The progress of Super c-tau factory in Russia

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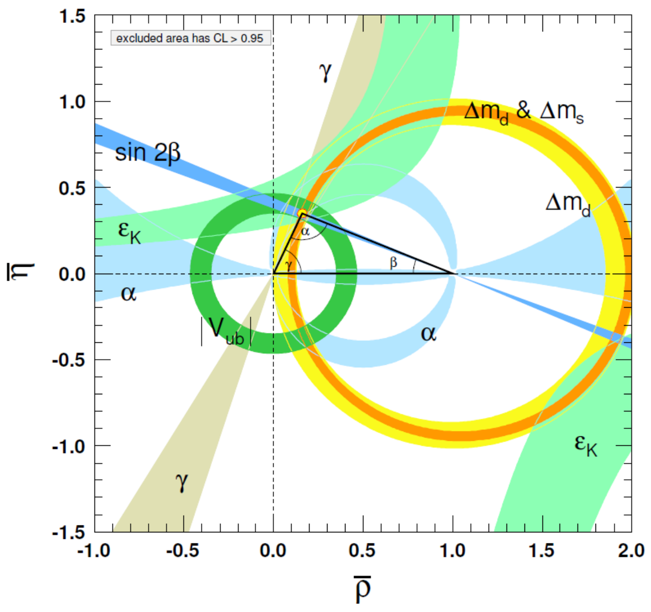
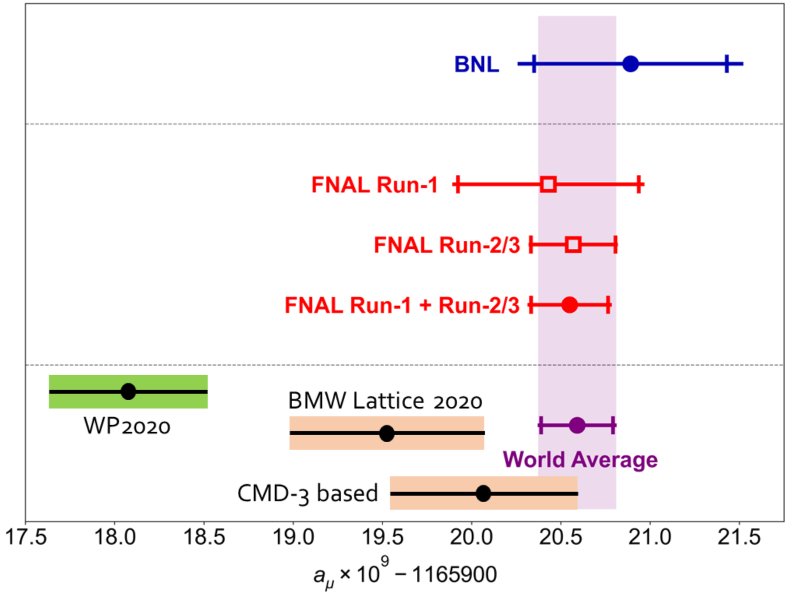
Flavor physics

Flavor physics – precise measurement of properties of (heavy) leptons and quarks (CP violation, rare decays, CLFV, magnetic moments,…) – one of key directions for understanding SM and searched beyond SM.

Unitarity triangle



Anomalous magnetic moment of muon



Precision is everything: The higher precision, the higher equivalent energies are reached

Snowmass 2021

"Snowmass" is HEP community forum for discussion of the future of the field (U.S. -> global)

HEP science drivers:

1. Use the Higgs Boson as a Tool for Discovery
2. Pursue the Physics Associated with Neutrino Mass
3. Identify the New Physics of Dark Matter
4. Understand Cosmic Acceleration: Dark Energy and Inflation
5. Explore the Unknown: New Particles, Interactions, and Physical Principles
6. Flavor physics as a tool for discovery New

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SLAC-PUB-17717

Report of the
2021 U.S. Community Study on the
Future of Particle Physics
(Snowmass 2021)

organized by the APS Division of Particles and Fields

Snowmass 2021 Study Conveners: Marina Artuso, Kétévi A. Assamagan, Phillip S. Barbeau, Laura Baudis, Robert Bernstein, Aaron S. Chou, Nathaniel Craig, Csaba Csáki, Aida X. El-Khadra, V. Daniel Elvira, Julia Gonski, Steven Gottlieb, Stephen Gourlay, Jeter Hall, Patrick Huber, Kevin T. Lesko, Petra Merkel, Benjamin Nachman, Meenakshi Narain†, John L. Orrell, Alexei A. Petrov, Breese Quinn, Fernanda Psihas Tor Raubenheimer, Laura Reina, Kate Scholberg, Vladimir Shiltsev, Marcelle Soares-Santos, Sara M. Simon, Tim M. P. Tait, Alessandro Tricoli, Elizabeth E. Worcester, Jinlong Zhang

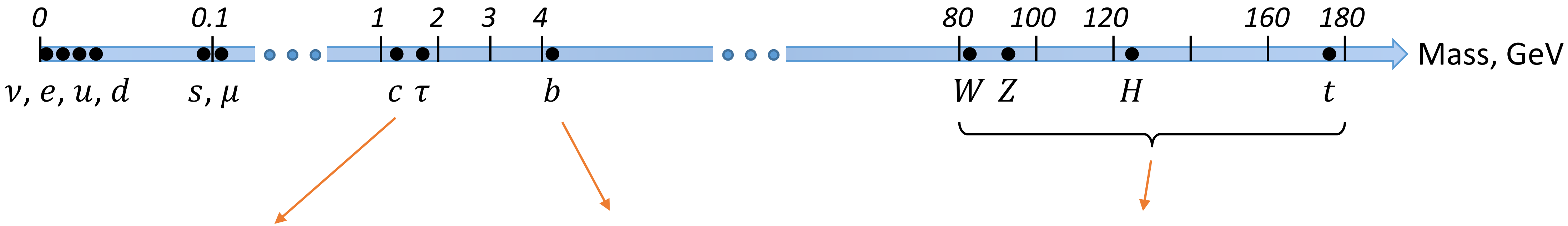
Snowmass 2021 Steering Group: Joel N. Butler, R. Sekhar Chivukula, André de Gouvêa, Tao Han, Young-Kee Kim, Priscilla Cushman, Glennys R. Farrar, Yury G. Kolomensky, Sergei Nagaitsev, Nicolás Yunes

Editorial Committee: Robert H. Bernstein, Sergei Chekanov, Michael E. Peskin

†deceased, Jan. 1, 2023.

Colliders-Factories

Energy ranges of high luminosity colliders (factories) correspond to production thresholds of known particles.



<u>cτ-factories</u>

BEPC-II (China)

⬇

x100 gain in luminosity

Super $c\tau$ factory
SCTF (Russia), STCF (China)

<u>B-factories</u>

PEP-II (USA), KEK-B (Japan)

⬇

Super KEK-B (Japan)
LHCb (CERN)

<u>Z- and H-factories</u>

LEP, LEP-2 (CERN)

⬇

FCC-ee (CERN)
CEPC (China)

Ultimate performance (precision) is determined by luminosity and detector quality

Generations of factories

Today:

LHCb: 5 fb^{-1} → x10-60 → Tomorrow: LHCb: 50/300 fb^{-1} (Run 3/4)

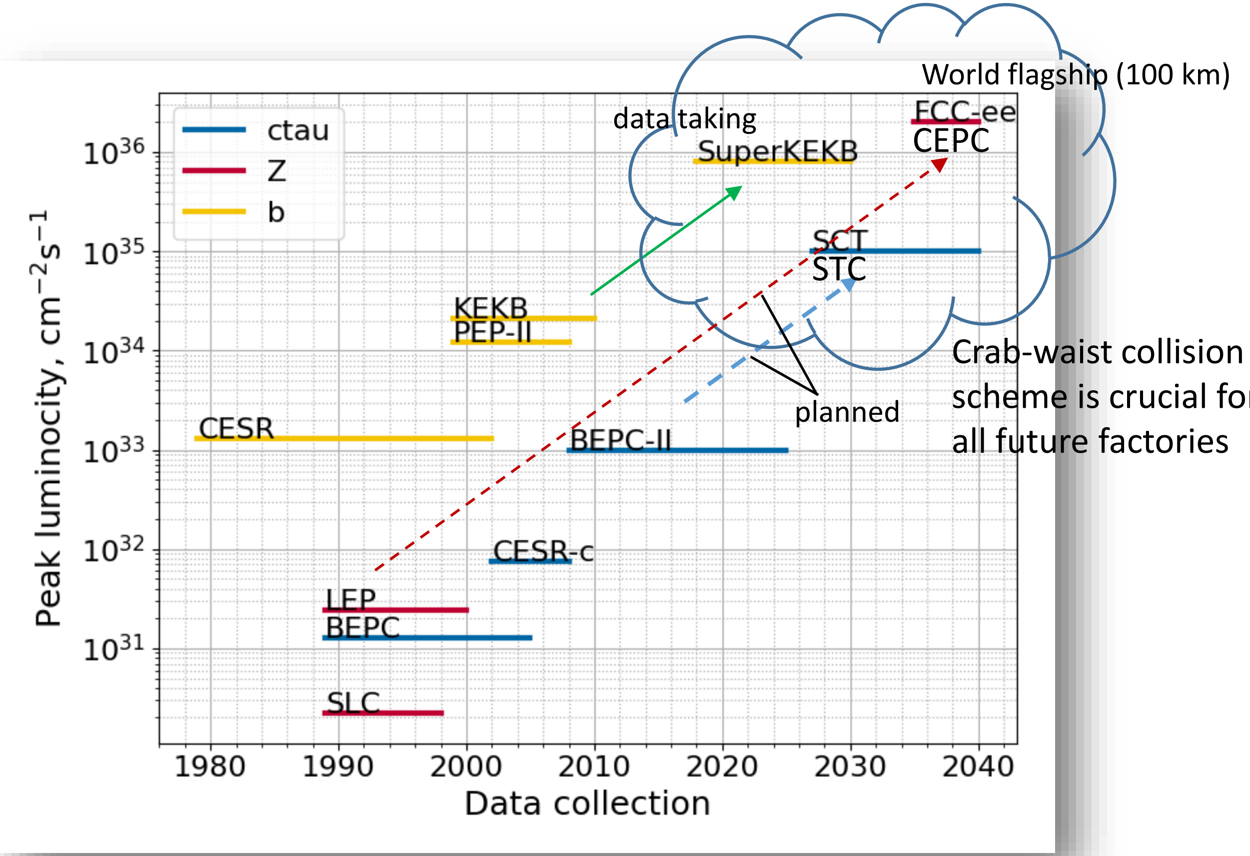
B-factories: 1 ab^{-1} → x50 → Super KEK-B: 50 ab^{-1}

BES-III: ~100 fb^{-1} → x100 → Super C-tau factory: ~10 ab^{-1}

- There is delicate balance between existing $c\tau$-factory and B-factories (BES-III, BABAR, BELLE, LHCb)
- Need to keep the same balance for the next generation of colliders

Super $c\tau$-factory is the natural element of global HEP strategy

Super factories today and tomorrow

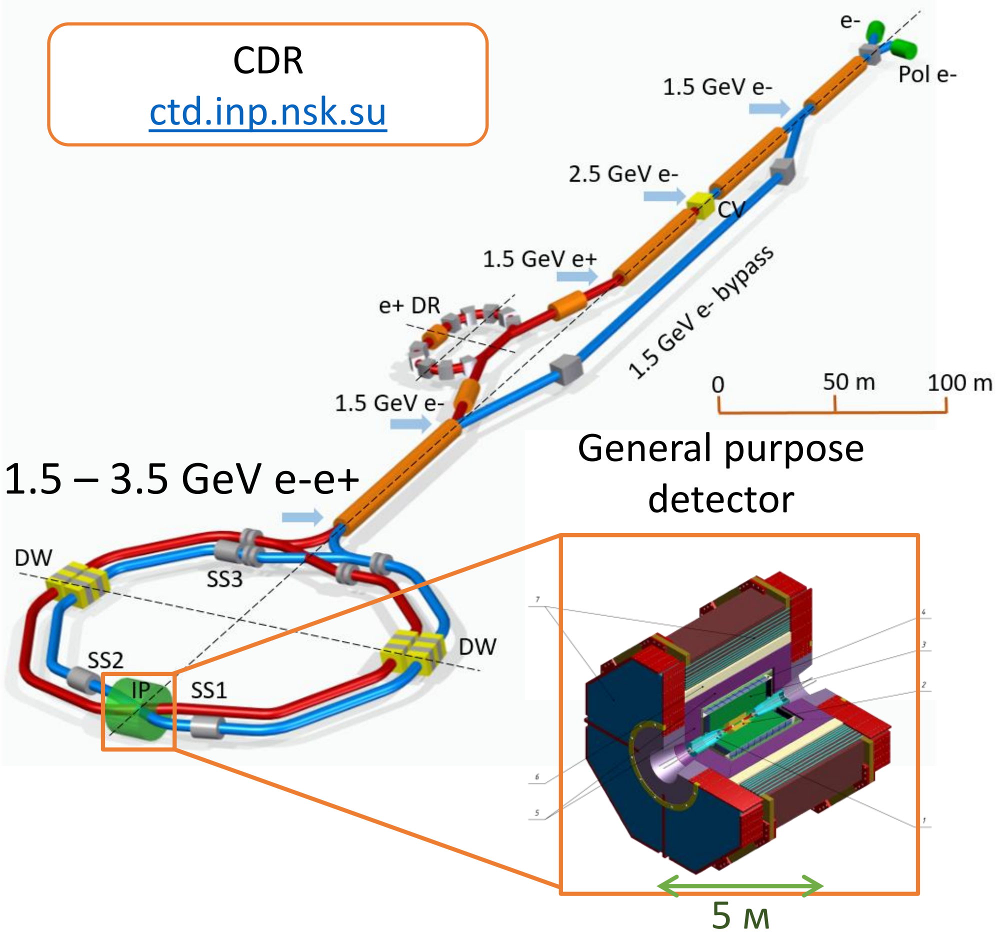


Crab-waist collision scheme is crucial for all future factories

Super charm-tau factory

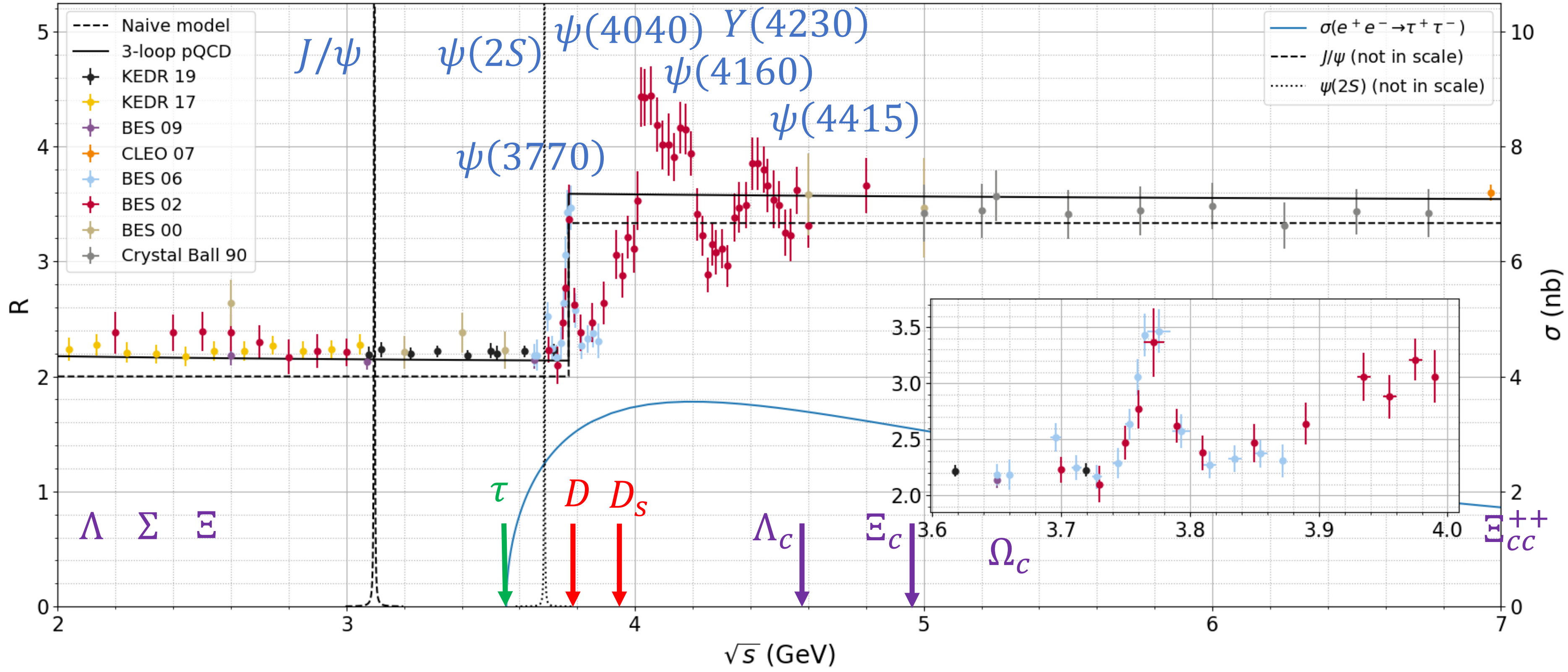
- Super charm-tau factory is e^+e^- collider, dedicated to precision study of properties of charm-quark, tau-lepton, study of strong interactions, search of BSM physics
  - Beam energy from 1.5 to 3.5 GeV
  - Luminosity $\mathcal{L} = 10^{35}\ cm^{-2}c^{-1}$ @ 2.5 GeV
  - Longitudinally polarized electron beam
- Experiments will be conducted using state-of-the-art general purpose detector
  - Tracking (including low p_t)
  - Calorimetry (high resolution, fast, π^0/γ sep.)
  - Particle ID ($\mu/\pi/K/p$ up to 1.5 GeV/c)

CDR
ctd.inp.nsk.su



Energy range of SCTF

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$$



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

A one-year dataset

$2E$, GeV	Events recorded
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	$10^{8}\ \Lambda_c^+\Lambda_c^-$

Threshold kinematics!

Energy range of SCTF

- ✓ Measurement of the strong phases of D decay amplitudes
- ✓ Measurement of absolute branching fractions
- ✓ Searches for rare and forbidden decays of the charm quark
- ✓ CP violation in charm
- ✓ …

Input for B meson studies at LHCb and Belle II

charm

QCD

- ✓ Physics of highly-excited quarkonium
- ✓ Molecular states (XYZ)
- ✓ Baryon interaction at threshold
- ✓ Search for glueballs in decays of J/ψ and $\psi(2S)$
- ✓ Measurement of $\sin^2\Theta_W$ at J/ψ
- ✓ …

Test of the electroweak sector of the SM

tau

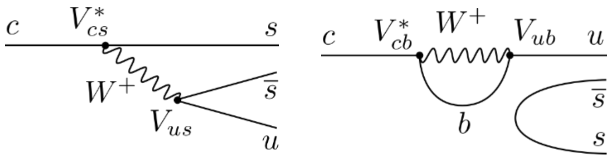
- ✓ Precision measurement of the τ lepton properties
- ✓ Michel parameters, tests of lepton universality
- ✓ Precision measurement of hadronic τ decays
- ✓ Search for CP and T violation in τ decays
- ✓ …

Test of the electroweak sector of the SM

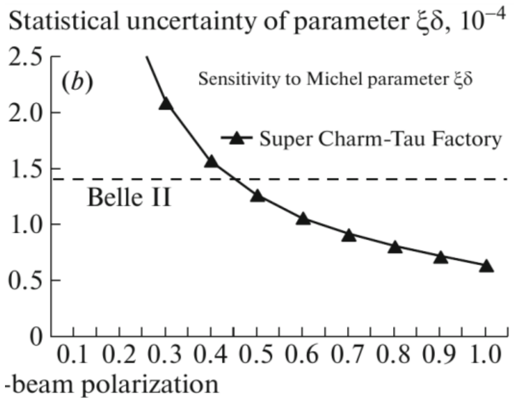
QCD, α_s, V_{us}. Test of the electroweak model, searches for non-standard contributions

Some key results expected from SCTF

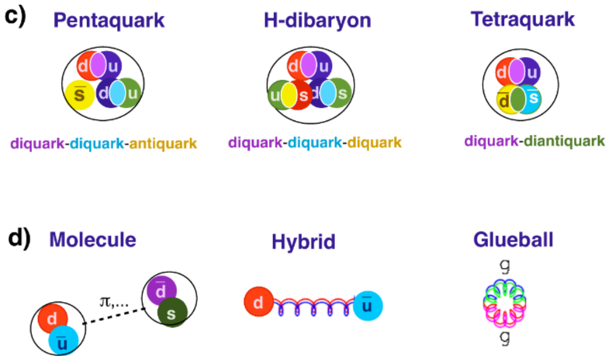
Systematic study of CP-violation in decays of D-mesons



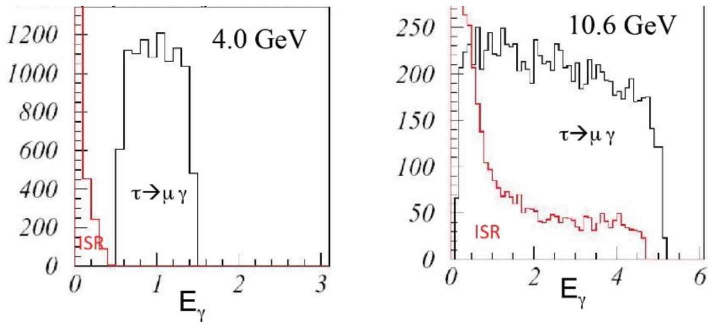
Lorentz-structure of weak currents in $\tau \to l\bar{\nu}\nu$



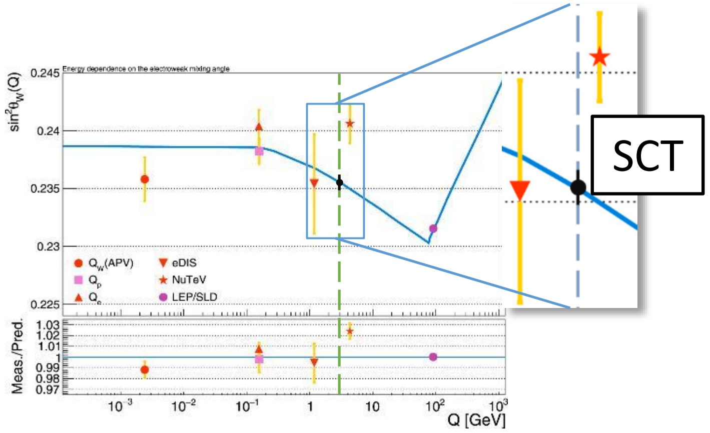
XYZ physics



Search of LFV decay $\tau \to \mu\gamma$



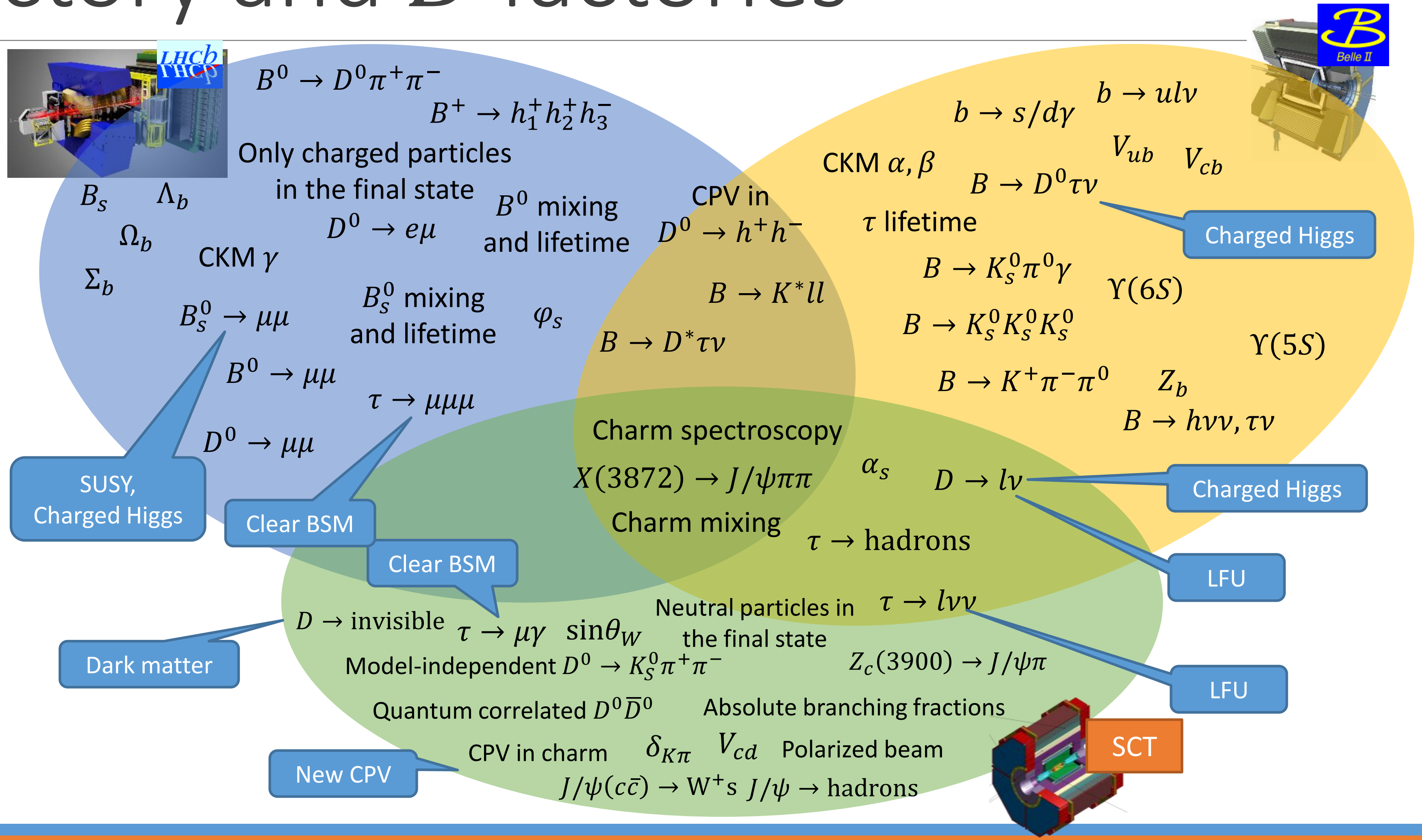
Measurement of $\sin^2 \Theta_W$ at J/ψ energy



Super $c\tau$ factory and B factories

The experiments at Super charm-tau factory are complement to experiments at Super KEK-B and LHCb, with unique possibilities:

- Threshold production of particles
- Pair production
- Quantum correlations in $D^0\overline{D}^0$ production
- Low multiplicity, full reconstruction of decay chain
- Polarization of electron beam



Physics program: 2022 revision

Оглавление

- 2021: ≈ 40 pages
- 2022: ≈ 120 pages
- Editors:
  - G.Pakhlova (LPI)
  - A.Bondar (BINP)

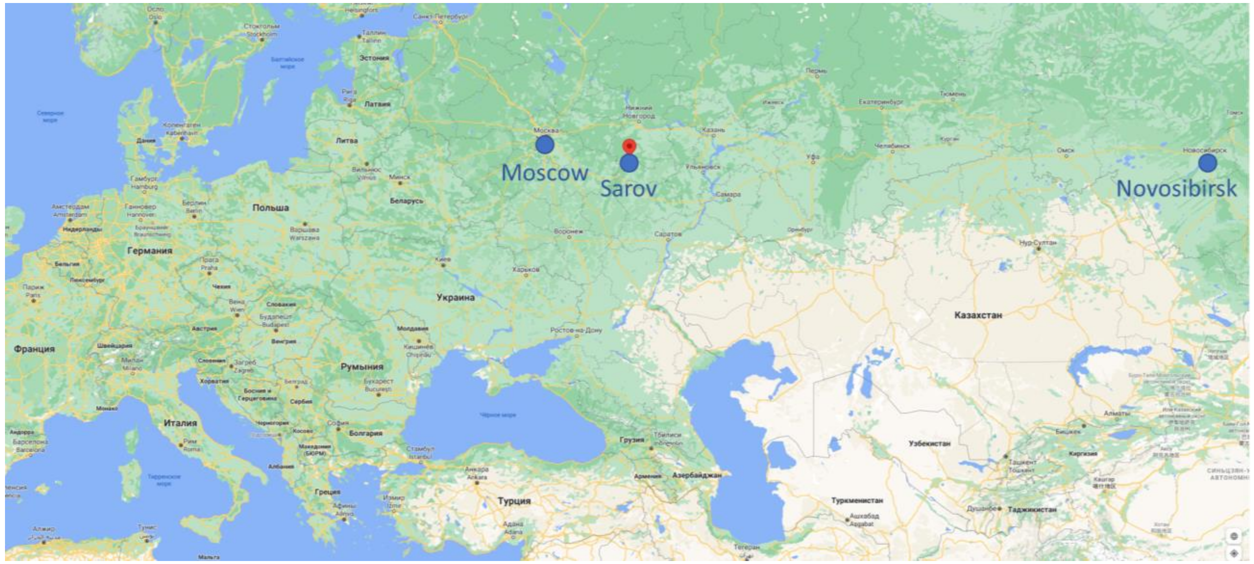
Available at ctd.inp.nsk.su

Shorter (extracted) version prepared as a white paper for Snowmass

UFN paper is in preparation

Potential location: NCPM, Sarov

- National Center of Physics and Matematics is a new scientific/university center (established in 2021), located near Sarov, the largest nuclear center in Russia.
- SCTF is discussed as one of the prospective science infrastructures for NCPM.
- The SCTF R&D program is supported at a part of NCPM scientific program (2023-2025).
- SCTF R&D program is realized by informal collaboration of Russian institutions.

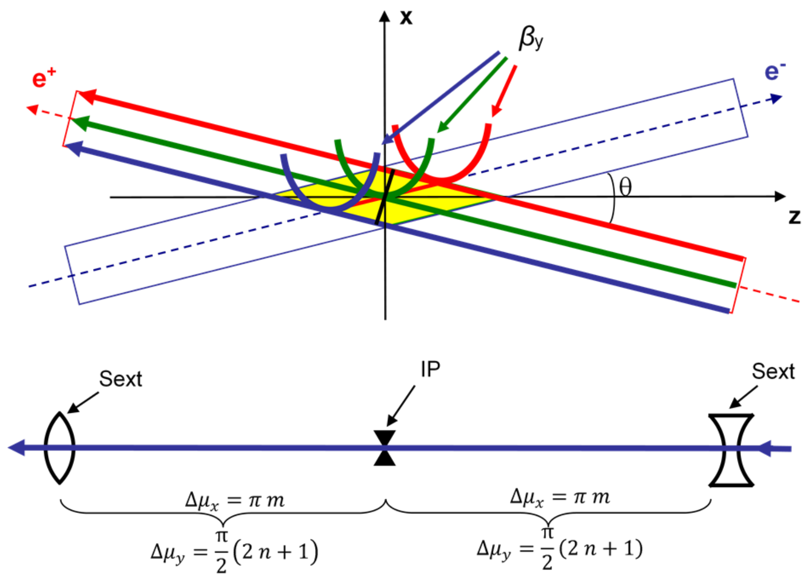


R&D program of Super c-tau factory

Collider studies

Achievements (in simulations):

- Optics for all collider elements (final focus, arcs, Siberian snakes, injector,…)
- Optimization of linear and nonlinear structure of collider allowed to reach (with Touschek effect taken into account) beam lifetime, which matches the capacity of the injector
- Positions of CRAB sextupoles are optimized to increase dynamic aperture
- Detailed conceptual project of final focus

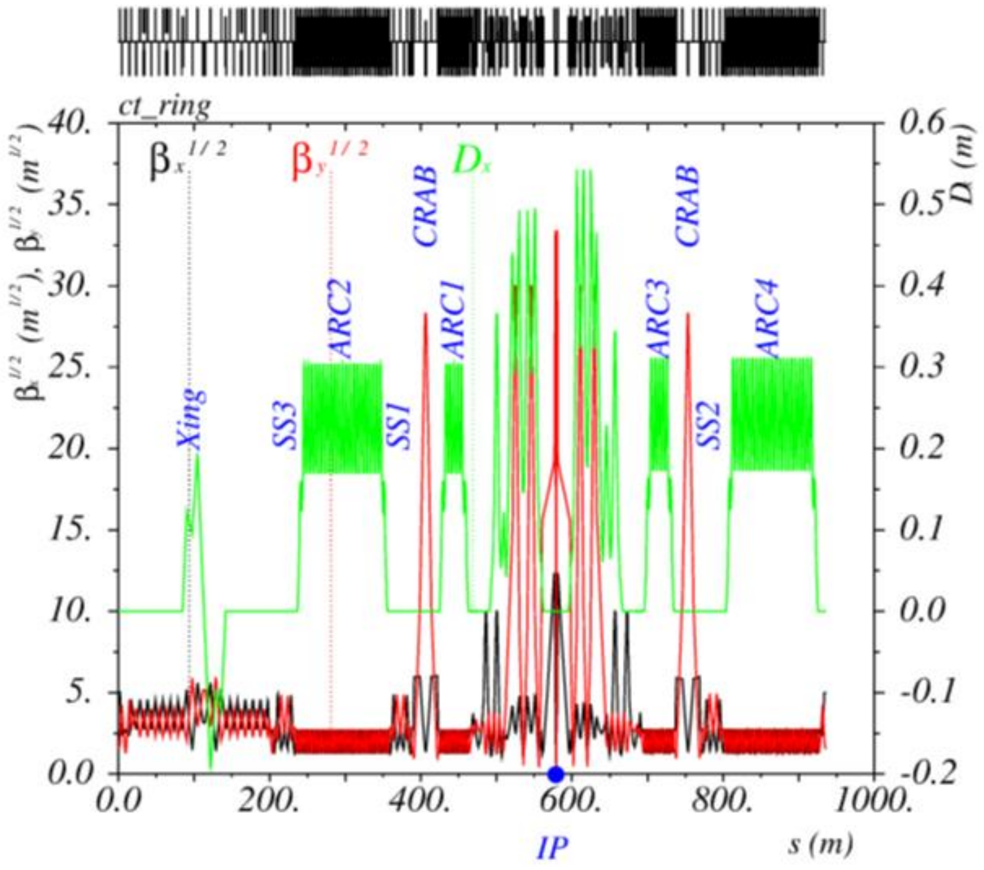


Crab waist collision scheme (P.Raimondi 2006)

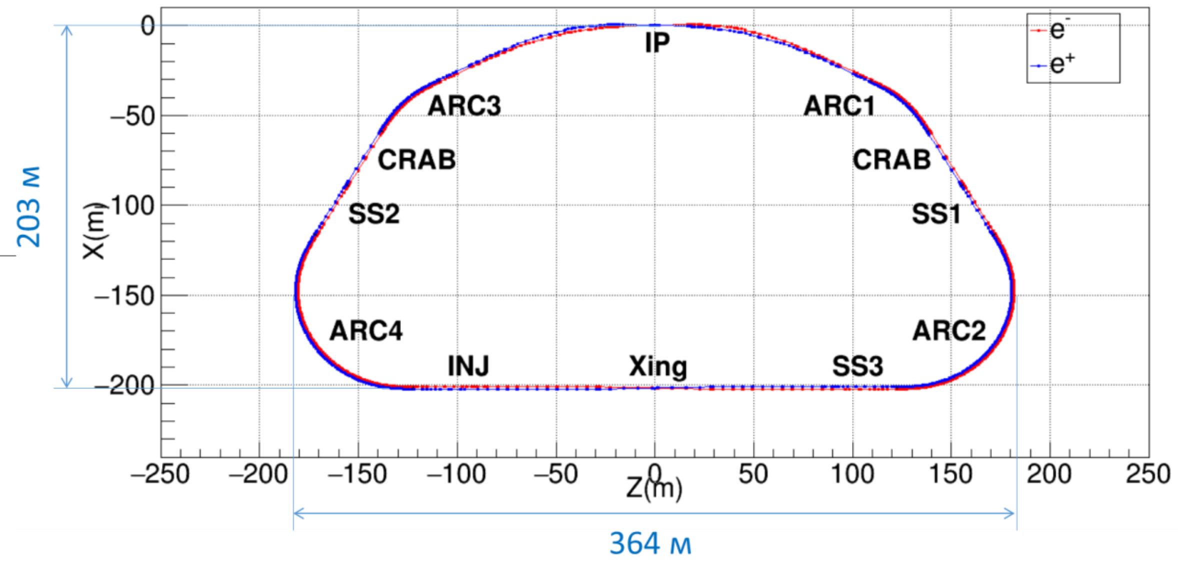
Critical for all future collider projects

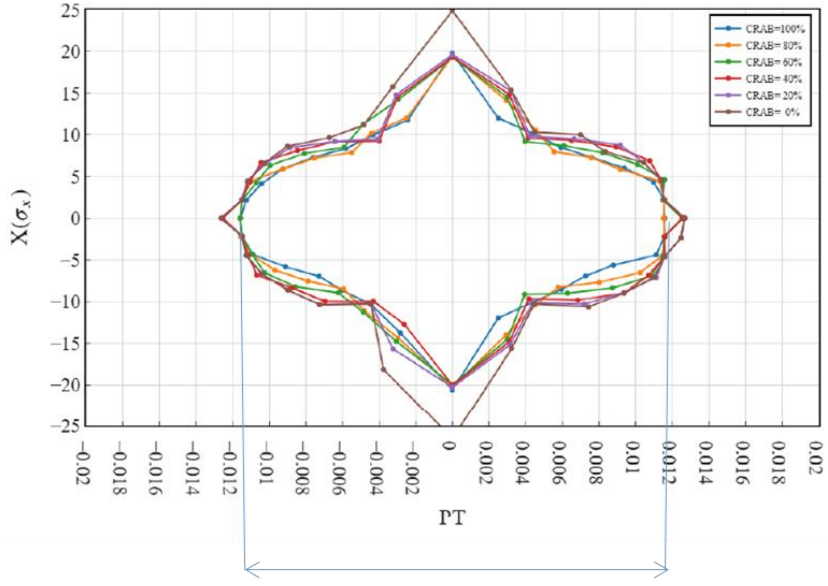
Major problem: dynamic aperture (phase space of stable motion) is reduced due to nonlinear elements

Collider studies



П = 935.9 м





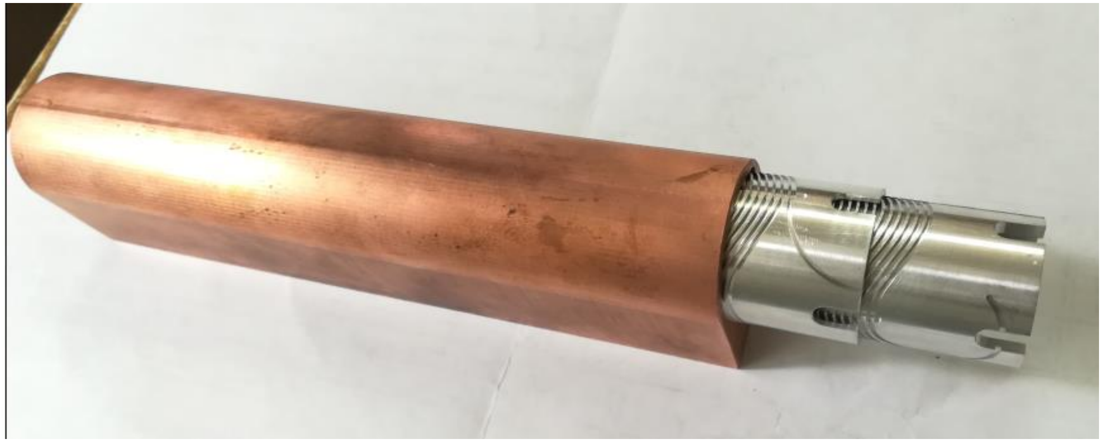
≈ ±1.2%

Dynamic aperture

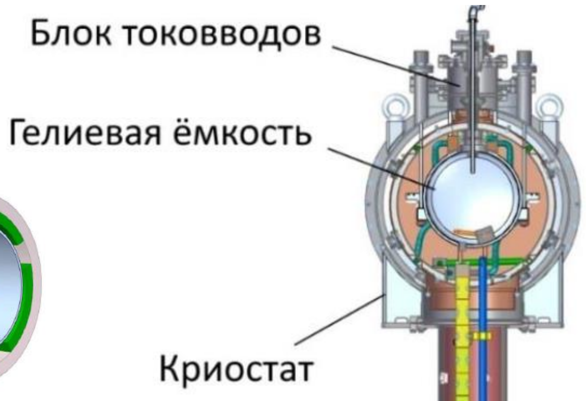
Collider parameters

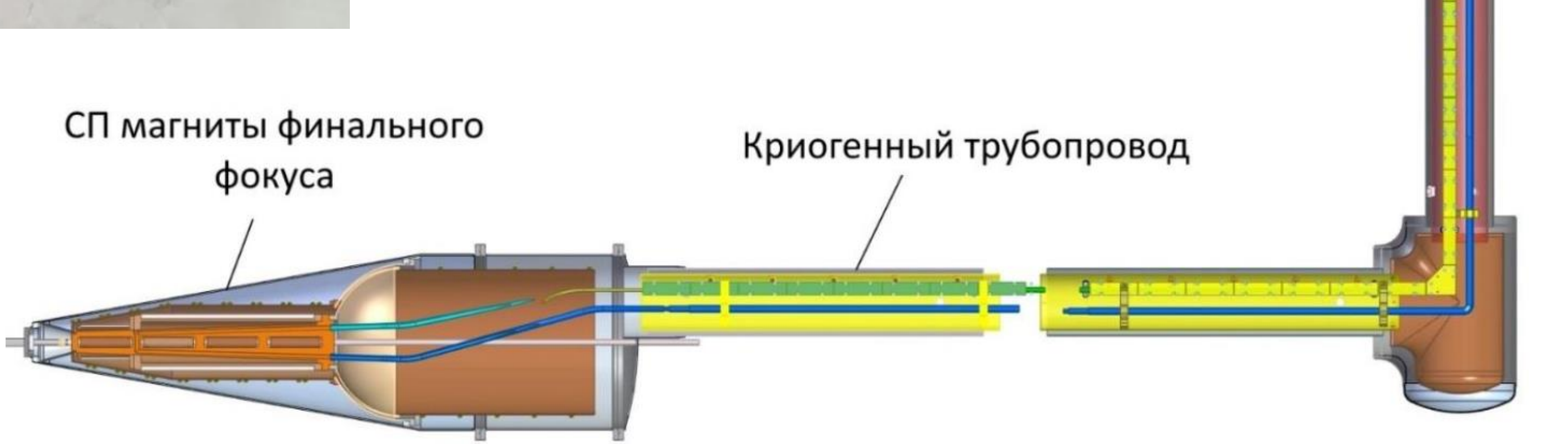
E, GeV	1.5	2.0	2.5	3.0	3.5
Π, m	935.874				
2θ, mrad	60				
β_x^*/β_y^*, cm	10/0.1				
Q_x/Q_y	30.545/29.61				
C_x/C_y	−64/−328				
$\alpha \times 10^3$	1.35				
I, A $/N_b$	2.9/941	1.64/983	2.5/983	2.7/983	2.9/974
$N_p \times 10^{-10}$	6	3.25	5	5.3	5.8
$\varepsilon_y/\varepsilon_x$ (%)	10	0.5	0.5	0.5	0.5
$\varepsilon_x(SR/IBS+WG)$, nm	2/2.9	3.5/3.5	5.5/3.2	7.9/4.1	10.7/5.7
$\sigma_e \times 10^3(SR/IBS+WG)$	0.3/0.9	0.4/1.1	0.45/1.2	0.5/1.2	0.6/1.3
σ_s, mm	17	15	14	14	14
ξ_x/ξ_y	0.003/0.03	0.002/0.06	0.002/0.08	0.002/0.065	0.002/0.053
ν_s/ξ_x	3	8	6.8	8	8
$\tau_x/\tau_y/\tau_e$, ms	102/102/51	43/43/22	31/31/15	23/23/11	17/17/9
$\mathcal{L} \times 10^{-35}$, cm^{-2}s^{-1}	0.29	0.4	1	1	1
T_t, s	304	304	302	560	1100

Final focus



Concept design of SC FF lens
Direct Double Helical (DDH) technology
2 concentric coil at 2 cylinders

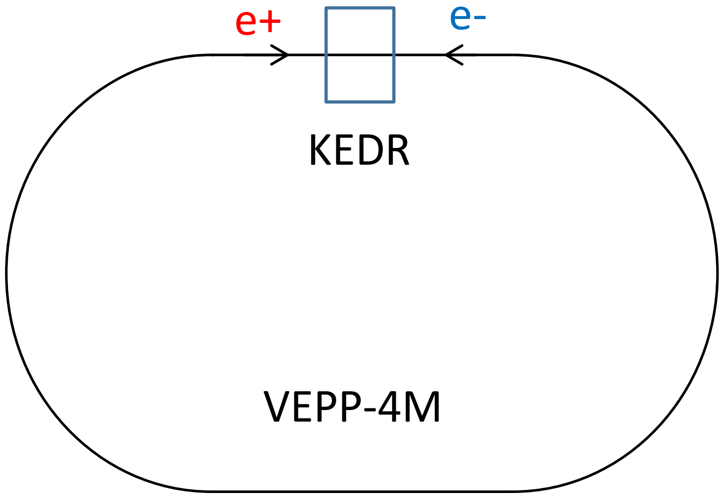


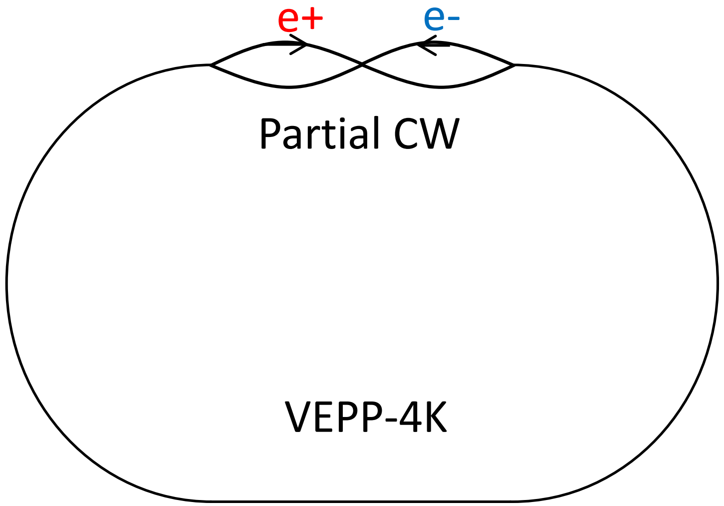


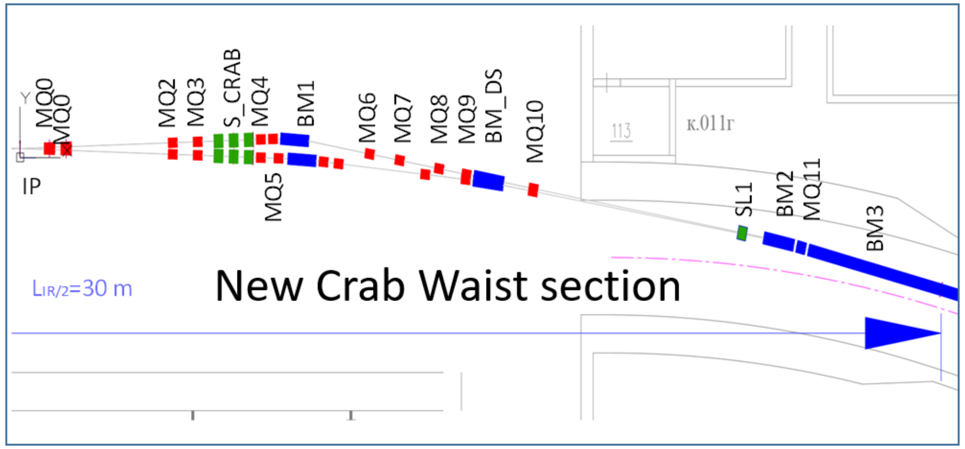
Prototypes of the elements of final focus

First measurements: 2023

Under consideration: CW at VEPP-4M







There is proposal to make a test of CW at VEPP-4M

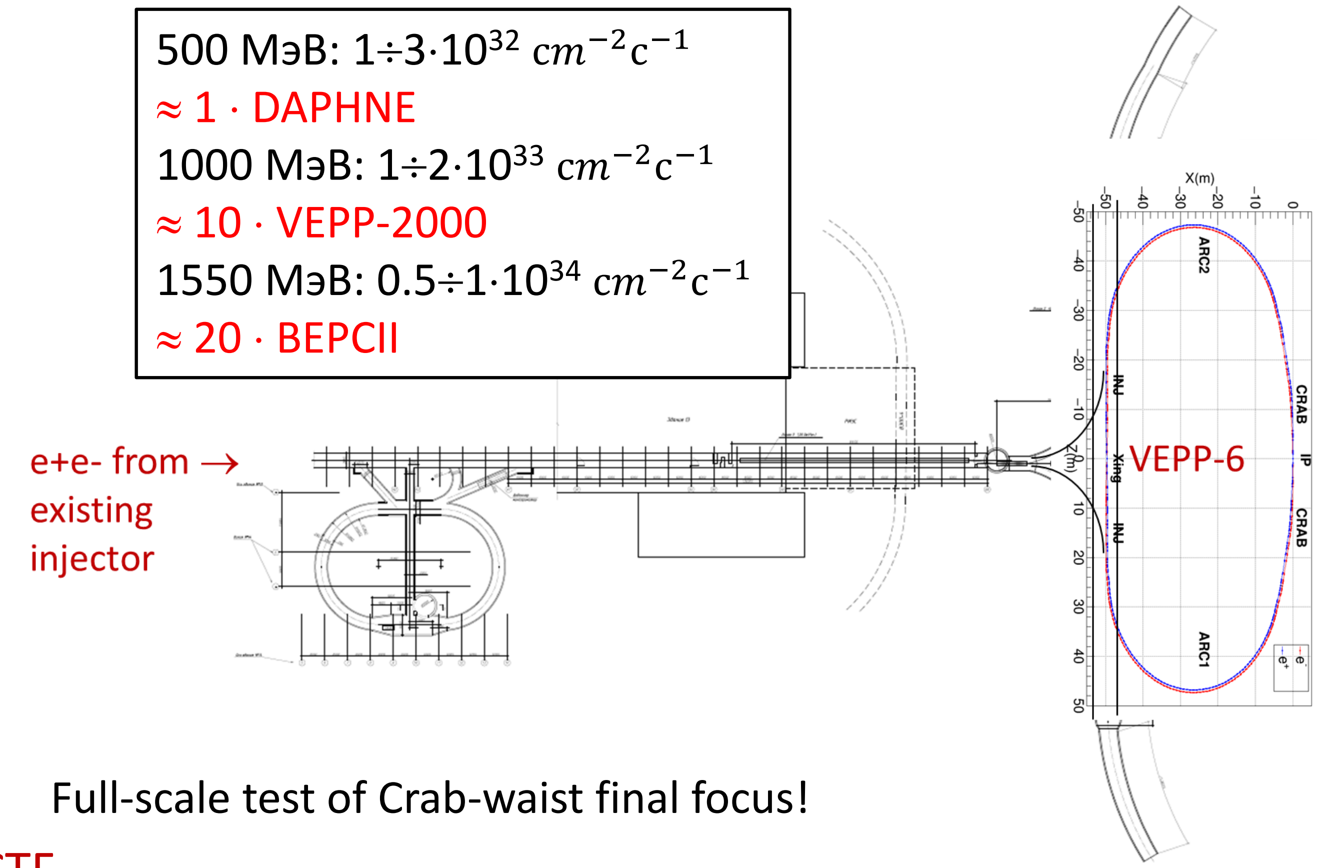
Beneficial for all future collider projects

What can be tested: final focus elements, nonlinear beam dynamics, beam-beam effects, backgrounds,…

Under consideration: VEPP-6

- e^+e^- collider
  - Beam energy from 0.5 to 1.6 GeV (J/ψ)
  - Luminosity $\mathcal{L} \approx 10^{34}\ cm^{-2}c^{-1}$ @ 1.6 GeV
- General purpose detector
  - Tracking
  - Calorimetry
  - Particle ID
- Physics
  - J/ψ decays
  - Baryon thresholds
  - Measurement of R
  - …

500 МэВ: 1÷3·10^{32} $cm^{-2}c^{-1}$
≈ 1 · DAPHNE
1000 МэВ: 1÷2·10^{33} $cm^{-2}c^{-1}$
≈ 10 · VEPP-2000
1550 МэВ: 0.5÷1·10^{34} $cm^{-2}c^{-1}$
≈ 20 · BEPCII



Full-scale test of Crab-waist final focus!

Complementary to SCTF

Detector at SCTF

Momentum resolution $\sigma_p/p \leq 0.4\%$ at 1 GeV

Very symmetric and hermetic

Able to detect soft tracks ($p_t \geq 50\ MeV/c$)
- Inner tracker should be able to handle 10^4 tracks/cm^{2}s

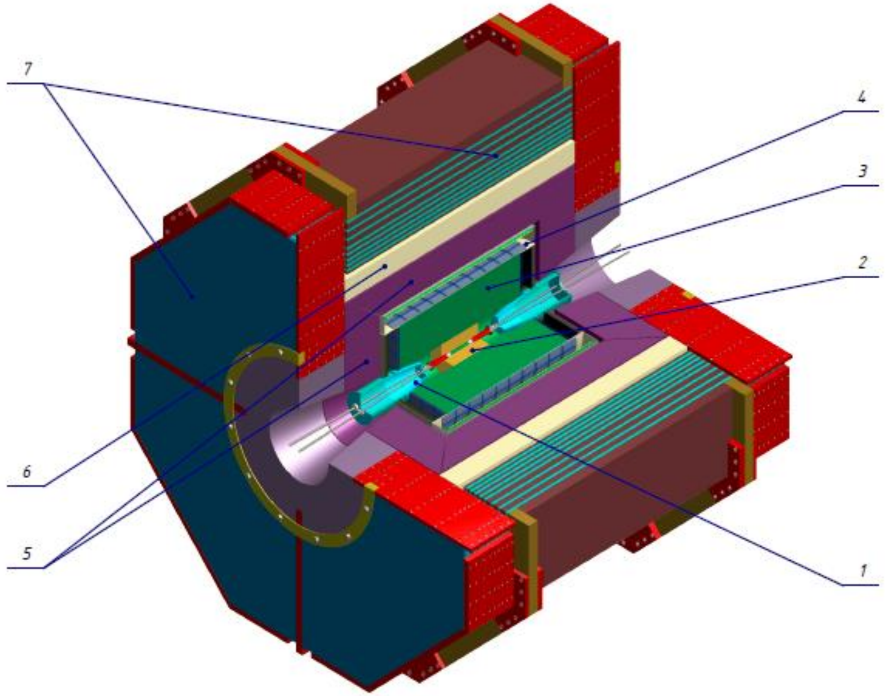
Very good particle identification: $e/\mu/\pi/K$
- π/K in the whole energy range, e.g. for $D\overline{D}$ mixing
- μ/π up to 1.5 GeV, e.g. for $\tau \to \mu\gamma$ search
- dE/dx better than 7%

Able to detect γ from 10 MeV to 3 GeV, good π^0/γ separation
- Calorimeter energy resolution $\sigma_E/E \leq 1.8\%$ at 1 GeV
- Calorimeter time resolution $\sigma_t \leq 1$ ns

Efficient "soft" trigger

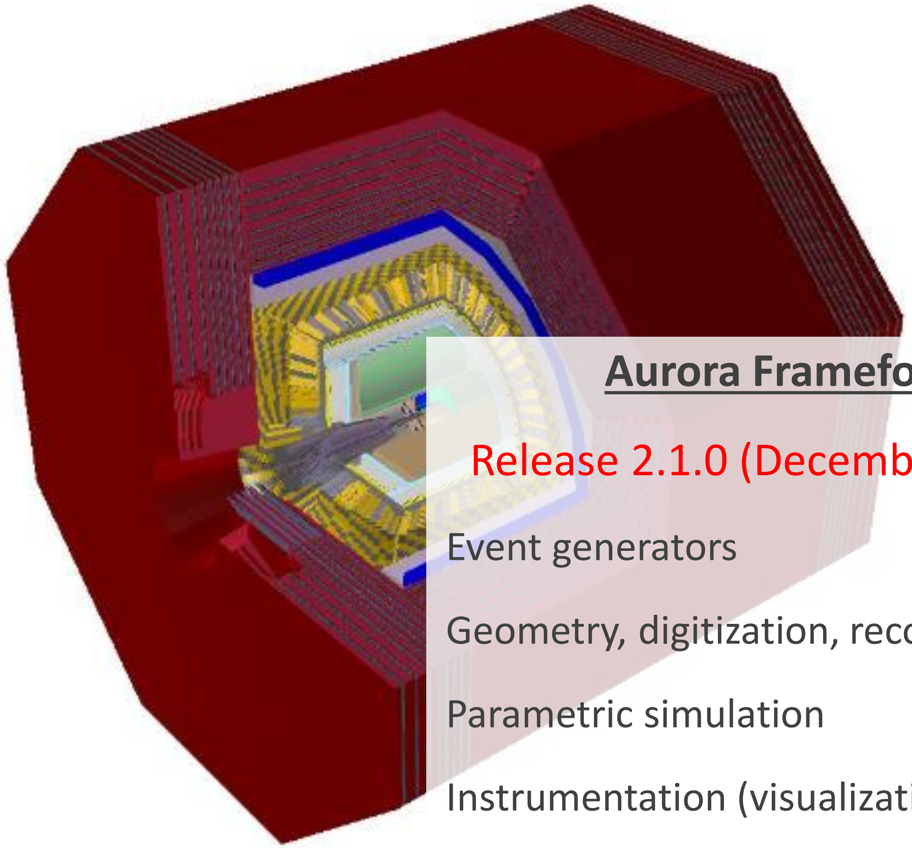
Ability to operate at high luminosity, up to 300 kHz at J/ψ

1. Vacuum pipe
2. Inner tracker
3. Drift chamber
4. PID
5. Calorimeter
6. SC magnet
7. Muon system



5.6 x 5.6 x 5.3 m^3

Simulation framework



<u>Aurora Framefork</u>

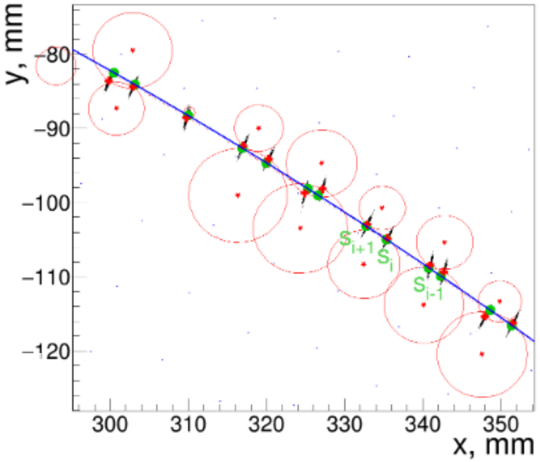
Release 2.1.0 (December 2022):

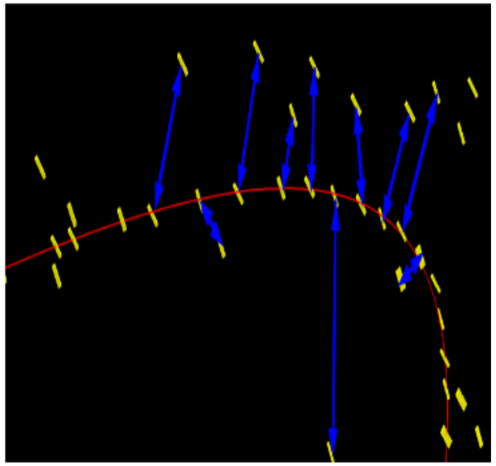
Event generators

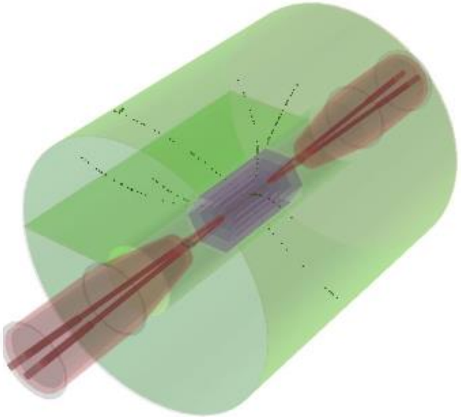
Geometry, digitization, reconstruction

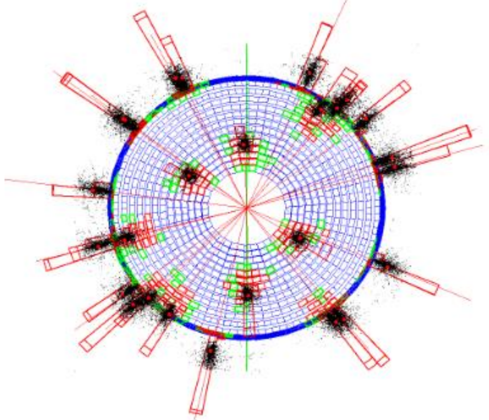
Parametric simulation

Instrumentation (visualization, tests,..)









Inner tracker options

Compact TPC:

- Large number of hits per track
- Reliable dE/dx measurement

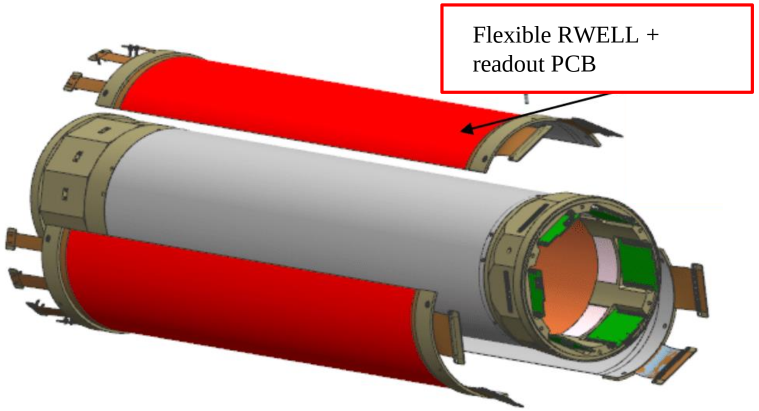
Length – 60 cm
Diameter – 40 cm
5-6 μs electron drift time

Effective track reconstruction at high background rate must be proven

Cylindrical μRWELL:

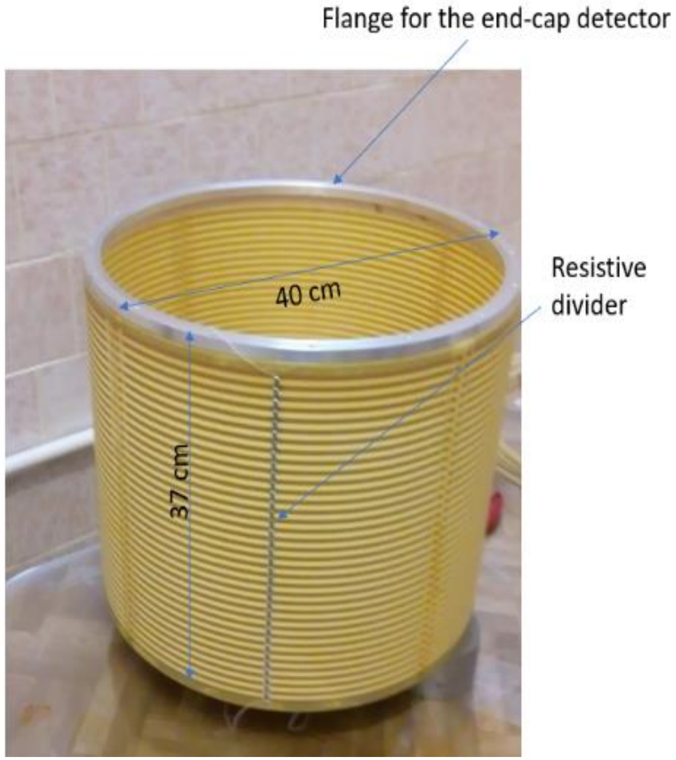
Modular roof-tile detector

4 layers
Length 60 cm
Diameter 10-40 cm

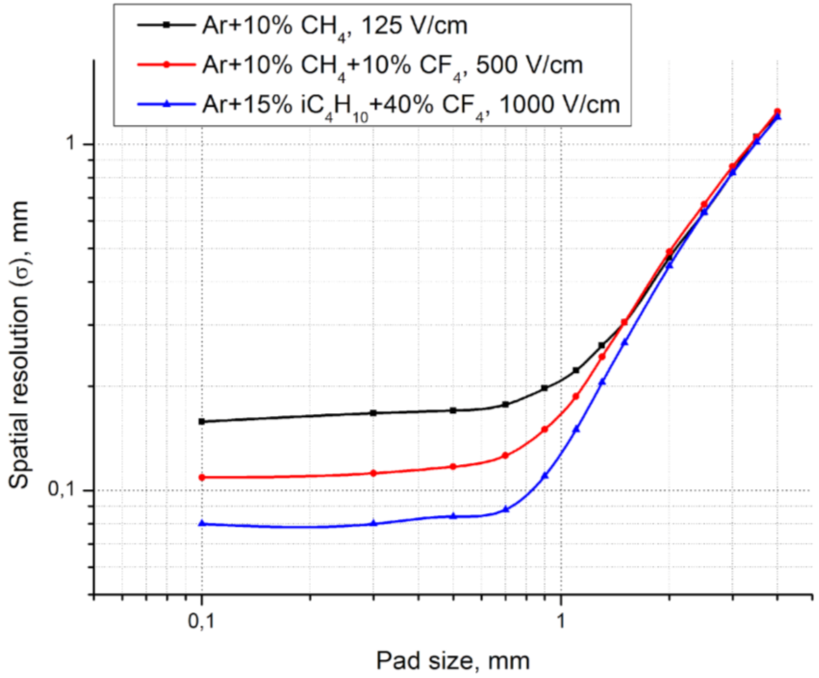


CREMLIN PLUS
Connecting Russian and European Measures for Large-scale Research Infrastructures

Inner tracker: TPC options



Gas volume with HV divider



Dependence of spatial resolution on RO structure pixel size

TPC prototype is under development

2023
- Construction

2024
- Production
- Full simulation package

Drift chamber: BINP option

~40000 wires
- 11k sensitive, W-Rh(Au)
- 29k field, Al(Au)

Hexagonal cell, 6.3-7.5 mm

41 layers

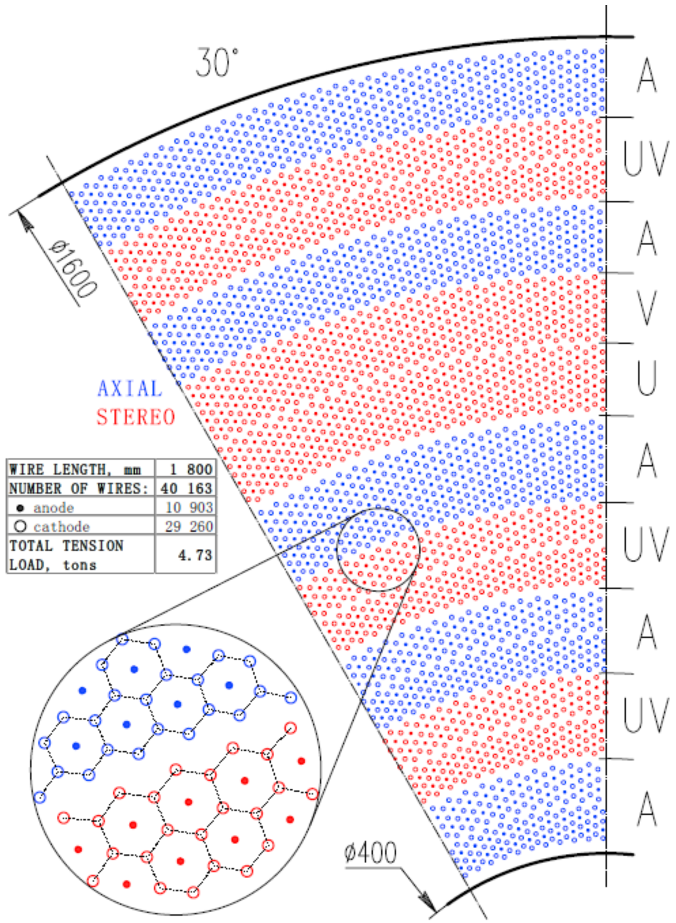
60% He + 40% C_3H_8

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

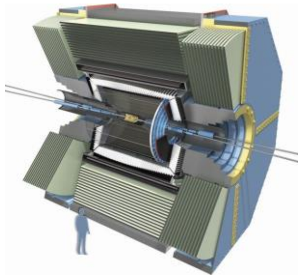
≈0.4% at 1 GeV

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

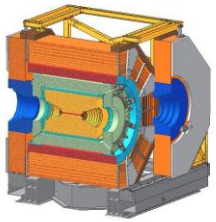
I.Yu.Basok et al., NIM A1009 (2021) 165490



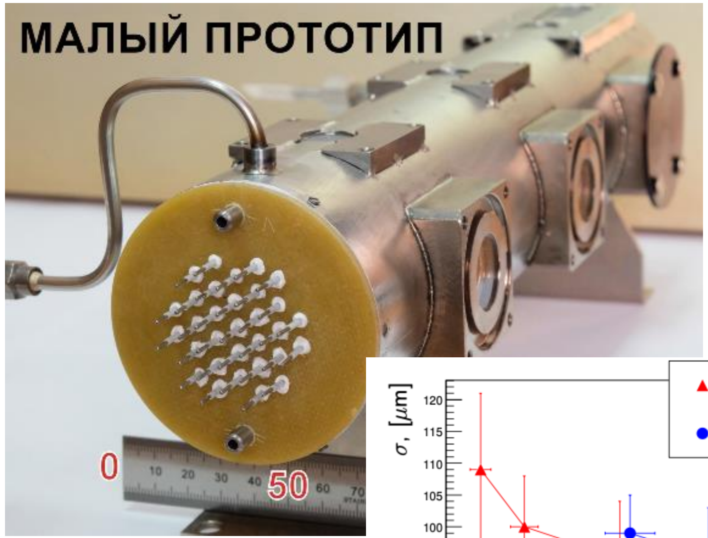
Belle-2



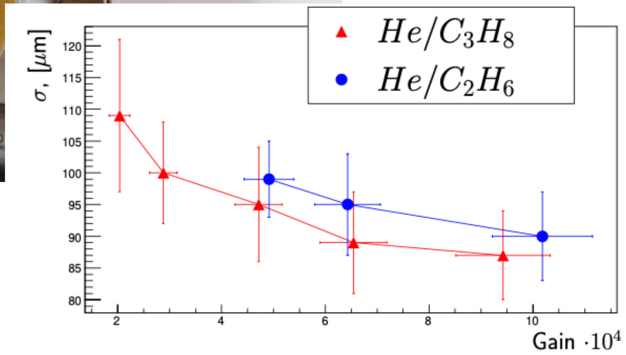
BES-III



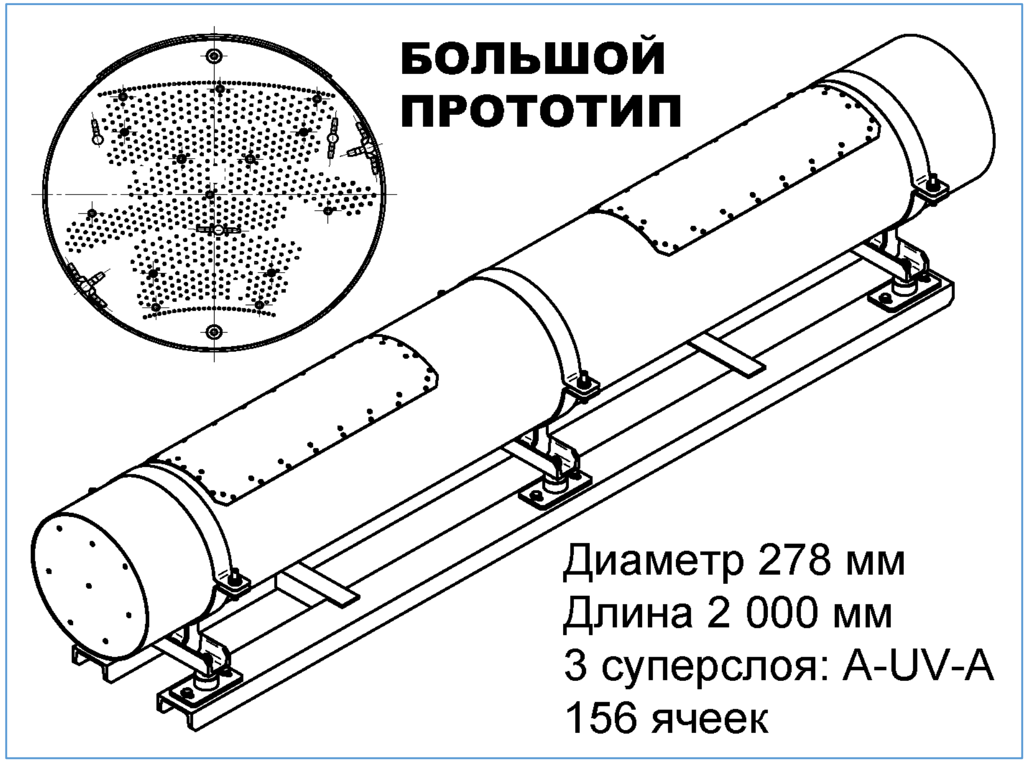
Drift chamber: prototyping



Small prototype
7 cells
In operation



The average spatial resolution for He/C_3H_8 and He/C_2H_6 at the different gas gains



Large prototype (under construction) – 156 cells

+ state-of-art simulation of cluster counting readout mode

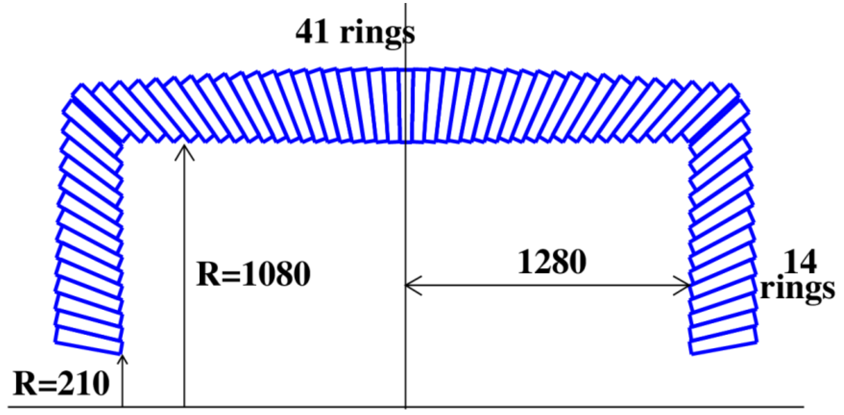
Calorimeter: pCsI option

7424 crystals, 16/18 X_0

- 5248 in barrel
- 2176 in endcap

$$\frac{\sigma_E}{E} \approx \frac{1.9\%}{\sqrt[4]{E(GeV)}} \oplus \frac{0.33\%}{\sqrt{E}} \oplus \frac{0.11\%}{E}$$

5.5 x 5.5 x 30(34) cm



TBeam June 2023 at the BINP:

CBS gammas were used for energy resolution calibration:

Two laser modes:
527 nm & 1064 nm

Five beam energies:
1.9, 2.5, 4.5, 4.75 GeV

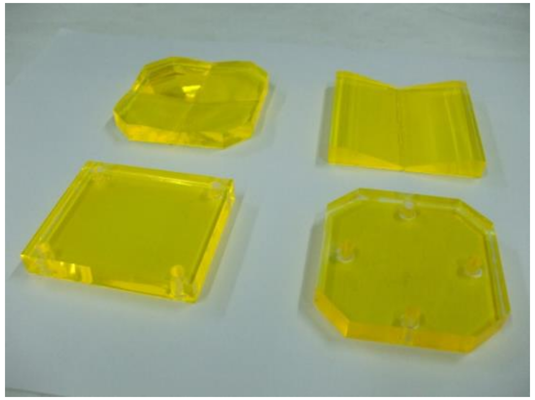
Eight CBS edges for calibration:
64, 111, 225, 361, 402, 441, 730, 812 MeV

Basic element:

pCsI crystal +

WLS +

4 APD



This option is being prototyped and optimized

PID

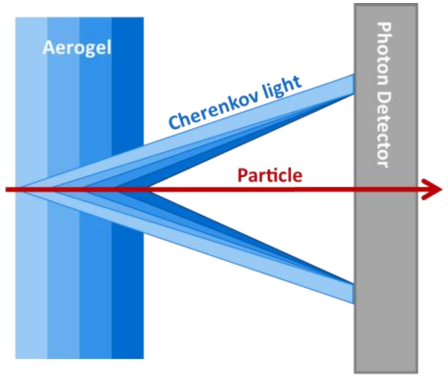
Requirements for PID system

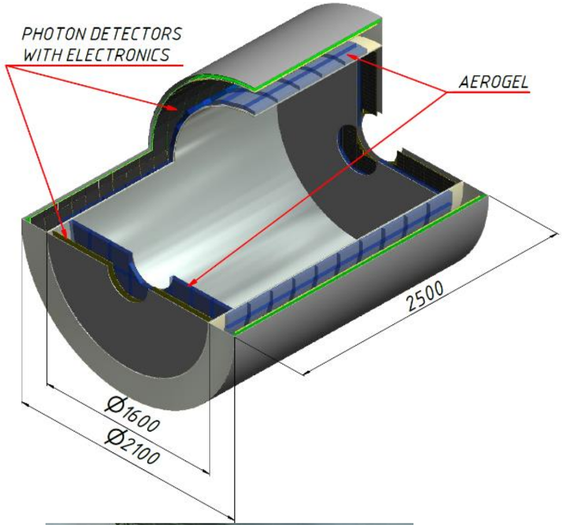
- π/K separation $> 4\sigma$ up to 2.5-3.5 GeV/c
  - TOF (BES-3): 3σ at 0.9 GeV/c, DIRC (BaBar): 4σ at 2.5 GeV/c
  - ASHIPH (KEDR): 4σ at 1.5 GeV/c
- μ/π suppression <1/40 for to 0.5-1.2 GeV/c
- good μ/π separation at low momentum

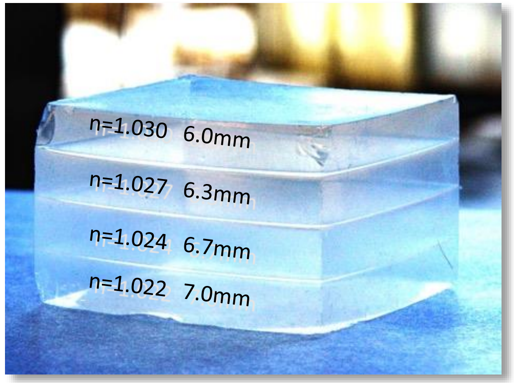
Several option are being considered:

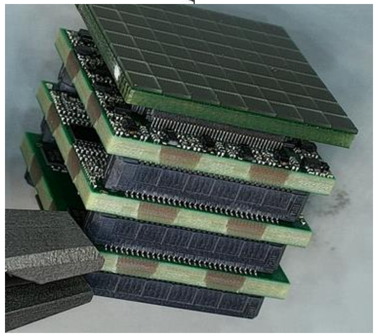
FARICH, ASHIPH, TOF, FDIRC

Simulations, studies with prototypes using test beams









Summary

- There is rich physics program of experiments at Super c-tau factory
- Super c-tau factory is deeply integrated in the global landscape of particle physics
- The conceptual design is ready and is regularly updated
- There is wide program of R&D studies realized by collaboration of BINP, VNIIEF (NCPM) and other institutions

Moving towards technical design