Flavour-exotic pentaquarks

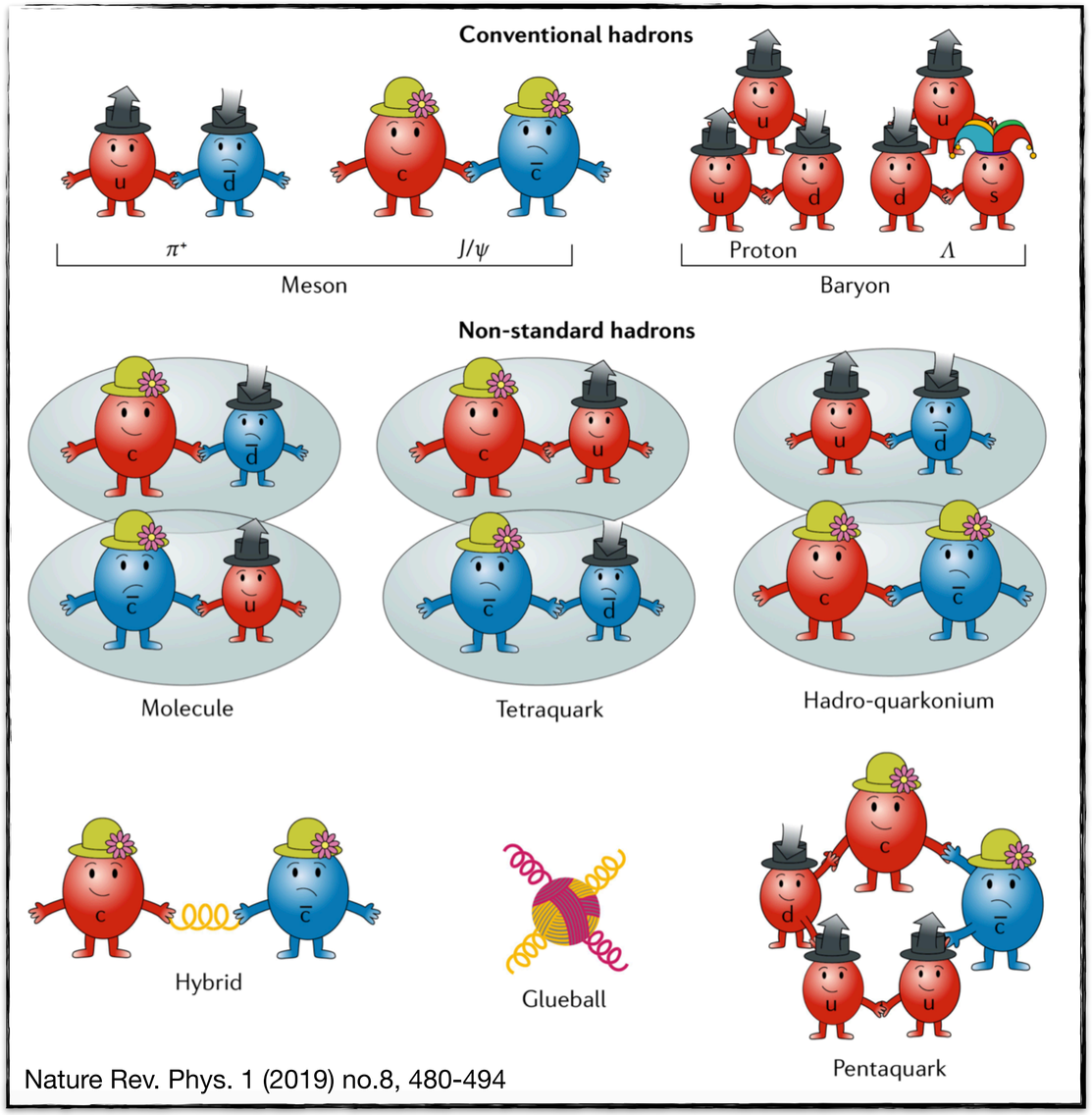
and where to find them

Nils Hüsken, QCD-at-FAIR workshop 2024

for context:
brought up as *exotic hadron* topic potentially unique to GSI
I am **not** an expert in this topic, just floating an idea!

Flavour-exotic hadrons

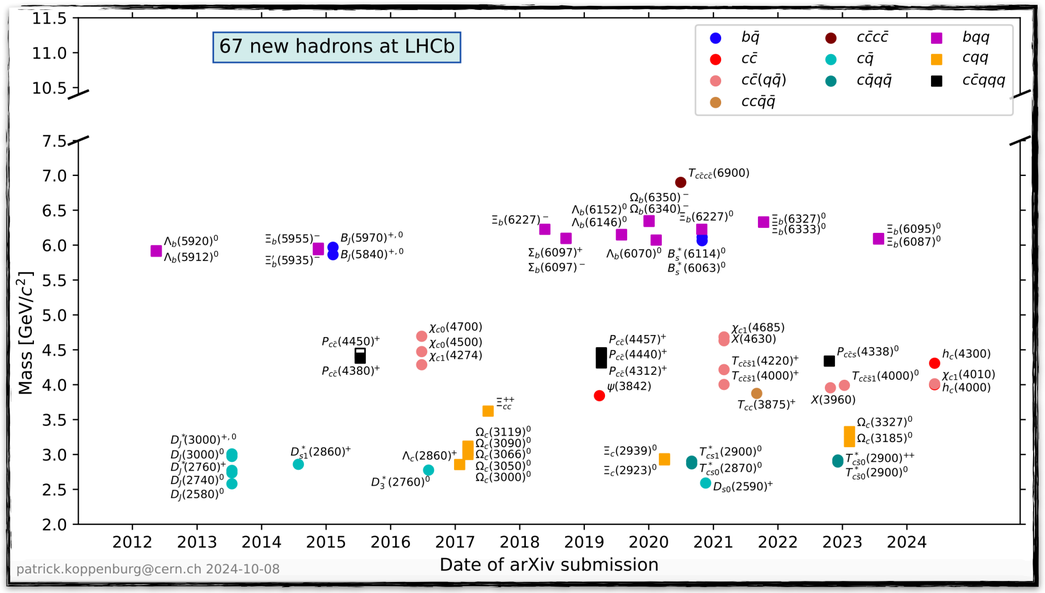
- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon

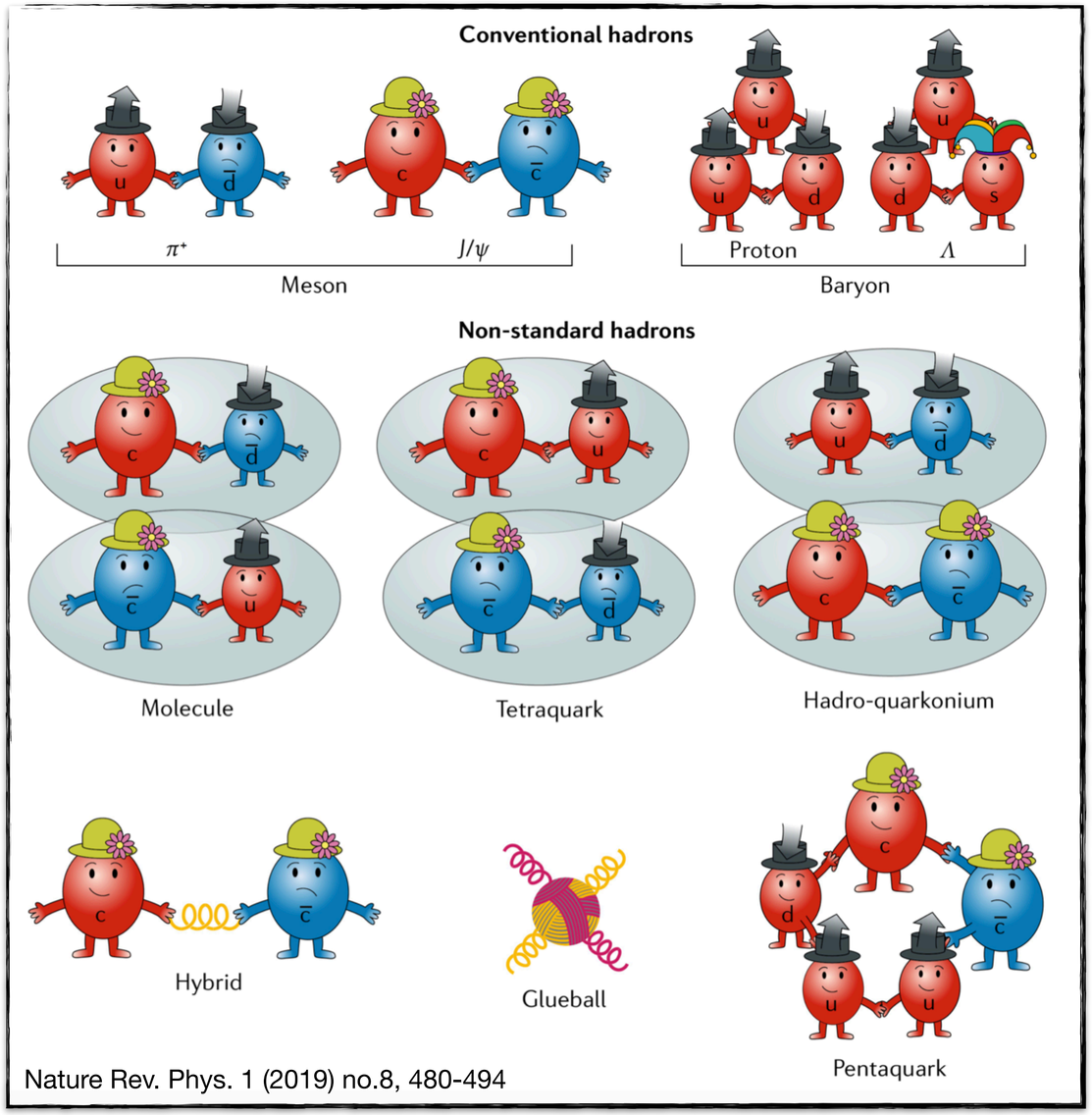


Nature Rev. Phys. 1 (2019) no.8, 480-494

Flavour-exotic hadrons

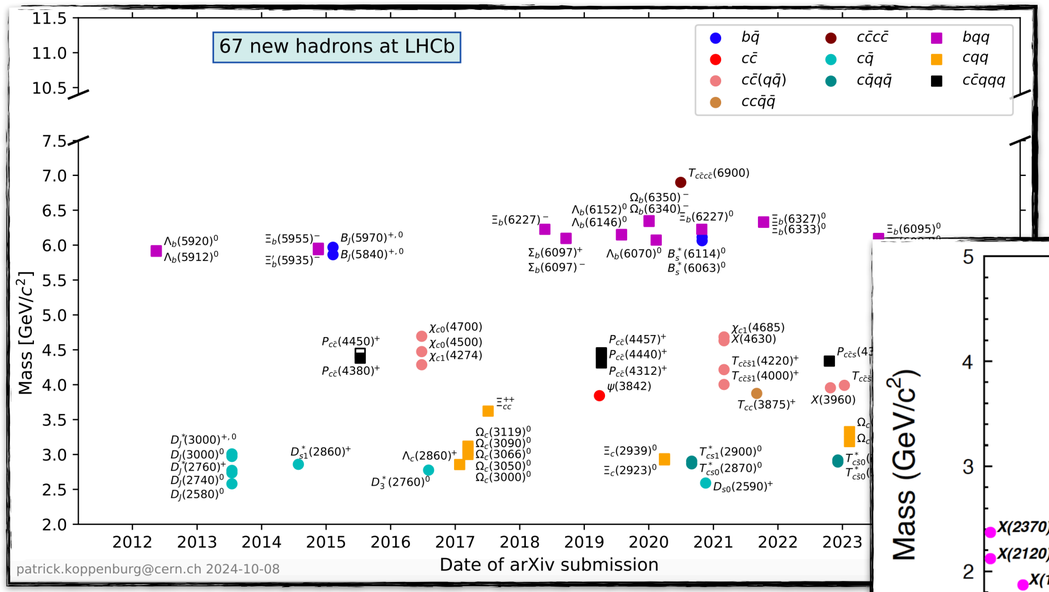
- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon

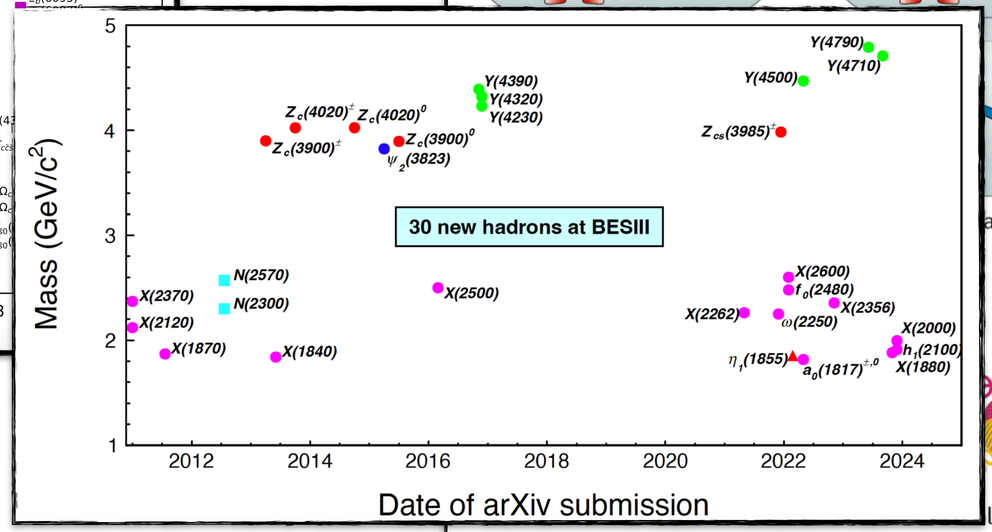




Flavour-exotic hadrons

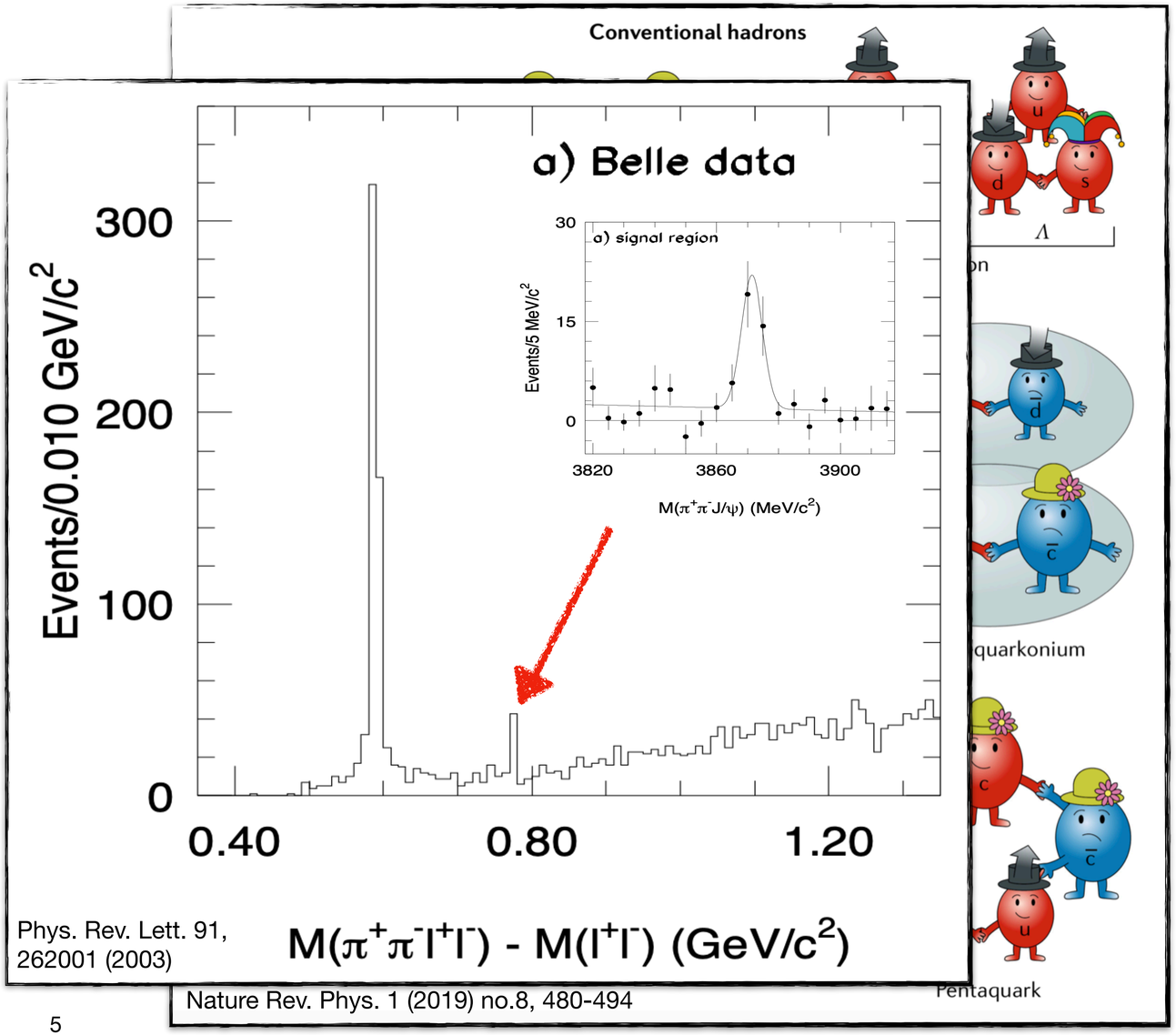
- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon





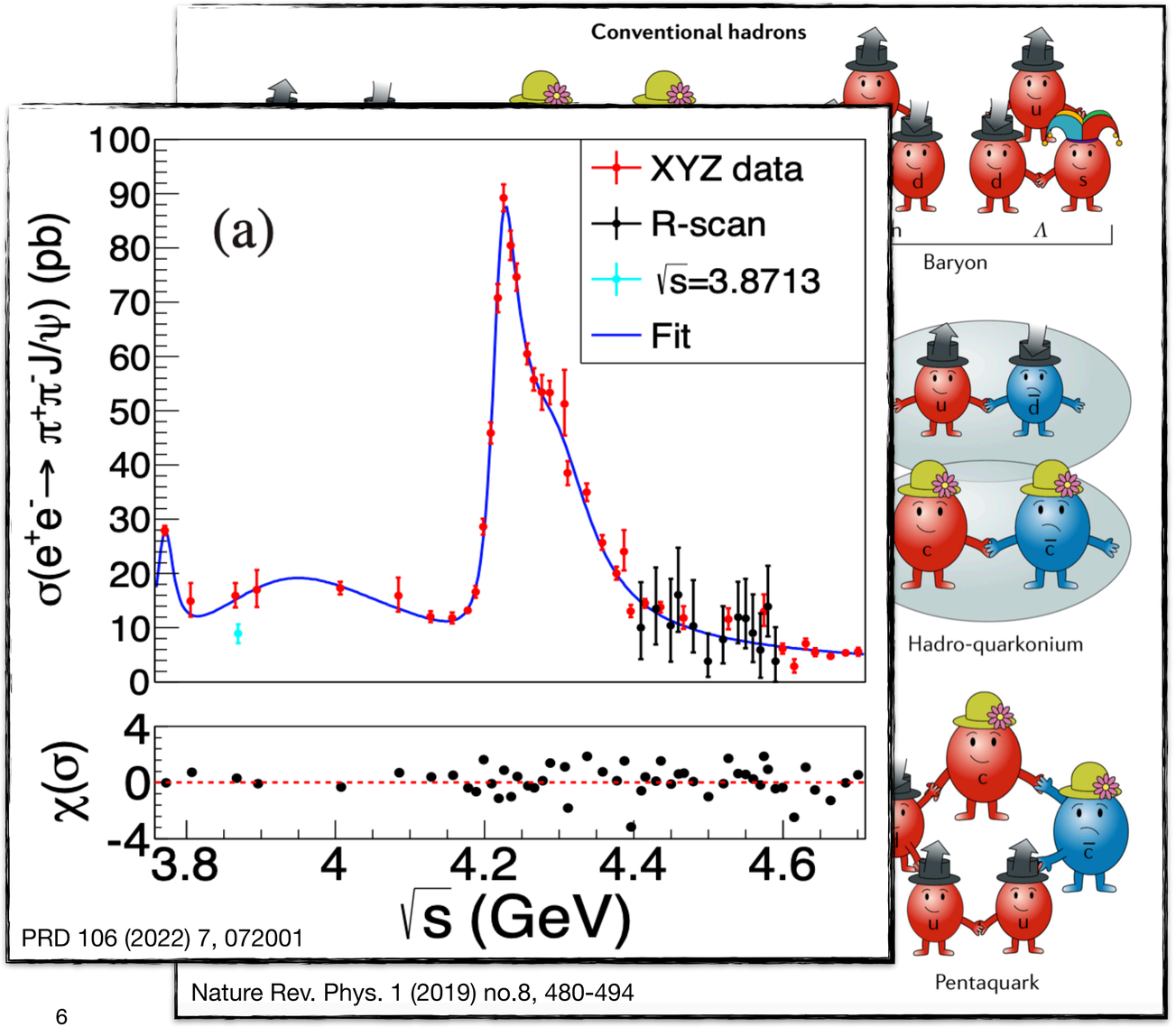
Flavour-exotic hadrons

- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon
- identification is often far from trivial:
  - mass close to two-body threshold



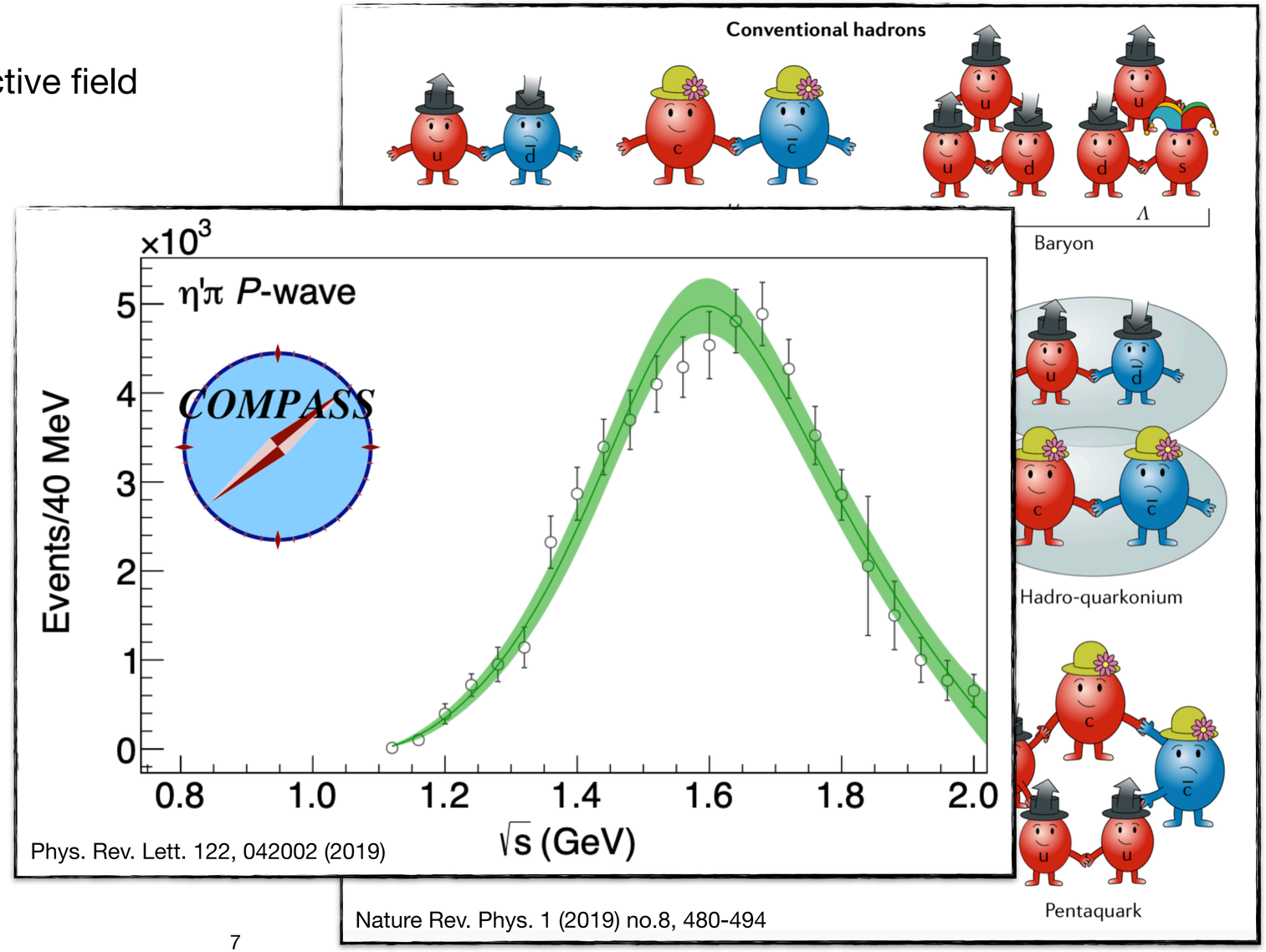
Flavour-exotic hadrons

- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon
- identification is often far from trivial:
  - mass close to two-body threshold
  - decay in an *unusual* way



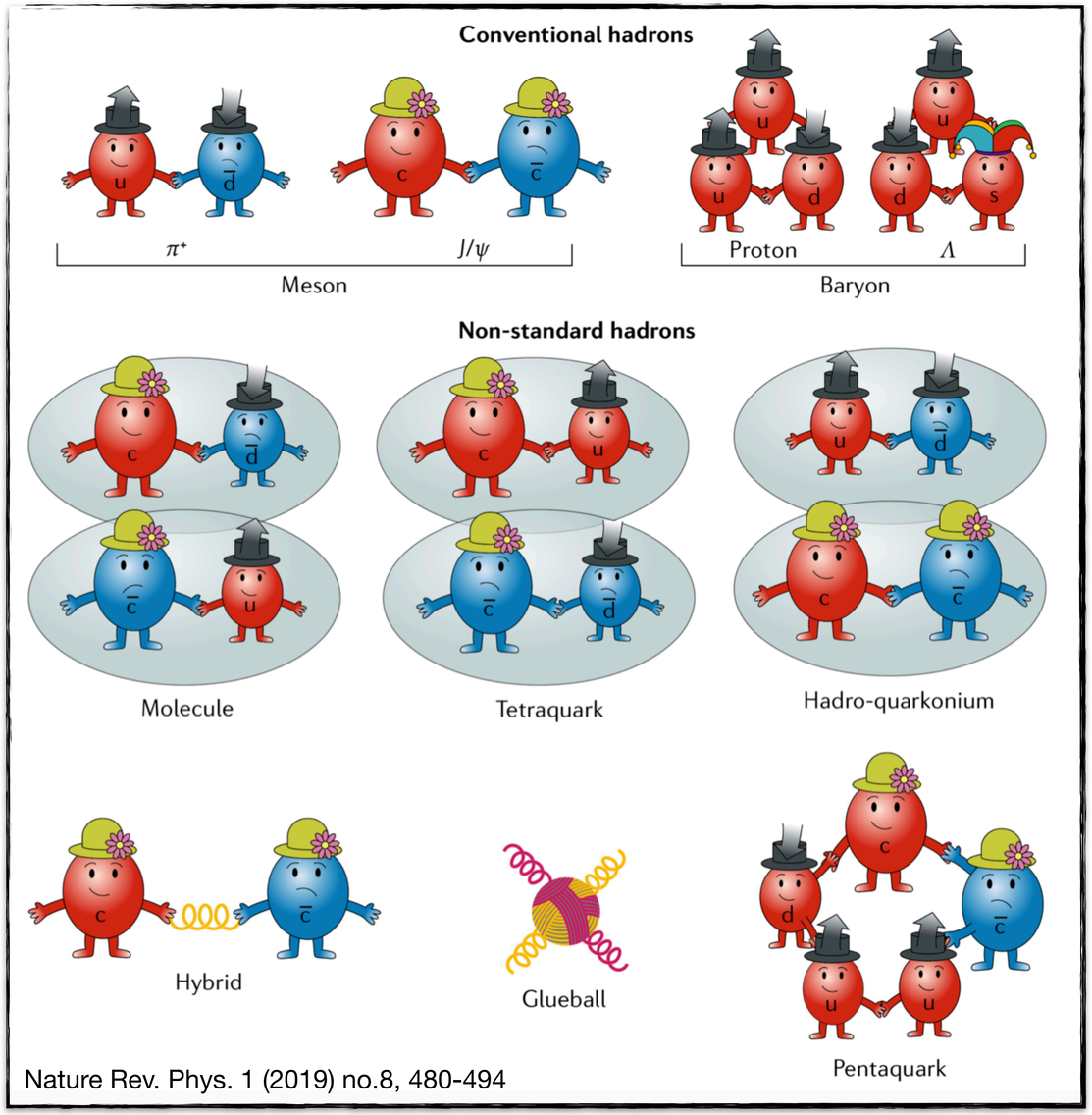
Flavour-exotic hadrons

- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon
- identification is often far from trivial:
  - mass close to two-body threshold
  - decay in an *unusual* way
  - exotic quantum numbers



Flavour-exotic hadrons

- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon
- identification is often far from trivial:
  - mass close to two-body threshold
  - decay in an *unusual* way
  - exotic quantum numbers
- but: also cases where exotic nature is clear
  → flavour-exotic: flavour quantum numbers not possible for a $q\bar{q}'$ meson or a $qq'q''$ baryon



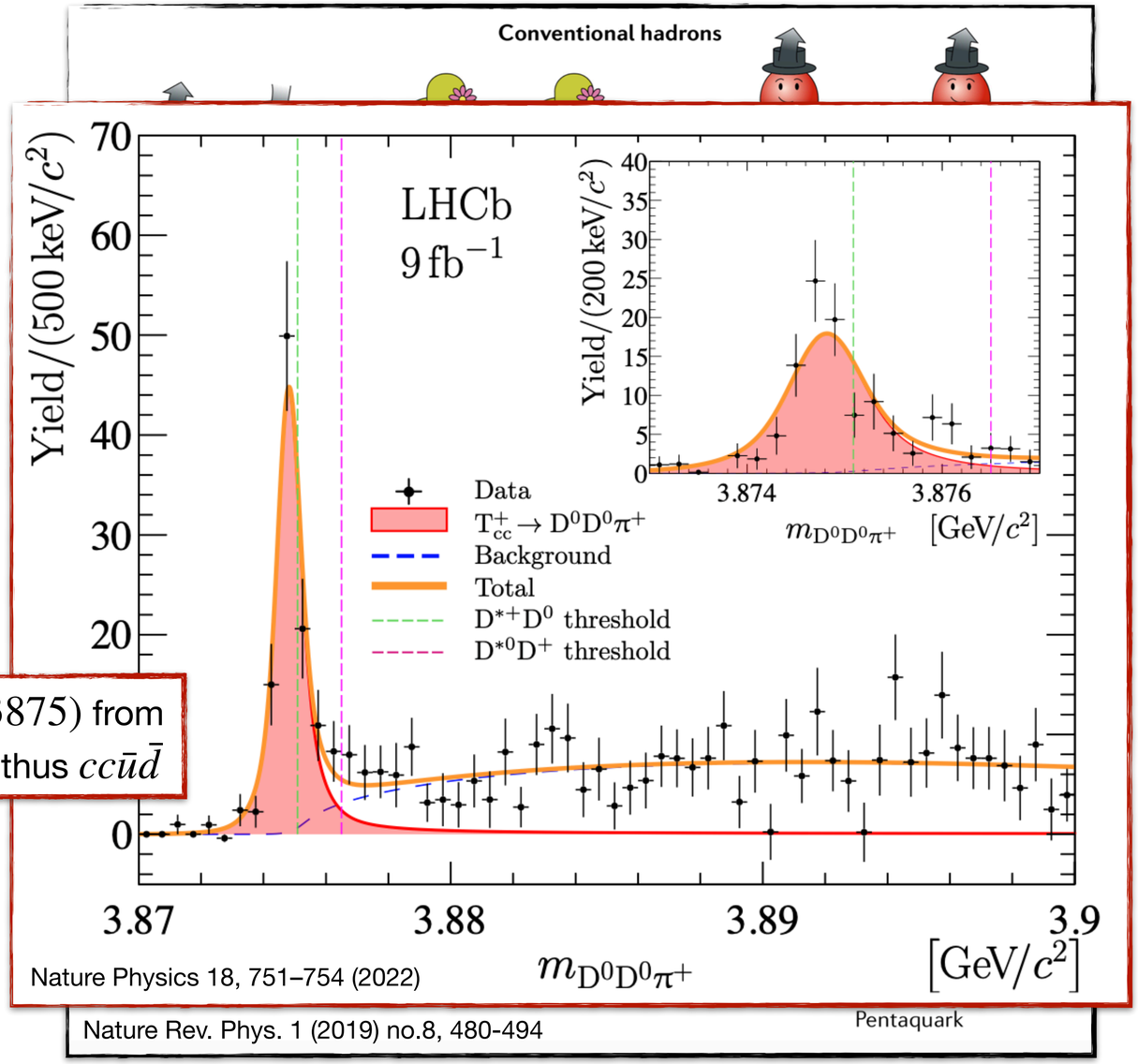
Nature Rev. Phys. 1 (2019) no.8, 480-494

Flavour-exotic hadrons

- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon
- identification is often far from trivial:
  - mass close to two-body threshold
  - decay in an *unusual* way
  - exotic quantum numbers
- but: also cases where exotic nature is clear
  → flavour-exotic: flavour quantum numbers not possible for a $q\bar{q}'$ meson or a $qq'q''$ baryon

  e.g.: doubly-charmed tetraquark

flavour-exotic $T_{cc}(3875)$ from LHCb in $D^0D^0\pi^+$, thus $cc\bar{u}\bar{d}$

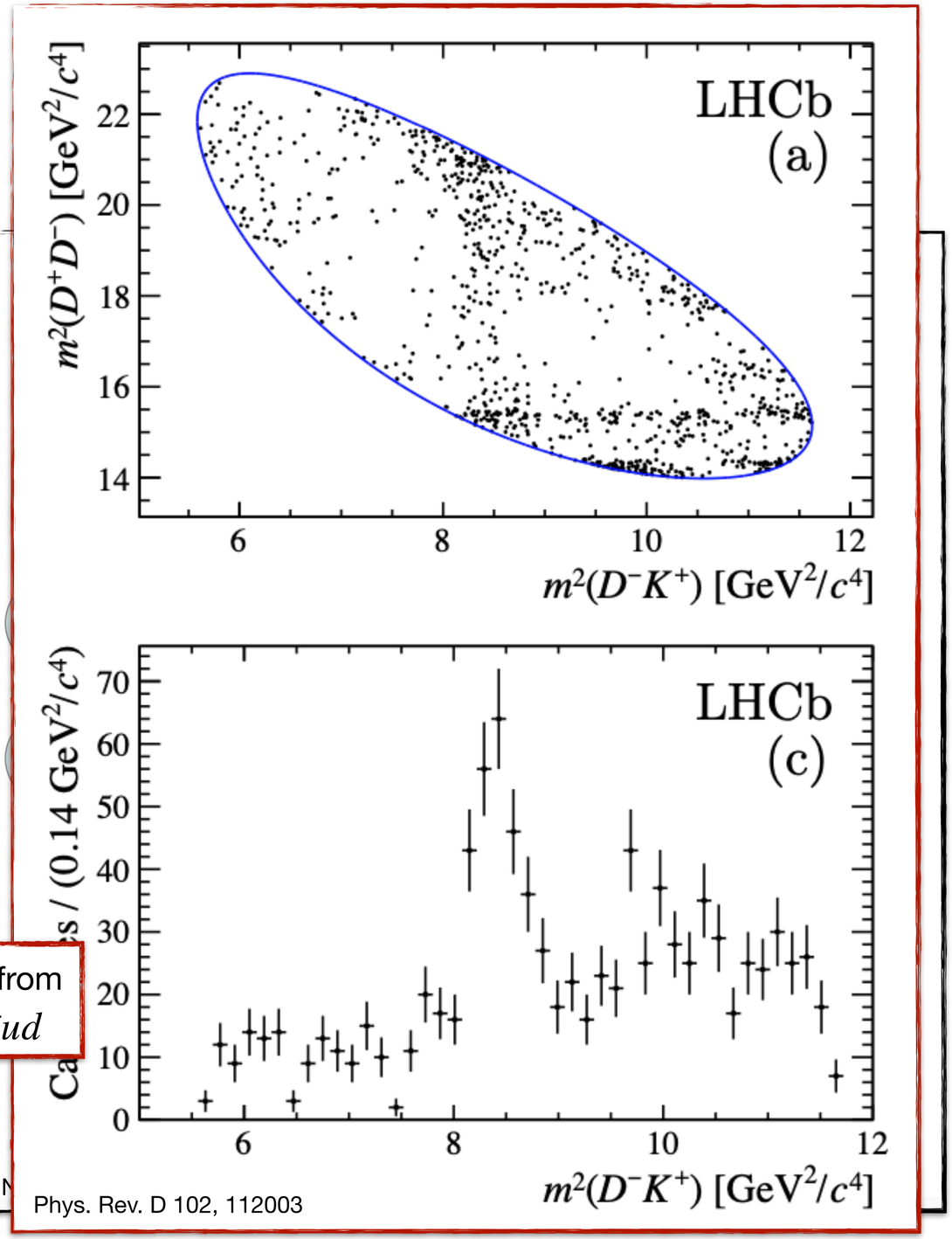


Flavour-exotic hadrons

- spectroscopy of exotic hadrons is a highly active field
- exotic: not a $q\bar{q}'$ meson or a $qq'q''$ baryon
- identification is often far from trivial:
  - mass close to two-body threshold
  - decay in an *unusual* way
  - exotic quantum numbers
- but: also cases where exotic nature is clear
  → flavour-exotic: flavour quantum numbers not possible for a $q\bar{q}'$ meson or a $qq'q''$ baryon

  e.g.: doubly-charmed tetraquark
  charmed-strange tetraquark

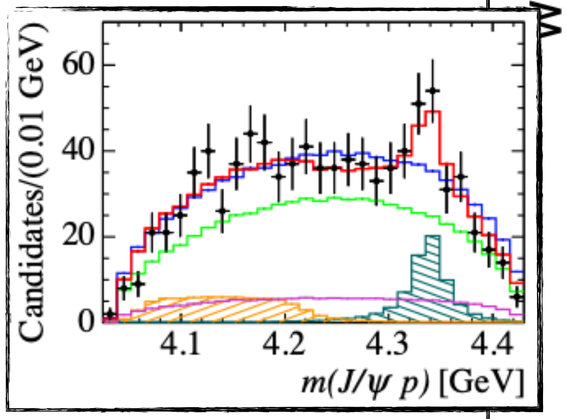
flavour-exotic $T_{cs}(2900)$ from LHCb in D^-K^+, thus $\bar{c}\bar{s}ud$



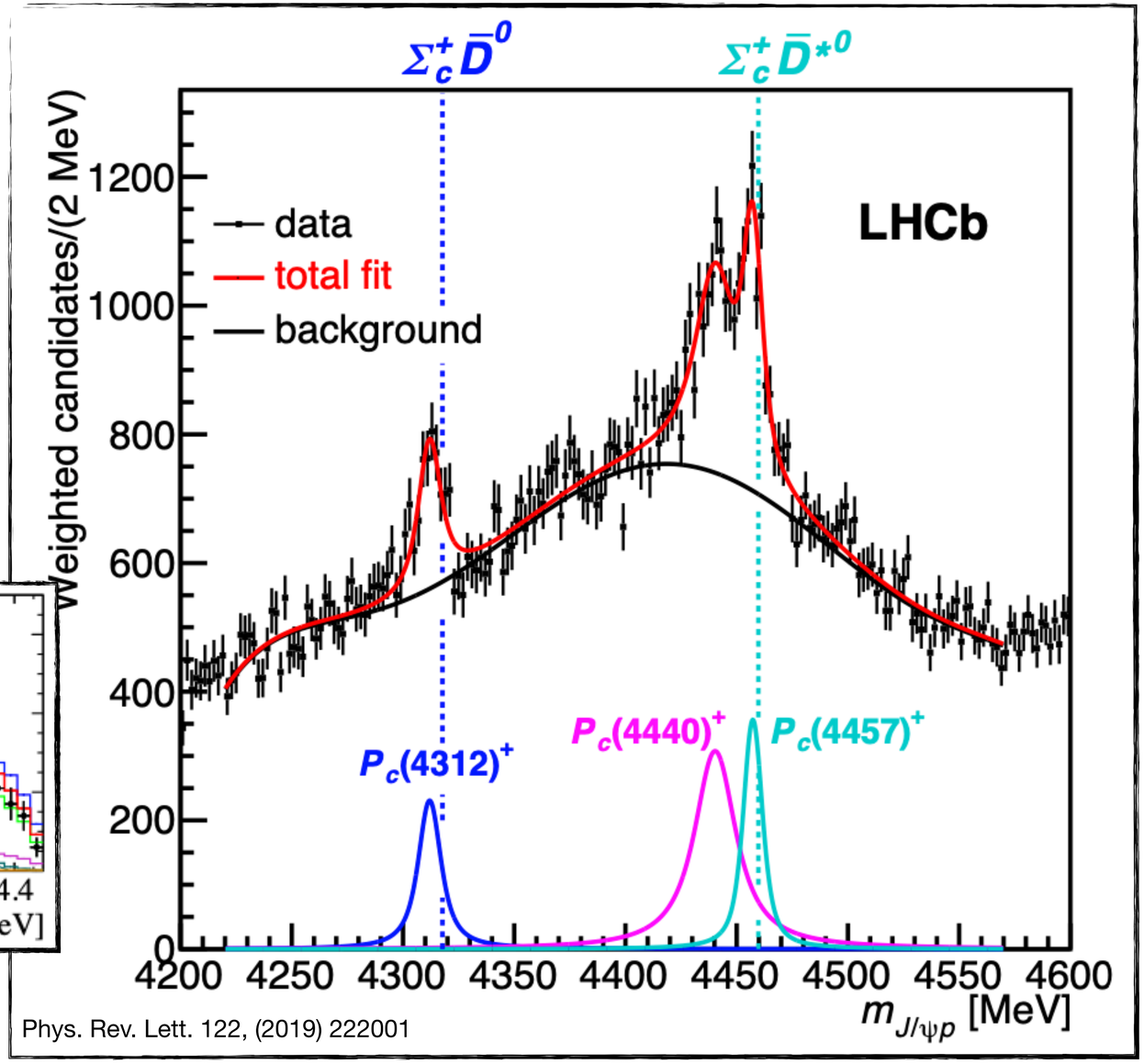
Phys. Rev. D 102, 112003

Pentaquarks

- LHCb has found multiple pentaquark candidates with hidden-charm in weak decays of bottom-hadrons
- first in 2015 in $\Lambda_b \to J/\psi p \bar{K}$, updated in 2019
- a different state in $B_s \to J/\psi p \bar{p}$



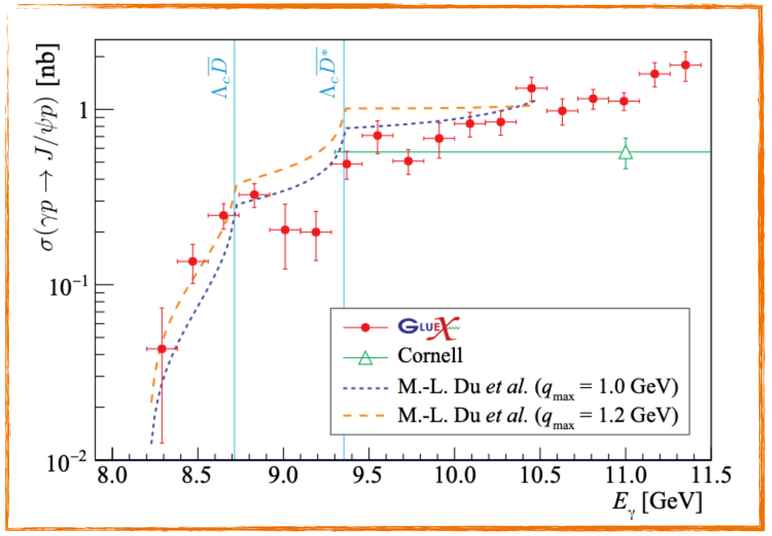
Phys. Rev. Lett. 128 (2022), 062001



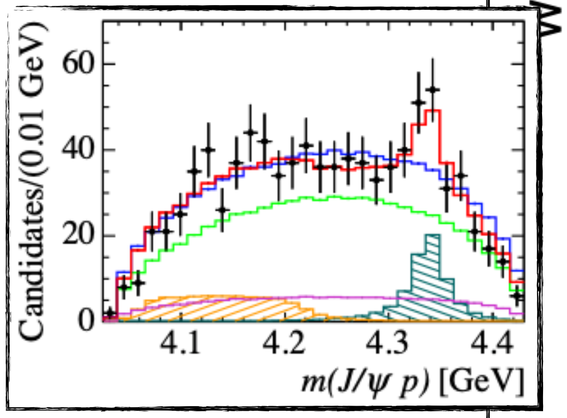
Phys. Rev. Lett. 122, (2019) 222001

Pentaquarks

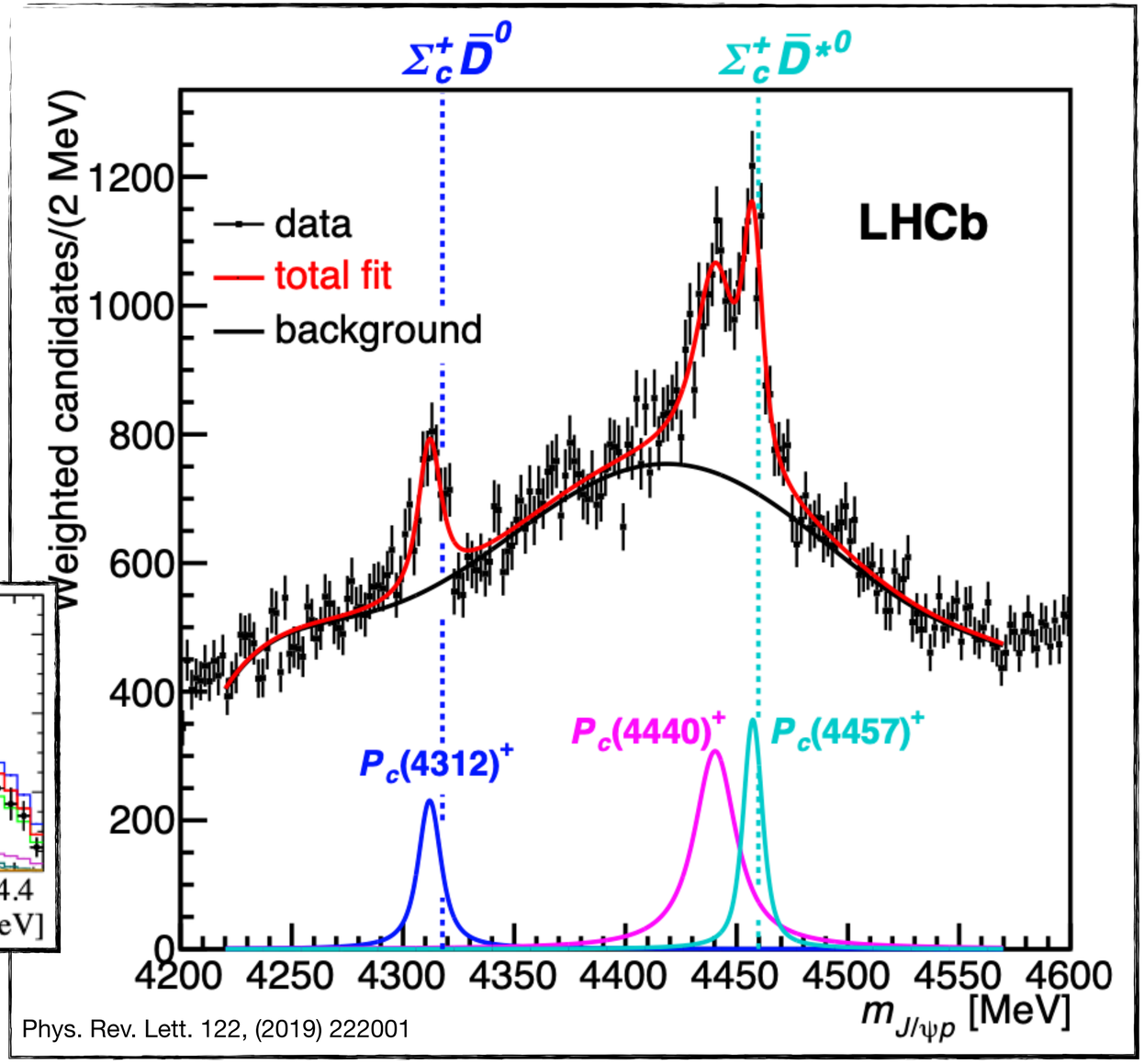
- LHCb has found multiple pentaquark candidates with hidden-charm in weak decays of bottom-hadrons
- first in 2015 in $\Lambda_b \to J/\psi p \bar{K}$, updated in 2019
- a different state in $B_s \to J/\psi p \bar{p}$
- photo-production not conclusive (yet!)



Phys. Rev. C 108 (2023), 025201
see also: Phys. Rev. D 108 (2023) 5, 054018



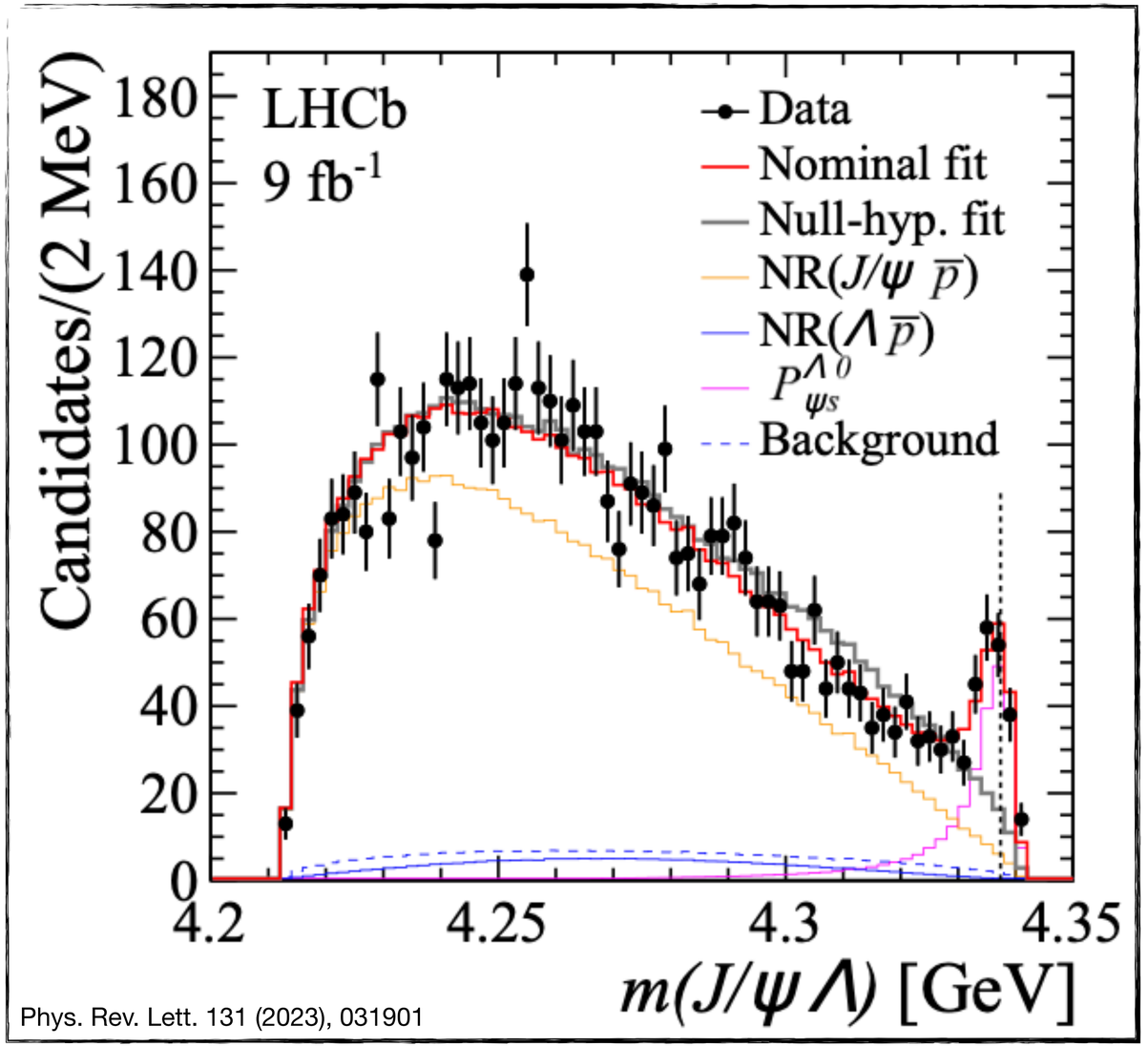
Phys. Rev. Lett. 128 (2022), 062001



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

Pentaquarks

- LHCb has found multiple pentaquark candidates with hidden-charm in weak decays of bottom-hadrons
- first in 2015 in $\Lambda_b \to J/\psi p \bar{K}$, updated in 2019
- a different state in $B_s \to J/\psi p \bar{p}$
- photo-production not conclusive (yet!)
- LHCb also found an open-strange candidate in $B \to J/\psi \Lambda \bar{p}$
- many of the LHCb pentaquark states are observed near two-body thresholds: $\Sigma_c \bar{D}^{(*)}, \Lambda_c \bar{D}^{(*)}, \Xi_c \bar{D}^{(*)}$

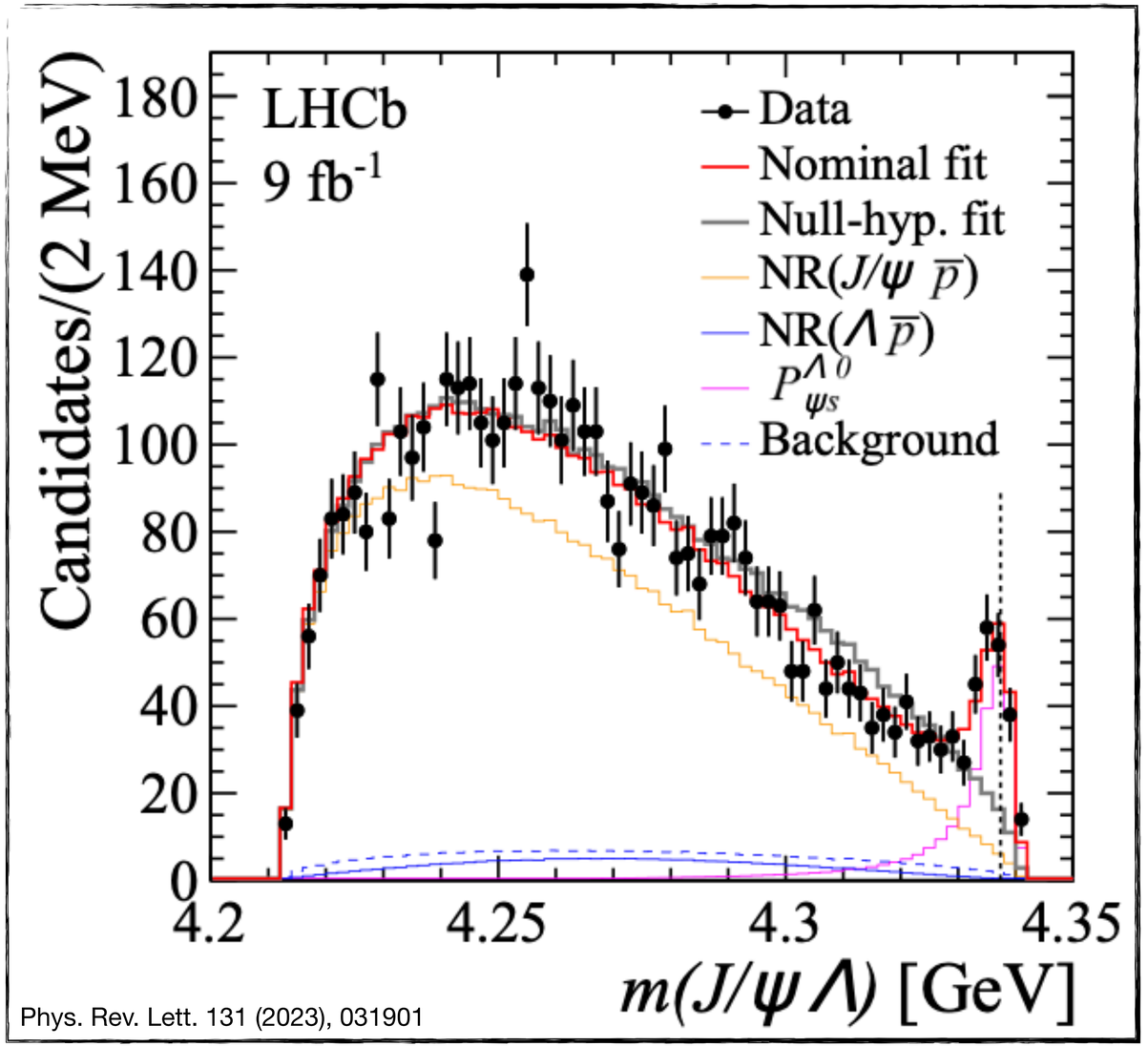


Phys. Rev. Lett. 131 (2023), 031901

Pentaquarks

- LHCb has found multiple pentaquark candidates with hidden-charm in weak decays of bottom-hadrons
- first in 2015 in $\Lambda_b \to J/\psi p \bar{K}$, updated in 2019
- a different state in $B_s \to J/\psi p \bar{p}$
- photo-production not conclusive (yet!)
- LHCb also found an open-strange candidate in $B \to J/\psi \Lambda \bar{p}$
- many of the LHCb pentaquark states are observed near two-body thresholds: $\Sigma_c \bar{D}^{(*)}, \Lambda_c \bar{D}^{(*)}, \Xi_c \bar{D}^{(*)}$

if we see flavour-exotic states, and we see pentaquarks - how about flavour-exotic pentaquarks?



Phys. Rev. Lett. 131 (2023), 031901

Flavour-exotic pentaquarks

old idea: potentially stable $\bar{Q}qqqq$ pentaquarks
(first mentioned 1987, actually coined the term pentaquarks)

→ flavour-exotic with anti-charm in a baryon
→ unique experimental signature

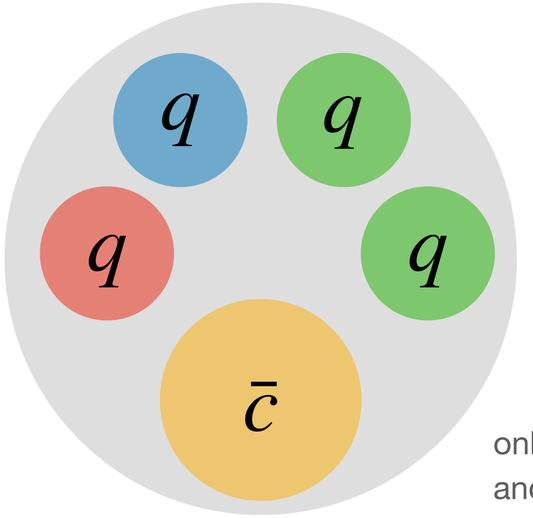
Gignoux, Silvester-Brac, Richard, Phys. Lett. B 193 (1987) 323-326
Lipkin, Phys. Lett. B 195 (1987) 484-488

$P_{\bar{c}s} = \bar{c}sqqq$ stable with respect to $N\bar{D}_s$ and $\Lambda\bar{D}$ thresholds

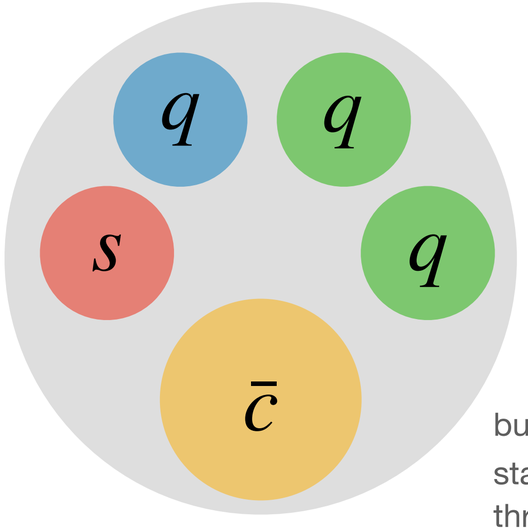
many additional works since

Eur. Phys. J. C 64:283-295, 2009
Phys. Lett. B 595 (2004) 293-300
Phys. Lett. B 590 (2004) 185-189
arXiv:2408.12881
arXiv:2407.05598
…

Phys. Rev. D. 109, 074035 (2024)
Phys. Rev. D 69 (2004) 114017
Phys. Rev. D 105, 034018 (2022)
Phys. Rev. D 105, 094026 (2022)
Phys. Rev. C 100, 015203 (2019)



only few models (among them Jaffe and Wilczek) find $P_{\bar{c}}$ as stable with respect to $p\bar{D}$ threshold



but many calculations find $P_{\bar{c}s}$ as stable with respect to $p\bar{D}_s$, $\Lambda\bar{D}$ thresholds

Flavour-exotic pentaquarks

old idea: potentially stable $\bar{Q}qqqq$ pentaquarks
(first mentioned 1987, actually coined the term pentaquarks)

→ flavour-exotic with anti-charm in a baryon
→ unique experimental signature

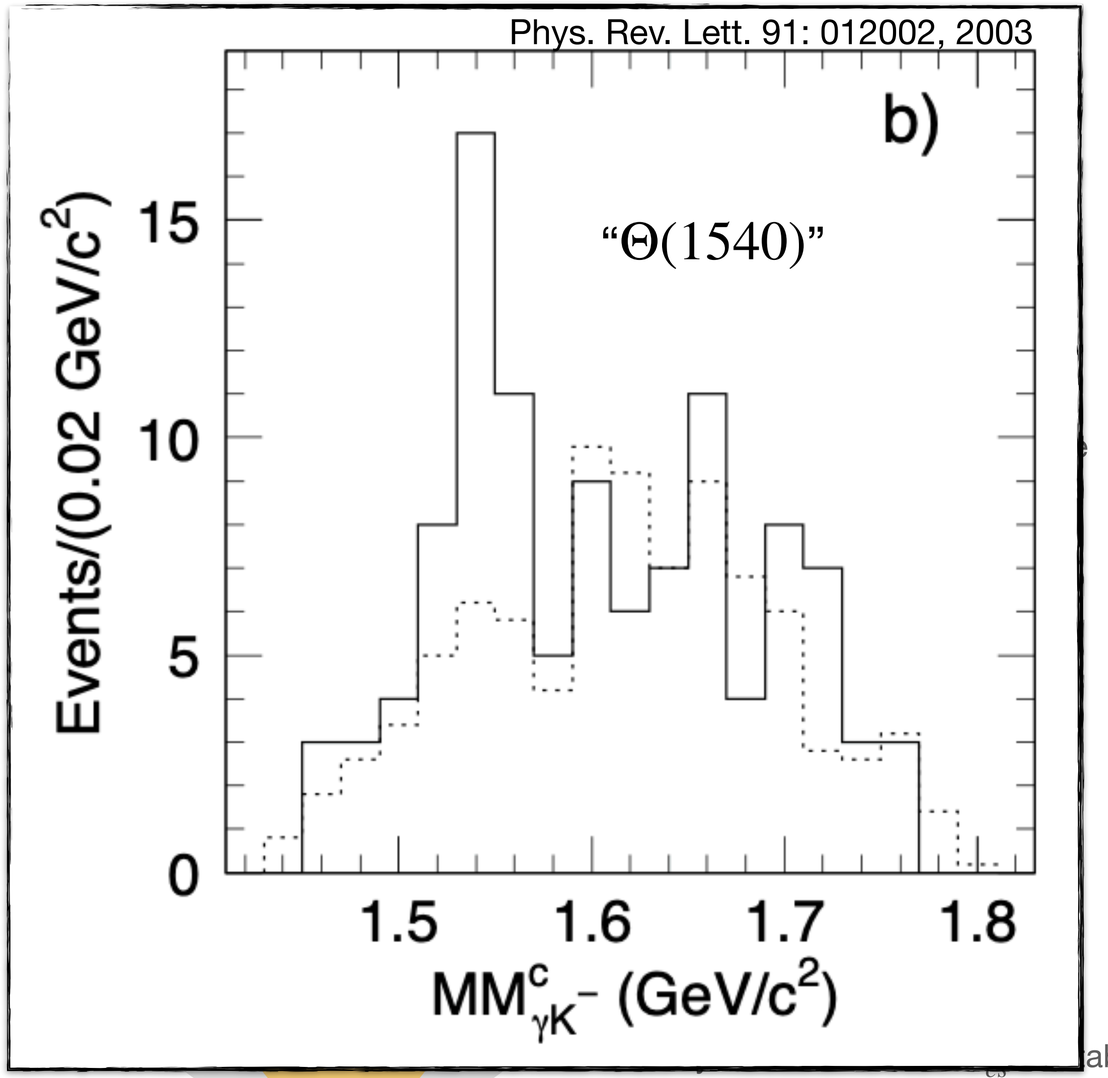
Gignoux, Silvester-Brac, Richard, Phys. Lett. B 193 (1987) 323-326
Lipkin, Phys. Lett. B 195 (1987) 484-488

$P_{\bar{c}s} = \bar{c}sqqq$ stable with respect to $N\bar{D}_s$ and $\Lambda\bar{D}$ thresholds

many additional works since

Eur. Phys. J. C 64:283-295, 2009
Phys. Lett. B 595 (2004) 293-300
Phys. Lett. B 590 (2004) 185-189
arXiv:2408.12881
arXiv:2407.05598
…

Phys. Rev. D. 109, 074035 (2024)
Phys. Rev. D 69 (2004) 114017
Phys. Rev. D 105, 034018 (2022)
Phys. Rev. D 105, 094026 (2022)
Phys. Rev. C 100, 015203 (2019)

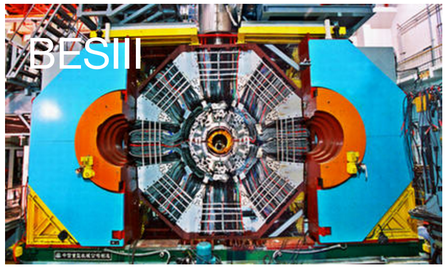


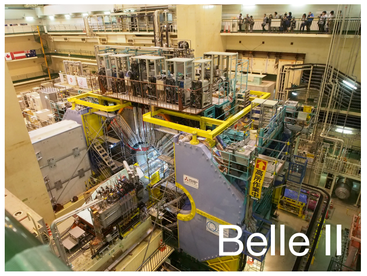
able
with respect to $p\bar{D}_s, \Lambda\bar{D}$ thresholds

Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$ pentaquark?

- e^+e^- annihilation?





→ stable: we would need pair-production

→ not stable: threshold $> 2m_p + 2m_D \approx 5.6$ GeV

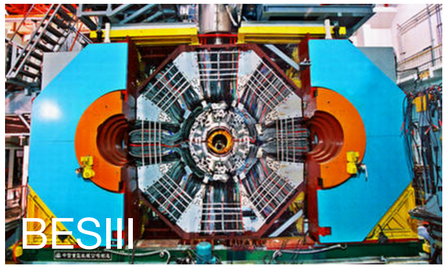
→ flavour + baryon number: $\gamma^* \to 4(q\bar{q}) + c\bar{c}$

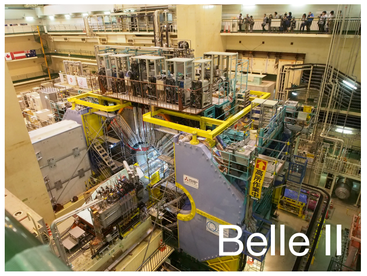
→ this seems very unlikely??

Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$ pentaquark?

- e^+e^- annihilation?





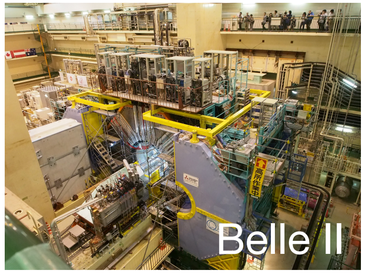
→ stable: we would need pair-production

→ not stable: threshold $> 2m_p + 2m_D \approx 5.6$ GeV

→ flavour + baryon number: $\gamma^* \to 4(q\bar{q}) + c\bar{c}$

→ this seems very unlikely??

- b-quark decays?



→ something like $B_{(s)} \to P_{\bar{c}(s)}\bar{N}$ could work

→ not stable: $P_{\bar{c}(s)} \to p\bar{D}_{(s)}$

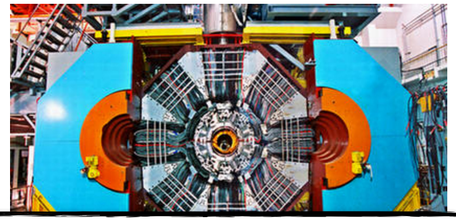
→ stable: need to reconstruct weak decay!

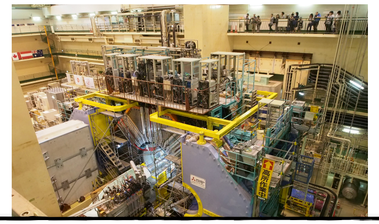
$P_{\bar{c}(s)} \to K^*\pi p,\ (\phi\pi p,\ K^*\bar{K}p)$

Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$ pentaquark?

- e^+e^- annihilation?





→ stable: we would need pair-production

→ not stable: threshold $> 2m_p + 2m_D \approx 5.6$ GeV

→ flavour + baryon number: $\gamma^* \rightarrow 4(q\bar{q}) + c\bar{c}$

nlikely??

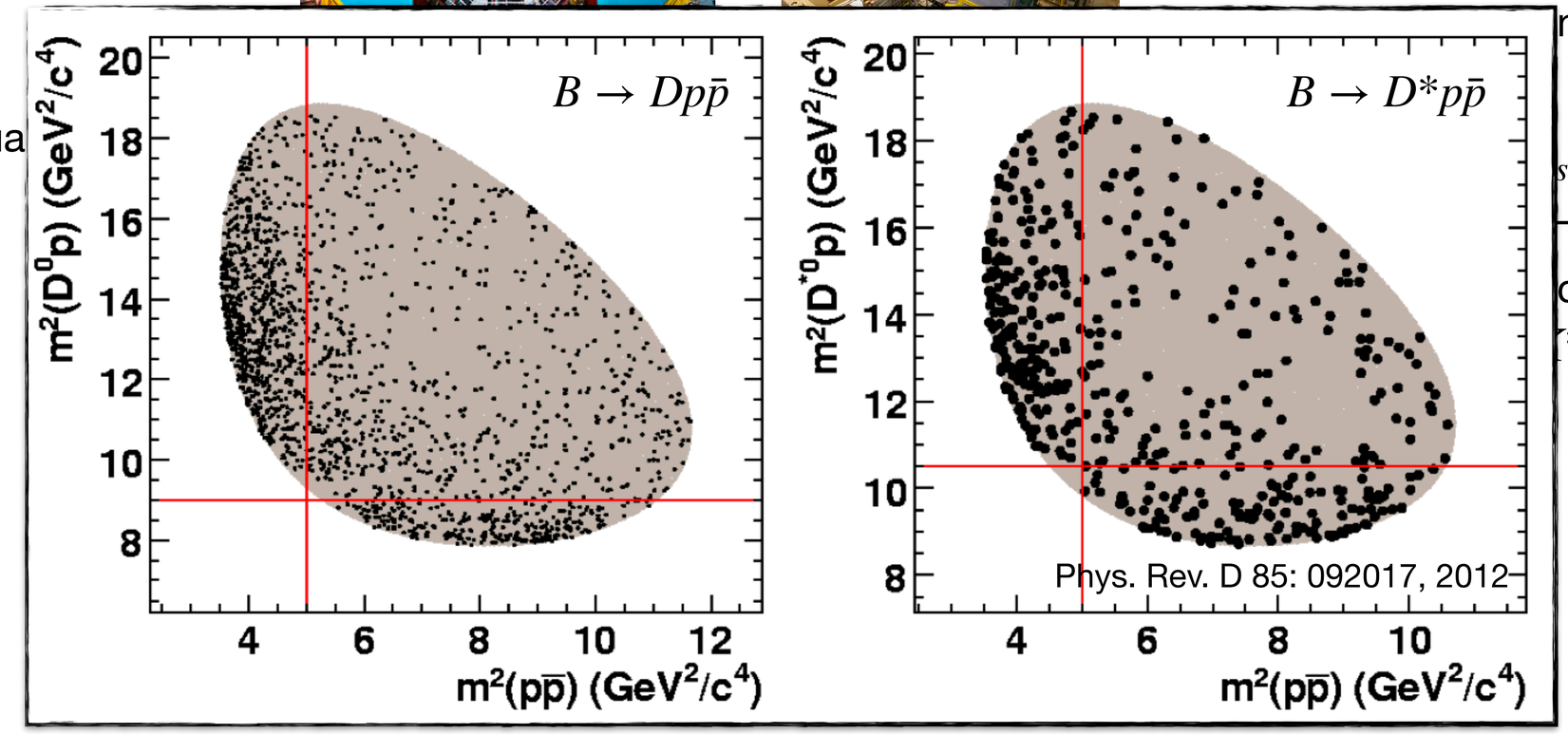
- b-qua

$_{s)} \rightarrow P_{\bar{c}(s)}\bar{N}$ could work

$\rightarrow p\bar{D}_{(s)}$

construct weak decay!

$^*\pi p$, $(\phi\pi p,\ K^*\bar{K}p)$



Flavour-exotic pentaquarks

how would we sear

- e^+e^- annihilation

d pair-production

$> 2m_p + 2m_D \approx 5.6$ GeV

ber: $\gamma^* \to 4(q\bar{q}) + c\bar{c}$

ely??

- b-quark decays?

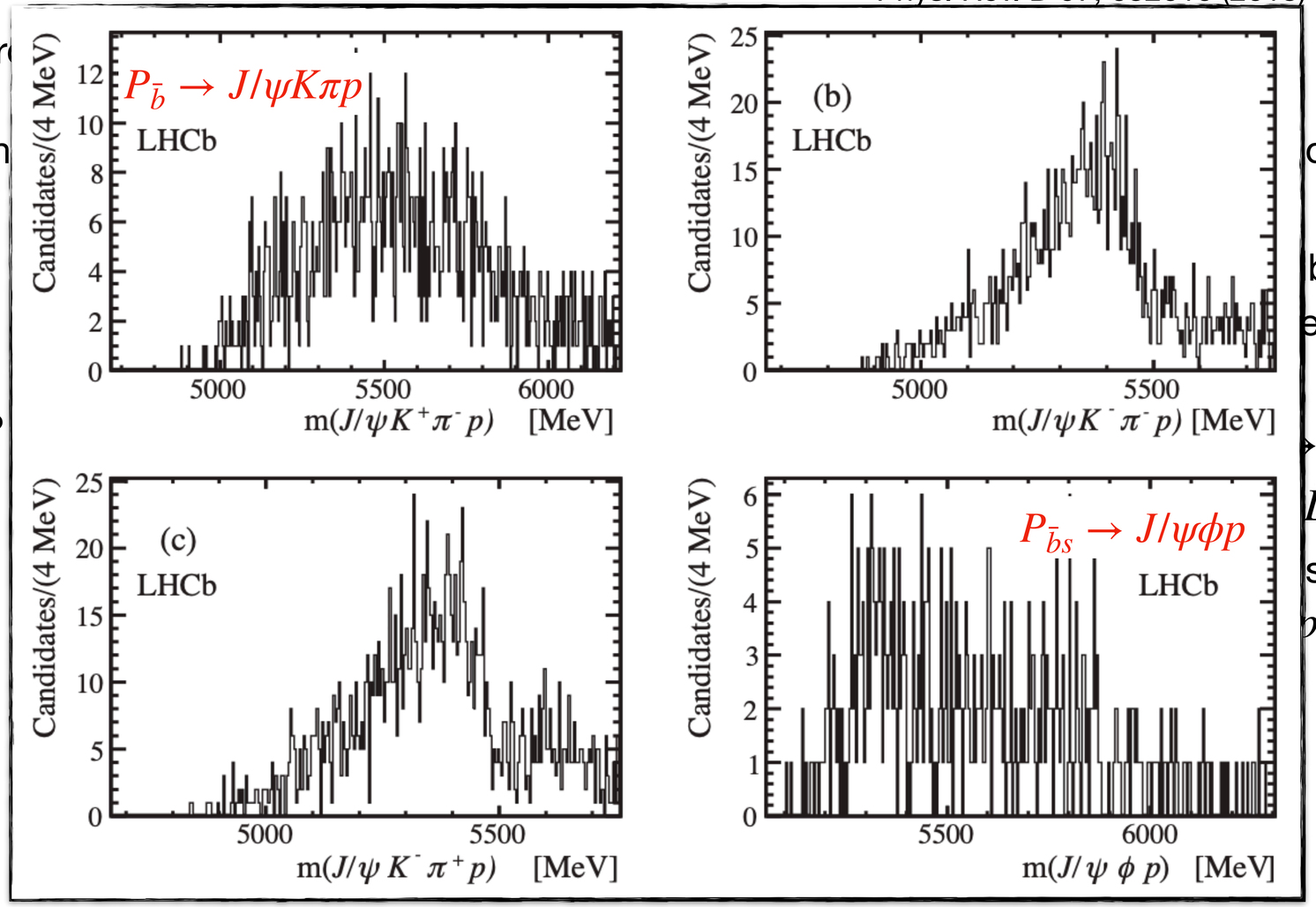
→ $P_{\bar{c}(s)}\bar{N}$ could work

$\bar{D}_{(s)}$

struct weak decay!

ρ, $(\phi\pi p,\ K^*\bar{K}p)$

Phys. Rev. D 97, 032010 (2018)

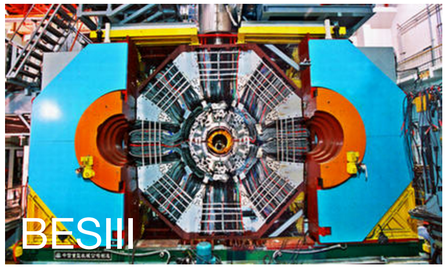


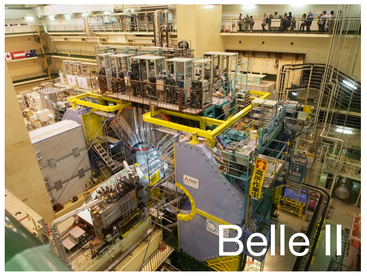
using $\bar{b} \to \bar{c}c\bar{s}$

Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$ pentaquark?

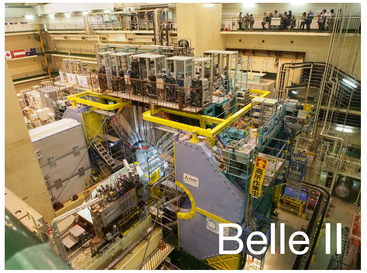
- e^+e^- annihilation?





→ stable: we would need pair-production
→ not stable: threshold $> 2m_p + 2m_D \approx 5.6$ GeV
→ flavour + baryon number: $\gamma^* \to 4(q\bar{q}) + c\bar{c}$
→ this seems very unlikely??

- b-quark decays?



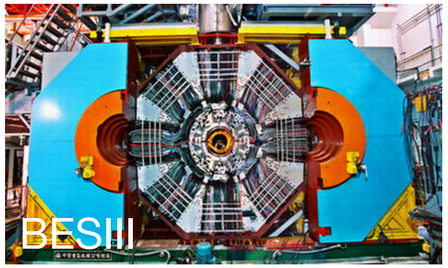
→ something like $B_{(s)} \to P_{\bar{c}(s)}\bar{N}$ could work
→ not stable: $P_{\bar{c}(s)} \to p\bar{D}_{(s)}$
→ stable: need to reconstruct weak decay!
$P_{\bar{c}(s)} \to K^*\pi p,\ (\phi\pi p,\ K^*\bar{K}p)$

- photo- or electro-production?

Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$

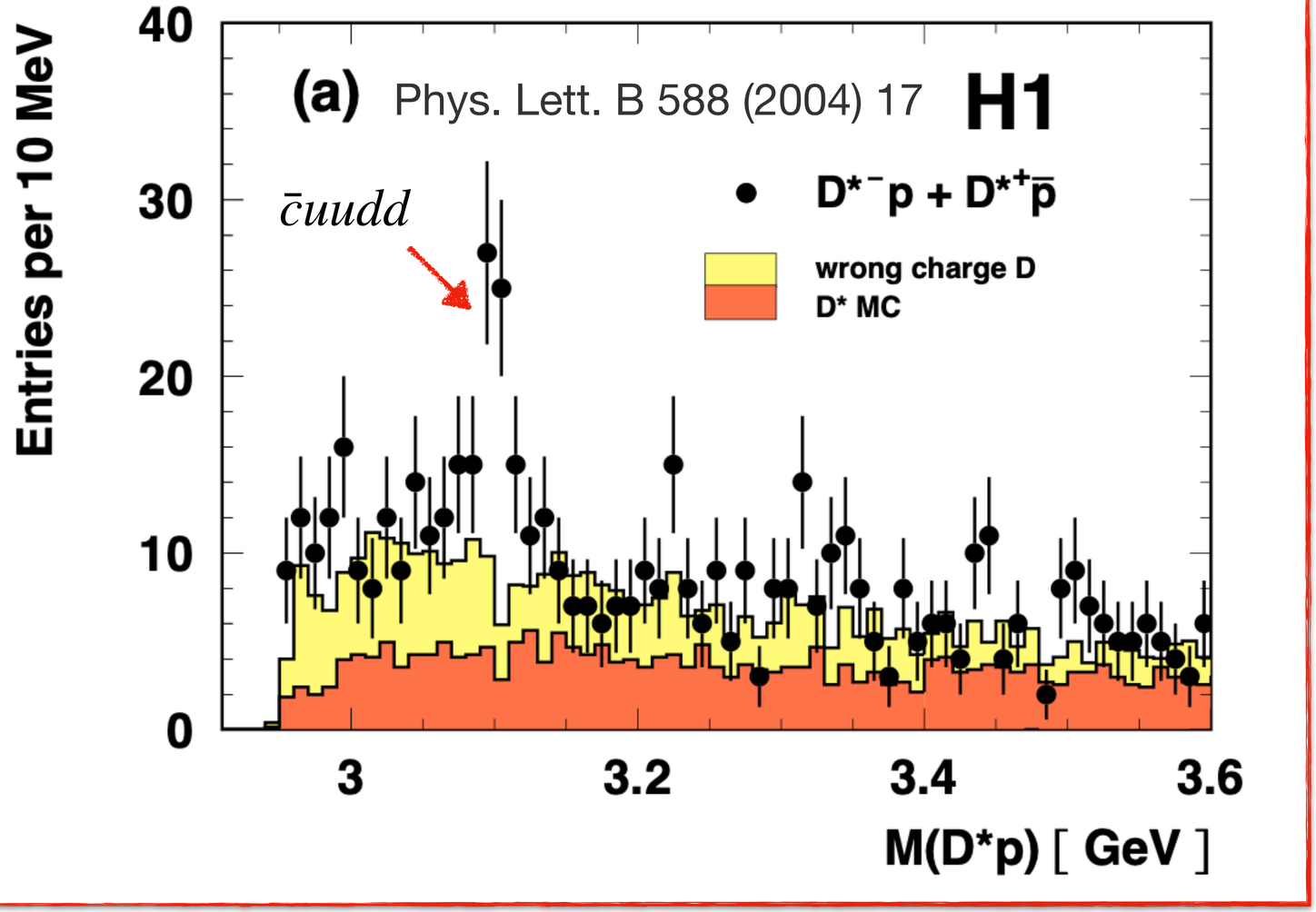
- e^+e^- annihilation?



- b-quark decays?

- photo- or electro-production?

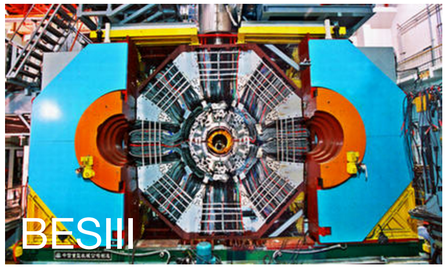
DIS



Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$ |

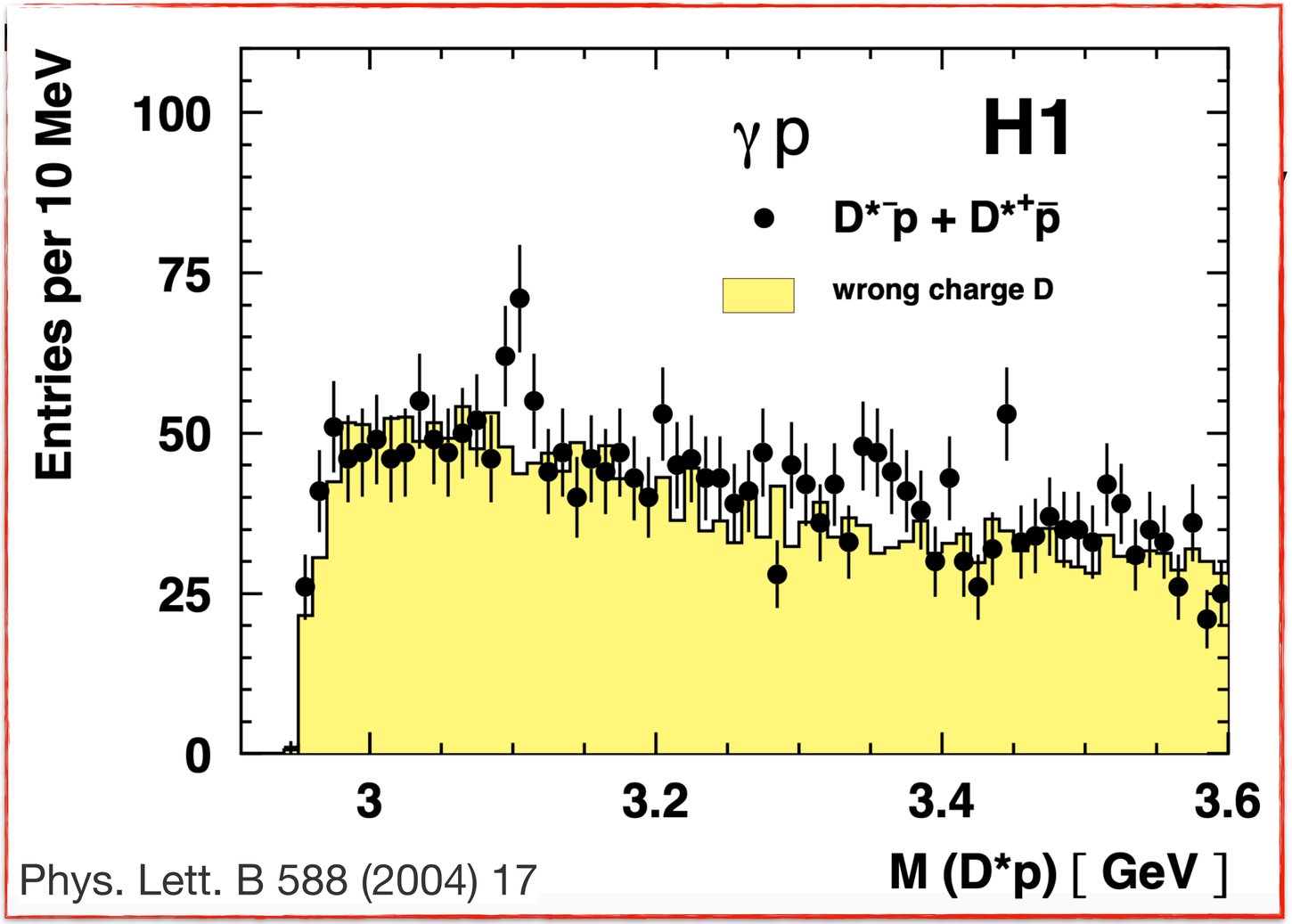
- e^+e^- annihilation?



- b-quark decays?

- photo- or electro-production?

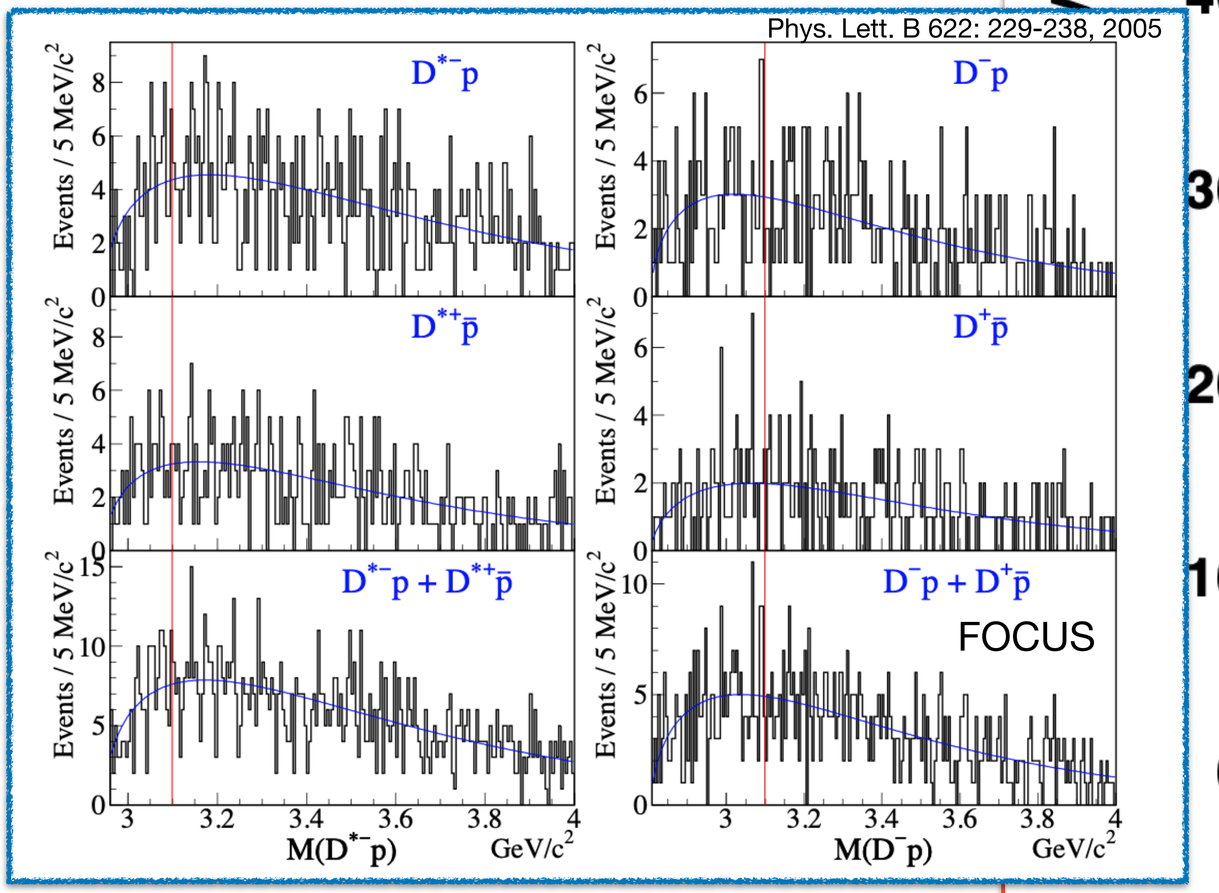
photo-production

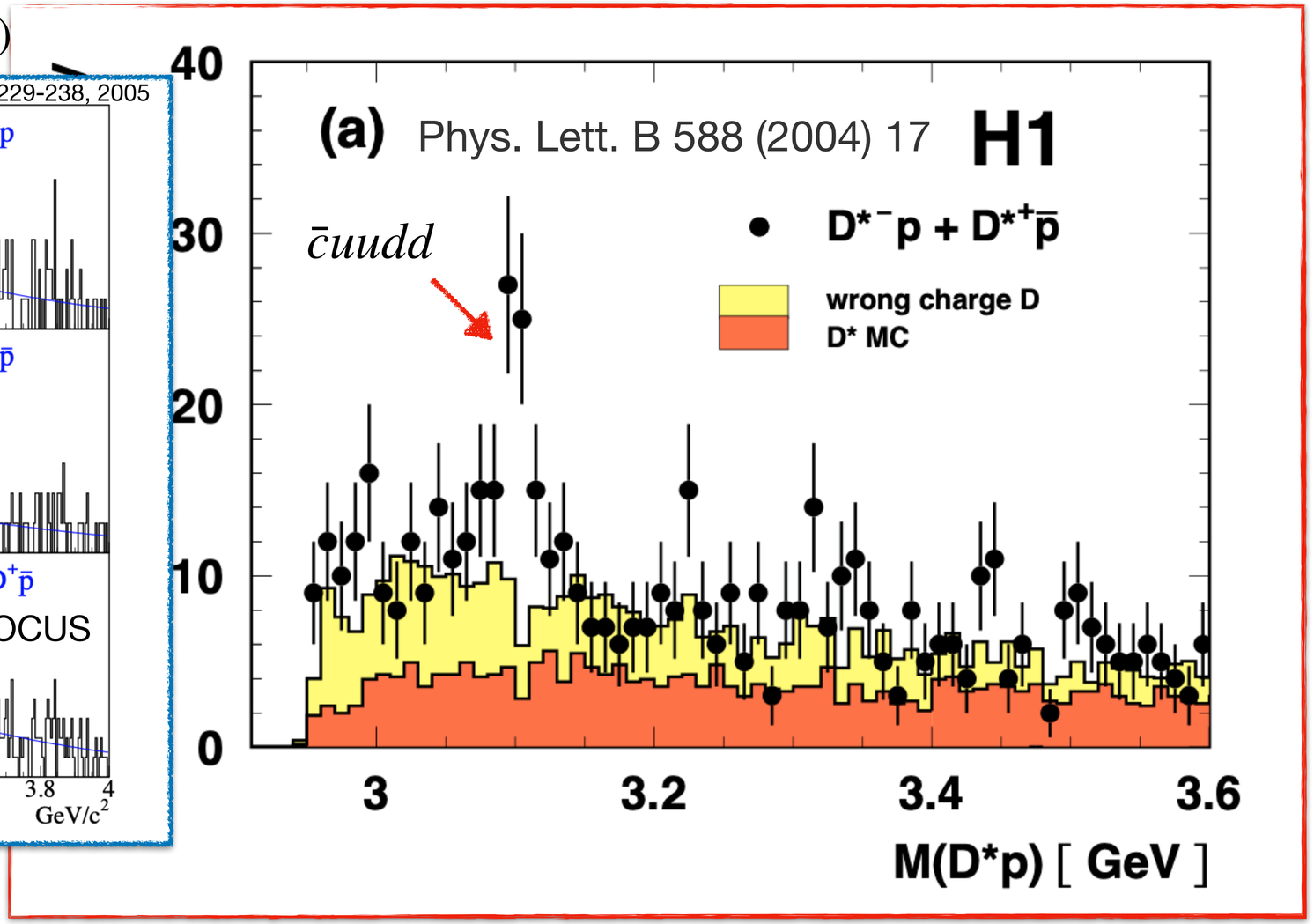


Phys. Lett. B 588 (2004) 17

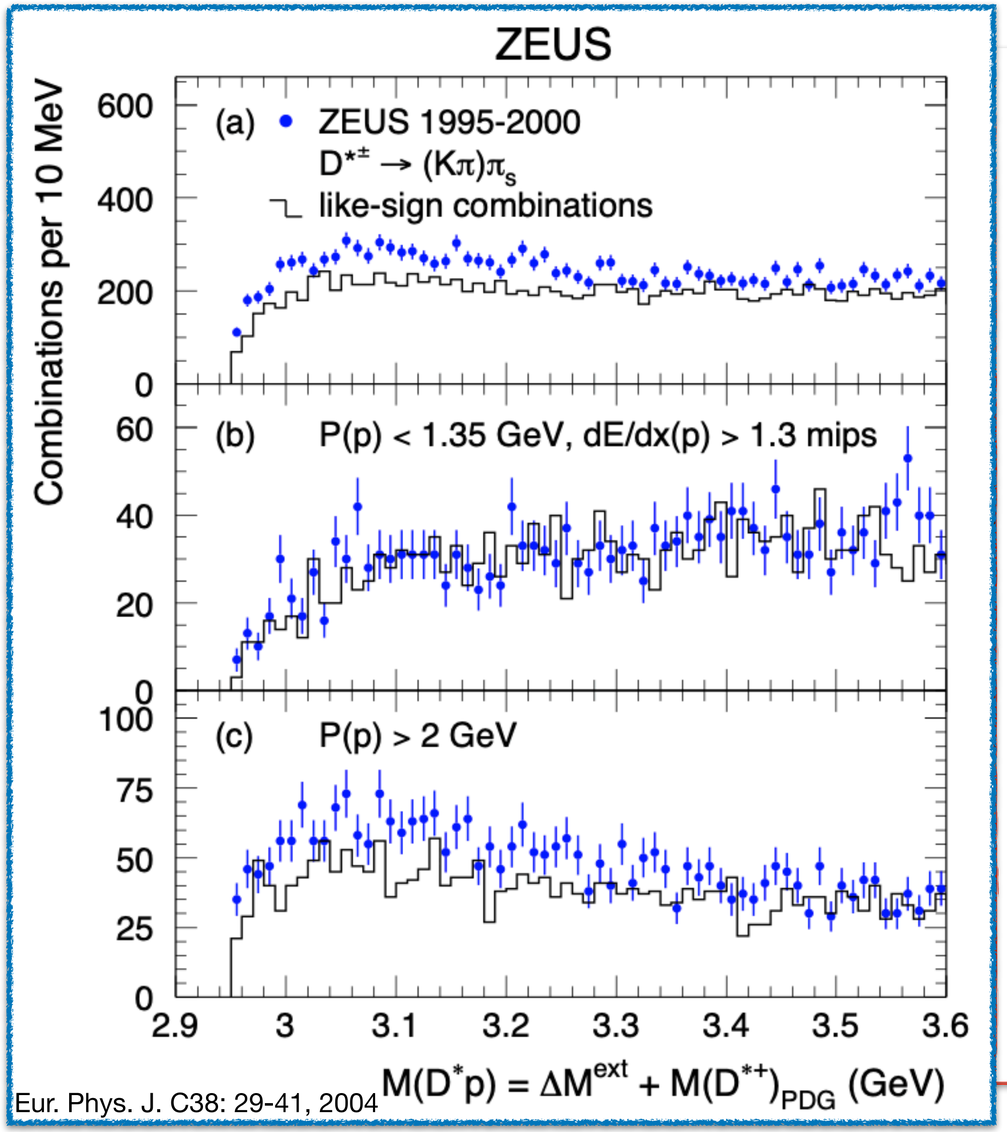
Flavour-exotic pentaquarks

how would we search for a $(qqqq\bar{c})$ or $(qqqs\bar{c})$

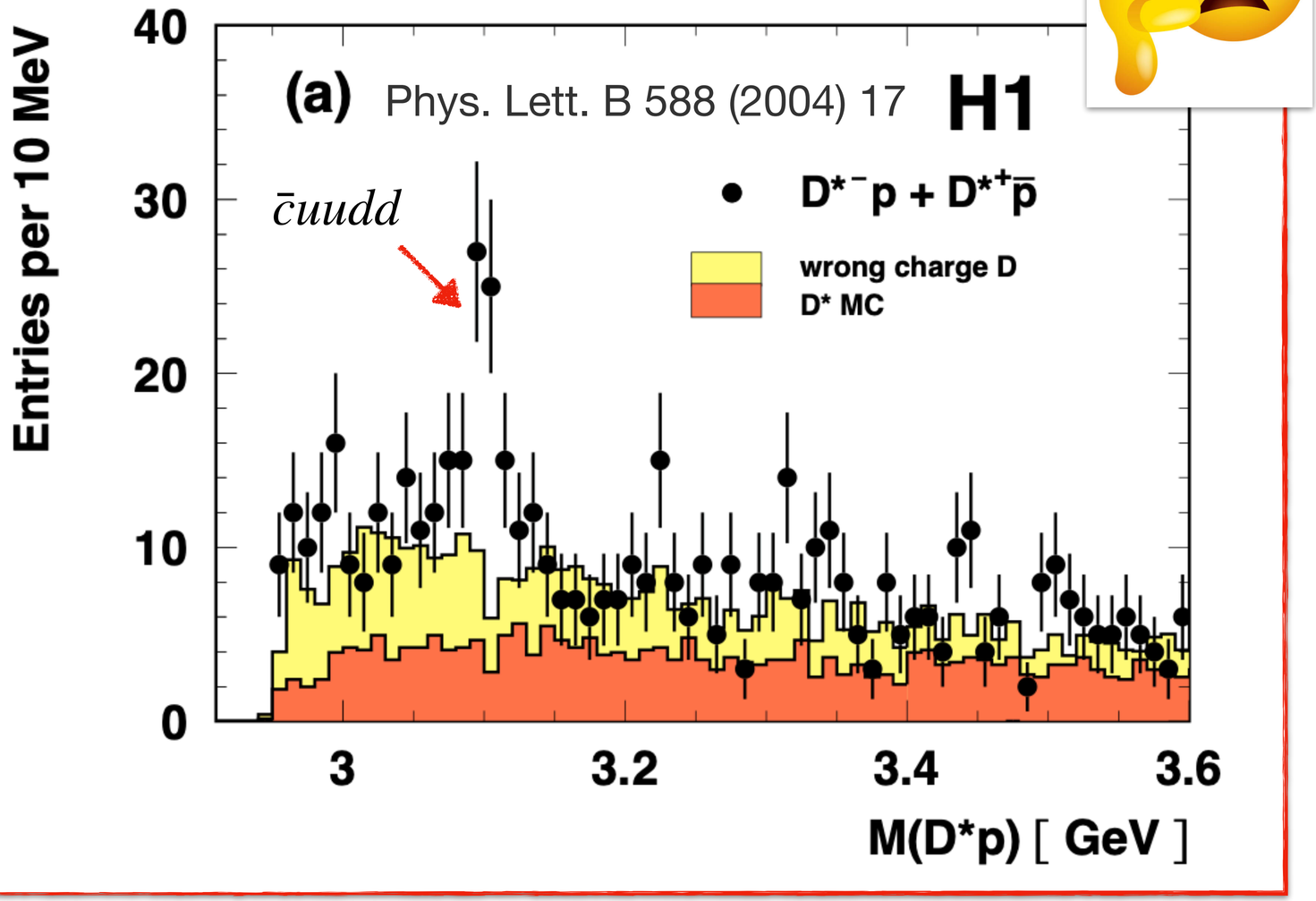


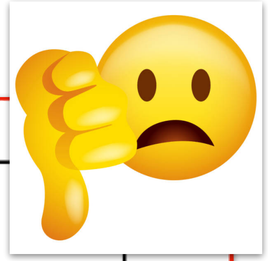


Flavour-exotic pentaquarks



Eur. Phys. J. C38: 29-41, 2004





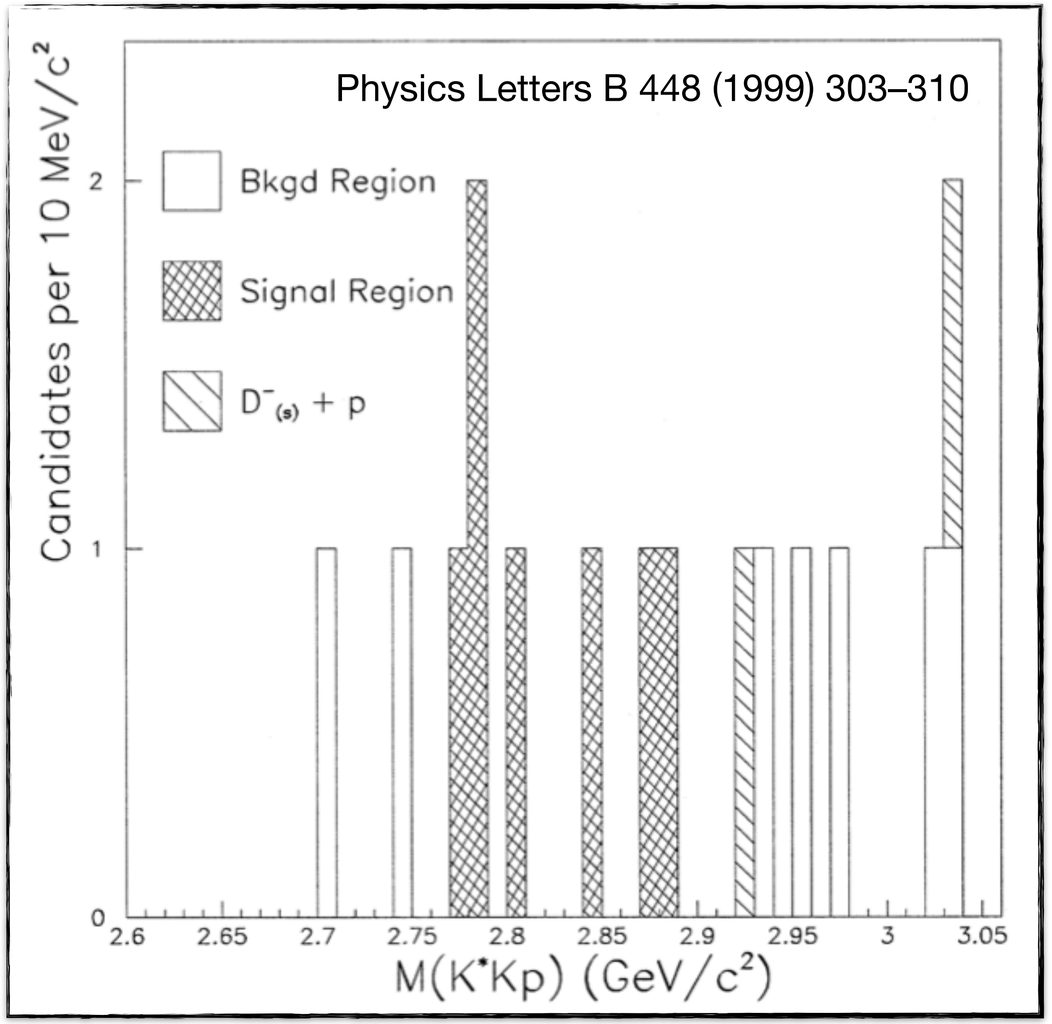
What about hadro-production?

- advantage: baryon number $B \neq 0$ in the initial state
- one past search: $P_{\bar{c}s} \rightarrow K^*\bar{K}p$ using 500 GeV/c pion beam at E791 Fermilab
  (also: $P_{\bar{c}s} \rightarrow \phi\pi p$ in Phys. Rev. Lett. 81 (1998) 44)
- if the $P_{\bar{c}(s)}$ really are stable against strong decays, lower center-of-mass energies might enable missing mass studies:

$$pp \rightarrow \Lambda_c P_{\bar{c}} \qquad pp \rightarrow K\Lambda_c P_{\bar{c}s} \qquad \text{(~5.7 GeV)}$$

$$\pi p \rightarrow D P_{\bar{c}} \qquad \pi p \rightarrow D_s P_{\bar{c}s}$$

- depending on production rates (??), experiments at GSI could be uniquely suited to address flavour-exotic pentaquarks!



What about hadro-production?

- advantage: baryon number B =
- one past search: $P_{\bar{c}s} \rightarrow K^*\bar{K}p$ at E791 Fermilab
  (also: $P_{\bar{c}s} \rightarrow \phi\pi p$ in Phys. Rev. Let
- if the $P_{\bar{c}(s)}$ really are stable aga
  center-of-mass energies might

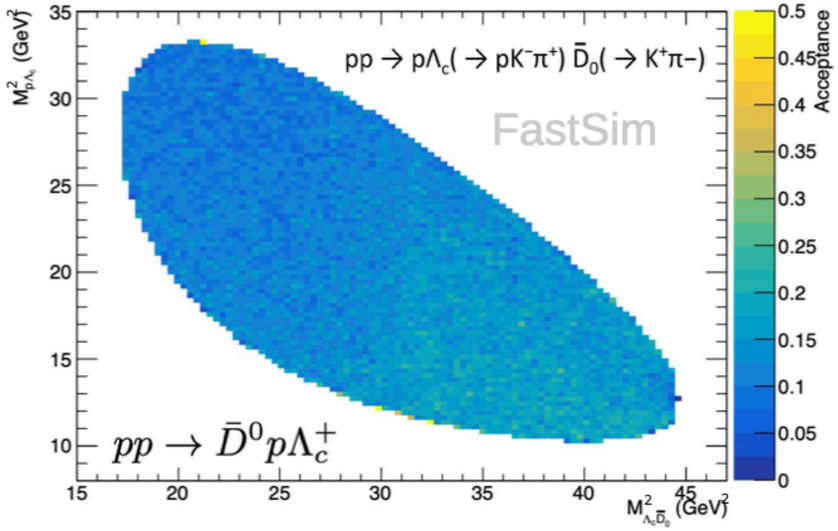
$$pp \rightarrow \Lambda_c P_{\bar{c}} \qquad pp \rightarrow K\Lambda$$

$$\pi p \rightarrow D P_{\bar{c}} \qquad \pi p \rightarrow D_s$$

- depending on production rates
  be uniquely suited to address f

this is the same quark content as $pp \rightarrow \Lambda_c P_{\bar{c}}$
(and the search channel, if $P_{\bar{c}}$ were unstable)

- SIS100 energies allow for charm production channels
- SU(4) estimates for exclusive charm hyperon production up to 1 µb @ SIS100
- All final state particles reconstructed
- Good phase space acceptance of the primary particles
- Detailed studies D-p and Λ_c-pInteractions possible with femtoscopy



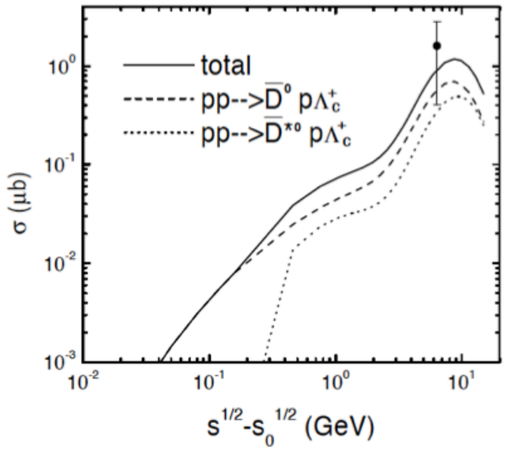
Johan Messchendorp

Expected reconstructed exclusive events / Day @ 30 GeV/*c*, σ = 1 µb	
1 MHz	$2.7 \cdot 10^4$
10 MHz ?	$2.7 \cdot 10^5$

Ab-initio calculations at low energies and perturbation calculations at high energies

Calculations describing interactions needed at intermediate energies!

Nucl. Phys. A728 (2003) 457-470



from: Opportunities with proton beams, Jenny Taylor

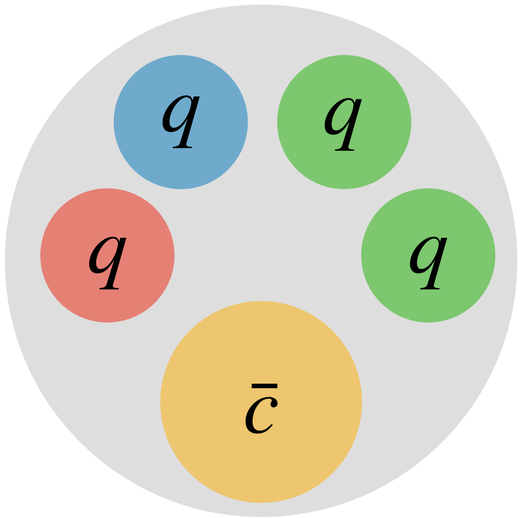
Summary

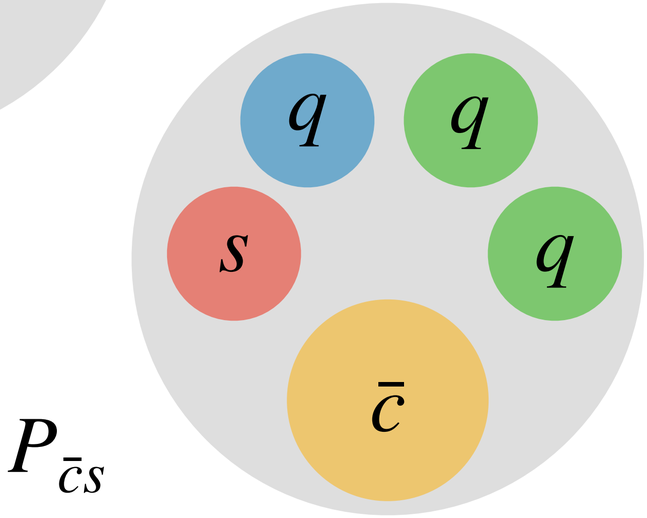
- open discussion: unique aspects of exotic hadron spectroscopy with hadron beams at GSI

- one idea: flavour-exotic pentaquarks
  - first suggested in 1987
  - unique signature: anti-charm in a baryon
  - could potentially be stable against strong decay
  - difficult to study elsewhere, especially if stable
  - but: production rates??

- if the $P_{\bar{c}}$ is unstable, search channel $\Lambda_c \bar{D} p$ is the same as for $P_{c\bar{c}}$ searches → we get this for free!

- my naive experimentalist's view: we have found exotic signatures at many, many two-body thresholds
  → investigating $p\bar{D}$ and $p\bar{D}_s$ thresholds is very natural!





Thank you for your attention!