Hadron Spectroscopy
Part I

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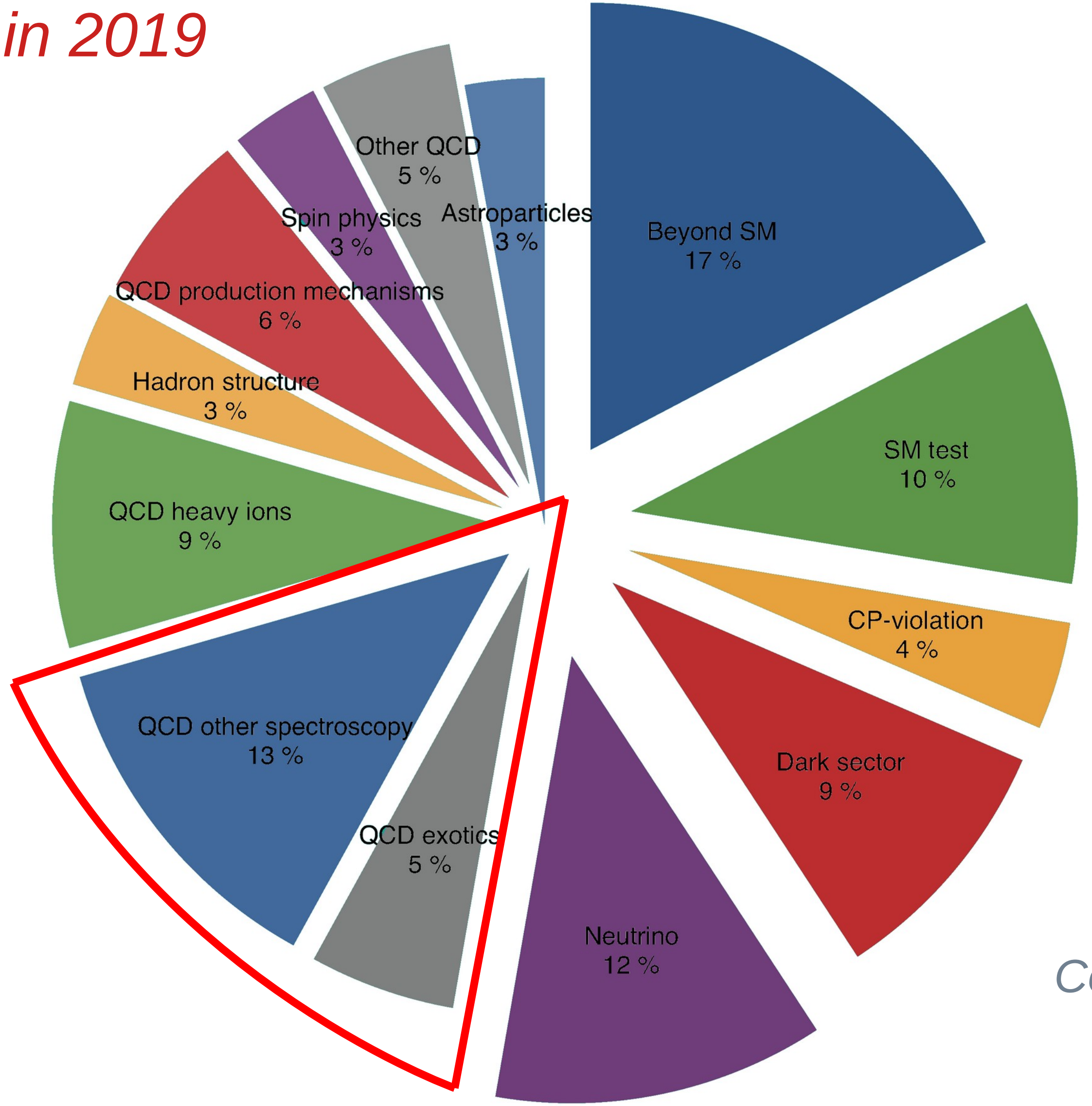
Outline

- Why do we call it spectroscopy?
- What are we really measuring?
- Conventional hadron spectra
- Light hadrons: hunt for glueballs, search for diquarks
- Heavy hadrons: multiquarks and other exotics

Special thanks to Wikipedia, HADRON21 and ICHEP22 contributors!

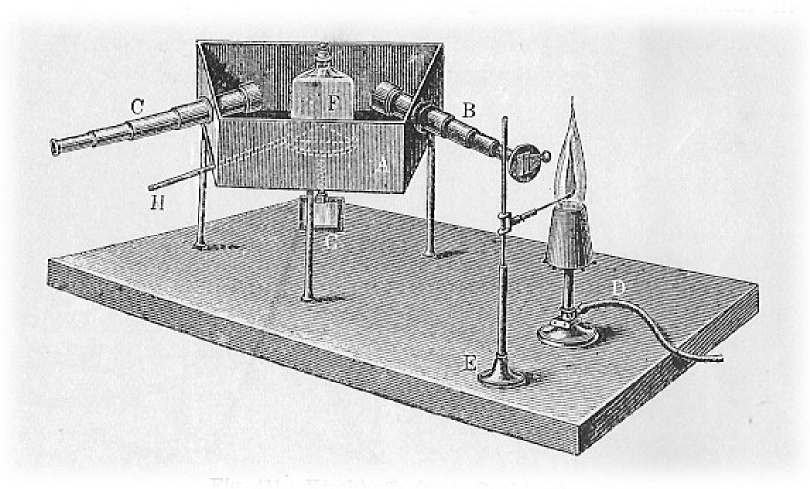
Particle physics in 2019

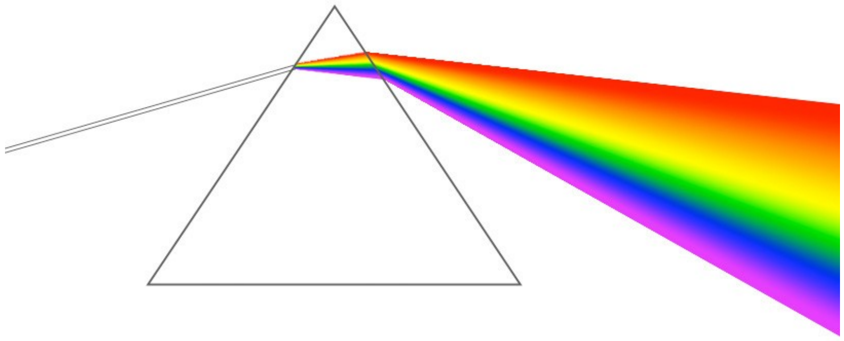


Courtesy of A.Guskov

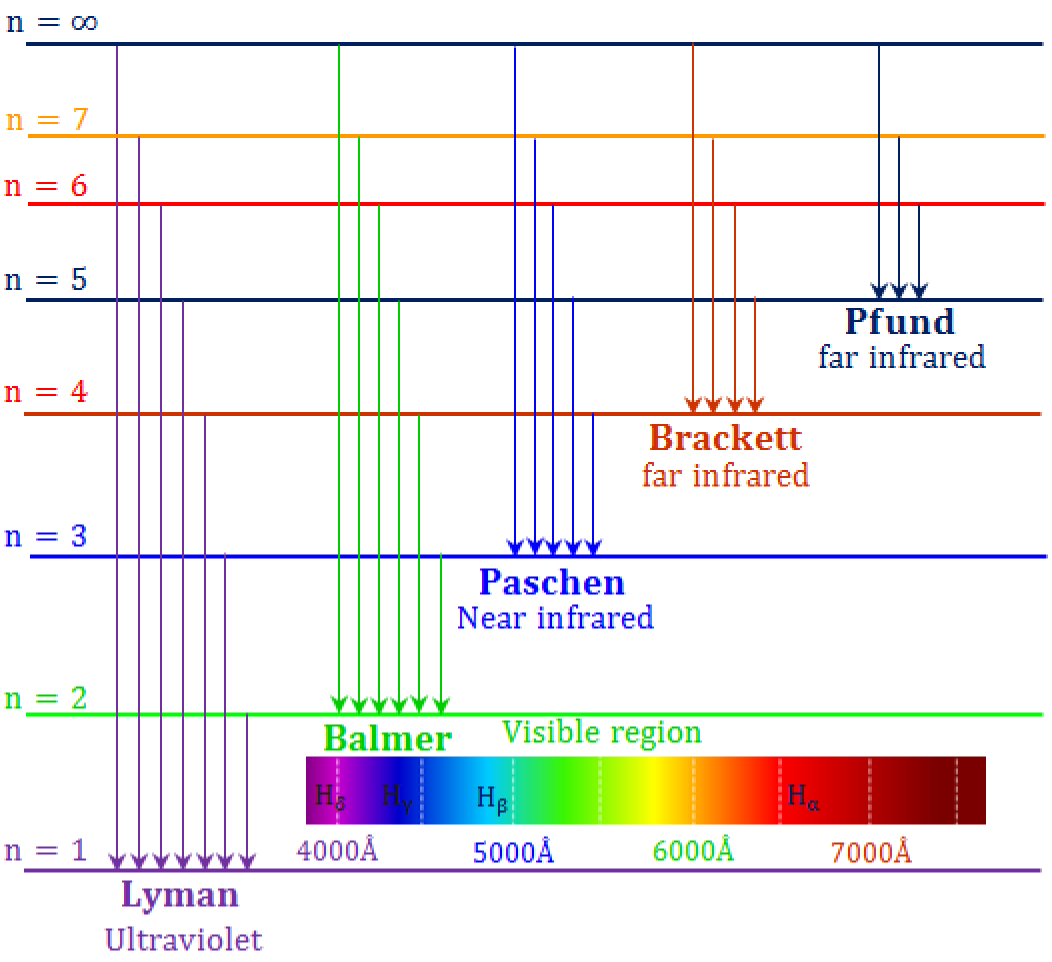
Why do we call it „spectroscopy“?

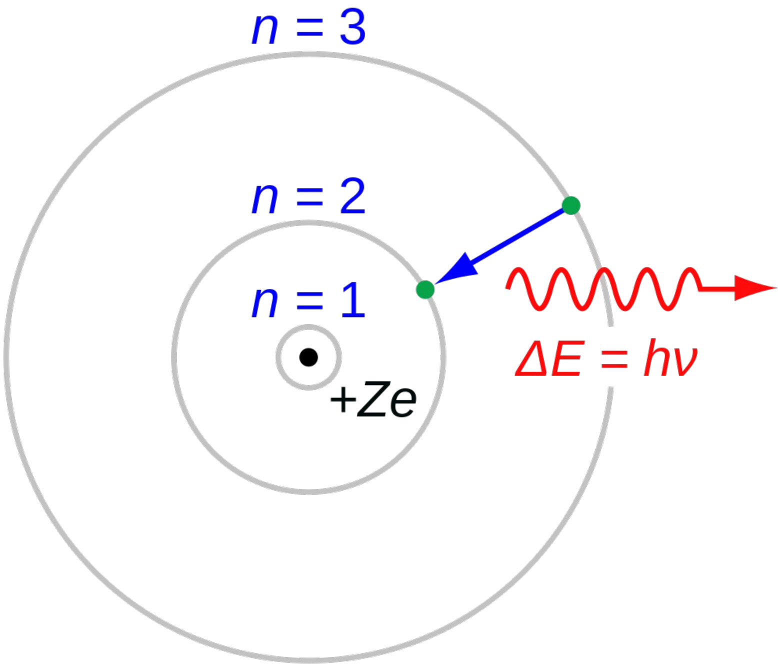
Robert Bunsen and Gustav Kirchhoff, 1860s





Atomic spectrum





Nuclear spectroscopy

Y^{89} (n,γ) Y^{90}

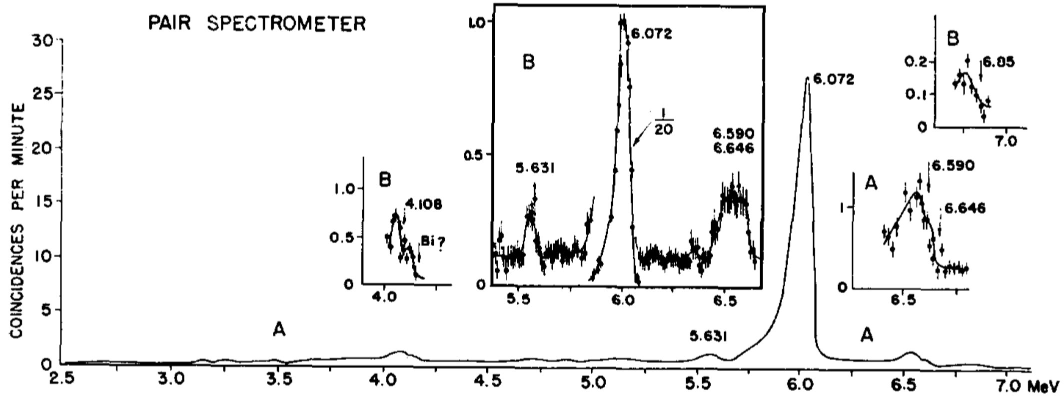


Fig. 1. Gamma-ray spectra from 0.18 to 7.0 MeV following thermal neutron capture in yttrium.

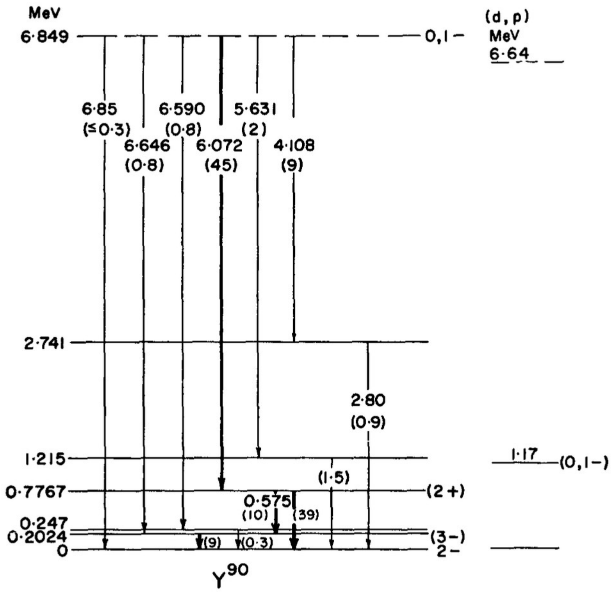


Fig. 8. Decay scheme for Y^{90}. The level energies on the left are obtained from the measured gamma ray energies with the assumption that the highest energy gamma rays in each cascade are emitted by the capturing state. The energies on the right are obtained from the (d, p) measurements of Wall [4]). Energies (in MeV) and absolute intensities in photons per 100 captures (in brackets) are given on the lines representing the transitions. The bracketed spin and parity assignments are tentative.

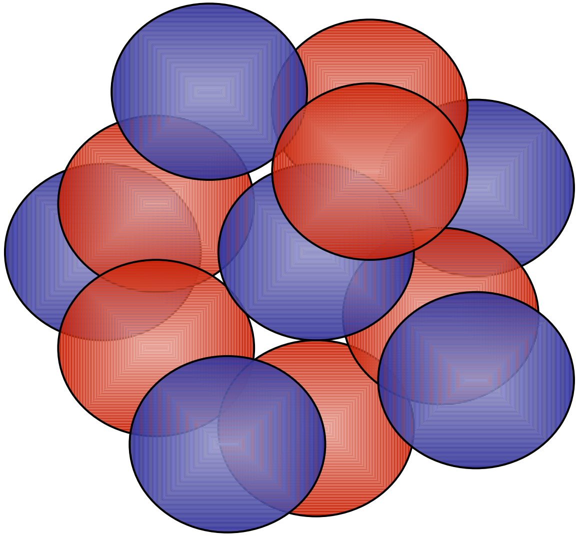
Bartolomew et al.,

Nuclear Physics, 10 (1959) 590-605

What about hadrons?

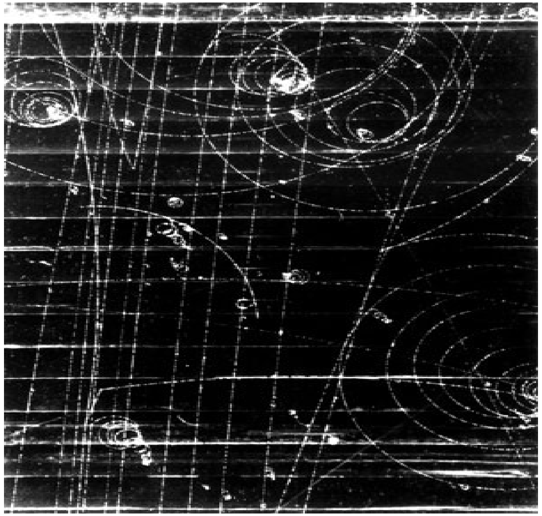
Nuclear forces. 1947.

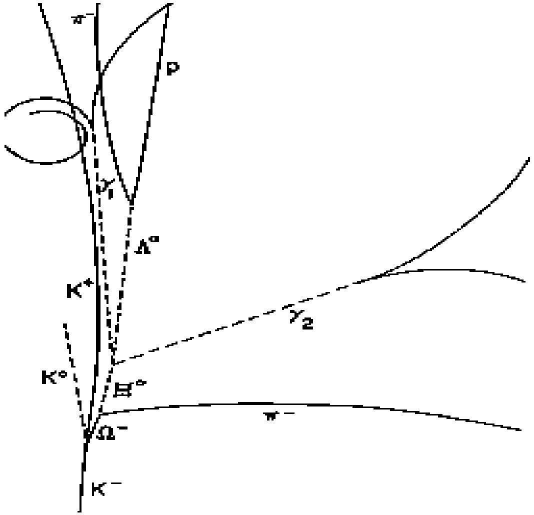
- Nucleus consists of nucleons - protons and neutrons
- Nucleons are bound strongly by π-meson (pion) exchange
- β-decay — weak nuclear forces
- Question: why **μ** meson is necessary?



Nuclear forces. 15 years later.

- K-mesons (1947, 1951)
- Λ — hyperon (1951)
- Δ(1232) (1952)
- Σ и Ξ hyperons (1953)
- ρ, ω, η mesons (1961)





Too many elementary particles

Too many nuclear force carriers

Courtesy of BNL

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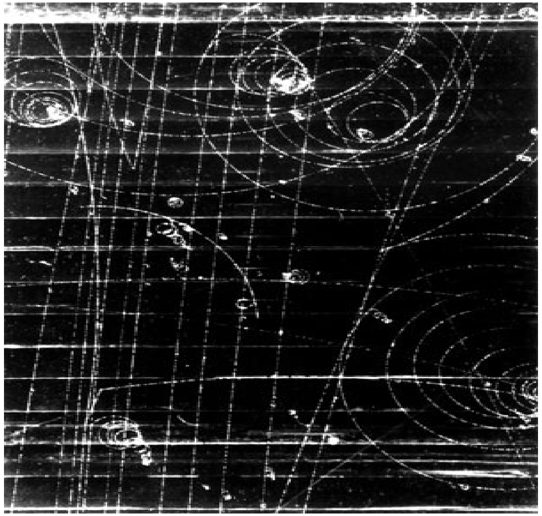
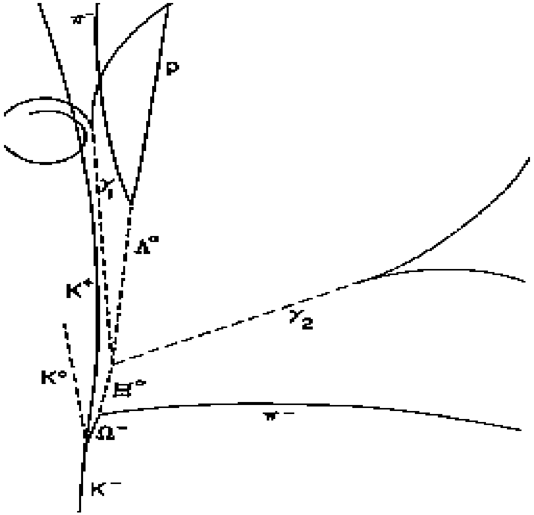




Too many elementary particles

Too many nuclear force carriers

Courtesy of BNL

Currenty PDG listing contains >250 established mesons and baryons!
More than 50 were discovered during last two decades

Hadron spectroscopy

- Which hadrons exist?
- What properties they possess?
- What reactions they can undergo?

The key source of experimental data for understanding hadron structure

What are we really measuring?

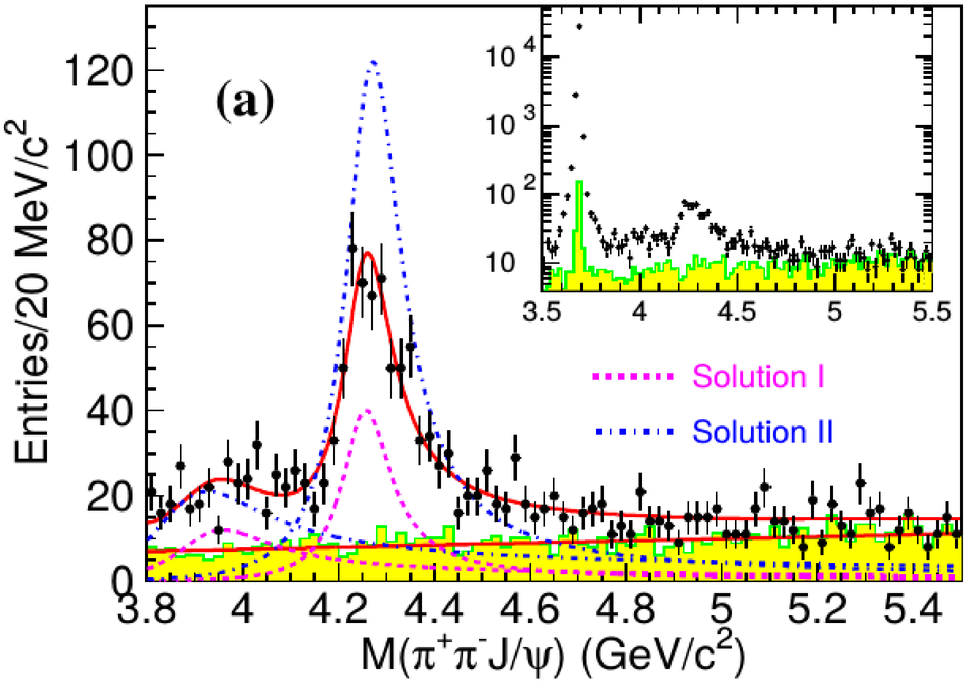
- Existence
- Mass and width
- Decay patterns
  - J^{pc}
  - Flavour quantum numbers: strangeness, charm, beauty, I_3
  - Baryonic number (= disparity of quarks and antiquarks)

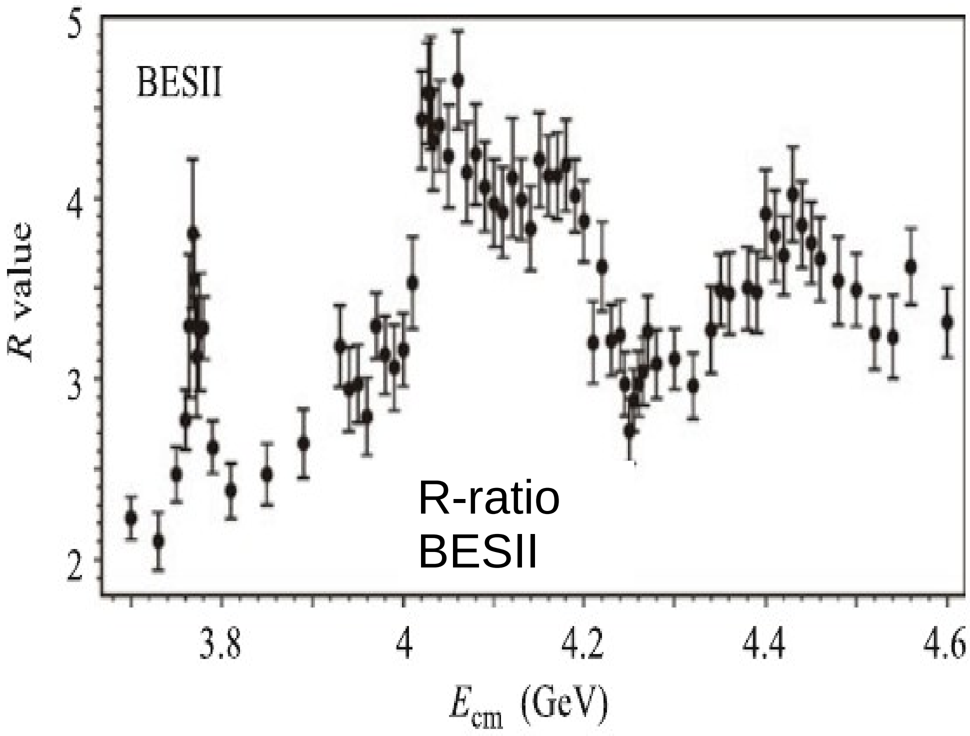
    ....

Many states may contribute to a final state

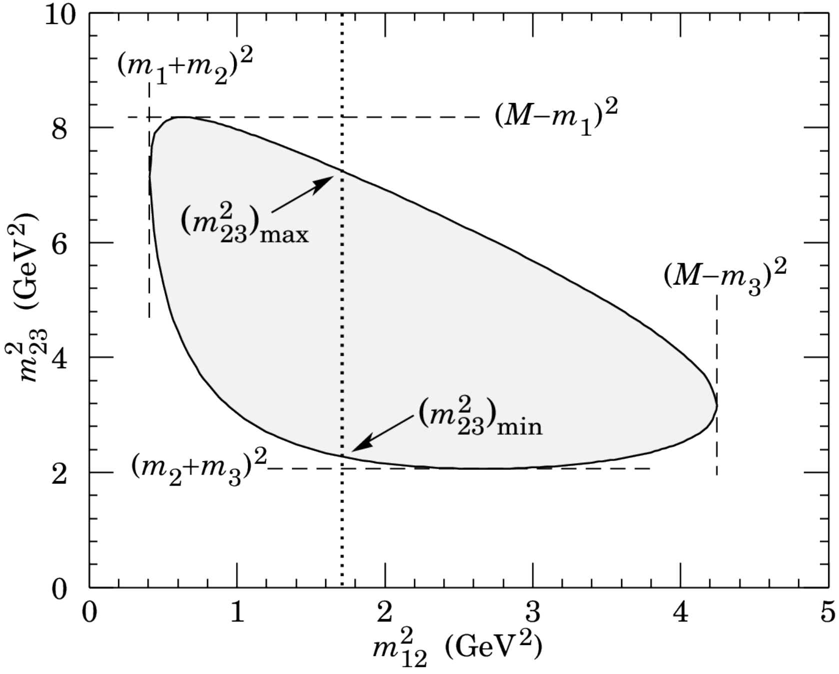
Invariant mass distribution

Belle, Phys.Rev.Lett. 110 (2013) 252002

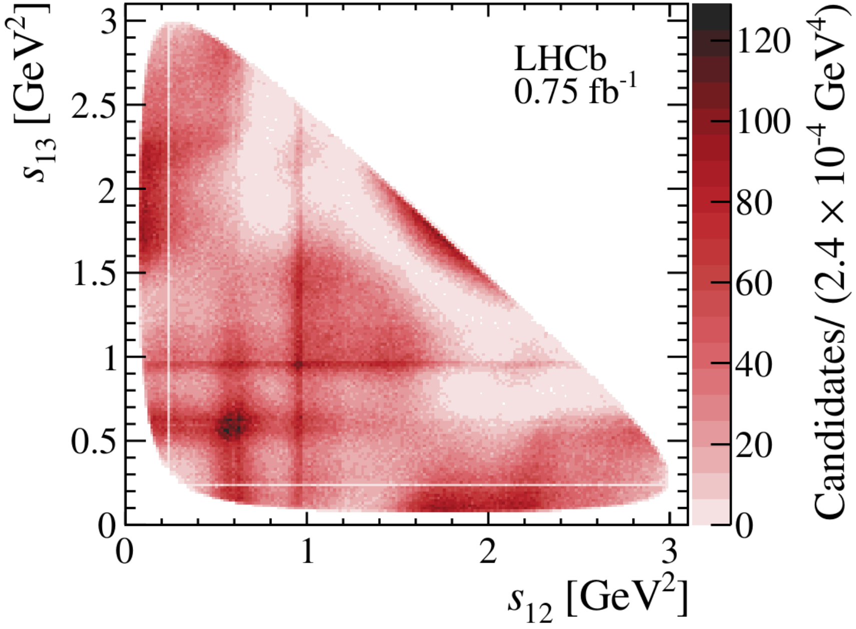




Dalitz plot



$D^+ \rightarrow \pi^-\pi^+\pi^+$



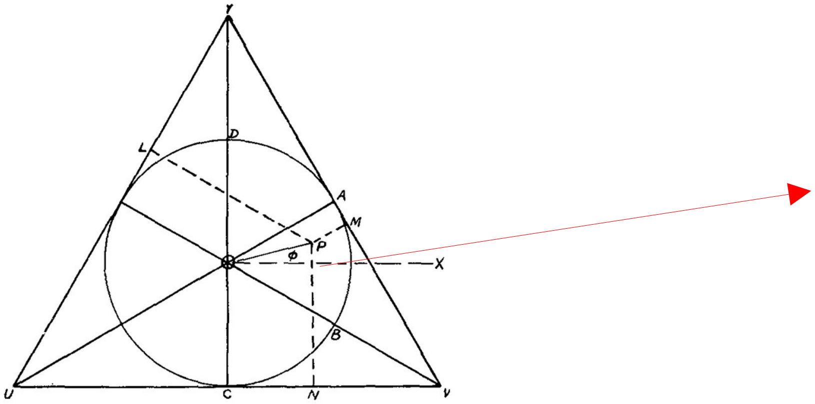
P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

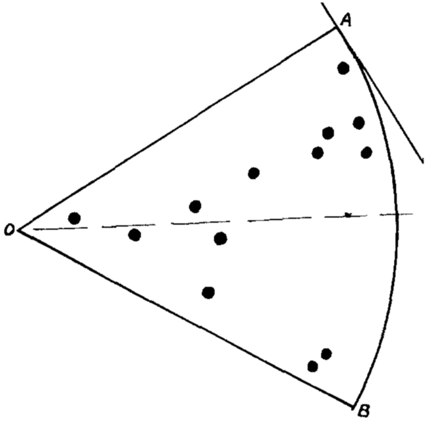
LHCb Collaboration, arXiv:2208.03300

Dalitz plot

Determination of spin and parity to resolve τ/θ puzzle

Fig. 1



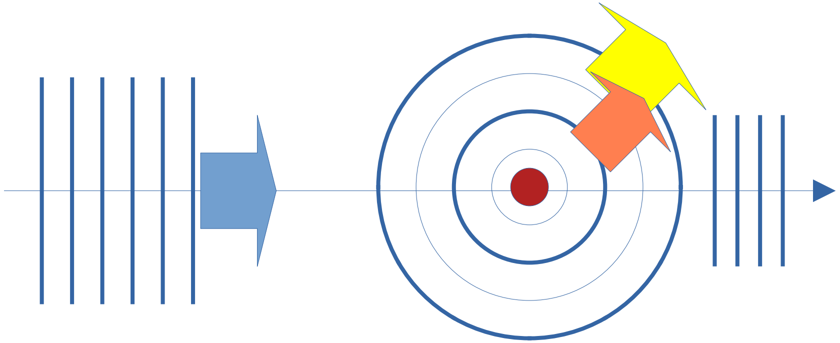


The data from 13 τ-meson decay events.

R.H. Dalitz (1953) CXII. On the analysis of τ-meson data and the nature of
the τ-meson, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science,
44:357, 1068-1080

Partial Wave Analysis

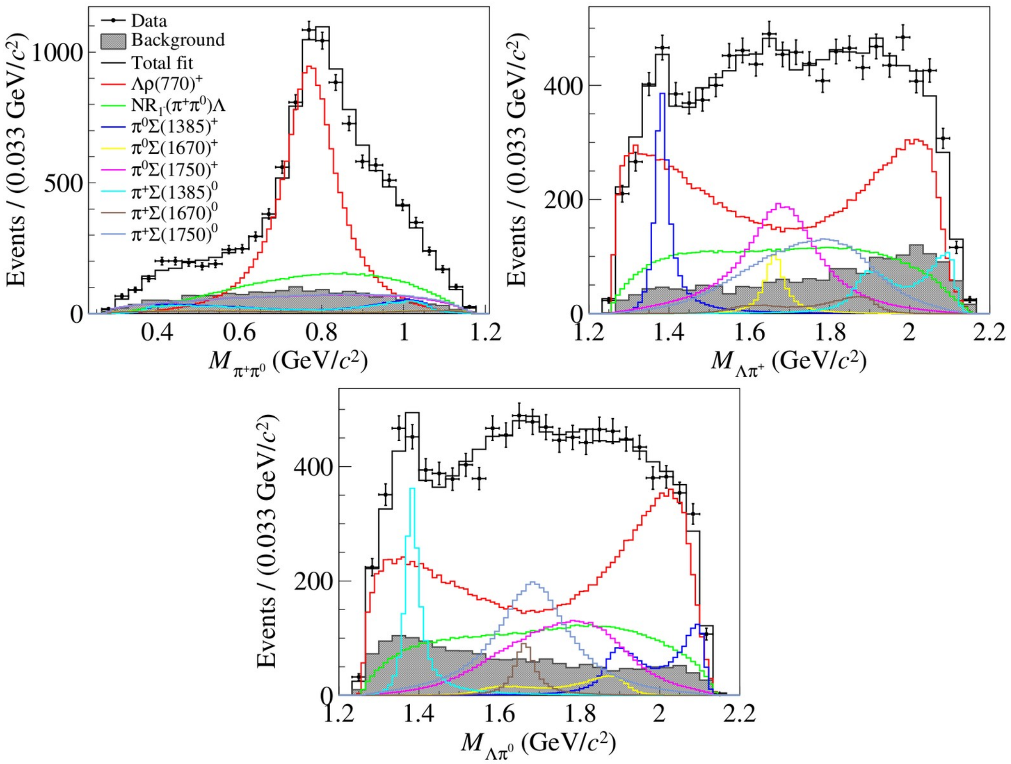
- The dynamics of particle interactions is modelled as a coherent sum of resonances.
- The resulting set of partial waves is fitted to data. Energy and angular information is used simultaneously.
- Works with broad and overlapping states
- Properly takes into account interference



Partial Wave Analysis

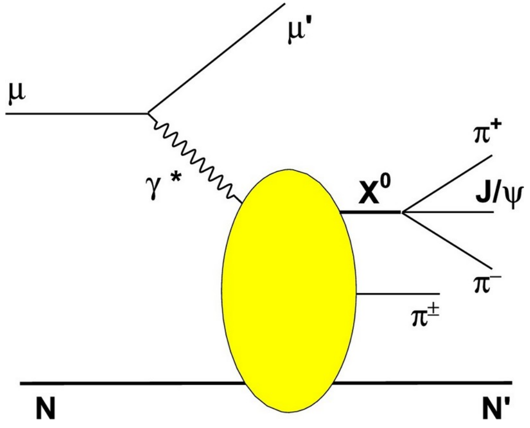
- A complicated technique
  - theoretical support is needed
  - heavy computation
- Interpretation of results is not easy
  - rescattering
  - multiple solutions possible (like in any fit with many free parameters)
- Systematic errors
  - background
  - detector performance

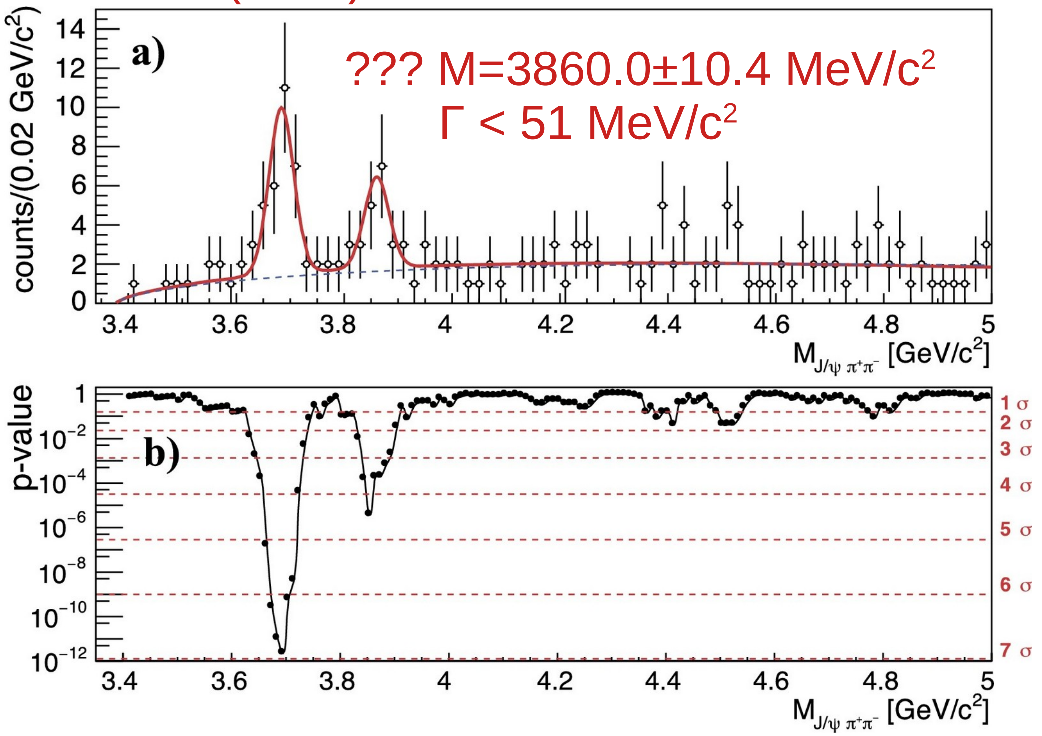
$\Lambda^{+}_{c} \rightarrow \Lambda\pi^{+}\pi^{0}$



BESIII Collaboration, arXiv:2209.08464 [hep-ex]

X̃(3872) at COMPASS



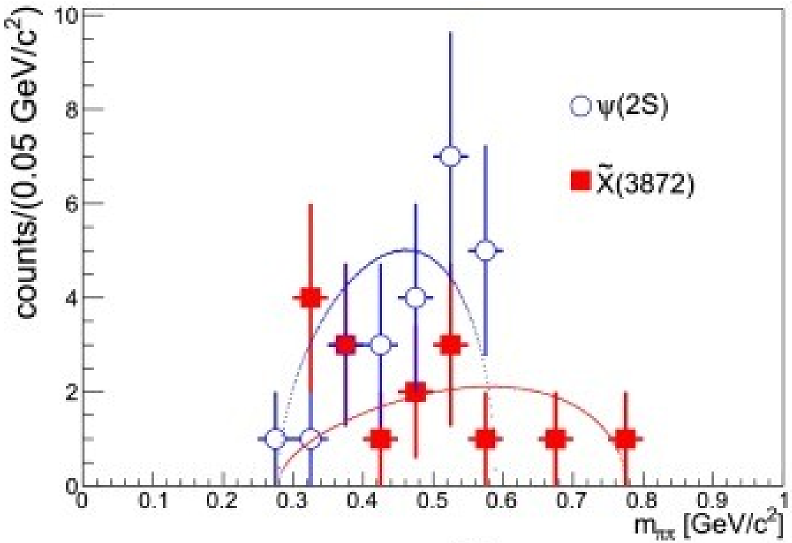


COMPASS Collaboration

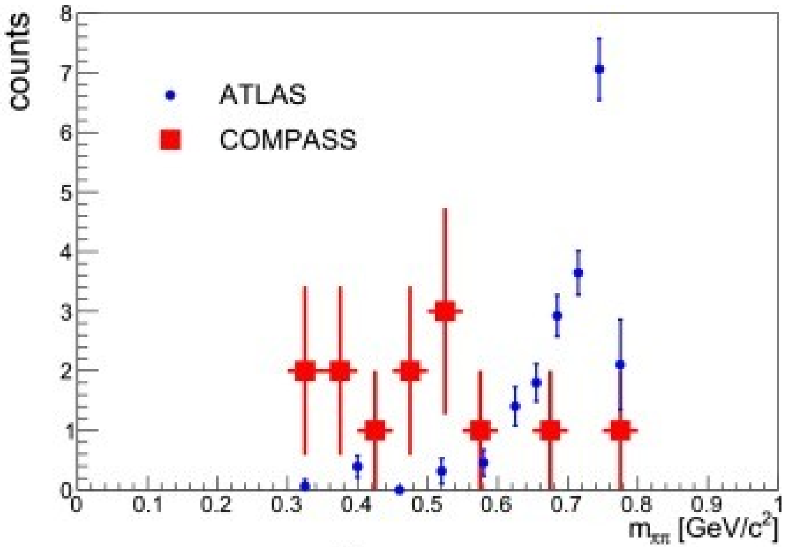
Physics Letters B783 (2018) 334-340

$\tilde{X}$(3872) at COMPASS

Two pion mass spectrum disagrees with X(3872) decay



(a)



(b)

A possible explanation could be that the observed state is the C=-1 partner of the X(3872)

Question

Do you see any difference between:

- Particle
- Resonance
- Excited state
- Structure?

Conventional hadron spectra

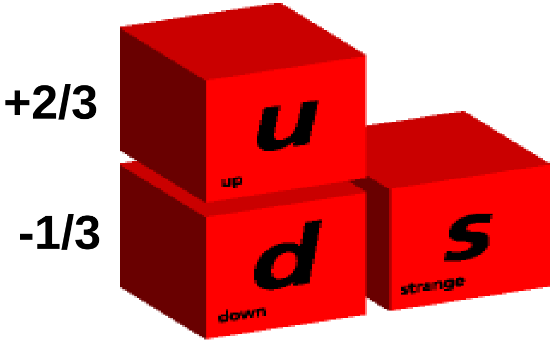
Quark model

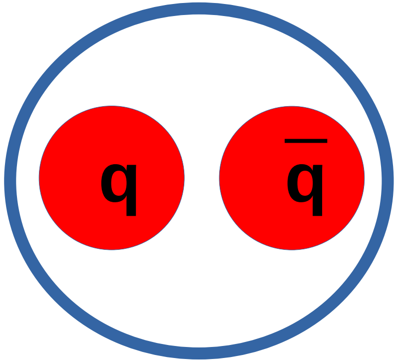
Invented to categorize known elementary particles

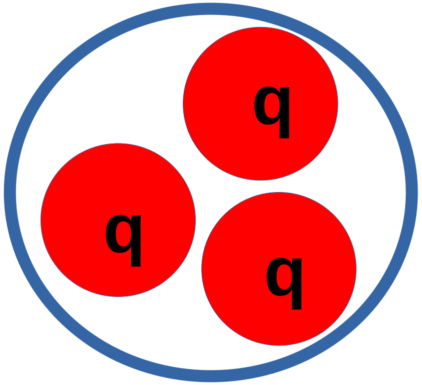
All hadrons consist of pointlike massive quarks, which have fractional electric charge:

- Mesons (π, K,...) — $q\bar{q}$
- Baryons (p, n,...) — qqq

Gell-Mann, Zweig. 1964







Hadron naming: mesons

J^{pc}	$0^{-+}, 2^{-+}, ...$	$1^{+-}, 3^{+-}, ...$	$1^{--}, 2^{--}, ...$	$0^{++}, 1^{++}, ...$
ud, uu-dd, du (I=1)	π	b	ρ	a
uu+dd (+ss) (I=0)	η	h	ω, φ	f
cc	η_c	h_c	ψ	χ_c
bb	η_b	h_b	Υ	χ_b

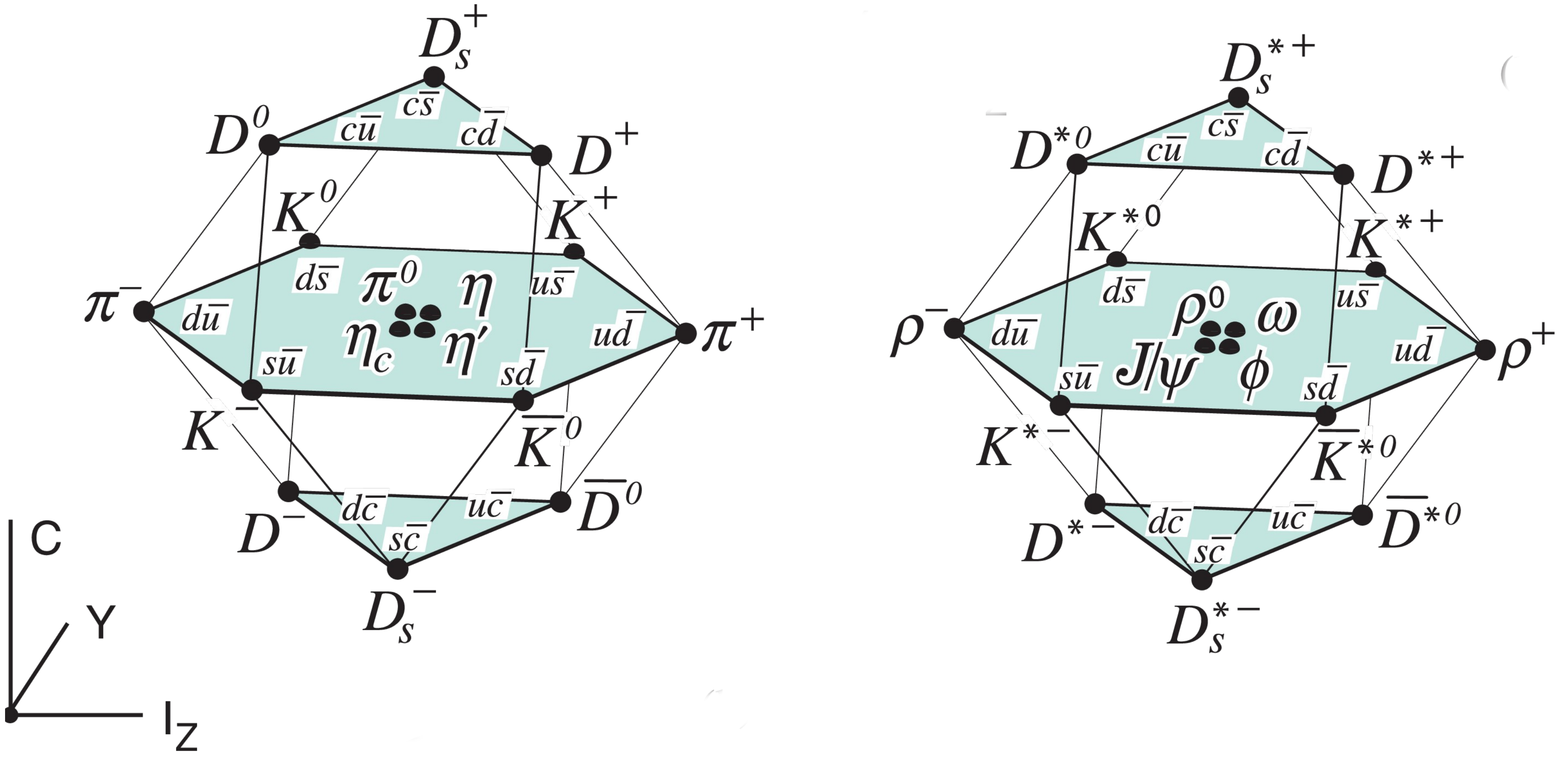
Hadron naming: mesons, cont'd

	$\bar{u}$	$\bar{d}$	$\bar{s}$	$\bar{c}$	$\bar{b}$
u			K^+	$\bar{D}^0$	B^+
d			K^0	D^-	B^0
s	K^-	$\bar{K}^0$		Ds^-	Bs^0
c	D^0	D^+	Ds^+		Bc^-
b	B^-	$\bar{B}^0$	$\overline{Bs}^0$	Bc^-	

Hadron naming: baryons

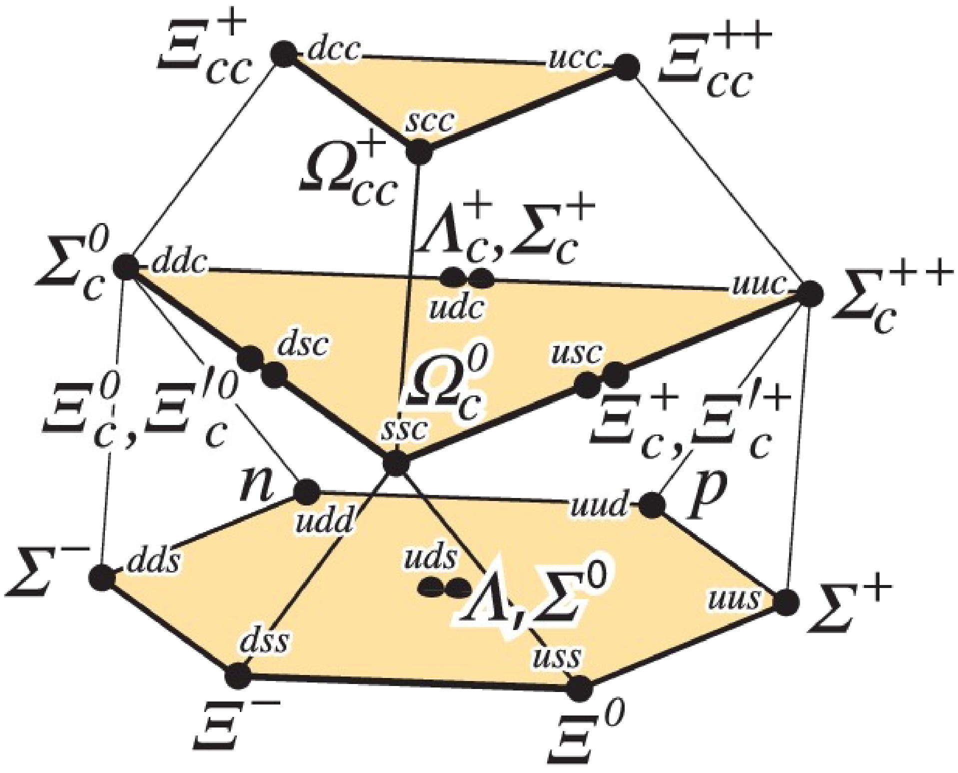
Isospin	I = 0	I=1/2	I=1	I=3/2
3 **u** and/or **d** quarks		p,n,N		Δ
2 **u** and/or **d** quarks	Λ, Λ_c, Λ_b		Σ, Σ_c, Σ_b	
1 **u** and/or **d** quarks		Ξ, Ξ_c, Ξ_b, Ξ_{cc} etc		
No u and/or d quarks	Ω, Ω_c, Ω_b, Ω_{cc} etc			

Mesons



D_s^+
$c\bar{s}$
D^0
$c\bar{u}$
$c\bar{d}$
D^+
K^0
K^+
$d\bar{s}$
π^0
η
$u\bar{s}$
π^-
$d\bar{u}$
η_c
η'
$u\bar{d}$
π^+
$s\bar{u}$
$s\bar{d}$
K^-
$\bar{K}^0$
$d\bar{c}$
$u\bar{c}$
D^-
$s\bar{c}$
$\bar{D}^0$
D_s^-
D_s^{*+}
D^{*0}
D^{*+}
K^{*0}
K^{*+}
ρ^0
ω
ρ^-
ρ^+
J/ψ
ϕ
K^{*-}
$\bar{K}^{*0}$
D^{*-}
$\bar{D}^{*0}$
D_s^{*-}
C
Y
I_Z

Baryons



dcc
ucc
scc
ddc
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udc
dsc
usc
ssc
udd
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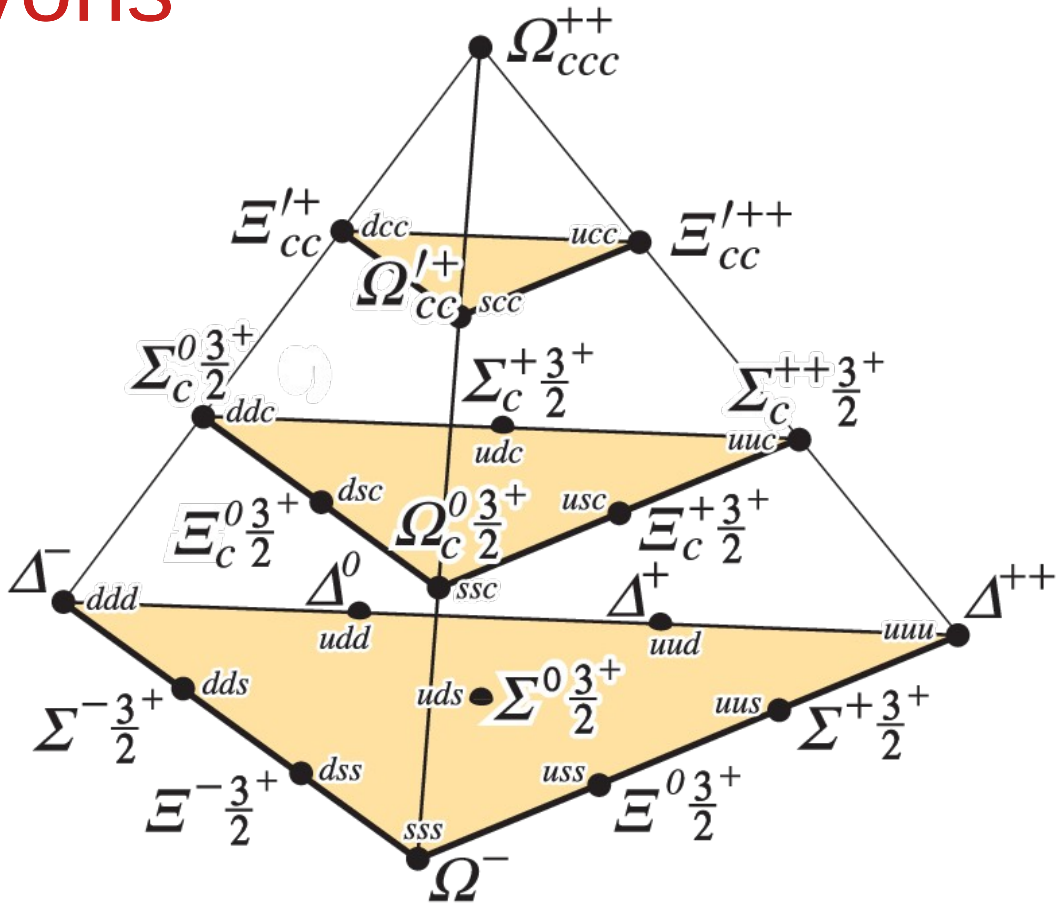
uus
dss
uss



dcc
ucc
scc
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usc
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uss
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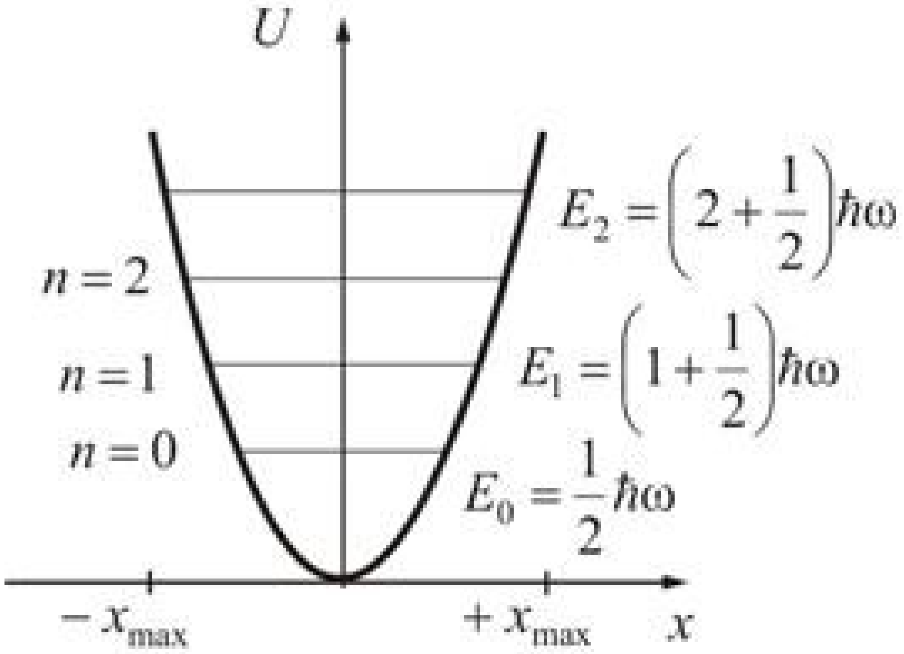
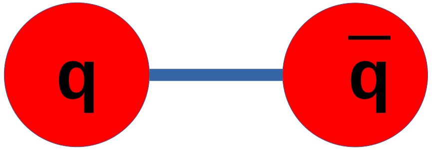
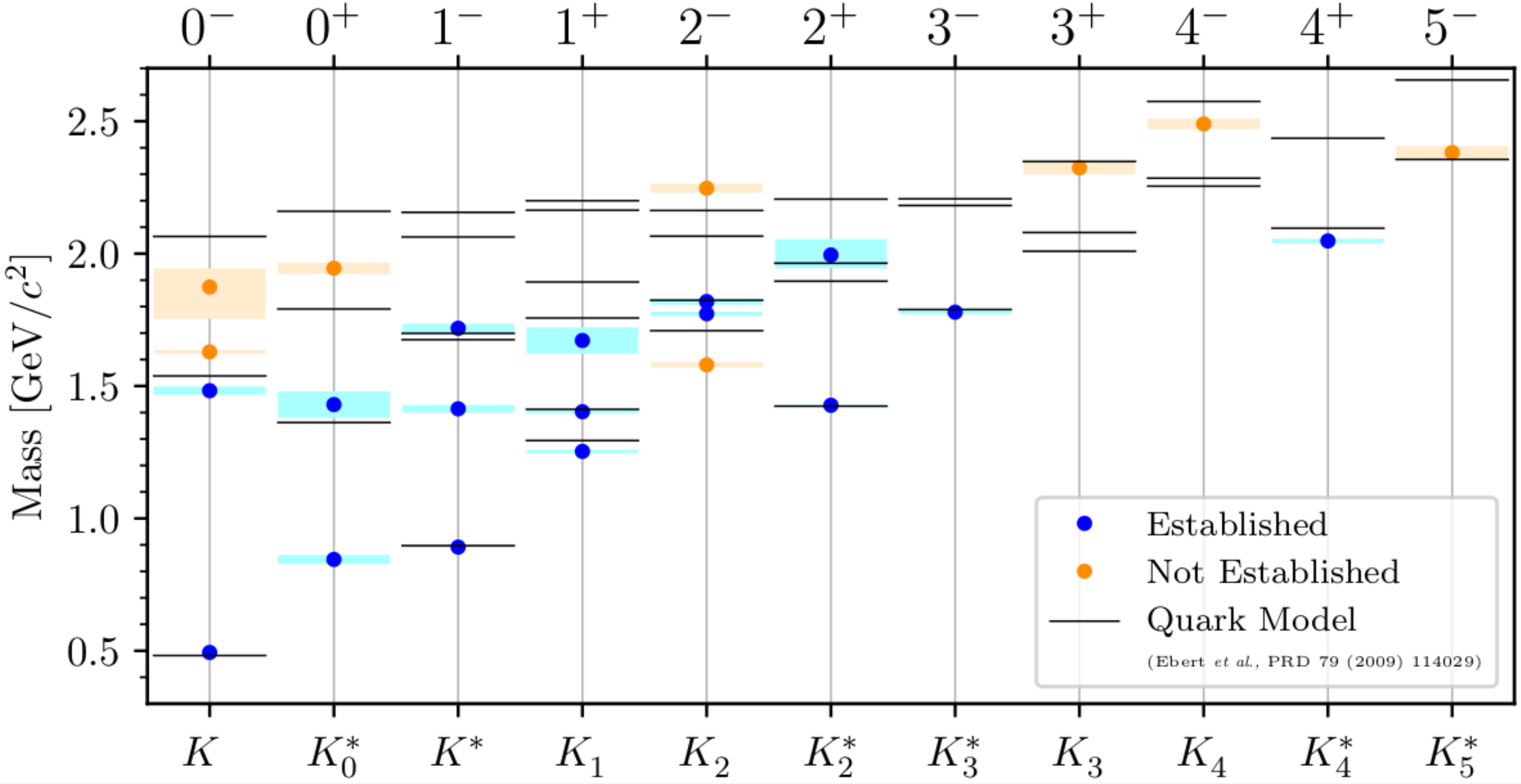
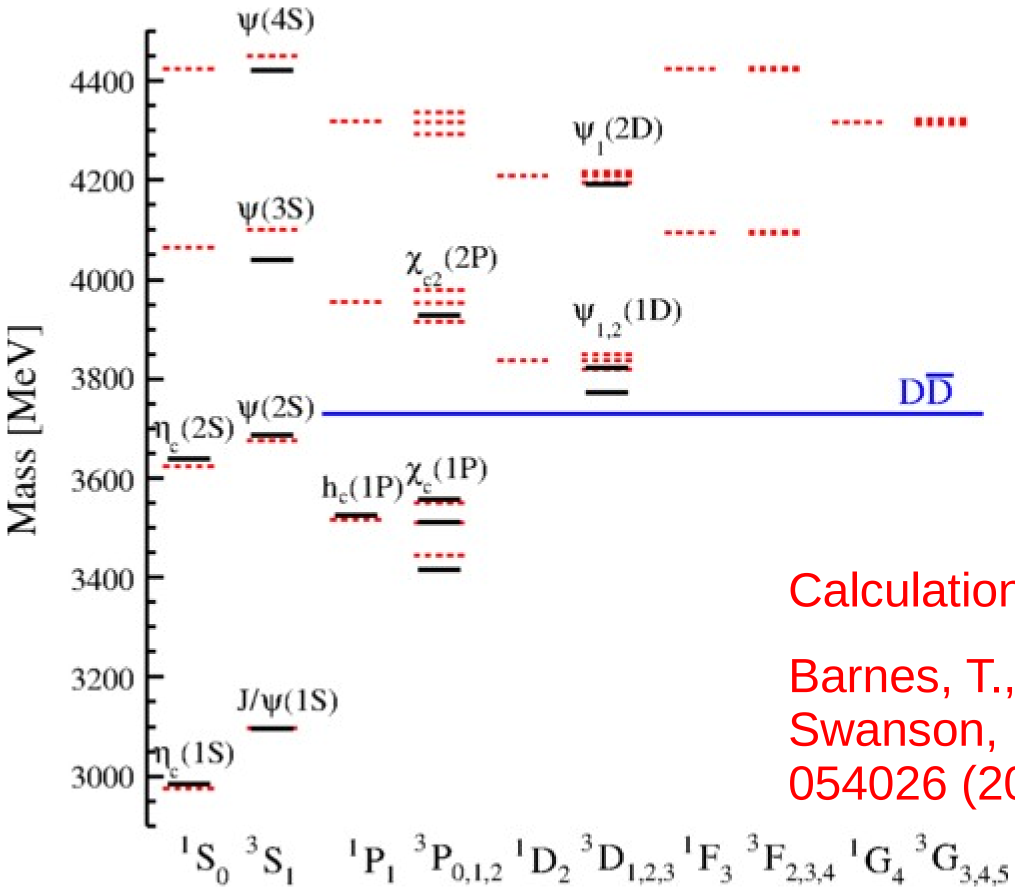

U
n = 2
n = 1
n = 0
$E_2 = \left(2 + \frac{1}{2}\right)\hbar\omega$
$E_1 = \left(1 + \frac{1}{2}\right)\hbar\omega$
$E_0 = \frac{1}{2}\hbar\omega$
$-x_{max}$
$+x_{max}$
x


q
$\bar{q}$

Strange mesons



Charmonium spectrum

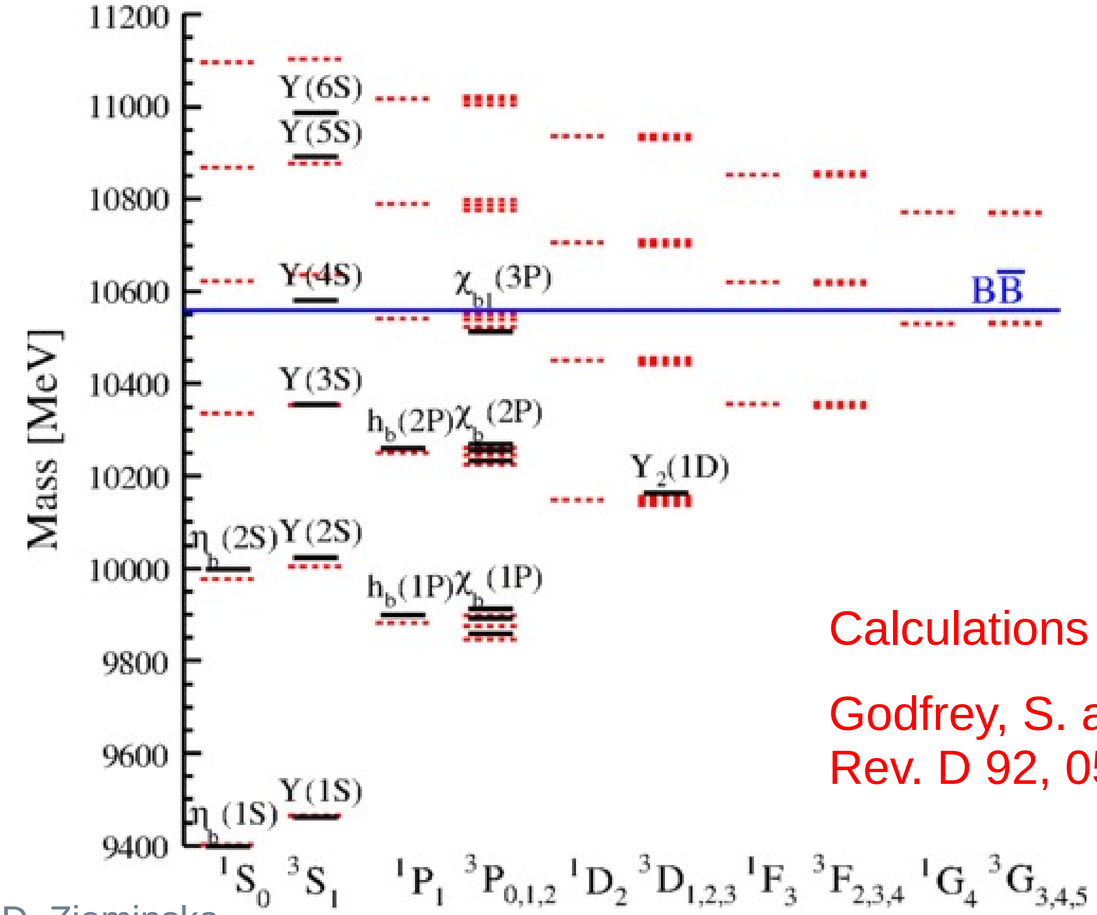


Calculations by

Barnes, T., S. Godfrey, and E. S. Swanson, Phys. Rev. D 72, 054026 (2005).

S. L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003

Bottomonium spectrum



Calculations by

Godfrey, S. and K. Moats, Phys. Rev. D 92, 054034 (2015).

S. L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003