Physics at Super c-τ factory

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«International school on muon dipole moments and hadronic effects»

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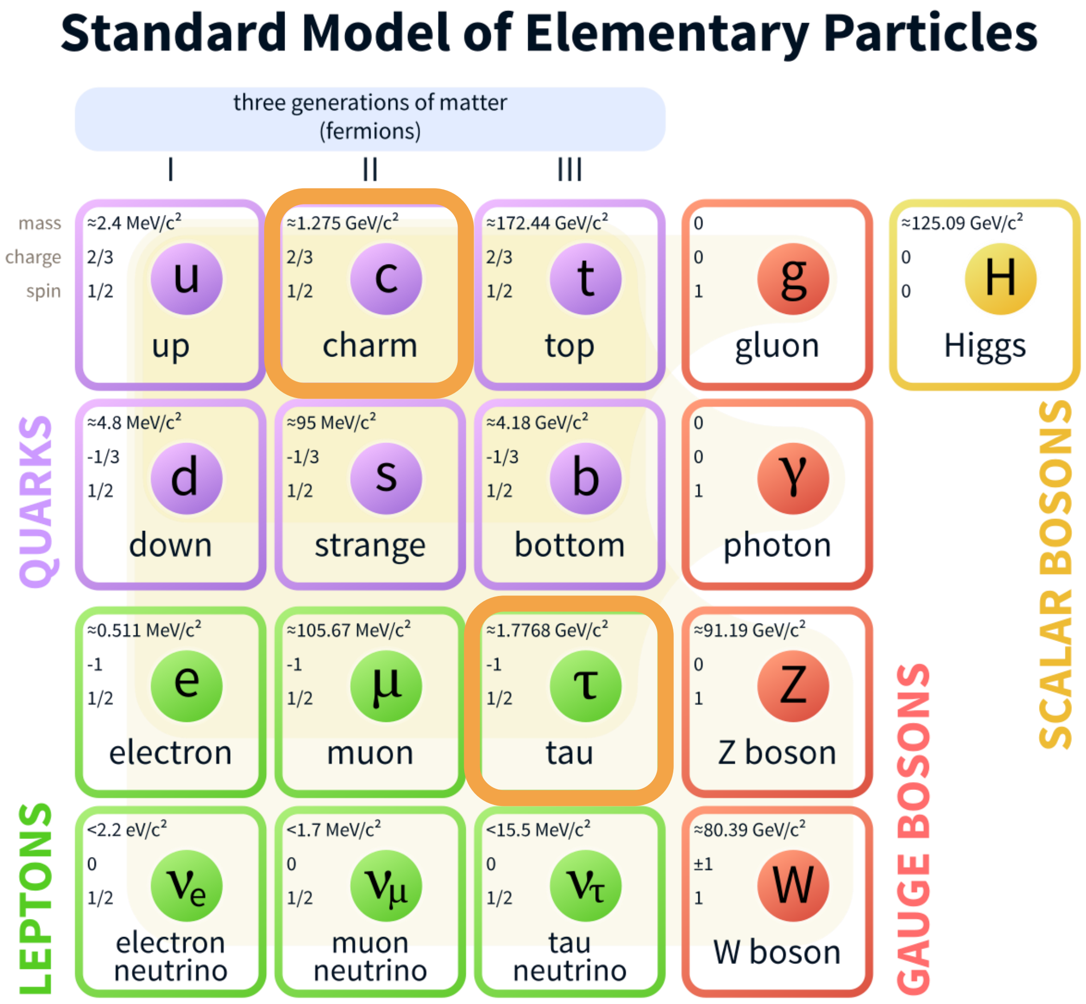
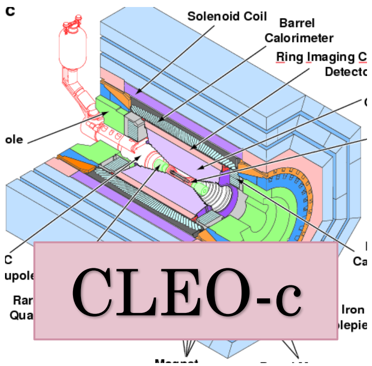
Charm quark and tau lepton

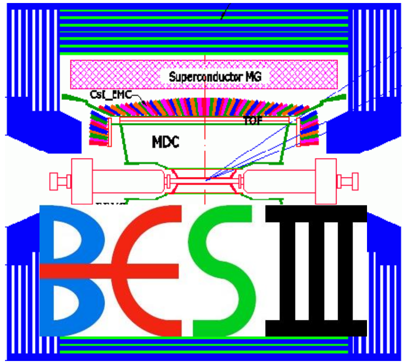
- Charm quark
  - The only heavy up-quark forming hadron systems
  - Open charm
    - Mesons: $D^{0,+}(c\bar{q})$ with $q \in \{u, d\}$, $D_s(c\bar{s})$
    - Baryons: $\Lambda_c^+(udc)$, $\Xi_c^+(usc)$, …
  - Hidden charm
    - Charmonia: $\eta_c, J/\psi$, …
    - Charmonium-like states: X, Y, Z
    - Pentaquarks $P_c(4450)^+$ and $P_c(4380)^+$ [Phys. Rev. Lett. 115 (2015) 072001]
- Tau lepton
  - Heaviest lepton
  - Tens of decay channels
  - The only lepton decaying into hadrons



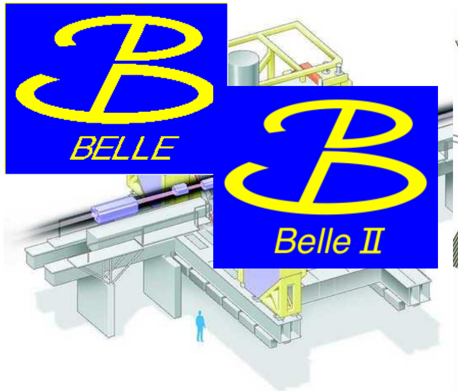
Experiments in charm (and tau)

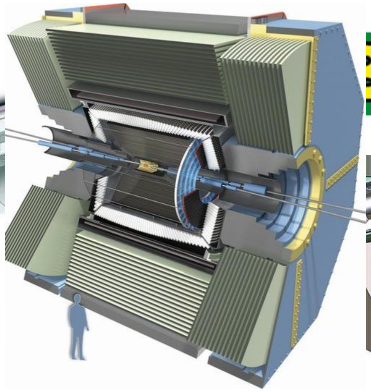
Threshold production

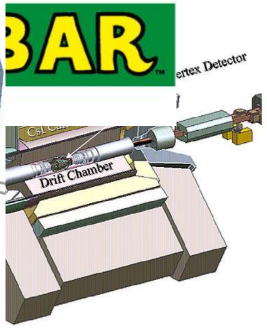




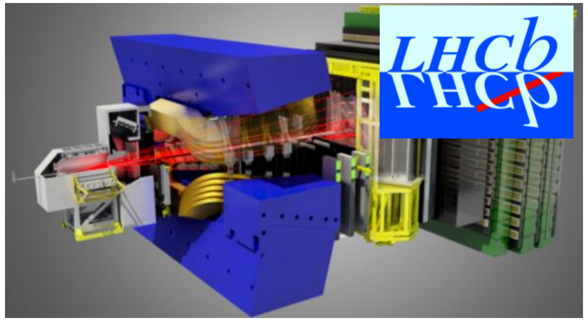
Asymmetric e^+e^- @ $\Upsilon(4S)$







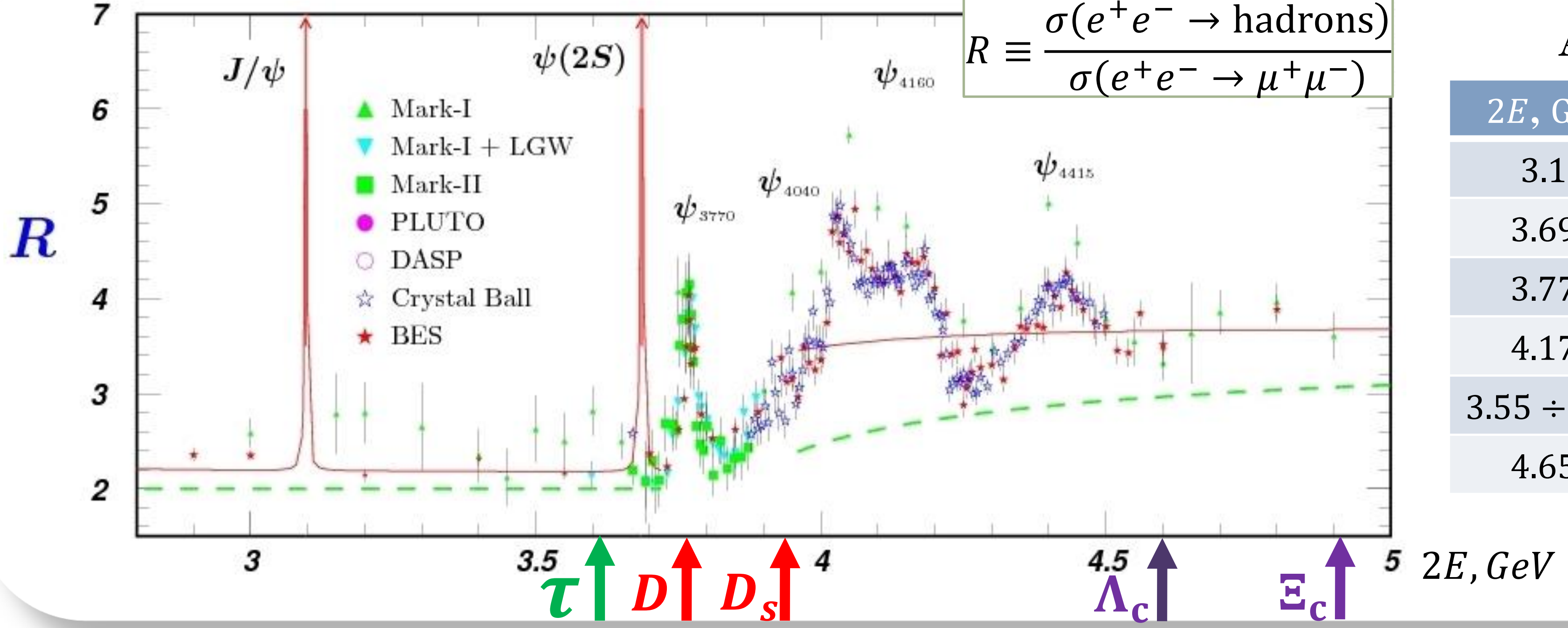
Proton collisions



Q: Do we need a new generation threshold experiment?

A: Yes.

Super c-τ factory: energy range



$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

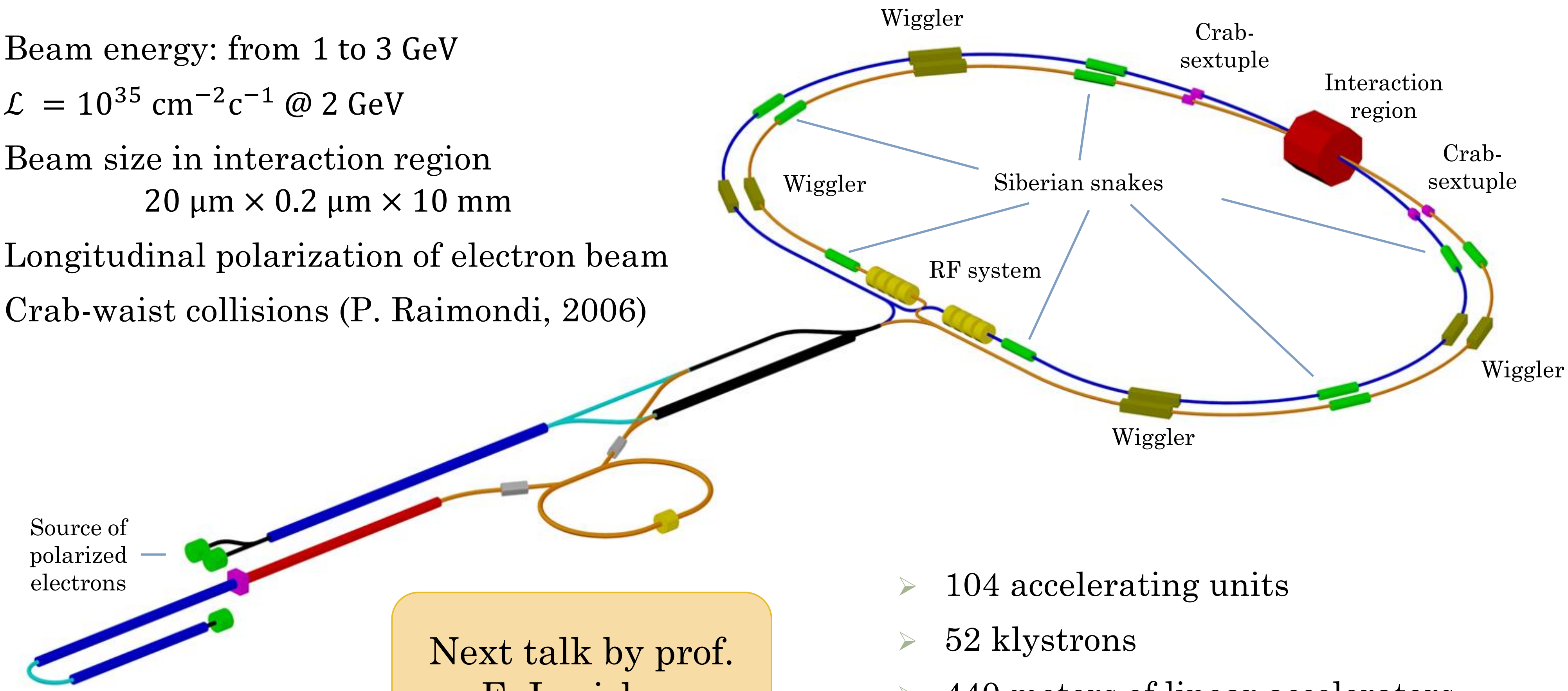
$\mathcal{L} = 10^{35}\ \text{cm}^{-2}\text{c}^{-1}$

Annual yields

$2E$, GeV	Yield
3.1	$10^{12}\ J/\psi$
3.69	$10^{11}\ \psi(2S)$
3.77	$10^{9}\ D\bar{D}$
4.17	$10^{8}\ D_s\bar{D}_s$
$3.55 \div 4.3$	$10^{10}\ \tau\ \tau$
4.65	$10^{8}\ \Lambda_c^+\Lambda_c^-$

Super c-τ factory: the BINP project

- Beam energy: from 1 to 3 GeV
- $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\mathrm{c}^{-1}$ @ 2 GeV
- Beam size in interaction region
  20 μm × 0.2 μm × 10 mm
- Longitudinal polarization of electron beam
- Crab-waist collisions (P. Raimondi, 2006)



Next talk by prof.
E. Levichev

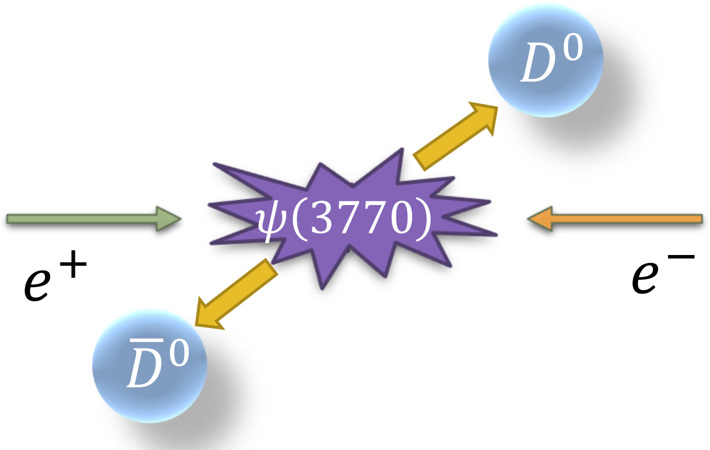
- 104 accelerating units
- 52 klystrons
- 440 meters of linear accelerators

Advantages of threshold production

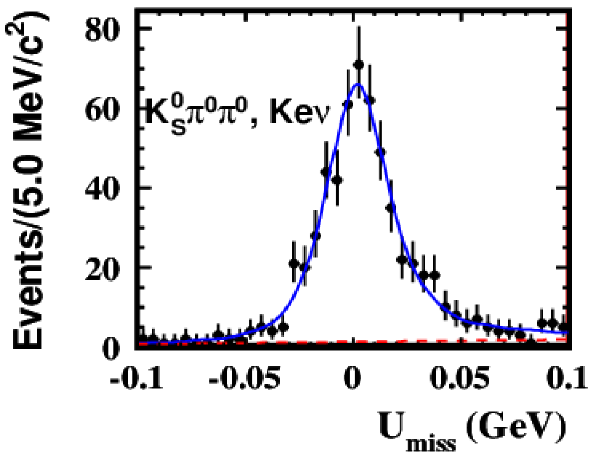
- Clean environment: ~2 times less final-state particles then at B-factories
- Kinematic constraints

$$m_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - p^2(D)}$$

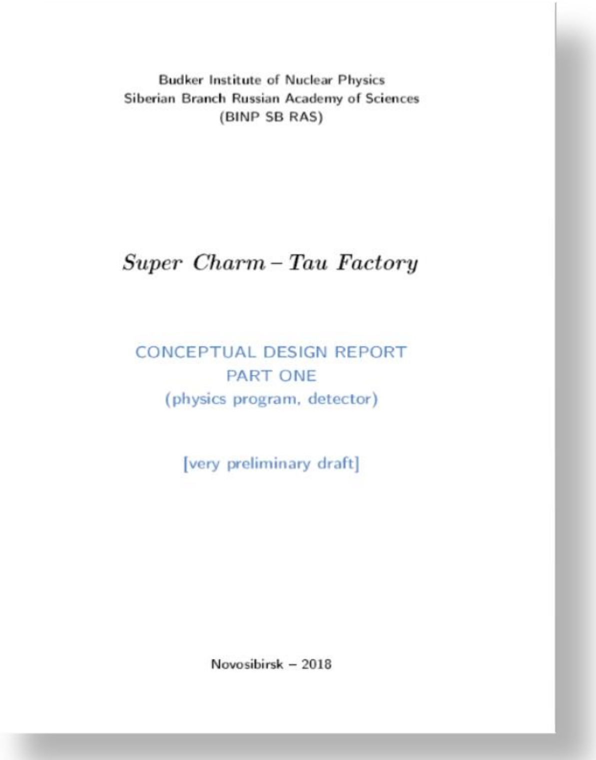
- Full event reconstruction (double tag) technique
  - Measurement of absolute branching fractions
  - Strong background suppression
  - Reconstruction of missing energy
- Low ISR backgrounds in τ decays analysis
- Quantum correlations in $D^0\overline{D}^0$



[BESIII, Phys. Lett. B744, 339 (2015)]



Physics program of Super c-τ factory


Budker Institute of Nuclear Physics
Siberian Branch Russian Academy of Sciences
(BINP SB RAS)

Super Charm – Tau Factory

CONCEPTUAL DESIGN REPORT
PART ONE
(physics program, detector)

[very preliminary draft]

Novosibirsk – 2018

Conceptual design report
ctd.inp.nsk.su

Charmonium
- Spectroscopy
- Decays
- Light states in J/ψ decays

Charm mesons
- Spectroscopy
- Decays
- Charm mixing
- $\mathcal{CP}$ symmetry violation

Charm baryons
- Spectroscopy
- Decays
- $\mathcal{CP}$ symmetry violation

τ lepton
- Michel parameters
- Spectral functions
- $\mathcal{CP}$ symmetry violation
- Lepton number conservation test
- Lepton flavor universality test

Two-photon physics
- Search for $\mathcal{C}$-even resonances
- $\sigma(\gamma\gamma \to \text{hadrons})$

$\sigma(e^+e^- \to \text{hadrons})$

τ physics
(some examples)

- Leptonic τ decays
  - Lepton flavor universality test
  - Lorentz structure of charged current
- Hadronic τ decays
  - Spectral functions
  - Second class currents
- Lepton number violating decays

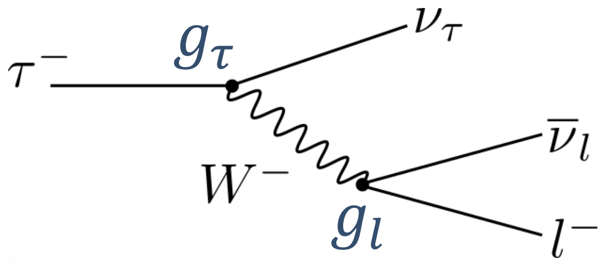
Leptonic τ decays I

Lepton flavor universality test

$$\tau^- \to l^- \bar{\nu}_l \nu_\tau$$

$$\Gamma(\tau^- \to \nu_\tau l^- \bar{\nu}_l) = \frac{G_\tau G_l m_\tau^5}{192\pi^3} f\left(\frac{m_l^2}{m_\tau^2}\right) r_{\text{EW}}$$

$$r_{\text{EW}} \approx 0.9915,\ f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x\,,\ G_l = \frac{g_l^2}{4\sqrt{2} m_W^2}$$



Parameter	Calculation	Best measurement
$\frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu)}{\mathcal{B}(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}$	0.972564 ± 0.000010	$0.9796 \pm 0.0016 \pm 0.0036$ [BaBar, PRL 105 (2010) 051602]

- A Super c-τ factory experiment can reach smaller systematic uncertainty

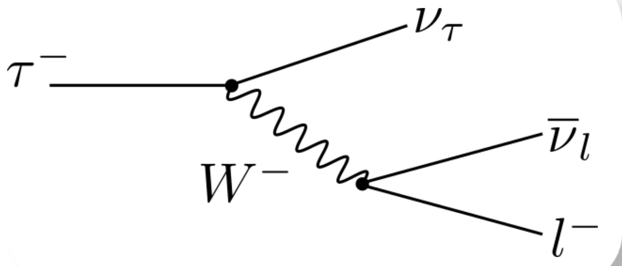
Leptonic τ decays II

Michel parameters

$$\frac{d\Gamma(\tau^{\mp})}{d\Omega dx} \propto x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x) \mp P_\tau \cos\theta_l \, \xi \sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right)\right],$$

$$x \equiv \frac{E_l}{E_{\max}}, \qquad x_0 \equiv \frac{m_l}{E_{\max}}$$

- Standard model weak charged current $(V-A)$ implies
$$\rho = \frac{3}{4}, \qquad \eta = 0, \qquad \xi = 1, \qquad \delta = \frac{3}{4}.$$
- Michel parameters can be measured at B-factories using spin-spin correlations of $\tau^+\tau^-$ pairs – it's a complex 6D analysis!
- A Super c-τ factory with polarized e^- beam allows one to measure Michel parameters with analysis of single τ decays



Hadronic τ decays

Spectral functions (SFs)

$$\frac{d\Gamma(\tau^- \to \text{had}\,\nu_\tau)}{d(\text{phsp})} = \frac{G_F^2}{4m_\tau}|V_{\text{CKM}}|^2 L_{\mu\nu}H^{\mu\nu}$$

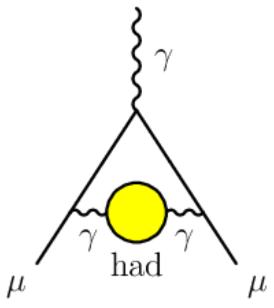
- Factorization of hadronic and leptonic currents
- SFs are sensitive to $|V_{ud}|$, $|V_{us}|$, $\alpha_s(m_\tau)$ and m_s
- Testing conservation of vector current (CVC)
- Information about hadronic vacuum polarization

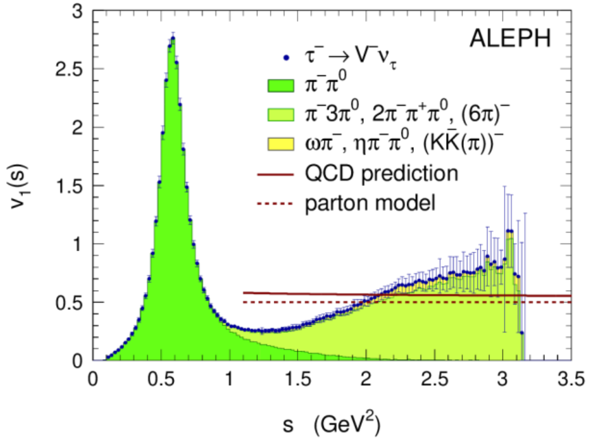
Second class currents

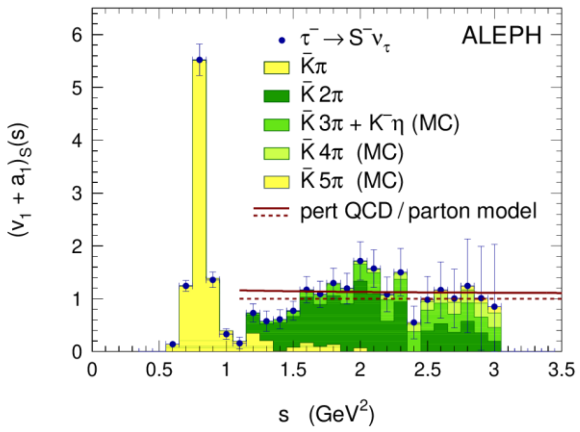
$$\mathrm{J}^{PG} = 0^{+-}\,(a_0),\, 1^{++}\,(b_1), \ldots$$

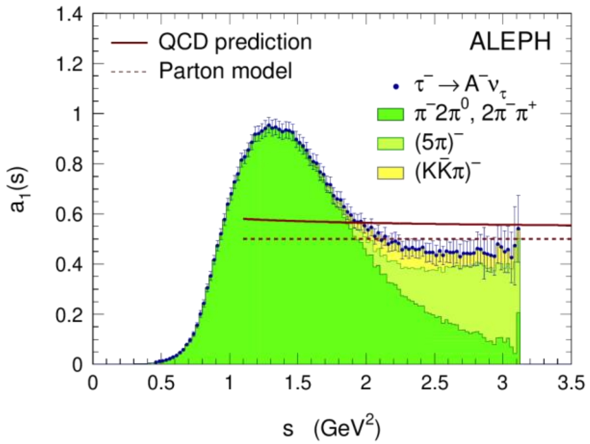
- Isospin suppressed decays ($\tau \to \eta^{(\prime)}\pi\nu, \ldots$)

[Rev. Mod. Phys. 78 (2006) 1043]





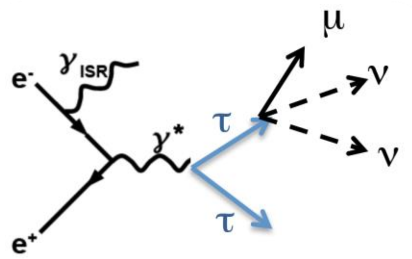




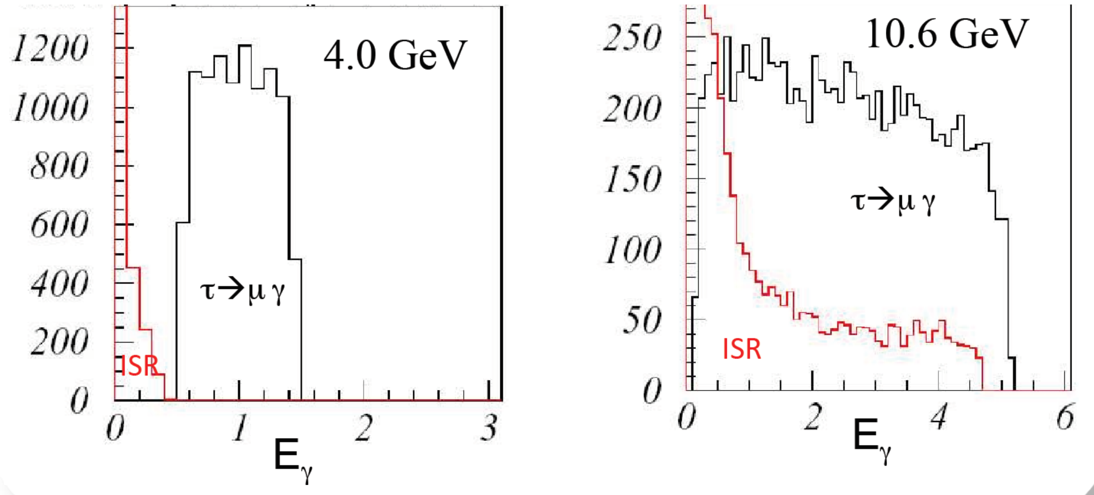
Forbidden τ decays

$\tau \to \mu\gamma$

- Exists in many scenario of new physics (supersymmetry, leptoquarks, technicolor, additional Higgs bosons, …)
- Main backgrounds
  - $\tau \to \mu\nu\nu$ + ISR photon
  - $\tau \to \mu\gamma\nu\nu$
  - $\tau \to \pi\nu$ + ISR or beam photon



ISR photon background [arXiv:1206.1909 [hep-ex]]



Threshold kinematics matters

- Expected experimental limits on $\tau \to \mu\gamma$ branching
  - Belle II: $\mathcal{O}(10^{-9})$
  - Super c-τ factory: $\mathcal{O}(10^{-10})$

Charm physics
(some examples)

- Charm mesons
  - (Semi-)leptonic decays
  - Spectroscopy
  - $\mathcal{CP}$ symmetry breaking
  - Dynamics of multibody decays
- Charmonium
  - Spectroscopy including $c\bar{c}$-like states
  - Rare J/ψ decays
- Quantum correlations
  - Phases of decay amplitudes
  - Charm mixing

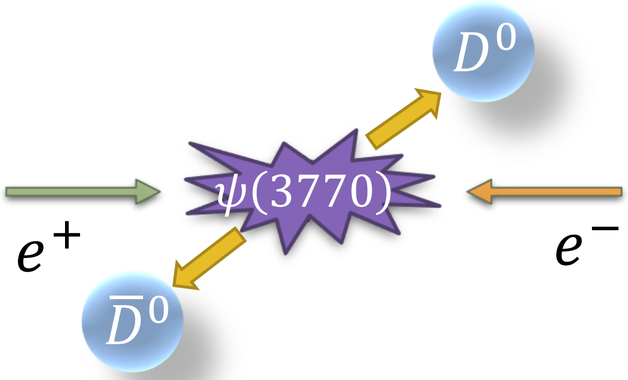
Absolute branching fractions

- LHCb can measure only *relative* branching fractions
- Many *absolute* branching fractions need to be measured at a threshold experiment
  - $D^0 \to K^-\pi^+$
  - $D^+ \to K^-2\pi^+$
  - $D_s^+ \to K^-K^+\pi^+$
  - $D_s^+ \to 3\pi X$
  - $\Lambda_c^+ \to pK^-\pi^+$
  - $\Xi_c^+ \to pK^-\pi^+$
  - $\Xi_c^0 \to p2K^-\pi^+$
  - $\Omega_c^0 \to p2K^-\pi^+$
  - …

[LHCb, Phys. Rev. D85 (2012), 032008]

Systematics on $f_{\Lambda_b}/(f_u + f_d)$.

Source	Error (%)
Bin dependent errors	2.2
$\mathcal{B}(\Lambda_b^{0\,0} \to D^0 pX\mu^-\overline{\nu})$	2.0
Monte Carlo modelling	1.0
Backgrounds	3.0
Tracking efficiency	2.0
$\Gamma_{\rm sl}$	2.0
Lifetime ratio	2.6
PID efficiency	2.5
Subtotal	6.3
$\mathcal{B}(\Lambda_c^{++} \to pK^-\pi^+)$	26.0
Total	26.8



Measurement idea

- «Single tag» events

$$y_j = N_{D\bar{D}}\mathcal{B}_j\epsilon_j$$

- «Double tag» events

$$y_{i\bar{j}} = N_{D\bar{D}}\mathcal{B}_i\mathcal{B}_j\epsilon_{i\bar{j}}$$

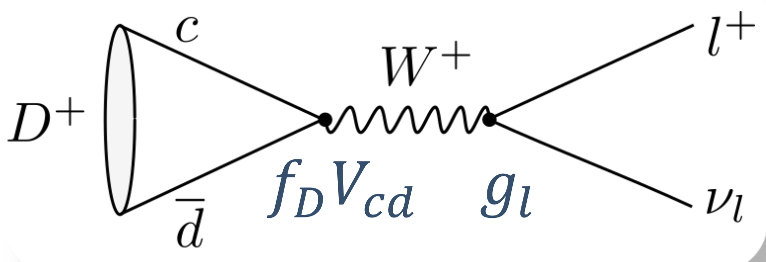
- The branching fraction

$$\mathcal{B}_i = \frac{y_{i\bar{j}}}{y_{\bar{j}}}\frac{\epsilon_{\bar{j}}}{\epsilon_{i\bar{j}}} \approx \frac{y_{i\bar{j}}}{\epsilon_i y_{\bar{j}}}$$

Leptonic $D^+_{(s)}$ decays

$$D^+_{(s)} \to l\nu$$

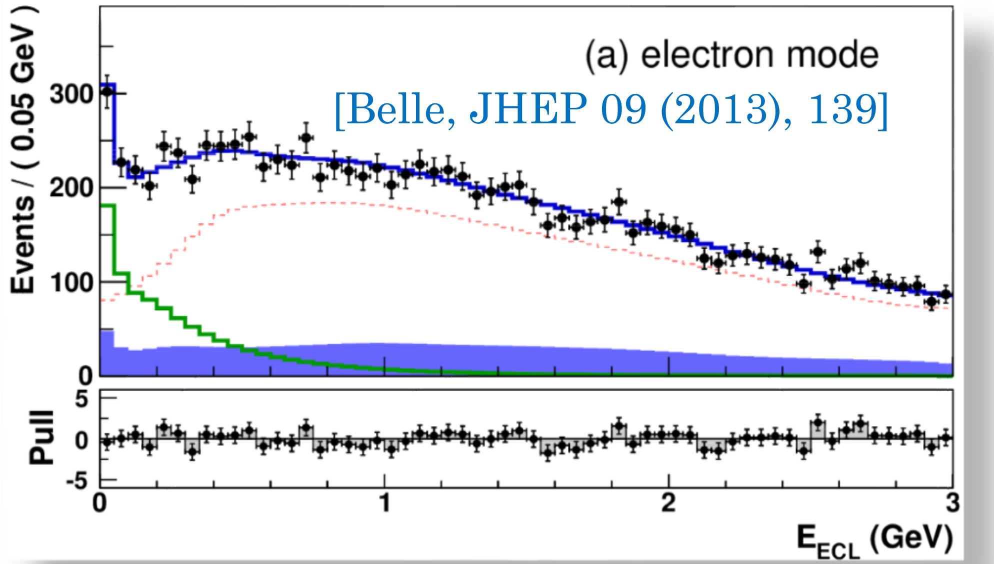
$$\Gamma(D^+ \to l\nu) = \frac{G_F^2}{8\pi} f_D^2 m_l^2 m_D \left(1 - \frac{m_l^2}{m_D^2}\right) |V_{cd}|^2$$



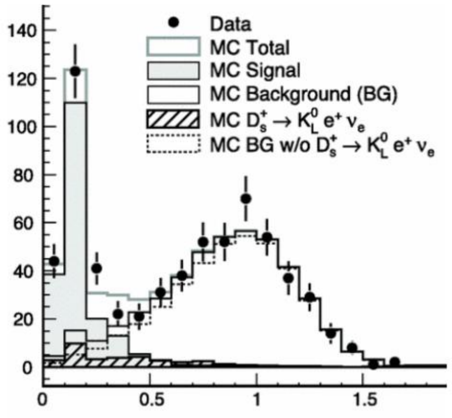
Parameter	Calculation	Best measurement	Super c-τ factory
f_D	$202.3 \pm 2.2 \pm 2.6$	$203.2 \pm 5.3 \pm 1.8$ (BESIII)	$Y \pm 0.x$
f_{D_s}	$258.7 \pm 1.1 \pm 2.9$	$255.5 \pm 4.2 \pm 5.1$ (Belle)	$Y \pm 0.x$
f_{D_s}/f_D	1.2788 ± 0.0264	$1.26 \pm 0.05 \pm 0.03$	$Y \pm 0.00x$

Lattice QCD calibration

Example: $D_s^+ \to \tau^+ \nu, \tau^+ \to e^+ \nu_e \bar{\nu}_\tau$



[CLEOc, PRD 79 (2009), 052002]



- Belle @ 913 fb^{-1}
- Signal / Background ~ 1 / 1

- CLEOc @ 600 pb^{-1} @ 4.17 GeV
- Signal / Background > 10 / 1

Direct $\mathcal{CP}$ violation in charm

Direct $\mathcal{CP}$ violation

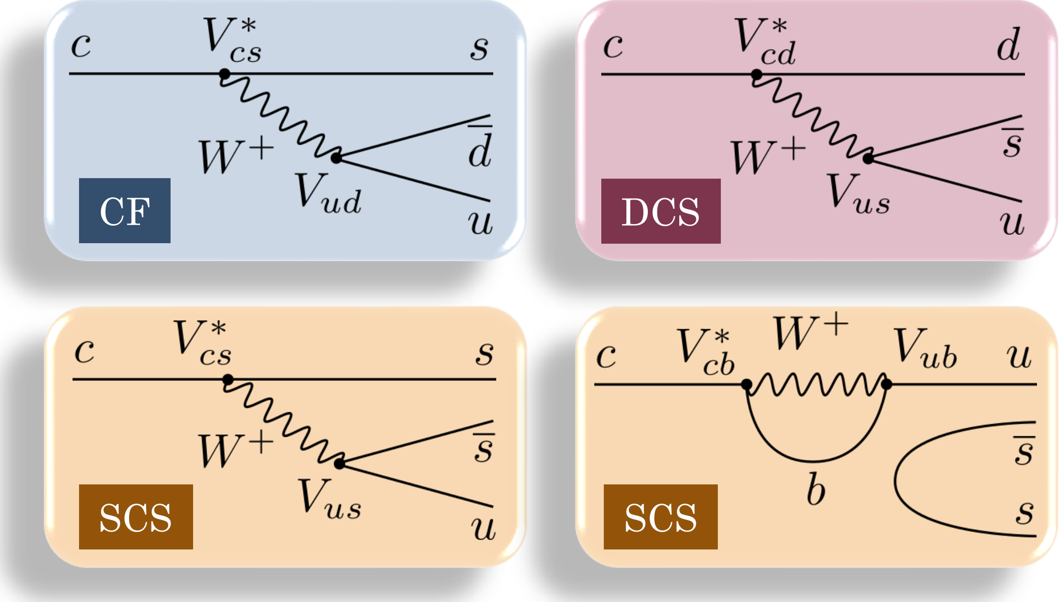
(At least) two interfering amplitudes with different «strong» and «weak» phases needed

$$A(D \to f) = a_1 e^{i(\varphi_1+\delta_1)} + a_2 e^{i(\varphi_2+\delta_2)}$$

$$A(\bar{D} \to \bar{f}) = a_1 e^{i(-\varphi_1+\delta_1)} + a_2 e^{i(-\varphi_2+\delta_2)}$$

where φ_i are weak phases and δ_i are strong phases

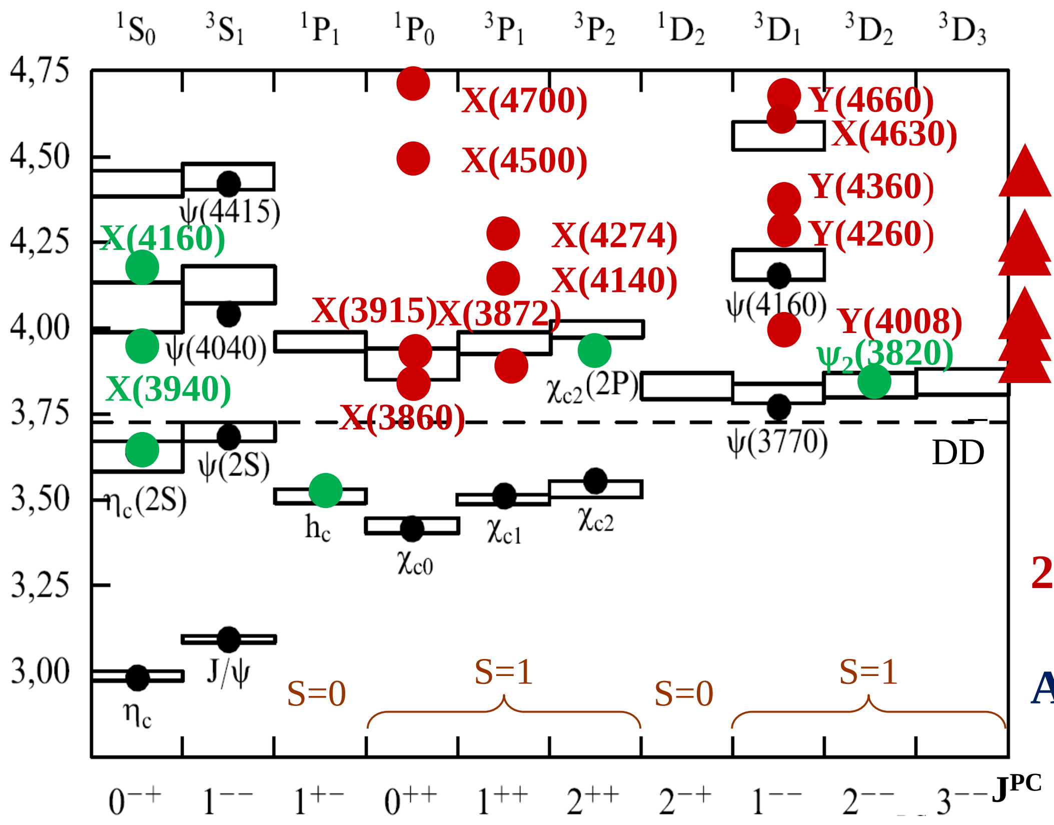
$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(D \to f) - \mathcal{B}(\bar{D} \to \bar{f})}{\mathcal{B}(D \to f) + \mathcal{B}(\bar{D} \to \bar{f})} \propto \sin\Delta\varphi \sin\Delta\delta$$

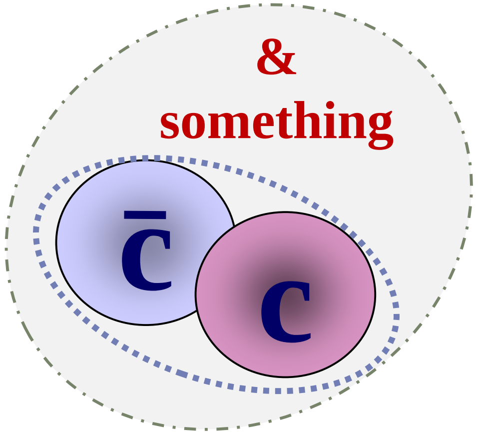


- Super c-τ factory prospects
  - Reaching the $\mathcal{O}(10^{-4})$ precision level
  - Measurements in many different final states

- Standard model expectations
  - Zero weak phase in allowed and doubly suppressed transitions
  - Very small weak phase in singly suppressed transitions leading to $\mathcal{A}_{CP} \lesssim 10^{-3}$

Quarkonium(-like) spectroscopy





2002-2016 Discovery of

18 exotic charmonium states

All of them above open charm threshold

[G. Pakhlova, December 19th 2017 at BINP]

- Super c-τ factory is a laboratory for presicion study of the $c\bar{c}$-like states

That's all?

- No. Many topics has not been mentioned (rare charmonia decays, baryon physics, $\mathcal{CP}$ violation in τ and baryon decays, search for glueballs, two-photon physics, …)
- Some references for further reading
  - arXiv:hep-ex/0309021 «A Cicerone for the Physics of Charm», S. Bianco, F. L. Fabbri, D. Benson, I. Bigi
  - arXiv:hep-ph/0507078 «The Physics of Hadronic Tau Decays», M. Davier, A. Hocker, Z. Zhang
  - arXiv:1310.7922 [hep-ph] «Precision Tau Physics», A. Pich
  - Super c-τ factory CDR
  - BES-III physics book
- Recent workshops on Super c-τ factories
  - BINP, December 2017
  - Beijing, March 2018
  - BINP, May 2018

Conclusions

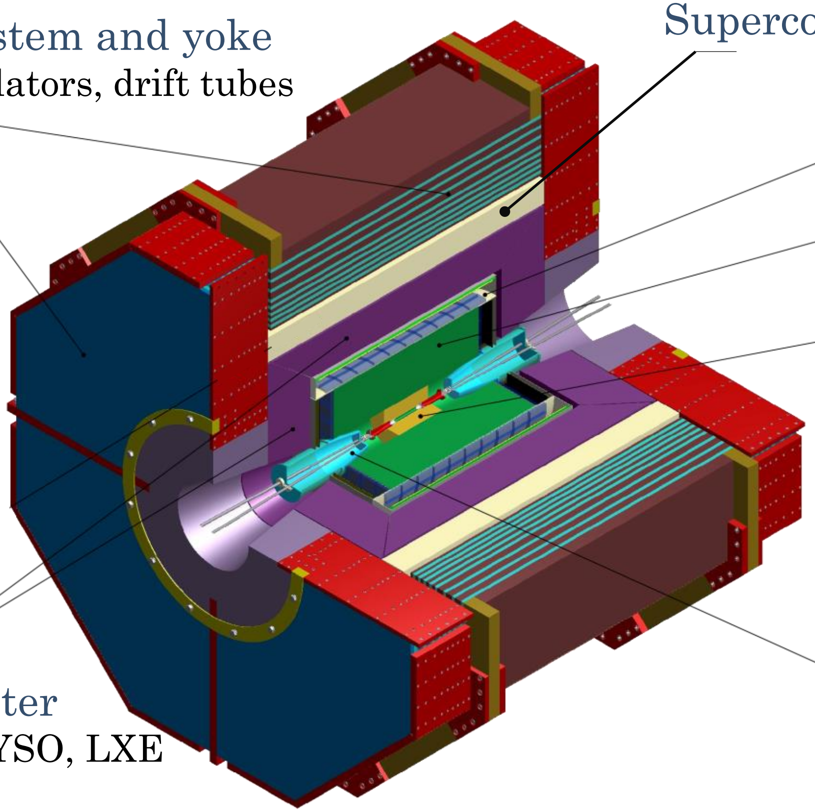
- A Super c-τ factory experiment has a broad and diverse physics program
- Super c-τ factory complements the Belle II and LHCb experiments
  - Quantum correlations
  - Absolute branching fractions of charm hadrons
- The Super c-τ factory project is a challenge for the new generation of HEP community

Back-up

Detector for Super c-τ factory (concept)

Requirements

- Occupancy 300 kHz
- Good energy and momentum resolution
- High detection efficiency of soft tracks
- Best possible π/K and π/μ separations
- Minimal $\mathcal{CP}$ detection asymmetry



✓ A high-end universal particle detector

Super c-τ factory: yields and data flow

Luminosity

$$\mathcal{L} = f\frac{n_1 n_2}{2\pi\sigma_x\sigma_y} = 10^{35}\ \mathrm{s^{-1}cm^{-2}}$$

- Cross-sections @ 3.8 GeV

$$\sigma(e^+e^- \to \tau^+\tau^-) = 2.9\ \mathrm{nb}$$
$$\sigma(e^+e^- \to D^0\bar{D}^0) = 3.6\ \mathrm{nb}$$
$$\sigma(e^+e^- \to D^+D^-) = 2.9\ \mathrm{nb}$$
$$1\ \mathrm{nb} = 10^{-33}\ \mathrm{cm^2}$$

- Annual yield

$$N_{\tau\tau} = 10^7\ \mathrm{s} \times 10^{35}\ \mathrm{s^{-1}cm^{-2}} \times 2.9\ \mathrm{nb} \approx 3 \times 10^9$$
$$N_{D\bar{D}} \approx 6.5 \times 10^9$$

Data flow and dataset volume

- Max frequency of event recording

  300 kHz @ J/ψ

- Event size

  $30 \div 50$ kB

- Number of recorded events

  2×10^{12}

- Dataset size

  100 PB (Peta $- 10^{15}$)

- Computing cluster

  0.6 Pflop

Coherent $D^0\overline{D}^0$ pairs production

$$e^+e^- \to \gamma^* \to D^0\overline{D}^0, \qquad \mathcal{C}(D^0\overline{D}^0) = -1$$

$$\langle ij|\mathcal{H}|D^0\overline{D}^0\rangle \propto \langle i|\mathcal{H}|D^0\rangle\langle j|\mathcal{H}|\overline{D}^0\rangle + \mathcal{C}\langle i|\mathcal{H}|\overline{D}^0\rangle\langle j|\mathcal{H}|D^0\rangle$$

- Measurement of phase parameters – a crucial input for some measurements at Belle II and LHCb

$$\delta_{K\pi} \equiv \arg\left(\frac{\mathcal{A}(\overline{D}^0 \to K^-\pi^+)}{\mathcal{A}(D^0 \to K^-\pi^+)}\right)$$

  - Coherence factors and average phases for multibody decays
  - Parameters C_i and S_i from model-independent analysis of $D^0 \to K_S^0\pi^+\pi^-$ decay
- Time-integrated measurement of charm mixing
- Unique techniques for $\mathcal{CP}$ violation studies

CKM mechanism

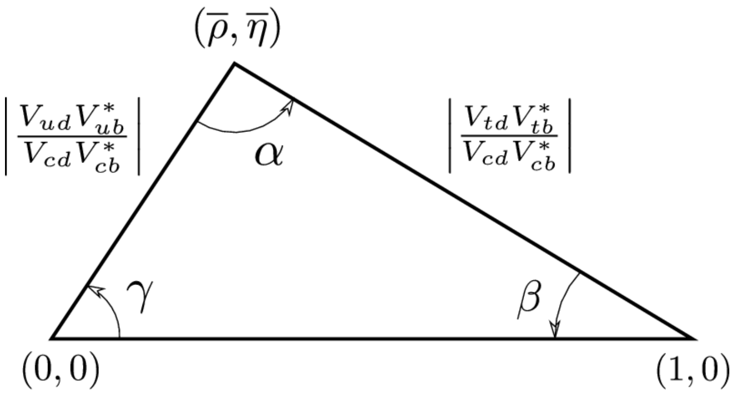
The CKM matrix

- The unitary matrix of quark mixing for charged weak currents (Cabibbo, Kobayashi and Maskawa, CKM)

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

- Four independent parameters
- Can be parametrized with three Euler angles and single phase.

The Unitarity Triangle



$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$

$$\mathcal{L} \propto -\frac{g}{\sqrt{2}}(\bar{u}_L, c_L, \bar{t}_L)\gamma^\mu W_\mu^+ V_{CKM}(d_L, s_L, b_L)^T + h.c.$$

Charm mixing (in a nutshell)

- Mass eigenstates

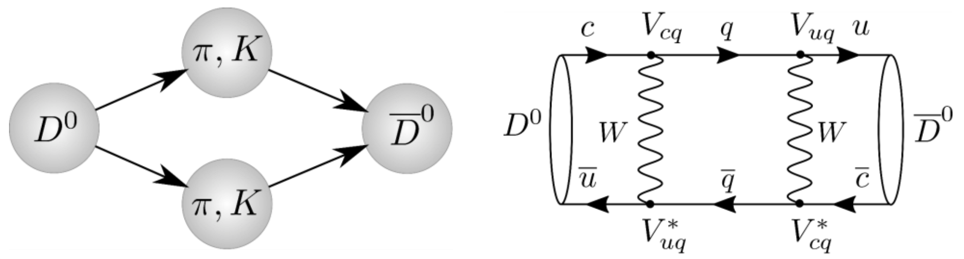
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \qquad |p|^2 + |q|^2 = 1$$

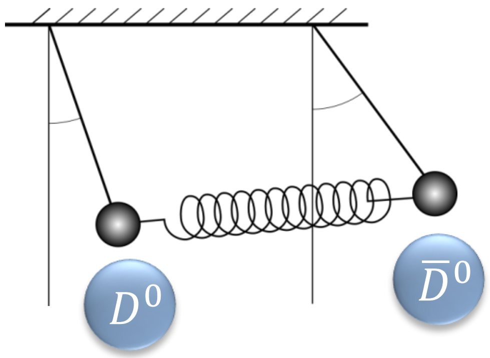
- Charm mixing parameters

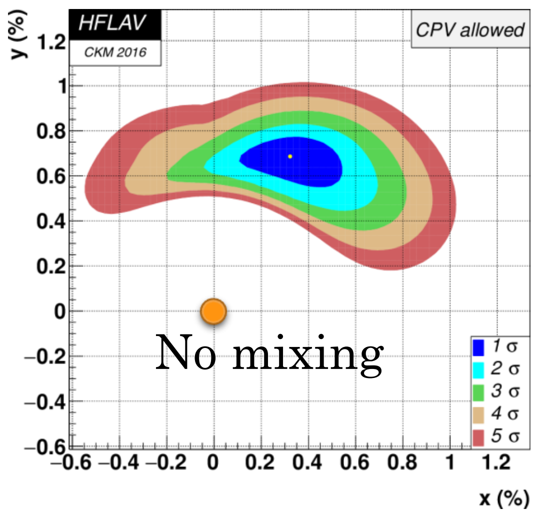
$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}$$

- Observable parameter

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}, \qquad \mathcal{A}_f \equiv \langle f|\mathcal{H}|D^0\rangle, \qquad \bar{\mathcal{A}}_f \equiv \langle f|\mathcal{H}|\bar{D}^0\rangle$$





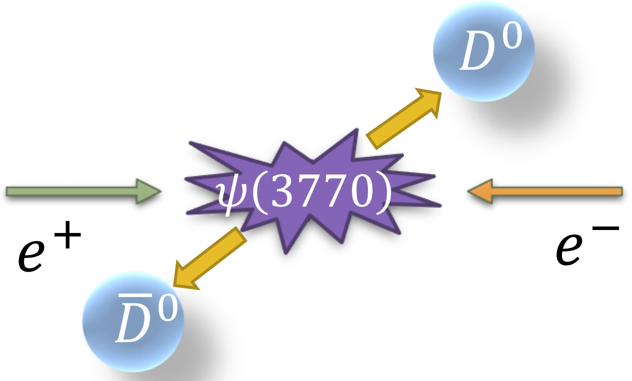


Charm mixing at Super c-τ factory

- Quantum correlations in action

$$\Gamma(K^-\pi^+, K^+\pi^-) \propto |A_{K\pi}|^4(1 - r_{K\pi}^2)^2$$
$$\Gamma(K^-\pi^+, X) = |A_{K\pi}|^2[1 + 2yr_{K\pi}\cos\delta_{K\pi} + r_{K\pi}^2]$$

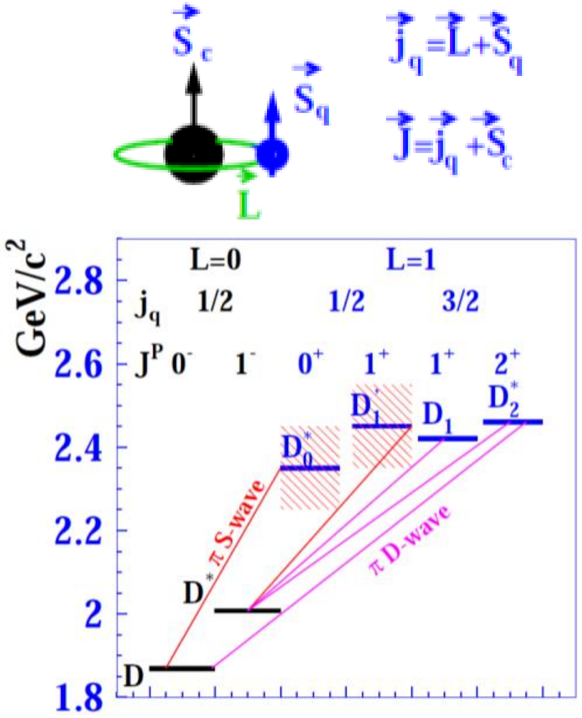
  - Many more relations with $\mathcal{CP}$-specific and multibody D^0 decays (see PRD 73 (2006) 034024)
  - This approach allows one to measure charm mixing together with phase $\delta_{K\pi}$
- There are other methods to measure charm mixing at Super c-τ factory
- Super c-τ factory is competitive with Belle II and LHCb in measurement of charm mixing

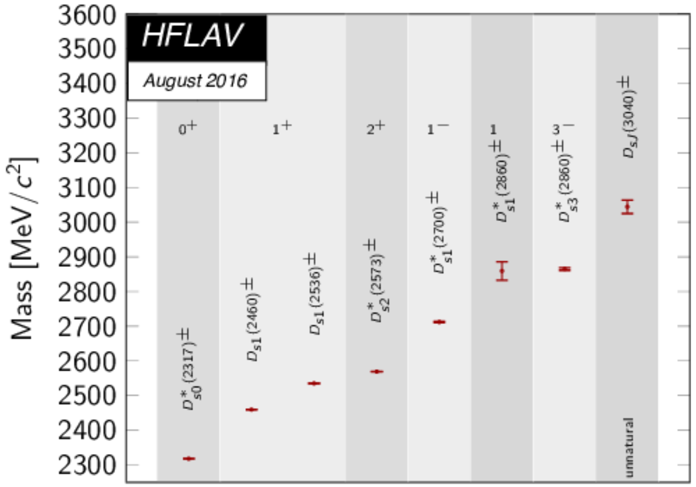


$$r_{K\pi}\cdot e^{i\delta_{K\pi}} \equiv \frac{\mathcal{A}(\overline{D}^0 \to K^-\pi^+)}{\mathcal{A}(D^0 \to K^-\pi^+)}$$
$$\mathcal{A}(D^0 \to K^-\pi^+) \equiv A_{K\pi}$$

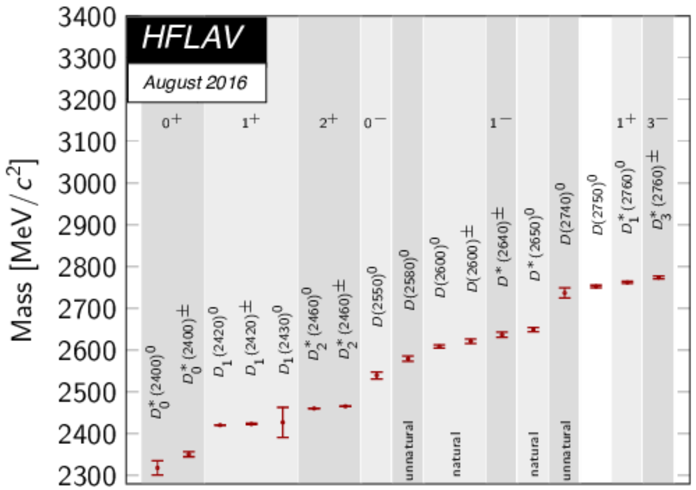
Charm mesons spectroscopy

- Observables
  - Exclusive and inclusive cross-sections
  - Decay branching fractions
- Example: $D_{s0}^{*}(2317)$ и $D_{s1}(2460)$
  - Masses are about 50 MeV lower then predicted by potential models
  - Decays with final-state neutrals (not accessible for LHCb)
  - Nature of these states is still not clear





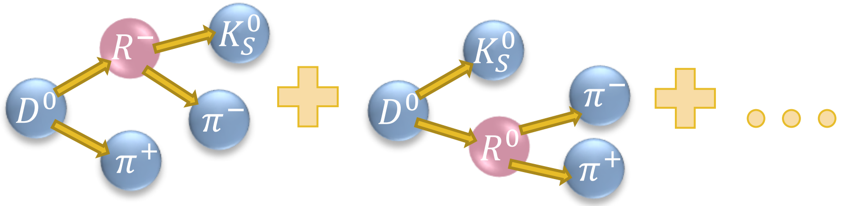
(a)



(b)

Dynamics of multibody decays

$$D^0 \to K_S^0 \pi^+ \pi^-$$



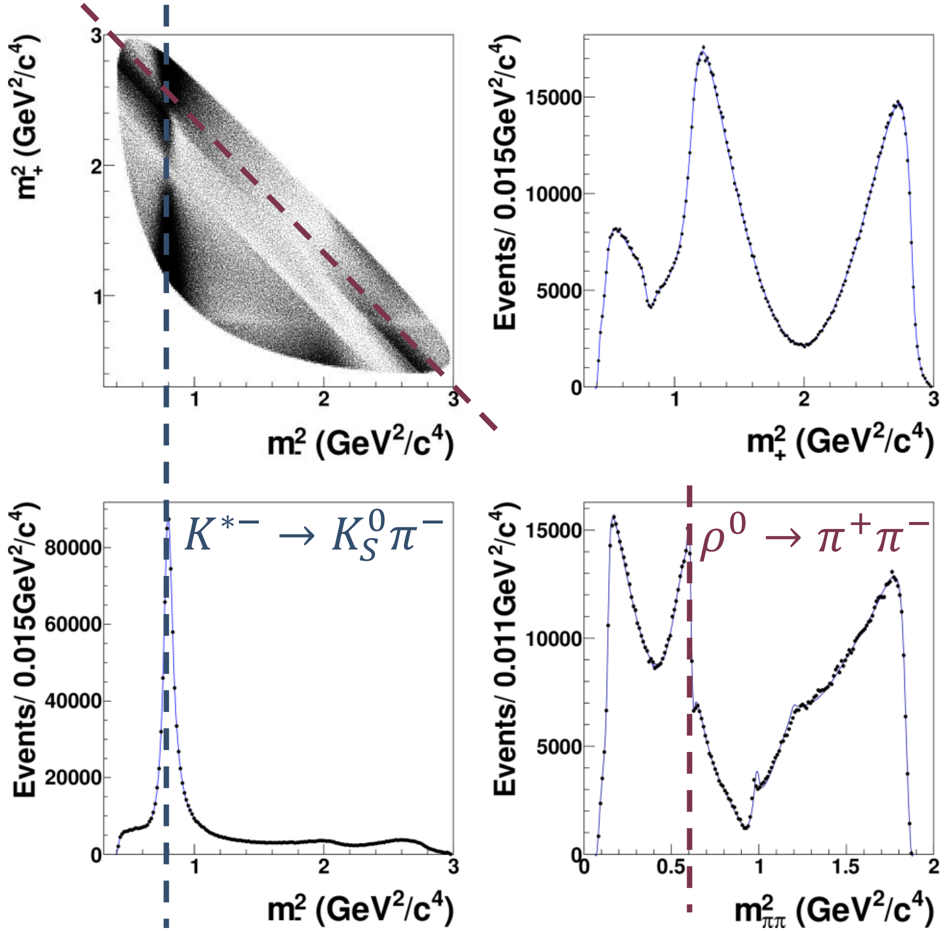
- Only probability density $|A(m_+^2, m_-^2)|^2$ is observable
- Isobar approach for amplitude parameterization

$$A(m_+^2, m_-^2) = \sum a_i F_i(m_+^2, m_-^2)$$

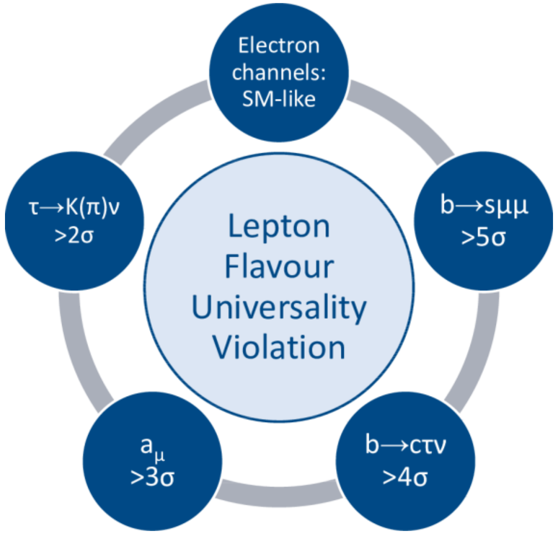
$$F_j(L, s,) = \boxed{R_j(s)} \times \boxed{F_D \times F_R} \times \boxed{T_j(L, \vec{p}_D, \vec{p}_R)}$$

Resonance term (Breit-Wigner)	Formfactors	Angular distribution

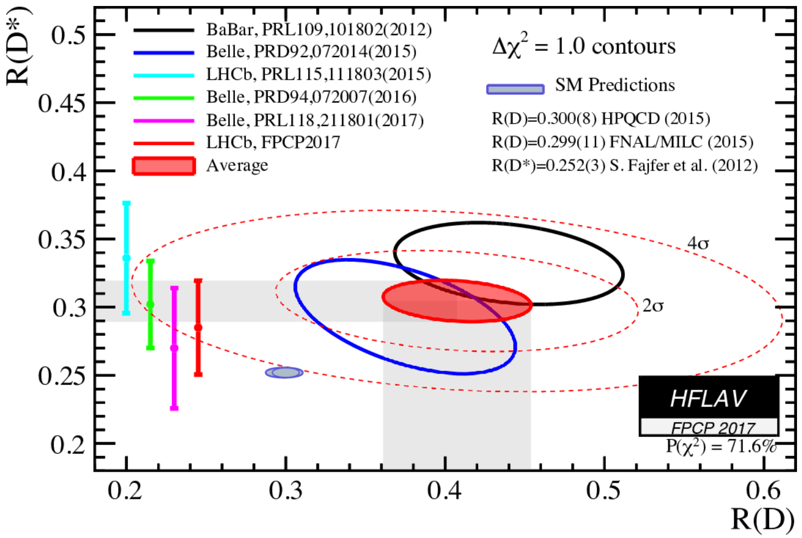
- The amplitude model obtained can be used in other measurements (ex. CKM phases β and γ, charm mixing)

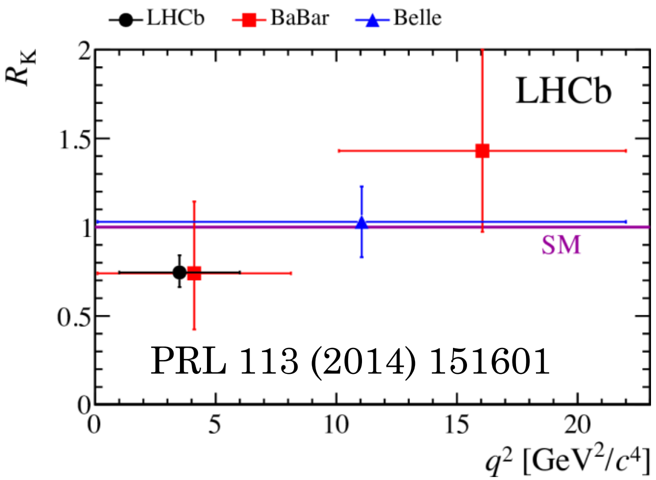


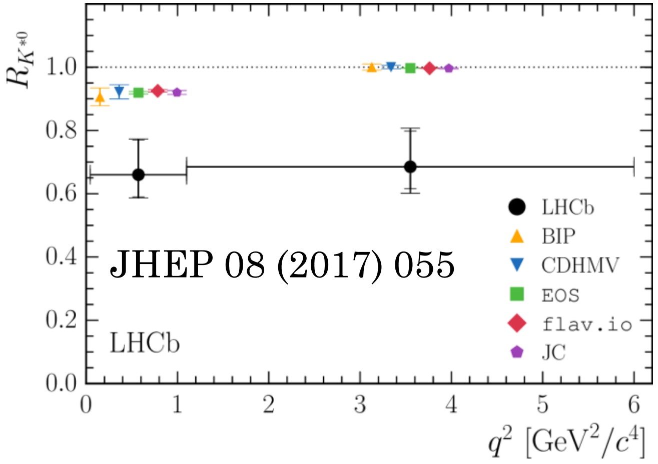
Lepton flavor universality violation



arXiv:1803.10097 [hep-ph]







$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu_\tau)}$$

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$$R_{K^{*0}} \equiv \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

Collider parameters

Energy	1.0 GeV	1.5 GeV	2.0 GeV	2.5 GeV
Circumference	813.1 m			
Emittance hor/ver	8 nm/0.04 nm @ 0.5% coupling			
Damping time hor/ver/long	50/50/25 ms	30/30/15 ms		
Bunch length	21 mm	12 mm	10 mm	10 mm
Energy spread	$8.7\cdot10^{-4}$	$11\cdot10^{-4}$	$9.3\cdot10^{-4}$	$7.2\cdot10^{-4}$
Momentum compaction	$8.73\cdot10^{-4}$	$8.81\cdot10^{-4}$	$8.82\cdot10^{-4}$	$8.83\cdot10^{-4}$
Damping wiggler field	50 kGs	50 kGs	35 kGs	10 kGs
Synchrotron tune	0.007	0.012	0.009	0.008
RF frequency	499.95 MHz			
Harmonic number	1356			
Particles in bunch	$7\cdot10^{10}$			
Number of bunches	406 (10% gap)			
Bunch current	4.2 mA			
Total beam current	1.7 A			
Beam-beam parameter	0.135	0.135	0.121	0.097
Luminosity	$0.6\cdot10^{35}$	$0.9\cdot10^{35}$	$1.0\cdot10^{35}$	$1.0\cdot10^{35}$

Status of the Super c-τ factory project

- In June 2017, the SCT project is included in the plan for the implementation of the first phase of the Strategy for Scientific and Technological Development of the Russian Federation
- In August, 2017, the Russian Ministry of Education and Science and Budker Institute signed an agreement for an amount of about 0,25 bln. Rbls, which foresees the development and upgrade of the accelerator complex of BINP and the creation of scientific and technical groundwork for the implementation of the SCT