Λ_c production simulation and di-ϕ production simulation within SPDRoot

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The study objects

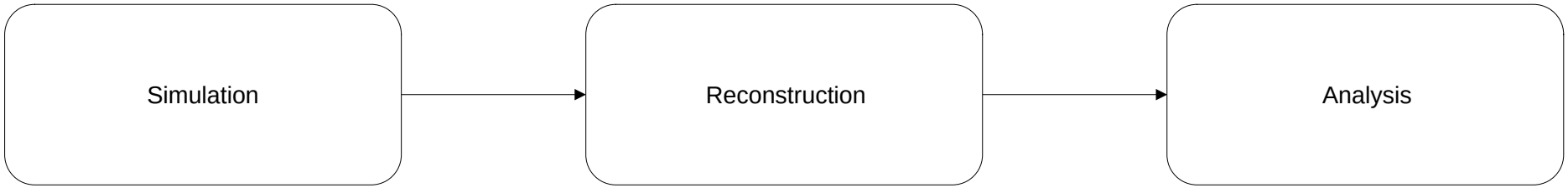
Λ_c production

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.

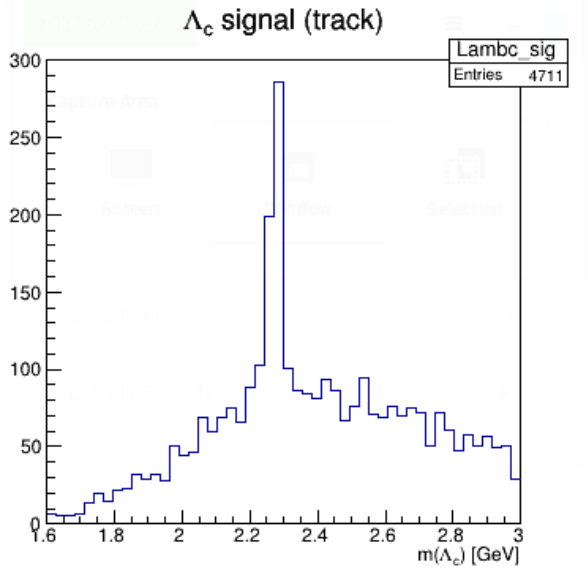
The SPDRoot pipeline has three stages:

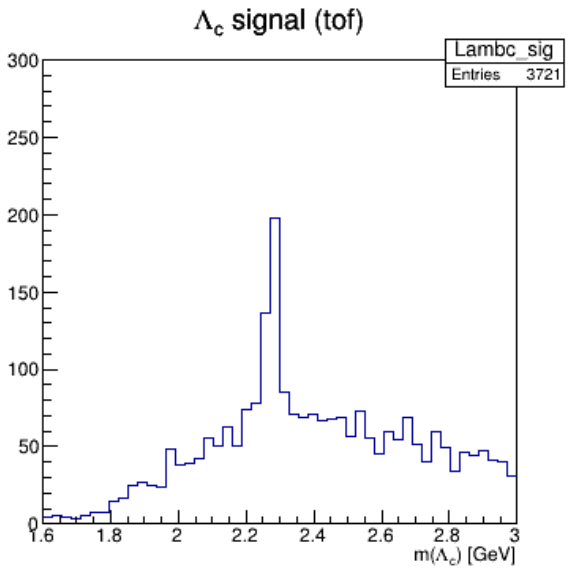
1. Simulation. Detector response is written to output Root file and geometry and material details are written to a separate parameter Root file. (Pythia8 + GEANT4)
2. Reconstruction. Finding and estimating the trajectory of a particle.
3. Analysis. The output of reconstruction processed and histograms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

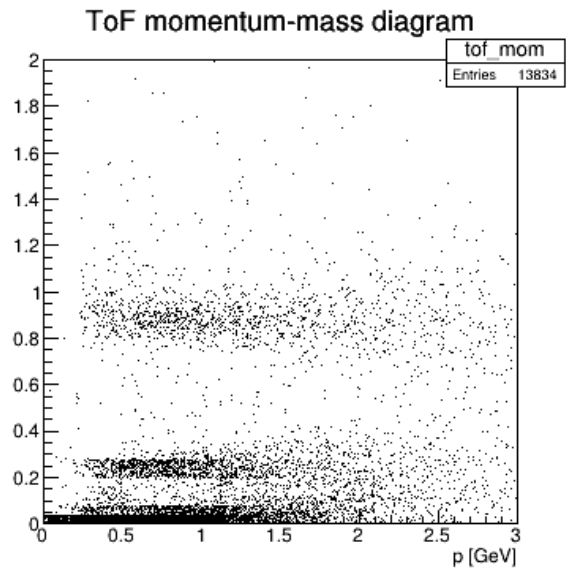
Events simulation

- 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

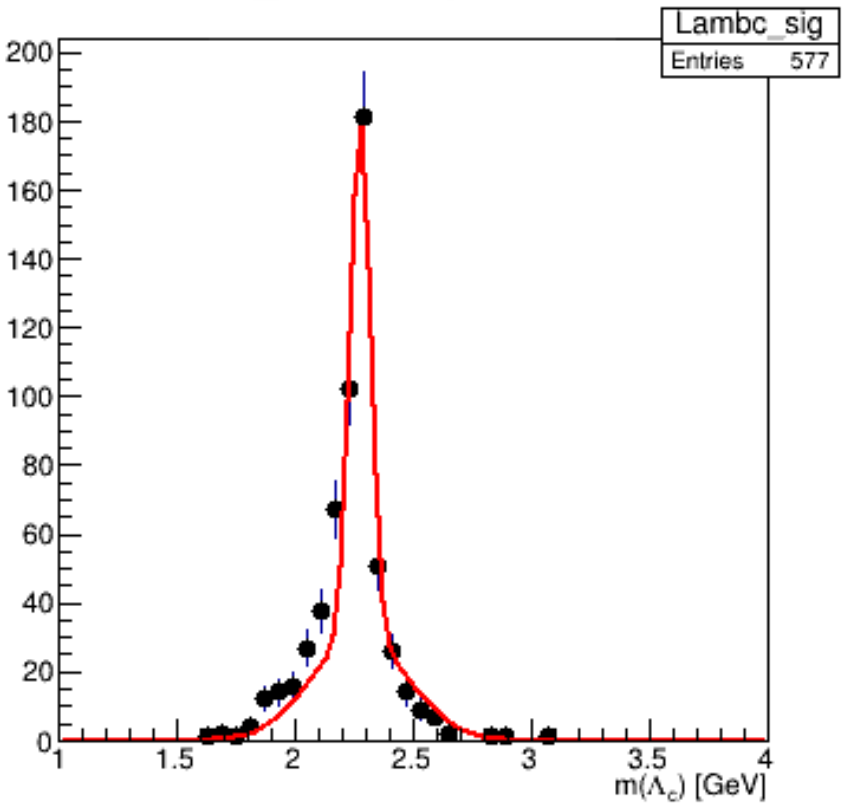






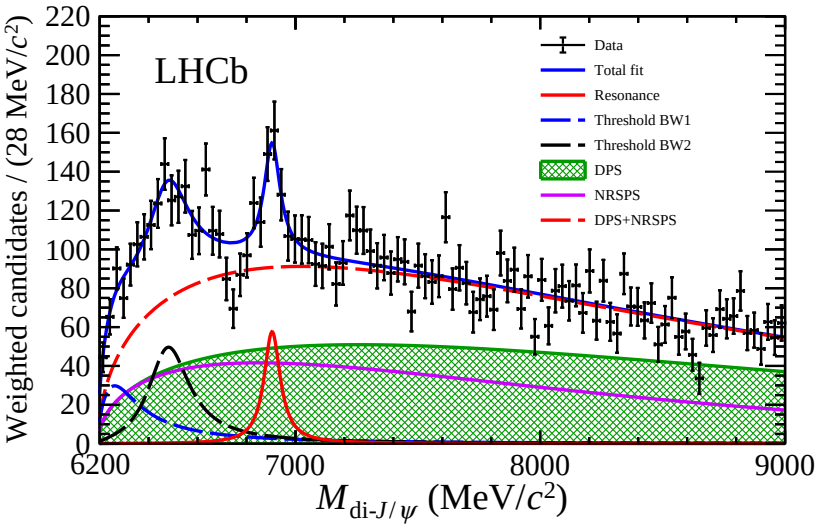
- All three decay products of Λ_c are identified by the Time-of-Flight system of SPD (TOF).
- The purpose of the TOF system is to distinguish pions, kaons and protons.
- In the SPDRoot the work of the detectors is stored separately from tracks and their real types of particles. Its details are put on them in analysis.

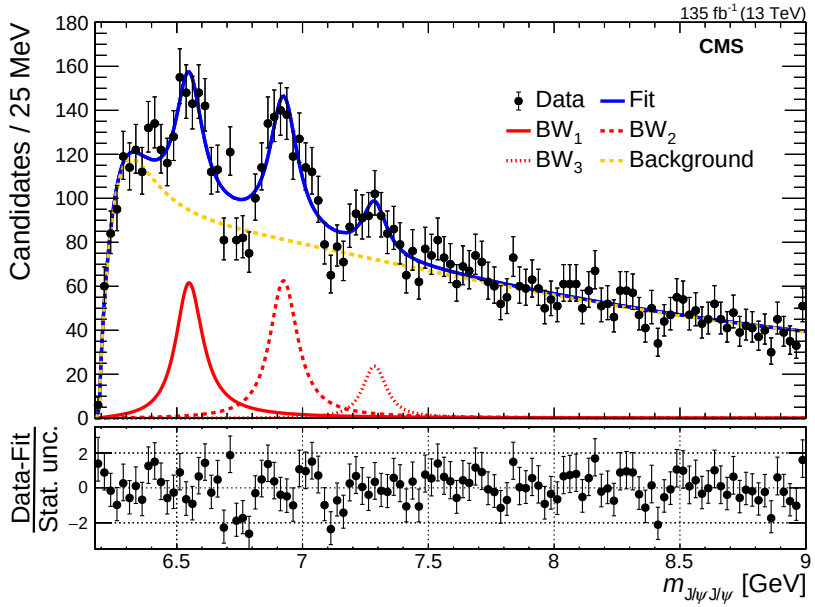
Λ_c fit



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)

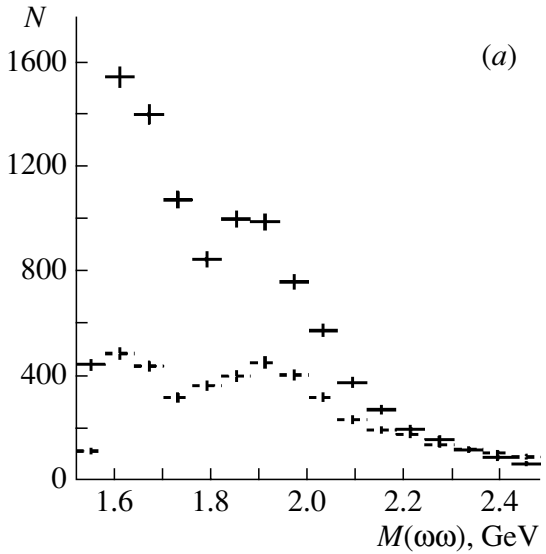




Original article (LHCb): LHCb Collaboration. "Observation of structure in the J/ψ-pair mass spectrum." Science Bulletin 65.23 (2020): 1983-1993.

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)



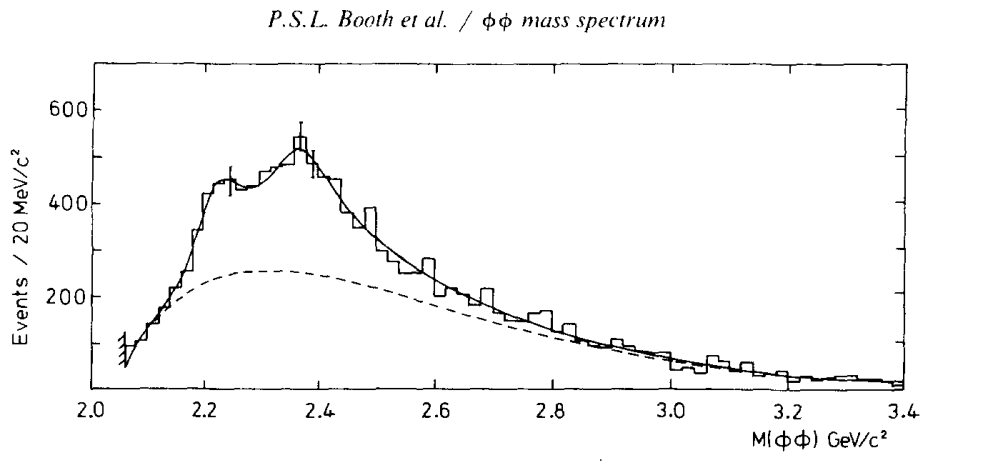


Fig. 6. The "true" $\phi\phi$ mass distribution with fitted Granet et al. background plus two Breit-Wigners.

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

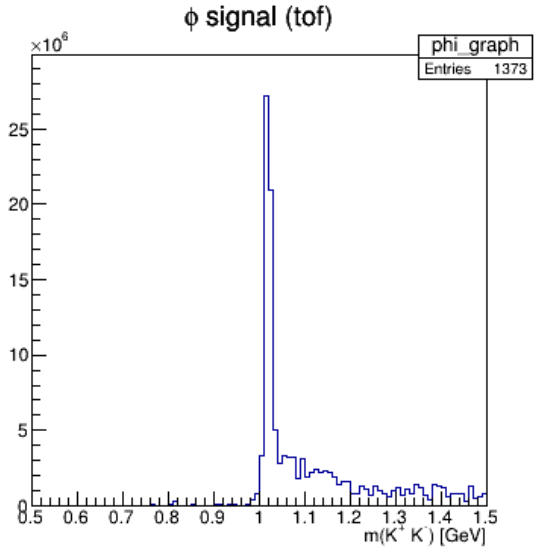
Total yield estimation

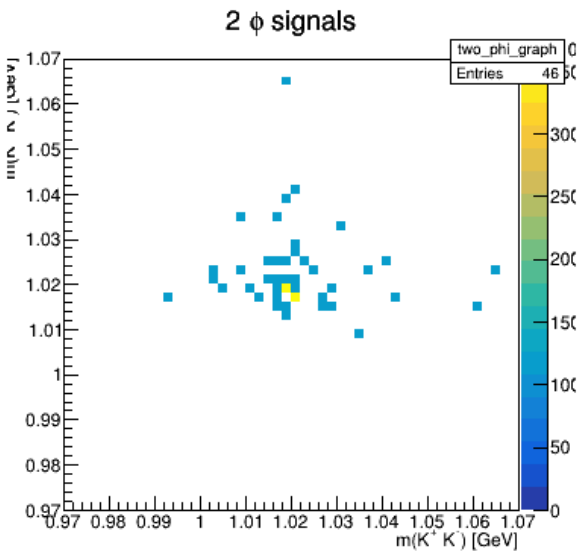
Luminosity (L): $10^{32}\ cm^{-2}s^{-1}$
Time (T): $10^{7}\ s$ ($\approx$ 1 year of operation)
Minimum-Bias (MB) cross-section: 40 mb
Supposed di-ϕ resonance production cross-section in $K^+K^-K^+K^-$ decay mode: 200 nb

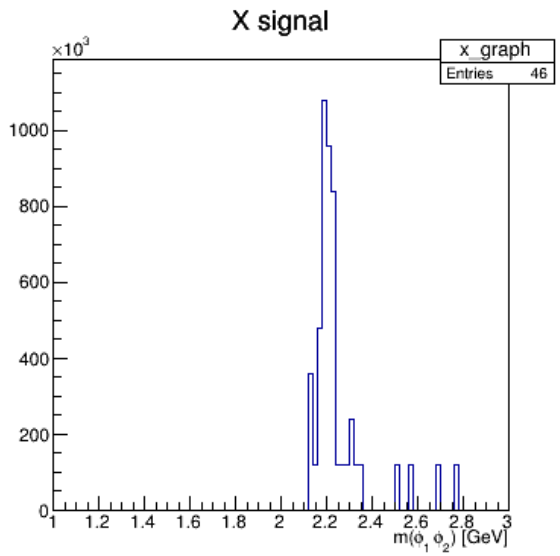
The selected events number is multiplied by the factor of

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

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.

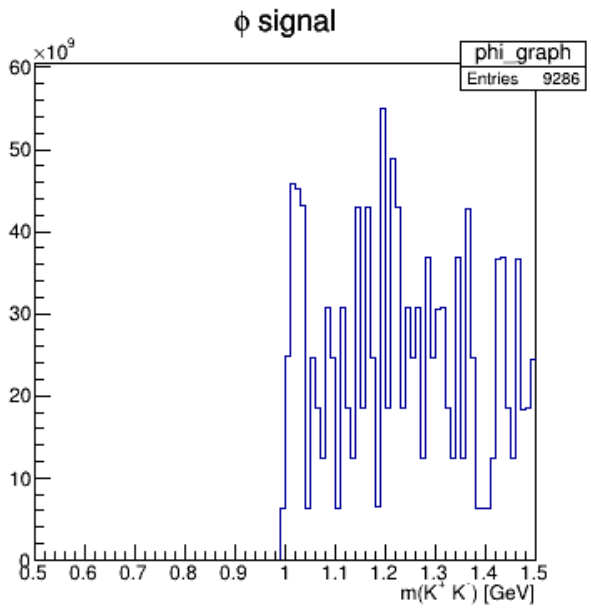
di-ϕ background

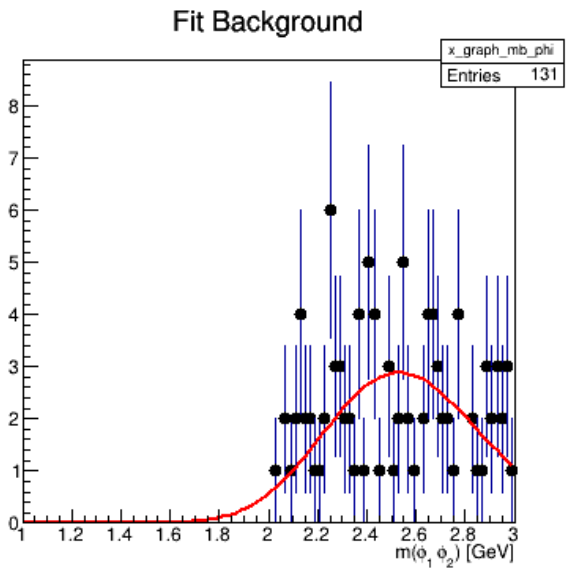
The multiple ϕ production rate is small: about 98 events per 100 000 MB events. Then the number of reconstructed events was scaled by

$$f_{MB} = \frac{L \times T \times \sigma_{MB} \times \frac{98}{100000}}{\text{number of generated MB events}} =$$

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 $N_{bg} \approx 6.73e+7$ (around 3σ). Therefore the background fluctuation value $N_{fluct} = \sqrt{N_{bg}} \approx 8200$ and the signal significance equals

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

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

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

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.

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Thank you for your attention!