Super-c-τ Factory (SCTF)

Simon Eidelman

Budker Institute of Nuclear Physics SB RAS
and Novosibirsk State University, Novosibirsk, Russia
and Lebedev Physical Institute RAS, Moscow, Russia

Outline

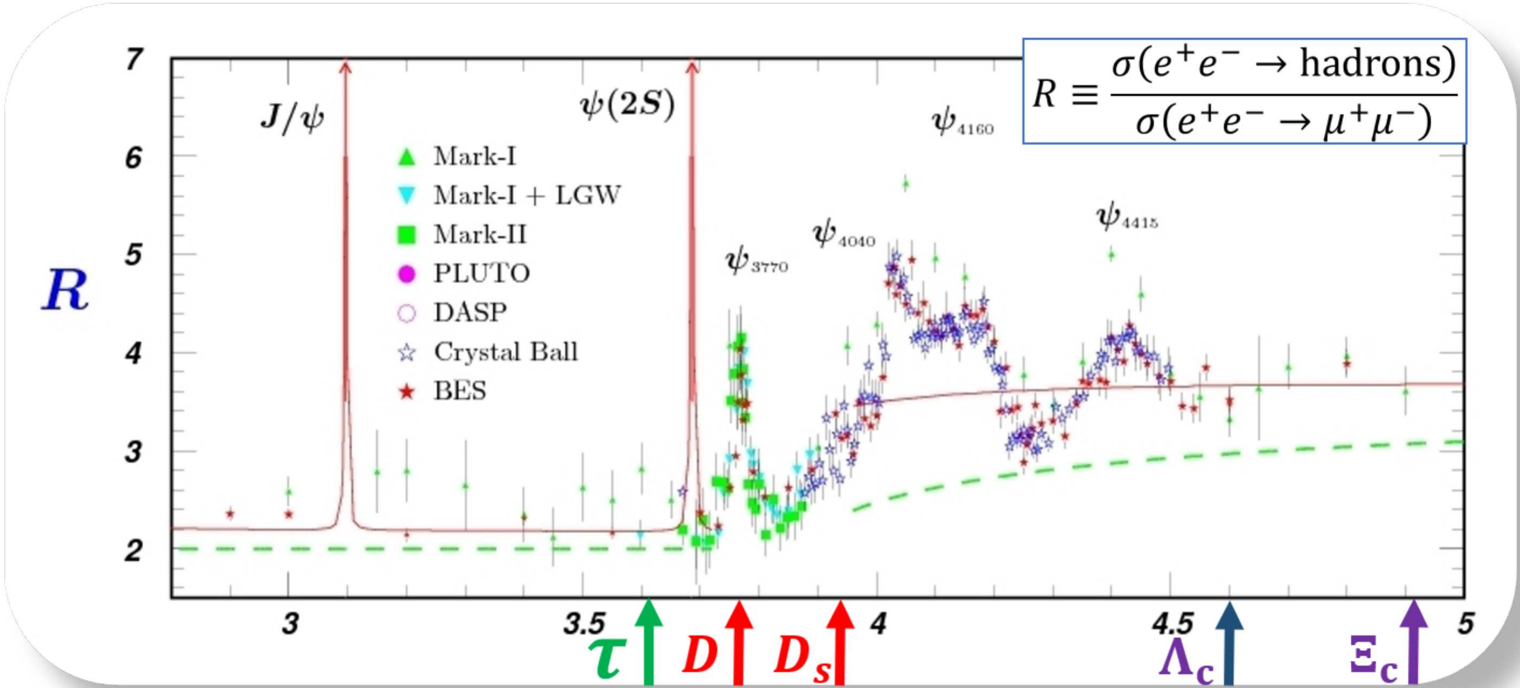
1. Physics case
2. Machine and Detector
3. HIEPA
4. Conclusions

What is Super-Charm-Tau Factory?

A Super-Charm-Tau Factory is an (e^+e^- collider) complex for high-precision measurements between 2 and 6 (7) GeV with instantaneous luminosity up to $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and longitudinal polarization of the initial e^- beam

Integrated luminosity of $\sim 10\ \mathrm{ab}^{-1}$ could be collected in 10 years

General View of the Energy Range



The energy range covers rich physics from light quark mesons to $\tau^+\tau^-$ threshold, charm mesons and baryons

General

Strategic tasks of SCTF

- Studies in non-perturbative QCD (formfactors, hadron spectroscopy, dynamics of multibody decays)
- Studies of weak interactions of leptons and quarks of the 1st and 2nd generations
- Searches for New Physics

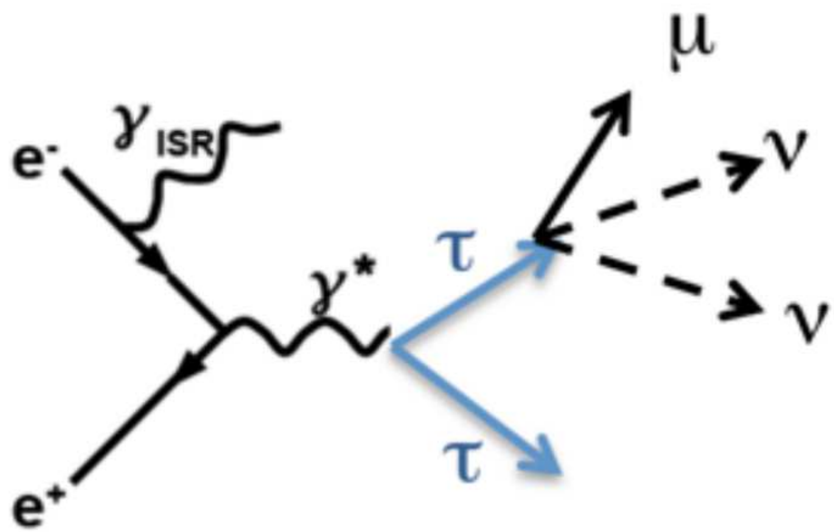
Advantages of SCTF

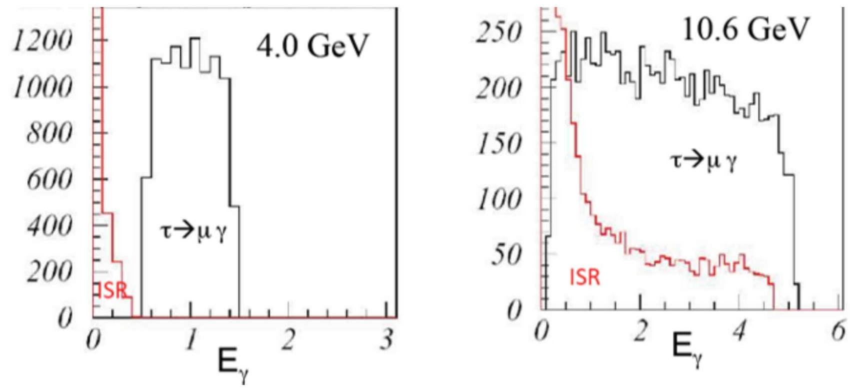
- Threshold production of pairs of τ leptons and charm hadrons
- Longitudinal polarization of initial electrons (CP violation in decays of charm baryons and τ leptons)
- Coherent production of $D^0\bar{D}^0$ mesons (measurement of phases)
- Double tagging (measurement of absolute branchings)

τ Lepton Physics

- $\sigma_{\tau\tau}$ grows from 0.1 nb near threshold to 3.5 nb at 4.25 GeV
- $\sim 10^{10}$ τ pairs can be collected
- Near threshold an additional kinematic constraint $2M_\tau E_h = M_\tau^2 + M_h^2$ suppresses background, with 1 ab^{-1} about 10^8 τ pairs can be produced
- LFV, suppression of ISR ($e^+e^- \to \tau^+\tau^-\gamma$)
- M_τ, M_{ν_τ}, lepton universality, a_τ, d_τ
- $V-A$ structure of the weak current in leptonic decays (Michel parameters)
- Rare hadronic decays (K^* spectroscopy)
- Vector, axial and strange spectral functions ($\alpha_s(m_\tau)$, $|V_{us}|$, ...)
- Second class currents
- CP violation in τ decays

Lepton Flavor Violation in $\tau^- \to \mu^- \gamma$





Dominant BG - $\tau^- \to \mu^- \nu_\mu \bar{\nu}_\mu \gamma_{\rm ISR}$

Best limit (BaBar):

$\mathcal{B}(\tau^- \to \mu^- \gamma) < 4.5 \times 10^{-8}$

Threshold kinematics - advantages

Good π/μ separation needed

Belle with 50 ab^{-1}: $\mathcal{B}(\tau^- \to \mu^- \gamma) < 6 \times 10^{-9}$

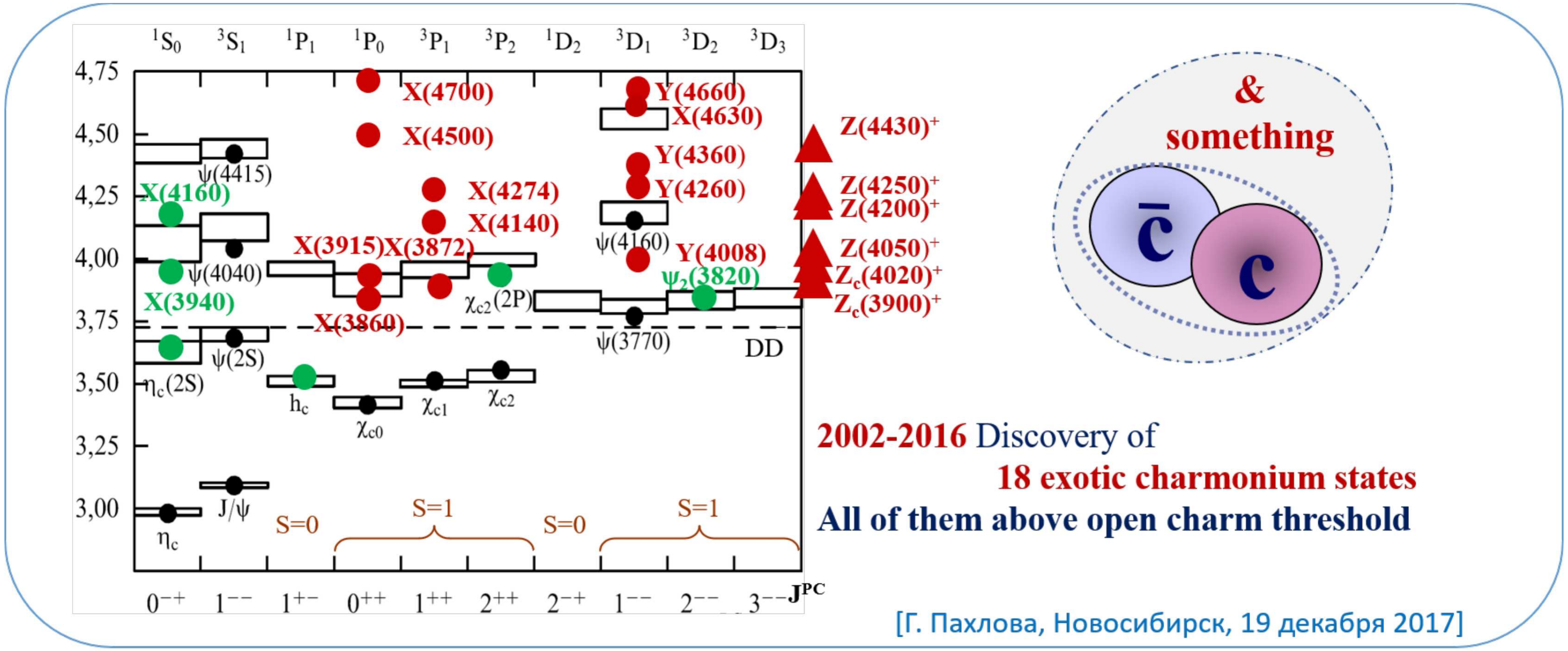
SCTF with 10 ab^{-1}: $\mathcal{B}(\tau^- \to \mu^- \gamma) < 10^{-9}$

Conventional Charmonia

State	J/ψ	$\psi(2S)$	$\psi(3770)$	$\psi(4040)$
M, GeV	3.097	3.686	3.773	4.040
Γ, MeV	0.093	0.294	27	84
$\int Ldt, \mathrm{fb}^{-1}$	800	250	400	10
N	10^{12}	10^{11}	$2 \cdot 10^{9}$	10^{8}

- Even for the J/ψ and $\psi(2S)$ full decay pattern is unclear
- Is the $\psi(3770)$ a $D\overline{D}$ factory?
- 20 (25) fb^{-1} needed to produce 10^8 $\psi(4160)$ ($\psi(4415)$) mesons
- $\sim 10^{10}$ χ_{cJ} and $\eta_c(1S)$ in radiative decays of the J/ψ and $\psi(2S)$
- About 10^8 h_c mesons in $\psi(2S) \to h_c\pi^0$
- $\eta_c(2S)$ mesons can be produced in $\psi(2S) \to \eta_c(2S)\gamma$ or $\gamma\gamma$ collisions
- Although believed to be conventional, these states are not well enough studied

Study of Charmonium-(like) States – I



Dots – good old guys, Dots – new states matching Quark Model

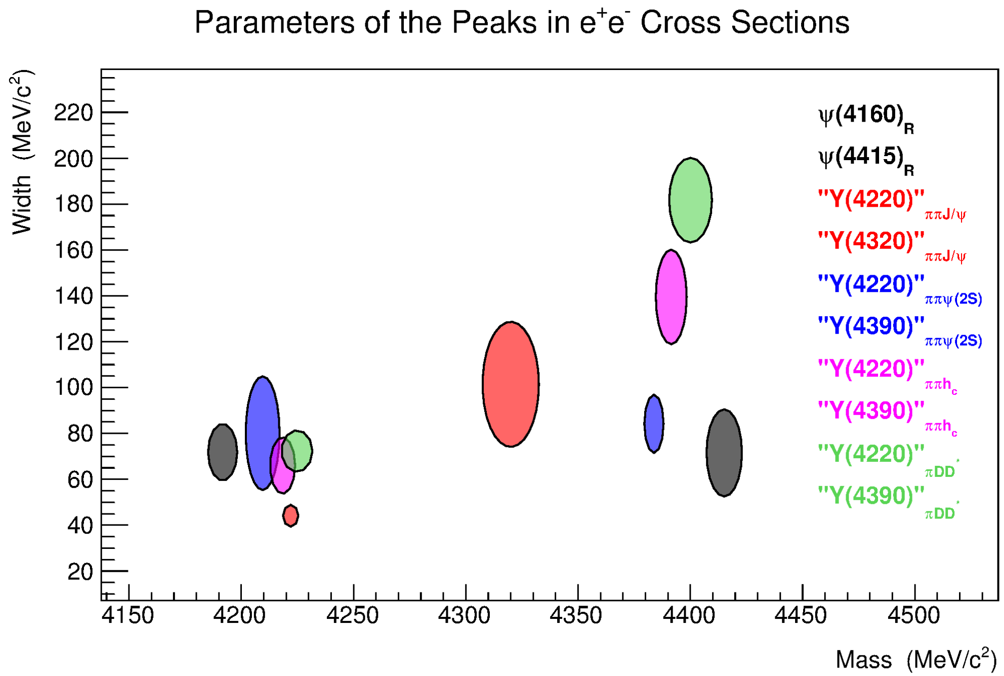
Dots – neutral, triangles – charged states, exotic?

Rectangulars – potential model predictions

Exotic because of the too large number of states with given $I^G J^{PC}$

or unexpected decay pattern ($J/\psi\pi^+\pi^-$ instead of open charm)

Study of Charmonium-(like) States – II



A figure from Bin Wang's talk

Huge data samples needed to perform a coupled-channel analysis resulting in a consistent set of resonance parameters

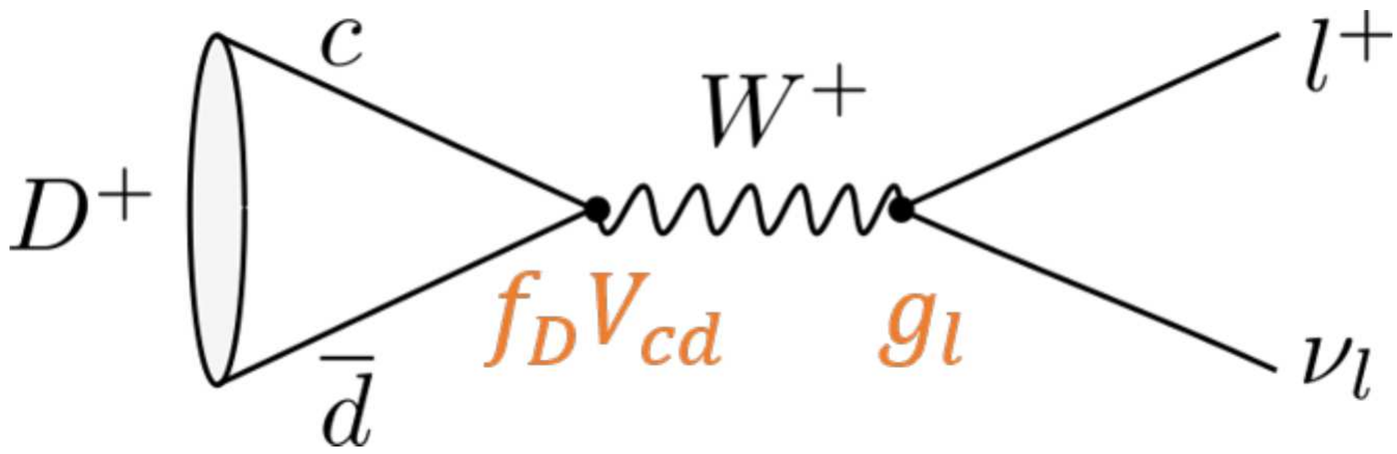
Study of Charmonium-(like) States – III

- All $\psi(Y)$ states with $J^{PC} = 1^{--}$ will be directly produced at $\sqrt{s} = M_Y$: $\psi(4260/4230)$, $\psi(4360)$, $\psi(4660)$
- Charged Z_c states can be produced by scanning the $\sqrt{s}$ range and studying the $J/\psi\pi\pi$, $h_c\pi\pi$, $D^{(*)}\bar{D}^{(*)}$ final states
- Neutral $c\bar{c}$ states with other quantum numbers can be studied in the recoil to $\pi\pi$, π^0, η, ω final states
- $C = +1$ states can be also produced in $\gamma\gamma$ collisions
- Between 6 and 7 GeV double $c\bar{c}$ production?

Charm Physics

- 10^9 pairs of $D^{\pm,0}$ and $2 \cdot 10^7$ D_s mesons can be collected in the reaction $e^+e^- \to D^+D^-,\ D^0\bar{D}^0,\ D_s^+D_s^-$
- More precise results can be expected at the $\psi(3770)$ with a data sample lower than at the $\Upsilon(4S)$
- The multiplicity of final particles is lower by a factor of 2
- Clean $D\bar{D}$ events are produced near threshold, additional kinematic constraints are possible (ν reconstruction), double-tagging: one D is fully reconstructed and for the other D absolute $\mathcal{B}$ are measured
- At threshold D and $\bar{D}$ are produced in QM coherent state, e.g., in $e^+e^- \to D\bar{D}(J^{PC} = 1^{--})$ making possible studies of $D - \bar{D}$ mixing, CP violation, with determination of strong phase shifts and probabilities for decays to CP-pure states
- 50 fb^{-1} between 4.3 and 5 GeV to study spectroscopy of D_J and D_{sJ} states produced in $e^+e^- \to D_0^*\bar{D}^*,\ D_1^{(\prime)}\bar{D}^{(*)},\ D_2^*\bar{D}^{(*)}$ with $\sigma \sim 1$ nb

$D_s^+ \to \tau^+\nu_\tau,\ \tau^+ \to e^+\nu_e\bar{\nu}_\tau$ – I

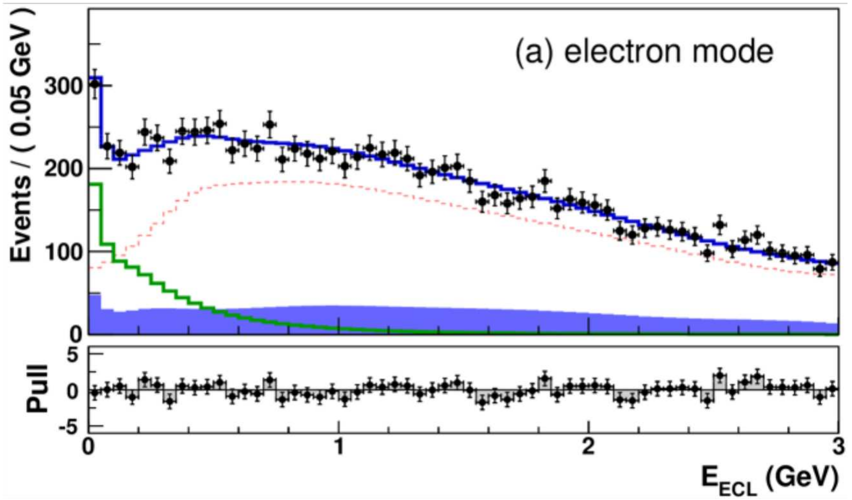


$$\Gamma(D_s^+ \to l^+\bar{\nu}_l) = \frac{G_F^2}{8\pi} f_{D_s}^2 m_l^2 m_D (1 - m_l^2/m_D^2)|V_{cd}|^2$$

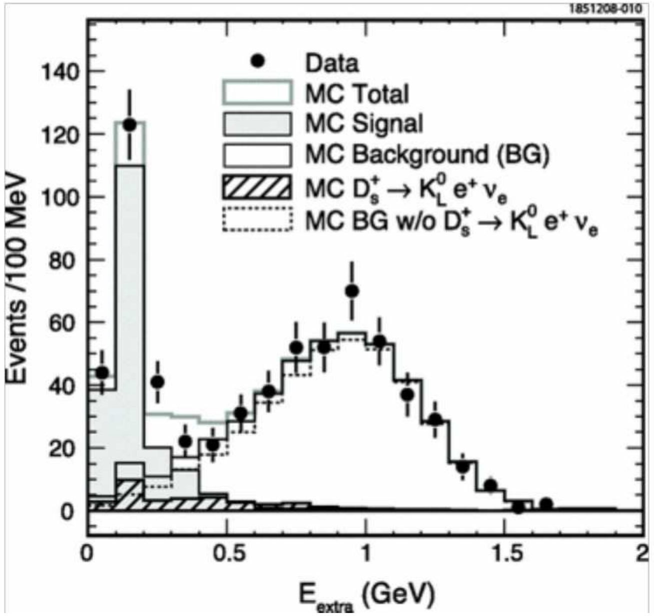
Helicity suppression $\Rightarrow \mathcal{B}(\tau) \gg \mathcal{B}(\mu) \gg \mathcal{B}(e)$

$D_s^+ \to \tau^+\nu_\tau,\ \tau^+ \to e^+\nu_e\bar{\nu}_\tau$ – II

[Belle, JHEP 09 (2013), 139]



[CLEO-c, PRD 79 (2009), 052002]



Belle, 913 fb^{-1}

Signal/BG $\sim 1/1$

$f_{D_s} = (255.5 \pm 4.2 \pm 5.1)$ MeV

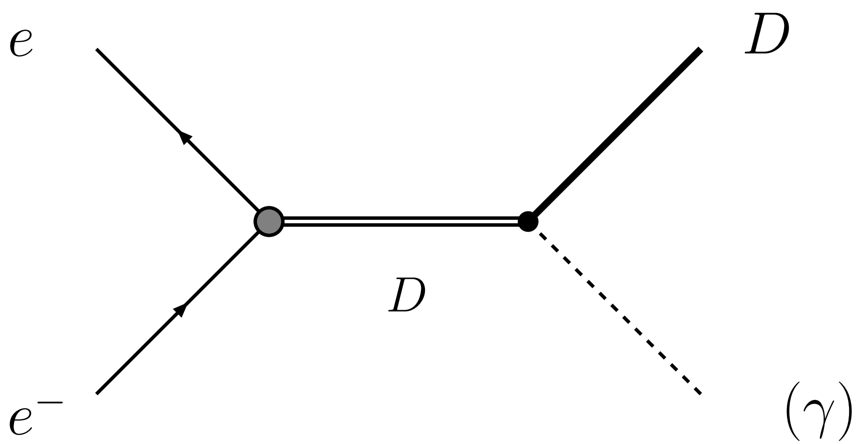
CLEO-c, 600 pb^{-1} @4.17 GeV

Signal/BG $> 10/1$

$f_{D_s} = (252.2 \pm 11.1 \pm 5.2)$ MeV

SCTF with 600 fb^{-1} @ 4.17 GeV should provide $\sigma \sim 0.35$ MeV

$e^+e^- \to D^{*0}$ (B_s^{*0}) as probes of FCNC



State	M, MeV	Γ, keV	$\mathcal{B}(e^+e^-)$
D^{*0}	2007	60	10^{-18}
B_s^{*0}	5415	0.07	10^{-11}

New Physics can significantly enhance $\mathcal{B}$

A. Khodjamirian, Th. Mannel, A.A. Petrov, JHEP 1511 (2015) 142

Search for $e^+e^- \to D^{*0}$ at VEPP-2000

- CMD-3 searched for $e^+e^- \to D^{*0}$ with 3.7 pb^{-1} collected during one week at $\mathcal{L} \sim 10^{31}$ cm^{-2} s^{-1}
- BSLL measures $E_{\text{cm}} = 2006.632 \pm 0.008$ MeV, $\sigma_{E_{\text{cm}}} = 0.954 \pm 0.053$ MeV
- $M_{D^{*0}} = 2006.85 \pm 0.05$ MeV, $\Gamma_{D^{*0}} \sim 60$ keV (from $\Gamma_{D^{*\pm}} = 83.4 \pm 1.8$ keV)
- $D^{*0} \to D^0\pi^0$, $D^0\gamma$, $D^0 \to K^-\pi^+\pi^-\pi^+$ (8.1%)
- Radiative corrections decrease N_{ev} by 40%, $\Gamma_{D^{*0}}/\sigma_{E_{\text{cm}}}$ by a factor ~ 30

N_{ev}	$D^0\pi^0$	$D^0\gamma$
Signal	2	1
BG	1.2 ± 0.5	1.5 ± 0.7

The result is $\mathcal{B}(D^{*0} \to e^+e^-) < 1.6 \times 10^{-6}$ at 90% CL

D.N. Shemyakin et al. (CMD-3 Collab.), Talk at PhiPsi2019

SCTF can improve sensitivity and UL by 3-5 orders depending on BG

Charmed Baryons

- Charmed baryons are produced via $e^+e^- \to B_{1c}\bar{B}_{2c}$ with $B_{ic} = q_1 q_2 c$
- From the QF-asymmetric antitriplet 3 spin-1/2 states (Λ_c^+, Ξ_c^+, Ξ_c^0)
- From the QF-symmetric sextuplet 6 spin-1/2 states ($\Sigma_c^{++,+,0}$, $\Xi_c^{\prime +}$, $\Xi_c^{\prime 0}$, Ω_c^0), 6 spin-3/2 states ($\Sigma_c^{*++,+,0}$, Ξ_c^{*+}, Ξ_c^{*0}, Ω_c^{*0}), all 15 S-wave discovered
- The quark model predicts 63 P-wave states, 16 discovered between 2.6 and 3.1 GeV
- Weak decays of the $\Lambda_c^+(2286)$, $\Xi_c^+(2468)$, $\Xi_c^0(2471)$ and $\Omega_c^0(2698)$ are of interest, the required maximum energies are 4.7, 5.1 and 5.5 GeV

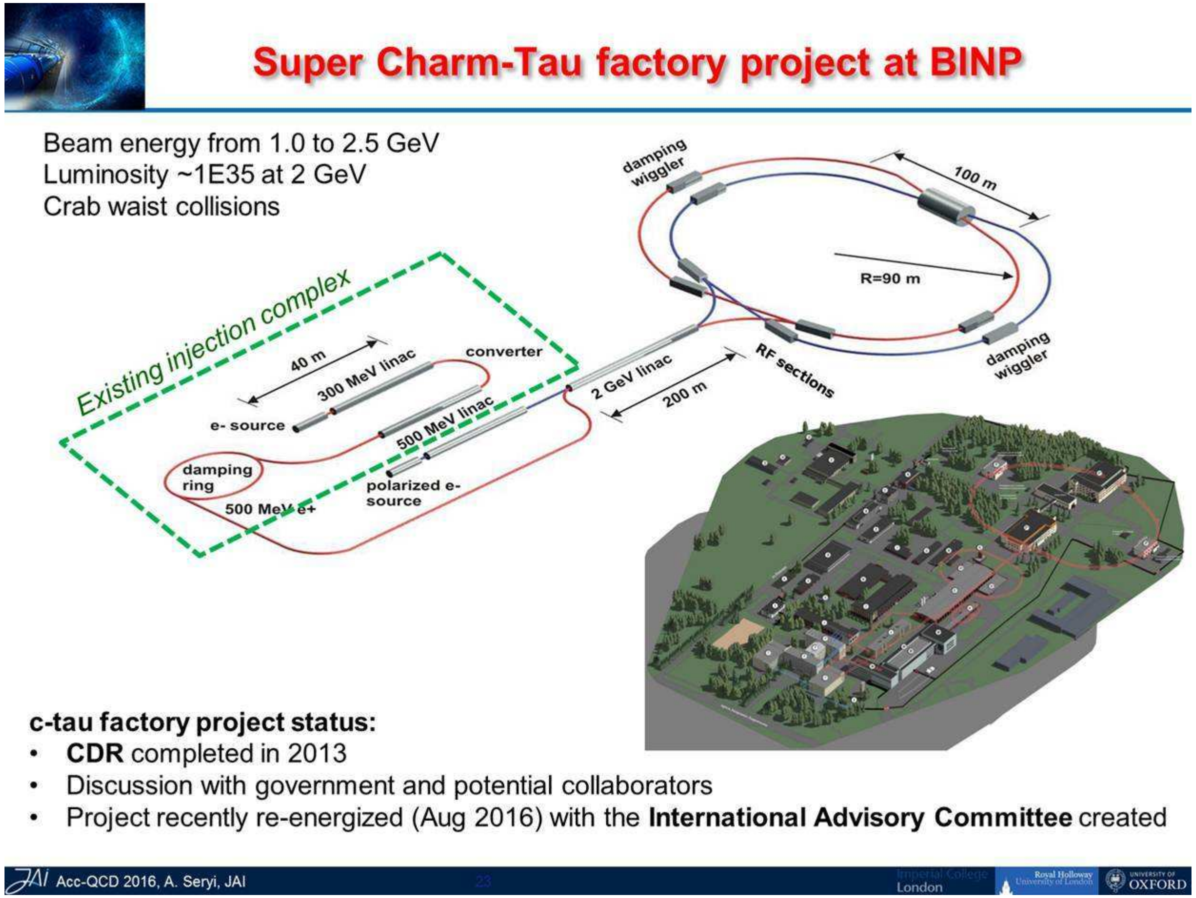
Measurements of e^+e^- Cross Sections

1. Detailed study of exclusive processes $e^+e^- \to (2-10)h, h = \pi, K, \eta, p, \ldots$, scan between 2 and 5 GeV and ISR for $\sqrt{s} < 2$ GeV
   - Meson Spectroscopy
   - Intermediate dynamics
   - Search for exotic states (tetraquarks, hybrids, glueballs)
2. High precision determination of $R = \sigma(e^+e^- \to \text{ hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at low energies and fundamental quantitites
   - $(g_\mu - 2)/2$, 92% from < 2 GeV, 7% for 2-5 GeV
   - $\alpha(M_Z^2)$, 19.0% from < 2 GeV, 18.1% for 2-5 GeV
   - QCD parameters (α_s, quark masses, quark and gluon condensates)

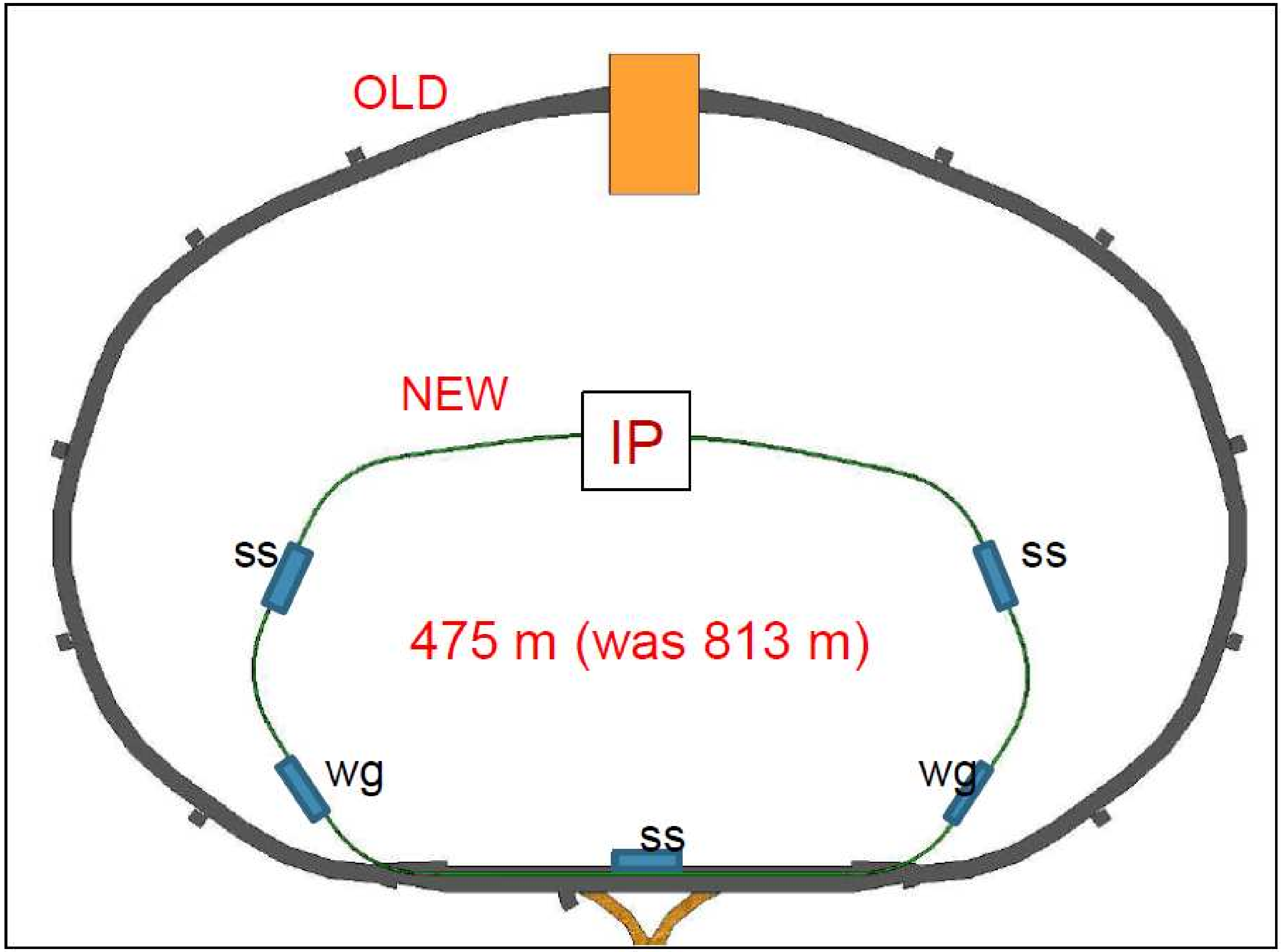
Two-Photon Physics

- Measurement of $\Gamma_{\gamma\gamma}$ for $J^{PC} = 0^{-+},\ 0^{++},\ 2^{-+},\ 2^{++}$ States
- Study of $\gamma\gamma^* \to R$, $J^{PC} = 1^{++}$
- Transition Form Factors in $\gamma^*\gamma^* \to R$
- Total Cross Section of $\gamma\gamma \to$ hadrons
- Exclusive cross sections for $\gamma\gamma \to \rho\rho,\ p\bar{p}, \phi\phi$
- Taggers needed for single- and double-tag measurements

General View (2016)



Current Vision

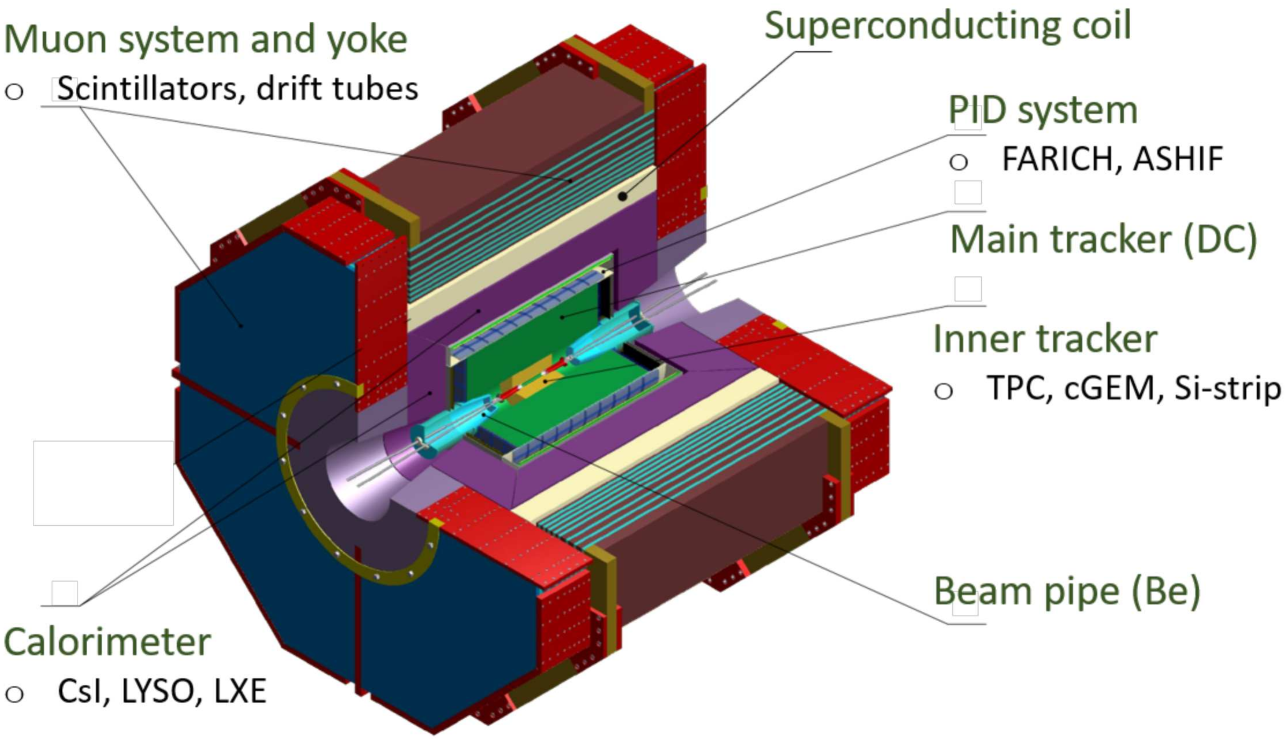


The scheme as of April 2019

Parameters

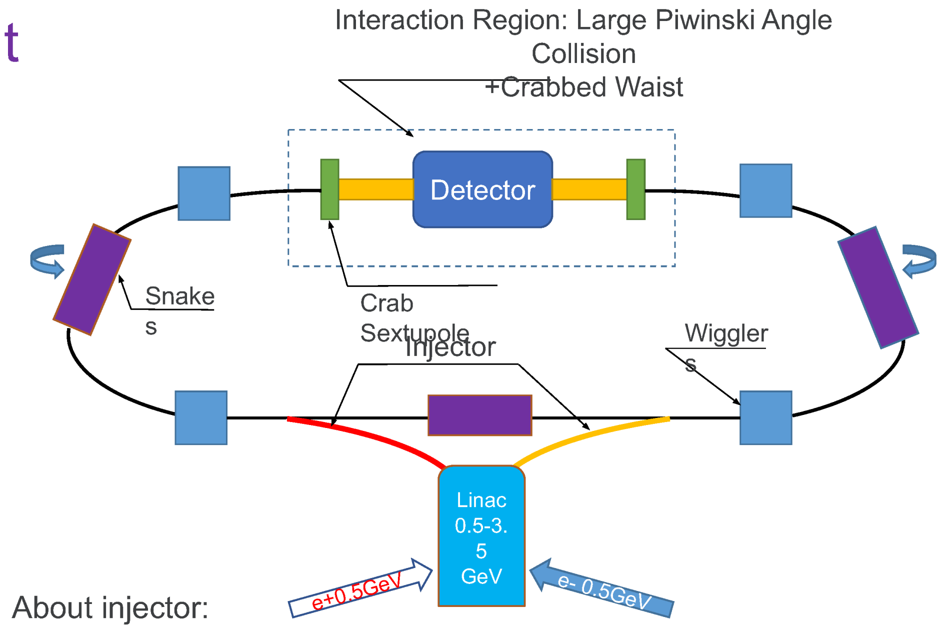
Energy	1.0 GeV	1.5 GeV	2.0 GeV	2.5 GeV
Circumference	780 m			
Emittance hor/ver	8 nm/0.04 nm @ 0.5% coupling			
Damping time hor/ver/long	30/30/15 ms			
Bunch length	16 mm	11 mm	10 mm	10 mm
Energy spread	$10.1 \cdot 10^{-4}$	$9.96 \cdot 10^{-4}$	$8.44 \cdot 10^{-4}$	$7.38 \cdot 10^{-4}$
Momentum compaction	$1.00 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$
Synchrotron tune	0.007	0.010	0.009	0.008
RF frequency	508 MHz			
Harmonic number	1300			
Particles in bunch	$7 \cdot 10^{10}$			
Number of bunches	390 (10% gap)			
Bunch current	4.4 mA			
Total beam current	1.7 A			
Beam-beam parameter	0.15	0.15	0.12	0.095
Luminosity	$0.63 \cdot 10^{35}$	$0.95 \cdot 10^{35}$	$1.00 \cdot 10^{35}$	$1.00 \cdot 10^{35}$

Detector for Novosibirsk SCTF



HIEPA – Layout

Layout



About injector:

For e+ and e-, no booster, 0.5GeV->1~3.5GeV
e+, a convertor, a linac and a damping ring, 0.5GeV
e-, a polarized e- source, accelerated to 0.5GeV

HIEPA - High Intensity Electron Positron Accelerator

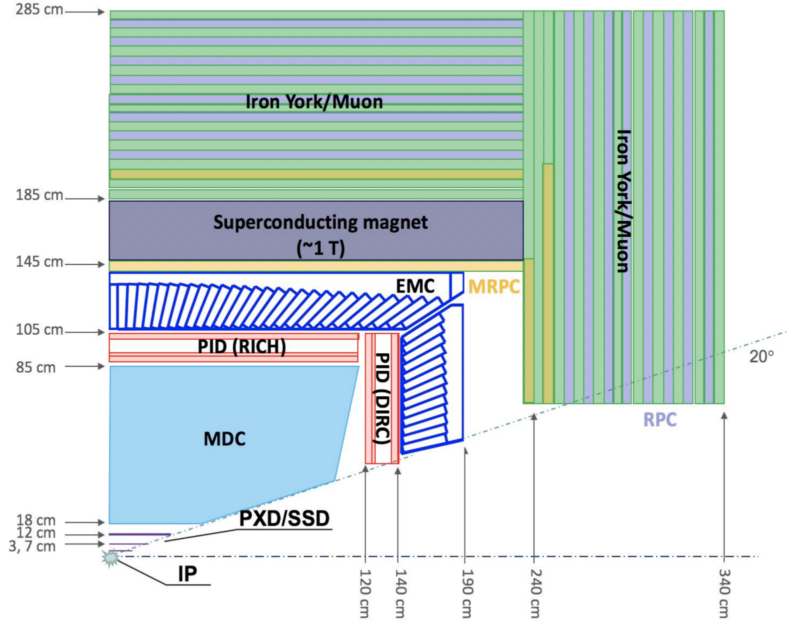
HIEPA is the project of SCTF in Hefei, China

HIEPA – Parameters

Parameter	Phase 1	Phase2
Circumference, m	600-800	600-800
Optimized beam energy, GeV	2	2
Current, A	1.5	2
Collision angle, mrad	60	60
Luminosity, 10^{35} cm^{-2} s^{-1}	0.5	1

HIEPA – Detector

A Detector Concept for STCF



PXD
- ~0.15%X_0 / layer
- σ_{xy}~50 μm

MDC
- σ_{xy}<~130 μm
- σ_p/p ~ 0.5% @ 1 GeV
- dE/dx~6%

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

EMC

E range: 0.02-3.5GeV

σ_E(%) @ 1 GeV

Barrel: 2

Endcap: 4

Pos. Res. : ~ 5 mm

MUD
- Down to <~0.4GeV
- π suppression >10

Conclusions

- SCTF is a unique facility for studying physics of τ lepton and c quark complementary to LHCb and BelleII
- Novosibirsk possesses expertise and infrastructure
- Three Workshops in 2018 (Beijing, Novosibirsk and Orsay) helped in starting an international collaboration
- Approved by the Russian government as well as various international bodies
- If properly funded, can be constructed in 5 years
- SCTF has a huge potential to search for New Physics