53rd International Winter Meeting on Nuclear Physics

26-30 January 2015 Bormio (Italy)

3RD PRE-CONFERENCE SCHOOL

Lecturer: P. Capel, L. Fabbietti, W. Kűhn, C. Sfienti

WHY THIS CONFERENCE?

53rd International Winter Meeting on Nuclear Physics

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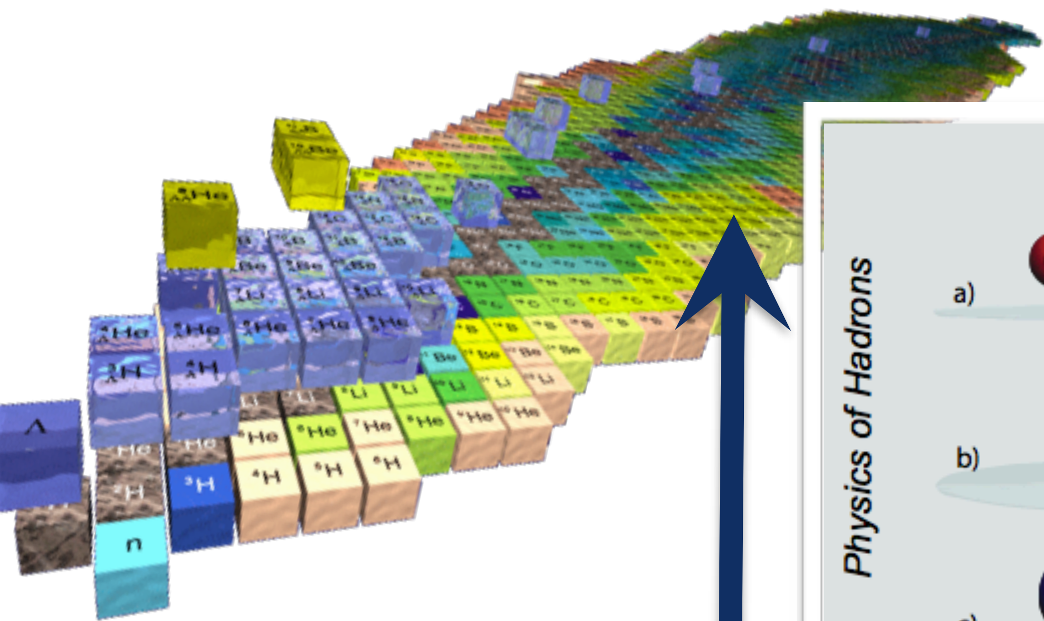
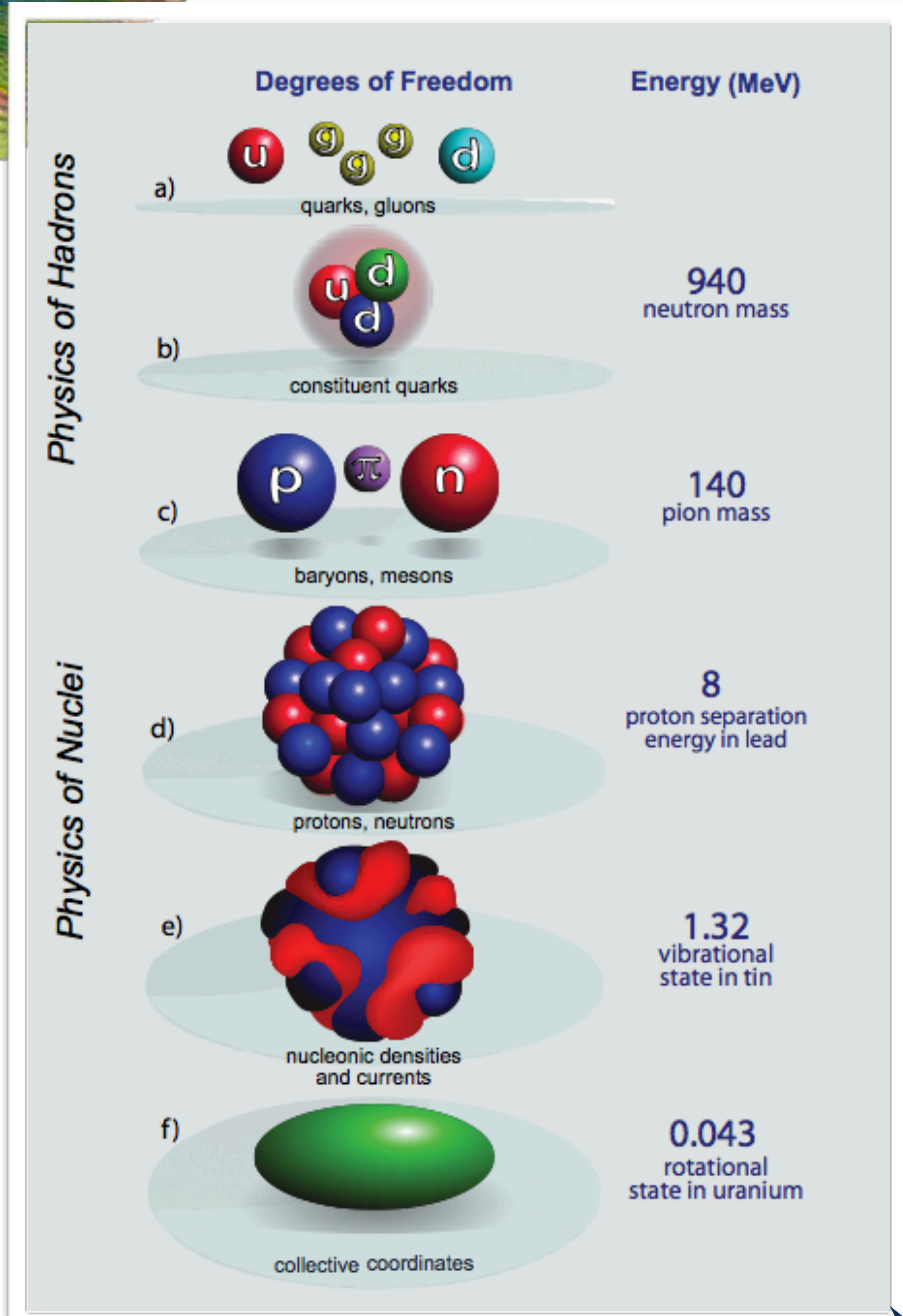
THE MANY FACETS OF THE NUCLEAR REALM



Resolution



LRP Nuclear Science Advisory Committee(2008)

Simplicity

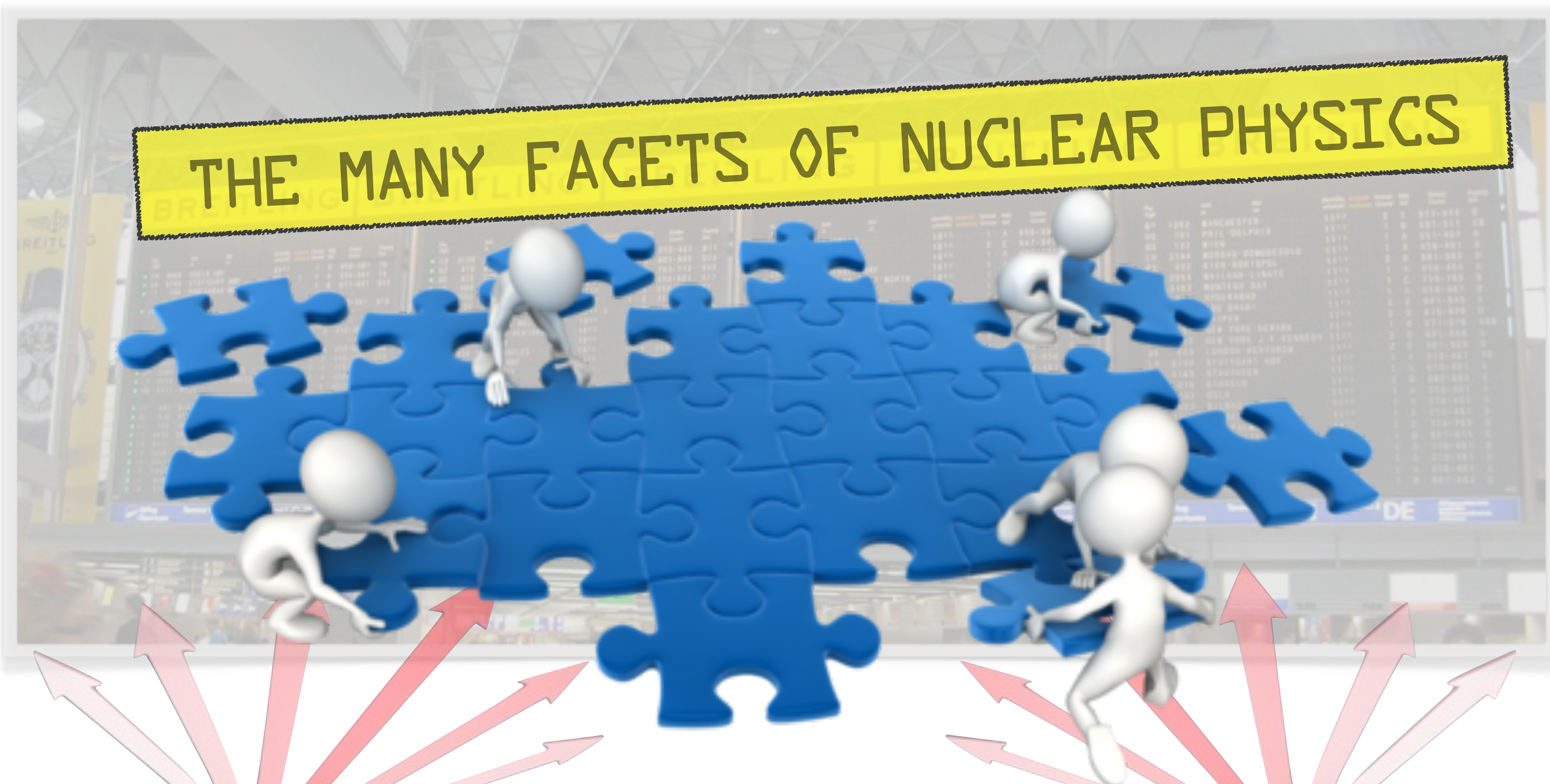
- Hot and dense quark-gluon matter
- Hadron structure
- Hadron-Nuclear interface
- Nuclear structure
- Nuclear reactions
- Nuclear astrophysics
- Applications of nuclear science

Complexity

Specialization

Differentiation

BORMIO IS THE OPPORTUNITY!



Differentiation

GAIN in scientific insight

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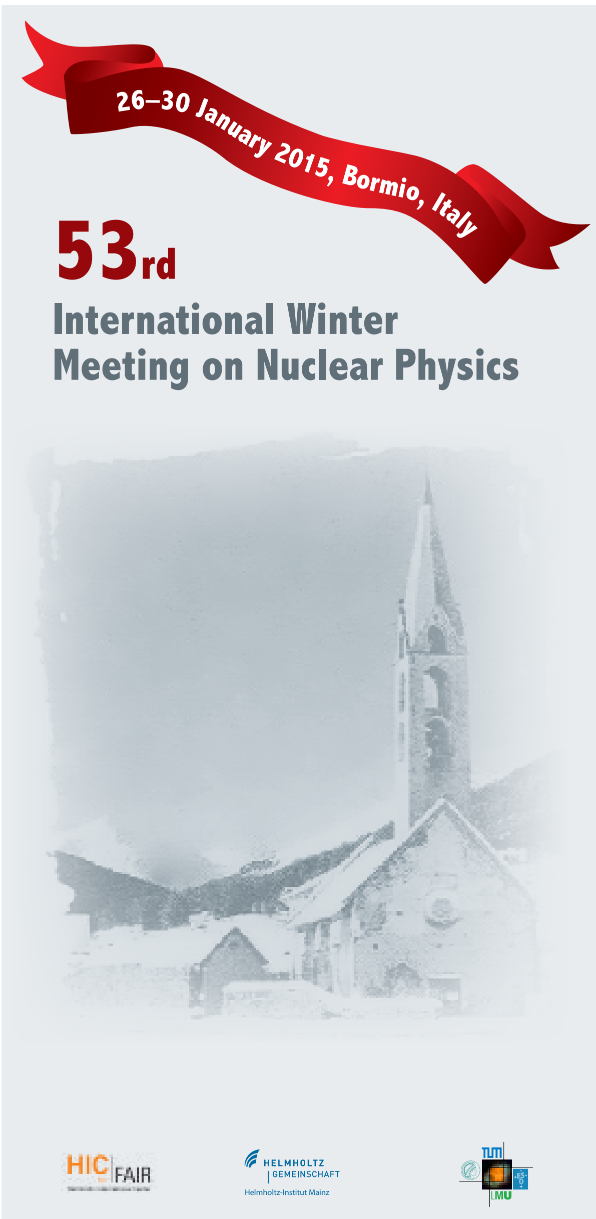


SCHEDULE

9:00 - 10:45 Hadron Physics: selected topics (CS)

10:45 - 11:15 Break

11:15 - 13:00 Nuclear Structure and Astrophysics: selected topics (PC)

13:00 - 14:00 Lunch

14:00 - 15:45 Heavy Ion Reactions: selected topics (LF)

15:45 - 16:15 Break

16:15 - 18:00 Flavor Physics: selected topics (WK)

This conference is sponsored by:

HIC for FAIR Helmholtz International Center

CAEN Tools for discovery

HELMHOLTZ GEMEINSCHAFT Helmholtz-Institut Mainz

TUM LMU

Hadron Physics: Selected Topics

MONDAY, 26th January 2015

➔ MORNING SESSION 09:00-12:20

9:00	Concettina Sfienti and Laura Fabbietti	Welcome
09:10	Robert Rutledge	The Neutron Star Mass-Radius Relationship and the Dense Matter Equation of State
09:50	Frank Maas	Newest Results and Future Perspectives of the Parity Violation Experiments
10:20	Coffee-break	
11:00	Maura Graziani	The latest results from the Alpha Magnetic Spectrometer on the International Space Station
11:40	Soeren Lange	Status and Physics of Belle II

➔ POSTER SESSION 17:00-19:00

17:00	Cross section measurements of the elastic electron - deuteron scattering at MAMI	Yvonne Kohl
17:03	Study of direct photon production at PANDA experiment.	Anna Skachkova
17:06	Search for intermediate states in the rare earth nucleus ^{150}Sm	Lumkile Msebi
17:11	Simulation of Hadronic Triangular Flow in Relativistic Heavy Ion Collisions	Jana Crkovska
17:14	Neutron skin studies in heavy nuclei with coherent π^0 photo-production	Maria Isabel Ferretti Bondy
17:17	Bose-Einstein Correlations of Charged Mesons in the SELEX Experiment	Grigory Nigmatkulov
17:20	Exploring Λ production in low-energy p-p reactions at HADES	Rafal Lalik
17:23	Non-Photonic Electrons in STAR Experiment	Katarina Gajdosova
17:26	Shear viscosity η to electric conductivity σ_{el} ratio for the Quark-Gluon Plasma	Armando Puglisi
17:29	Isospin breaking effects in the leading hadronic contribution to the muon g-2	Jan Haas
17:32	LUNA 400 and LUNA-MV: present and future of Nuclear Astrophysics at LNGS	Carlo Gustavino
17:35	Measurement of the Analysing Power in Proton-Proton Elastic Scattering at Small Angles	Zara Bagdasarian
17:38	Two-photon exchange corrections in elastic electron-proton scattering	Oleksandar Tomalak

TUESDAY, 27th January 2015

➔ MORNING SESSION 09:00-12:30

09:00	Achim Schwenk	From neutron-rich nuclei to matter in astrophysics
09:40	Peter Braun-Munziger	Relativistic nuclear collisions from RHIC to the LHC, the quark-gluon plasma, and QCD
10:20	Coffee break	
10:50	Haik Simon	Status of the ELISE Project
11:30	Jelena Ninkovic	New Developments in Silicon Detectors
12:00	Peter Egelhof	Direct Reactions with Exotic Beams at Low Momentum Transfer: Inverstigations with Stored Beams and with Active Targets

➔ AFTERNOON SESSION 17:00-19:00

17:00	Iowani Zimba	First observation of E1 transitions from the octupole band to the excited 0_2^+ Pairing Isomer band in the rare earth nucleus ^{154}Dy
17:20	Alexander Austregesilo	Precision Hadron Spectroscopy at COMPASS
17:40	Matteo Cardinali	Fast Frontend Electronics for high luminosity particle detectors
18:00	Giovanni Bencivenni	The Resistive-WELL detector: a compact spark-protected single amplification-stage MPGD
18:20	Michaela Thiel	From deep inside to outer space: exploring neutron skins
18:40	Salvatore Plumari	Anisotropic flows and shear viscosity of the Quark-Gluon plasma within a transport approach.

WEDNESDAY, 28th January 2015

➔ MORNING SESSION 09:00-12:20

09:00	David D' Enterria	Overview of the CMS Results
09:40	Wolfgang Gradl	BESIII: the lastest data harvest
10:20	Coffee break	
10:50	Lyn Evans	Beyond the LHC Accelerator
11:20	Alessandro Grelli	Charm physics at hadron colliders and beyond
11:50	Bernhard Ketzer	Latest results from COMPASS

➔ AFTERNOON SESSION 17:00-19:00

17:00	Francesca Balestra	Measurements of Carbon ion fragmentation on a thin Carbon target by the FIRST collaboration at GSI.
17:20	Claudia Behnke	Reconstruction of neutral mesons with the HADES detector
17:40	Barbara Trzeciak	STAR's latest results on quarkonia production
18:00	Ruben Pampa Condori	Experiments with a double solenoid system: Measurements of the 6He+p Resonant Scattering
18:20	Dolezal Zdenek	ATLAS studies of spectroscopy and B-decays
18:40	Martin Schaefer	Structure of light hypernuclei in the framework of Fermionic Molecular Dynamics

Hadron Physics: Selected Topics

THURSDAY, 29th January 2015

➔ MORNING SESSION 09:00-12:20

09:00	Jean-Come Lanfranchi Dark Matter Search with CREST
09:40	Michael Block Super Heavy Elements
10:20	Coffee-break
10:50	Germano Bonomi Muons: civil applications
11:20	Christian Fischer Hadron physics from Dyson-Schwinger equations
11:50	Davide Trezzi Looking the Universe from Deep Underground

➔ AFTERNOON SESSION 17:00-19:00

17:00	Kgotlaesele Johnson Senosi Measurements of W boson production in p-Pb collisions at the LHC with ALICE
17:20	Matthias Holl Quasi-Free Scattering from Relativistic Carbon and Oxygen Isotopes
17:40	Elisabetta Prencipe Hadrons with c-s quark content: past, present and future
18:00	Daniele Cortinovis EndoTOFPET-US: an endoscopic Positron Emission Tomography detector for a novel multimodal medical imaging tool
18:20	Lena Heijkenskjöld Hadronic decays of the omega meson measured with WASA-at-COSY
18:40	Tomas Kosek Recent Results on Hard Probes of the Quark-Gluon Plasma with the ATLAS Experiment at the LHC

FRIDAY, 30th January 2015

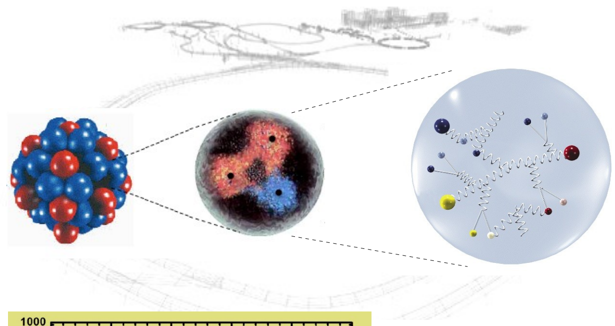
➔ MORNING SESSION 09:00-12:30

09:00	Juergen Krosberg Overview of the ATLAS Results
09:40	LHCb Collaboration Whats new at the LHCb?
10:20	Coffee break
10:50	Stephen Lars Olsen A New Hadron Spectroscopy
11:30	Dariusz Miskowiec QCD-matter studies with ALICE at the LHC
12:00	Torsten Dahms Low-mass dileptons: A thermometer for the hottest stuff in the universe

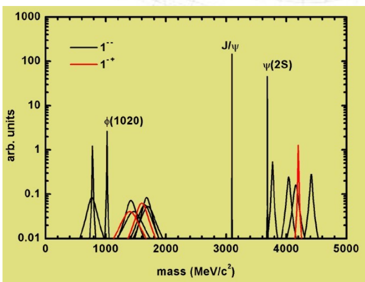
➔ AFTERNOON SESSION 17:00-19:10

17:00	Cecilia Voena A novel dual-mode tracking device for online dose monitoring in hadron therapy
17:20	Johannes Rausch Singly Cabibbo Suppressed Charm Decay : CP Violation, Branching Ratio Measurement, and Partial Wave Analysis
17:40	Ruediger Haake Centrality dependence of charged jets in p-Pb collisions measured with the ALICE detector
18:00	Leonard Koch Concept of the K^0_s rescue system for the Belle II PXD
18:20	LHCb Collaboration Flavour Physics at LHCb
18:40	Luciano Moretto The Little Hagedorn That Could

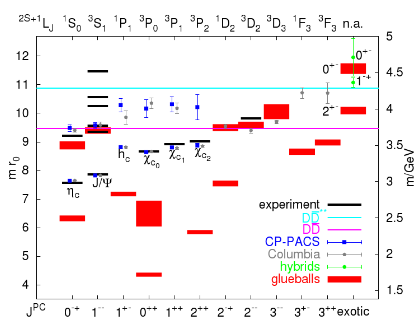
Hadron Physics: Selected Topics



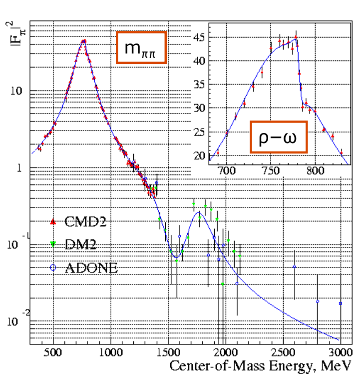
THE BASIC



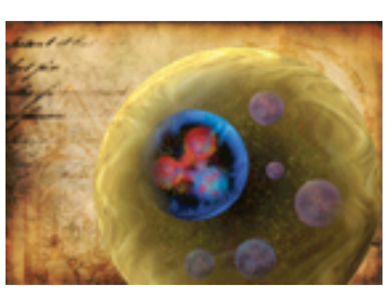
HADRONS IN QCD



EX1: CHARMONIUM



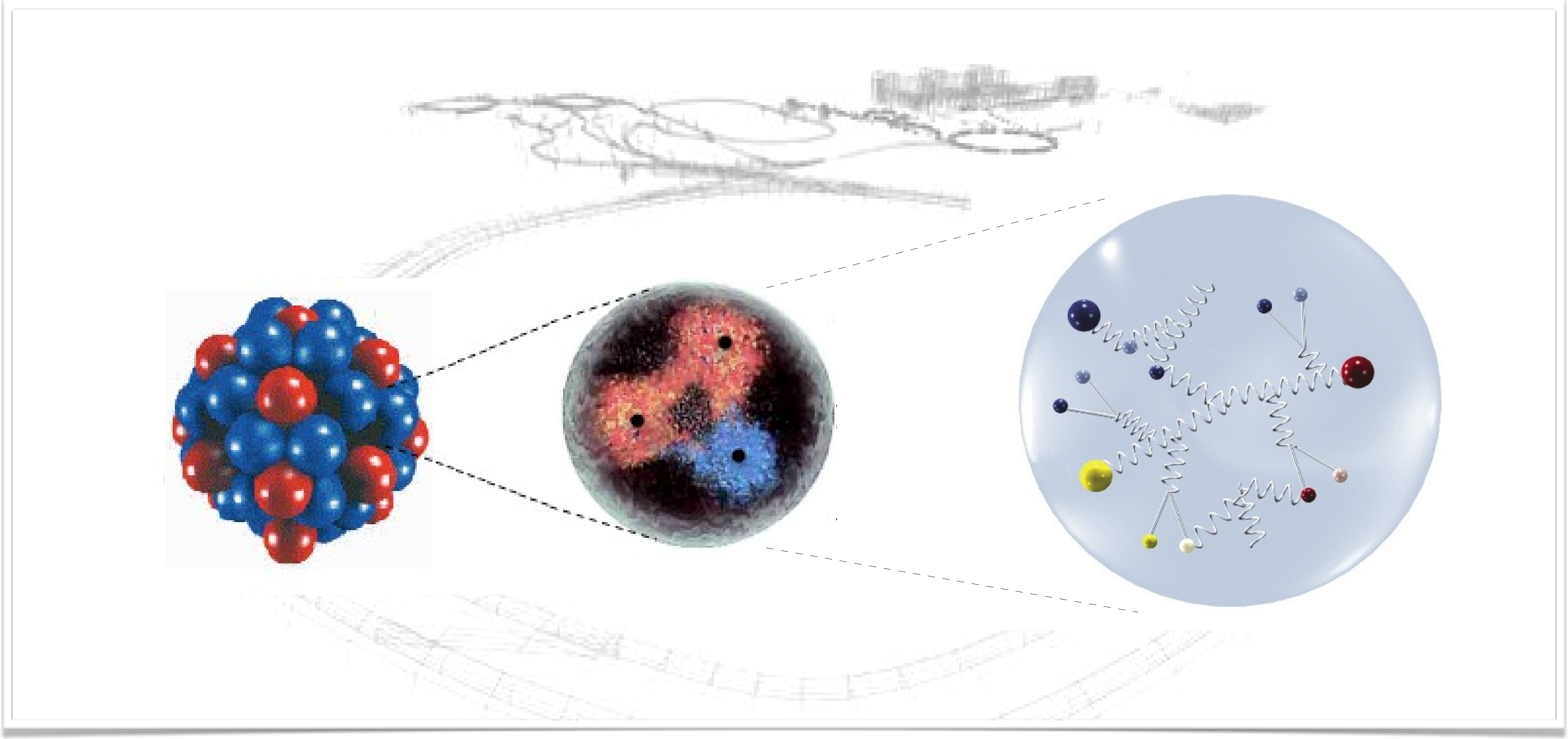
EXP. TECHNIQUE:PWA



EX2: STRANGE HADRONS

Hadron Physics: Selected Topics

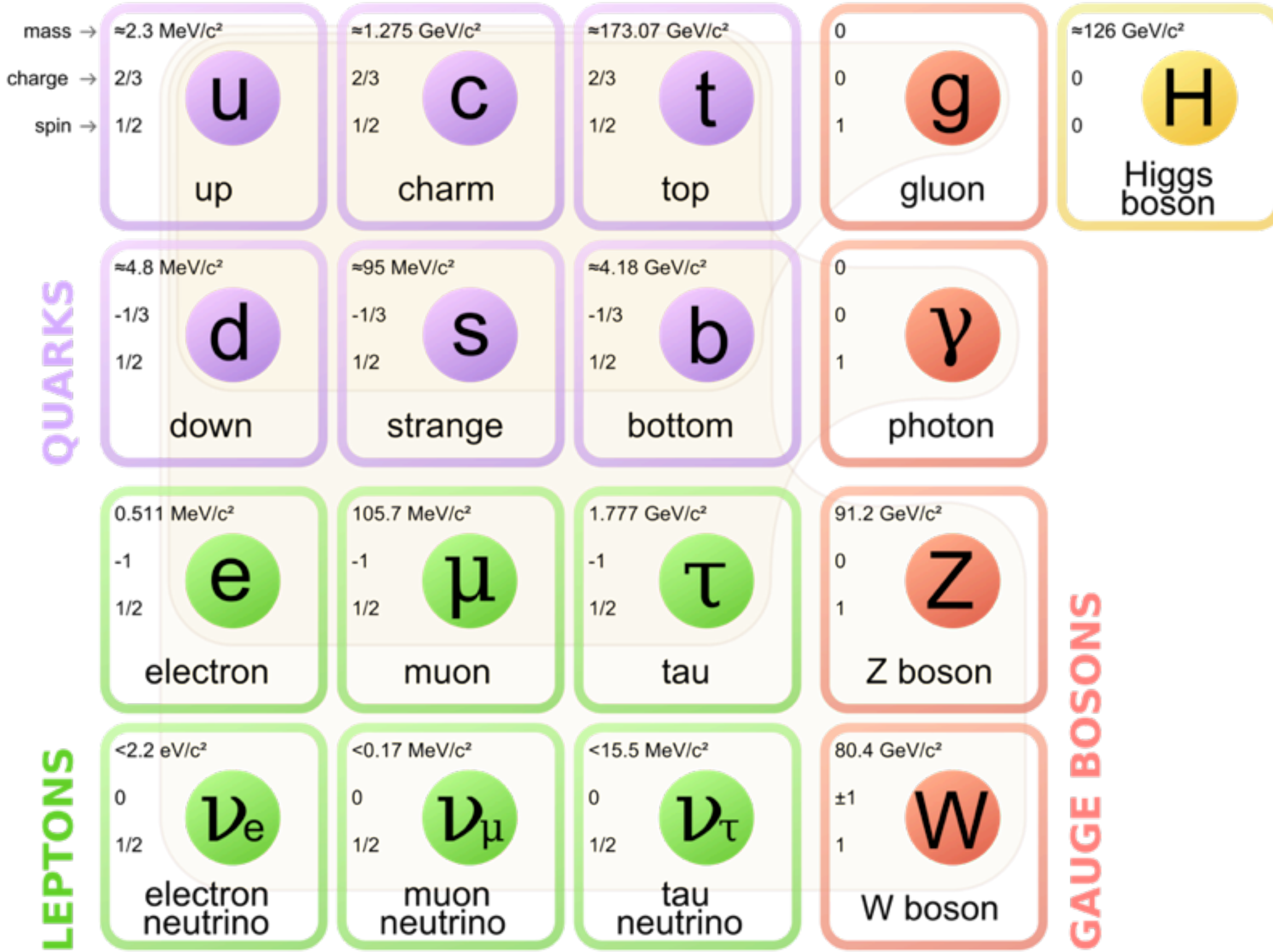
...THE BASIC ...



WHAT YOU SHOULD ALREADY KNOW ...

The building blocks

i.e. first slide in almost all talks, before you switch off!



Constituent Quark Model

1964 The model was proposed independently by Gell-Mann and Zweig
Three fundamental building blocks 1960's $(p,n,\lambda) \Rightarrow$ 1970's (u,d,s)

<u>mesons</u> are bound states of a of quark and anti-quark:

$$\pi^+ = u\bar{d} \quad \pi^0 = \tfrac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = d\bar{u}$$

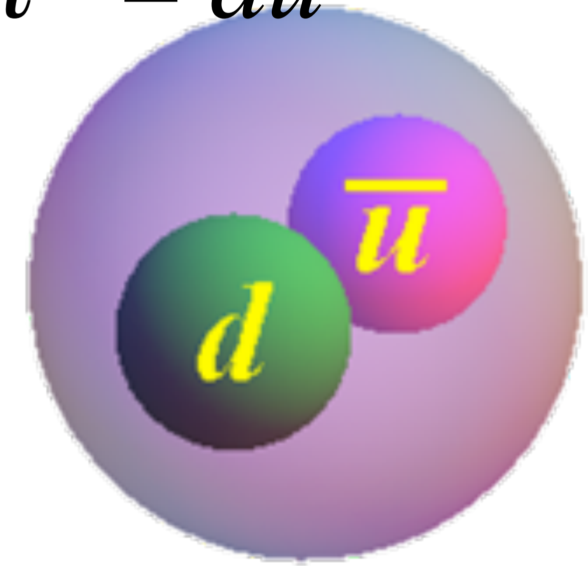
$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

<u>baryons</u> are bound state of 3 quarks:

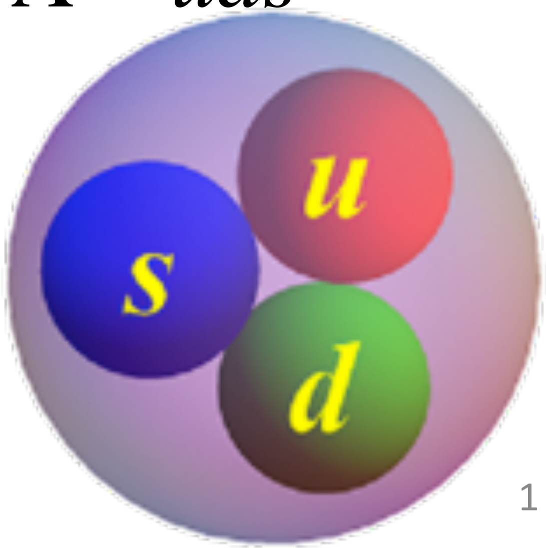
$$p = uud \quad n = udd \quad \Lambda = uds$$

$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

$$\pi^- = d\bar{u}$$



$$\Lambda = uds$$

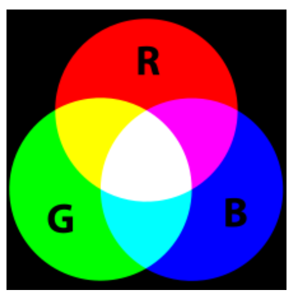


From QPM to QCD

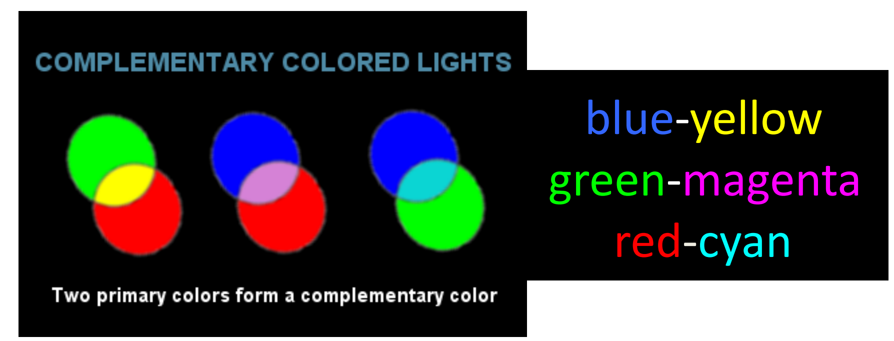
COLOR necessary for antisymmetric wave function

$$\Delta^{++} = \underbrace{|u\,u\,u\rangle}_{\text{Flavour}} \cdot \underbrace{|\uparrow\uparrow\uparrow\rangle}_{\text{Spin}} \cdot \underbrace{|\ell = 0\rangle}_{\text{Orbital-}\ell} \cdot \underbrace{\left|\frac{1}{\sqrt{6}} \varepsilon^{ijk} q_i q_j q_k\right\rangle}_{\text{Farbfreiheitsgrade}}$$

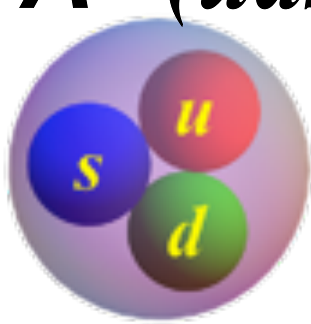
3 primary colors → white



color + complementary color → white

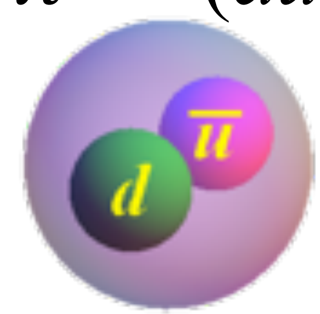


Λ= (uds)



Baryons are red-blue-green triplets

$\pi^- = (d\bar{u})$



Mesons are color-anticolorpairs

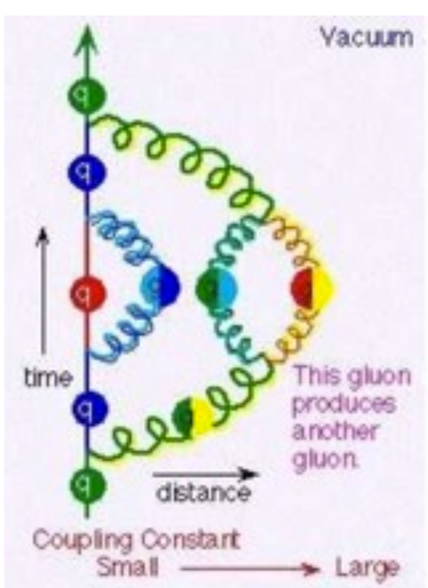
...OBSERVED PARTICLES ARE COLOR SINGLETS

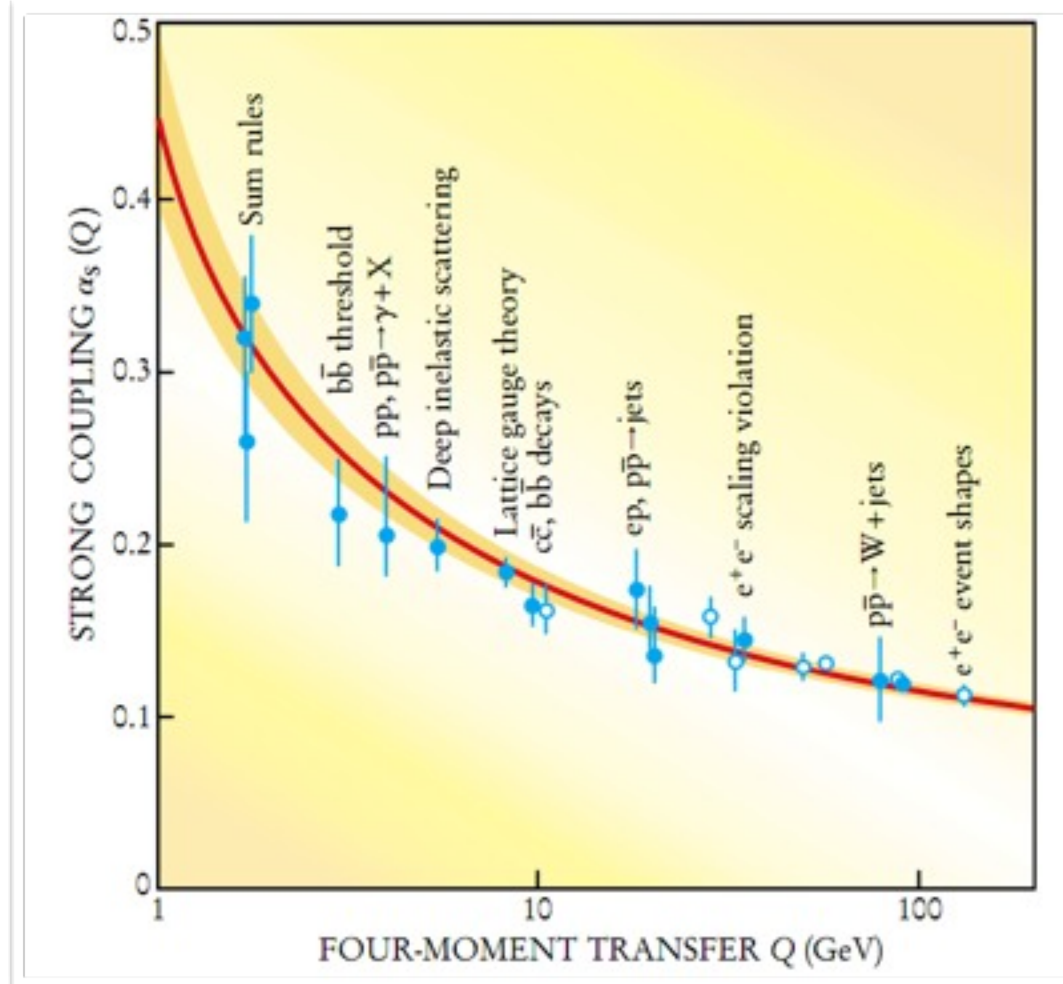
Properties of QCD

Lagrangian of QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}\left(i\gamma_\mu \mathcal{D}^\mu - \mathbf{m}\right)\psi - \frac{1}{4}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}$$

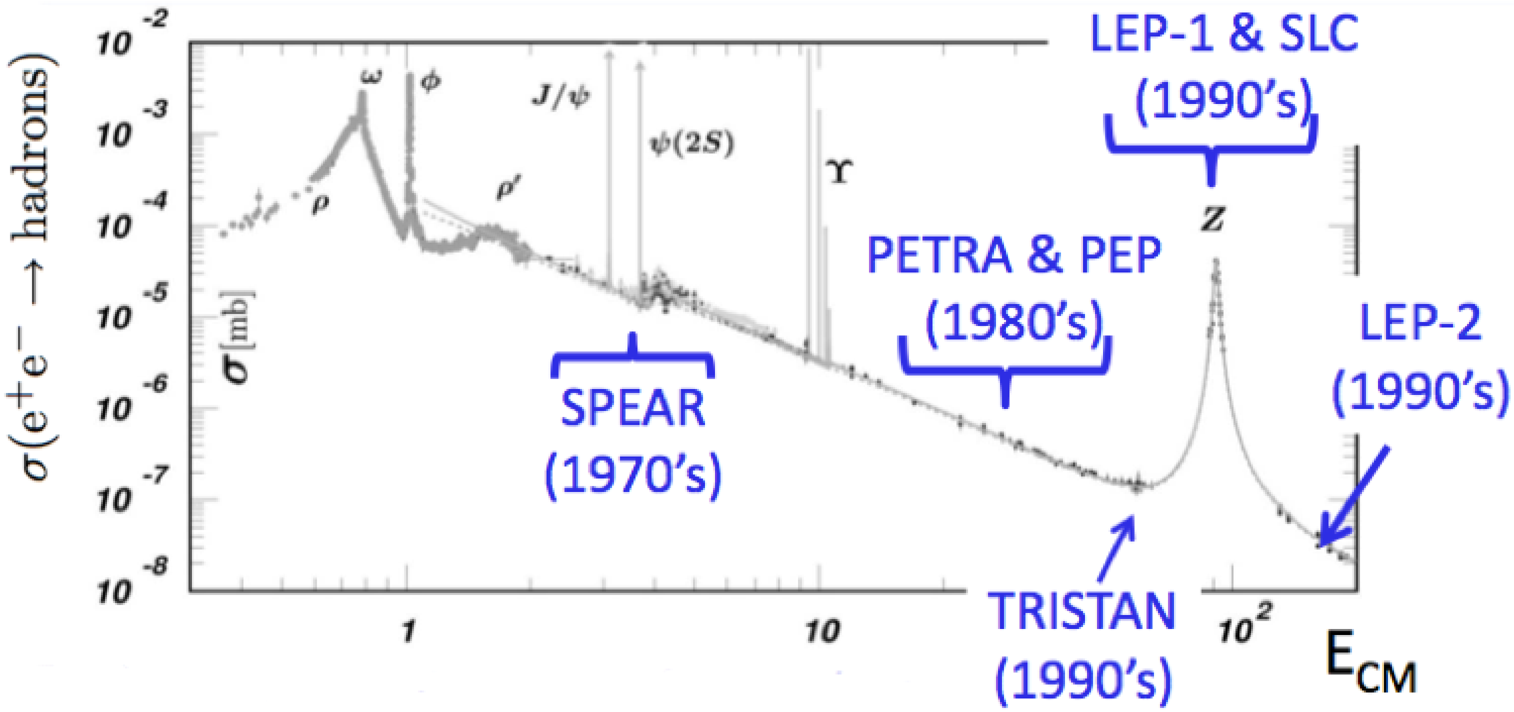
- There are 3 color charges
- Gluons carry color
- → *Self-interactions of gluons*
- The strong coupling varies
- → *small at high energies*
  asymptotic freedom
- → *very large at low energies*
  confinement

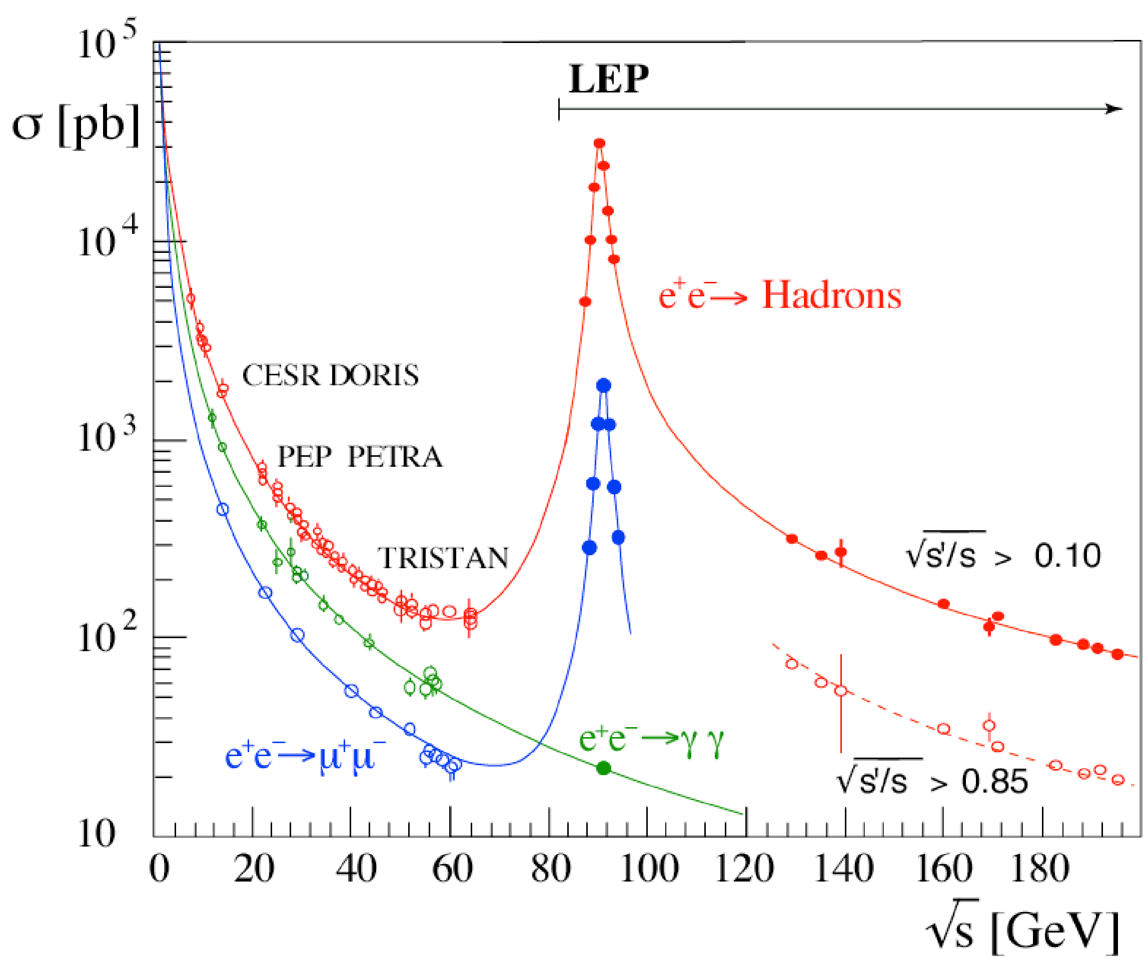




„If the Lord Almighty had consulted me before embarking upon creation,
I would have recommended something simpler."
King Alphonse X. of Castille and Léon (1221-1284), on having the Ptolemaic system of epicycles explained to him

$e^+e^- \to$ Hadrons





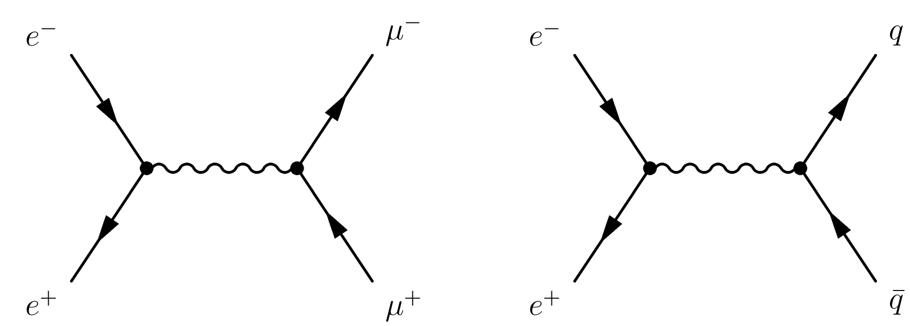
Two step process:

$e^+e^- \to q\bar{q} \to$ hadrons

Basic QED Process:

$$\sigma^{e^+e^-\to\mu^+\mu^-} = \frac{4\pi\alpha_{\rm em}^2}{3s} = \frac{86.9\,{\rm nbGeV}^2}{s}$$

...then compare (Feynman LO)

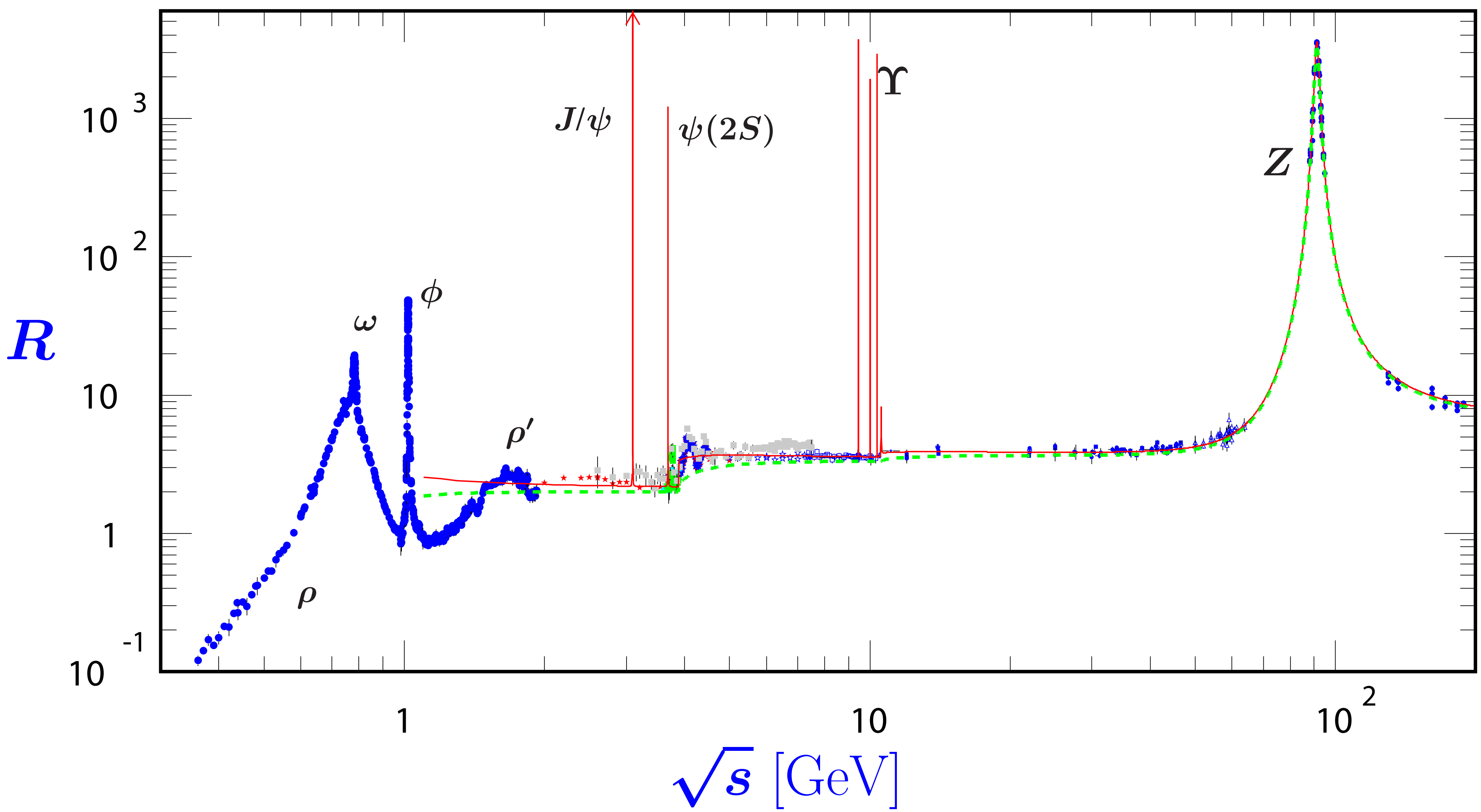


$$\sigma_0^{e^+e^-\to q\bar{q}} = \frac{4\pi\alpha_{\rm em}^2}{3s}e_q^2 N_c = \frac{86.9\,{\rm nbGeV}^2}{s}e_q^2 N_c.$$

$e^+e^- \rightarrow$ Hadrons

and construct:

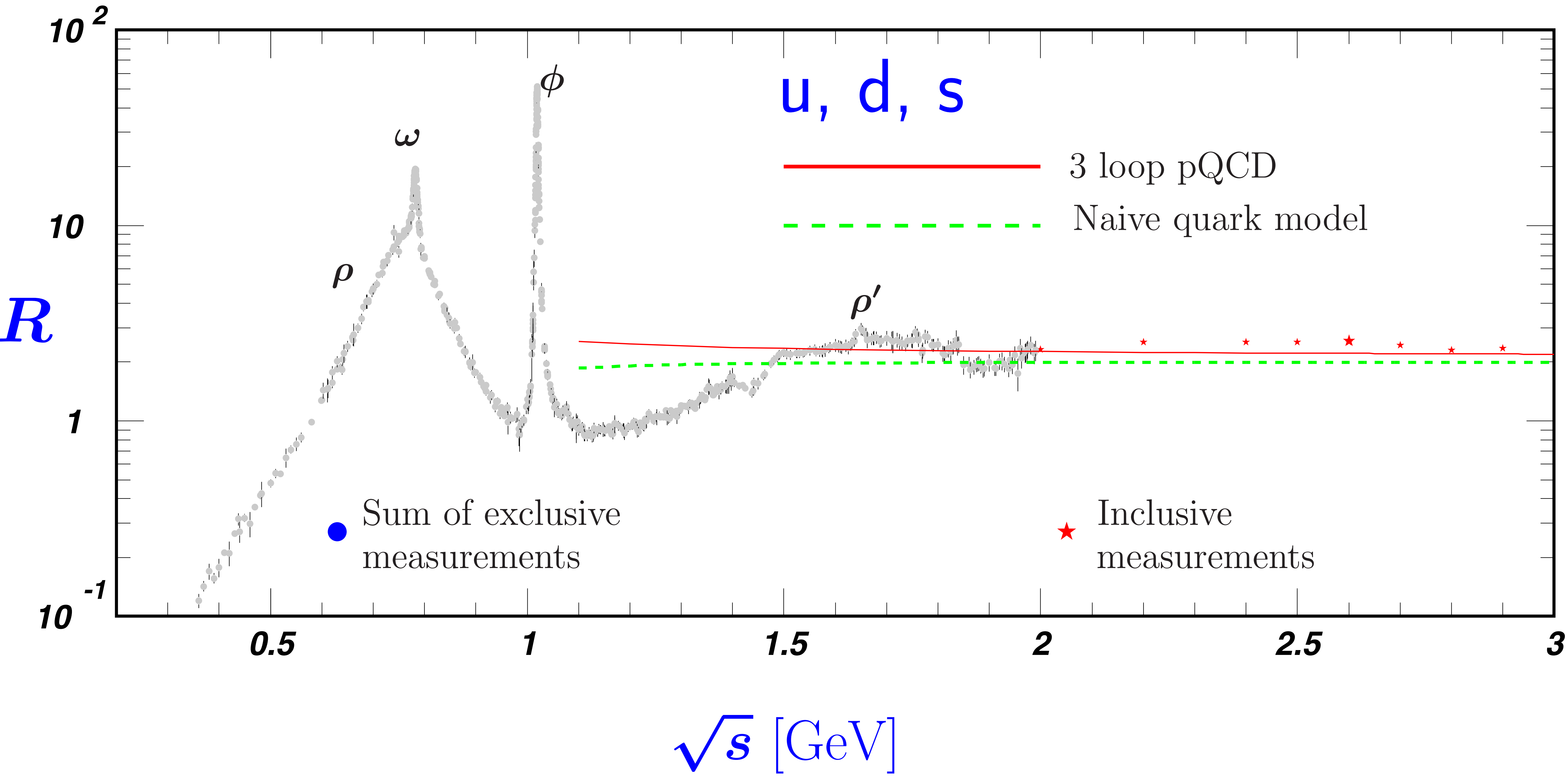
$$R = \frac{\sigma^{e^+e^- \to \text{hadrons}}}{\sigma^{e^+e^- \to \mu^+\mu^-}} = N_c \sum_q e_q^2 .$$



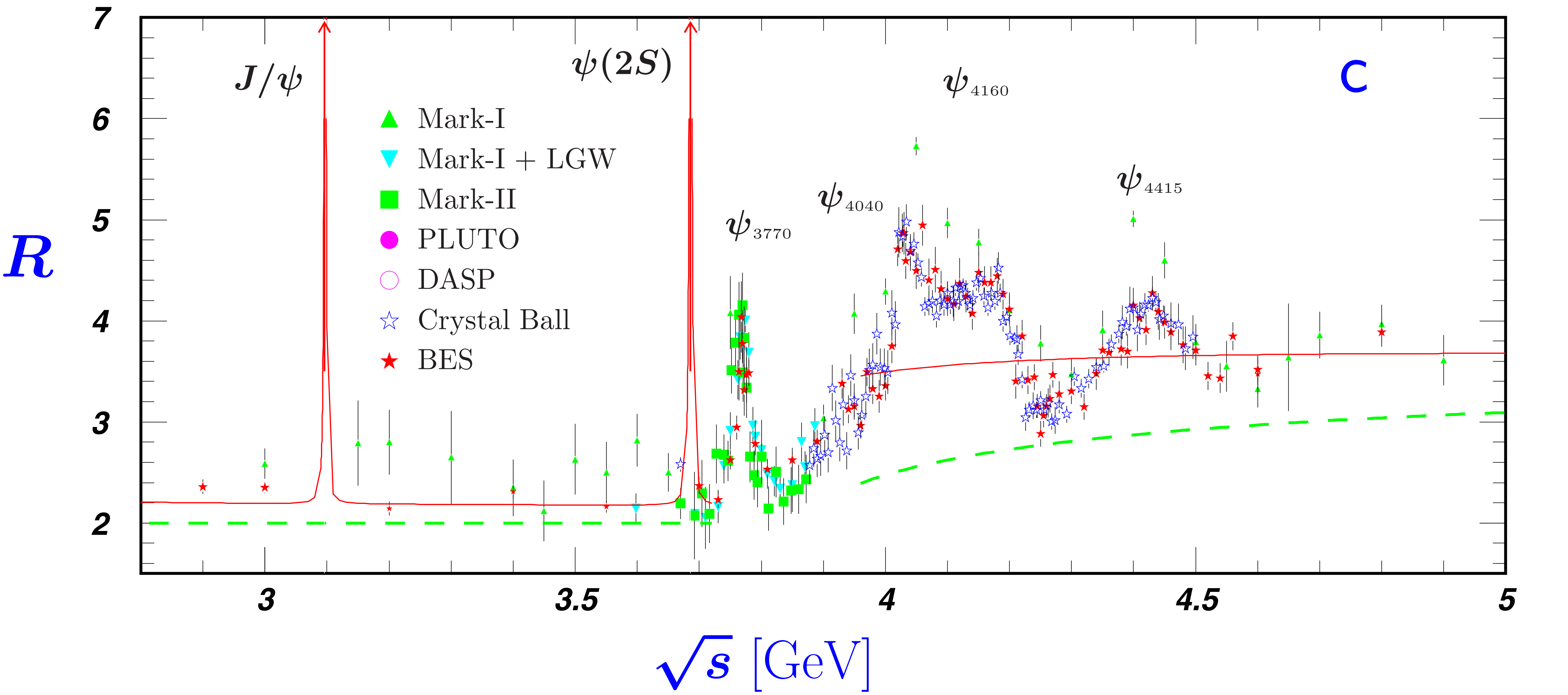
❶ Confirmed Color hypothesis

❷ Production thresholds for Quark-flavours production

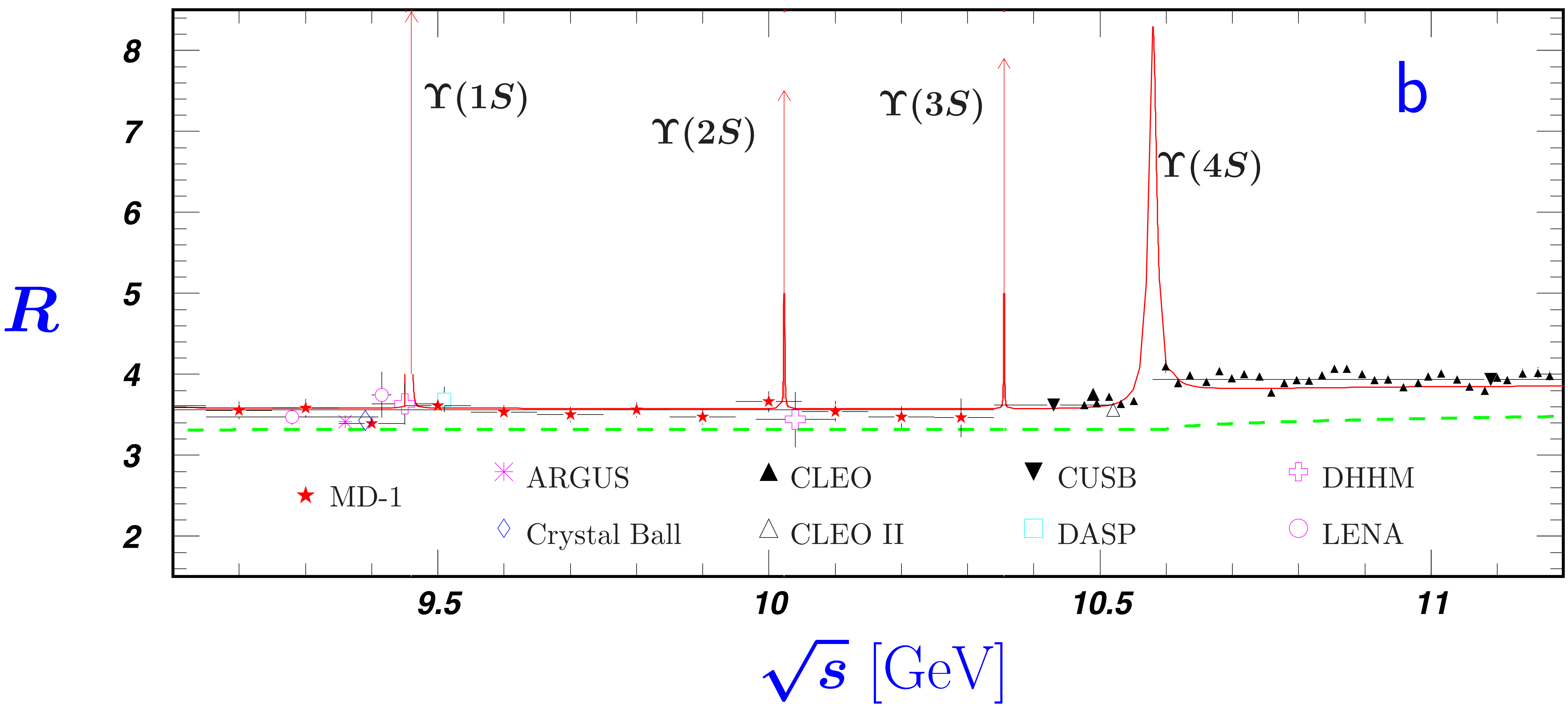
$e^+e^- \rightarrow$ Hadrons



$e^+e^- \to$ Hadrons



$e^+e^- \to$ Hadrons



How to study hadrons?

☞ Build them together in a controlled manner

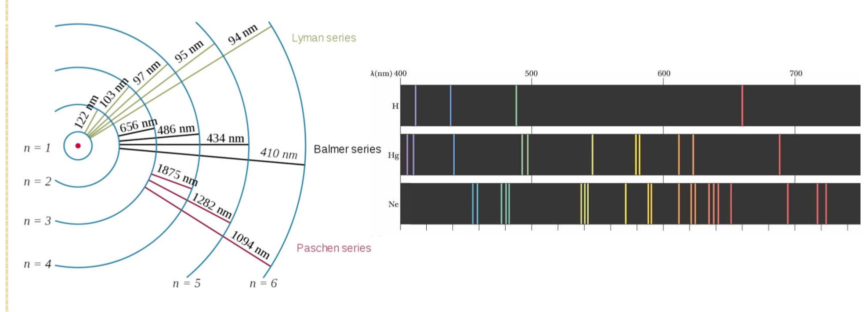
- e^+e^- collider can produce vector mesons (other particles in decays) [BES-III/BELLE]
- hadron beams have high production cross sections but little control [PANDA]

☞ Observe them as existing particles

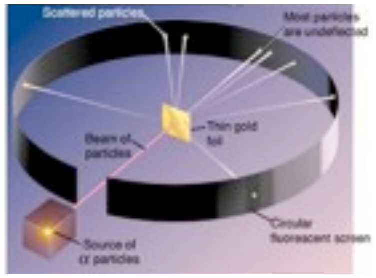
- γ / lepton beams are excellent probes (mostly of the nucleon) [MAMI-JLAB]

☞ Study their interaction among each others

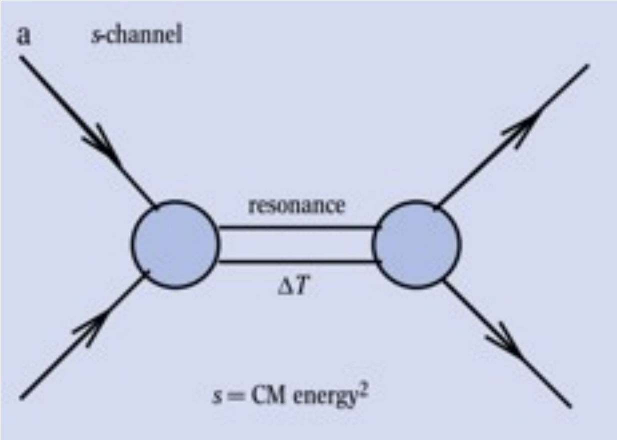
Investigation structure of matter through:

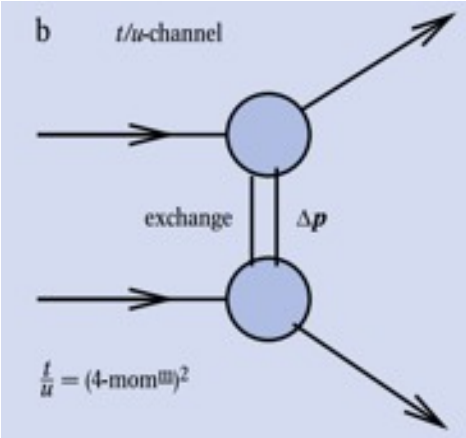


SPECTROSCOPY

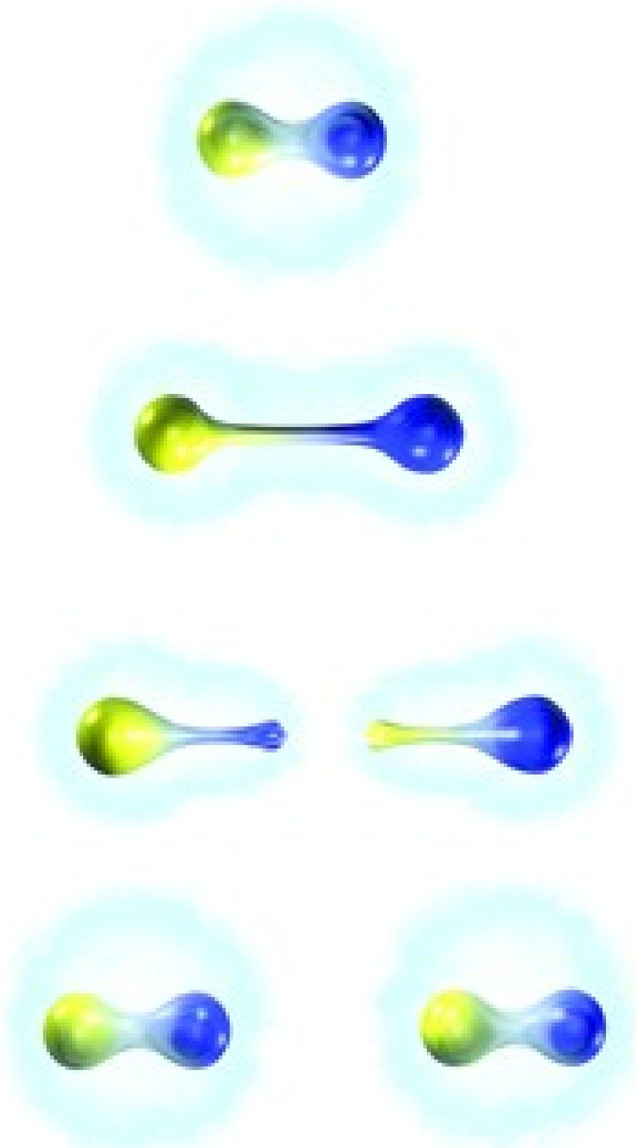


SCATTERING





Strong Interaction



Strong interactions and *confinement*

- No free quarks
- No colored objects
- No fractional charges

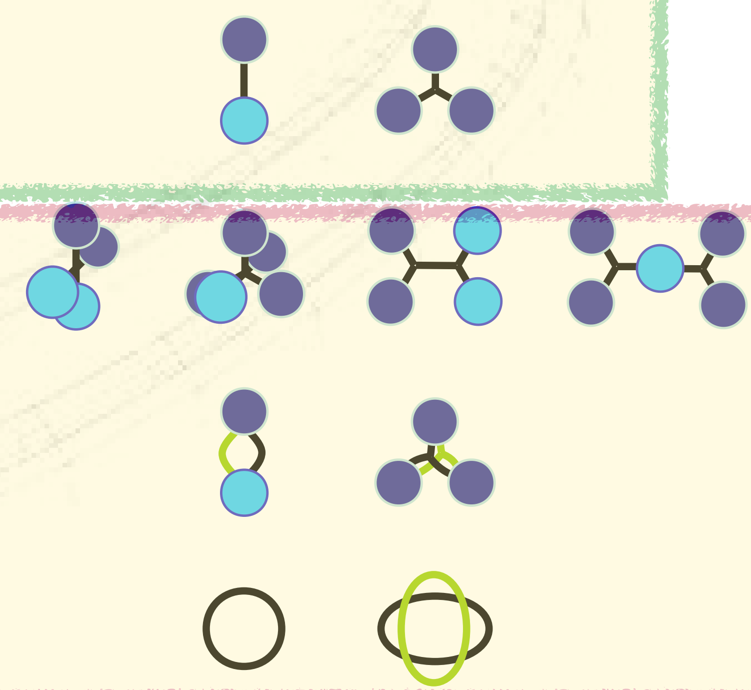
WE KNOW

Mesons, Baryons

Multi-quark states

Hybrids

Glueballs



QCD ALSO ALLOWS

Totalitarian principle: Everything not forbidden is compulsory

Prediction from QCD

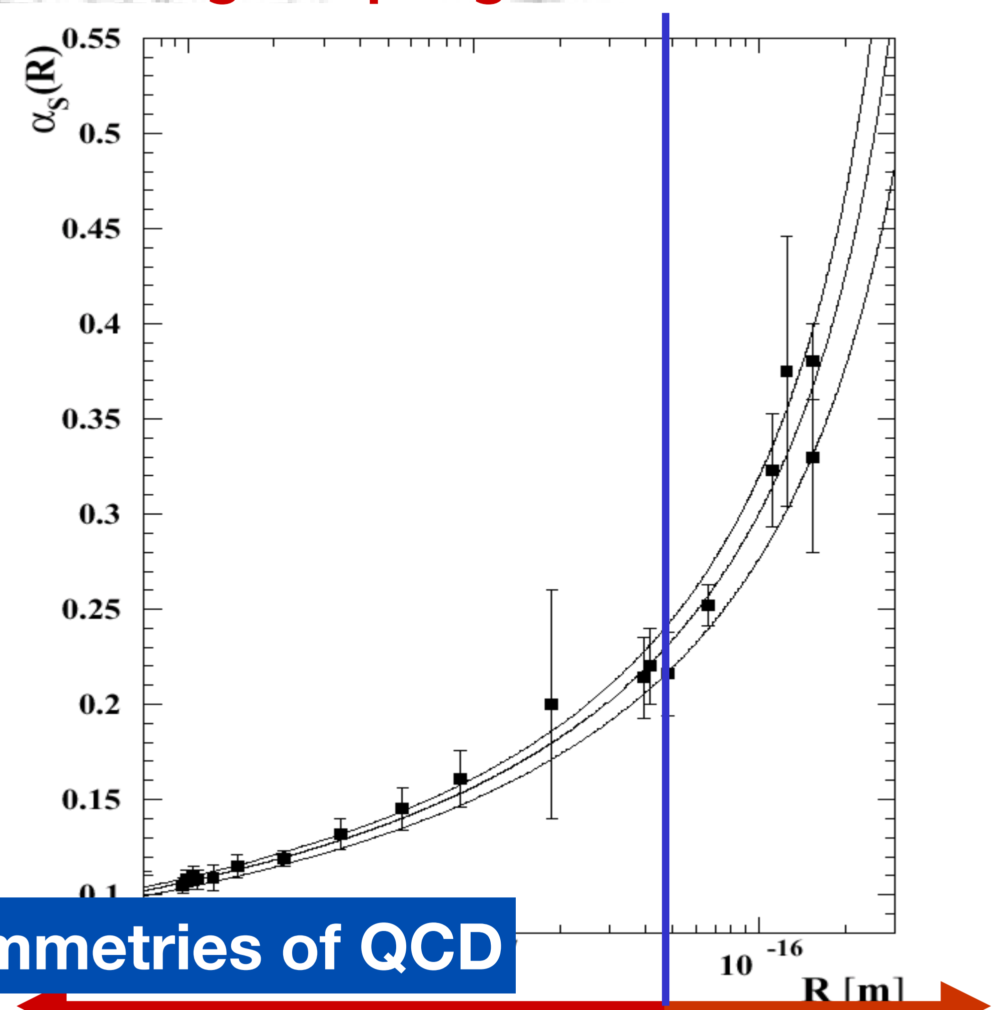
QCD is complex

- At high Q (small distance): Expansion in powers of α_s
  - ➔ Perturbation theory
- At low Q (long distance): Non-perturbative regime, approximations difficult

Methods for low energy QCD

- Phenomenological models
- ➔ *Potential models, quark model*
- Effective degrees of freedom
- ➔ *Chiral perturbation theory* **Approximate Symmetries of QCD**
- Discrete space-time
- ➔ *Lattice QCD* **Implement QCD numerically**

Strong coupling constant vs R



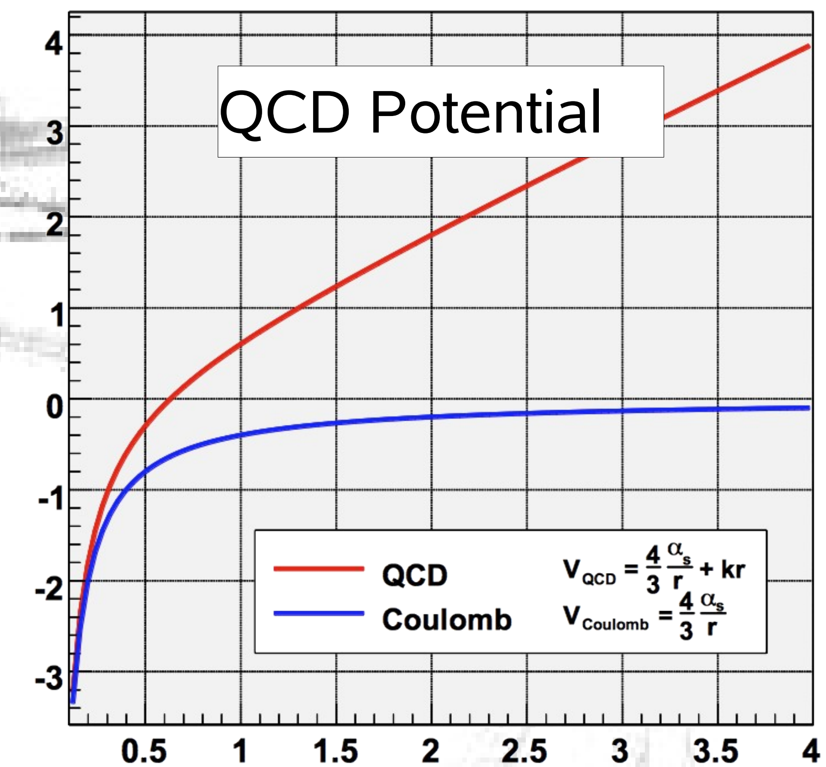
perturbative QCD strong

Phenomenological Models

Asymptotic behaviour of QCD

- Non-relativistic potential
- Confinement region (large r):

$$V_{QCD} \xrightarrow[r\to\infty]{} kr \quad \textbf{Spring-like}$$



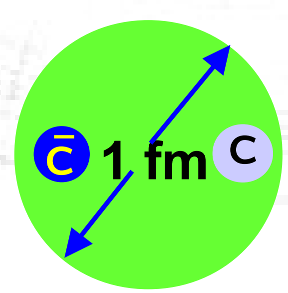
- Region of asymptotic freedom (small r):

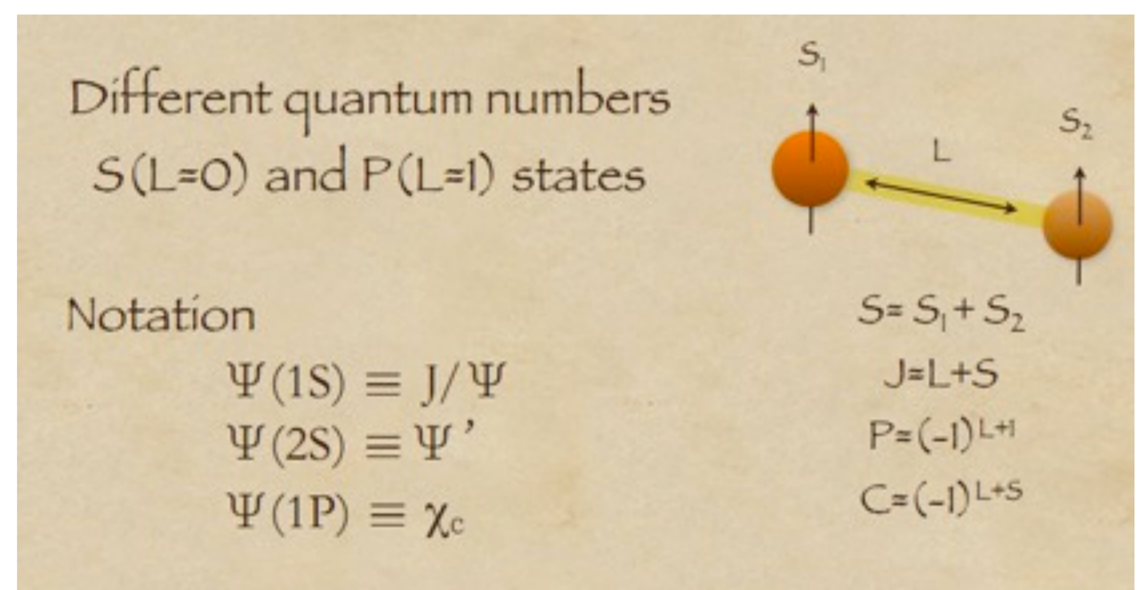
$$V_{QCD} \xrightarrow[r\to 0]{} \frac{4}{3}\frac{\alpha_s}{r} \quad \textbf{Coulomb-like}$$

Bound states in QCD

- Example: $Q\bar{Q}$ states
  - Resonances in the QCD potential
  - Spectrum like positronium

→ Spectroscopy





Effective Field Theories

- Usually Effective Theories replace the Quarks and Gluons by the the degrees of freedom which are “relevant” at this scale.

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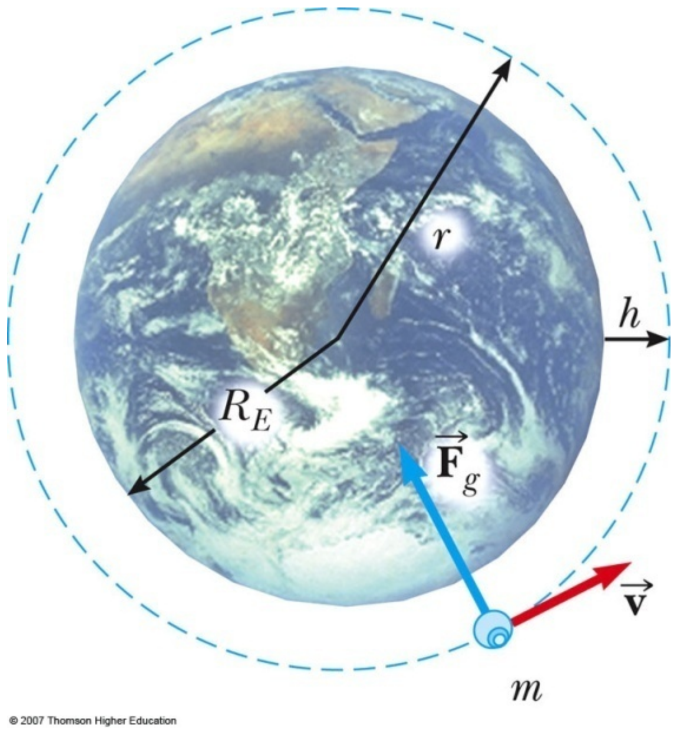
A CLASSICAL EXAMPLE

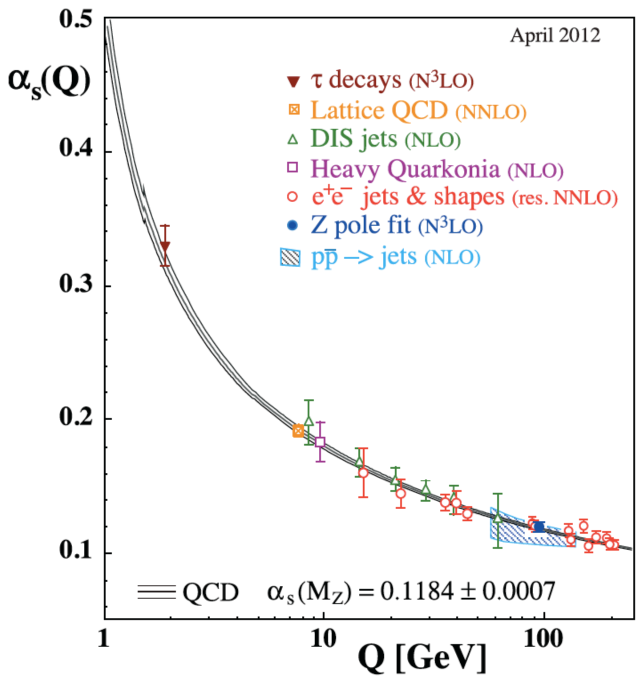
degree of freedom = mass m
symmetries = translations parallel to the earth's surface and rotations about an axis normal to it.

$$V(h) = mgR\sum_{i=0}^{\infty}(-1)^{i-1}\left(\frac{h}{R}\right)^{i},$$



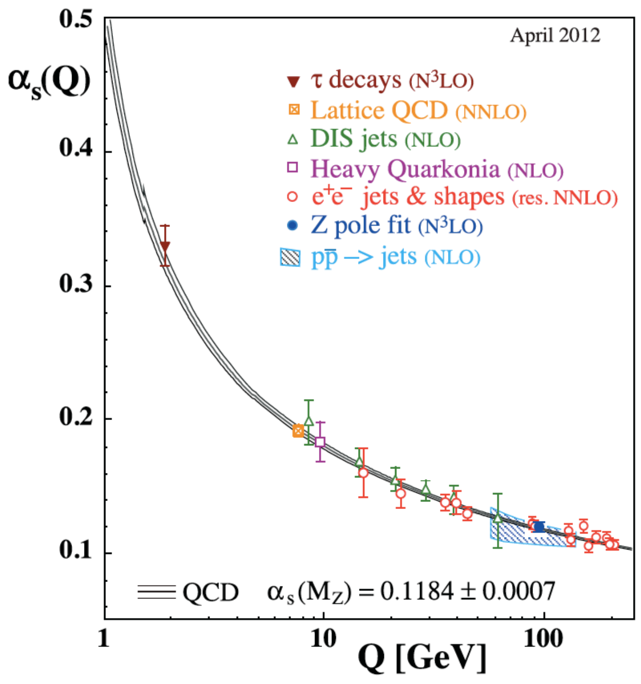
Effective Field Theories

- Usually Effective Theories replace the Quarks and Gluons by the the degrees of freedom which are “relevant” at this scale.
- Effective Theories are systematic expansion of QCD



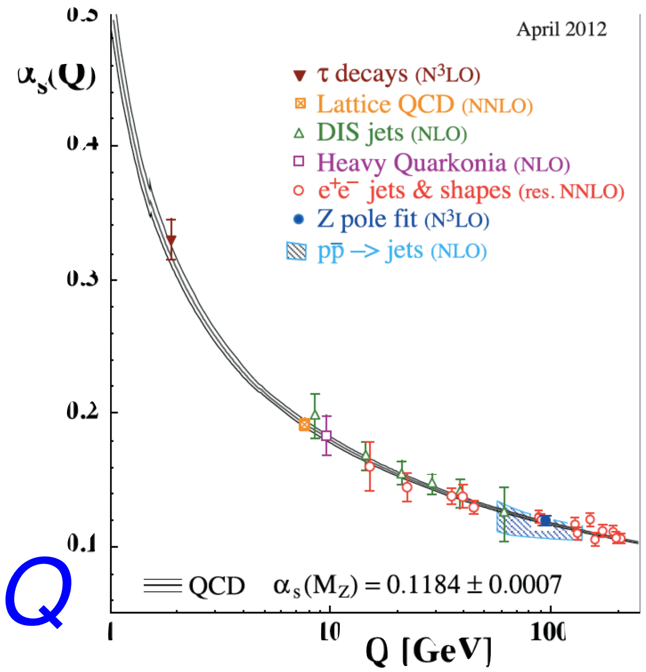
Effective Field Theories

- Usually Effective Theories replace the Quarks and Gluons by the the degrees of freedom which are "relevant" at this scale.
- Effective Theories are systematic expansion of QCD
- High Energies ($Q \to \infty$):
  Quarks and Gluons are relevant
  $\to$ perturbative QCD, Expansion in $1/Q$



Effective Field Theories

- Usually Effective Theories replace the Quarks and Gluons by the the degrees of freedom which are "relevant" at this scale.
- Effective Theories are systematic expansion of QCD
- High Energies ($Q \to \infty$):
  Quarks and Gluons are relevant
  $\to$ perturbative QCD, Expansion in $1/Q$
- Very slow hadrons ($Q \to 0$):
  Pions and Kaons are relevant
  $\to$ approximate symmetries, Expansion in Q



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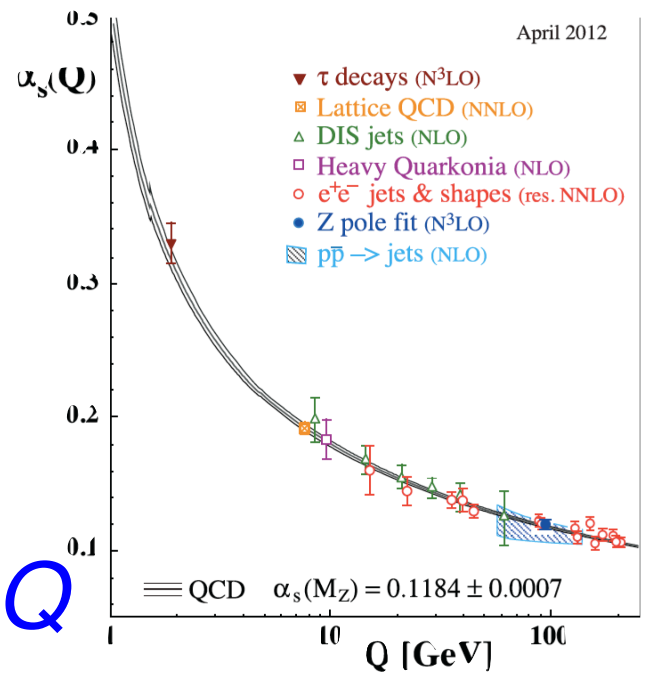
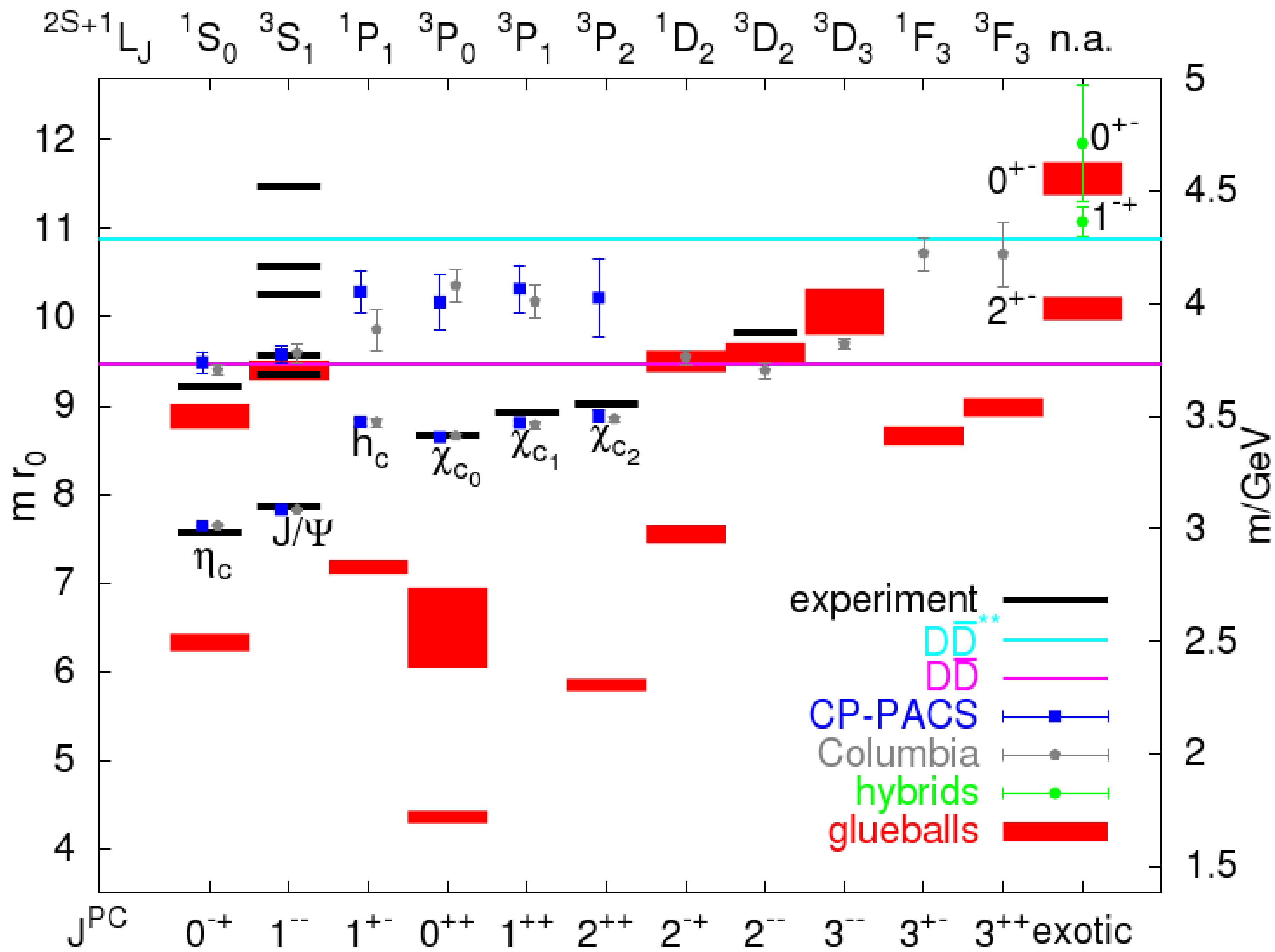
  $\to$ perturbative QCD, Expansion in $1/Q$
- Very slow hadrons ($Q \to 0$):
  Pions and Kaons are relevant
  $\to$ approximate symmetries, Expansion in Q
- Heavy Quarks ($m_Q \to \infty$):
  Light Quarks and Gluons are relevant
  $\to$ Use approximate symmetries, Expansion in $1/m_Q$



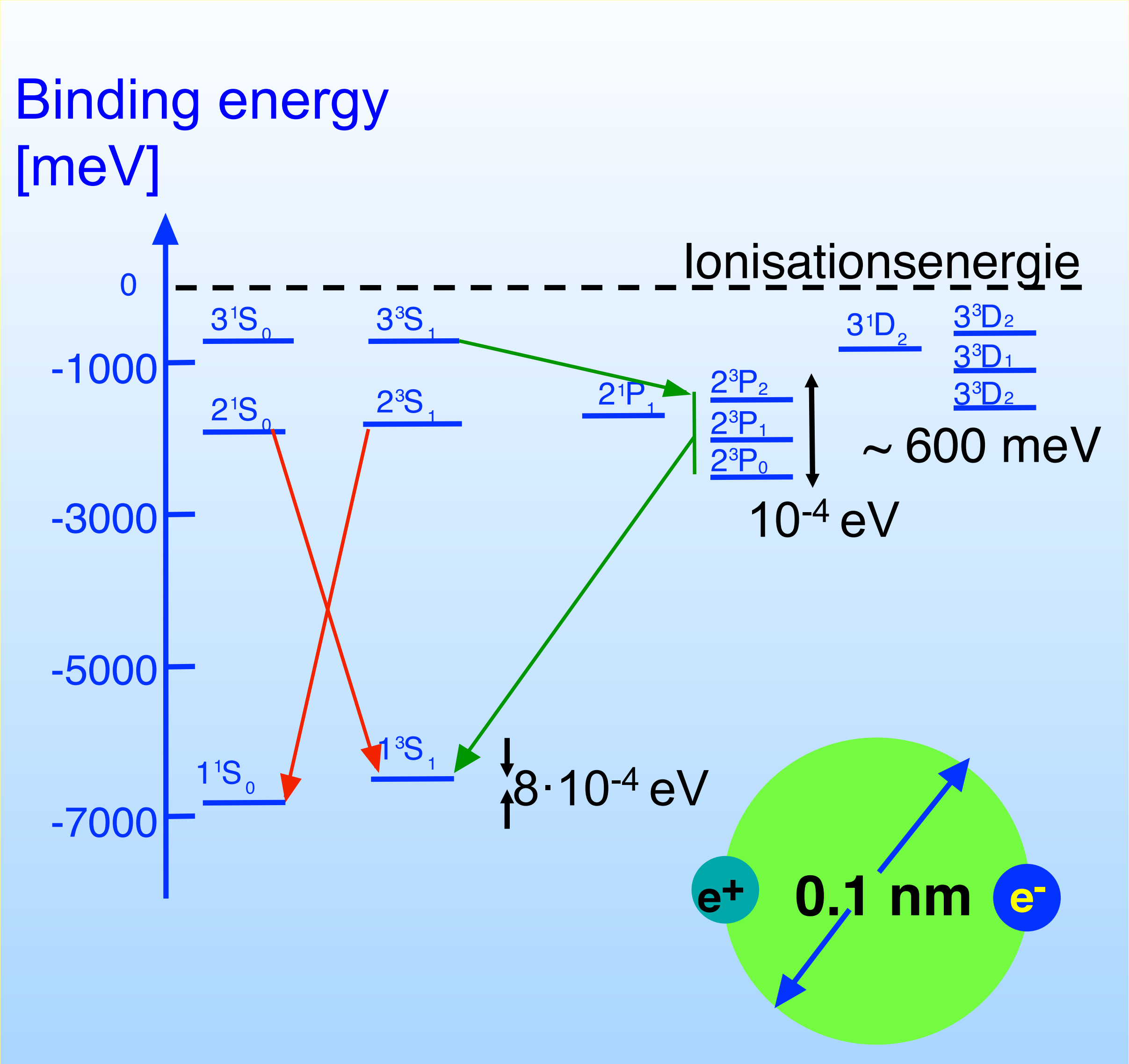
Charmonium



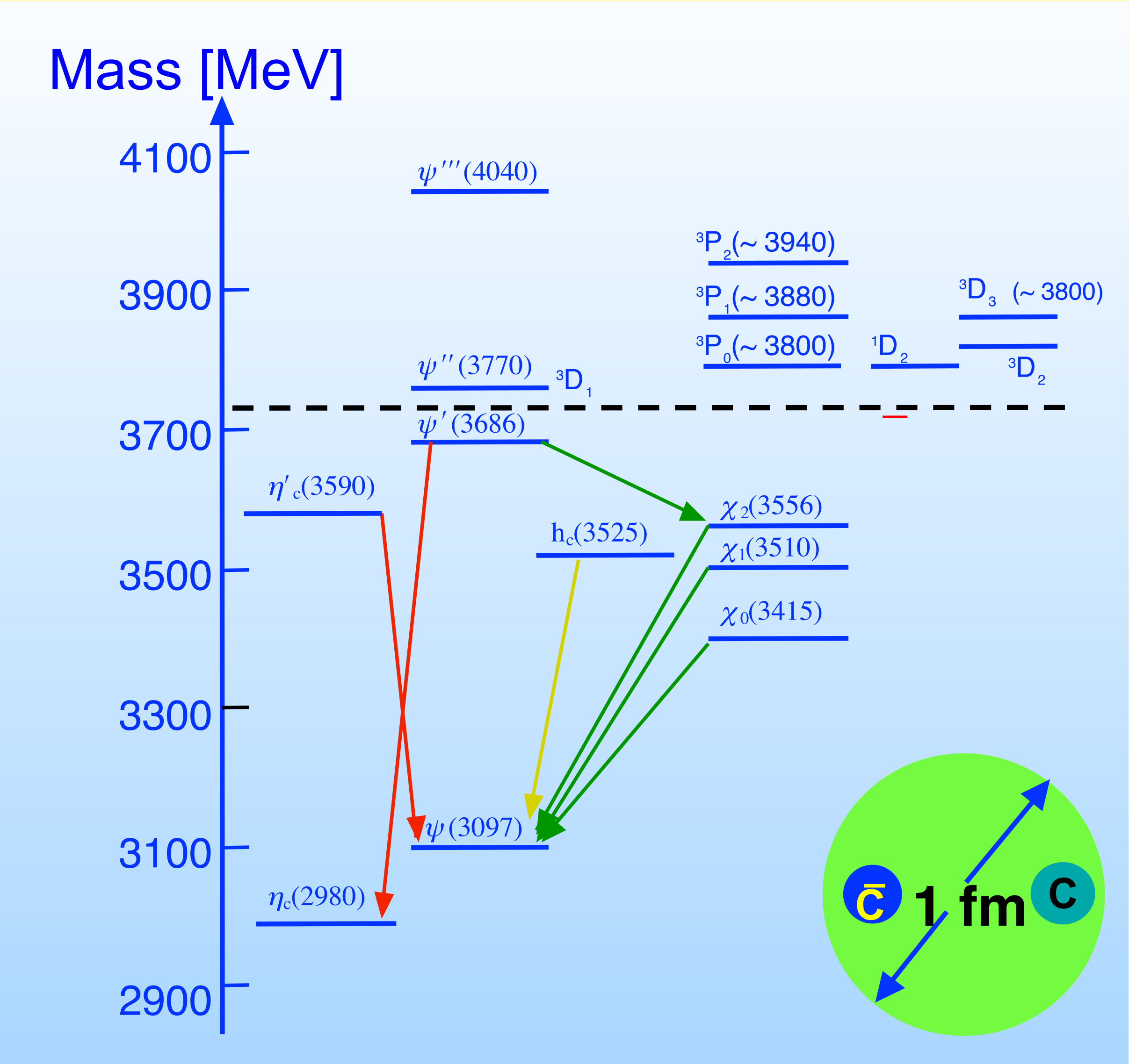
2S+1 L J
1S0 3S1 1P1 3P0 3P1 3P2 1D2 3D2 3D3 1F3 3F3 n.a.
m r0
m/GeV
ηc
J/Ψ
hc
χc0
χc1
χc2
0+-
1-+
2+-
experiment
DD̄**
DD̄
CP-PACS
Columbia
hybrids
glueballs
JPC
0-+ 1-- 1+- 0++ 1++ 2++ 2-+ 2-- 3-- 3+- 3++ exotic

...the positronium of QCD

Positronium



Charmonium



…the positronium of QCD

Positronium (lives ≈100 ns, discovered 1951 by Martin Deutsch, MIT)

- quasi stable system of electron and positron (exotic atom)
- decays to *n* photons (more than 1, spin argument 2 *vs* 3)
- compares closely to hydrogen atom: energy levels (Bohr)

$$E_n = \frac{-m^* q_e^4}{8h^2\varepsilon_0^2}\frac{1}{n^2}$$

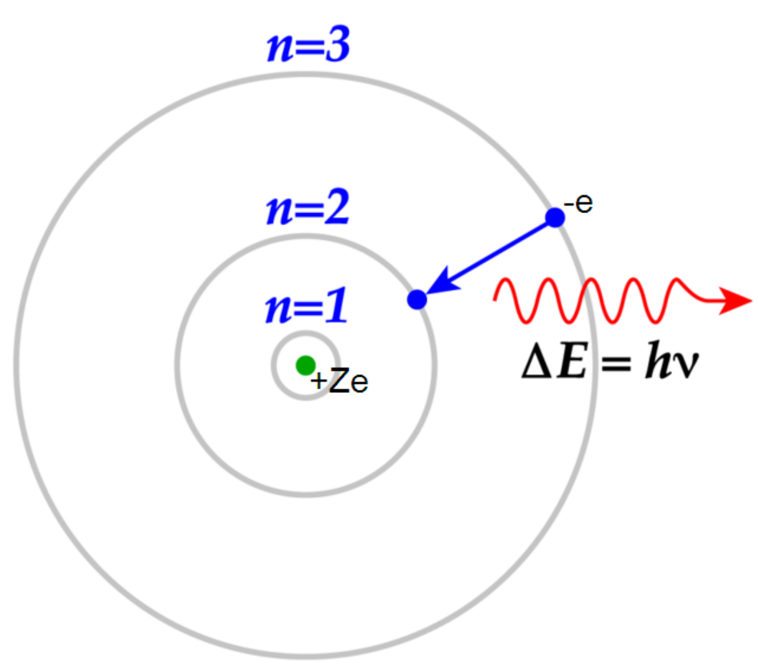
h – Planck's constant
ε_0 – electric constant
q_e – electron charge

- difference to hydrogen: reduced mass (m^*)

$$m^* = \frac{m_e m_p}{m_e + m_p} = \frac{m_e}{2}$$

- plugging in the numbers we find

$$E_n = \frac{-m_e q_e^4}{16h^2\varepsilon_0^2}\frac{1}{n^2} = \frac{-6.8\text{ eV}}{n^2}$$



Aims

- Analogous to known two-particle bound systems (ie: hydrogen, positronium)
- Charmonium potential models (phenomenological):
  - non-relativistic (charm quarks are “heavy” compared to binding energy)
  - strong force potential via one gluon exchange (similar to Coulomb force)
  - quark confinement (increases linearly with separation)
- Typical representation:

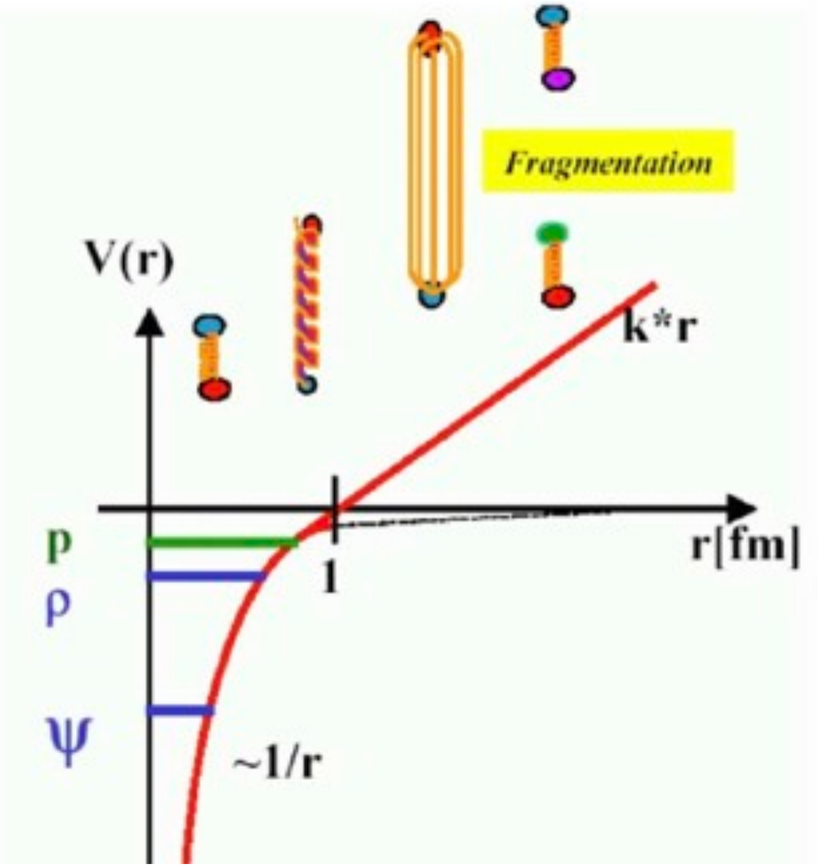
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \ldots$$

Phys. Rev. D 17, 3090 (1978)
Phys. Rev. D 32, 189 (1985)
Phys. Rev. D 72, 054026 (2005)

Experiment: Systematic determination of particle properties
- Mass
- Lifetime or width of resonance
- Quantum number J^{PC}

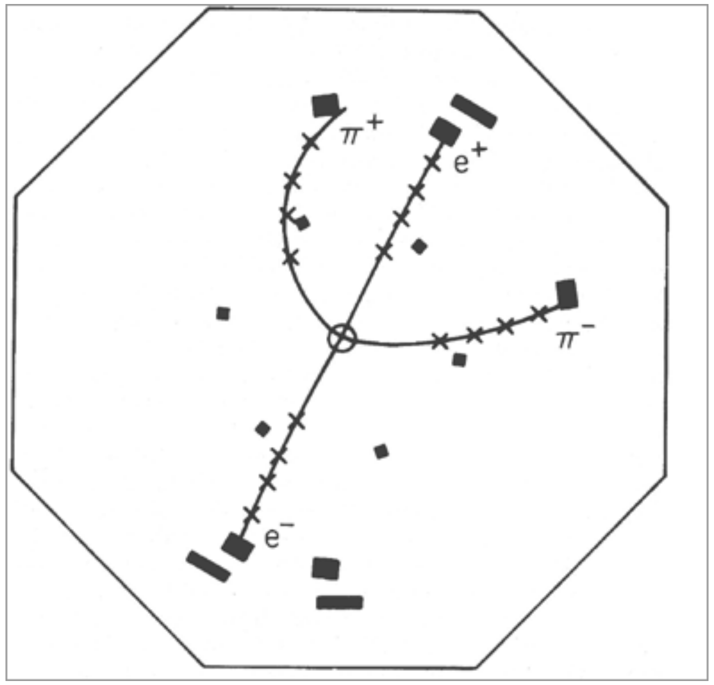
Theory: Calculation of spectra
- Knowing interaction allows prediction
- Tuning accounting for experimental data

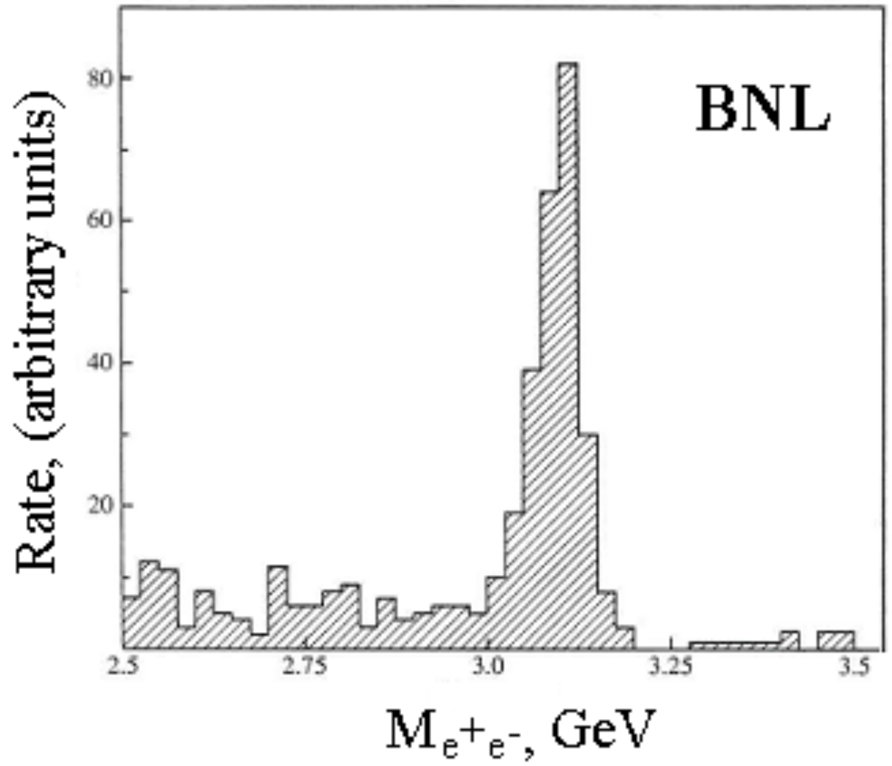
Final aim: Understand composition and dynamics of matter
- In QCD we are still far away from precision of QED

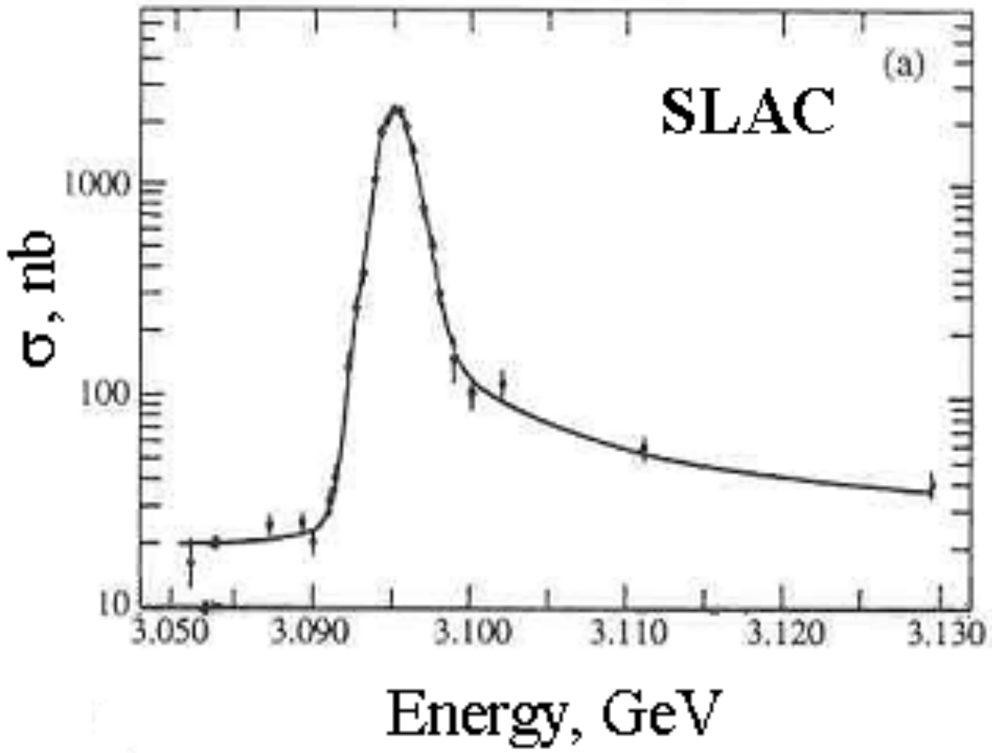


...in the beginning

- November Revolution: simultaneous (SLAC/BNL) discovery of the J/ψ in 1974
- Bound state of c-cbar quarks: "charmonium"
- First evidence of the charm quark
  - Strong confirmation of the quark model
- Discovery of $\psi(2S) \rightarrow J/\psi(e^+e^-)\ \pi^+\pi^-$ soon followed

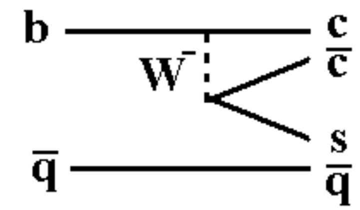






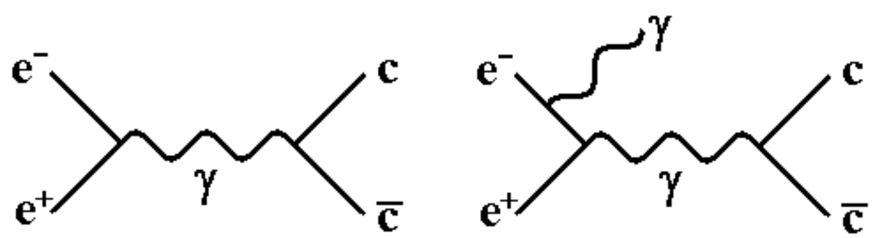
Production

- Colour-suppressed b→c decay
  - Predominantly from B-meson decays

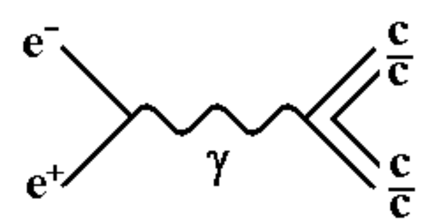


BELLE

- e^+e^- annihilation/Initial State Radiation (ISR)
  - e+e- collision below nominal c.m. energy
  - $J^{PC} = 1^{--}$

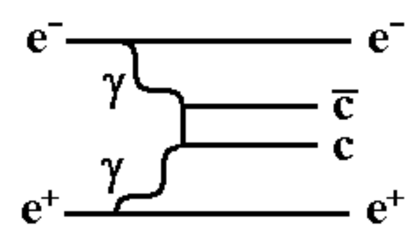


- Double charmonium production
  - Typically one J/ψ or ψ, plus second ccbar state



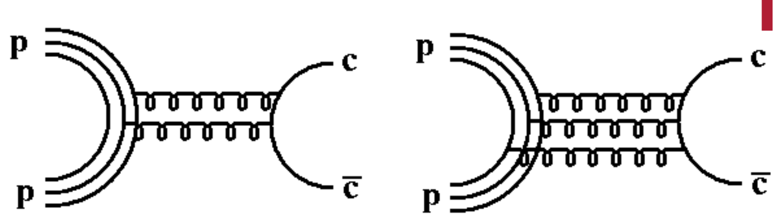
BESIII

- Two-photon production
  - Access to C = +1 states



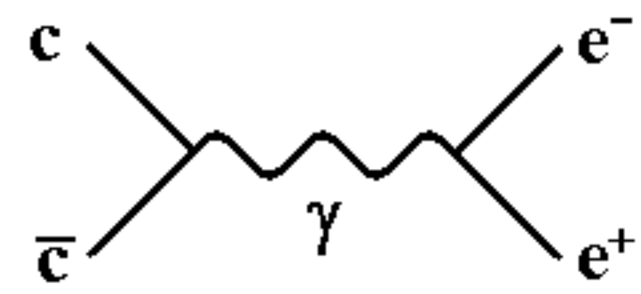
PANDA

- pp annihilation
  - All quantum numbers available

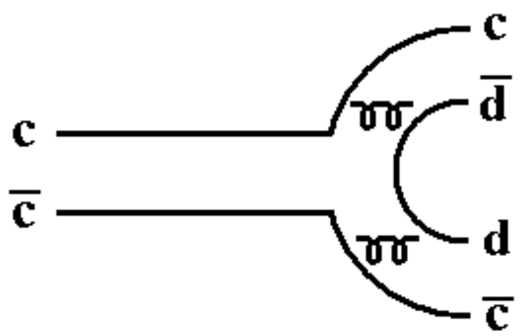


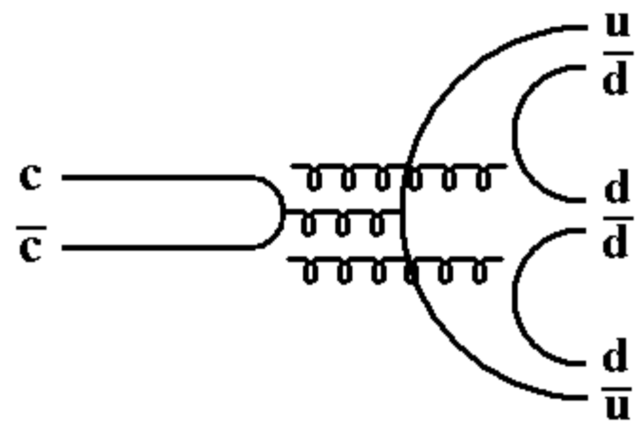
...and decay

- Annihilation:
  - Generally suppressed for bound state
  - Decay to leptons is a clean experimental signal

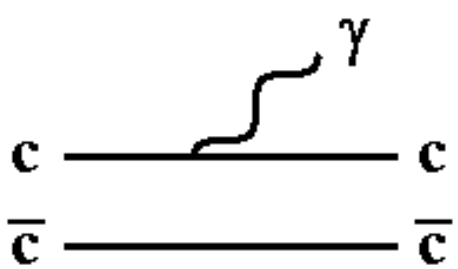


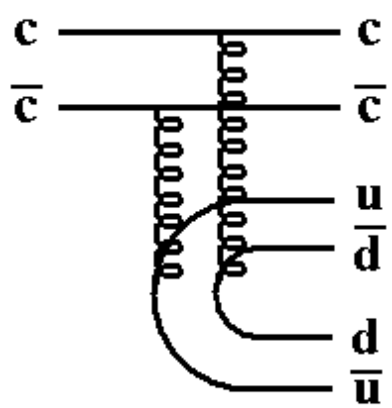
- Strong interaction:
  - Dominant above ~3.72 GeV (D mesons)
  - Suppressed below this mass threshold





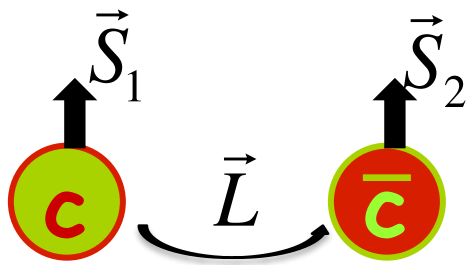
- Radiative:
  - EM radiative transition emitting photon
  - Emit gluons producing light quarks





- Features:
  - Suppression of strong decays leads to (relatively) long lifetimes, narrow widths
  - Radiative decays are competitive; often most accessible transitions

The *ABC's* of Charmonium



J^{PC} quantum numbers

$$\vec{S} = \vec{S}_1 + \vec{S}_2$$
$$\vec{J} = \vec{L} + \vec{S}$$

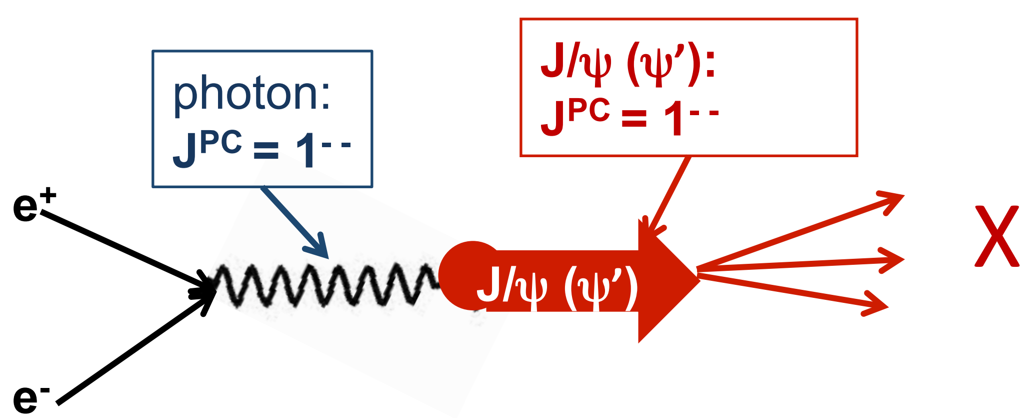
S=1 ➔ triplet of state
S=0 ➔ singlet

$$P = (-1)^{L+1}$$

Parity (x,y,z) ↔ (-x,-y,-z)

$$C = (-1)^{L+S}$$

C-Parity quark ↔ antiquark



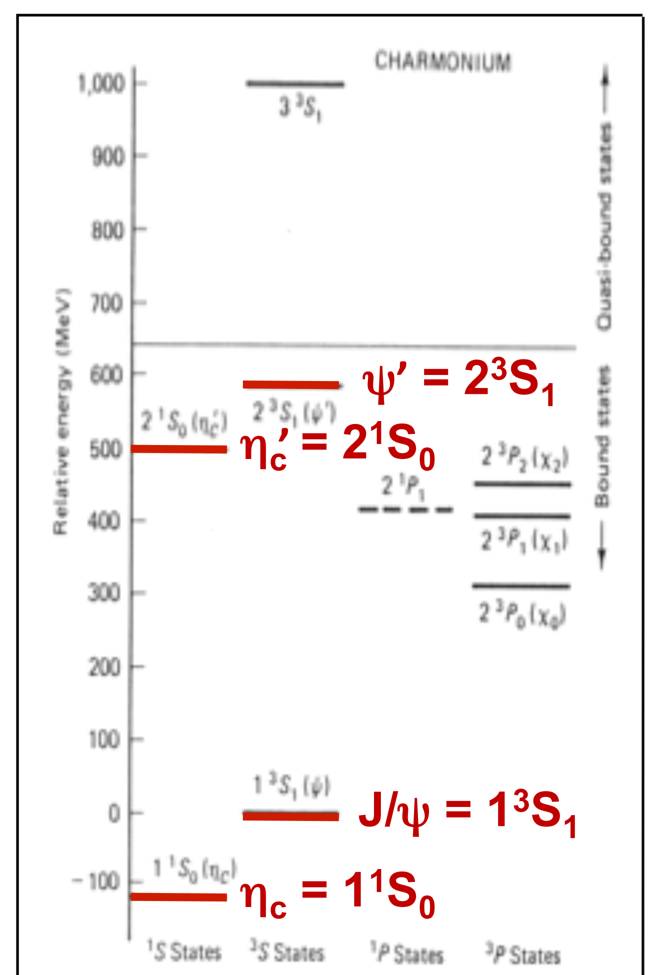
S= spin (0 or 1)

J= total ang. mom.

$$n^{(2S+1)}L_J$$

n=radial quant. nmbr

L= S, P, D, F, …
0, 1, 2, 3, …

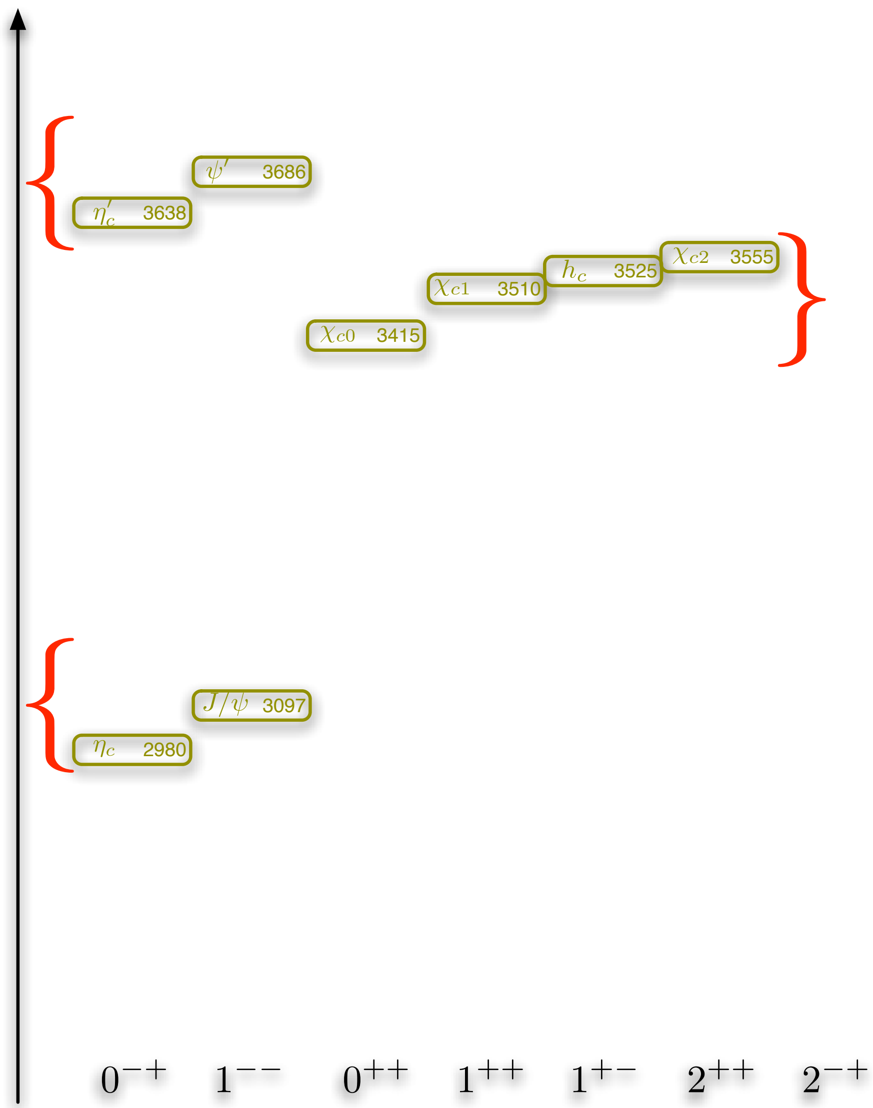


The easy case

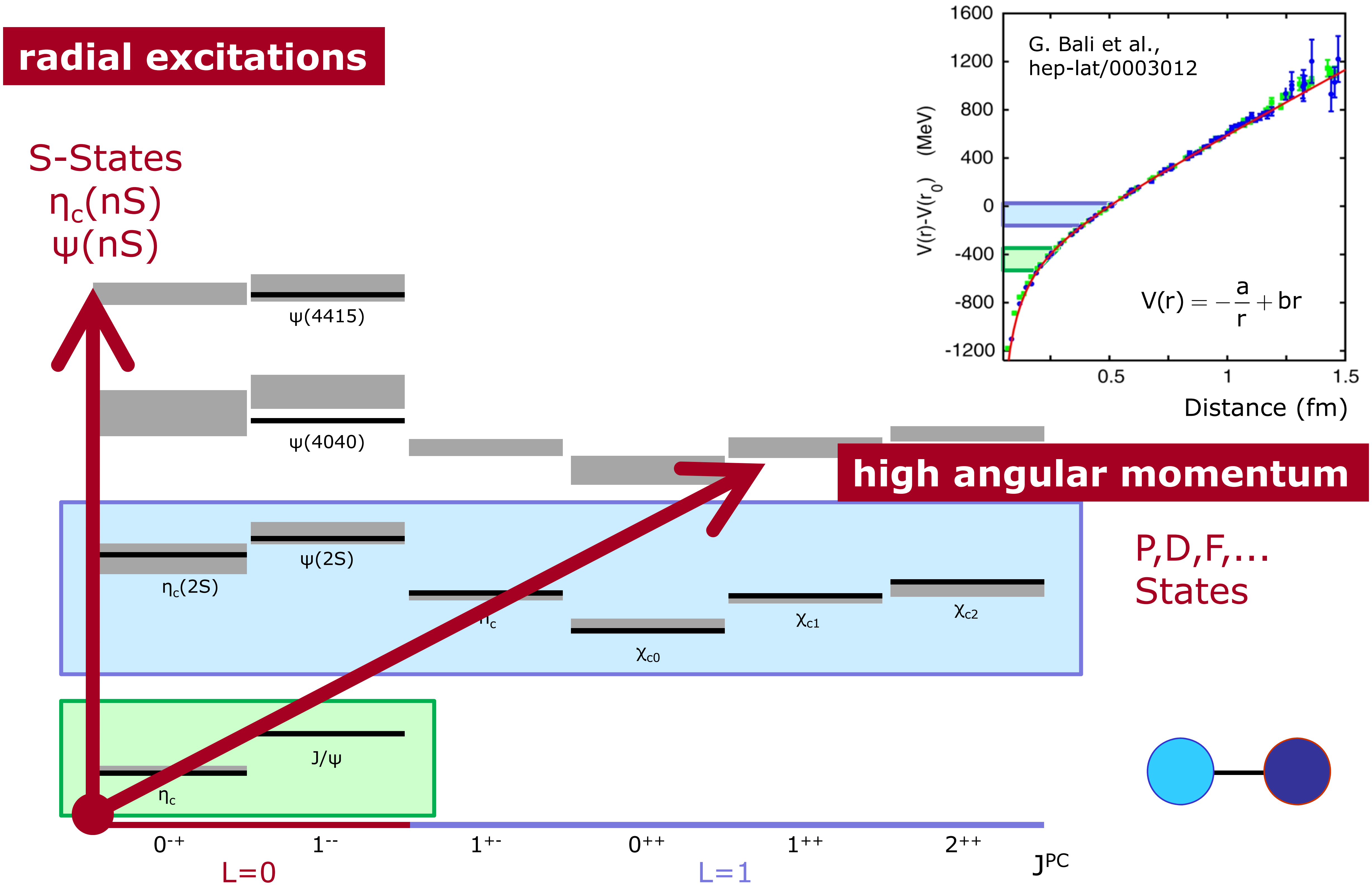
- one set of hadrons that are particularly simple are the charmonium mesons
  - each box represents an observed particle
  - particles fall in groups - 'gross structure'
  - splitting within a group - 'fine structure'
  - reminds us of quantum mechanics of atoms
  - a reasonable description of the spectrum of charmonium comes from solving a Schrödinger equation assuming a potential between a charm quark and an anti-charm quark

$$m_n = 2m_c + E_n$$

$$-\frac{1}{m_c}\nabla^2\psi + V(r)\psi = E_n\psi$$



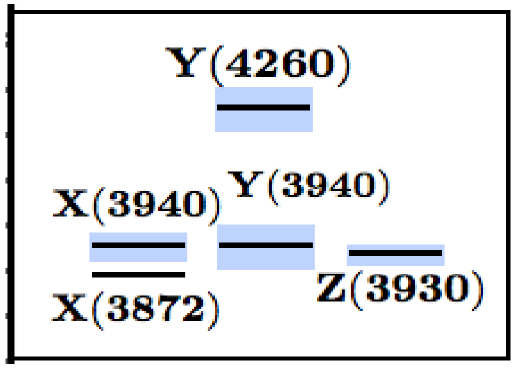
The easy case



New Charmonium States

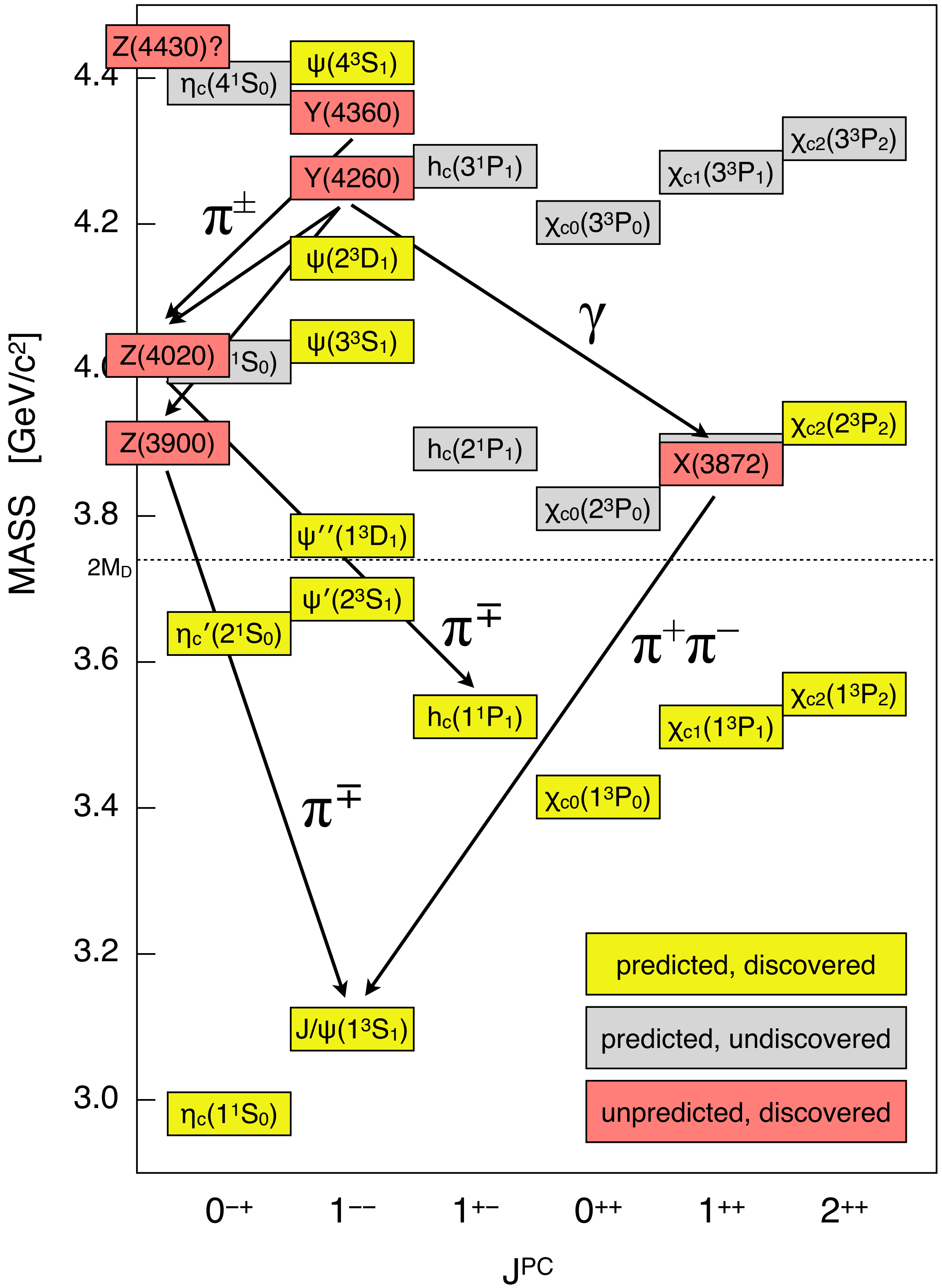
Renaissance in Charmonium Spectroscopy:

- Belle, BaBar, CLEO, CDF and D0 find new states above $D\bar{D}$
- Many of these states are problematic: mass not predicted, width too small, decay pattern unusual
- Challenge for better understanding and high precision data



State	Experiments	Nature/Remarks
X(3872)	Belle, BaBar, CDF, D0	$D^0 D^{0*}$ molecule, 4-quark state
X(3943)	Belle	maybe η''_c
Y(3940)	Belle	maybe 2^3P_1
Z(3930)	Belle	maybe χ'_{c2}
Y(4260)	BaBar, Belle, CLEO-c	Hybrid, $\omega\chi_{c1}$ -molecule, 4q state
Y(4350)	BaBar, Belle	?
$Z^{\pm}$(4430)	Belle	No charged $c\bar{c}$, molecule or 4q state
Y(4660)	Belle	?

New Charmonium States



(I) The quark model describes most of charmonium remarkably well. $(c\bar{c})$

(II) But the "*XYZ*" states point beyond the quark model. $(c\bar{c}g, c\bar{q}q\bar{c}, (c\bar{q})(q\bar{c}), c\bar{c}\pi\pi)$

(III) BESIII can directly produce the **Y(4260)** and **Y(4360)** in e^+e^- annihilation.

(IV) BESIII has observed "charged charmoniumlike structures" — the **Z_c(3900)** and the **Z_c'(4020)**.

(V) BESIII has also observed a transition to the **X(3872)**.

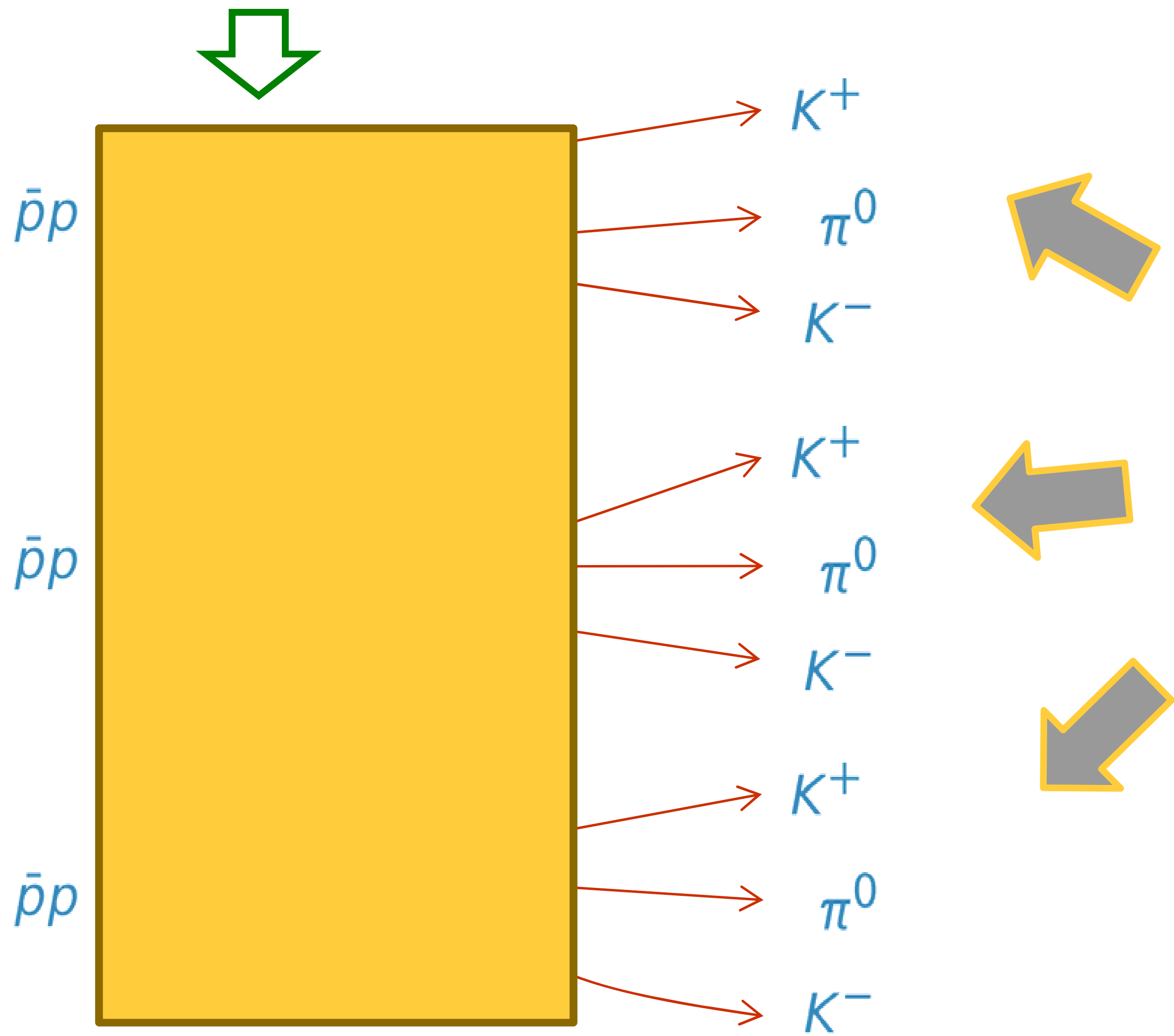
(VI) We are building connections.

R. Mitchell Bormio 2014

The need for PWA

Example: Consider the reaction $\bar{p}p \rightarrow K^+K^-\pi^0$

What *really* happened...

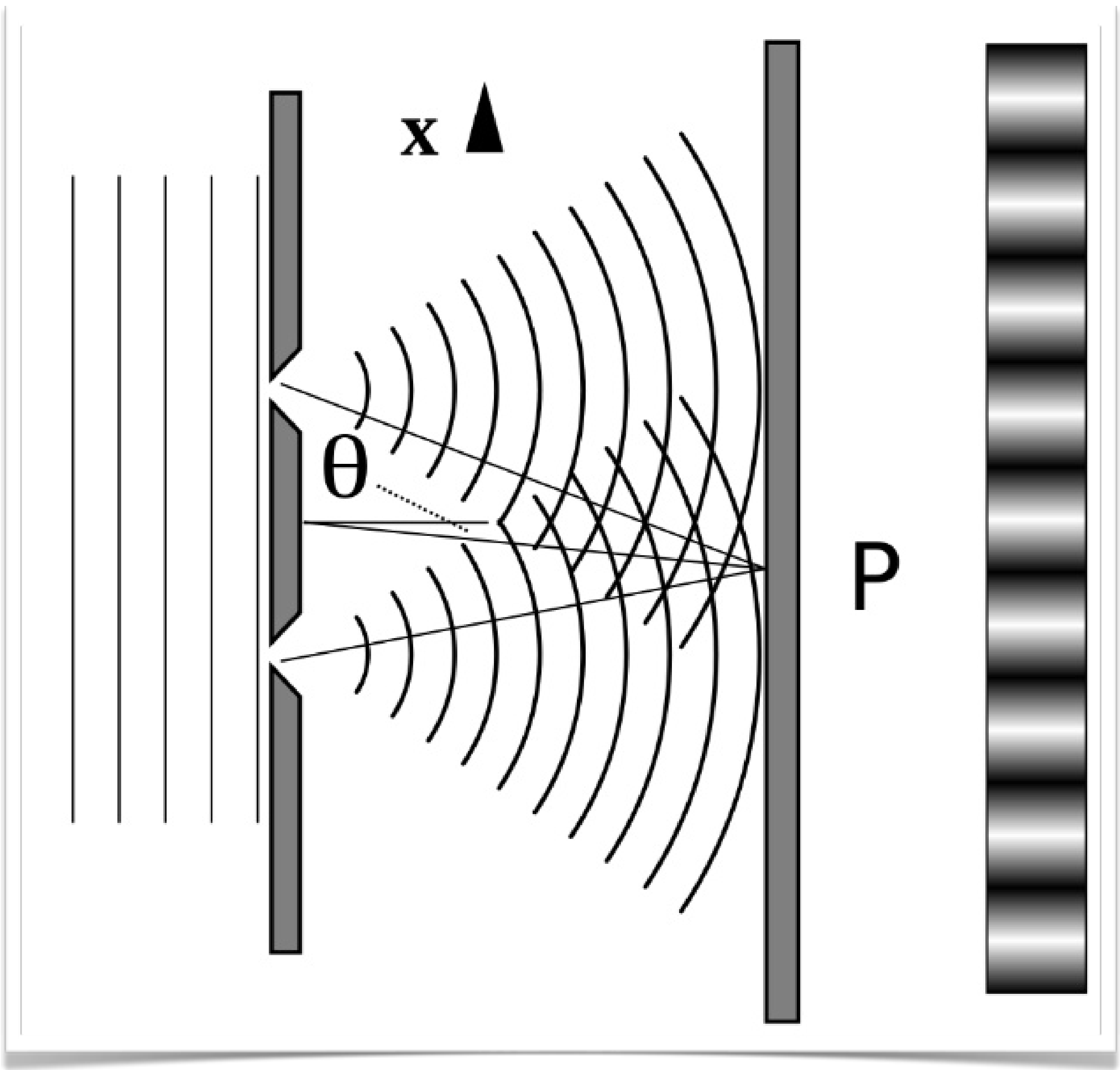


What you see is
always the same ...

...
etc.

PWA = technique to find
out what happens in between

Double Slit as analogue



Result ≠ ∑ (Single slits)

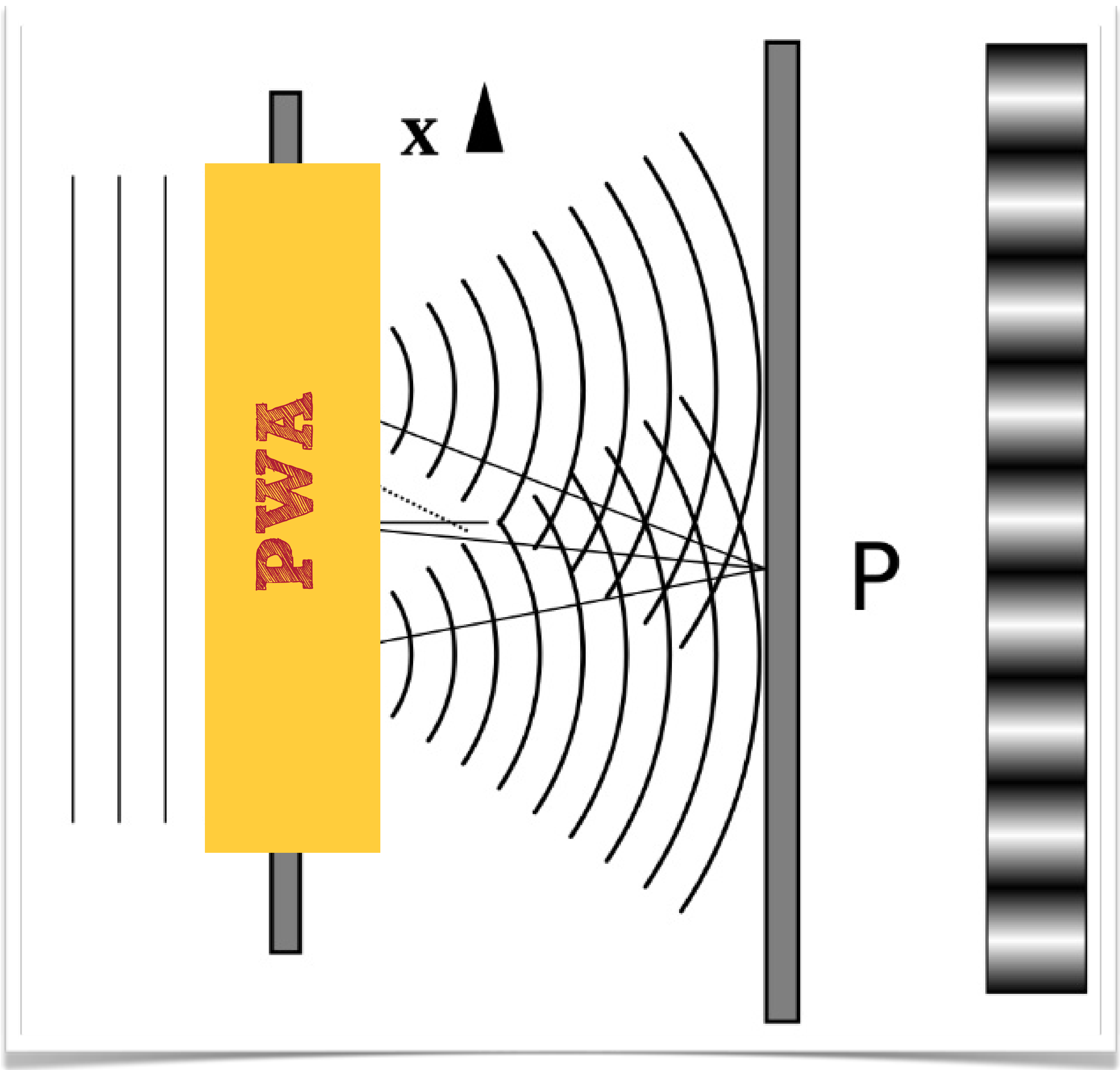
➜ Interference!

☞ Light behaves as a wave.

Which slit did one photon cross? Both!

☞You only have interference in case you can't distinguish between the paths.

Double Slit as analogue



Optics	PWA
slit	resonance
position	mass
size	width

...as in optics one can't say for one event which resonance was produced

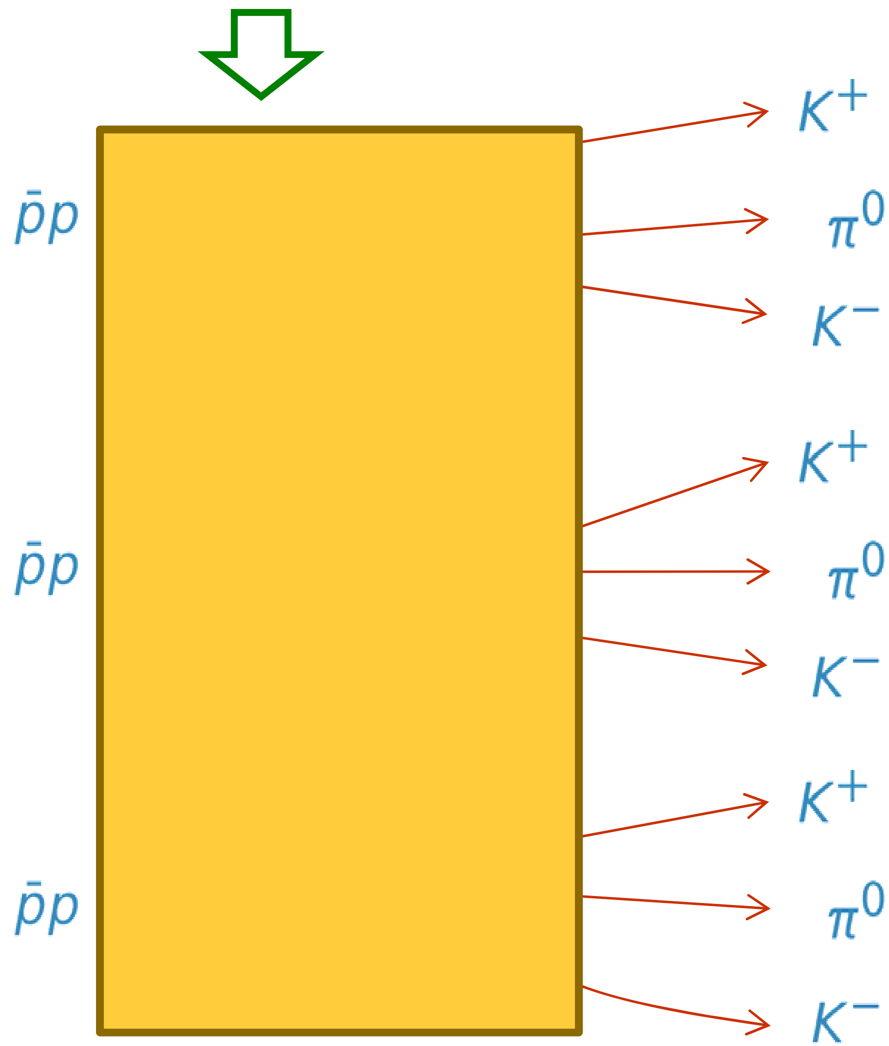
Interference pattern changes with number and parameter of resonances

➜ PWA: fit a model describing resonances to the data

The need for PWA

Example: Consider the reaction $\bar{p}p \rightarrow K^+K^-\pi^0$

What *really* happened...



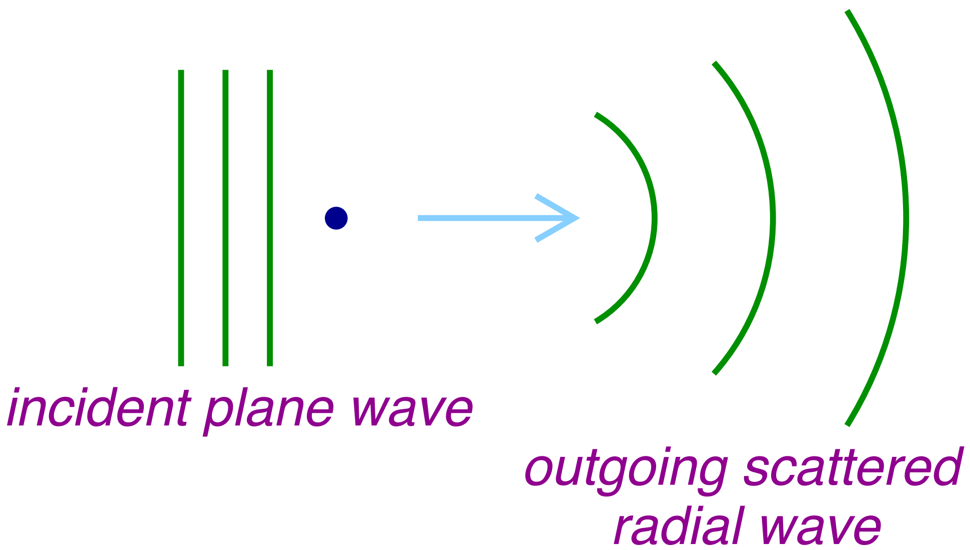
...
etc.

Goals of PWA:

- N-particle phase space
- Description of resonance properties:
  - mass
  - width
  - quantum numbers
- Treatment of interferences

PWA = technique to find out what happens in between

Partial Wave Analysis



$$\psi(r,\theta,\phi) \longrightarrow e^{ikz} + f(\theta,\phi)\frac{e^{ikr}}{r}$$

$$f(\theta,\phi) = \text{scattering amplitude}$$

- Differential cross section: $\dfrac{d\sigma}{d\Omega} = |f(\theta,\phi)|^2$

$$f(\theta,\phi) = \frac{-m}{2\pi\hbar^2}\int d\vec{r}\, e^{i\vec{q}\cdot\vec{r}/\hbar} V(\vec{r})$$

Fourier transform of potential
(First Born approximation)

- More generally,

$$\psi_s = \psi_f - \psi_i = \frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\frac{\eta_l e^{2i\delta_l}}{2i}P_l(\cos\theta)\frac{e^{ikr}}{r}$$

phase shifts

scattering amplitude

Partial Wave Analysis

- The cross section can be written as:

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2}\left|\sum_{l=0}^{\infty}(2l+1)\frac{\eta_l e^{2i\delta_l}-1}{2i}P_l(\cos\theta)\right|^2 = |f(\theta)|^2$$

$$= \frac{1}{k^2}\left|\sum_{l=0}^{\infty}(2l+1)T_l P_l(\cos\theta)\right|^2$$

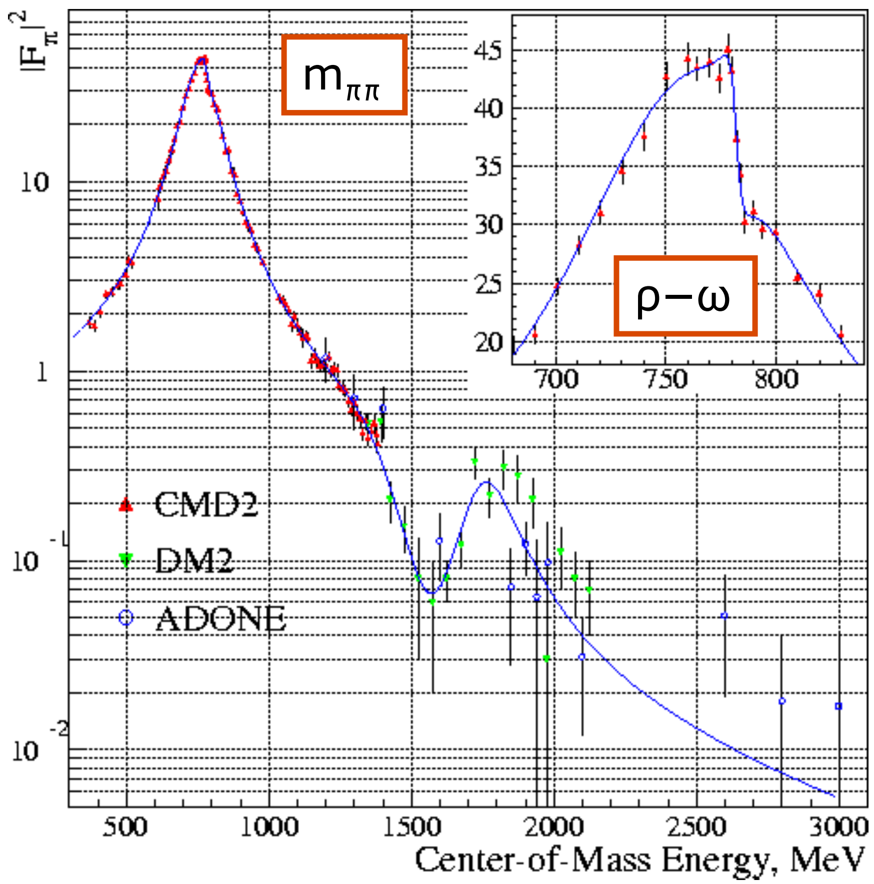
with $$T_l = \frac{\eta_l e^{2i\delta_l}-1}{2i}$$ *T–matrix*

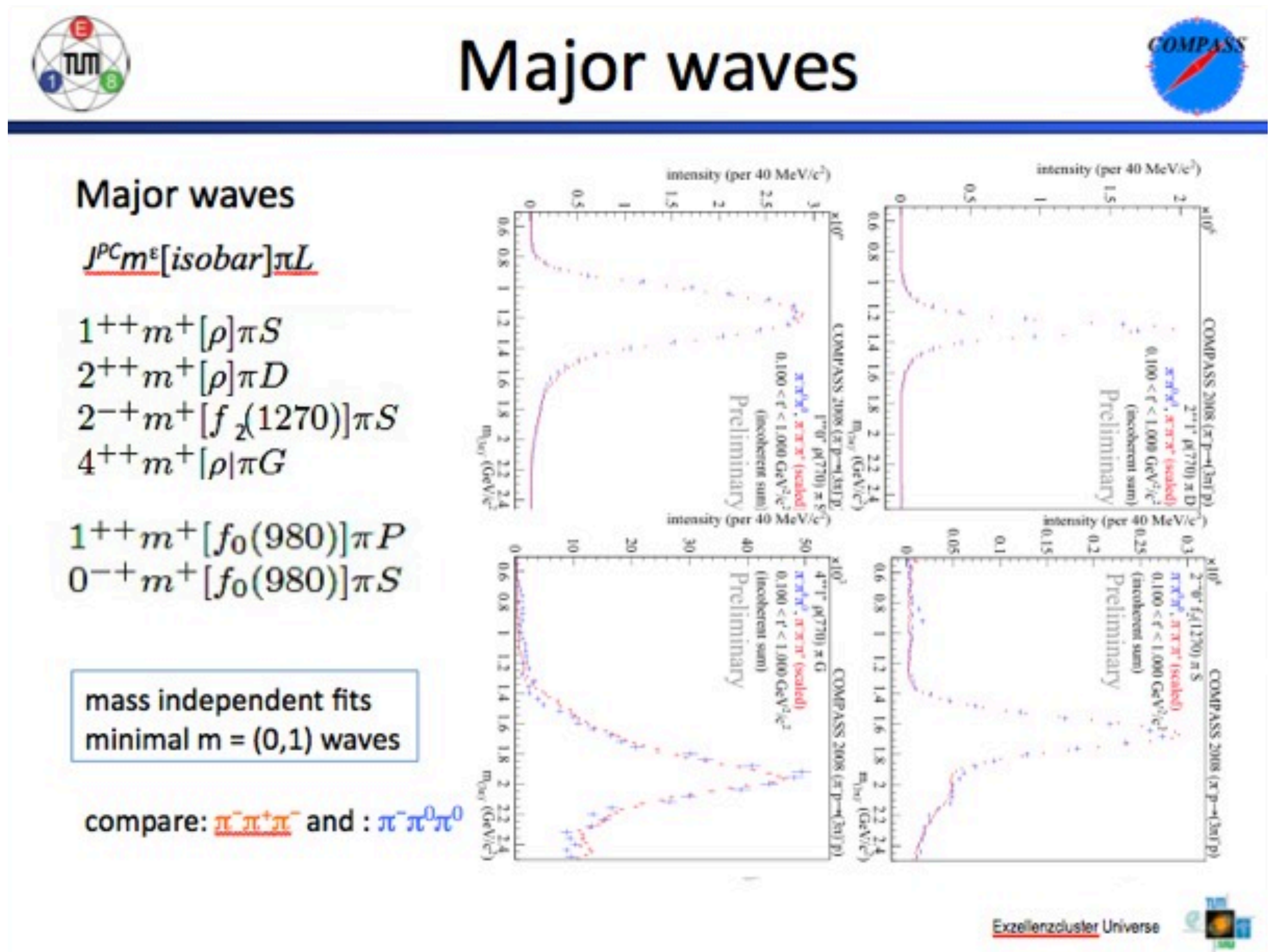
- A complete set of phase shifts contains all information about the underlying dynamics.

- Typically the analysis is carried out by looking at phase differences between a purported state and a well–known "reference" state.

Partial Wave Analysis

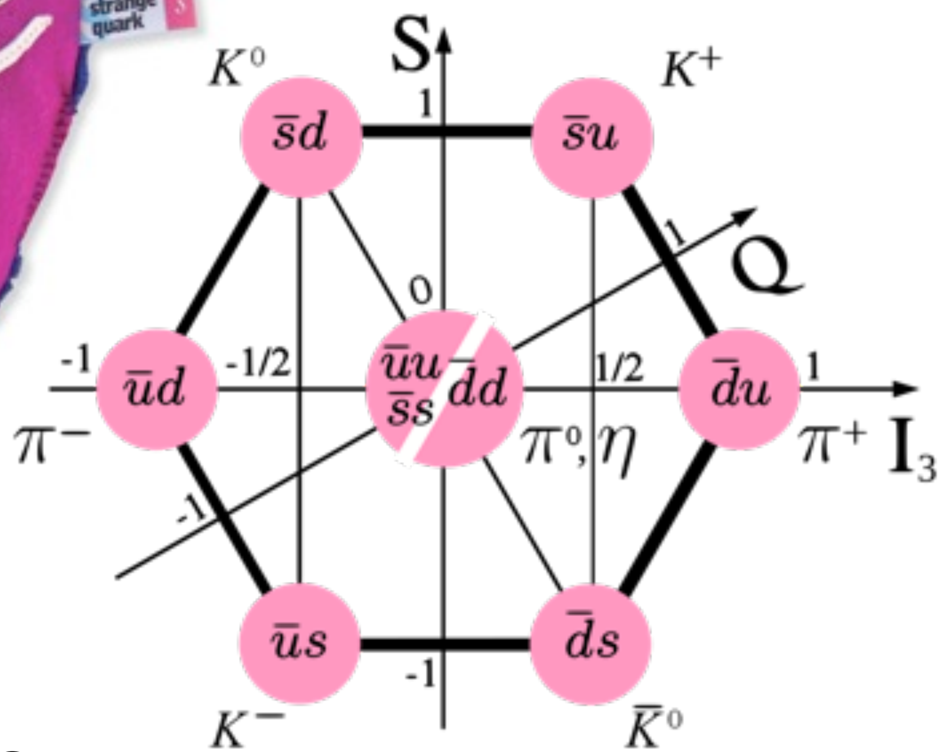
- $e^+e^- \to \pi\pi$



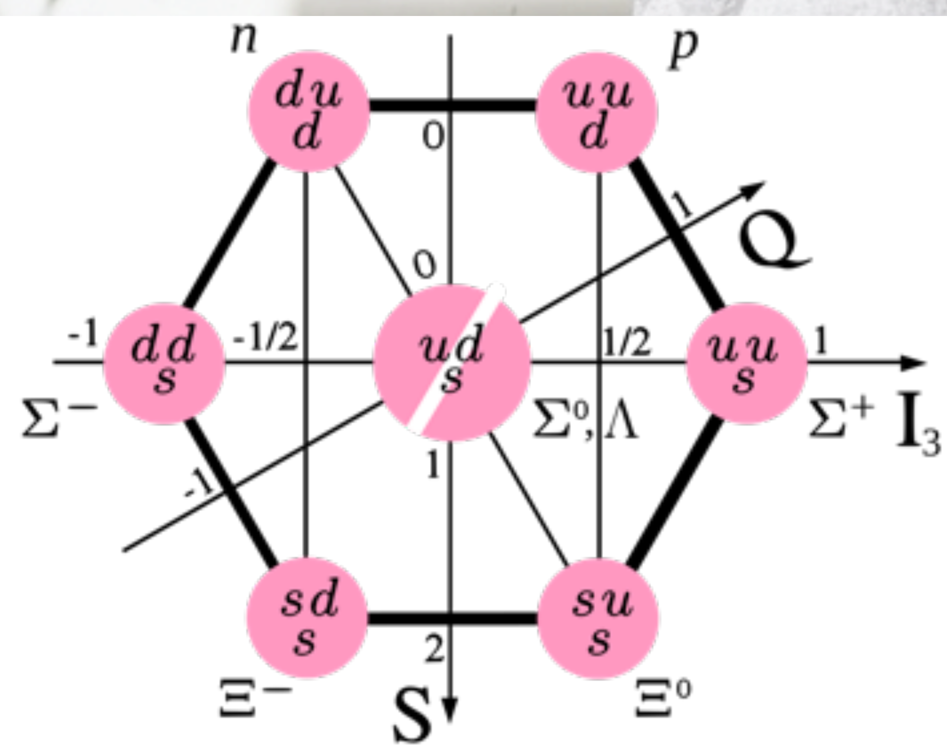


S. Paul Hirschegg (2014)

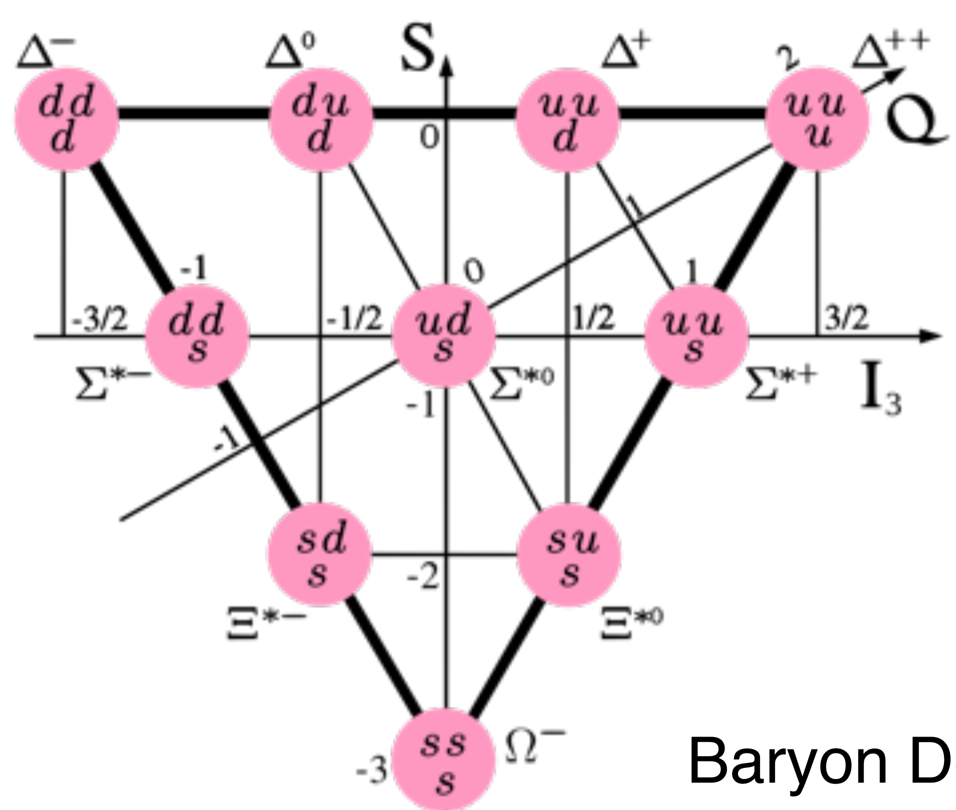
Strange Hadrons



Meson Octet



Baryon Octet



Baryon Decuplet

The strange nuclear realm

The Alchemist by Joseph Wright of Derby (1771)

Alchemy

Either Stick an hyperon into a nucleus

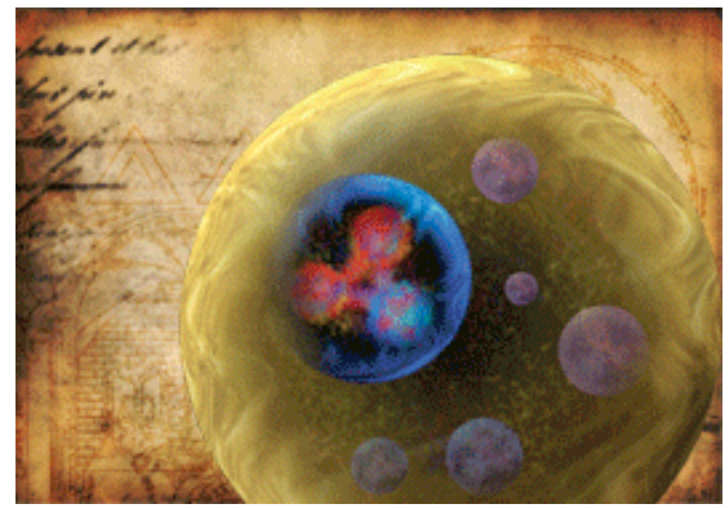
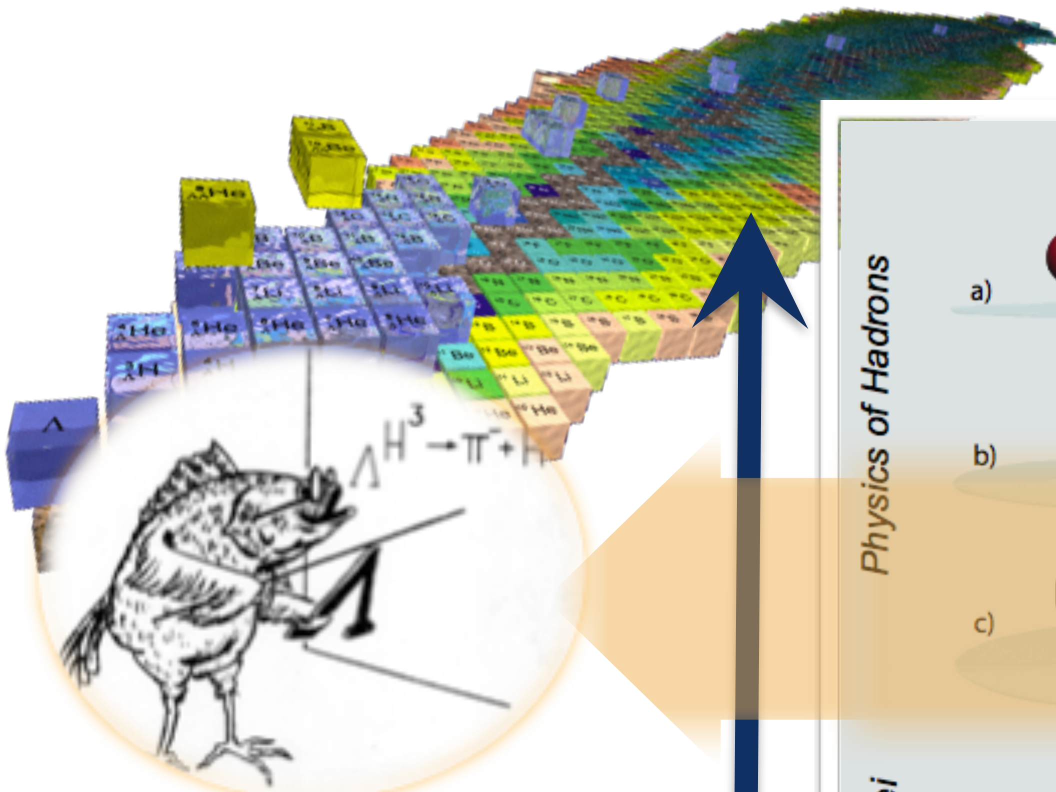


Image courtesy: Jefferson lab

or Boil and compress nuclear matter

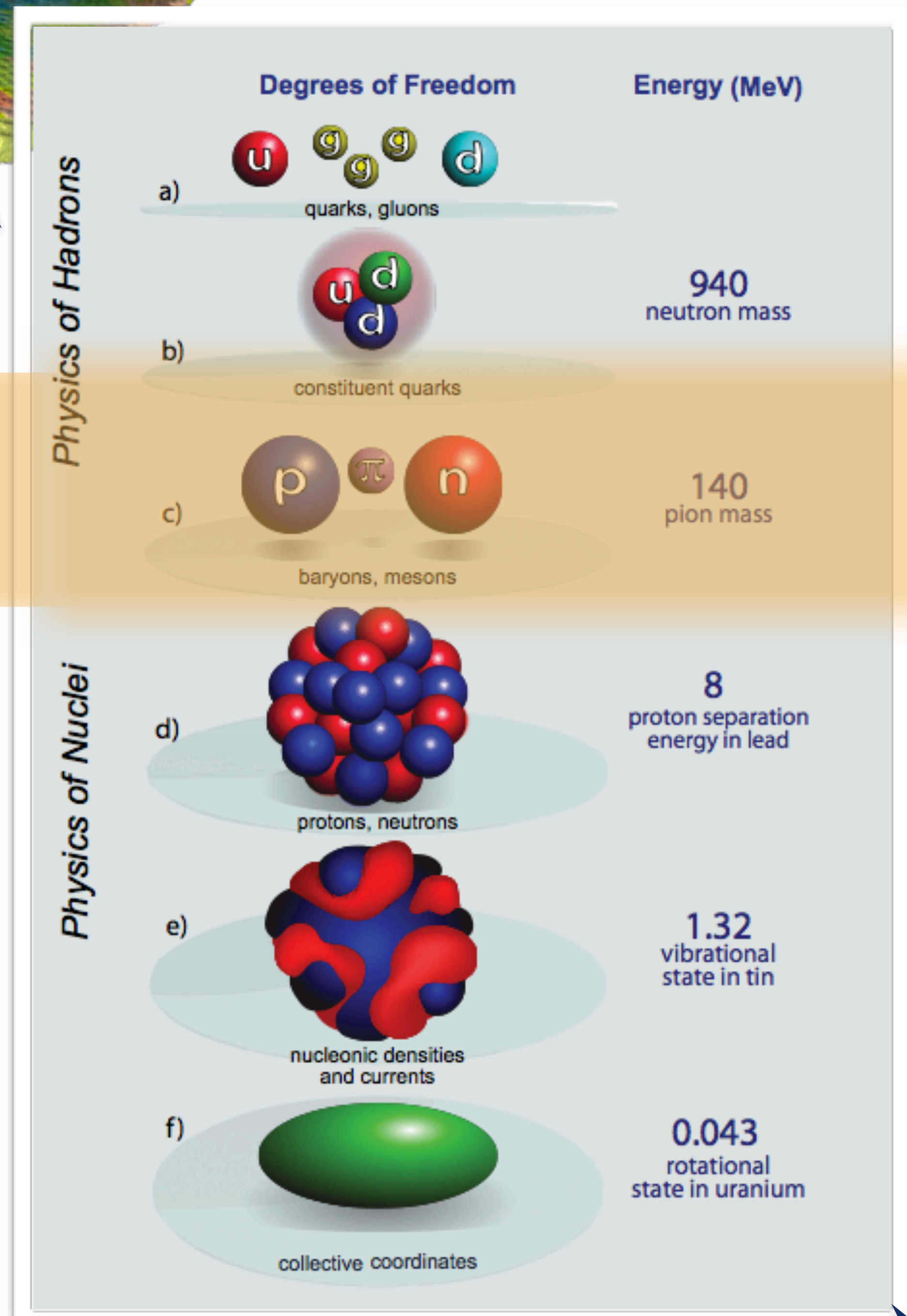
THE STRANGE NUCLEAR REALM



"Hypernuclear physics is **neither fish nor fowl**. "

from a book review by J.D. Jackson, Science (1968)

Resolution



LRP Nuclear Science Advisory Committee(2008)

Simplicity

- Hot and dense quark-gluon matter
- Hadron structure
- Hadron-Nuclear interface
- Nuclear structure
- Nuclear reactions
- Nuclear astrophysics
- Applications of nuclear science

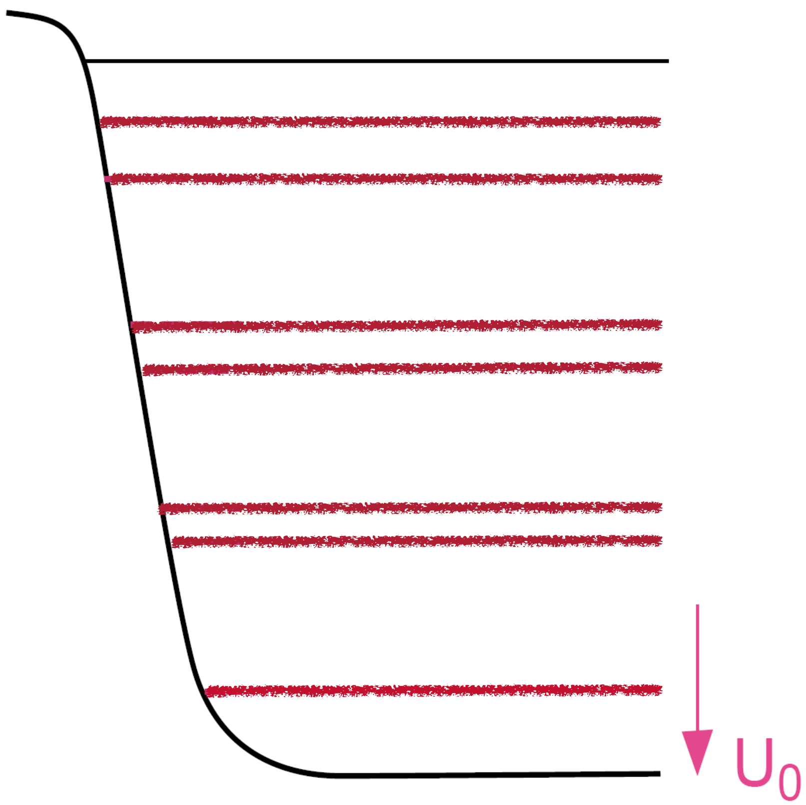
Complexity

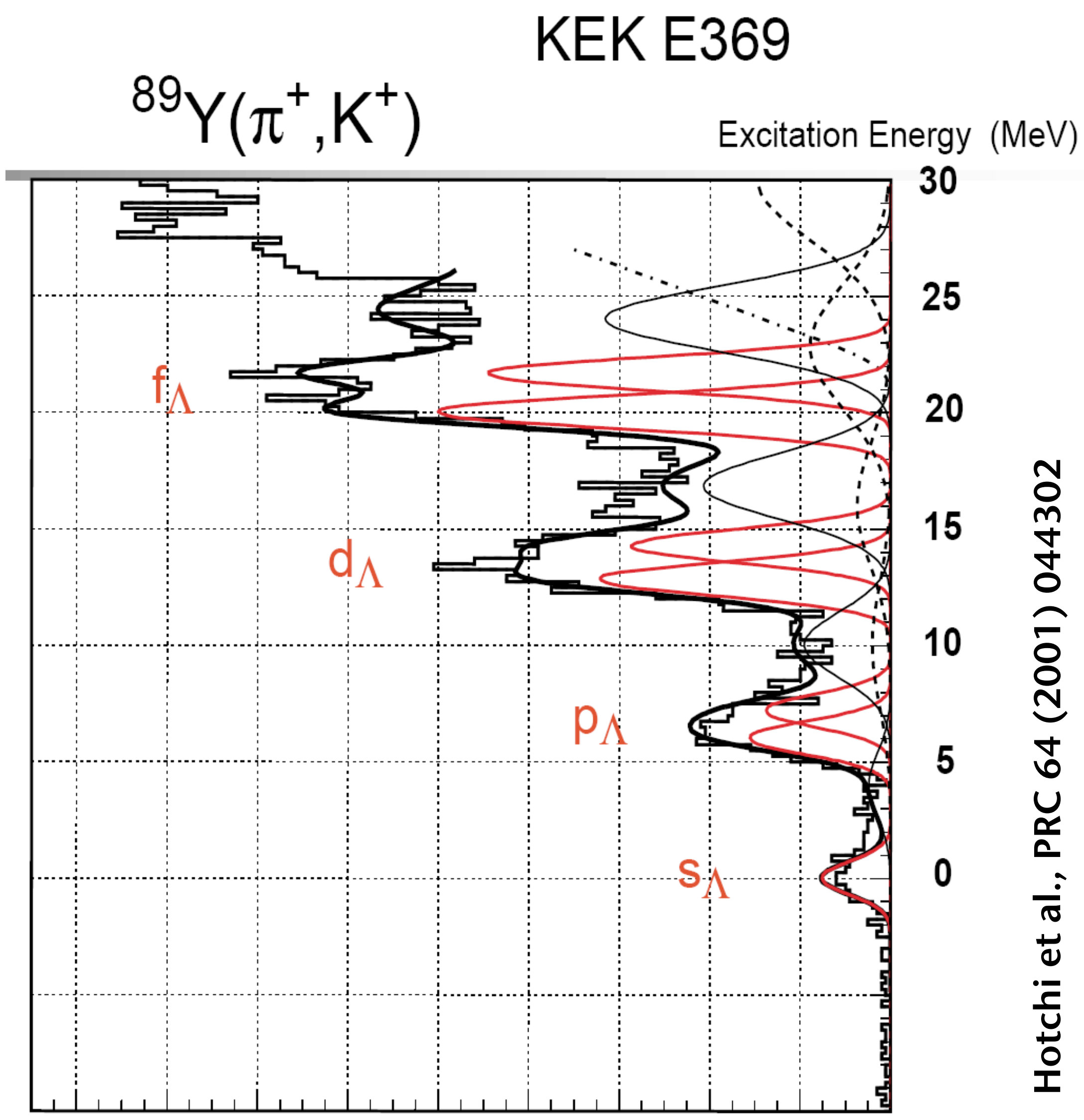
Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked





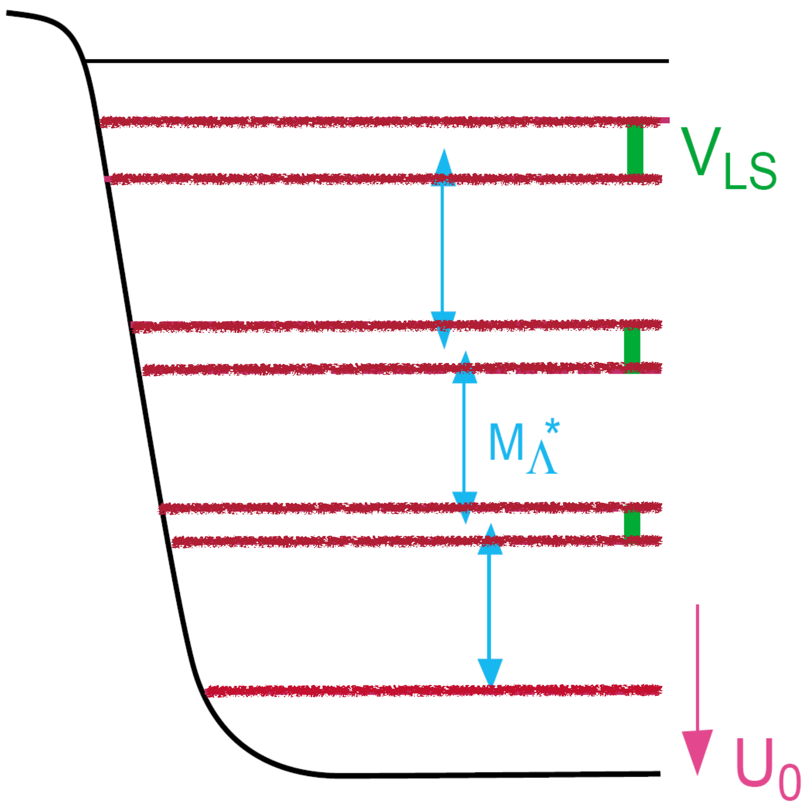
Hotchi et al., PRC 64 (2001) 044302

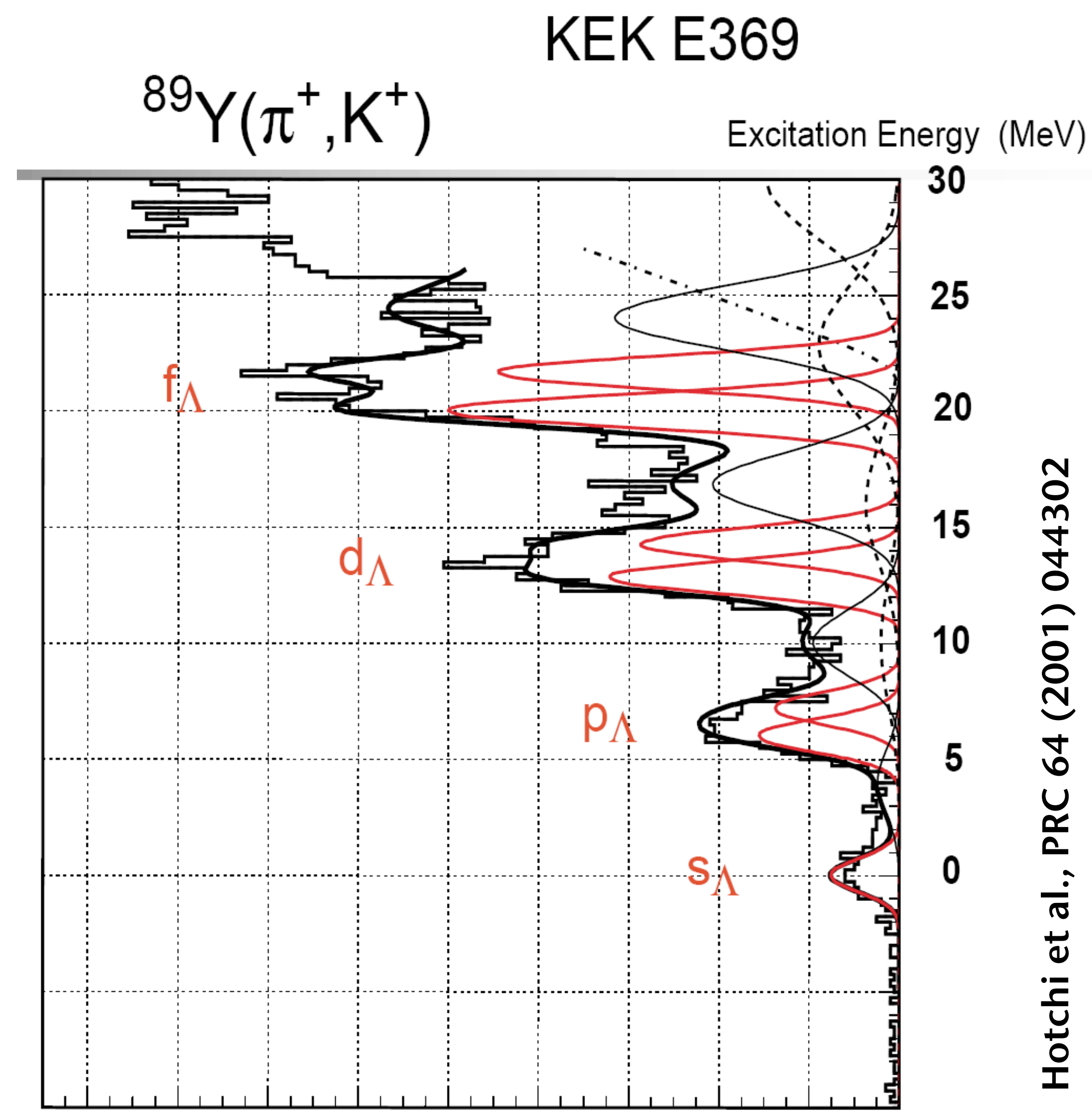
- ✎ **Tagged Nuclear Physics**
- ✐ **Higher Density**

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

❷ Requires the knowledge of YN, YY, …





Strangeness Nuclear Physics

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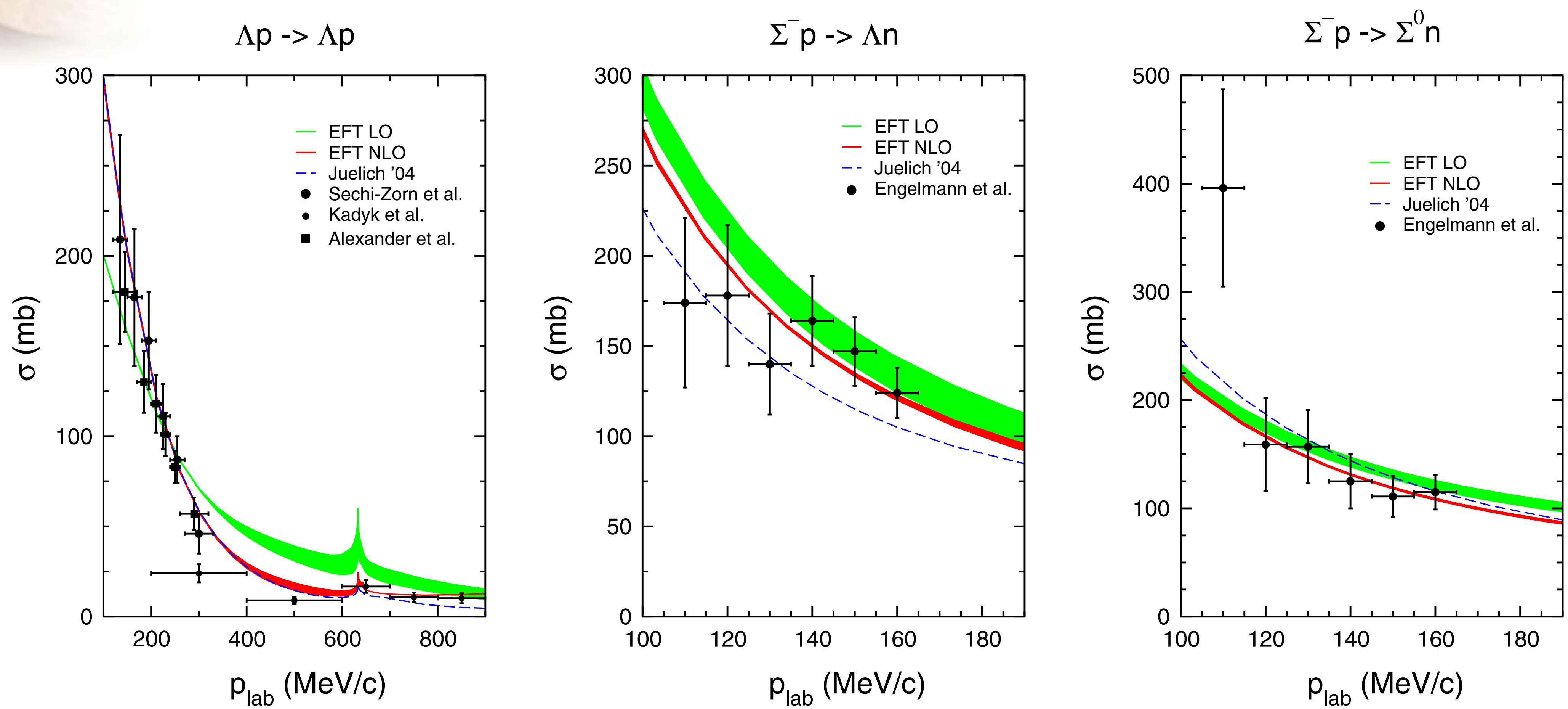

J. Haidenbauer Few Body Systems (2012)

Hyperons live only for a fraction of a ns

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

❷ Requires the knowledge of YN, YY, …

❸ Spectroscopy *… a two-fold way*

Strangeness Nuclear Physics

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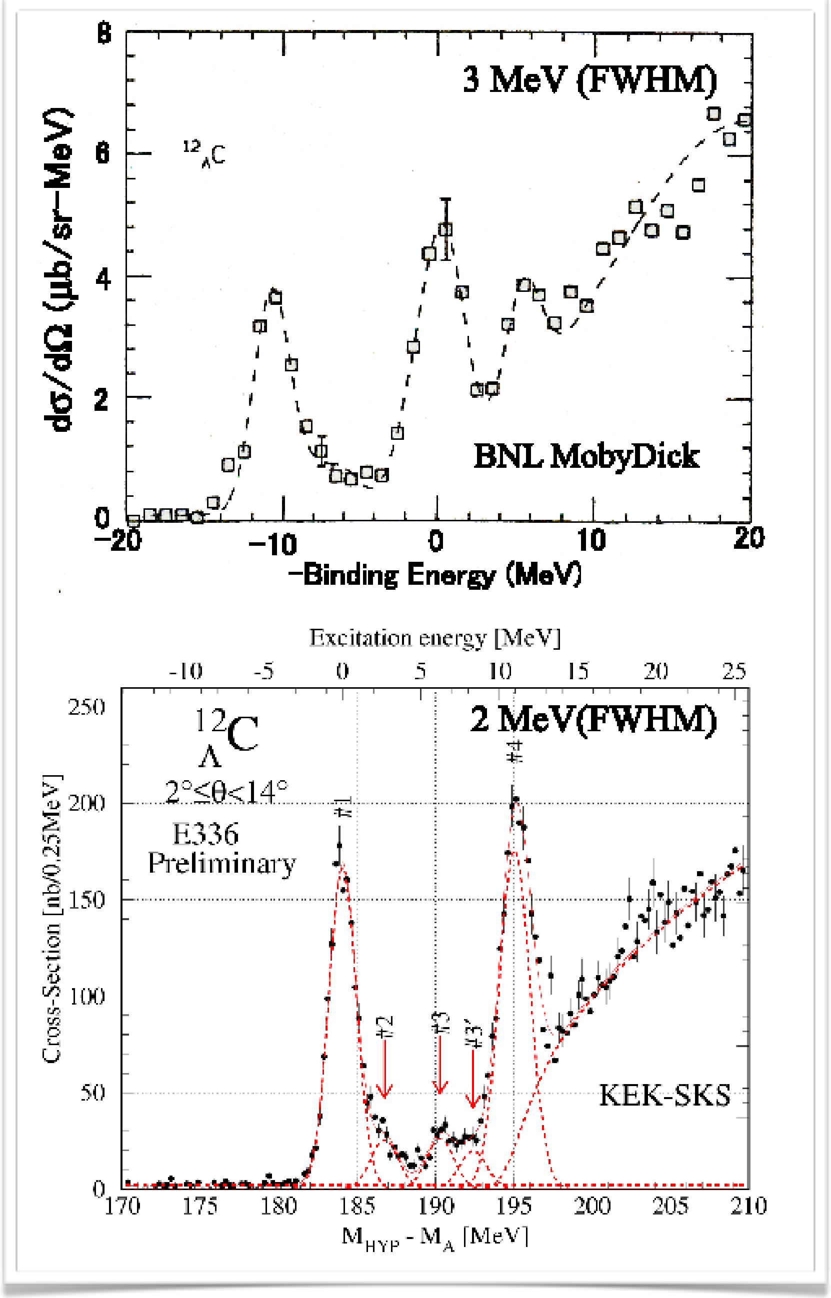
❸ Spectroscopy: DIRECT PRODUCTION



O.Hashimoto, H.Tamura, PPNP 57 (2006) 564.

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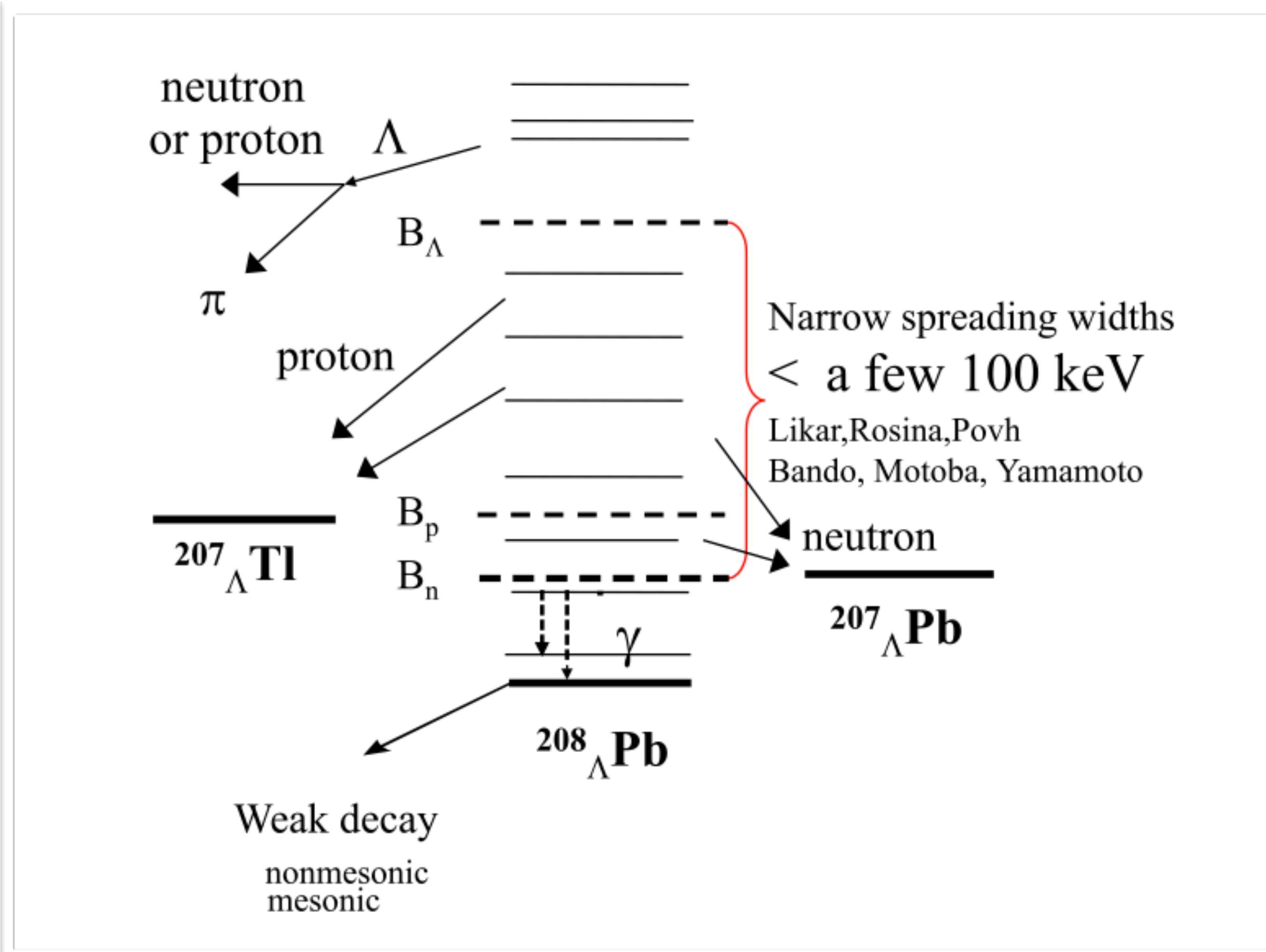

O.Hashimoto, H.Tamura, PPNP 57 (2006) 564.

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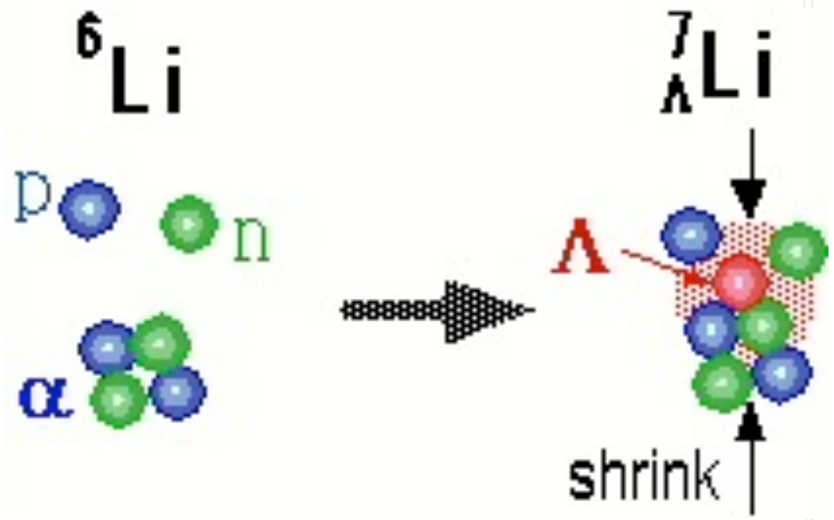

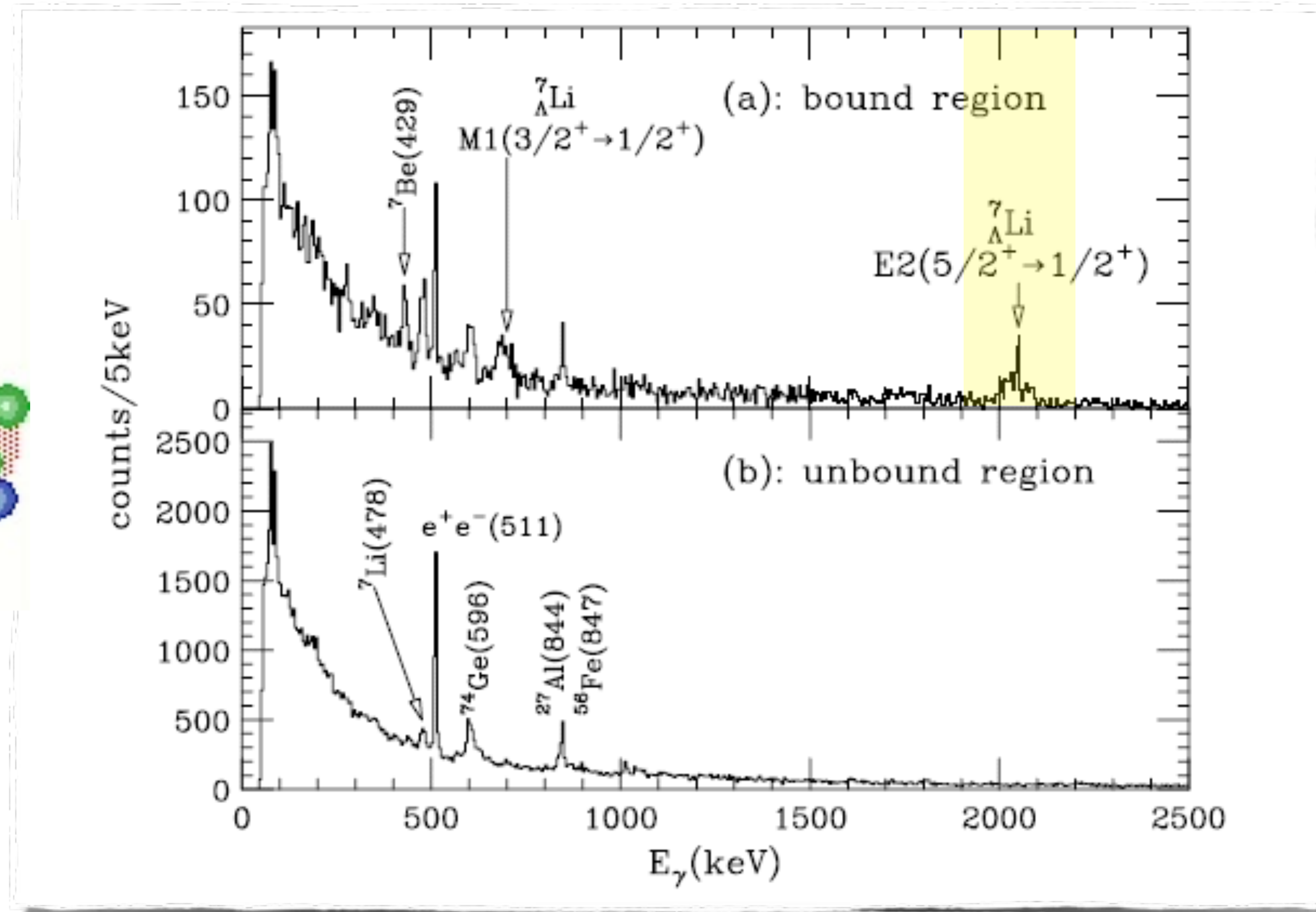

K. Tanida et al., Phys. Rev. Lett. 86 (2001)

Strangeness Nuclear Physics

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2. Requires the knowledge of YN, YY, ...
3. Spectroscopy

4 Lesson learned

O.Hashimoto, H.Tamura, PPNP 57 (2006) 564.

Nuclear potential of Λ:

V_0^Λ =-30MeV (c.f. U_N =-50MeV)

ΛN force is attractive
(but weaker than NN)

Small spin-orbit force
(~few percent of NN case)

Precision is the key issue