Search for Hexaquarks in CMS at the LHC – feasibility study

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What are hexaquarks?

Bound states of 6 quarks

- 6 quarks (anti-quarks) – sexaquarks; DM candidate
- 3 quarks + 3 anti-quarks – hexaquarks

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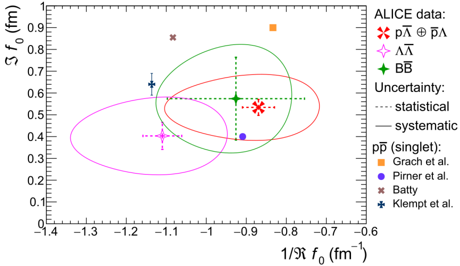
Example:
$p + \bar{\Lambda} = uud\bar{u}\bar{d}\bar{s}$
Expected mass $> m_p + m_\Lambda = 2053$ MeV
Expected width: 0.1-1 GeV (general lifetime of systems decaying through strong interaction)

Why should we search for hexaquarks now?

- recent discovery of pentaquarks at LHCb (2015)
- PDG
  - $K_2(2250) \to K\pi\pi$ based on papers from 70s, 80s
  - $K_3(2320) \to p\bar{\Lambda}$ "needs confirmation"
- femtoscopic correlations



Measurement of strange baryon–antibaryon interactions with femtoscopic correlations, S. Acharya et al. Physics Letters B, Volume 802, 2020, 135223

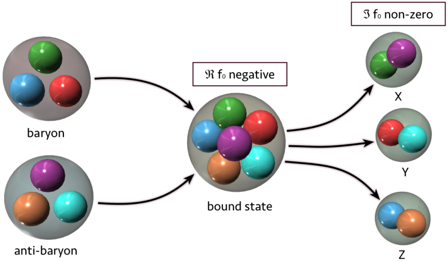
3 meson decay

$$p + \bar{\Lambda} = uud\bar{u}\bar{d}\bar{s}$$

- $u\bar{s} + d\bar{u} + u\bar{d} = K^+ + \pi^+ + \pi^-$
- $u\bar{s} + u\bar{u} + d\bar{d} = K^+ + \pi^0 + \pi^0$
- $d\bar{s} + u\bar{u} + u\bar{d} = K^0 + \pi^+ + \pi^0$

$$\Lambda_c + \bar{\Lambda}_c = udc\bar{u}\bar{d}\bar{c}$$

- $u\bar{u} + d\bar{d} + c\bar{c} = \pi^0 + \pi^0 + J/\psi$
- $u\bar{u} + d\bar{c} + c\bar{d} = \pi^0 + D^- + D^+$
- $d\bar{u} + u\bar{c} + c\bar{d} = \pi^- + \bar{D}^0 + D^+$
- $d\bar{u} + u\bar{d} + c\bar{c} = \pi^- + \pi^+ + J/\psi$
- $c\bar{u} + u\bar{c} + d\bar{d} = D^0 + \bar{D}^0 + \pi^0$
- $c\bar{u} + u\bar{d} + d\bar{c} = D^0 + \pi^+ + D^-$



Background

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  - solution: event mixing – take 3 particles from different events to recreate combinatorial background

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  - solution: event mixing – take 3 particles from different events to recreate combinatorial background
- particles decaying to 2 mesons will contribute to background in a way that is not recreated by event mixing

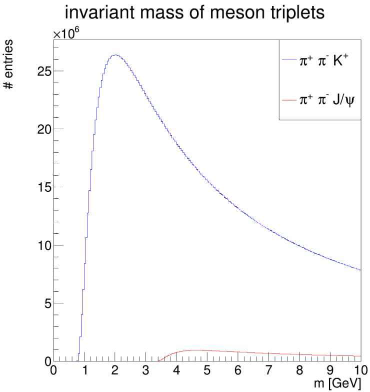
Simulating hexaquarks with Pythia

A hexaquark can be simulated by changing properties of a particle that already exists in Pythia.

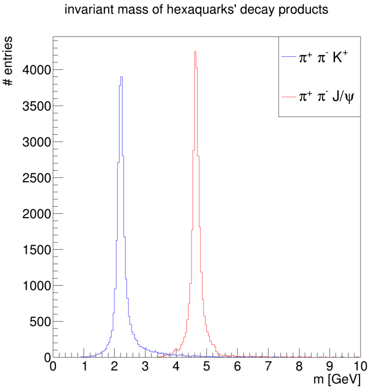
The following commands change B^0 meson's mass to 4.650 GeV and width to 0.2 GeV. The decay channels are set to $\pi^0\ \pi^0\ J/\psi$ and $\pi^+\ \pi^-\ J/\psi$

```
511:all = lclc anti_lclc 1 0 0 4.650 0.2 0 -1 0.
511:oneChannel = 1 1 0 111 111 443 # pi0 pi0 J/psi
511:addChannel = 1 1 0 211 -211 443 # pi+ pi- J/psi
```

Invariant mass of meson triplets



(a) Invariant mass of all meson triplets



(b) Invariant mass of all meson triplets originating from a hexaquark decay

Figure: Red color indicates hexaquark$(\Lambda_c\bar{\Lambda}_c) \to \pi^+\ \pi^-\ J/\psi$ signal sample; blue color indicates hexaquark$(p\bar{\Lambda}) \to \pi^+\ \pi^-\ K^+$ signal sample

Leading muon p_T

Signal:
hexaquark$(\Lambda_c \bar{\Lambda}_c) \rightarrow$
$\pi\ \pi\ J/\psi$
$J/\psi \rightarrow \mu\ \mu$

Background:
default settings – no hexaquark

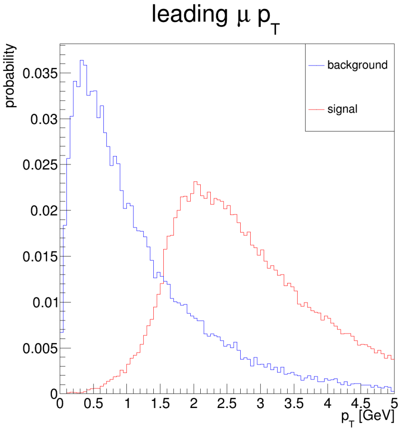


Figure: Transverse momentum of a leading μ in background and signal sample

CMS triggers efficiency

- HLT_Dimuon0_Jpsi3p5_Muon2_v
  - at least 2 μ with opposite charge
  - at least 1 μ with $p_T > 2$ GeV
  - at least 1 J/ψ with $p_T > 3.5$ GeV
- HLT_AK8PFJet550_v
  - at least 1 jet with $p_T > 550$ GeV
- HLT_PFHT1050_v
  - sum of all jets' $p_T > 1050$ GeV
- HLT_IsoMu24_eta2p1_v
  - at least 1 μ with $p_T > 24$ GeV; $|\eta_\mu| < 2.1$
- HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_Mass3p8_v
  - at least 2 μ with opposite charge
  - at least 1 μ with $p_T > 17$ GeV
  - at least 1 μ with $p_T > 8$ GeV
  - invariant mass of μ pair > 3.8 GeV

$|\eta_{jet}| < 3.0$ and $|\eta_\mu| < 3.5$ for all triggers

CMS triggers efficiency

$p\bar{\Lambda}$ – hexaquark($p\bar{\Lambda}$) $\to \pi^+ \pi^- K^+$ signal sample
$\Lambda_c\bar{\Lambda}_c$ – hexaquark($\Lambda_c\bar{\Lambda}_c$) $\to \pi^+ \pi^- J/\psi$ signal sample
background – sample without a hexaquark implemented

	$p\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	background
HLT_Dimuon0_Jpsi3p5_Muon2_v	$< 0.02\%$	**2.4%**	0.05%
HLT_AK8PFJet550_v	$< 0.004\%$	$< 0.004\%$	$< 0.004\%$
HLT_PFHT1050_v	$< 0.004\%$	$< 0.004\%$	$< 0.004\%$
HLT_IsoMu24_eta2p1_v	$< 0.004\%$	$< 0.007\%$	$< 0.004\%$
HLT_Mu17_TrkIsoVVL_Mu8 _TrkIsoVVL_DZ_Mass3p8_v	$< 0.004\%$	$< 0.004\%$	$< 0.004\%$

Table: Fraction of events that fulfil the trigger conditions. Upper limits are given at 95% C.L.

Relatively low (2.4 %) passing rate for $\Lambda_c\bar{\Lambda}_c$ is due to 5% BR of $J/\psi \to \mu\mu$

Conclusions

- changing particle properties is a viable method of simulating hexaquarks in `Pythia`
- heavier hexaquarks may be easier to discover
  - smaller combinatorial background
  - ability to use J/ψ triggers
- high rate (in comparison to background) of events containing a $\Lambda_c\bar{\Lambda}_c$ hexaquark passing a J/ψ trigger