Λ_c production simulation and di-ϕ production simulation within SPDRoot

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SPD seminar, 26 September 2023

The study objects

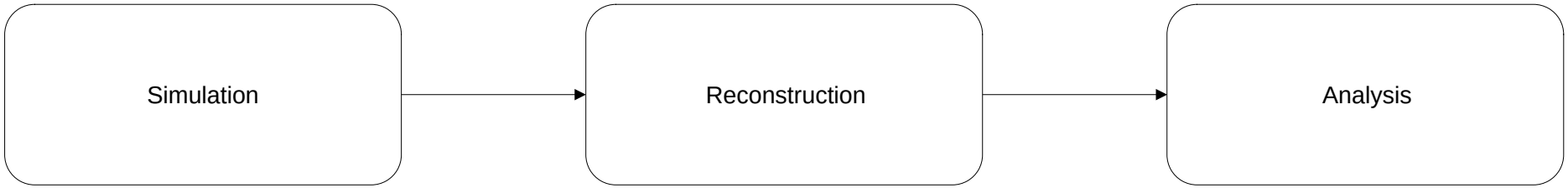
Λ_c production

An open charm production in proton-proton collisions at medium and low energy allows to study in detail heavy quark hadronization processes, as well as to better understand the proton structure.

di-ϕ production

More recently, experiments LHCb and CMS observed structures in the spectrum of two J/ψ mesons, which with a high probability can be interpreted as $cc\bar{c}\bar{c}$ tetraquarks. Tetraquark states similar to those could be observed in other di-meson spectra, such as $\omega\omega$ and $\phi\phi$. There are theoretical indications that $f_0(2200)$ and $f_2(2340)$ may be candidates of $ss\bar{s}\bar{s}$ tetraquarks.

SPDRoot



The SPDRoot is an offline framework for the SPD experiment.

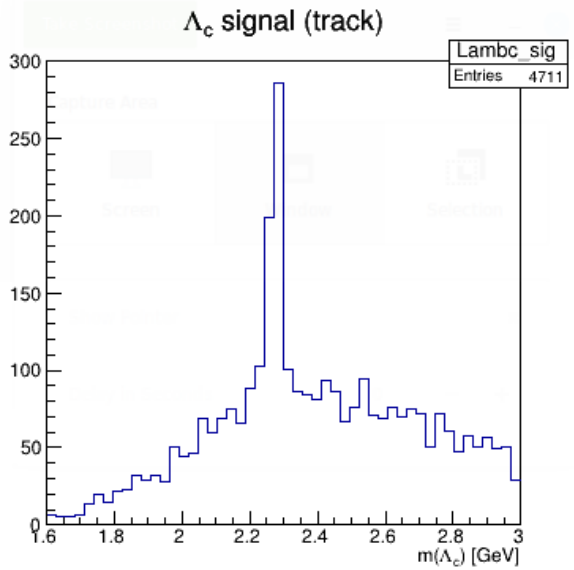
The SPDRoot pipeline has three stages:

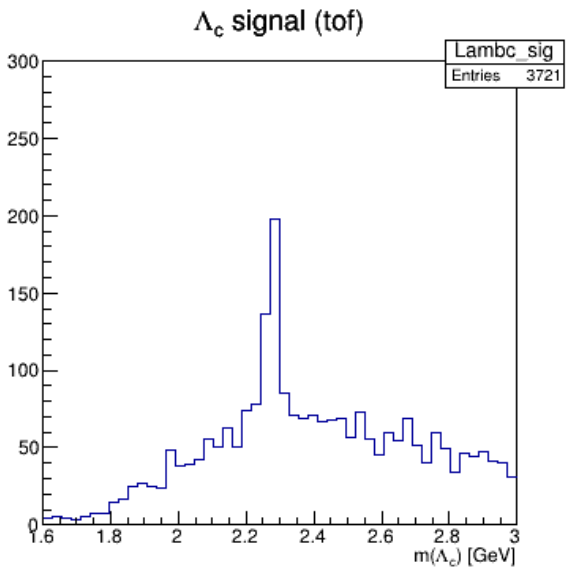
1. Simulation. Detector response is written to output Root file and geometry and material details are written to a separate parameter Root file. (Pythia8 + GEANT4)
2. Reconstruction. Finding and estimating the trajectory of a particle.
3. Analysis. The output of reconstruction processed and histograms drawn.

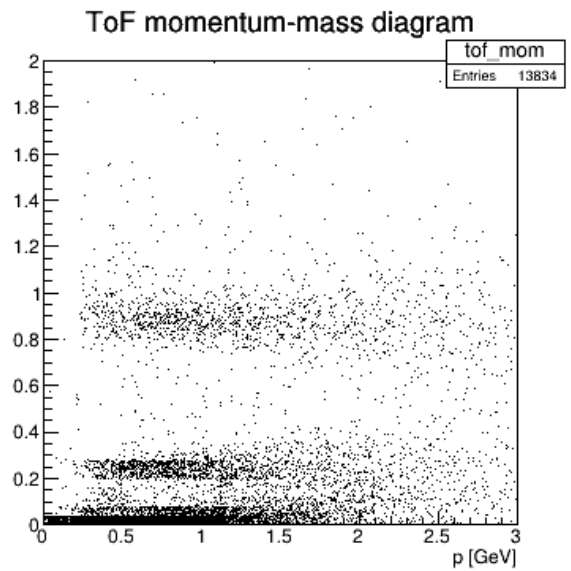
Events simulation

- Events with open charm have been generated within the Pythia8 framework using the hard subprocesses $gg \to c\overline{c}$ and $q\overline{q} \to c\overline{c}$: SetParameters("HardQCD:hardccbar = on")
- The events with Λ_c^+ has been selected using P8EventFilter
- All Λ_c^+ baryons have been enforced to decay to $p^+K^-\pi^+$ combination
- $\Lambda_c^+ \to (\Delta^{++} \to p^+\pi^+)K^-$ has been temporary used instead of complete decay model due to the technical reasons SelectForcedDecay(4122, 35)

Λ_c signal

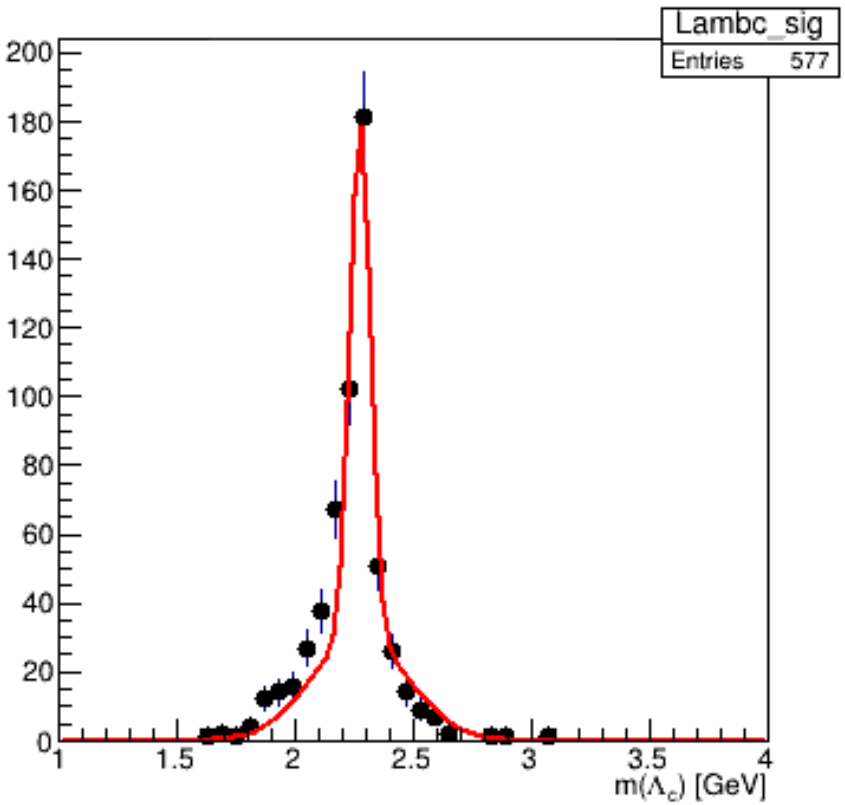






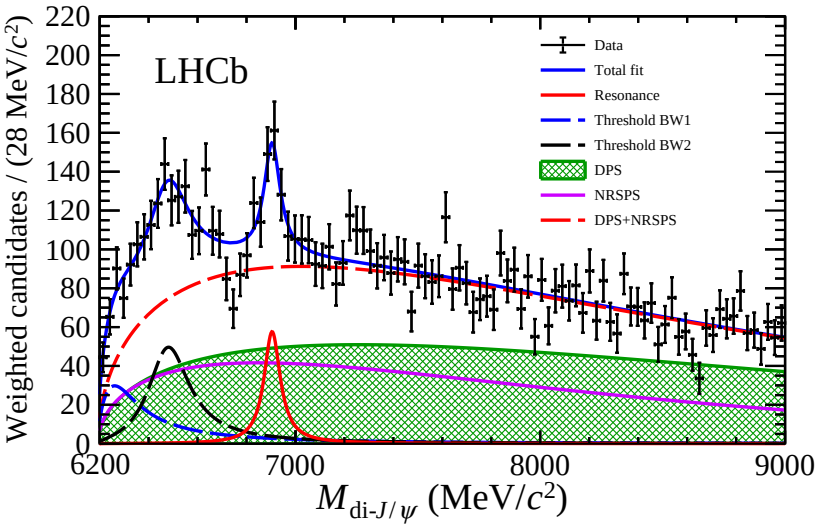
- All three decay products of Λ_c are identified by the Time-of-Flight system of SPD (TOF).
- The purpose of the TOF system is to distinguish pions, kaons and protons.

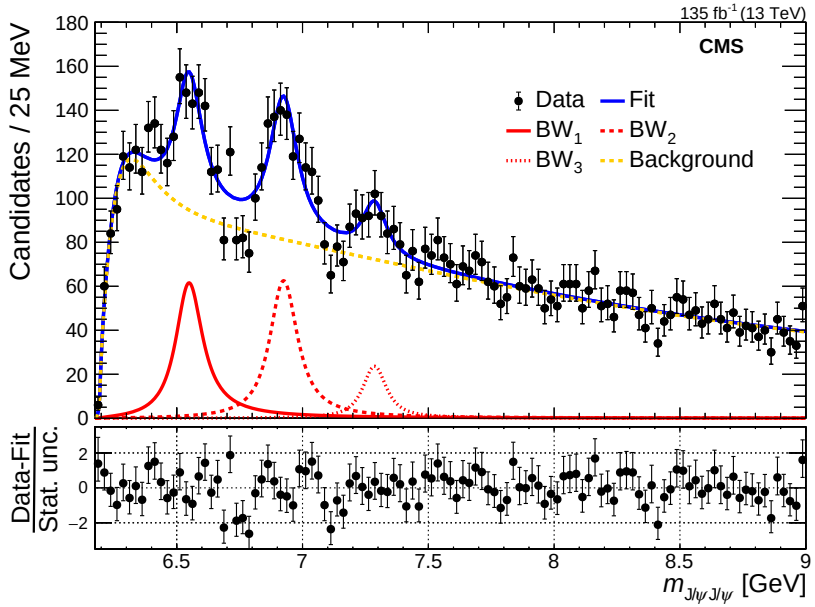
Λ_c fit



FUNCTION:
Double Gaussian function
FIT OUTPUT:
$\mu = 2.269 \pm 0.004$ [GeV]
$\sigma_1 = 0.205 \pm 0.009$ [GeV]
$\sigma_2 = 0.044 \pm 0.004$ [GeV]

Examples of the structures in a di-meson spectrum ($J/\psi J/\psi$, LHCb & CMS)

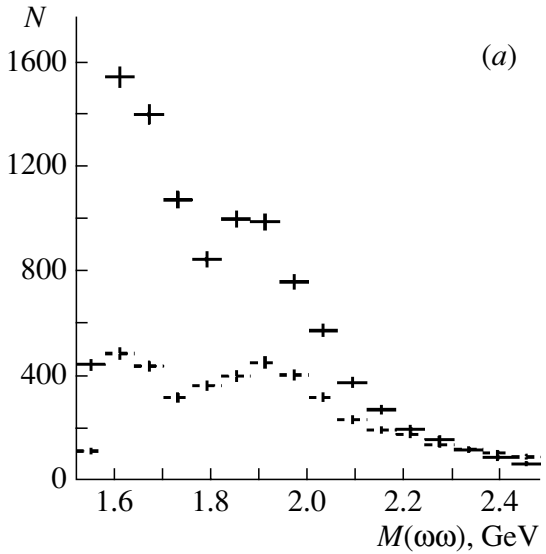




Original article (LHCb): LHCb Collaboration. "Observation of structure in the J/ψ-pair mass spectrum." Science Bulletin 65.23 (2020): 1983-1993.

Original article (CMS): CMS Collaboration. "Observation of new structure in the $J/\psi J/\psi$ mass spectrum in proton-proton collisions at $\sqrt{s} = 13$ TeV." arXiv preprint arXiv:2306.07164 (2023).

Examples of the structures in a di-meson spectrum ($\pi^-_{28\ \&\ 37\ \mathrm{GeV}} p \to \omega\omega n$, VES; $\pi^-_{85\ \mathrm{GeV}} Be \to \phi\phi + X$, WA67)



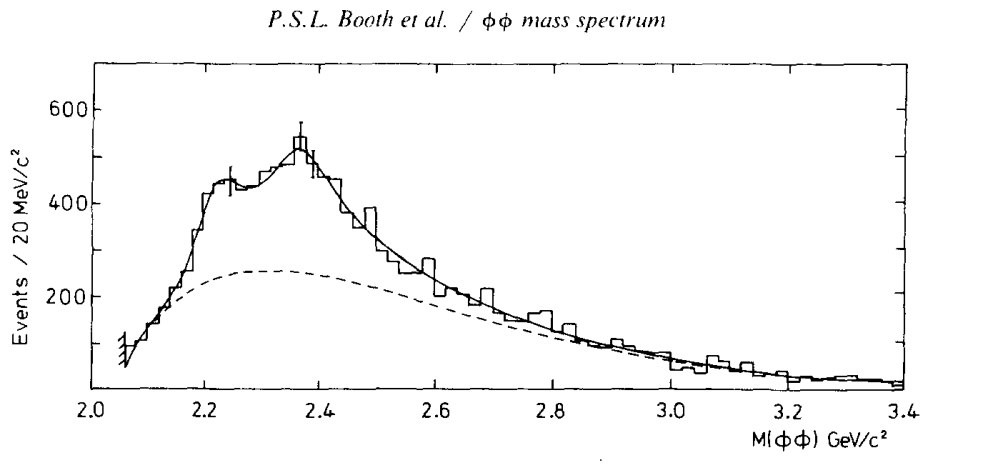


Fig. 6. The "true" $\phi\phi$ mass distribution with fitted Granet et al. background plus two Breit-Wigners.

Original article ($\omega\omega$): Amelin, D. V., et al. "Resonances in the $\omega\omega$ system." Physics of Atomic Nuclei 69 (2006): 690-698.

Original article ($\phi\phi$): Booth, P. S. L., et al. "A high statistics study of the $\phi\phi$ mass spectrum." Nuclear Physics B 273.3-4 (1986): 677-688.

Review article ($\phi\phi$): Stephen Godfrey and Jim Napolitano. "Light-meson spectroscopy." Reviews of Modern Physics 71.5 (1999): 1411.

di-ϕ simulation

- There are several ways to add a particle initially not available in Pythia (previously reported by A. Anufriev).
- Changing the existing particle was chosen for its simplicity though some di-ϕ properties were ignored.
- To generate the di-ϕ the J/ψ meson in Pythia was modified:
  443:m0 = 2.2 [GeV]
  443:mMin = 2.03 [GeV]
  443:mMax = 2.37 [GeV]
  443:mWidth = 0.05 [GeV]
  443:oneChannel = 1 1 0 333 333
- The detector response was simulated within SPDRoot

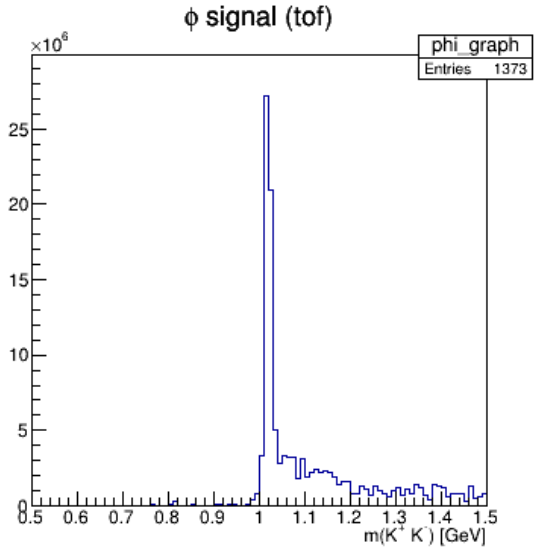
Total yield estimation

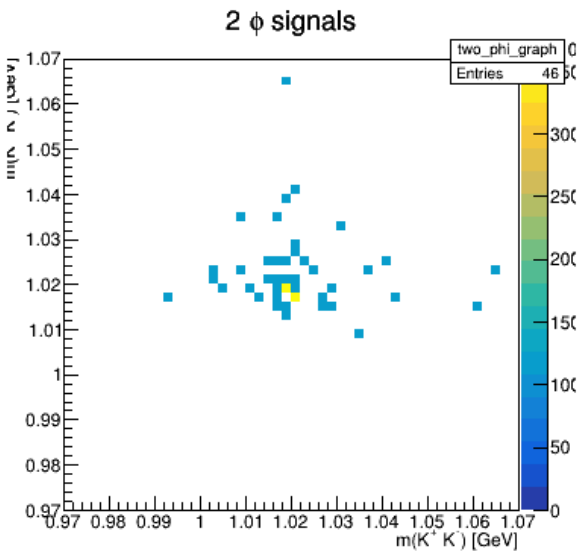
Luminosity (L): $10^{32}\ cm^{-2}s^{-1}$
Time (T): $10^{7}\ s$ ($\approx$ 1 year of operation)
Minimum-Bias (MB) cross-section: 40 mb
Supposed di-ϕ resonance production cross-section in $K^+K^-K^+K^-$ decay mode: 200 nb

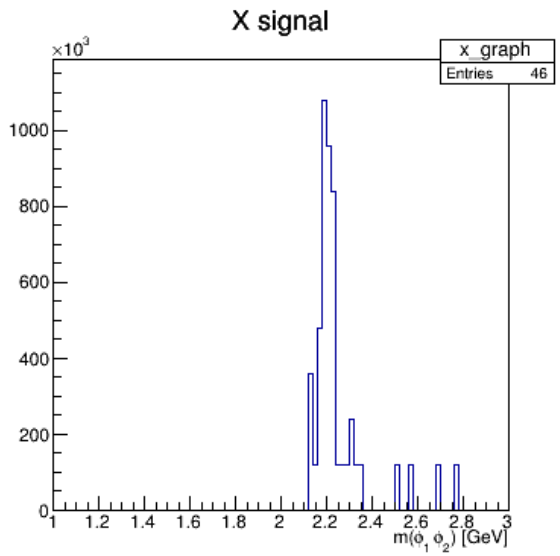
The selected events number is multiplied by the factor of

$$f_{signal} = \frac{L \times T \times \sigma_{signal}}{\text{number of generated events}} = 1.2 \times 10^5$$

di-ϕ signal ($\sim$1 year scale)







Selection

- Two pairs of kaons were found.
- The mass of each pair is constrained to be in the interval $[0.97\ \text{GeV}, 1.07\ \text{GeV}]$.
- Candidates for di-ϕ resonance are searched in the mass spectrum of two selected pairs.

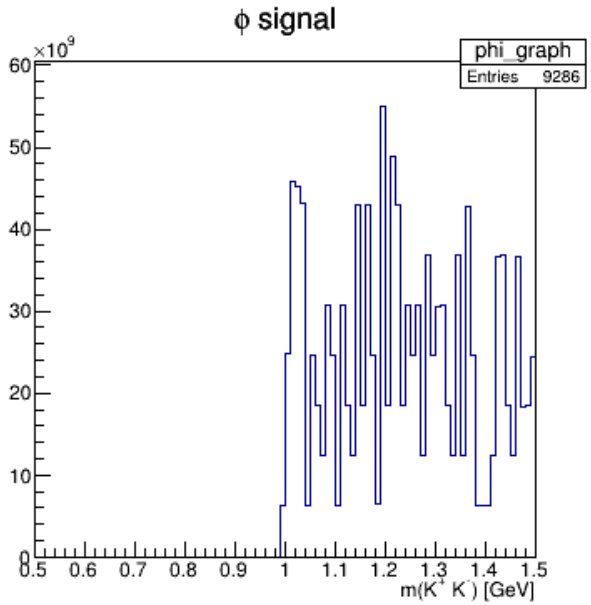
di-ϕ background

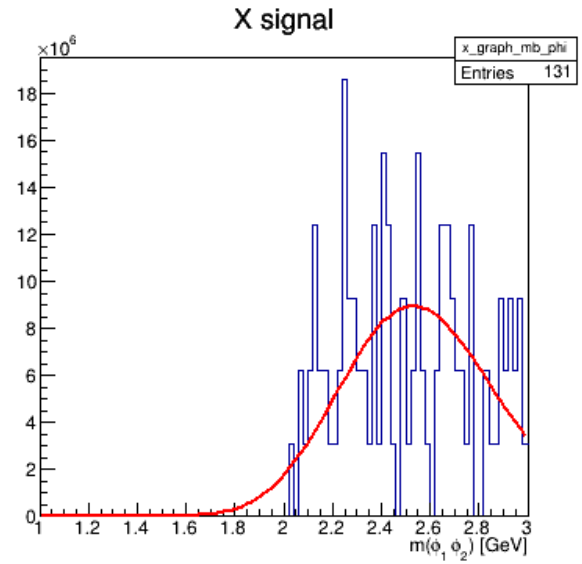
The multiple ϕ production rate is small: about 98 events per 100 000 MB events. That is why the background events with several ϕ-mesons were selected on generator level before detector simulation. Then the number of reconstructed events was scaled by

$$f_{\text{MB}} = \frac{L \times T \times \sigma_{MB} \times \frac{98}{100000}}{\text{number of generated MB}_{>2\phi}} \approx 3.1e+06$$

Because of small number of entries in the resulting histogram, it was approximated by the function:

$y = (x - x_{\text{thresh}})^a \times \exp(-bx)$





Signal significance estimation

The number of background events in the [2.1-2.35] interval (around 3σ) $N_{bg} \approx 6.73e+7$. Therefore the background fluctuation value $N_{fluct} = \sqrt{N_{bg}} \approx 8200$ and the signal significance equals

$$\frac{N_{signal}}{N_{fluct}} \approx 130$$

The signal can be observed if it is five times greater than the fluctuations, thus

$$\sigma_{min} = 200 \text{ nb} \times \frac{N_{fluct}}{N_{signal}} \times 5 \approx 7.6 \text{ nb}$$

σ_{min} can be recalculated into a more convenient value ($\sigma_X \times \text{Br}(X \to \phi\phi)$):

$$\sigma'_{min} = \frac{\sigma_{min}}{\text{Br}(\phi \to K^+K^-)^2} = 31.5 \text{ nb}$$

Conclusions

The results of the work:

- Estimated Λ_c width: $\sigma = 0.044 \pm 0.004$ [GeV]
- Estimated the visible cross-section of di-ϕ: 7.6 nb (31.5 nb)

To do:

- Non-symmetrical fit function can be tried for Λ_c fit (e.g. Double Crystal Ball is actively used by LHCb collaboration).
- di-ϕ production in Pythia can be treated more rigorously and with high statistics.

Many thanks to Igor Denisenko for the leadership of this work and fruitful discussions.

This study was carried out within the project "Production of open charm and tau leptons at the NICA SPD: phenomenology and simulation" supported by JINR.

Thank you for your attention!