– Hadron Physics –
Lecture on Selected Topics of the Conference

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Bormio, January 19^{th}, 2020

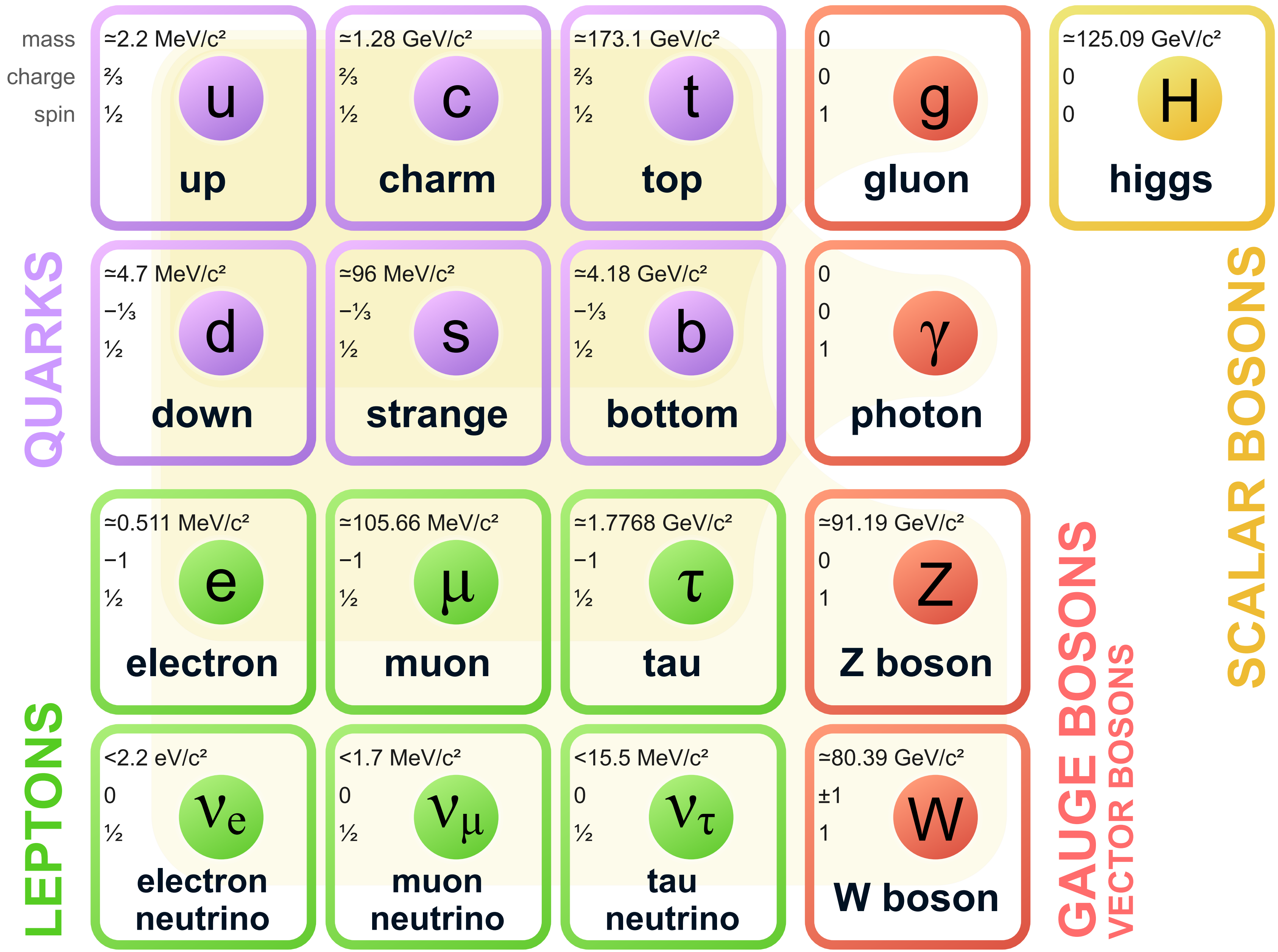
- From Hadrons to QCD $\rightarrow$ brief motivation of the fundamental theory
  - Quarks as building blocks $\rightarrow$ QCD Lagrangian
- From QCD to Hadrons $\rightarrow$ deriving expectations from QCD Lagrangian
  - e.g. Symmetries of QCD $\rightarrow$ potential models, Effective theories, Lattice
- Determination of Hadron properties
  - Methods: e^+e^- Annihilation, γ+Baryon, Hadron-Hadron Collisions, Electron Scattering
  - $\Rightarrow$ Mass, Width, Decays, Quantum Numbers,
    Wave-Function (Form-Factor, Polarizabilities, ...)
- Compare experiments with expectations: Exotics, ...

Hadron Physics

Invited Speakers (Hadron Physics only) Bormio 2020:

- *Christoph Blume* (University of Frankfurt)
  Recent Results from HADES
- *David Hornidge* (University of Mount Allison)
  Hadron polarizability measurements
- *Stefano Spataro* (University of Torino)
  Exotic results from BESIII
- *Wolfram Weise* (TU-München)
  Hyperon-nuclear interactions and strangeness in neutron stars
- *Hartmut Wittig* (University of Mainz)
  A glimpse of the H dibaryon from a lattice QCD perspective

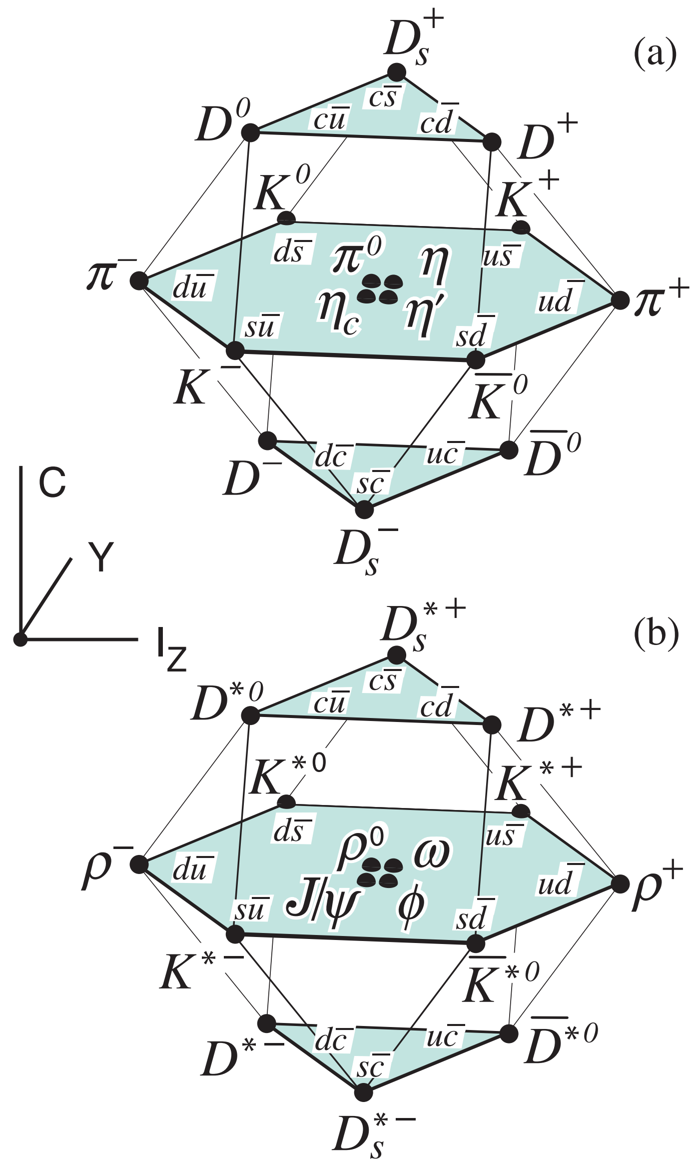
The Standard Model of Elementary Particles



Quark Model

Introduced 1964 by Gell-Mann/Zweig to clean up “particle zoo”

Mesons as Quark-Antiquark Pair:



Pions:

π^+	π^0	π^-	η_1
$\lvert u\bar{d}\rangle$	$\frac{1}{\sqrt{2}}\left(\lvert u\bar{u}\rangle - \lvert d\bar{d}\rangle\right)$	$\lvert d\bar{u}\rangle$	$\frac{1}{\sqrt{2}}\left(\lvert u\bar{u}\rangle + \lvert d\bar{d}\rangle\right)$

Kaons:

K^+	K^0	$\overline{K}^0$	K^-
$\lvert u\bar{s}\rangle$	$\lvert s\bar{u}\rangle$	$\lvert u\bar{s}\rangle$	$\lvert s\bar{u}\rangle$

… 6 flavours → 36 Mesons?

C: Charm, Y: Hypercharge, I_z: Isospin

Baryons

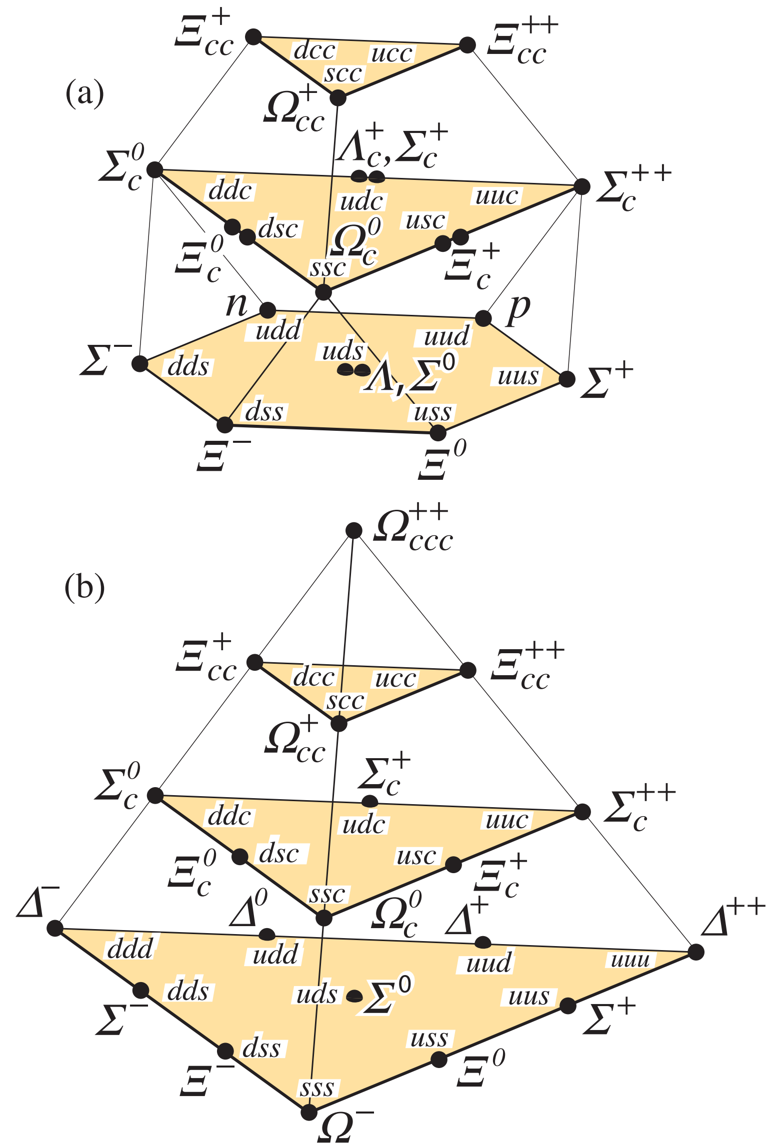
Baryons as three quark states

Examples:

$$p: \quad |u\uparrow u\downarrow d\uparrow\rangle$$
$$n: \quad |u\uparrow d\downarrow d\uparrow\rangle$$
$$\Delta(1232): \quad |u\uparrow u\uparrow d\uparrow\rangle$$
$$\Lambda: \quad |u\uparrow d\downarrow s\uparrow\rangle$$

...

Ground states are OK, excited states?



Color

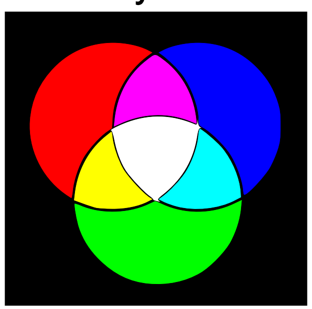
Problem: Δ^{++} with angular momentum $J = \frac{3}{2}$:

$$\Delta^{++} = \underbrace{|uuu\rangle}_{\text{flavour}} \cdot \underbrace{|\uparrow\uparrow\uparrow\rangle}_{\text{spin}} \cdot \underbrace{|l=0\rangle}_{\text{orbital } l}$$

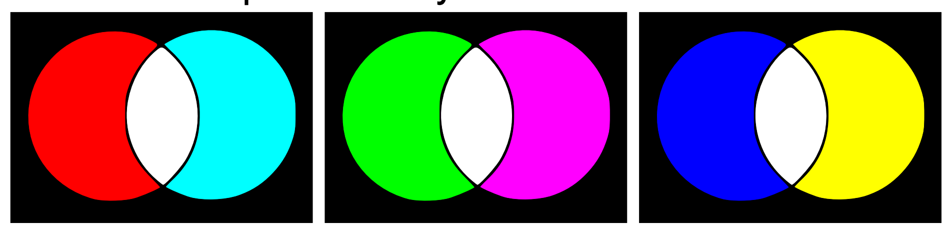
- Not possible for Fermions $\rightarrow$ additional antisymmetric charge neccessary
- Not visible for three- and two-quark states

Color Analogy:

Three colors:
Primary Colors



Two Colors:
Color – complementary Color



Physical objects are colorless (*i.e.* $SU(3)$ Color-Singulets):

Baryons: red–green–blue tripletts

$$|qqq\rangle = \sqrt{\frac{1}{6}}(|RGB\rangle - |RBG\rangle + |BRG\rangle - |BGR\rangle + |GBR\rangle - |GRB\rangle)$$

Mesons: color–anti-color pairs

$$|q\overline{q}\rangle = |R\overline{R}\rangle + |G\overline{G}\rangle + |B\overline{B}\rangle$$

$\Rightarrow SU(3)$ Symmetry of Gluons

QCD Lagrangian

Lagrangian field theory:

$$L = T - V \qquad \text{and} \qquad \text{Lagrange's Equation} \quad \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = 0$$

or with continuous field $\phi(x_\mu)$ $\quad \frac{\partial}{\partial x_\mu}\left(\frac{\partial \mathcal{L}}{\partial(\partial\phi/\partial x_\mu)}\right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0$

Only two ingredients for $\mathcal{L}_{\text{QCD}}$:

- Quarks are massive spin $\frac{1}{2}$ particles $\Rightarrow$ Dirac equation for free lagrangian

$$\mathcal{L}_0 = \overline{q}_j(i\gamma^\mu\partial_\mu - m)q_j$$

- Gauge invariant under $SU(3)$ color symmetry
  i.e. invariant under local phase rotation: $q(x) \to e^{i\alpha_a(x)T_a}q(x)$ with eight 3×3 matrices T_a

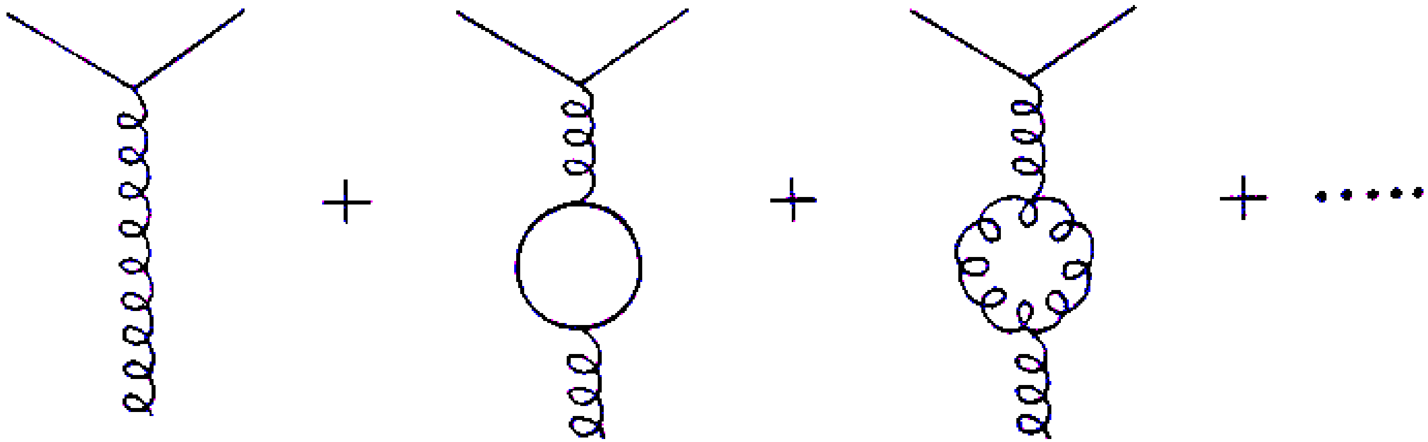
$$\mathcal{L}_{\text{QCD}} = \overline{q}(i\gamma^\mu\partial_\mu - m)q - g(\overline{q}\gamma^\mu T_a q)\,G^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

with 8 massless vector gauge fields transforming like $\quad G^a_\mu \to G^a_\mu - \frac{1}{g}\partial_\mu\alpha_a - f_{abc}\alpha_b G^c_\mu$

gauge field strength tensor $\quad G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g\,f_{abc}G^b_\mu G^c_\nu$

$SU(3)$ structure constants given by $\quad [T_a, T_b] = i\,f_{abc}T_c \qquad \Rightarrow$ "non abelian"

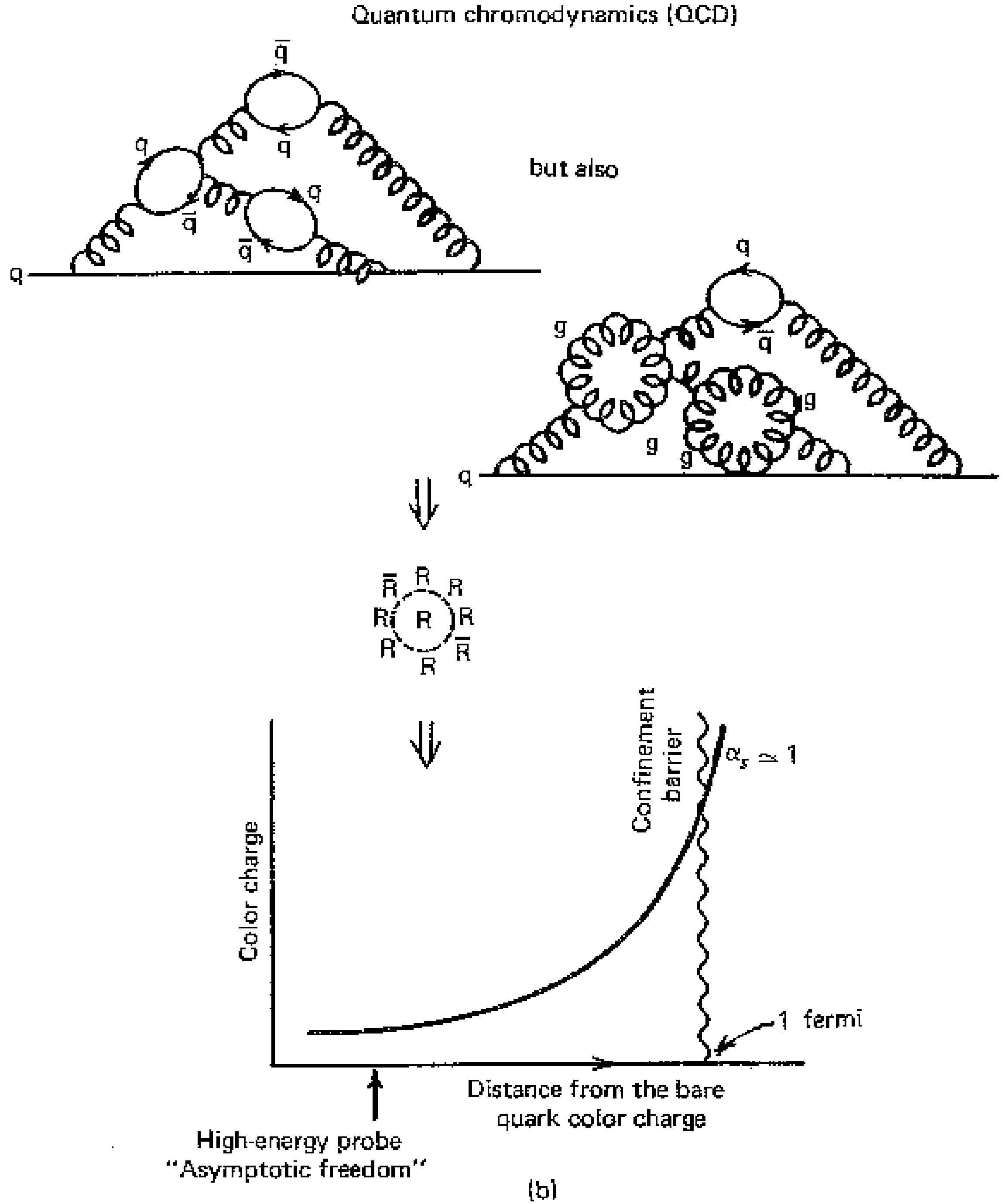
Charge Screening

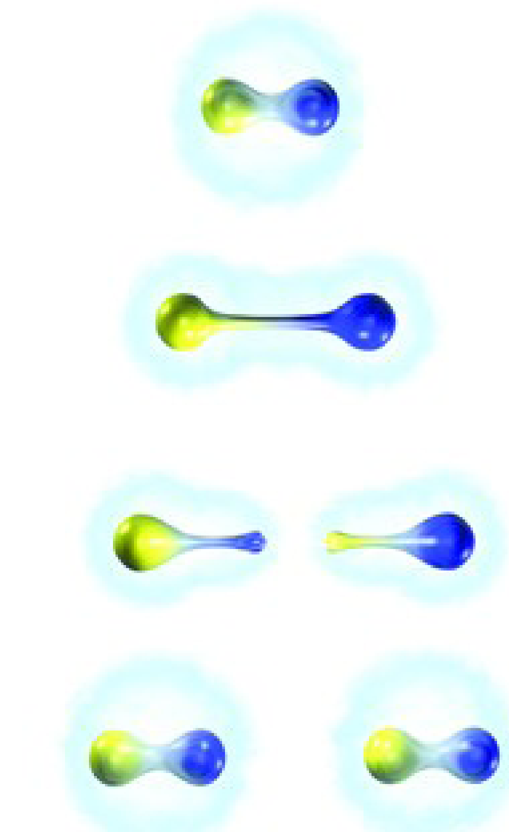


- Quark loops like lepton loops in QED
- For each flavour, large mass supressed
- Additional:
  - Gluon Loops
  - Large contribution: 8 gluons
  - opposite sign!

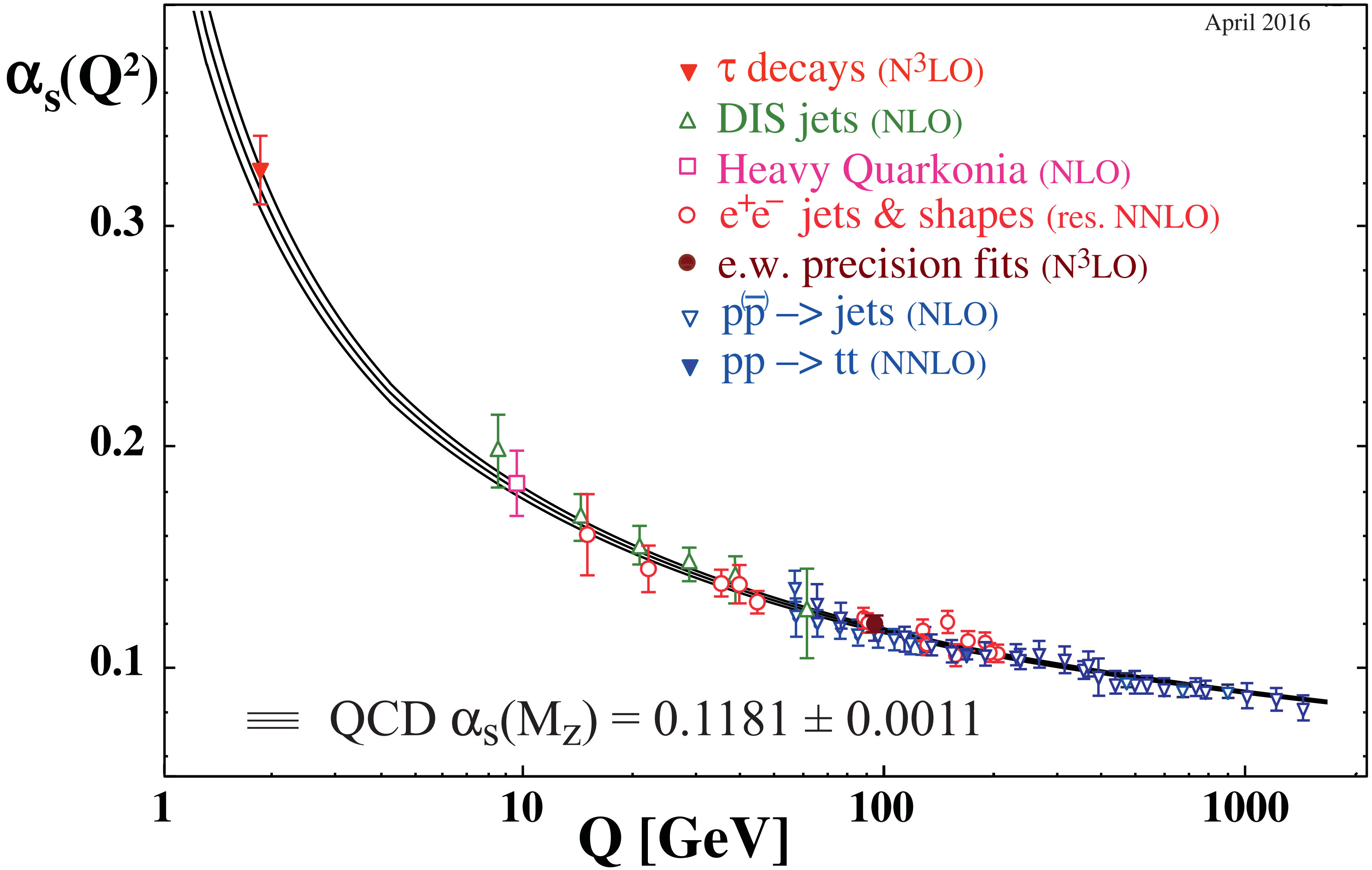
F. Halzen, A. Martin, Quarks and Leptons

Strong Coupling Constant



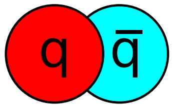


Strong Coupling Constant

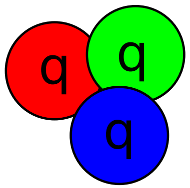


⇒ running of α_s ⇒ non-abelian structure of QCD!

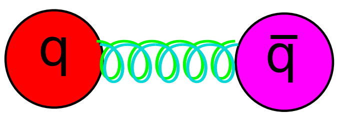
Possible Quark States



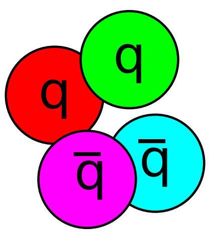
$q\bar{q}$ Meson



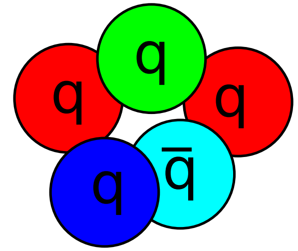
qqq Baryon



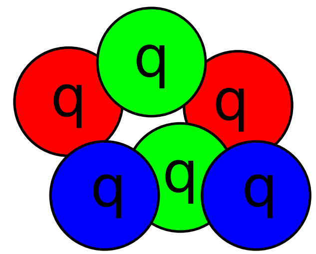
$q\bar{q}g$ Hybrid



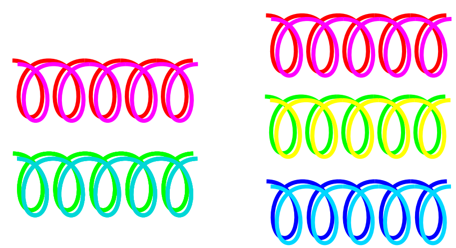
$q\bar{q}q\bar{q}$ Tetraquark



$qqqq\bar{q}$ Pentaquark



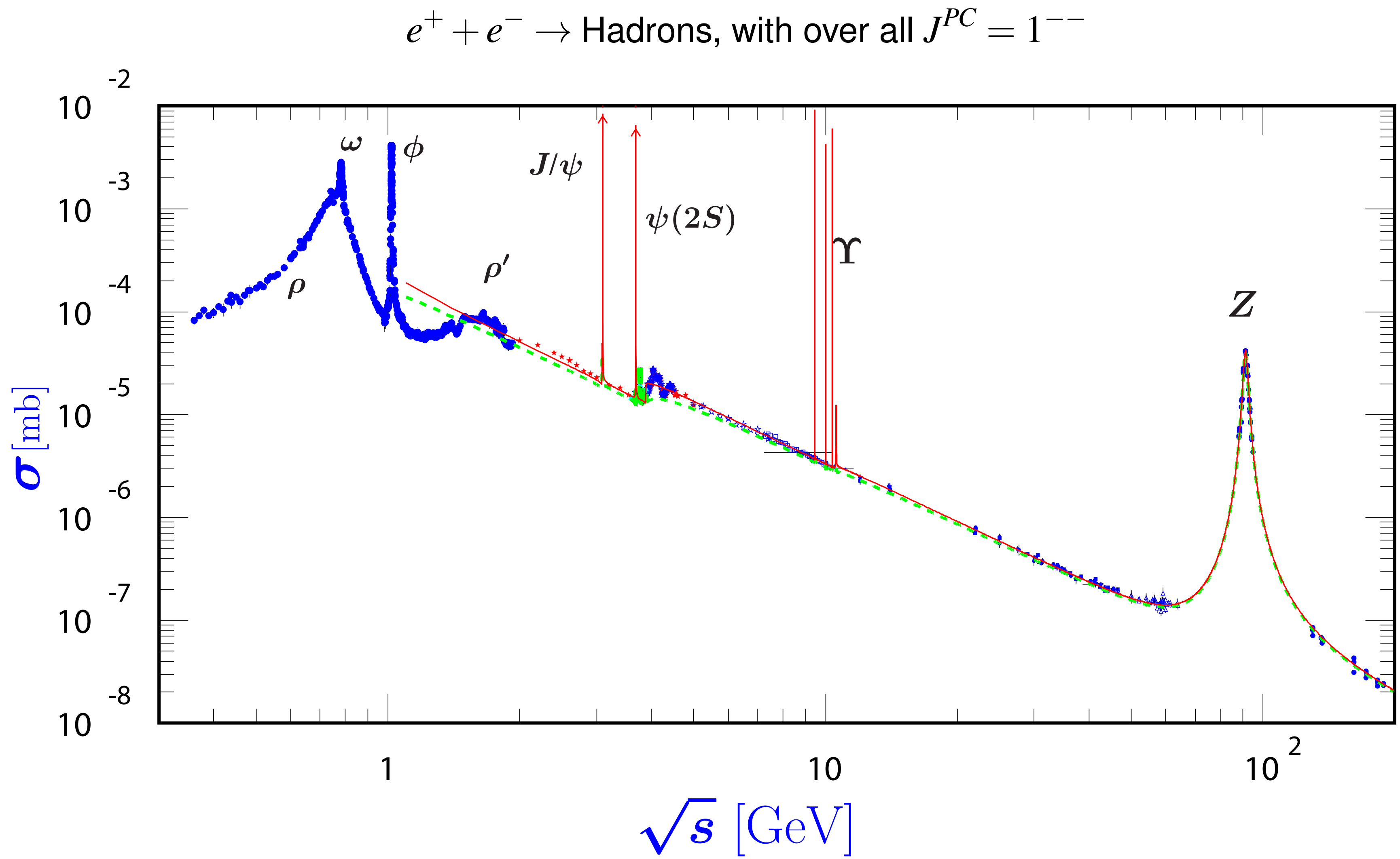
$qqqqqq$ Dibaryon
$qqq\overline{qqq}$



$g\bar{g}$, ggg Glueballs

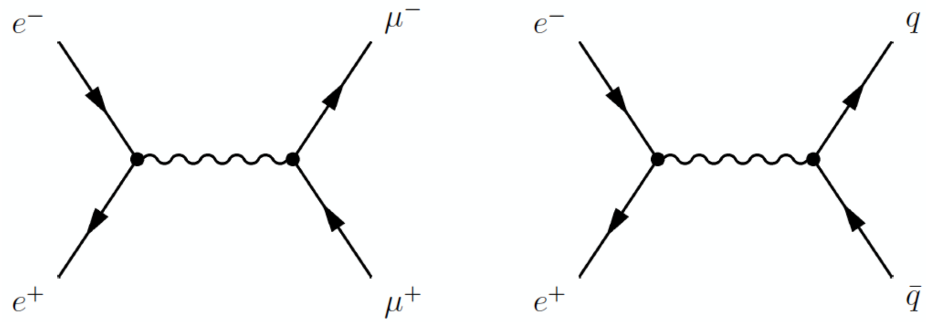
- Not only $q\bar{q}$ and qqq states $\Rightarrow$ a new zoo of "Exotics" is expected!
- Important for most of them: "Color-Singulet" does not mean "white"!
  Two singulets are always decoupled $\rightarrow$ non-trivial binding (e.g. "white" exchange) neccessary

e^+e^- Annihilation: Cross Section



e^+e^- Annihilation: general features

Idea: Relate $q\bar{q}$ cross section to known (i.e. QED) cross section (μ to be distinguishable from e):



$\mu^+\mu^-$ cross section from QED:

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

$q\bar{q}$ cross section (also only QED!):

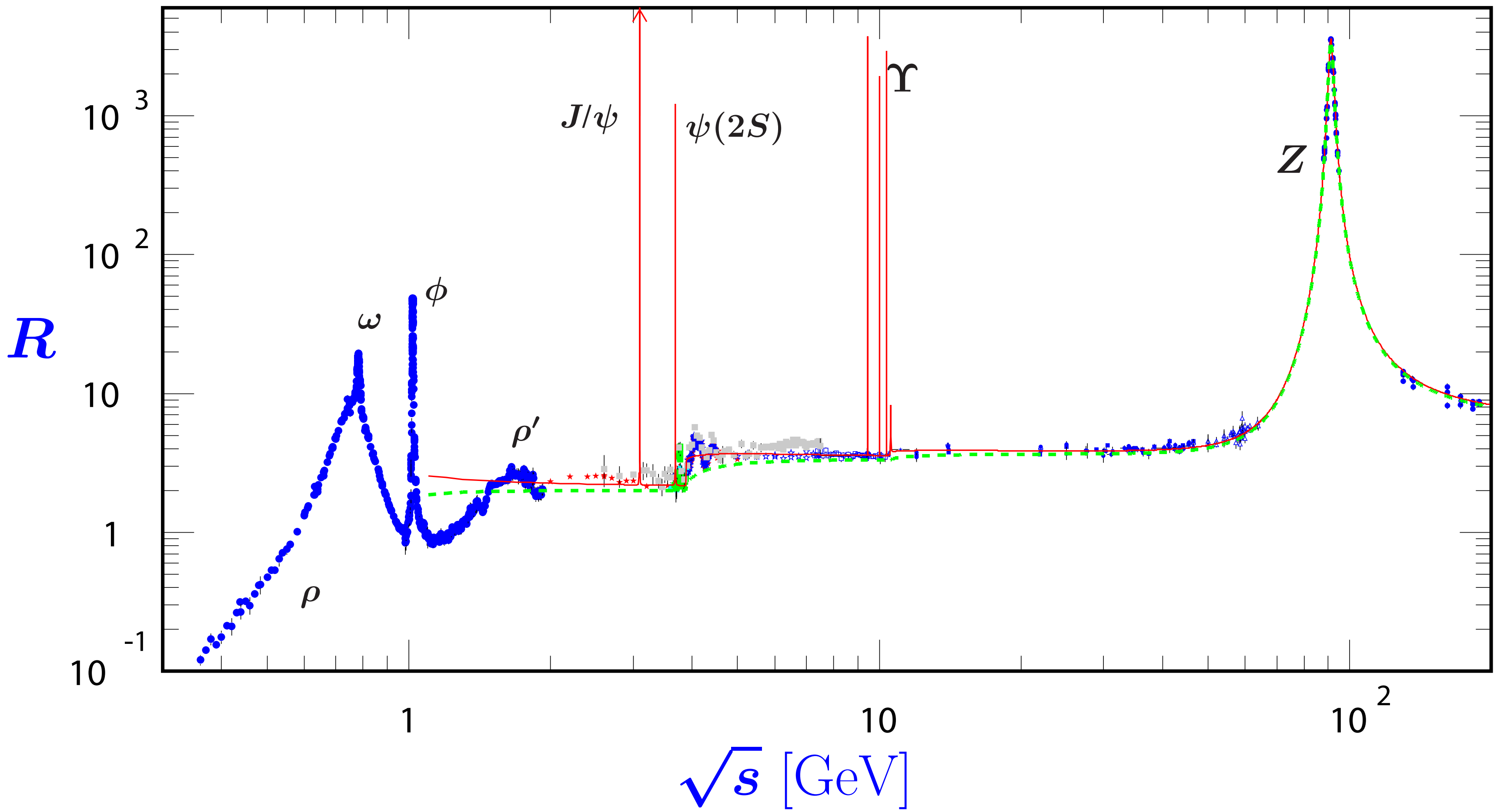
$$\sigma(e^+e^- \to q\bar{q}) = N_c e_q^2 \, \sigma(e^+e^- \to \mu^+\mu^-)$$

$$\text{with} \quad e_q = \begin{cases} -\frac{1}{3} & \text{for } q = d,s,b \\ +\frac{2}{3} & \phantom{\text{for } q =} u,c,t \end{cases}$$

and $\quad N_c = 3 \quad$ number of colors.

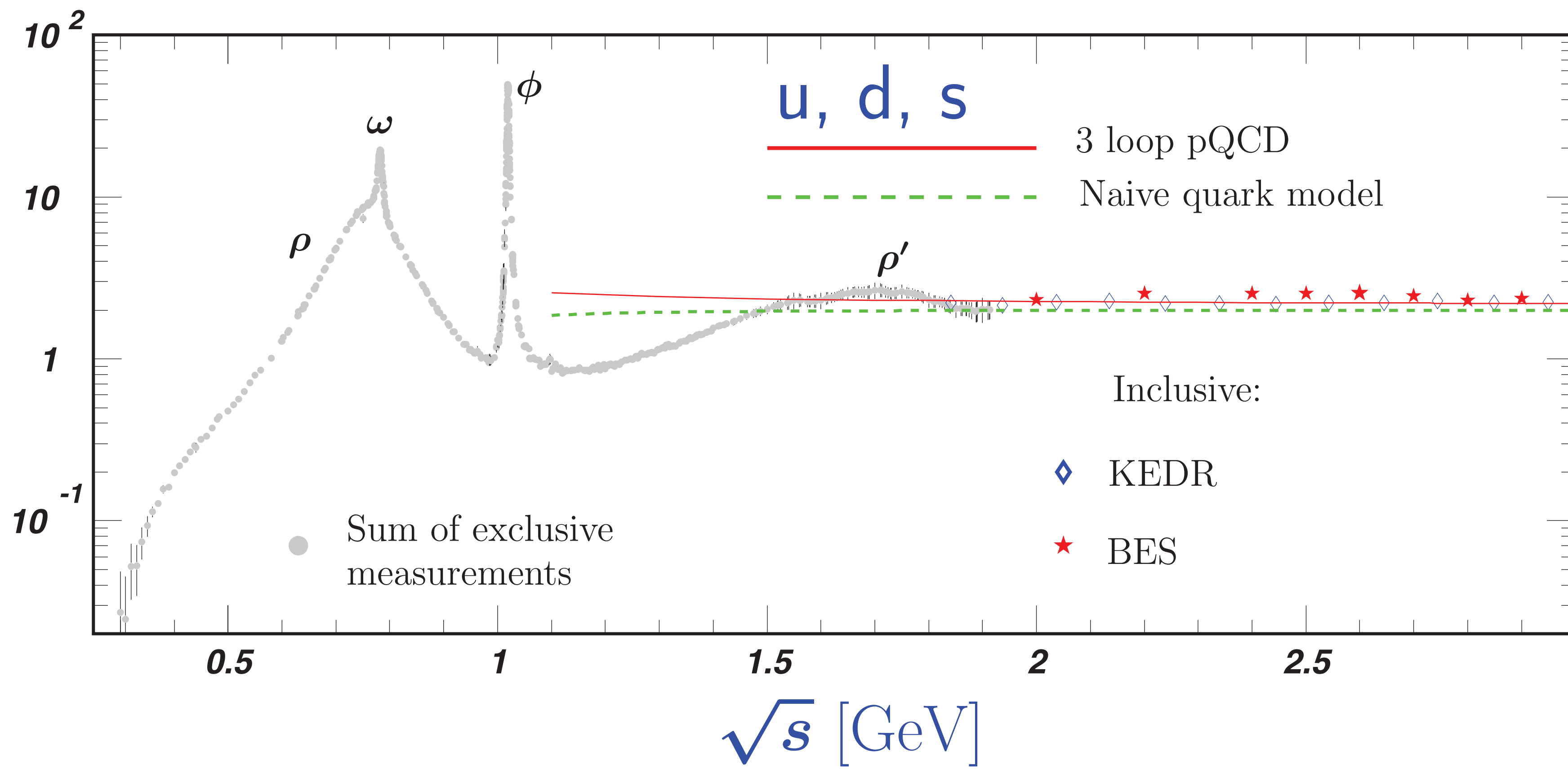
$$R = \frac{\sigma(e^+e^- \to \text{Hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_q 3e_q^2$$

e^+e^- Annihilation



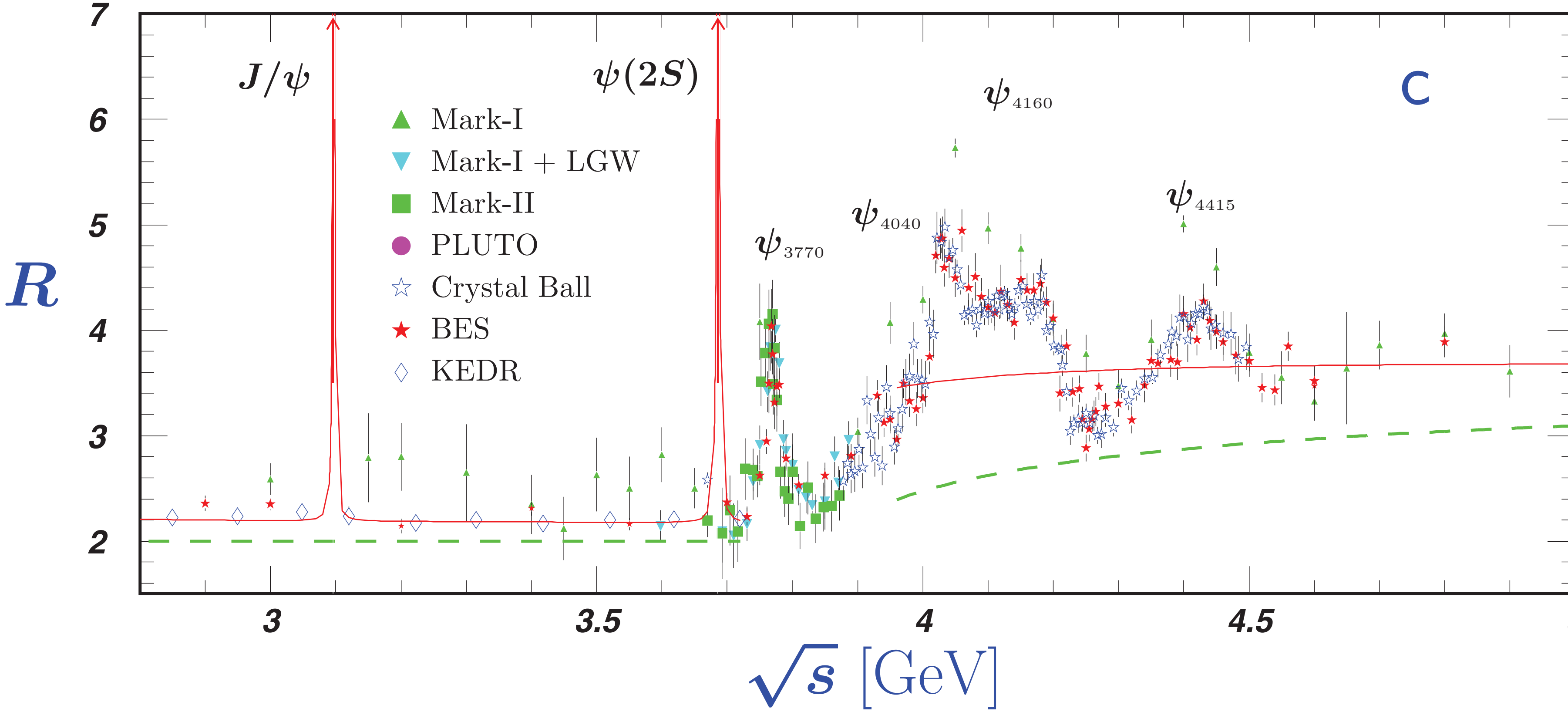
- with QCD corrections: $R = \sum_q 3e_q^2 (1 + \frac{\alpha_s(Q^2)}{\pi})$
- confirms quark charge
- confirms (again) $N_c = 3$ colors

R-Ratio: u, d, s



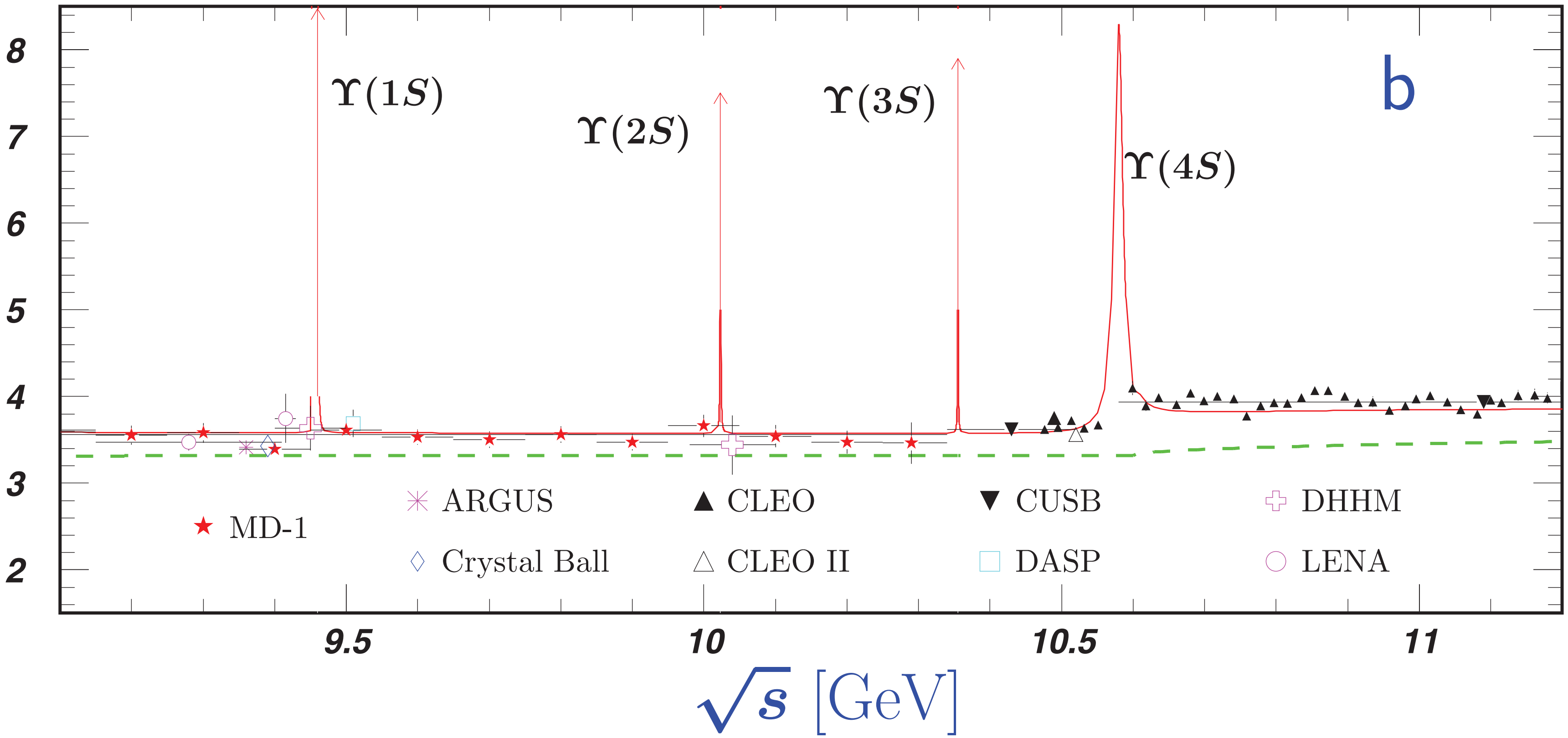
$$R = \sum_q 3e_q^2 = 3\left(\left(\frac{2}{3}\right)^2 + 1\left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right) = 2$$

R-Ratio: c



$$R = \sum_q 3e_q^2 = 3\left(\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2\right) = \frac{10}{3}$$

R-Ratio: b



$$R = \sum_q 3e_q^2 = 3\left(\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right) = \frac{11}{3}$$

Consequences from QCD for Hadron Properties

Symmetries of the QCD Lagrangian: Parity

$\mathcal{L}_{\text{QCD}}$ is invariant under parity transformation (*i.e.* point reflection)

$$\hat{P} : (t, \vec{x}) \to (t, -\vec{x})$$

Eigenvalues:

$$\hat{P}^2(\phi(t,\vec{x})) = \hat{P}(\hat{P}(\phi(t,\vec{x})) = \hat{P}(\phi(t,-\vec{x})) = \phi(t,\vec{x})$$

$\Rightarrow \quad \hat{P}(\phi(t,\vec{x}) = P\,\phi(t,\vec{x})$ with Eigenvalues $P = \pm 1$ (actually $\pm e^{i\varphi}$, but we can redefine $\hat{P}$)

Consequences for Hadrons:

- All states can be decomposed into states with $P = +1$ or $P = -1$
  - Might be degenerated?
- System of Hadrons

  $$\hat{P}\left(\phi_1(t,\vec{x}) \otimes \phi_2(t,\vec{x}) \otimes \cdots \otimes \phi_N(t,\vec{x})\right) = P_1\left(\phi_1(t,\vec{x})\right) \times P_2\left(\phi_2(t,\vec{x})\right) \times \cdots \times P_N\left(\phi_N(t,\vec{x})\right)$$

  Parity is a “multiplicative” quantum number
- Hadrons produced via QED/QCD from a state with defined total parity have same total parity
- Additional $U(1)$ Symmetries for Baryon-Number, Charge, Lepton Number $\Rightarrow$ combined parity operators
- Define intrinsic parity $P_{\text{Proton}} = P_{\text{Neutron}} = P_{\text{Electron}} = +1$:

Symmetries of the QCD Lagrangian: Experimental determination of Parity

Example: Parity of the pion

$$^2H + \pi^- \to n + n$$

- measure angular momentum (i.e. angular distribution)
- intrinsic parity $P(p) = P(n) = 1$
- Deuteron has Spin $S_d = 1$
  Pion has Spin $S_\pi = 0$
  s-Wave $L = 0$
  n antisymmetric
  $\Rightarrow$ total orbital momentum of final state $L = 1 \Rightarrow P = (-1)^L$
- Sum

$$\underbrace{(1)}_{p\uparrow}\underbrace{(1)}_{n\uparrow}\underbrace{(P_\pi)}_{\text{Pion}} = \underbrace{(-1)}_{L=1}\underbrace{(1)}_{n\uparrow}\underbrace{(1)}_{n\uparrow}$$

$\Rightarrow$ Pion has parity $P_\pi = -1$, it is a “pseudoscalar” particle

General approach:

- calculate parity of initial state
- examine strong and electromagnetic (not weak!!!) decays, determine angular momenta
- tie to defined intrinsic parity

Symmetries of the QCD Lagrangian: Charge Conjugation

$\mathcal{L}_{\text{QCD}}$ is invariant under Charge Conjugation (*i.e.* exchange particle $\rightarrow$ antiparticle)

$$\hat{C} : |\phi\rangle \rightarrow |\overline{\phi}\rangle$$

Same properies as a parity operator

- Eigenvalues $C = \pm 1$
- Multiplicative quantum number for a system
- New: only neutral particles can be eigenstates!

Experimental determination: e.g. C-Parity of the pion from decay:

$$\pi^0 \rightarrow \gamma + \gamma$$

- C-Parity of photon $C(\gamma) = -1$ from QED
- Multiplicative $\Rightarrow C(\pi^0) = (-1)_\gamma (-1)_\gamma = 1$

Quantum numbers of the Pion: $J^{PC} = 0^{-+}$

C-Parity only for neutral particles

- Combination with Isospin Rotation $\hat{R} : |I, I_z > \rightarrow |I, -I_z >$
- Define G-Parity: $\hat{G} = \hat{C}\hat{R}$ for charged mesons

Natural Quantum numbers

- "Natural" quantum numbers for mesons: J^{PC} with $|L-S| \leq J \leq |L+S|$

$$\left.\begin{array}{l} \hat{P}(Y_{lm}(\theta,\phi)) = Y_{lm}(\pi-\theta,\phi+\pi) = (-1)^l Y_{lm}(\theta,\phi) \\ \text{intrinsic parity from Dirac Equation: } \quad P(q) \neq P(\bar{q}) \end{array}\right\} \quad \Rightarrow \quad \hat{P}|q\bar{q}\rangle = (-1)^{L+1}|q\bar{q}\rangle$$

- Charge Parity of a Meson as a Quark-Antiquark pair:

$$\hat{C}(|q\bar{q}\rangle) = C|q\bar{q}\rangle$$

  - Charge Conjugation corresponds to exchange of quark/antiquark

$$\left.\begin{array}{ll} \text{Exchange of Wavefunctions (see above)} & C = (-1)^{L+1} \\ \text{Spin flip/No Spin flip for } S=0/S=1 & C = (-1)^{S+1} \end{array}\right\} \quad \Rightarrow \quad \hat{C}(|q\bar{q}\rangle) = (-1)^{L+S}|q\bar{q}\rangle$$

- Allowed: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{--}, 2^{-+}, 2^{++}, 3^{--}, 3^{+-}, 3^{++}$, ...
  Not allowed: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$, ... $\Rightarrow$ Exotic Mesons

$^{2S+1}L_J$	S	L	J	P	C	J^{PC}	Mesons				Name
$^1S_0$	0	0	0	$-$	$+$	0^{-+}	π	η	η'	K	pseudo-scalar
$^3S_1$	1	0	0	$-$	$-$	1^{--}	ρ	ω	ϕ	K^*	vector
$^1P_1$	0	1	1	$+$	$-$	1^{+-}	b_1	h_1	h'_1	K_1	pseudo-vector
$^3P_0$	1	1	0	$+$	$+$	0^{++}	a_0	f_0	f'_0	K^*_0	scalar
$^3P_1$	1	1	1	$+$	$+$	1^{++}	a_1	f_1	f'_1	K_1	axial vector
$^3P_2$	1	1	2	$+$	$+$	2^{++}	a_2	f_2	f'_2	K^*_2	tensor

Theoretical Approaches

The “brute force” approach: Lattice QCD

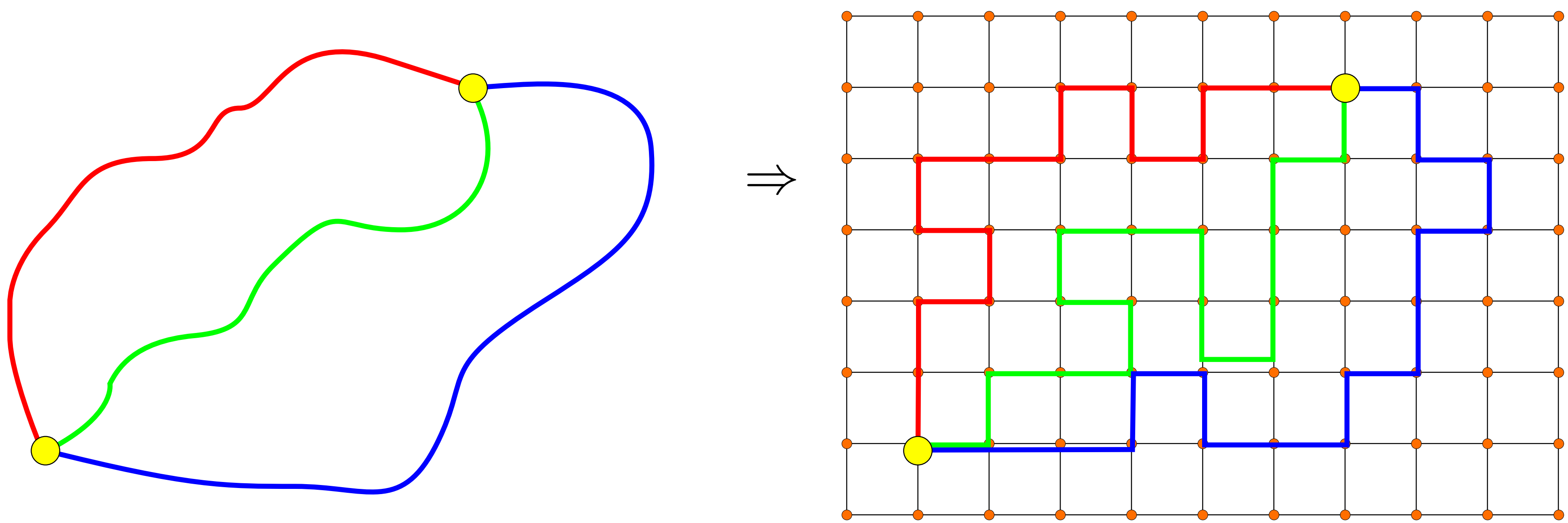
Starting point: Feynman’s Path Integral formulation of Quantum Mechanics:

$$\psi(x_2,t_2) = \frac{1}{Z}\int e^{iS}\psi(x_1,t_1)\ \mathcal{D}x$$

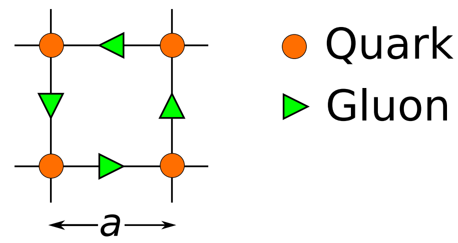
with $\int \mathcal{D}x$: Integration over *all* paths $x(t)$ with $x(0) = x_1$

and the action $S = \int_{t_1}^{t_2} L(x,\dot{x},t)\ \mathrm{d}t$

(a.k.a. Fermat’s principle, Hamilton’s principle, principle of least action)



Lattice QCD



- Transform to Euclidean Space (neccessary to use Monte-Carlo-Methods):

$$t \to i\tau$$
$$-(\mathrm{d}t^2) + \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 \to \mathrm{d}\tau^2 + \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2$$

- Define Link Variables for gluonic field

$$U_\mu = \exp\left(iaG_\mu\left(n + \frac{\hat{\mu}}{2}\right)\right)$$

$U_{\mu\nu}(n)$: closed loop around one tile, "plaquette"

- Fermion action bei discretizing derivatives $\partial\phi_t \approx \frac{\phi(t+a)-\phi(t-a)}{2a}$

$$S = \int \overline{u}(iD_\mu\gamma_\mu + m)u\, d^4x \quad \to \quad D_\mu = \frac{1}{2a}\left[U_\mu(x)q(x+a\hat{\mu}) - U_\mu(x-a\hat{\mu})^\dagger q(x-a\hat{\mu})\right]$$

- Gluonic action:

$$S = -\frac{1}{2g^2}\mathrm{Tr}\int G_{\mu\nu}G^{\mu\nu}d^4x \quad \to \quad S_L = -\frac{1}{2g^2}\sum a^4\mathrm{Tr}\left(1 - U_{\mu\nu}(n)\right)$$

Lattice

Final Step: Numeric solution via Markov-chain Monte-Carlo:

- Choose a start-configuration C_0
- Accept a random next configuration C_{n+1} with probability

$$P = \min\left(1, \frac{W(C_{n+1})}{W(C_n)}\right)$$

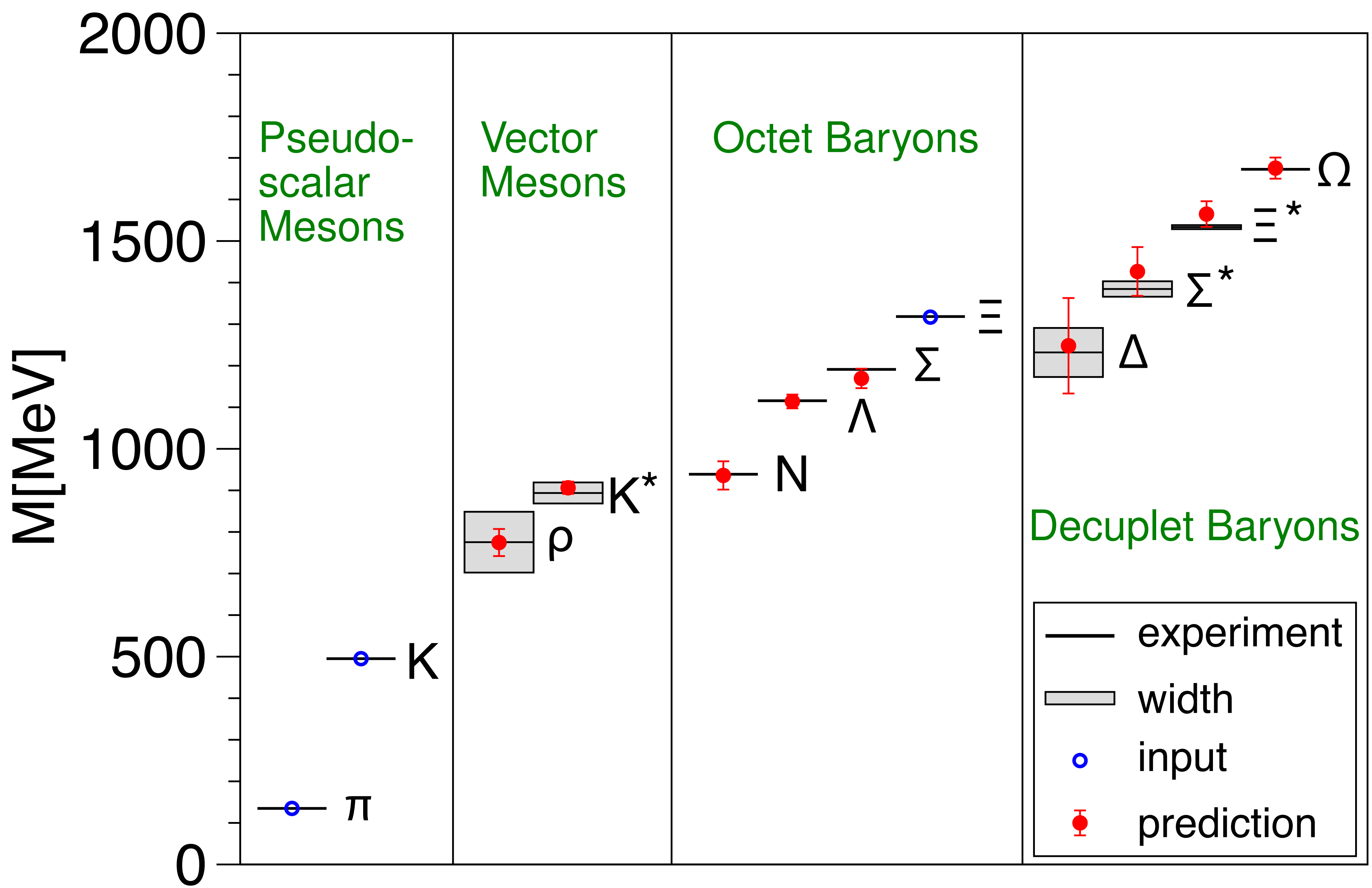
$\Rightarrow$ We don't need to know the probability density function,
we need only the *relative* weight $W(C)$,
calculated by discretized path integral!

- Repeat until "thermalization", i.e. distribution of configurations corresponds to $W(C)$
- Repeat everything with different Lattice spacing a
- Extrapolation $a \to 0$

Summary:

- Gauge invariant
- Works in the non-perturbative regime
- Finite volume, finite momentum

Hadron Spectrum from Lattice QCD

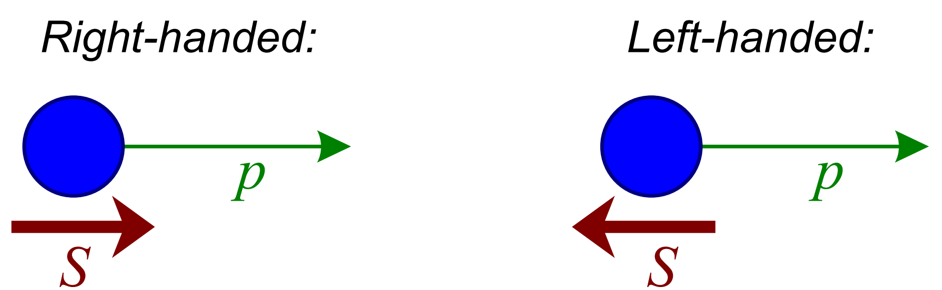


S. Durr, *et al.*, Science 322 (2008)

Still one symmetry of QCD not used...

Chirality

Helicity: Spin projection in direction of motion



Not a good quantum number: inversion by "overtaking" reference frame!

Better: **Chirality**

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

For massless particles:

$$\gamma^5 \cdot u_+ = \gamma^5 \cdot \begin{pmatrix} \chi \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m} \end{pmatrix} = \gamma^5 \cdot \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} = +u_+ \quad \text{and} \quad \gamma^5 \cdot u_- = \gamma^5 \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix} = -u_-$$

Eigenvalues of γ^5 are the eigenvalues of helicity for particles with $m \to 0$

Chirality $\approx$ Lorentz invariant version of Helicity

Chiral Symmetry

Projection Operator

$$\frac{1}{2}(1+\gamma^5)u = u_R \qquad \frac{1}{2}(1-\gamma^5)u = u_L$$

Consequences for *Dirac Equation* $(i\gamma^\mu p_\mu - m)u = 0$:

$$\overline{u}\gamma^\mu u = (\overline{u}_R + \overline{u}_L)\gamma^\mu(u_R + u_L) = \overline{u}_R\gamma^\mu u_R + \overline{u}_L\gamma^\mu u_L$$

for $m \to 0$: left-/right-handed particles interact only with left-/right-handed particles

Def.: Chiral Symmetry: invariant under separate rotations

$$\psi_L \to e^{-i\theta_L}\psi_L \quad \text{and} \quad \psi_R \to \psi_R$$

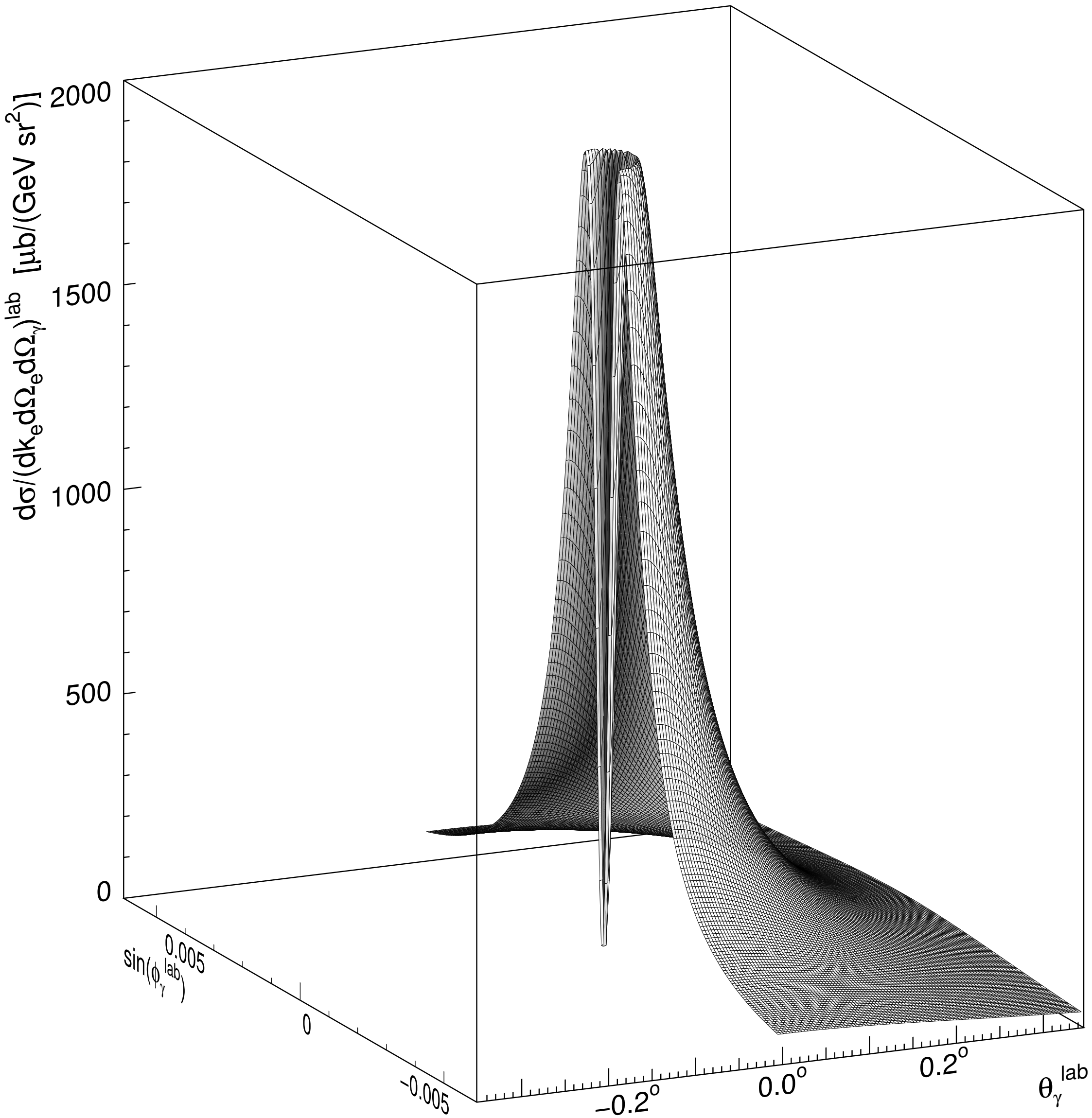
$$\text{or} \quad \psi_R \to e^{-i\theta_R}\psi_R \quad \text{and} \quad \psi_L \to \psi_L$$

Chiral Symmetry in QCD: combination with Isospin rotation of $q = \begin{pmatrix} u \\ d \end{pmatrix}$:

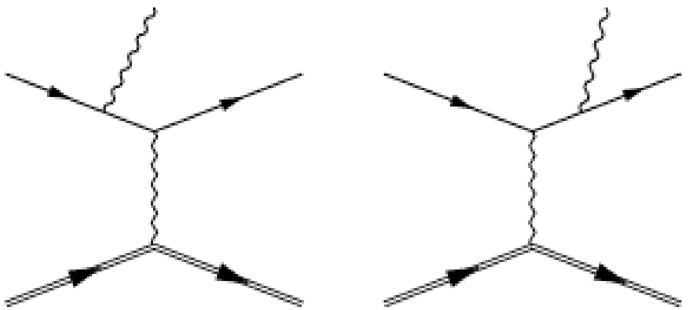
$$U(2)_L \times U(2)_R = \underbrace{SU(2)_L \times SU(2)_R}_{\text{Chiral Symmetry}} \quad \underbrace{\times U(1)_V \times U(1)_A}_{\text{Baryon number, Quan. anomaly}}$$

Chiral Symmetry: QCD invariant under separate isospin rotation for left- and right-handed quarks in the limit of massless quarks

The Power of Chiral Symmetry...



QED Example: Bremsstrahlung



- Virtual intermediate electron
- $\frac{1}{\not p - m} \to 0$ Peak in electron direction
- Exactly at $\theta_{\gamma e} = 0$:
  - Emmission of Spin 1 Photon
  - No orbital angular momentum
  - $\Rightarrow$Spin Flip of electron breaks Chiral Symmetry
  - Cross section $\to 0$

$\Rightarrow$ Chiral symmetry is powerfull

Expectations from Chiral Symmetry for Hadron Physics

Mass of light quarks:

$$m_u = 2.2\,\text{MeV} \qquad\qquad m_d = 4.7\,\text{MeV}$$

$$m_q \ll m_{\text{Hadrons}}$$

Chiral symmetry $SU(2)_R \times SU(2)_L$ should be conserved at least at 1% level!

Expectations:

- Parity doublets: all light quark states have partner with oposite parity

Observation:

- No parity doubletts in baryon or meson spectrum seen! e.g. $\rho(770) < a_1(1200)$
- Three ridiculous light mesons π^0, π^+, π^- with $m_\pi \ll \frac{2}{3} m_p$

Hypothesis:

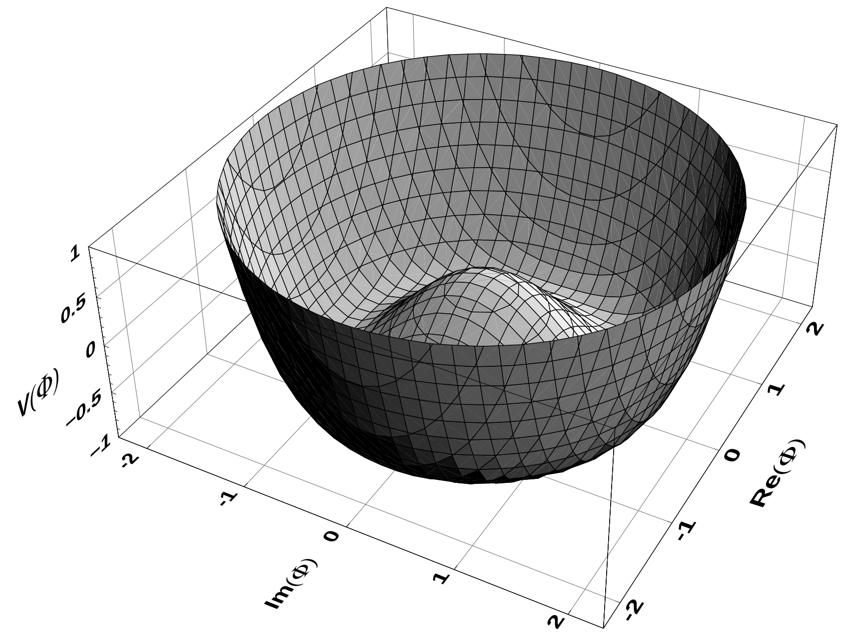
- Chiral Symmetry is spontaneously broken
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \times SU(2)_A$

  of standard vector $SU(2)_V$ and rest ($SU(2)_A \equiv SU(2)_L \times SU(2)_R / SU(2)_V$ is not a group!)

Spontaneous Symmetry Breaking and Goldstone-Theoreme

2-dimensional Example:

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi^*\phi - \frac{\lambda}{4}(\phi^*\phi)^2$$



Minimum at

$$|\phi| = k = \sqrt{-m^2/\lambda}$$

Replace complex scalar field $\phi = ke^{i\theta/k}, \quad \theta \in \mathbb{R}$

$$\Rightarrow \mathcal{L} = \frac{1}{2}(-ie^{-i\theta/k}\partial^\mu\theta)(ie^{i\theta/k}\partial_\mu\theta) - \frac{1}{2}m^2k^2 - \frac{\lambda}{4}k^4 = \frac{1}{2}\partial^\mu\theta\partial_\mu\theta - \underbrace{\frac{1}{2}m^2k^2 - \frac{\lambda}{4}k^4}_{\text{const. in }\theta}$$

$\Rightarrow$ Real scalar field θ ist massless!

Spontaneous Symmetry Breaking $\Rightarrow$ massless Goldstone-Bosons. $\Rightarrow$ QCD: Pions

Chiral Effective Field Theories

What are the relevant degrees of freedom? $\Rightarrow$ *e.g.* pions as Goldstone-Bosons

Ingredients for an effective field theory:

- Choose degrees of freedom: $\Rightarrow$ Pions
- Most general Lagrangian in theses DoF respecting the Symmetries of $\mathcal{L}_{QCD}$
  $\Rightarrow$ series in terms of derivatives, fields
  $\Rightarrow$ this is a perturbative theory!
- Most important: sort these terms!
  - Expansion in mass terms (explicit symmetry breaking by $-\overline{q}_f M q_f$)
  - Simultaneously expansion in p
  - Order Scheme $\rightarrow$ define what is LO, NLO, NNLO!
- Derive Feynman rules, calculate observables order by order, ...

To deal with:

- Regularization $\Rightarrow$ Low Energy Constants   Fit to experiment, limits predictive power
- Degrees of freedom: e.g. better to include resonances?
- Convergence of series
- ...

Systematic expansion, not a Model!

N.B.: Theorists' "Slang"

If a theorist uses the word

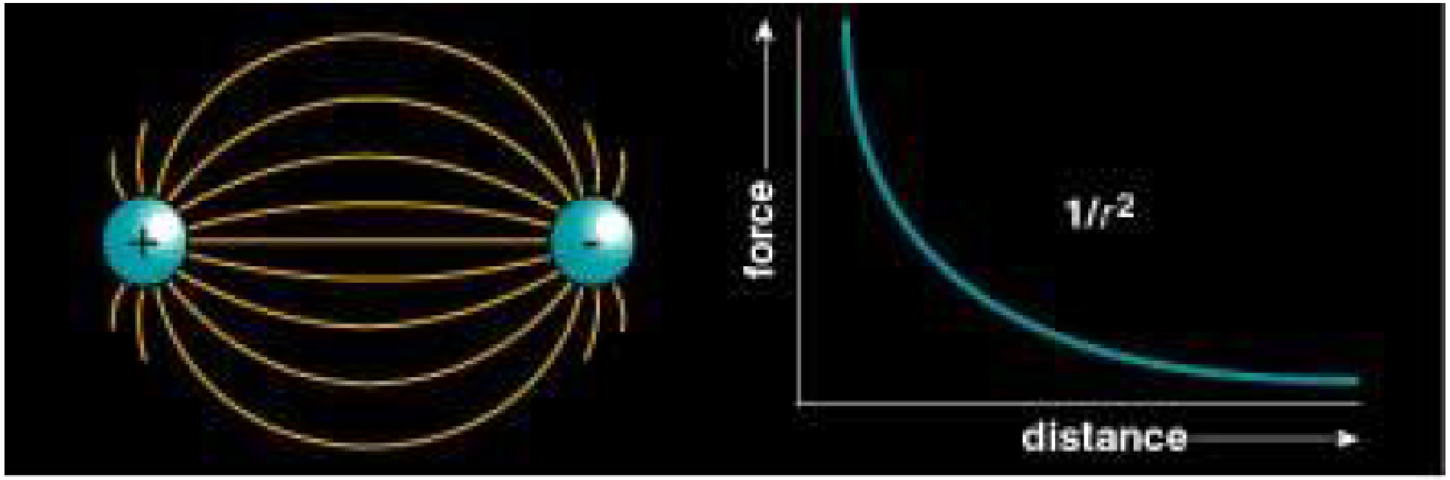
"chiral"

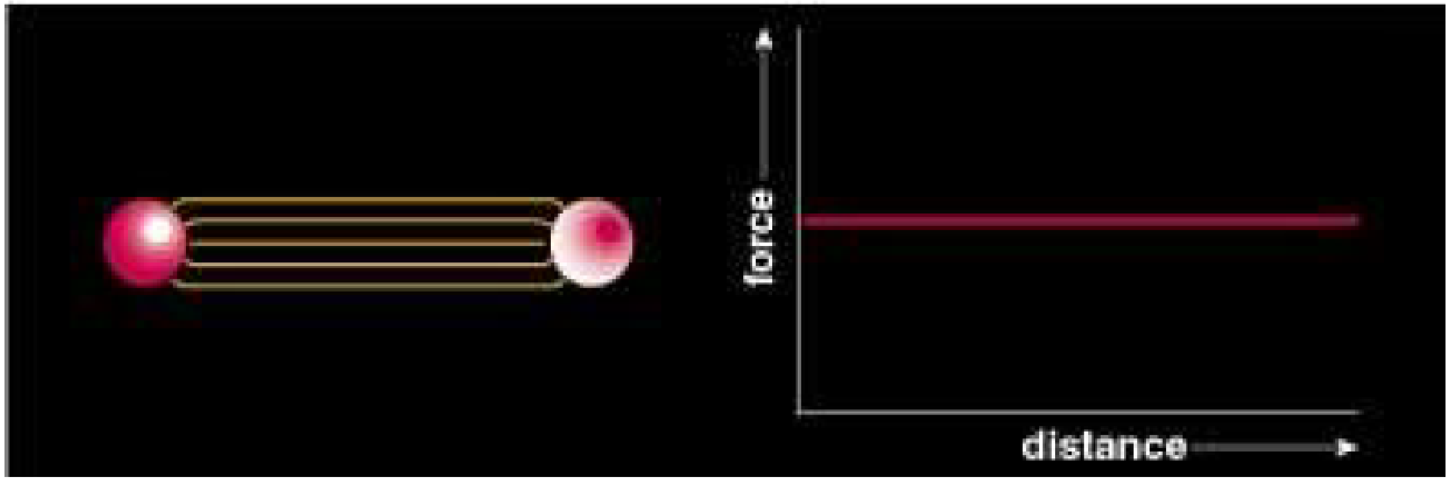
like *e.g.* in "Chiral Extrapolation of Lattice QCD" this usually means

"Using methodes from Effective Field Theories
using the Chiral Symmetry of QCD"

Potential Models

The qq Force of QCD





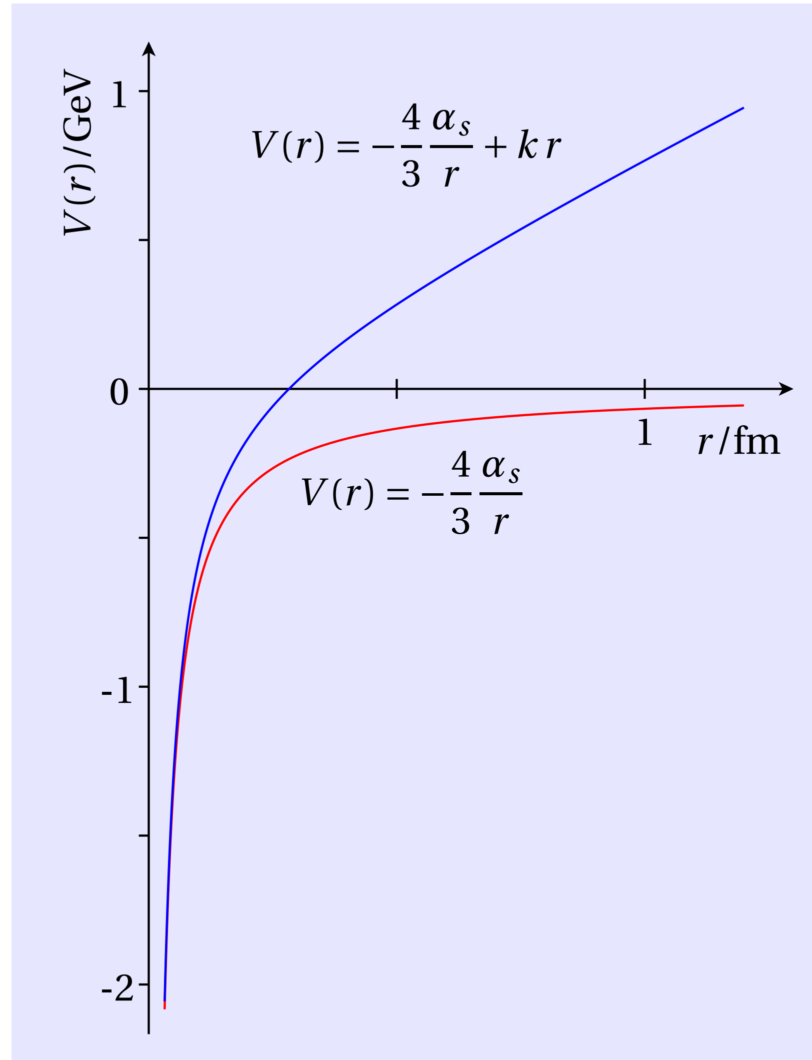
- Idea: heavy quarks → non-relativistic
- A quark in the potential of a mean field

Simple Model: Non-relativistic Potential Model

Model: quarks in the potential of the rest of the meson/baryon

- $V(r \to 0)$
  - Asymptotic freedom
  - Massless gluons
    $\to$ infinite range Coulomb like potential $\frac{1}{r}$
- $V(r \to \infty)$
  - Confinement potential $k \cdot r$
  - Running coupling constant

$$V(\vec{r}) = -\frac{4}{3}\frac{\alpha_s}{r} + k \cdot r$$



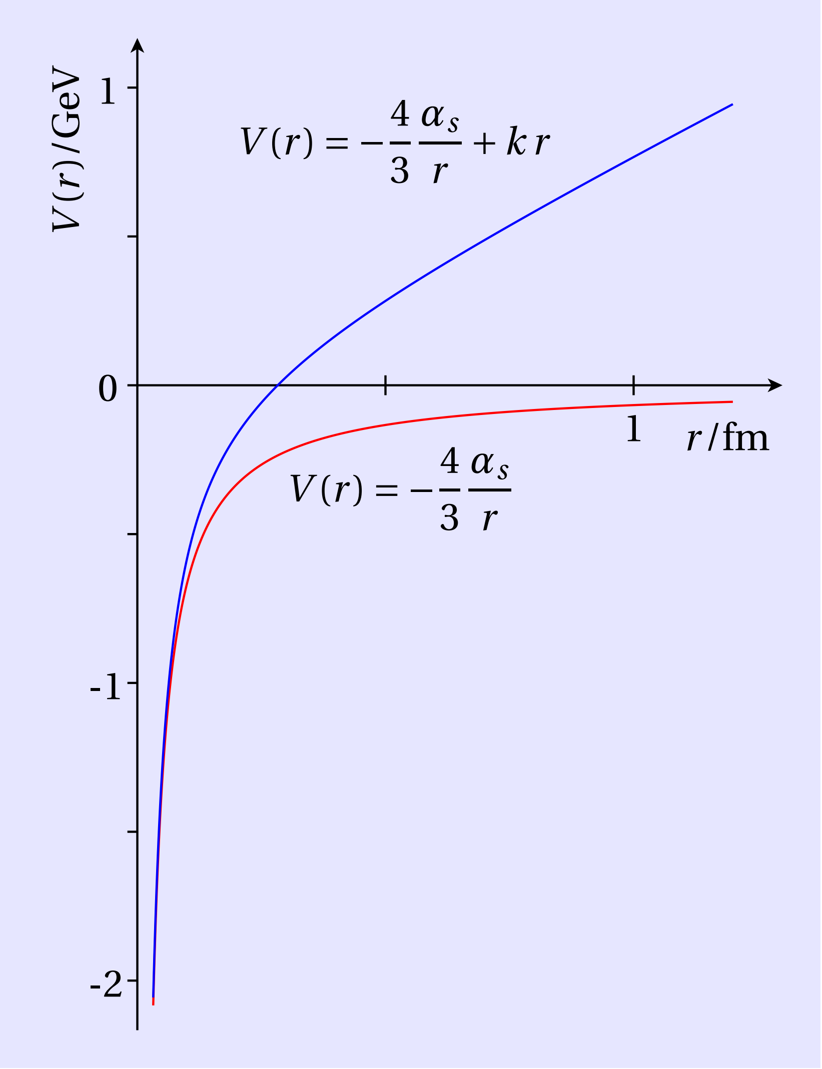
Simple Model: Non-relativistic Potential Model

Non-relativistic $q\bar{q}$ potential:

$$V(\vec{r}) = -\frac{4}{3}\frac{\alpha_s}{r} + k \cdot r$$

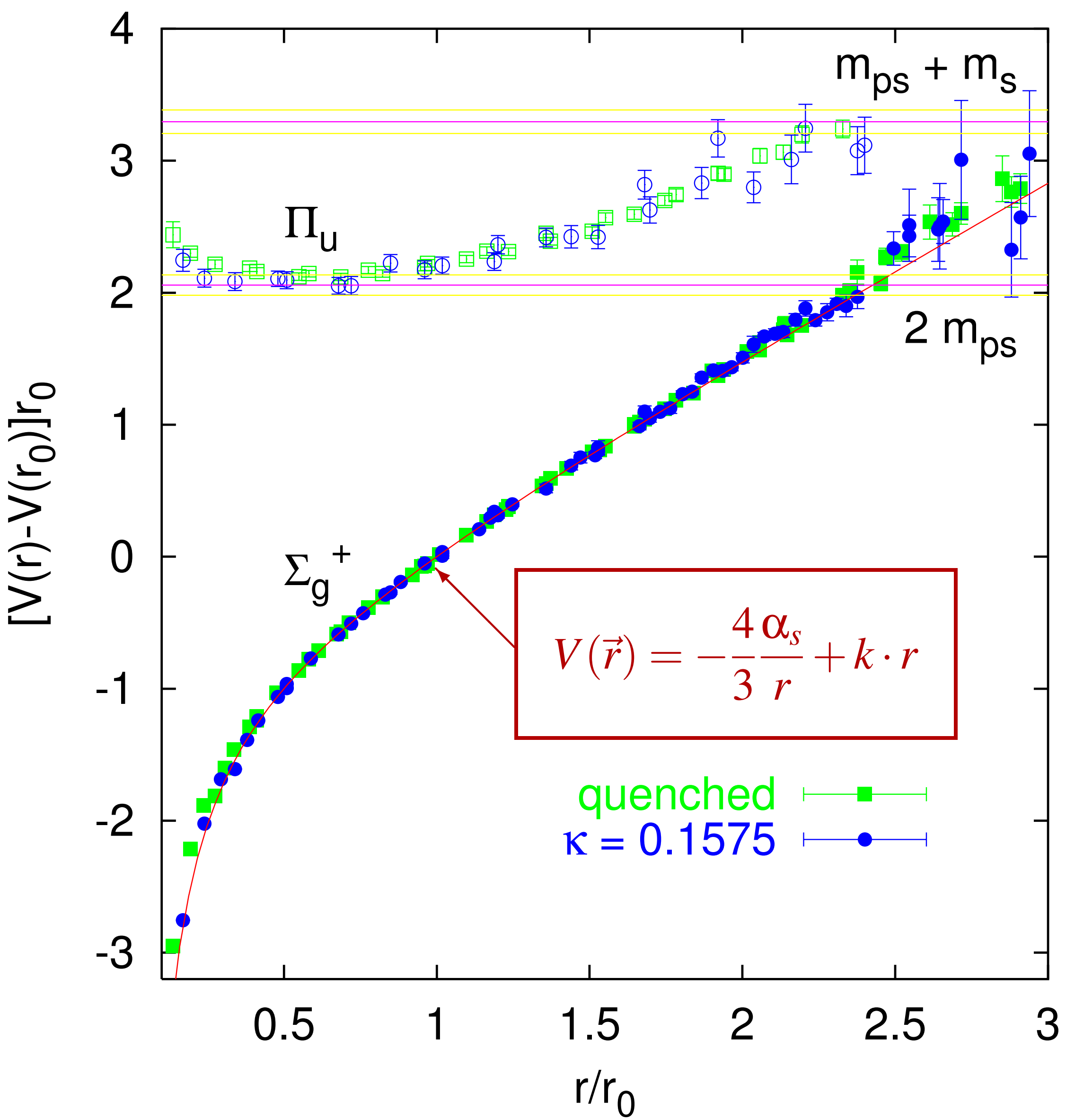
Running Coupling constant:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - n_f)\log\left(\frac{Q^2}{\Lambda^2}\right)}$$



n_f:	number of flavours
$\Lambda \approx 0.2\,$GeV:	QCD Scale parameter
$k \approx 1\,\frac{\text{GeV}}{\text{fm}}$:	QCD String constant

$q\bar{q}$ Potential from Lattice calculation



Quenched approximation, *i.e.* no disconnected quark loops

G. S. Bali et al., PRD62 (2000)

Other usefull Ingredients: Spin Dependent Potential

Neccessary extensions of potential model:

- Spin-Orbit (fine structure)

$$V_{LS} = \frac{1}{2m_c^2 r}(\vec{L}\cdot\vec{S})\left(3\frac{\mathrm{d}V_V}{\mathrm{d}r} - \frac{\mathrm{d}V_V}{\mathrm{d}r}\right)$$

- Spin-Spin (hyperfine structure)

$$V_{SS} = \frac{2}{3m_c^2 r}(\vec{S}_1\cdot\vec{S}_2)\nabla^2 V_V(r)$$

- Tensor force

$$V_T = \frac{2}{12m_c^2}(3(\vec{S}\cdot\hat{r})(\vec{S}\cdot\hat{r}) - S^2)\left(\frac{1}{r}\frac{\mathrm{d}V_V}{\mathrm{d}r} - \frac{\mathrm{d}^2V_V}{\mathrm{d}r^2}\right)$$

with V_V, V_S vector and scalar part of the previous potential

Finding Hadrons

$\Rightarrow$ Just looking for Bumps?

What is a Bump? The Line Shape:

- Strong Decay $\Rightarrow$ Lifetime $\tau \approx 10^{-23}$ s
  $\Rightarrow$ Width $\Gamma_0 \approx 100\,\frac{\text{MeV}}{c}$

- Breit-Wigner Amplitude (complex mass in Dirac-propagator)

$$BW(m) = \frac{\Gamma_0/2}{m_0 - m - i\Gamma_0/2}$$

valid for $\Gamma_0 \ll m_0$
$m_0 \gg$ Threshold Energy

- Better (relativistic, orbital momentum, phase space included):

$$BW(m) = \frac{m_0\Gamma(m)}{m_0^2 - m^2 - i m_0 \Gamma(m)}$$

with $$\Gamma(m) = \Gamma_0 \frac{m_0}{m}\frac{p}{p_0}\frac{F_l^2(p)}{F_l^2(p_0)}$$

angular momentum barrier:

$$F_0(p) = 1$$

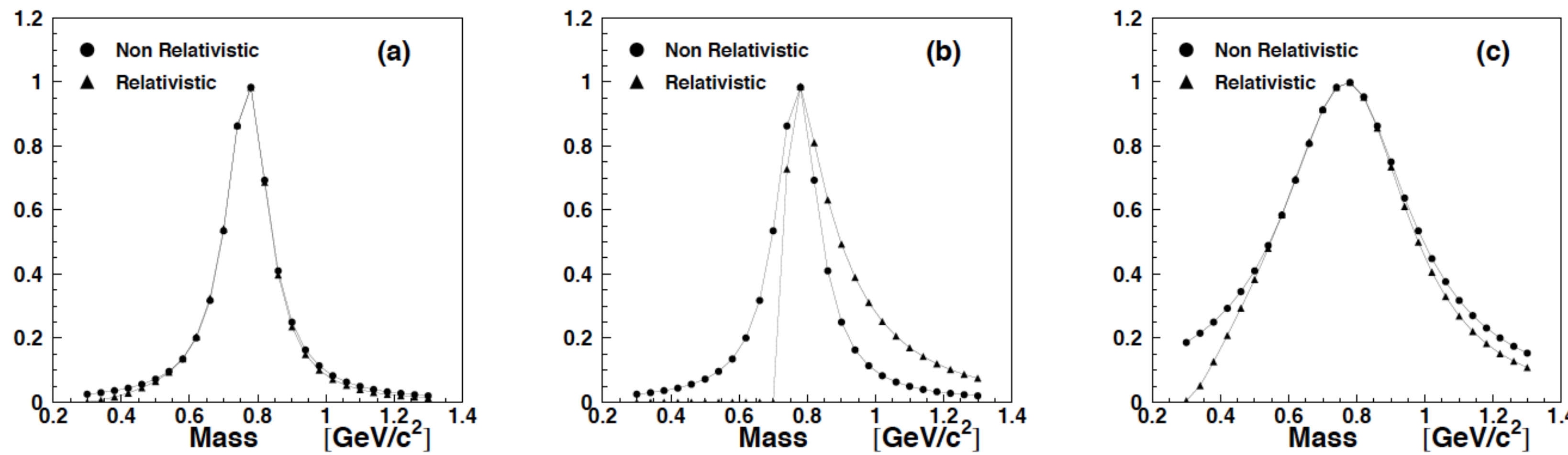
$$F_1(p) = \sqrt{2z/(z+1)}$$

with $z = (p/p_R)^2$

$$F_2(p) = \sqrt{13z^2/((z-3)^2+9z)}$$

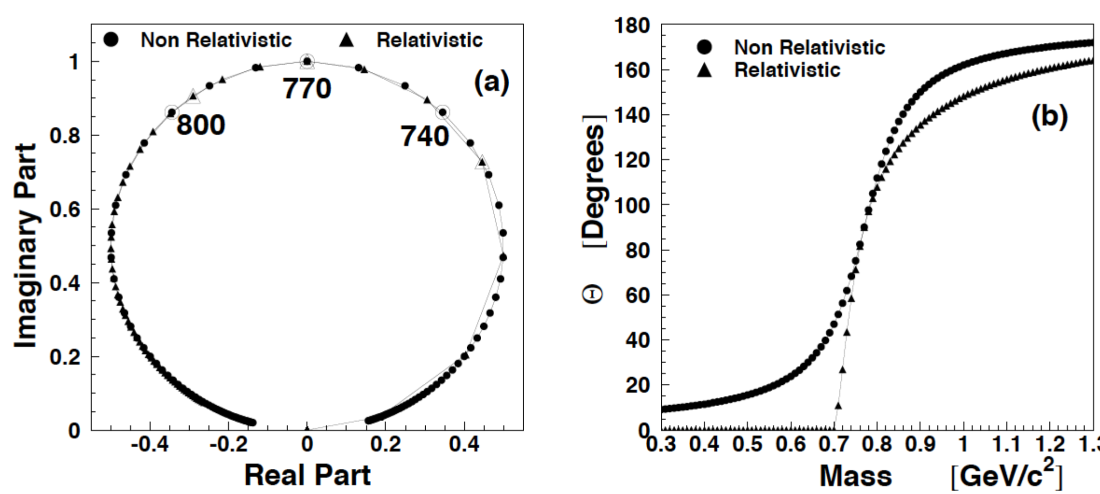
$$\ldots$$

Example $\rho(770)$

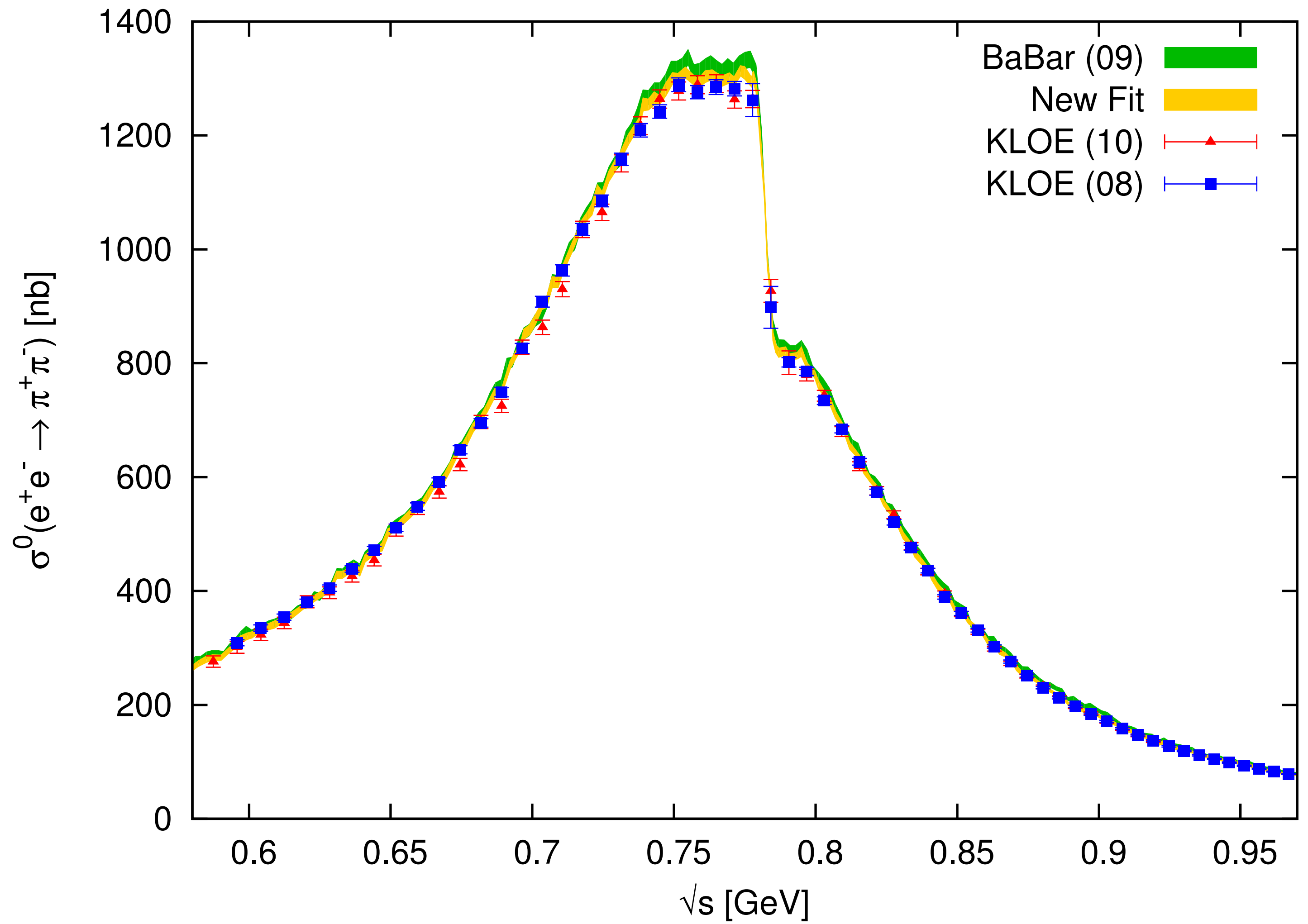


$\Gamma_0 =$	150 MeV	150 MeV	350 MeV
$m_1 = m_2 =$	140 MeV	350 MeV	140 MeV

Argand-Diagramm:



Reality Check: $\rho \to \pi^+\pi^-$



no clean Breit-Wigner $\to$ $\rho - \omega$ interference at the position of the ω mass

$\to$ amplitude and phase changed

$\Rightarrow$ all open channels have to be considered on complex amplitude level!

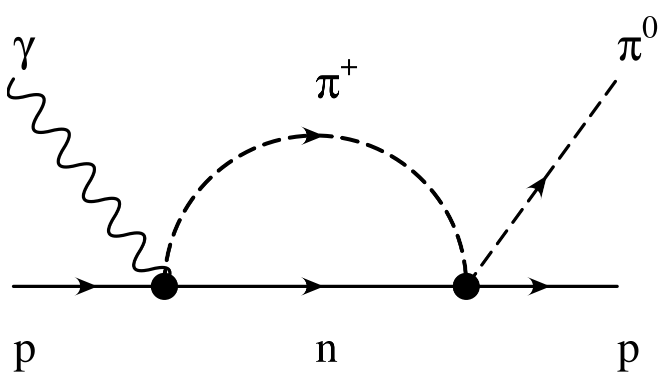
Coupled channels

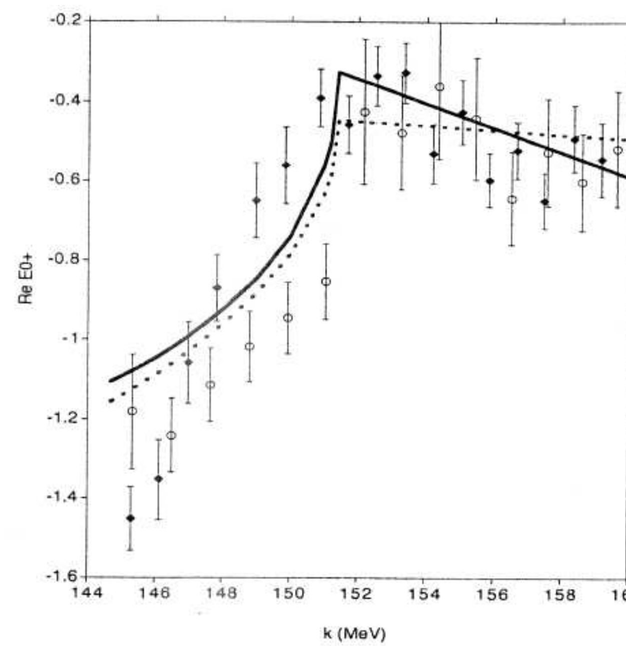
Simplest Example: proton around the pion production threshold
three open channels: $\gamma + p$, $n + \pi^+$, $p + \pi^0$

- Scattering matrix (S-Matrix) of complex transition amplitudes:

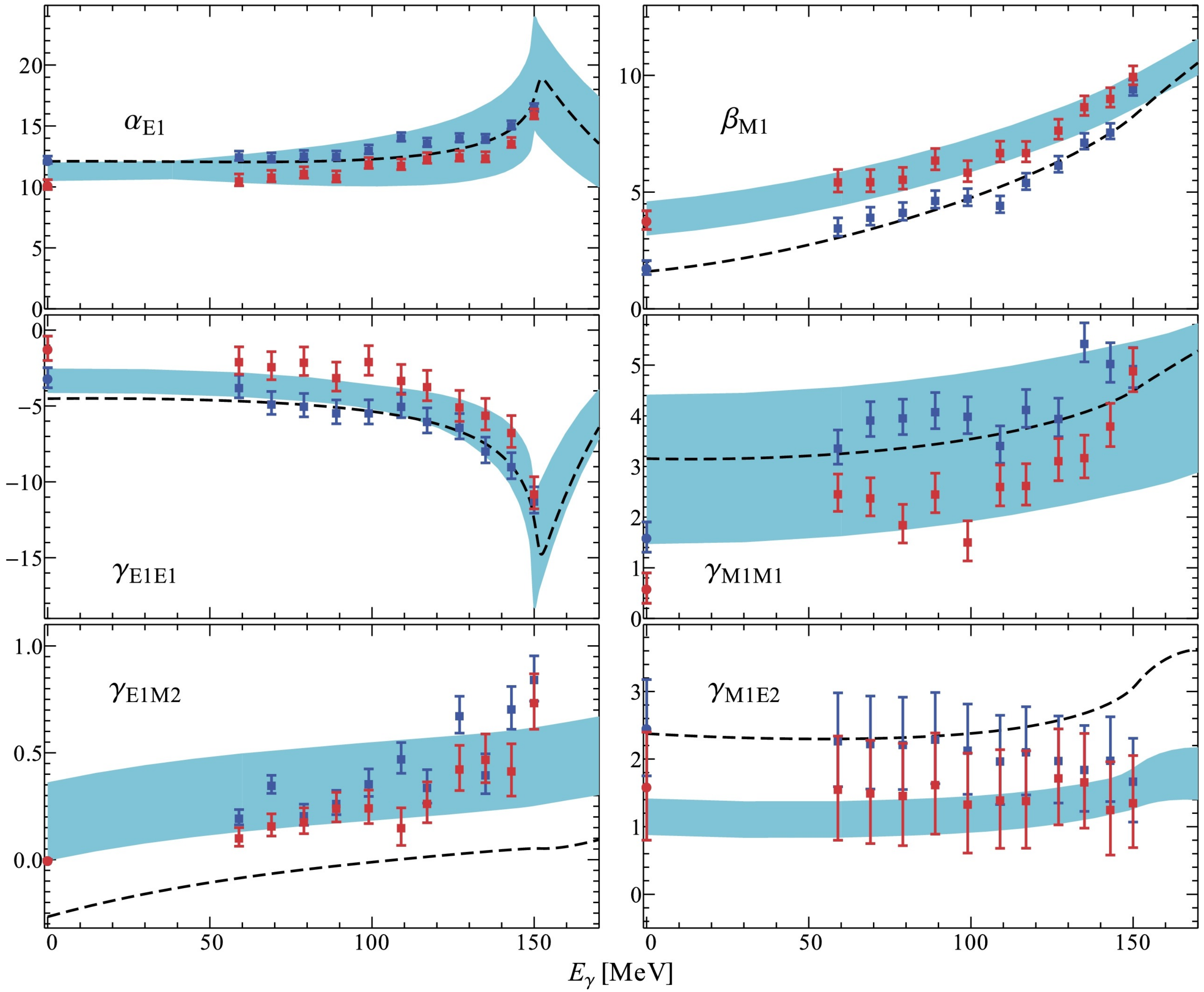
$$\begin{pmatrix} p+\gamma \\ n+\pi^+ \\ p+\pi^0 \end{pmatrix}_{\text{final}} = \begin{pmatrix} A_{\gamma\gamma} & A_{\gamma\pi} & A_{\gamma\pi} \\ A_{\gamma\pi} & A_{\pi\pi} & A_{\pi^+\pi^0} \\ A_{\gamma\pi} & A_{\pi^+\pi^0} & A_{\pi\pi} \end{pmatrix} \cdot \begin{pmatrix} p+\gamma \\ n+\pi^+ \\ p+\pi^0 \end{pmatrix}_{\text{initial}}$$

- Conservation of Probability ⇔ Unitarity of S-matrix
- All channels are seen in all other channels
- $\gamma + p \to p + \pi^0$, s-wave:





Polarizabilities in Compton Scattering (partial waves):



Is the Scattering Phase an Observable?

Quantum-mechanics: An absolute phase is not measureable!

But:

- Elastic scattering: optical Theorem

$$\sigma = \frac{4\pi}{k} \mathrm{Im}\{f(\theta = 0)\}$$

- Elastic phase is a *transition phase*
- Direct measureable at forward direction ($\theta = 0$) in

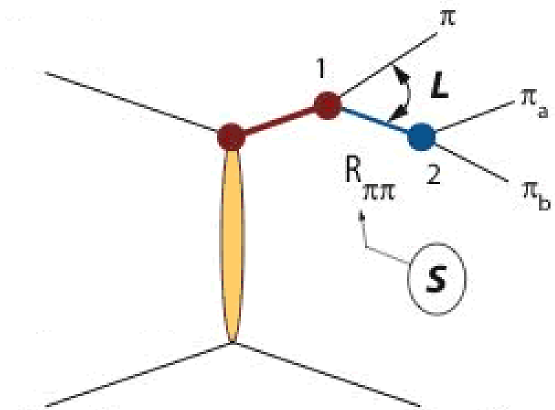
$$\gamma + p \to \gamma + p$$
$$\pi^+ + n \to \pi^+ + n$$
$$\pi^0 + p \to \pi^0 + p \qquad \text{(not measured yet...)}$$

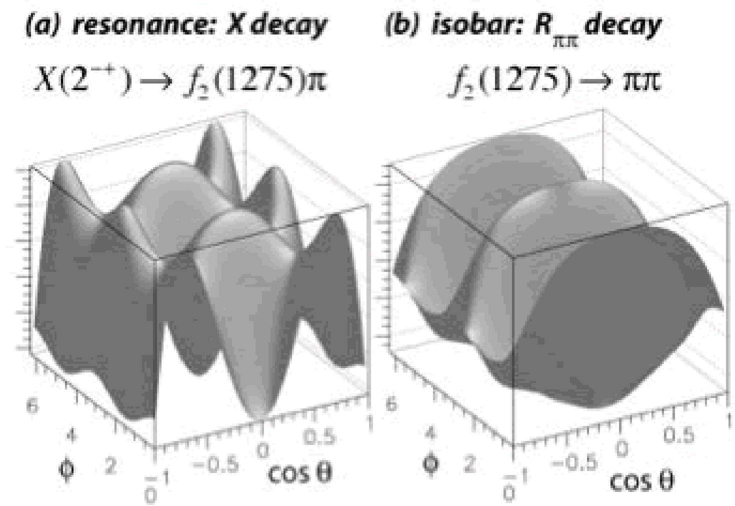
- Unitarity of S-matrix fixes phase of *all scattering amplitudes*

$\Rightarrow$ Scattering amplitudes have relative phases (inital state $\to$ final state)!

$\Rightarrow$ Production amplitudes are also **Observables** (but in reality hard to determine absolute)

The Art of Partial Wave Analysis





- Limited significance of single channels (even if this presentation is “standard” in talks...)
- All open channels have to be fitted simultanously
- Separate for every angular momentum (Partial Wave)
- Fit on *Amplitude* level (not cross section!)
- Polarization degrees of freedom
- Resonances: Breit-Wigner width (line shape, pole position), mass
- Background contributions
- Combinatorical background
- ...

Hundreds of parameters, most determined with limited significance

...choose wisely

I only believe in peaks seen

. . . in several channels

. . . by different groups,

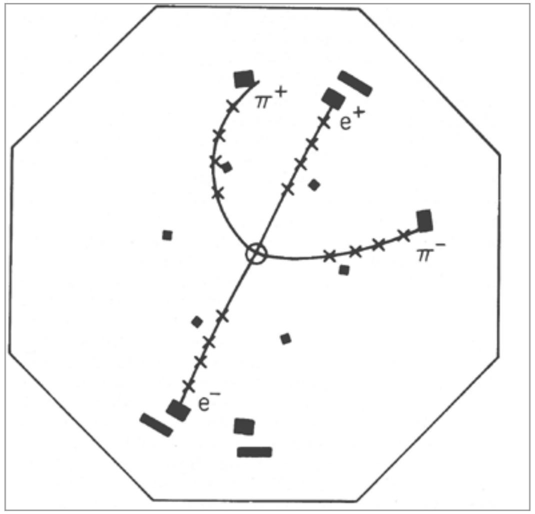
. . . measured with different apparatus,

. . . with different analysis

and still I have doubts...

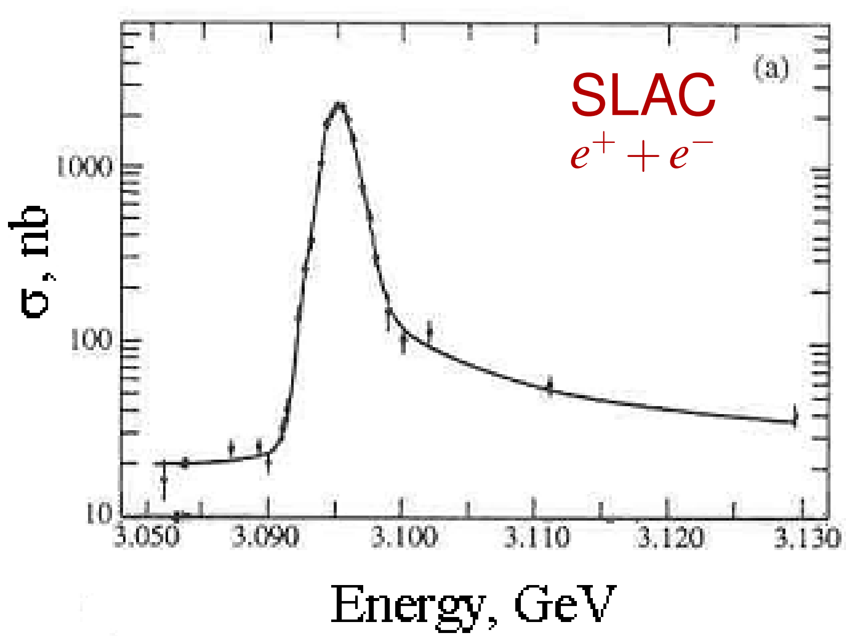
Heavy Quark Mesons

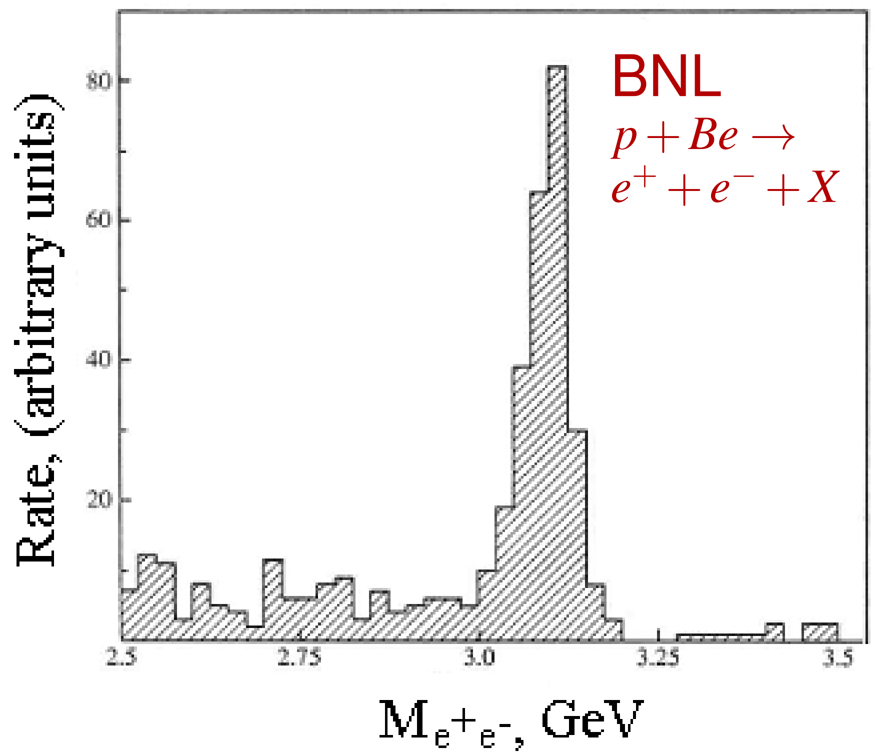
The J/ψ discovery



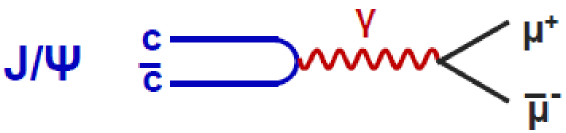
- Simultanious discovery 1974 in BNL and SLAC
- First evidence of a new quark: charm
- Confirmation of quark model (c missing partner of s)
- Bound state of $c\bar{c}$ quarks

$\Rightarrow$ new era of heavy quark physics

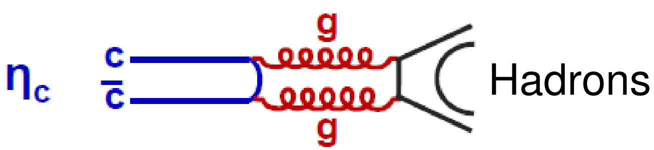




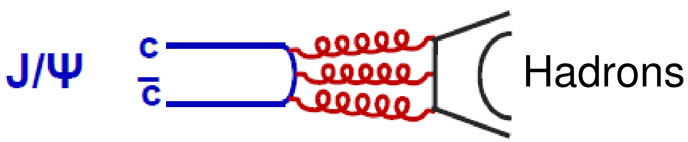
Below open charm threshold:



$J^{--} \Rightarrow$ electromagnetic decay possible



States with $C = +1$ can decay via two gluons

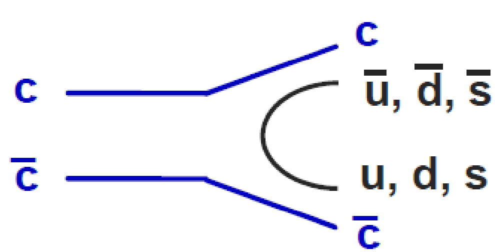


States with $C = -1$ can only decay via three gluons

$\Rightarrow$ electro-magnetic decay of same order of magnitude as strong decay

$\Rightarrow$ J/ψ is a very small resonance

Above open charm threshold:



$\Rightarrow$ broad resonances

Heavy Quark Systems

Heavy Quarks:

$$m_c = 1.3\,\mathrm{GeV} \qquad m_b = 4.2\,\mathrm{GeV} \qquad m_t = 170\,\mathrm{GeV}$$

- Heavy Quark Systems are *non-relativistic*:

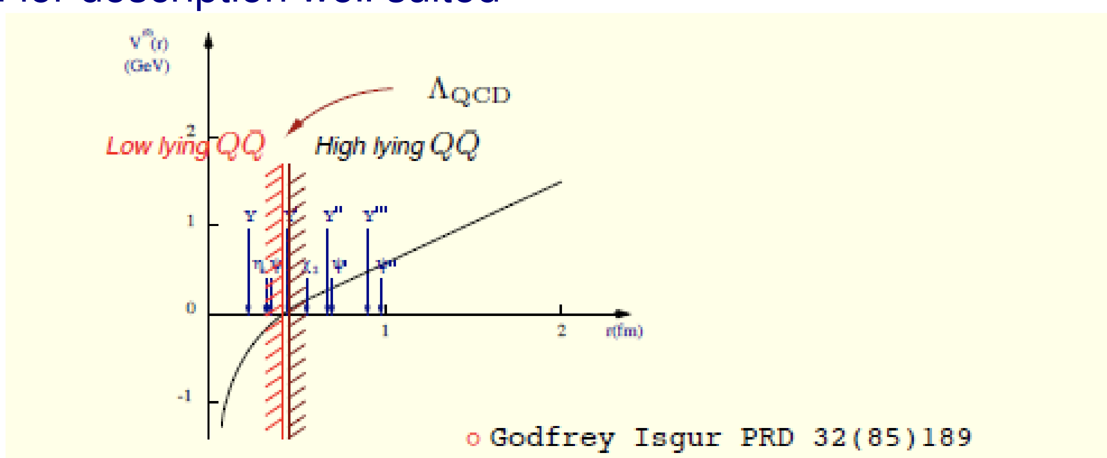
$$m_{J/\psi} = 3.1\,\mathrm{GeV} = 2\times m_c + 2\times 0.25\,\mathrm{GeV}$$

$$\Rightarrow \qquad \beta = \frac{p}{E} \approx \frac{0.25\,\mathrm{GeV}}{1.3\,\mathrm{GeV}} = 0.2$$

- The mass scale is *perturbative*:

$$m_Q \gg \Lambda_{QCD}$$

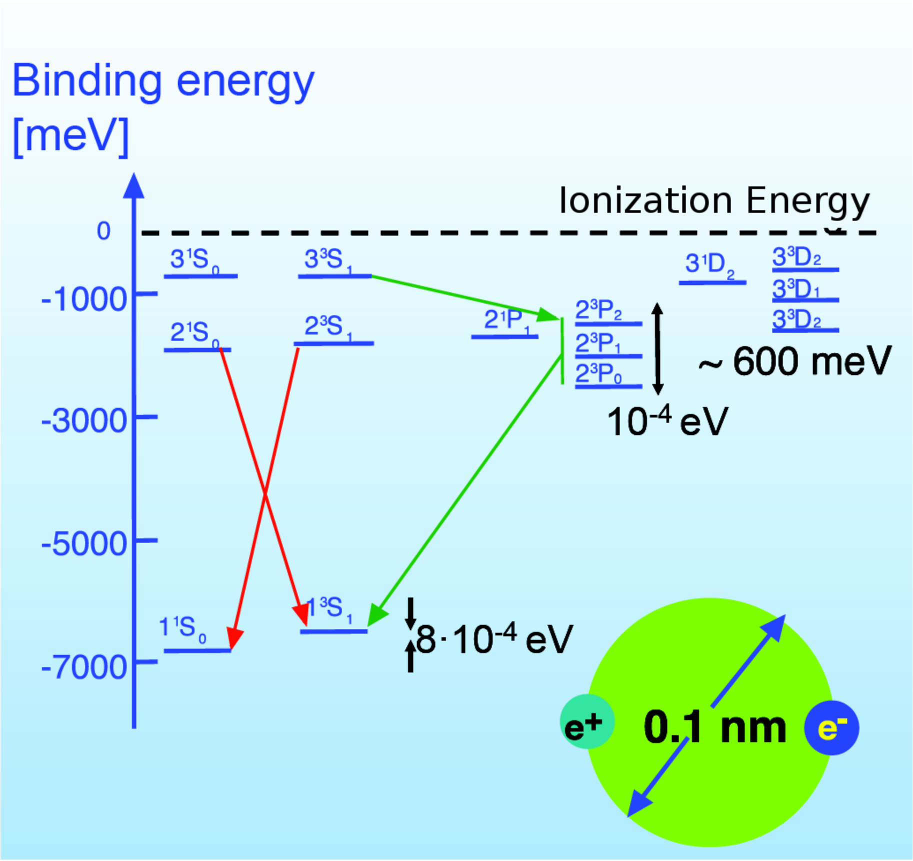
- Potential model for description well suited



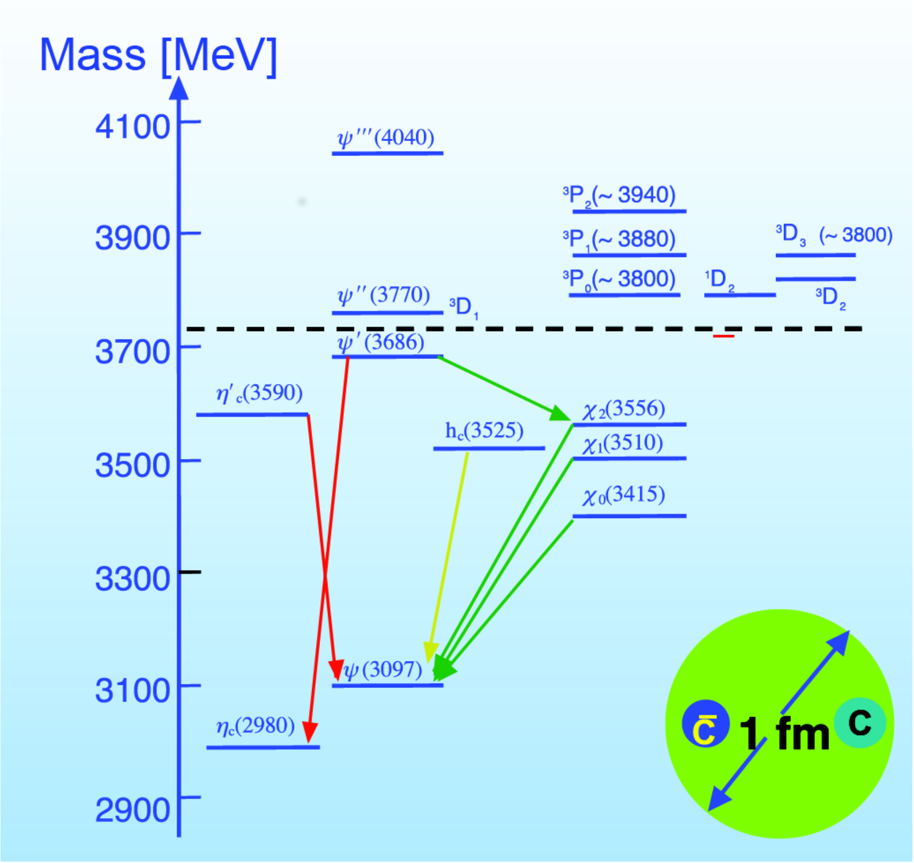
non-perturbativ – transition – perturbative regime

Positronium as Model for Quarkonium (Charmonium or Bottomonium)

Positronium

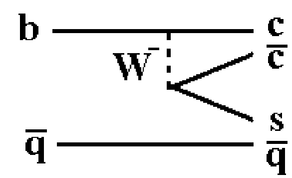


Charmonium



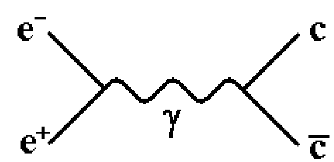
Production channels

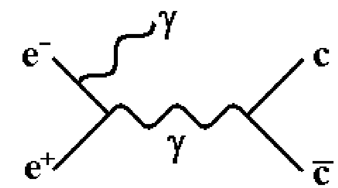
- Weak decay



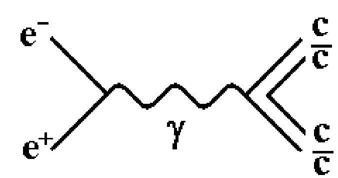
Belle

- e^+e^- annihilation and initial state radiation
  - only $J^{PC} = 1^{--}$
  - $0 <$E$<$c.m. energy



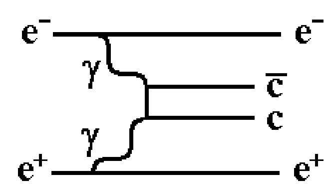


- Double Charmonium
  - $J/\psi + c\overline{c}$

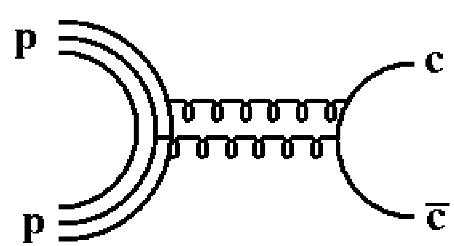


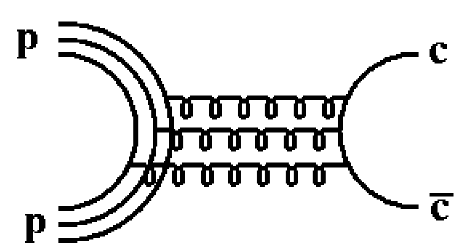
BES III

- Two-photon production
  - $C = +1$



- $p\overline{p}$ annihilation
  - 2 gluons: 0^{-+}, 0^{++}, 2^{++}
  - 3 gluons: 1^{--}, 1^{-+}

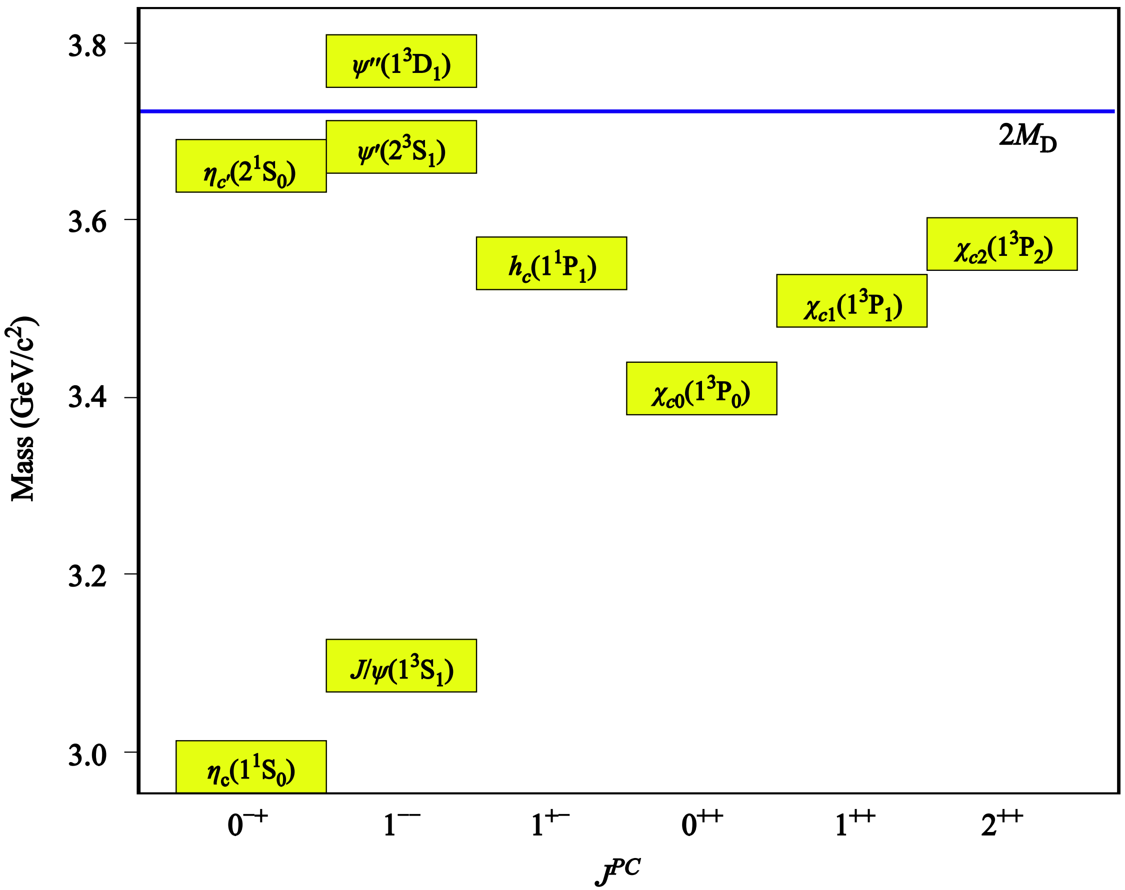




PANDA

Charmonium States below open charm threshold

Discovered Charmonium States:



- Solution of non rel. Schrödinger-Equation
- Notation:

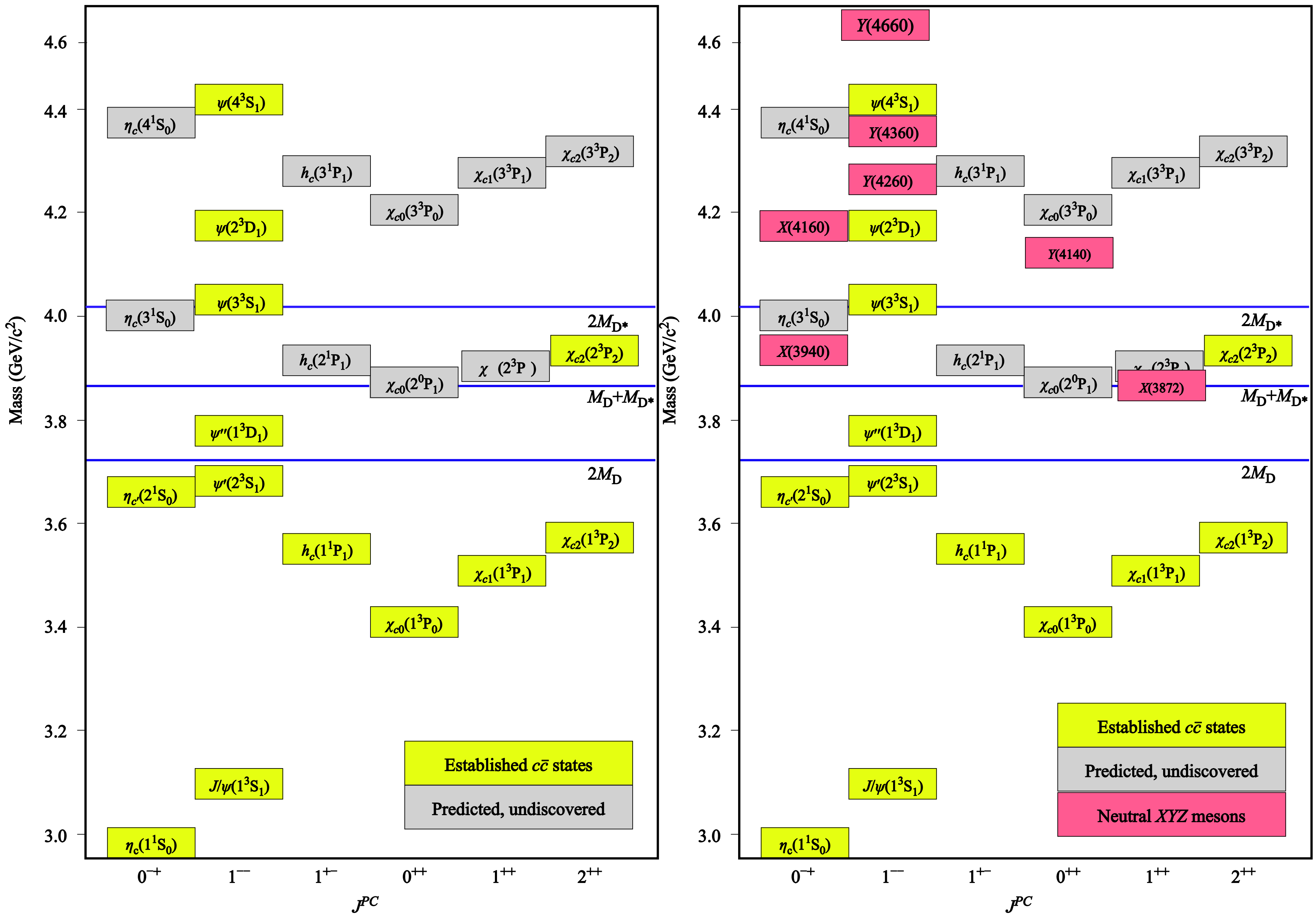
0^{-+}	1^{--}	1^{+-}	J^{++}
η_c	ψ	h_c	$\chi_{1,2,3}$

- 8 States well established
- Hyperfine splitting to adjust spin dependent potential V_{SS}

$$\Delta m_{hf}(1S) = m(J/\Psi) - m(\eta_c) = 116\,\text{MeV}$$

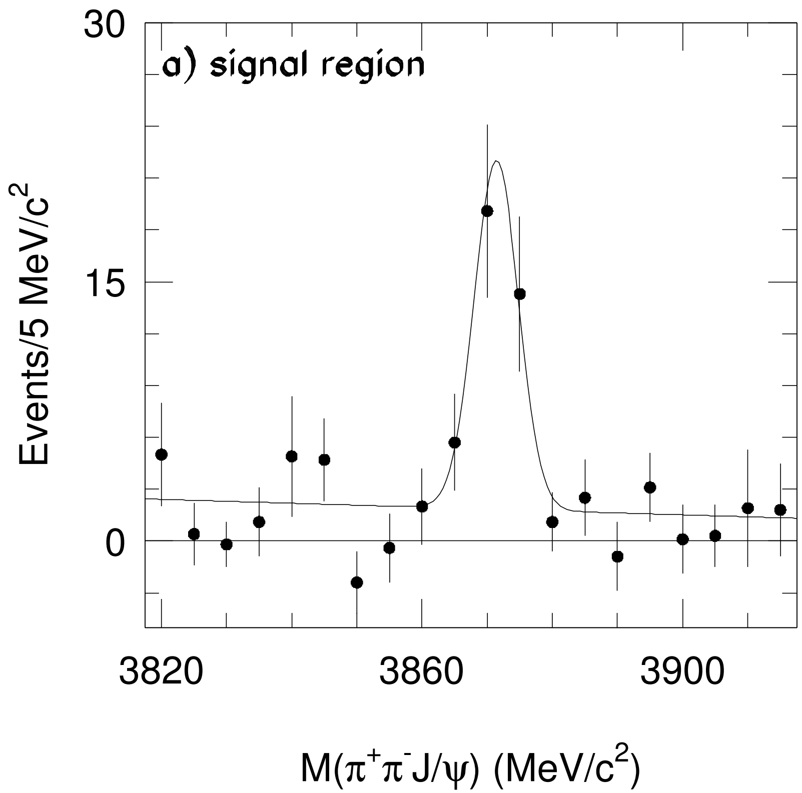
- Look for
  - Missing States
  - Additional States

Charmonium Spectrum



The $X(3872)$ (new PDG2018 naming scheme: $\chi_{c1}(3872)$)

Belle (2013): A new state, not quite fitting into spectrum:



Discovery channel:

$$e^+e^- \to \Upsilon(4S) \to B^+B^-$$
$$B^+ \to K^+ \underbrace{\pi^+\pi^- J/\psi}_{\text{subsystem}}$$

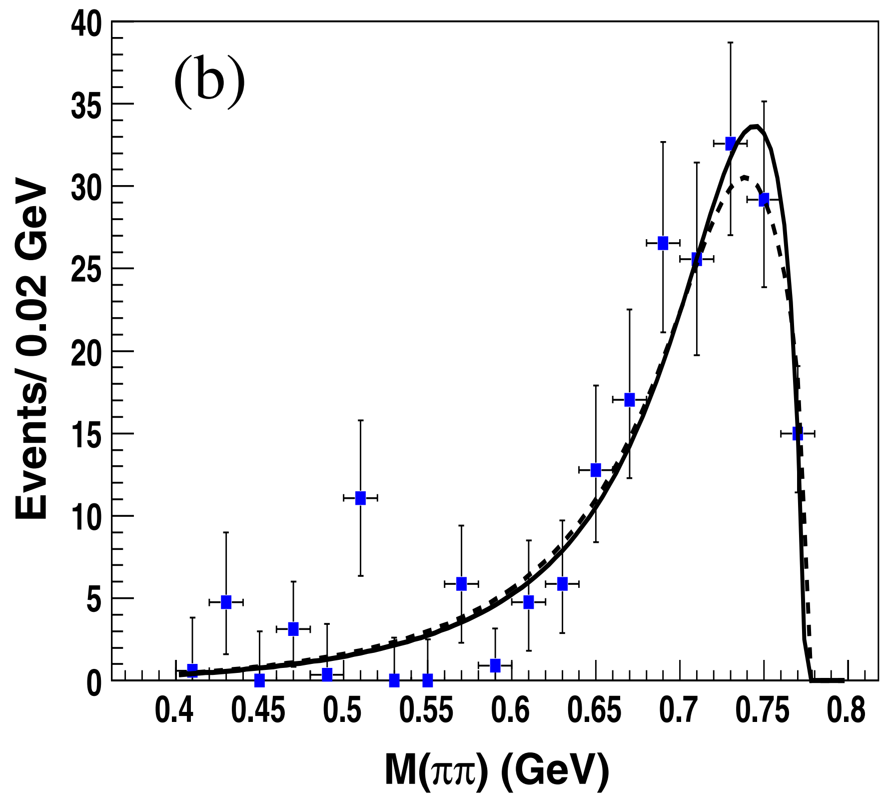
- Decay to J/ψ: $c\bar{c}$ content neccessary
- Isospin: Decay via $\rho \to \pi^+\pi^-$ or $\omega \to \pi^+\pi^-$
- ρ decay is isospin violating $\to$ suppressed
- Both channels are of same order

$\Rightarrow$ additional u and d content?

- Resonance confirmed by BaBar, BES, CDF, D0, LHCb, ...
- LHCb: Quantum Numbers $J^{PC} = 1^{++}$, $I = 0$ (these are not exotic!)

$X(3872)$ Decay to $\rho J/\psi$

$$X(3872) \rightarrow \rho + J/\psi$$
$$\rho \rightarrow \pi^+ + \pi^-$$



- Two Pion distribution described by Breit-Wigner with known $\rho(770)$ width
- Violates Isospin conservation $\Rightarrow$ at least two gluons
- Should be suppressed compared to decay via $\omega \rightarrow \pi^+\pi^-\pi^0$

Interpretations of the $X(3872)$

$X(3872)$ Properties

- Mass is very close to open charm threshold $\overline{D}_0 D_0*$
- Width is very narrow $< 1.2\,$MeV
- small binding $\Rightarrow$ huge separation
- Decays to $\rho J/\psi$
- Decays to $\omega J/\psi$
- Decays dominant to $\overline{D}_0 D_0*$

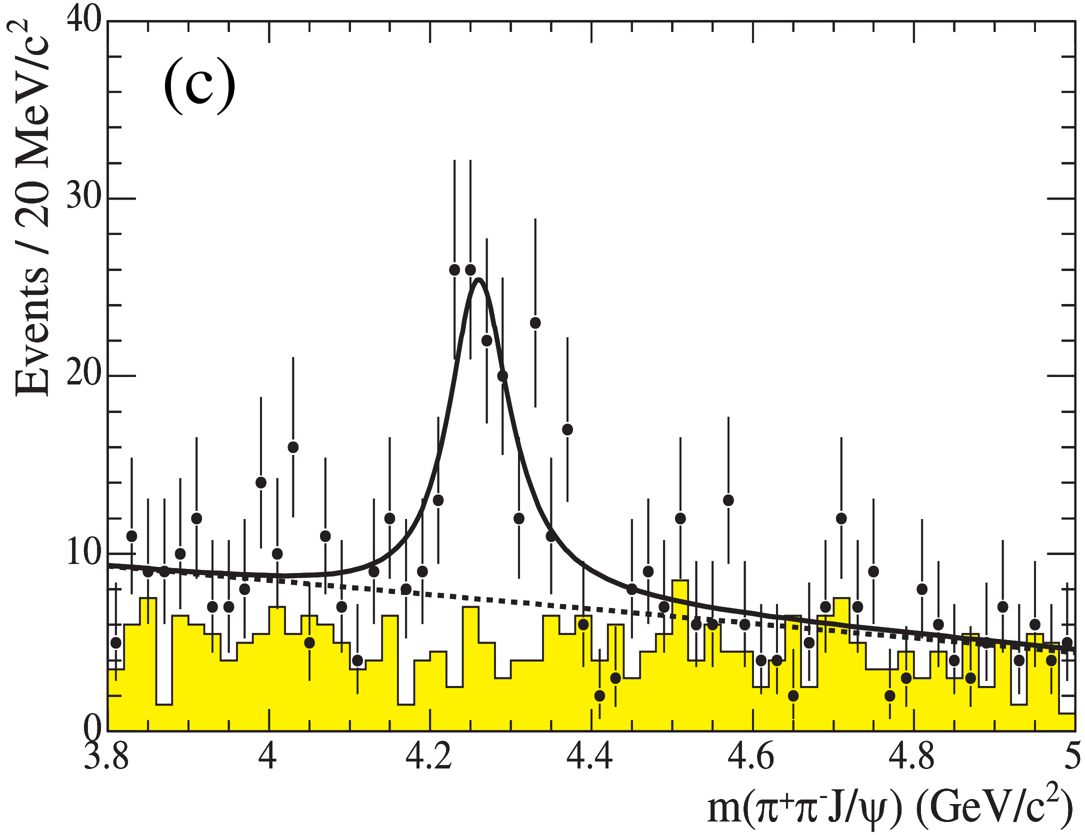
Interpretation:

- Exotic nature? Probably...
- Many interpretations on the market
- Loosely bound $\overline{D}_0 D_0*$ molecule?

$Y(4260)$

BaBar (2005) via Initial State Radiation

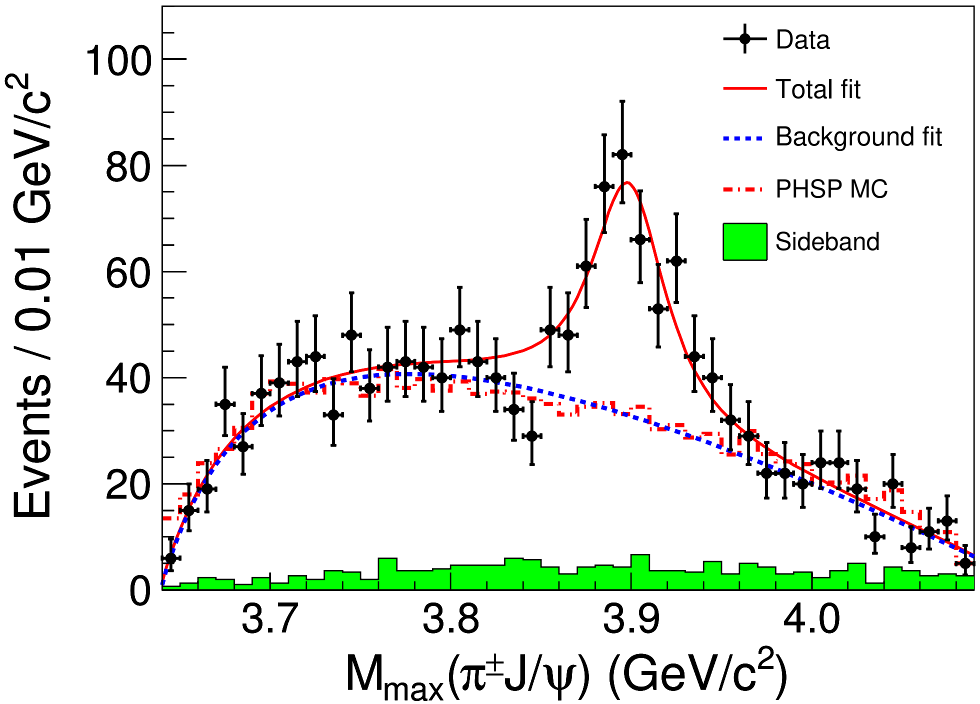
$$e^+ e^- \rightarrow \gamma_{ISR}\, \pi^+ \pi^- J/\psi$$



- Quantum numbers are now $J^{PC} = 1^{--}$
- Confirmed by CLEAO, CLEOIII, Belle, BESIII
- Weak coupling consistent with hybrid meson

$Z_c^+(3900)$

BES III (2013)



$$e^+e^- \to \pi^- \underbrace{\pi^+ J/\psi}_{\text{subsystem}}$$

- Decay to J/ψ:
  $\Rightarrow c\bar{c}$ content neccessary
- Charged!!!!!!
  $\Rightarrow$ at least $c\bar{c}u\bar{d}$

Status:

- Confirmed by several experiments
- Several states
- also Z_b^+ states seen
- PDG 2018 naming scheme:

X	now χ	Isospin 0
Y	now ψ	
Z		Isospin 1

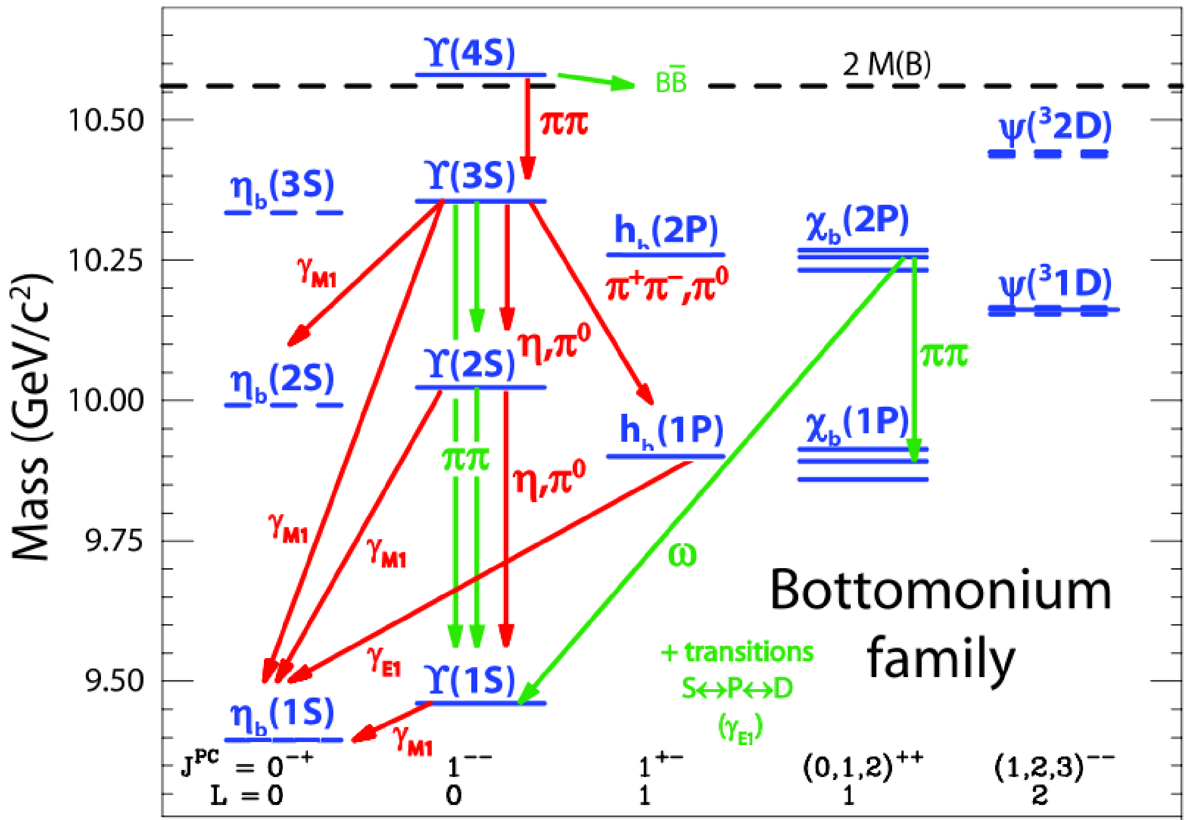
Growing number of states...

Particle Data Group (2018): States near open $c\bar{c}$ or $b\bar{b}$ threshold

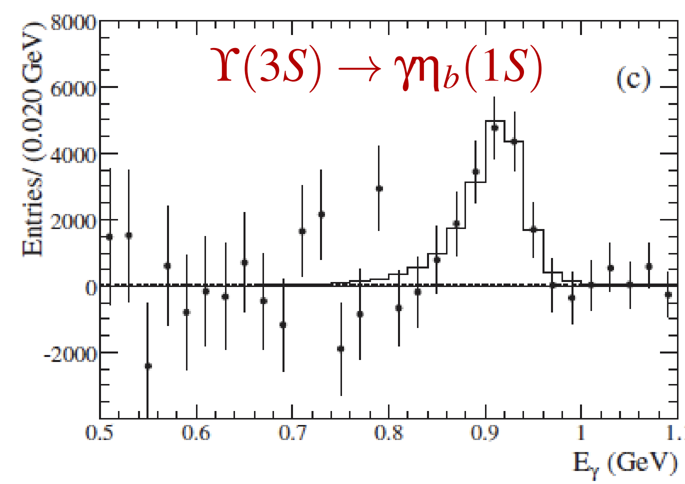
PDG Name	Former/Common Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\chi_{c1}(3872)$	$X(3872)$	3871.69±0.17	< 1.2	$0^+(1^{++})$	$B \to KX$ $p\bar{p} \to X...$ $pp \to X...$ $e^+e^- \to \gamma X$	$\pi^+\pi^- J/\psi$ $3\pi J/\psi$ $D^{*0}\overline{D}^0$ $\gamma J/\psi$ $\gamma\psi(2S)$	2003	YES
$Z_c(3900)$		3886.6 ± 2.4	28.2 ± 2.6	$1^+(1^{+-})$	$\psi(4260) \to \pi^- X$ $\psi(4260) \to \pi^0 X$	$\pi^+ J/\psi$ $\pi^0 J/\psi$ $(D\bar{D}^*)^+$ $(D\bar{D}^*)^0$	2013	YES
$X(4020)$	$Z_c(4020)$	4024.1 ± 1.9	13 ± 5	$1^+(?^{?-})$	$\psi(4260, 4360) \to \pi^- X$ $\psi(4260, 4360) \to \pi^0 X$	$\pi^+ h_c$ $\pi^0 h_c$ $(D^*\bar{D}^*)^+$ $(D^*\bar{D}^*)^0$	2013	YES
$Z_b(10610)$		10607.2 ± 2.0	18.4 ± 2.4	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$ $\Upsilon(10860) \to \pi^0 X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^0\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B\bar{B}^*)^+$	2011	YES
$Z_b(10650)$		10652.2 ± 1.5	11.5 ± 2.2	$1^+(1^{+-})$	$\Upsilon(10860) \to \pi^- X$	$\pi^+\Upsilon(1S, 2S, 3S)$ $\pi^+ h_b(1P, 2P)$ $(B^*\bar{B}^*)^+$	2011	YES

...and ≈ 25 more unassigned states above threshold

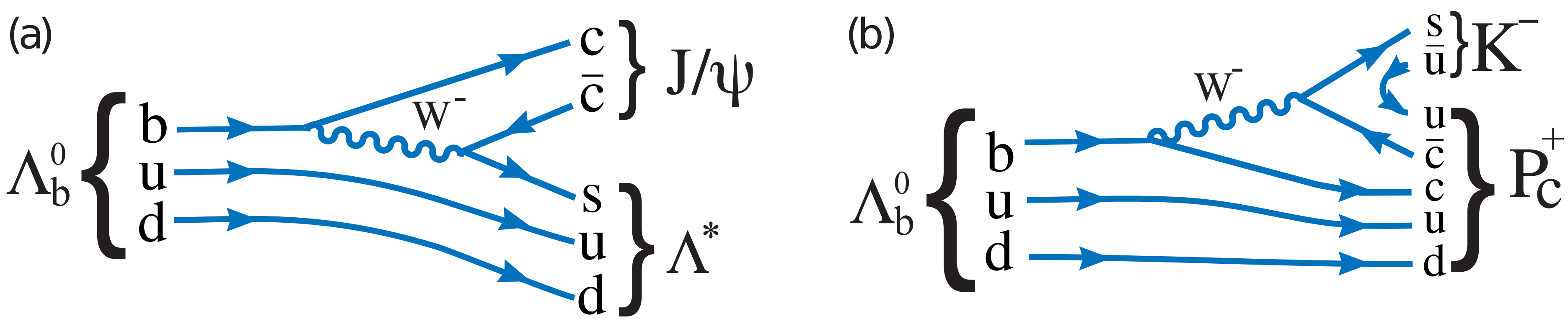
Bottomonium

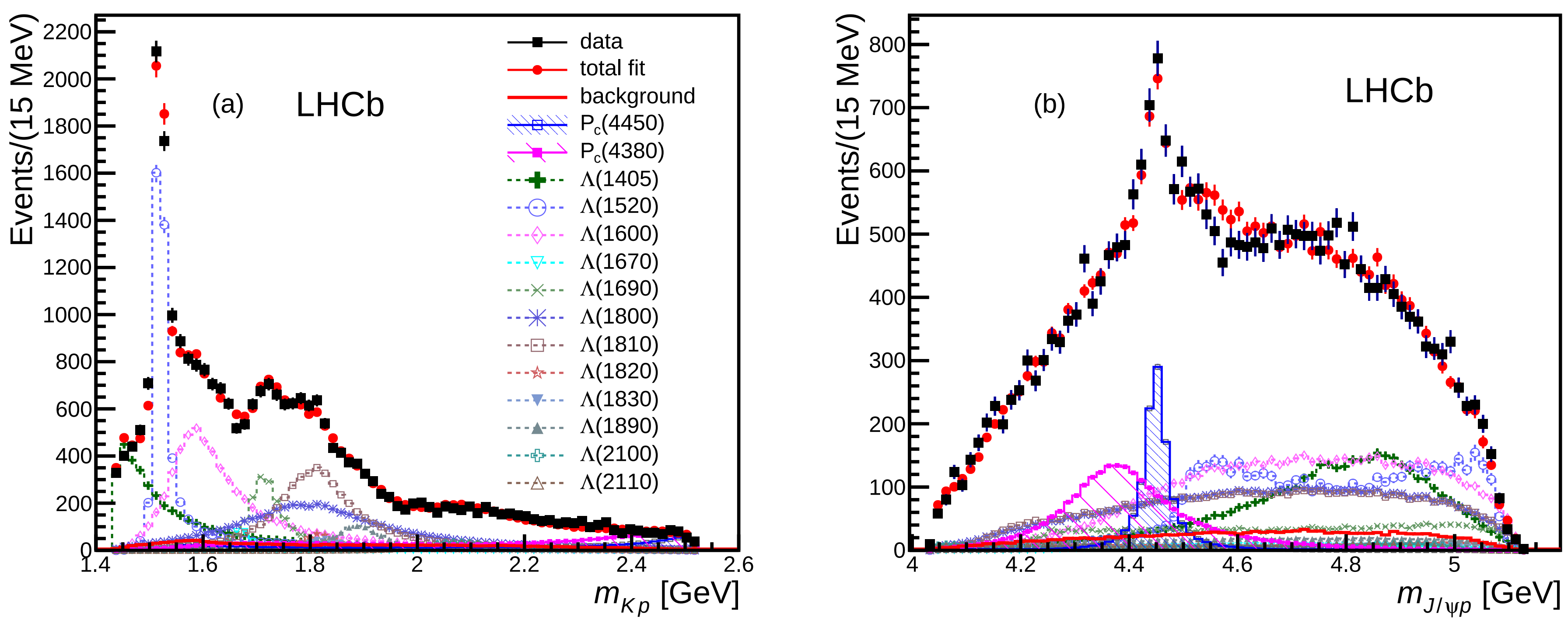


- higher b-quark mass
- lower coupling $\alpha_s(Q^2)$
- dominated by Coulomb term of the potential
- better description by potential models
- ground state $\eta_b(1S)$ discovered 2008



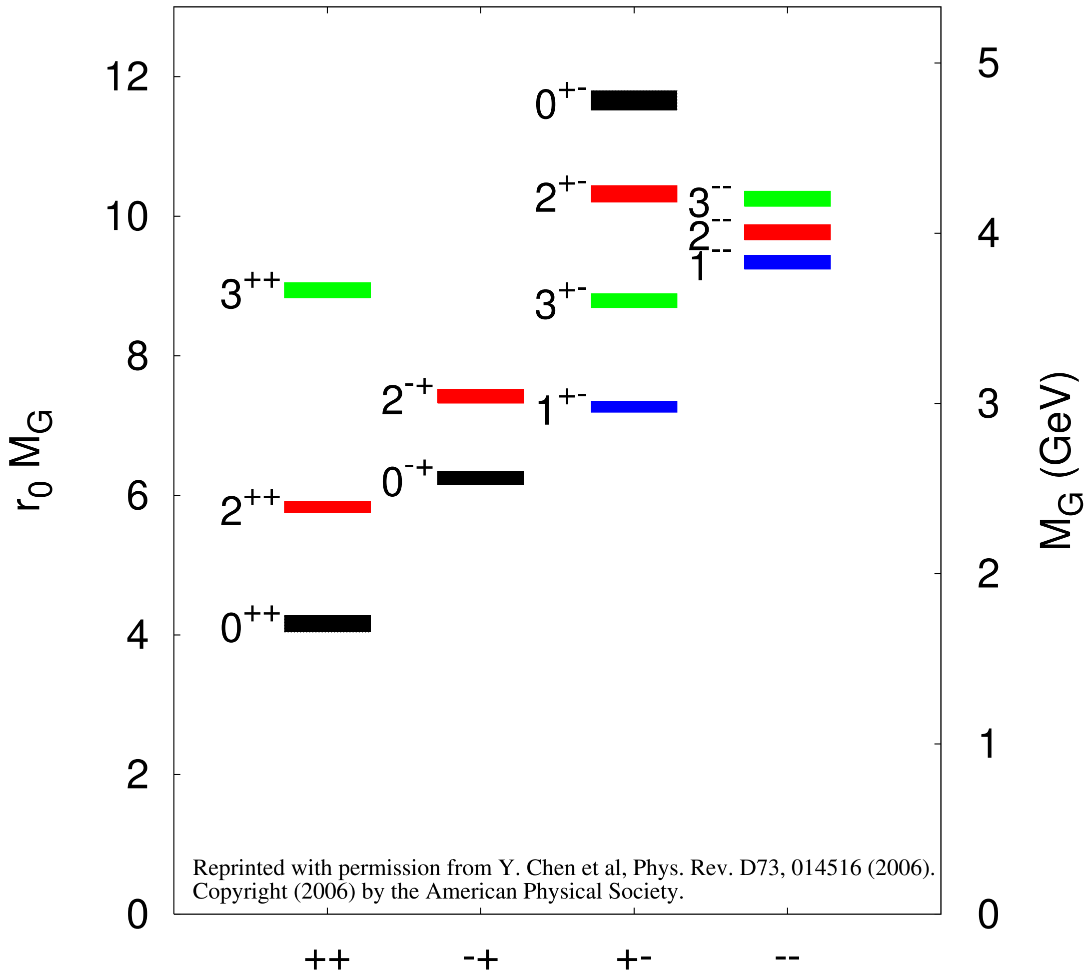
Pentaquark (LHCb 2015)

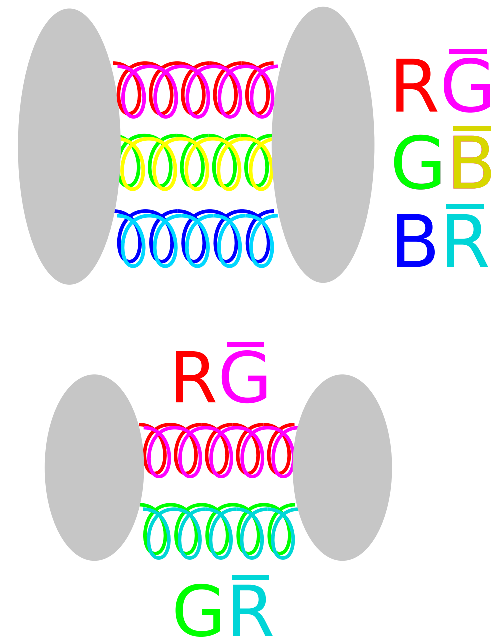




$$\Lambda_b^0 \to J/\psi + K^- + p$$

Glueballs





- Calculable in Lattice QCD
- Predictions:

$$J^{PC} = 0^{++}, 2^{++}$$

- Mixing with scalar mesons $f_0(1370)$
- Candidates $f_0(1500)$, $f_0(1710)$, ...
- No clear signature yet

Strangeness

What can we do with the s-quark?

Is the s-quark a light quark?

- Use $SU(3)$ Chiral Perturbation Theory
- $m_u = 2.2\,\mathrm{MeV}/c \approx m_d = 4.4\,\mathrm{MeV}/c \approx 0$

  $m_s = 96\,\mathrm{MeV}/c$

$\Rightarrow$ ChPT works “fairly well”

Is the s quark a heavy quark?

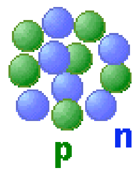
- Use a potential model
- Use constituent quark masses
- $m_\Lambda = 1116\,\mathrm{MeV}/c \Rightarrow m_u = m_d = 300\,\mathrm{MeV}/c; \quad m_s = 500\,\mathrm{MeV}/c \gg 96\,\mathrm{MeV}/c$

$\Rightarrow$ Potential model works “fairly well”

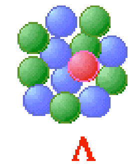
$\Rightarrow$ no precission expected

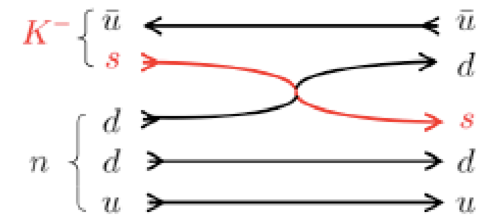
Hypernuclei

Idea: Use strangeness to mark e.g. a single particle in a nuclei!



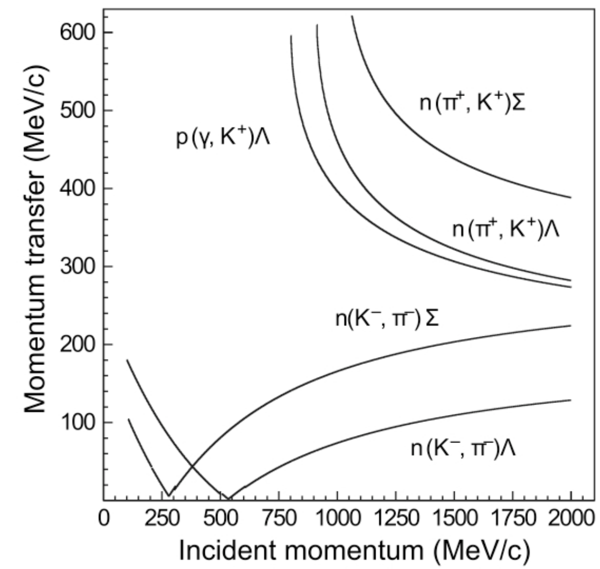
$$K^- + A \to {}_\Lambda A + \pi^-$$



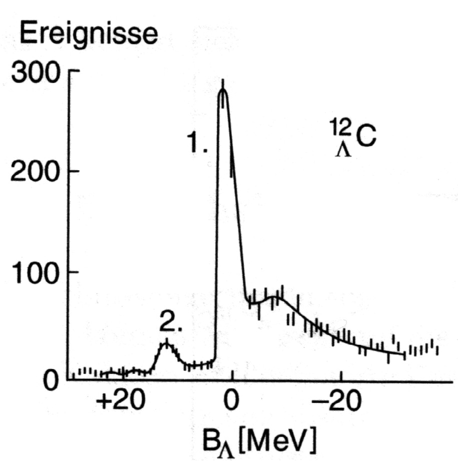


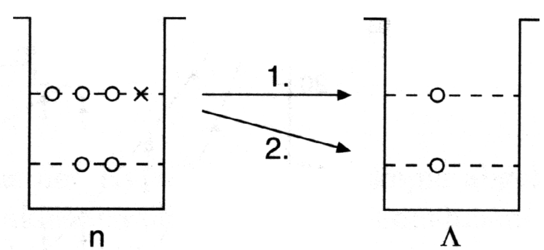
Recoil-less production possible!

$\Rightarrow$ no momentum transfer to the nuclear target

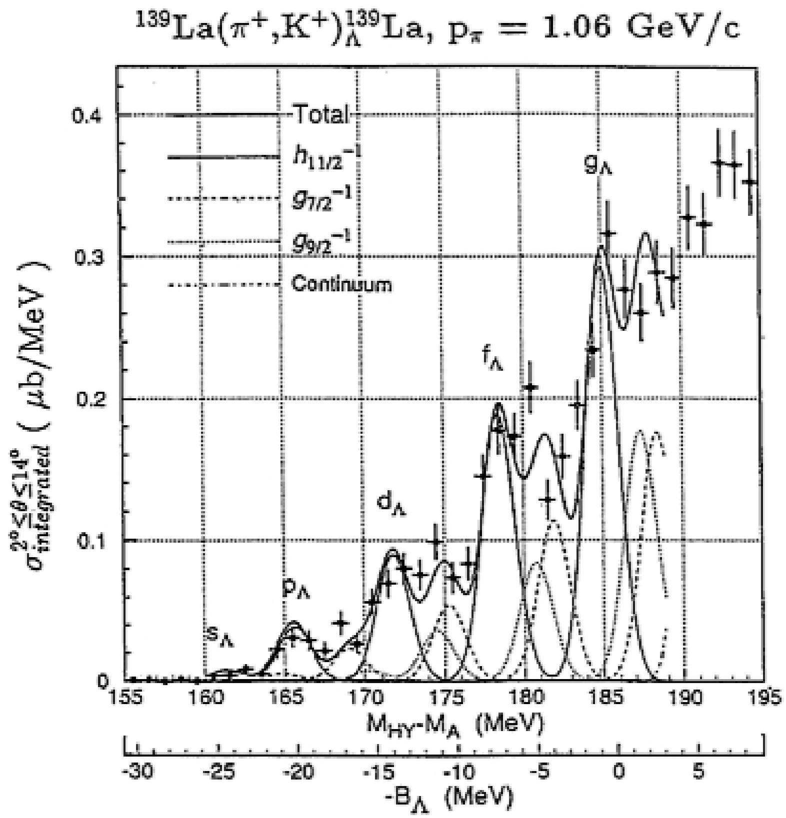


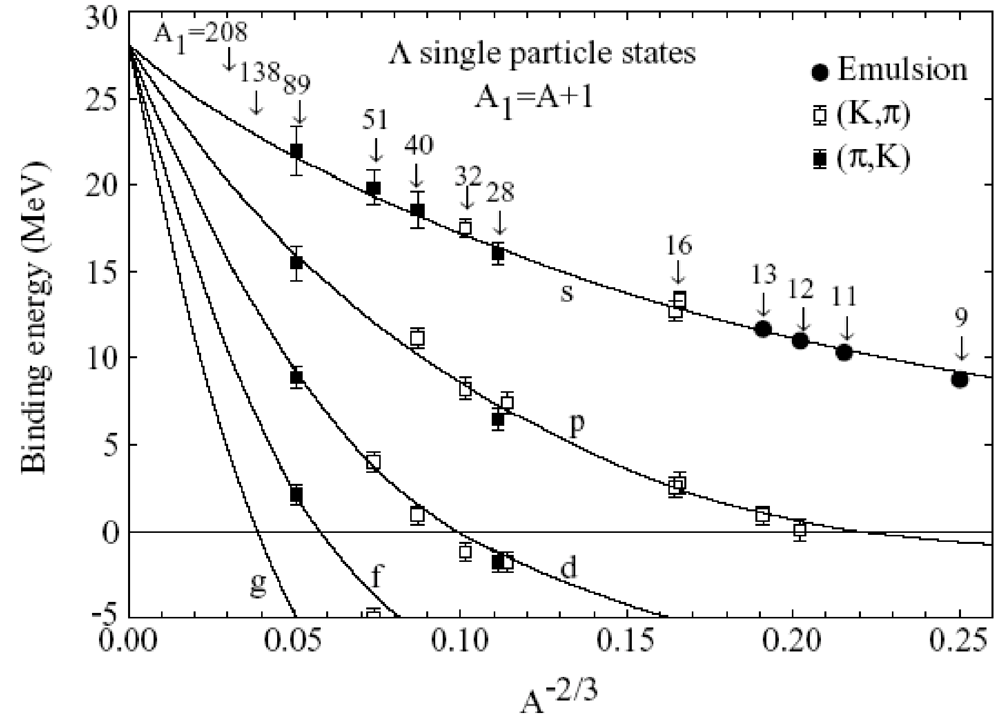
No Pauli-blocking! Hyperons test all states of the potential





Hypernuclei





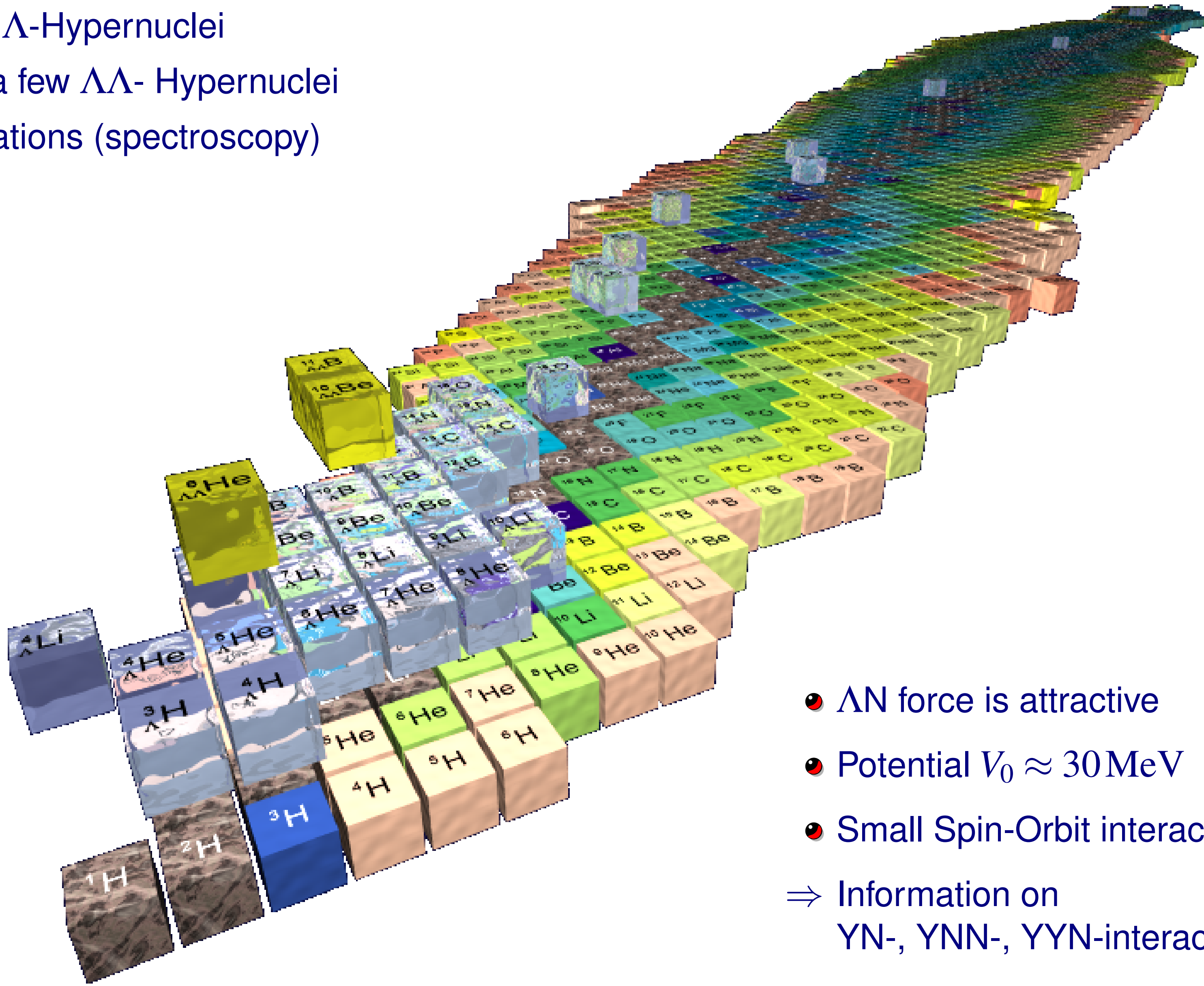
- Complete mapping of the shell structure (single particle states)
- Model potential → deduce hyperon-N interaction
- Excitation spectrum, e.g. via electron scattering

Hypernuclei

≈ 40 Λ-Hypernuclei

only a few $\Lambda\Lambda$- Hypernuclei

Excitations (spectroscopy)



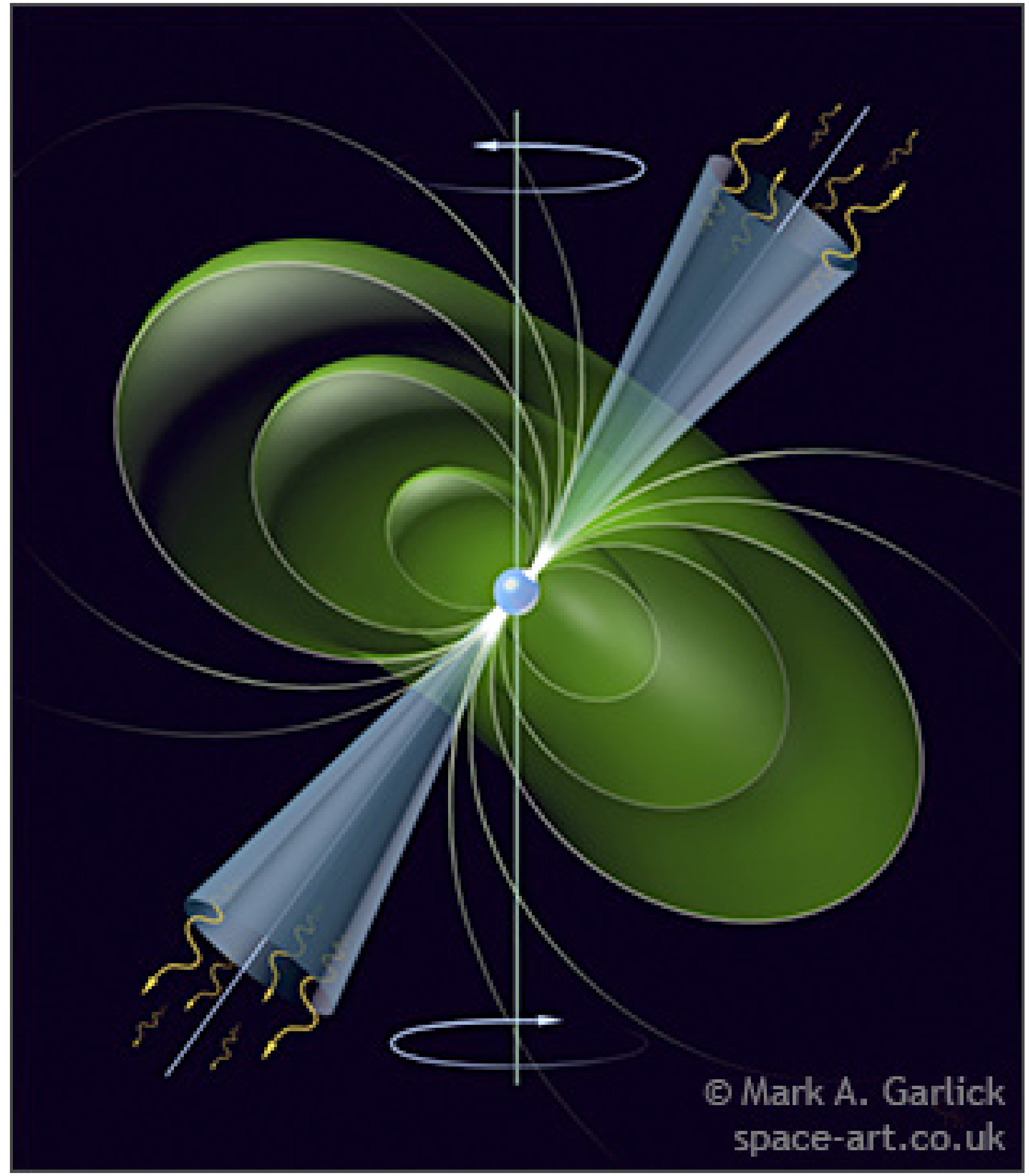
- ΛN force is attractive
- Potential $V_0 \approx 30\,\mathrm{MeV}$
- Small Spin-Orbit interaction

$\Rightarrow$ Information on
YN-, YNN-, YYN-interaction

Neutron Stars

Neutron Stars

Baronic Number	N_B	$\sim$	10^{57}
Mass	M	$\sim$	$1-2\,M_\odot$
Radius	R	$\sim$	$10-12\,\mathrm{km}$
Density	ρ	$\sim$	$10^{15}\,\frac{\mathrm{g}}{\mathrm{cm}^3}$
Magnetic Field	B	$\sim$	$10^{8\cdots 16}\,\mathrm{G}$
Electric Field	E	$\sim$	$10^{18}\,\frac{\mathrm{V}}{\mathrm{cm}}$
Temperature	T	$\sim$	$10^{6\cdots 11}\,\mathrm{K}$
shortest Rotation	t	$\sim$	$1.58\,\mathrm{ms}$



Equilibrium of electro-weak force:

$$n \quad \leftrightarrow \quad p + e^- + \overline{\nu}$$

Definition Baryo-Chemical Potential:

$$\mu = \frac{\mathrm{d}E}{\mathrm{d}n}$$ Change of energy with number

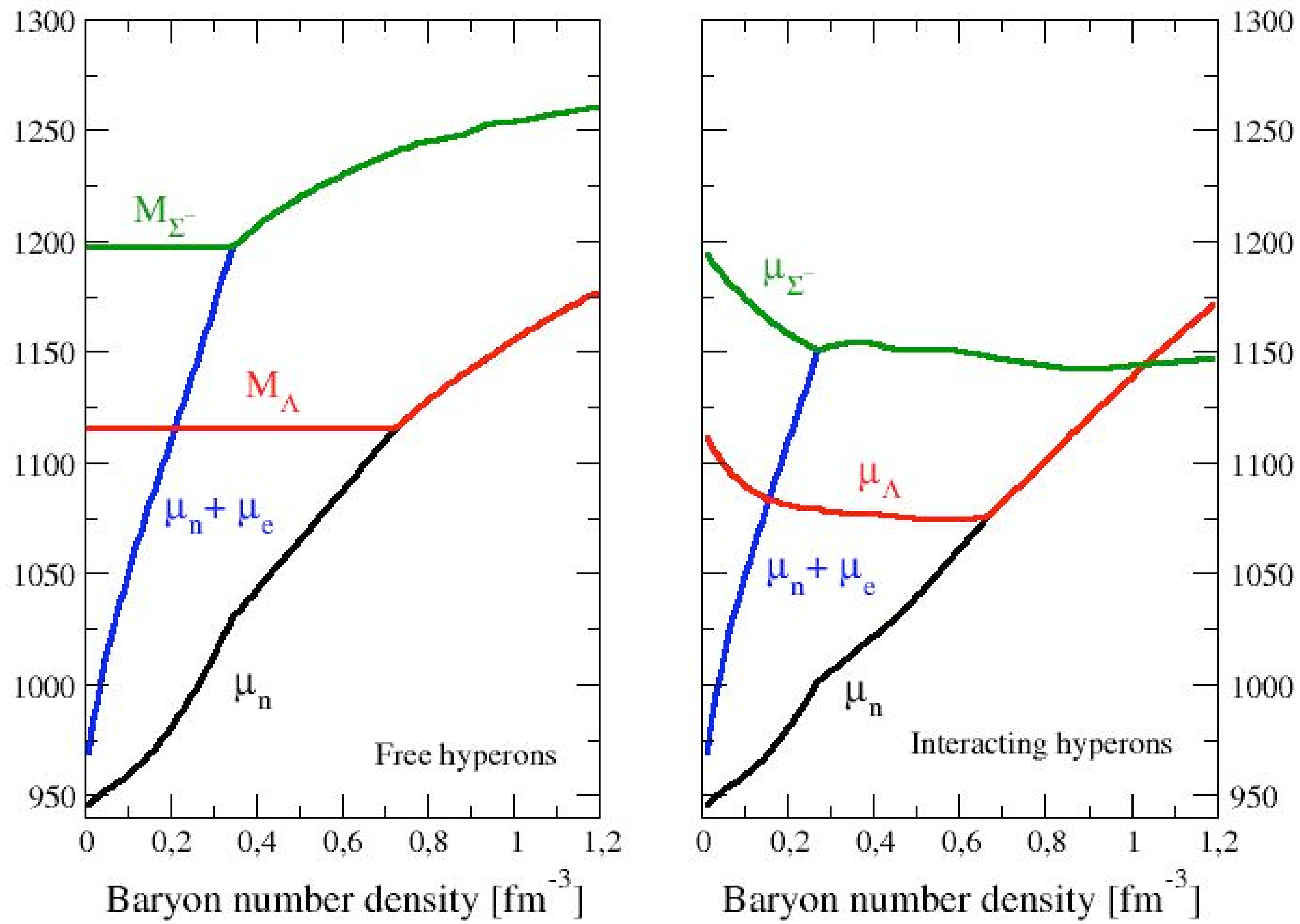
simplifies equilibrium condition for n, p:

$$\mu_n = \mu_p + \mu_e + \mu_{\overline{\nu}}$$

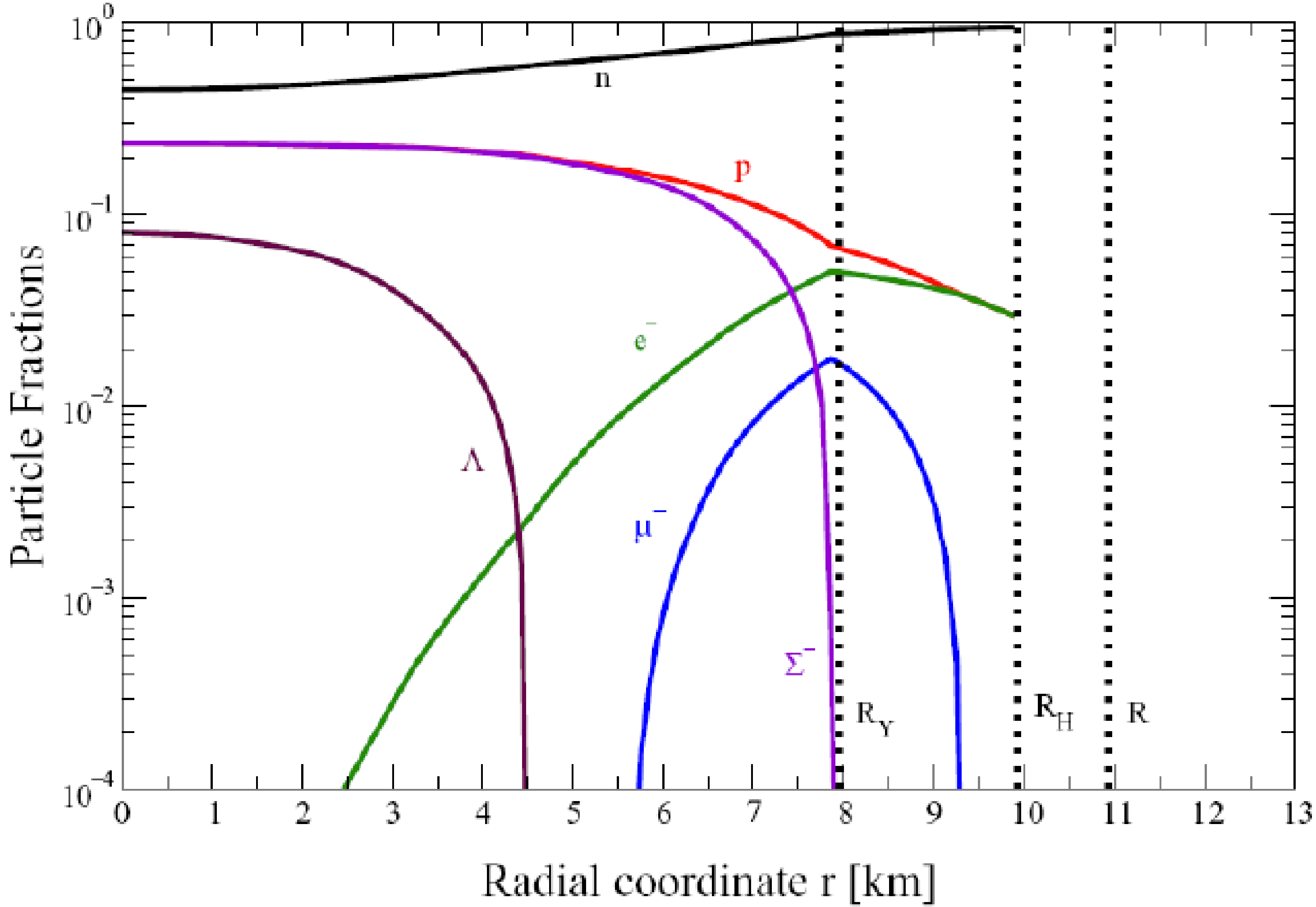
Hyperon content of Neutron Stars

$$\begin{aligned} n + n &\rightarrow n + \Lambda \\ p + e^- &\rightarrow \Lambda + \nu_e \\ n + n &\rightarrow p + \Sigma^- \\ n + e^- &\rightarrow \Sigma^- + \nu_e \end{aligned}$$

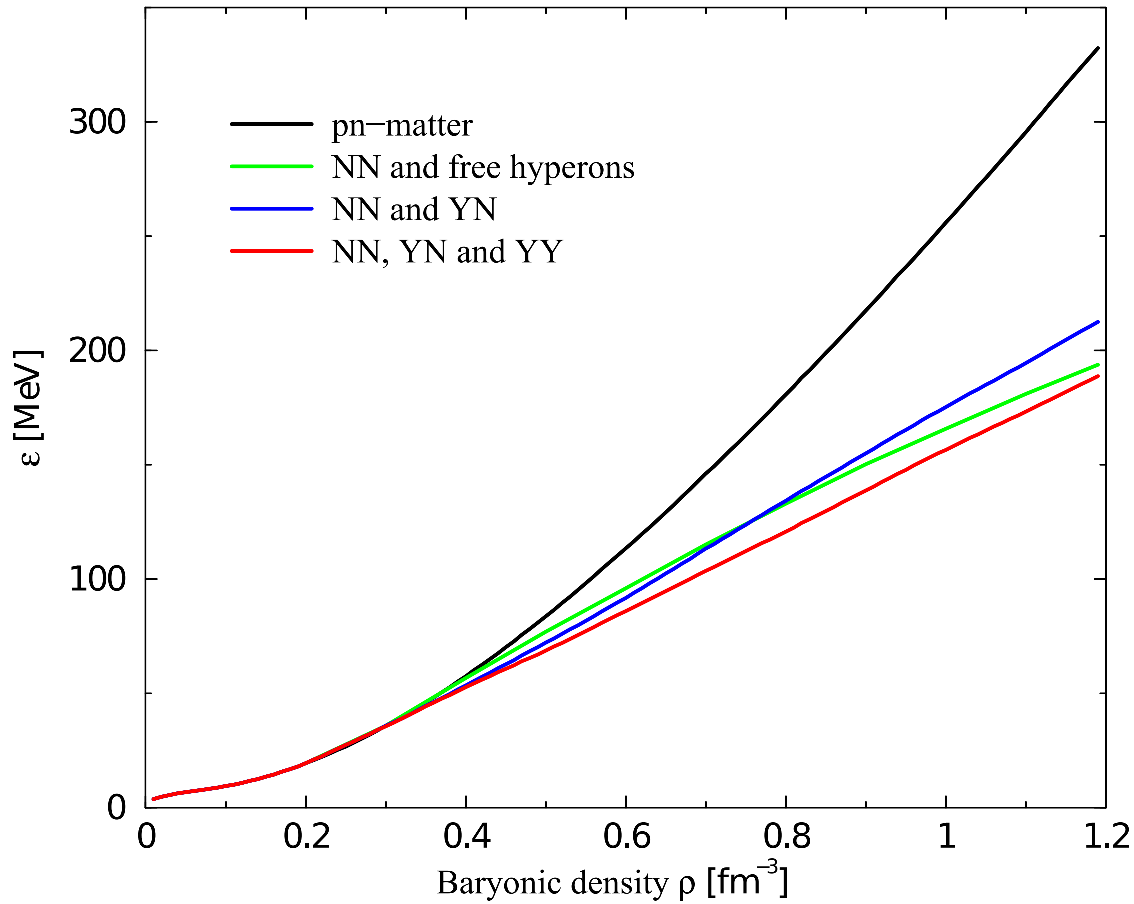
$$\begin{aligned} \mu_{\Sigma}^{-} &= \mu_n + \mu_{e^-} + \mu_{\nu_e} \\ \mu_\Lambda &= \mu_n \end{aligned}$$



Hyperon content of Neutron Stars



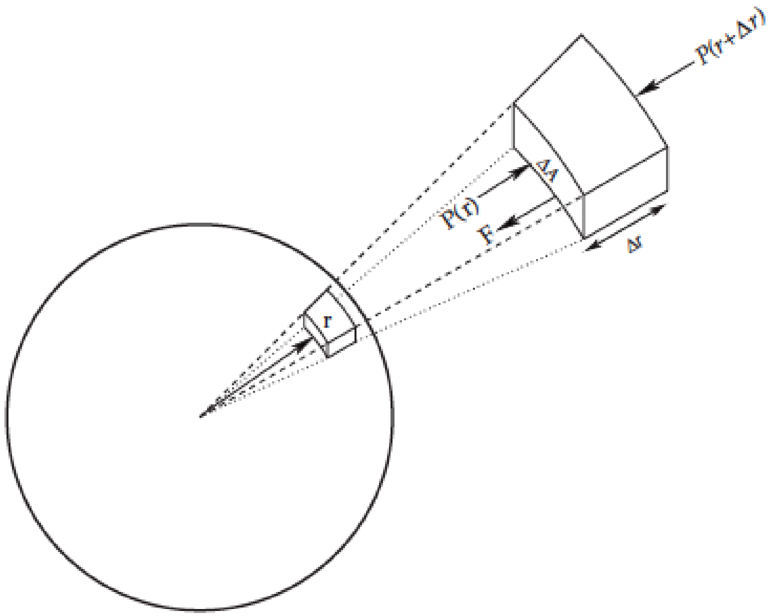
Equation of State



- Equation of State $\varepsilon(\rho)$ (or equivalent $P(\rho) = \rho^2 d(\varepsilon/\rho)/d\rho$) defines hydrostatic properties
- Hyperons "soften" the Equation of State
- What does this mean for a neutron star?

Neutron Star Structure

Newtonian Approach:



Differential Force:

$$F_r = -\frac{GM(r)\Delta m}{r^2} - P(r+\Delta r)\Delta A + P(r)\Delta A = \Delta m \frac{\mathrm{d}^2 r}{\mathrm{d}t^2}$$

Equilibrium ($\ddot{r} = \dot{r} = 0$) :

$$-\frac{GM(r)\rho(r)}{r^2} - \frac{\mathrm{d}P(r)}{\mathrm{d}r} = \rho(r)\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = 0$$

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GM(r)\rho(r)}{r^2} \qquad P(0) = P_c$$

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \rho(r) \qquad m(0) = m_c$$

Neutron star structure

Relativistic Approach:

- Escape velocity

$$\frac{1}{2}mv^2 = \frac{GMm}{R} \quad \Rightarrow \quad v \approx \frac{c}{2}$$

  $\Rightarrow$ relativistic effects are important

- Solve Einstein's field Equation with Energy-Density Tensor of stellar matter $T^{\mu\nu}(\varepsilon, P(\varepsilon))$

$$\begin{aligned} G^{\mu\nu} &= 8\pi T^{\mu\nu}(\varepsilon, P(\varepsilon)) \\ \varepsilon &= \rho c^2 \end{aligned}$$

- Solution possible for symmetric, non-rotating star:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm\varepsilon}{c^2r^2}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi r^3 P}{c^2 m}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

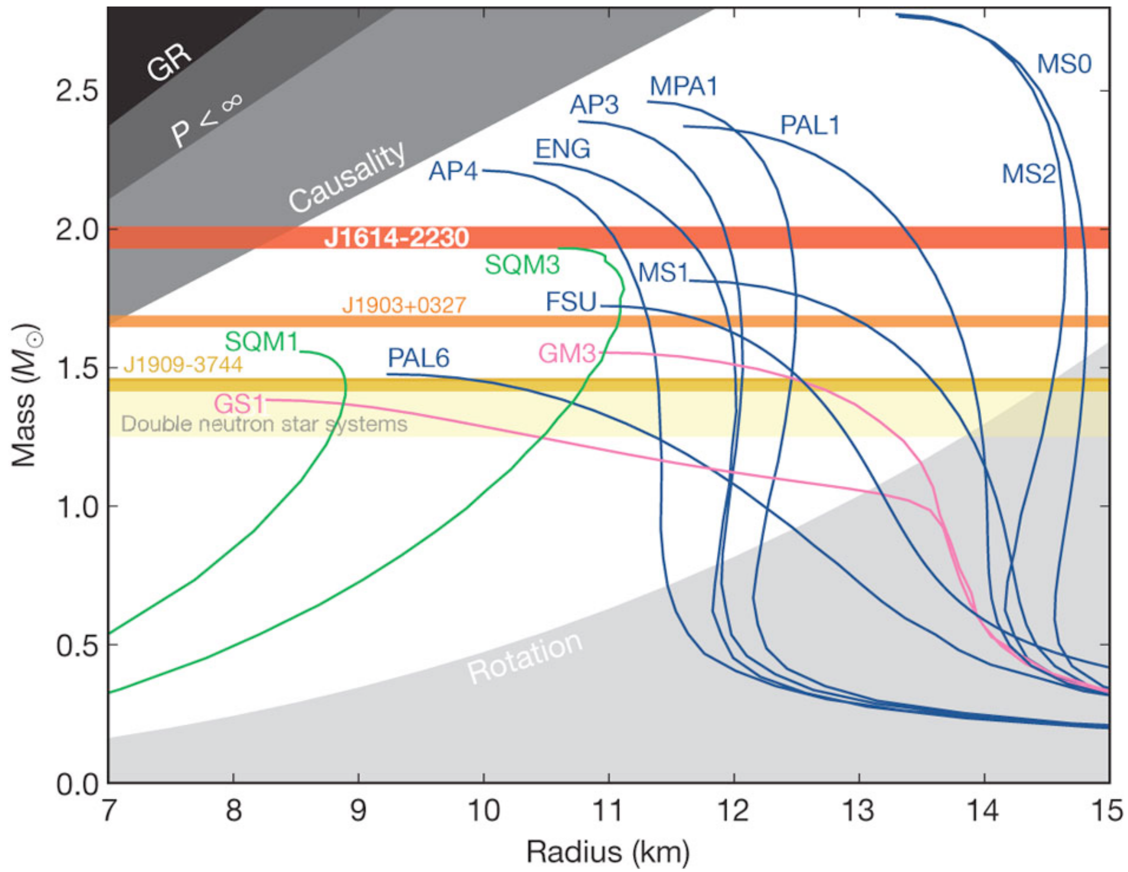
$$\frac{\mathrm{d}m}{\mathrm{d}r} = \frac{4\pi r^2\varepsilon}{c^2}$$

$$P(0) = P(\varepsilon_c) \quad P(R) = 0$$

$$m(0) = 0 \quad m(R) = M$$

Tolman-Oppenheimer-Volkoff equations

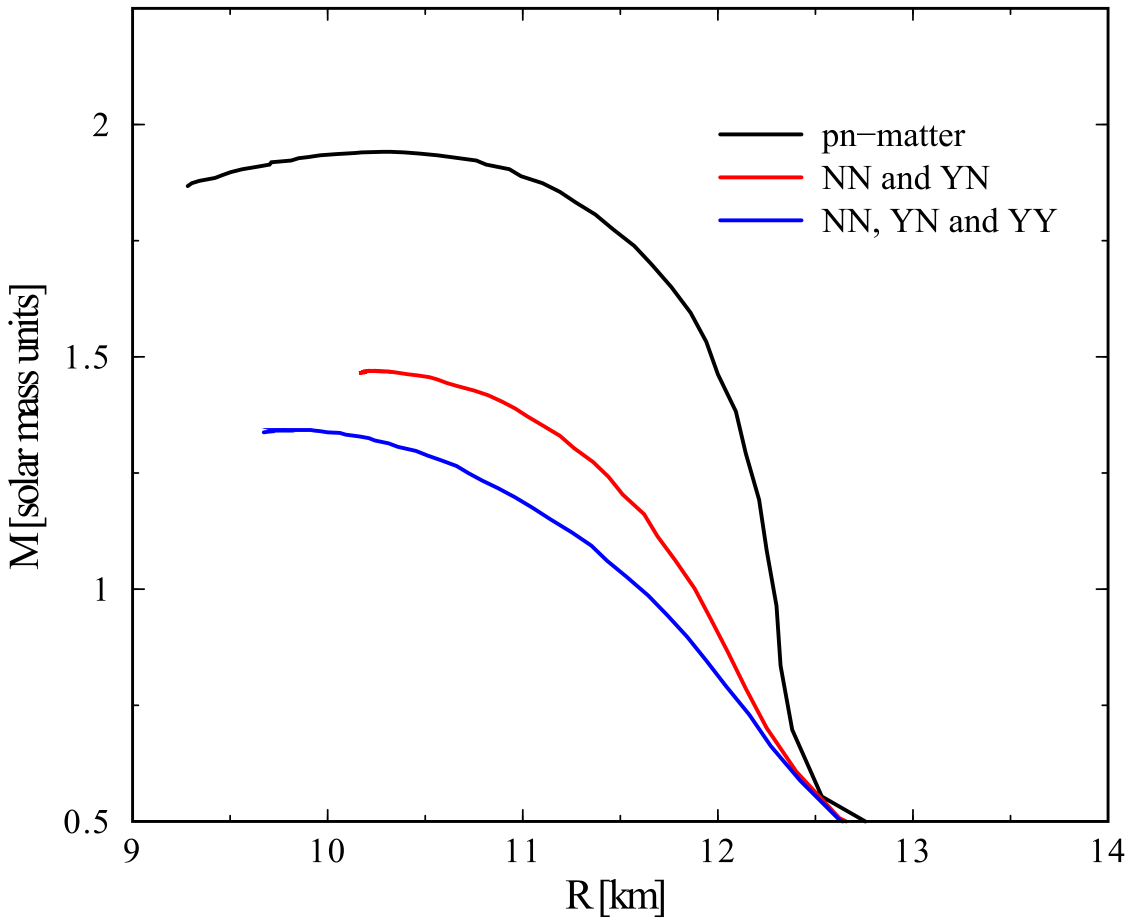
Mass – Radius Plots



Constraints:

- General Relativity (GR): Neutron Star is not a black hole $\Rightarrow R > \frac{2GM}{c^2}$
- Compressibility (Stability): $dP/d\rho > 0$ $\Rightarrow R > \frac{9}{4}\frac{GM}{c^2}$
- Causality: Speed of sound less than speed of light $\Rightarrow R > \frac{9}{4}\frac{GM}{c^2}$
- Rotation: Centrifugal force less than gravitational force $\Rightarrow R < \left(\frac{GM}{2\pi}\right)^{1/3}\frac{1}{\nu^{2/3}}$

Neutron Star with Strangeness



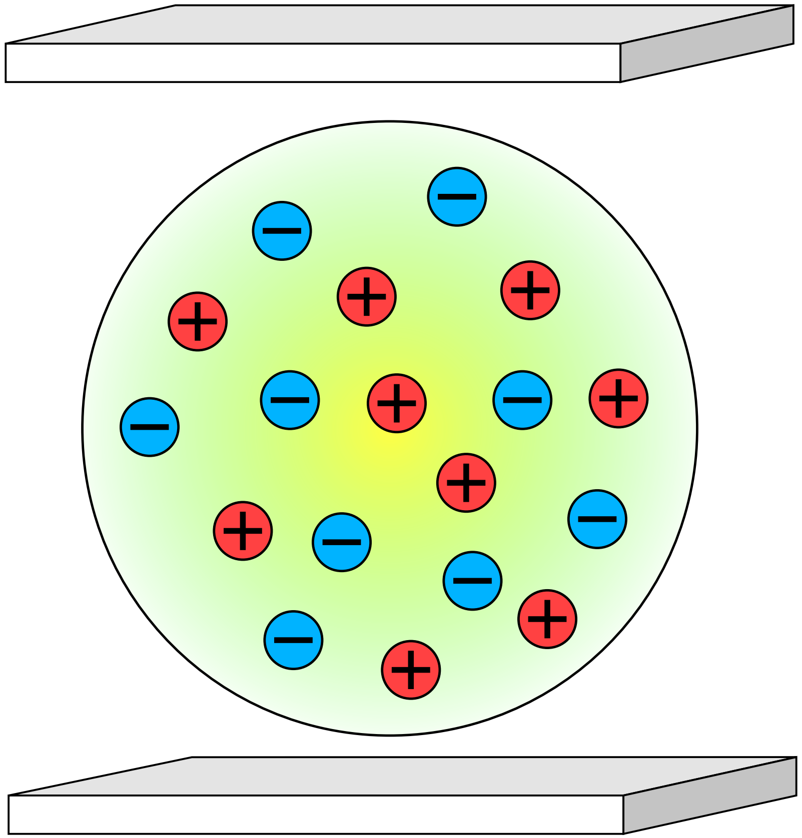
Hyperon Puzzle:

- Softening of Equation of State by Hyperons
- Reduction of maximal Neutron Star Mass by $0.5\,M_\odot$
- Clear contradiction to observation of $2\,M_\odot$

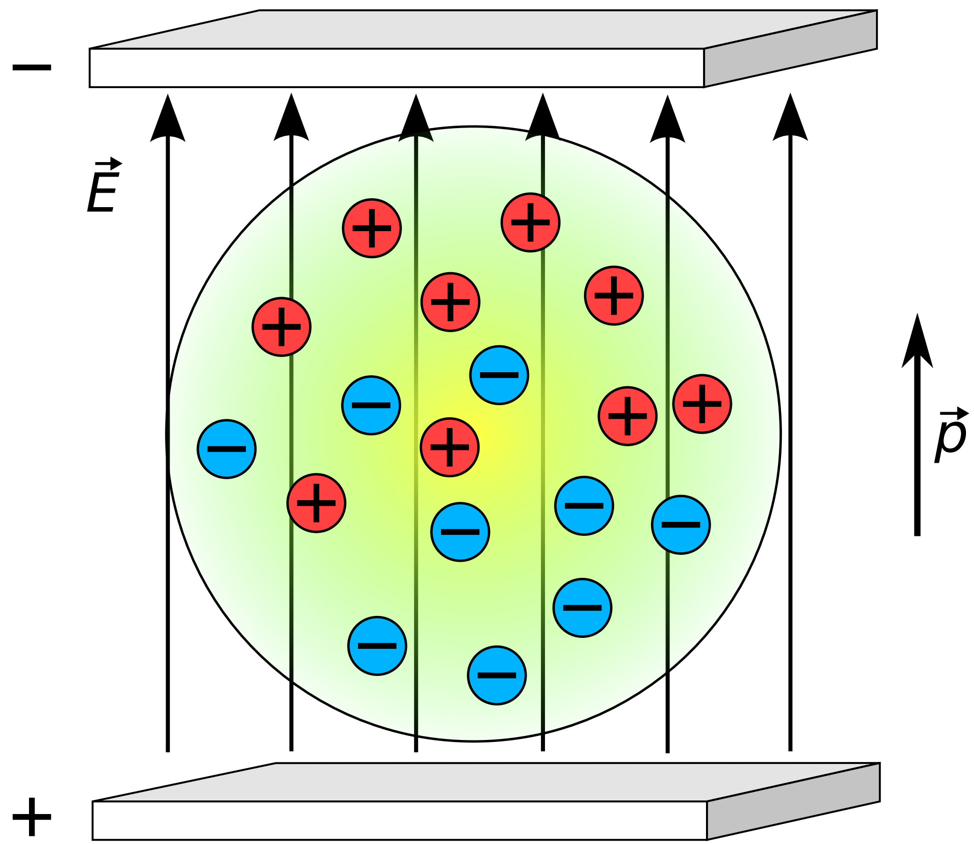
$\Rightarrow$ Study hyperons in medium in Experiment/Theory

Polarizabilities

Electric Polarizability: α



Electric Polarizability: α

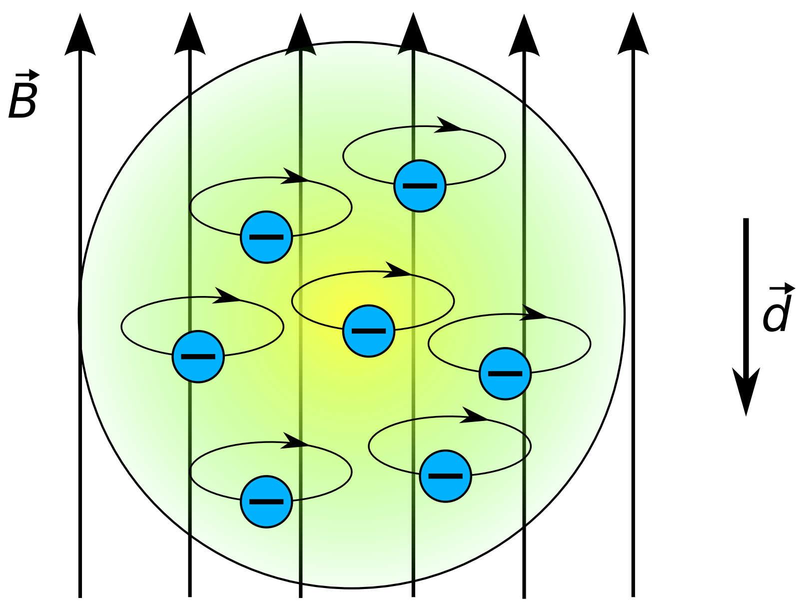


Polarizability α: induced dipole moment $\vec{p} = \alpha \vec{E}$

$$\left.\begin{array}{rcl} |\vec{p}| &=& e \cdot 1\,\mathrm{fm} \\ \alpha &=& 10 \cdot 10^{-4}\,\mathrm{fm}^3 \end{array}\right\} \Rightarrow |\vec{E}| = 1.4\,\frac{\mathrm{GV}}{\mathrm{fm}}$$

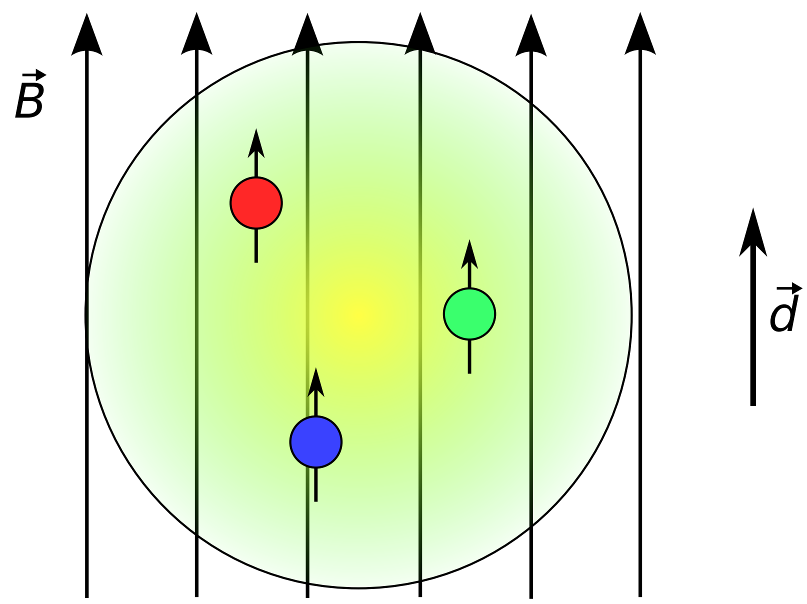
Magnetic Polarizability: β

Diamagnetic



- Induced circular eddy currents
- $\vec{p}$ opposite to external field $\vec{B}$
- Polarizability $\beta < 0$

Paramagnetic



- Alignment of spins
- $\vec{p}$ parallel to external field $\vec{B}$
- Polarizability $\beta > 0$

What do we expect?

Diamagnetic:

- Only a fraction of the charge is carried by valence quarks
- χPT: Relevant degrees of freedom:

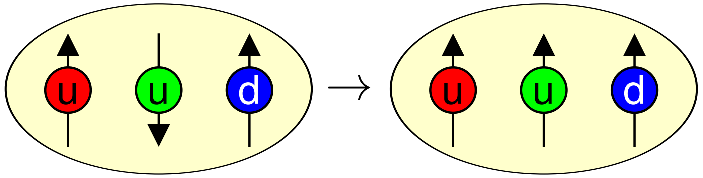
$$\pi^+, \pi^-, \pi^0$$

- Pion cloud

$\Rightarrow$ Currents of spinless charged particles

Paramagnetic:

- Resonance Structure of Nucleons
- Example: $N \to \Delta(1232)$ excitation:



$\Rightarrow$ Photon induced spin flip $\frac{1}{2} \to \frac{3}{2}$

Questions:

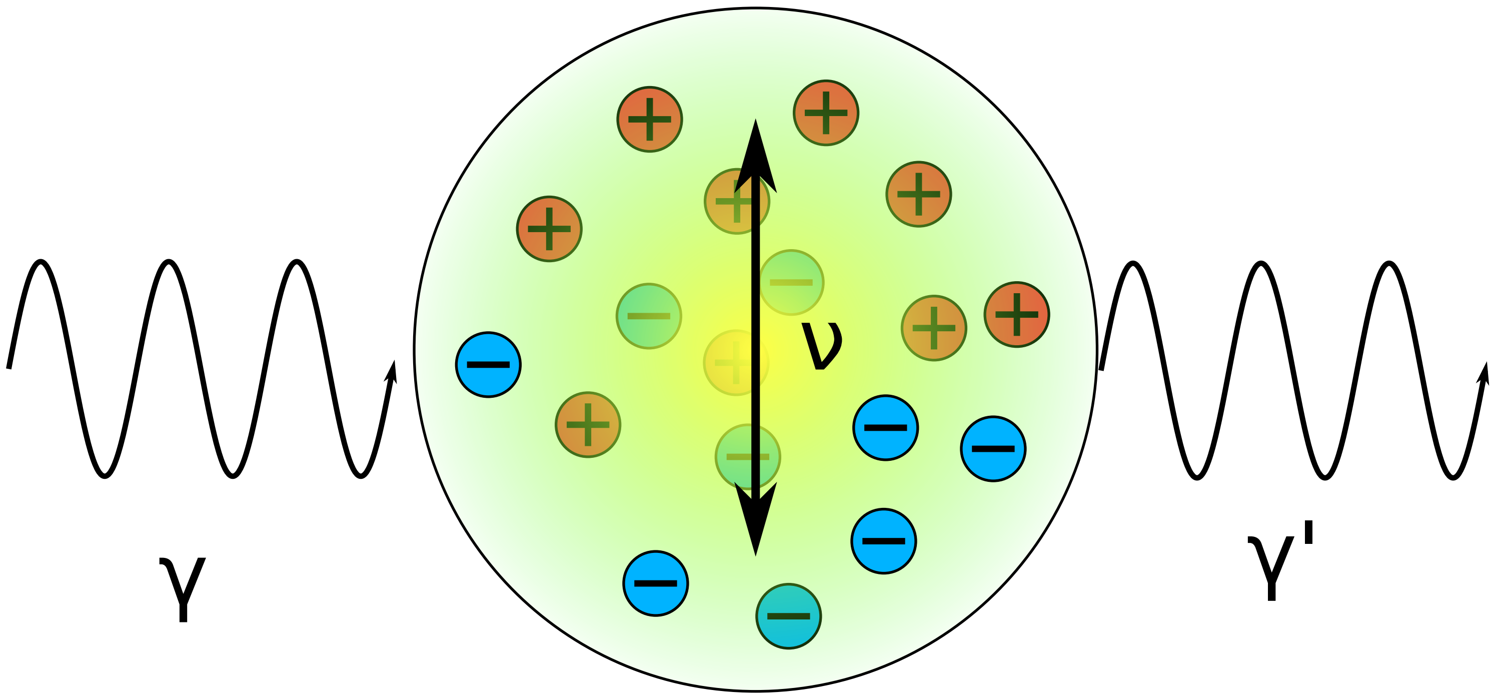
- How to distinguish? $\Rightarrow$ Sign of β
- Transition with energy?
- Transition with resolution (photon virtuality q^2)?

Dynamical Measurement

Huge fields required:

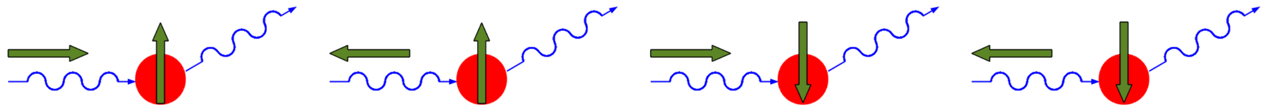
$$\left.\begin{array}{rcl}|\vec{p}| & = & e\cdot 1\,\mathrm{fm}\\ \alpha & = & 10\cdot 10^{-4}\,\mathrm{fm}^3\end{array}\right\}\Rightarrow |\vec{E}| = 1.4\,\frac{\mathrm{GV}}{\mathrm{fm}}$$

Absorbtion and Emission of photon ⇒ COMPTON SCATTERING



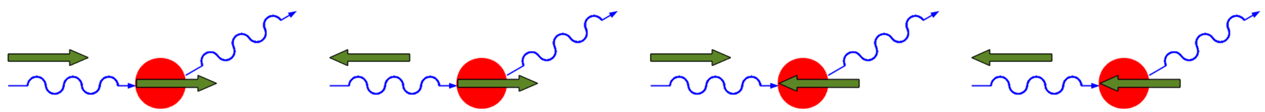
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} - \frac{e^2}{4\pi m_p}\left(\frac{q'}{q}\right)^2 q\,q'\left\{\frac{1}{2}(\bar{\alpha}+\bar{\beta})(1+\cos\theta)^2 + \frac{1}{2}(\bar{\alpha}-\bar{\beta})(1-\cos\theta)^2\right\} + \cdots$$

Polarized Target and polarized beam



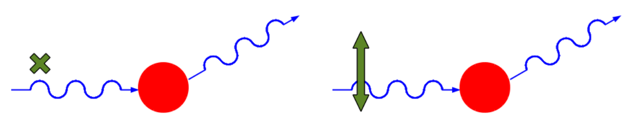
σ^R_{+x} σ^L_{+x} σ^R_{-x} σ^L_{-x}

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}}$$



σ^R_{+z} σ^L_{+z} σ^R_{-z} σ^L_{-z}

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}}$$

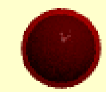
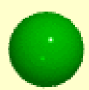
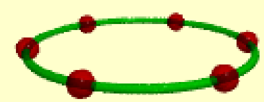
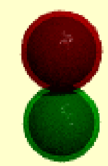
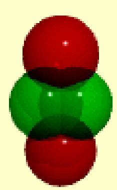
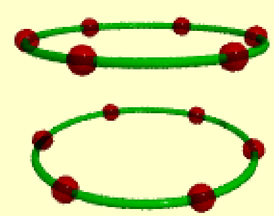
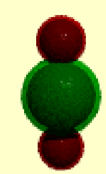


$\sigma_\perp$ $\sigma_{||}$

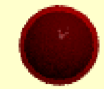
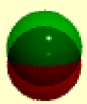
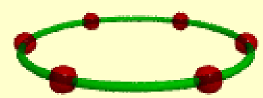
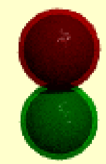
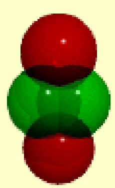
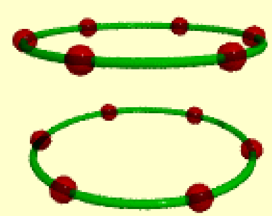
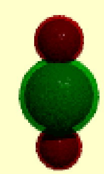
$$\Sigma_3 = \frac{\sigma_\perp - \sigma_{||}}{\sigma_\perp + \sigma_{||}}$$

$\Rightarrow$ spin polarizabilites γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, γ_{M1E2}

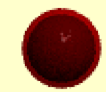
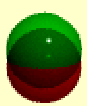
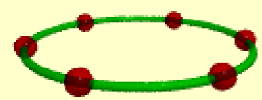
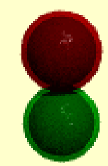
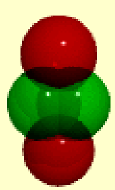
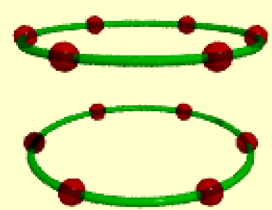
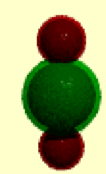
Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

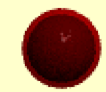
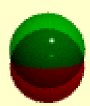
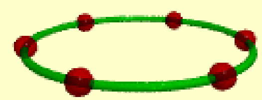
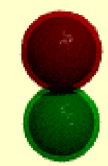
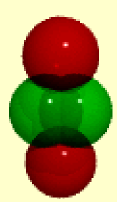
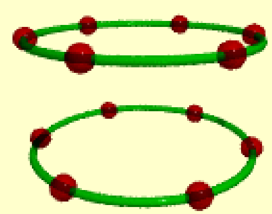
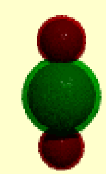
Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

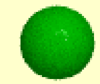
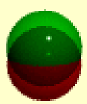
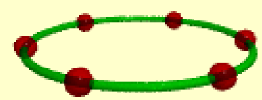
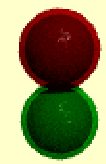
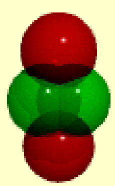
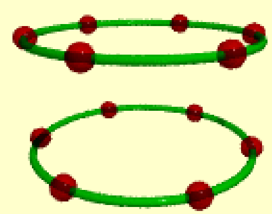
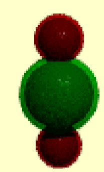
Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

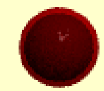
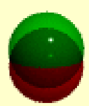
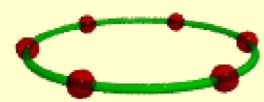
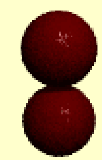
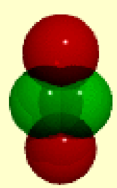
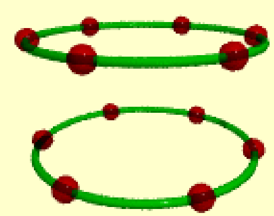
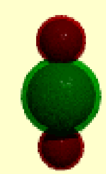
Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

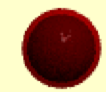
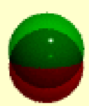
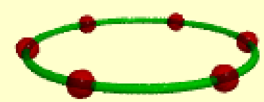
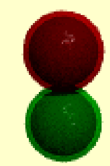
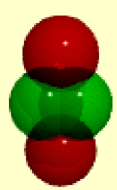
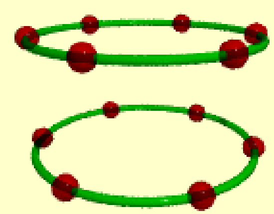
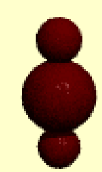
Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

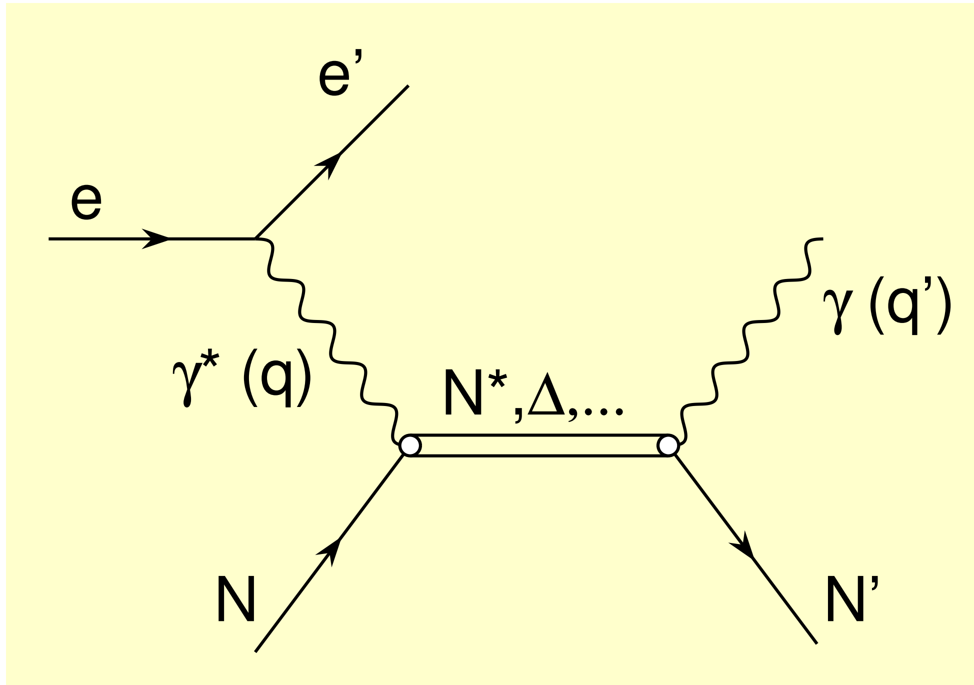
Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

Spin Polarizabilities

	Electric	Magnetic	Longitudinal
L=0			
L=1			
L=2			

Virtual Compton Scattering



- Polarizabilities depend on photon virtuality Q^2
  $\Rightarrow$ Generalized Polarizabilities
- Polarizabilities are defined in static limit $q' \to 0$
- Interpretation of GP(Q^2):
  $\Rightarrow$ "Form Factor" measurement in external field
  $\Rightarrow$ Fouriertransform of local distribution of polarizabilities

Hadron Physics Conclusions

- An invaluable tool for a deep understanding of strong interaction and QCD
- Exciting experimental Results
  - New discoveries $\approx$ 1/year
  - XYZ and clear signatures of Exotic States
- Continuing Progress in Theory
  - Lattice QCD
  - Modelling of exotic states
- Running and new Facilities for Spectroscopy
  - LHC, e^+e^- Colliders
  - JLab 12
  - PANDA at FAIR
- Connection to Astrophysics
  - Neutron Stars as dense hadronic matter
- Precission Physics
  - Determination of Wave Functions
  - Polarizabilities
- And still a lot to do ...