河南師範大學
HENAN NORMAL UNIVERSITY

超级陶粲装置
Super Tau-Charm Facility

Flavor physics at STCF

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Henan Normal University

(On behalf of the STCF physics group)

Oct. 27, 2025

HFCPV2025 第二十二届全国重味物理和CP破坏研讨会
THE 22nd NATIONAL SYMPOSIUM ON HEAVY FLAVOR PHYSICS AND CP VIOLATION

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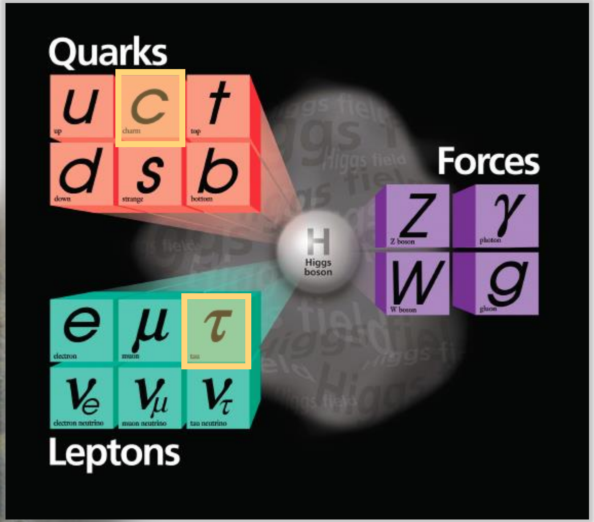
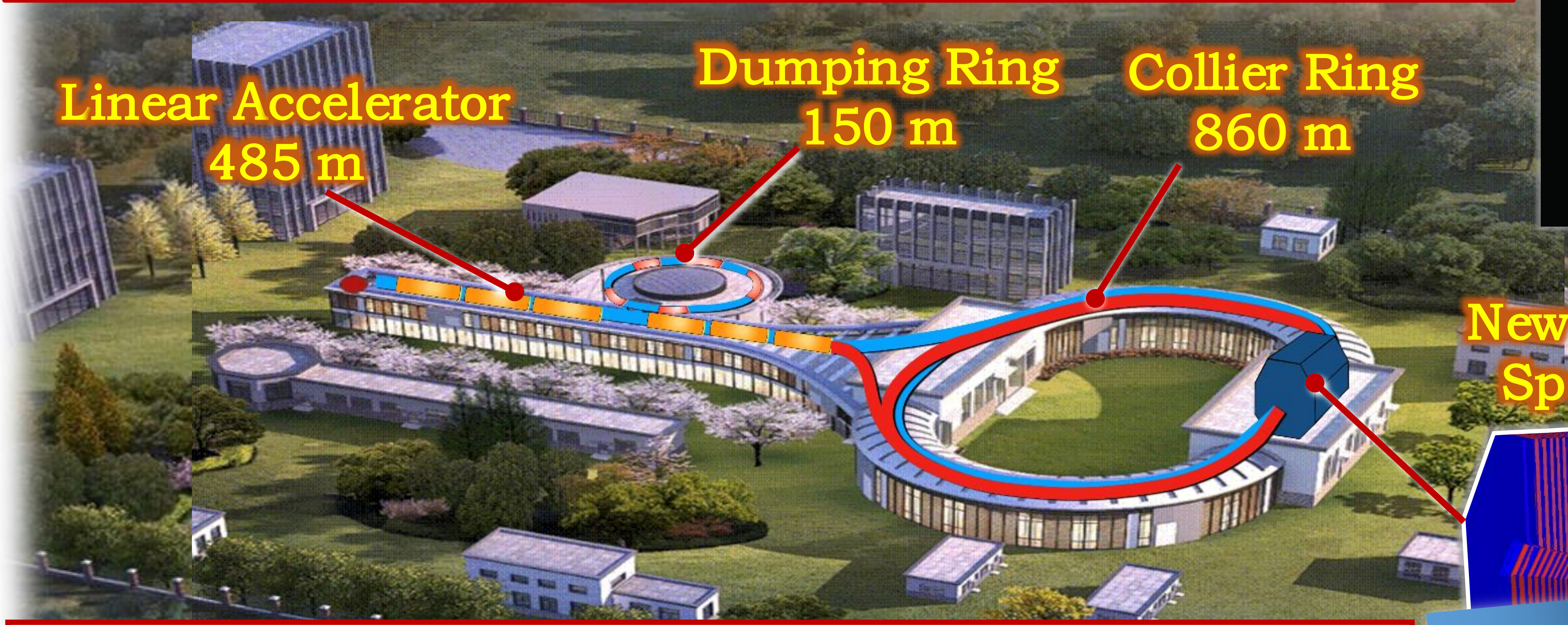
Outline

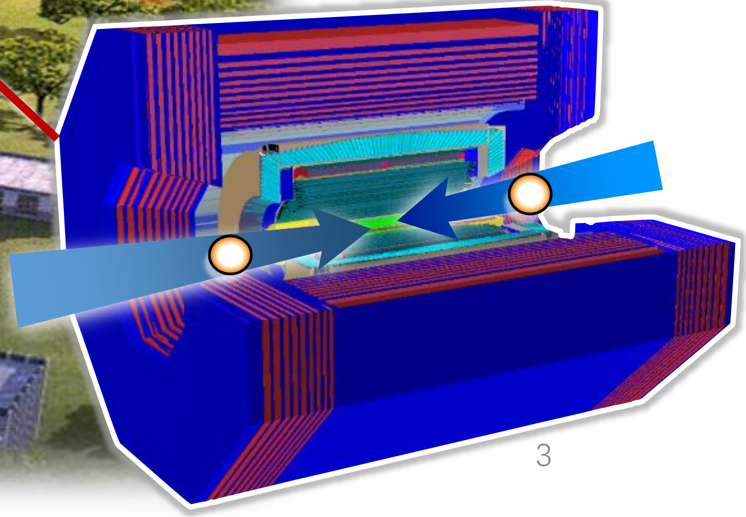
- STCF Physics Overview
- Full-simulation Physics Studies
- Summary and Outlook

Super Tau Charm Facility (STCF)

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

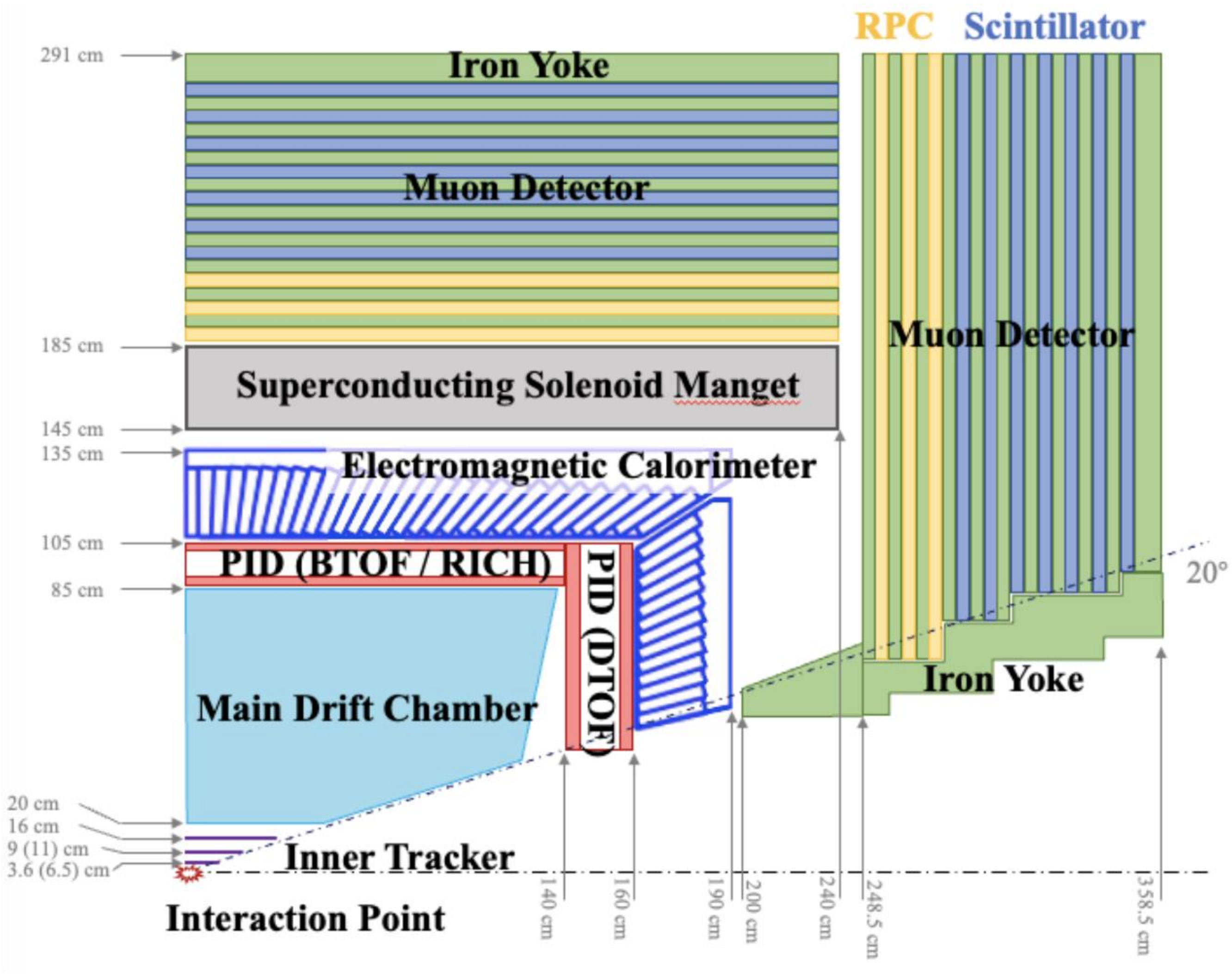






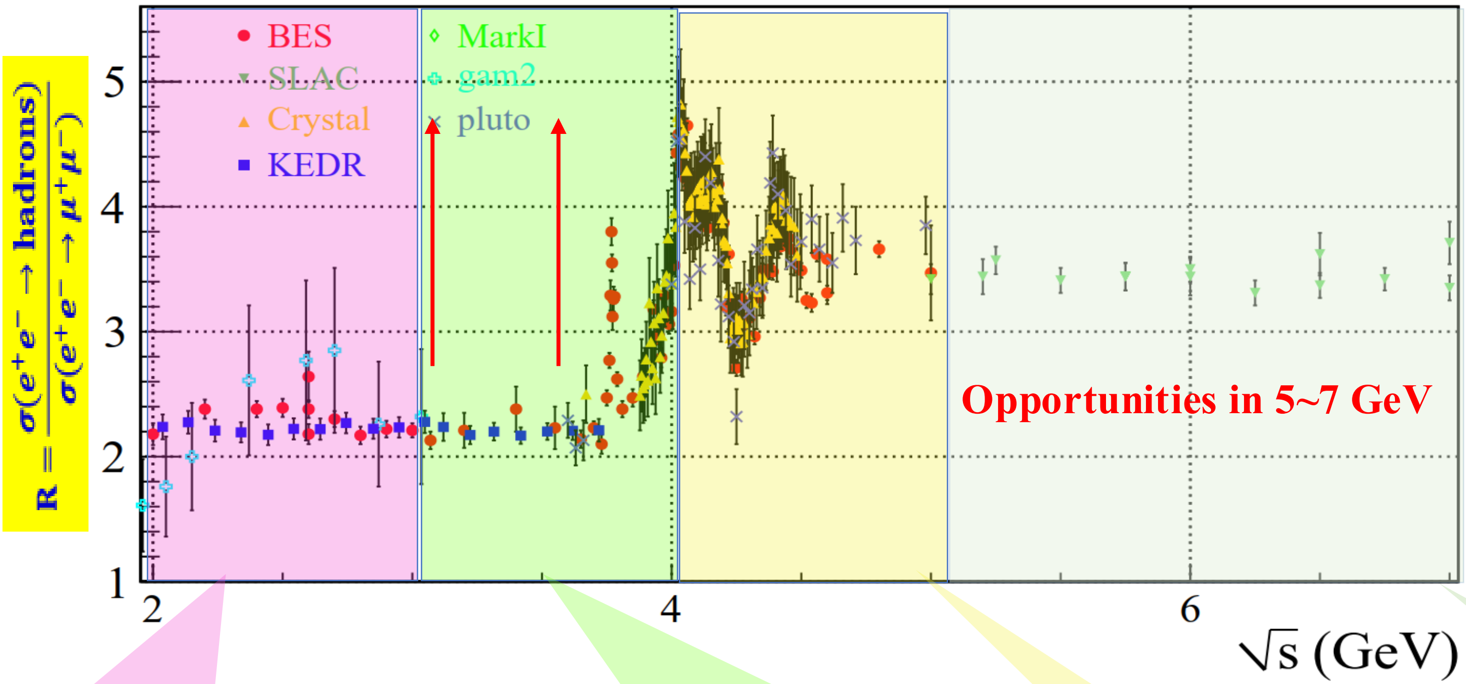
- E_{cm}= 2-7 GeV， $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}
- Potential for upgrade to **increase luminosity** and realize **polarized beam.**

STCF Detector



- ITK: Inner Tracker
  - ITKW: cylindrical MPGD
  - ITKM: CMOS M-MAPS
- MDC: Main Drift Chamber, Central tracker
  - π^+/π^- track Reconstruction
- PIDE: Particle Identification-Endcap
  - DTOF: DIRC-like TOF
  - PIDB: Particle Identification-Barrel
  - RICH: Ring Imaging Cherenkov detectors CsI-MPGD
  - BTOF: Barrel-TOF
  - π^+/π^- Identificaton
- ECAL(EMC): Electromagnetic Calorimeter pure CsI + APD
  - π^0 Reconstruction
- MUD: Muon Detector RPC + scintillator

Physics at the Tau-Charm Energy Region



Unique Features in tau-charm region:

- **Transition** region between perturbative and non-perturbative QCD.
- **Threshold effects and quantum correlation** of pair production of hadrons and tau leptons.
- **Rich resonance** structures, **large production cross section** 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

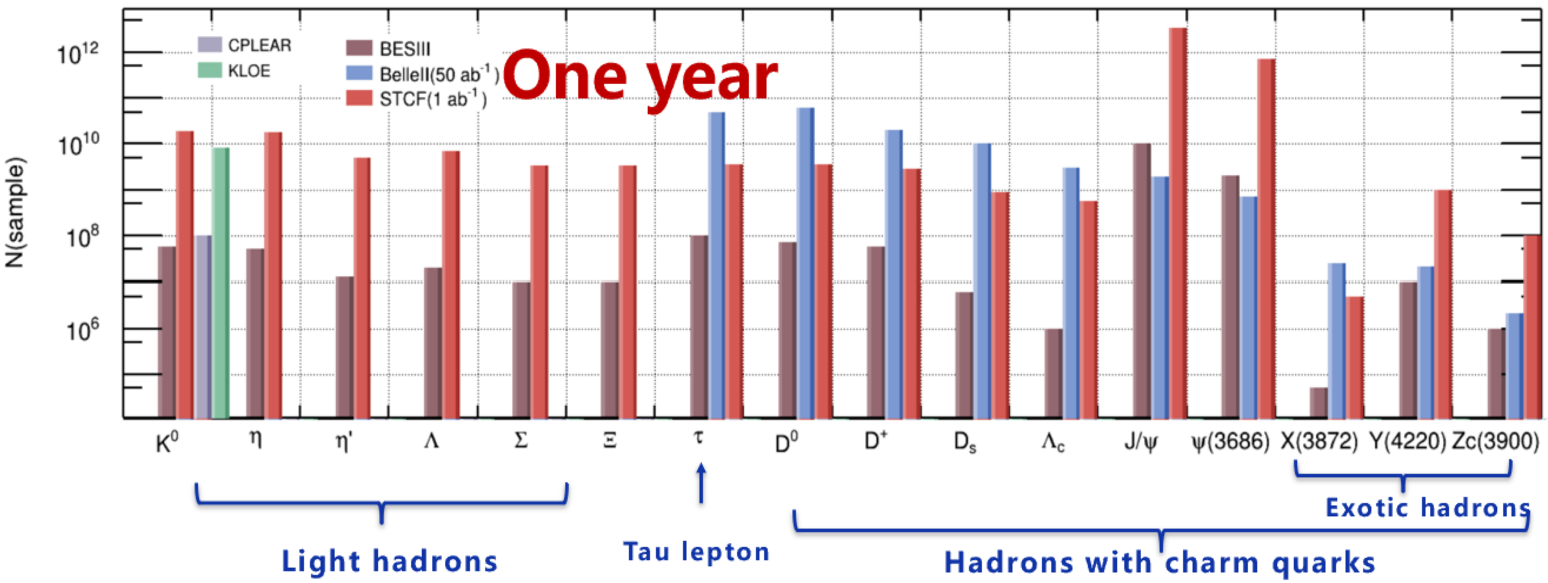
- *XYZ* particles
- Physics with D mesons
- f_D and f_{D_s}
- $D^0 - \bar{D}^0$ mixing
- Charm baryons

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

Physics Flagships & Expected Data Production

- Three-fold physics flagships:

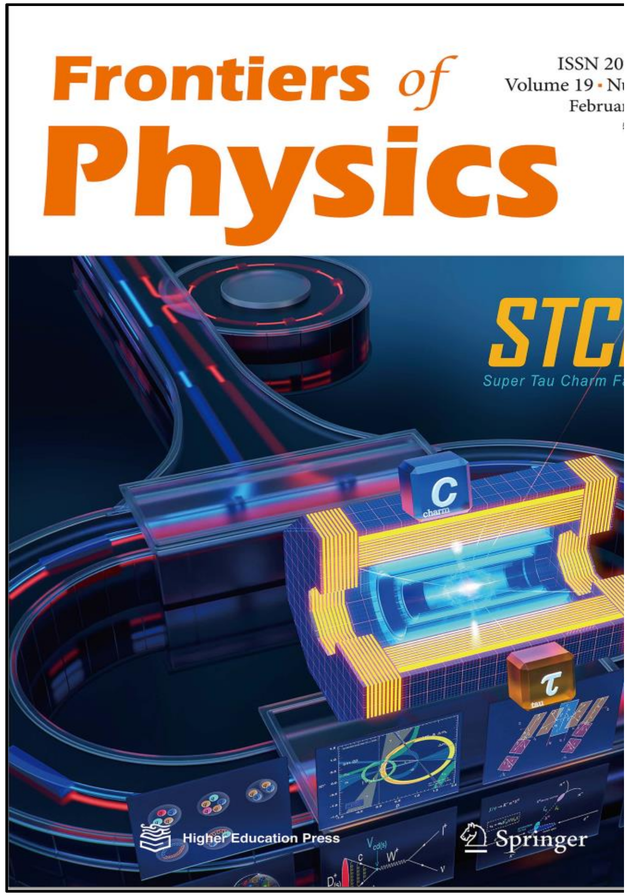
Tests of fundamental Symmetries	Exploring QCD nature and confinement	Precision Measurement of Fundamental Physical Parameters
• CP : Hyperons, tau, EDM • CPV : $K^0 - \overline{K}^0$ system • CLFV : Tau, meson decays	• Hadron Spectroscopy • Nuclear Structure • Fragmentation function	• R-Value, Tau mass • Running of fine structure constant $\Delta\alpha_{em}$ • CKM elements



- About 1 ab^{-1} integrated luminosity at STCF per year.
- STCF shows superior statistics and purity compare to other experiments.
- The physics sensitivity studies are based on, but not limited to, data samples of these size.

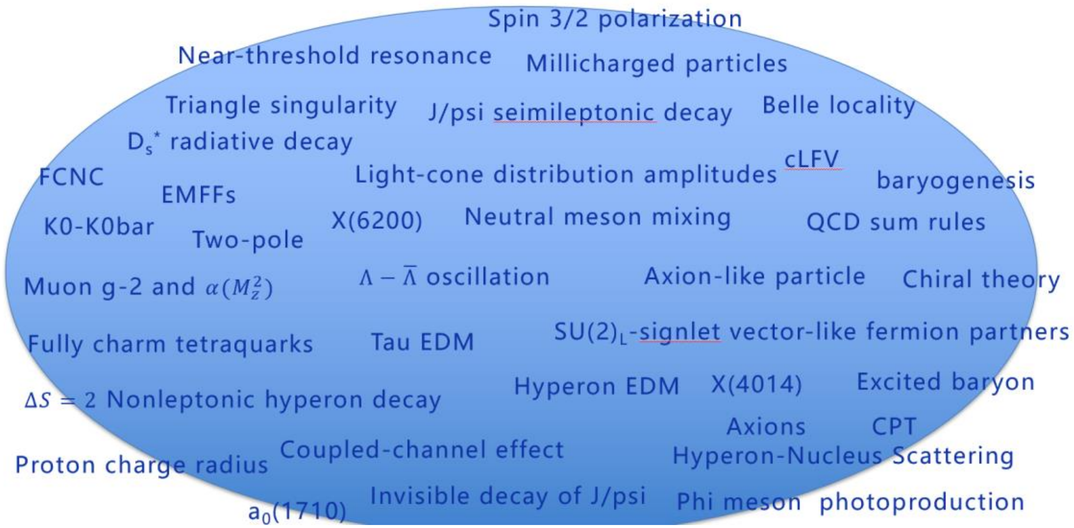
Physics Program at STCF

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



Contents

Rich physics potential beyond the CDR content



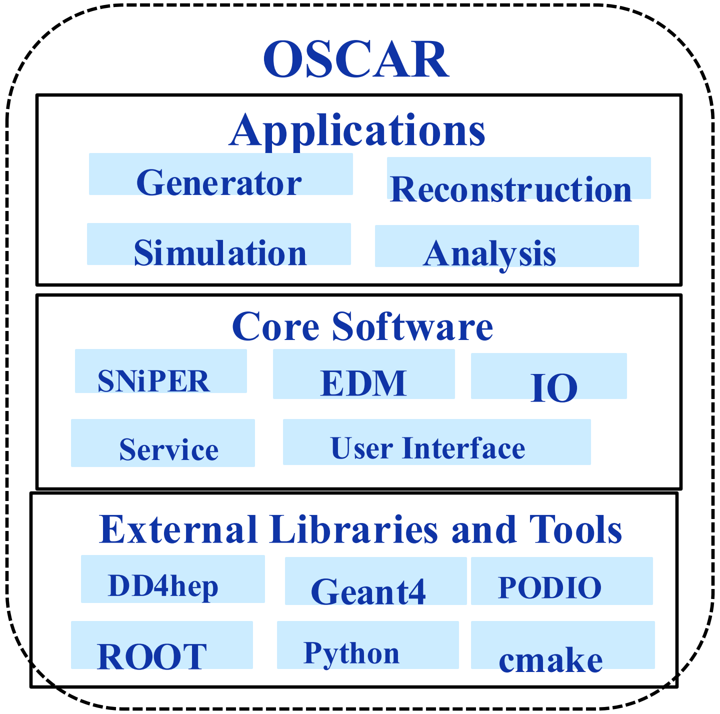
Expected Sensitivities

Physics goal	Observable	BESIII	Current world best	STCF prospect(1 ab^{-1})
Fundamental Symmetry	A_{CP} in hyperon decay	0.005	0.005	$\mathcal{O}(10^{-4})$
	weak phase in hyperon decay	1.2°	1.2°	0.04°
	Δ_{CP} in tau decay	-	0.25%	$\mathcal{O}(10^{-3})$
	EDM of hyperon	-	$\mathcal{O}(10^{-16})$ ecm	$\mathcal{O}(10^{-21})$ ecm
	EDM of tau	-	$\mathcal{O}(10^{-17})$ ecm	$\mathcal{O}(10^{-18})$ ecm
	cLFV in $\tau \to \mu\mu\mu$	-	2.1×10^{-8}	$\mathcal{O}(10^{-9})$
	cLFV in $J/\psi \to e\mu$	4.5×10^{-9}	4.5×10^{-9}	$\mathcal{O}(10^{-11})$
	cLFV in $J/\psi \to e\tau$	7.5×10^{-8}	7.5×10^{-8}	$\mathcal{O}(10^{-10})$
Quark Confinement	$N_{Y(4260)/Z_c/X(3872)}$	$10^7/10^6/10^4$	$10^6/10^5/10^6$	$10^9/10^8/10^6$
	Pentaquarks	-	P_cs in $J/\psi p(\Lambda)$	$\sigma_{J/\psi p\bar{p}} \simeq 4$ fb
	Di-charmonium	-	di-ψ	$\sigma_{J/\psi c\bar{c}} \simeq 10$ fb
	$N_{J/\psi/\psi(3686)}$	$10^{10}/10^9$	$10^{10}/10^9$	$10^{12}/10^{11}$
	Collins effects	0.3	0.3	$\mathcal{O}(10^{-3})$
	Baryon form factors	10%	10%	$\mathcal{O}(10^{-2})$
Physical Quantities	R value	3%	3%	$\mathcal{O}(10^{-3})$
	tau mass	160 keV	120 keV	$\mathcal{O}(10)$ keV
	$\lvert V_{us}\rvert$	-	1%	$\mathcal{O}(10^{-3})$
	$\lvert V_{cd}\rvert$	1.2%	1%	$\mathcal{O}(10^{-3})$
	$\lvert V_{cs}\rvert$	1.4%	1.4%	$\mathcal{O}(10^{-3})$
	Sys. unc. of γ from D decay	0.4°	0.4°	0.1°
	α_s	-	1.5%	$\mathcal{O}(10^{-3})$

- **Based on Fast simulation**
- **Next task, conduct full-simulation for these physics processes and writing TDR.**

Full Software Chain for STCF

- 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



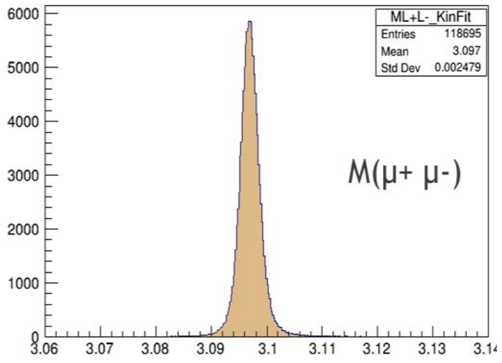
Detectors	Simulation	Digitization	Reconstruction	Analysis tools		
				Global PID	Traditional combined PID	Kinematic & Vertex Fit
ITK	✅	✓	✅	Charged tracks: ✅ Neutral tracks: 🟠	✓	✅
MDC	✅	✓				
RICH	✅	✅	✅			
DTOF	✅	✅	✅			
BTOF	✅	✅	✓			
EMC	✅	✅	✅			
MUD	✅	✅	✓			

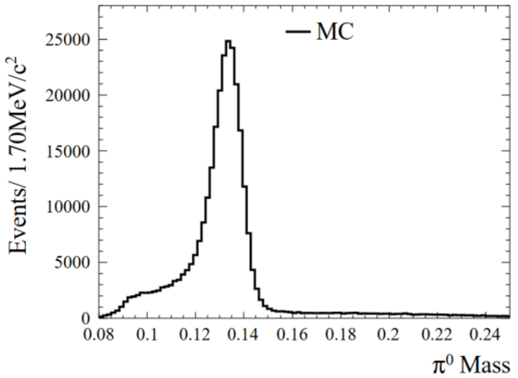
✅ Good state
✓ Under optimization
🟠 Under development

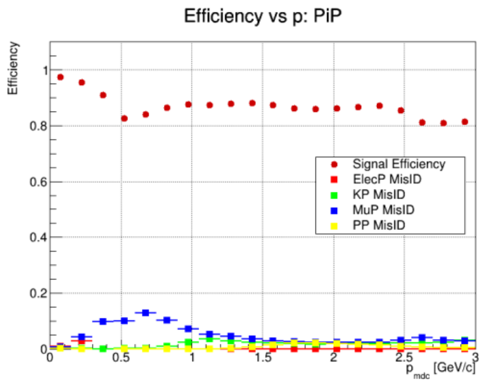
W.H. Huang et al 2023 JINST 18 P03004

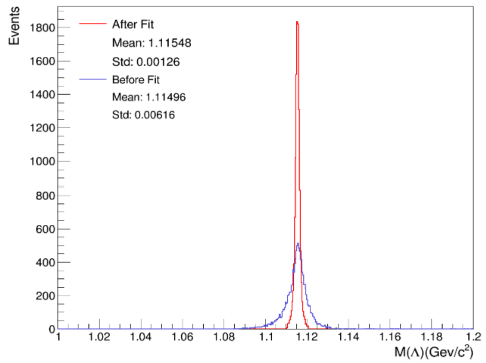
Physics Full-simulation

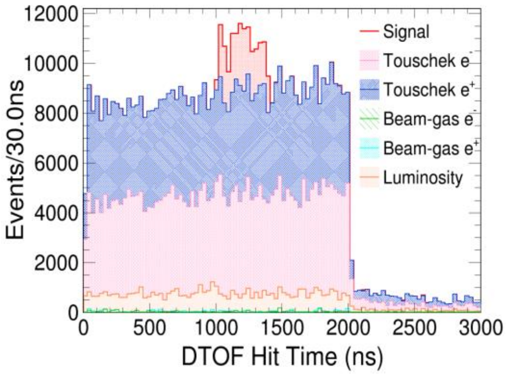
- **Testing of OSCAR full-simulation chain**







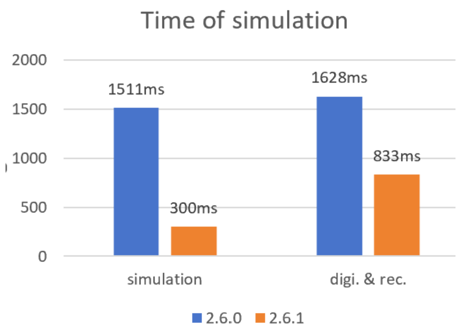


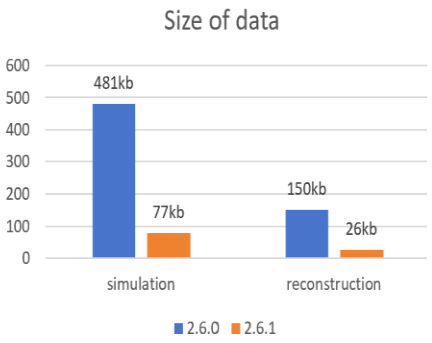


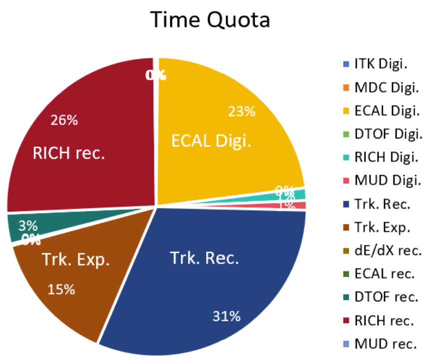
✓ **Tracking** ✓ **Neutral** ✓ **Global PID** ✓ **Kinematic fit** ✓ **Background**

- **Generators in OSCAR**
  - Babayaga (bhabha, dimu, digam), Phokhara, Conexc (ISR)
  - Madgraph + Pythia (ditau)
  - Ekhara, Diag36, Gluga (two-photon)
  - KKMC + EvtGen (charmonium decay)
  - LundArlw, Pythia (qqbar)

- **Computing optimization**

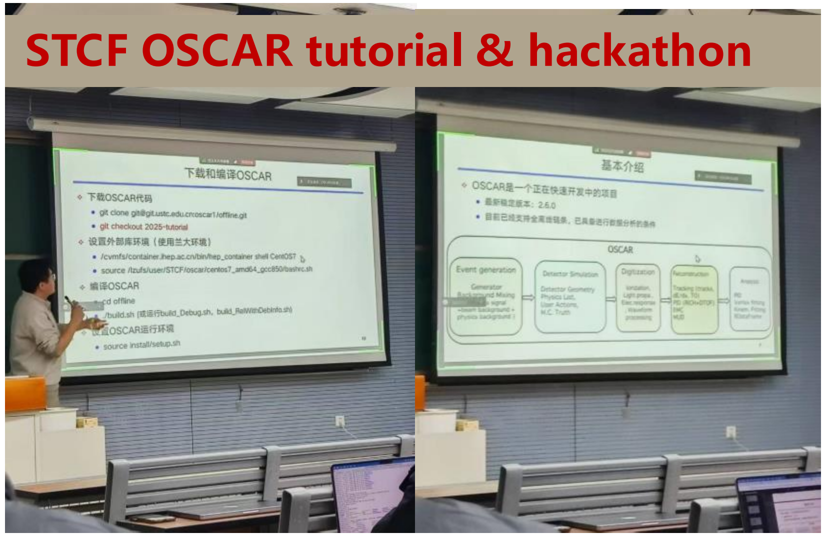






Full Software Chain for STCF

- With the refinement of OSCAR framework, full simulation for more physics processes can be performed
  - Jan. 21, 2025: kick-out of OSCAR full simulation, three physics working groups formed
  - Feb.21-23,2025: STCF OSCAR tutorial & hackathon, about 20 analysis underway
  - May-June, 2025: summarized the results, preparing the TDR drafting for physics performance
  - End of this year: Finish the preliminary version of TDR



June 2025

- Jun 04 tau physics weekly discussion NEW

May 2025

- May 28 tau physics weekly discussion
- May 26 STCFWG1-Precision test of fundamental symmetries
- May 21 tau physics weekly discussion
- May 19 STCFWG1-Precision test of fundamental symmetries
- May 14 tau physics weekly discussion
- May 12 STCFWG1-Precision test of fundamental symmetries
- May 07 tau physics weekly discussion

Physics -- Physics/Simulation Meeting	
Physics -- Symmetry	
Physics -- Confinement	
Physics -- SM parameters	12 events

February 2025

- Feb 21 - Feb 23 STCF Oscar tutorial & hackathon

WG1: Fundamental Symmetries

WG1 Conveners: 张宇 (南华大学), 刘明依(中科大)

Physics goal	Processes	Contributors
Baryon CPV and EDM	$J/\psi \to \Lambda\bar{\Lambda}$	于明玉 (山大), 张剑宇 (国科大)
	$J/\psi \to \Xi^{+}\bar{\Xi}^{-}$	徐月 (复旦大学)
τ physics (QE, EDM, rare decay)	$\tau \to \pi(\pi\pi^{0})\nu$	鲍晨涛 (浙大)， 刘明依 (中科大)
	$\tau \to 3\mu$	李睿翔 (中科大)
	Radiative decay	李昊霖 (郑大)
	τ EDM	李晓康（北大)
Charm mixing, strong phase	C-even correlated $D\bar{D}$	王英豪 (兰大)，兰强 (南华大学)
	$D^{*}_{(s)} \to \gamma/\pi^{0}+D^{0}_{(s)}$	
CPV in Λ_c^{+} decays	$\Lambda K^{+}, \Sigma^{0}K^{+}, \Sigma^{+}K^{0}_{S}$	王泓鉴(兰大)
CP and CPT in $K^{0}_{S} \to \pi^{+}\pi^{-}$ decay	$J/\psi \to K^{0}_{S}K\pi$	张慧斌 (国科大)
CLFV decay	$J/\psi \to \gamma l l'$	陶智博 (吉大)
	$D^{0} \to \bar{\Lambda} + ALP$	唐馨茹(南华大学)

WG2: Quark Confinement

WG2 Conveners: 耿聪 (中大), 罗涛 (复旦大学), 康晓珅 (辽大)

Topic	Processes	Contributors
Charmonium-like, tetra- and penta-quarks	$X(3872)$	
	$e^+e^- \to \pi Z_c(3900)$	周杭 (中科大)
	$e^+e^- \to P_c\bar{p} \to J/\psi p\bar{p}$	董焯娟 (中大)
	$e^+e^- \to J/\psi\eta_c$	陈梓康 (中大)
Collins FFs	$e^+e^- \to KK, \pi\pi, K\pi$	翟云聪 (山大)
Hadron EMFFs	$e^+e^- \to p\bar{p}$	田文辉 (中大)
Form factors in hyperon decay	$J/\psi \to e^+e^-\pi^0/\eta$	Vindhyawasini Prasad (吉大)
	$\Sigma^+ \to \gamma p$	宋勇 (中科大)
	$\Lambda \to pe\nu$	周俊贤 (复旦大学)
	$\Xi^- \to \Lambda e\nu$	韩许 (中科大)

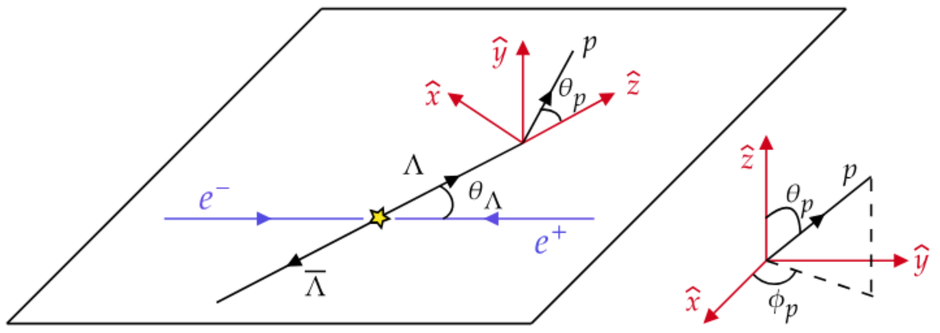
WG3: Physical Fundamental Parameters

WG3 Conveners: 康晓琳 (地大), 李惠静 (河南师大)

Topic	Simulated Process	Contributors
R scan	$e^+e^- \to hadrons$	
Two-photon physics	$\gamma\gamma \to hadrons$	王杰 (地大)
	$\eta_c \to \gamma\gamma$	景新媚 (国科大)
Tau mass	$e^+e^- \to \tau^+\tau^-$ near threshold	宋海林 (中科大)
CKM matrix	$D \to \pi\mu\nu$	黄清源 (国科大)
	$D \to \mu\nu$	乔佳辉 (河南师大)
	$D \to inclusive$	粟佳元, 刘弘锐 (华科)
	$\tau \to K\nu$	
Strong phase	$D^0 \to K^-\pi^+\pi^0$	王程 (兰大)
α_s	$e^+e^- \to \tau^+\tau^-, \tau \to l\nu\nu, \tau \to \pi\pi^0\nu_\tau$	李珊珊 (湖南大学)

Search for CPV and d_Λ in $J/\psi \to \Lambda\bar{\Lambda}$ decay

- **Angular distribution of hyperon production**



➢ Described by EM form factors $G_{1,2}$

$$\alpha_\psi = \frac{s^2|G_1|^2-4m^2|G_2|^2}{s^2|G_1|^2+4m^2|G_2|^2},\quad \frac{G_1}{G_2} = \left|\frac{G_1}{G_2}\right| e^{-i\Delta\Phi}$$

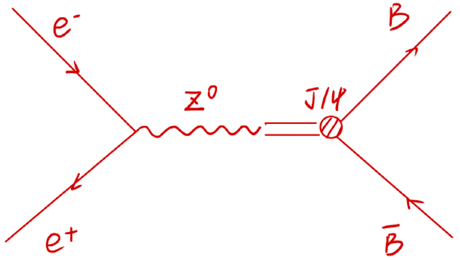
$$\boxed{\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta}$$

➢ Non-zero $\sin(\boldsymbol{\Delta\Phi})$ signatures hyperon polarization

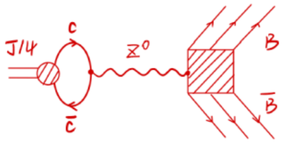
$$\boxed{P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}}$$

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

- ***P*, *CP* violating terms in J/ψ production and decay**
  - P_L: J/ψ longitudinal polarization induced by Z boson
  - F_A: P violating form factors
  - H_T: CP violating form factors associated with EDM

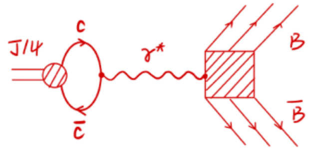


$$P_L = \frac{\rho_{++} - \rho_{--}}{\rho_{++} + \rho_{--}}$$



F_A : P violation term

Complex form factor, $F_A \neq 0$ indicate P violation



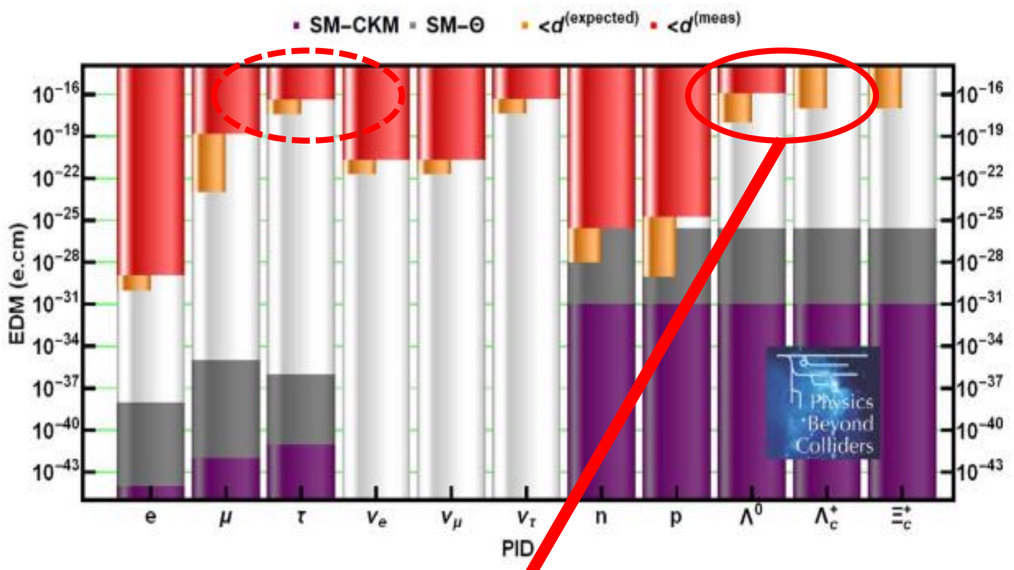
H_T: CP violation term

$$H_T(q^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
$d_B(0)$: electric dipole moment
Physics Letters B 551 (2003) 16–26

Search for CPV and d_Λ in $J/\psi \to \Lambda\bar{\Lambda}$ decay

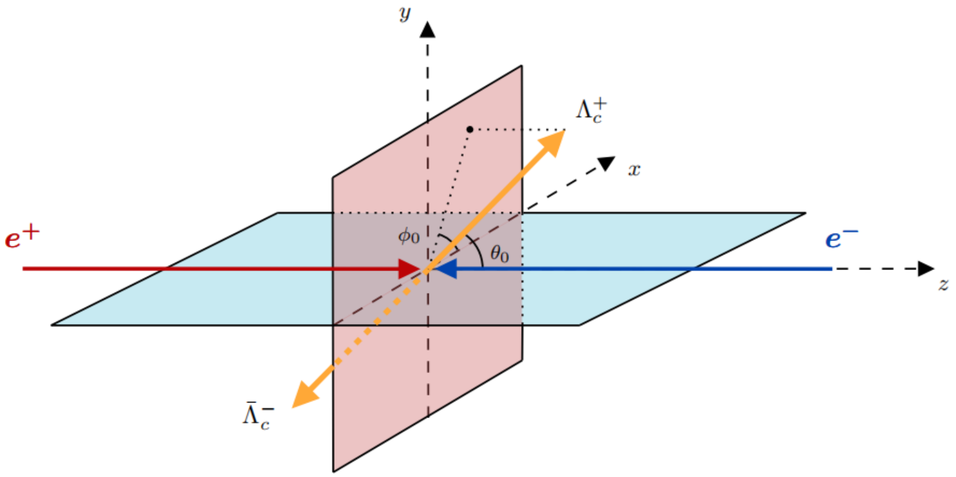


- EDM measurement only performed for Λ hyperon
- **d_Λ can be improved 10,000 in STCF**
- Search for EDM of the other strange and charmed baryons

- Based on OSCAR simulation, **statistical precision** improved by more than one order comparing to BESIII
- **Systematic uncertainty** dominated by **detector resolution effects**, could be improved by correcting resolution effect in MC with control samples, which is under study

Parameter	Stat.	BESIII Stat.	BESIII Sys.
$\alpha_{J/\psi}$	1.3×10^{-4}	2.2×10^{-3}	1.7×10^{-3}
$\Delta\Phi$	2.4×10^{-4}	4.2×10^{-3}	1.3×10^{-3}
A_{cp}	2.7×10^{-4}	4.6×10^{-3}	1.1×10^{-3}
$\sin W^2$	4.7×10^{-4}	1.2×10^{-3}	2.6×10^{-3}
$Re(d_\Lambda)$	1.9×10^{-20}	3.2×10^{-19}	0.5×10^{-19}
$Im(d_\Lambda)$	1.5×10^{-20}	2.6×10^{-19}	0.6×10^{-19}

Search for CPV in Λ_c^+ decays



- Λ_c^+ pair production in STCF
  - ✓ $\sqrt{s} = 4682$ MeV
- Signal channels:

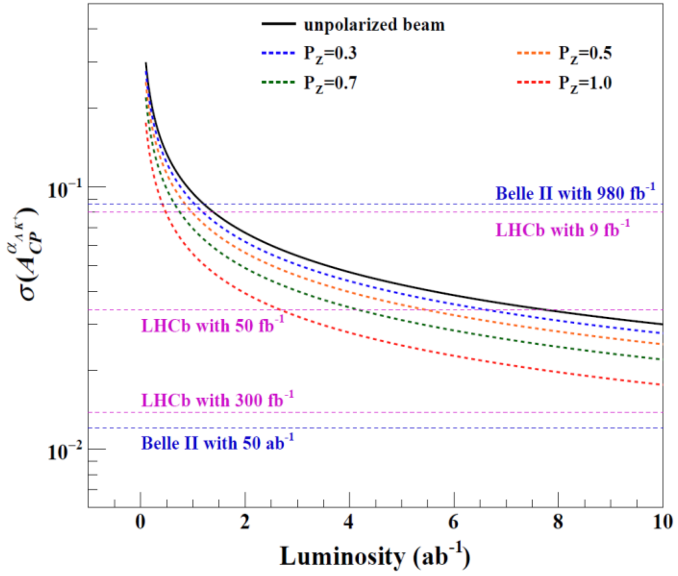
  $\Lambda K, \Sigma^0 K, \Sigma^+ K_S^0$
- MC simulation: OSCAR

$$A_{CP}^{\alpha} = \frac{\alpha_f - \bar{\alpha}_{\bar{f}}}{\alpha_f + \bar{\alpha}_{\bar{f}}} \propto -\tan\phi\tan\delta$$

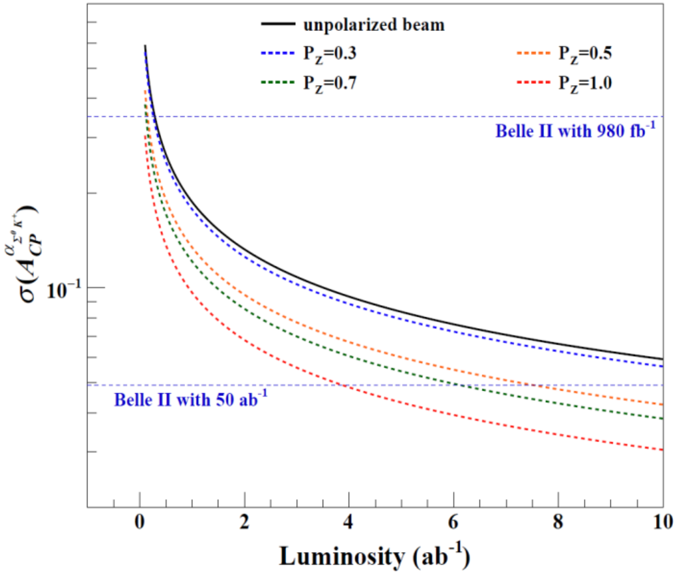
$$A_{CP}^{\beta} = \frac{\beta_f - \bar{\beta}_{\bar{f}}}{\beta_f + \bar{\beta}_{\bar{f}}} \propto \tan\phi/\tan\delta$$

ϕ is the CP-odd weak phase and δ the CP-even strong phase

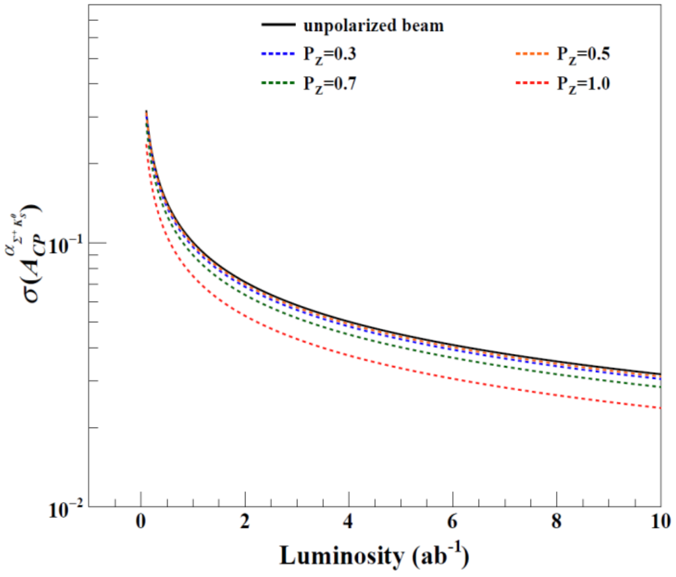
$A_{CP}^{\alpha\Lambda K}$



$A_{CP}^{\alpha\Sigma^0 K}$

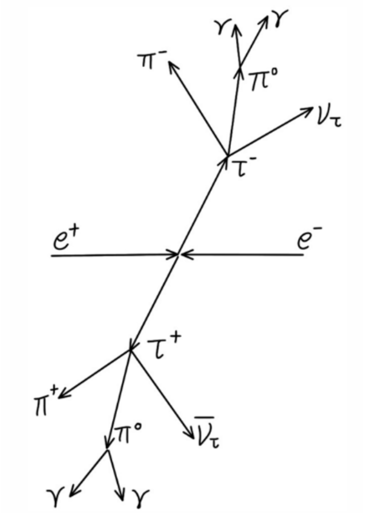


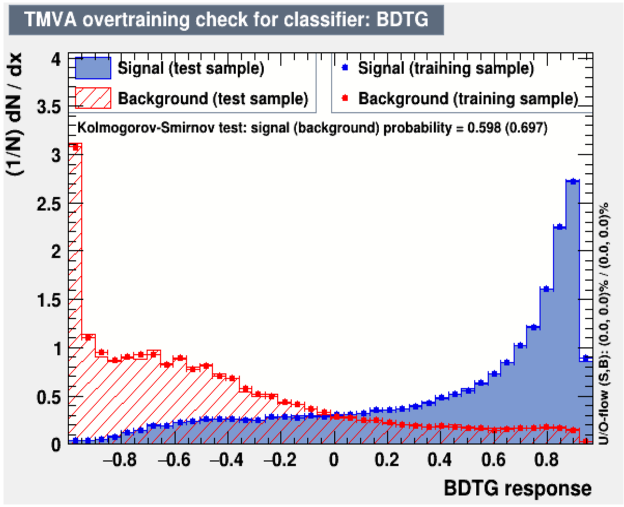
$A_{CP}^{\alpha\Sigma^+ K_S^0}$



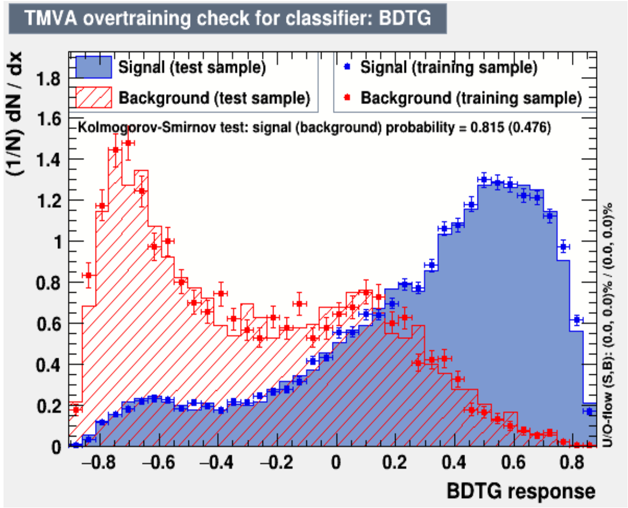
Search for d_τ in $e^+e^- \to \tau^+\tau^-$

- Signal channel: $\tau^+\tau^- \to \pi^+\pi^-\nu\bar{\nu},\ \rho^+\rho^-\bar{\nu}\nu$ at 4.26 GeV
- Finished Truth level, full OSCAR simulation is ongoing
- γ-level machine learning selection (select π^0 gamma from ISR)
- Event-level machine learning selection (select $\rho\rho$ from ρa)
- Overall efficiency: 0.37% , Signal efficiency: 4.9% , Signal purity: 91.2%

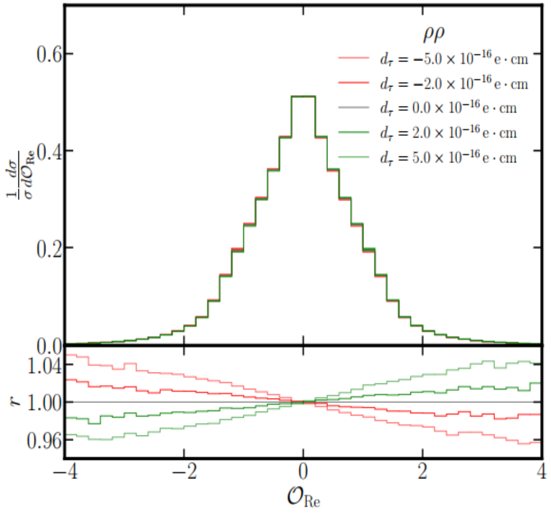


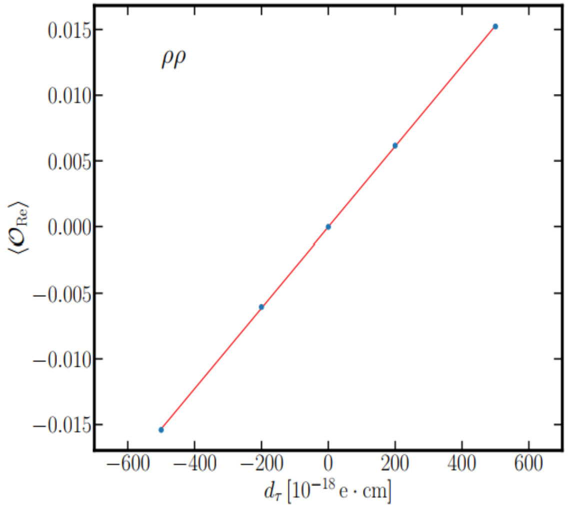


γ-level BDTG



Event-level BDTG

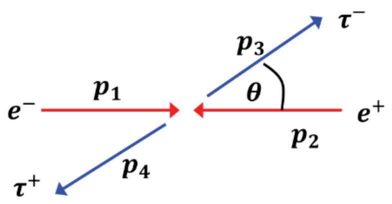


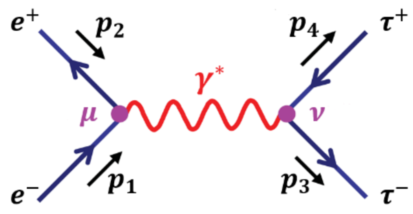


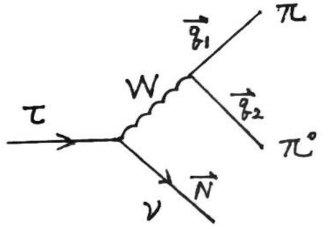
Quantum Entanglement in $e^+e^- \to \tau^+\tau^-$

- Tau pair production in STCF
  - ✓ Energy points: **4.26/6/7 GeV**
  - ✓ 1 ab^{-1}/year → ~10^9 tau pairs/year
- Signal channels: $\tau^+\tau^- \to \pi^+\pi^-/\pi^\pm\rho^\mp/\rho^+\rho^-\bar{\nu}\,\nu$
- MC simulation: aMC@NLO + Pythia8
  - Tau production and Tau decay
  - ISR, parton showering
- **Event selection ready**

- **Quantum state <u>tomography</u>: reconstruct the spin density matrix (SDM) based on decay products.**





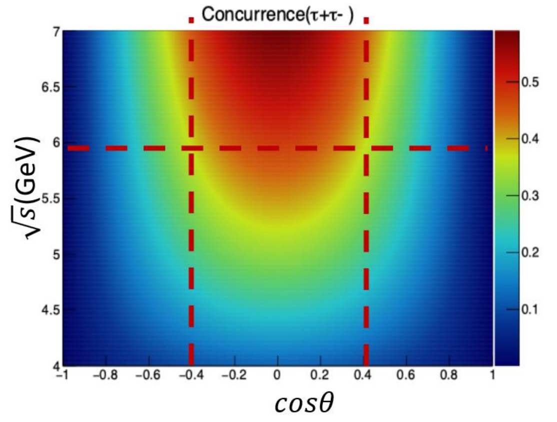


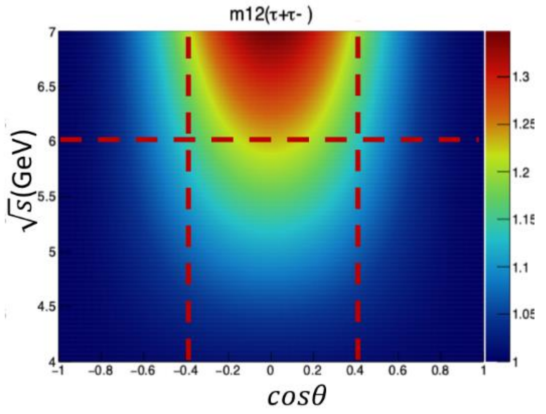
$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^+(\sigma_i \otimes \mathbf{1}_2) + \sum_{j=1}^{3} B_j^-(\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij}(\sigma_i \otimes \sigma_j)\right],$$

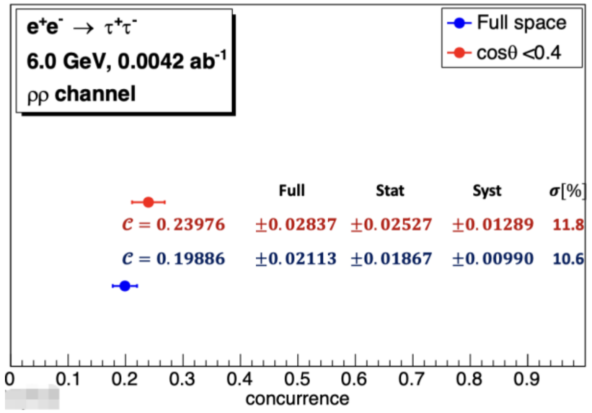
$$B_i^\pm = \frac{3}{\kappa_\pm}\frac{1}{\sigma}\int d\Omega^\pm \frac{d\sigma}{d\Omega^\pm}(\vec{n}^\pm \cdot \hat{e}_i), \qquad C_{ij} = \frac{9}{\kappa_+\kappa_-}\frac{1}{\sigma}\int d\Omega^+ d\Omega^- \frac{d\sigma}{d\Omega^+ d\Omega^-}(\vec{n}^+ \cdot \hat{e}_i)(\vec{n}^- \cdot \hat{e}_j)$$

- Reconstruct spin density matrix
  - Entanglement monotone: **Concurrence** $\mathcal{C}[\rho]$
  - Bell-inequality: optimized operator $m\mathbf{12}[\mathcal{C}]$

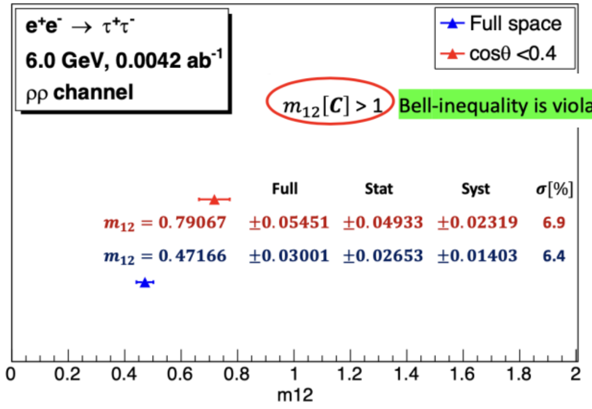
no entanglement $0 \le \mathcal{C}[\rho] = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\} \le 1$ maximally entangled





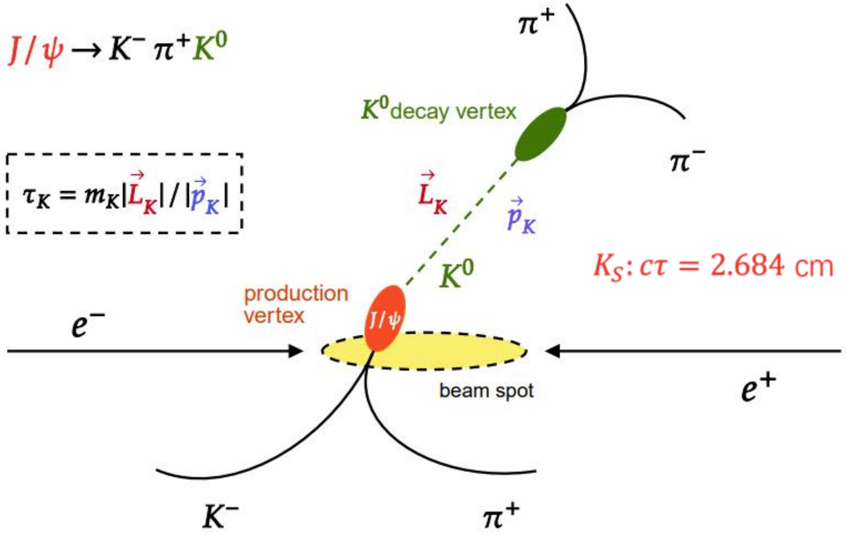


$m_{12}[\mathcal{C}] > 1$ Bell-inequality is violated



CPT Symmetry Test in $K^0 - \bar{K}^0$ System

Based on Fast simulation



CP asymmetry:

$$A_{\mathrm{CP}}^f(\tau) = \frac{\bar{R}_f(\tau) - R_f(\tau)}{\bar{R}_f(\tau) + R_f(\tau)}$$

$$= 2\mathrm{Re}(\varepsilon - \delta) - 2\frac{\boxed{|\eta_f|}\, e^{(1/2)(\Gamma_S - \Gamma_L)\tau} \cos\left(\Delta m\tau - \boxed{\phi_f}\right)}{1 + |\eta_f|^2 e^{(\Gamma_S - \Gamma_L)\tau}}$$

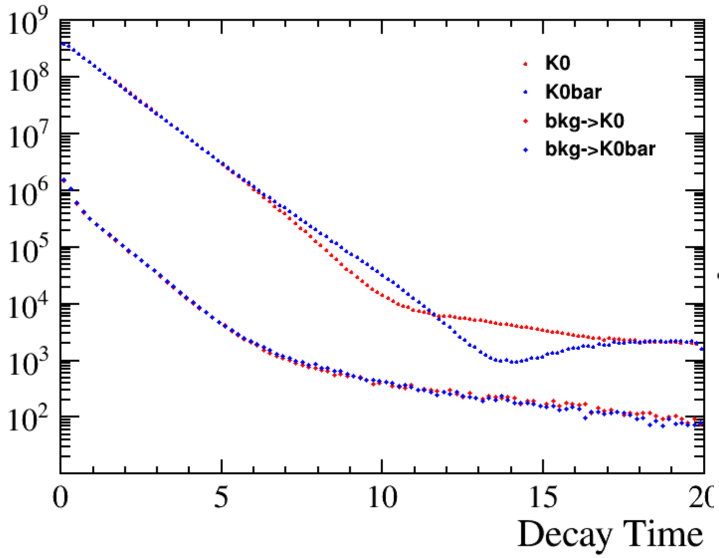
待测量

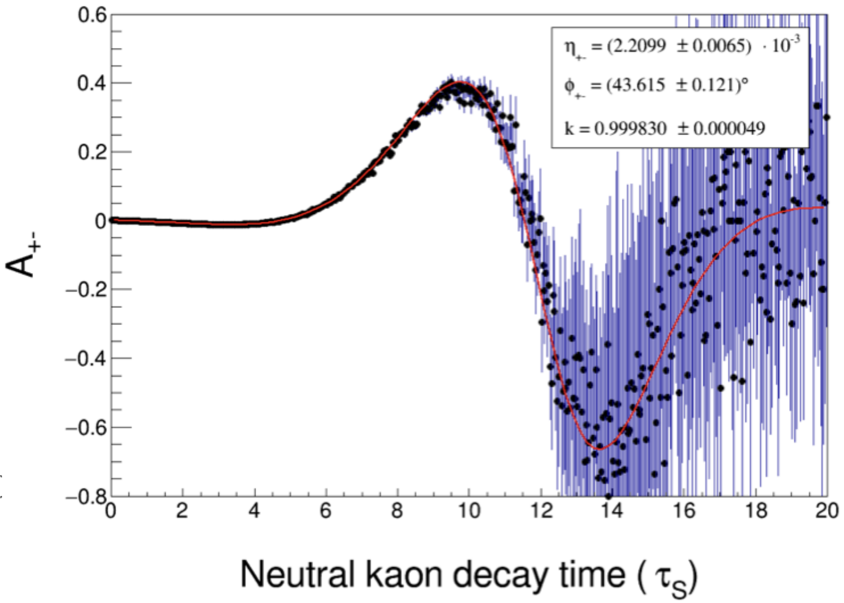
$f = \pi^+\pi^-, \pi^0\pi^0$

Decay rate:

$$R_f(\tau) = \frac{[1 - 2\mathrm{Re}(\epsilon - \delta)]}{2}\Gamma_S^f \times \left[e^{-\Gamma_S\tau} + |\eta_f|^2 e^{-\Gamma_L\tau} + 2|\eta_f| e^{-(1/2)(\Gamma_S + \Gamma_L)\tau}\cos(\Delta m\tau - \phi_f)\right]$$

$$\bar{R}_f(\tau) = \frac{[1 + 2\mathrm{Re}(\epsilon - \delta)]}{2}\Gamma_S^f \times \left[e^{-\Gamma_S\tau} + |\eta_f|^2 e^{-\Gamma_L\tau} - 2|\eta_f| e^{-(1/2)(\Gamma_S + \Gamma_L)\tau}\cos(\Delta m\tau - \phi_f)\right]$$





Parameter	$\lvert\eta_f\rvert(10^{-3})$	ϕ_f(degree)
PDG	2.232 ± 0.011	43.4 ± 0.5
STCF expected	2.2099 $\pm$ 0.0065	43.615 $\pm$ 0.121

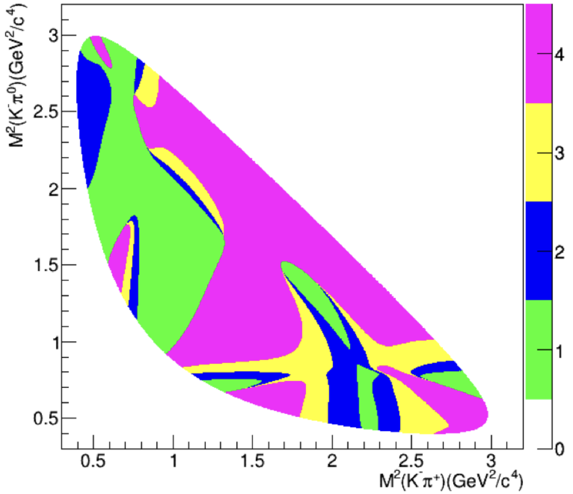
Considering the measurement error, efficiency, and the background

$D^0 - \bar{D}^0$ mixing

- $E_{cms} = 4030$ MeV, $\int L = 1\text{ab}^{-1}$.

	Component	Final State	$\mathcal{C}(D^0\bar{D}^0)$
Coherent	$D^0\bar{D}^0$	$D^0\bar{D}^0$	Odd
	$D^{*0}\bar{D}^0$	$\gamma D^0\bar{D}^0$	Even
		$\pi^0 D^0\bar{D}^0$	Odd
	$D^{*0}\bar{D}^{*0}$	$\gamma\pi^0 D^0\bar{D}^0$	Even
		$\gamma\gamma(\pi^0\pi^0)D^0\bar{D}^0$	Odd
Incoherent	$D^{*+}D^{*-}$	$\pi^+\pi^- D^0\bar{D}^0$	-
	$D^{*+}D^-$	$\pi^+ D^0 D^-$	-

- Decay modes: $K\pi\pi^0$.
  - Flavor tag: $K\pi\pi$, $K\pi\pi^0$, $K\pi\pi\pi$
  - CP-even tag: KK, $\pi\pi$, $\pi\pi\pi^0$.
  - CP-odd tag: $K_S\pi^0$, $K_S\eta$.
  - Self-conjugate tag: $K_S\pi\pi$.



- **The charm mixing parameters are extracted in a ratio between C-even and C-odd production processes**

$$N_{sig}^{C-even} = N_{D^{*0}\bar{D}^0} \cdot R^{C-even} \cdot \mathcal{B}(D^{*0} \to D^0\gamma) \cdot \varepsilon_{sig}$$

decay rate

$$N_{sig}^{C-odd} = N_{D^{*0}\bar{D}^0} \cdot R^{C-odd} \cdot \mathcal{B}(D^{*0} \to D^0\pi^0) \cdot \varepsilon_{sig}$$

$$\frac{N_{sig}^{C-even}}{N_{sig}^{C-odd}} = \frac{R^{C-even} \cdot \mathcal{B}(D^{*0} \to D^0\gamma)}{R^{C-odd} \cdot \mathcal{B}(D^{*0} \to D^0\pi^0)}$$

$K^-\pi^+\pi^0$	I	II	III	Belle II **50 ab^{-1}**
$\sigma_x(\%)$	0.062	0.200	0.080	0.057
$\sigma_y(\%)$	0.021	0.067	0.030	0.049
$\sigma_{r_{CP}}$	0.060	0.060	0.060	-
$\sigma_\phi(°)$	3.31	3.34	3.31	-
$\sigma_r(\%)$	-	0.045	-	-
σ_R	-	0.014	-	-
$\sigma_\delta(°)$	-	2.43	-	-

- I: Unbinned results of fixed strong phase parameters.
- II: Unbinned results of floated strong phase parameters.
- III: Unbinned results of consider the uncertainties (1ab^{-1}) of strong phase parameters as one Gaussian constrain.

CKM Matrix

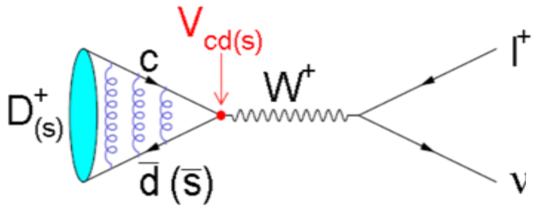
- **The CKM matrix elements describe the mixing of quark flavors. The unitarity of the CKM matrix ensures three quark generations and violation suggests a fourth!**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \boxed{V_{cd} \quad V_{cs}} & & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- **Leptonic** and **semileptonic** decays of charmed hadrons (D^0, D^+, D_s^+, Λ_c^+) provide ideal testbeds to explore **weak** and **strong** interactions

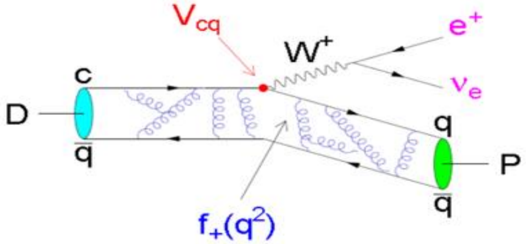
1. $|V_{cs(d)}|$: better test on CKM matrix unitarity
2. (Semi-)leptonic $D_{(s)}$ decays enable tests for LFU
3. $f_{D_s^+}$, $f^{+K(\pi)}(0)$: test of LQCD

Purely Leptonic:



$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

Semi-Leptonic:



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs(d)}|^2 p^3_{K(\pi)} |f_+^{K(\pi)}(q^2)|^2$$

CKM Matrix

	BESIII	STCF	Belle II
Luminosity	2.93 fb^{-1} at 3.773 GeV	1 ab^{-1} at 3.773 GeV	50 ab^{-1} at $\Upsilon(nS)$
$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$	$5.1\%_{\rm stat}\ 1.6\%_{\rm syst}$ [8]	$0.28\%_{\rm stat}$	–
f_{D^+} (MeV)	$2.6\%_{\rm stat}\ 0.9\%_{\rm syst}$ [8]	$0.15\%_{\rm stat}$	–
$\lvert V_{cd}\rvert$	$2.6\%_{\rm stat}\ 1.0\%^{*}_{\rm syst}$ [8]	$0.15\%_{\rm stat}$	–
$\mathcal{B}(D^+ \to \tau^+\nu_\tau)$	$20\%_{\rm stat}\ 10\%_{\rm syst}$ [9]	$0.41\%_{\rm stat}$	–
$\frac{\mathcal{B}(D^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D^+ \to \mu^+\nu_\mu)}$	$21\%_{\rm stat}\ 13\%_{\rm syst}$ [9]	$0.50\%_{\rm stat}$	–
Luminosity	3.2 fb^{-1} at 4.178 GeV	1 ab^{-1} at 4.009 GeV	50 ab^{-1} at $\Upsilon(nS)$
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$	$2.8\%_{\rm stat}\ 2.7\%_{\rm syst}$ [10]	$0.30\%_{\rm stat}$	$0.8\%_{\rm stat}\ 1.8\%_{\rm syst}$
$f_{D_s^+}$ (MeV)	$1.5\%_{\rm stat}\ 1.6\%_{\rm syst}$ [10]	$0.15\%_{\rm stat}$	–
$\lvert V_{cs}\rvert$	$1.5\%_{\rm stat}\ 1.6\%_{\rm syst}$ [10]	$0.15\%_{\rm stat}$	–
$f_{D_s^+}/f_{D^+}$	$3.0\%_{\rm stat}\ 1.5\%_{\rm syst}$ [10]	$0.21\%_{\rm stat}$	–
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	$1.9\%_{\rm stat}\ 2.3\%^{\dagger}_{\rm syst}$	$0.24\%_{\rm stat}$	$0.6\%_{\rm stat}\ 2.7\%_{\rm syst}$
$f_{D_s^+}$ (MeV)	$0.9\%_{\rm stat}\ 1.2\%^{\dagger}_{\rm syst}$	$0.11\%_{\rm stat}$	
$\lvert V_{cs}\rvert$	$0.9\%_{\rm stat}\ 1.2\%^{\dagger}_{\rm syst}$	$0.11\%_{\rm stat}$	–
$\overline{f}^{\mu\&\tau}_{D_s^+}$ (MeV)	$0.9\%_{\rm stat}\ 1.0\%^{\dagger}_{\rm syst}$	$0.09\%_{\rm stat}$	$0.3\%_{\rm stat}\ 1.0\%_{\rm syst}$
$\lvert \overline{V}^{\mu\&\tau}_{cs}\rvert$	$0.9\%_{\rm stat}\ 1.0\%_{\rm syst}{}^{\dagger}$	$0.09\%_{\rm stat}$	–
$\frac{\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)}$	$3.6\%_{\rm stat}\ 3.0\%^{\dagger}_{\rm syst}$	$0.38\%_{\rm stat}$	$0.9\%_{\rm stat}\ 3.2\%_{\rm syst}$

Theory : 0.2%(0.1% expected)

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Summary and Outlook

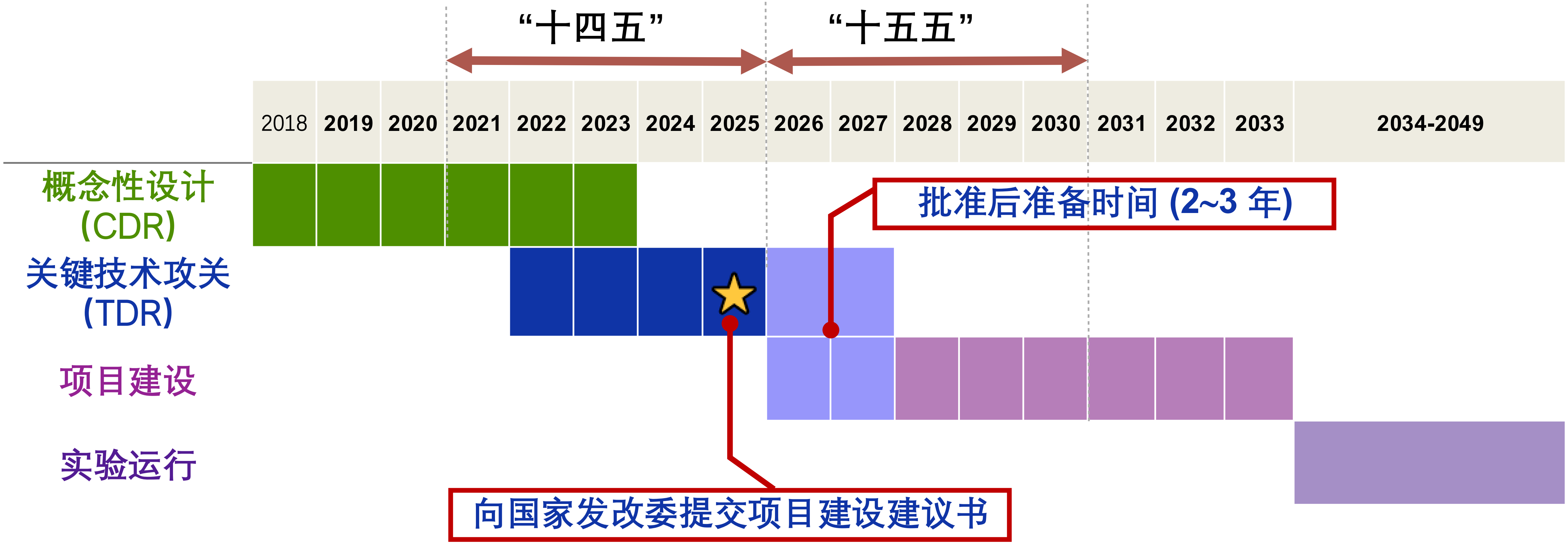
- The uniqueness at STCF can be defined by **three flagships physics goals**: fundamental symmetry; quark confinement; and fundamental parameters.

- Full-simulations are underway to evaluate **physics sensitivities** and **optimize** detector/software performance. **Further studies** are required to fully validate detector-physics alignment and finish the TDR of physics simulation.

- We look forward to **closer collaboration between theorists and experimentalists**, and welcome to **join the physics simulation group!**

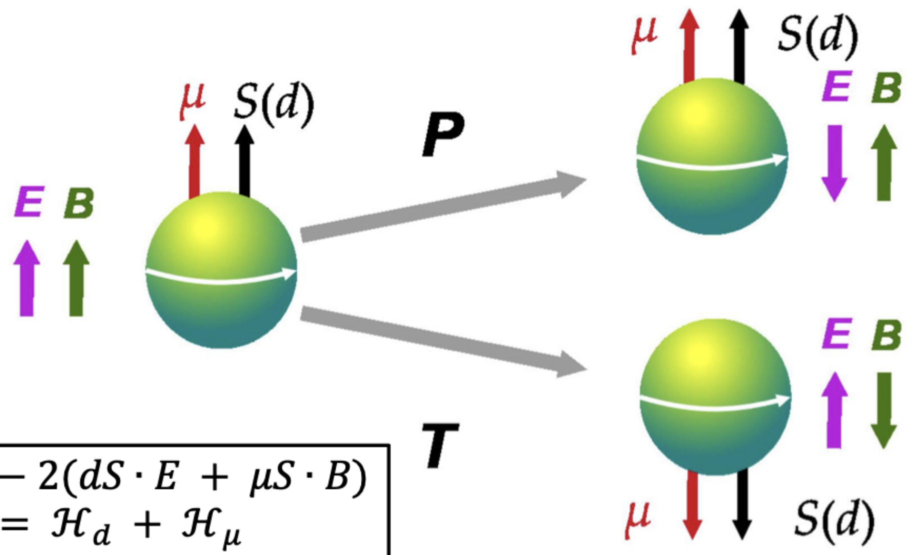
Back up

项目时间表



- 十四五期间：概念性设计、关键技术攻关, 3.64 亿
- 十五五期间：开建前准备、建设，6 年, ~50亿
- 运行10-15年，升级2-3年，再运行10年

$$\mathcal{H} = -2(dS\cdot(-E) + \mu S\cdot B) = -\mathcal{H}_d + \mathcal{H}_\mu$$



$$\mathcal{H} = -2(dS\cdot E + \mu S\cdot B) = \mathcal{H}_d + \mathcal{H}_\mu$$

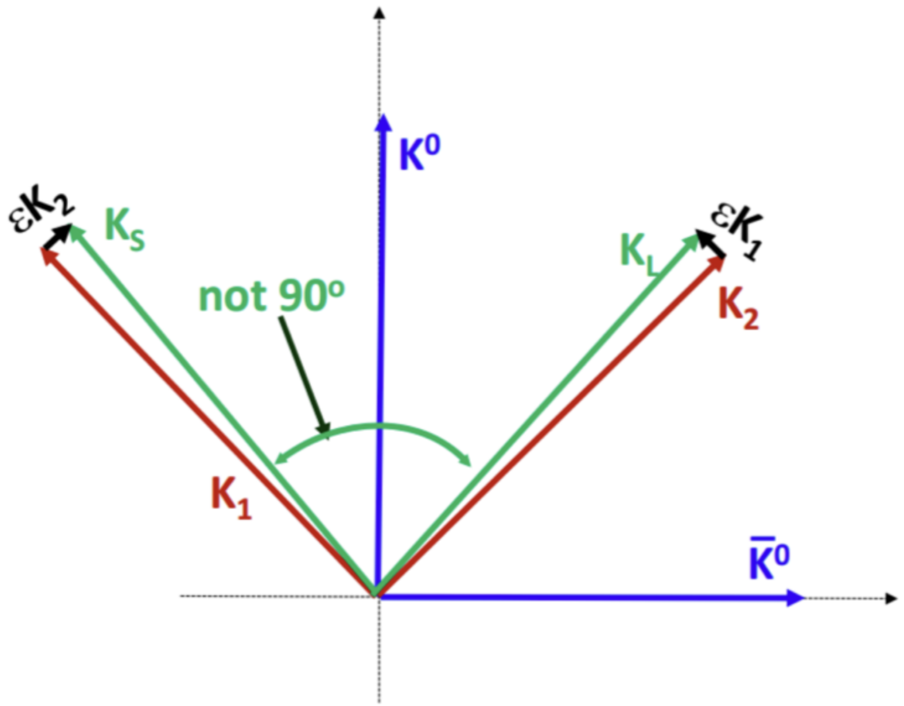
$$\mathcal{H} = -2(d(-S)\cdot E + \mu(-S)\cdot(-B)) = -\mathcal{H}_d + \mathcal{H}_\mu$$

- 非0的电偶极矩会破坏P和T的守恒：
  - 根据CPT守恒定理，T破坏↔ CP破坏

EDM对于研究CP破坏有重要意义

μ: 磁偶极矩　　B:磁场
d: 电偶极矩　　E:电场

三种中性 K 介子表象



$K^0-\bar{K}^0$ 味道本征态	有确定的夸克组分和奇异数
K_1-K_2 CP 本征态	有确定的 CP
K_S-K_L 质量本征态	有确定的寿命和质量

如果 $\varepsilon \neq 0$，K_S 和 K_L 不是 CP 本征态

ε: 表征由于 K 介子混合引起的间接 CP 破坏

$$
\begin{aligned}
R^{C-even}(K^-\pi^+\pi^-\pi^+;K^+\pi^-) \propto A^2_{K3\pi}A^2_{K\pi}\{&3(x^2+y^2)[K_i(r_{CP}^{-1})^2(r_D^{K\pi})^2+\bar{K}_i(r_{CP})^2(r_D^{K3\pi})^2 \\
&+2\sqrt{K_i\bar{K}_i}R^i_{K3\pi}r_D^{K3\pi}r_D^{K\pi}\cos(\delta_D^{i,K3\pi}-\delta_D^{K\pi}-2\phi)] \\
&+[2-3(x^2-y^2)][K_i+\bar{K}_i(r_D^{K\pi})^2(r_D^{K3\pi})^2 \\
&+2\sqrt{K_i\bar{K}_i}r_D^{K\pi}R^i_{K3\pi}r_D^{K3\pi}\cos(\delta_D^{i,K3\pi}+\delta_D^{K\pi})] \\
&-4y[r_D^{K\pi}(K_ir_{CP}^{-1}+\bar{K}_ir_{CP}(r_D^{K3\pi})^2)\cos(\delta_D^{K\pi}+\phi) \\
&+\sqrt{K_i\bar{K}_i}R^i_{K3\pi}r_D^{K3\pi}(r_{CP}+r_{CP}^{-1}(r_D^{K\pi})^2)\cos(\delta_D^{i,K3\pi}-\phi)] \\
&-4x[r_D^{K\pi}(K_ir_{CP}^{-1}-\bar{K}_ir_{CP}(r_D^{K3\pi})^2)\sin(\delta_D^{K\pi}+\phi) \\
&+\sqrt{K_i\bar{K}_i}R^i_{K3\pi}r_D^{K3\pi}(r_{CP}-r_{CP}^{-1}(r_D^{K\pi})^2)\sin(\delta_D^{i,K3\pi}-\phi)]\}
\end{aligned}
$$

$$
\begin{aligned}
R^{C-odd}(K^-\pi^+\pi^-\pi^+;K^+\pi^-) \propto A^2_{K3\pi}A^2_{K\pi}\{&(x^2+y^2)[K_i(r_{CP}^{-1})^2(r_D^{K\pi})^2+\bar{K}_i(r_{CP})^2(r_D^{K3\pi})^2 \\
&-2\sqrt{K_i\bar{K}_i}R^i_{K3\pi}r_D^{K3\pi}r_D^{K\pi}\cos(\delta_D^{i,K3\pi}-\delta_D^{K\pi}-2\phi)] \\
&+[2-(x^2-y^2)][K_i+\bar{K}_i(r_D^{K\pi})^2(r_D^{K3\pi})^2 \\
&-2\sqrt{K_i\bar{K}_i}r_D^{K\pi}R^i_{K3\pi}r_D^{K3\pi}\cos(\delta_D^{i,K3\pi}+\delta_D^{K\pi})]
\end{aligned}
$$

Strong phase parameters are fixed.