Super Charm-Tau Factory

Denis Epifanov (BINP, NSU)

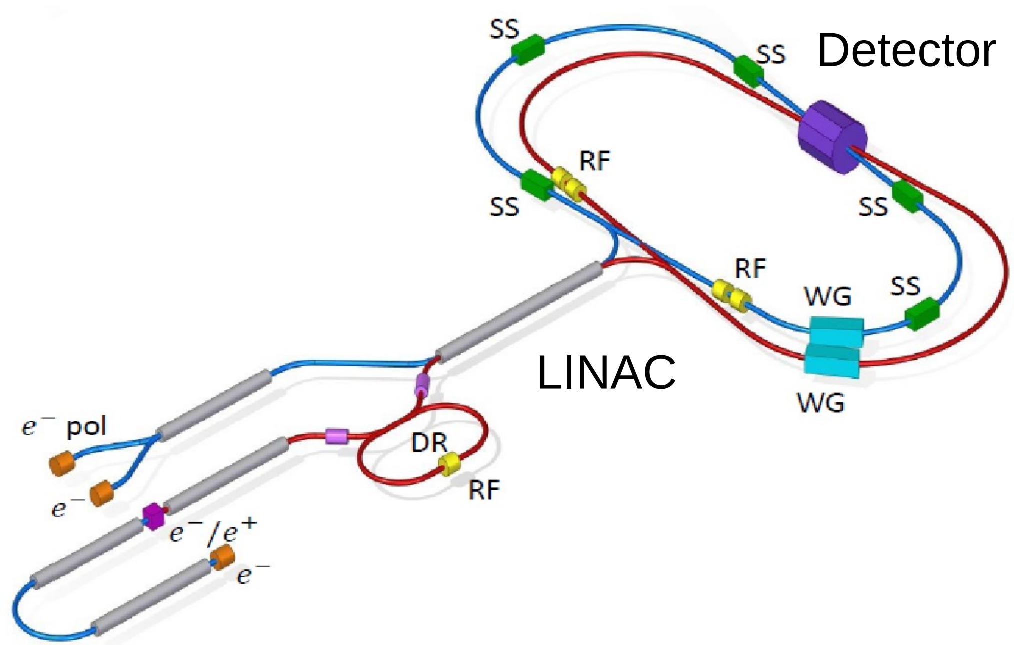
Conference of DNP, RAS, 10-12 March, 2020, Novosibirsk

Introduction
Physics program
Collider and detector
Status of the project in Novosibirsk

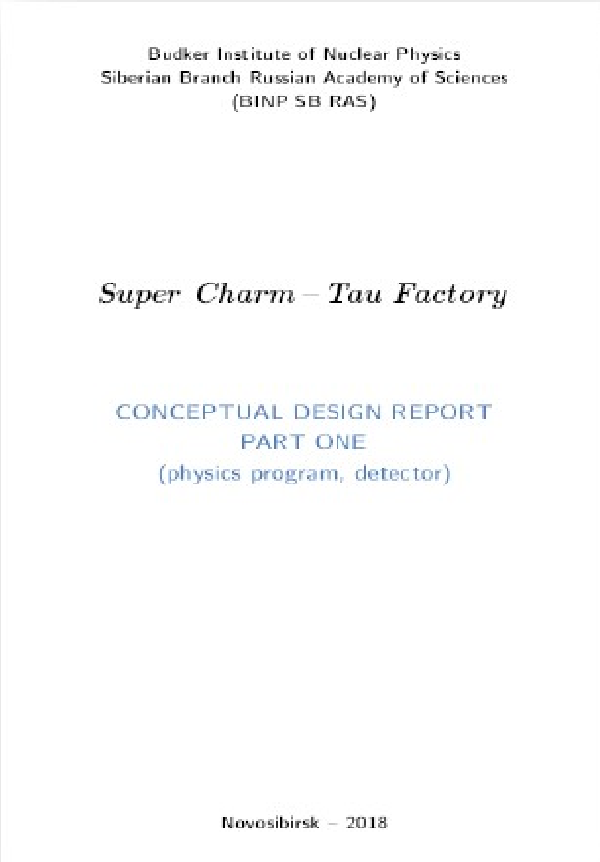
Introduction

- e+ e- Super Flavor Factory, Belle II, started data taking in 2018. This intensity frontier experiment will allow one to study physics of b-, c-quark, tau lepton on the record level of precision.
- The appropriate candidate to establish competitive and in many aspects complementary activity to study physics of charm, tau lepton and baryons is Super Charm-Tau e+ e- factory (SCTF) in Novosibirsk.

- **2E = 2 ÷ 6 GeV**
- **L = 10^{35} 1/cm^{2}s**
- **Crab-waist collisions**
- **Modern general purpose detector**



Physics program


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)

Novosibirsk – 2018

Charmonia
- Spectroscopy
- BR`s
- Light mesons on J/ψ decays

Charm mesons
- Spectroscopy
- BR's
- Mixing
- $\mathcal{CP}$ violation

Charm baryons
- Spectroscopy
- Br`s
- $\mathcal{CP}$ violation

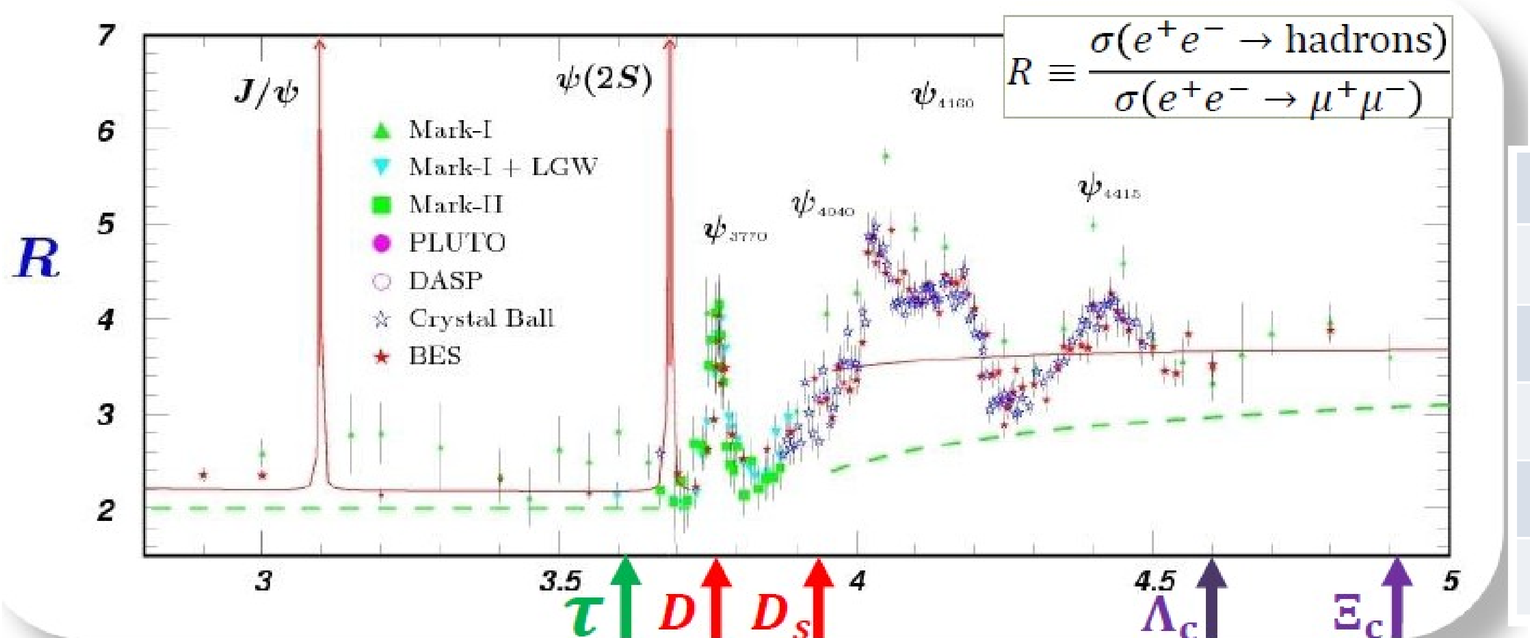
τ lepton
- Michel parameters
- Spectral functions
- $\mathcal{CP}$ violation
- Lepton flavour violation
- Lepton universality

Two-photon processes
- Search for C-even states
- $\sigma(\gamma\gamma \to$ hadrons)

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

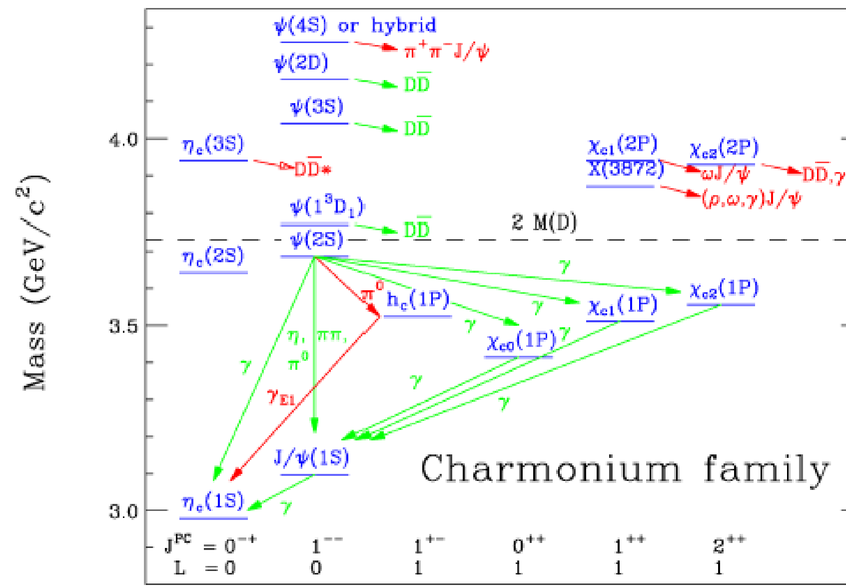
- The Conceptual Design Report (CDR) was recently (2018) updated
- The basic topics of the Physics Program are established
- **The advantages of e- beam polarization have been started to discuss in the last SCTF project meetings (twice per year)**
- **Complementarity of SCTF and Belle II in charm and tau sectors**

Expected statistics and tasks

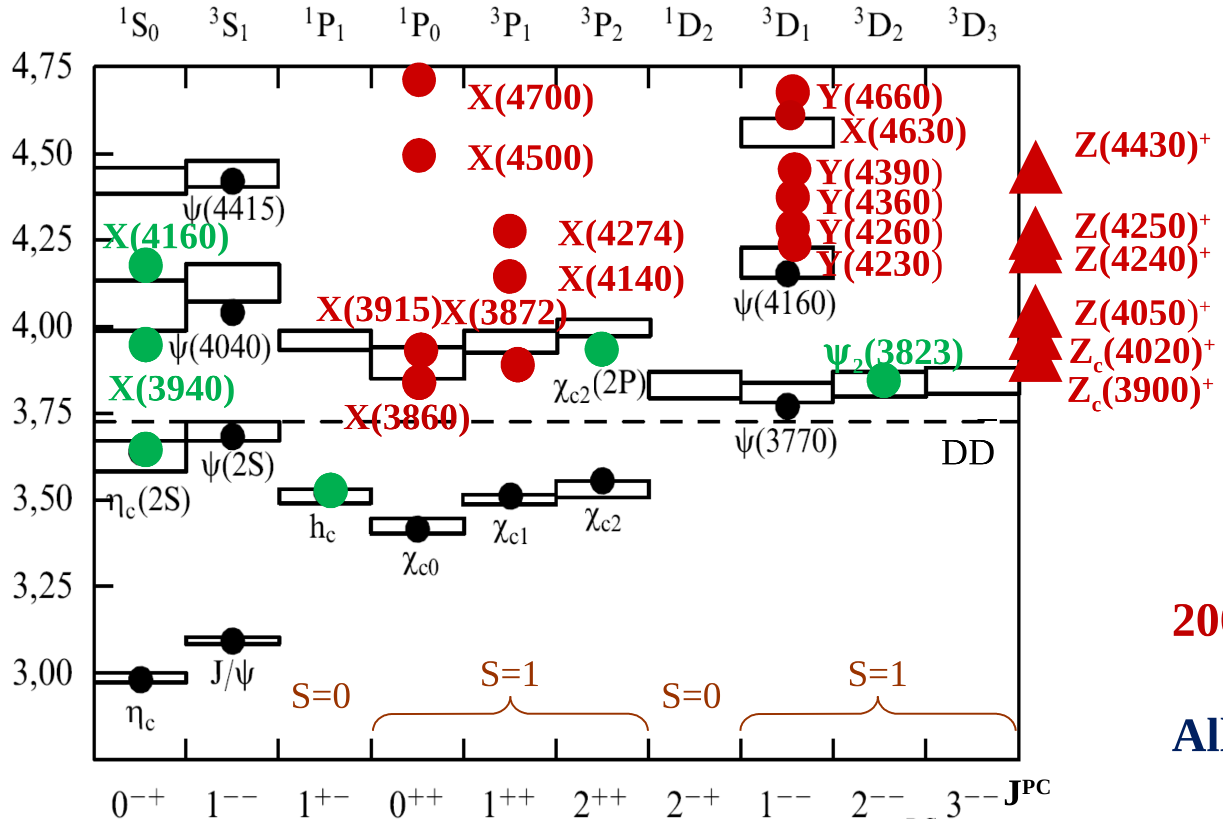


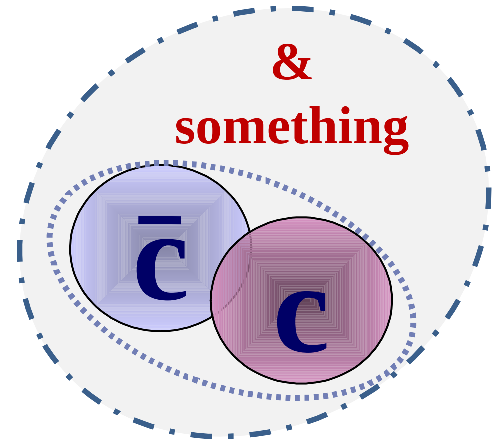
2E (GeV)	N / year
3.1	$10^{12}\, J/\psi$
3.69	$10^{11}\, \psi(2S)$
3.77	$10^{9}\, D\bar{D}$
4.17	$10^{8}\, D_s\bar{D}_s$
3.55 ÷ 4.3	$10^{10}\, \tau\, \tau$
4.65	$10^{8}\, \Lambda_c^+\Lambda_c^-$

- **J/Ψ, ψ(2S) factory:**
  - Big samples of light charmonia (η_c, h_c, χ_{cJ}), precise measurement of their parameters, study of (radiative) transitions between them.
  - J/Ψ hadronic decays, observation of weak decays
  - Search for LFV J/Ψ decays, c-quark EDM (J/Ψ → γφφ)
- **Study of exotic charmonia**
- **Clean D D production**, lower multiplicity and background, precision measurement of absolute branching fractions
- **Coherent production of D^0 D^0**: mixing of D mesons, measurement of strong phases (needed by Belle II), seach for CPV in D decays
- **$\tau^+\tau^-$ production:**
  - near threshold kinematics (τ → π / K ν (γ)), suppression of ISR background (τ → μ γ)
  - e- beam polarization → polarized single tau → tau spin-dependent effects (Michel par., CPV), monitor of the e- beam polarization (τ → ρ ν)



Charmoniumlike states





2002-2016 Discovery of **two dozens exotic charmonium states**

All of them above open charm threshold

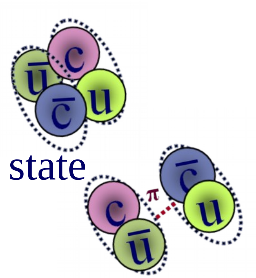
Multiquark states

Tetraquark

tightly bound four-quark state

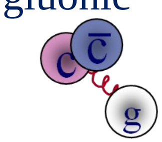
Molecular state

two loosely bound charm mesons

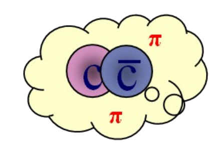


Charmonium hybrids

States with excited gluonic degrees of freedom



Hadrocharmonium



Specific charmonium state "coated" by excited light-hadron matter

Rescattering

Two D-mesons, produced closely, exchange quarks

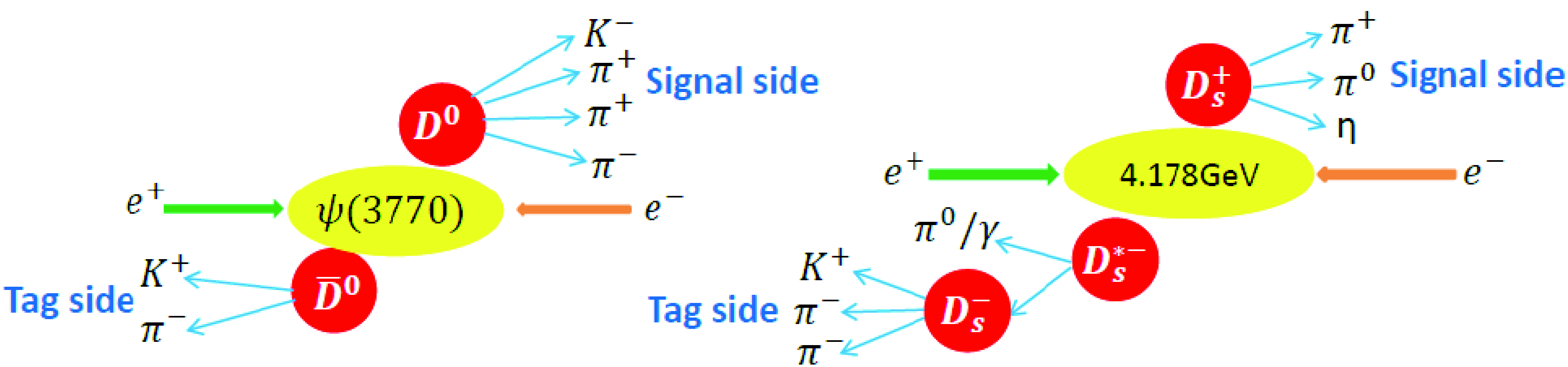
Threshold effects

Virtual states at thresholds

Charmonium states with masses shifted by nearby $\mathbf{D_{(s)}^{(*)}D_{(s)}^{(*)}}$ thresholds

Double tag for D meson studies

- 100% of beam energy converted to D pair (Clean environment, kinematic constrains ν Recon.)
- $D_{(S)}$ generated in pair ⇒ absolute Branching fractions
- Fully reconstruct about 15% of $D_{(S)}$ decays



$$\Delta E = E_D - E_{\text{Beam}}$$

$$M_{\text{BC}} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$$

◆ **Double tag techniques: Hadronic tag on one side, on the other side for missing-mass studies**

Test of lepton flavor universality in D decays

Pure-leptonic modes

$$R_{D^+_{(s)}} = \frac{\Gamma(D^+_{(s)} \to \tau^+\nu_\tau)}{\Gamma(D^+_{(s)} \to \mu^+\nu_\mu)} = \frac{m^2_{\tau^+}\left(1 - \frac{m^2_{\tau^+}}{m^2_{D^+_{(s)}}}\right)^2}{m^2_{\mu^+}\left(1 - \frac{m^2_{\mu^+}}{m^2_{D^+_{(s)}}}\right)^2}.$$

SM prediction: R_D=2.66±0.01

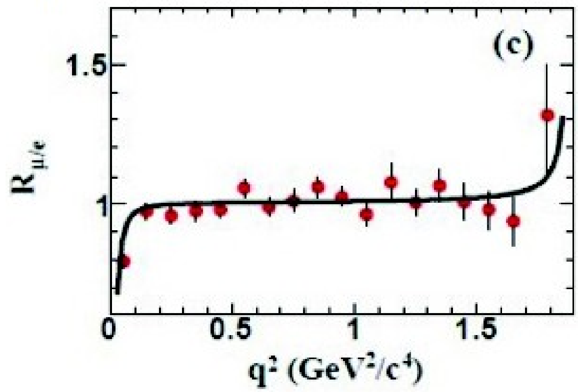
BESIII: R_D=3.21±0.64 (preliminary)

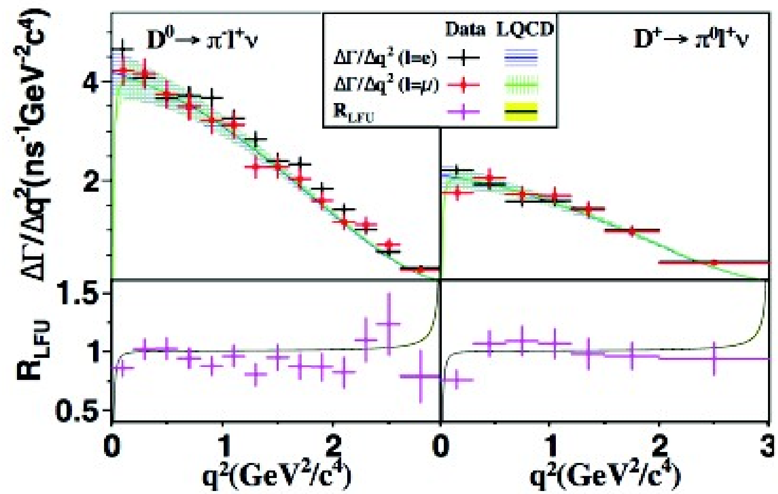
1σ difference?

1/ab at STCF: $\delta R_{D(s)}/R_{D(s)}$~0.5% (systematic dominant)

Semi-leptonic modes

$$R_{\mu/e} = \Gamma_{D^0\to K^-\mu^+\nu_\mu}/\Gamma_{D^0\to K^-e^+\nu_e}$$





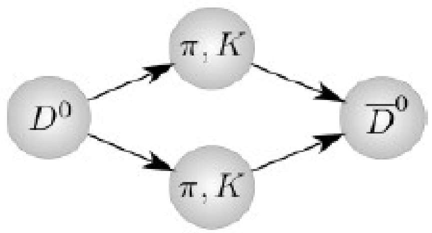
2.93/fb@3773MeV;
3.19/fb@4178MeV

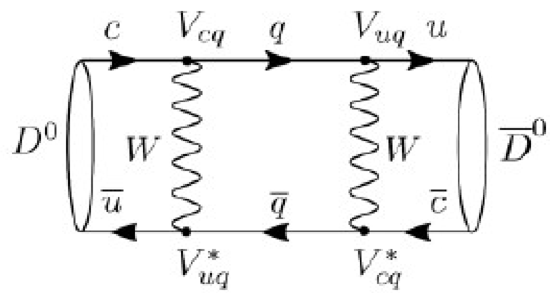
	$R(D_s^+)$	$R(D^+)$	$R(K^-)$	$R(\bar{K}^0)$	$R(\pi^-)$	$R(\pi^0)$
SM	9.74(1)	2.66(1)	0.975(1)	0.975(1)	0.985(2)	0.985(2)
BESIII	10.19(52)	3.21(64)	0.974(14)	1.013(29)	0.922(37)	0.964(45)

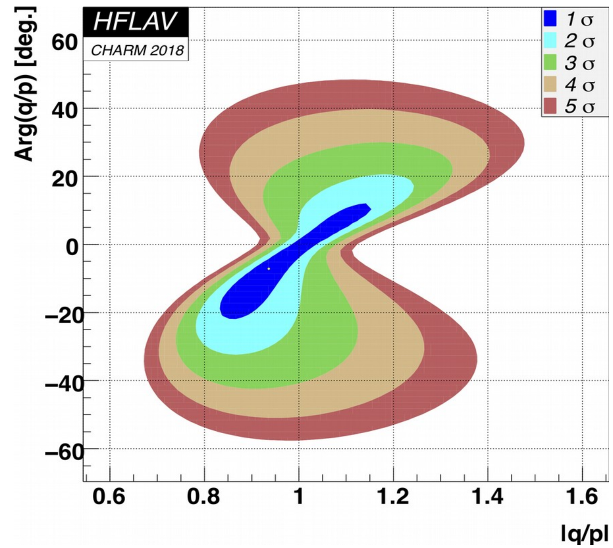
2σ difference?

Future STCF data will large constrain these tests.

Mixing of neutral D mesons







The mass eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$
$$|p|^2 + |q|^2 = 1$$
$$m(D_{1,2}) \equiv m_{1,2},\ \Gamma(D_{1,2}) \equiv \Gamma_{1,2}$$

The phase convention

$$CP|D^0\rangle = -|\overline{D}^0\rangle$$

The SM expectations

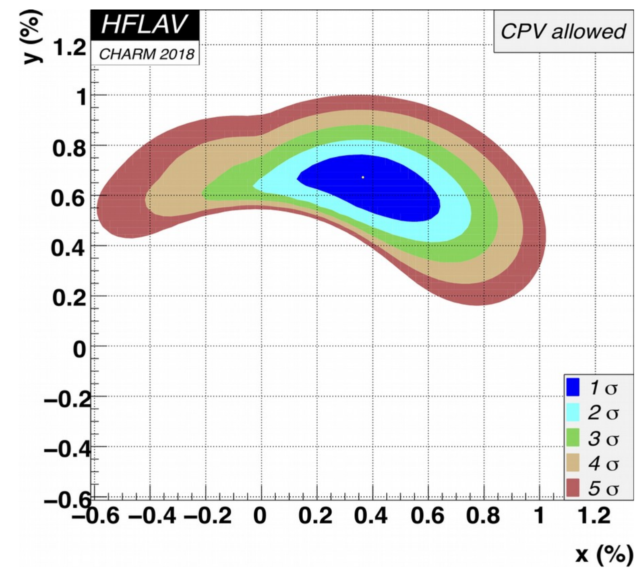
Short distances $x \sim y \sim 10^{-3}$
Long distances $x \sim y \sim 10^{-2}$

The mixing parameters

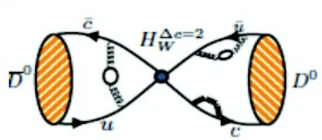
$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$
$$\Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}$$

The first evidences

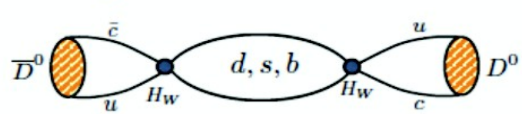
Phys. Rev. Lett. 98, 211802 (2007)
Phys. Rev. Lett. 98, 211803 (2007)



$$M_{12} - \frac{i}{2}\Gamma_{12} \propto \langle D^0|H_W^{\Delta c=2}|\overline{D}^0\rangle + \sum_n \frac{\langle D^0|H_W^{\Delta c=1}|n\rangle\langle n|H_W^{\Delta c=1}|\overline{D}^0\rangle}{M_D - E_n + i\epsilon}$$



Short distance
Lattice QCD helps !



Long distance
difficult to determine

Parameter	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.36^{+0.21}_{-0.16}$	[0.06, 0.70]
y (%)	$0.67^{+0.06}_{-0.13}$	[0.46, 0.79]

Time independent analysis

Due to the quantum correlations, the time-integrated decay rates are sensitive to mixing parameters

$$|\psi> \to \frac{1}{\sqrt{2}}(|D^0>_1|\bar{D}^0>_2 - |\bar{D}^0>_1|D^0>_2)$$

$$R_M = (x^2+y^2)/2\,, \qquad r_f e^{-\delta_f} = -\langle f|\overline{D^0}\rangle / \langle f|D^0\rangle, \qquad z_f = 2\cos\delta_f\,, w_f = 2\sin\delta_f$$

- f – CF/DCS
- (ex: $K^- \pi^+$)
- ℓ – semileptonic
- (ex: $K^- e^+ \nu$)
- $S_{\pm}$ – CP-even/odd
- (ex: K^+K^-)

	$C=-1$	$C=+1$
$(1/4)\cdot(\Gamma_{\ell S_+}\Gamma_{S_-}/\Gamma_{\ell S_-}\Gamma_{S_+} - \Gamma_{\ell S_-}\Gamma_{S_+}/\Gamma_{\ell S_+}\Gamma_{S_-})$	y	$-y$
$(\Gamma_{f\ell^-}/4\Gamma_f)\cdot(\Gamma_{S_-}/\Gamma_{\ell S_-} - \Gamma_{S_+}/\Gamma_{\ell S_+})$	y	$-y$
$(\Gamma_{f\bar{f}}/4\Gamma_f)\cdot(\Gamma_{S_-}/\Gamma_{\bar{f}S_-} - \Gamma_{S_+}/\Gamma_{\bar{f}S_+})$	$y+r_f z_f$	$-(y+r_f z_f)$
$(\Gamma_f \Gamma_{S_+S_-}/4)\cdot(1/\Gamma_{fS_-}\Gamma_{S_+} - 1/\Gamma_{fS_+}\Gamma_{S_-})$	$y+r_f z_f$	0
$(\Gamma_{\bar{f}}/2)\cdot(\Gamma_{S_+S_+}/\Gamma_{\bar{f}S_+}\Gamma_{S_+} - \Gamma_{S_-S_-}/\Gamma_{\bar{f}S_-}\Gamma_{S_-})$	0	$y+r_f z_f$
$\Gamma_{ff}/\Gamma_{f\bar{f}}$	R_M	$2r_f^2 + r_f(z_f y - w_f x)$
$\Gamma_{f\ell^+}/\Gamma_{f\ell^-}$	r_f^2	$r_f^2 + r_f(z_f y - w_f x)$
$\Gamma_{\ell^\pm\ell^\pm}/\Gamma_{\ell^+\ell^-}$	R_M	$3R_M$

$D^0\overline{D}^0$(C=+1) is from $e^+e^- \to D^0\overline{D}^0\gamma$

SCTF is competitive with Belle II and LHCb in the measurement of the $D^0 - \overline{D}^0$ mixing

CPV in charm

$\mathcal{CP}$ violation

$\left|\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right|^{\pm 2} \approx 1 \pm A_d$ Direct

Indirect

$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m$ In mixing

$\mathrm{Im}\,\lambda_f \neq 0$ In interference between mixing and decay

D^0 to $\mathcal{CP}$ eigenstate

- The decay rate asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx a_{CP}^{\mathrm{dir}} - A_\Gamma \frac{\langle t \rangle}{\tau},$$

where $\langle t \rangle$ is the average decay time of candidates

- The effective lifetime ratio

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}$$

- The lifetime $\mathcal{CP}$ asymmetry

$$\Delta Y_f \equiv \frac{\hat{\Gamma}(\bar{D}^0 \to f) - \hat{\Gamma}(D^0 \to f)}{2\Gamma} = (1 + y_{CP}) A_\Gamma$$

Belle

- $921\ \mathrm{fb}^{-1}, D^{*+} \to D^0\pi^+, D^0 \to K_S^0\pi^+\pi^-$ [1]
  - Time-dependent Dalitz analysis

$$\left|\frac{q}{p}\right| = 0.90 \pm 0.16 \pm 0.05 \pm 0.06$$

$$\arg\left(\frac{q}{p}\right) = (-6 \pm 11 \pm 3 \pm 4)^\circ$$

[1] Phys. Rev. D89, 091103(R) (2014) (Belle)
[2] arXiv:1002.5012 [hep-ex]
[3] A. Bondar et al., Phys. Rev. D82, 034033 (2010)

Future precision

Parameter	Belle II @ $50\ \mathrm{ab}^{-1}$	Super c-τ @ $10\ \mathrm{ab}^{-1}$
$\left\|\frac{q}{p}\right\|$	0.05 [2]	~ 0.01 [3]
$\arg\left(\frac{q}{p}\right)$	3°[2]	$\sim 1^\circ$[3]

Physics of tau lepton at SCTF

In the SM τ decays due to the charged weak interaction described by the exchange of $W^{\pm}$ with a pure vector coupling to only left-handed fermions. There are two main classes of tau decays:

- Decays with leptons, like: $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma$, $\tau^- \to \ell^- \ell'^+ \ell'^- \bar{\nu}_\ell \nu_\tau$; $\ell, \ell' = e, \mu$. They provide very clean laboratory to probe electroweak couplings, which is complementary/competitive to precision studies with muon (in experiments with muon beam). Plenty of New Physics models can be tested/constrained in the precision studies of the dynamics of decays with leptons.
- Hadronic decays of τ offer unique tools for the precision study of low energy QCD.

In five c.m.s. energy points ($2E = 3.554,\ 3.686,\ 3.770,\ 4.170,\ 4.650\,\mathrm{GeV}$) it is planned to accumulate $7\,\mathrm{ab}^{-1}$, which corresponds to $\boldsymbol{N_{\tau\tau} = 21 \times 10^9}$, which is 2.2 times smaller than the planned $\tau\tau$ statistics at Belle II.

However, the crucial feature of the Super Charm-Tau Factory project, the **polarized electron beam** and **lower c.m.s. energies**, might give some advantages in τ lepton studies in comparison with Belle II, thus, compensating smaller statistics of taus.

Measurement of Michel parameters in tau

In the SM, charged weak interaction is described by the exchange of $W^{\pm}$ with a pure vector coupling to only left-handed fermions ("V-A" Lorentz structure). Deviations from "V-A" indicate New Physics. $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ $(\ell = e, \mu)$ decays provide clean laboratory to probe electroweak couplings.

The most general, Lorentz invariant four-lepton interaction matrix element:

$$\mathcal{M} = \frac{4G}{\sqrt{2}} \sum_{\substack{N=S,V,T \\ i,j=L,R}} g_{ij}^N \left[\bar{u}_i(l^-) \Gamma^N v_n(\bar{\nu}_l) \right] \left[\bar{u}_m(\nu_\tau) \Gamma_N u_j(\tau^-) \right],$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \frac{i}{2\sqrt{2}}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$$

Ten couplings g_{ij}^N, in the SM the only non-zero constant is $g_{LL}^V = 1$

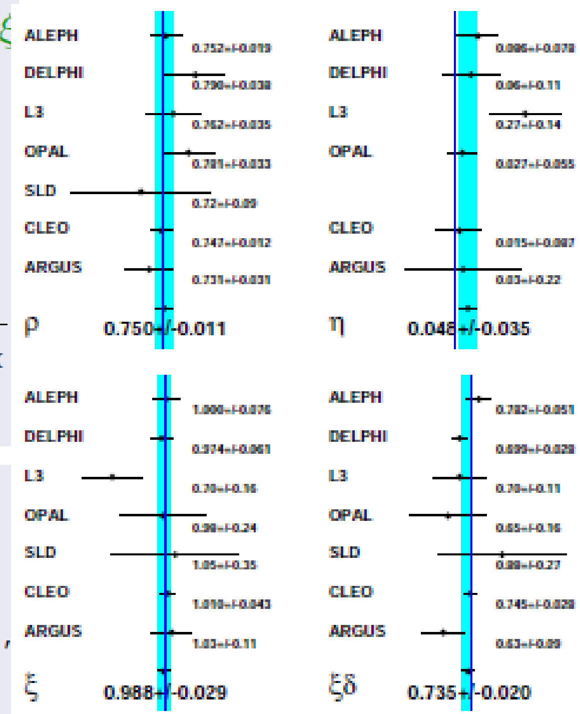
Four bilinear combinations of g_{ij}^N, which are called as Michel parameters (MP): ρ, η, ξ and δ appear in the energy spectrum of the outgoing lepton:

$$\frac{d\Gamma(\tau^\mp)}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\max}^4}{(2\pi)^4} \sqrt{x^2 - x_0^2} \Bigg(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$\mp \frac{1}{3} P_\tau \cos\theta_\ell \xi \sqrt{x^2 - x_0^2} \left[1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right) \right] \Bigg),\quad x = \frac{E_\ell}{E_{\max}},\quad x_0 = \frac{m_\ell}{E_{\max}}$$

In the SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\delta = \frac{3}{4}$

Michel par.	Measured value	Experiment	SM value
ρ (e or μ)	$0.747 \pm 0.010 \pm 0.006$ 1.2%	CLEO-97	3/4
η (e or μ)	$0.012 \pm 0.026 \pm 0.004$ 2.6%	ALEPH-01	0
ξ (e or μ)	$1.007 \pm 0.040 \pm 0.015$ 4.3%	CLEO-97	1
$\xi\delta$ (e or μ)	$0.745 \pm 0.026 \pm 0.009$ 2.8%	CLEO-97	3/4
ξ_h (all hadr.)	$0.992 \pm 0.007 \pm 0.008$ 1.1%	ALEPH-01	1



- **Type II 2HDM:** $\eta_\mu(\tau) = \frac{m_\mu M_\tau}{2}\left(\frac{\tan^2\beta}{M_{H^\pm}^2}\right)^2$; $\frac{\eta_\mu(\tau)}{\eta_e(\mu)} = \frac{M_\tau}{m_e} \approx 3500$
- **Tensor interaction:** $\mathcal{L} = \frac{g}{2\sqrt{2}} W^\mu \left\{ \bar{\nu}\gamma_\mu(1-\gamma^5)\tau + \frac{\kappa_\tau^W}{2m_\tau}\partial^\nu \left(\bar{\nu}\sigma_{\mu\ nu}(1-\gamma^5)\tau \right) \right\}$,
  $-0.096 < \kappa_\tau^W < 0.037$: DELPHI Abreu EPJ C16 (2000) 229.
- **Unparticles:** Moyotl PRD 84 (2011) 073010, Choudhury PLB 658 (2008) 148.
- **Lorentz and CPTV:** Hollenberg PLB **701** (2011) 89
- **Heavy Majorana neutrino:** M. Doi *et al.*, Prog. Theor. Phys. **118** (2007) 1069.

Michel parameters in tau at SCTF

At the Super Charm-Tau factory with polarized electron beam the average polarization of single τ is nonzero, hence the differential decay probability will contain both, τ spin-dependent and spin-independent parts.

$$\frac{d\sigma(\vec{\zeta}^-,\vec{\zeta}^+)}{d\Omega_\tau} = \frac{\alpha^2}{64E_\tau^2}\beta_\tau(D_0 + D_{ij}\zeta_i^-\zeta_j^+ + \mathcal{P}_e(F_i^-\zeta_i^- + F_j^+\zeta_j^+))$$

$$D_0 = 1+\cos^2\theta + \frac{1}{\gamma_\tau^2}\sin^2\theta,\ \mathcal{P}_e = \frac{N_e(+)-N_e(-)}{N_e(+)+N_e(-)}$$

$$D_{ij} = \begin{pmatrix} (1+\frac{1}{\gamma_\tau^2})\sin^2\theta & 0 & \frac{1}{\gamma_\tau}\sin 2\theta \\ 0 & -\beta_\tau^2\sin^2\theta & 0 \\ \frac{1}{\gamma_\tau}\sin 2\theta & 0 & 1+\cos^2\theta - \frac{1}{\gamma_\tau^2}\sin^2\theta \end{pmatrix}$$

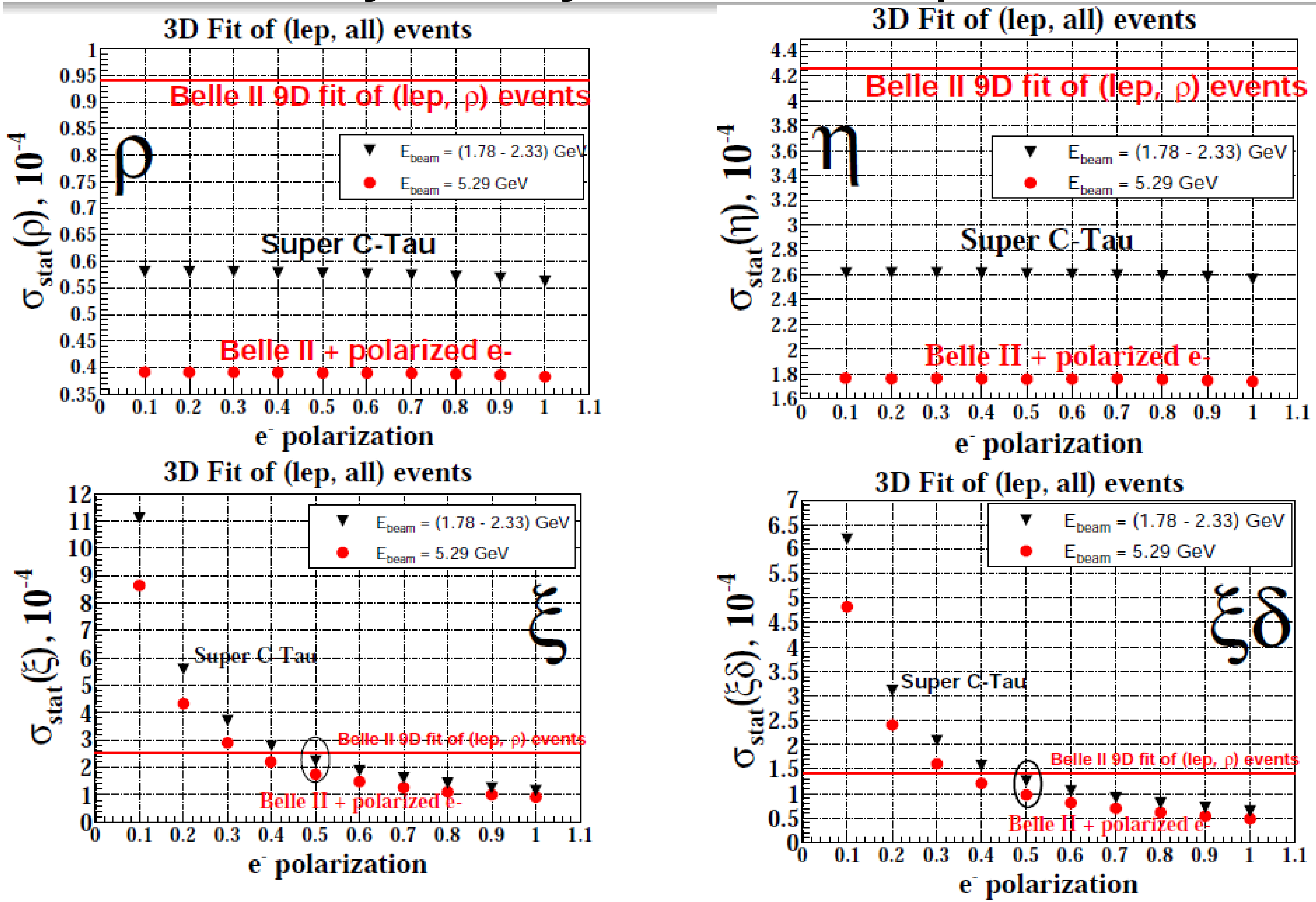
Single τ studies at the Super Charm-Tau factory:

$$\frac{d\sigma(\vec{\zeta}^-)}{d\Omega_\tau} = \frac{\alpha^2}{32E_\tau^2}\beta_\tau(D_0 + \mathcal{P}_e F_i^-\zeta_i^-)$$

As a result, there are two methods to measure MP:

- **(I) Unbinned fit of the $(\ell,\ \rho)$ events in 9D phase space (spin-spin correlations + polarized e^- beam)**
- **(II) Unbinned fit of the $(\ell,\ \mathrm{all})$ events in 3D lepton phase space (only polarized e^- beam)**

Feasibility study of Michel parameters



Starting from e- beam polarization of P_e = 0.5 the sensitivity to all Michel parameters at the SCTF becomes better than at Belle II

Study of hadronic tau decays

Cabibbo-allowed decays ($\mathcal{B} \sim \cos^2\theta_c$)

$\mathcal{B}(S=0) = (61.85 \pm 0.11)\%$ (PDG)

Cabibbo-suppressed decays ($\mathcal{B} \sim \sin^2\theta_c$)

$\mathcal{B}(S=-1) = (2.88 \pm 0.05)\%$ (PDG)

$$iM_{\rm fi}\left\{\begin{array}{c} S=0 \\ S=-1 \end{array}\right\} = \frac{G_F}{\sqrt{2}}\bar{u}_{\nu_\tau}\gamma^\mu(1-\gamma^5)u_\tau \cdot \left\{\begin{array}{c} \cos\theta_c \cdot \langle \mathrm{hadrons}(q^\mu)|\hat{J}_\mu^{S=0}(q^2)|0\rangle \\ \sin\theta_c \cdot \langle \mathrm{hadrons}(q^\mu)|\hat{J}_\mu^{S=-1}(q^2)|0\rangle \end{array}\right\}, \quad q^2 \le M_\tau^2$$

The main tasks

- Measurement of branching fractions with highest possible accuracy
- Measurement of low-energy hadronic spectral functions
  - Determination of the decay mechanism (what are intermediate mesons and their contributions)
  - Precise measurement of masses and widths of the intermediate mesons
- **Search for CP violation**
- Comparison with hadronic formfactors from e^+e^- experiments to check CVC theorem
- Measurement of $\Gamma_{\rm inclusive}(S=0)$ to determine α_S
- Measurement of $\Gamma_{\rm inclusive}(S=-1)$ to determine s-quark mass and V_{us}:

$$|V_{us}| = \sqrt{\frac{R_{\rm strange}}{\frac{R_{\rm non-strange}}{|V_{ud}|^2} - \delta R_{\rm theory}}}$$

- $R_{\rm strange} = \mathcal{B}_{\rm strange} / \mathcal{B}_e$
- $R_{\rm non-strange} = \mathcal{B}_{\rm non-strange} / \mathcal{B}_e$
- $\delta R_{\rm theory}$ - SU(3)-breaking contribution

CPV in hadronic tau decays at B factories

- CPV has not been observed in lepton decays
- It is strongly suppressed in the SM ($A^{\rm CP}_{\rm SM} \lesssim 10^{-12}$) and observation of large CPV in lepton sector would be clean sign of New Physics
- τ lepton provides unique possibility to search for CPV effects, as it is the only lepton decaying to hadrons, so that the associated strong phases allows us to visualize CPV in hadronic τ decays.

I. CPV in $\tau^- \to \pi^- K_S (\geq 0\pi^0)\nu_\tau$ at BaBar (Phys. Rev. D 85, 031102 (2012))

Data sample of $\int Ldt = 476$ fb^{-1} was analyzed

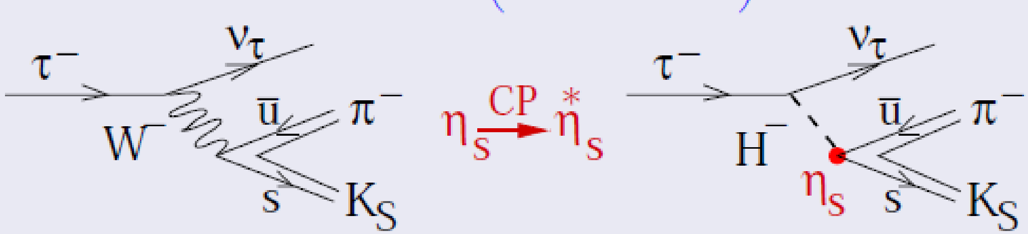
$$A_{\rm CP} = \frac{\Gamma(\tau^+ \to \pi^+ K^0_S(\geq 0\pi^0)\bar\nu_\tau) - \Gamma(\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K^0_S(\geq 0\pi^0)\bar\nu_\tau) + \Gamma(\tau^- \to \pi^- K^0_S(\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

2.8σ **deviation** from the SM expectation: $A^{K^0}_{\rm CP} = (+0.36 \pm 0.01)\%$

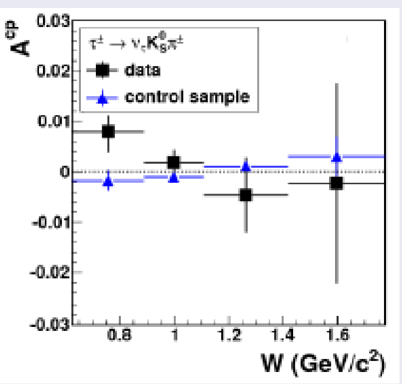
II. CPV in $\tau^- \to K^0_S \pi^- \nu_\tau$ at Belle (Phys. Rev. Lett. 107, 131801 (2011)) $\int$Ldt=699 fb^{-1}

Angular distributions were analyzed, $A_{\rm CP}(W = M_{K_S\pi})$ was measured ($d\omega = d\cos\beta\, d\cos\theta$):

$$A_{\rm CP}(W) = \frac{\int \cos\beta\cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\int \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega} \simeq \langle \cos\beta\cos\psi\rangle_{\tau^-} - \langle \cos\beta\cos\psi\rangle_{\tau^+}$$



$|Im(\eta_S)| < 0.026$



CPV in hadronic tau decays at SCTF

At the center-of-mass energies close to the $\tau^+\tau^-$ production threshold the τ lepton is produced with the polarization
$|\vec{P}_\tau| = P_e \frac{2E_{\rm beam}\sqrt{p^2_{\rm beam}\cos^2\theta + M^2_\tau}}{E^2_{\rm beam} + M^2_\tau + p^2_{\rm beam}\cos^2\theta} \approx P_e$ along electron beam polarization
$((P_\tau)_Z = P_e \frac{E_{\rm beam}\cos^2\theta + M_\tau \sin^2\theta}{\sqrt{p^2_{\rm beam}\cos^2\theta + M^2_\tau}} \approx P_e)$.
In case of New Physics contribution, the amplitudes for the decays $\tau^- \to (K\pi)^-\nu_\tau$ and $\tau^+ \to (K\pi)^+\bar{\nu}_\tau$ are:

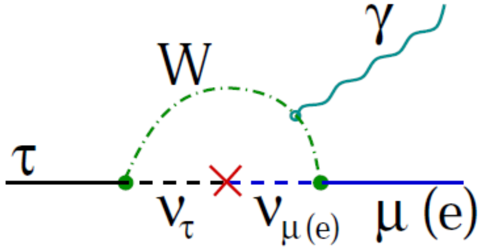
$$\mathcal{A} = A_1 + A_2 e^{i\phi} e^{i\delta}, \;\; \overline{\mathcal{A}} = A_1 + A_2 e^{-i\phi} e^{i\delta}$$

where ϕ and δ are relative weak (CP-odd) and strong (CP-even) phases. CPV is studied comparing $|\mathcal{A}|^2$ and $|\overline{\mathcal{A}}|^2$, there are three possibilities to construct CPV asymmetry:

- decay rate asymmetry $\sim \sin\delta \sin\phi$
- weighted rate asymmetry $\sim \sin\delta \sin\phi$
- asymmetry based on $\vec{P}_\tau(\vec{p}_K \times \vec{p}_\pi)$ triple product $\sim \cos\delta \sin\phi$

At the Super Charm-Tau factory, with nonzero single τ polarization, nonzero strong-phase difference, δ, is not needed to measure CPV.

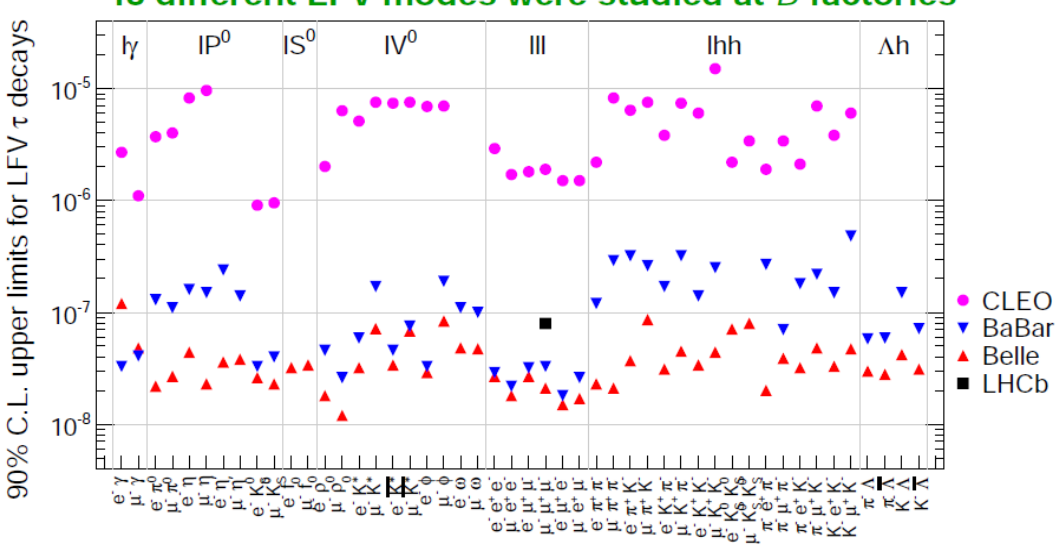
LFV τ decays



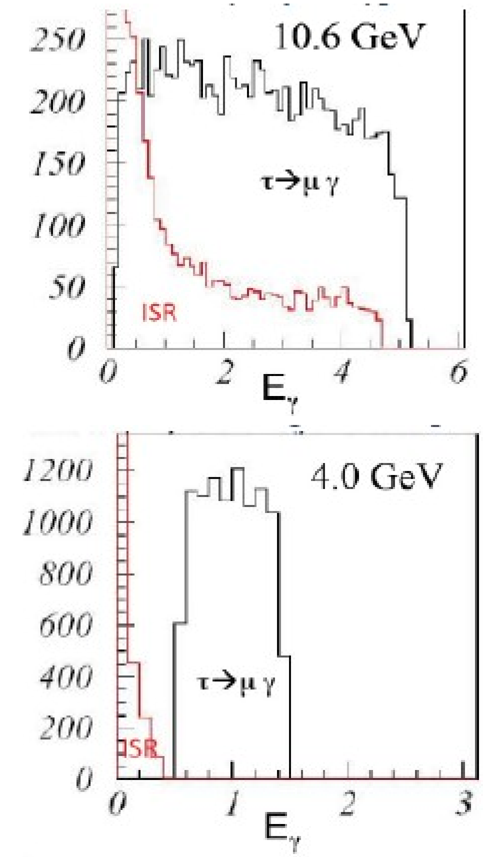
Model	$\mathcal{B}(\tau\to\mu\gamma)$	$\mathcal{B}(\tau\to\ell\ell\ell)$
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z′	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

- Probabililty of LFV decays of charged leptons is extremely small in the Standard Model, $\mathcal{B}(\tau\to\ell\gamma)\sim\left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$
- Many models beyond the SM predict LFV decays with the branching fractions up to $\lesssim 10^{-8}$. As a result observation of LFV is a clear signature of New Physics (NP).
- τ lepton is an excellent laboratory to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes
- Study of the different τ LFV decay modes allows us to test various NP models.

48 different LFV modes were studied at *B* factories



τ→μγ at SCTF



Notable background from τ→μνν + ISR γ can be essentially suppressed at the ττ production threshold at SCTF

Expected BR(τ→μγ) limit at the SCTF is O(10^{-10})

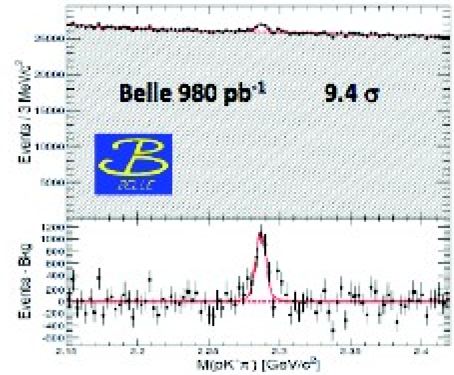
Activities on Λ^+_c

EPJC77, 895 · PRL116, 052001 · PRL113, 042002

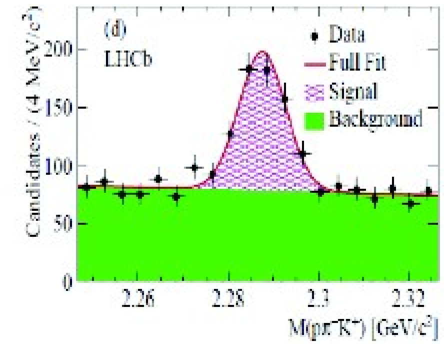
$\Lambda_c^\pm$ Mode	HFLAV 2016 (%)	BESIII (%)	PDG 2014 (%)	BELLE (%)
pK^0_S	1.59 ± 0.07	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	6.46 ± 0.24	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK^0_S\pi^0$	2.03 ± 0.12	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK^0_S\pi^+\pi^-$	1.69 ± 0.11	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	5.05 ± 0.29	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	1.28 ± 0.06	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	7.09 ± 0.36	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	3.73 ± 0.21	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	1.31 ± 0.07	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	1.25 ± 0.09	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	4.64 ± 0.24	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	1.77 ± 0.21	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	
$\Lambda e^+\nu_e$	3.18 ± 0.32	$3.63 \pm 0.38 \pm 0.20$	2.1 ± 0.6	

Observation of DCS decay $\Lambda_c^+ \to p\pi^- K^+$

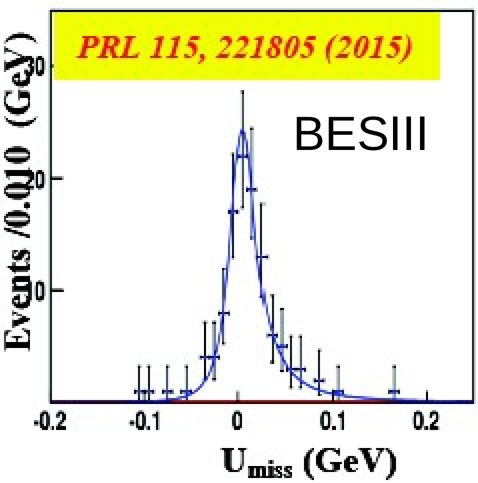
PRL 117, 011801(2016)

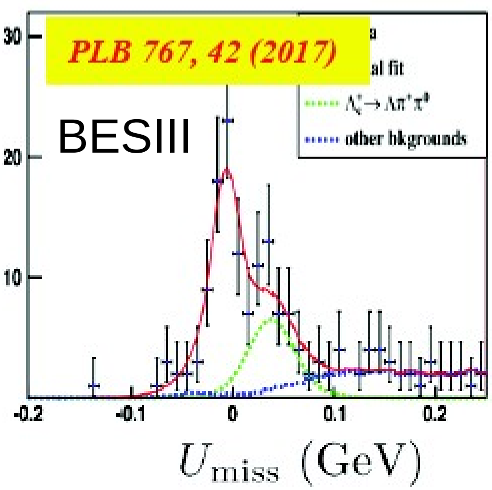


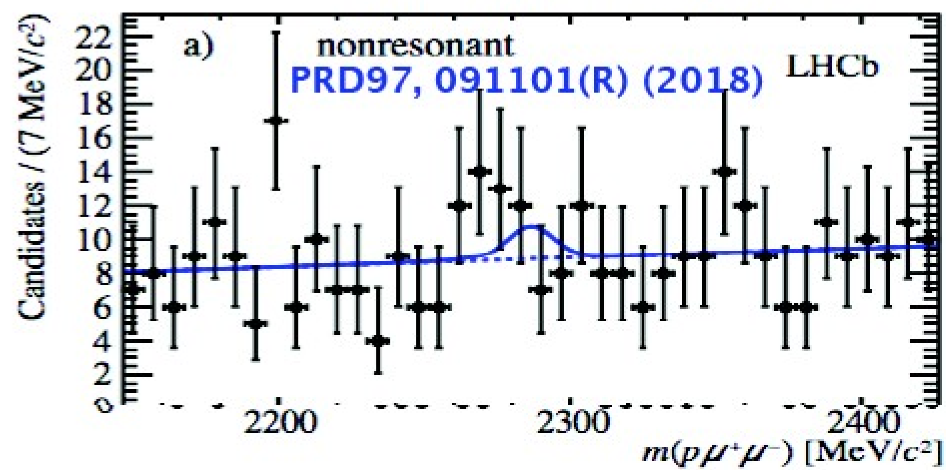
JHEP03, 043(2018)



$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7\ (9.6) \times 10^{-8}$







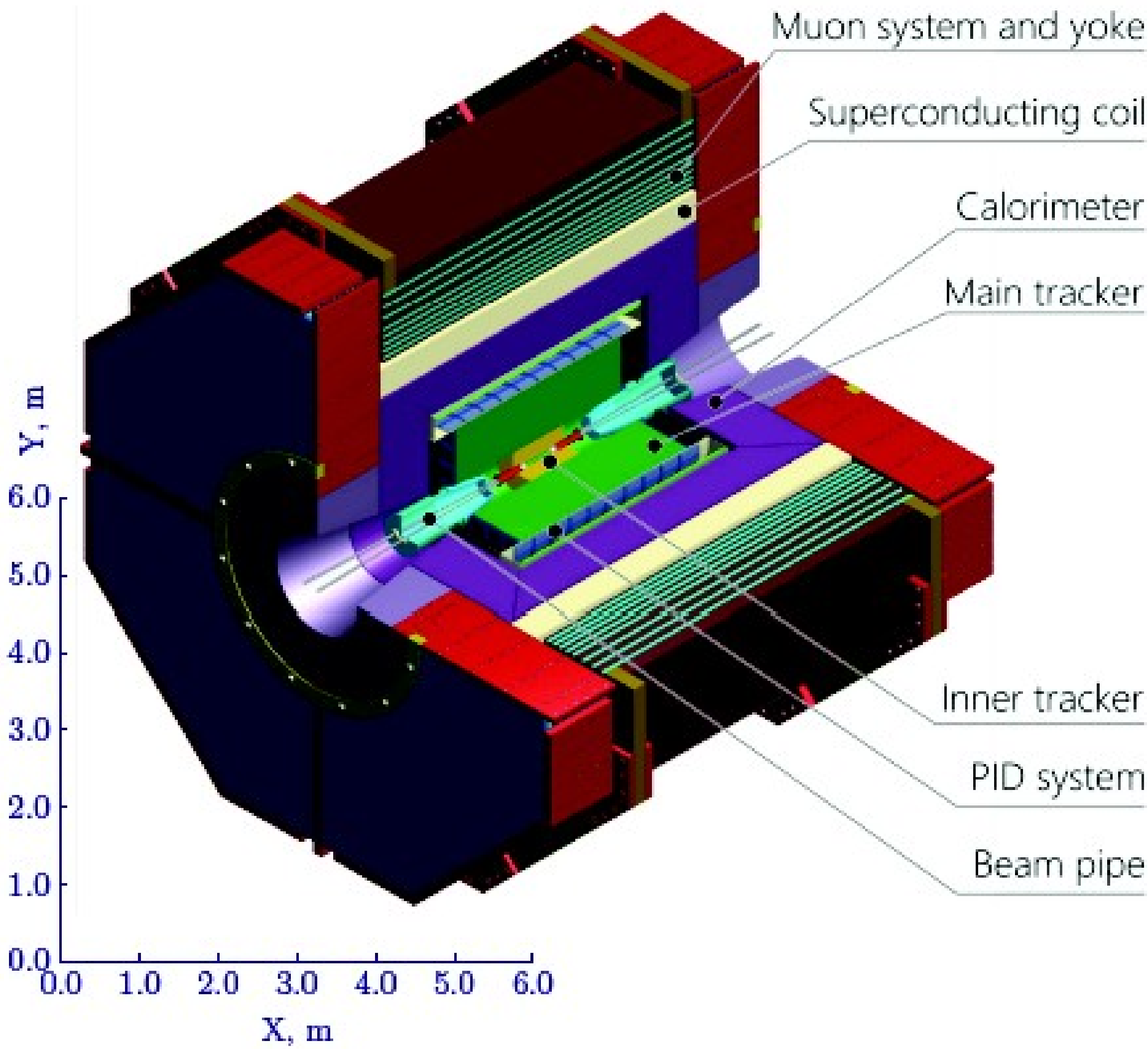
$\Gamma[\Lambda_c^+ \to \Lambda\mu^+\nu_\mu]/\Gamma[\Lambda_c^+ \to \Lambda e^+\nu_e] = 0.96 \pm 0.16 \pm 0.04$

LHCb, JHEP 03, 182 (2018)

$$\Delta A_{CP}^{\rm wgt} = A_{CP}(pK^-K^+) - A_{CP}^{\rm wgt}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\,\%,$$

SCTF allows us to improve essentially the accuracy of LFU test and search for CPV

Detector for SCTF



Physics requirements:

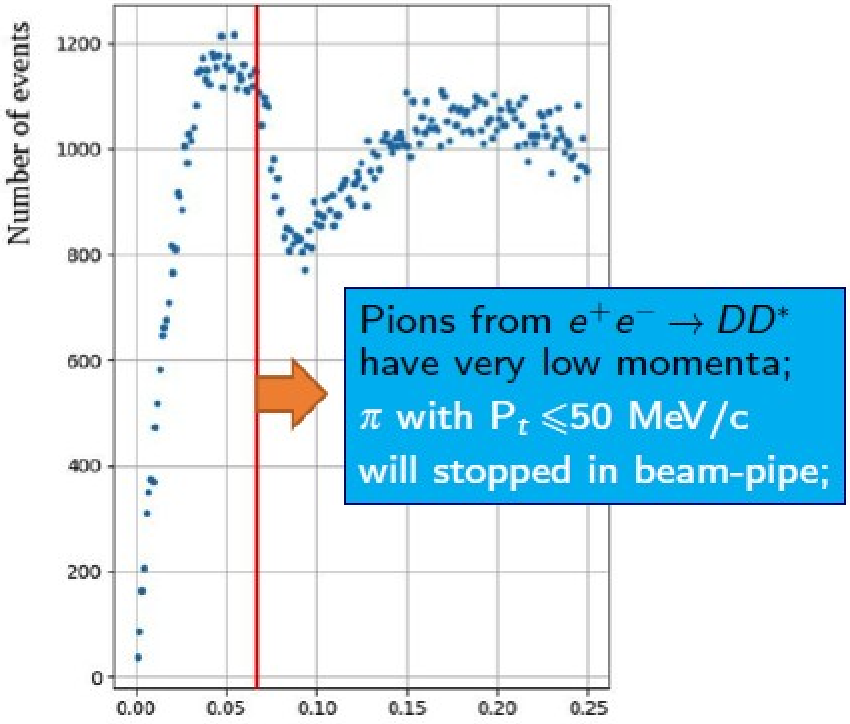
- Good $\frac{\sigma_P}{P}$ for charged particles.
- Good symmetry and hermeticity;
- Soft track detection;
  - Inner tracker to work with rate of charged tracks $\geqslant 10^4 \frac{\mathbf{tracks}}{cm^2 \cdot s}$;
- Good $\mu/\pi/K$-sep. up to 1.5 GeV/c;
  - Good $\frac{dE}{dx}$ resolution;
  - Specialized PID system for μ/π and π/K-separation;
- Good π^0/γ-separation and γ detection with E_γ=10÷3000 MeV;
  - EM calorimeter with σ_E as close as possible to physics limit;
  - Fast calorimeter ($\sigma_t \leqslant$1 ns and small shaping time) to suppress beam background and pileup noise;
- DAQ rate ~ 300 kHz at J/ψ-peak.

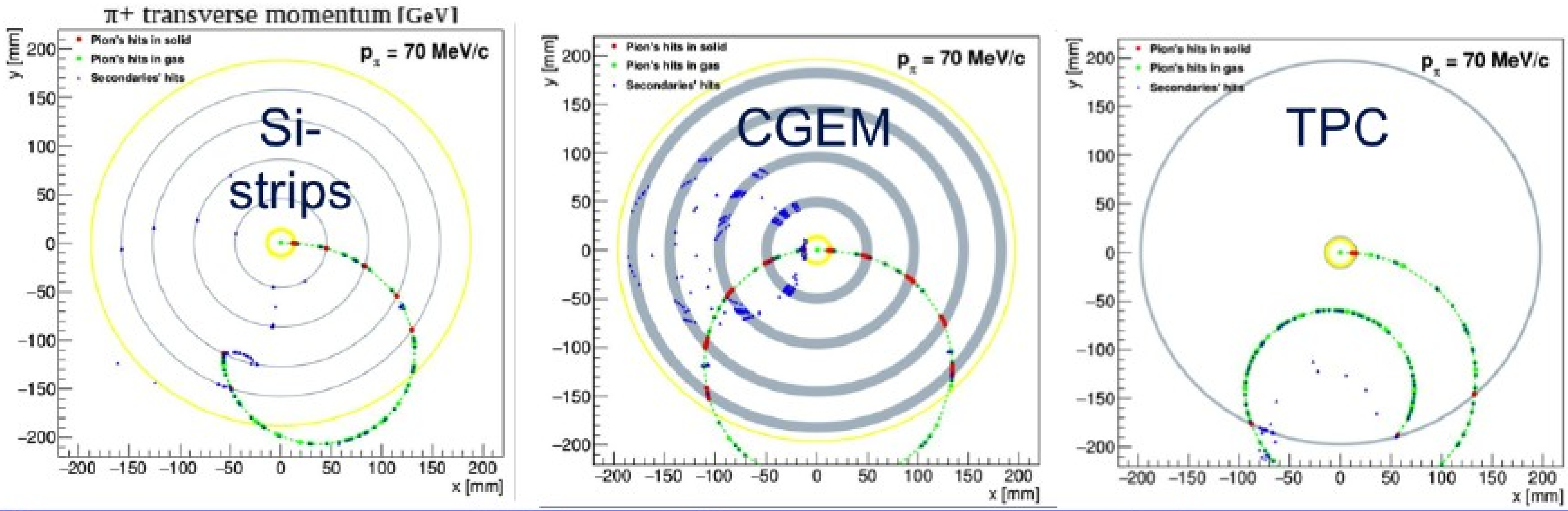
$\tau \to \mu\gamma$

Inner tracker

- Good resolution, better than 100 um (rec. of K_S and Λ)
- Increase hermiticity of the tracker
- Detection of particles starting from 50 MeV/c
- Handle high particle rate

- The TPC is more attractive option:
  - More hits per track,
  - more reliable dE/dx – measurements.
- TPC capability to reconstruct the tracks in expected experimental conditions will be checked with full simulation soon.





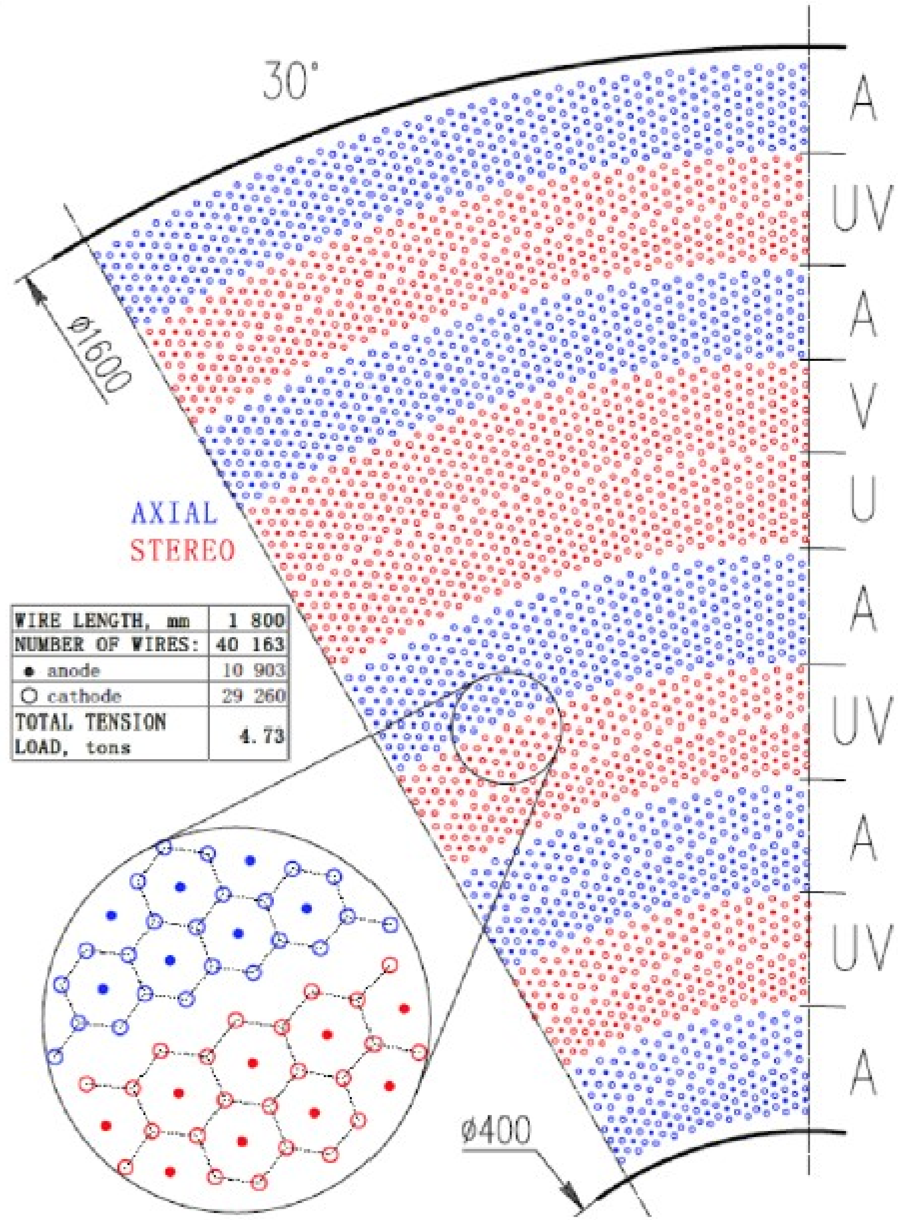
Drift chamber

- ~40000 wires
  - 11k sensitive, W-Re(Au)
  - 29k field, Al(Au)
- Hexagonal cell, 6.3-7.5 mm
- 41 layers
- 60% He + 40% C_3H_8
- < 450 ns drift time (1.5 T)

$$\frac{\sigma_{p_t}}{p_t} \approx \sqrt{0.21\%^2 p_t^2 + 0.31\%^2}$$

$\approx 0.4\%$ at 1 GeV

$$\frac{\sigma_{dE/dx}}{dE/dx} \approx 6.9\%$$

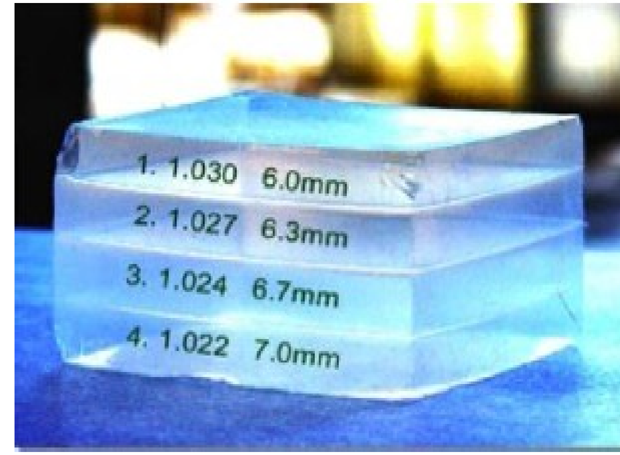


Other variants are also considered

Particle identification

- π/K separation >4σ up to 3.0 GeV/c [TOF(BESIII): 3σ at 0.9 GeV/c; DIRC(BABAR): 4σ at 2.5 GeV/c; ASHIPH(KEDR): 4σ at 1.5 GeV/c]
- Good μ / π separation at P < 1.2 GeV/c
- Several options are considered: FARICH, ASHIPH, TOF

Focusing **A**erogel **RICH (FARICH)**



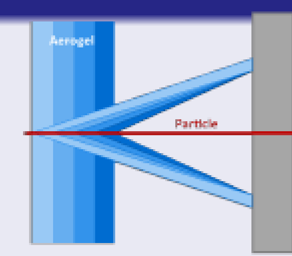
FARICH system parameters:

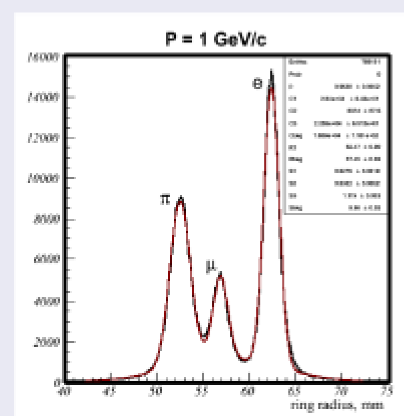
- Focusing aerogel with $n_{\mathbf{max}}$=1.05(1.07?), 4 layers, total thickness 35 mm
- Aerogel area: 14 m^2
- Photon detectors (3×3 mm^2):
  - Barrel – SiPMs (16 m^2)
  - Endcap – MCP PMT (5 m^2) LAPPD?
- 1÷2·10^6 channels (it depends on pitch)
- Load 0.5÷1.0 MHz/channel
- Cooling system (⩽-30°C) is needed
- R&D for read out electronics is required.

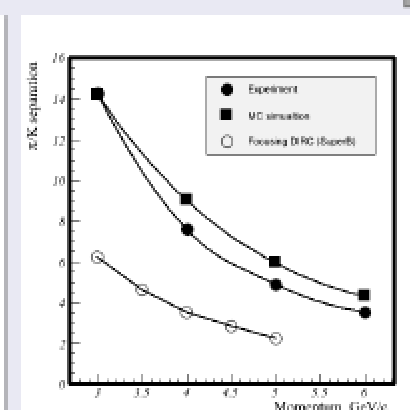
FARICH method

- Increase $N_{\mathbf{pe}}$ w/o σ_{Θ_c} increase;
- μ/π-sep.∼ 5σ at 1 GeV/c

was obtained in beam tests;

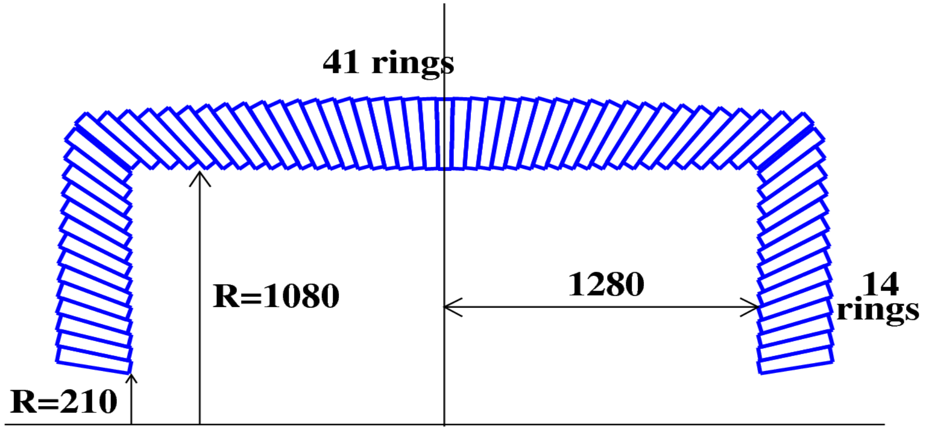






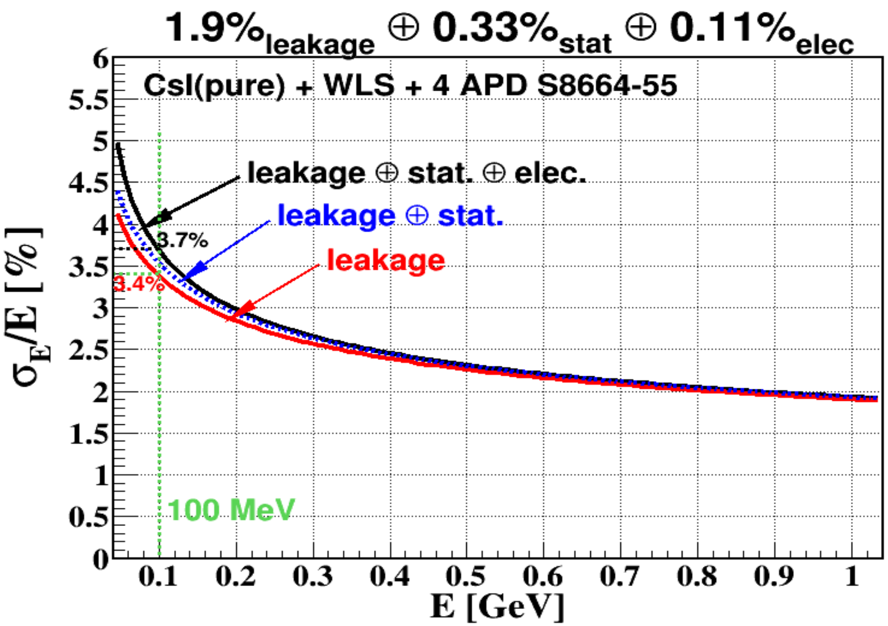
Electromagnetic calorimeter

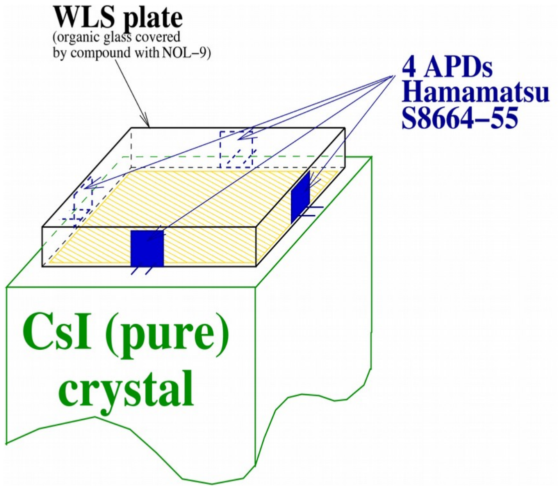
The main option is the calorimeter based on CsI(pure) scintillation crystals

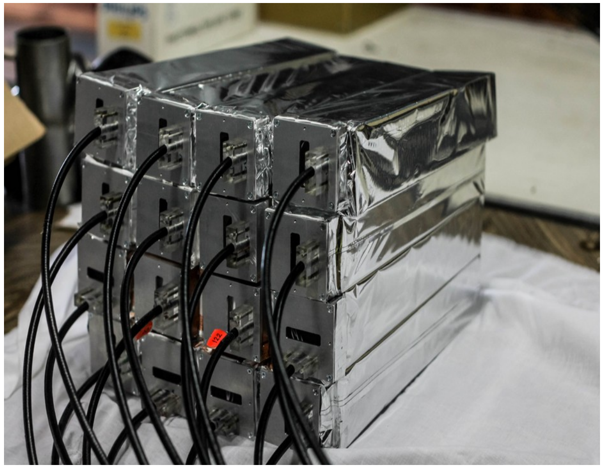


- Crystal of truncated pyramidal form (small facet ~(5.5 x 5.5) cm²) with the length of 30 cm (16 X_0)
- The barrel part includes 5248 counters = 41 θ-rings x 128 counters, total weight is 26 tons
- Two endcap parts: 2 x 16 sectors x 68 = 2 x 1088 = 2176 counters, total weight is 10 tons
- The whole calorimeter: 7424 counters (36 tons)

CsI(pure) + WLS + 4APD





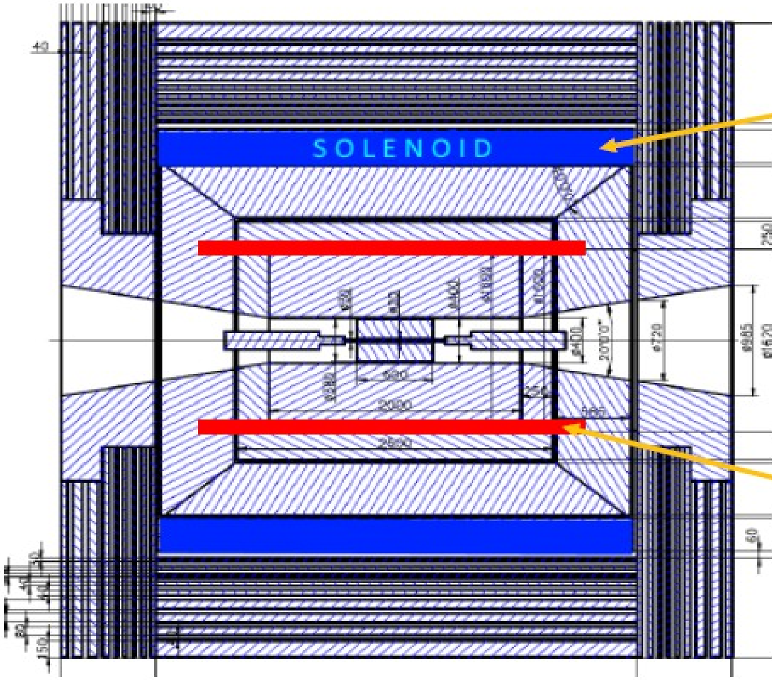


16-counter prototype is ready

Cosmic runs have been started with the prototype, test

beam study of the prototype at ROKK-1M facility in BINP is planned in 2020

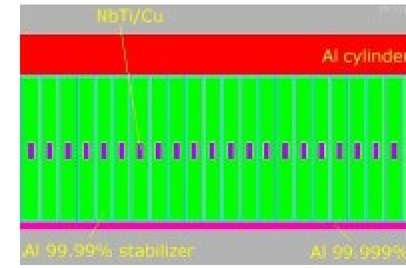
Magnet and muon system



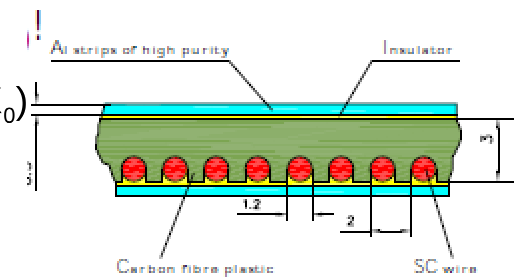
1.0 or 1.5 T

Baseline option

- “Thick” design outside calorimeter
- Al-stabilized coil, established technology
- Similar to PANDA magnet



- “Thin” design inside calorimeter ($0.1X_0$)
- CMD-3 and KEDR experience

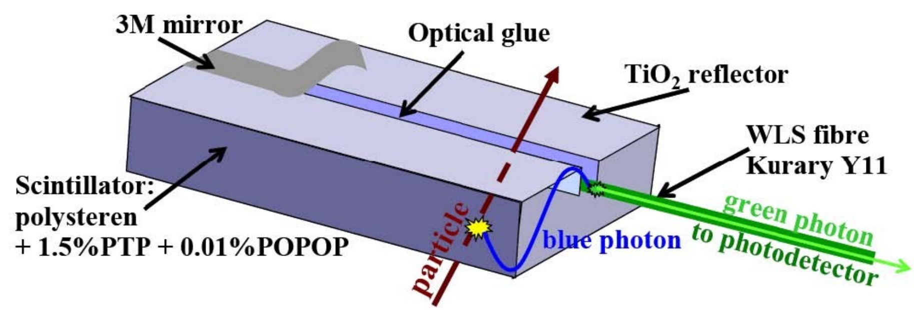


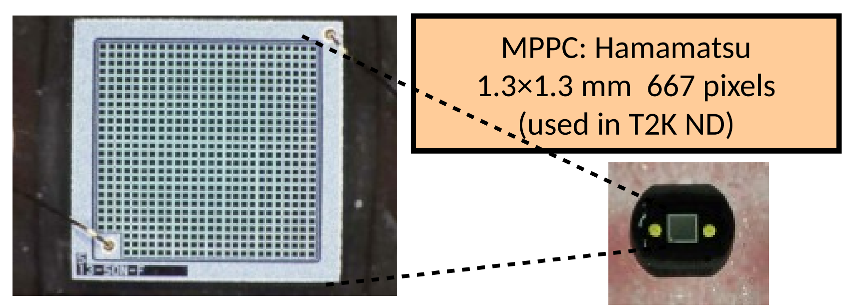
Belle-II KLM system as a base option:

There are 9 and 8 gapes in the barrel and end-cap parts of the yoke correspondingly;

Active elements are scintillator strips which readout with help of WLS fibres coupled with SiPM (as Belle-II KLM system);

R&D and Belle-II experience adaptation is carrying out in LPI (Moscow).

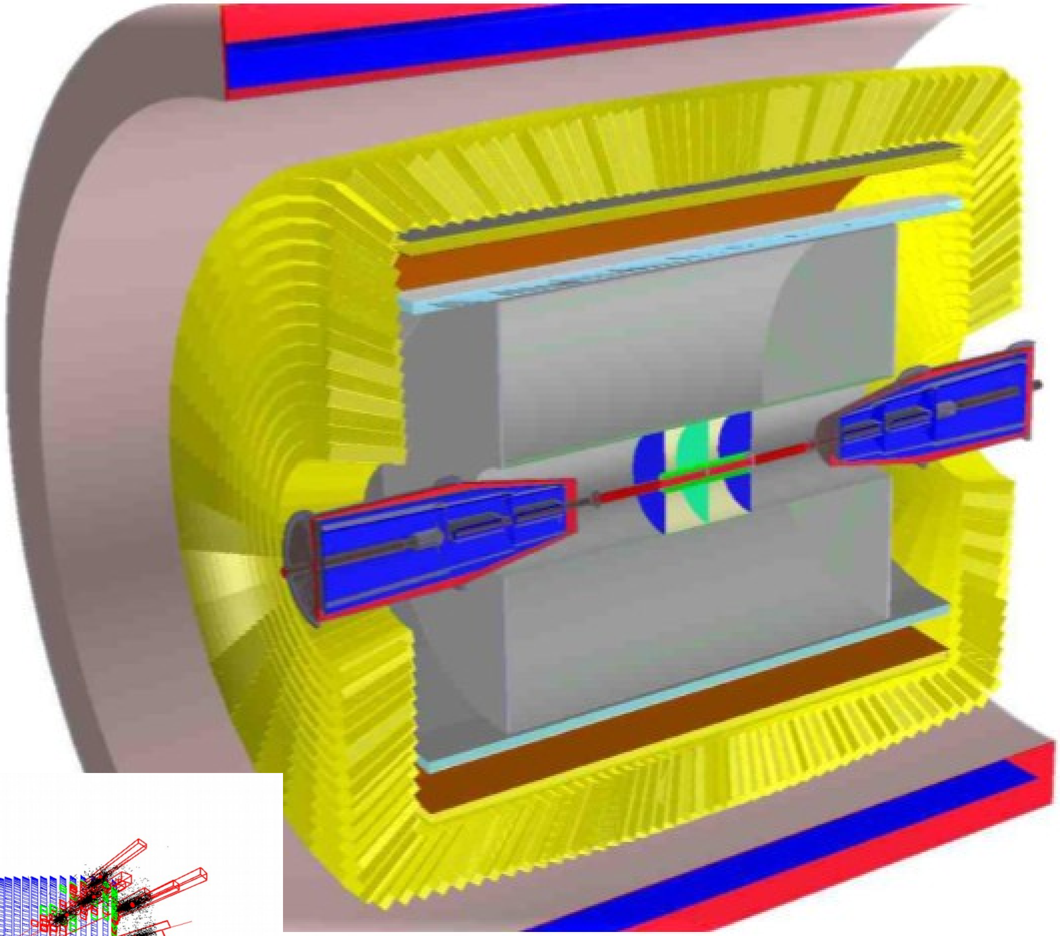


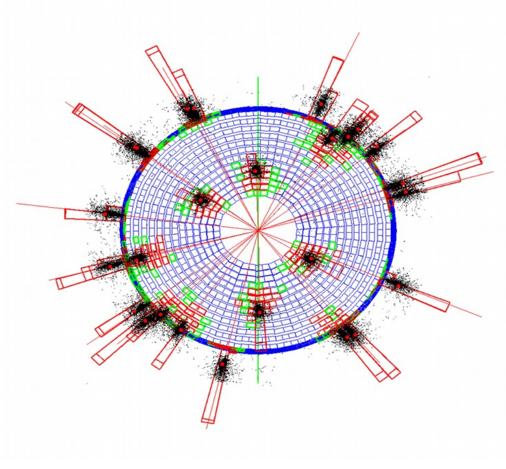


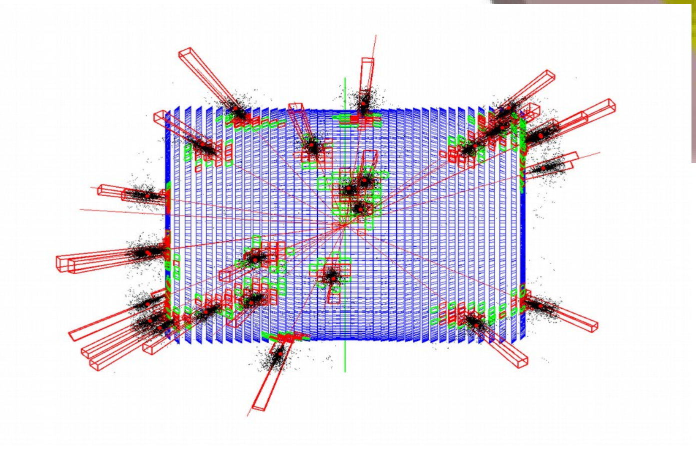
Simulation and analysis software

Full simulation is being developed intensively

- Aurora framework
- ROOT, Geant4
- Gaudi & Athena-inspired build and config system
- FCCSW (DD4Hep, PODIO, ...)



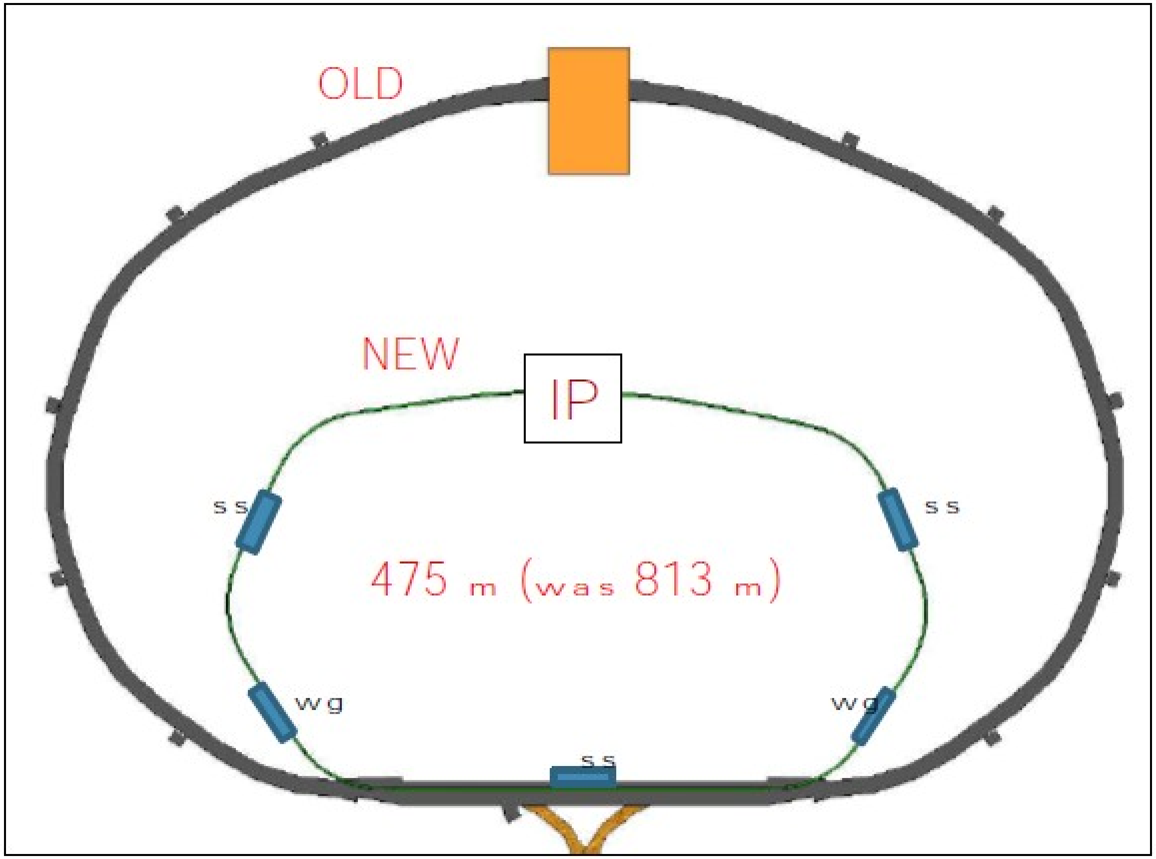




Updated accelerator design (2018)

The accelerator project continues to evolve

2018: smaller ring more robust and realistic design



	1 GeV	2 GeV	3 GeV
П [м]	475.768		
2θ [мрад]	60		
N_{part} $[10^{10}]$	5.5 (2.1)	5.2	13 (7)
N_{bunch}	400 (500)	420	280 (150)
I [A]	2.2 (1)	2.2	2
β_x^*/β_y^* [см]	5/0.05		
ε_x [нм]	20 (15)	6.5	11
$\varepsilon_y/\varepsilon_x$ [%]	0.5	0.5	0.5
$\mathcal{L}$ $[10^{35}]$	0.5 (0.14)	1	1.9 (1)
V_{RF} [MB]	1	0.7	2

Status of the project

- 2011: selected as one of six mega-science projects in Russia
- We have: roadmap, conceptual design, preliminary civil engineering design
- CERN, IHEP, INFN, KEK and other oragizations expressed their interest in the project
- In 2017 included in the plan for the implementation of the first phase of the Russian Strategy for Science and Technology Development
- In 2019 updated conceptual design report was submitted to Russian government
- Submitted proposal to the Update of European Strategy for Particle Physics

Summary

- Super Charm-Tau factory has very fruitful physics program in flavor physics
- SCTF is competitive and complementary to Belle II and LHCb
- The physics program is further developed to unveil rich potential of the e- beam polarization option
- **Collaboration** of the SCTF project is growing, we invite interested physicists:

Working groups:

- Inner tracker
- Drift chamber
- PID
- Calorimeter
- Muon system
- Magnet
- Physics and simulation
- Computing
- DAQ and trigger
- Beam background
- Engineering

- International advisory committee
- SCTF international workshop:
  - May 2018, BINP
  - December 2018, Orsay
  - September 2019, Moscow