Studies of Δ^{++} resonance production and properties and searches for triply charged pentaquarks

Egor Zhulev (MSU)
Leonid Gladilin (SINP MSU / DLNP JINR)

2nd SPD Phase-I workshop, March 31, 2026

Outline:

$\Delta^{++} \rightarrow p\,\pi^+$ at SPD

$(uuuu\bar{d}) = \Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ at SPD

Current work, Summary and Requirements at Phase-I

Interesting options for NICA :

Triply charged pentaquarks: $(uuuu\bar{d}) = \Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$

$(uuuu\bar{s}) = \Delta_s^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,K^+$

Information on the Δ resonances in PDG is based on the partial wave analysis of the πN and γN scatterings.

SPD allows one to study the Δ^{++} resonance production and properties in final states of the pp collisions at relatively low energies.

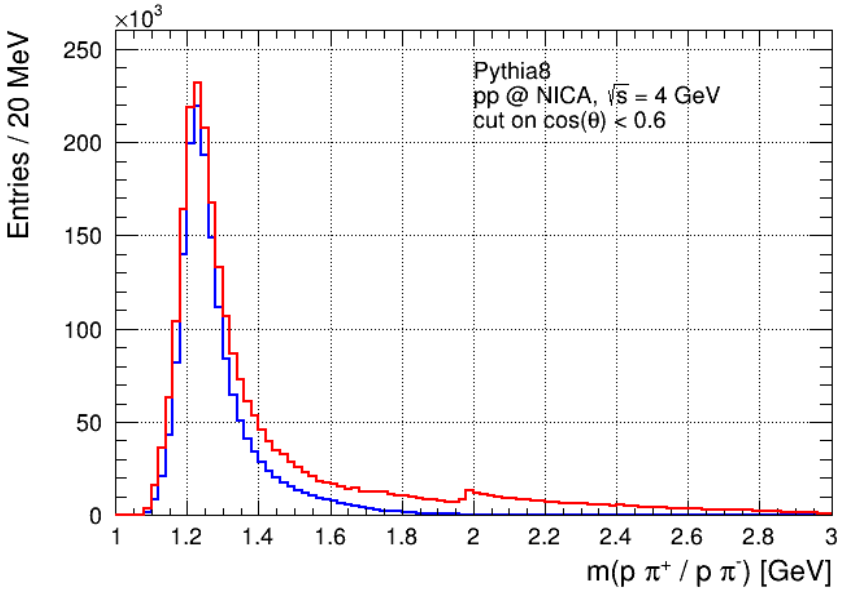
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^{+})\,\pi^{+}$ tracks' acceptances

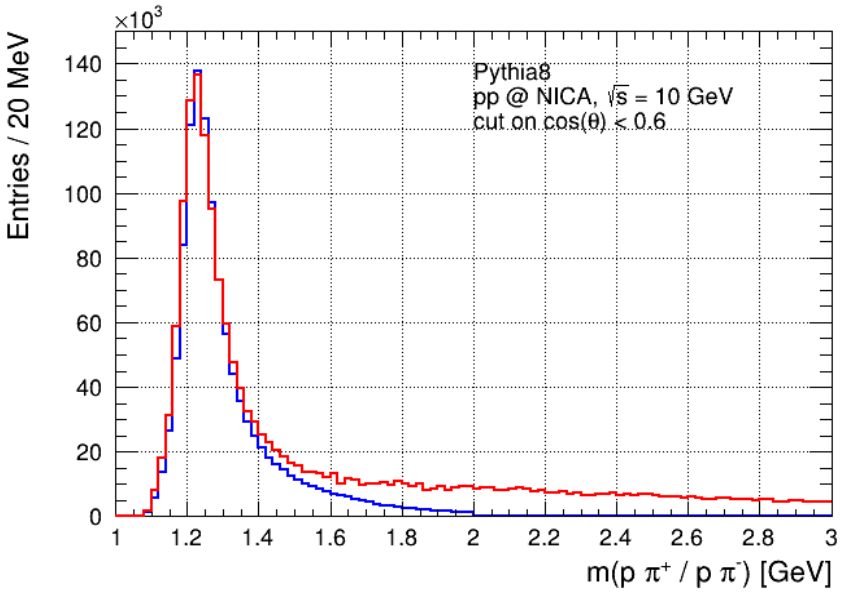
For all 3 tracks	$\lvert\eta_{track}\rvert < 2.5$ $\sqrt{s}$ = 4 / 10 / 27 GeV	$\lvert\eta_{track}\rvert < 2.0$ $\sqrt{s}$ = 4 / 10 / 27 GeV	$\lvert\eta_{track}\rvert < 1.5$ $\sqrt{s}$ = 4 / 10 / 27 GeV
$p_{T,track} >$ 100 MeV	54% / 51% / 31%	52% / 40% / 20%	45% / 25% / 12%
$p_{T,track} >$ 150 MeV	22% / 25% / 16%	22% / 21% / 11%	21% / 14% / 7%
$p_{T,track} >$ 200 MeV	6% / 9% / 6%	6% / 8% / 4%	6% / 5% / 3%

for further plots: $p_{T,track} >$ 150 MeV && $\lvert\eta_{track}\rvert < 2.5$

Δ^{++} ($\rightarrow$ p π^+) with Pythia8

Θ – angle between proton momentum in Δ r.f. and Δ momentum in lab



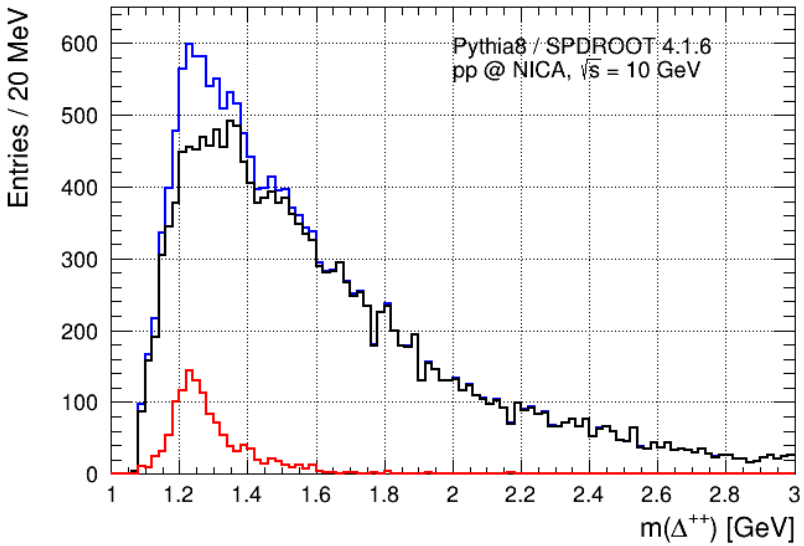


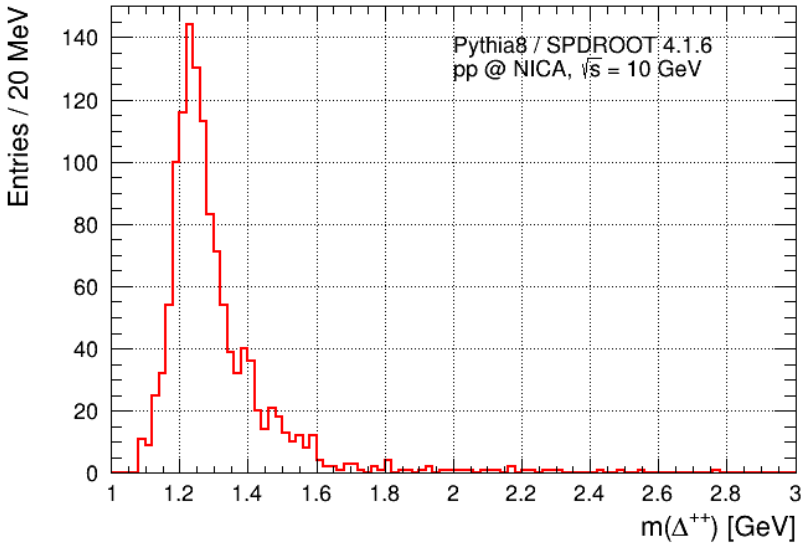
Blue - Δ^{++} signal distribution

Red - m($p\pi^+$) distr. - m($p\pi^-$) distr. (normalized above signal)

(Δ^{++} can decay only to $p\pi^+$ and Δ^0 to both $p\pi^-$ and $n\pi^0$)

Δ^{++} in SPD with SPDroot





(uuuud̄) = $\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ at NICA

Pythia 8.310, NNPDF40_lo_as_01180

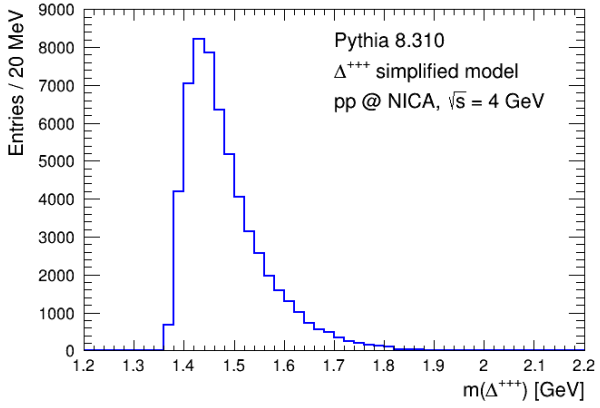
pp at √s = 4, 10 and 27 GeV, SoftQCD:inelastic = on

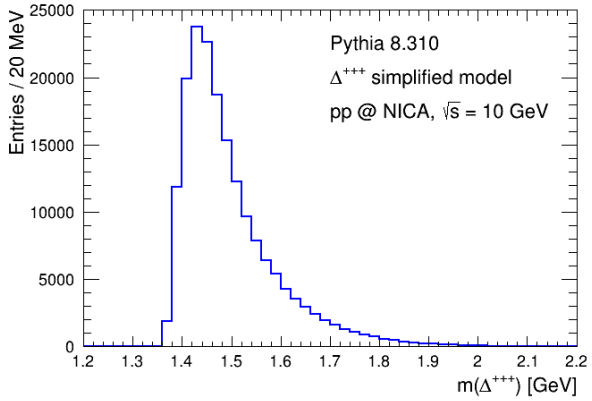
Simplified $\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ model

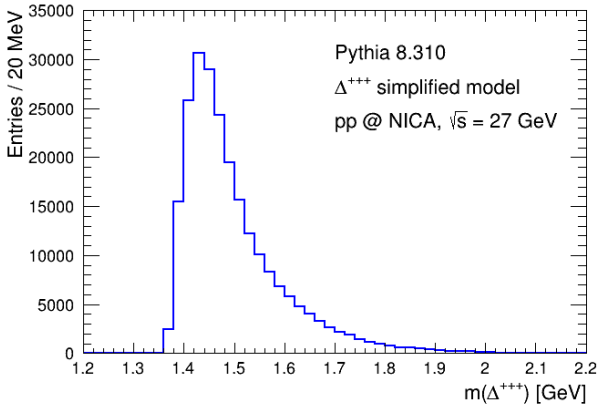
$m(\Delta^{+++})$ = 1450 MeV

$\Gamma(\Delta^{+++})$ = 150 MeV in comp. with $\Gamma(\Delta^{++})$ ~ 117 MeV

produced in decays of heavy (~2 GeV) Δ-like states





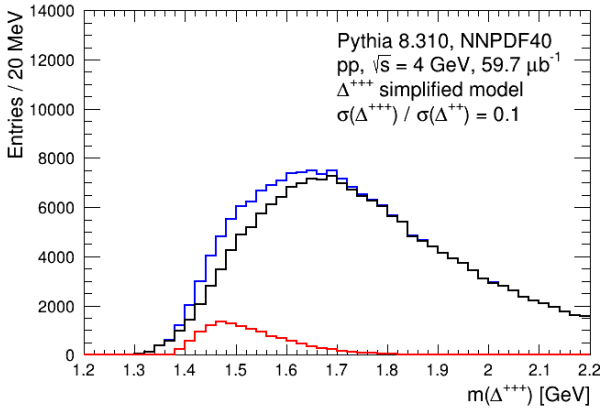


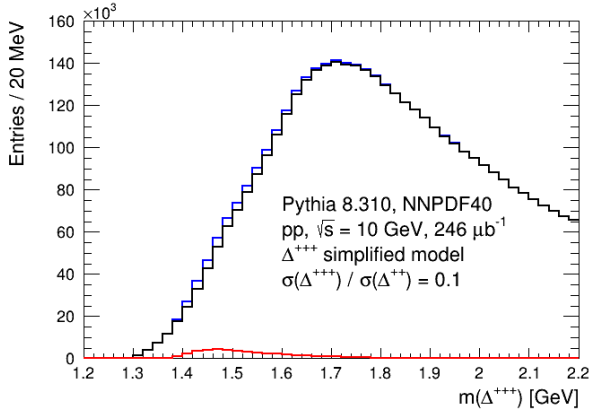
$\sigma(\Delta^{+++})^{4\ GeV}$ = 1.0 a.u. **$\sigma(\Delta^{+++})^{10\ GeV}$ = 2.9 a.u.** **$\sigma(\Delta^{+++})^{27\ GeV}$ = 3.9 a.u.**

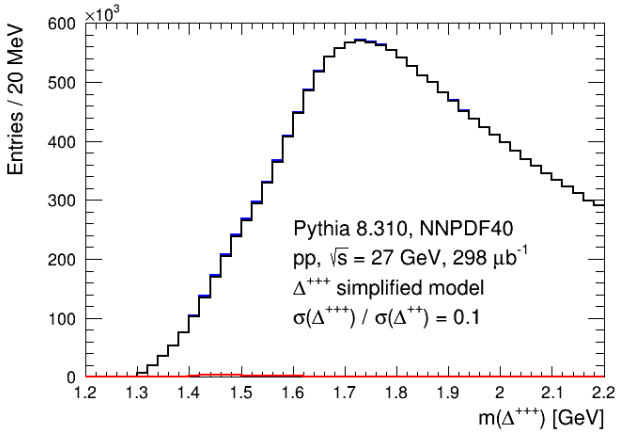
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\ \pi^+)\ \pi^+$, reconstructed mass

combine proton with two positively charged pions

require (1.14 < m(p π_1^+) < 1.32) || (1.14 < m(p π_2^+) < 1.32) (~97% eff.)

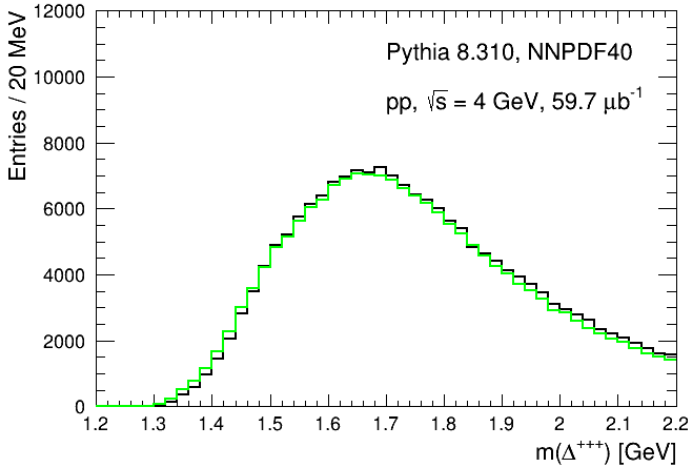




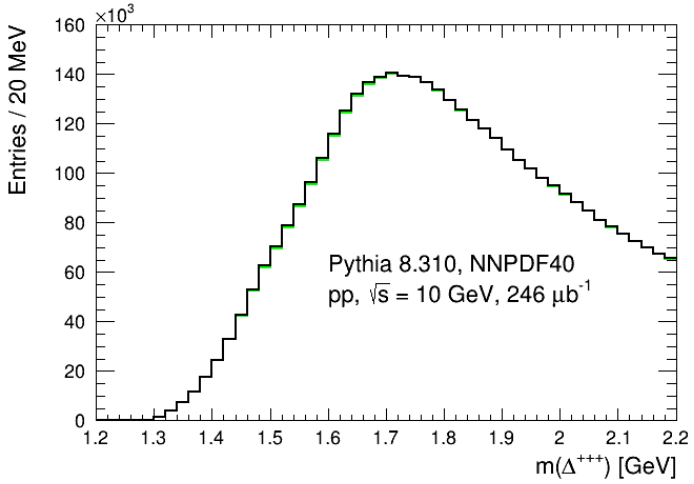


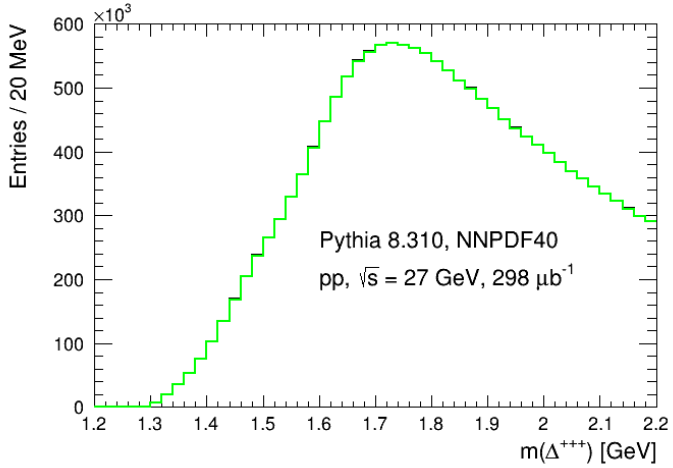
data-driven background shape estimation is needed

$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^{+})\,\pi^{+}$, background shape



4 GeV : $p/\pi_1/\pi_2$ from another event



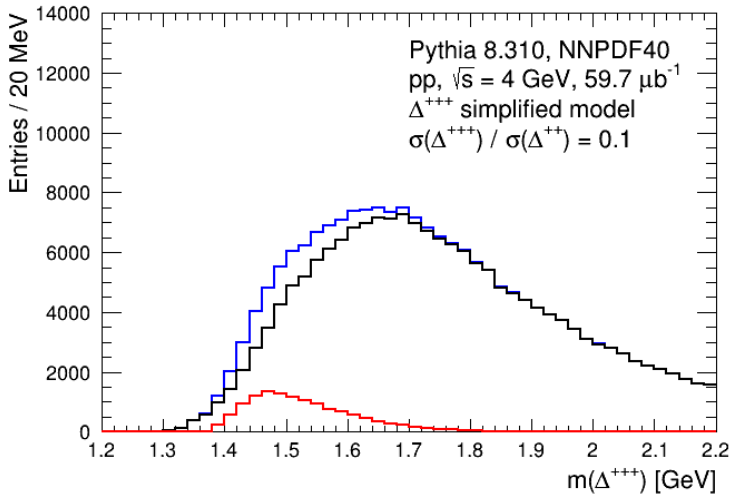


10 and 27 GeV:
p from another event

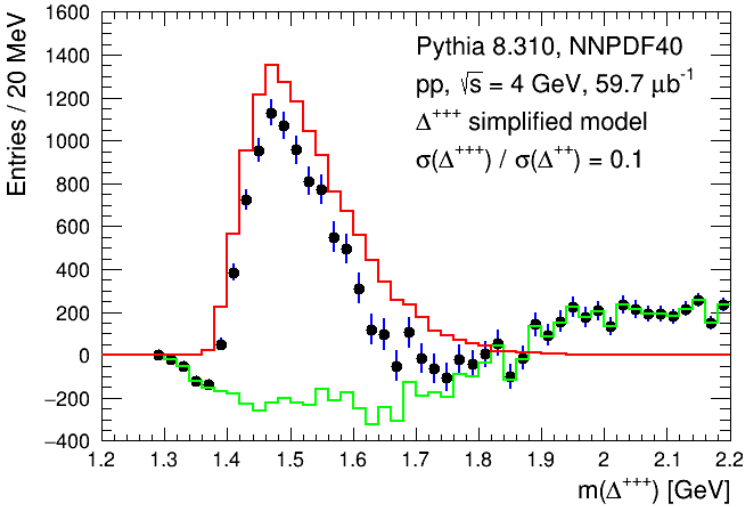
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\ \pi^+)\ \pi^+$, reconstructed mass

combine proton with two positively charged pions

require (1.14 < m(p π_1^+) < 1.32) || (1.14 < m(p π_2^+) < 1.32) (~97% eff.)

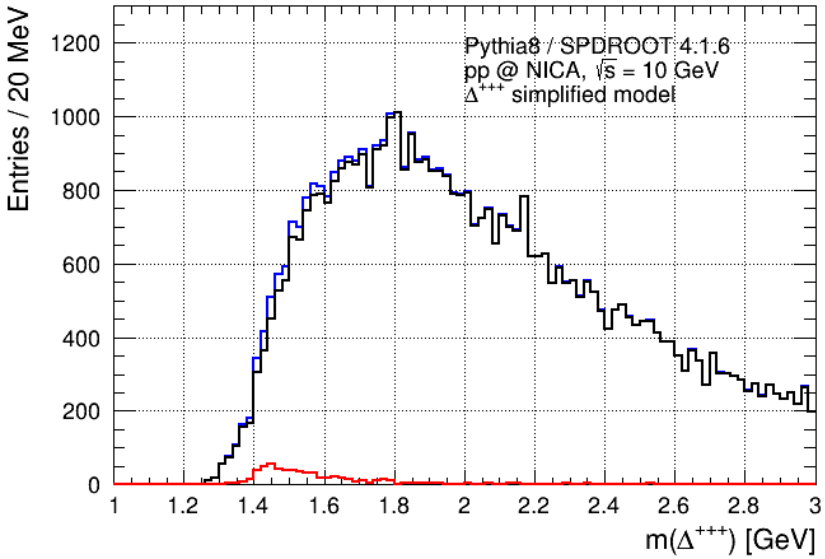


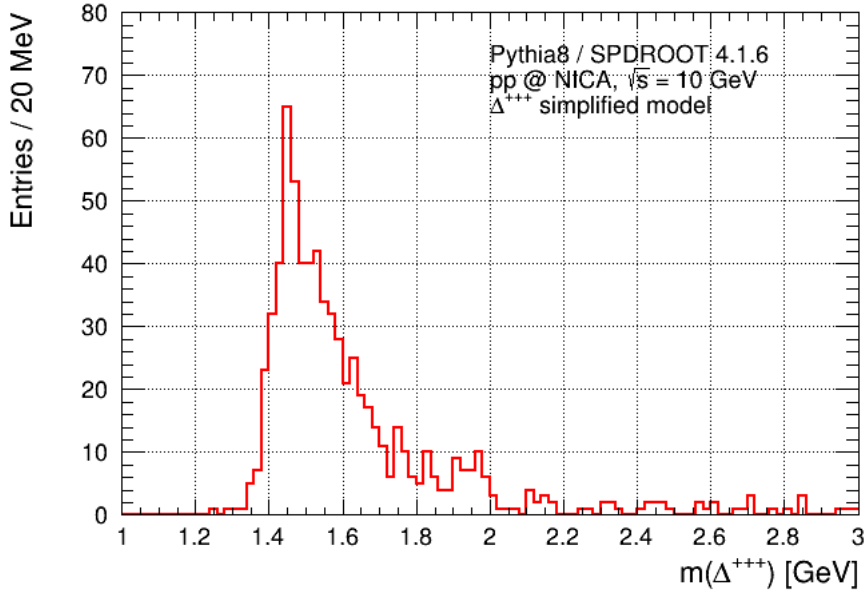
before background subtraction



after background subtraction

Δ^{+++} in SPD with SPDroot





Current work

Testing of various background estimation methods

Studies of angle variables

SPDroot with new tracking

Summary

Δ^{++} resonance can be studied and triply charged pentaquarks can be searched already at Phase-I of SPD@NICA

Requirements at Phase-I:

Beam species: pp
Collision energy: 3,5 -13 GeV
Luminosity: $10^{30\text{-}31}$ cm^{-2} s^{-1}
Polarization: not necessarily
Involved SPD subsystems: MCT, Straw tracker
Optimal duration of data taking: 6 months
Minimal duration of data taking: ~1 month (~50 μb^{-1} to start)

Simulation information used:
Pythia8 MC, simplified pentaquark model, SPDroot

Backup

Interesting options for NICA :

Triply charged pentaquarks: $(uuuu\bar{d}) = \Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$

$(uuuu\bar{s}) = \Delta_s^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,K^+$

Pentaquarks with hidden strangeness: $(uuus\bar{s}) = P_s^{++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\phi\,(\rightarrow K^+K^-)$

$(uuds\bar{s}) = P_s^{+} \rightarrow p\,\phi\,(\rightarrow K^+K^-)$

$(udds\bar{s}) = P_s^{0} \rightarrow \Lambda^0 (\rightarrow p\,\pi^-)\,K^0_S\,(\rightarrow \pi^+\pi^-)$

Check for $(ud\bar{u}d\bar{s}) = \theta^+ : \theta^+ \rightarrow K^0_S p$, $\theta^+ \rightarrow K^+ n$ (?)

and with charm at NICA II :

Charmed pentaquarks: $(uuuu\bar{c}) = \Delta_c^{++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\bar{D}^0\,(\rightarrow K^+\,\pi^-)$

$(uuud\bar{c}) = \Delta_c^{+} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,D^-\,(\rightarrow K^+\,\pi^-\pi^-)$

Search for $(ud\bar{u}d\bar{c}) = \theta_c^0 \rightarrow \theta^+\pi^-,\ pK^0\pi^-,\ D^{(*)-}p,\ \ldots$

Pentaquarks with hidden charm $(uuuc\bar{c}) = P_c^{++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,J/\psi\,(\rightarrow \mu^+\mu^-)$

$(uudc\bar{c}) = P_c^{+} \rightarrow p\,J/\psi,\ \Lambda_c^+ (\rightarrow K^-\,p\,\pi^+)\,\bar{D}^0\,(\rightarrow K^+\,\pi^-)$

$(uddc\bar{c}) = P_c^{0} \rightarrow \Lambda_c^+ (\rightarrow K^-\,p\,\pi^+)\,D^-\,(\rightarrow K^+\,\pi^-\pi^-)$

Can we register (uuuud̄) = $\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ at NICA?

Pythia 8.310, NNPDF40_lo_as_01180

pp at √s = 4, 10, 27 GeV, SoftQCD:inelastic = on

Simplified $\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ model

Gerasyuta, Kochkin (hep-ph/0310225, Int .J. Mod. Phys. E 15 (2006) 71-86

Relativistic five-quark equations and u, d- pentaquark spectroscopy

(uuuuū)

Table II. Low-lying Δ - isobar pentaquark masses and contributions of subamplitudes BM, $D\bar{q}D$, $Mqqq$ and $Dqq\bar{q}$ to pentaquark amplitude in percentage of probability (diquark with $J^P = 1^+$).

Fig. №	Meson J^{PC}	J^P	Mass, MeV	A_1 (BM)	A_2 $(D\bar{q}D)$	A_3 $(Mqqq)$	A_4 $(Dqq\bar{q})$
4	0^{++}	$\frac{1}{2}^+, \frac{3}{2}^+$	1485(1600)	31.60	6.42	33.93	28.05
4	1^{++}	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	1550(1750)	28.08	8.88	42.09	20.95
4	2^{++}	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	1736(1920)	24.53	13.25	44.07	18.15
5	2^{++}	$\frac{7}{2}^+$	1950(1950)	24.99	-	75.01	-
5	0^{-+}	$\frac{1}{2}^-$	1453(1620)	38.13	-	61.87	-
5	1^{--}	$\frac{1}{2}^-, \frac{3}{2}^-$	1920(1940)	25.97	-	74.03	-

Parameters of model: quark mass m = 410 MeV, cut-off parameter Λ =20,1; gluon constant g =0.417. Experimental mass values of Δ - isobar pentaquarks are given in parentheses [12].

Can we register (uuuud̄) = $\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ at NICA?

Pythia 8.310, NNPDF40_lo_as_01180

pp at √s = 4, 10, 27 GeV, SoftQCD:inelastic = on

Simplified $\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^+)\,\pi^+$ model

Gerasyuta, Kochkin (hep-ph/0310225, Int .J. Mod. Phys. E 15 (2006) 71-86

Relativistic five-quark equations and u, d- pentaquark spectroscopy

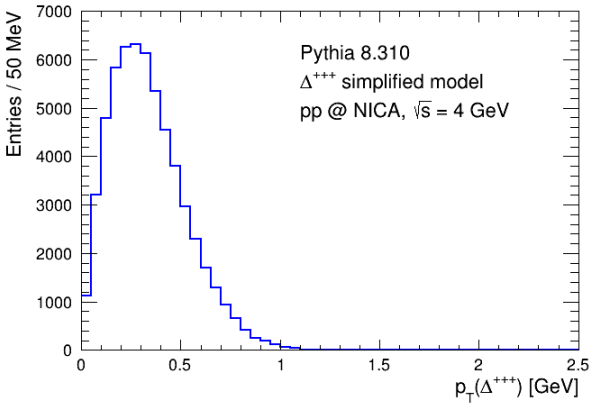
(uuuuū)

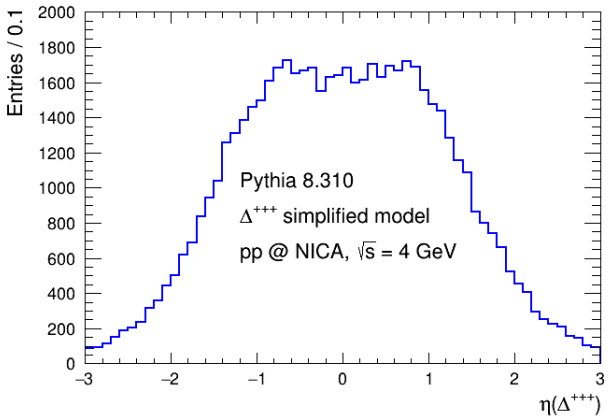
Table II. Low-lying Δ - isobar pentaquark masses and contributions of subamplitudes BM, $D\bar{q}D$, $Mqqq$ and $Dqq\bar{q}$ to pentaquark amplitude in percentage of probability (diquark with $J^P = 1^+$).

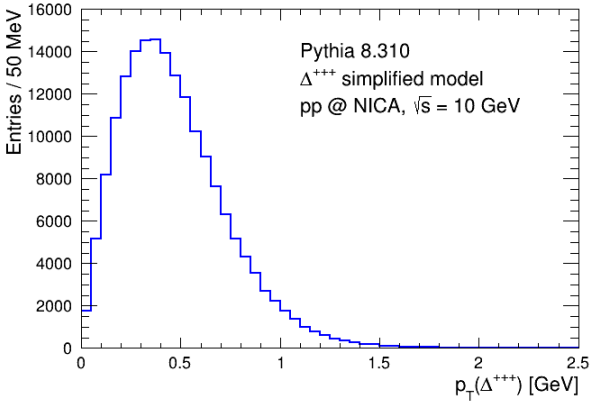
Fig. №	Meson J^{PC}	J^P	Mass, MeV	A_1 (BM)	A_2 $(D\bar{q}D)$	A_3 $(Mqqq)$	A_4 $(Dqq\bar{q})$
4	0^{++}	$\frac{1}{2}^+, \frac{3}{2}^+$	1485(1600)	31.60	6.42	33.93	28.05
4	1^{++}	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	1550(1750)	28.08	8.88	42.09	20.95
4	2^{++}	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	1736(1920)	24.53	13.25	44.07	18.15
5	2^{++}	$\frac{7}{2}^+$	1950(1950)	24.99	-	75.01	-
5	0^{-+}	$\frac{1}{2}^-$	1453(1620)	38.13	-	61.87	-
5	1^{--}	$\frac{1}{2}^-, \frac{3}{2}^-$	1920(1940)	25.97	-	74.03	-

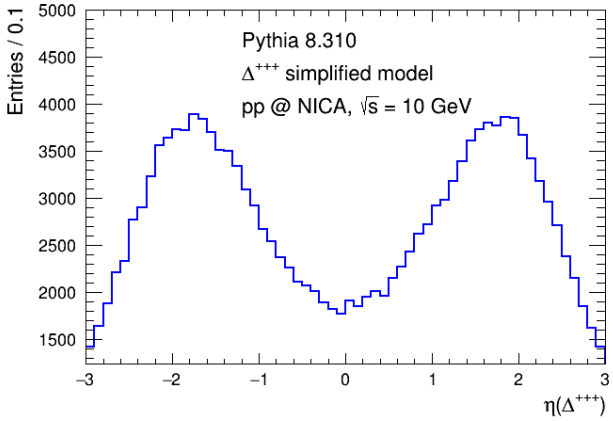
Parameters of model: quark mass m = 410 MeV, cut-off parameter Λ =20,1; gluon constant g =0.417. Experimental mass values of Δ - isobar pentaquarks are given in parentheses [12].

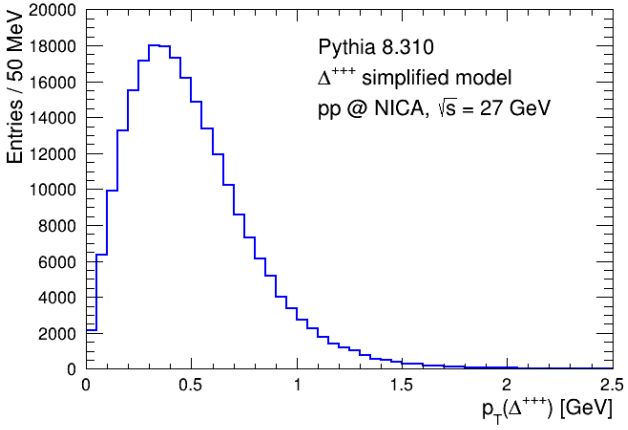
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^{+})\,\pi^{+}$ kinematics

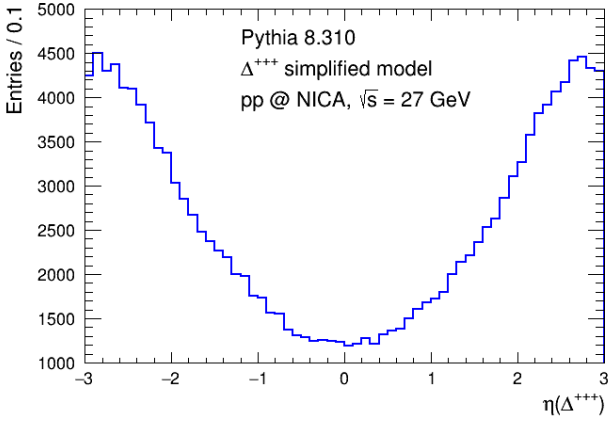




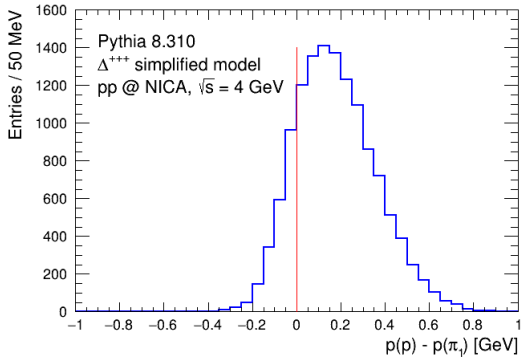


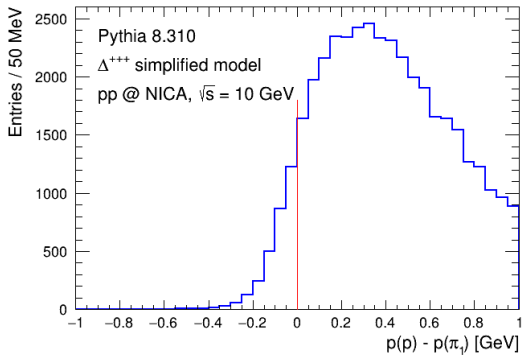


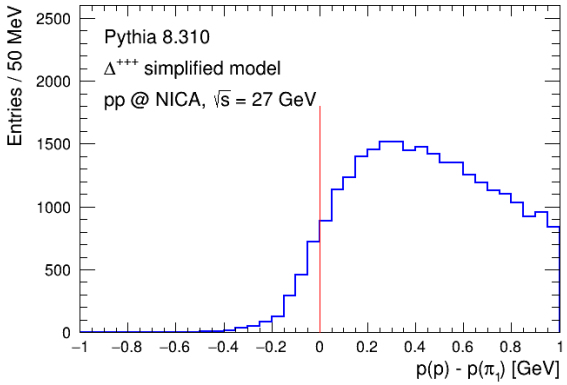


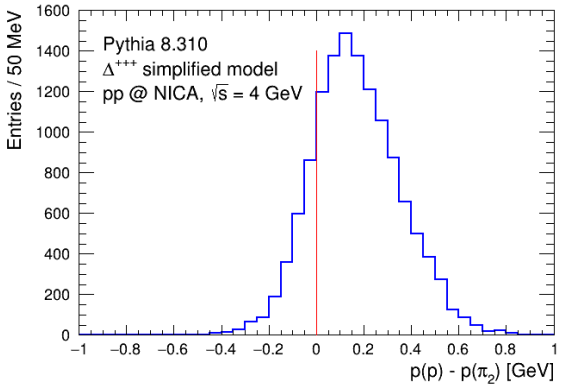


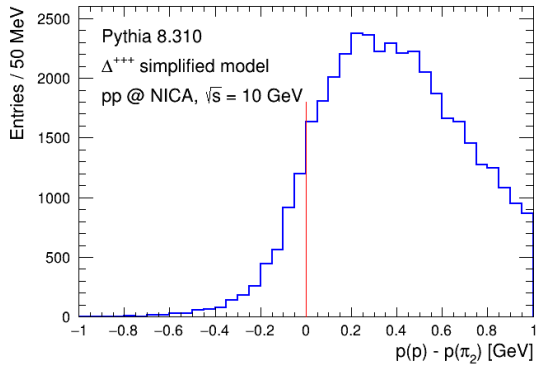
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\ \pi_1^+)\ \pi_2^+$, proton identification?

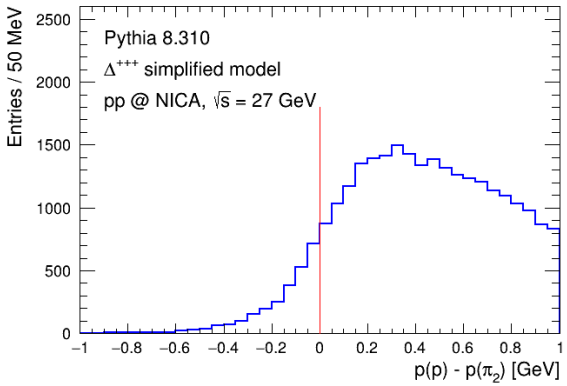












proton is typically fastest track

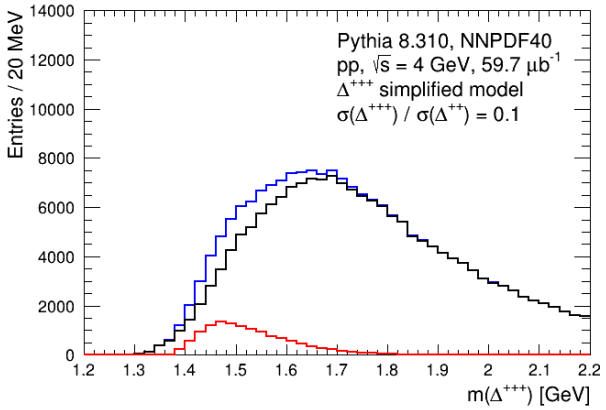
can be used in case of no PID

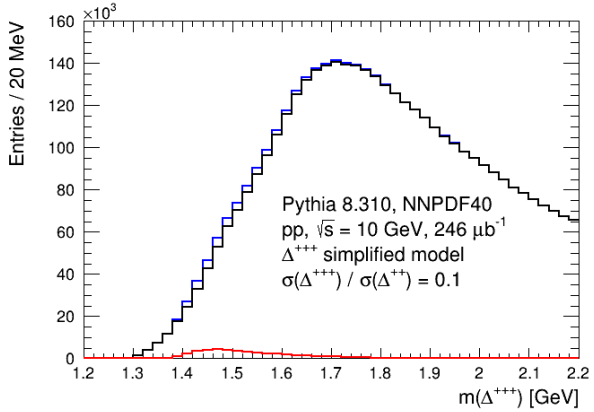
for further plots, proton detector identification is assumed

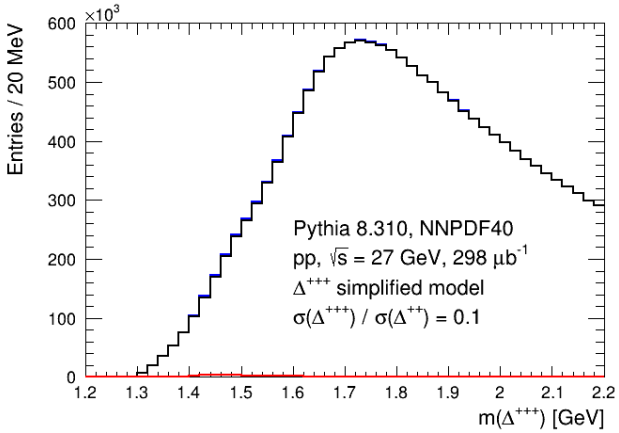
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\,\pi^{+})\,\pi^{+}$, reconstructed mass

combine proton with two positively charged pions

require (1.14 < m(p π_1^+) < 1.32) || (1.14 < m(p π_2^+) < 1.32) (~97% eff.)







data-driven background shape estimation is needed

