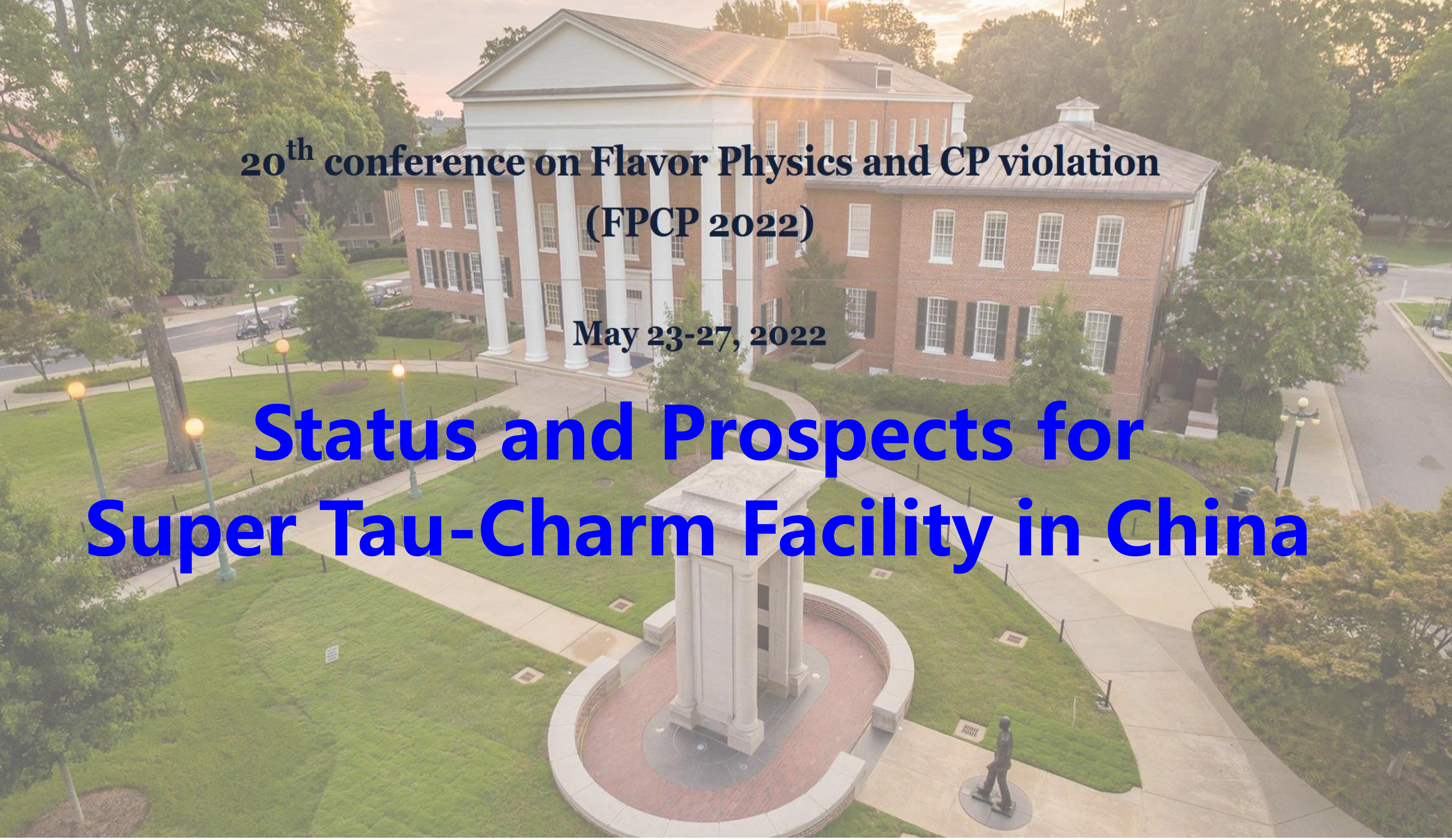


20th conference on Flavor Physics and CP violation (FPCP 2022)

May 23-27, 2022

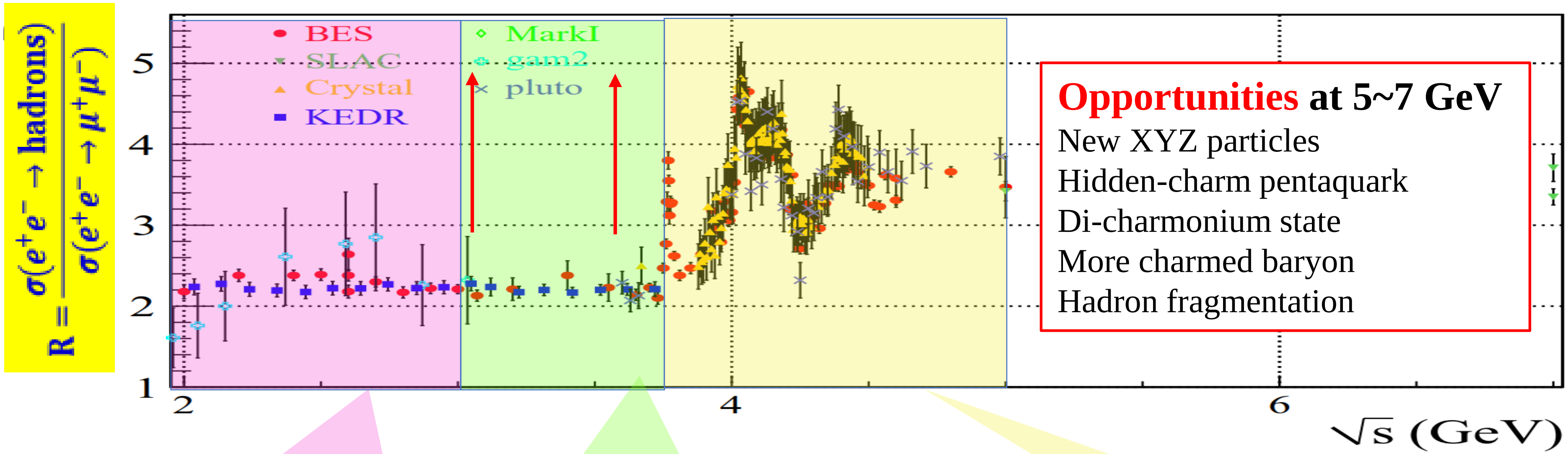
Status and Prospects for Super Tau-Charm Facility in China

Haiping Peng (On behalf of STCF working group)

State Key Laboratory of Particle Detection and Electronics

University of Science and Technology of China

Physics at Tau-Charm Region



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark,
- MLLA/LPHD and QCD sum rule predictions

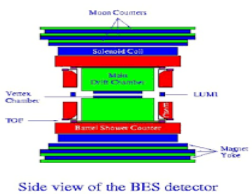
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- fD and fDs
- D0-D0 mixing
- Charm baryons

- **Rich of physics program, unique for physics with *c* quark and τ lepton**
- **important playground for study of nature of non-pQCD, exotic hadrons, flavor physics and search for new physics.**

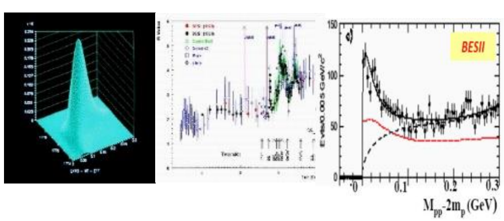
Tau-Charm Factory in China

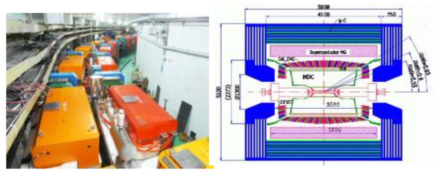
30 yields history, Successful and fruitful physics results



BEPCI /BESI-II
($10^{31}cm^{-2}s^{-1}$)

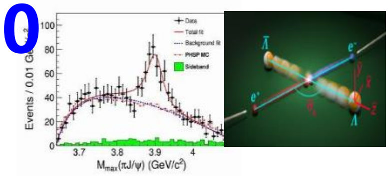
1990





BEPCII/BESIII
($10^{33}cm^{-2}s^{-1}$)

2010



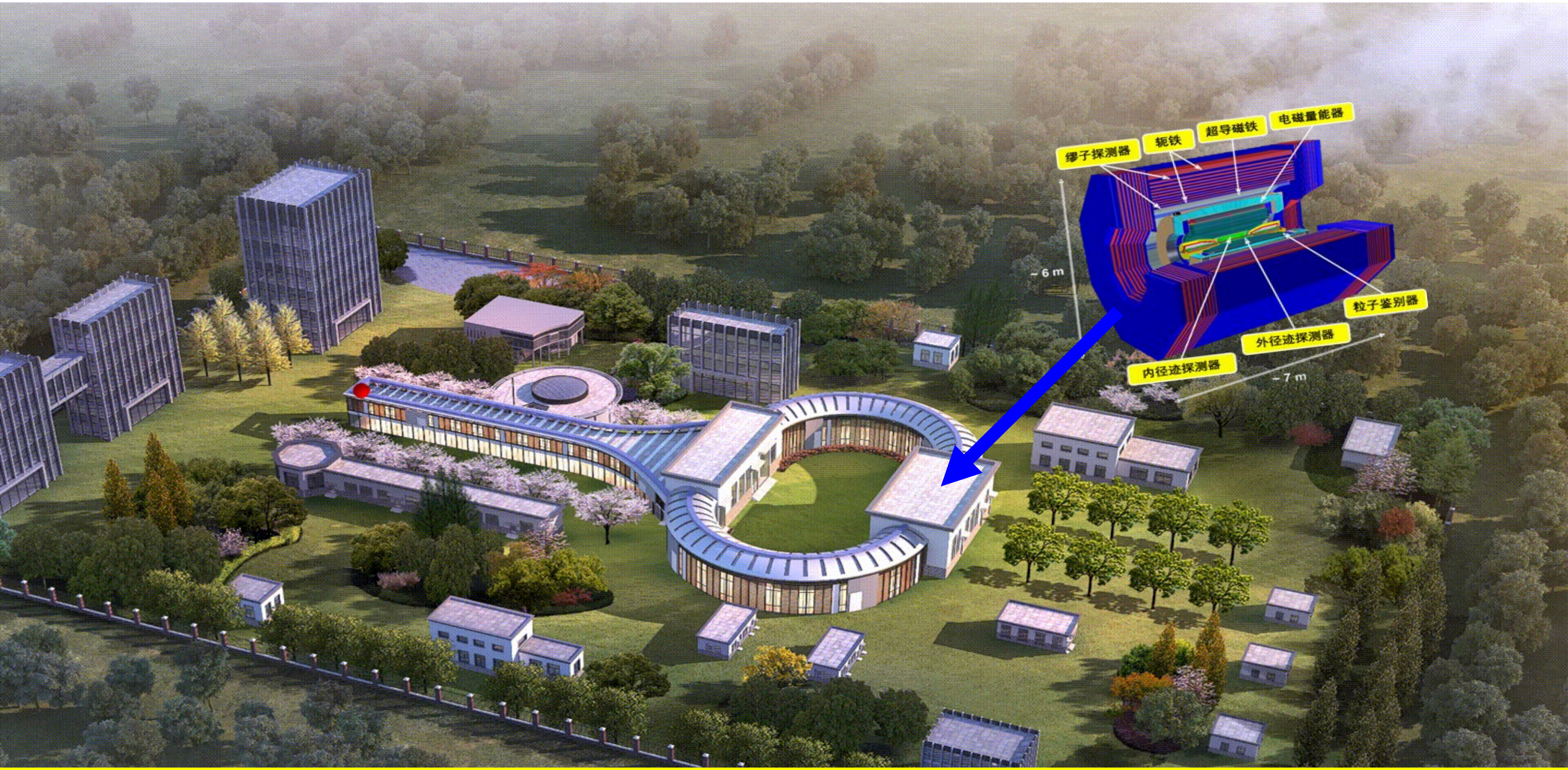
2030

STCF?
($10^{35}cm^{-2}s^{-1}$)?
BEPCII/BESIII
Natural extension

Challenge of BEPCII/BESIII experiment:

- **Successful** operation for 13 years, but **limited potential** for further upgrade
- BEPCII/BESIII lifetime is less than **10 years**。
- Some **key scientific questions** require higher luminosity and more wider CME.

STCF in China

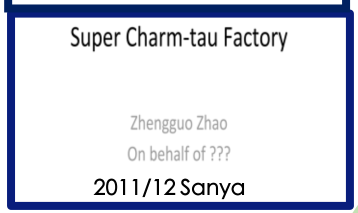


- CME : 2-7 GeV
- Peaking $\mathcal{L}$: $>0.5\times10^{35}$ cm^{-2} s^{-1}
- Potential to further improve the lumi and realize polarized beam
- Double storage ring: ~800 m, injection: ~ 300m
- BESIII-Like detector
- Cost 4.5B RMB

Project progress and plan

Several domestic and international workshop

Workshop for acc. based high energy physics development strategy


Super Charm-tau Factory

Zhengguo Zhao

On behalf of ???

2011/12 Sanya

2011
First proposed


香山科学会议简报

第 534 期

2-7GeV 高亮度正负电子加速器上的

物理、应用及其关键技术

——香山科学会议第 533 次学术讨论会

2015
Xiangshan Science Conference


中国科学技术大学"双一流"重点建设项目

"超级陶-粲（τ-C）装置预先研究"论证意见

2018 年 3 月 12 日，中国科学技术大学对"双一流"重点建设项目："超级陶-粲装置（Super Tau-charm Facility, STCF）的预先研究"进行了论证。会议成立了论证专家委员会（名单附后），听取了项目负责人赵政国院士的项目汇报。经认真讨论与质询，形成论证意见如下：

1、粒子物理学（也称高能物理）是研究比原子核更深层次物质的基本构成、相互作用以及自然界最基本规律的前沿

2018
USTC double first-class key projects

2021
Conceptual design report


STCF

Conceptual Design Report

Volume I - Physics

STCF

Conceptual Design Report

Volume II - Accelerators

STCF

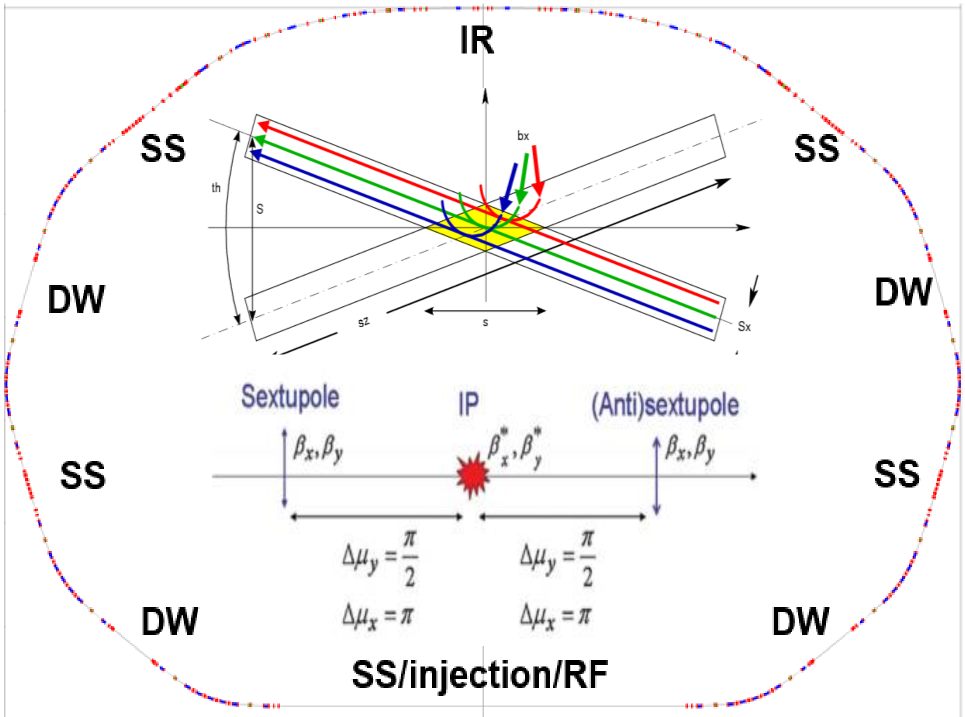
Conceptual Design Report

Volume III - Detector

Key technology R&D

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031-40	2041-43
CDR	■	■	■	■											
TDR	■	■	■	■	■	■	■	■							
Construction									■	■	■	■	■		
Commission														■	
Upgrade															■

Accelerator Conceptual Design



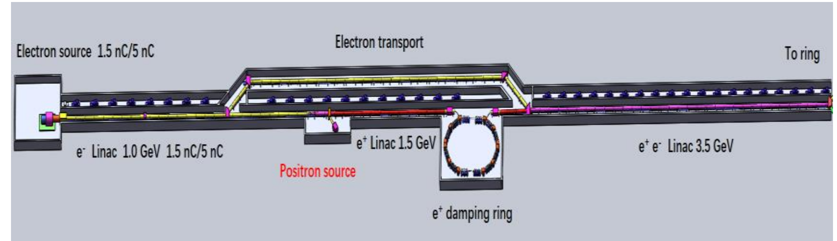
Parameters	Unit	Value
Circumference	m	574.78
Distance from final defocusing quadrupole to IP	m	0.9
Optimized energy	GeV	2.0
Total beam current	A	2
Horizontal/Vertical beta @ IP	m	0.09/0.0006
Total crossing angle (2θ)	mrad	60
Piwinski angle (ϕ)	rad	18.9
Beam-beam tune shift (ξ_x/ξ_y)	—	0.0038/0.0835
Coupling ratio	—	0.5%
Natural chromaticities (C_x/C_y)	—	-87/-513
Horizontal emittance (ϵ_x) without/with IBS	nmrad	2.76/4.17
Horizontal beam size @ IP without/with IBS	μm	15.77/19.37
Vertical beam size @ IP without/with IBS	μm	0.091/0.117
Energy spread ($\frac{\sigma_{\Delta E}}{E}$) without/with IBS	$\times10^{-4}$	5.3/7.2
Momentum compaction factor	—	7.2×10^{-4}
RF frequency	MHz	499.67268
RF voltage	MV	1.2
Harmonic number	—	958
Bunch length (σ_z)	mm	12.2
Particle number per bunch (N_b)	—	5.0×10^{10}
Energy loss per turn	MeV	0.1315
Synchrotron tune (ν_s)	—	0.00388
Damping times ($\tau_x/\tau_y/\tau_s$)	ms	58.51/58.33/29.12
Peak luminosity	$cm^{-2}s^{-1}$	1.2×10^{35}
Touschek lifetime	s	35

Interaction region :

- Large Piwinski-Angle Collision + Crabbed Waist

Linac Injector:

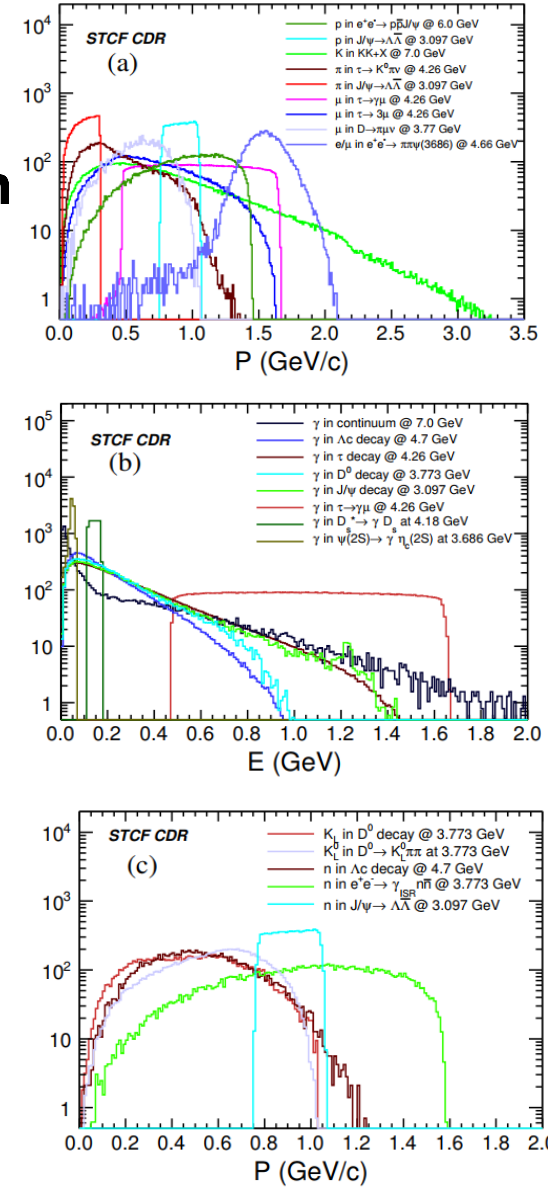
- No booster, full energy injection (1-3.5 GeV)
- e^-, a (polarized) e- source with high current, accelerated
- e^+, a convertor, a linac and a damping ring, accelerated



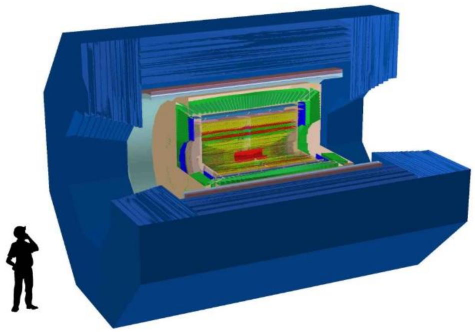
STCF Detector

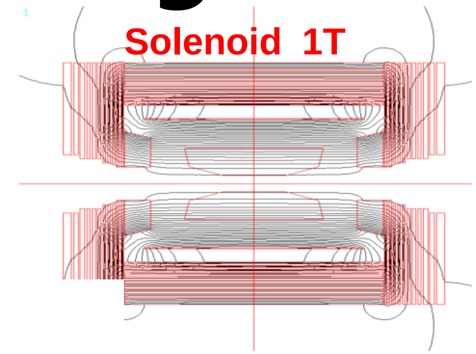
A BESIII-like detector with large solid angle coverage, excellent momentum and energy resolution, superior PID capability, and much higher event rate and radiation hardness

- **Inner Tracker**
  - ~0.15% X_0 / layer
  - σ_{xy} ~ 50 μm
- **Out Tracker**
  - σ_{xy}~130 μm, σ_p/p~0.5%@1 GeV/c
  - dE/dx ~ 6%
- **PID system**
  - π/K (K/p) 3-4σ separation up to 2 GeV/c
- **Electromagnetic Calorimeter**
  - Range: 0.02 – 3 GeV
  - Resolution (1 GeV): 2.5% (barrel) and 4% (endcap)
- **Muon system**
  - π suppression power: >10 and lower to 0.4 GeV/c

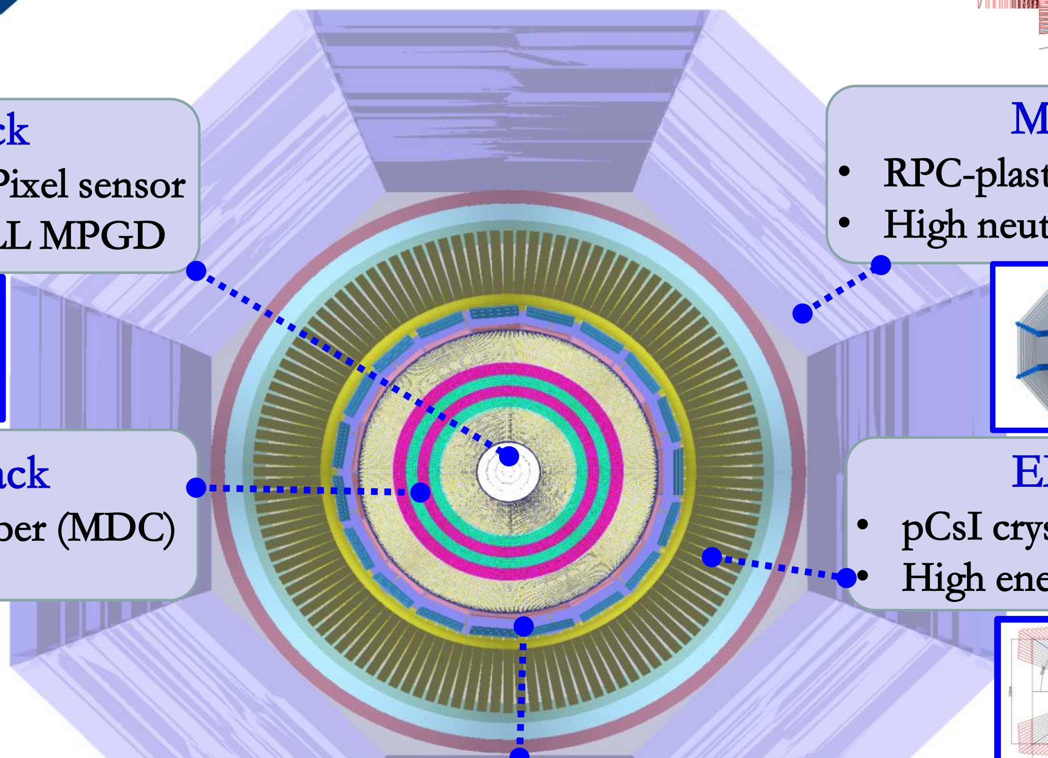


Detector Conceptual Design

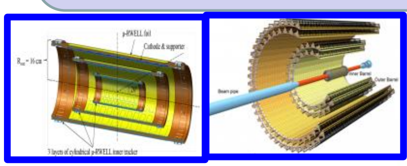




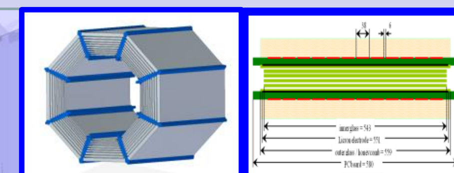
Micro/Fast Readout Electronics
High capability of Trigger, DAQ, Storage



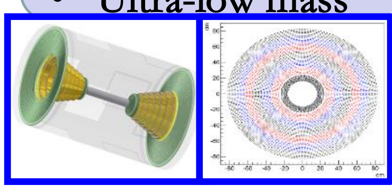
Inner Track
- Monolithic active Pixel sensor
- Low mass μRWELL MPGD



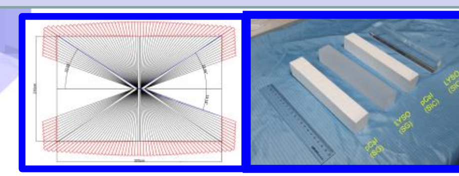
Muon detector
- RPC-plastic scintillator mixture
- High neutral hadron ID efficiency



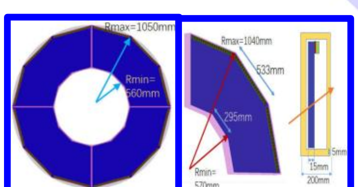
Outer Track
- Main Drift Chamber (MDC)
- Ultra-low mass

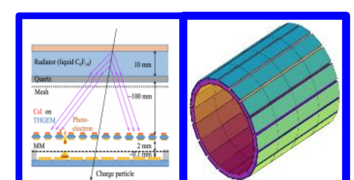


EM Calorimeter
- pCsI crystal based : fast
- High energy and timing resolution



Particle Identification
- MPGD-based RICH (barrel)
- High-precision timing DIRC (Endcap)





Data Samples

1 ab^{-1} data expected per year

Table 1: The expected numbers of events per year at different energy points at STCF

CME (GeV)	Lumi (ab^{-1})	samples	σ(nb)	No. of Events	remark
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\psi(3686)$ $\tau^+\tau^-$ $\psi(3686)\to\tau^+\tau^-$	640 2.5	6.4×10^{11} 2.5×10^{9} 2.0×10^{9}	
3.770	1	$D^0\bar{D}^0$ $D^+\bar{D}^-$ $D^0\bar{D}^0$ $D^+\bar{D}^-$ $\tau^+\tau^-$	3.6 2.8 2.9	3.6×10^{9} 2.8×10^{9} 7.9×10^{8} 5.5×10^{8} 2.9×10^{9}	 Single Tag Single Tag
4.040	1	$\gamma D^0\bar{D}^0$ $\pi^0 D^0\bar{D}^0$ $D_s^+D_s^-$ $\tau^+\tau^-$	0.40 0.40 0.20 3.5	4.0×10^{6} 4.0×10^{6} 2.0×10^{8} 3.5×10^{9}	$CP_{D^0\bar{D}^0}=+1$ $CP_{D^0\bar{D}^0}=-1$
4.180	1	$D_s^{+*}D_s^-$+c.c. $D_s^{+*}D_s^-$+c.c. $\tau^+\tau^-$	0.90 3.6	9.0×10^{8} 1.3×10^{8} 3.6×10^{9}	 Single Tag
4.230	1	$J/\psi\pi^+\pi^-$ $\tau^+\tau^-$ $\gamma X(3872)$	0.085 3.6	8.5×10^{7} 3.6×10^{9}	
4.360	1	$\psi(3686)\pi^+\pi^-$ $\tau^+\tau^-$	0.058 3.5	5.8×10^{7} 3.5×10^{9}	
4.420	1	$\psi(3686)\pi^+\pi^-$ $\tau^+\tau^-$	0.040 3.5	4.0×10^{7} 3.5×10^{9}	
4.630	1	$\psi(3686)\pi^+\pi^-$ $\Lambda_c\bar{\Lambda}_c$ $\Lambda_c\bar{\Lambda}_c$ $\tau^+\tau^-$	0.033 0.56 3.4	3.3×10^{7} 5.6×10^{8} 6.4×10^{7} 3.4×10^{9}	 Single Tag
4.0-7.0	3	300 points scan with 10 MeV step, 1 fb^{-1}/point			
> 5	2-7	several ab^{-1} high energy data, details dependent on scan results			

Hyperon Factory

Decay mode	$\mathcal{B}$(units 10^{-4})	Angular distribution parameter α_ψ	Detection efficiency	No. events expected at STCF
$J/\psi\to\Lambda\bar{\Lambda}$	$19.43\pm0.03\pm0.33$	0.469 ± 0.026	40%	1100×10^6
$\psi(2S)\to\Lambda\bar{\Lambda}$	$3.97\pm0.02\pm0.12$	0.824 ± 0.074	40%	130×10^6
$J/\psi\to\Xi^0\bar{\Xi}^0$	11.65 ± 0.04	0.66 ± 0.03	14%	230×10^6
$\psi(2S)\to\Xi^0\bar{\Xi}^0$	2.73 ± 0.03	0.65 ± 0.09	14%	32×10^6
$J/\psi\to\Xi^-\bar{\Xi}^+$	10.40 ± 0.06	0.58 ± 0.04	19%	270×10^6
$\psi(2S)\to\Xi^-\bar{\Xi}^+$	2.78 ± 0.05	0.91 ± 0.13	19%	42×10^6

Light meson Factory

Decay Mode	$\mathcal{B}$ ($\times10^{-4}$) [2]	η/η' events
$J/\psi\to\gamma\eta'$	52.1 ± 1.7	1.8×10^{10}
$J/\psi\to\gamma\eta$	11.08 ± 0.27	3.7×10^{9}
$J/\psi\to\phi\eta'$	7.4 ± 0.8	2.5×10^{9}
$J/\psi\to\phi\eta$	4.6 ± 0.5	1.6×10^{9}

XYZ Factory

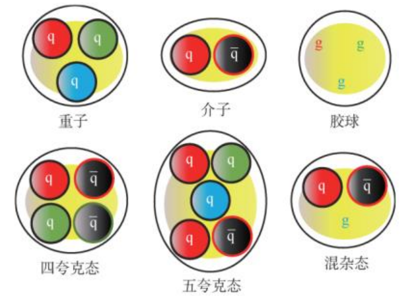
XYZ	$Y(4260)$	$Z_c(3900)$	$Z_c(4020)$	$X(3872)$
No. of events	10^{10}	10^{9}	10^{9}	5×10^{6}

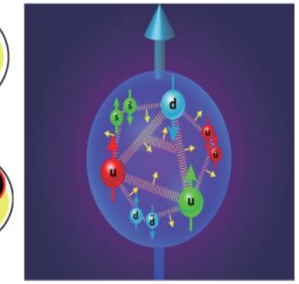
- **Belle-II : more statistics (50/ab) has**
- **LHCb: much more statistics, huge bkg**

- **STCF : high detection efficiency, excellent resolution, kinematic constraining, low background, threshold production**

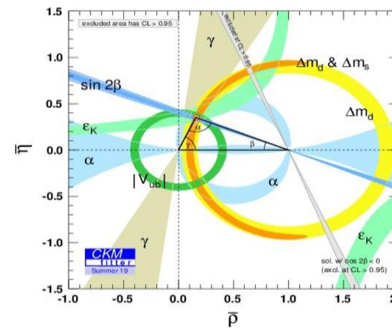
Highlighted physics

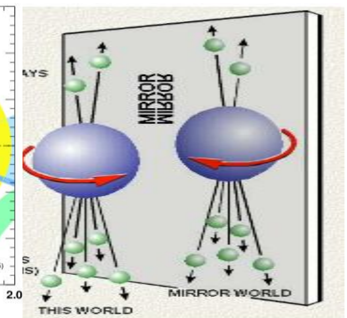
- **QCD and Hadronic Physics**
  - Exotic states and hadron spectroscopy
  - Hadron structures
  - Precision test of SM parameters



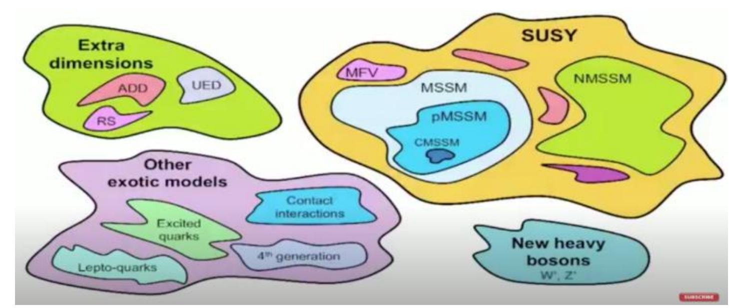


- **Flavor Physics and CP violation**
  - CKM matrix, $D^0 - \overline{D}^0$ mixing
  - CP violation in lepton, hyperon, charm





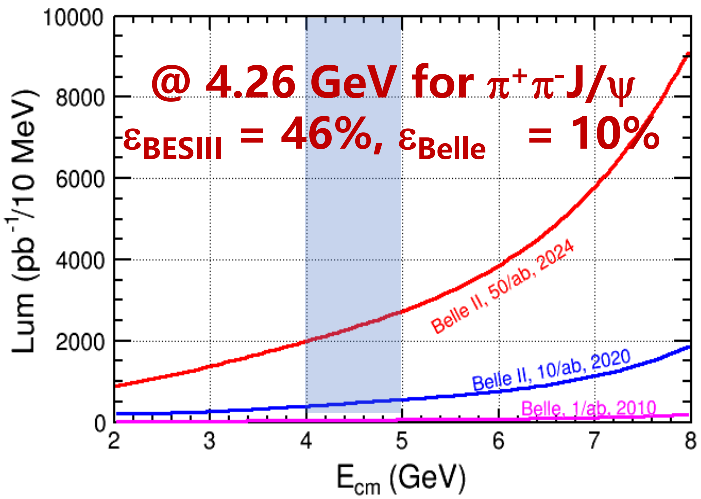
- **New Physics Search**
  - Rare/Forbidden
  - Universality test
  - Dark particle search

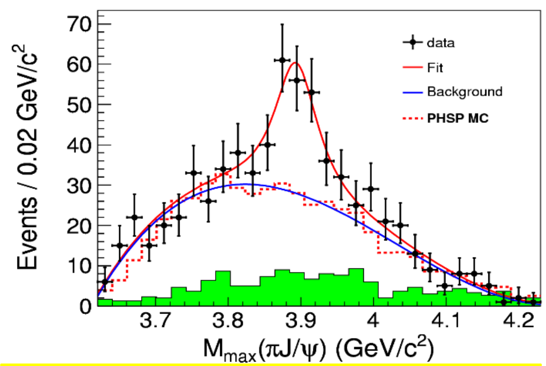


Several benchmark processes analyses have been performed to optimize the detector design, and obtain potential sensitivities

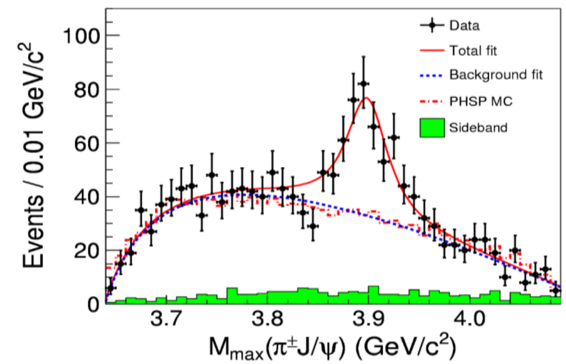
Charmonium(Like) Spectroscopy

platform to explore non-pQCD, Fruitful results in past decade, a new territory to study exotic hadrons, but controversy





Belle with ISR: PRL110, 252002
967/fb in 10 years running



BESIII at 4.260 GeV: PRL110, 252001
0.525/fb in three month running

- **Belle-II : integrate eff. Lumi. between 4-5 GeV is 0.23 ab^{-1} for 50 ab^{-1} data**
- **STCF : scan in 4-5 GeV, 10 MeV/step, 10 fb^{-1}/point/year, 5 × Belle-II (50 ab^{-1})**
- **STCF : much higher efficiency and low background than Belle-II**

STCF : XYZ Factory

XYZ	$Y(4260)$	$Z_c(3900)$	$Z_c(4020)$	$X(3872)$
No. of events	10^{10}	10^9	10^9	5×10^6

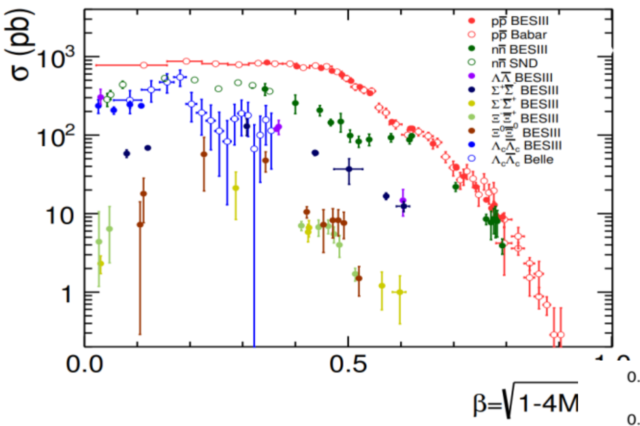
Large statistics and much wider CME data provide opportunity to perform precise analysis and to pine down the nature of Charmomium-like states

Fengkun Guo' s Snowmass talk https://indico.fnal.gov/event/51844/contributions/240619/attachments/155336/202232/Snowmass_RF7_STCF_FKGuo.pdf

Electromagnetic Form Factors

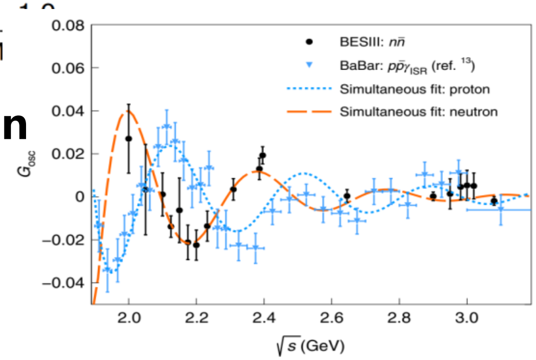
Fundamental properties of the nucleon, connected to charge and magnetization distributions, crucial testing ground for models of the nucleon internal structure

Several "Surprise" results from BESIII



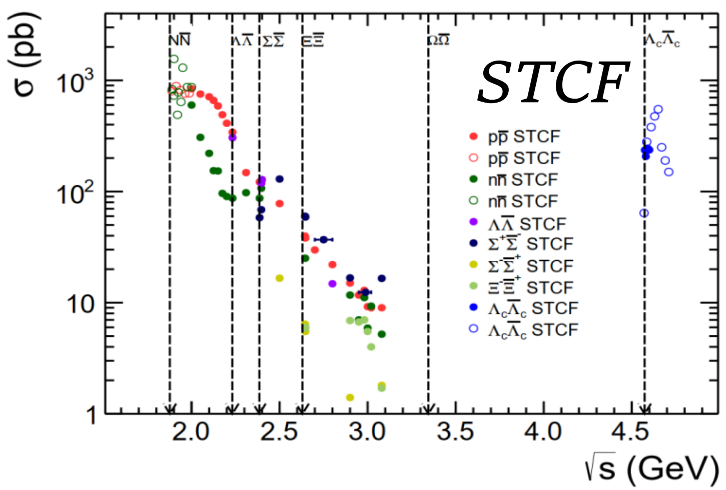
Abnormal X-sec at production threshold

Oscillation as function of CME
Orthogonal between neutron and proton



STCF unique features :

- **Threshold Production**
- **Low background**
- **Almost all baryons**
- **Incomparable precision**



STCF provide opportunities for systematical and precise measurements, and to understand the nature the nucleons

QCD and Hadronic Physics

Physics at STCF	Benchmark Processes	Key Parameters*
XYZ properties	$e^+e^- \to Y \to \gamma X, \eta X, \phi X$ $e^+e^- \to Y \to \pi Z_c, KZ_{cs}$	$N_{Y(4260)/Z_c/X(3872)}\sim$ $10^{10}/10^9/10^6$
Pentaquarks, Di-charmonium	$e^+e^- \to J/\psi p\bar{p}, \Lambda_c\bar{D}\bar{p}, \Sigma_c\bar{D}\bar{p}$ $e^+e^- \to J/\psi\eta_c, J/\psi h_c$	$\sigma(e^+e^- \to J/\psi p\bar{p})$~4 fb; $\sigma(e^+e^- \to J/\psi c\bar{c})$~10 fb (prediction)
Hadron Spectroscopy	Excited $c\bar{c}$ and their transition, Charmed hadron spectroscopy, Light hadron spectroscopy	$N_{J/\psi/\psi(3686)/\Lambda_c}\sim$ $10^{12}/10^{11}/10^8$
Muon g-2	$e^+e^- \to \pi^+\pi^-, \pi^+\pi^-\pi^0, K^+K^-$ $\gamma\gamma \to \pi^0, \eta^{(\prime)}, \pi^+\pi^-$	$\Delta a_\mu^{HVP} \ll 40 \times 10^{-11}$
R value, τ mass	$e^+e^- \to inclusive$ $e^+e^- \to \tau^+\tau^-$	Δm_τ~0.012 MeV (with 1 month scan)
Fragmentation functions	$e^+e^- \to (\pi, K, p, \Lambda, D) + X$ $e^+e^- \to (\pi\pi, KK, \pi K) + X$	$\Delta A^{Collins} < 0.002$
Nucleon Form Factors	$e^+e^- \to B\bar{B}$ from threshold	δR_{EM}~1%

*Sensitivity estimated based on $\mathcal{L} = 1\ \text{ab}^{-1}$

A unique Charm factory

Low backgrounds and high efficiency; missing technique and absolute measurement; Quantum correlations and CP-tagging

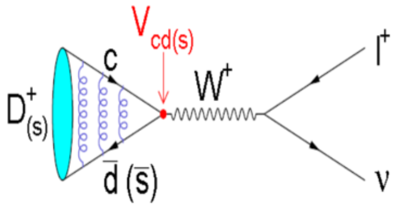
STCF data/year : 4×10^9 pairs of $D^{\pm,0}$, 10^8 D_s and Λ_c pairs

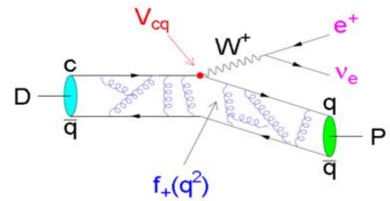
Highlighted Physics programs

- **Precise measurement of (semi-)leptonic decay (f_D, f_{Ds}, CKM)**
- **$D^0-\bar{D}^0$ mixing, CPV**
- **Strong phase, decay parameters…**
- **Rear decay (FCNC, LFV, LNV….),**
- **Charmed baryons (J^{PC}, Decay modes, absolute BF)**
- **Excited charmed meson and baryon states: like D_J, D_{sJ} , Λ_c^* (mass, width, J^{PC}, decay modes)**
- **Light meson and hyperon spectroscopy studied in charmed hadron decays**

Xiaorui Lyu's Snowmass talk https://indico.fnal.gov/event/51844/contributions/240647/

Charm meson Leptonic Decays





Excellent platform for CKM elements and decay constants and universality test

	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%$_{\rm syst}$ [6]	0.28%$_{\rm stat}$	–
f_{D^+} (MeV)	2.6%$_{\rm stat}$ 0.9%$_{\rm syst}$ [6]	0.15%$_{\rm stat}$	–
$\|V_{cd}\|$	2.6%$_{\rm stat}$ 1.0%$^{*}_{\rm syst}$ [6]	0.15%$_{\rm stat}$	–
$\mathcal{B}(D^+ \to \tau^+\nu_\tau)$	20%$_{\rm stat}$ 10%$_{\rm syst}$ [7]	0.41%$_{\rm stat}$	–
$\frac{\mathcal{B}(D^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D^+ \to \mu^+\nu_\mu)}$	21%$_{\rm stat}$ 13%$_{\rm syst}$ [7]	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%$_{\rm syst}$ [8]	0.30%$_{\rm stat}$	0.8%$_{\rm stat}$ 1.8%$_{\rm syst}$
$f_{D_s^+}$ (MeV)	1.5%$_{\rm stat}$ 1.6%$_{\rm syst}$ [8]	0.15%$_{\rm stat}$	–
$\|V_{cs}\|$	1.5%$_{\rm stat}$ 1.6%$_{\rm syst}$ [8]	0.15%$_{\rm stat}$	–
$f_{D_s^+}/f_{D^+}$	3.0%$_{\rm stat}$ 1.5%$_{\rm syst}$ [8]	0.21%$_{\rm stat}$	–
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	2.2%$_{\rm stat}$ 2.6%$^{\dagger}_{\rm syst}$	0.24%$_{\rm stat}$	0.6%$_{\rm stat}$ 2.7%$_{\rm syst}$
$f_{D_s^+}$ (MeV)	1.1%$_{\rm stat}$ 1.5%$^{\dagger}_{\rm syst}$	0.11%$_{\rm stat}$	–
$\|V_{cs}\|$	1.1%$_{\rm stat}$ 1.5%$^{\dagger}_{\rm syst}$	0.11%$_{\rm stat}$	–
$\bar{f}^{\mu\&\tau}_{D_s^+}$ (MeV)	0.9%$_{\rm stat}$ 1.0%$^{\dagger}_{\rm syst}$	0.09%$_{\rm stat}$	0.3%$_{\rm stat}$ 1.0%$_{\rm syst}$
$\|\bar{V}^{\mu\&\tau}_{cs}\|$	0.9%$_{\rm stat}$ 1.0%$_{\rm syst}$†	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%$_{\rm syst}$

LQCD : 0.2% (0.1% expected)

LQCD : 0.2% (0.1% expected)

LQCD : 0.2% (0.1% expected)

* assuming Belle II improved systematics by a factor 2

Statistical uncertainties are close to theory precision
Systematic uncertainties are challenging

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

STCF provide an unique place for the study of D^0-$\bar{D}^0$ mixing and CPV by means of quantum coherence of D^0 and $\bar{D}^0$ produced through

$$\psi(3770) \to (D^0\bar{D}^0)_{\mathrm{CP}=-} \text{ or } \psi(4140) \to D^0\bar{D}^{*0} \to \pi^0(D^0\bar{D}^0)_{\mathrm{CP}=-} \text{ or } \gamma(D^0\bar{D}^0)_{\mathrm{CP}=+}$$

as well as incoherent flavor specific D^0 samples: $D^{*+} \to D^0\pi^+$

- **Mixing rate $R_M = \frac{x^2+y^2}{2} \sim 10^{-5}$ with 1 ab-1 data at 3.773 GeV via same charged final states $(K^\pm\pi^\mp)(K^\pm\pi^\mp)$ or $(K^\pm l^\mp v)(K^\pm l^\mp v)$**
- **$\Delta A_{CP} \sim 10^{-3}$ for KK and ππ channels**

	1/ab @4009 MeV (only QC | QC+incoherent) (very preliminary estimation)		BELLEII(50/ab) [PTEP2019,123C01]	LHCb(50/fb) (SL | Prompt) [arXiv:1808.08865]	
$x(\%)$	0.036	0.035	0.03	0.024	0.012
$y(\%)$	0.023	0.023	0.02	0.019	0.013
r_{CP}	0.017	0.013	0.022	0.024	0.011
$\alpha_{CP}(^\circ)$	1.3	1.0	1.5	1.7	0.48

- The only QC results: contains $D^0 \to K_S\pi\pi, D^0 \to K^-\pi^+\pi^0$ and general CP tag decay channels; needs to be tuned
- The QC+incoherent results: combines coherent and incoherent D^0 meson samples
- The BELLE II and LHCb results only contain incoherent $D^0 \to K_S\pi\pi$ channel

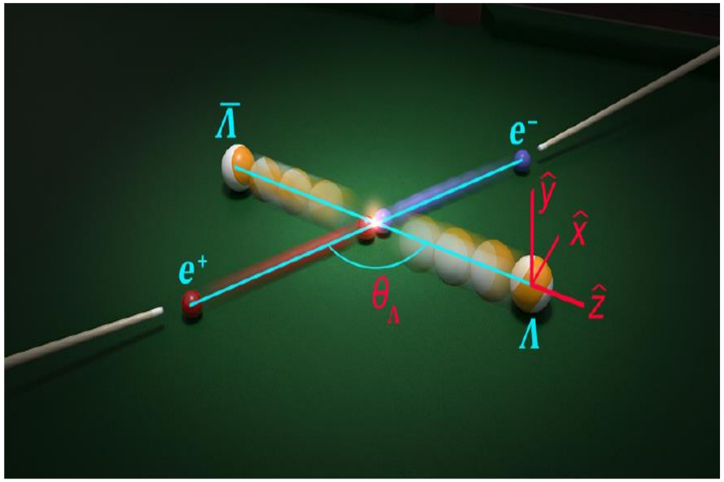
Precision Study of Charm Baryon

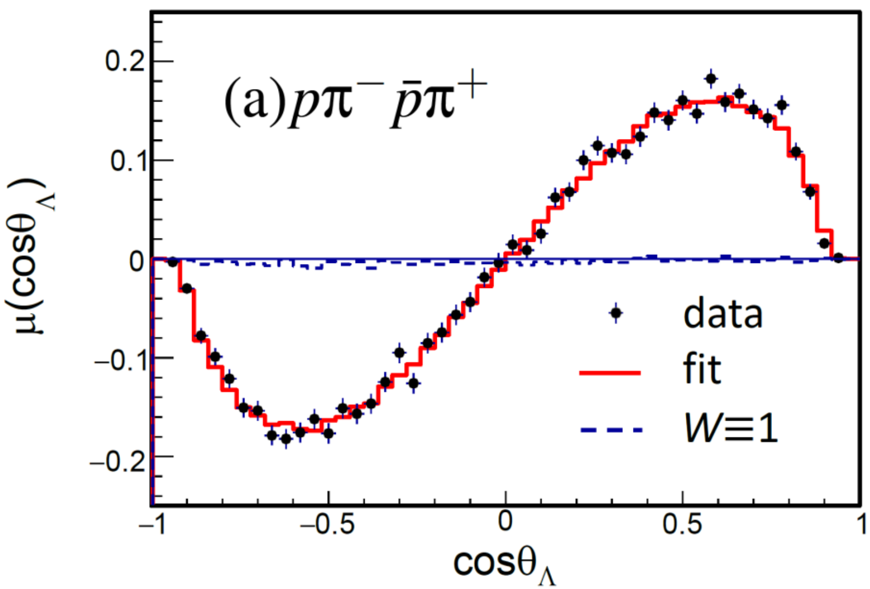
Era of precision study of the charmed baryon (Λ_c, Ξ_c and Ω_c) decays
to help developing more reliable QCD-derived models in charm sector

- **Hadronic decays:**
  to explore as-yet-unmeasured channels and understand full picture of intermediate structures in B_c decays, esp., those with neutron/Σ/Ξ
- **Semi-leptonic decays:**
  to test LQCD calculations and LFU
- **CPV in charmed baryon:**
  BP and BV two-body decay asymmetry, charge-dependent rate of SCS
- **Charm-flavor-conserving nonleptonic decays:** $\Xi_c \rightarrow \Lambda_c^+\pi$, $\Omega_c^0 \rightarrow \Xi_c\ \pi$
- **Electro-weak radiative decays :** $\Sigma_c^+ \rightarrow \Lambda_c^+\gamma$, $\Lambda_c^+ \rightarrow \Sigma\gamma, p\gamma$, $\Xi_c^{+/0} \rightarrow \Sigma^{+/0}\gamma$
- **Rare decays:** LFV, BNV, FCNC

STCF will provide very precise measurements of their overall decays, up to the unprecedented level of $10^{-6} \sim 10^{-7}$

Polarization of hyperons and CPV





Nature Phys. 15, 631–634 (2019) BESIII

1.31 B J/ψ events
Quantum correlation in Λ pair

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [14]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [16]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [16]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [16]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

2% level sensitivity for CPV test

SM prediction: $10^{-4} \sim 10^{-5}$

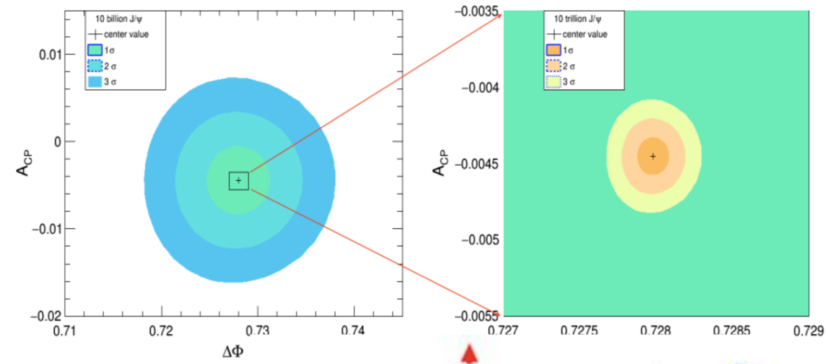
CP test $A_{CP} = \dfrac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$

18

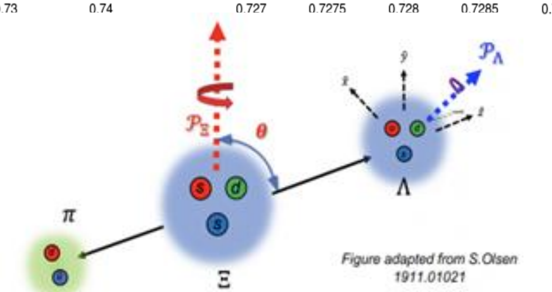
Polarization of hyperons and CPV

4 trillion J/ψ events ⇒ $A_{CP}\sim 10^{-4}$

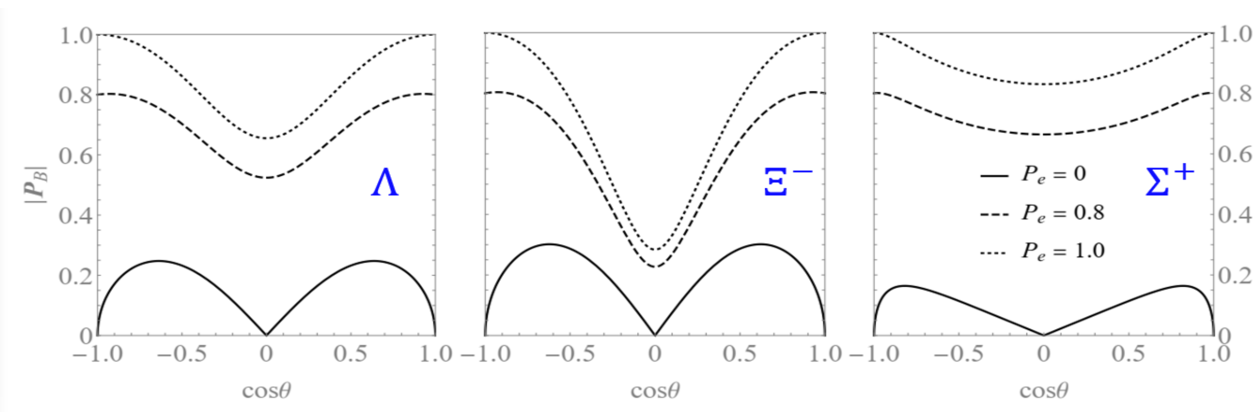
- Luminosity of STCF: × 100
- No polarized beams are needed
- Systematic is challenging



	$\sigma(A_{CP}^{[\Lambda p]})$	$\sigma(A_{CP}^{[\Xi-]})$	$\sigma(B_{CP}^{[\Xi-]})$	Comment
BESIII	1.0×10^{-2} [a]	1.3×10^{-2}	3.5×10^{-2}	1.3×10^{9} J/ψ [28, 29]
BESIII	3.6×10^{-3}	4.8×10^{-3}	1.3×10^{-2}	1.0×10^{10} J/ψ (projection)
SCTF	2.0×10^{-4}	2.6×10^{-4}	6.8×10^{-4}	3.4×10^{12} J/ψ (projection)



$$A_{CP}^{D} := \frac{\alpha_D+\overline{\alpha}_D}{\alpha_D-\overline{\alpha}_D} \quad \text{and} \quad B_{CP}^{D} := \frac{\beta_D+\overline{\beta}_D}{\alpha_D-\overline{\alpha}_D},$$



- Magnitudes of the hyperon polarization versus e^- polarization

Flavor Physics and CPV

Physics at STCF	Benchmark Processes	Key Parameters*
CKM matrix	$D^+_{(s)} \to l^+\nu_l, D \to Pl^+\nu_l$	$\delta V_{cd/cs}$~0.15%; $\delta f_{D/D_s}$~0.15%
γ/ϕ_3 measurement	$D^0 \to K_s\pi^+\pi^-, K_sK^+K^-$ ...	$\Delta(\cos\delta_{K\pi})$ ~0.007; $\Delta(\delta_{K\pi})$ ~2°
$D^0-\bar{D}^0$ mixing	$\psi(3770) \to (D^0\bar{D}^0)_{CP=-}$, $\psi(4140) \to \gamma(D^0\bar{D}^0)_{CP=+}$	Δx~0.035%; Δy~0.023%
Charm hadron decay	$D_{(s)}, \Lambda_c^+, \Sigma_c, \Xi_c, \Omega_c$ decay	$N_{D/D_s/\Lambda_c}$~$10^9/10^8/10^8$
γ polarization	$D^0 \to K_1e^+\nu_e$	$\Delta A'_{UD}$~0.015
CPV in Hyperons	$J/\psi \to \Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$, $\Xi^-\bar{\Xi}^-$, $\Xi^0\bar{\Xi}^0$	ΔA_Λ~10^{-4}
CPV in τ	$\tau \to K_s\pi\nu$, EDM of τ, $\tau \to \pi/K\pi^0\nu$ for polarized e^-	$\Delta A_{\tau\to K_s\pi\nu}$~$10^{-3}$; Δd_τ~5×10^{-19} (e cm)
CPV in Charm	$D^0 \to K^+K^-/\pi^+\pi^-$, $\Lambda_c \to pK^-\pi^+\pi^0$ ...	ΔA_D~10^{-3}; ΔA_{Λ_c}~10^{-3}

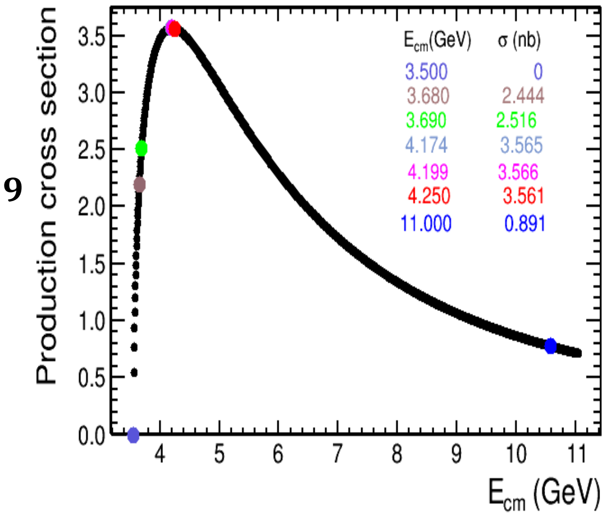
*Sensitivity estimated based on $\mathcal{L} = 1\ \text{ab}^{-1}$

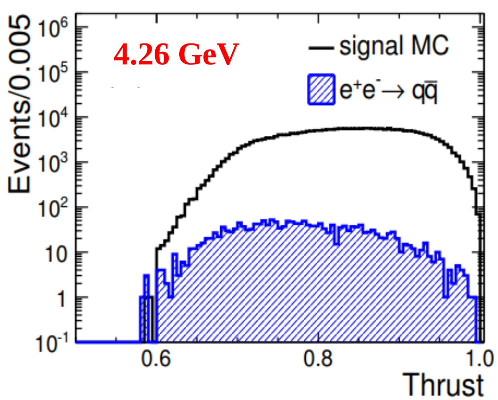
LFV in τ decays

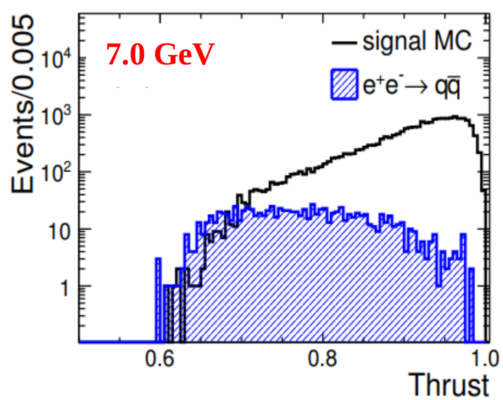
LFV is a sensitive probe for NP, τ decays are an ideal processes for LFV

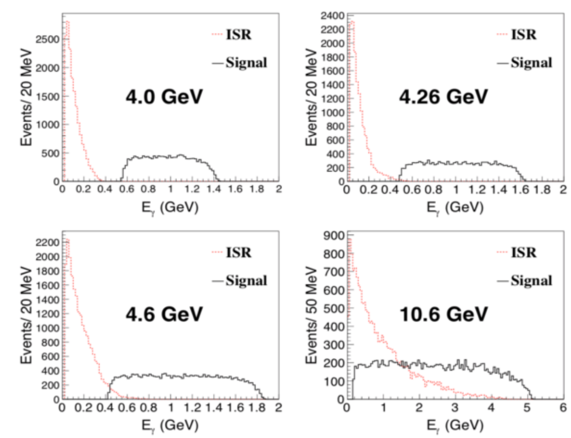
τ production at STCF :

- Peaking x-Sec in 4-5 GeV
- At 4.26 GeV, tau pair number/year: 3.5×10^{9}
- $e^+e^- \to \gamma\tau^+\tau^-$ is not the main background
- Improved π/μ mis-id rate at STCF
- **Entangled topology** of $e^+e^- \to \tau^+\tau^-$
- Large $e^+e^- \to q\bar{q}$ background at low c.m.e

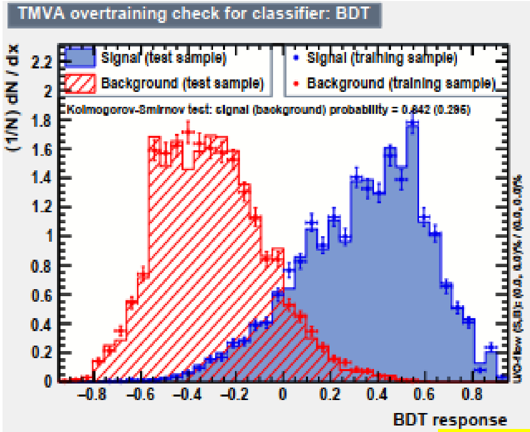


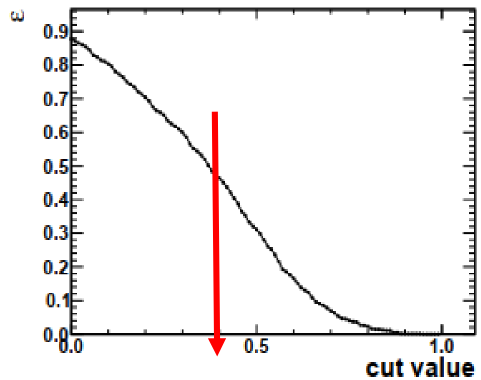






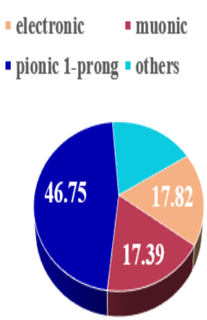
LFV decay of $\tau \to \gamma\mu / lll$

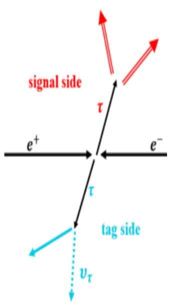


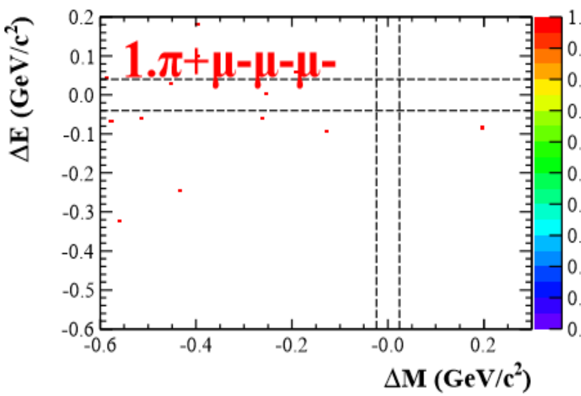


- Tag side: $\tau \to e\upsilon\bar{\upsilon},\ \pi\upsilon,\ \pi\pi^0\upsilon$ ($\mathcal{B}r = 54\%$)
- **Dominant background:** $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$, $\tau^+ \to \pi\pi^0\upsilon, \tau^- \to \mu\upsilon\bar{\upsilon}$

$$\mathcal{B}_{UL}^{90}(\tau \to \gamma\mu) < \frac{N_{UL}^{90}}{2\varepsilon N_{\tau\tau}} \sim 1.2 \times 10^{-8}\ (1\text{ab}^{-1})$$







- Tag side: $\tau \to e\upsilon\bar{\upsilon},\ \mu\upsilon\bar{\upsilon},\ \pi\upsilon + n\pi^0$ ($\mathcal{B}r = 82\%$)
- Almost background free, **the sensitivity : $\mathcal{B}_{UL}^{90}(\tau \to \mu\mu\mu) \sim 1/\mathcal{L}$**
- Best efficiency ($\tau \to \mu\mu\mu$): 22.5% **(including tag branching fraction)**

$$\mathcal{B}_{UL}^{90}(\tau \to \mu\mu\mu) < \frac{N_{UL}^{90}}{2\varepsilon N_{\tau\tau}} \sim 1.5 \times 10^{-9} (1\text{ab}^{-1})$$

LFV in J/ψ decays

- The cLFV decays of vector mesons $V \to l_i l_j$ are also predicted **in various of extension models** of SM:

$$\mathcal{B}_{UL}^{90}(J/\psi \to e\mu) < 10^{-13}$$

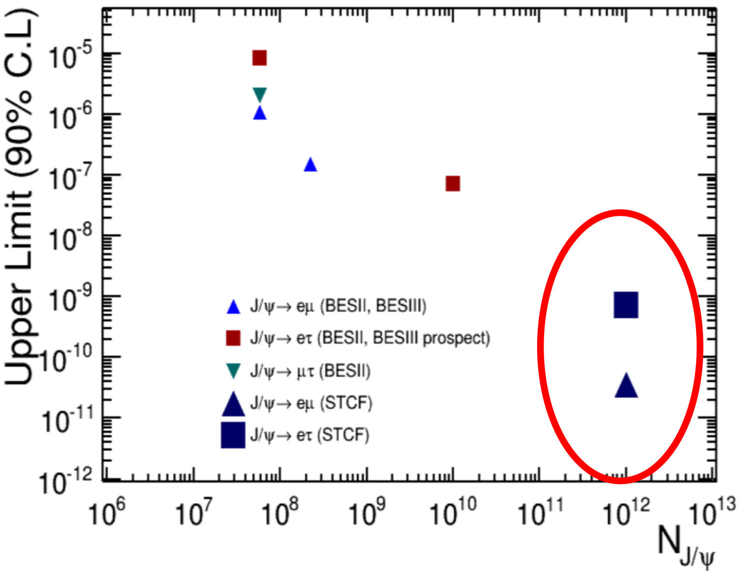
$$\mathcal{B}_{UL}^{90}(J/\psi \to \mathrm{e}(\mu)\tau)\ ) < 10^{-9}$$

- Taking efficiency from BESIII, 1 **trillion J/ψ result** the upper limit to be:

$$\mathcal{B}_{UL}^{90}(J/\psi \to e\mu) < 3.6 \times 10^{-11}$$

$$\mathcal{B}_{UL}^{90}(J/\psi \to \mathrm{e}\tau)\ ) < 7.1 \times 10^{-10}$$

- The $\mathcal{B}_{UL}^{90}(J/\psi \to \mathrm{e}\tau)$) can be further **optimized** with better PID.



Forbidden/Rare decay and NP

Physics at STCF	Benchmark Processes	Key Parameters* (U.L. at 90% C.L.)
LFV decays	$\tau \to \gamma l, lll, lP_1P_2$ $J/\psi \to ll', D^0 \to ll'(l' \neq l)\ldots$	$\mathcal{B}(\tau \to \gamma\mu/\mu\mu\mu)$<12/1.5$\times 10^{-9}$; $\mathcal{B}(J/\psi \to e\tau)<0.71\times 10^{-9}$
LNV, BNV	$D^+_{(s)} \to l^+l^+X^-, J/\psi \to \Lambda_c e^-$, $B \to \bar{B}\ldots$	$\mathcal{B}(J/\psi \to \Lambda_c e^-) < 10^{-11}$
Symmetry violation	$\eta^{(\prime)} \to ll\pi^0, \eta' \to \eta ll\ldots$	$\mathcal{B}(\eta' \to ll/\pi^0 ll) < 1.5/2.4 \times 10^{-10}$
FCNC	$D \to \gamma V, D^0 \to l^+l^-, e^+e^- \to D^*, \Sigma^+ \to pl^+l^-\ldots$	$\mathcal{B}(D^0 \to e^+e^-X) < 10^{-8}$
Dark photon, millicharged	$e^+e^- \to (J/\psi) \to \gamma A'(\to l^+l^-)\ldots$ $e^+e^- \to \chi\bar{\chi}\gamma$ ...	Mixing strength $\Delta\epsilon_{A'} \sim 10^{-4}$; $\Delta\epsilon_{\chi} \sim 10^{-4}$

*Sensitivity estimated based on $\mathcal{L} = 1\ \text{ab}^{-1}$

Summary

- **STCF is an unique facility in precision frontier**
  - **E_{cm} = 2-7GeV, peaking $\mathcal{L} > 0.5\times10^{35}\ cm^{-2}s^{-1}$, polarized beam (PhaseII)**
  - **Symmetric, double ring with circumference around 600~1000 m**
- **Important playground for studying non-pQCD, constrain EW theory and test the SM**
- **Complementary to Belle II and LHCb in understanding the QCD/EW models and searching for new physics**
- **STCF is one of the critical project for China HEP**
- **Great progress, have finished CDR, toward to technical R&D stage**

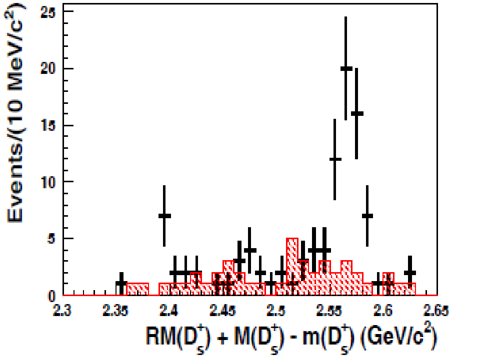
Thanks for your attention!

Welcome to join the effort!

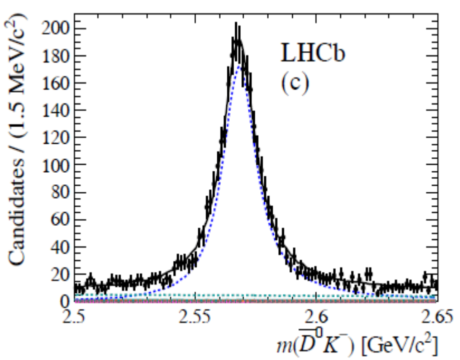
Features in Charm Hadron Decays

	STCF	Belle II	LHCb
Production yields	★★	★★★★	★★★★★
Background level	★★★★★	★★★	★★
Systematic error	★★★★★	★★★	★★
Completeness	★★★★★	★★★	★
(Semi)-Leptonic mode	★★★★★	★★★★	★★
Neutron/K_L mode	★★★★★	★★★	☆
Photon-involved	★★★★★	★★★★	★
Absolute measurement	★★★★★	★★★	☆

0.5 fb^{-1} ~ 80 Events
1.0 ab^{-1} ~ 160000 Events



3.0 fb^{-1} ~ 4000 Events
60 fb^{-1} ~ 80000 Events



- Most are **precision** measurements, which are mostly dominant by the **systematic** uncertainty
- STCF has **overall advantages** in several studies

Precision Measurements of CKM Elements

CKM matrix elements are fundamental SM parameters that describe the mixing of quark fields due to weak interaction.

- **A precise test of EW theory**
- **New physics beyond SM?**

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

BESIII + B factories + LQCD

Three generations of quark?

Unitary matrix?

Expected precision < 2% at BESIII

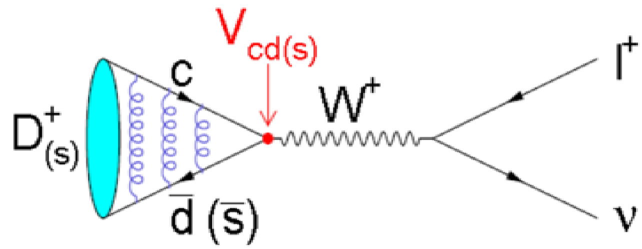
BESIII + B factories + LHCb + LQCD

A direct measurement of $V_{cd(s)}$ is one of the most important task in charm physics

$D_{(s)}$ (Semi-)Leptonic decay

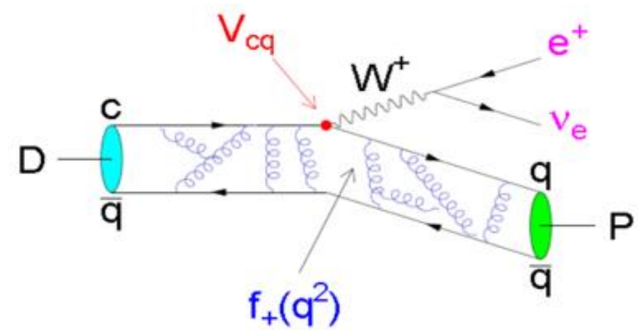
Purely Leptonic:

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



Semi-Leptonic:

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

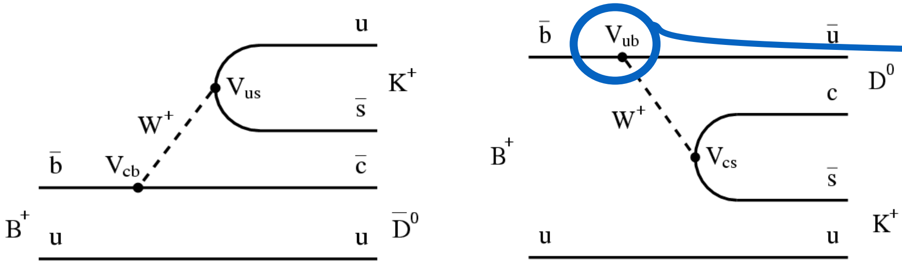


Directly measurement : $|V_{cd(s)}|$ x $f_{D(s)}$ or $|V_{cd(s)}|$ x FF

- Input $f_{D(s)}$ or $f^{k(\pi)}(0)$ from LQCD $\Rightarrow$ $|V_{cd(s)}|$
- Input $|V_{cd(s)}|$ from a global fit $\Rightarrow$ $f_{D(s)}$ or $f^{k(\pi)}(0)$
- Validate LQCD calculation of Input $f_{B(s)}$ and provide constrain of CKM-unitarity

Determination of γ/ϕ_3 angle

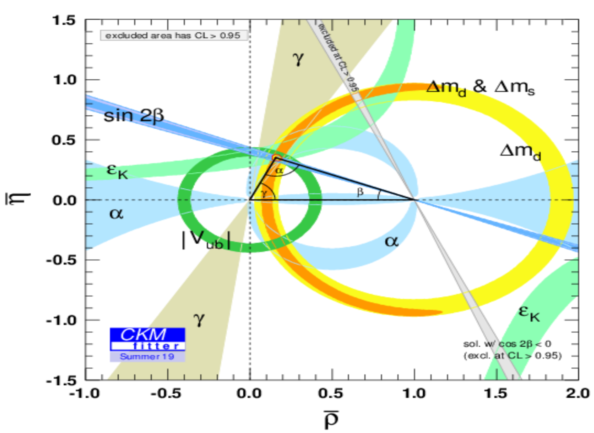
- The cleanest way to extract γ is from $B \to DK$ decays:

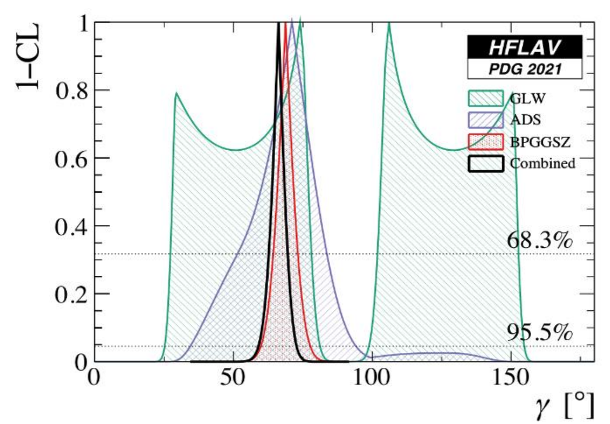


$$\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \overline{D^0} K^+)} \equiv r_B e^{i(\delta_B + \phi_3)}$$

  – Interference between tree-level decays; theoretically clean
  – current uncertainty $\sigma(\gamma) \sim 5^0$
  – however, theoretical relative error $\sim 10^{-7}$ (very small!)

- Information of *D decay strong phase* is needed
  – Best way is to employ quantum coherence of DD production at threshold





Determination of γ/ϕ_3 angle

Runs	Collected / Expected integrated luminosity	Year attained	γ/ϕ_3 sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	8°
LHCb Run-2 [13 TeV]	5 fb^{-1}	2018	4°
Belle II Run	50 ab^{-1}	2025	1.5°
LHCb upgrade I [14 TeV]	50 fb^{-1}	2030	$< 1^\circ$
LHCb upgrade II [14 TeV]	300 fb^{-1}	(>)2035	$< 0.4^\circ$

BESIII 20/fb:
$\sigma(\gamma) \sim 0.4^o$

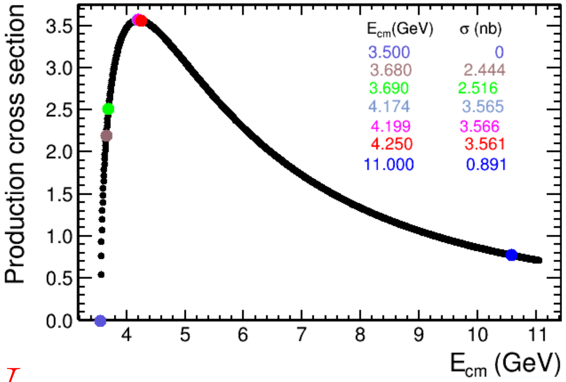
STCF is needed!

Three methods for exploiting interference (choice of D^0 decay modes):

- Gronau, London, Wyler (GLW): Use CP eigenstates of $D^{(*)0}$ decay,
  e.g. $D^0 \rightarrow K_s\pi^0$, $D^0 \rightarrow \pi^+\pi^-$
- Atwood, Dunietz, Soni (ADS): Use doubly Cabibbo-suppressed decays, e.g. $D^0 \rightarrow K^+\pi^-$
  - With 1 ab^{-1} @ STCF : $\sigma(\cos\delta_{K\pi}) \sim 0.007$; $\sigma(\delta_{K\pi}) \sim 2^o$ ➔ $\sigma(\gamma) < 0.5^o$
- Giri, Grossman, Soffer, Zupan (GGSZ): Use Dalitz plot analysis of 3-body D^0 decays, e.g. $K_s\pi^+\pi^-$; high statistics; need precise Dalitz model
  - STCF reduces the contribution of *D* Dalitz model to a level of $\sim 0.1^o$

τ Lepton Physics

- X sec grows from 0.1nb near threshold to 3.5 nb at 4.25 GeV
  - 1×10^8 tau pairs/year at threshold (0.1 nb)
  - 3.5×10^9 tau pairs/year at 4.25 GeV (3.5 nb)
  - 10^{10} τ pairs per year for Belle II (1 nb)



- Highlighted Physics program
  - τ properties : m_τ, $(g\text{-}2)_\tau/2$
  - SM properties : universality test, Michel parameters, α_s, V_{us}
  - CPV test : $\tau^- \to K_S^0 \pi^- \nu_\tau$, T-odd triple product in polarization beam
  - LFV : $\tau \to \ell\gamma$, $\ell\ell\ell$, ℓh
- Comparison to Belle II
  - Threshold effect is important for controlling and understanding background
  - Relatively high efficiency
  - Longitudinal polarization of the initial beams will significantly increase sensitivity in searches for CPV in lepton decays.

CPV in τ decay

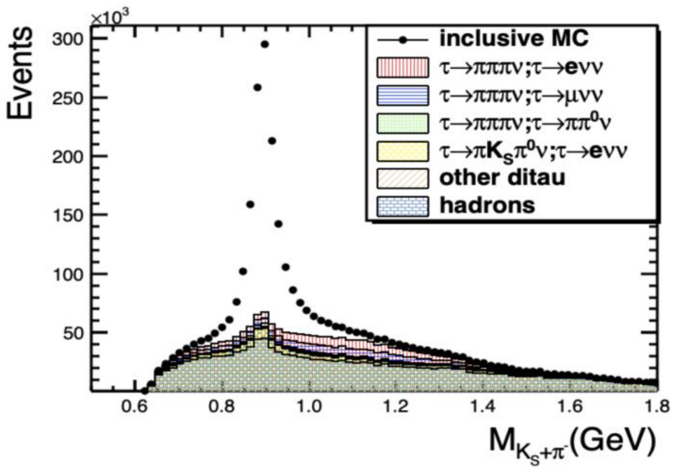
- The CPV source in $K^0-\bar{K}^0$ **mixing** produces a difference in tau decay rate

In Theory : $A_Q = \frac{B(\tau^+ \to K_S^0\pi^+\bar{\nu}_\tau) - B(\tau^- \to K_S^0\pi^-\nu_\tau)}{B(\tau^+ \to K_S^0\pi^+\bar{\nu}_\tau) + B(\tau^- \to K_S^0\pi^-\nu_\tau)} = (+0.36 \pm 0.01)\%$

BaBar experiments : $A_{CP}(\tau^- \to K_S\pi^-\nu[\geq 0\pi^0]) = (-0.36 \pm 0.23 \pm 0.11)\%$

2.8σ away from the SM prediction

Theorist try to reconcile the deviation, but not coverage even NP included



The CPV sensitivity with 1ab^{-1} @ 4.26 GeV[1]:

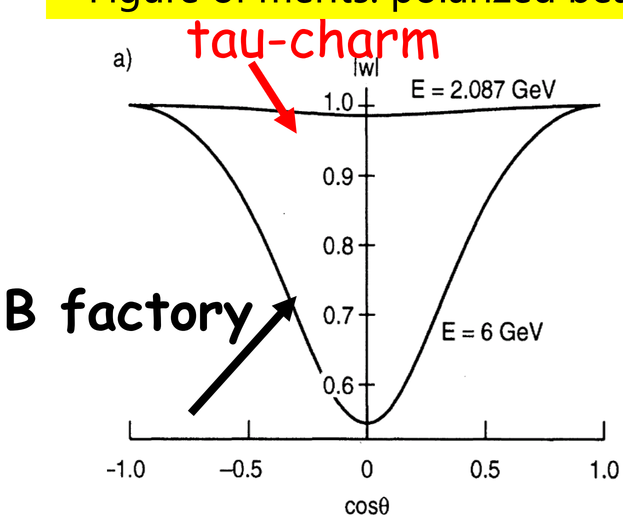
$A_{STCF} \sim 9.7 \times 10^{-4}$

With 10 ab^{-1} data:

$A_{STCF} \sim 3.1 \times 10^{-4}$

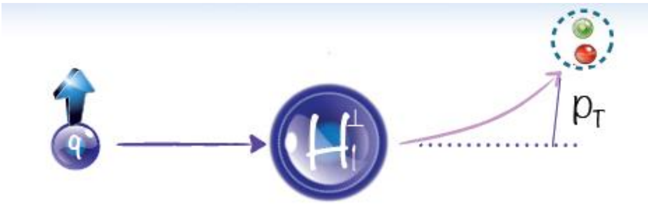
[1]. H. Sang, *et al.*, Chin. Phys. C 45, no.5, 053003 (2021)

Possible choice to increase the Figure of merits: polarized beam



$$\text{merit} = \text{luminosity} \times \bar{w}_Z \times \text{ total cross section}$$
$$\propto \text{luminosity} \times (w_1 + w_2)$$
$$\times \sqrt{1 - a^2 a^2}(1 + 2a) \,,$$

Collins Fragmentation Function (FF)



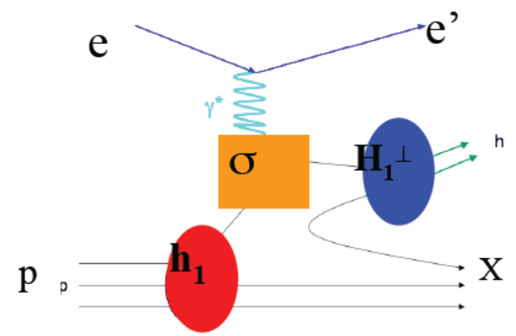
J. C. Collins, Nucl. Phys. B396, 161 (1993)

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

D_1: the un-polarized FF
H_1: Collins FF
→ describes the fragmentation of a transversely polarized quark into a spin-less hadron *h*.
→ depends on $z = 2E_h/\sqrt{s}$,
→ leads to an azimuthal modulation of hadrons around the quark momentum.

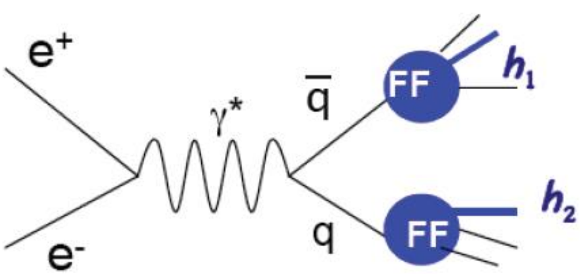
SIDIS

Transversity ⊗ Collins FF



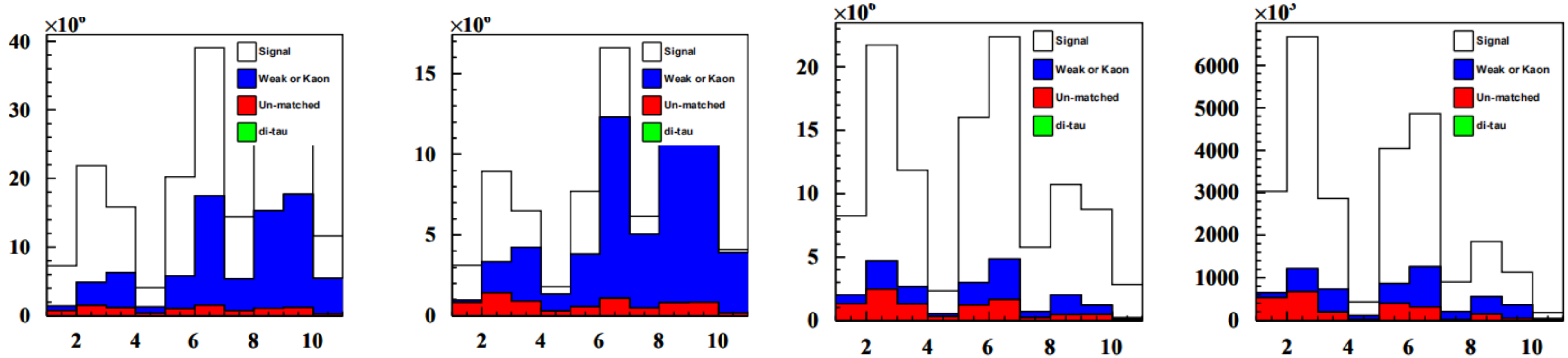
e+ e-

Collins FF ⊗ Collins FF



Collins FF at STCF

- STCF is a perfect machine for studying Collins effect
- Poor performance for the traditional dE/dx & TOF PID system for tracks > 0.8GeV
- This measurement suffer from systematic uncertain from $K-\pi$ mis-PID.
- The mis-PID is even worse in the case of KK Collins measurement.
- With 2.5 fb^{-1} 7GeV $q\bar{q}$ MC ($\sigma \approx$ 5nb LundArlw), we study Collins effect at STCF.

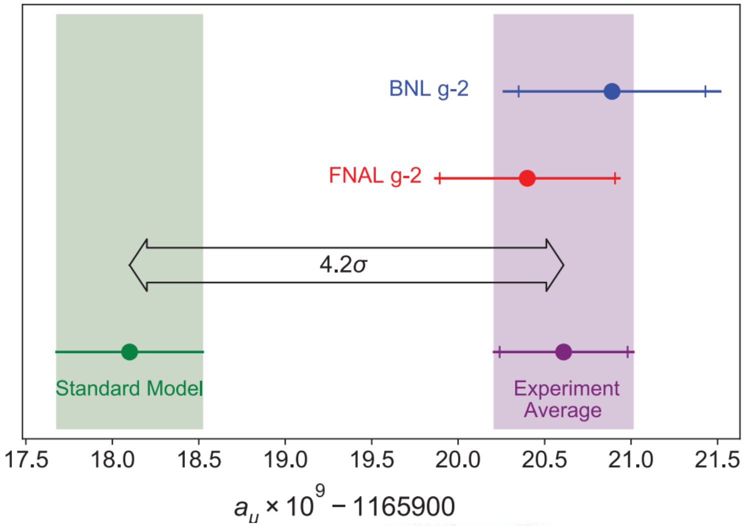


Blue: π/K mis-PID in KK Collins measurement.
Left) de/dx&TOF. Right) a 1% mis-PID set in FastSim

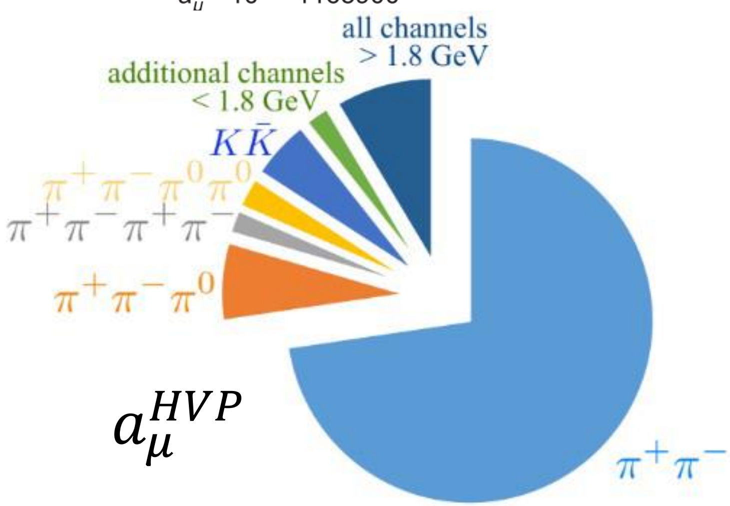
- By setting the K/π mis-PID at 1%, we obtain[1]:
  - The statistical uncertainty for $25\mathrm{fb}^{-1}$ MC is ~10^{-3} to 10^{-2}
  - The statistical uncertainty for $1\mathrm{ab}^{-1}$ MC is ~10^{-4} to 10^{-3}

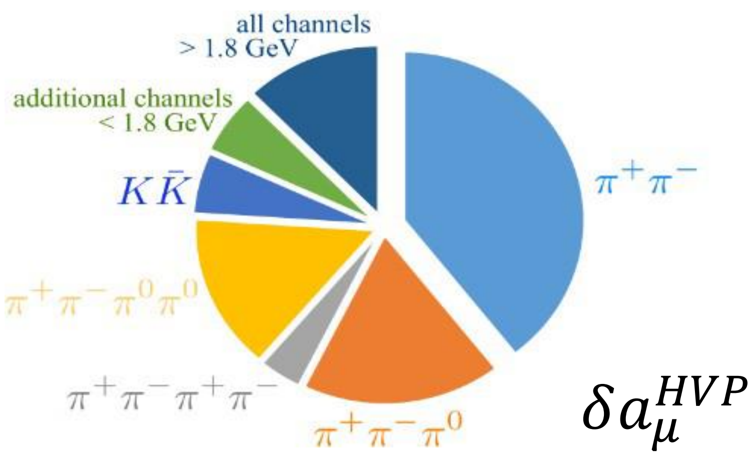
[1]. Wang B L, Lv X R, Zheng Y H. Journal of University of Chinese Academy of Sciences, 2021, 38(4):433-441

HVP Contribution to $(g-2)_\mu$



- **4.2σ discrepancy => Strong indication for physics beyond the SM?**
- **Dominant uncertainty of SM prediction comes from Hadronic vacuum polarization (HVP)**

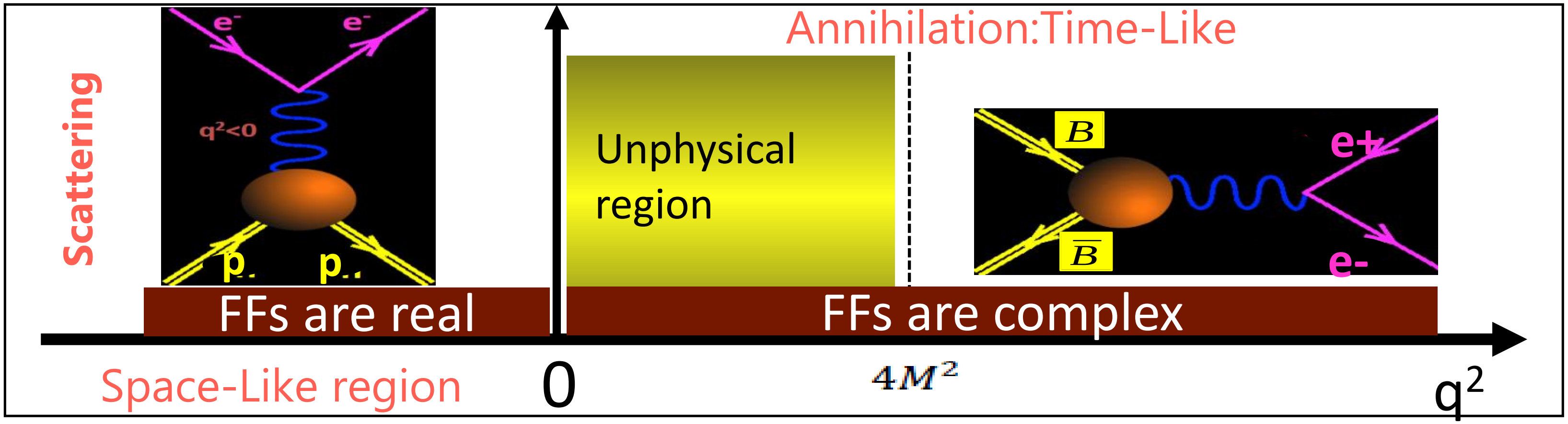




High Luminosity of STCF will largely improve the SM precisions !

Electromagnetic Form Factors

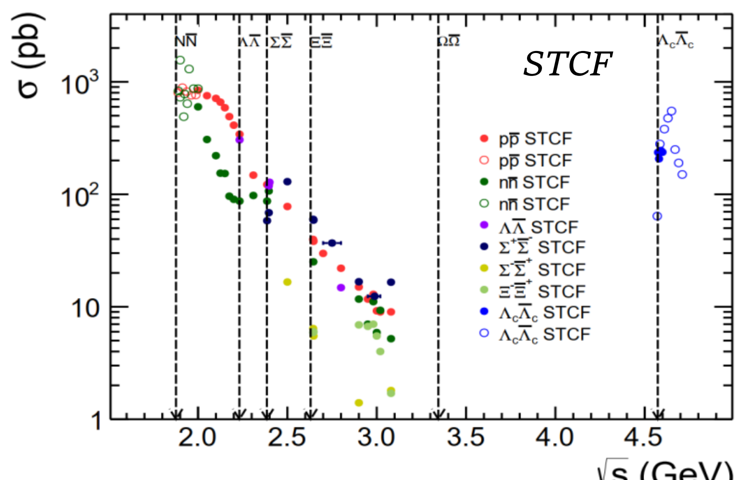
- **Fundamental properties of the nucleon**
  - **Connected to charge, magnetization distribution**
  - **Crucial testing ground for models of the nucleon internal structure**



$$\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)$$

$$G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2),$$

$$G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$$



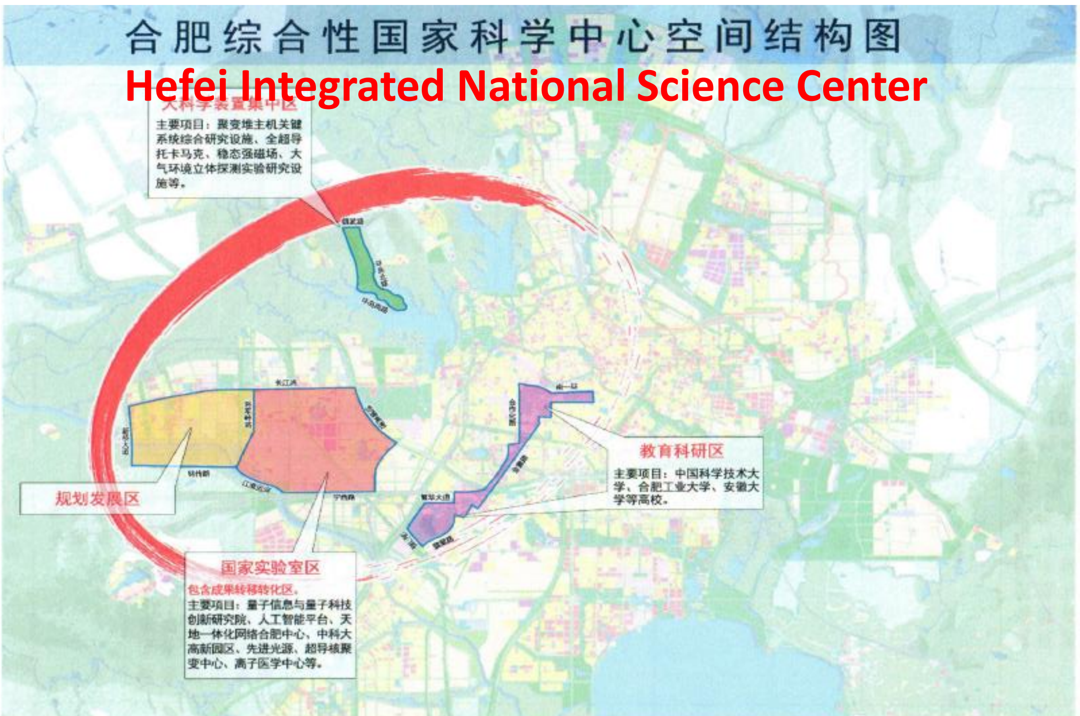
Strategy & Activities

CDR → TDR → project application → construction → commissioning

- Strategy: focus on CDR (4 years) and TDR (7 years) depend on the available resources. the construction site open.
- Domestic Workshops (2011, 12, 13, 14, 16, 20)
- International Workshops (2015, 18, 19, 20)
- 2015 Fragrance Hill-Science Conference (No. 533)
- Report to USTC Scientific Committee and USTC presidents
- Report to local government
- Form the Organization (including project manager, physics/detector/accelerator work groups ....)
- Regular weekly meetings for Accelerator/Detector/Physics !

Candidate Site : Hefei

One of three integrated national science centers, which will play important role in 'Megascience' of China in near future



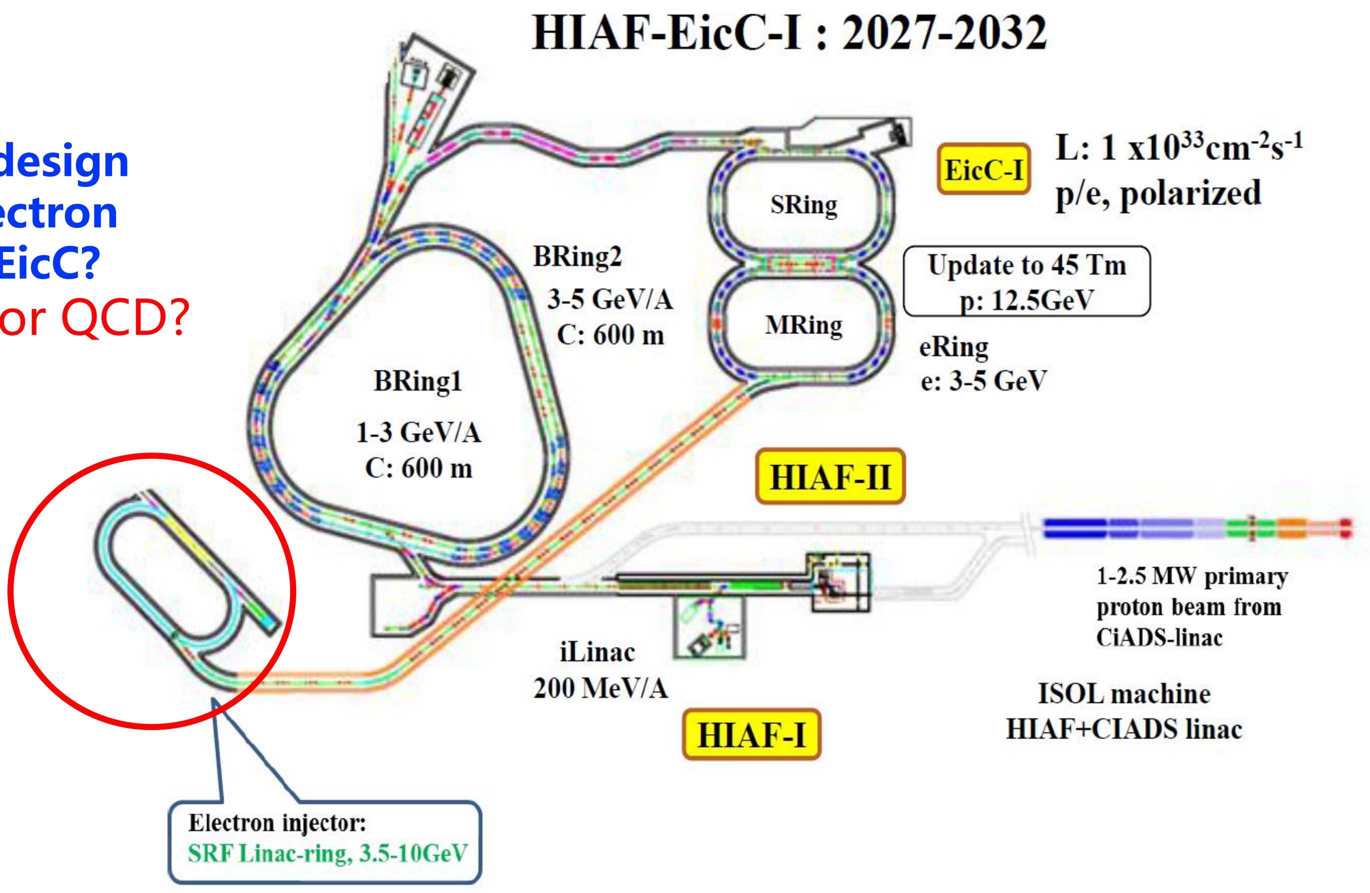
- University of Science and Technology of China (USTC)
- National Synchrotron Radiation Lab and Hefei Light Source, operated by USTC
- The only National Lab operated by University in China. (Totally Four officially approved National Labs in China)

- **Pay a lot of attention on accelerator facilities**
- **Hefei Advanced light source is under design**
- **STCF is listed in future plan**

Candidate Site : Huizhou

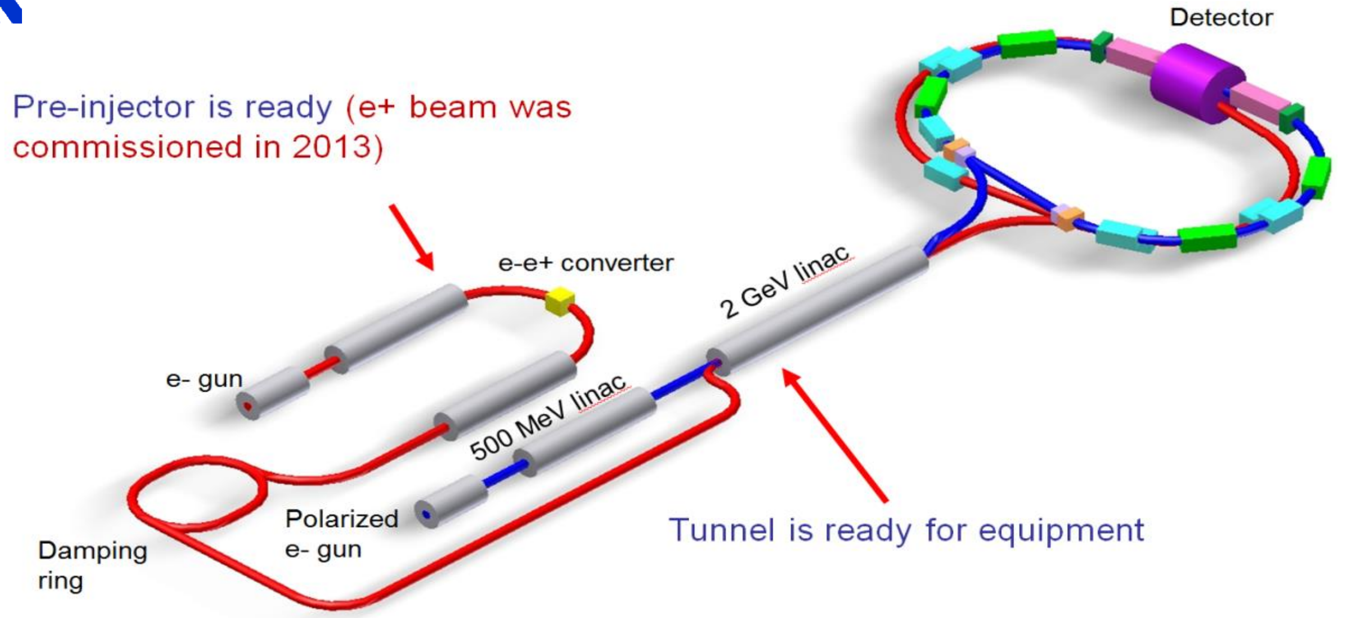
Institute of Modern Physics, CAS, proposed building HIAF-EicC in Huizhou, Canton

STCF Share the design effort of the electron accelerator of EicC?
National Center for QCD?



International Collaboration

Super Charm-Tau at Novosibirsk, RUSSIA,
Budker Institute of Nuclear Physics (BINP)



- Pre-Agreement of Joint effort on R&D, details are under negotiation
- Joint workshop between China, Russia, and Europe
  - 2018 UCAS (March), Novosibirsk (May), Orsay (December)
  - 2019 Moscow(September), 2020 Online (November)