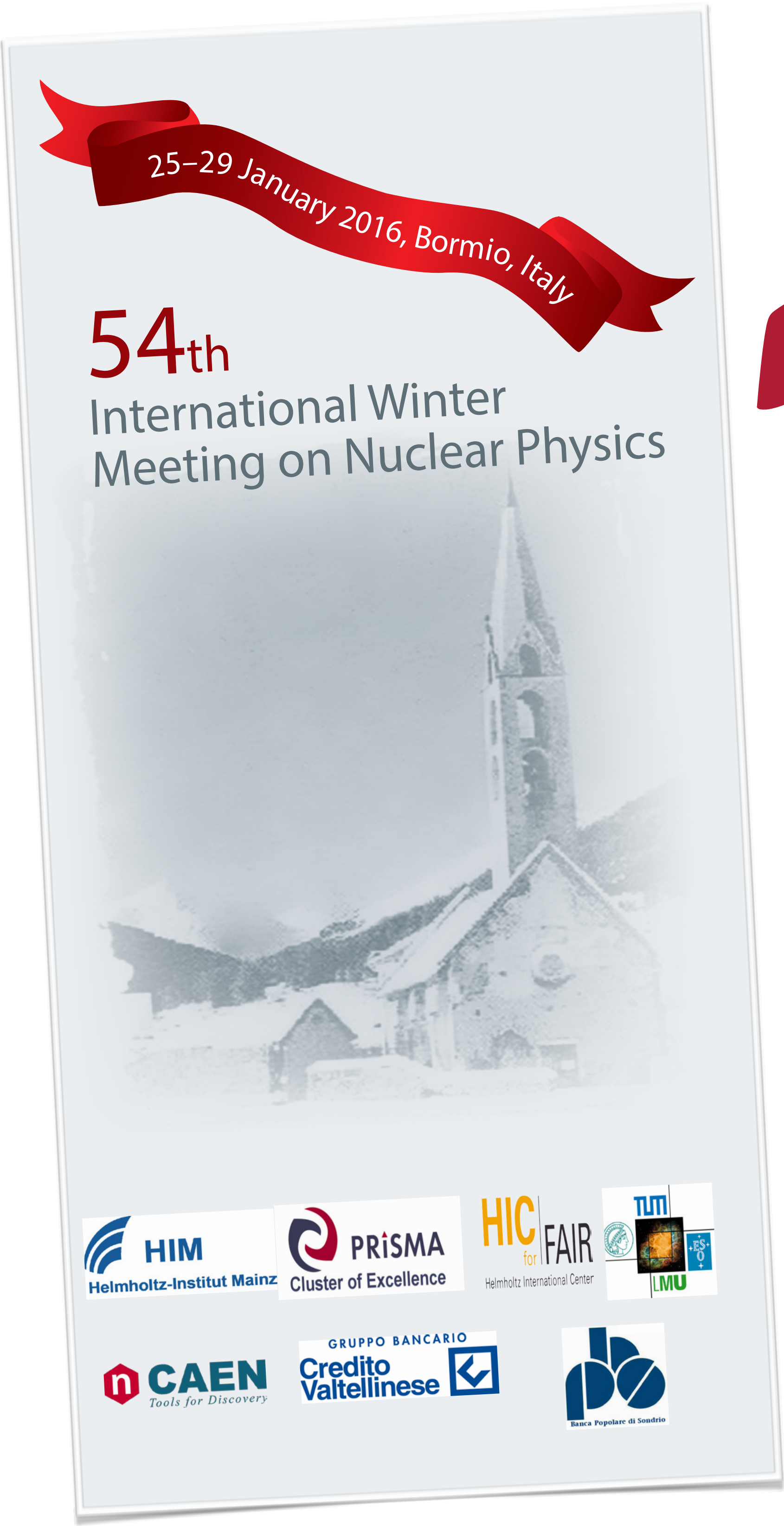


4TH PRE-CONFERENCE SCHOOL

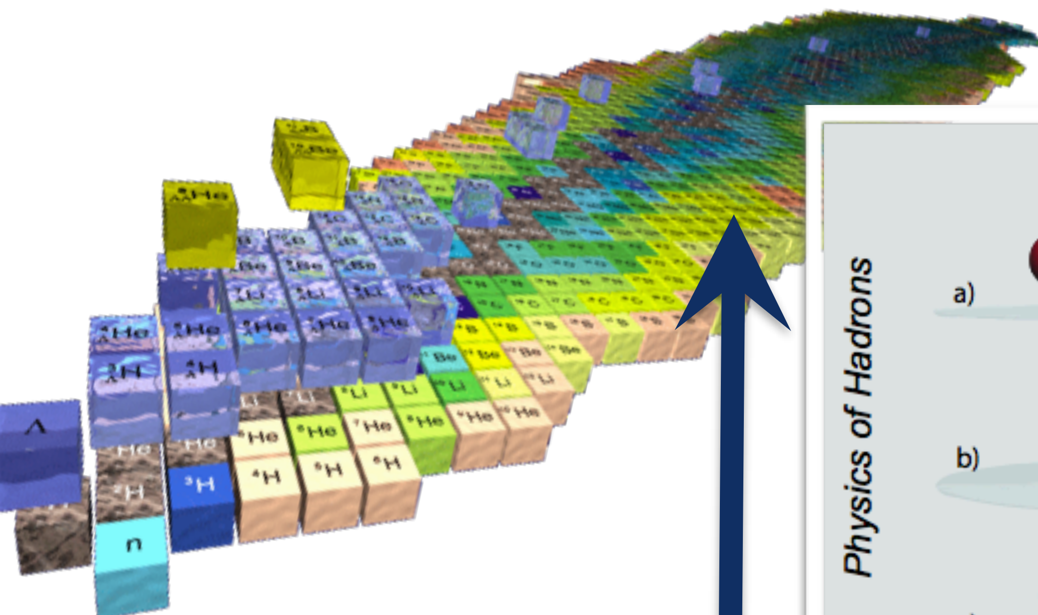
Lecturer: P. Capel, L. Fabbietti, W. Kűhn, C. Sfienti

WHY THIS CONFERENCE?

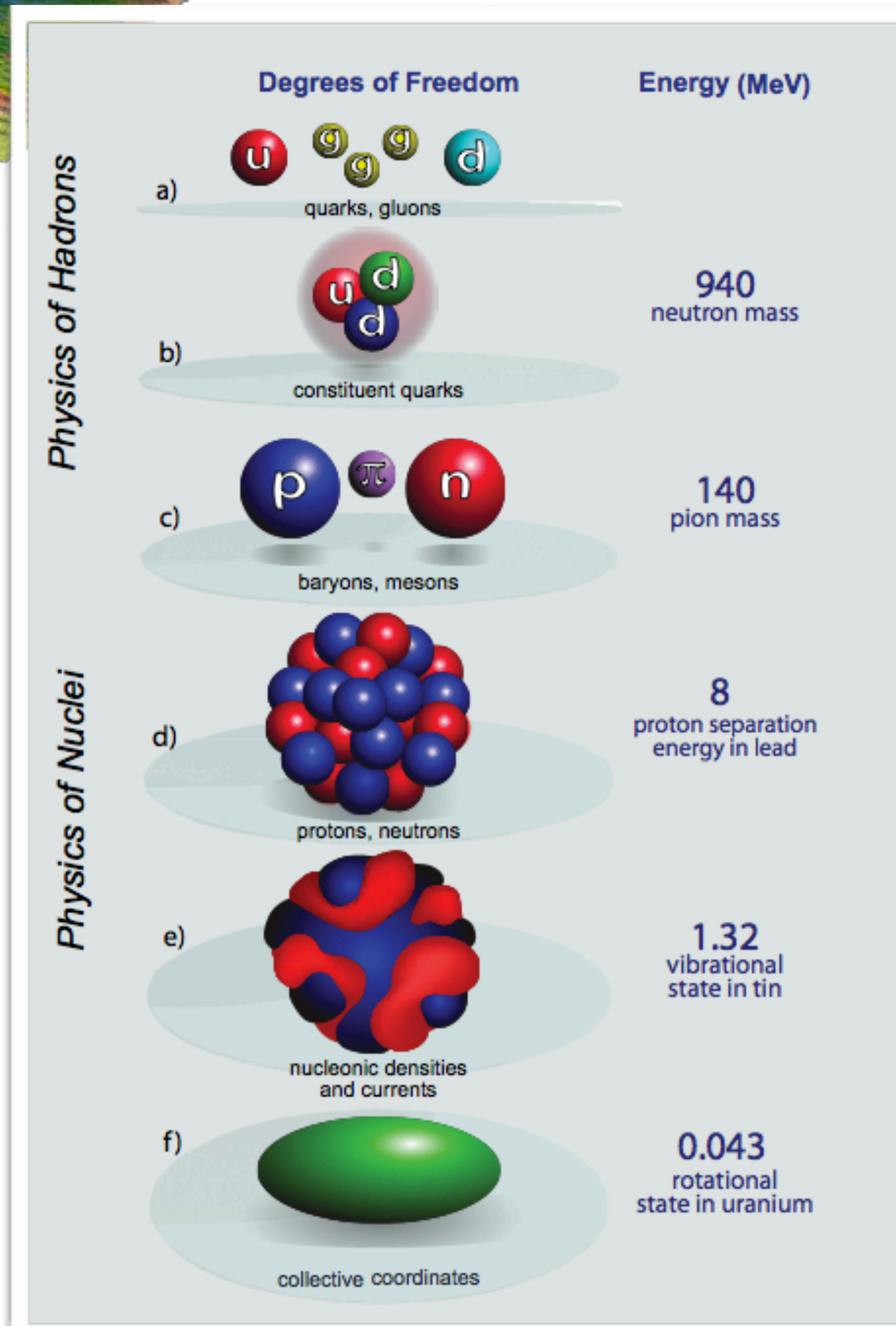
54th International Winter Meeting on Nuclear Physics

25-29 January 2016 Bormio (Italy)

THE MANY FACETS OF THE NUCLEAR REALM



Resolution



LRP Nuclear Science Advisory Committee(2008)

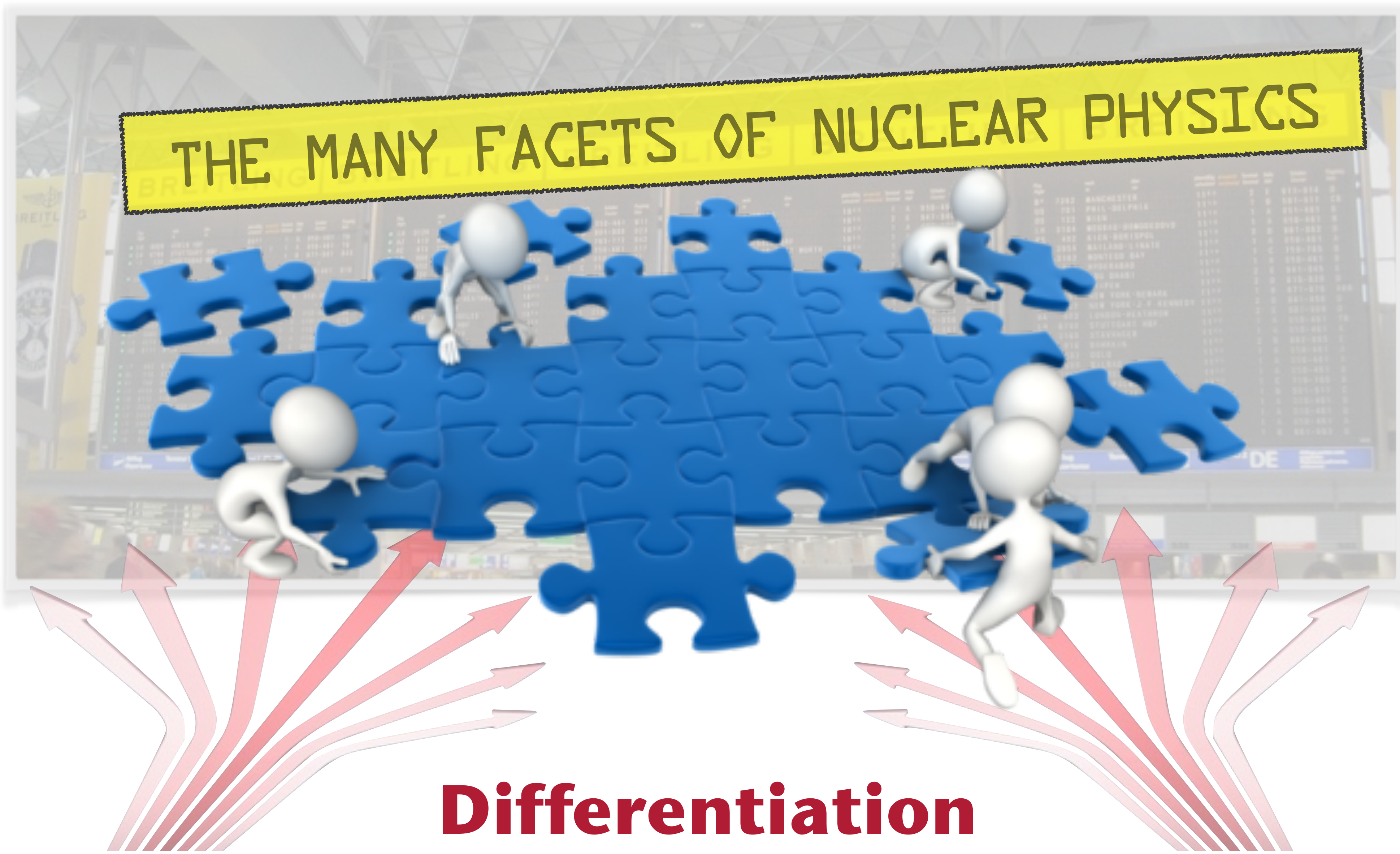
Simplicity

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

Complexity

Specialization

Differentiation

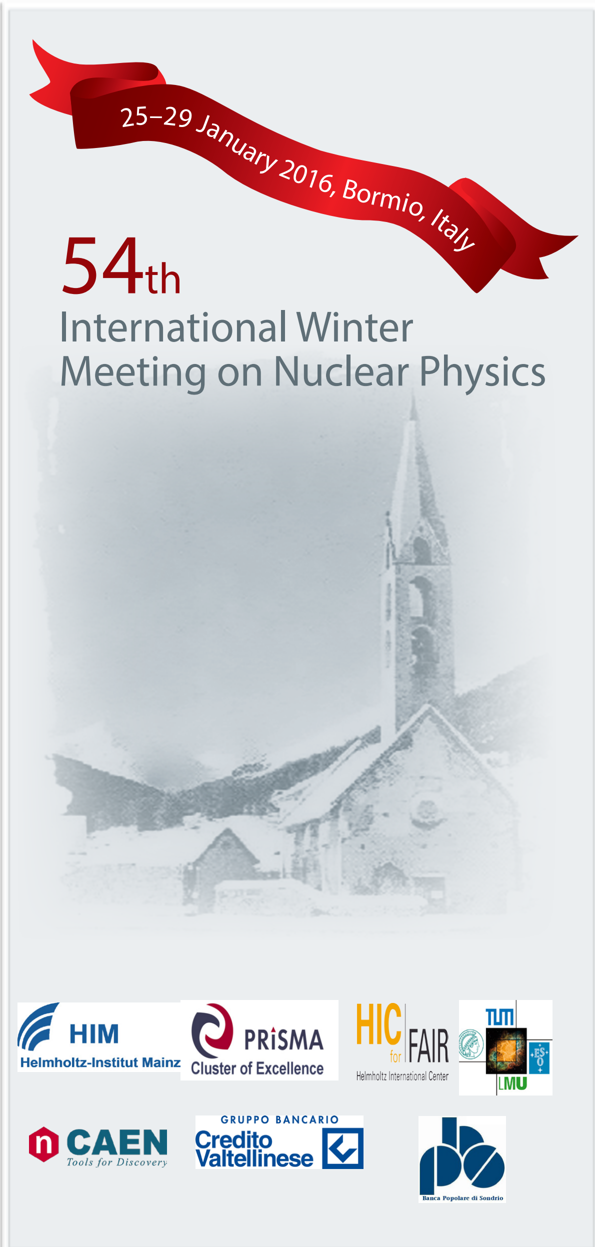


Differentiation

GAIN in scientific insight

54th International Winter Meeting on Nuclear Physics

25-29 January 2016 Bormio (Italy)



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:

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Hadron Physics: Selected Topics

MONDAY, 25th January 2016

MORNING SESSION 09:00-12:30

9:00	Concettina Sfienti and Laura Fabbietti Welcome
09:10	Matthias NEUBERT Beyond the Higgs Boson
09:55	Steen HANNESTAD Neutrino physics and precision cosmology
10:30	Coffee-break
11:00	Ryugo HAYANO The Fukushima-Daiichi Nuclear Power Plant Accident
11:45	Wolfgang GRADL Highlights on BESIII results

POSTER SESSION 17:00-19:00

17:00	Measurement of the proton form factor at very low Q^2	Adrian WEBER
17:03	Extension of the ratio method to low energy	Frederic COLOMER
17:06	Study of Improved K^0_S Detection for the Belle II Detector	Leonard KOCH
17:09	Progresses on Light hadron spectroscopy	Giulio MEZ-ZADRI
17:11	Analysis of He-4 Inclusive Electron-Scattering-Experiments	Simon KEGEL
17:14	Modelling Early Stages of Relativistic Heavy Ion Collisions: Coupling Relativistic Transport Theory to Decaying Color-Electric Flux Tubes	Lucia OLIVA
17:17	Forward production of neutrons in fragmentation of high energy heavy nuclei	Vladimir YUREVICH
17:20	Computing for the LHC: operations during Run2 and getting ready for Run 3	Dagmar ADAMOVA
17:23	Performance of the ALICE secondary vertex b-tagging algorithm	Lukas KRA-MARIK
17:26	K^- multi-nucleon absorption processes in hadronic interaction studies by AMADEUS	Raffaele DEL GRANDE

TUESDAY, 26th January 2016

MORNING SESSION 09:00-12:30

09:00	Marco VAN LEEUWEN Recent results of the ALICE experiment
09:45	Siegfried BETHKE Results from ATLAS and CMS: Strong Interactions and New Physics
10:30	Coffee break
11:00	Stefano GANDOLFI Recent results on hyperons and the EOS
11:30	Alexander SCHMAH News from RHIC
12:00	Romain HOLZMANN Recent Results from the HADES Experiment

AFTERNOON SESSION 17:00-19:00

17:00	Patrick ACHENBACH Experimental Tests of Charge Symmetry Breaking in Hypernuclei
17:20	John F. SHARPEY-SCHAFER No Low-Lying Nuclear Vibrations: Configuration Dependent Pairing and Axial Asymmetry
17:40	Vinzent STEINBERG SMASH - A new hadron transport approach for heavy ion collissions
18:00	Roman LYSAK Recent results on soft QCD topics from ATLAS
18:20	Jason HOLT Ab initio valence-space theory for exotic nuclei
18:40	Georg WOLSCHIN Beyond the thermal model

17:29	XYZ studies at BESIII	Gianfranco MORELLO
17:32	The RUN-2 ATLAS Trigger System	Savanna Marie SHAW
17:35	PANDA Forward Spectrometer Calorimeter	Pavel SE-MENOV

WEDNESDAY, 27th January 2016

MORNING SESSION 09:00-12:4e0

09:00	Georg BOLLEN Facility for Rare Isotope Beams – Science and Status
09:45	Paolo AZZURRI Results from CMS and ATLAS: Electro-weak Symmetry Breaking and Beyond
10:30	Coffee break
11:00	Gaute HAGEN Current topics in nuclear structure theory
11:45	Michael SCHMELLING Heavy Ion Results from LHCb
12:15	Horst STÖCKER Signatures of the early Yang Mills phase in a novel high multiplicity event class in pBar-p and pA colliders FAIR, NICA, RHIC and LHC

AFTERNOON SESSION 17:00-19:05

17:00	Harald MERKEL Internal Target Experiments at the MESA accelerator
17:25	Dinko ATANASOV Precision mass measurements of neutron-rich cadmium for r-process studies
17:45	Mikhail MIKHASENKO Beyond the isobar model
18:05	Michael Ryan CLARK Measurement of the ridge and bose-enstein correlations in pp and pPb collisions with the ATLAS detector at the LHC
18:25	Anselm ESSER Measurement of the beam normal single-spin asymmetry of Carbon-12
18:45	Li LEI Charm Physics at BES III

17:38	Study of the 2H(p,γ)3He reaction in the BBN energy range at LUNA	Viviana MOSSA
17:41	Electron Identification and Hadron Contamination Studies in Proton-Proton Collisions with ALICE	Anisa DASHI
17:44	study of the eta meson production with polarised proton beam	Iryna SCHÄTTI-OZE-RIANSKA

Hadron Physics: Selected Topics

THURSDAY, 28th January 2016

MORNING SESSION 09:00-12:40

09:00	Bronson MESSER	Recent progress on core-collapse supernovae: simulations and connections to observations,
09:45	Thomas MANNEL	Charm Physics: Where Color meets Flavor
10:30	Coffee-break	
11:00	Marcel MERCK	Flavour results from LHCb
11:45	Wolfgang BAUER	Replacing hydrodynamic simulations with transport theory
12:10	Vincenzo PATERA	Novel developments in imaging and dosimetry for Hadron therapy

AFTERNOON SESSION 17:00-19:05

17:00	Pierre CAPEL	From Coulomb breakup of halo nuclei to neutron radiative capture
17:25	Oliver ARNOLD	Proton-proton and Lambda-proton correlations measured in p+Nb collisions at 3.5 GeV with HADES
17:45	Diego LONARDONI	From hypernuclei to neutron stars: looking for the pieces of the puzzle
18:05	Dima LEVIT	DEPFET for BELLEII
18:25	Denise GODOY	Measurements of heavy flavours with the ALICE experiment at the LHC
18:45	Leonardo CRISTELLA	Exotic quarkonium states in CMS

FRIDAY, 29th January 2016

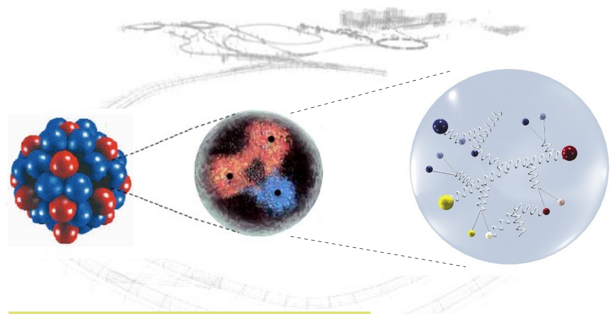
MORNING SESSION 09:00-12:45

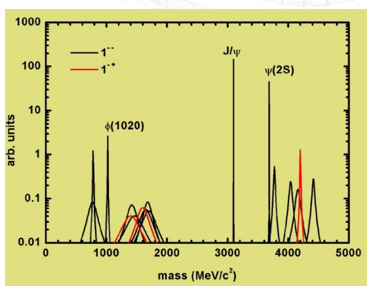
09:00	Peter KRIZAN	The Belle2 Experiment
09:45	Ryan SINEAD	Lattice QCD in 2016: recent results and what to expect
10:30	Coffee break	
11:00	Alexandre OBERTELLI	Recent and future studies of exotic nuclei.
11:45	Sebastian NEUBERT	Hadron Spectroscopy at LHCb
12:15	Or HEN	Correlations in nuclei.

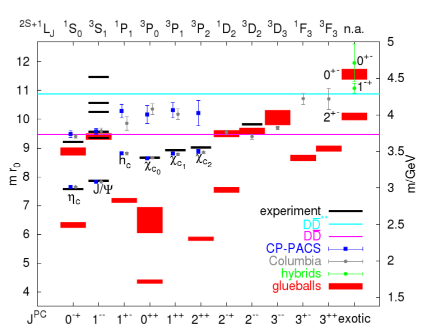
AFTERNOON SESSION 17:00-19:10

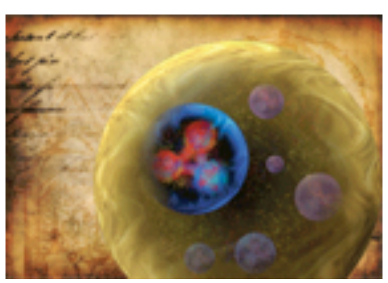
17:00	Wouter RYSSENS	Symmetry unrestricted Skyrme mean-field study of heavy nuclei
17:20	Lucia LEARDINI	Measurement of neutral mesons in pp and Pb-Pb collisions at midrapidity with the ALICE experiment at the LHC
17:40	Leyla ATAR	Quasi-free one-nucleon Knockout Reactions on neutron-rich Oxygen Isotopes
18:00	Marco TOPPI	Measurements of 12C ion fragmentation on thin Au target from the FIRST collaboration at GSI
18:20	Wolfgang TRAUTMANN	Symmetry energy and density

Hadron Physics: Selected Topics









THE BASIC

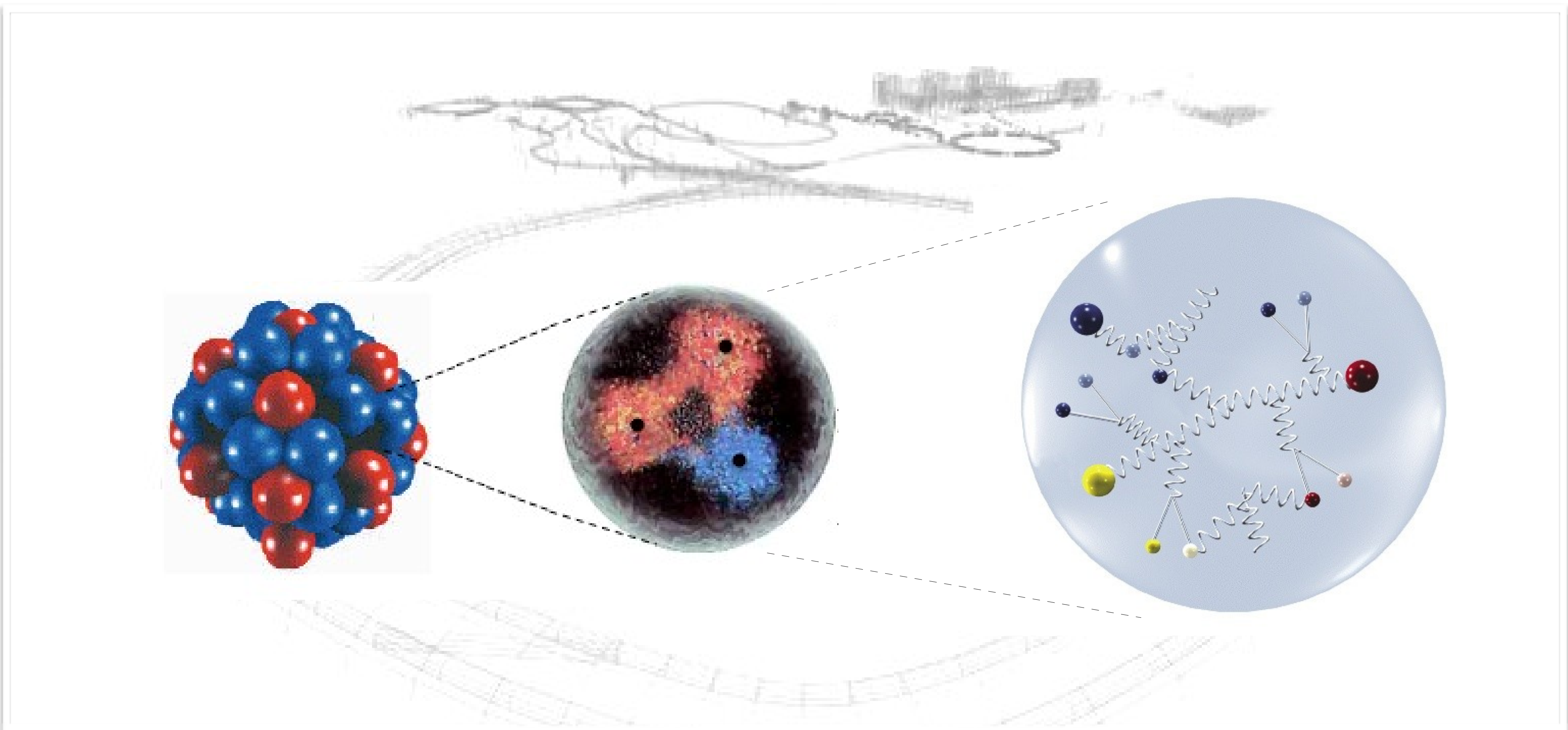
HADRONS IN QCD

EX1: CHARMONIUM

EX2: STRANGE HADRONS

Hadron Physics: Selected Topics

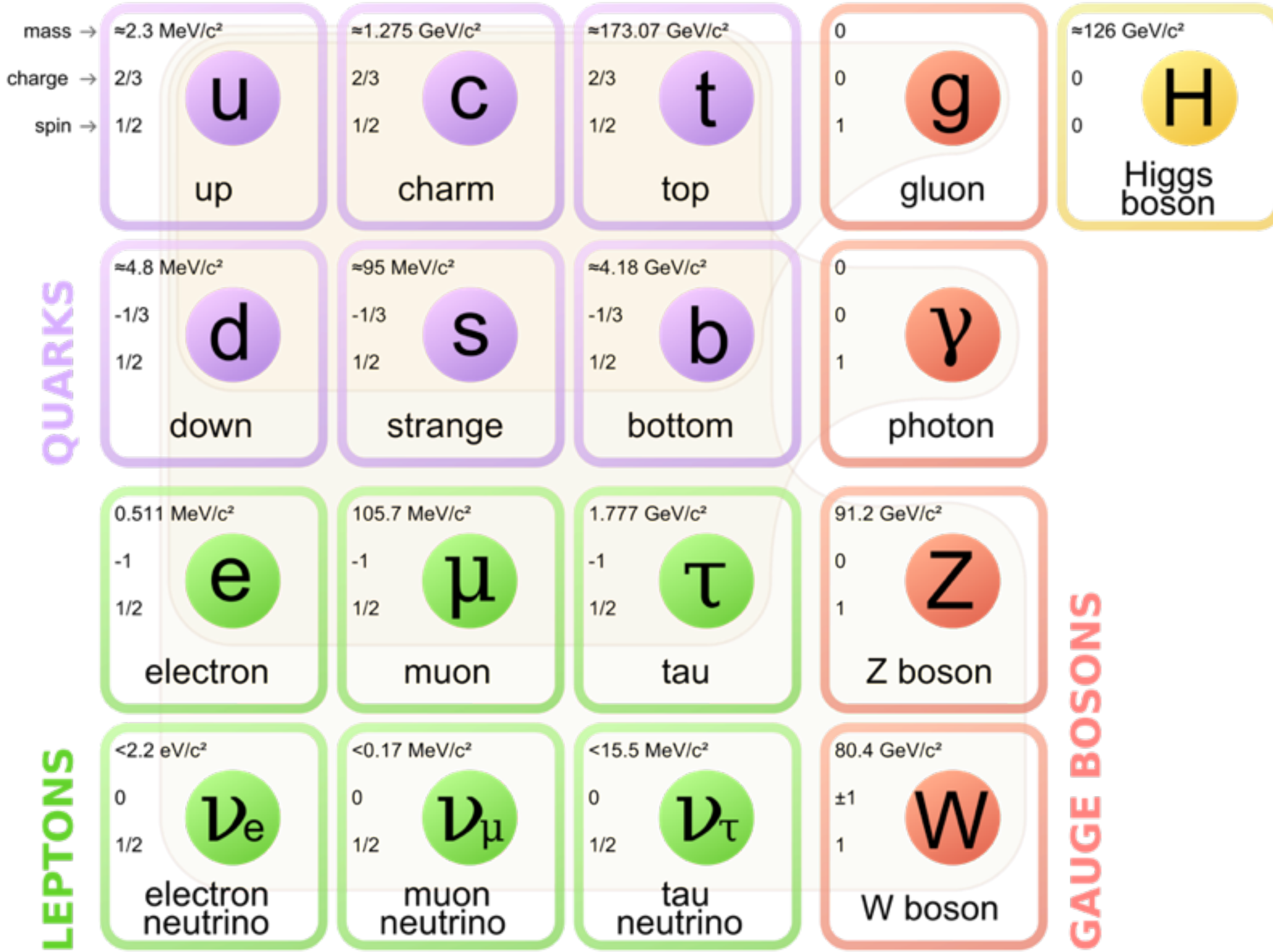
...THE BASIC ...



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,λ) $\Rightarrow$ 1970's (u,d,s)

mesons are bound states of a of quark and anti-quark:

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

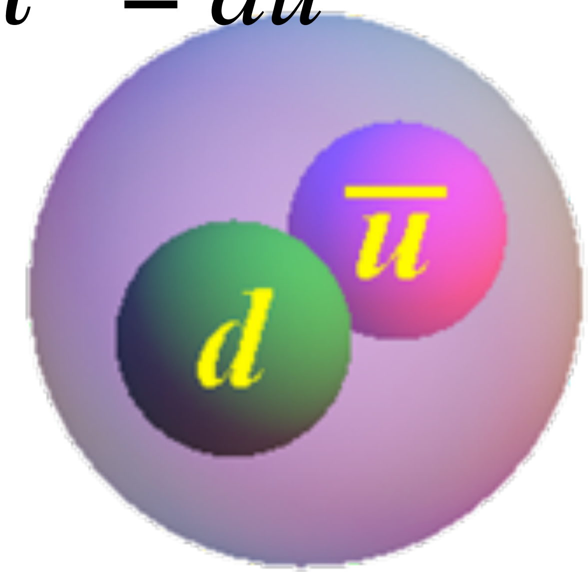
$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

baryons are bound state of 3 quarks:

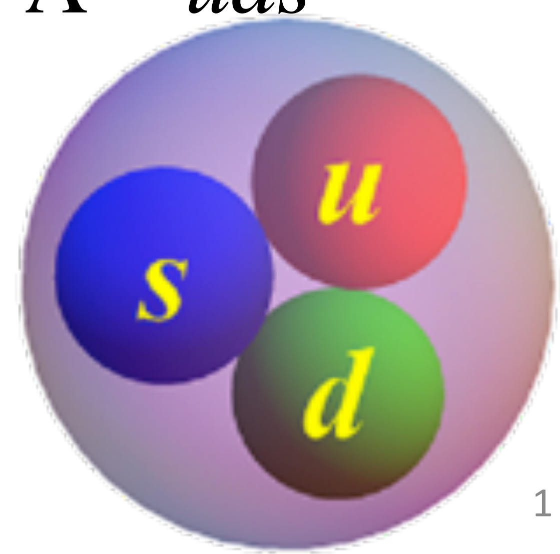
$$p = uud \quad n = udd \quad \Lambda = uds$$

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

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



$\Lambda = uds$

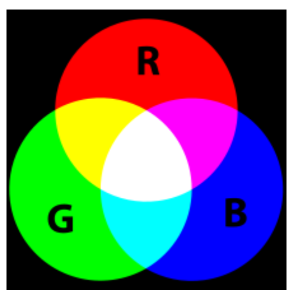


From QPM to QCD

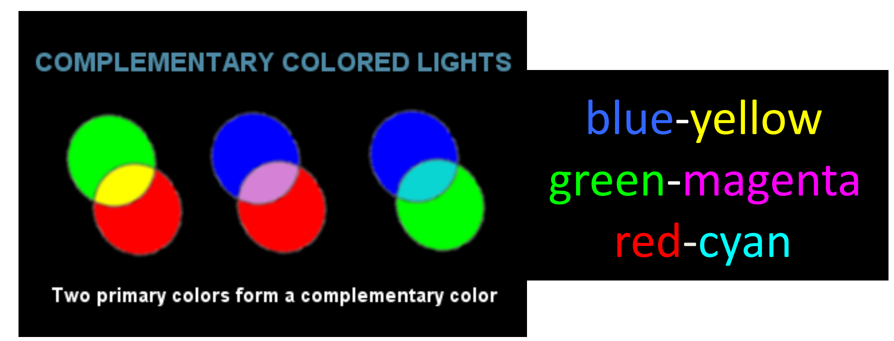
COLOR necessary for antisymmetric wave function

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

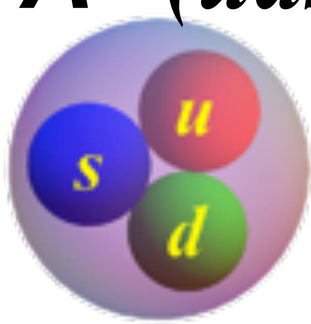
3 primary colors ➔ white



color + complementary color ➔ white

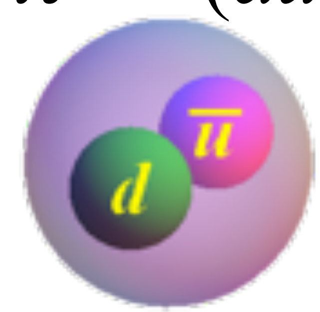


$\Lambda = (uds)$



Baryons are red-blue-green triplets

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



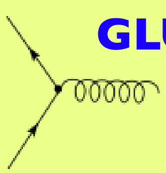
Mesons are color-anticolorpairs

...OBSERVED PARTICLES ARE COLOR SINGLETS

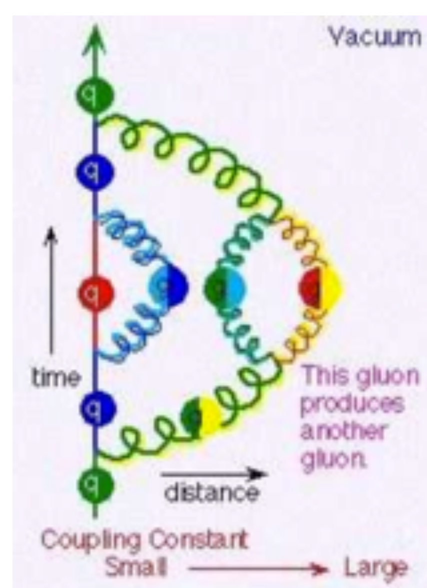
Properties of QCD

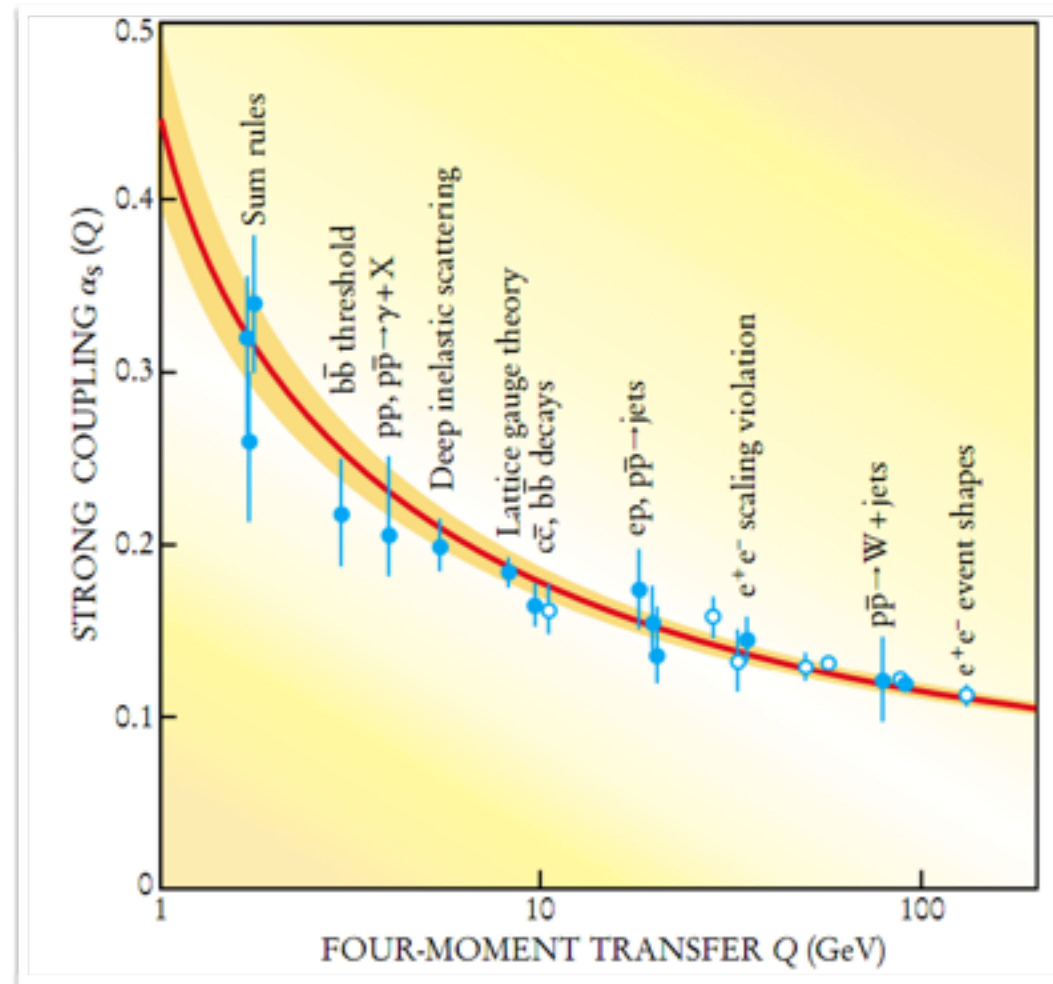
Lagrangian of QCD

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



- 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

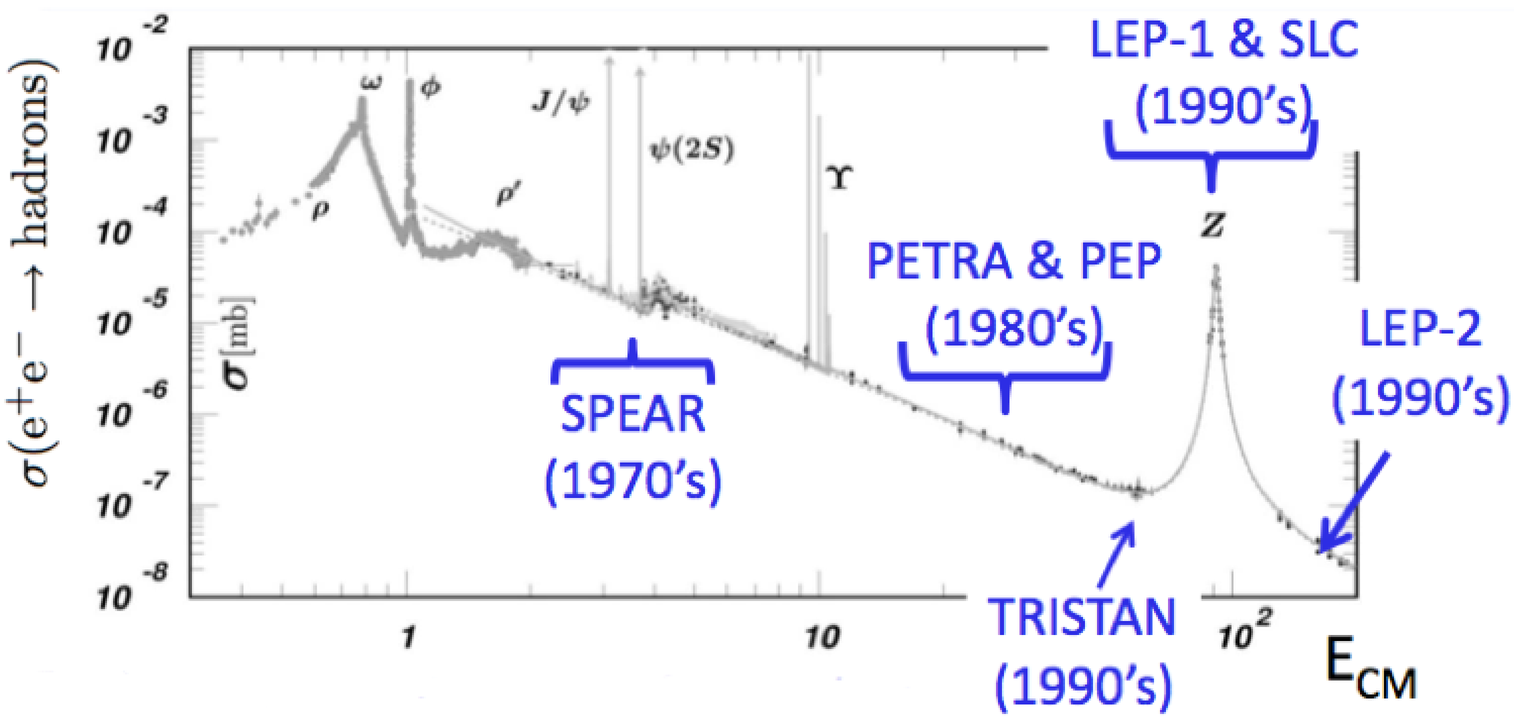


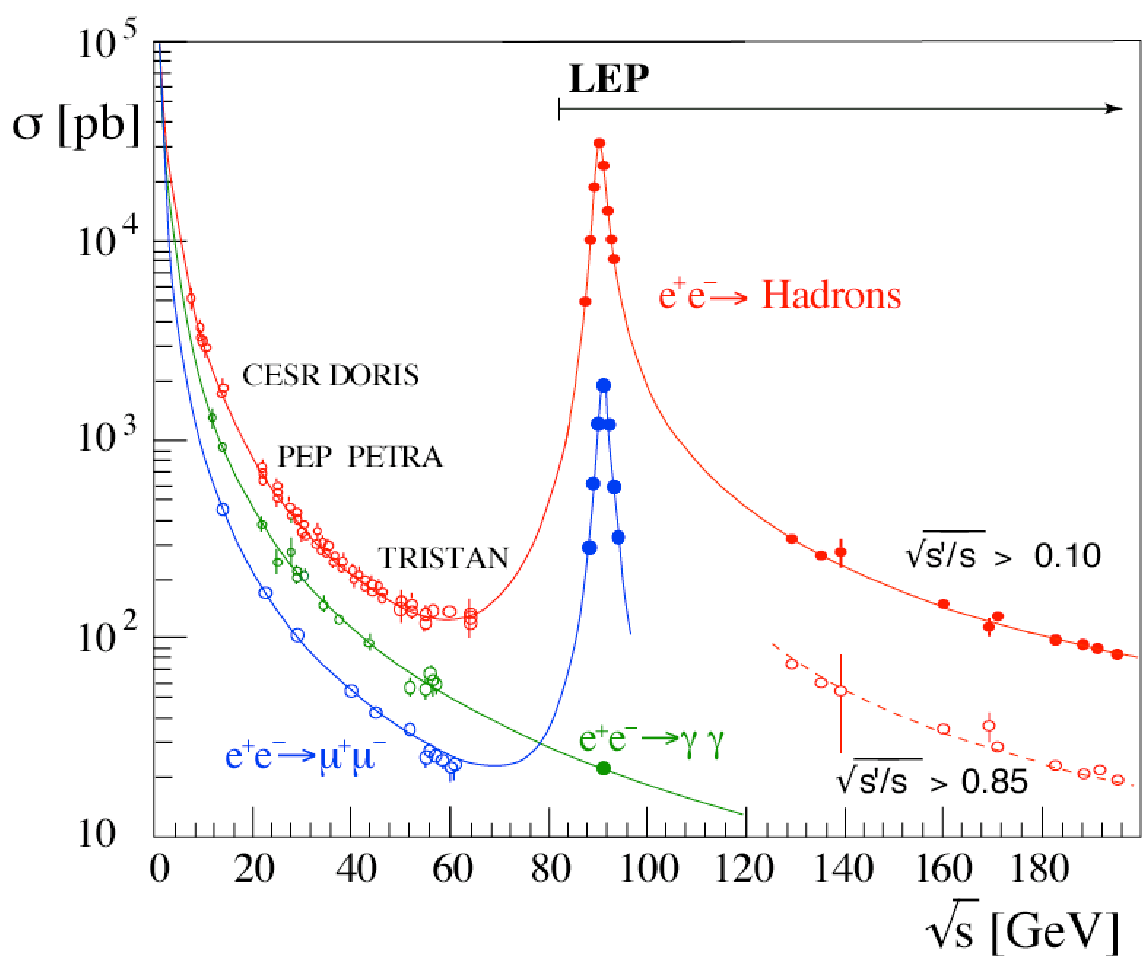


„If the Lord Almighty had consulted me before embarking upon creation, I would have recommended something simpler."

King Alphonse X. of Castille and Léon (1221-1284), on having the Ptolemaic system of epicycles explained to him

$e^+e^- \rightarrow$ Hadrons





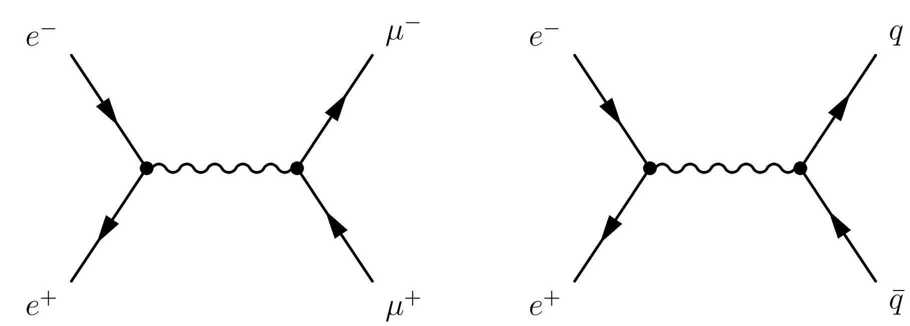
Two step process:

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

Basic QED Process:

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

...then compare (Feynman LO)

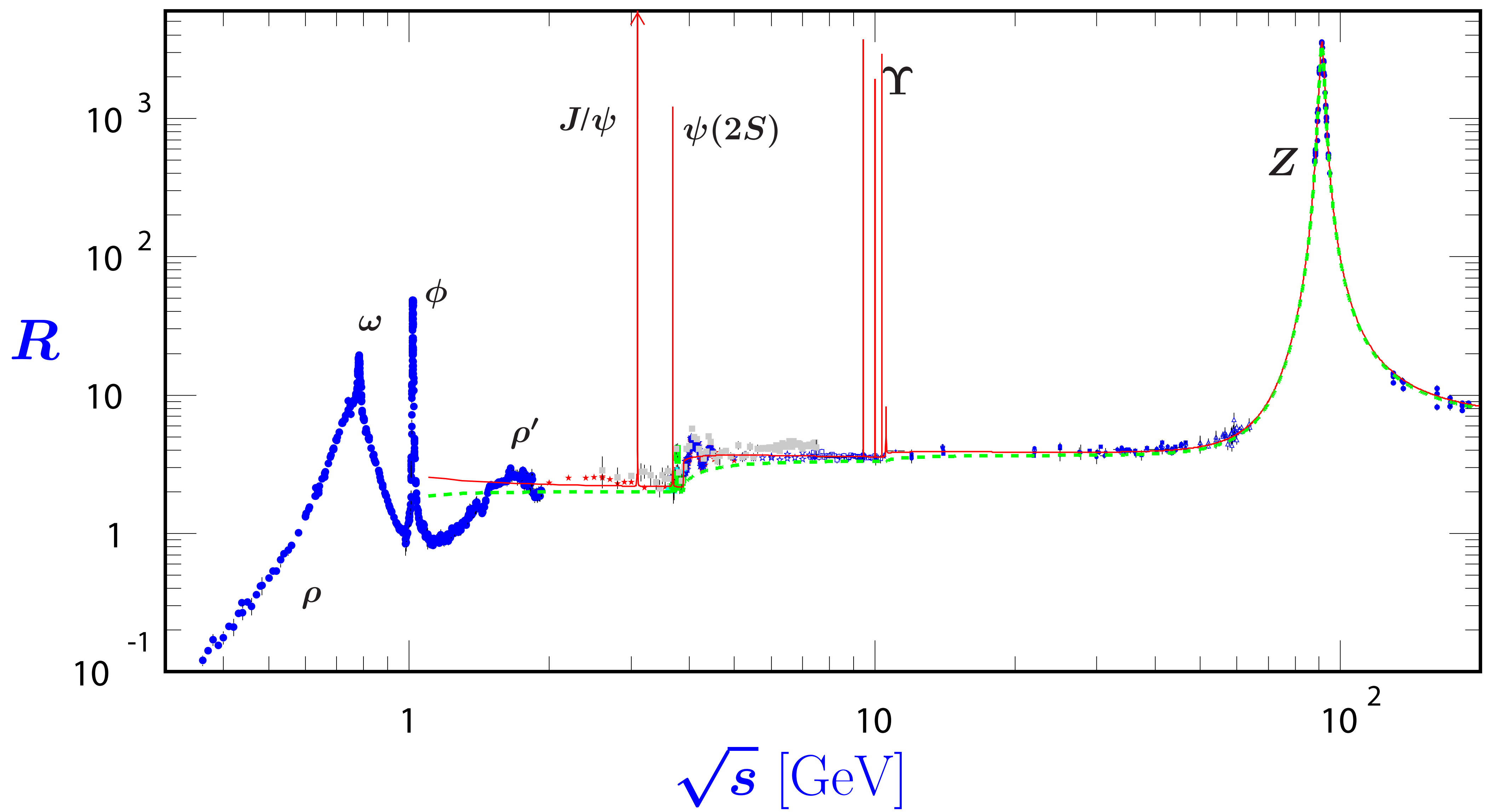


$$\sigma_0^{e^+e^- \rightarrow q\bar{q}} = \frac{4\pi\alpha_{\rm em}^2}{3s} e_q^2 N_c = \frac{86.9\,\mathrm{nbGeV}^2}{s} e_q^2 N_c.$$

$e^+e^- \to$ Hadrons

and construct:

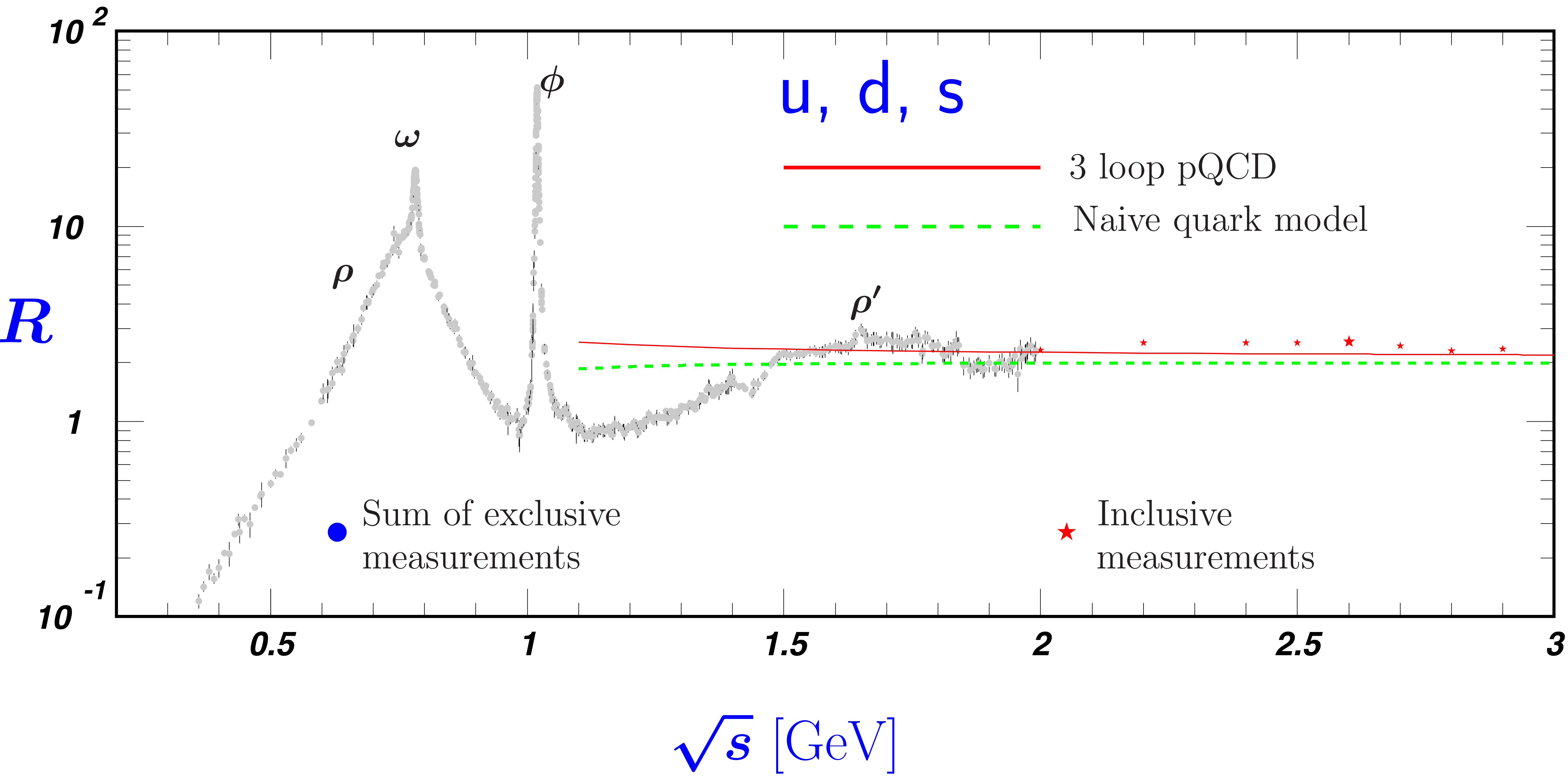
$$R = \frac{\sigma^{e^+e^-\to \text{hadrons}}}{\sigma^{e^+e^-\to\mu^+\mu^-}} = N_c \sum_q e_q^2 .$$



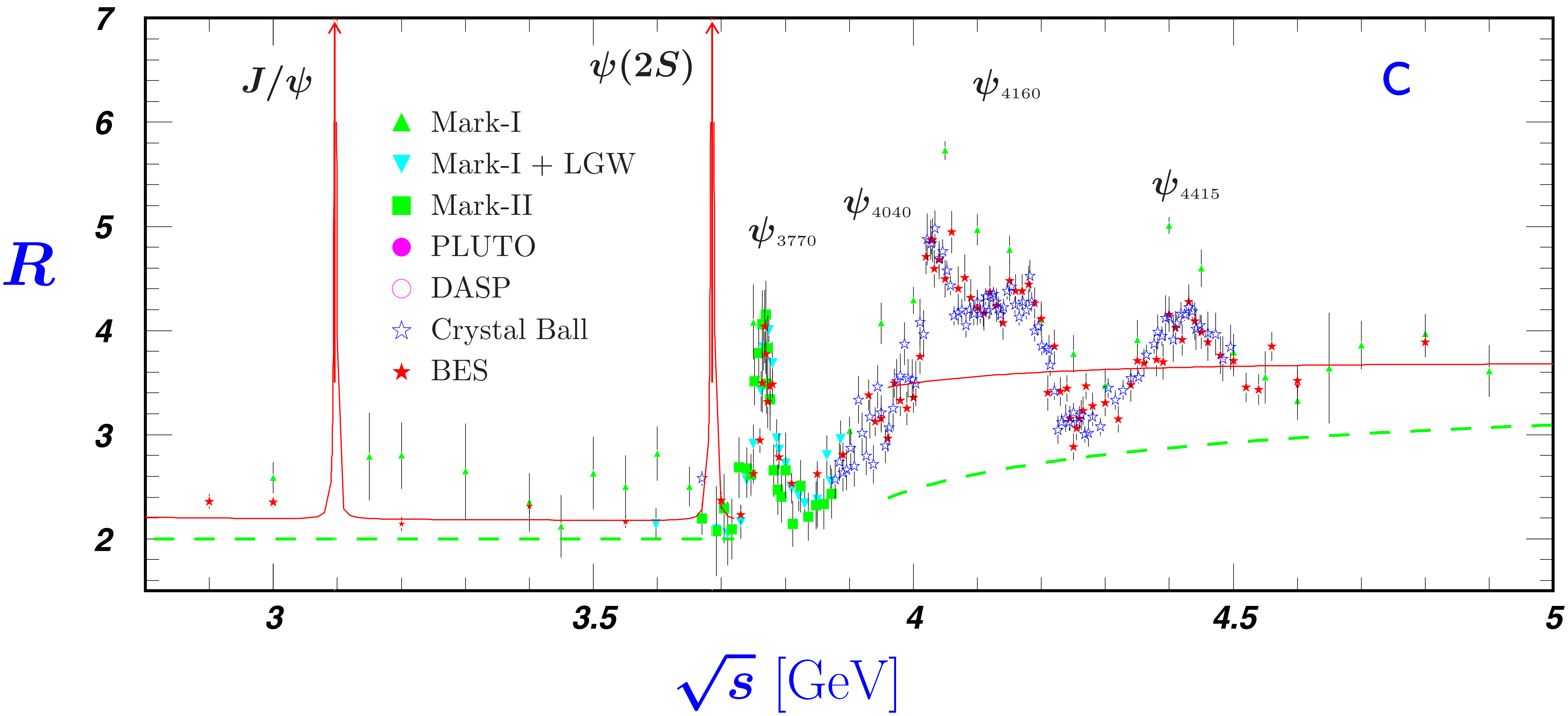
❶ Confirmed Color hypothesis

❷ Production thresholds for Quark-flavours production

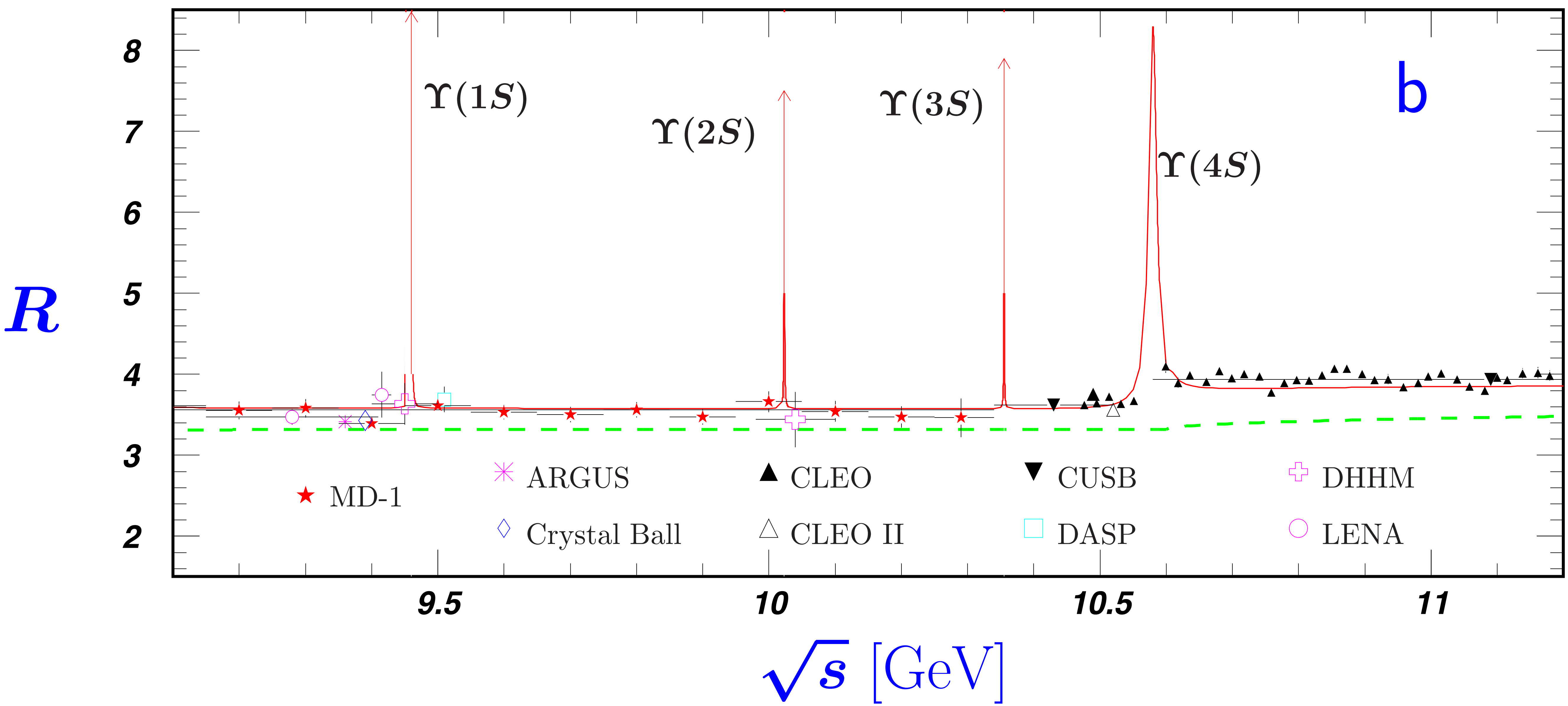
$e^+e^- \rightarrow$ Hadrons



$e^+e^- \to$ Hadrons



$e^+e^- \rightarrow$ Hadrons



How to study hadrons?

☞ Build them together in a controlled manner

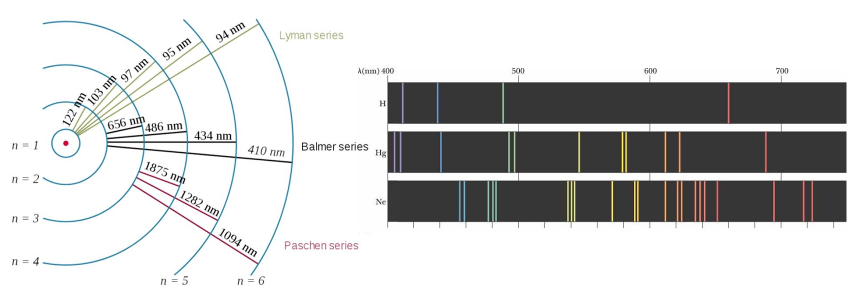
- e^+e^- collider can produce vector mesons (other particles in decays) [BES-III/BELLE]
- hadron beams have high production cross sections but little control [PANDA]

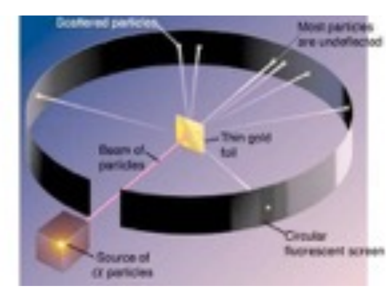
☞ Observe them as existing particles

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

☞ Study their interaction among each others

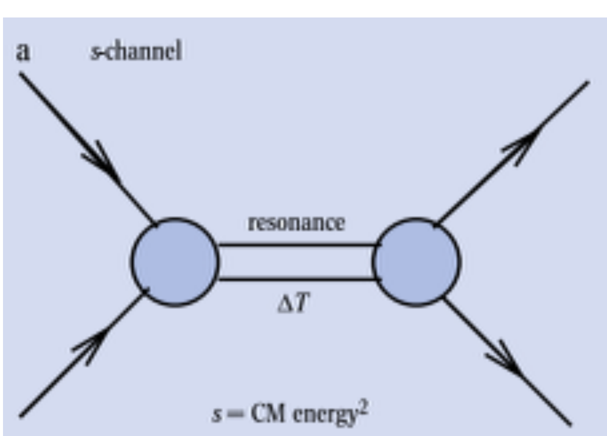
Investigation structure of matter through:

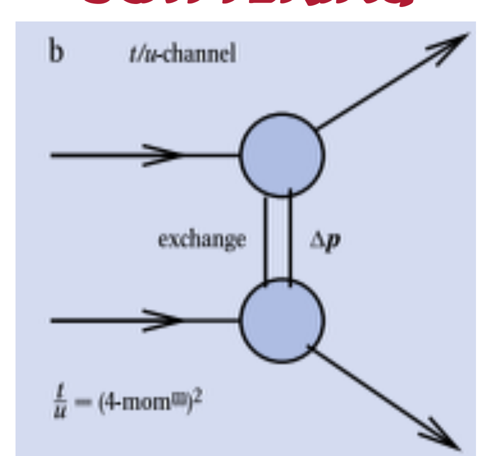




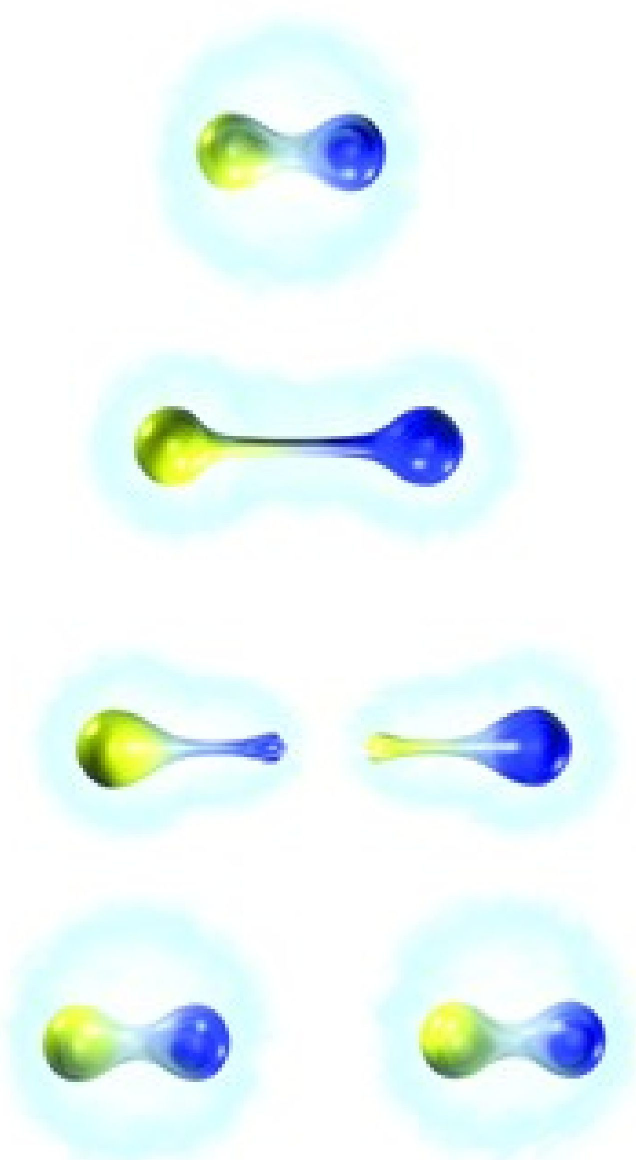
SPECTROSCOPY

SCATTERING





Strong Interaction

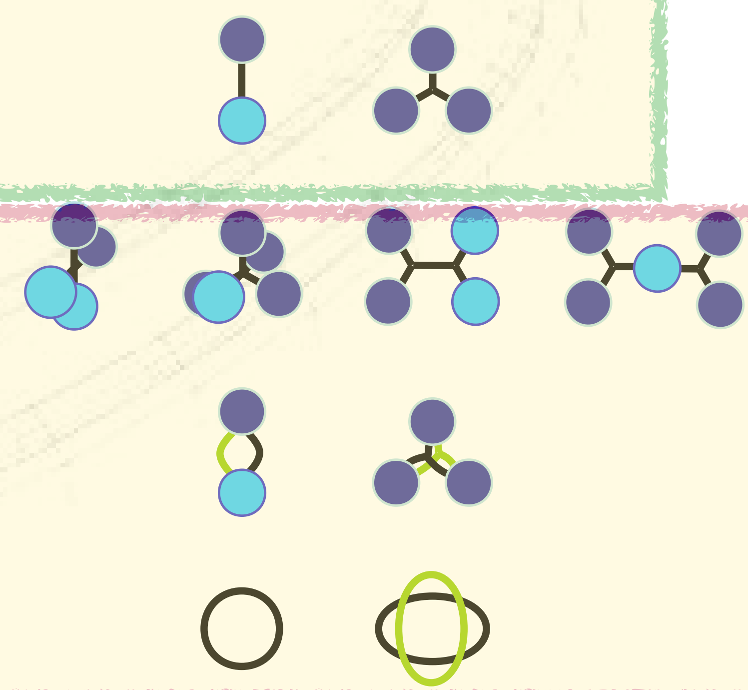


Strong interactions and *confinement*

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

WE KNOW

Mesons, Baryons	
Multi-quark states	
Hybrids	
Glueballs	



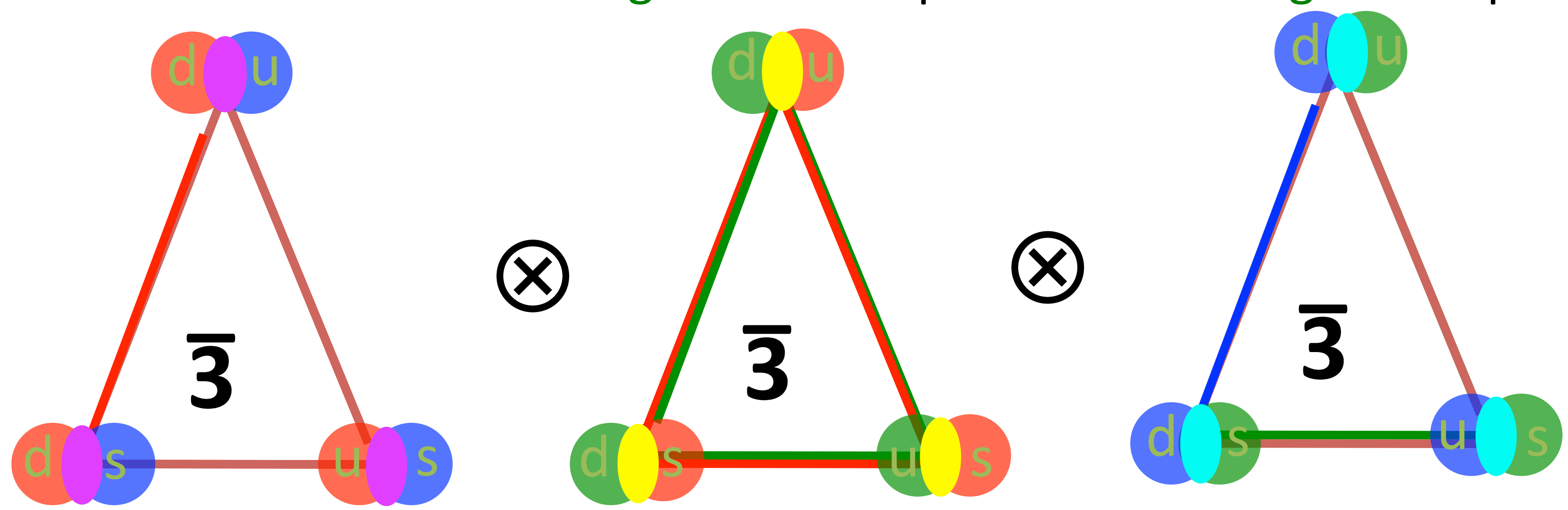
QCD ALSO ALLOWS

Totalitarian principle: Everything not forbidden is compulsory

Prediction of QCD (I)

...MULTIQUARK STATES FROM DIQUARKS AND ANTIQUARKS

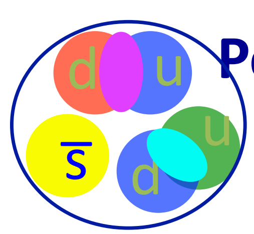
red-blue diquark | green-red diquark | blue-green diquark



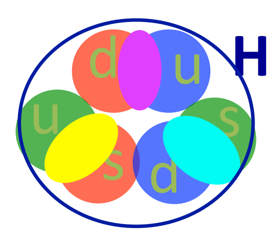
magenta (anti-green) **anti-triplet**

yellow (anti-blue) **anti-triplet**

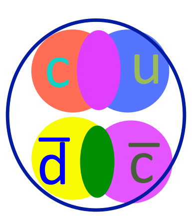
cyan (anti-red) **anti-triplet**



Pentaquark



H-dibaryon



tetraquark meson

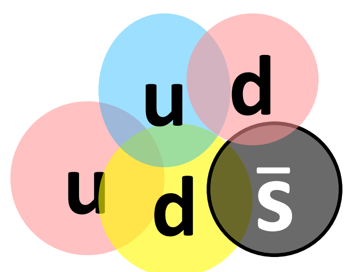
magenta-cyan-yellow
color singlet 5-q state

magenta-cyan-yellow
color singlet 6-q state

green-magenta (anti-green)
color singlet 4-q state

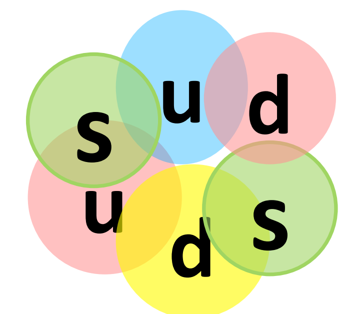
Prediction of QCD (II)

...NON $Q\bar{Q}$ MESONS OR NON QQQ BARYONS

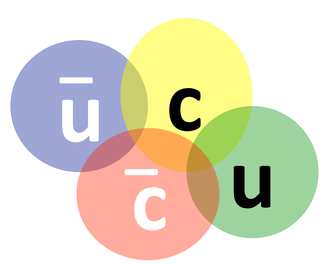


pentaquarks

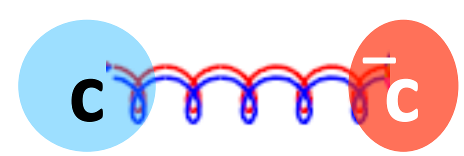
glueballs



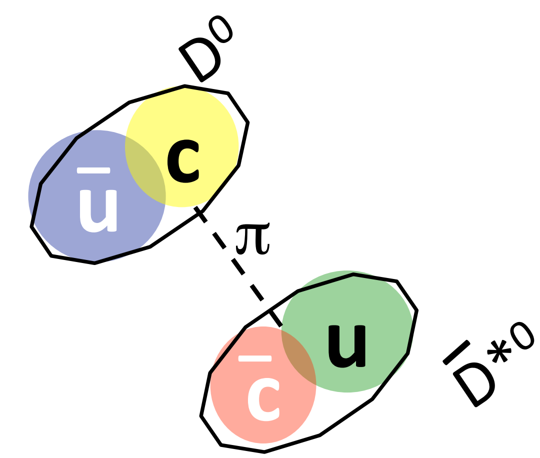
H-dibaryon



diquark-diantiquarks

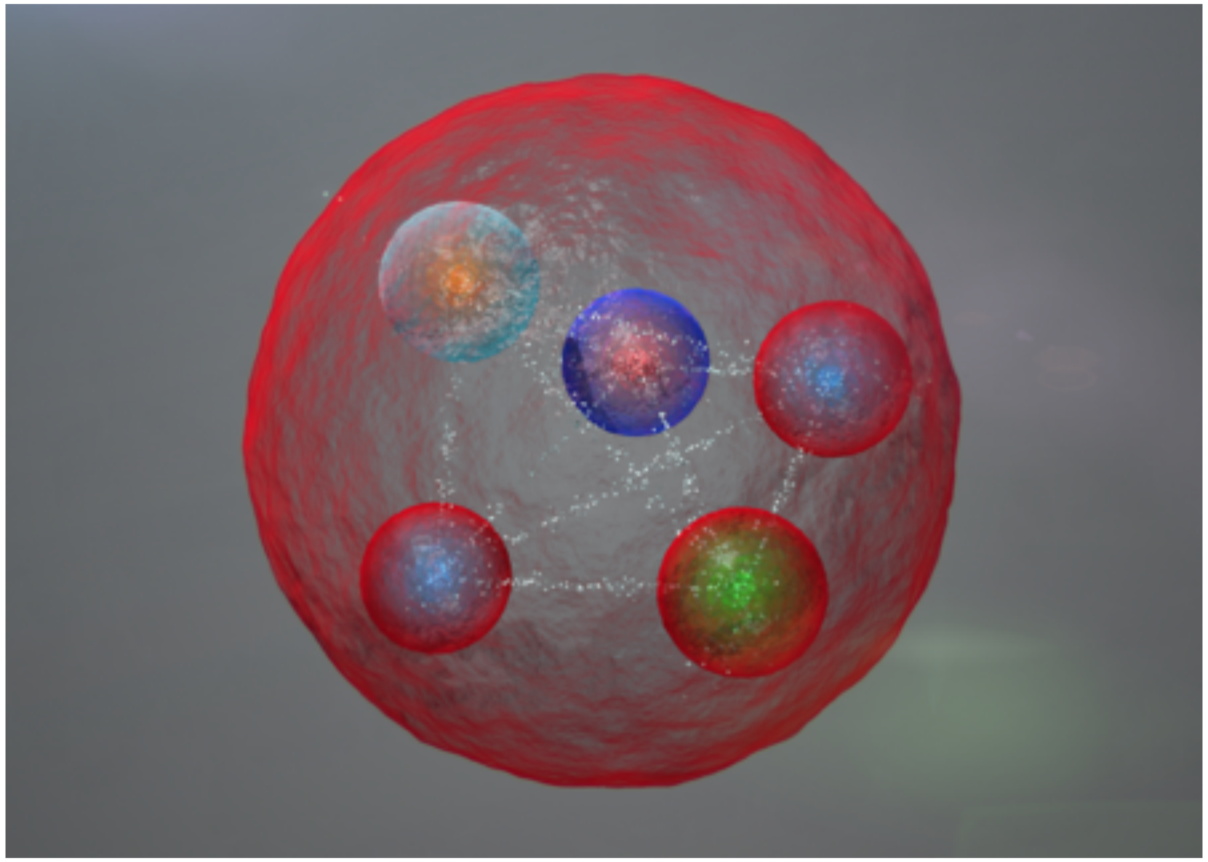


hybrids



molecules

non-$q\bar{q}$ & non-qqq color-singlet combinations

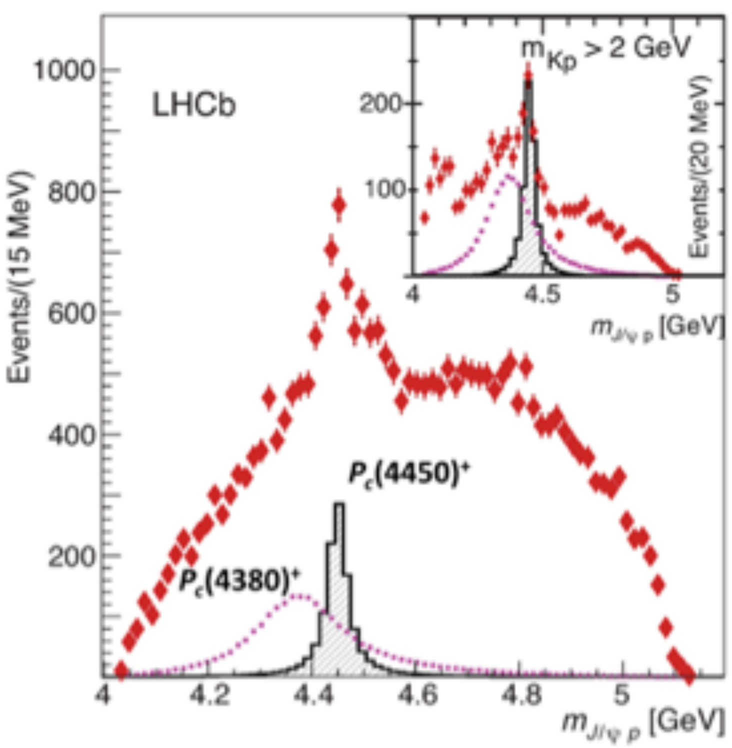


Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

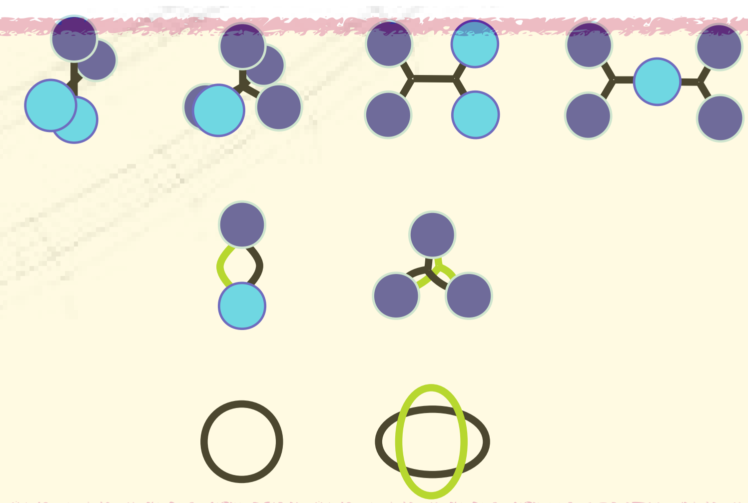
(Received 13 July 2015; published 12 August 2015)



Multi-quark states

Hybrids

Glueballs



QCD ALSO ALLOWS

Totalitarian principle: Everything not forbidden is compulsory

Theoretical approaches

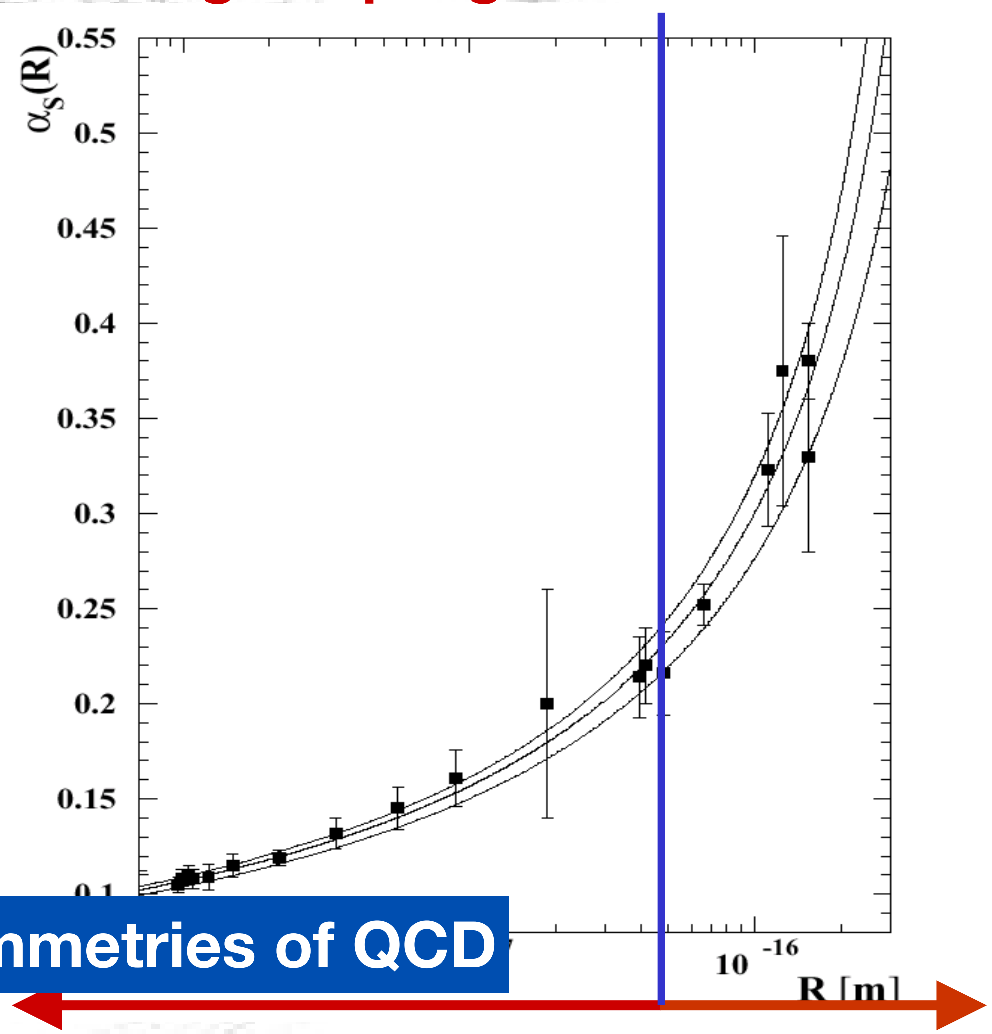
QCD is complex

- 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

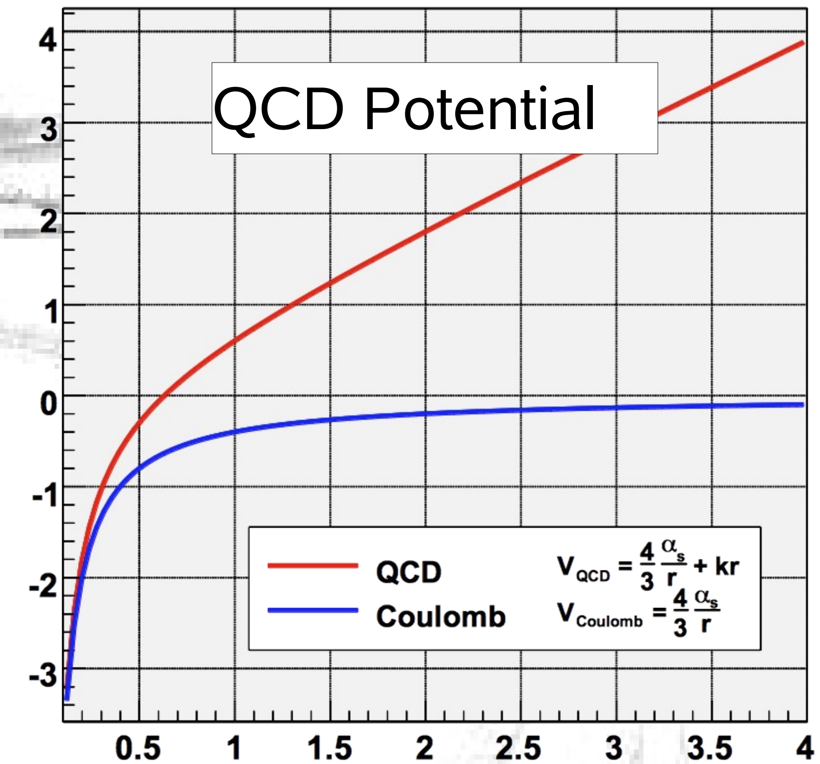
Asymptotic behaviour of QCD

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

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

- Region of asymptotic freedom (small r):

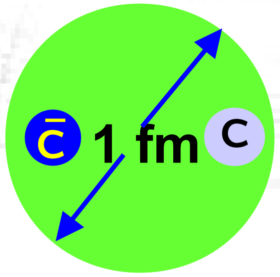
$$V_{QCD} \xrightarrow[r \to 0]{} \frac{4}{3}\frac{\alpha_s}{r} \quad \textbf{Coulomb-like}$$

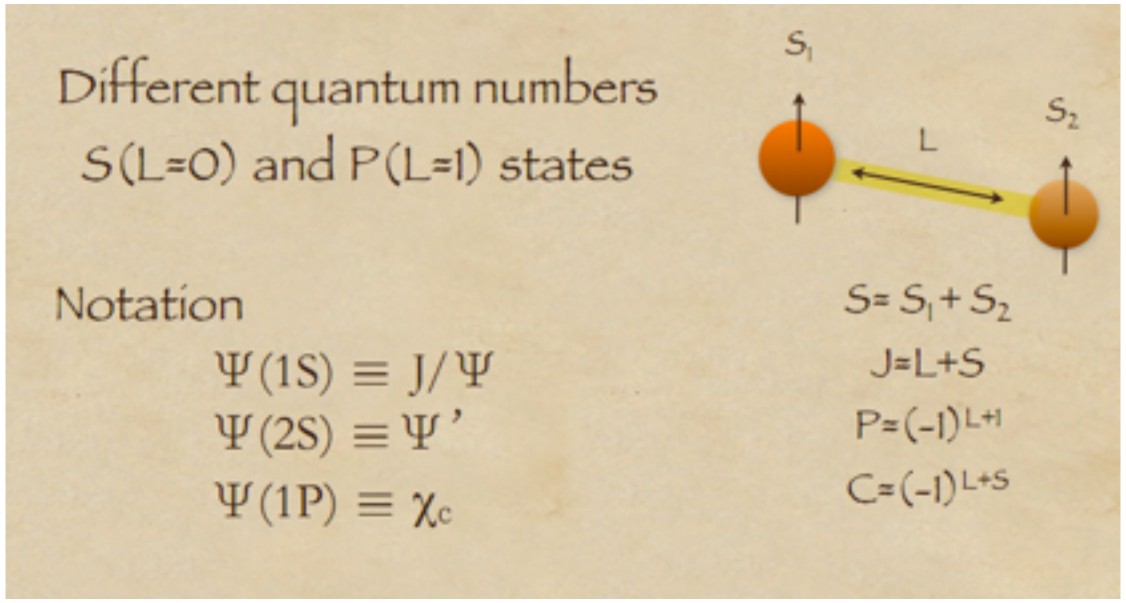


Bound states in QCD

- 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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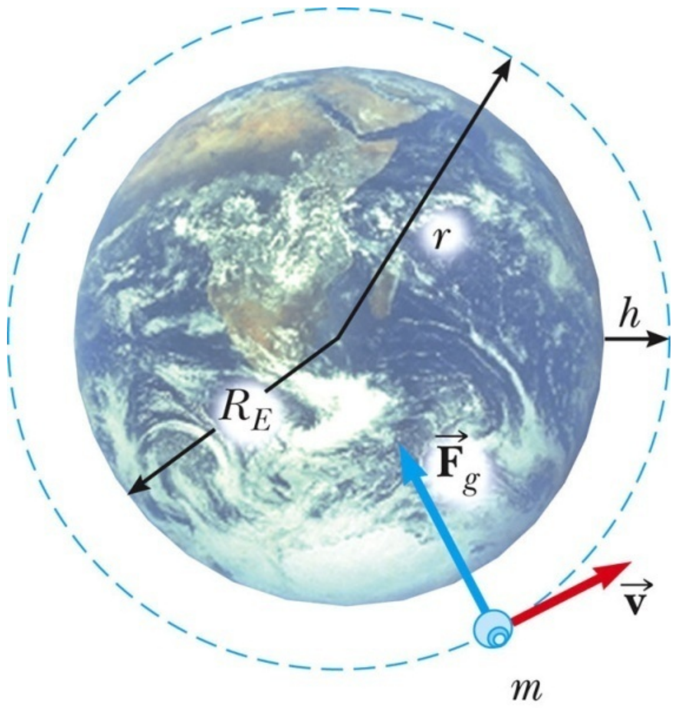
A CLASSICAL EXAMPLE

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

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



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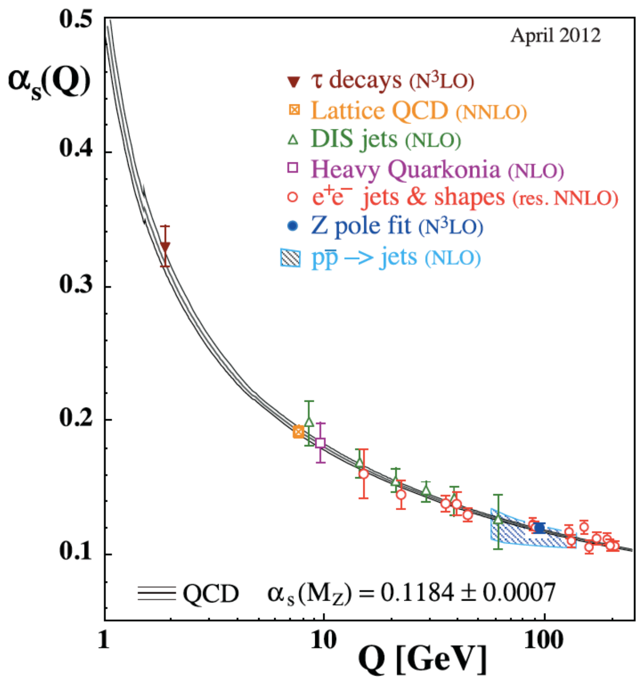
- Effective Theories are systematic expansion of QCD



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- High Energies ($Q \to \infty$):
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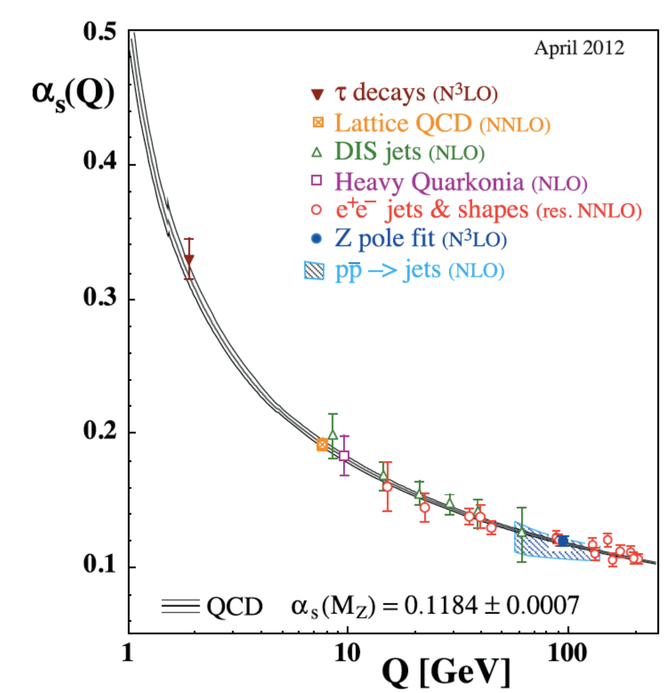
  $\to$ perturbative QCD, Expansion in $1/Q$



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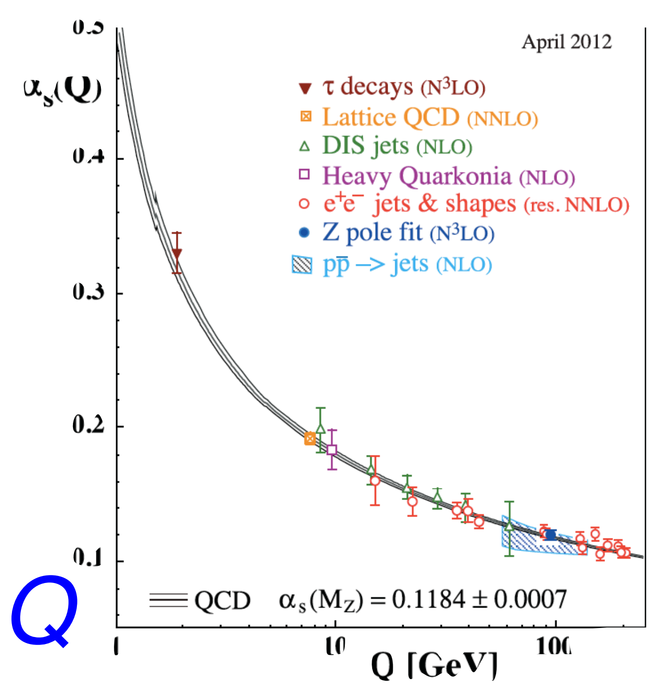
  Pions and Kaons are relevant
  $\to$ approximate symmetries, Expansion in Q



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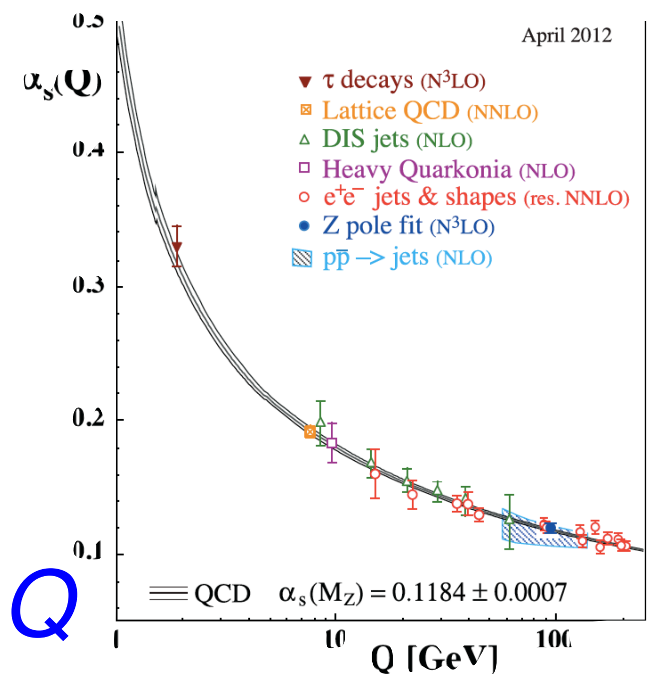


- Heavy Quarks ($m_Q \to \infty$):
  Light Quarks and Gluons are relevant
  $\to$ Use approximate symmetries, Expansion in $1/m_Q$

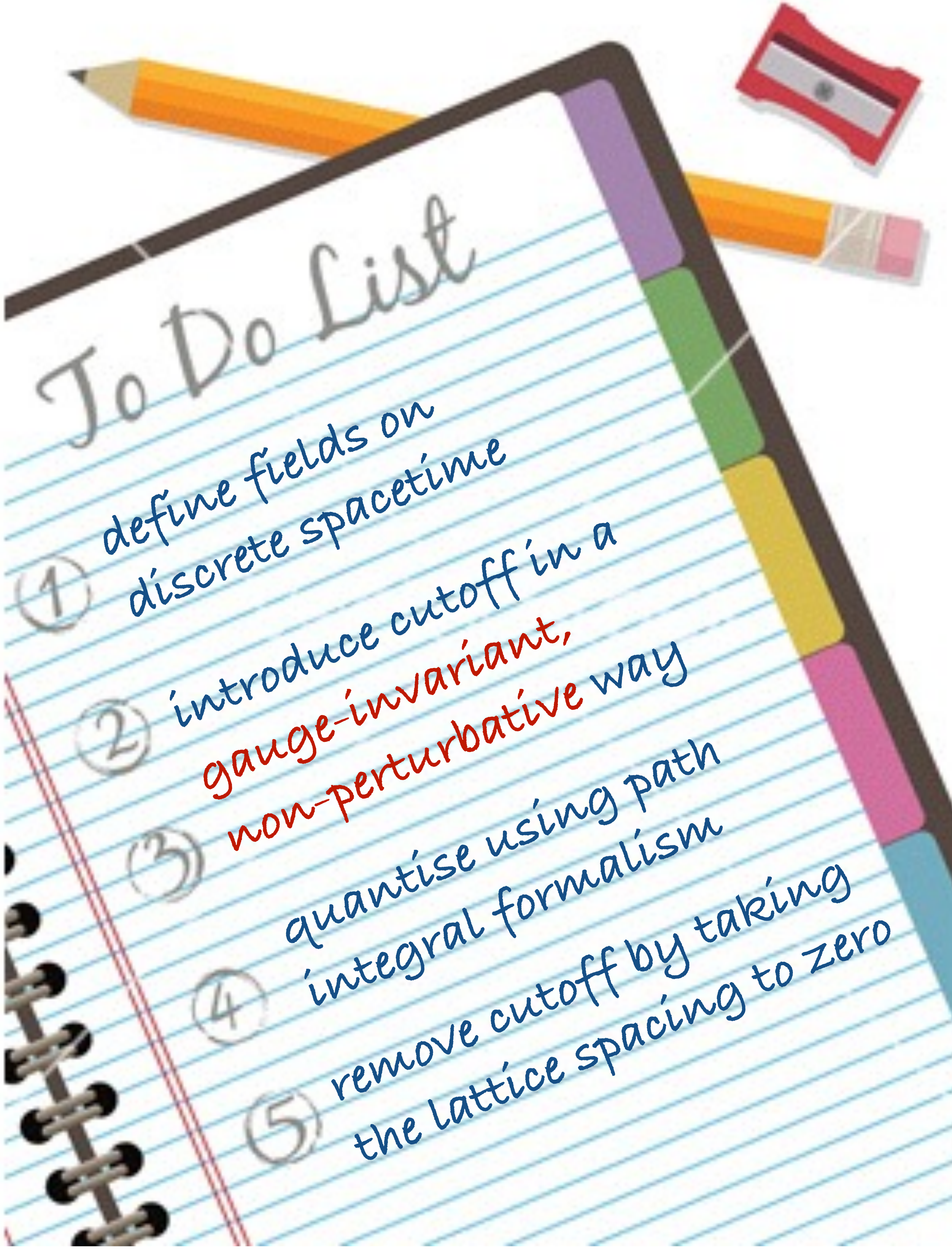
Lattice QCD

“Lattice field theory is the non-perturbative approach to QFT through **regularised** **Euclidean** **functional integrals**.

The regularisation is based on discretisation of the action which preserves **gauge invariance** at all stages”

H. Wittig, JGU, Mainz

Lattice QCD

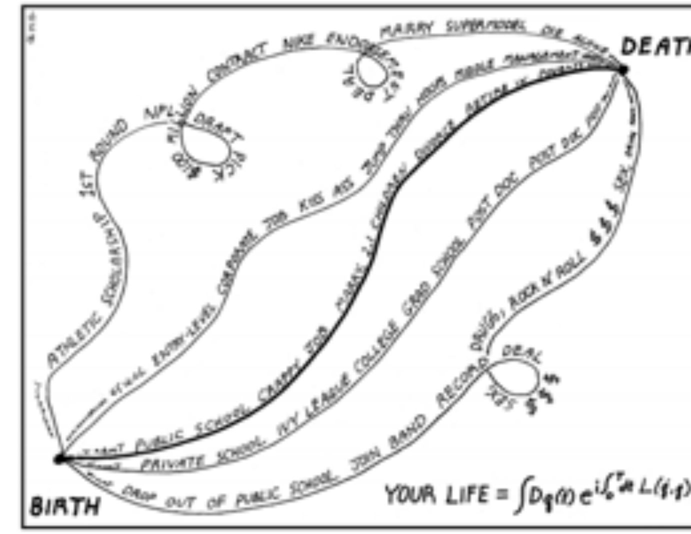


$$\mathcal{L}_{\mathrm{QCD}} = -\tfrac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \sum_f \overline{\psi}_f \left(i\gamma^\mu D_\mu - m_f \right) \psi_f,$$

$$D_\mu = \partial_\mu - ig(\tfrac{1}{2}\lambda^a) A^a_\mu$$

"Lattice field theory is the non-perturbative approach to QFT through **regularised Euclidean functional integrals**. The regularisation is based on discretisation of the action which preserves **gauge invariance** at all stages"

Path integrals and observables



Lattice formulation . . .

. . . preserves gauge invariance

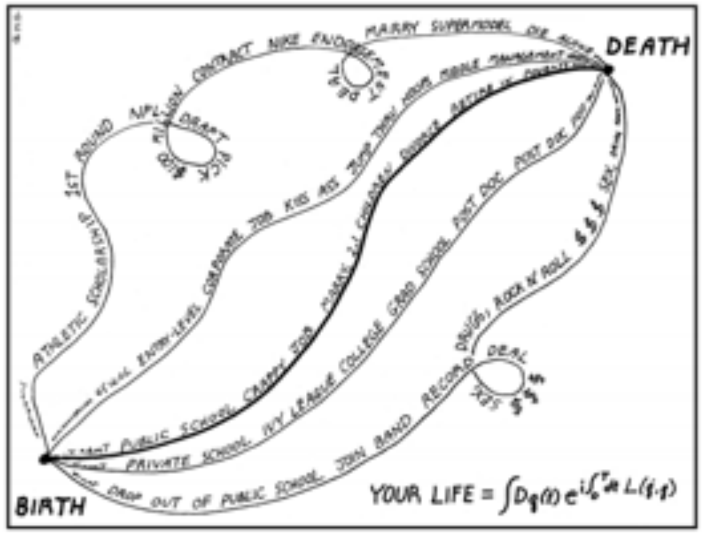
. . . defines observables without reference to perturbation theory

. . . allows for stochastic evaluation of observables

Expectation value:

$$\langle\Omega\rangle \quad = \quad \frac{1}{Z}\int D[U]D[\overline{\psi}]D[\psi]\,\Omega\,\mathrm{e}^{-S_\mathrm{G}[U]-S_\mathrm{F}[U,\overline{\psi},\psi]}$$

Path integrals and observables



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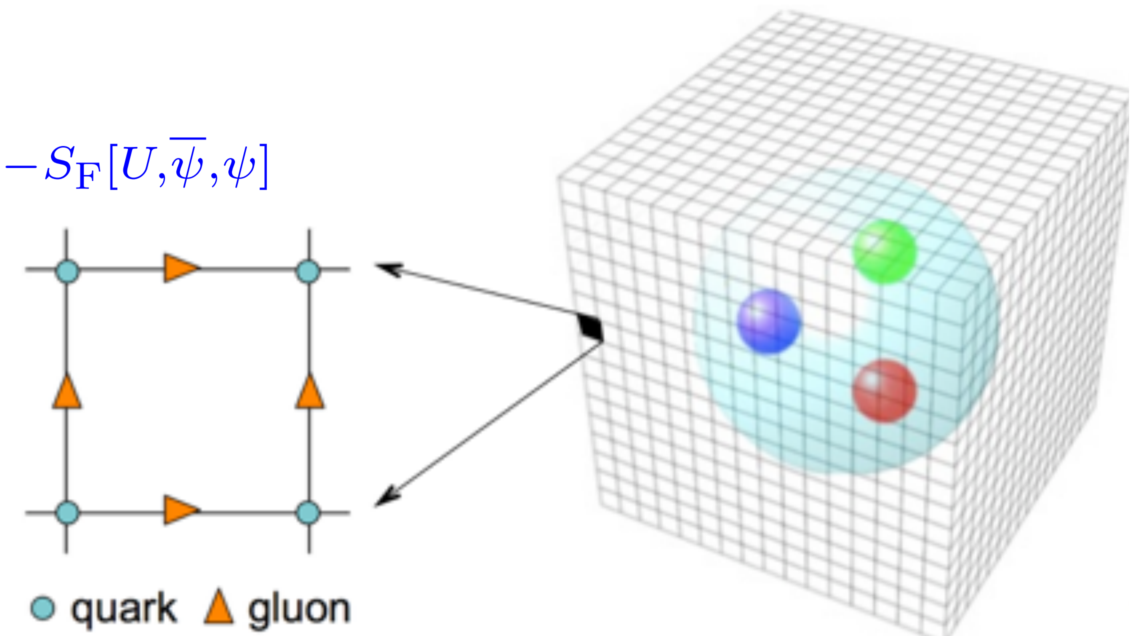


Lattice spacing: $a, \quad x_\mu = n_\mu a, \quad a^{-1} = \Lambda_{\mathrm{UV}}$

Finite volume: $L^3 \cdot T$

$$\langle\Omega\rangle = \frac{1}{Z}\int \prod_{x,\mu} dU_\mu(x)\,\Omega\,\prod_f \det\left(\not{D}^{\mathrm{lat}} + m_f\right)\,\mathrm{e}^{-S_{\mathrm{G}}[U]}$$

H. Wittig, JGU, Mainz

Monte Carlo Simulation

1. Generate set of N_c configurations of gauge fields $\{U_\mu(x)\}\,,\; i=1,\ldots,N_c$, with probability distribution

$$W = \prod_f \det\left(D_{\rm lat}+m_f\right)\, \mathrm{e}^{-S_{\rm G}[U]}$$

$\rightarrow$ "Importance sampling"

$\rightarrow$ Define an algorithm based on a Markov process:

Generate sequence $\quad \{U\}_1 \longrightarrow \{U\}_2 \longrightarrow \ldots \longrightarrow \{U\}_{N_c}$

Transition probability given by W

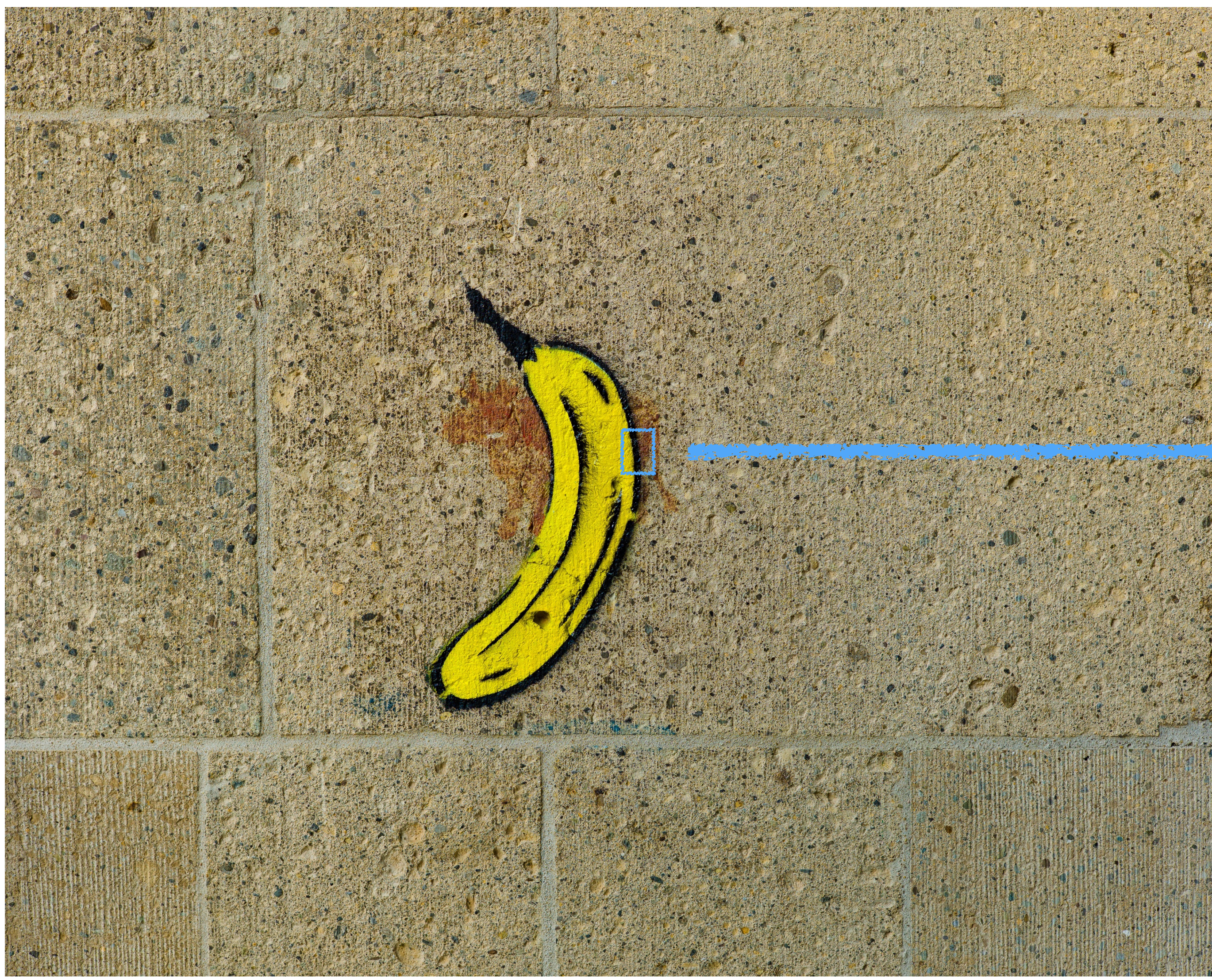
2. Evaluate observable for configuration i

$$\overline{\Omega} = \frac{1}{N_c}\sum_{i=1}^{N_c}\Omega_i, \quad \langle\Omega\rangle = \lim_{N_c\to\infty}\overline{\Omega}, \qquad \text{statistical error: } \propto 1/\sqrt{N_c}$$

Systematic effects

- Lattice artefacts: $$\left\langle \frac{m_N}{f_\pi} \right\rangle^{\text{lat}} = \left\langle \frac{m_N}{f_\pi} \right\rangle^{\text{cont}} + O(a^p), \quad p \geq 1$$

$\longrightarrow$ extrapolate to continuum limit from $a \approx 0.05 - 0.12\,\text{fm}$



H. Wittig, JGU, Mainz

Systematic effects

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$a \to 0$

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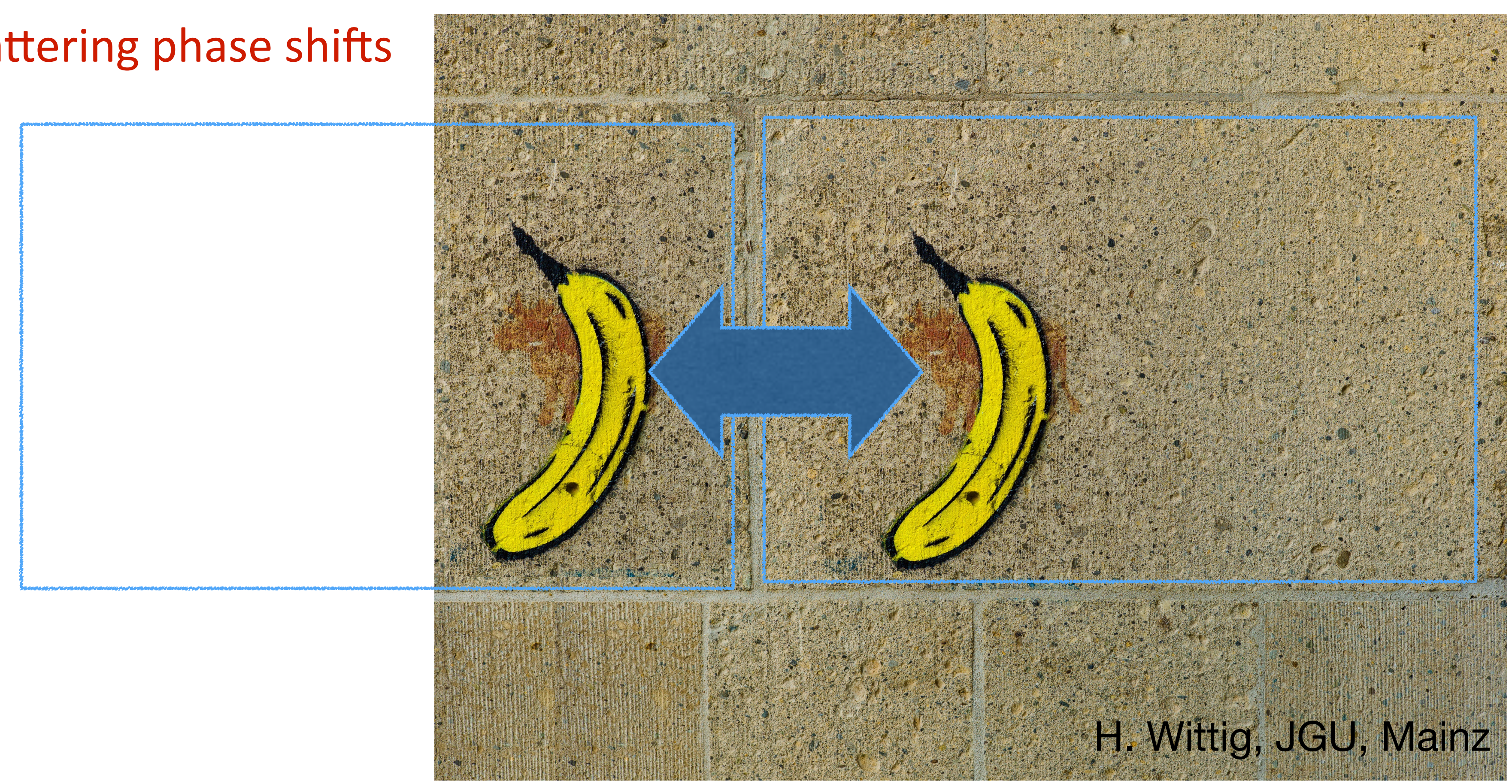
❖ Finite volume effects

- Empirically: $m_\pi L \geq 4$ sufficient for many purposes
- Could be more severe for multi-baryon systems
- Provide information on scattering phase shifts



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❖ Finite volume effects

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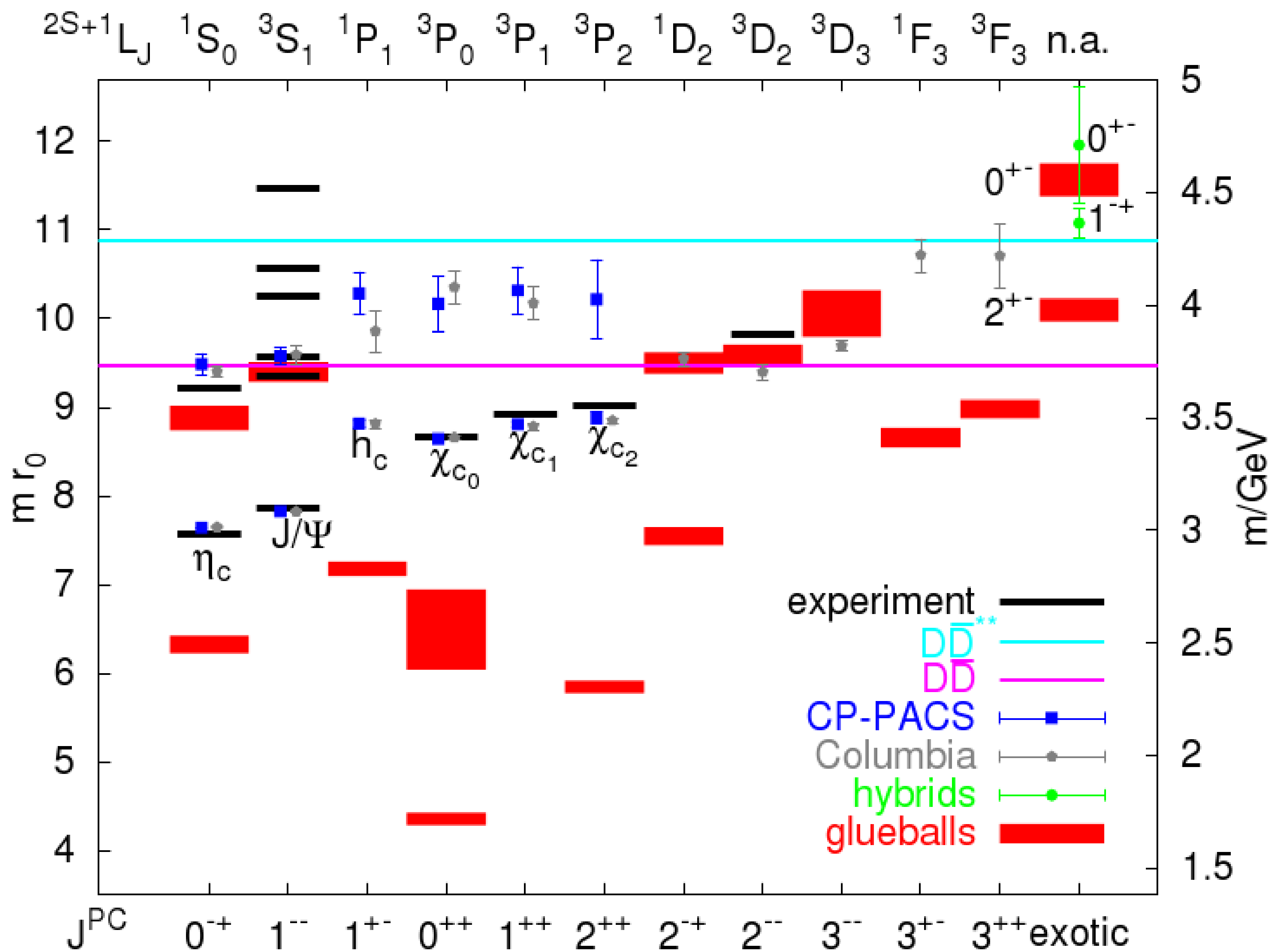
- Could be more severe for multi-baryon systems
- Provide information on scattering phase shifts

❖ Unphysical quark masses

- Chiral extrapolation to physical values of m_u, m_d becomes obsolete

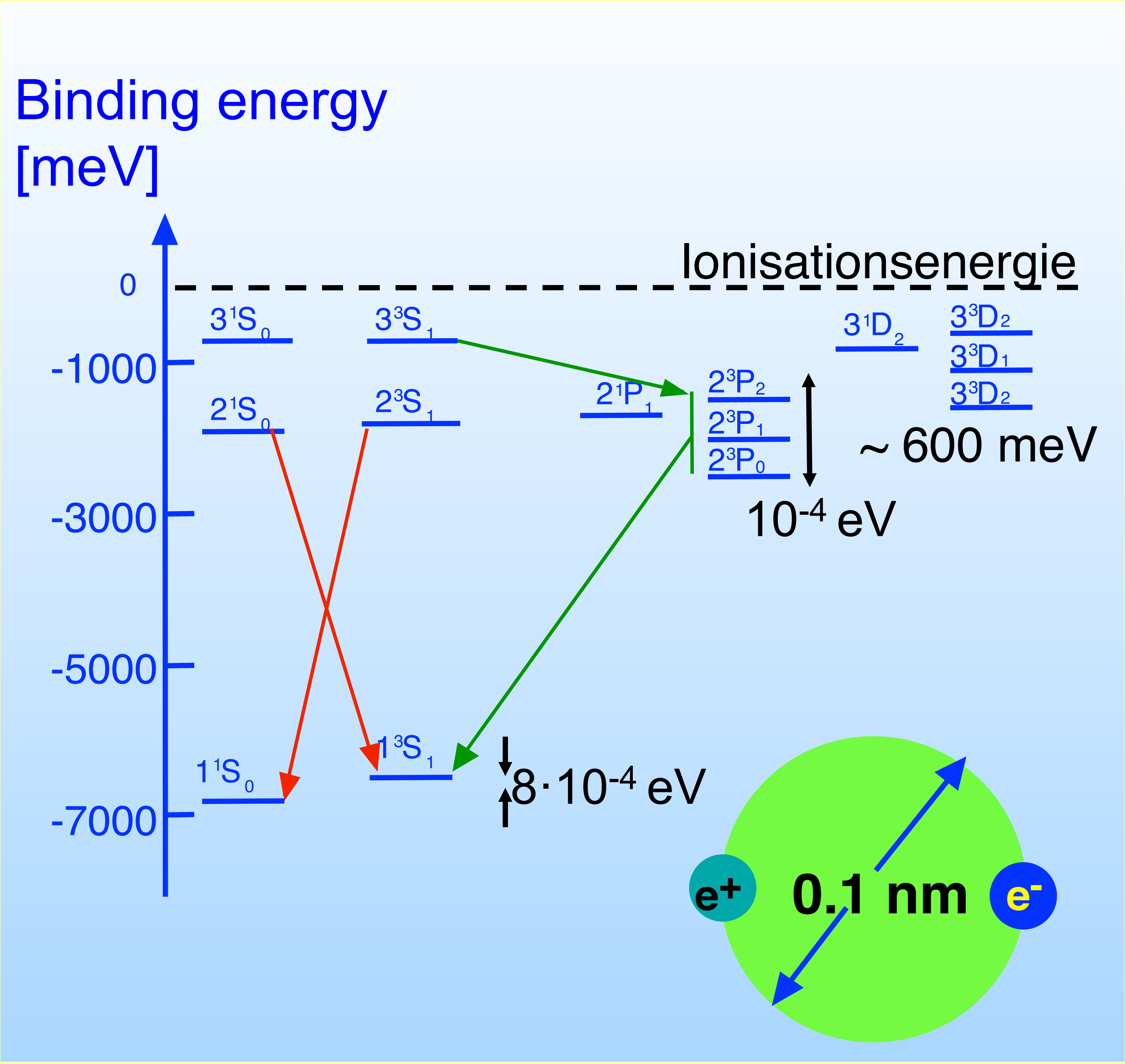
Charmonium



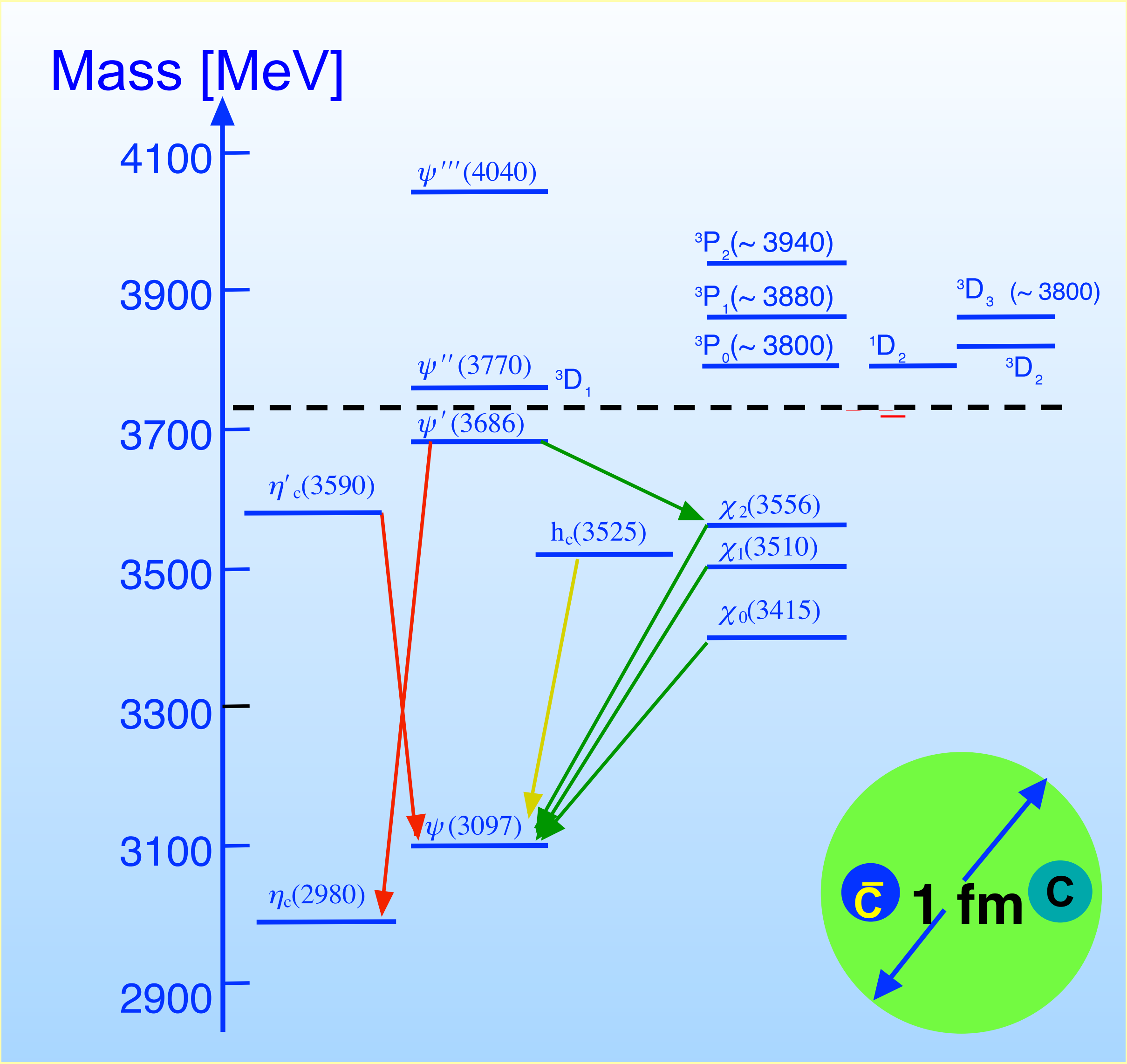
$^{2S+1}L_J$ $^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_3$ n.a.
m r_0
m/GeV
η_c
J/Ψ
h_c
χ_{c_0}
χ_{c_1}
χ_{c_2}
0^{+-}
1^{-+}
2^{+-}
experiment
$D\bar{D}^{**}$
$D\bar{D}$
CP-PACS
Columbia
hybrids
glueballs
J^{PC} 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 2^{--} 3^{--} 3^{+-} 3^{++} exotic

...the positronium of QCD

Positronium



Charmonium



Aims

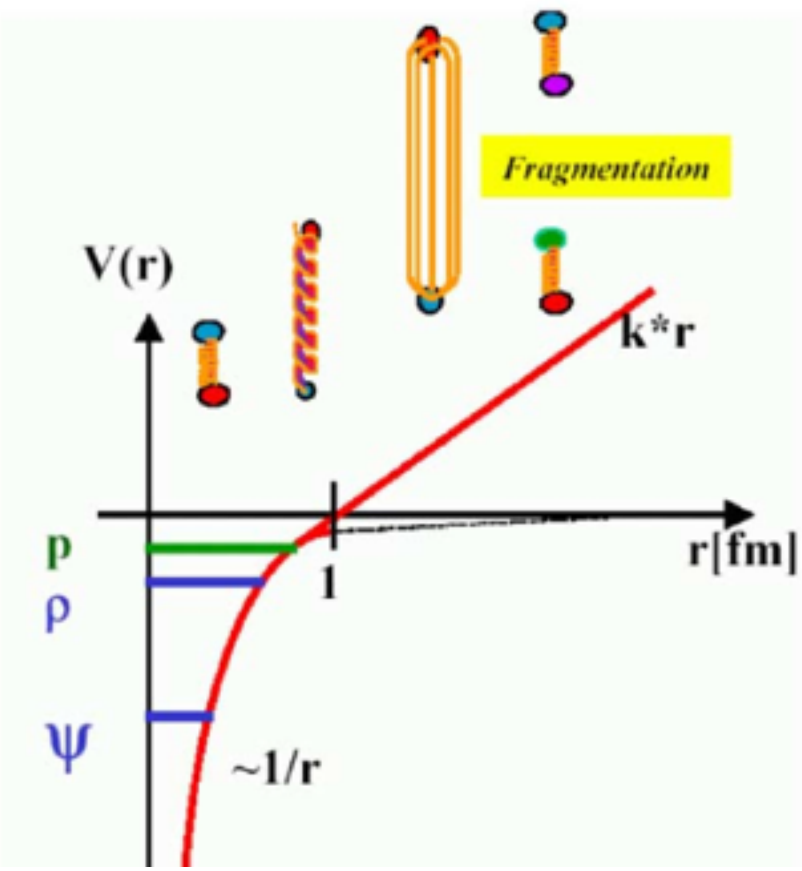
- Analogous to known two-particle bound systems (ie: hydrogen, positronium)
- Charmonium potential models (phenomenological):
  - non-relativistic (charm quarks are “heavy” compared to binding energy)
  - strong force potential via one gluon exchange (similar to Coulomb force)
  - quark confinement (increases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

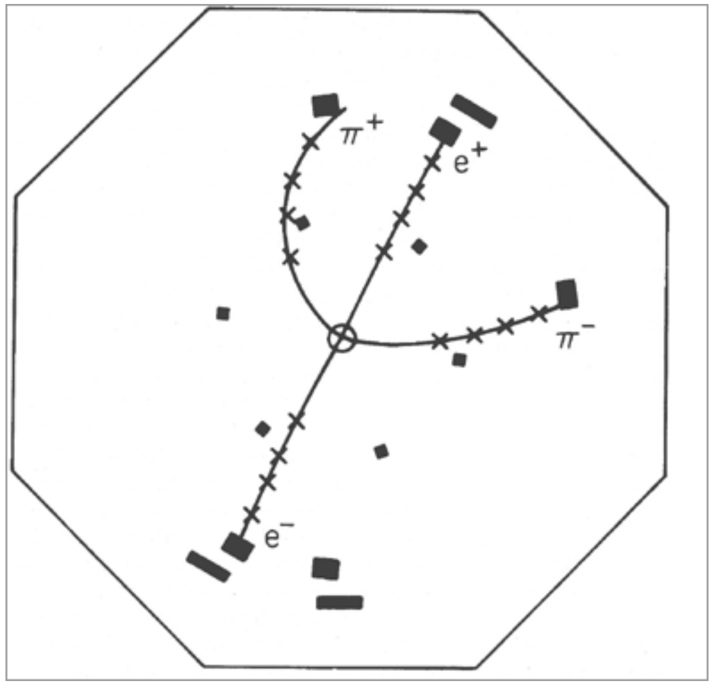
Theory: Calculation of spectra
- Knowing interaction allows prediction
- Tuning accounting for experimental data

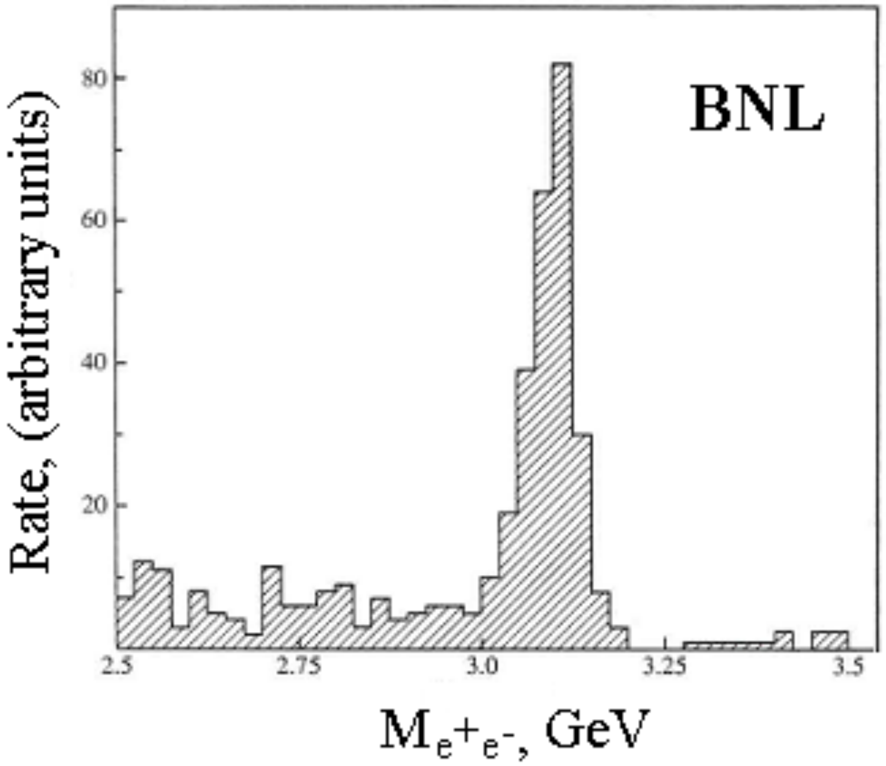
Final aim: Understand composition and dynamics of matter
- In QCD we are still far away from precision of QED

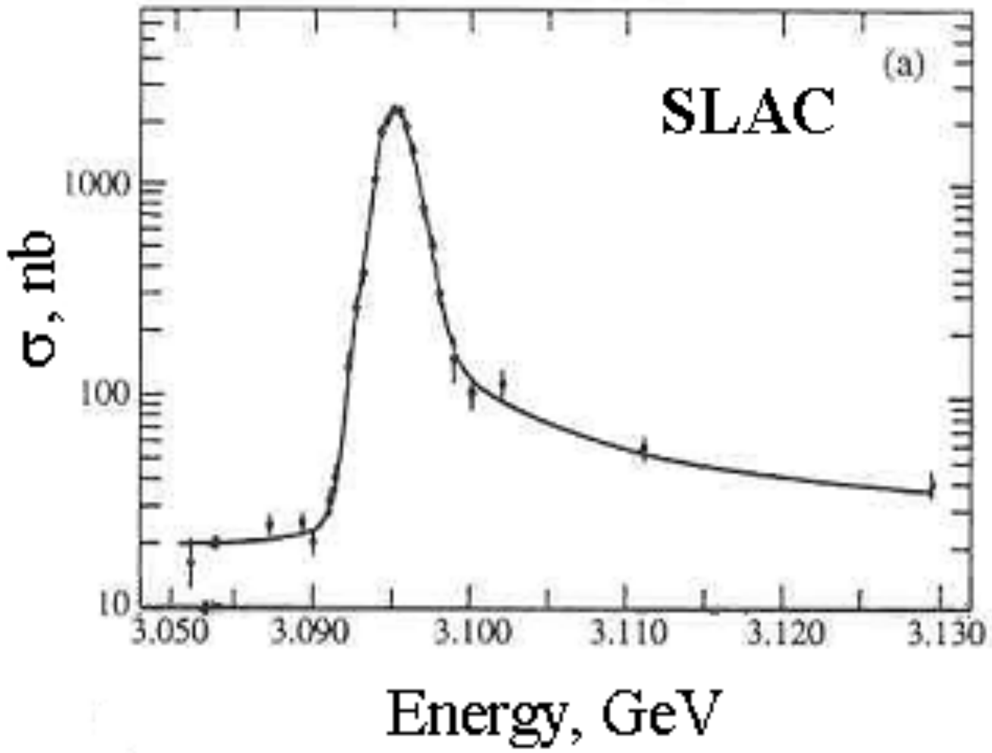


…in the beginning

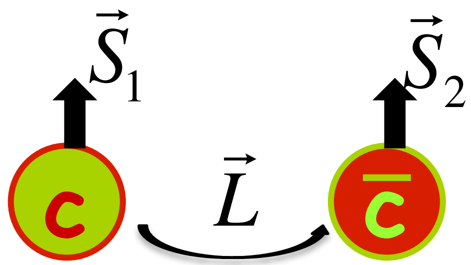
- November Revolution: simultaneous (SLAC/BNL) discovery of the J/ψ in 1974
- Bound state of c-cbar quarks: "charmonium"
- First evidence of the charm quark
  - Strong confirmation of the quark model
- Discovery of $\psi(2S) \rightarrow J/\psi(e^+e^-)\ \pi^+\pi^-$ soon followed







The *ABC's* of Charmonium



J^{PC} quantum numbers

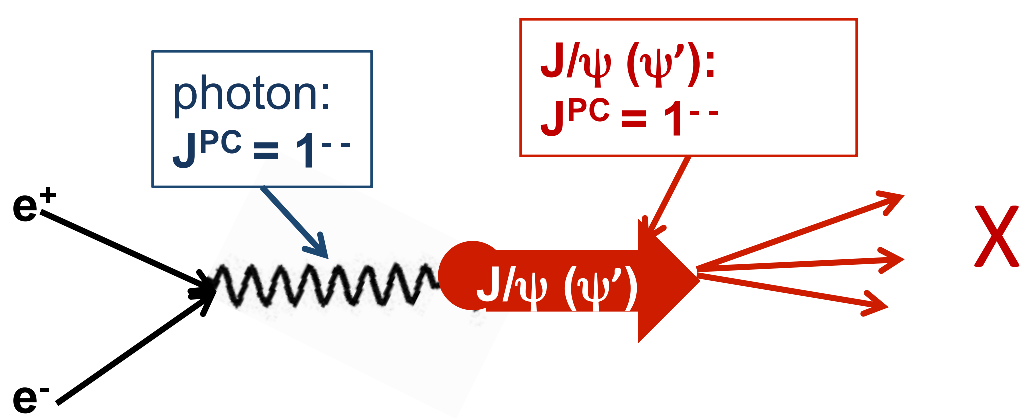
$$\vec{S} = \vec{S}_1 + \vec{S}_2$$

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

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



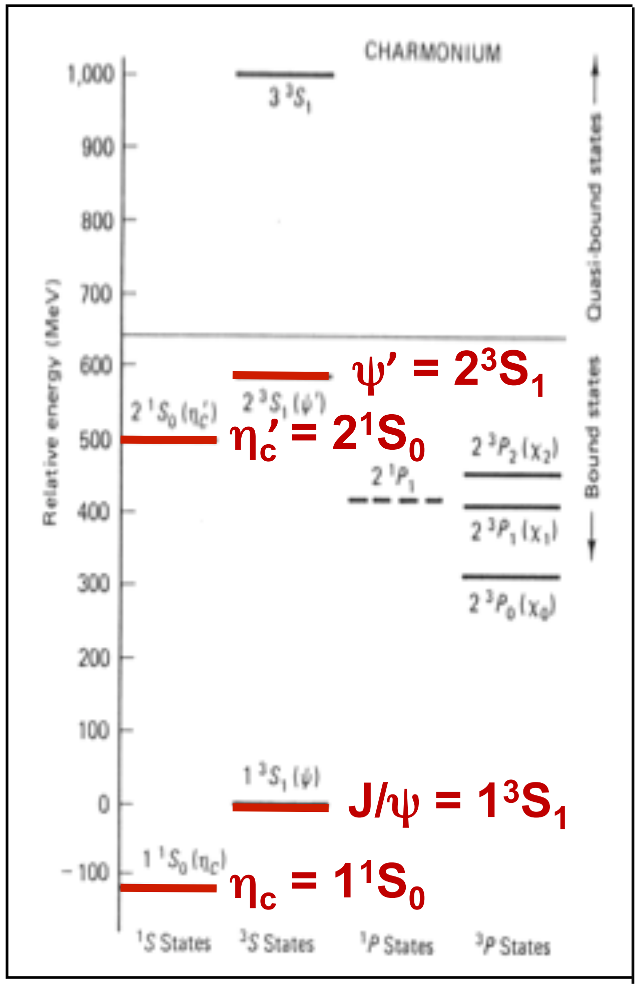
S= spin (0 or 1)

J= total ang. mom.

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

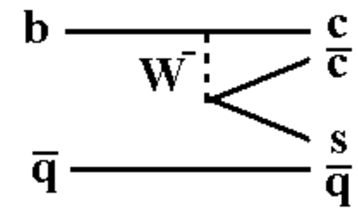
n=radial quant. nmbr

L= S, P, D, F, …
0, 1, 2, 3, …



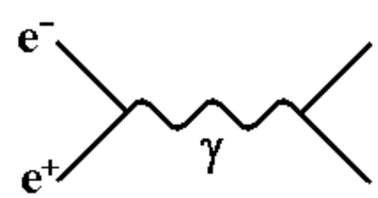
Production

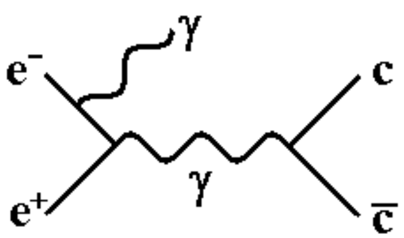
- Colour-suppressed b→c decay
  - Predominantly from B-meson decays



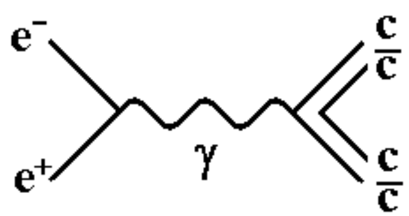
BELLE

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



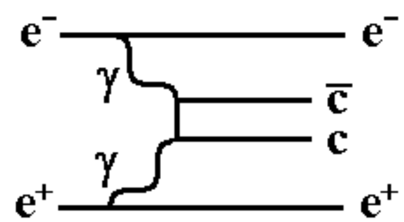


- Double charmonium production
  - Typically one J/ψ or ψ, plus second ccbar state



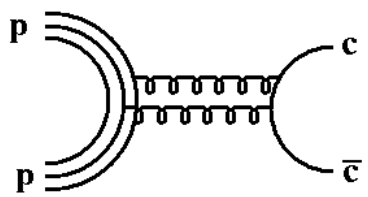
BESIII

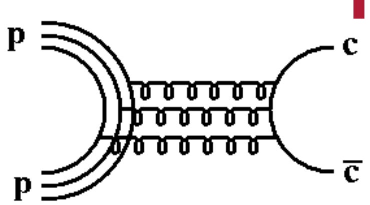
- Two-photon production
  - Access to C = +1 states



PANDA

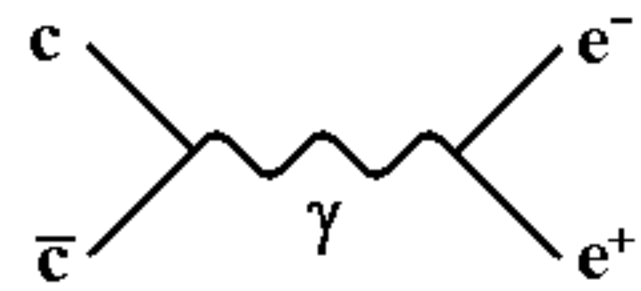
- pp annihilation
  - All quantum numbers available



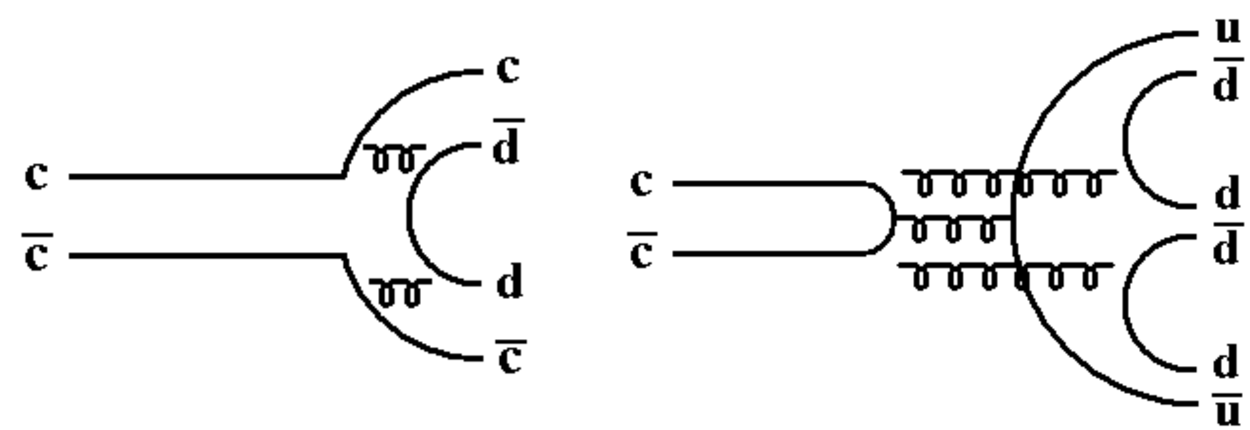


…and decay

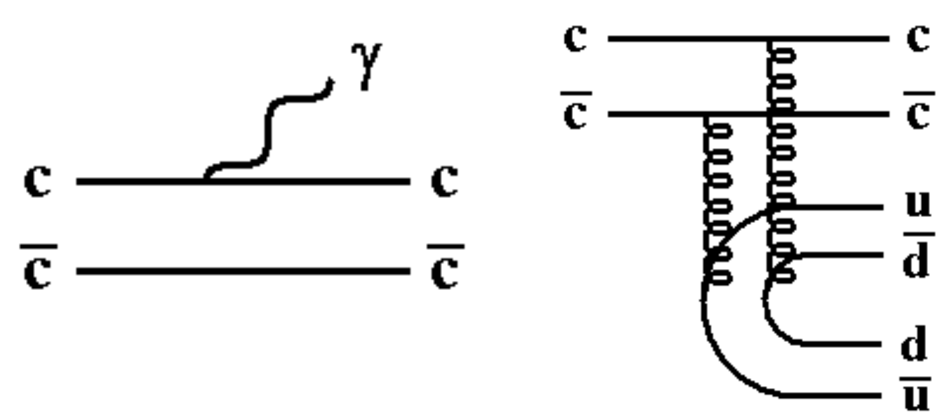
- Annihilation:
  - Generally suppressed for bound state
  - Decay to leptons is a clean experimental signal



- 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



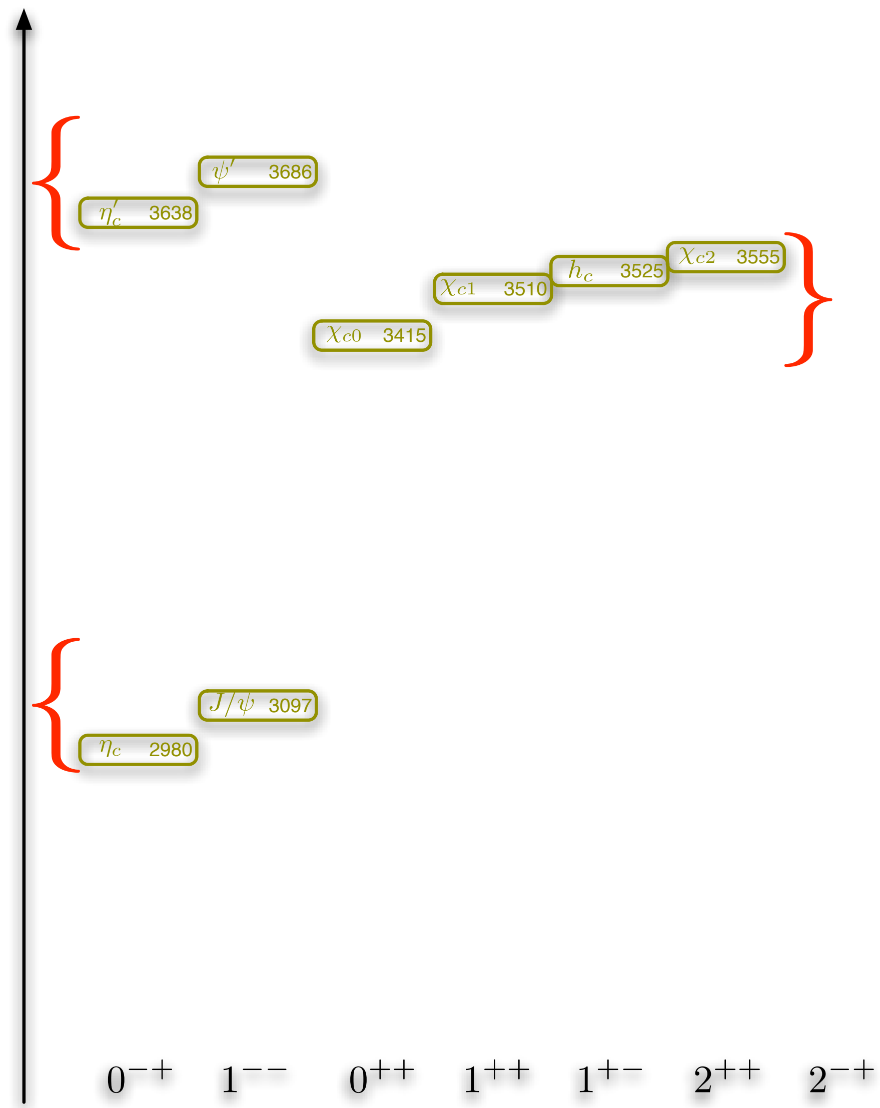
- Features:
  - Suppression of strong decays leads to (relatively) long lifetimes, narrow widths
  - Radiative decays are competitive; often most accessible transitions

The easy case

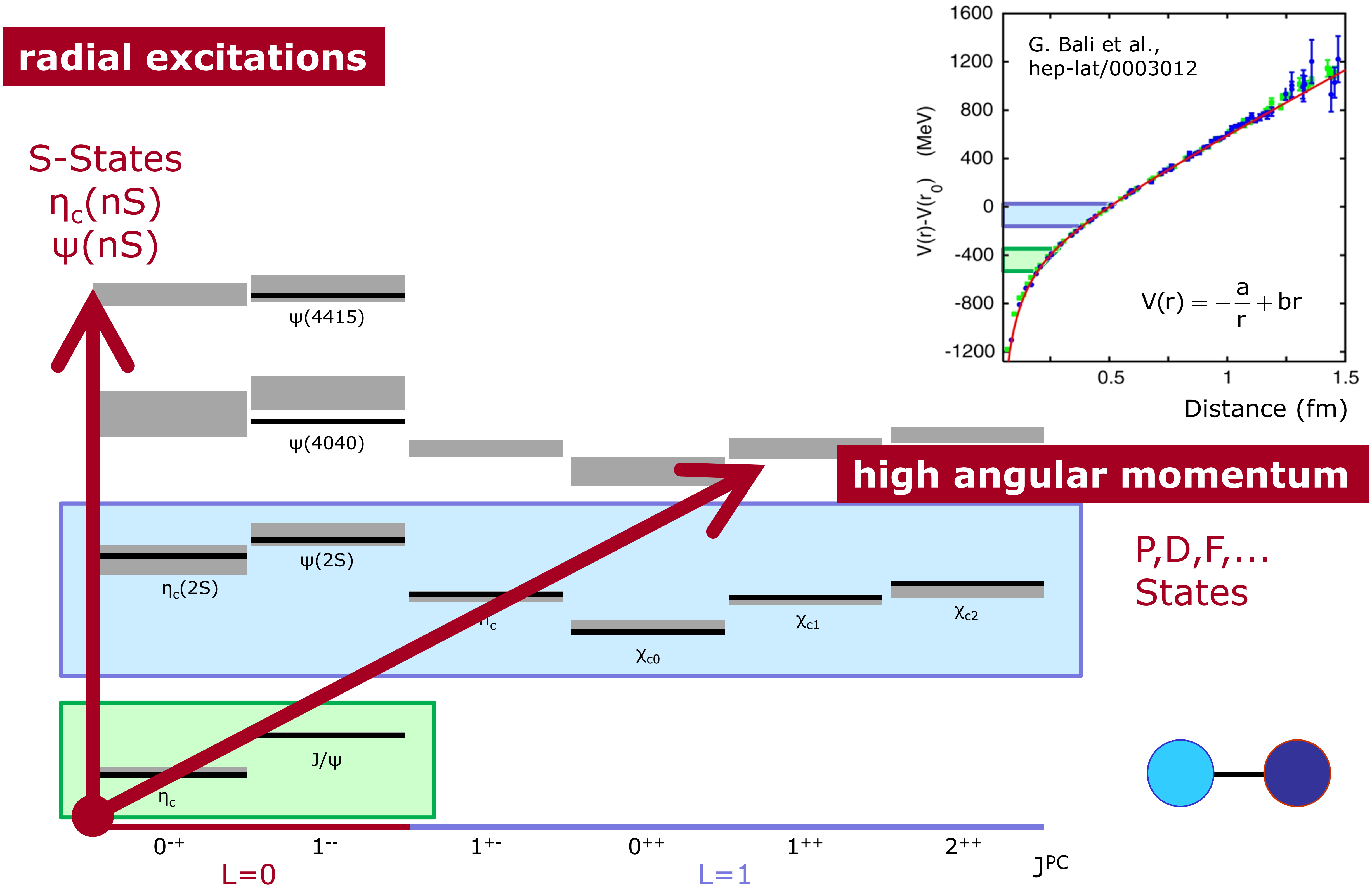
- one set of hadrons that are particularly simple are the charmonium mesons
  - each box represents an observed particle
  - particles fall in groups - ‘gross structure’
  - splitting within a group - ‘fine structure’
  - reminds us of quantum mechanics of atoms
  - a reasonable description of the spectrum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

$$m_n = 2m_c + E_n$$

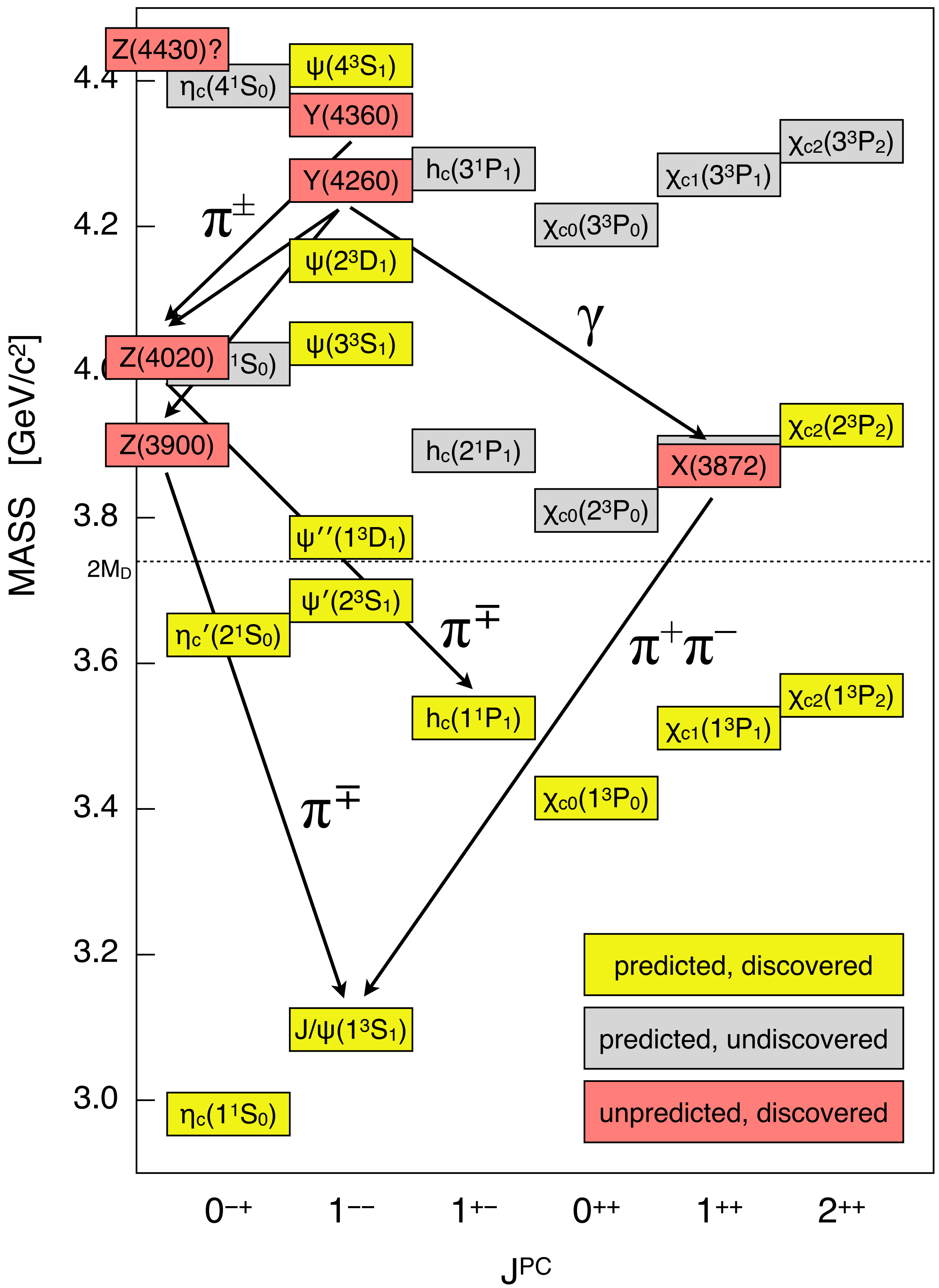
$$-\frac{1}{m_c}\nabla^2\psi + V(r)\psi = E_n\psi$$



The easy case



New Charmonium States



(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.

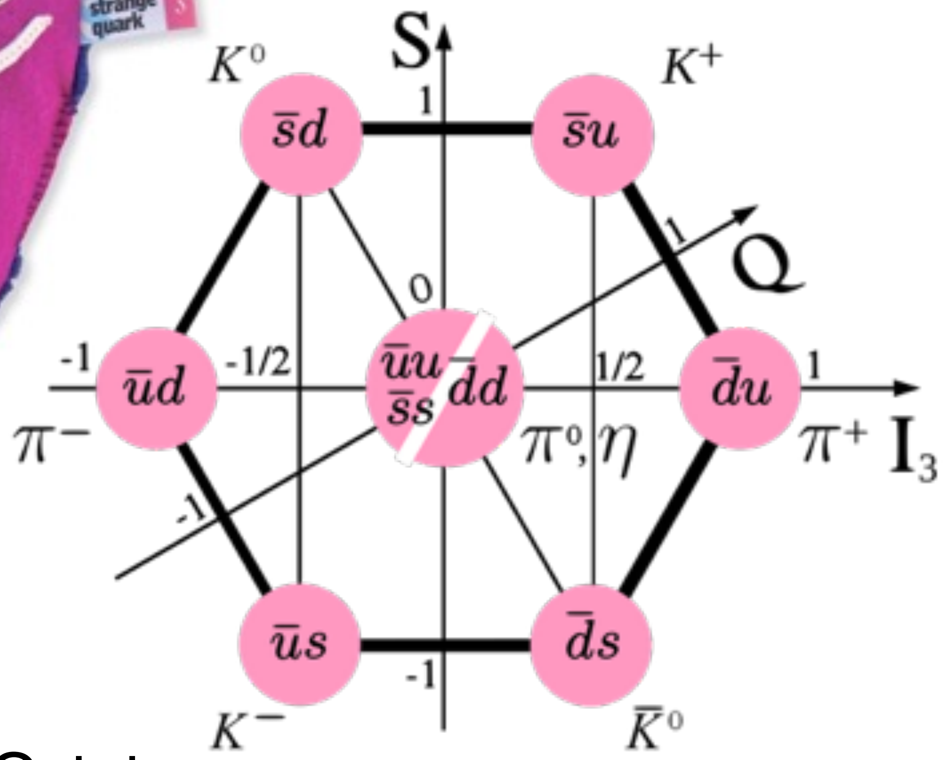
(IV) BESIII has observed "charged charmoniumlike structures" — the **Z_c(3900)** and the **Z_c'(4020)**.

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

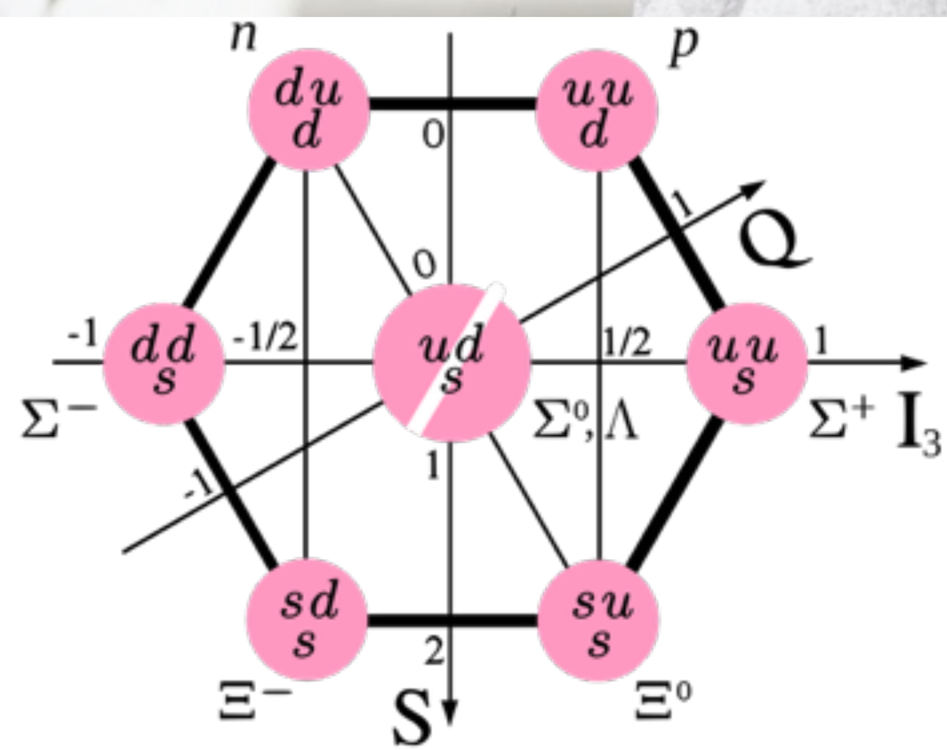
(VI) We are building connections.

R. Mitchell Bormio 2014

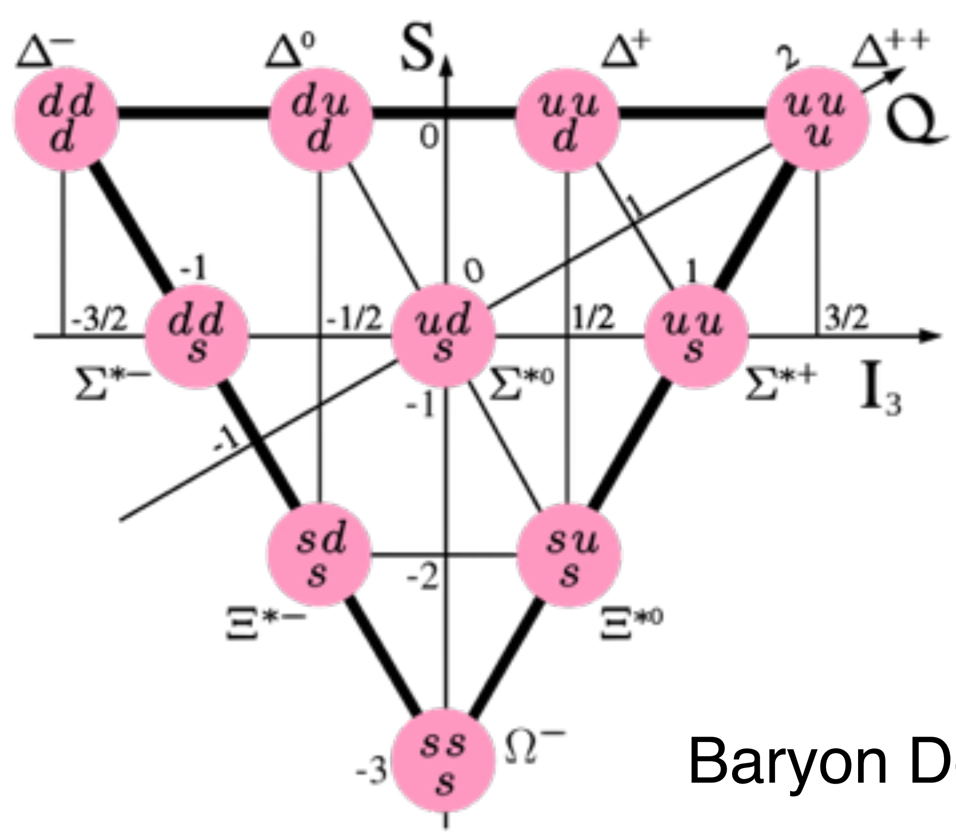
Strange Hadrons



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

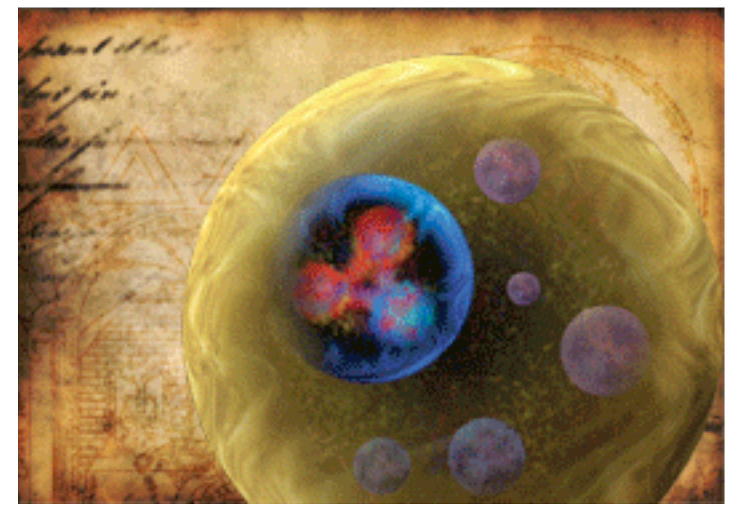
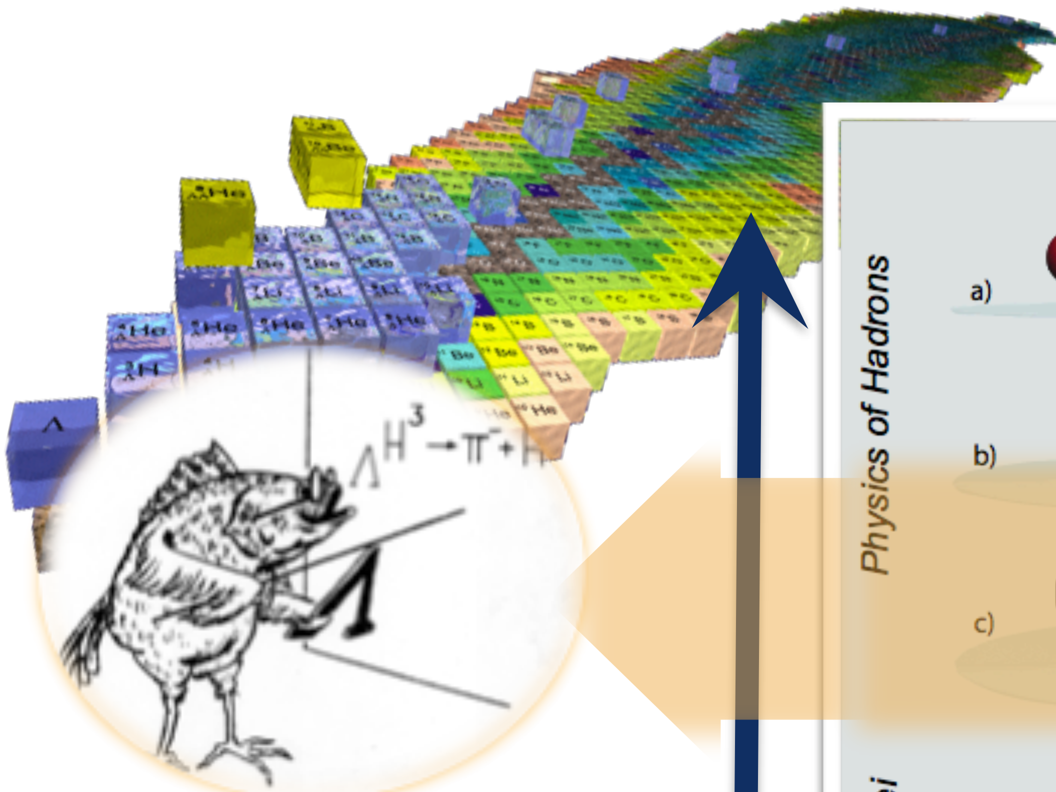


Image courtesy: Jefferson lab

or Boil and compress nuclear matter

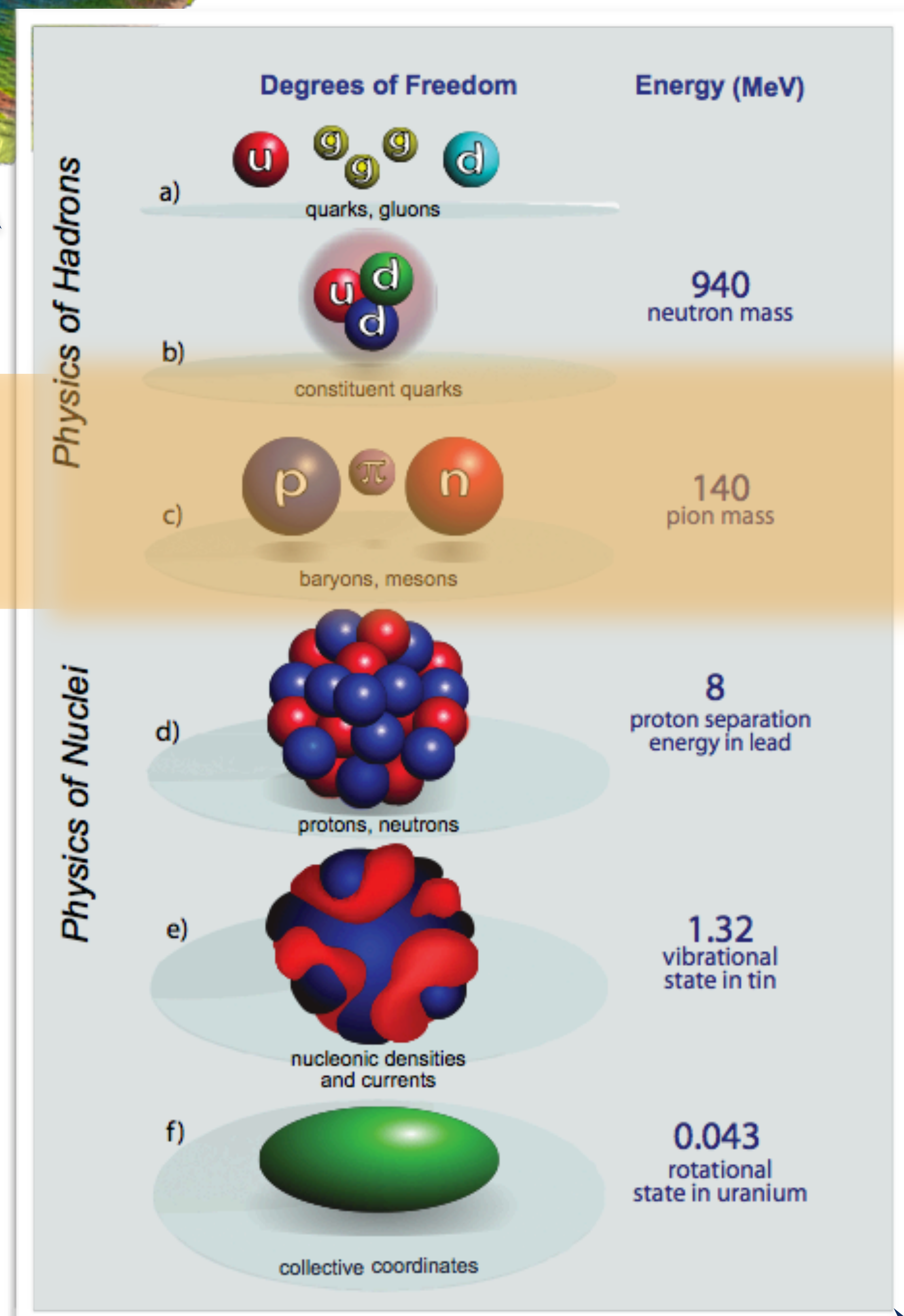
THE STRANGE NUCLEAR REALM



"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

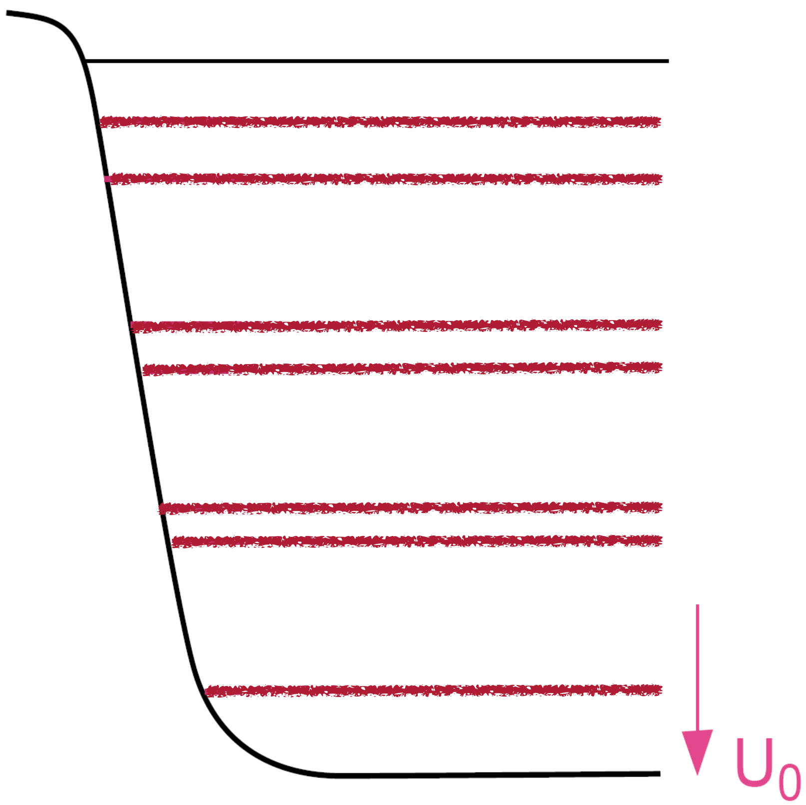
Complexity

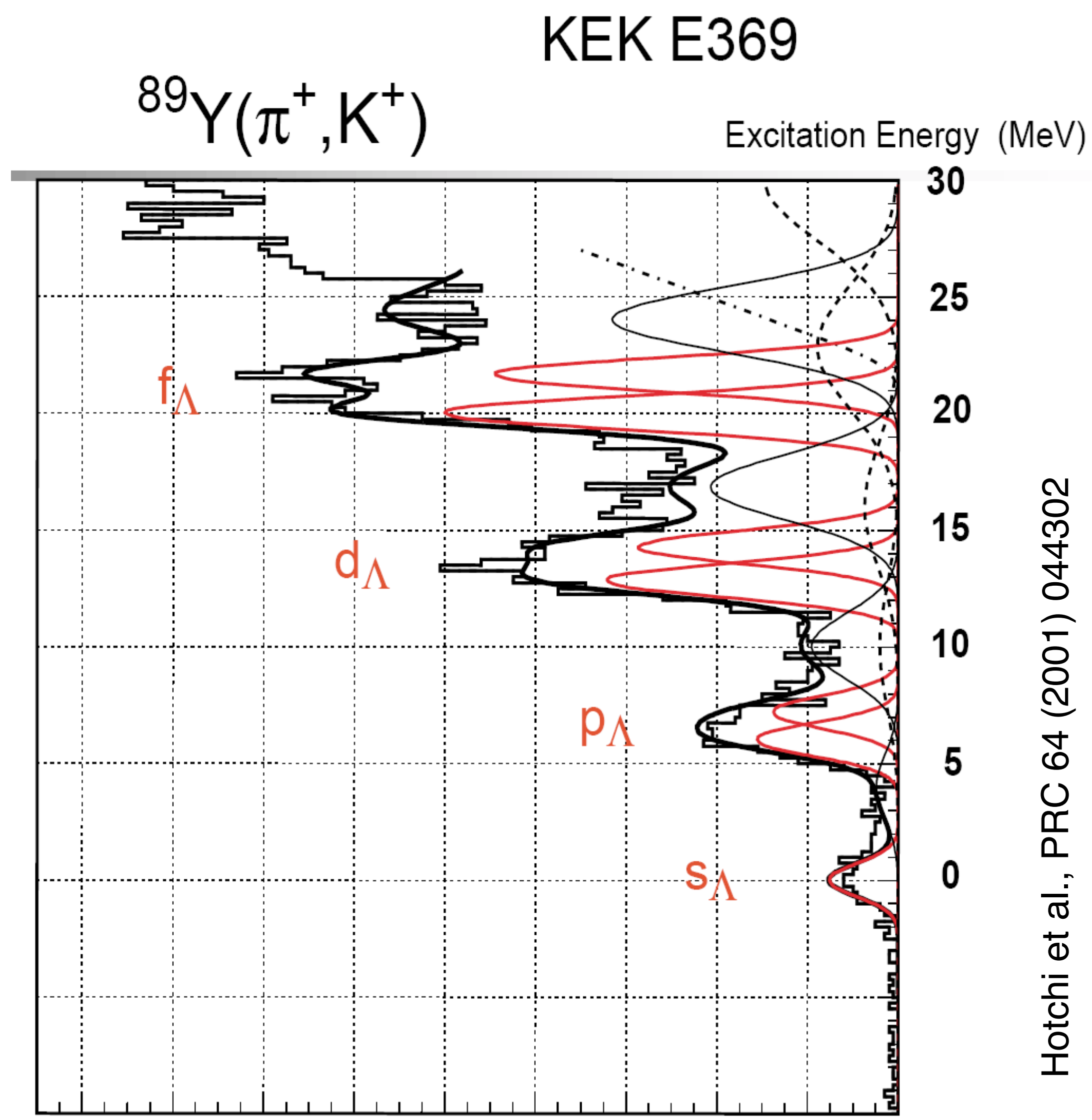
Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked





Hotchi et al., PRC 64 (2001) 044302

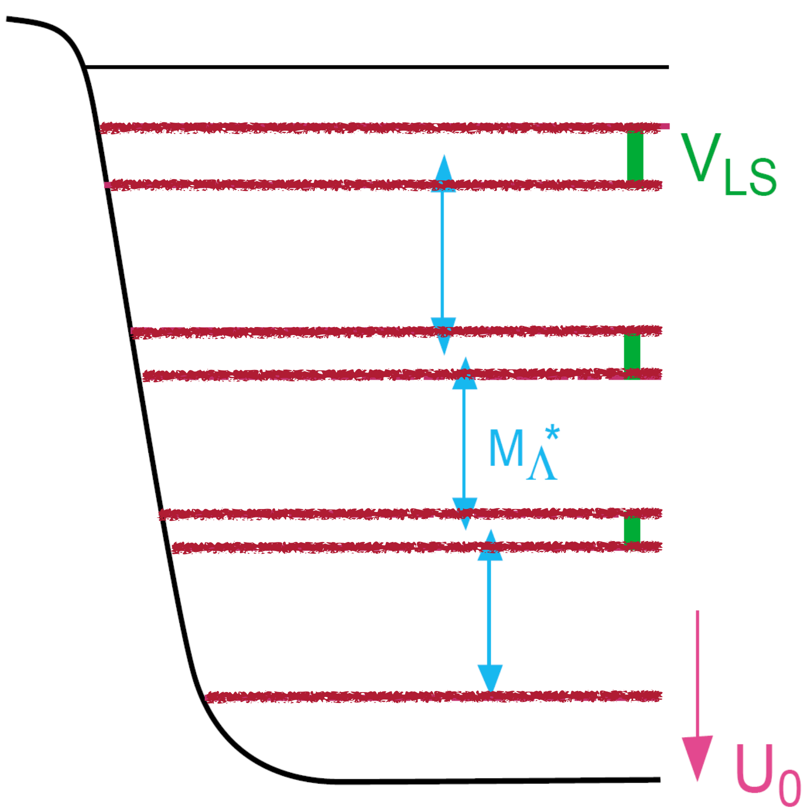
. Tagged Nuclear Physics

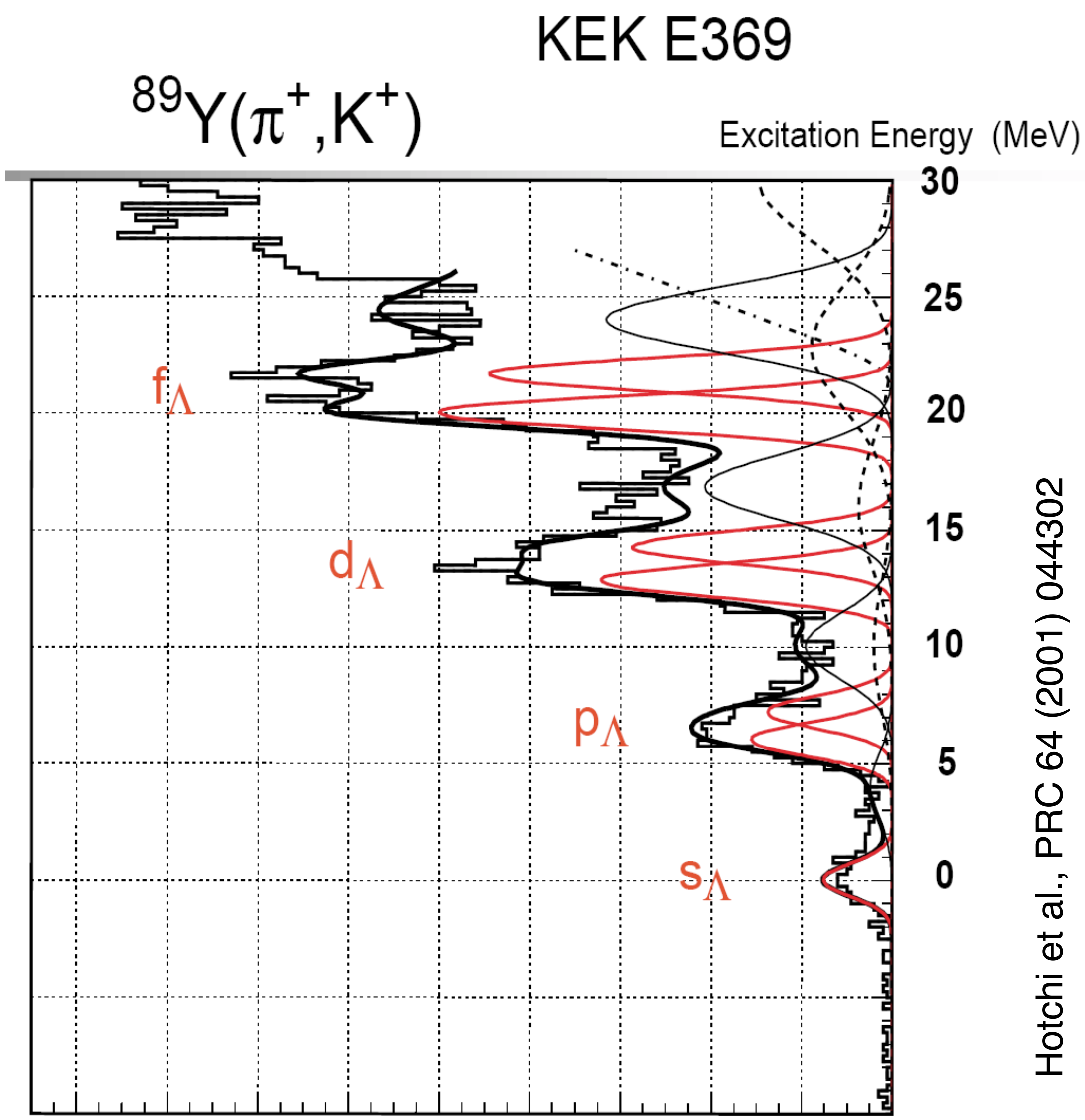
0 Higher Density

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

❷ Requires the knowledge of YN, YY, …





Strangeness Nuclear Physics

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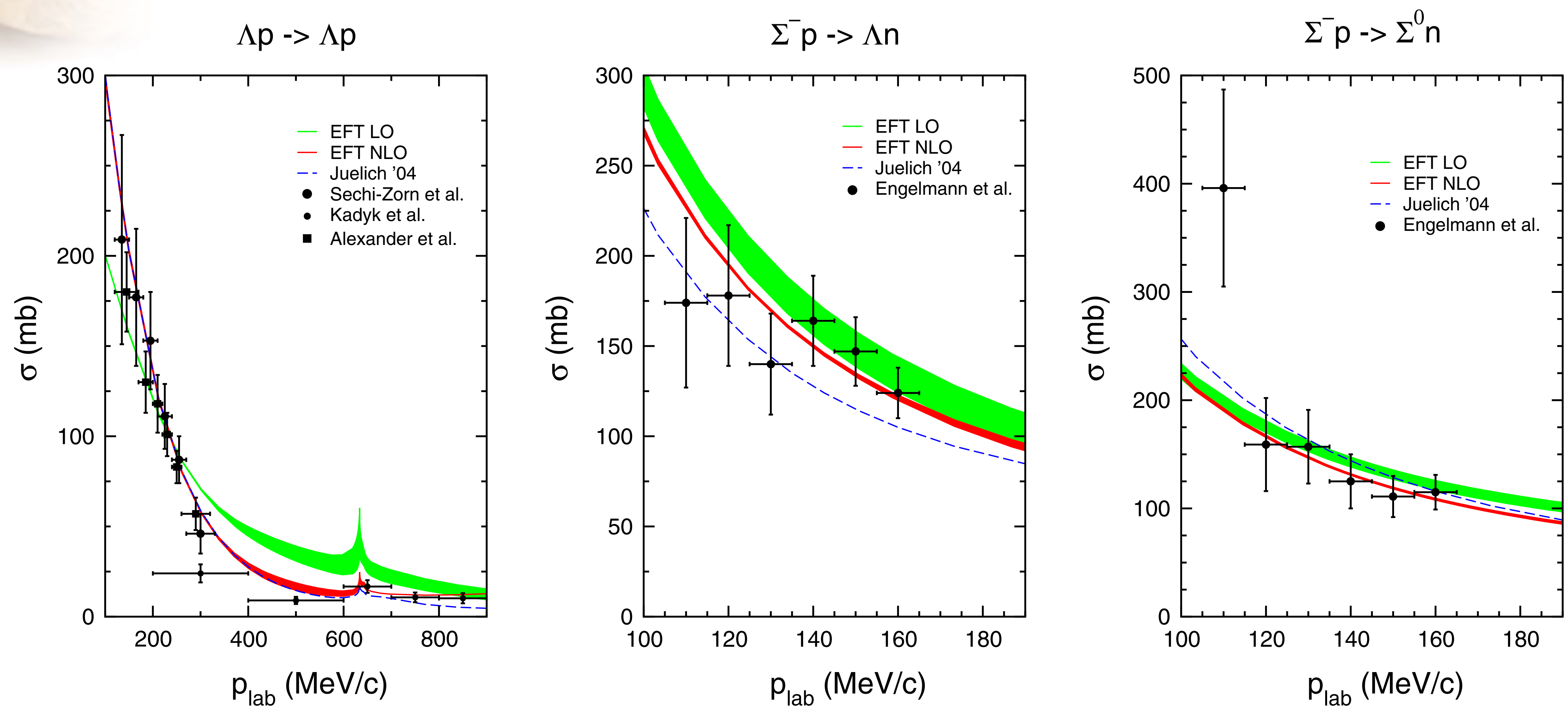


J. Haidenbauer Few Body Systems (2012)

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, ...

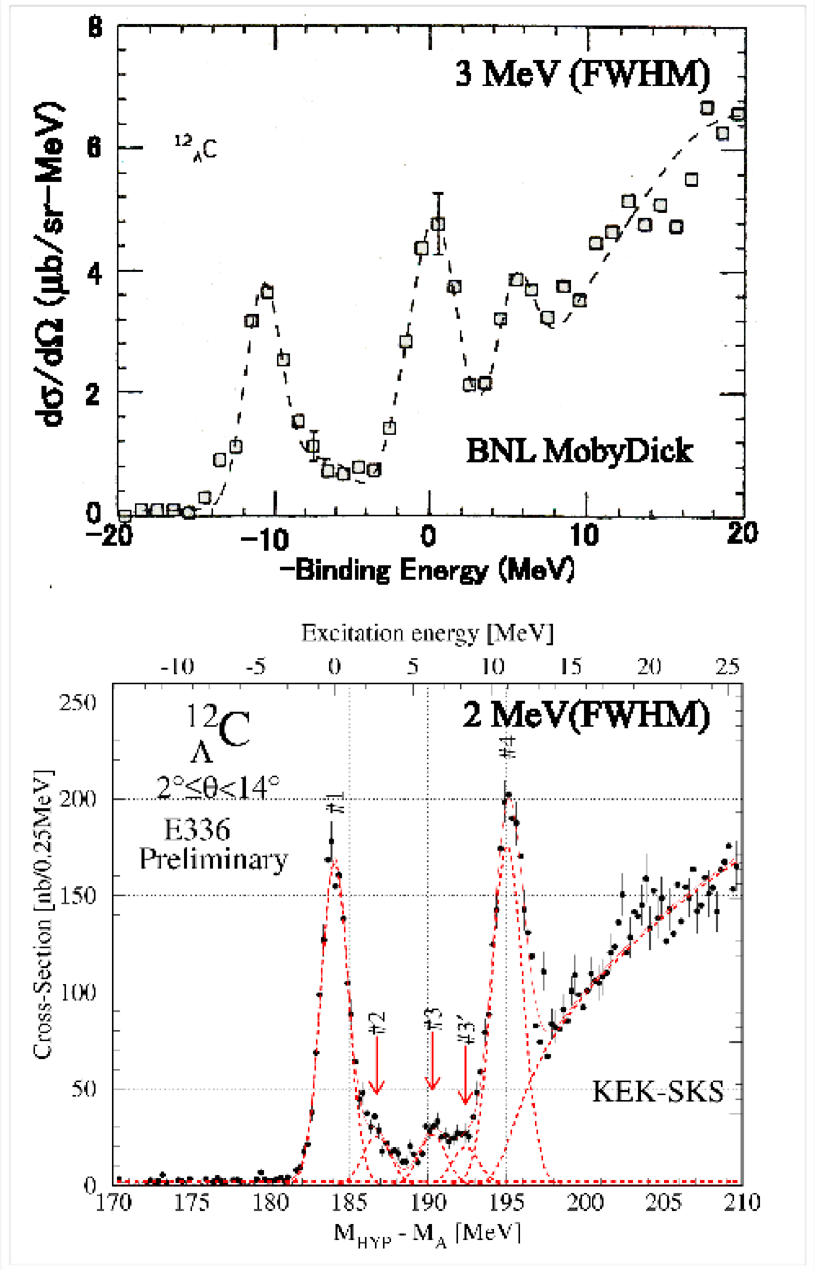
❸ Spectroscopy *... a two-fold way*

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

❷ Requires the knowledge of YN, YY, ...

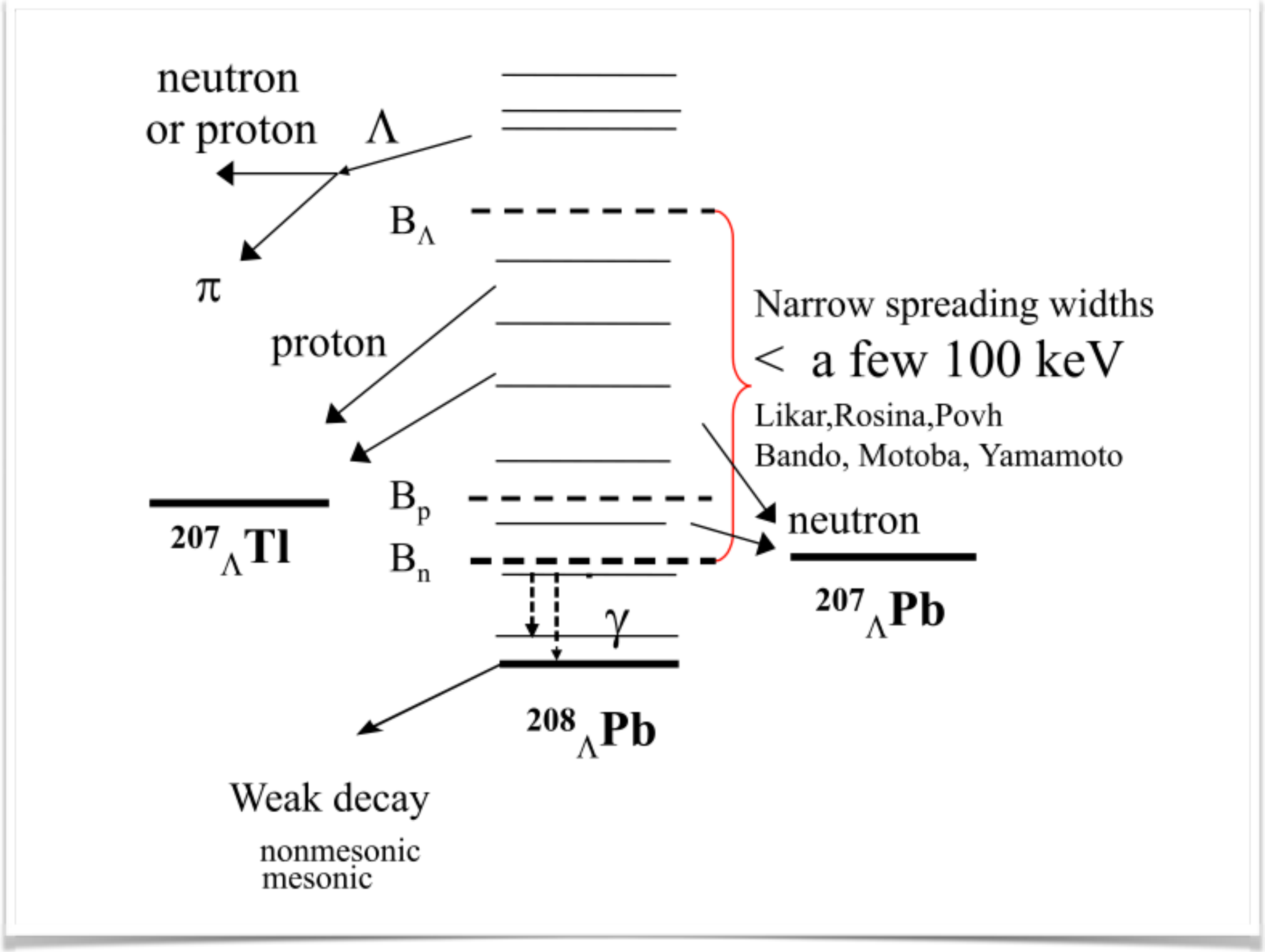
❸ Spectroscopy: DIRECT PRODUCTION



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

Strangeness Nuclear Physics

1. **Hyperons are NOT Pauli-blocked**
2. **Requires the knowledge of YN, YY, …**
3. **Spectroscopy: DECAY**



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

Strangeness Nuclear Physics

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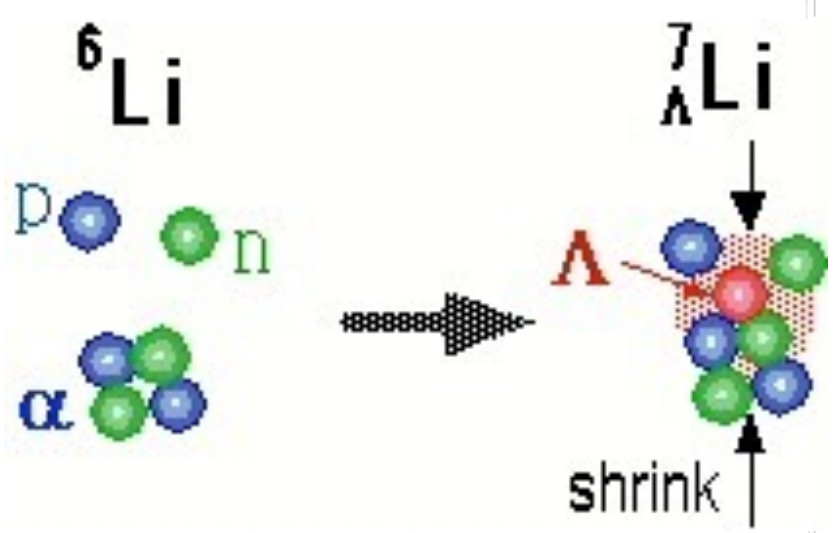
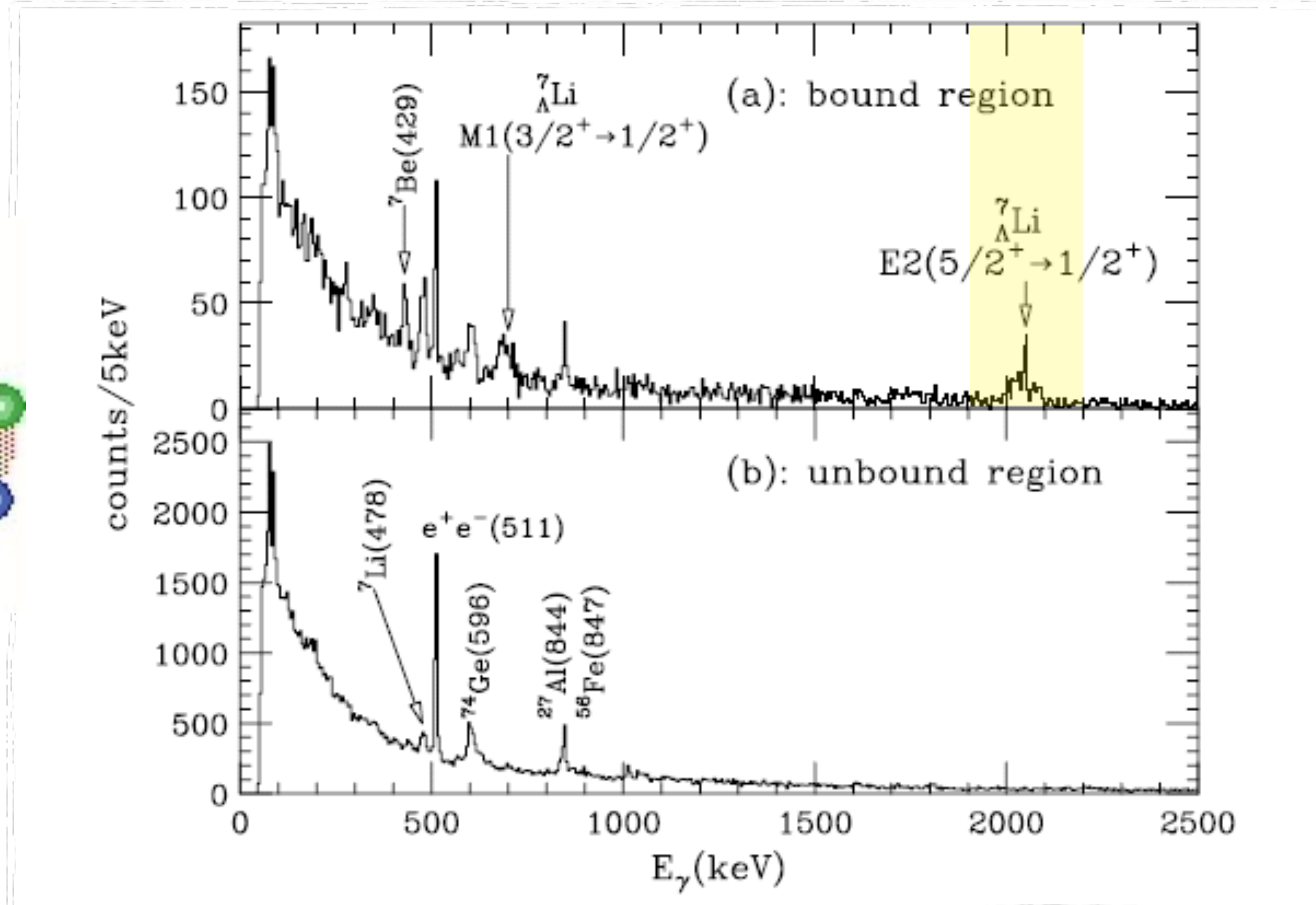
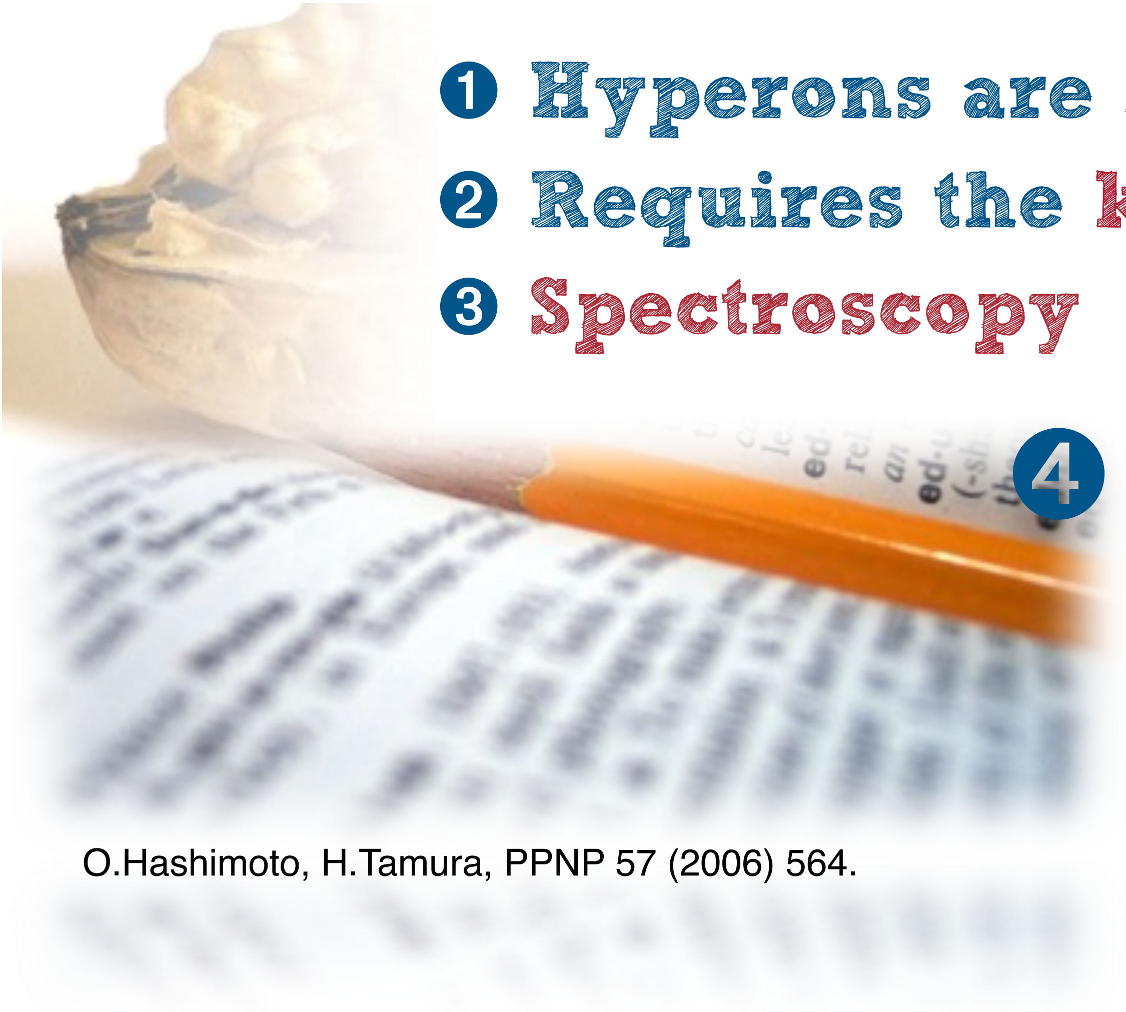




K. Tanida et al., Phys. Rev. Lett. 86 (2001)

Strangeness Nuclear Physics



❶ Hyperons are NOT Pauli-blocked

❷ Requires the knowledge of YN, YY, …

❸ Spectroscopy

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

❹ Lesson learned

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