Status of the SCT Detector simulation software and feasibility studies

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The International Workshop on Future Tau Charm Facilities (FTCF2024-Guangzhou)

Budker Institute of Nuclear Physics, Novosibirsk, Russia

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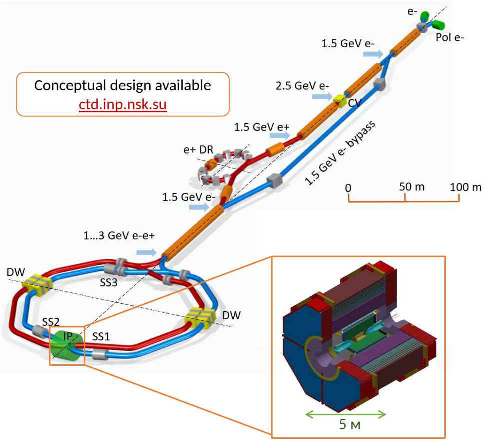
BINP

SCT Experiment overview

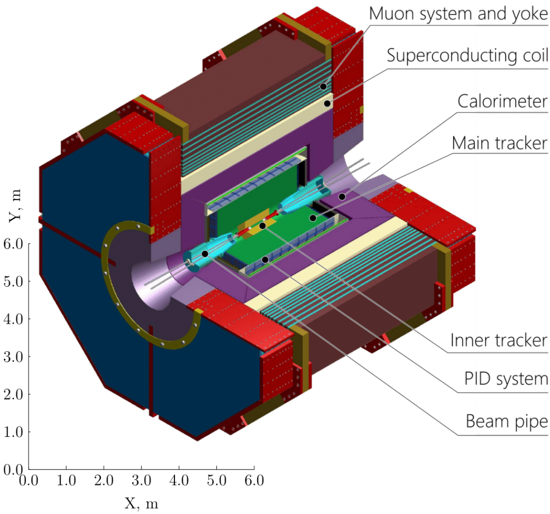
- Precision experiments with tau lepton and charmed hadrons, and search for BSM phenomena
- Electron-positron collider
  - Beam energy varying between 1.5 and 3.5 GeV
  - Luminosity $\mathcal{L} = 10^{35} cm^{-2} s^{-1}$ @ 2.5 GeV
  - Longitudinal polarization of the e^{-} beams
- Universal particle detector
  - Tracking system
  - Crystal electromagnetic calorimeter
  - Particle identification system



Detector overview

Requirements:

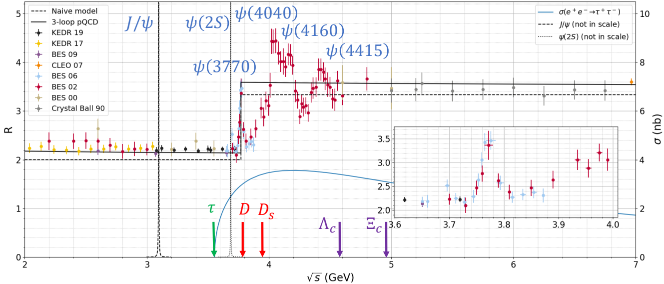
- $10^4 cm^{-2}s^{-1}$ tracks at $R \leq 20$ cm
- $\sigma_p/p \leq 0.4\%$ at 1 GeV/c
- Good π^0/γ separation, $E_\gamma = 10 - 3000$ MeV, $\sigma_E \leq 1.8\%$ at 1 GeV
- Dedicated PID system
  - $\frac{dE}{dx} < 7\%$,
  - μ/π separation up to 1.5 GeV/c,
  - π/K separation up to 3.0 GeV/c.
- Minimal CP detection asymmetry



The SCT energy range

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

Threshold production of nonrelativistic particles provides best conditions for their comprehensive study



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

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	$10^{8}\ D_s\bar{D}_s$
$3.55 \div 4.3$	$10^{10}\ \tau\ \tau$
4.65	$10^{8}\ \Lambda_c^+\Lambda_c^-$

5

Software for the project

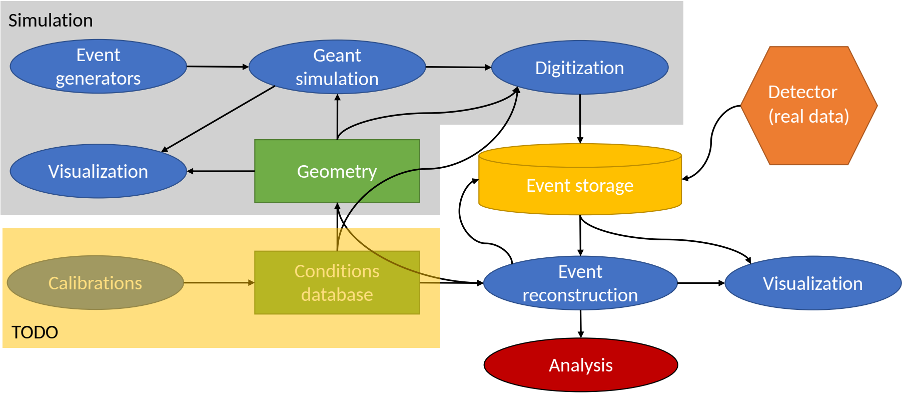
A HEP software framework

A typical HEP experiment requires complete stack of relevant software:

- event generators,
- parametric(fast) and full detector simulation,
- event reconstruction algorithms,
- online event interpretation for trigger decisions,
- event data model (EDM),
- I/O interface to conditions data base,
- I/O interface to data storage,
- offline data analysis algorithms,
- build system and release management software.

Software for the project

Framework elements and data flows



All software for our detector is impemented in framework named Aurora

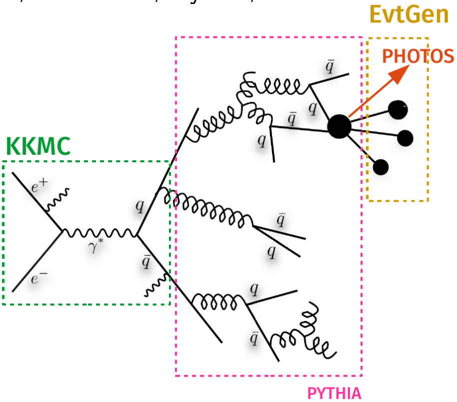
The Aurora framework

- Based on Gaudi
- Uses conventional and recently emerged HEP software tools:
  - ROOT, Geant4
  - DD4Hep (Key4HEP), PODIO
- When possible we reuse peaces of other experiments software
  - Belle II, FCCSW. . .
- Build & configuration system inspired by ATLAS Athena
- `lcgcmake` system to build external packages
- Nightly builds
- Standard computing environment is Scientific Linux 7 x86_64, GCC9, Python3 in process of transition to AlmaLinux 8 (9).

Event Generators

e^--beam has polarization, generators must take this fact into account.
The conventional set of event generators available:

- EvtGen, Tauola, PHOTOS, Pythia, KKMC...

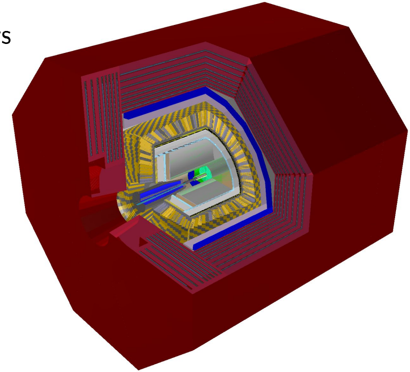


[Fragmentation and Monte Carlo generators at Belle II, Excited QCD 2017]

Status of the software

Geometry in Aurora

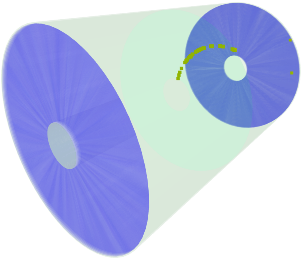
- Subsystems implemented to the moment:
  - Beam pipe & final focus magnets
  - Inner tracker (three options)
  - Advanced DC with StereoLayers
  - Particle ID
  - Crystal calorimeter
  - Simplified s/c coil
  - Muon system & yoke
- Geometry testing tools for CI (overlaps, material scans. . .)

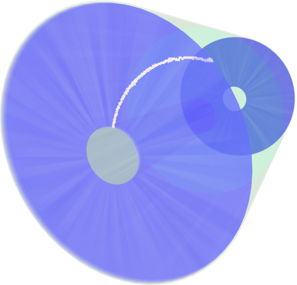


We have geometry for at least one option for each subsystem

Time Projection Chamber

- Sensitive to very low momentum tracks, since 50–70 MeV.
- TPC drift time is $\sim 6\ \mu s$, while bunch-bunch time is 6 *ns*.
  Up to 1000 independent collisions exists in TPC volume and mixed between each other.



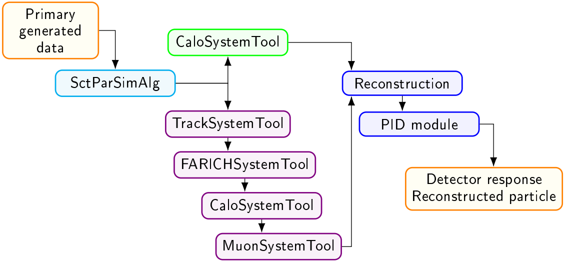


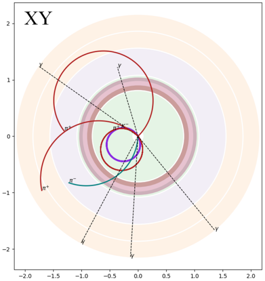
Digitization and reconstruction challenge!

Status of the software

Simulation

Fast simulation for quick estimations of the detector response

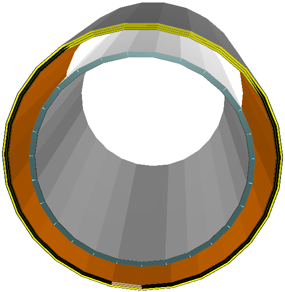


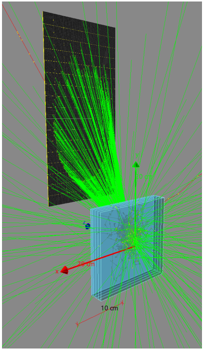


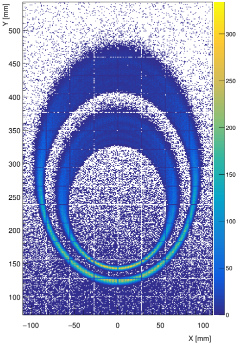
Takes primary particles from generator, produces result equivalent to reconstruction output (momentums, energies, PID)

Status of the software
Simulation

Full (Geant 4 based) simulation





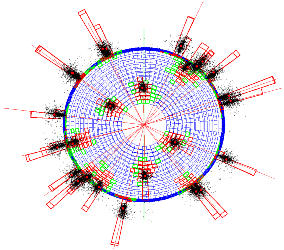


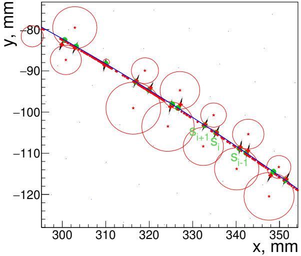
Takes primary particles from generator, G4 hits saved for later processing (digitization)

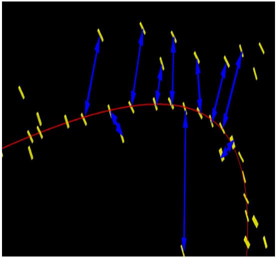
Status of the software

Digitization & Reconstruction

- Current focus of the software development is Digitization (detector and electronics effects)
  - based on standalone studies
  - works for several subsystems: Silicon Strip, Calorimeter, Muon system
  - in active development: TPC, Drift Chamber
- Reconstruction developped at individual subsystem level
  - Calorimeter, DC (standalone still) and Muon system



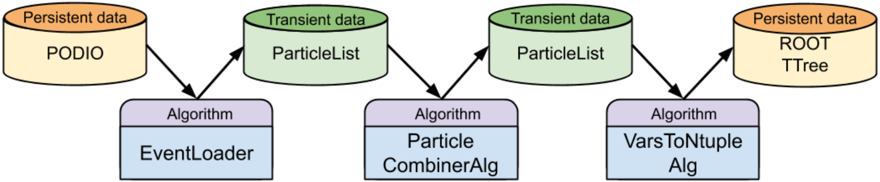




Status of the software

Data Analysis

- Adopting Belle II recipes and solutions for analysis
- Base set of analysis algorithms ready:



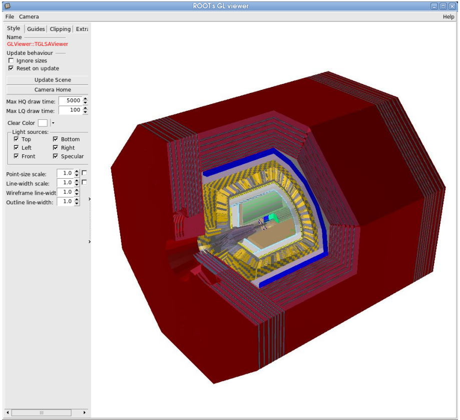
- final particles processing
- kinematic cuts

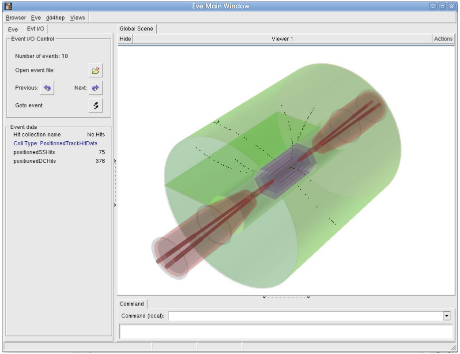
- reconstructuion of decayed particle
- kinematic cuts

- kinematic parameters calculation
- particle selection

Status of the software

Detector/Event Display



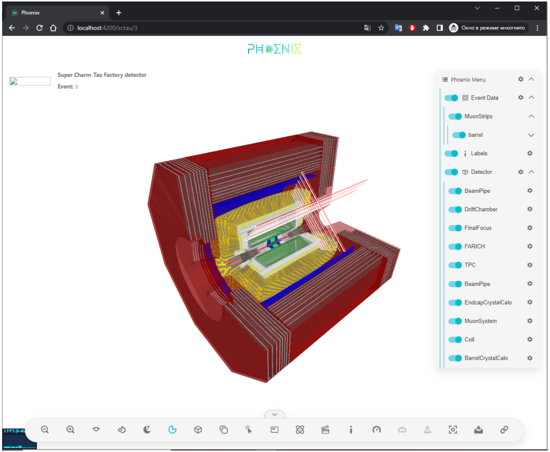


$\psi(4040) \to$ hadrons

- Geometry display tool is ready
- Base Event display (DDEve-based) available, lots of things to improve

Status of the software

Detector/Event Display - Phoenix



- Development Phoenix-based Event display available, lots of things to do

Further software development

The nearest goals for the software development are:

- Generic
  - implementation of digitization modules for all subsystems
  - further reconstruction improvements
  - improvement of detector and event visualization tools
- Core and infrastructure related
  - data model and processing model for TPC digitization and reconstruction (event mixing and separation)
  - distribution of the software via CvmFS, done for external software

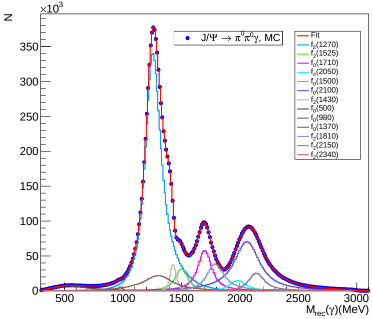
Prospects of J/ψ radiative decays study

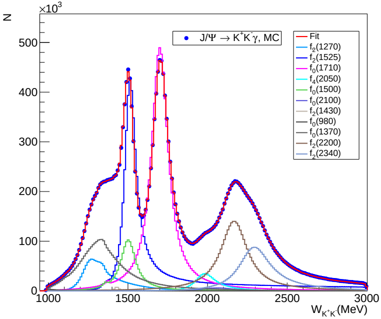
- *Work is at the very beginning*
- Simple simulation of radiative J/ψ decays to resonances with their decays to $2\pi^0$, K^+K^-, $2K_s$, 2η to estimate uncertainties at statistics of the c-tau factory:
  - Sum of 0^{++}, 2^{++}, 4^{++} cross sections
  - Branching fractions and helicity amplitudes from RPP and recent publications
  - Interference of resonnances with the same quantum numbers if interference phase is known
  - Dozen of resonances in total

NB: Data from different experiments are not in good agreement

- Generated data after parametric detector simulation are fitted as 'experimental data'
- Fit is done with a sum of interfering Breit-Wigner amplitudes, the branching fractions and phases are free parameters
- Simulated data and the result of the fit for $2\pi^0$ and K^+K^- channels are presented below

Prospects of J/ψ radiative decays study





(contribution of interference is not drawn)

- $60 \cdot 10^9$ J/ψ decays (40 fb^{-1} at $\sigma_W \simeq 1.5$ MeV, $\sim$ 1 week at L=10^{35}):
  - Statistical accuracy of $Br(J/\psi \to \gamma f(M)) Br(f(M) \to X) = 10^{-5}$ about 2% for M$\simeq$ 2.2 GeV, X = $2\pi^0$, K^+K^-
  - Systematic uncertainty due to $\Gamma(W)$ dependance is of order 5%
- *The final goal of the study is couple-channel analysis of J/ψ radiative decays*

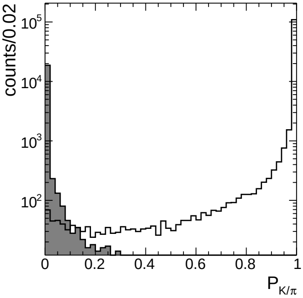
$e^+e^- \to D^*(2007)^0$

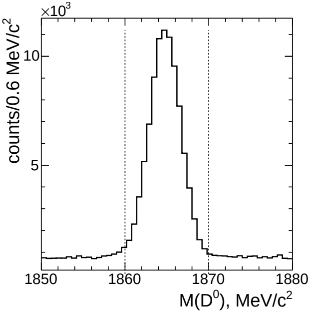
- $D^*(2007)^0$ — neutral vector charmed meson $I(J^P) = 1/2(1^-)$, $D^* = c\bar{u}$, $m_{D^*} = 2006.85 \pm 0.05$ MeV, $\Gamma_{D^*} < 2.1$ MeV CL $= 90\%$
- $D^* \to e^+e^-$ is a good probe for the New Physics. In [JHEP 1511, 142 (2015)] the authors estimate $\mathcal{B}_{D^* \to e^+e^-} \sim (0.1 - 5) \times 10^{-19}$ (SM) , but they also show that it can grow significantly in some extension models: $\mathcal{B}_{D^* \to e^+e^-} < 2.5 \times 10^{-11}$ (Z'), $\mathcal{B}_{D^* \to e^+e^-} < 1.7 \times 10^{-14}$ (RPV SUSY).
- search for $e^+e^- \to D^*(2007)^0$ allows to set an upper limit for $B_{D^* \to e^+e^-}$. It has been performed with the CMD-3 detector at the VEPP-2000 collider yielding the upper limit at the level of order 10^{-7}, we consider a possibility to decrease the upper limit with SCT factory

Search for $e^+e^- \to D^*$ at SCT factory

- we consider the signal process $D^{*0} \to [D^0 \to K^-\pi^+\pi^-\pi^+]\pi^0$
- background events are generated according to the set of exclusive hadronic cross sections for the center-of-mass energy 2 GeV
- simple parametric simulation of the detector using the following set of the resolution parameters:
  - momentum resolution in the tracking system $\sigma_p/p = 0.4\%$,
  - 5σ for K/π separation for the particle identification system,
  - energy resolution $\sigma_E/E = 1\%$, and angular resolution $\sigma_\theta = \sigma_\phi = 0.01$ for the calorimeter.
- selection criteria:
  - K/π-separation response $\log(P_{K/\pi}) < -3$ for kaons, $\log(1 - P_{K/\pi}) < -3$ for pions
  - reconstructed D^0 invariant mass $|M(D^0) - 1865| < 5$ MeV/$c^2$and momentum $|P(D^0) - 43| < 6$ MeV/c,
  - reconstructed D^{*0} invariant mass $|M(D^{*0}) - 2007| < 7$ MeV/c^2,
  - $|M(\pi^+\pi^-) - 497| > 20$ MeV/c^2 for all $\pi^+\pi^-$ pairs in the final state to suppress the background from K_S intermediate states.

SCT feasibility in search for $e^+e^- \to D^*$





- signal detection efficiency is about $\epsilon = 35\%$
- we obtain $N = 3$ events passed the selection criteria out of $\sim 3 \times 10^9$ generated background events corresponding to the integrated luminosity $L = 87600\text{pb}^{-1}$ (a "month" of SCT factory operation)
- we expect a significanly better sensitivity in comparison with the CMD-3: an improvement in the momentum resolution and in the K/π separation would allow to decrease an upper limit $\mathcal{B}_{D^* \to e^+e^-} < 10^{-11}$

Search for rare decay $\tau \to \mu\gamma$

- Branching fraction in SM is about 10^{-54}, some extensions expects $10^{-8} - 10^{-9}$. Highly sensible for new physics!
- Probably can be detected by Belle II or by planned Charm-Tau factories.

Experiment setup:

- Belle II: $\tau^+\tau^-$ production at $E_{CM} = 10.58$ GeV, has unavoidable background from $e^+e^- \to \gamma\tau^+\tau^-$
- SCT: $\tau^+\tau^-$ production at $E_{CM} = 3.77$ GeV, much more clean environment, better sensitivity expected.

Search for rare decay $\tau \to \mu\gamma$

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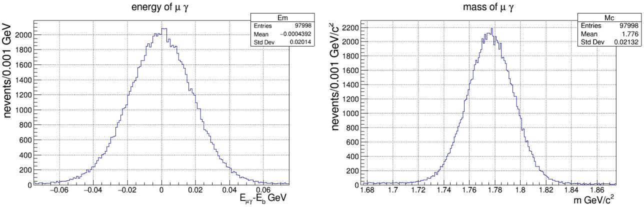
Tagging τ detected in decays: $\tau^- \to e^-\nu\nu$, $\tau^- \to \mu^-\nu\nu$, $\tau^- \to \pi^-\nu$, $\tau^- \to \pi^-\pi^0\nu$, $\tau^- \to \pi^-\pi^0\pi^0\nu$ и $\tau^- \to \pi^-\pi^+\pi^-\nu$ ($\sim$90 %).



- signal detection efficiency is about $\epsilon = 13\%$
- expected upper limit $< 5 \times 10^{-9}$ for one year dataset

CP asymmetry

The CP asymmetry is given by

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}. \quad (1)$$

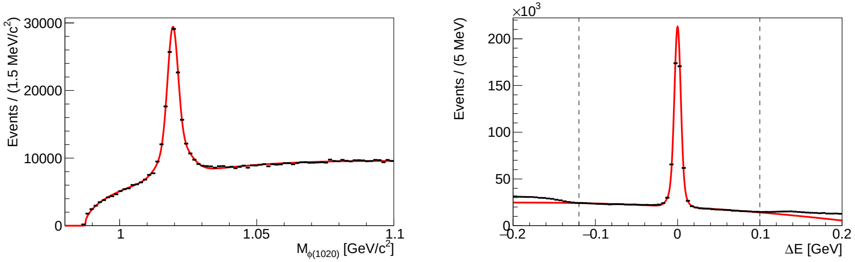
Taking the efficiency difference in data and MC into account, it can be expressed as

$$A_{CP} = A\left(\frac{N_{D\to f}}{\epsilon_f^{(\mathrm{MC})}}\right) - \sum_i A\left(\left(\frac{\epsilon^{(\mathrm{data})}}{\epsilon^{(\mathrm{MC})}}\right)_i\right), \quad (2)$$

where summation is performed over final-state particles. The efficiency ratios need to be determined from calibration channels and determine the systematic error of the asymmetry. Kaon identification is assumed to be applied. There is no detailed calibration procedure; the channels $\phi(1020) \to K^+K^-$ and $D^+ \to K^-\pi^+\pi^+$ are used to get samples of kaons. The error is estimated from yield statistical uncertainty with a loose kaon PID cut.

Calibration channels

Generic MC sample, 1 fb^{-1}:

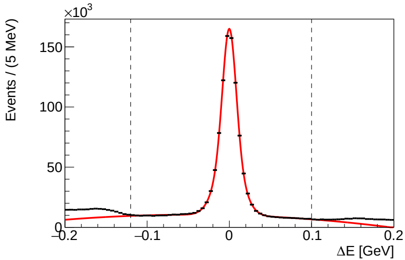


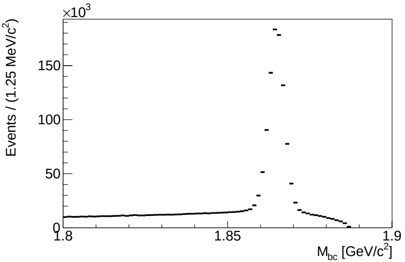
Channel	Signal yield
$\phi(1020) \to K^+K^-$	95410 ± 640
$D^+ \to K^-\pi^+\pi^+$	413700 ± 910

Estimated statistics and error:

$$N_{K^-} = N_{\phi(1020)} + \frac{N_{D^+}}{2} \approx 301760,$$
$$\delta N_{K^-} = \sqrt{(\delta N_{\phi(1020)})^2 + \frac{(\delta N_{D^+})^2}{2}} \approx 910. \quad (3)$$

Signal channel: $D^0 \to K^-\pi^+\pi^0$





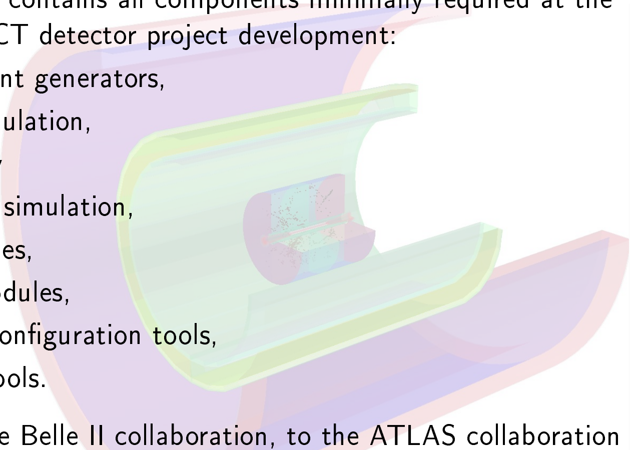
Yield: $N(D^0 \to K^-\pi^+\pi^0) = 801530 \pm 1320$.
Rescaling this result and calcibration error to 1 ab^{-1} (one year of operation), one gets

$$\delta A_{CP}(D^0 \to K^-\pi^+\pi^0)_{\text{stat}} \sim 5 \times 10^{-5},$$
$$\delta A_{CP}(D^0 \to K^-\pi^+\pi^0)_{\text{syst}} \sim 7 \times 10^{-5}. \quad (4)$$

Conclusions

The Aurora framework contains all components minimally required at the present stage of the SCT detector project development:

- set of primary event generators,
- parameterized simulation,
- detector geometry
- full Geant4-based simulation,
- digitization modules,
- reconstruction modules,
- analysis and job configuration tools,
- test and service tools.



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Thank you for your attention

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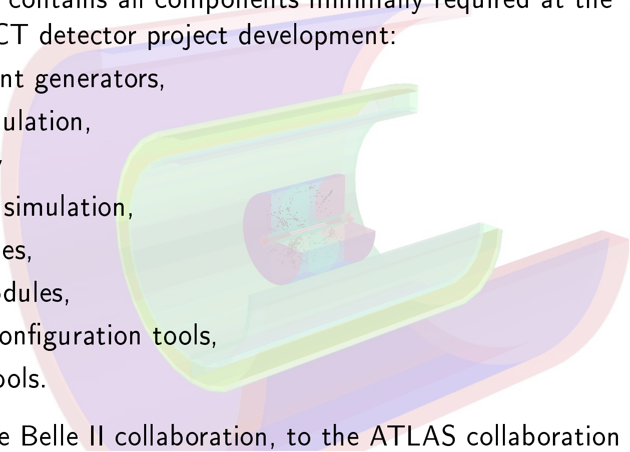

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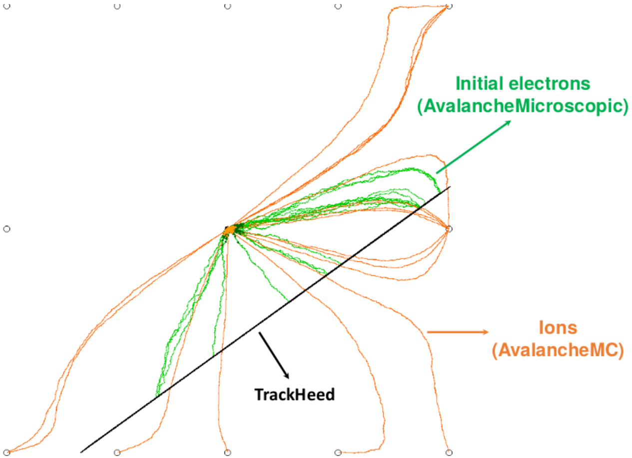
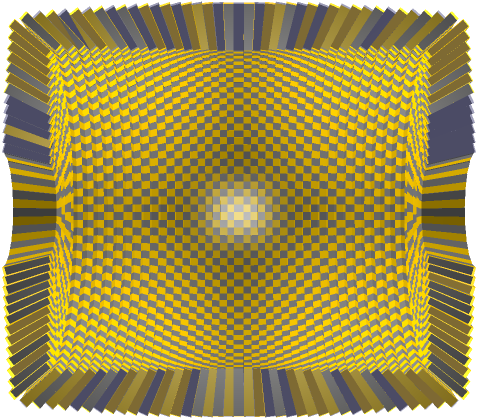
Standalone DC studies

Gas mixture studies and electric field simulations with Garfield for TPC and DC electrons and ions drift lines presented



Calorimeter

Crystal calorimeter based on pure CsI with about 7000 crystals



SCT Physics in a nutshell

- ✓ 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
- ✓ Baryon interaction at threshold
- ✓ Search for glueballs in decays of J/ψ and $\psi(2S)$
- ✓ …

tau

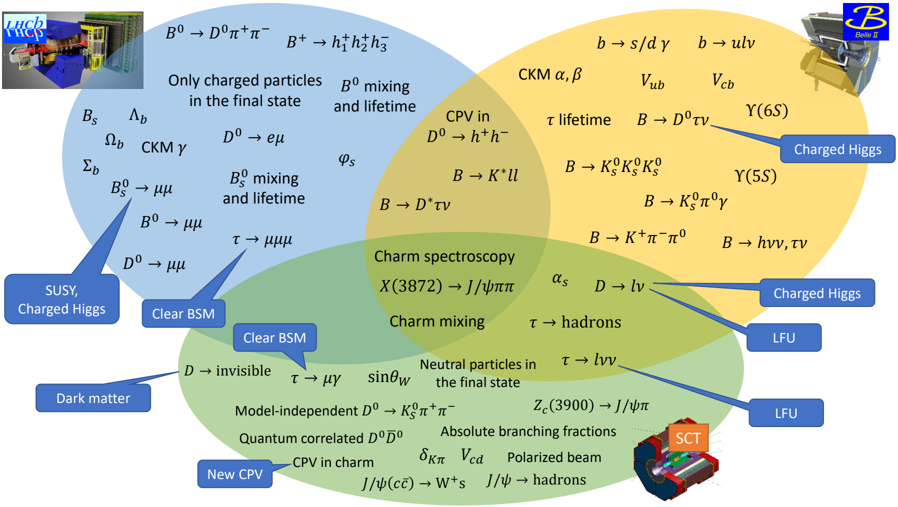
Test of the electroweak sector of the SM

- ✓ 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
- ✓ …

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

6

[V. Vorobyev]



$B^0 \to D^0\pi^+\pi^-$
$B^+ \to h_1^+ h_2^+ h_3^-$
Only charged particles in the final state
B^0 mixing and lifetime
B_s
Λ_b
Ω_b
CKM γ
Σ_b
$D^0 \to e\mu$
φ_s
$B_s^0 \to \mu\mu$
B_s^0 mixing and lifetime
$B^0 \to \mu\mu$
$\tau \to \mu\mu\mu$
$D^0 \to \mu\mu$
SUSY, Charged Higgs
Clear BSM
$b \to s/d\,\gamma$
$b \to ul\nu$
CKM α, β
V_{ub}
V_{cb}
Belle II
CPV in $D^0 \to h^+h^-$
τ lifetime
$B \to D^0\tau\nu$
$\Upsilon(6S)$
Charged Higgs
$B \to K^* ll$
$B \to K_S^0 K_S^0 K_S^0$
$\Upsilon(5S)$
$B \to D^*\tau\nu$
$B \to K_S^0 \pi^0 \gamma$
$B \to K^+\pi^-\pi^0$
$B \to h\nu\nu, \tau\nu$
Charm spectroscopy
$X(3872) \to J/\psi\pi\pi$
α_s
$D \to l\nu$
Charged Higgs
Charm mixing
$\tau \to$ hadrons
LFU
Clear BSM
$D \to$ invisible
$\tau \to \mu\gamma$
$\sin\theta_W$
Neutral particles in the final state
$\tau \to l\nu\nu$
Dark matter
LFU
Model-independent $D^0 \to K_S^0\pi^+\pi^-$
$Z_c(3900) \to J/\psi\pi$
Quantum correlated $D^0\bar{D}^0$
Absolute branching fractions
SCT
New CPV
CPV in charm
$\delta_{K\pi}$
V_{cd}
Polarized beam
$J/\psi(c\bar{c}) \to W^+s$
$J/\psi \to$ hadrons

[V. Vorobyev]

Software complexity

Stage	t_{event}	RMS(t_{event})	t_{init}	RMS(t_{init})
Geant 4 simulation	84 ms	113 ms	10.2 s	0.9 ms
Digitization	1 – 10 order of sim time		—	—
Reconstruction	1 – 10 order of sim time		—	—

No strong requirement for extensive use of multithreading.