Результаты лаборатории тяжёлых частиц и резонансов ОЭФВЭ

Гладилин Л.К.

Конференция НИИЯФ МГУ по итогам 2023 года, 26.02.2024

Результаты в коллаборации ATLAS

- **J/ψJ/ψ и J/ψ+ψ(2S) резонансы, PRL 131 (2023) 151902** ⟸ **слайды**
- $B^0_s \to \mu^+\mu^-$ эффективное время жизни, JHEP 09 (2023) 199
- активная работа над несколькими статьями (последними в ATLAS)

Детекторный и софтверный вклад в NA64

- Поиск легкой темной материи, PRL 131 (2023) 161801

Первые шаги в SPD @ NICA

- тестирование возможностей изучения пентакварков ⟸ **слайды**

На перспективу

- Подготовка к исследованиям на CEPC / SppC

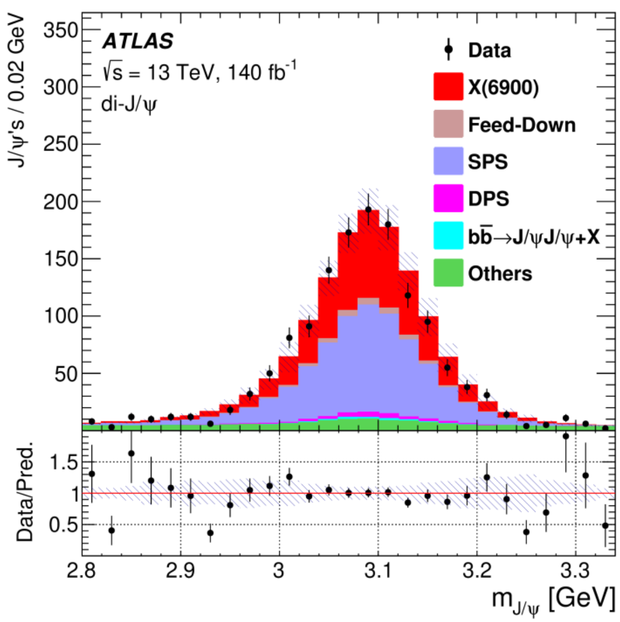
  CEPC Technical Design Report – Accelerator, arXiv:2312.14363

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at √s = 13 TeV

Event selection, reconstruction and definition of signal and control regions

PRL 131 (2023) 151902

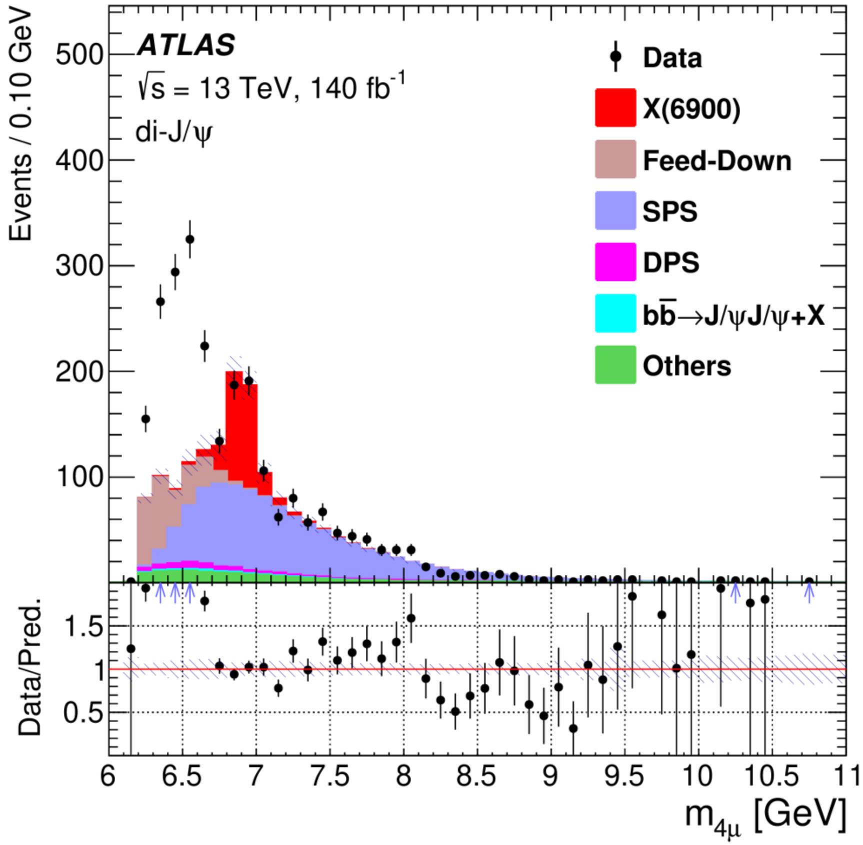
Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_T^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\|\eta_{1,2,3,4}\| < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi^2_{4\mu}/N < 40$ ($N = 5$) and $\chi^2_{\text{di-}\mu}/N < 100$ ($N = 2$),		
Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\|L^{\text{di-}\mu}_{xy}\| < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi^2_{4\mu}/N > 6$,
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	or $\|L^{\text{di-}\mu}_{xy}\| > 0.4$ mm



"Others": (J/ψ μ "fake μ")
Data-driven: use a track instead of a tagged μ
Normalized in m(J/ψ) side-bands

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at √s = 13 TeV

Feed-downs from X→J/ψ ψ(2S) to m(J/ψ J/ψ) via ψ(2S)→J/ψX and ψ(2S)→γ χ_{cJ} with χ_{cJ}→γ J/ψ

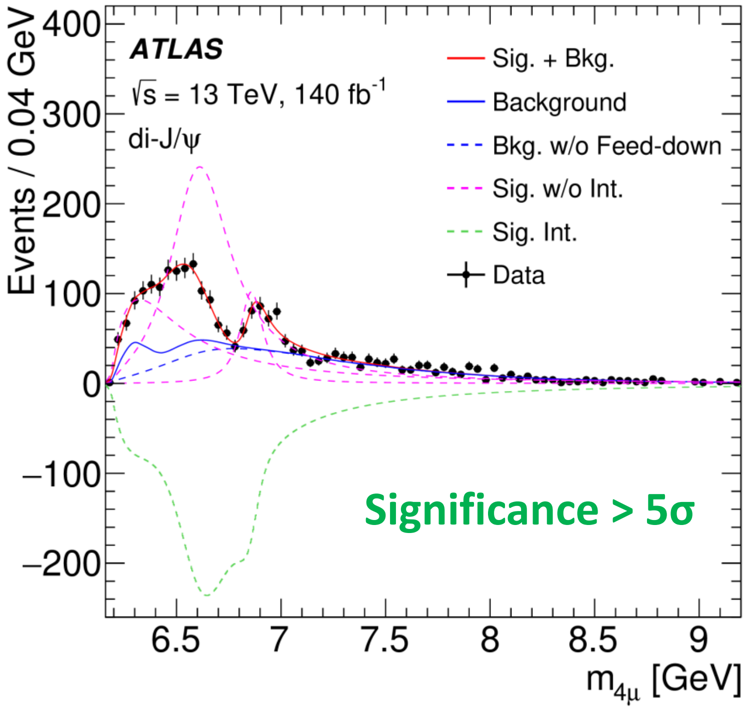


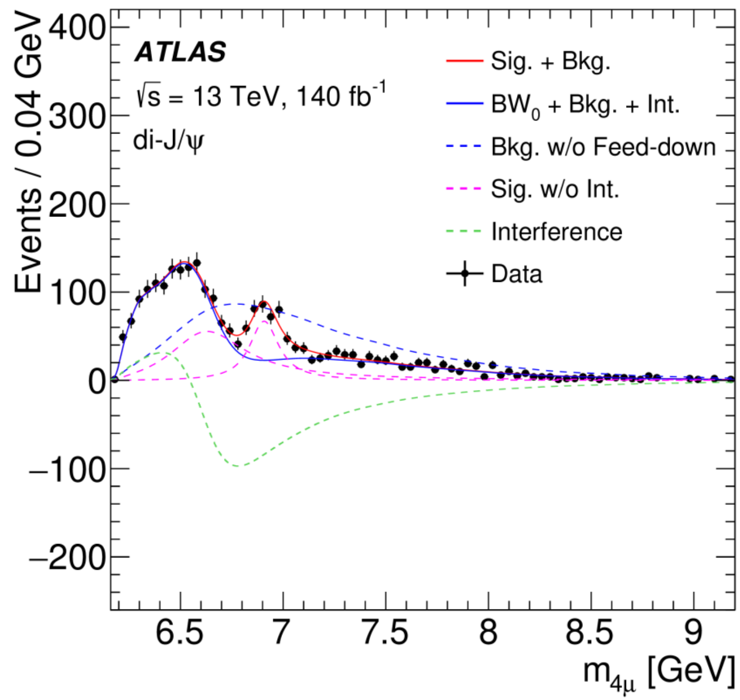
$$N_{\text{fd}} = \frac{\mathcal{B}'\epsilon'}{\mathcal{B}\left(\psi(2S) \rightarrow \mu\mu\right)\epsilon} N$$

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at √s = 13 TeV

m(J/ψ J/ψ) : Unbinned max. likelihood fits

$$\mathcal{L} = \mathcal{L}_{SR}\left(\vec{\theta},\vec{\lambda}\right)\cdot\mathcal{L}_{CR}\left(\vec{\theta}\right)\cdot\prod_{j}^{K} G\left(\theta'_j;\theta_j,\sigma_j\right)$$





Model A: 3 BW's

$$f_s(x) = \left|\sum_{i=0}^{2}\frac{z_i}{m_i^2 - x^2 - im_i\Gamma_i(x)}\right|^2\sqrt{1-\frac{4m_{J/\psi}^2}{x^2}}\otimes R(\theta)$$

Model B: 2 BW's, 1st one interferes with SPS

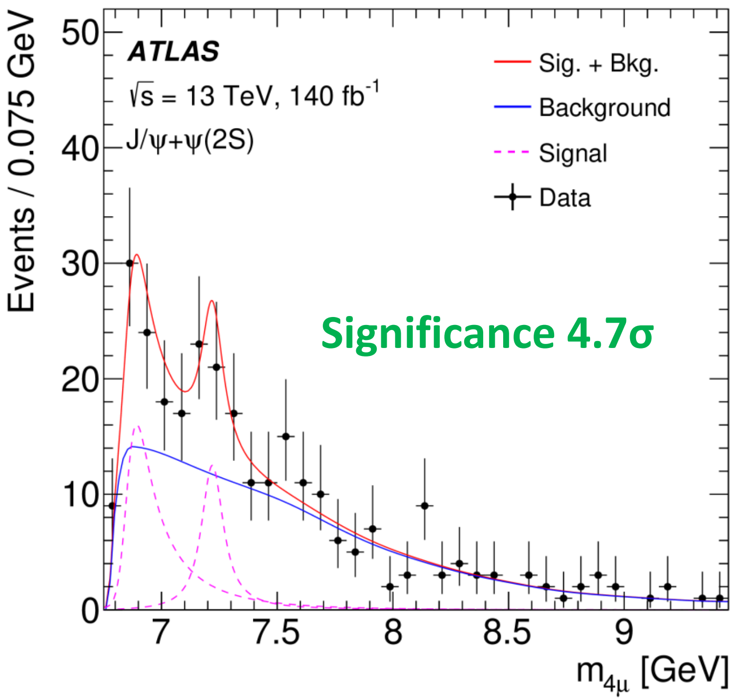
$$f(x) = \left(\left|\frac{z_0}{m_0^2 - x^2 - im_0\Gamma_0(x)} + Ae^{i\phi}\right|^2 + \left|\frac{z_2}{m_2^2 - x^2 - im_2\Gamma_2(x)}\right|^2\right)\sqrt{1-\frac{4m_{J/\psi}^2}{x^2}}\otimes R(\theta)$$

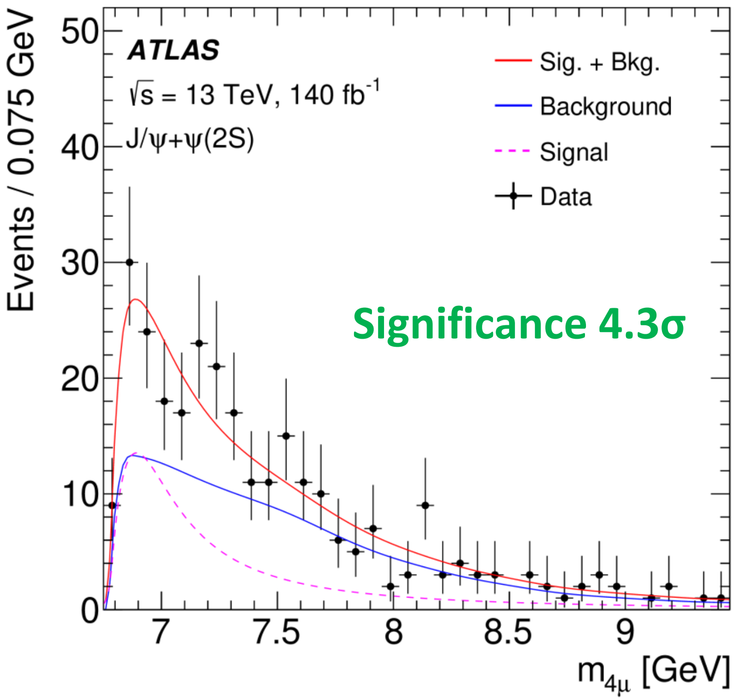
**Models with 2 BW's with interference and 3 BW's w/o interference
Excluded on 95% CL w.r.t. model A (with toy MC)**

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at √s = 13 TeV

m(J/ψ ψ(2S)) : Unbinned max. likelihood fits

$$\mathcal{L} = \mathcal{L}_{SR}\left(\vec{\theta},\vec{\lambda}\right)\cdot\mathcal{L}_{CR}\left(\vec{\theta}\right)\cdot\prod_{j=1}^{K} G\left(\theta'_j;\theta_j,\sigma_j\right)$$





Model α: 3 BW's (tails) + 1 BW

Model β: single BW

$$f_s(x) = \left(\left|\sum_{i=0}^{2}\frac{z_i}{m_i^2 - x^2 - i m_i\Gamma_i(x)}\right|^2 + \left|\frac{z_3}{m_3^2 - x^2 - i m_3\Gamma_3(x)}\right|^2\right)\sqrt{1-\left(\frac{m_{J/\psi}+m_{\psi(2S)}}{x}\right)^2}\otimes R(\theta)$$

Significance for 4th resonance 3.0σ

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at √s = 13 TeV

Systematics:

Systematic Uncertainties (MeV)	X(6900) di-J/ψ m_2	Γ_2	X(7200) $J/\psi+\psi(2S)$ m_3	Γ_3
Muon calibration	±6	±7	<1	±1
SPS model parameter	±7	±7	<1	
SPS di-charmonium p_T	±7	±8	<1	
Background MC statistics	±7	±8	±1	<1
Mass resolution	±4	-3	-1	$+2/-4$
Fit bias	-13	$+10$	$+9/-10$	$+50/-16$
Non-closure	<1		±4	±6
Transfer factor	—		±5	±23
→ Presence of 4th resonance	<1		—	
Feed-down	$+4/-1$	$+6/-2$	—	
Interference of 4th resonance	—		-32	-11
→ P and D-wave BW	$+9$	$+19$	<1	±1
ΔR and muon p_T requirements	$+3/-2$	$+6/-4$	$+1/-2$	-2

$J/\psi J/\psi$ and $J/\psi+\psi(2S)$ in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at √s = 13 TeV

di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—
$J/\psi+\psi(2S)$	model α	model β
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\% \pm 14\%$	$\pm 20\% \pm 12\%$

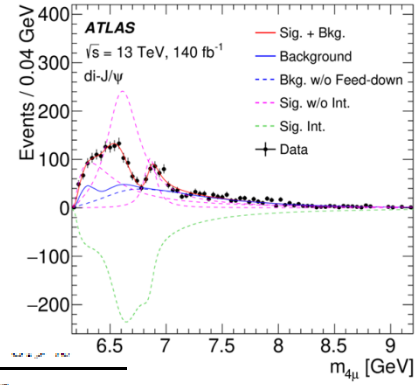
X(6900)
> 5σ

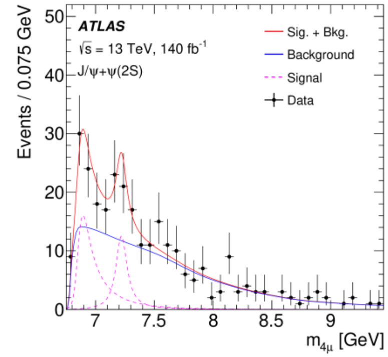
X(7200)
3.0σ

Di-charmonia tetraquarks ($c\bar{c}c\bar{c}$)

di-J/ψ	model A
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$

ATLAS



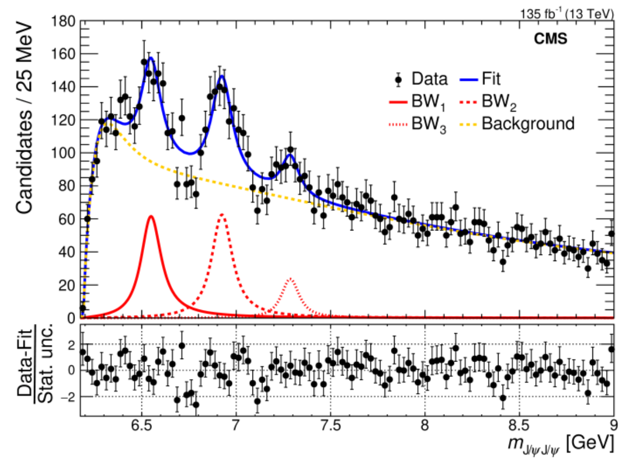


$J/\psi+\psi(2S)$	model α
m_3 or m	$7.22 \pm 0.03^{+0.01}_{-0.03}$
Γ_3 or Γ	$0.09 \pm 0.06^{+0.06}_{-0.03}$

arXive:2306.07164

CMS

		BW_1	BW_2	BW_3
No-interference	m [MeV]	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
	Γ [MeV]	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
	N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}
Interference	m [MeV]	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
	Γ [MeV]	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

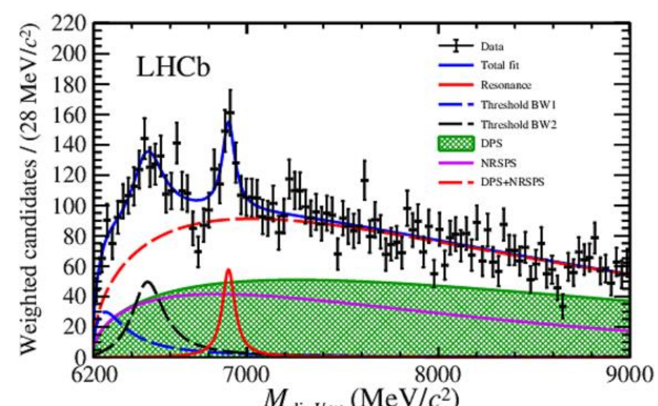


X(6900) well seen by all 3 experiments

Sci.Bull. 65 (2020) 1983

Signatures for a bump at 7.2-7.3 GeV
In all 3 experiments

Nature of the low-mass bump to be further studied



Role of other feed-downs to be clarified, e.g.,

$$T_{cc\bar{c}\bar{c}} \rightarrow \chi_{cJ}\chi_{cJ'} \rightarrow J/\psi J/\psi\gamma\gamma$$

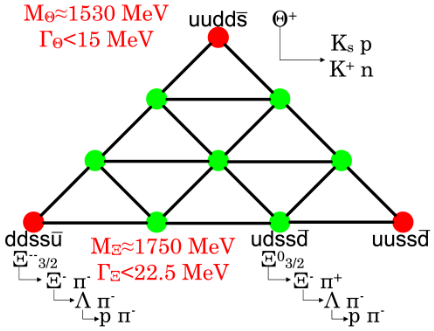
Изучение пентакварков в SPD @ NICA ?

Brief pentaquarks' story, θ^+:

$\Theta(1540)^+$

Diakonov, Petrov, Polyakov (hep-ph/9703373, Z.Phys. A359, 305 (1997)

Exotic Anti-Decuplet of Baryons: Prediction from Chiral Solitons



2003: seen in exotic decay ($\theta^+ \rightarrow K^+ n$) by LEPS, CLAS, SAPHIR

non-exotic decay ($\theta^+ \rightarrow K^0_S p$) seen by many exp's

Unseen by many exp's including CLAS with increased statistics

Current status of θ^+ : removed from PDG after 2006

reputation below plinth

Attempts to explain differences between exp's:

Dementiev R.K., Phys. Atom. Nucl. 76 (2015) 301

On the mechanism of Θ^+-pentaquark production

phase-shift effects

Azimov, Goeke, Starkowsky , Phys.Rev.D76 (2007) 074013

An explanation why the Theta+ is seen in some experiments and not in others

short-term fluctuations of initial hadrons

"studies of the hadron remnants in hard processes"

at NICA?

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 $(udud\bar{s}) = \theta^{+}$: $\theta^{+} \rightarrow K^{0}_{S}p$, $\theta^{+} \rightarrow K^{+}n$ (?)

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 $(udud\bar{c}) = \theta_c^{0} \rightarrow \theta^{+}\pi^{-}$, $pK^{0}\pi^{-}$, $D^{(*)-}p$, …

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

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

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

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 (udud$\bar{s}$) = θ^+ : $\theta^+ \rightarrow K^0_S p$, $\theta^+ \rightarrow K^+ n$ (?)

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 (udud$\bar{c}$) = $\theta_c^0 \rightarrow \theta^+\pi^-$, $pK^0\pi^-$, $D^{(*)-}p$, …

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

Pythia 8.310, NNPDF40_lo_as_01180

pp at √s = 4 GeV and 10 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

$(uuuu\bar{u})$

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) = $\Delta^{+++} \to \Delta^{++} (\to p\,\pi^+)\,\pi^+$ with SPD?

Pythia 8.310, NNPDF40_lo_as_01180

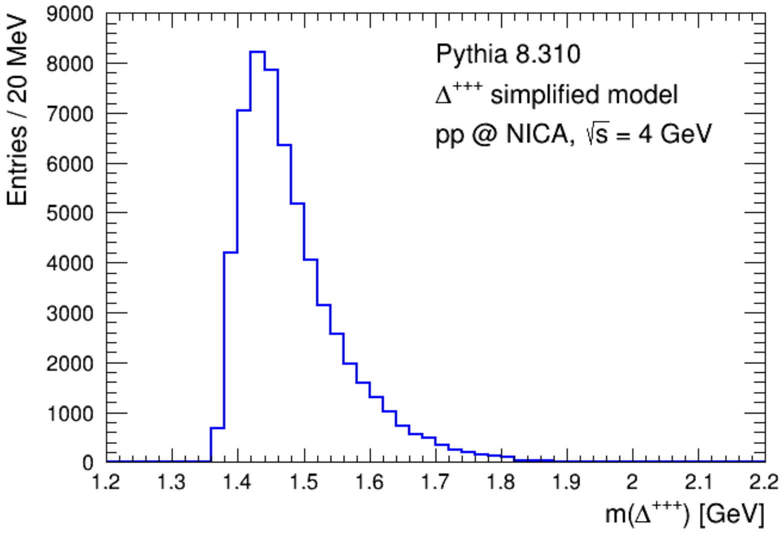
pp at √s = 4 GeV and 10 GeV, SoftQCD:inelastic = on

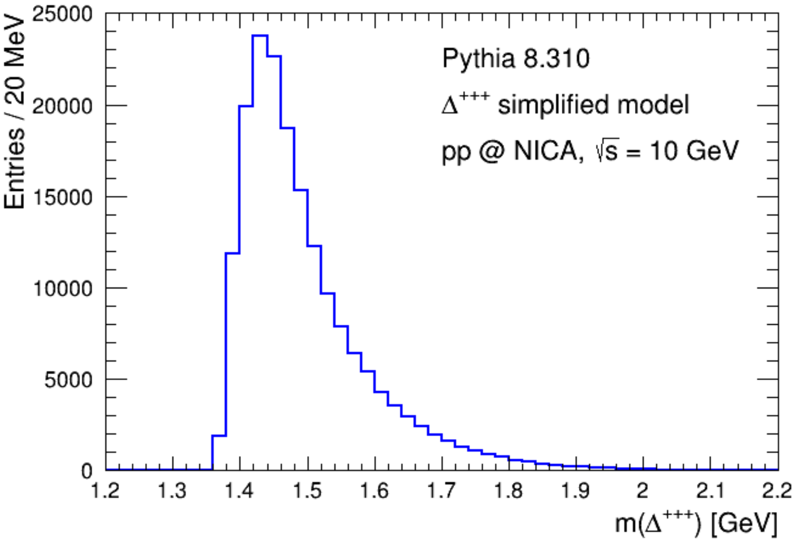
Simplified $\Delta^{+++} \to \Delta^{++} (\to p\,\pi^+)\,\pi^+$ model

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

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

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



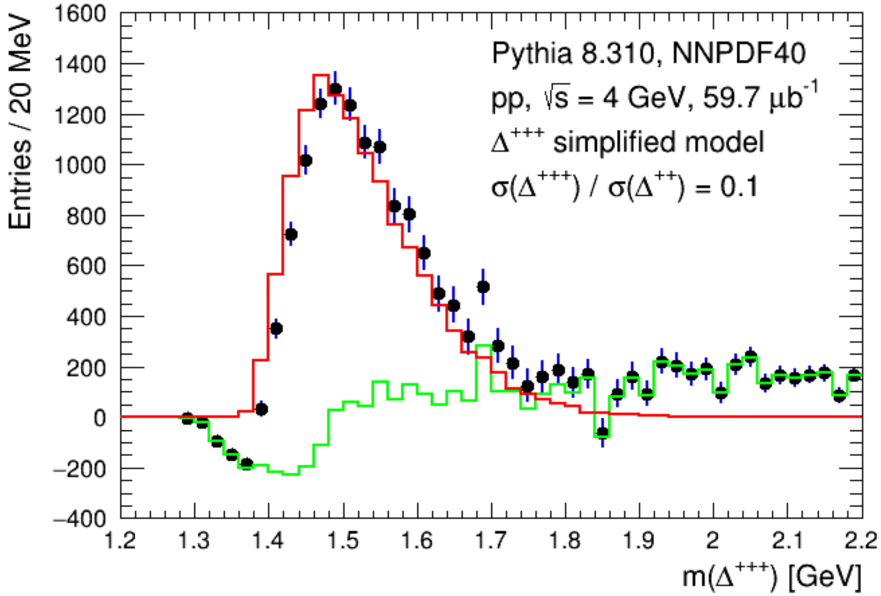


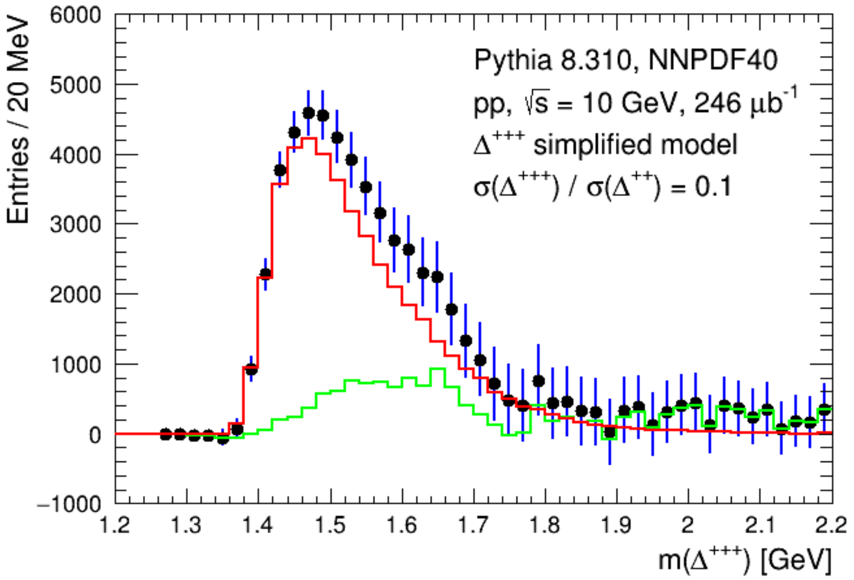
$\Delta^{+++} \rightarrow \Delta^{++} (\rightarrow p\ \pi^+)\ \pi^+$ tracks' acceptances

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

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

$\Delta^{+++} \to \Delta^{++} (\to p\, \pi^+)\, \pi^+$,
background-subtracted mass distribution





$\sigma(\Delta^{+++})/\sigma(\Delta^{++}) = 10\%$

such large fraction looks like measurable

careful background study is needed for 1% measurement or upper limit

it can be a few overlapping Δ^{+++} states

Результаты и планы

лаборатории тяжёлых частиц и резонансов

Результаты в коллаборации ATLAS

- **$J/\psi J/\psi$ и $J/\psi+\psi(2S)$ резонансы, PRL 131 (2023) 151902**
- $B^0_s \to \mu^+\mu^-$ время жизни, JHEP 09 (2023) 199
- активная работа над несколькими статьями (последними в ATLAS)

Детекторный и софтверный вклад в NA64

- Поиск легкой темной материи, PRL 131 (2023) 161801

Первые шаги в SPD @ NICA

- тестирование возможностей изучения пентакварков

На перспективу

- Подготовка к исследованиям на CEPC / SppC

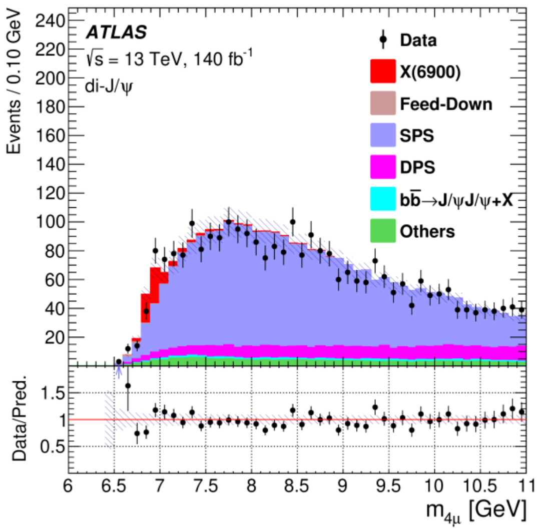
  CEPC Technical Design Report – Accelerator, arXiv:2312.14363

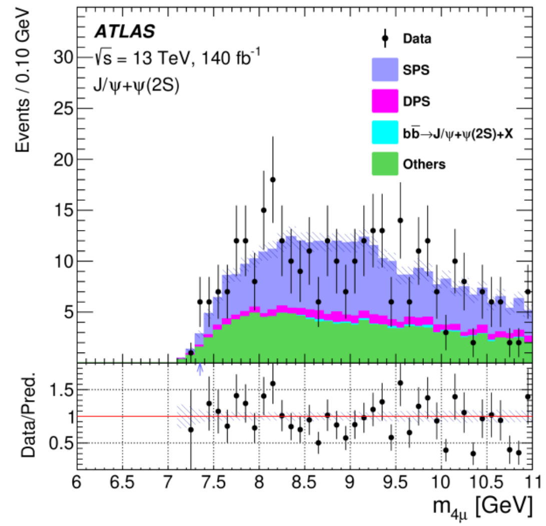
Back-up Slides

J/ψJ/ψ and J/ψ+ψ(2S) in 4μ final state studied at ATLAS using 140 fb^{-1} of pp at $\sqrt{s}$ = 13 TeV

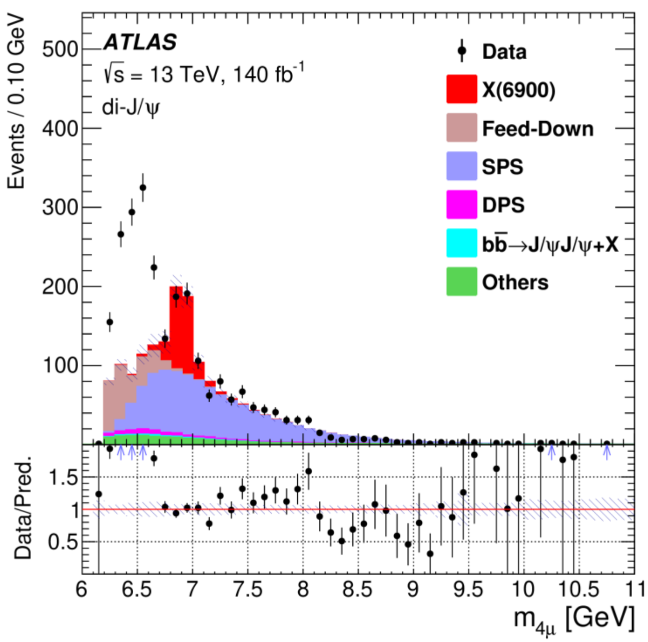
m(J/ψ J/ψ)

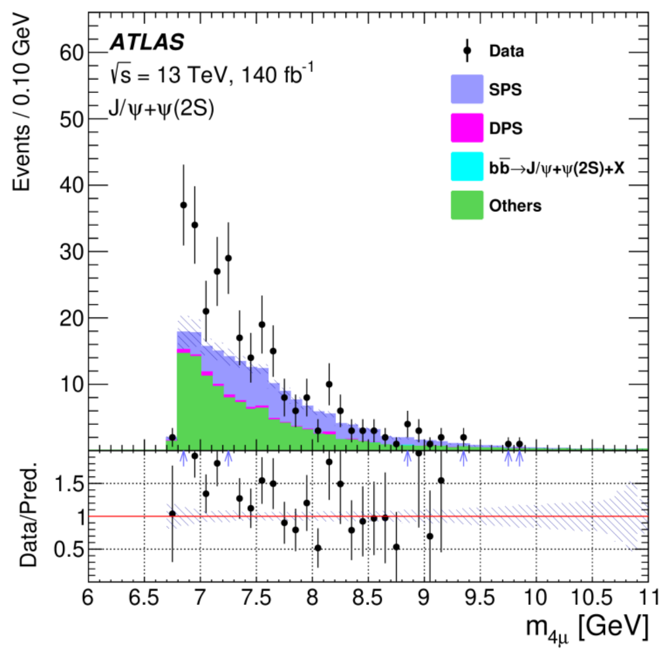
m(J/ψ ψ(2S))





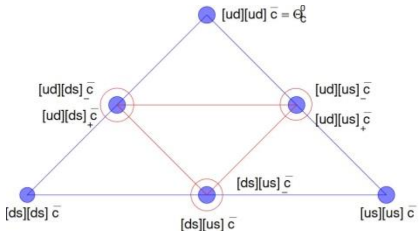
ΔR > 0.25





ΔR < 0.25

Brief pentaquarks' story, Θ_c^0 :



$\Theta_c^0 = (ud)^2\,\bar{c}$

Jaffe-Wilczek (hep-ph/0307341): $m(\Theta_c^0)$ = 2710 MeV

Karliner-Lipkin (hep-ph/0307343): $m(\Theta_c^0)$ = 2985±50 MeV

$\Gamma(\Theta_c^0)$ ~ 21 MeV

2004: seen in the decay ($\theta_c^0 \rightarrow D^{*-}p$) with $m(\Theta_c^0)$ = 3099 MeV by only H1 @ HERA

Unseen by many exp's including ZEUS @ HERA and H1 with increased statistics

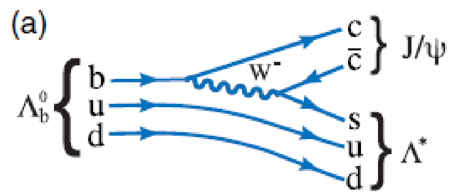
Can be searched again in various decays: $\theta_c^0 \rightarrow \theta^+\pi^-$, $pK^0\pi^-$, $D^{(*)-}p$, …

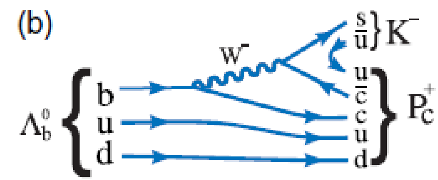
at NICA?

Brief pentaquarks' story, pentaquarks with hidden charm :

LHCb Collaboration

PRL **115**, 072001 (2015)





Partially confirmed by D0, ATLAS

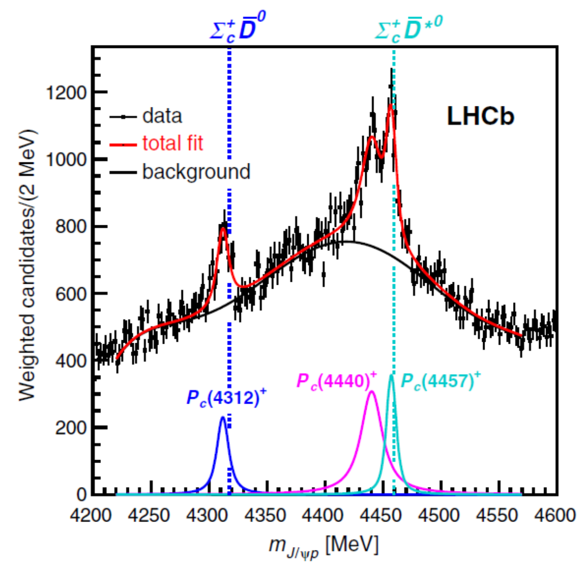
Not seen by GLueX → limits on branchings of decays to (J/ψ p)

Current status in PDG 2023:

$P_c(4312)^+$ $P_c(4440)^+$ $P_c(4457)^+$

$P_c(4380)^+$

Strange pentaquarks candidates are not yet in PDG

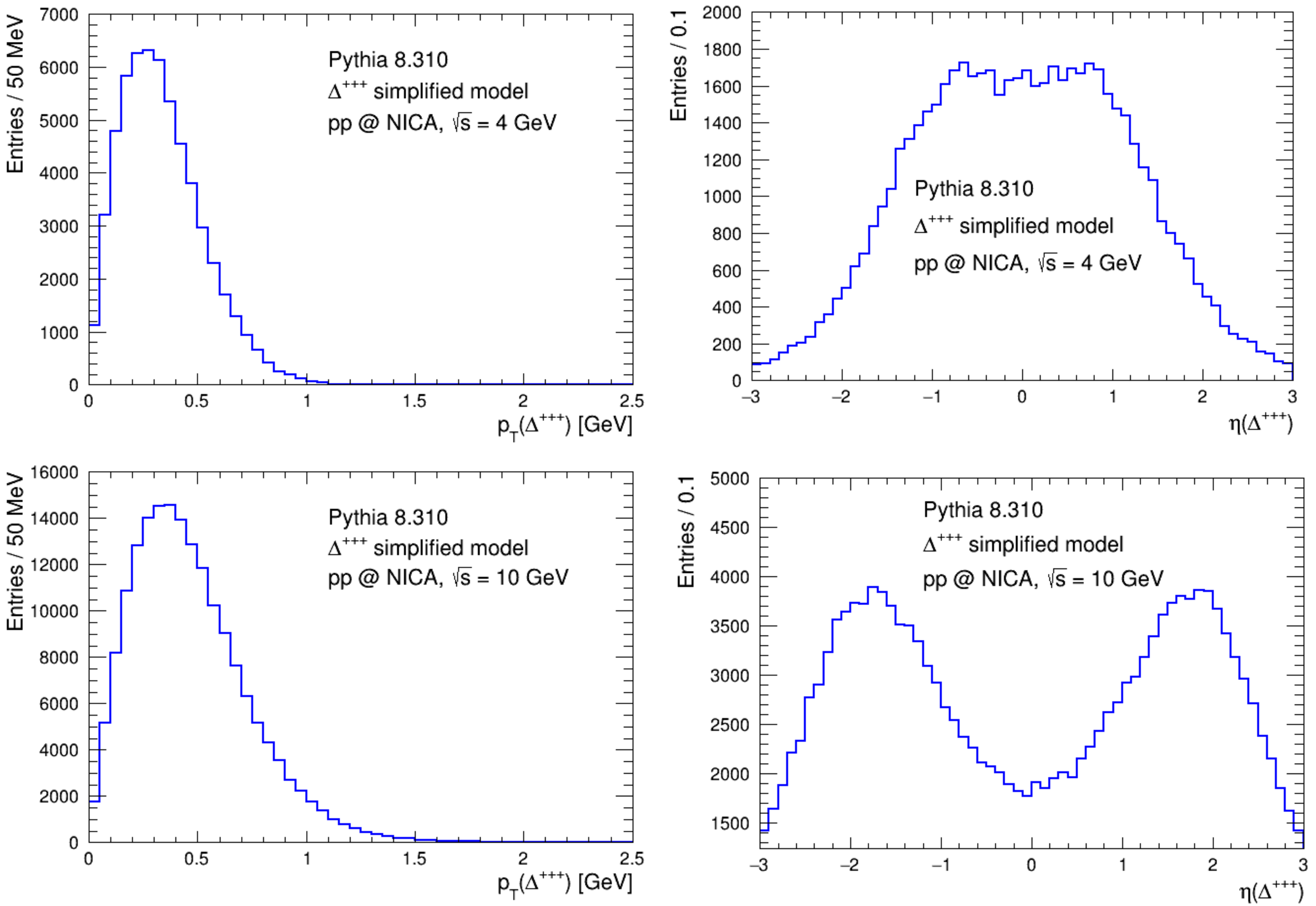


Most popular description – molecular states

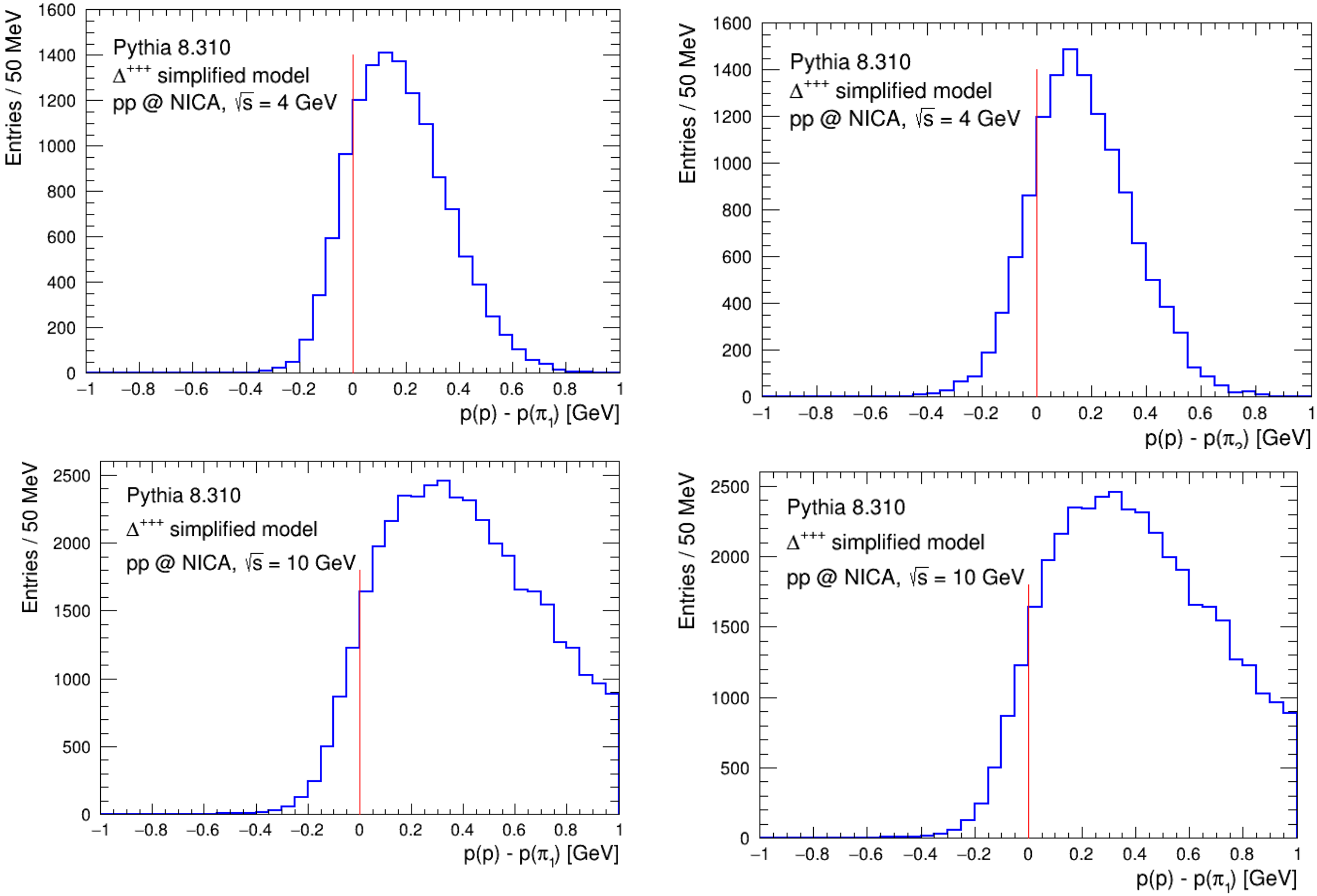
Many phenomenological papers on pentaquarks with hidden charm, beauty and strangeness

at NICA?

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



$\Delta^{+++} \to \Delta^{++}$ ($\to p\, \pi^{+}$) π^{+} , proton identification?



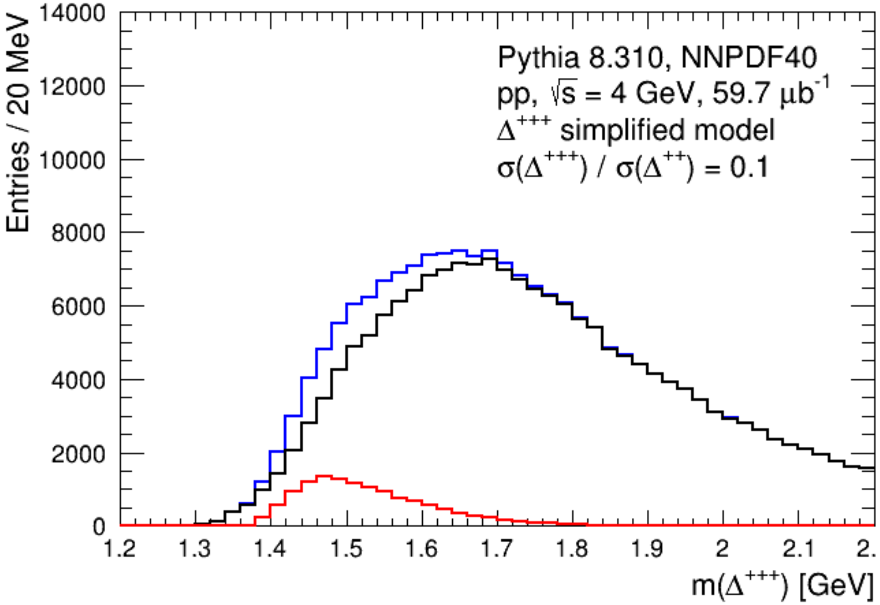
proton is typically fastest track

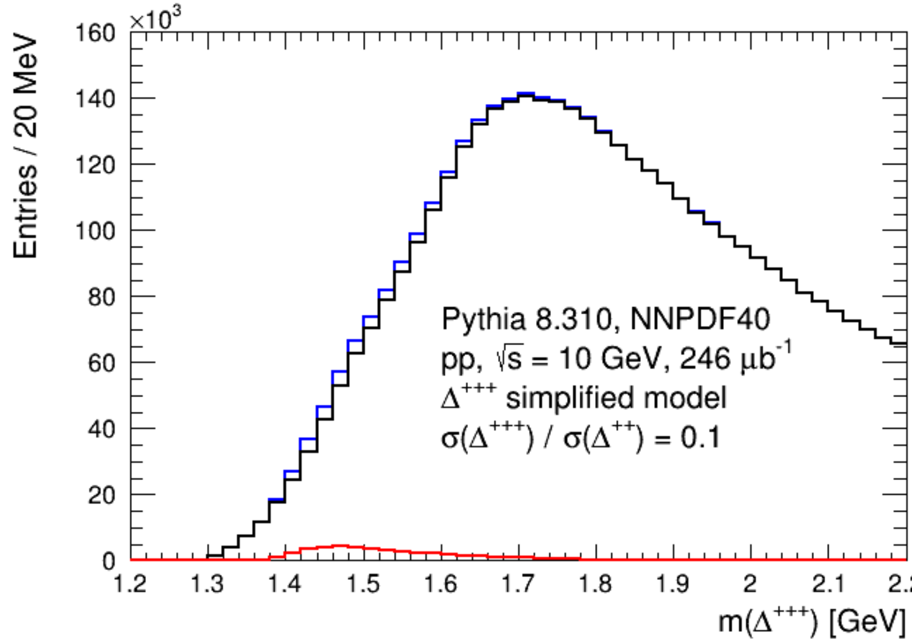
can be used in case of no PID

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

combine proton with two positively charged pions

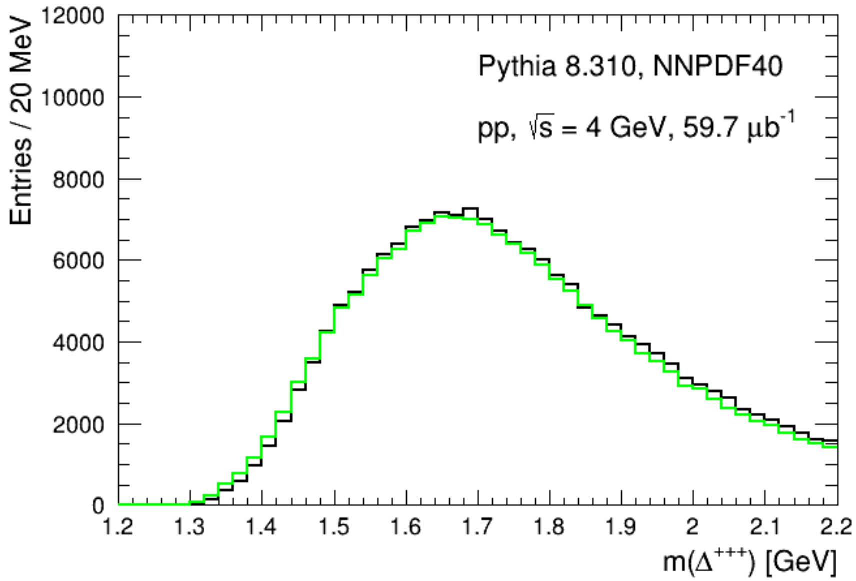
require ($1.14 < m(p\, \pi_1^+) < 1.32$) || ($1.14 < m(p\, \pi_2^+) < 1.32$) (~97% eff.)

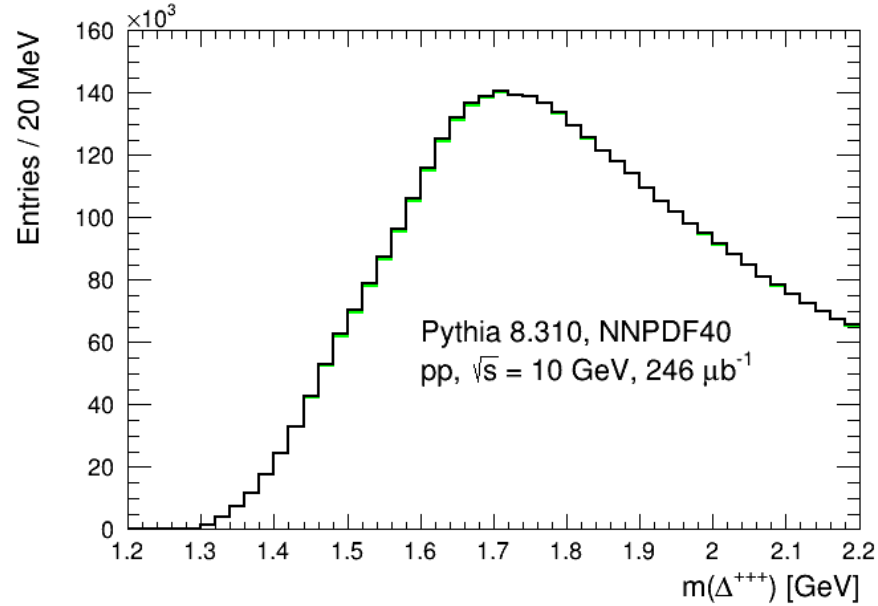




data-driven background shape estimation is needed

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





$p/\pi_1/\pi_2$ from another event

p from another event

CEPC Technical Design Report – Accelerator, arXiv:2312.14363

- ❑ The CEPC aims to start operation in 2030's, as a Higgs (Z / W) factory in China.
- ❑ To run at $\sqrt{s}$ ~ 240 GeV, above the **ZH** production threshold for ≥1 M Higgs; at the **Z** pole for ~Tera Z; at the **W^+W^-** pair and then $t\bar{t}$ pair production thresholds.
- ❑ Higgs, EW, flavor physics & QCD, probes of physics BSM.
- ❑ Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the far future.

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Energy (GeV)	120	45.5	80	180
Bunch number	268	11934	1297	35
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5