Exotic hadron naming scheme

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Based on many discussions with LHCb colleagues
and others (MITP workshop, PDG authors, etc.)

The 13th International Workshop on e+e- collisions from Phi to Psi

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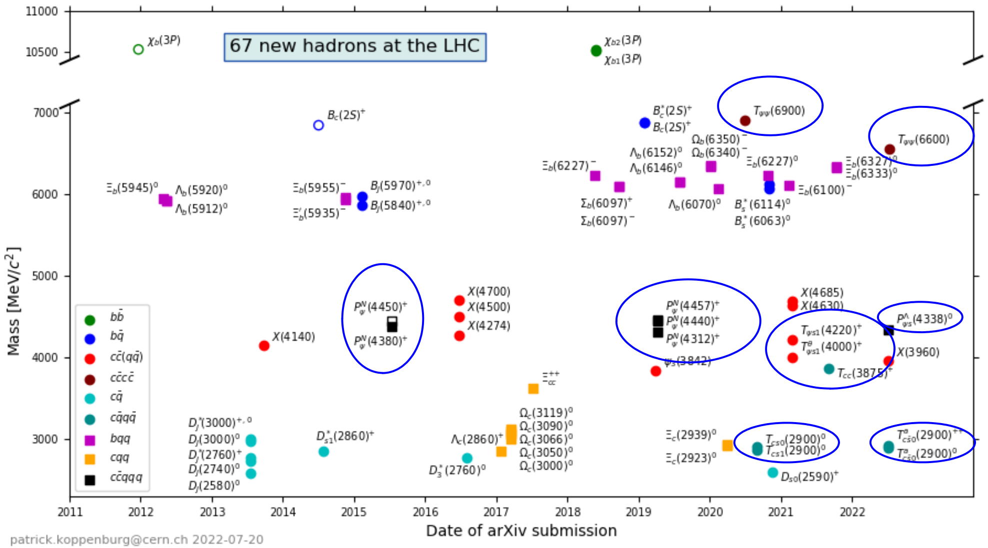
What is the problem?

- Several discoveries that do not fit into PDG naming convention.
- Mostly (not always) following PDG rule to use “X” for states where not all QNs measured
- Names assigned ad-hoc
  - Problems/conflicts likely if current rate of discoveries continues
- Names may become popularised even if not used in LHCb papers
  - e.g. T_{cccc} for X(6900)



https://www.nikhef.nl/~pkoppenb/particles.html or
https://gitlab.cern.ch/lhcb-docs/FIGURE/LHCb-FIGURE-2021-001

PDG naming convention -- based only on quantum numbers

https://pdg.lbl.gov/2021/reviews/rpp2020-rev-naming-scheme-hadrons.pdf

Table 8.1: Symbols for mesons with strangeness and heavy-flavor quantum numbers equal to zero. States that do not yet appear in the RPP are listed in parentheses.

$J^{PC} =$	0^{-+}, 2^{-+}, $\vdots$	1^{+-}, 3^{+-}, $\vdots$	1^{--}, 2^{--}, $\vdots$	0^{++}, 1^{++}, $\vdots$
Minimal quark content				
$u\bar{d}$, $u\bar{u}-d\bar{d}$, $d\bar{u}$ ($I=1$)	π	b	ρ	a
$d\bar{d}+u\bar{u}$ and/or $s\bar{s}$ ($I=0$)	η,η'	h,h'	ω,ϕ	f,f'
$c\bar{c}$	η_c	h_c	ψ^*	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b
$I=1$ with $c\bar{c}$	(Π_c)	Z_c	R_c	(W_c)
$I=1$ with $b\bar{b}$	(Π_b)	Z_b	(R_b)	(W_b)

- $X(3872)$ will appear as '$\chi_{c1}(3872)$ also known as $X(3872)$';
- $X(3900)^{\pm}$ will appear as '$Z_c(3900)^{\pm}$';
- $X(4260)$ will appear as '$\psi(4260)$ also known as $Y(4260)$';

No rule for exotic mesons with s, c, b QNs

1. Baryons with miminal content of *three* u and/or d quarks are N's (isospin 1/2) or Δ's (isospin 3/2).
2. Baryons with *two* u and/or d quarks are Λ's (isospin 0) or Σ's (isospin 1). If the third quark is a c or b quark, its identity is given by a subscript.
3. Baryons with *one* u or d quark are Ξ's (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus Ξ_c, Ξ_{cc}, Ξ_b, etc.*
4. Baryons with *no* u or d quarks are Ω's (isospin 0), and subscripts indicate any heavy-quark content.
5. A baryon that decays strongly has its mass in parentheses. Examples are the $\Delta(1232)\ 3/2^+$, $\Sigma(1385)\ 3/2^+$, $N(1440)\ 1/2^+$, $\Xi_c(2645)\ 3/2^+$.

In short, the minimal number of u plus d quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A Σ always has isospin 1, an Ω always has isospin 0, etc.

More recently, the LHCb collaboration found a series of candidates for pentaquark states in the $J/\psi p$ system extracted from data on $\Lambda_b^0 \to J/\psi K^- p$ [4,5].** These have the quantum numbers of excited nucleons, but have a minimal quark content of $c\bar{c}uud$. Following the name established by the LHCb collaboration, we label these $P_c^+(\text{mass})J^P$, with the mass given in parentheses.

No obvious way to extend to other PQ states

Examples

- $X_0(2900)$ and $X_1(2900)$ discovered as D^-K^+ resonances [LHCb-PAPER-2020-025]
  - All QNs except isospin determined (could be I=0,1)
  - If/when isospin measured (discovery/absence of partners), what should these states be called?
- $Z_{cs}(4000)$ and $Z_{cs}(4220)$ discovered as $J/\psi K^+$ resonances [LHCb-PAPER-2020-044]
  - All QNs determined (J^P still ambiguous for $Z_{cs}(4220)$)
  - Chosen name breaks PDG convention: Z should be I=1 but these are I=½
- P_c states discovered as $J/\psi\, p$ resonances [LHCb-PAPER-2015-029, LHCb-PAPER-2019-014]
  - spin-parity not yet known
    - [J^P should be stated explicitly in name, but often not done in practice for baryons]
  - $J/\psi\, p$ resonances are I = ½, but what should we call I = 3/2 states?
- Possible $J/\psi\, \Lambda$ resonances denoted P_{cs} [LHCb-PAPER-2020-039]
  - These are I=0. What should we call I=1 states ($J/\psi\, \Sigma$ resonances)?
  - How would this scheme be extended to PQ states with open charm?

Need for a new naming scheme

- Many states discovered at LHC experiments (mainly LHCb) in recent years
  - 15 manifestly exotic (not fitting into existing naming scheme); 13 in last ~3 years
  - Complementing discoveries at other experiments, notably BESIII, Belle & BaBar
  - Assumption that many more will following in coming years
- Naming will rapidly become confusing without an explicit scheme
  - different groups may invent separate, conflicting, schemes
- Scientific tradition that those making discoveries get naming rights
  - LHCb has discussed, and put forward, a scheme
  - Process included significant input from other experiments and the rest of the community
  - n.b. Next PDG update in 2024

Desirable features of a naming scheme

- Should be backwards-compatible, to the extent possible
  - Both with existing PDG scheme and previous publications
- Should be as simple as possible
  - Understandable by non-experts (will inevitably require effort, as the current scheme does!)
  - Avoid overly tortuous naming, e.g. with multiple sub/superscripts
  - No conflicts with existing particles names
    - avoid B, D, H, J, K, N, W, a, b, f, g, h, n & basically all greek letters) + X for unknown QNs
    - conflict in use of Z already exists, but don't make worse
    - Y not ideal as barely distinguishable from Υ (Upsilon) in many fonts
- Should be based on measurable properties, not interpretation
  - i.e. follow PDG convention that name depends on quantum numbers (and mass) only
- Should be future-proof, to the extent possible
  - Avoid having to repeat this discussion in future, if we can
  - Cannot foresee every possible discovery
    - aim to cover all possible 4- and 5-quark combinations, but (e.g.) what about 6, or 7?

Attempts at proposals

Started process with “straw” proposals as a basis for discussion within LHCb

- A lot of feedback received, including conflicting opinions!
- The proposal that follows seems the “best” among options considered
- No “perfect” solution, but outcome seems to avoid most significant pitfalls

The new exotic hadron naming scheme

Outline

- Basic idea:
  - T for tetra, P for penta
  - Superscript, based on existing symbols, to indicate isospin, parity and G-parity
    - n.b. superscript to avoid multiple subscripts

T states, zero net S, C, B

(P, G)	$I = 0$	$I = 1$
$(-,-)$	ω	π
$(-,+)$	η	ρ
$(+,+)$	f	b
$(+,-)$	h	a

T states, non-zero net S, C, B

(P)	$I = 0$	$I = \frac{1}{2}$	$I = 1$
$(-)$	η	τ	π
$(+)$	f	θ	a

P states

$I = 0$	$I = \frac{1}{2}$	$I = 1$	$I = \frac{3}{2}$
Λ	N	Σ	Δ

Extension to allow I=2, 5/2 states may be needed later

n.b. hat-tip to historical naming of kaons

Proposal outline

- Basic idea:
  - T for tetra, P for penta
  - Superscript, based on existing symbols, to indicate isospin, parity and G-parity
    - n.b. superscript to avoid multiple subscripts
- Subscript Υ, ψ, φ to denote hidden beauty, charm, strangeness
  - in order of mass, and repeated if necessary
- Subscript b, c, s to denote open flavour content
  - in order of mass, where more than 1 needed, e.g. T_{cs}
  - repeated if necessary, e.g. T_{bb} for a $bb\bar{u}\bar{d}$ state
  - overlines on subscripts only where necessary (only with >1 open flavour QN)
    - e.g. $\overline{T}_{bb}$ is the antiparticle I=0 $\bar{b}\bar{b}ud$ state, but T_{bc} and $T_{b\bar{c}}$ denote different states
    - first subscript (heaviest quark) defines whether symbol has overline: $T_{b\bar{c}}$ contains $b\bar{c}$, $\overline{T}_{b\bar{c}}$ contains $\bar{b}c$

Proposal outline

- T states:
  - Additional subscript for spin
  - Overline only to distinguish neutral particle/antiparticle
- P states:
  - Spin parity specified after symbols
  - Overline never (always) included for baryons (antibaryons)
- Mass in parentheses, followed by superscript for charge
  - Charge superscript can be dropped when not necessary (I=0 states)
- All as for conventional hadrons (T states are mesons; P states are baryons)

- Proposal should be extendable for 6 or 7 quark states (not considered in detail yet)
- No change for any state that does not manifestly have 4- or 5-quark content

Exotic hadrons: impact on existing states

Minimal quark content	Current name	$I^{(G)}, J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+,\ J^{PC} = 1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2},\ J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2},\ J^P = 1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+,\ J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+,\ J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

No change

No change unless 4-quark content clearly established

Exotic hadrons: examples of hypothetical states

Minimal quark content	Potential decay channel(s)	$I^{(G)},\ J^{P(C)}$	Proposed name
$bc\bar{u}\bar{d}$	B^-D^{*+}	$I=0,\ J^P=1^+$	$T^f_{bc1}(\mathrm{mass})^0$
$b\bar{c}\bar{u}d$	B^-D^{*-}	$I=1,\ J^P=1^+$	$T^a_{b\bar{c}1}(\mathrm{mass})^{--}$
$bb\bar{u}\bar{d}$	$B^-\pi^-D^+,\ \overline{B}^0J/\psi K^-$	$I=0,\ J^P=1^+$	$T^f_{bb1}(\mathrm{mass})^-$
$c\bar{c}b\bar{d}$	$J/\psi\overline{B}^0$	$I=\frac{1}{2},\ J^P=1^+$	$T^\theta_{\psi b1}(\mathrm{mass})^0$
$c\bar{s}u\bar{d}/c\bar{s}\bar{u}d$	$D_s^+\pi^+/D_s^+\pi^-$	$I=1,\ J^P=0^+$	$T^a_{c\bar{s}0}(\mathrm{mass})^{++}/T^a_{c\bar{s}0}(\mathrm{mass})^0$
$b\bar{b}uud$	Υp	$I=\frac{1}{2}$	$P^N_\Upsilon(\mathrm{mass})^+$
$b\bar{c}uud$	B_c^-p	$I=\frac{1}{2}$	$P^N_{b\bar{c}}(\mathrm{mass})^0$
$b\bar{u}cds$	$B^-\Xi_c^0$	$I=1$	$P^\Sigma_{bcs}(\mathrm{mass})^-$
$c\bar{d}cus$	$D^+\Xi_c^+$	$I=1$	$P^\Sigma_{ccs}(\mathrm{mass})^{++}$
$c\bar{c}cud$	$J/\psi\Lambda_c^+$	$I=0$	$P^\Lambda_{\psi c}(\mathrm{mass})^+$
$c\bar{c}cus$	$J/\psi\Xi_c^+$	$I=\frac{1}{2}$	$P^N_{\psi cs}(\mathrm{mass})^+$

assume weak decays here; all others strong arXiv:2206.15233

Summary

- New exotic hadron naming scheme set out, addressing a clear need
  - main concept is simple (T for tetra, P for penta)
  - largely follows existing (PDG) principles and reuses existing symbols as superscripts
  - can accommodate a range of possible future discoveries, extendable for others
- Satisfies most desiderata, but not all
  - multiplicity of super/subscripts is awkward
    - in practice, some likely to be omitted for convenience (as already done)
  - perfect backwards-compatibility not possible, so some changes of well-established names
- Hope that this scheme will be accepted in the community
  - Also working on code & webpage implementation to allow easy translations

History repeats itself

CERN Courier, November 1985

Thanks @NikoSarcevic

https://twitter.com/NikoSarcevic/status/1455440739219951617?t=x5n5xCEBD8hT2y-n5nWOoQ&s=19

New names for old mesons

The Particle Data Group collates information on particle properties from experiments carried out at Laboratories all over the world and brings out regular editions of its 'Review of Particle Properties' – the particle physicists' handbook.

Twenty years ago, the Group introduced a new convention for naming baryons (half-integer spin particles), which has gone on to become standard. This contrasts with the mesons (integer spin particles), which use an alphabet soup of largely uninformative names, some particles with related quantum numbers having very different names, while other disparate particles have inherited confusingly similar labels.

CERN Courier, November 1985

It is easy to invent logical and consistent naming schemes, however it is unpleasant and confusing to have to learn lots of new names. Thus having considered schemes of various degrees of radicalism (and having exposed part of the physics community to them) the Particle Data Group now ends up with a set of new names. The exception is the celebrated J/psi, which has such a monstrous name that nearly everybody wants to keep it!

Under the new meson scheme, the quantum numbers (spin, parity, isospin, etc.) and the quark content define the names. The spin is indicated by subscript, except for the spin zero, negative parity (pseudoscalar) and spin one, negative parity (vector) particles, where the subscript is omitted.

For mesons which are not bound states of quarks and antiquarks (such as 'glueballs'), the quantum numbers (when non-exotic) determine their names, just as for quark-antiquark bound states. This seems appropriate since such states will be difficult to distinguish from quark-antiquark ones and will likely mix with them.

A difficulty arises with related isospin singlet particles (eta and eta prime, omega and phi, f and f prime). For the lightest such states, the existing conventions will be followed. Primes are being reserved for use in these cases, so the old habit of using primes to denote radial excitations has been dropped.

Many familiar names stay – pi, eta, rho, omega, eta prime, phi, J/psi, chi, upsilon, etc. Some names undergo minor changes: $A_2(1320)$ for example, becoming $a_2(1320)$, while others get a complete face-lift, $S^*(975)$ becoming $f'_0(975)$.

For mesons containing strange and other heavy quarks, the heavier of the two quarks provides the label – K for a strange quark, D for a charmed quark, B for beauty and T for top. A letter subscript is added for the lighter quark, unless it is 'up' or 'down'. Thus the F (charm/strange) meson becomes D_s. Another subscript gives the spin (again omitted for pseudoscalar and vector mesons). Finally a superscript asterisk is added for states with 'normal' spin-parity assignments from a quark model picture (zero plus, one minus, two plus, etc.). Thus the names K, K^*, D, D^* and B do not change, but K^* (1430) becomes K_2^* (1430), L (1770) becomes K_2 (1770), etc.

The new scheme admittedly can lead to cumbersome notations, but not for states that are likely to be common. To facilitate the transition, the Particle Data Group will use both the old and the new meson labelling schemes for a few editions of the Review of Particle Properties.

From Matts Roos

CERN Courier, November 1985

Back up

Existing PDG naming scheme

Mesons, no net S,C,B

J^{PC} (1)	0^{-+}	1^{+-}	1^{--}	0^{++}
Minimal quark content				
$u\bar{d}$, $u\bar{u}-d\bar{d}$, $\bar{u}d$ $(I=1)$	π	b	ρ	a
$u\bar{u}+d\bar{d}$ and/or $s\bar{s}$ $(I=0)$	$\eta^{(\prime)}$	$h^{(\prime)}$	ω, ϕ	$f^{(\prime)}$
$c\bar{c}$	η_c	h_c	ψ (2)	χ_c
$b\bar{b}$	η_b	h_b	Υ	χ_b

Mesons, non-zero S,C or B

	$\bar{u}$	$\bar{d}$	$\bar{s}$	$\bar{c}$	$\bar{b}$
u	See Table 1		K^+	$\overline{D}^0$	B^+
d			K^0	D^-	B^0
s	K^-	$\overline{K}^0$		D_s^-	B_s^0
c	D^0	D^+	D_s^+		B_c^+
b	B^-	$\overline{B}^0$	$\overline{B}_s^0$	B_c^-	

Baryons

Three u/d quarks

$I=\frac{1}{2}$	$I=\frac{3}{2}$
N	Δ

Two u/d quarks

$I=0$	$I=1$
Λ	Σ
Λ_c	Σ_c
Λ_b	Σ_b

One or zero u/d quarks

$I=\frac{1}{2}$	$I=0$
Ξ	Ω
$\Xi_c^{(\prime)}$	Ω_c
$\Xi_b^{(\prime)}$	Ω_b
Ξ_{cc}	Ω_{cc}
$\ldots$	$\ldots$

Aside: numbering scheme

MC generators need a unique numbering scheme for hadrons (and all particles)

Existing scheme does not cover all known states

https://pdg.lbl.gov/2021/reviews/rpp2020-rev-monte-carlo-numbering.pdf

Developers expressing desire for a future proof scheme

Should ideally have a one-to-one matching between naming and numbering

Suggest to leave this aside for now. Figure out a naming scheme first, then figure out how to best match it to a numbering scheme