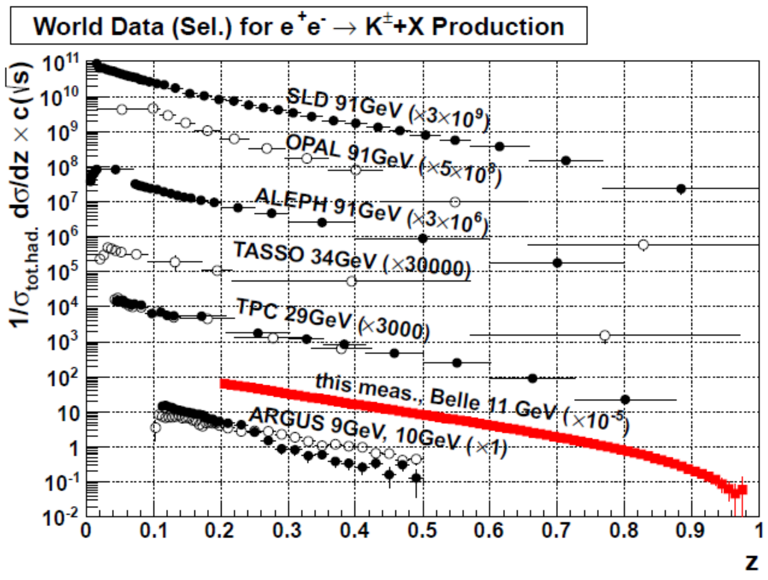


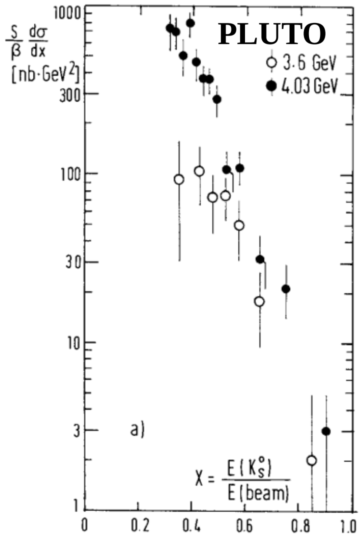
Fragmentation function $D_q^h(z)$: probability that hadron h is found in the debris of a hadron carrying a fraction $z=2E_h/\sqrt{s}$ of parton's momentum.

World data: Pion



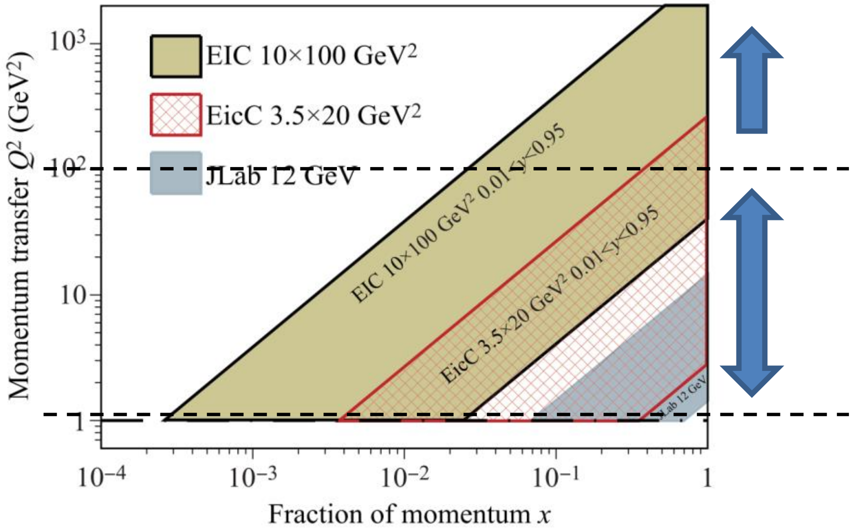
World data: Kaon

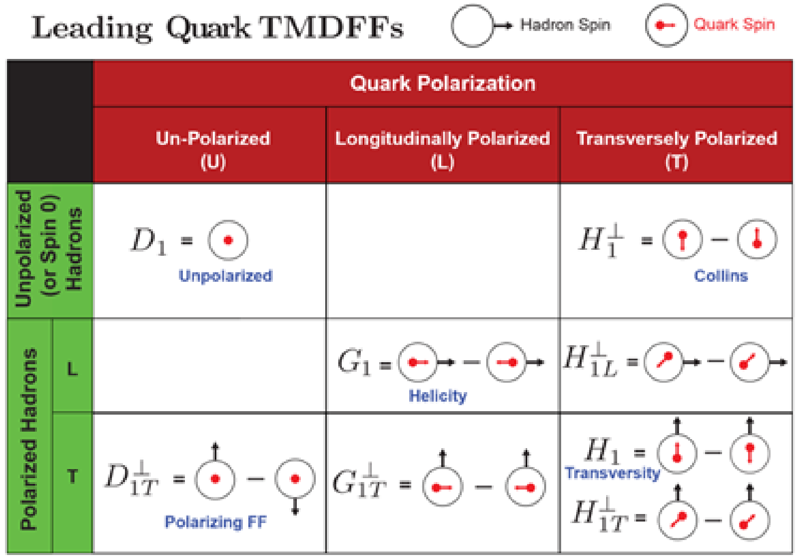




Fragmentation functions at STCF

- e^+e^- collider experiment provides the cleanest input for fragmentation functions (FFs) fitting. To accurately extract Parton Distribution Functions (PDFs), more precise FFs are required.
- Two types of FFs can be studied at an unpolarized e^+e^- collider: D and $H_1^{\perp}$. Multi-dimensional binning of the measurements can be provided.
- With polarized electron beam, more FFs can be studied. There is a task-force group working on it.





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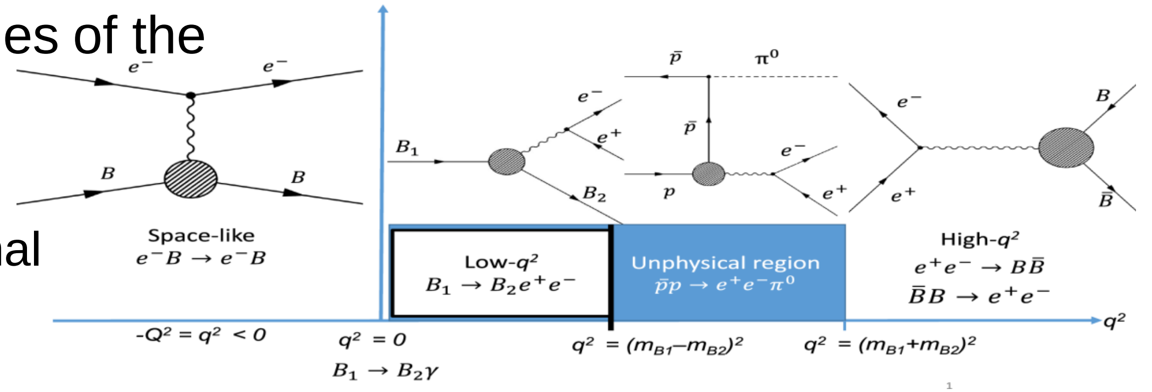
Electromagnetic form factors (EMFFs)

Electromagnetic Form Factors are fundamental properties of the nucleon

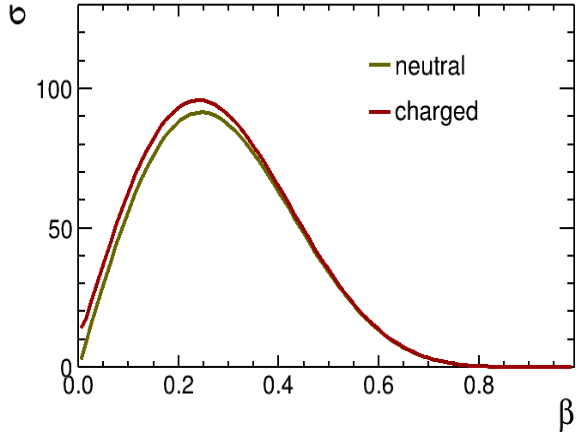
- ➢ Connected to charge, current distribution
- ➢ Crucial testing ground for models of the nucleon internal structure



pQCD predicts continuous transition at high q^2, with the scaling behavior: $F_1 \propto q^{-4}, F_2 \propto q^{-6}$

Modified scaling expression in **nonperturbative** region: $\frac{q^2 F_2}{F_1} \propto \ln(\frac{q^2}{\Lambda^2})$, with $\Lambda \approx$ 0.3 GeV

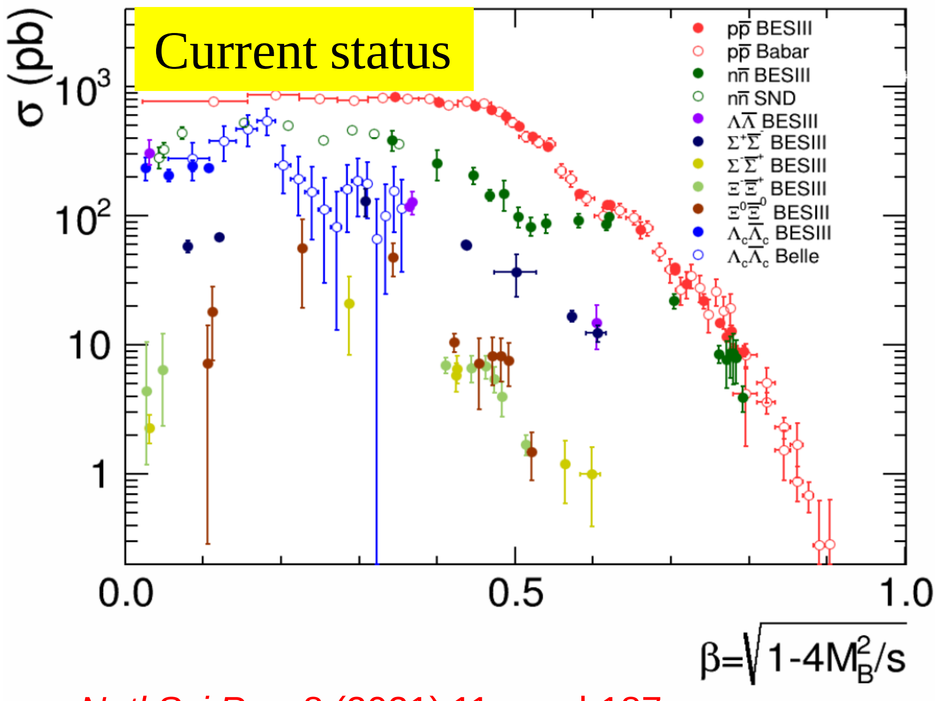
VMD model described the effect of meson cloud $|G_{\mathrm{eff}}| = \frac{\mathcal{A}}{\left(1+\frac{q^2}{m_a^2}\right)[1-q^2/q_0^2]^2}$



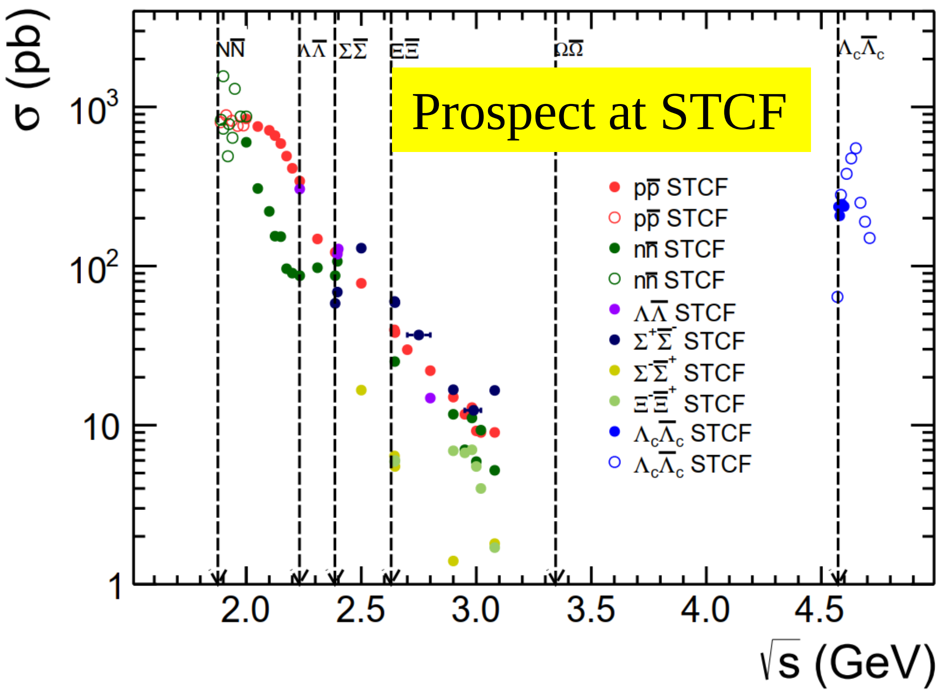
- Various theoretical models describe TLFF in non-perturbative region: ChEFT, VMD, relativistic CQM, parton model, pQCD etc.
- Dispersion theoretical analysis, provide a coherent framework for the joint interpretation of SL and TL EMFFs over the entire physical range of q^2.

Prospect of TL-EMFF at 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.
  - The asymptotic behavior of TL-EMFFs

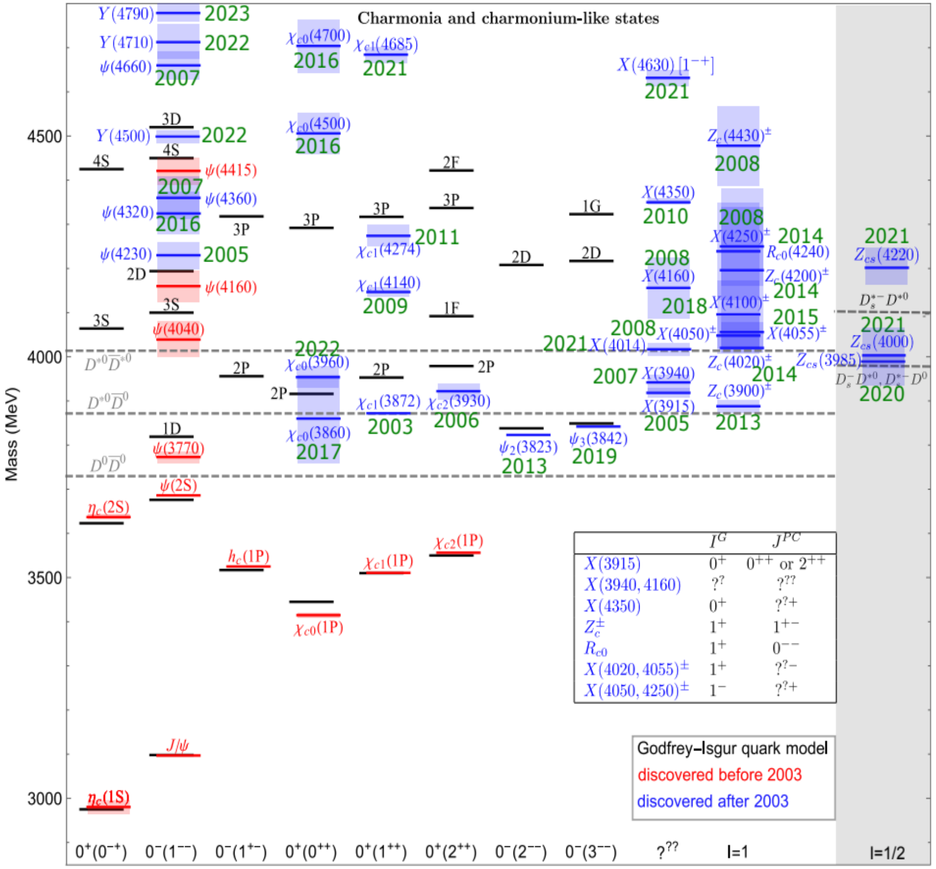


Natl.Sci.Rev. 8 (2021) 11, nwab187



Charmonium (like) States

- **The overpopulated charmonium spectrum is a unique territory to study exotic hadrons**

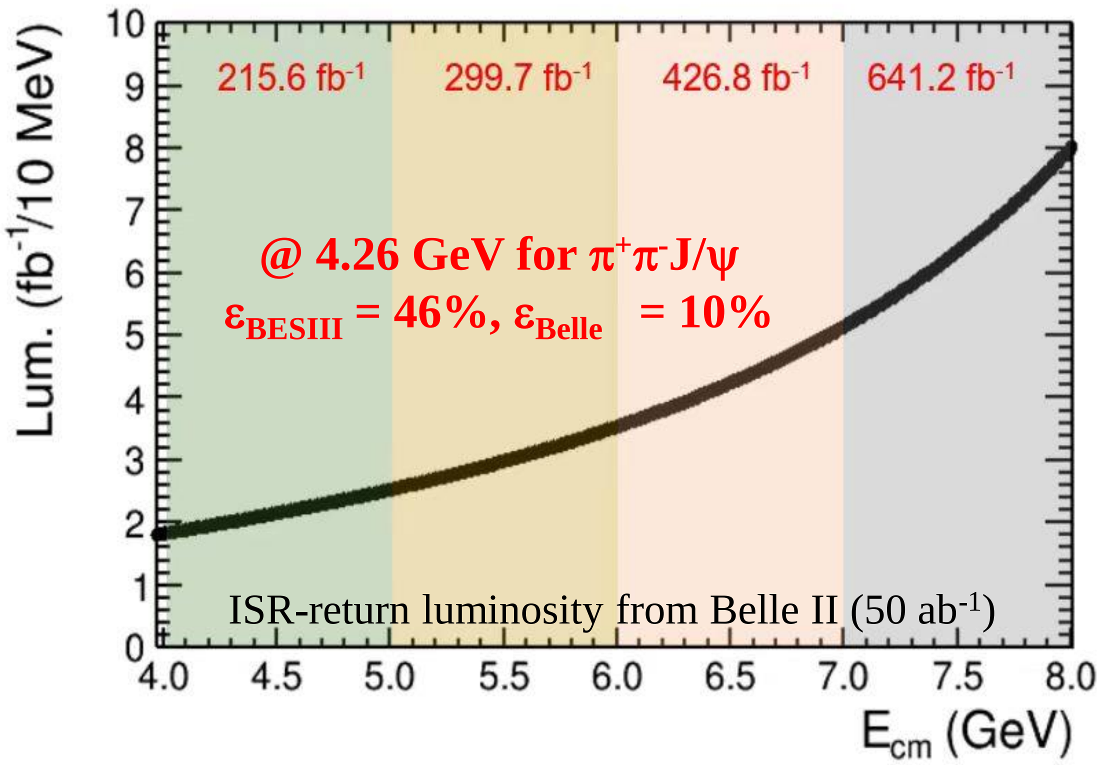


Existing XYZ puzzles:

- **Masses away from quark model predictions, *e.g.* X(3872), Y(4230) and Y(4260)**
- **Many seen in final states of charmonium, instead of open-cham channels (Not all)**
- **Charged structures like $Z_{c(s)}$ must contain at least four quarks. Their connections to Y and X are of interest**
- **An overall classification is still lacking**

Charmonium(like) States at STCF

- STCF provides unique **fine scan** of the exotic hadron states
- 1 ab^{-1}/year luminosity at STCF can produce: **1B Y(4230)**, **100M Z_c(3900)** and **5M X(3872)**



More opportunities at STCF:

- Energy dependent structures of $Z_{c(s)}$
- Structures in more channels, with larger production rates above 5 GeV
- Charged hadron final states of the whole energy range
- Hybrid candidates
- Missing charmonium states and their transitions

Light Hadron Opportunity at STCF

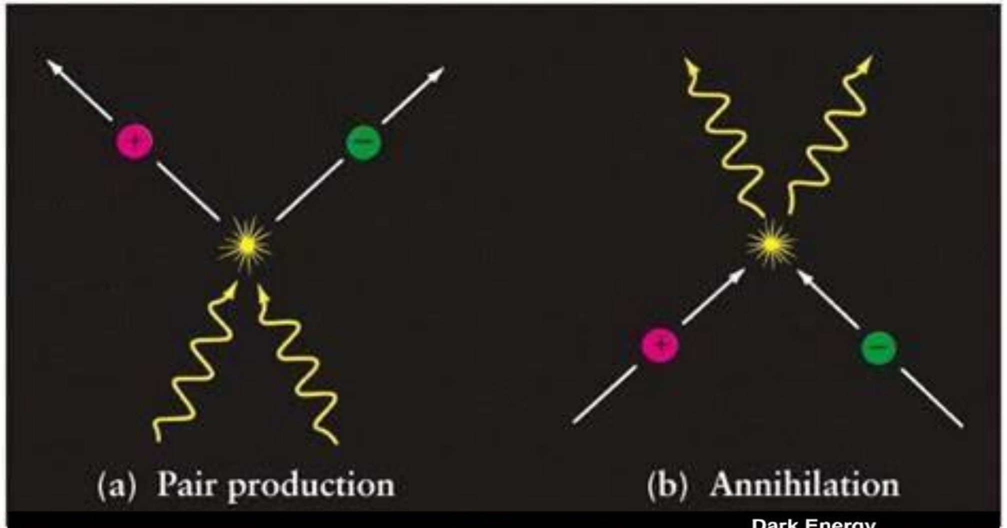
High Statistical Data : 1 ab^{-1}/year

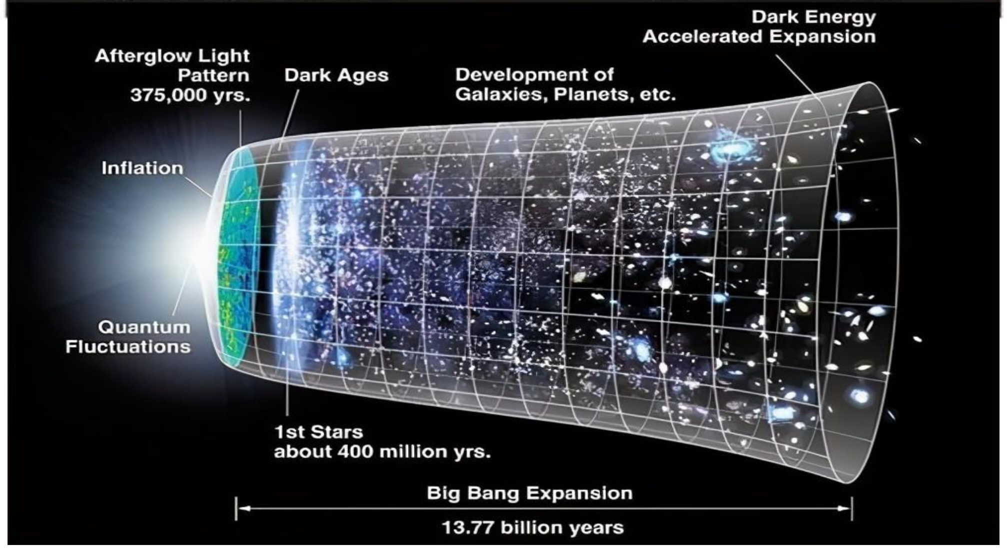
CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^{9}	
		$\psi(3686)\to\tau^+\tau^-$	[illegible]	2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^{9}	
		$D^+\bar{D}^-$	2.8	2.8×10^{9}	
		$D^0\bar{D}^0$		7.9×10^{8}	Single tag
		$D^+\bar{D}^-$		5.5×10^{8}	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$D^{*0}\bar{D}^0+c.c$	4.0	1.4×10^{9}	$CP_{D^0\bar{D}^0}=+$
		$D^{*0}\bar{D}^0+c.c$	4.0	2.6×10^{9}	$CP_{D^0\bar{D}^0}=-$
		$D_s^+D_s^-$	0.20	2.0×10^{8}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^{8}	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^{8}	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^{7}	
		$\tau^+\tau^-$	3.6	3.6×10^{9}	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^{7}	
		$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^{7}	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^{8}	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^{7}	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

$J/\psi\sim10^{12}$
$\psi(3686)\sim10^{11}$

- Large number of J/ψ and $\psi(3686)$ events for exploring light hadron physics
- Traces of glueballs and hybrid states may be found in more ways
- Search for more production and decay modes of hybrid candidates and glueball candidates
- Electromagnetic couplings to glueball candidates:
  - radiative transition rates
  - transition form factors in the time-like region
  - couplings to $\gamma\gamma$

Key Question: matter-antimatter asymmetry





The very fact that we exist in a matter-dominated universe.

Sakharov Condition (1967)

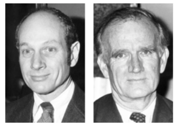
1. Baryon number B violation
2. C and CP symmetry violation
3. Interactions out of thermal equilibrium

Andrei Sakharov
（1921-1989）

K meson CP violation[2] — **B meson CP violation [3,4]** — **D meson CP violation [5]**

1964

James Watson Cronin



Val Logsdon Fitch

Nobel Prize 1980

2001

Belle II

BABAR

2019

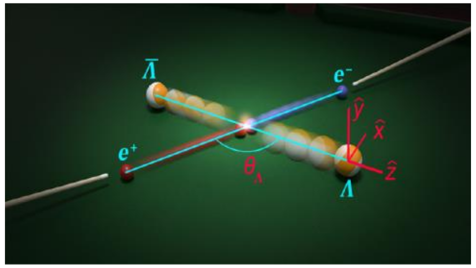
LHCb

[1] Phys. Rev. 104 (1956) 254-258
[2] Phys. Rev. Lett., 1964, 13: 138-140
[3] Phys. Rev. Lett., 2001, 87: 091801
[4] Phys. Rev. Lett., 2001, 87: 091802
[5] Phys. Rev. Lett., 2019, 122(21): 211803

Huge numbers of K, τ, hyperons, D will be produced at STCF. With unprecedented high statistics, studies of the particles and their decays can reveal new information

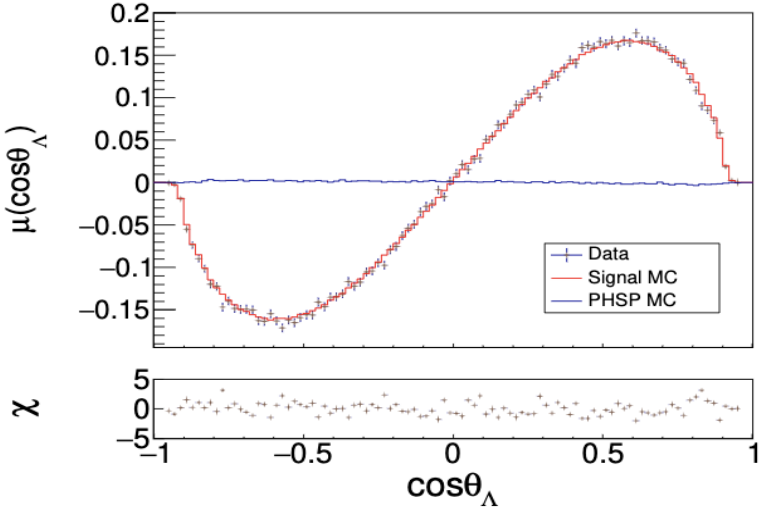
Polarization of Λ Hyperons and CP Test

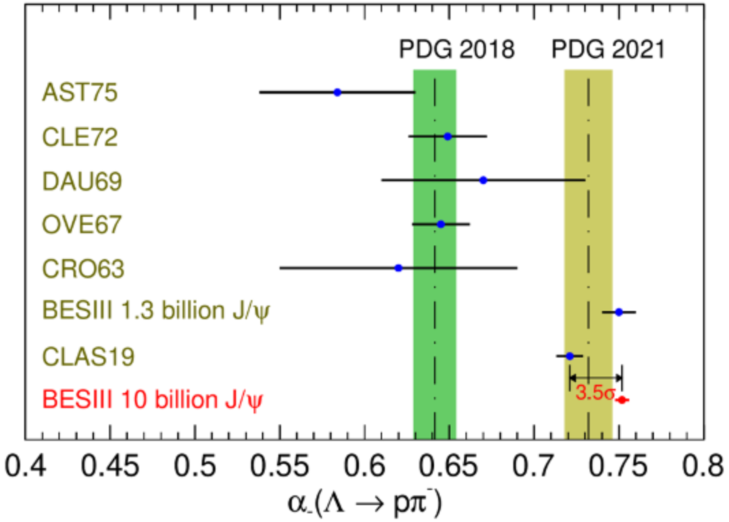
- **Updated results based on 10B J/ψ events: ~0.42M signals**
- **Decay asymmetries with best precisions ever**

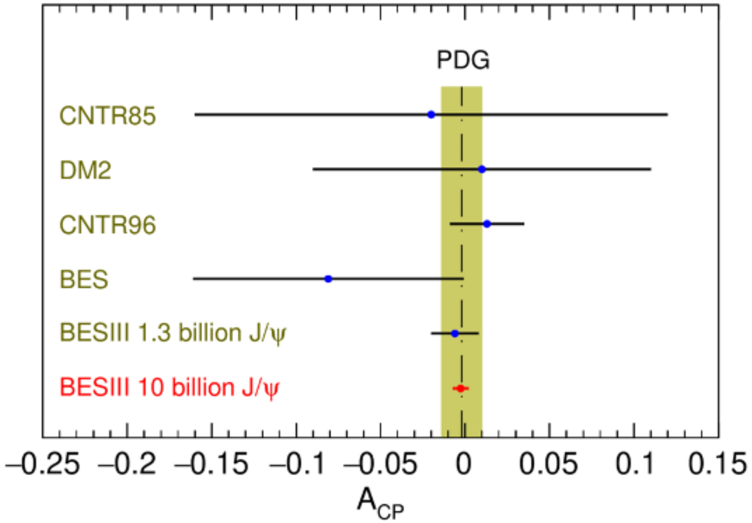


CP test $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$

PRL 129, 131801 (2022)





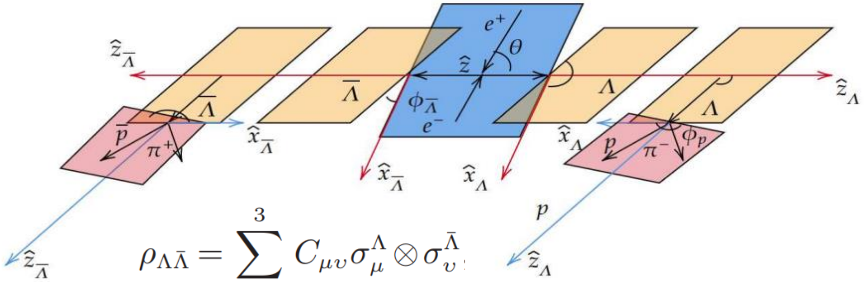


Par.	This Work*	Previous results **	PDG 2018 ***
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0024$	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027
$\Delta\Phi$	$0.7521 \pm 0.0042 \pm 0.0080$	$0.740 \pm 0.010 \pm 0.009$	-
α_-	$0.7519 \pm 0.0036 \pm 0.0019$	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013
α_+	$-0.7559 \pm 0.0036 \pm 0.0029$	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08
A_{CP}	$-0.0025 \pm 0.0046 \pm 0.0011$	$0.006 \pm 0.012 \pm 0.007$	-
$\alpha_{\pm,avg.}$	$0.7542 \pm 0.0010 \pm 0.0020$	$0.754 \pm 0.003 \pm 0.002$	-

~7σ upward shift from all previous measurements

0.5% level sensitivity for CPV test
SM prediction: 10^{-4}~10^{-5}

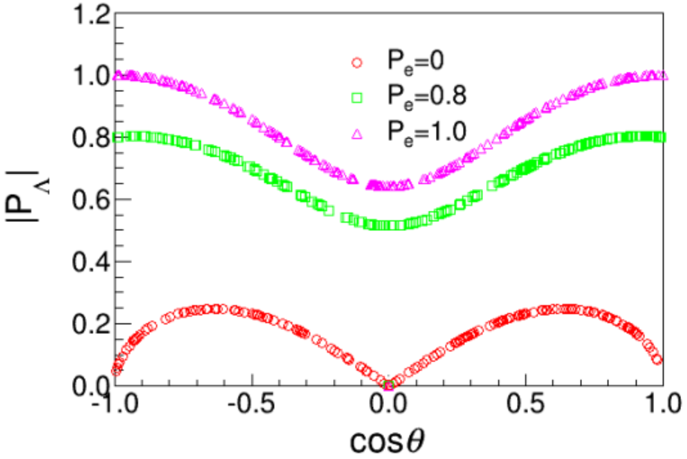
CP Test in Λ Decay with Polarized Electron Beam

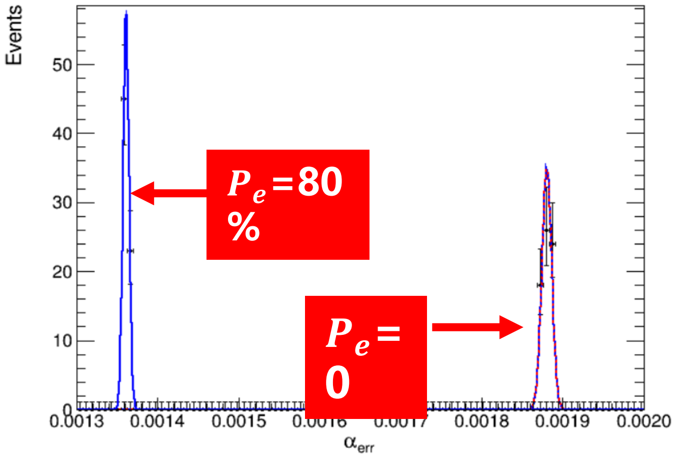


$$\rho_{\Lambda\bar{\Lambda}} = \sum_{\mu\upsilon=0}^{3} C_{\mu\upsilon}\sigma_{\mu}^{\Lambda}\otimes\sigma_{\upsilon}^{\bar{\Lambda}}$$

$$\begin{bmatrix} 1+\alpha_\psi\cos^2\theta & \gamma_\psi P_e\sin\theta & \beta_\psi\sin\theta\cos\theta & (1+\alpha_\psi)P_e\cos\theta \\ \gamma_\psi P_e\sin\theta & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & -\beta_\psi P_e\sin\theta \\ -(1+\alpha_\psi)P_e\cos\theta & -\gamma_\psi\sin\theta\cos\theta & -\beta_\psi P_e\sin\theta & -\alpha_\psi-\cos^2\theta \end{bmatrix},$$

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



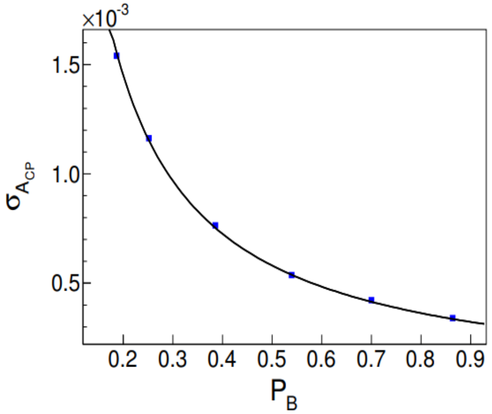


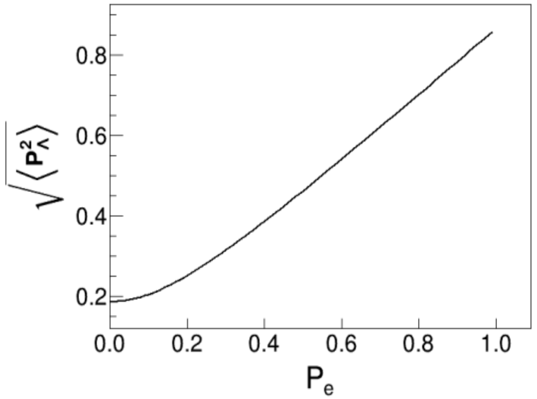
- **Large statistics and electron polarization will improve the sensitivity of CPV significantly**
- **The sensitivity of CPV follows :**

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

$$1\times10^9\ \Lambda\bar{\Lambda},\ \langle P_B^2\rangle=0.1 \Longrightarrow \sigma_{A_{CP}}\sim1.4\times10^{-4}$$

$$1\times10^9\ \Lambda\bar{\Lambda},\ \langle P_B^2\rangle=0.8 \Longrightarrow \sigma_{A_{CP}}\sim0.5\times10^{-5}$$



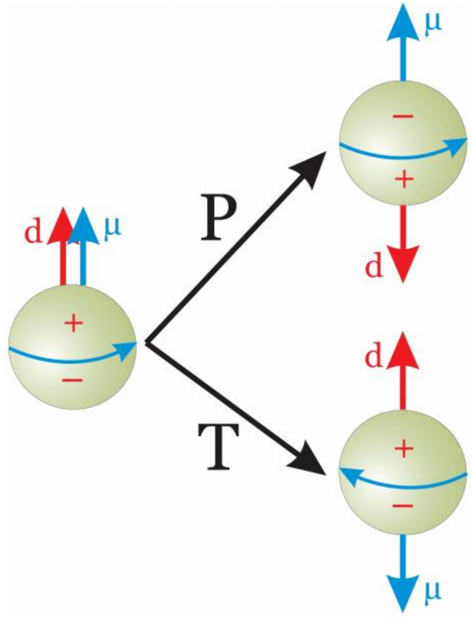


Searching for Hyperon EDM

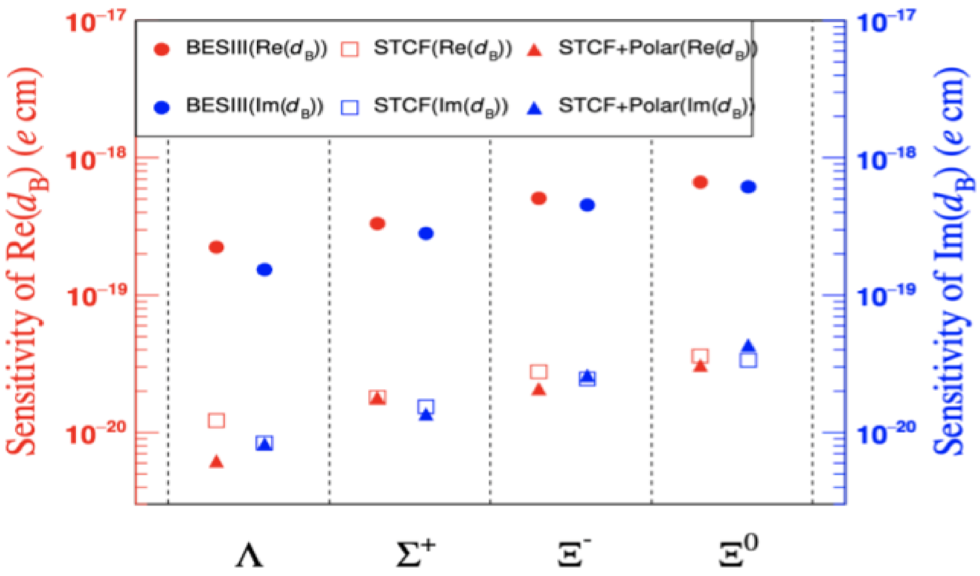
Detailed dynamics in J/ψ decay to hyperon pair have been studied:

μ: magnetic dipole moment
d: electric dipole moment

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



Systematic measurement of the EDMs of the hyperon family!



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

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

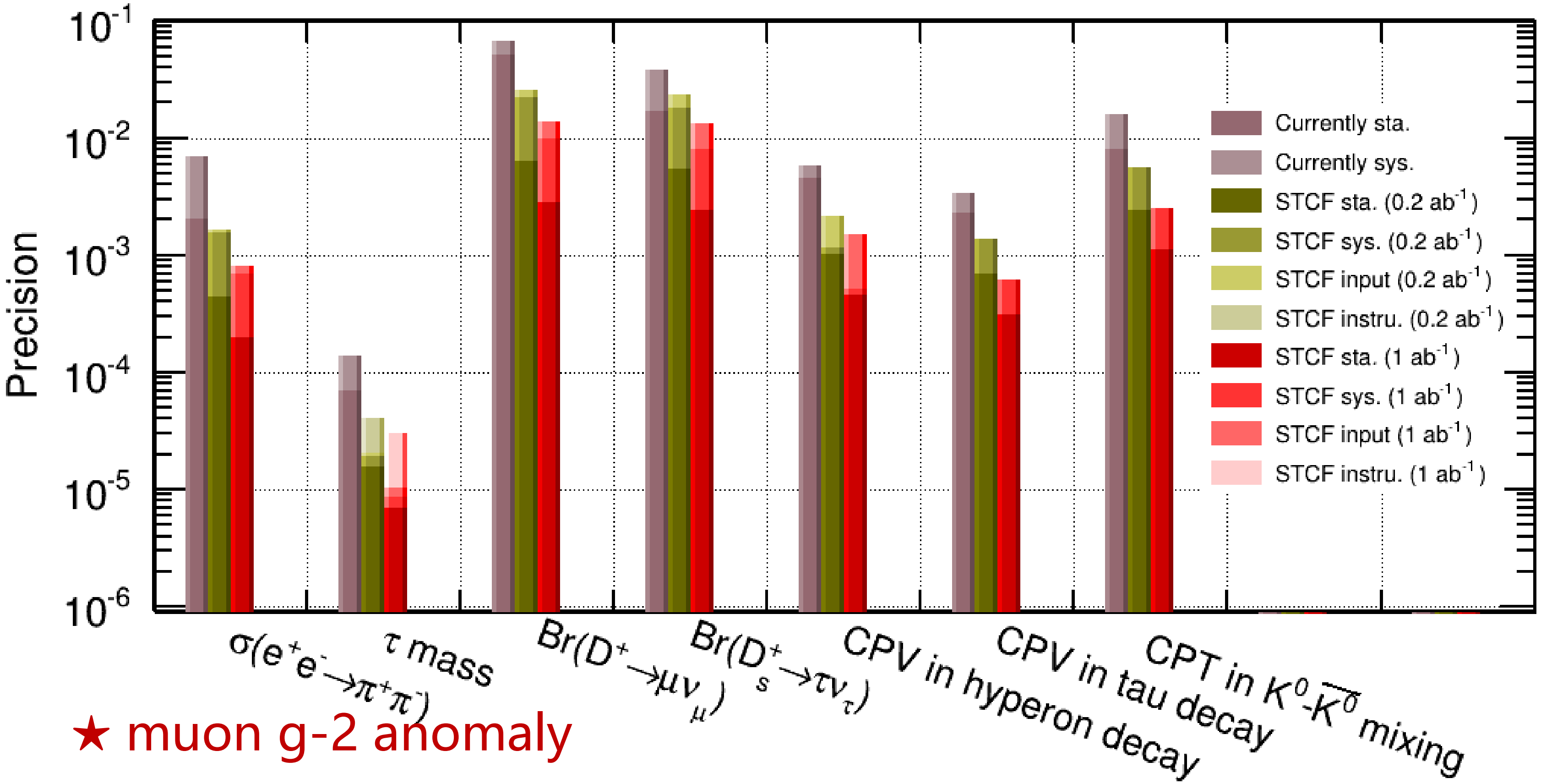
SM: $\sim 10^{-26}$ e cm

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 $\leftrightarrow$ CP violation, if CPT holds.

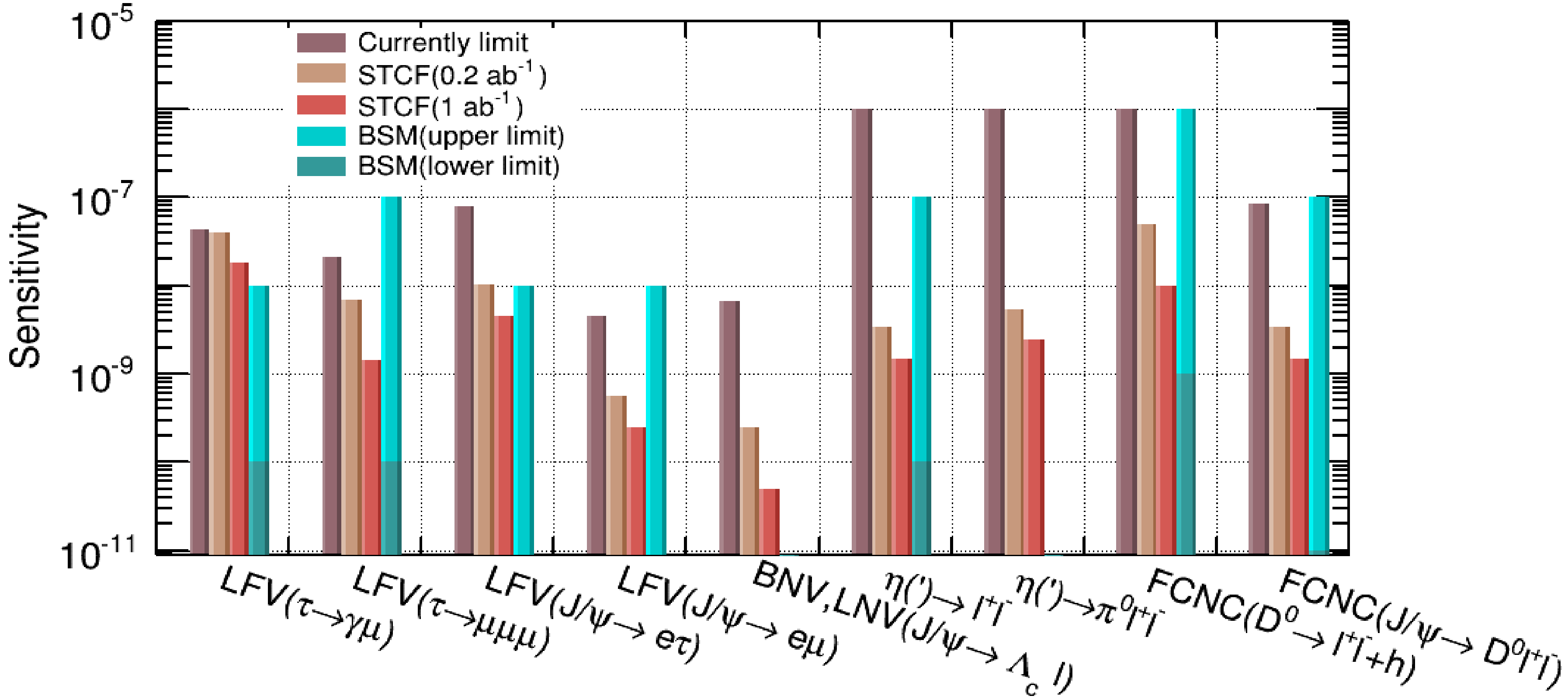
Sensitivity of Precision Measurements



★ muon g-2 anomaly

- **The precision frontier for testing of SM parameters**
- **Uncertainties from reducible (selection-based), and irreducible sources (theoretical input, instrument effect)**

Sensitivity of Rare or Forbidden Decays

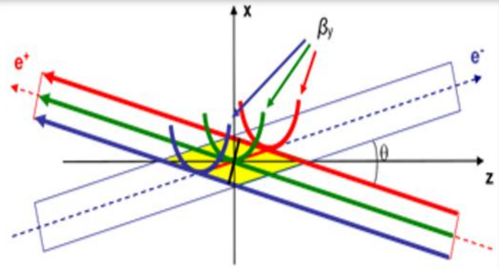


- Sensitivity of **various rare/forbidden decays** measurements at STCF are compared with various **BSM models**
- The excellent precision at STCF can be used to distinguish between various BSM models

Challenges of STCF Accelerator

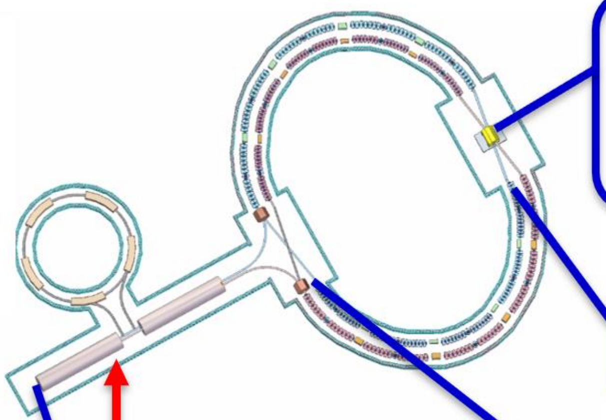
Goal: **ultra-high luminosity in tau charm energy region (2-7 GeV), high-quality beam, stable operation**

Characteristics: **extremely small bunch size, high current intensity, strong nonlinearity and collective effect**



$$L = \frac{\gamma n_b I_b}{2 e r_e \beta_y^*} \xi_y H$$

Big Piwinski angle + Crab Waist



Injection into CR (small DA): high I_b and low ε e+/e- sources

Collider Ring and IR AP design: IP beam size (Y) nm scale, Crab-Waist, nonlinear compensation extremely difficult

IR Technologies: SC magnets, MDI

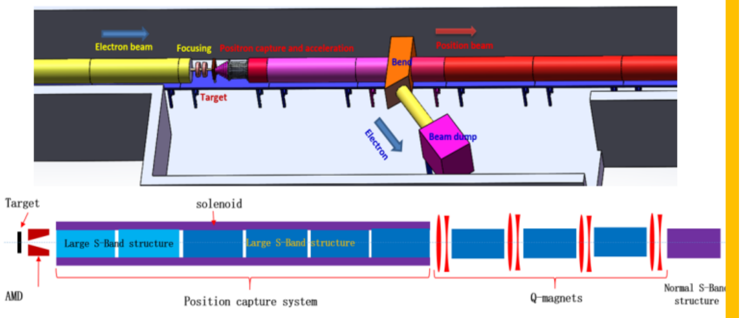
Other key technologies: Ring RF, beam instrum. and control, beam injection...

Preliminary machine parameters

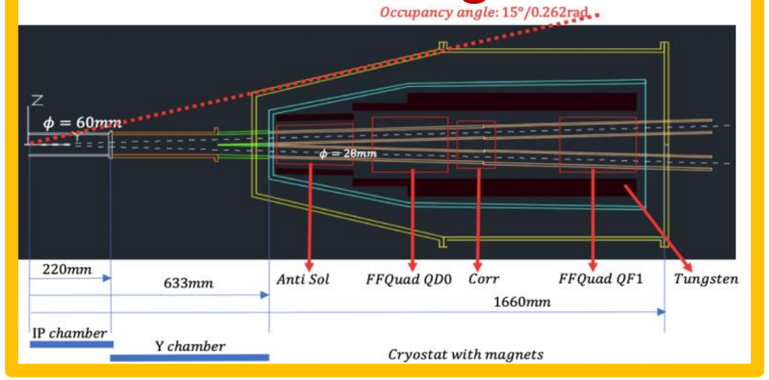
Parameters	Units	STCF (April. 2024)
Optimal beam energy, *E*	GeV	**2**
Circumference, *C*	m	**848.4**
Crossing angle, *2q*	mrad	**60**
Horizontal emittance, *ex*	nm	**6.919**
Coupling, *k*		**0.50%**
Vertical emittance, *ey*	pm	**34.595**
Ver. beta function at IP, β_y	mm	**0.6**
Ver. beam size at IP, *sy*	mm	**0.144**
Beam current, *I*	A	**2**
Single-bunch charge	nC	**8.04**
SR power per beam, P_{SR}	MW	**0.572**
Bunch length, *sz*	mm	**8.43**
Ver. beam-beam parameter, ξ_y		**0.094**
Luminosity, *L*	10^{35} cm^{-2} s^{-1}	**1.19**

STCF Accelerator R&D

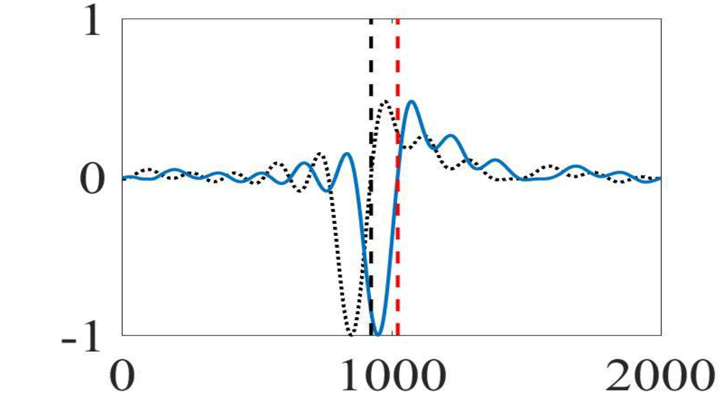
Positron Source Design

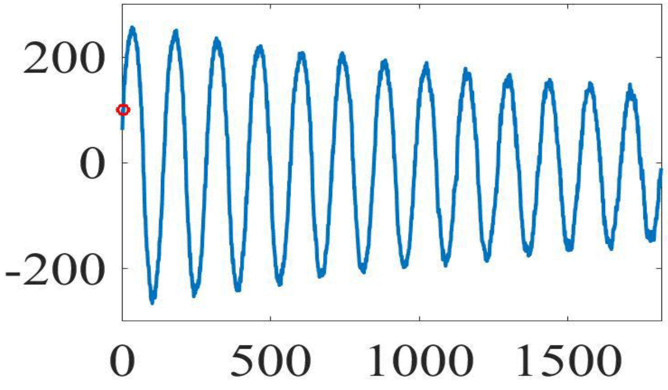


MDI Design



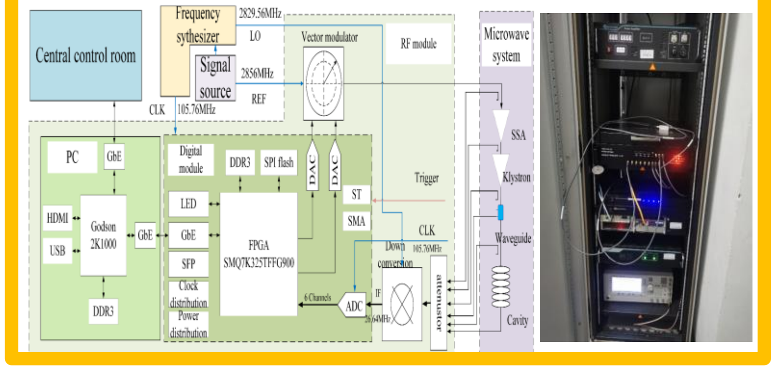
Bunch-by-Bunch 3D position measurement



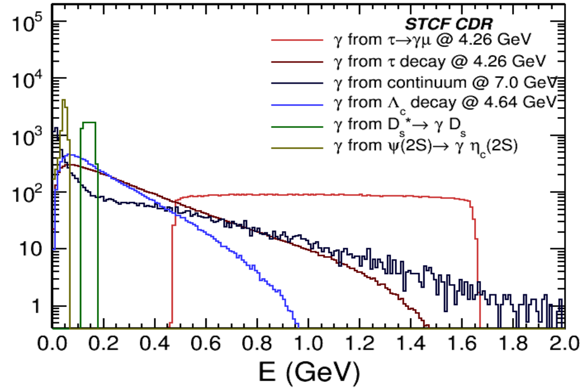


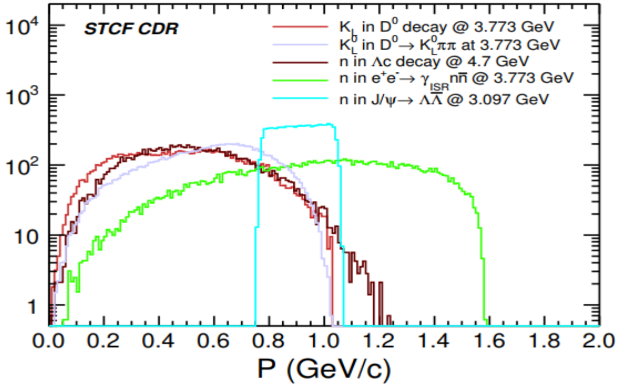
Photocathode RF gun

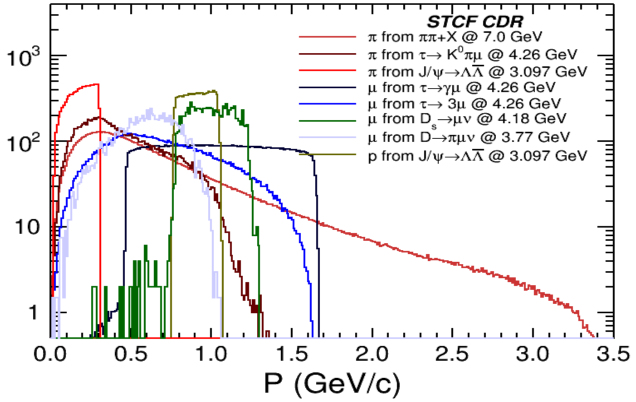
Low level RF system

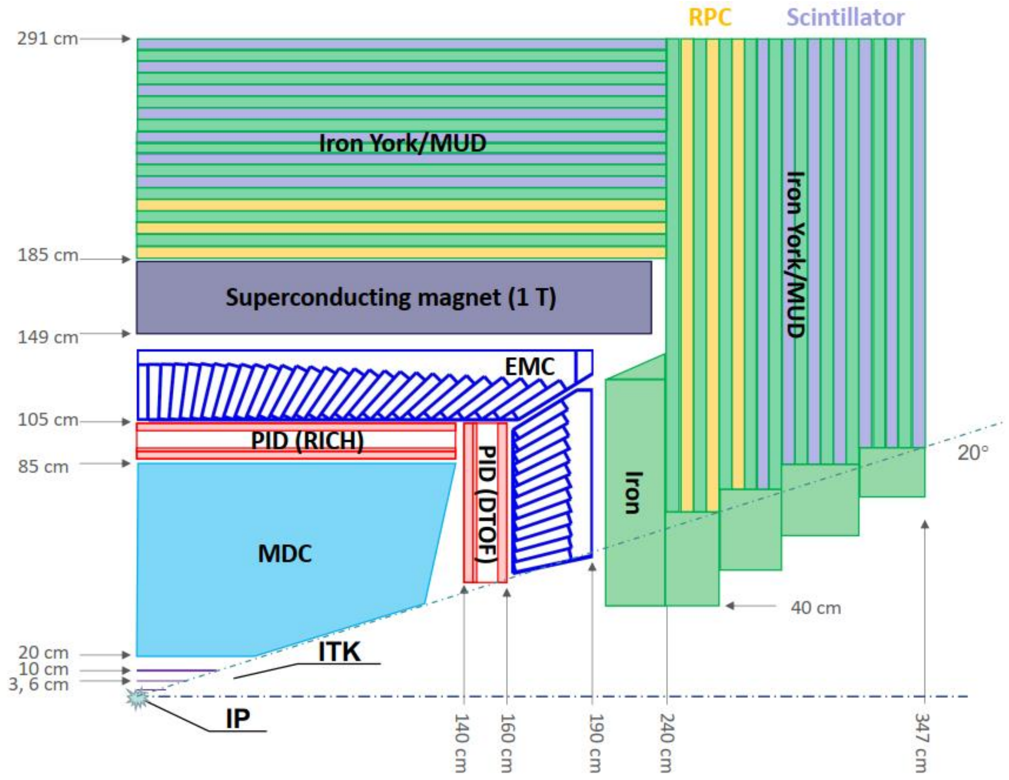


STCF detector









Requirement:

- High detection efficiency and good resolution
- Superior PID ability
- Tolerance to high rate/background environment

ITK

<0.25%X0 / layer

σ_{xy}< 100 μm

MDC

σ_{xy}< 130 μm

$\sigma p/p$ ~ 0.5% @ 1 GeV

PID

π/K (and K/p) 3-4σ separation up to 2GeV/c

EMC

E range: 0.025-3.5 GeV

σ_E @ 1 GeV: 2 .5% in barrel, 4% at endcaps

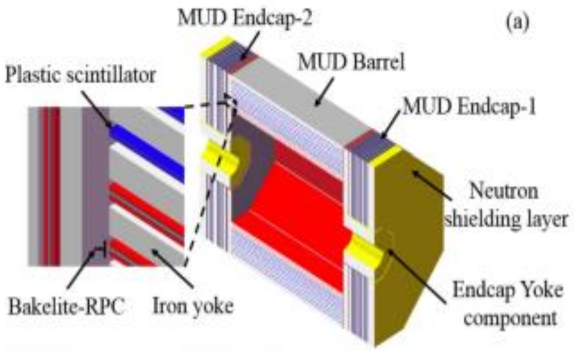
Pos. Res. : ~ 4 mm

MUD

0.4 - 1.8 GeV

π suppression >30

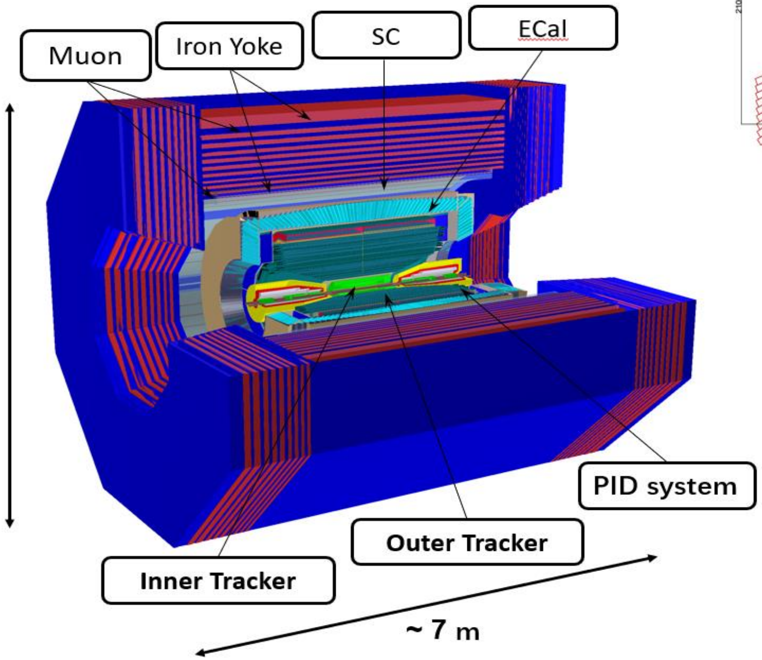
STCF Detector Conceptual Design

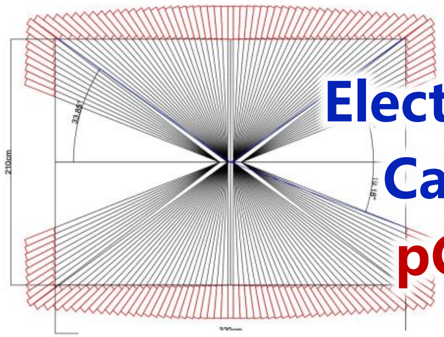


Muon Detector

Resistive Plate Chamber+

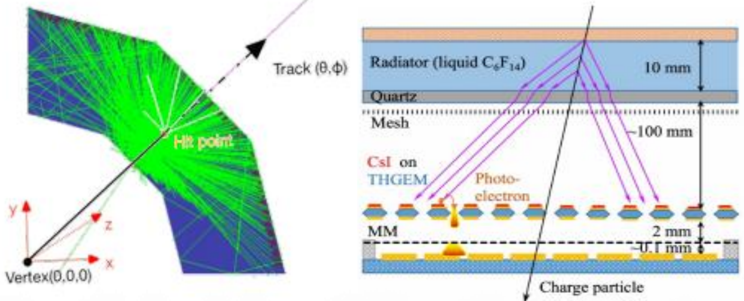
Plastic scintillator





Electromagnetic Calorimeter

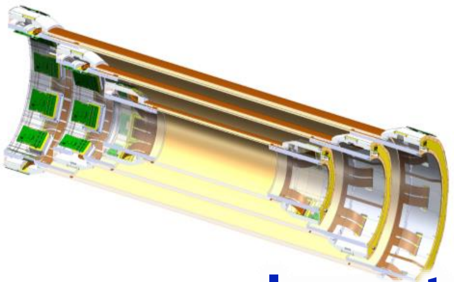
pCsI +APD

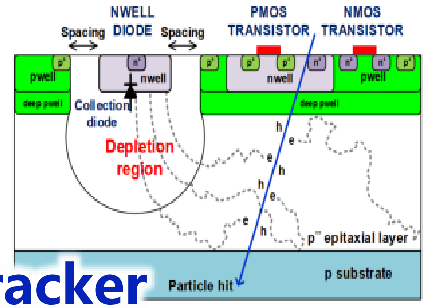


Particle Identification System

Barrel：RICH-like

Endcap：DIRC-like

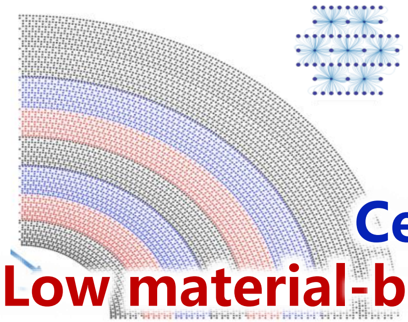




Inner tracker

μRWELL Detector

CMOS MAPS

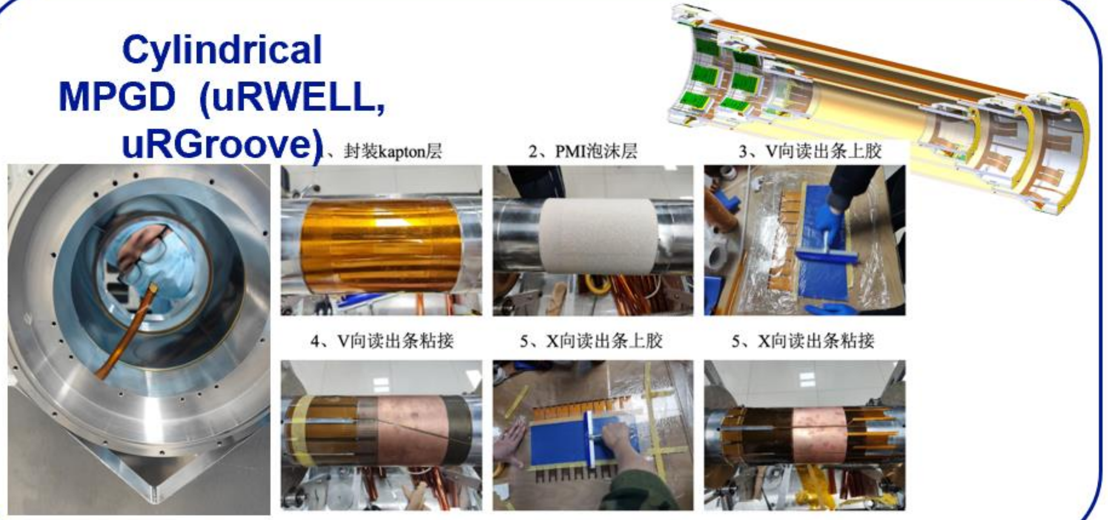


Central Tracker

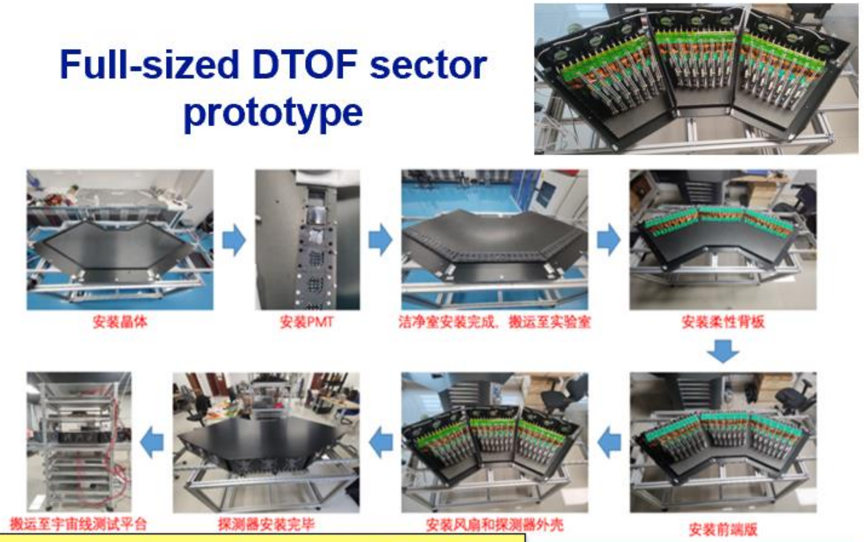
Low material-budget Main Drift Chamber

STCF Detector R&D — Detector Prototypes

Cylindrical MPGD (uRWELL, uRGroove)

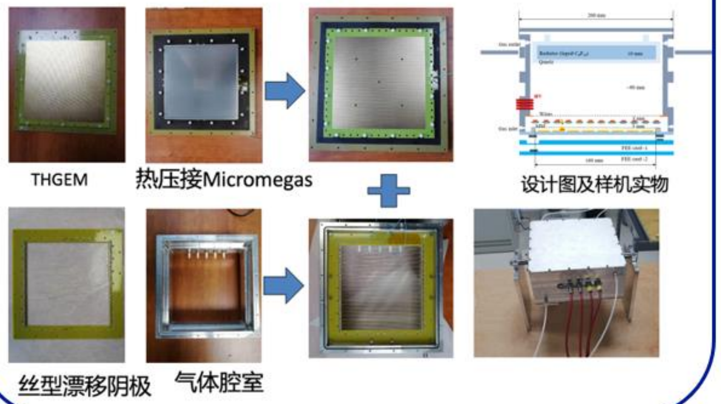


Full-sized DTOF sector prototype

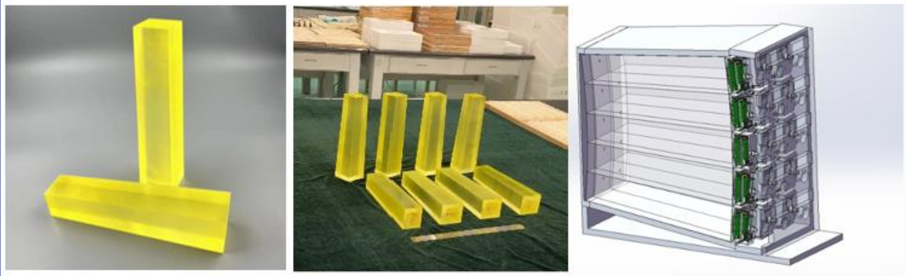


ECal, RICH, DTOF and DAQ beam test scheduled at CERN

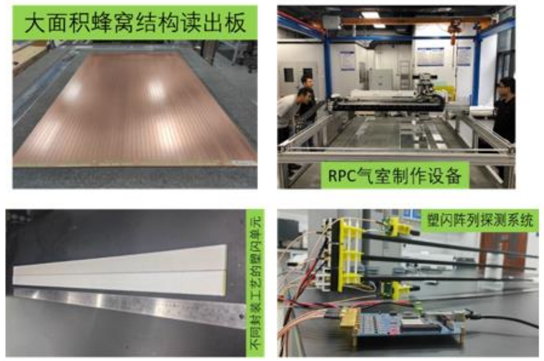
30 cm × 30 cm RICH prototype



pCsI ECAL

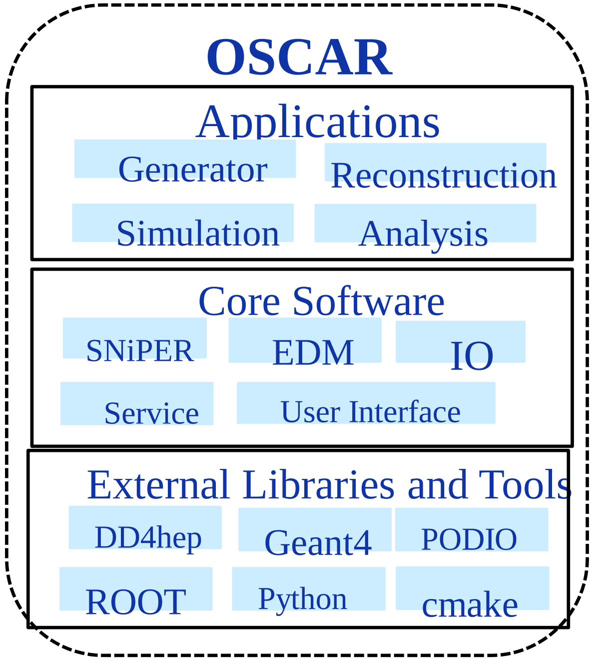


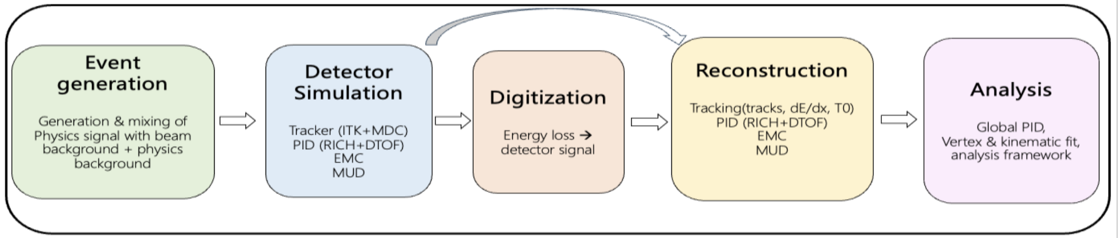
Large sized RPC and scintillator strips

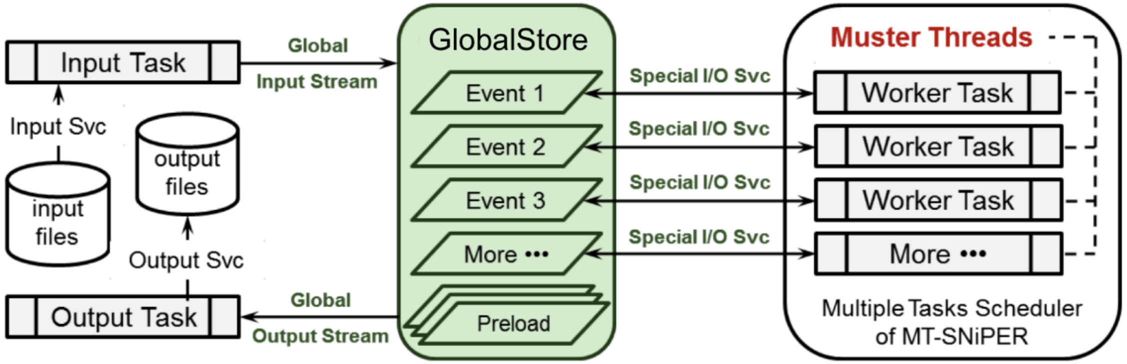


Offline Software

- Offline Software System of Super Tau-Charm Facility (OSCAR)
  - External Interface+ Framework +Offline
- SNiPER framework provides common functionalities for whole data processing
- Offline including Generator, Simulation, Calibration, Reconstruction and Analysis



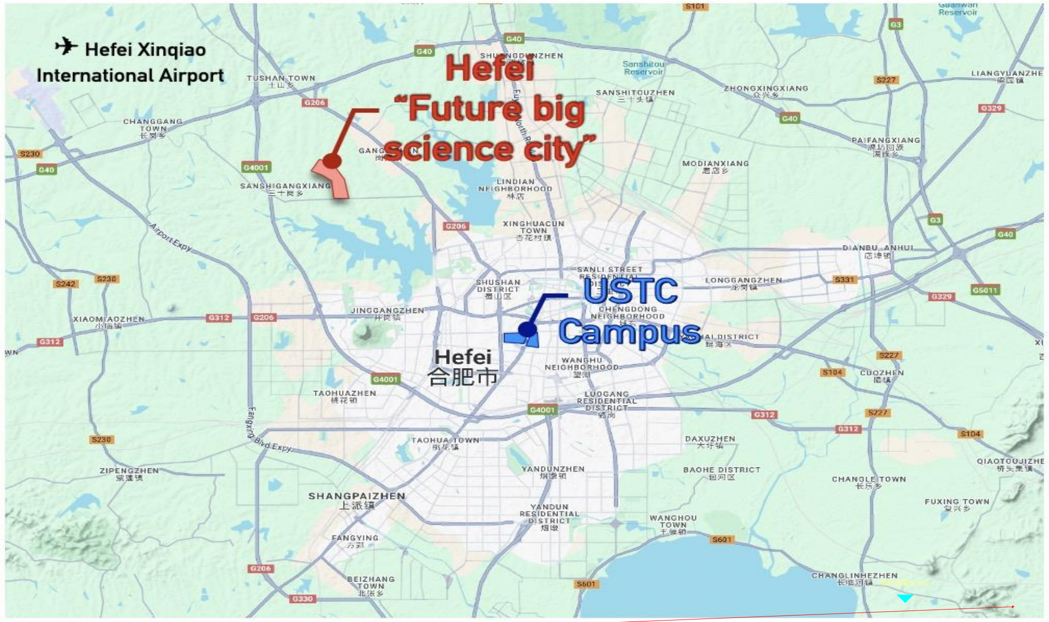


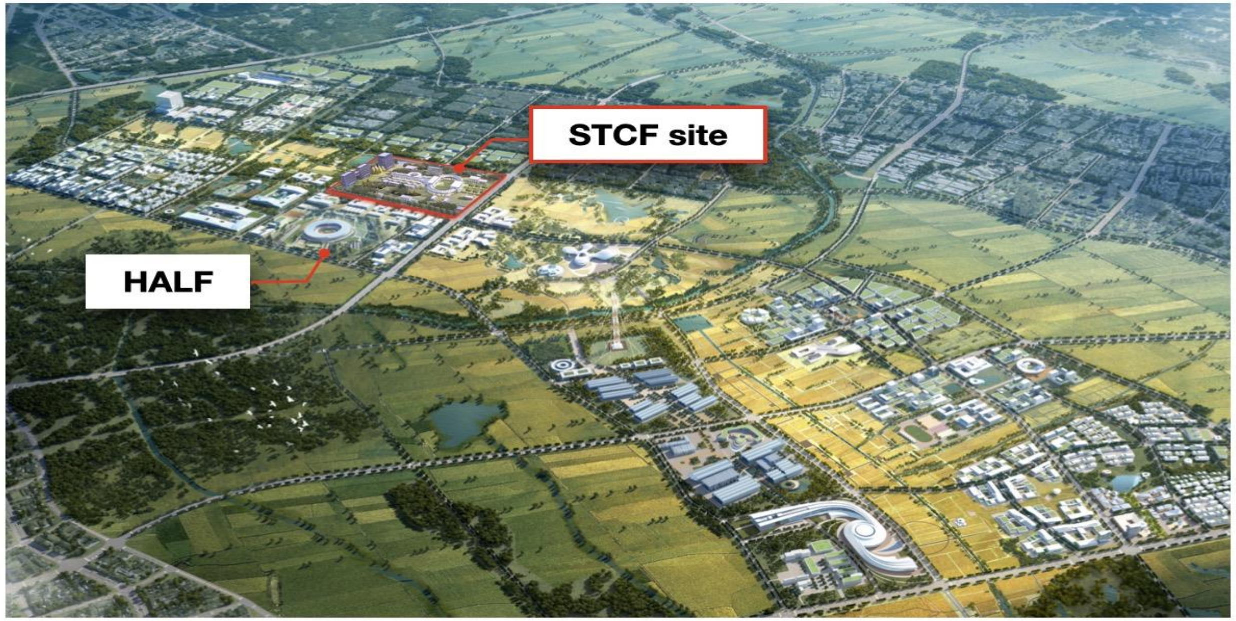


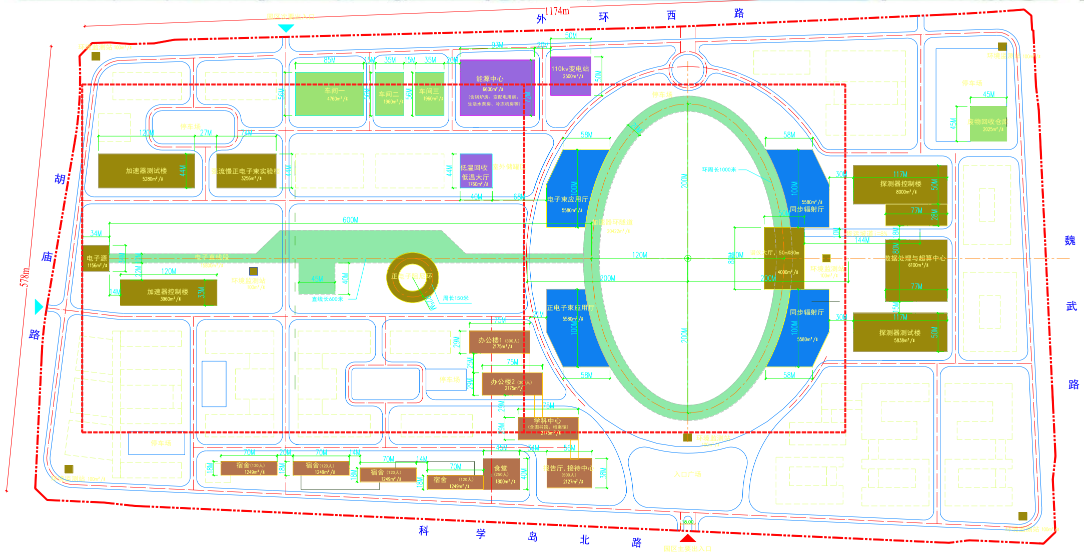
W.H. Huang et al 2023 JINST 18 P03004

- Full simulation under OSCAR is undergoing: $e^+e^- \to \pi^+\pi^- J/\psi$, $\Lambda\bar{\Lambda}$, $\pi\pi/K\pi/KK+X$, $D^0\bar{D}^0$...

Site of STCF : Hefei

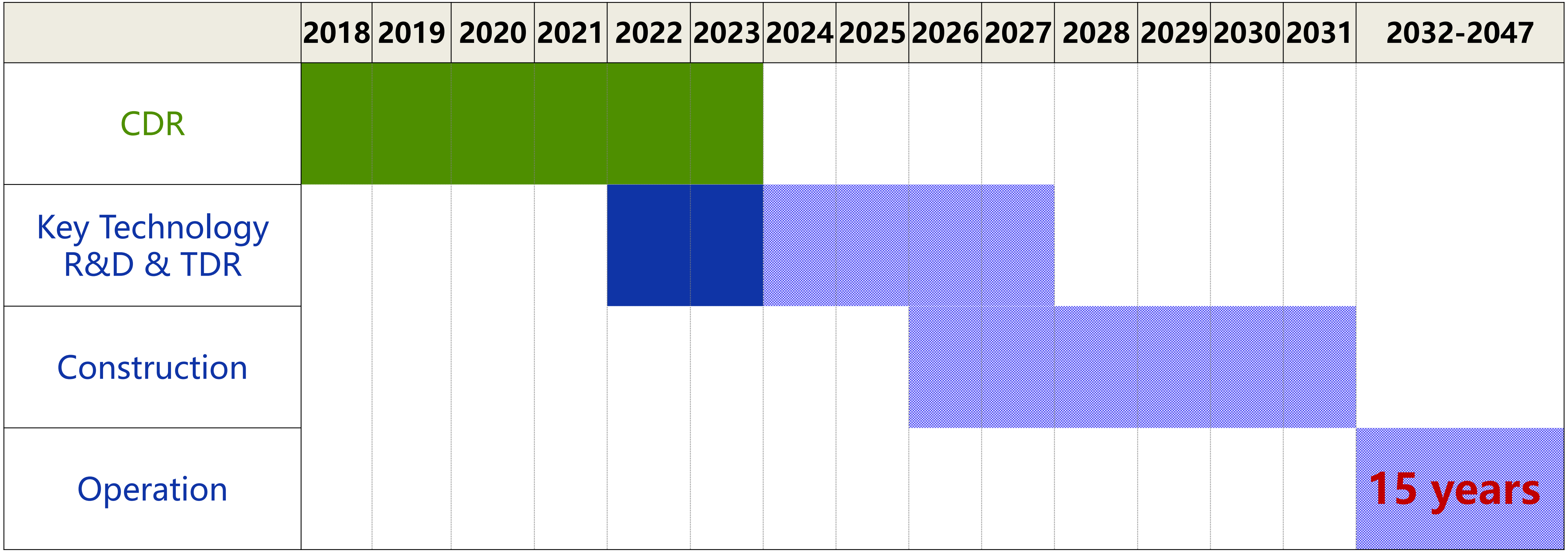






- **Funded R&D**: 0.4 Billion CNY funded by the Anhui government
- Construction budget: 4.5 Billion CNY

Tentative Project Schedule for STCF



Summary

- STCF covers a unique transition region between perturbative and non-perturbative QCD, providing precision measurements aimed at answering key questions in QCD and search for new physics BSM
- STCF will utilized and challenge key technologies accelerator, particle detection and data processing, computing and networking
- Anhui province and USTC have committed support, aiming for applying construction approval during the 15th five-year plan (2026-2030)
- International collaboration is crucial, with ongoing efforts to expand collaborations both domestically and internationally

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/

Thanks for your listening!