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Petersburg Nuclear Physics Institute
OF NATIONAL RESEARCH CENTRE «KURCHATOV INSTITUTE»

Study of feasibility to detect pentaquark $\theta^+(\bar{\theta}^-)$ in PANDA

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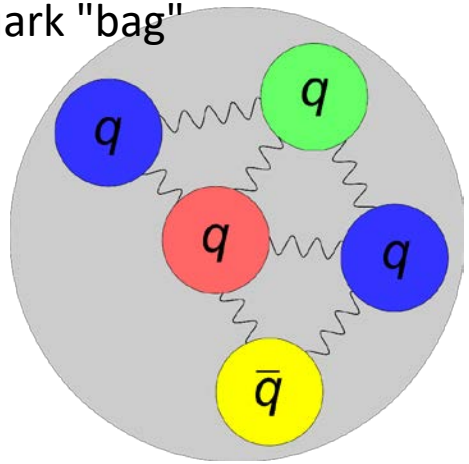
PANDA collaboration meeting 19/3,
November 4-8, 2019, GSI

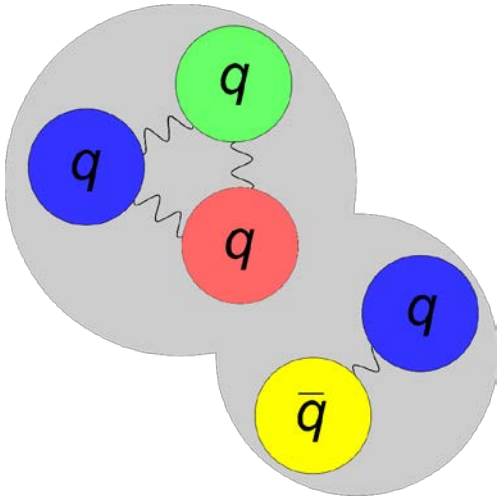
History of θ^+

- Possibility of five-quark particles was identified as early as 1964 by M. Gell-Mann and name pentaquark was coined by H.J. Lipkin in 1987
- D. Diakonov, V. Petrov, M. Polyakov. “Exotic anti-decuplet of baryons: prediction from chiral solitons” // **Zeitschrift für Physik A Hadrons and Nuclei, 1997, Vol. 359, no.3, p.305-314.**
- Nine independent experiments (LEPS, DIANA, SAPHIR …) reported seeing narrow peaks from nK^+ and pK_0, with masses between 1522 MeV and 1555 MeV, all above 4σ significance
- Ten experiments then looked for the Θ^+, but found nothing. In particular one at BELLE and the other at CLAS had nearly the same conditions as other experiments which claimed to have detected the Θ^+ (DIANA and SAPHIR, respectively)
- The 2008 Review of Particle Physics says “*There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist*”
- Despite of these, LEPS continued to show the existence of a narrow state with a mass of 1524±4 MeV with a statistical significance of 5.1σ

five-quark "bag"

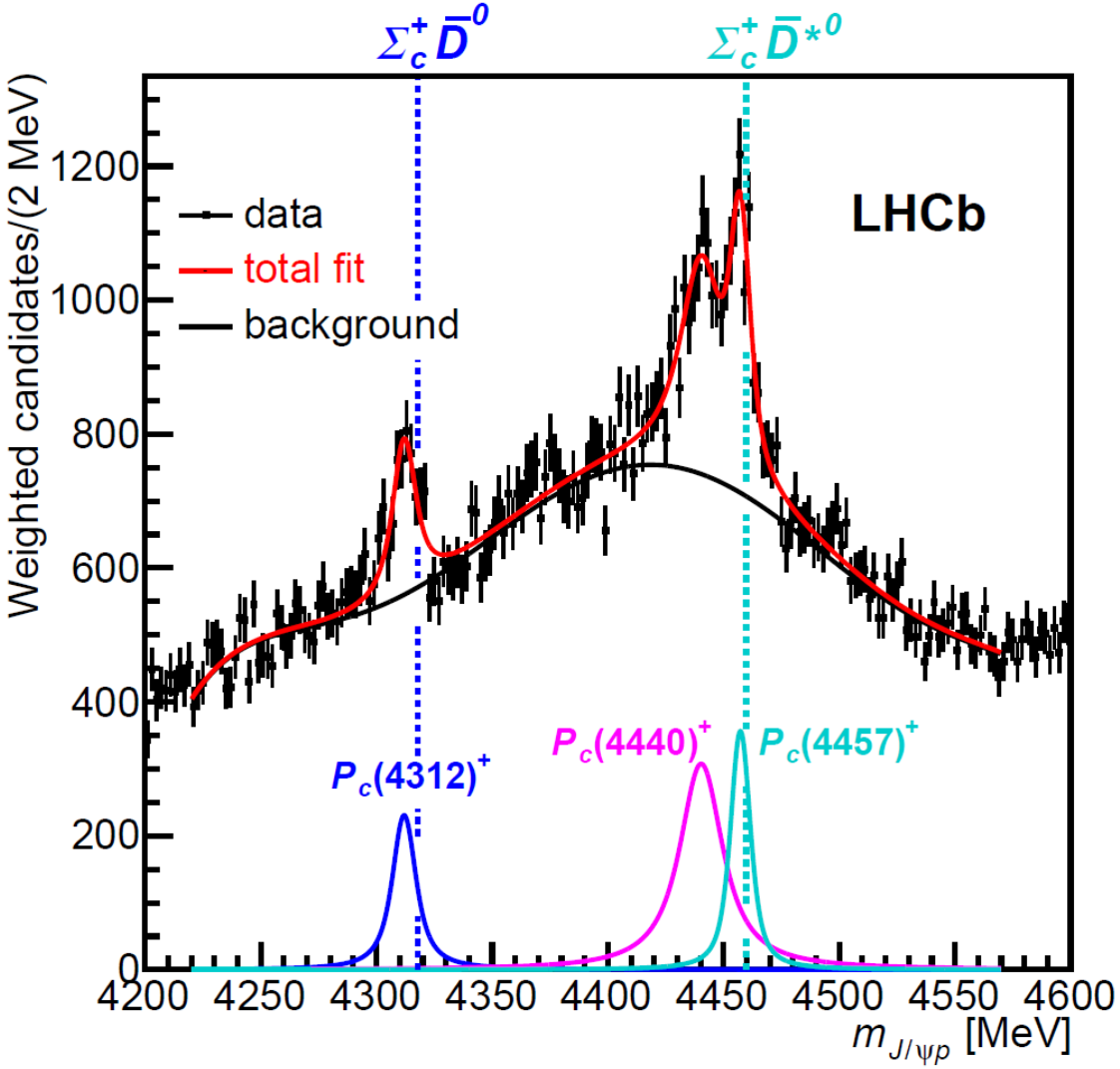


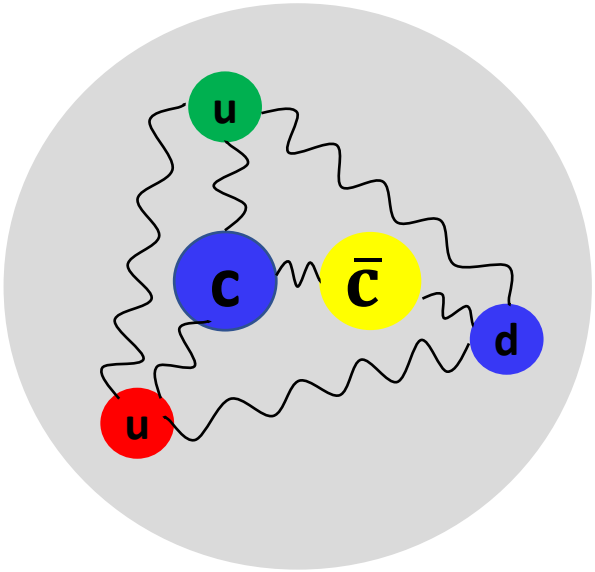
"meson-baryon molecule"



Recent LHCb data for heavy pentaquark P_c

Phys. Rev. Lett. 122, 222001 (2019)





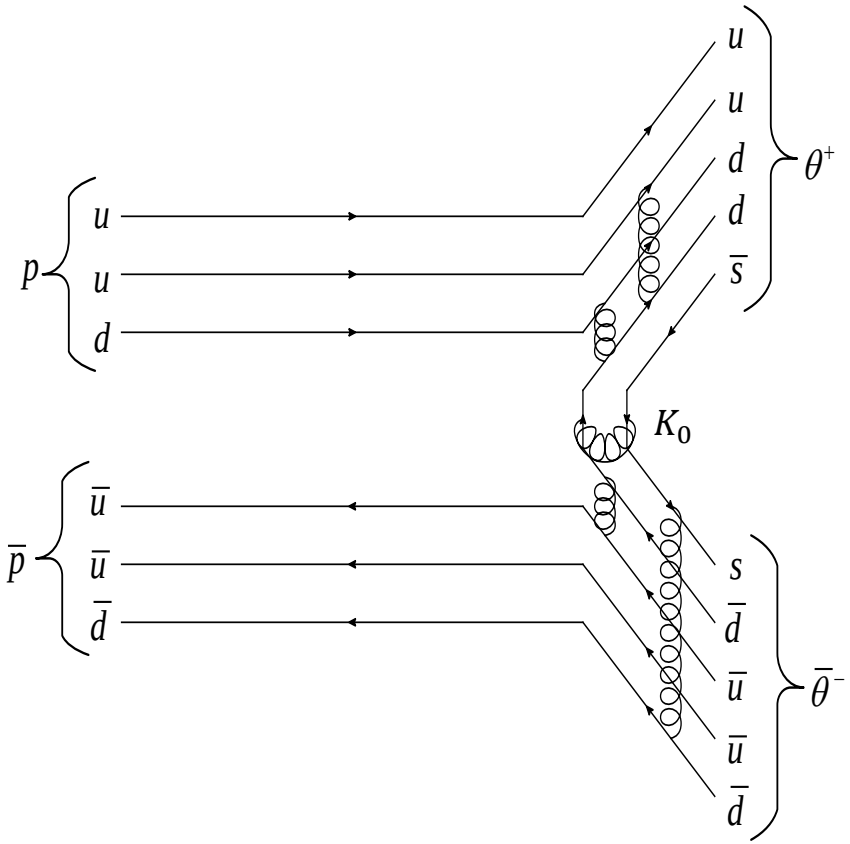
Model of P_c by V.Petrov

State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

After observation of pentaquarks P_c existence of θ^+ looks more plausible

Exclusive $\theta^+(\bar{\theta}^-)$ production in p anti-p collision

Pentaquark production by K-meson exchange



Differential cross-section
(V.Petrov, S.Manaenkov)

$$\frac{d\sigma}{dt} = \frac{g^4[(M_\theta - m_N)^2 - t]^2}{16\pi s(s-4m_N^2)(M_K^2 - t)^2}$$

m_N is nucleon mass
M_K is K^0 mass
M_θ is pentaquark mass
s, t are the Mandelstam variables

Total cross-section

$$\sigma_{tot} = \frac{g^4}{16\pi s(s-4m_N^2)}\left\{[(M_\theta - m_N)^2 - M_K^2]^2\left[\frac{1}{M_K^2 - t_{max}} -\right.\right.$$

θ^+ total width

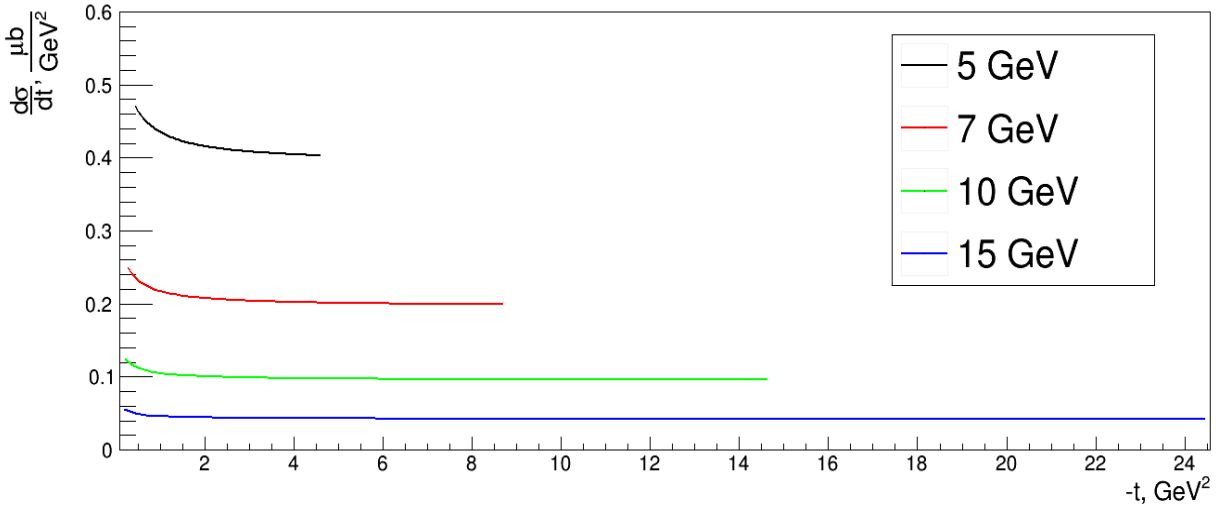
$$\Gamma_{tot} = \frac{g^2 P_0^3}{\pi[(M_\theta + m_N)^2 - M_K^2]}$$

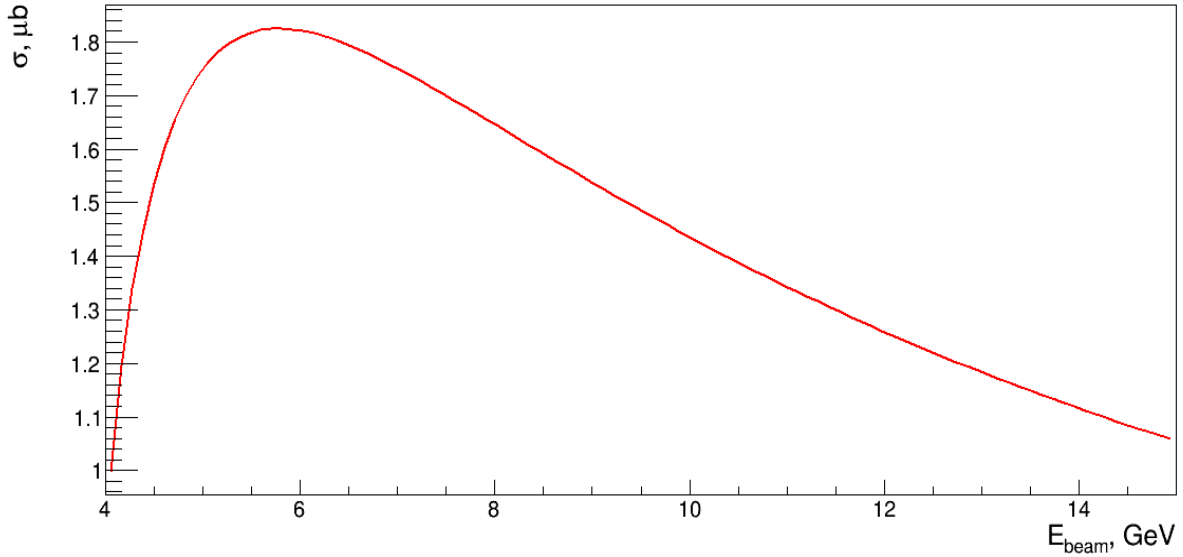
P_0 is momentum of K^0 in θ^+ rest system

Other anti-proton experiments

- PANDA's anti-protons momentum (1.5 – 15 GeV/c) ideally fits for pentaquark measurements.
- LEAR experiments at CERN
  - LEAR maximum anti-proton momentum < 3.5 GeV/c, real experiments measurements at momentum < 1 GeV/c, so it below production threshold
- Tevatron experiments at Fermilab
  - In this model cross-section $\sigma \sim \frac{1}{s^2}$ and comparing with PANDA total cross-section is more then 10 000 time less

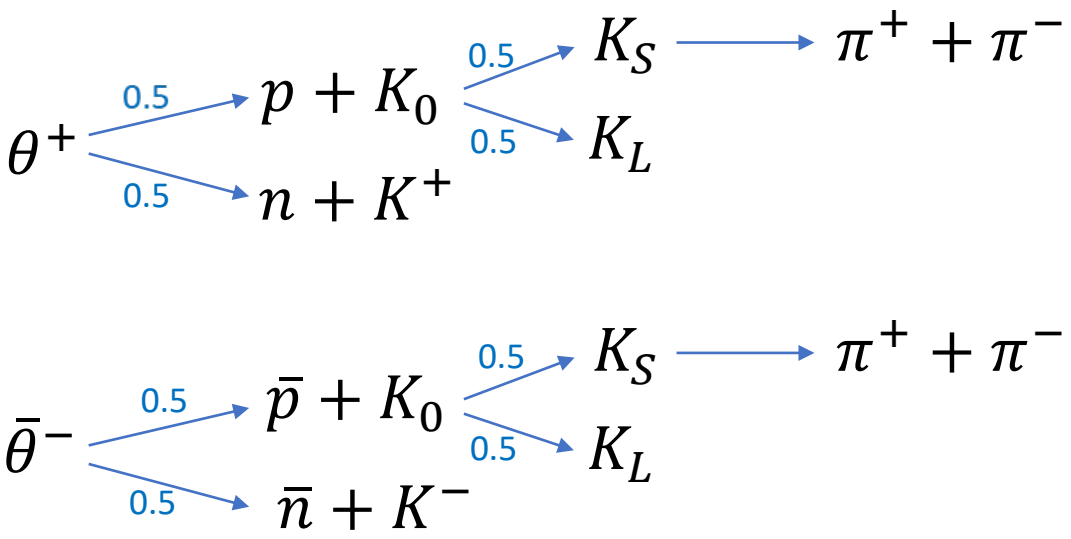
Cross-section dependencies

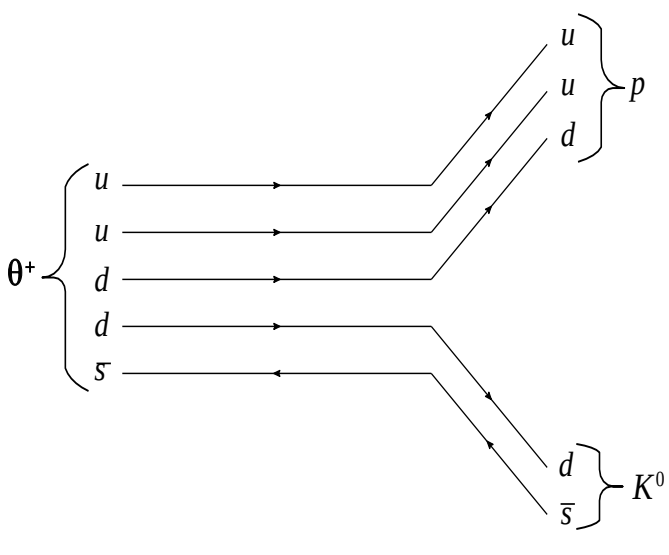


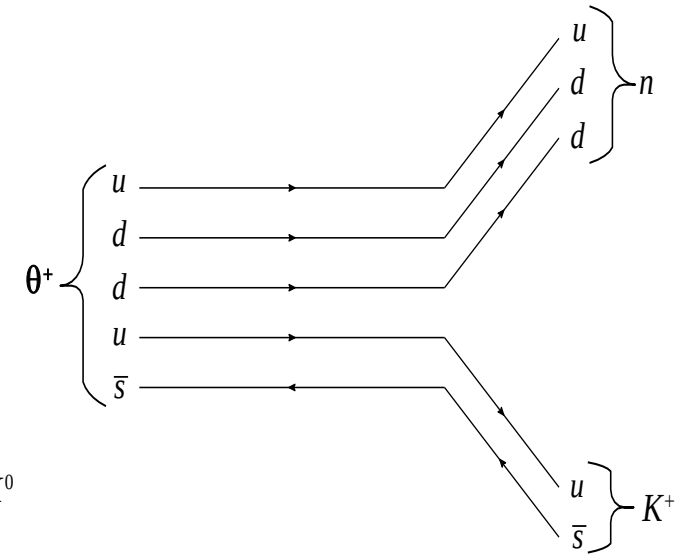


- Assuming 1 MeV width we get 1.8 μb total cross-section at 5.8 GeV beam energy
- Cross-section is proportional to $g^4 \sim (\Gamma_{tot})^2$, so for 0.1 MeV width it drops to 18 nb
- Total cross-section gets maximum at 5.8 GeV beam energy
- Differential cross-section almost flat over all kinematical range

θ^+ reconstruction







$p\bar{p} \to \theta^+\bar{\theta}^- \to p\pi^+\pi^- + \bar{p}\pi^+\pi^-$ easy to detect and sufficient to measure particle mass, but not possible to prove strangeness of particle. It can be negative (hyperon) or positive (pentaquark).

To be sure that we have pentaquark (not a baryon) we need exclusive production $p\bar{p} \to \theta^+\bar{\theta}^-$ and one charged K-meson (K^+or K^-) at final state:

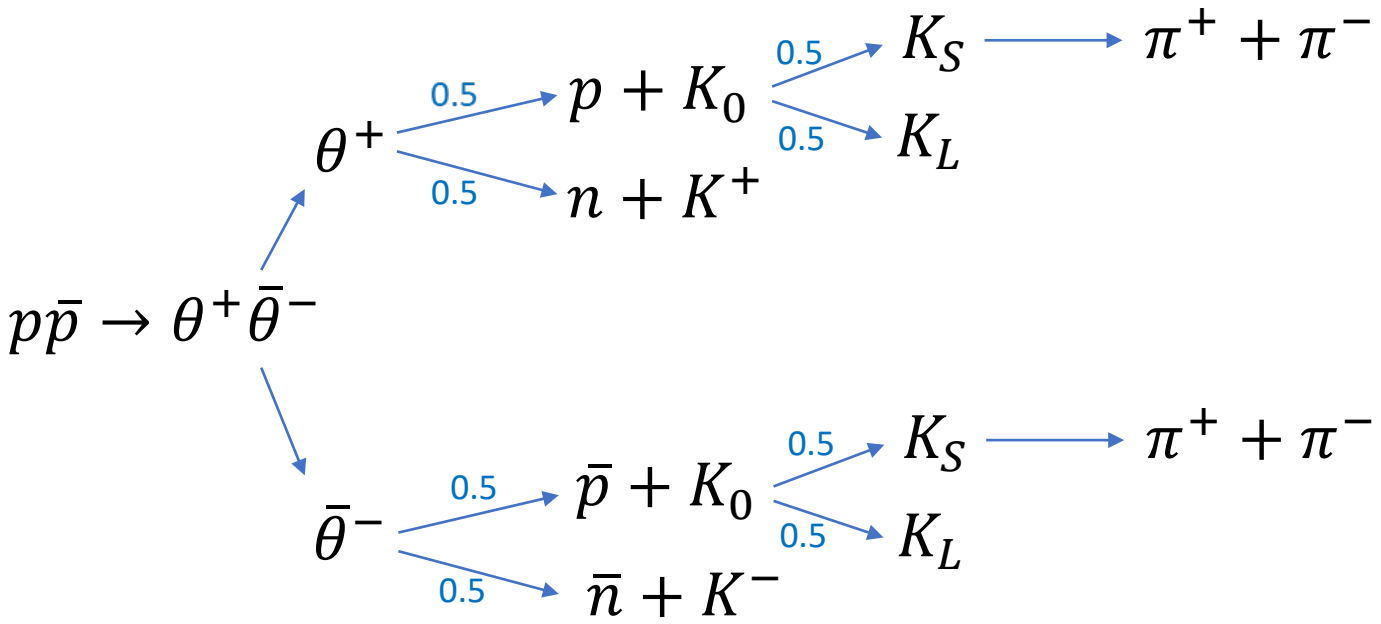
$p\bar{p} \to \theta^+\bar{\theta}^- \to p\pi^+\pi^- + \bar{n}K^-$ anti-neutron $\bar{n}$ can be detected by missing mass and calorimeter signal

$p\bar{p} \to \theta^+\bar{\theta}^- \to nK^+ + \bar{p}\pi^+\pi^-$ neutron n can be detected by missing mass

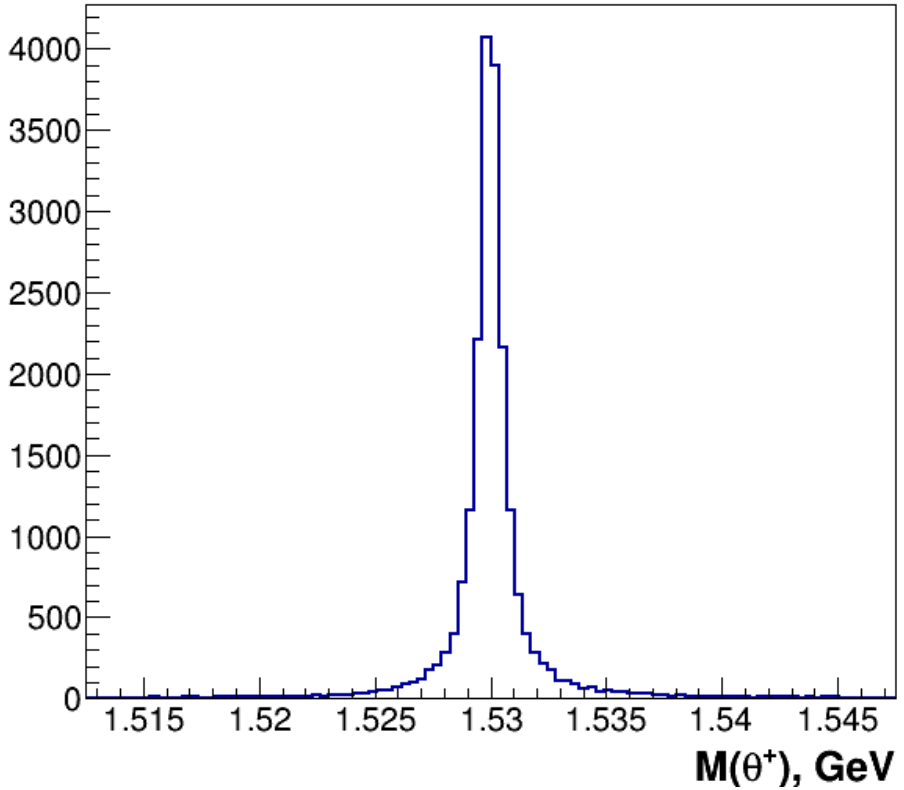
$p\bar{p} \to \theta^+\bar{\theta}^- \to nK^+ + \bar{n}K^-$ two neutral particle in final state, basically not possible to reconstruct

Monte Carlo generation of $\theta^+(\bar{\theta}^-)$

- EvtGen
- Generate $p\bar{p} \rightarrow \theta^+\bar{\theta}^-$ in phase space
- 10000 events at 6.23 GeV beam
- M(Θ⁺) set as 1530 MeV
- Total width = 1 MeV
- Branching ratio for $\theta^+(\bar{\theta}^-)$ decays sets to 50%

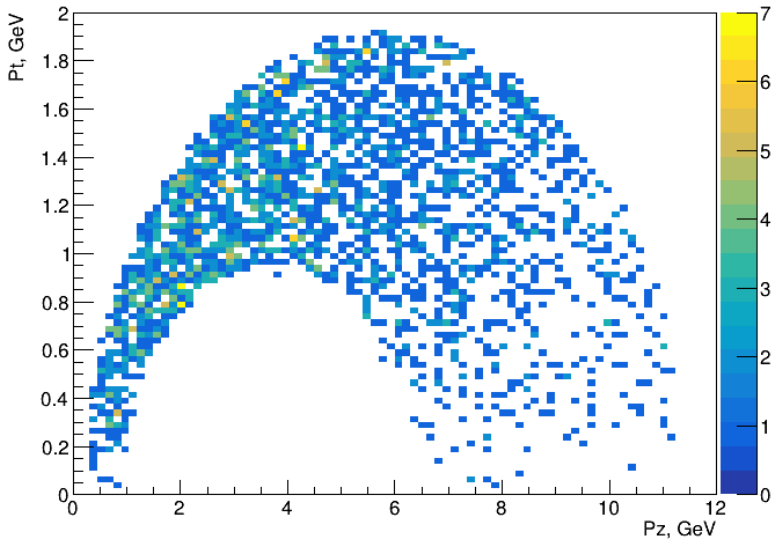


Invariant mass spectra for generated $\theta^+(\bar{\theta}^-)$

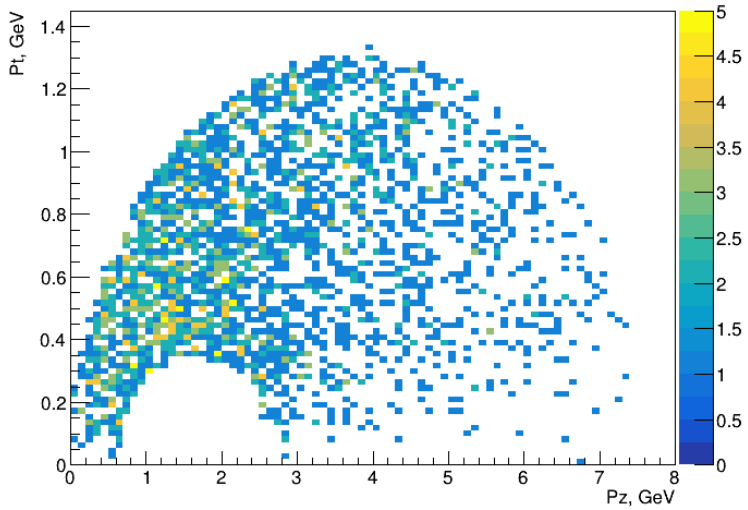


Generated distributions

neutron



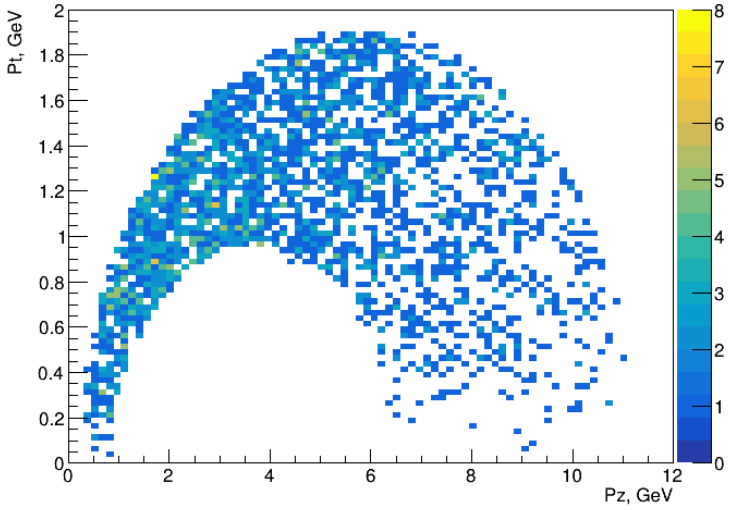
K+



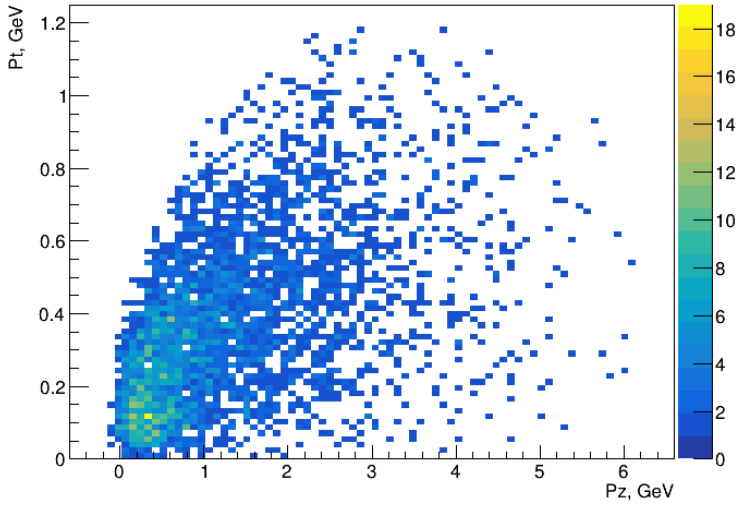
$\overline{n}, K^-$ same as n, K^+ distributions

$\overline{p}, \pi^+, \pi^-$ same as p, π^+, π^-

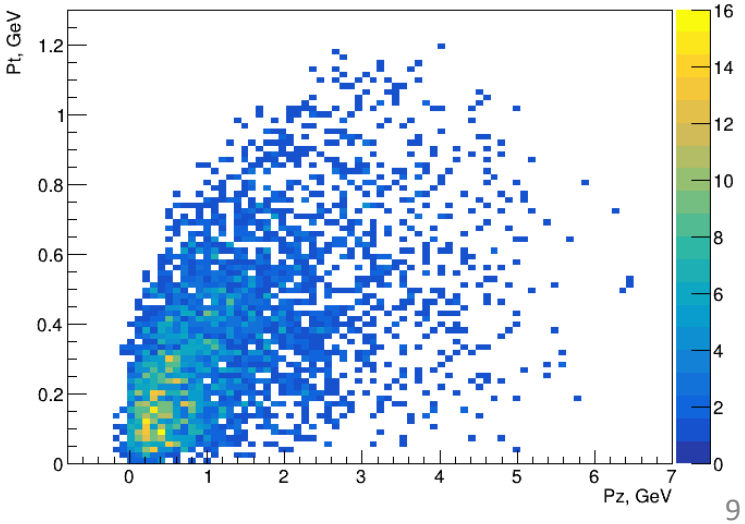
proton



π+

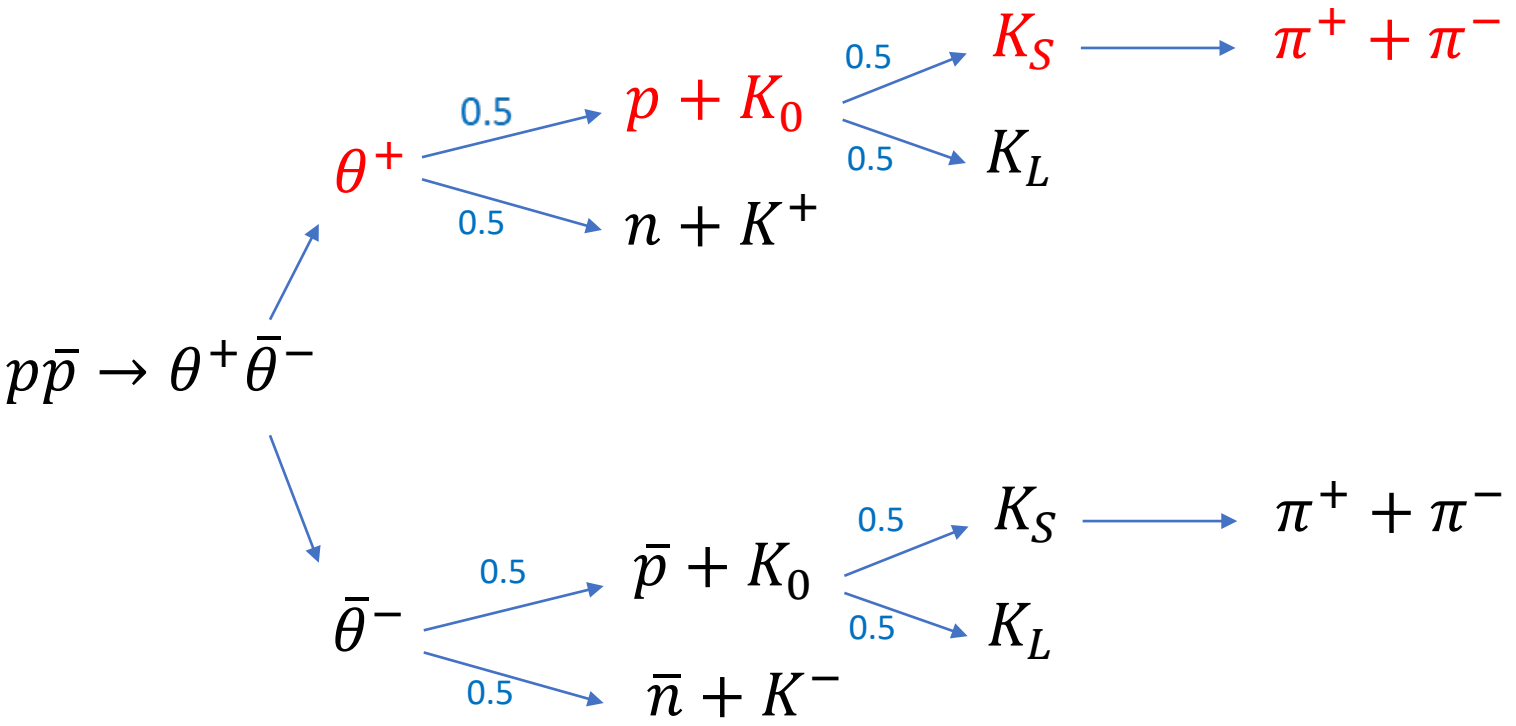


π-



θ^+ reconstruction

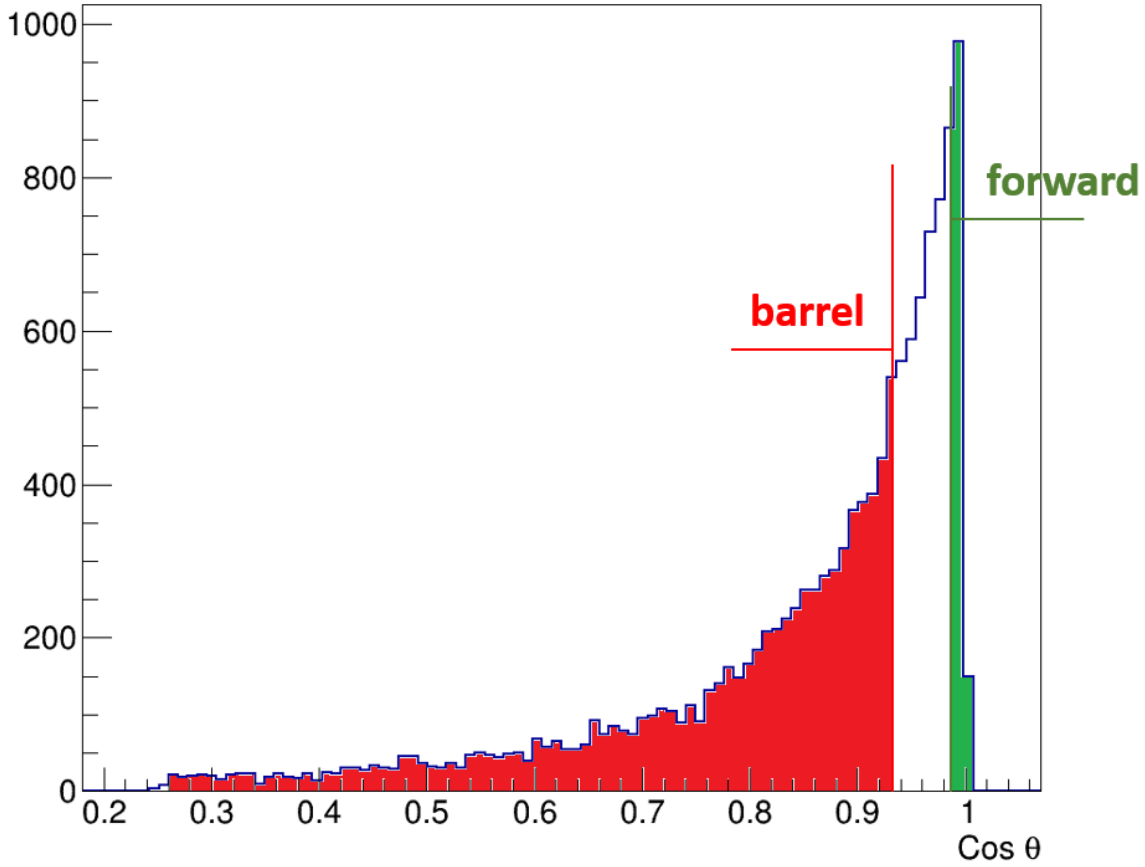
- As starting point take simplest (from reconstruction point of view) decay channel
- Branching ratio 0.25



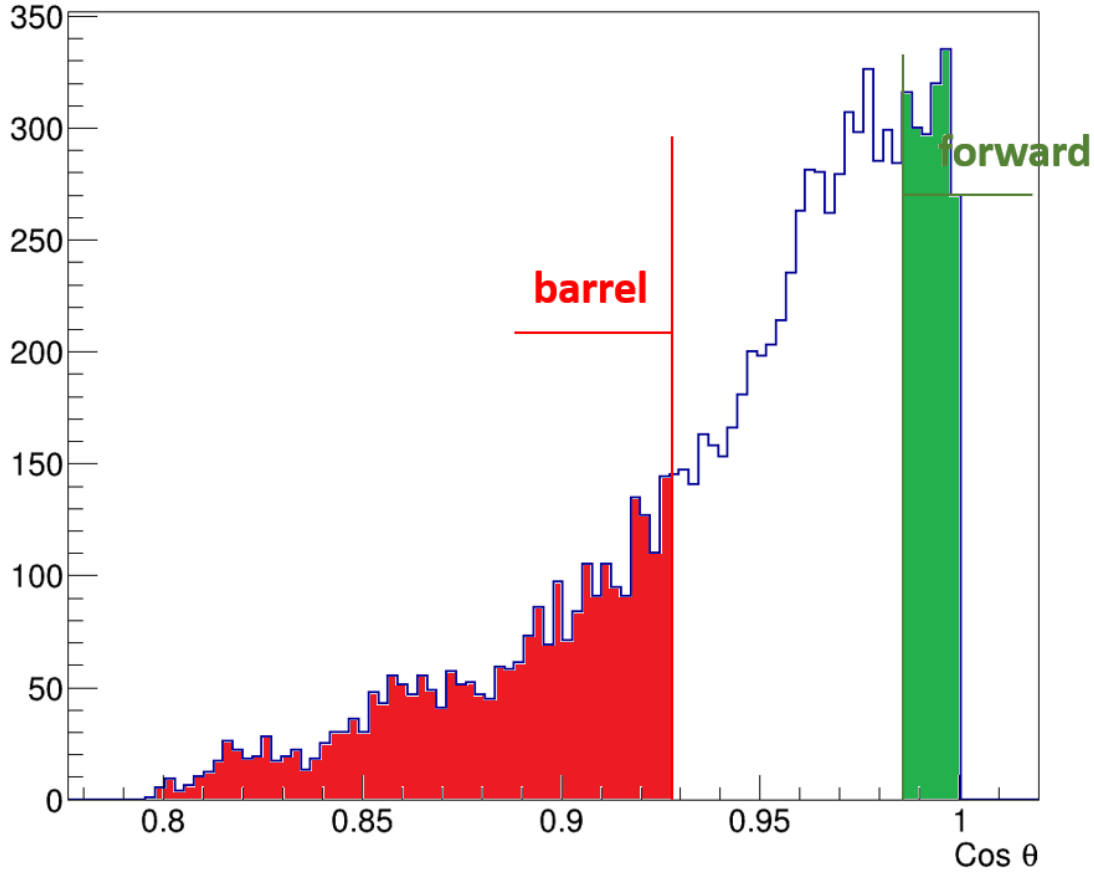
Angular distribution for proton and pions from θ^+ decay

Barrel part of acceptance > 22 deg, forward part < 10 deg

Generated $\pi^+(\pi^-)$ in lab system



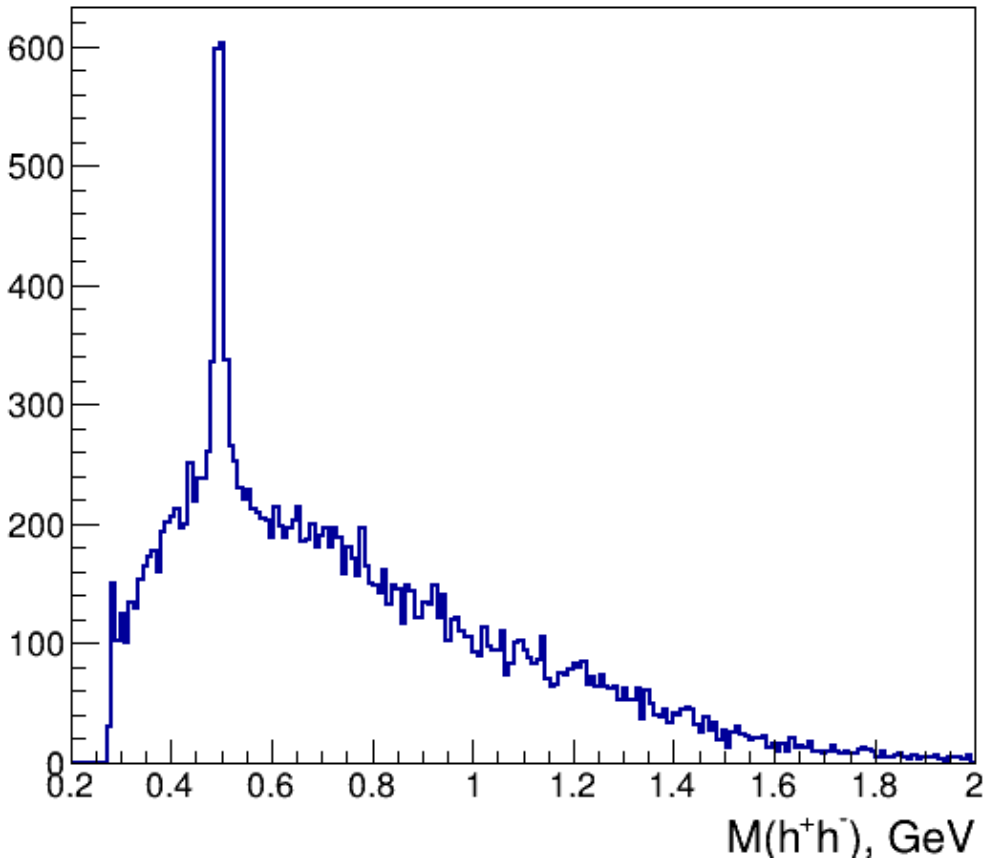
Generated proton (anti-proton) in lab system



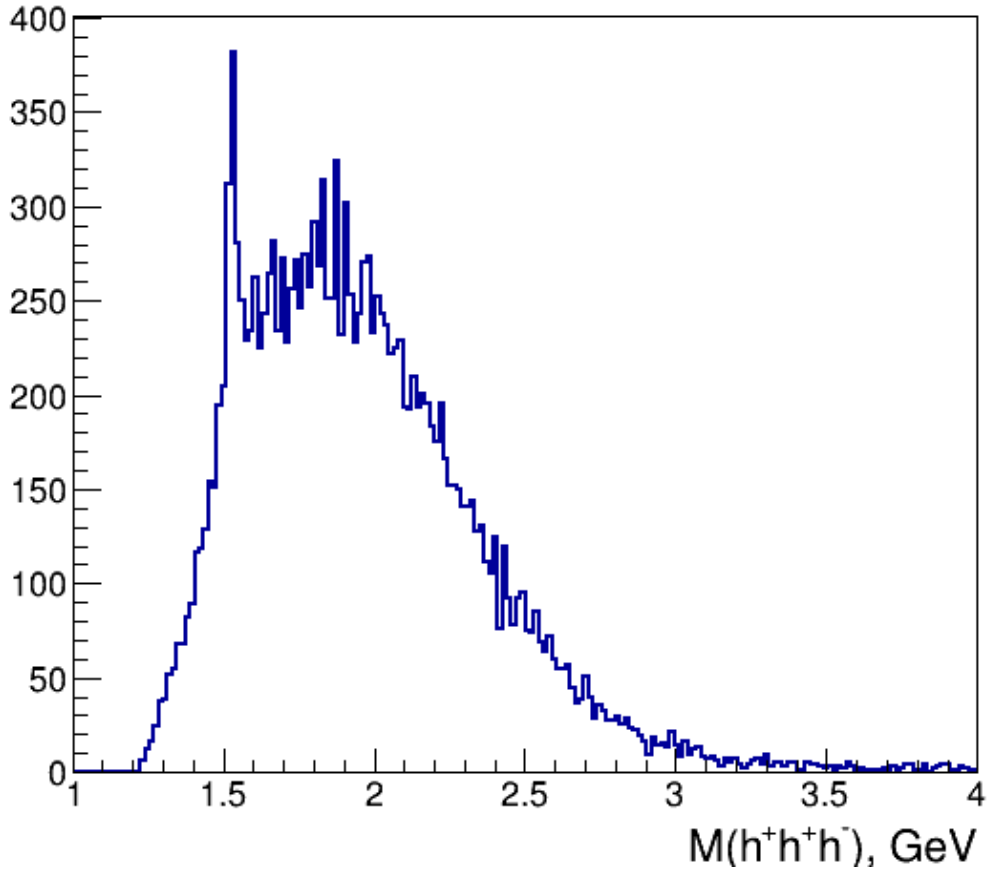
Invariant mass spectra of K_S and θ^+ without PID

All hadrons with corresponding charge are combined

K_S candidates



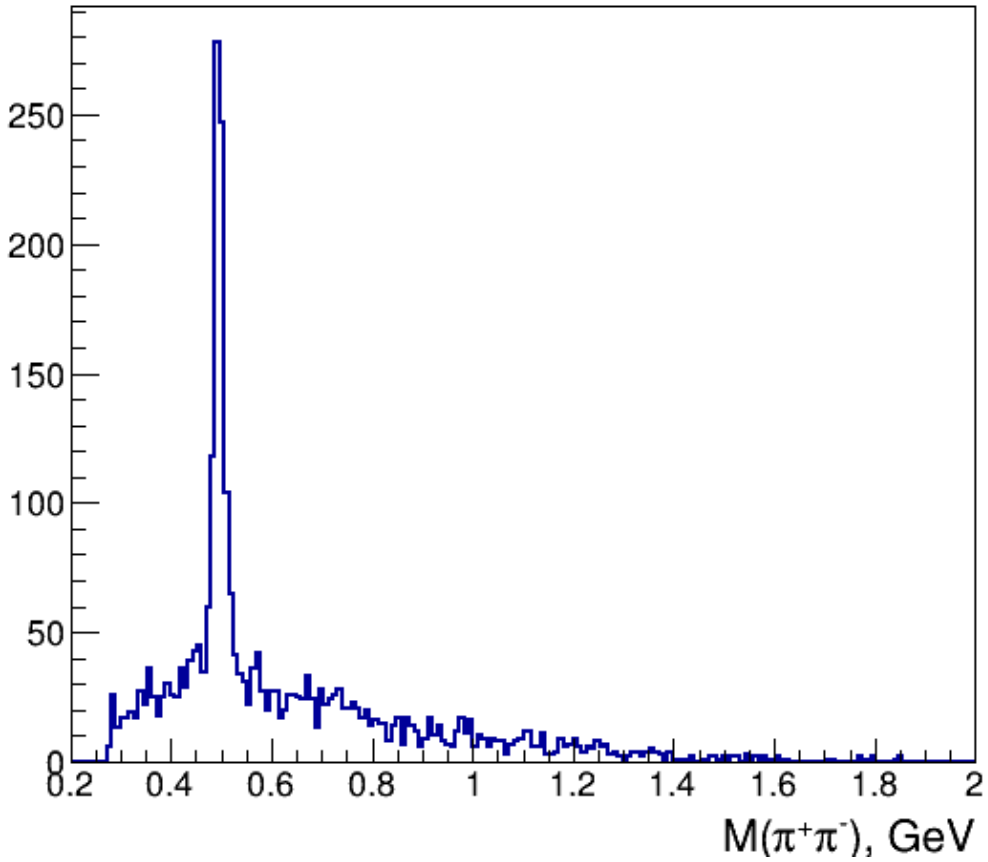
θ^+ candidates



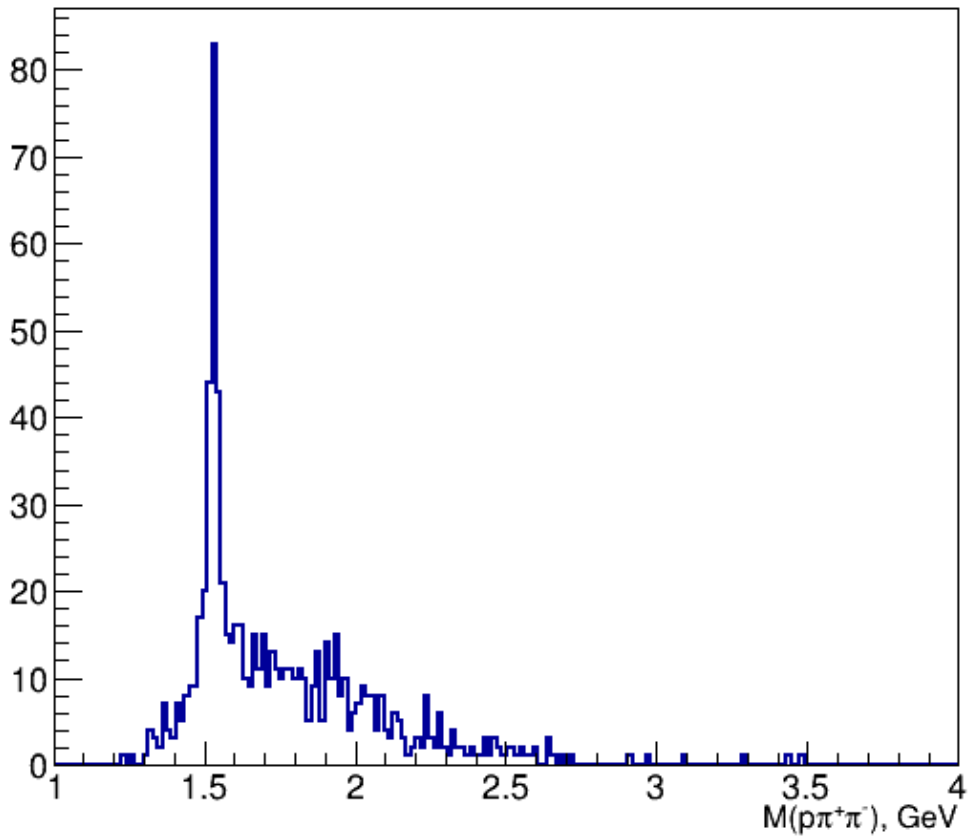
Invariant mass spectra of K_S and θ^+ with “real” PID

All hadrons with corresponding charge are combined and additional cut on PID probability (Prob > 0.5) was applied

K_S candidates



θ^+ candidates

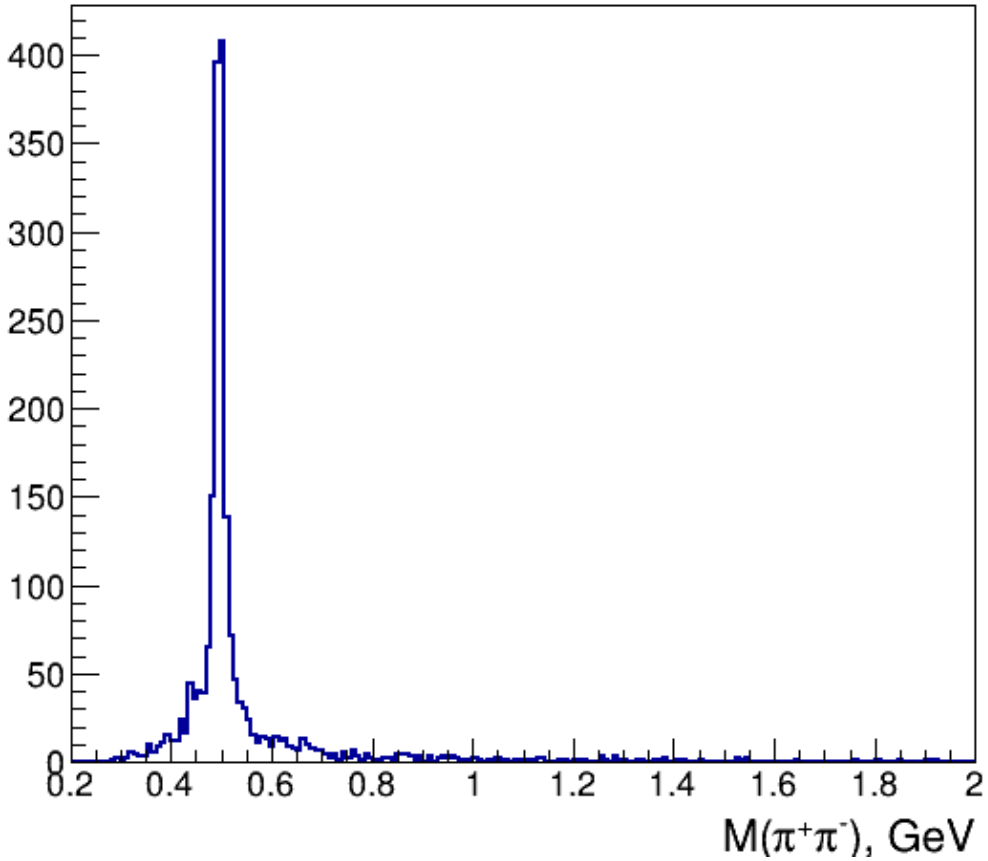


Invariant mass spectra of K_S and θ^+ with ideal PID

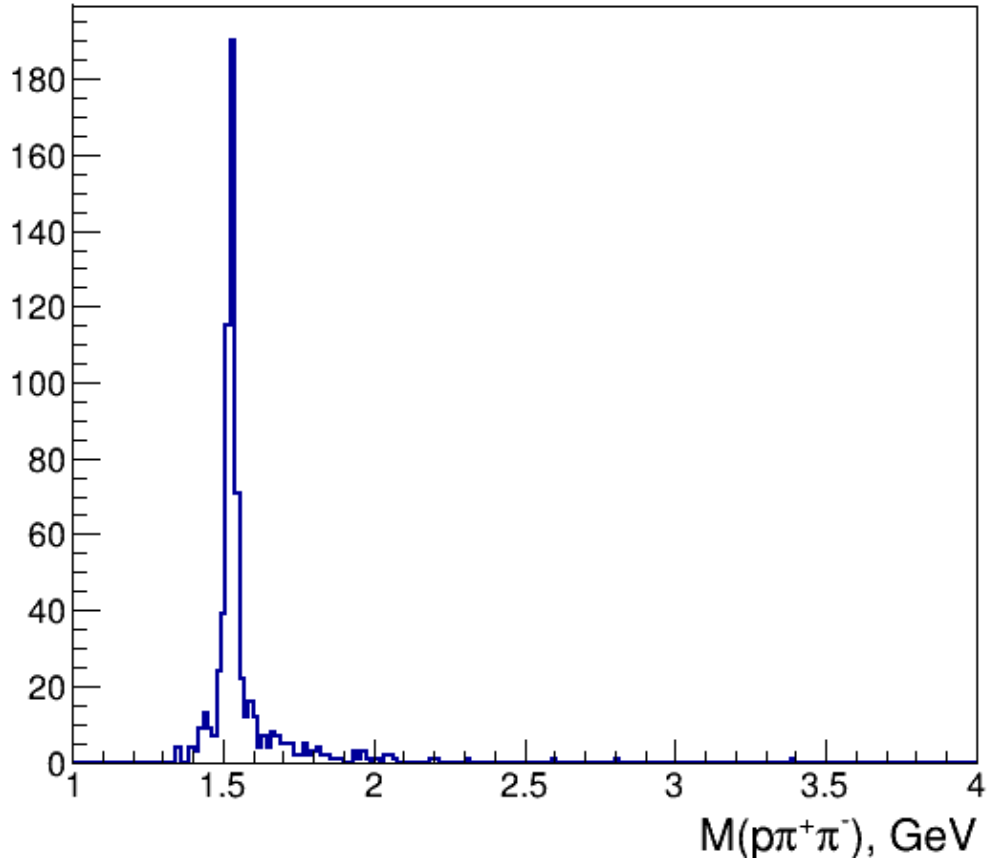
PID for particles was taken from Monte Carlo

From initial 10 000 produced θ^+ about 600 (6%) can be detected in ideal case

K_S candidates



θ^+ candidates



Conclusion and outlook

Conclusion

- Model is proposed for exclusive light pentaquark production by K-meson exchange
- Relatively high total cross-section about 1.8 μb (for 1 MeV width) is predicted
- In ideal case, detection efficiency is estimated to be 6%

Outlook

- Use model cross-section for Monte Carlo generation
- Combine Evt events with DPM background
- Study a possibility to detect neutron (anti-neutron) using missing mass