Meson Spectroscopy

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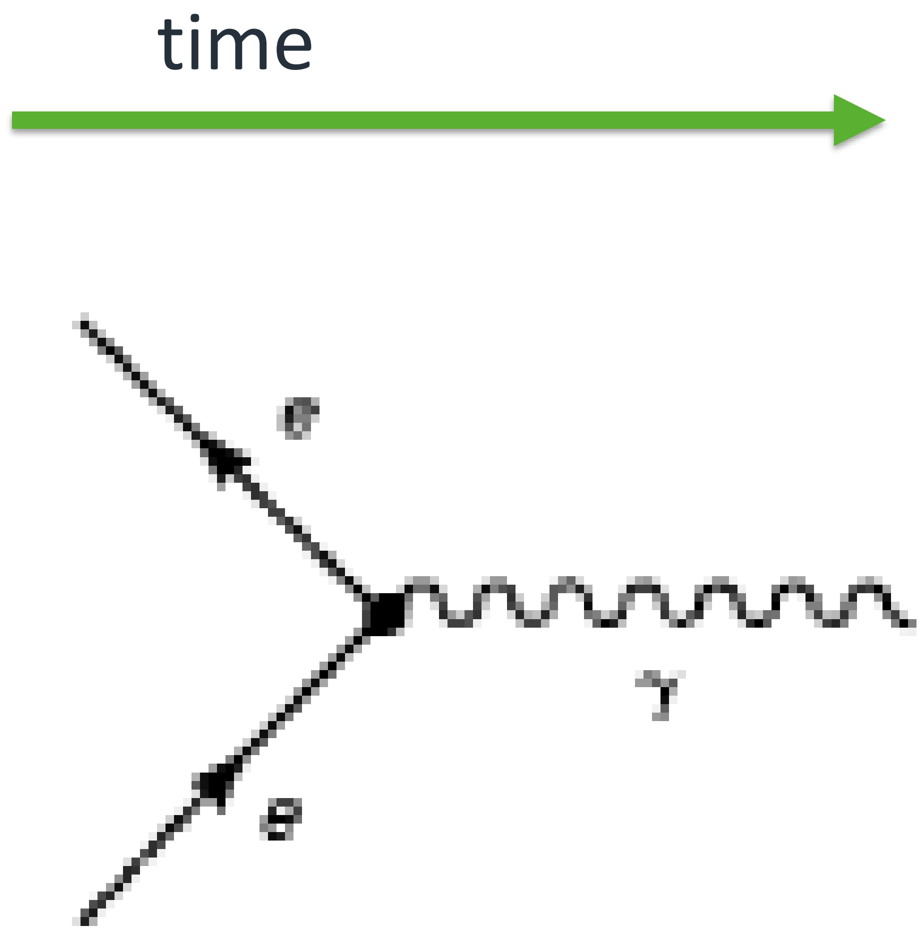
Outlook

- QCD
  - Quarks
  - Colour
- Light meson spectroscopy
  - Quantum numbers
- Quarkonia as an evidence
  - OZI rule
- Exotics

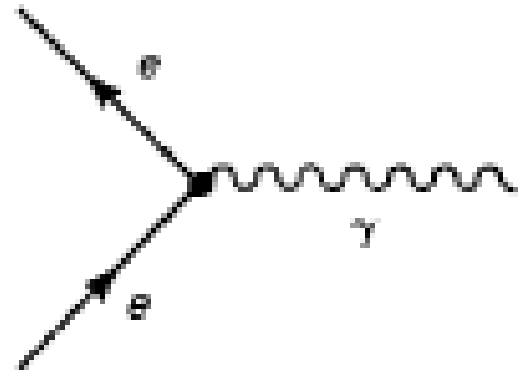
Quantum Chromo Dynamics

QED

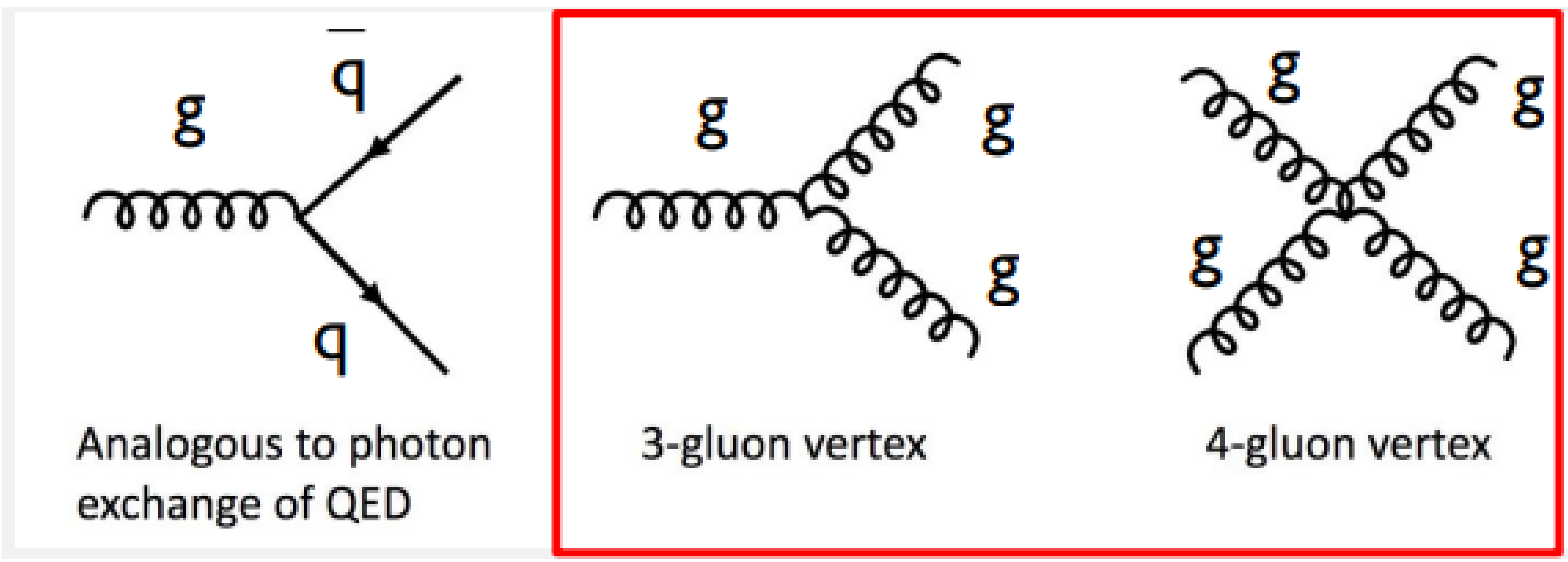


e^+e^- annihilation

QED $\Rightarrow$ QCD



$$\alpha = e^2 = \frac{1}{137}$$



$$\alpha_s = g_s^2 \sim 1$$

Strong interaction is STRONG

QCD basics

- Charges: 3 colour chargers (red, green, blue)
  - And 3 anti-colours (anti-red, anti-green, anti-blue) carried by anti-quarks
- Mediators: gluons (8 gluons) carry colour and anticolour
  - Interact with colour objects only
- Range of interactions: $\sim 1fm$
  - Only colourless objects outside 1fm

Gluons

- 3 colour * 3 anti-colour = 9 possibilities
  - Why do we have 8 orthogonal gluons?

$$r\bar{b},\ r\bar{g},\ b\bar{r},\ b\bar{g},\ g\bar{b},\ g\bar{r},\ \frac{1}{\sqrt{2}}(r\bar{r}-b\bar{b}),\ \frac{1}{\sqrt{6}}(r\bar{r}+b\bar{b}-2g\bar{g}),\ \frac{1}{\sqrt{6}}(r\bar{r}+b\bar{b}+g\bar{g})$$

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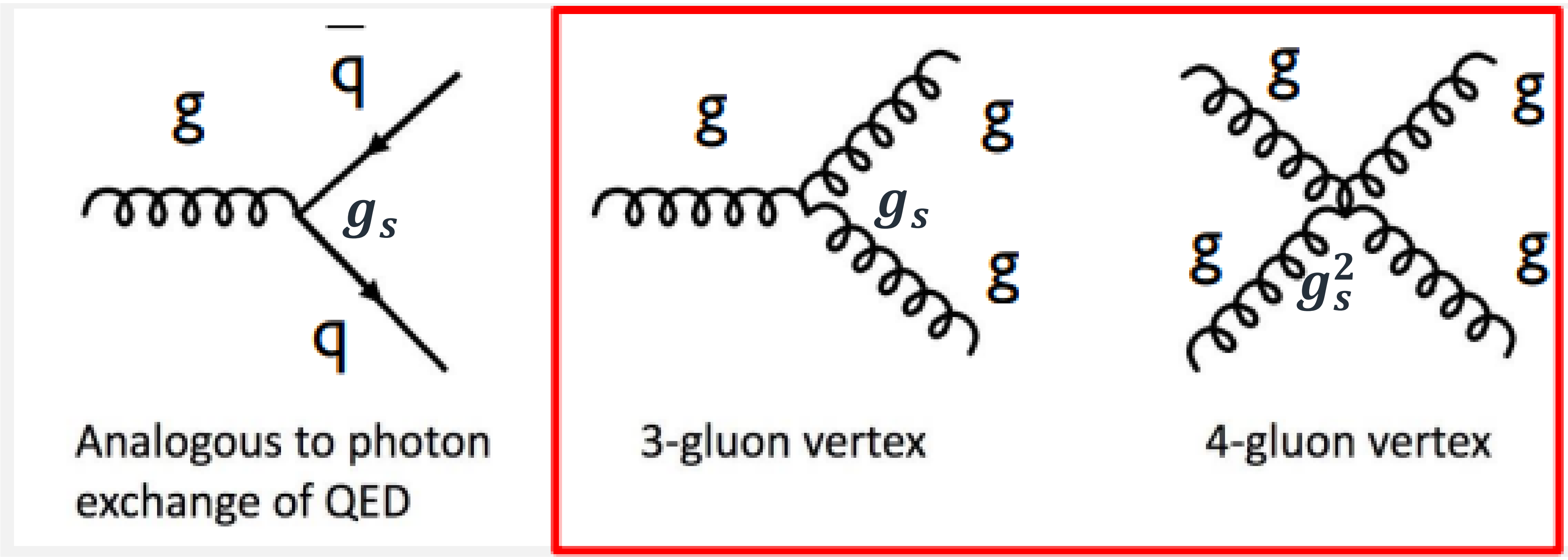
Colourless

Colourless gluon cannot exist in nature, otherwise the range of the strong force would be infinite (like E-M)

QCD



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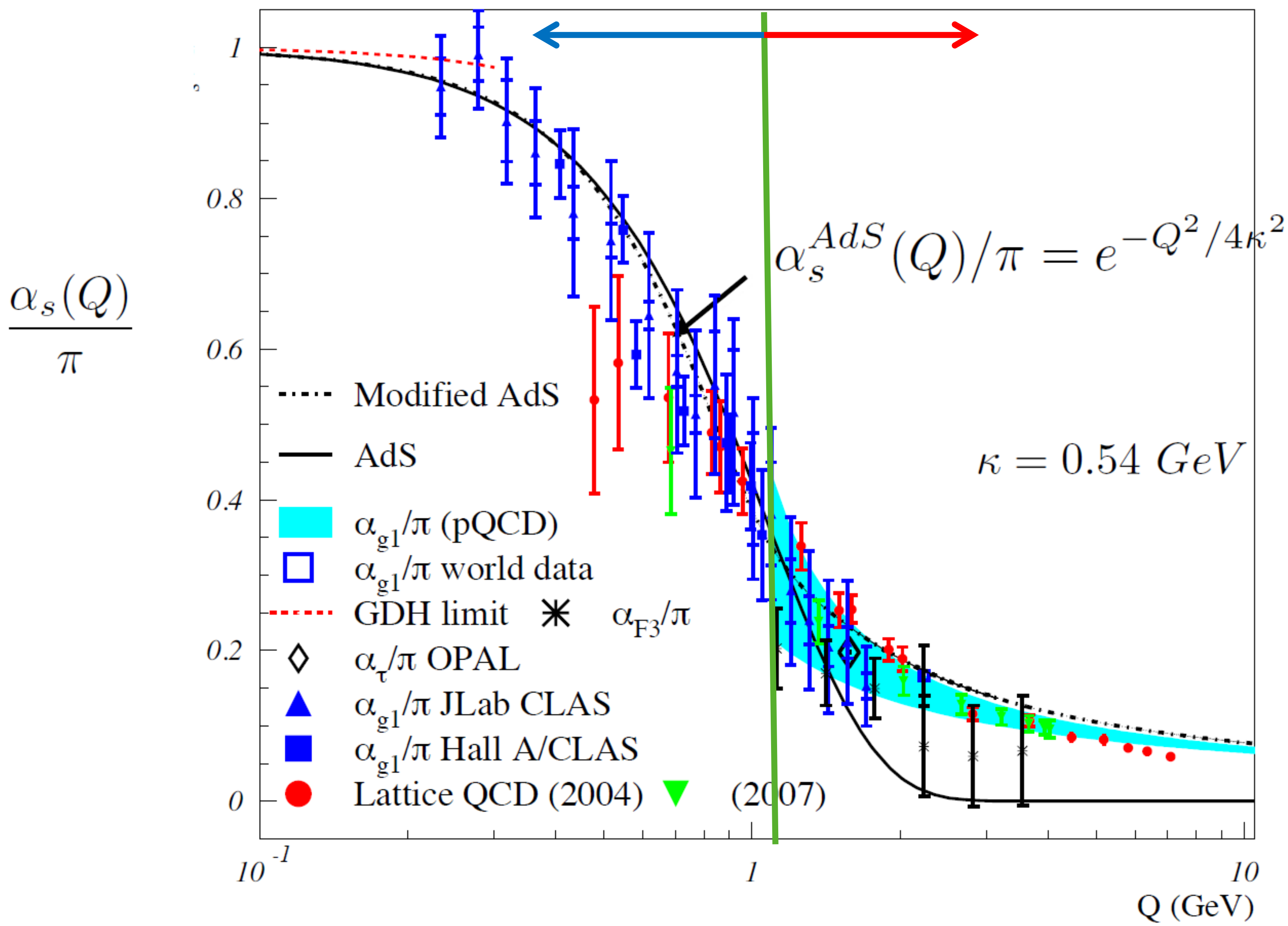
QCD strength

Nonperturbative QCD
Nuclear Physics

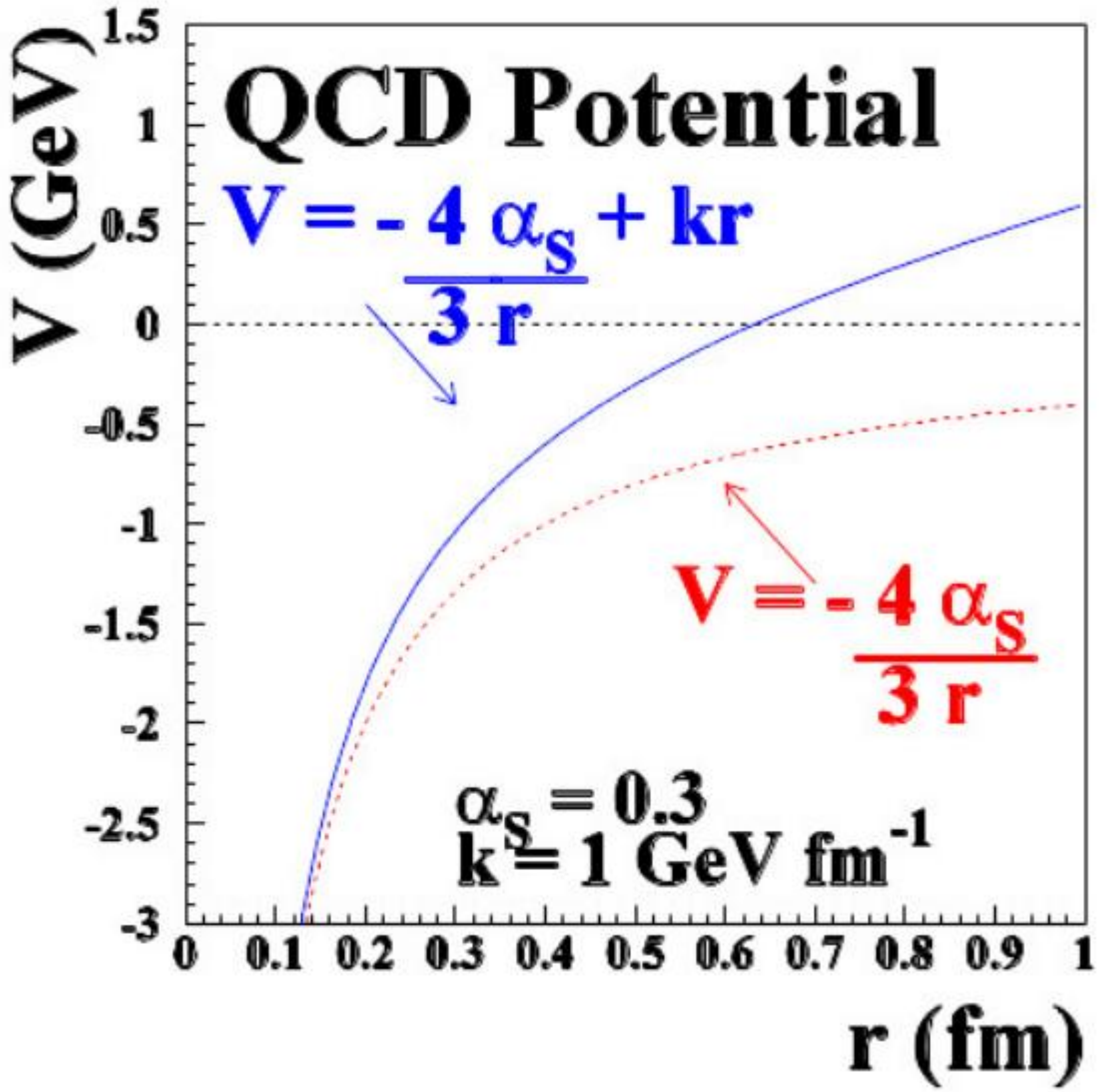
Perturbative QCD
Particle Physics



Large scale

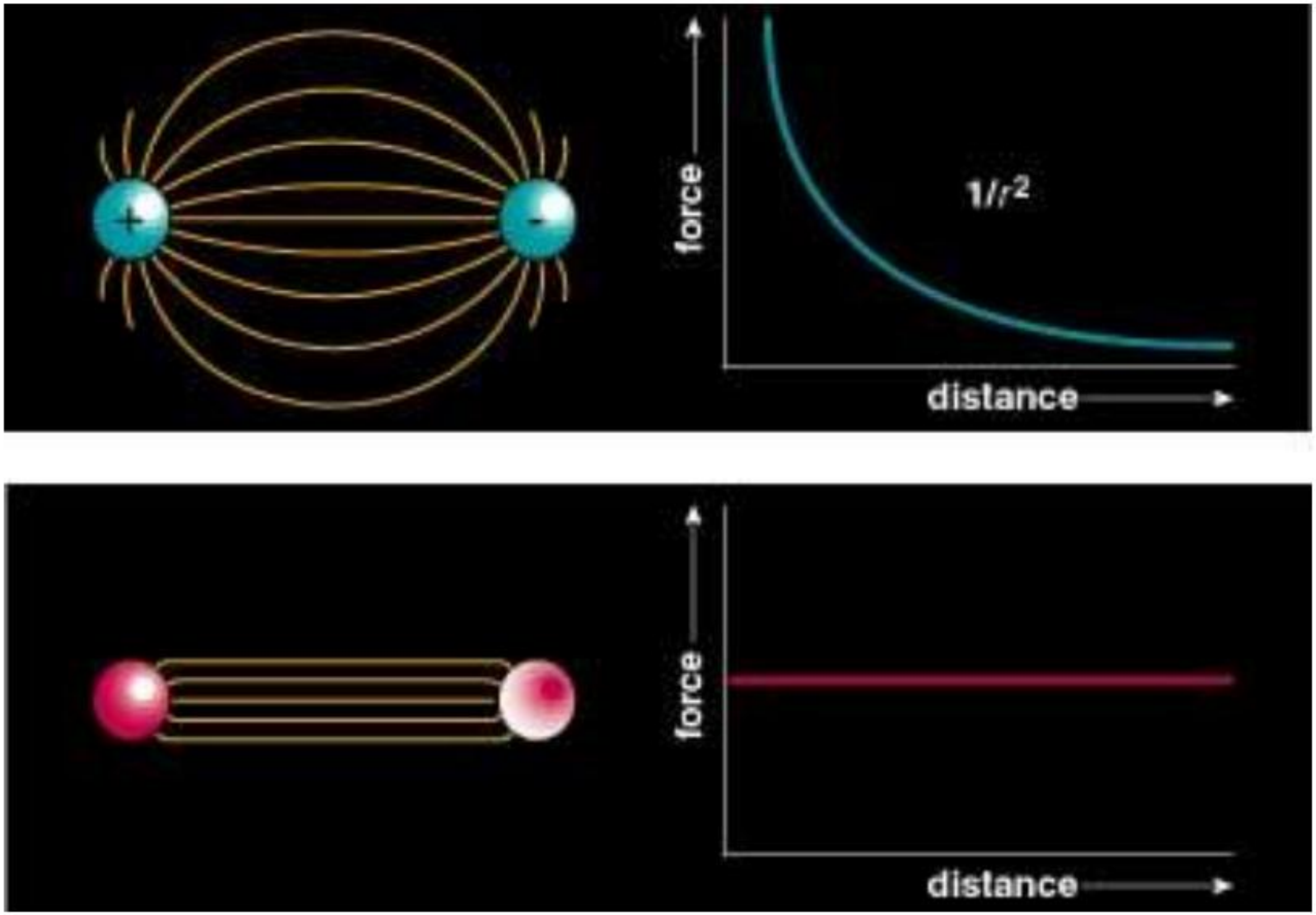
Small scale

QCD Confinement

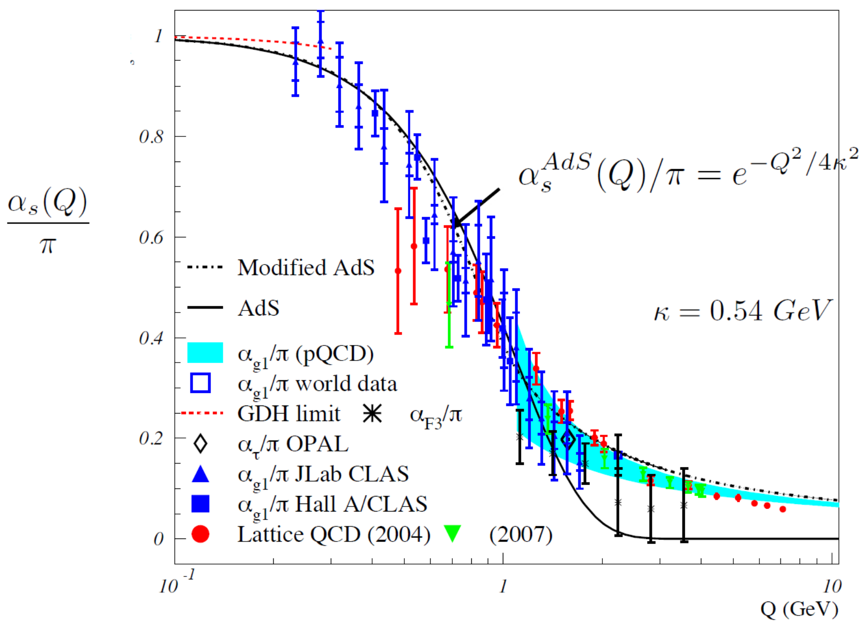


- Quarks cannot be separated
  - The more you pull them apart, the more energy you need to pump in
- At small distance QCD behave similar to QED

QCD force



Quarks asymptotic freedom



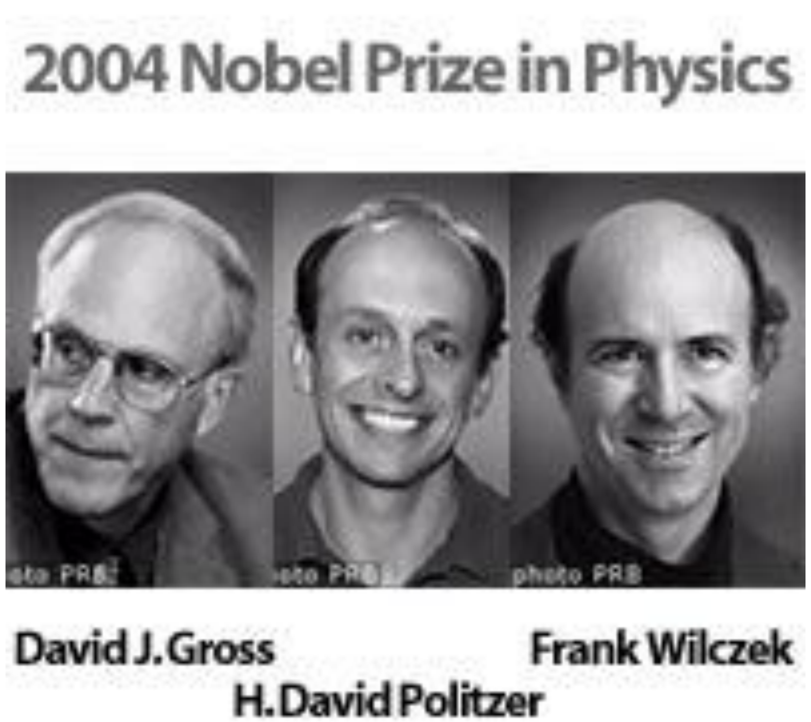
$$\alpha_s(q^2) = \frac{\alpha_s(\mu^2)}{\left(1 + \beta\alpha_s(\mu^2)\ln\left(\frac{q^2}{\mu^2}\right)\right)}$$

Here μ is an energy scale at which we know α_s

$$\beta = \frac{11n - 2f}{12\pi}$$

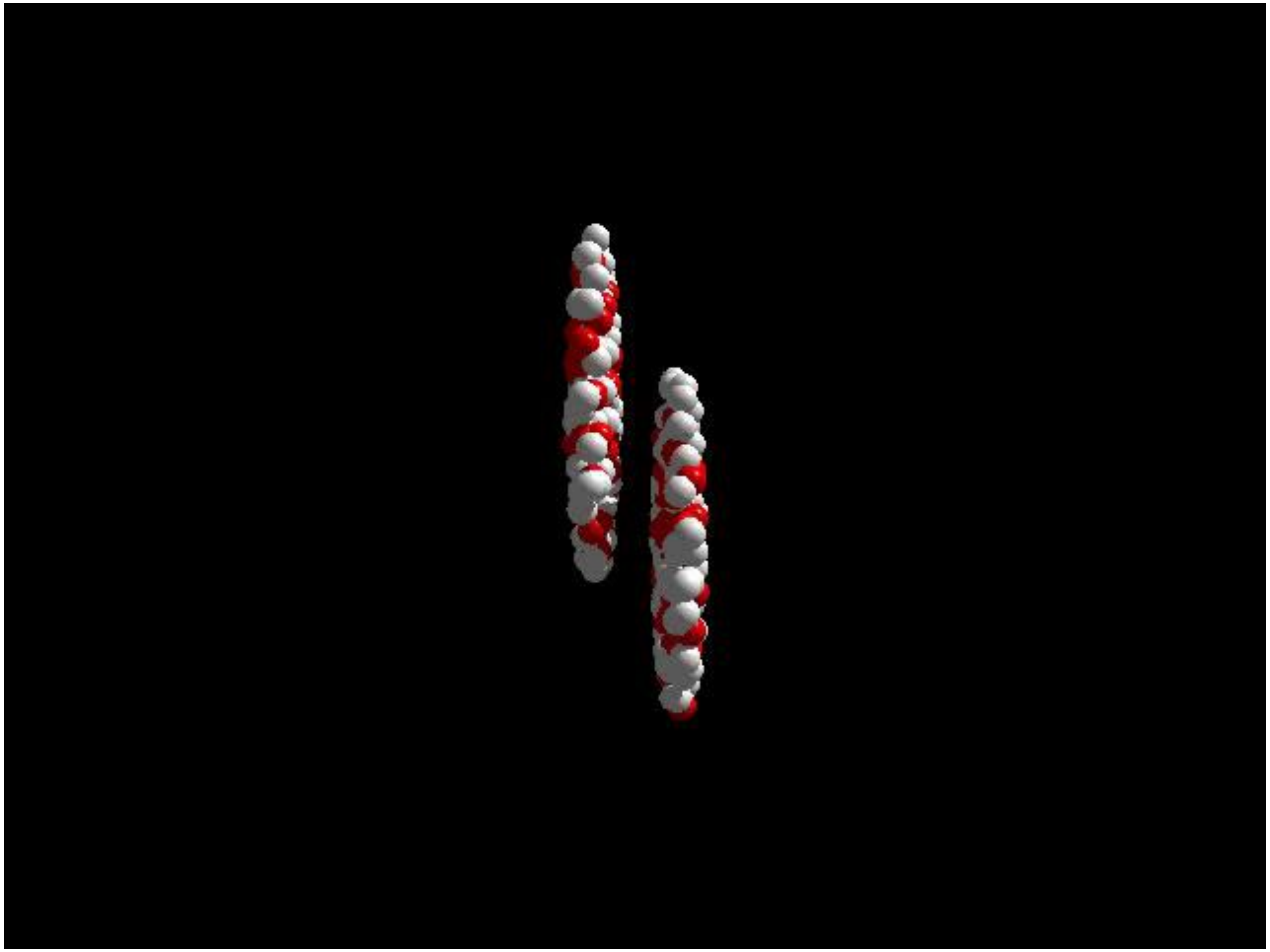
n – number of colours

f – number of flavours



- QCD strength depends on number of colours and number of flavours.
- At high energy strong interaction become very weak.
- Quarks and gluons – non-interacting ideal gas, quark-gluon plasma

Quark Gluon Plasma

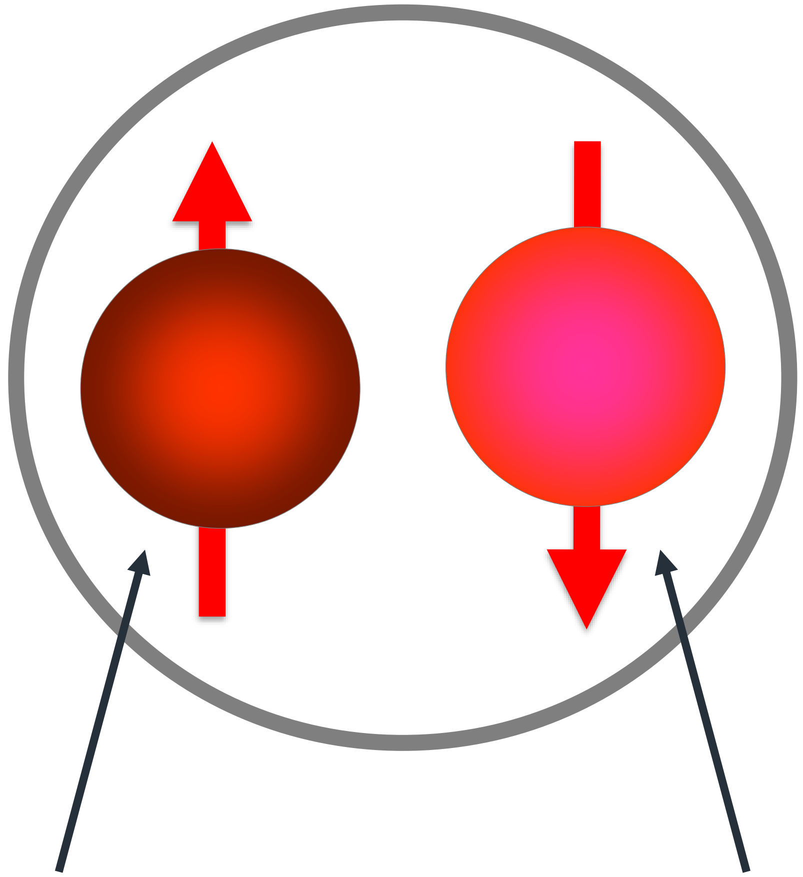


Light Mesons:
Spin and Parity

Types of particles/resonances

Meson

$\boldsymbol{\pi}$



$J^P = 0^-$
$L = 0$

Quark $J^P = \frac{1}{2}^+$ Antiquark $J^P = \frac{1}{2}^-$

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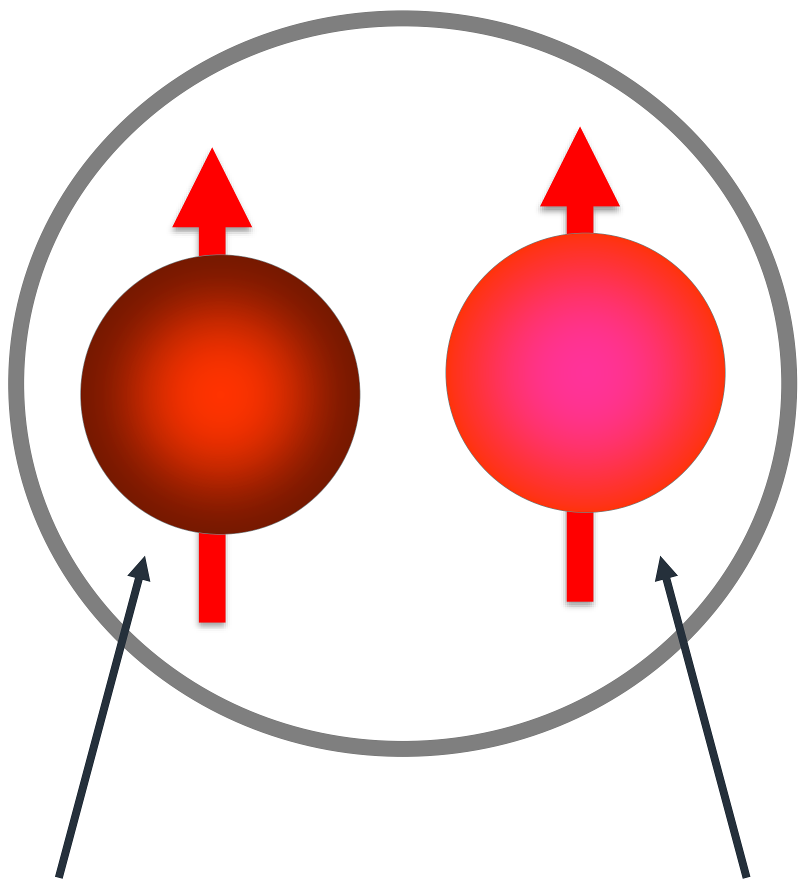
$\boldsymbol{\rho}$



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Meson quantum numbers, $\bar{q}q$

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  - Either 0 (↑↓) or 1 (↑↑)

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  - For $S = 0$ it is simple: $J \equiv L$
  - For $S = 1$ and $L > 0$ we have 3 states:
    - $J_1 = |L| + 1$
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- Charge parity $C(q\bar{q}) = (-1)^{L+S}$

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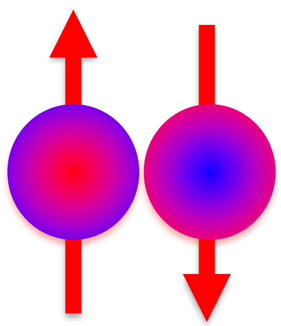

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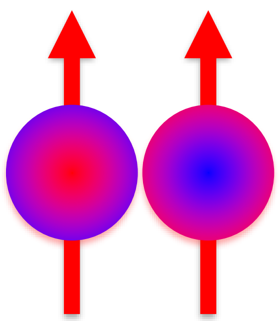

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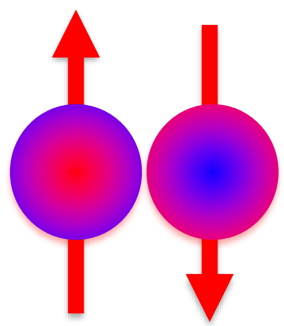

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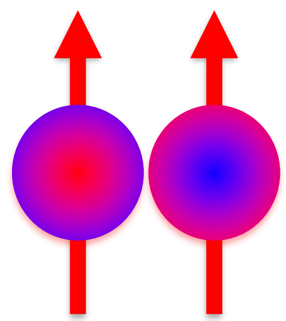

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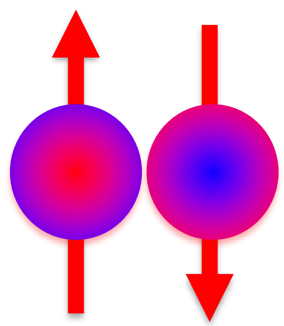

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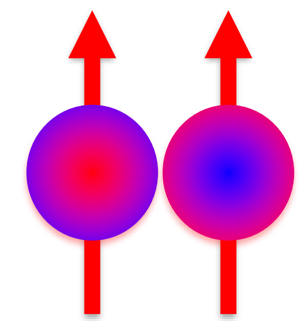

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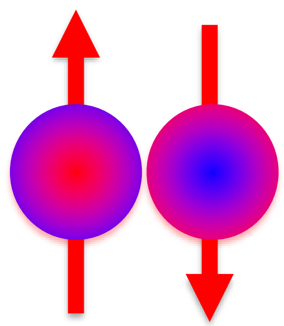

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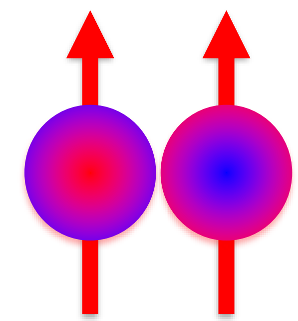

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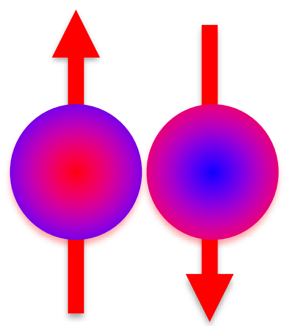

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Pseudoscalar: $\downarrow\uparrow$ $\quad J^P = 0^{-+}$

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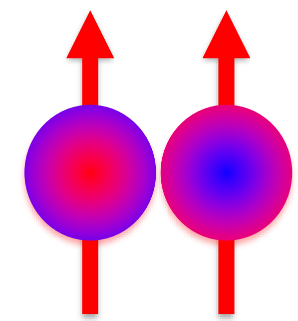

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Vector: $\uparrow\uparrow$ $J^P = 1^{--}$

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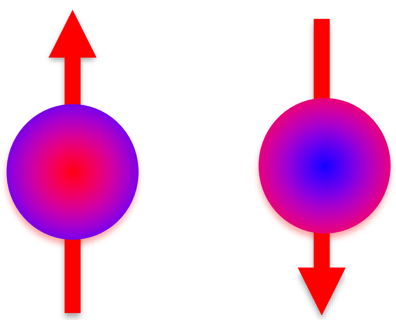

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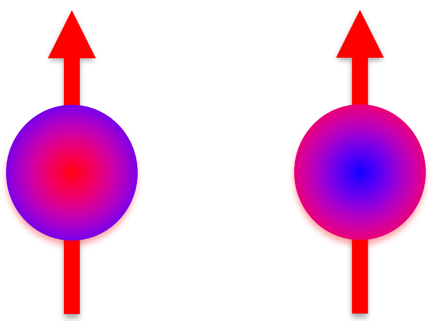

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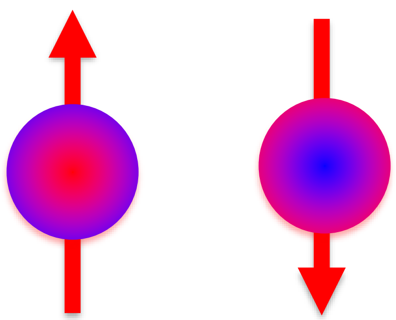

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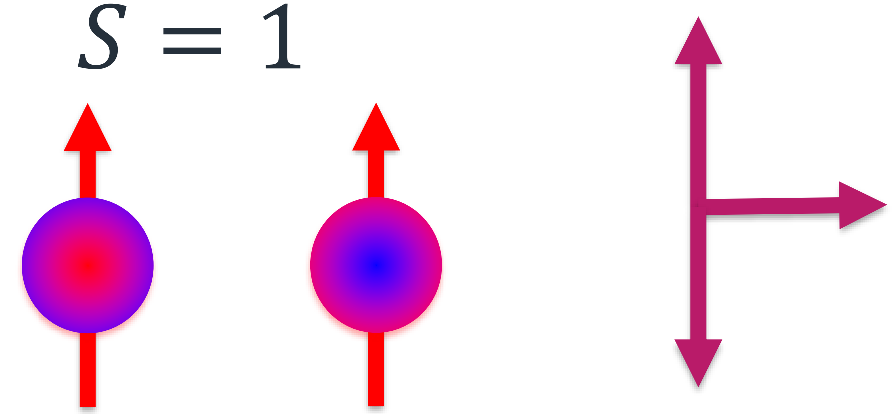

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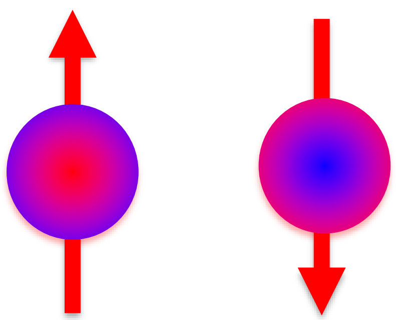

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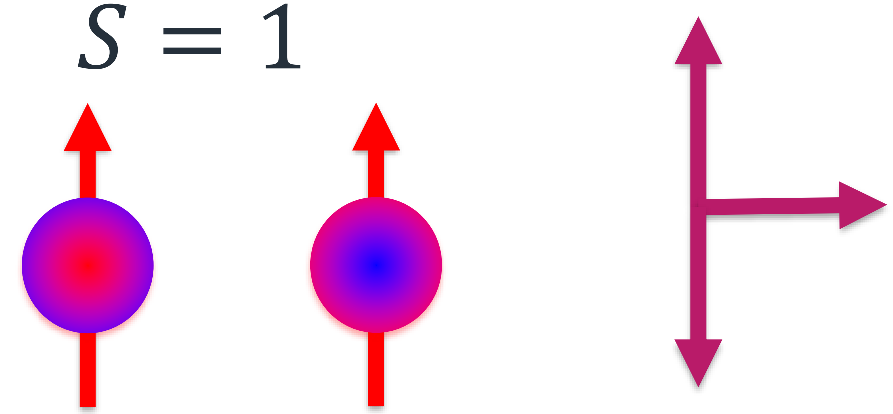

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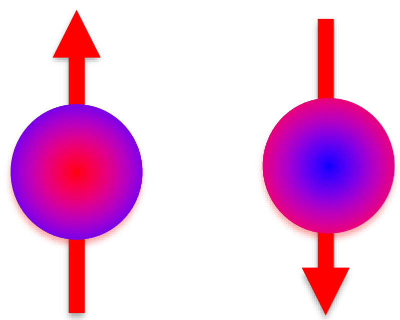

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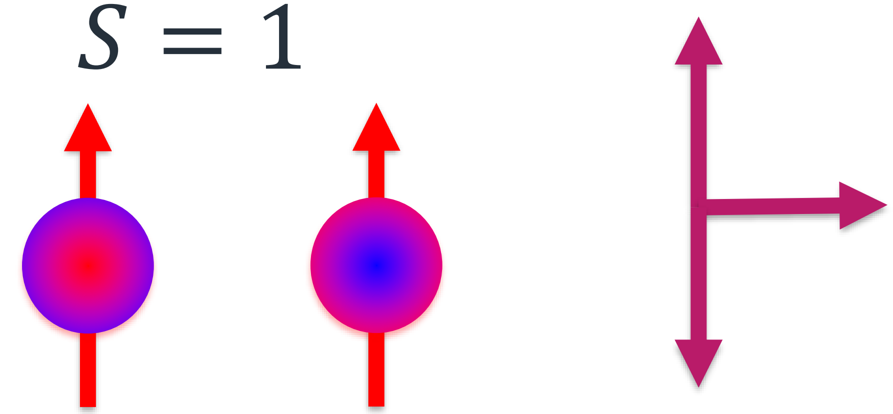

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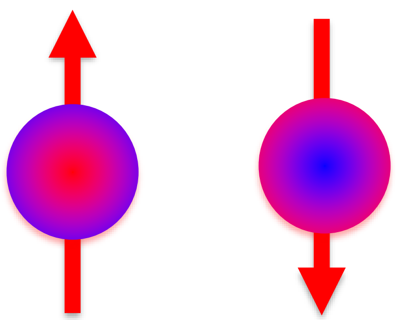

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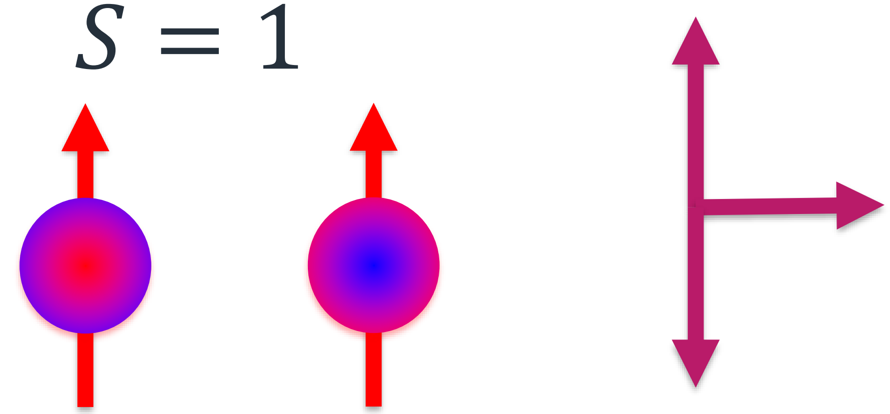
$J^P = \mathbf{1}^{+\,-}$

$L = 1$

$S = 1$



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$J^P = \mathbf{2}^{+\,+}, \mathbf{1}^{+\,+}, \mathbf{0}^{+\,+}$

Spin/parities

spin	Natural parities	
0	$J^P = 0^+$ scalar	$J^P = 0^-$ pseudoscalar
1	$J^P = 1^-$ vector	$J^P = 1^+$ axial vector(pseudovector)
2	$J^P = 2^+$ tensor	$J^P = 2^-$ pseudotensor

The allowed J^{PC} quantum numbers for $\bar{q}q$systems

L	S	J^{PC}	L	S	J^{PC}	L	S	J^{PC}
0	0	0^{-+}	1	0	1^{+-}	2	0	2^{-+}
0	1	1^{--}	1	1	0^{++}	2	1	1^{--}
			1	1	1^{++}	2	1	2^{--}
			1	1	2^{++}	2	1	3^{--}

$$\boldsymbol{P(\bar{q}q) = -1 \cdot (-1)^L}$$

$$\boldsymbol{C(\bar{q}q) = (-1)^{L+S}}$$

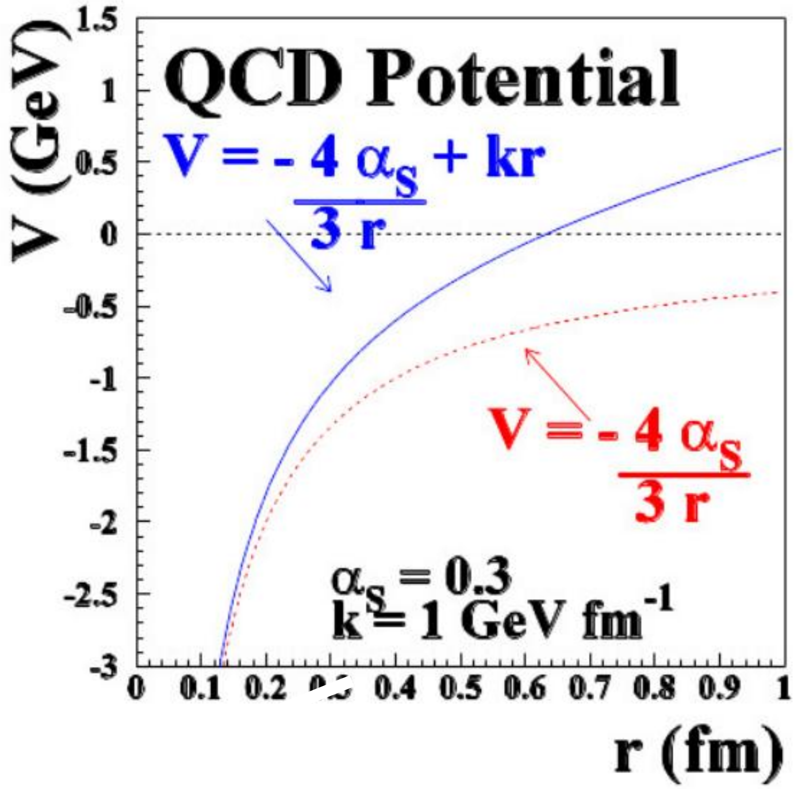
$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}$ are exotic

Light Meson Naming

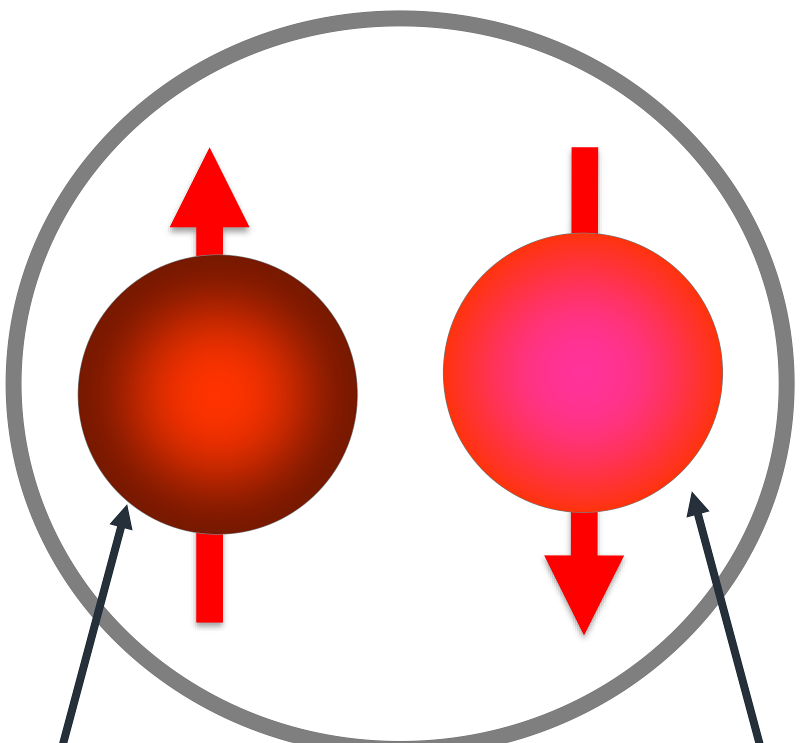
	$J^{P} = 0^{++}$	$J^{P} = 1^{++}$	$J^{P} = 2^{++}$
I=0	f_0	f_1	f_2
I=1	a_0	a_1	a_2
	$J^{P} = 0^{-+}$	$J^{P} = 1^{-+}$	$J^{P} = 2^{-+}$
I=0	η	η_1	η_2
I=1	π	π_1	π_2
	$J^{P} = 0^{--}$	$J^{P} = 1^{--}$	$J^{P} = 2^{--}$
I=0	ω_0	ω	ω_2
I=1	ρ_0	ρ	ρ_2
	$J^{P} = 0^{+-}$	$J^{P} = 1^{+-}$	$J^{P} = 2^{+-}$
I=0	h_0	h_1	h_2
I=1	b_0	b_1	b_2

Experimental evidences of quarks

What is inside?
1) Heavy quarkonia

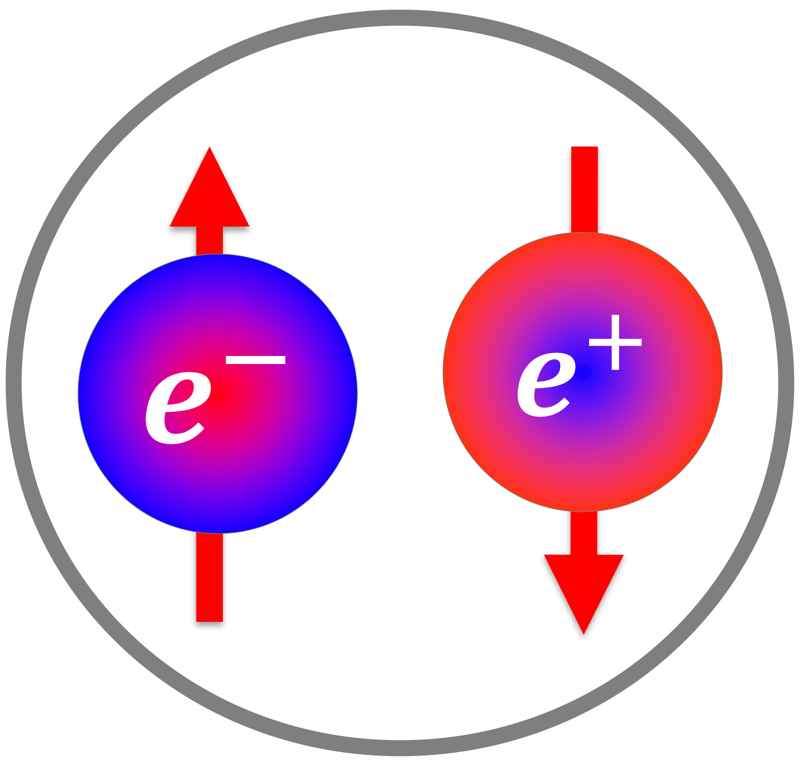


meson



Quark $J^P = \frac{1}{2}^+$ Antiquark $J^P = \frac{1}{2}^-$

positronium



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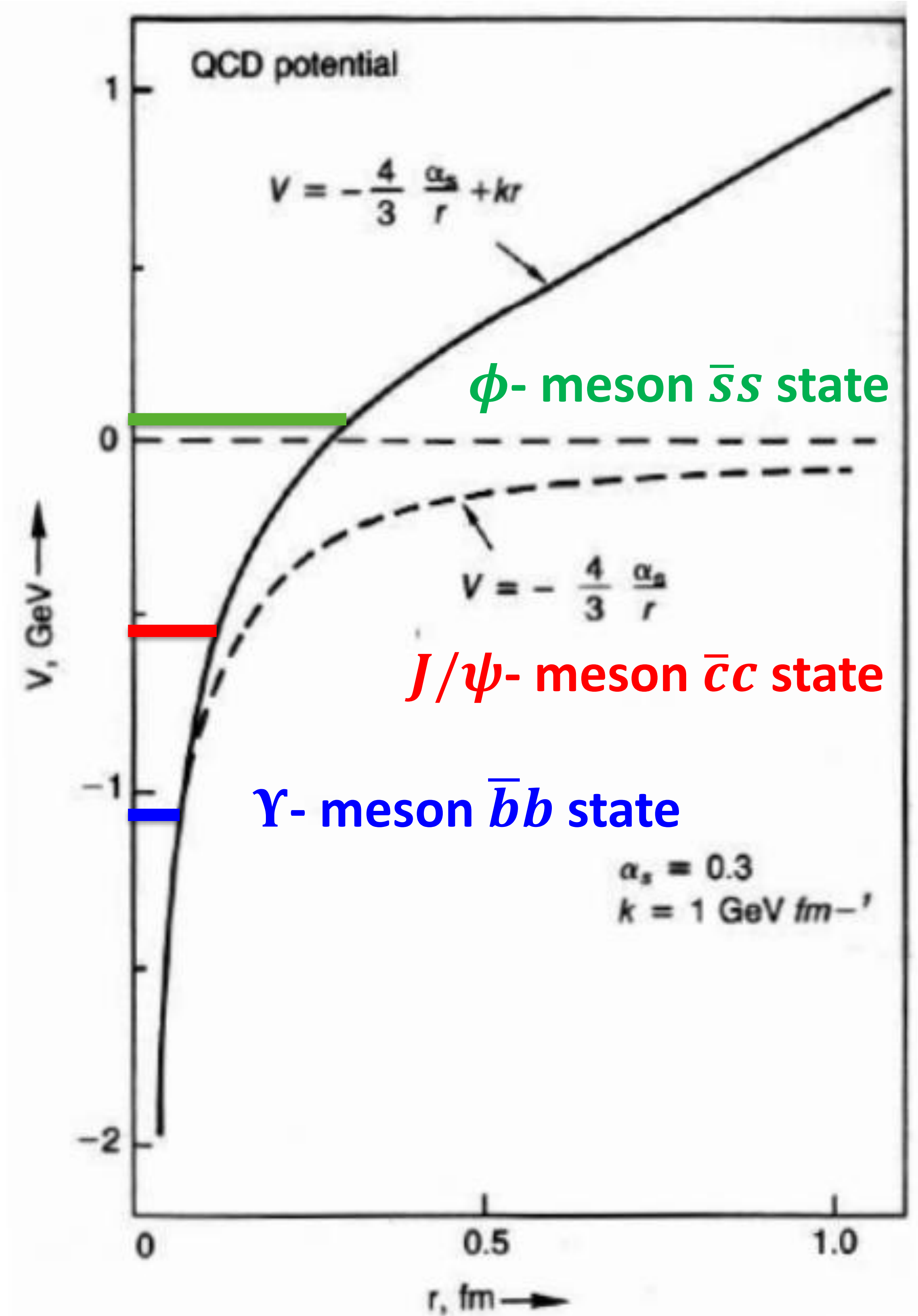
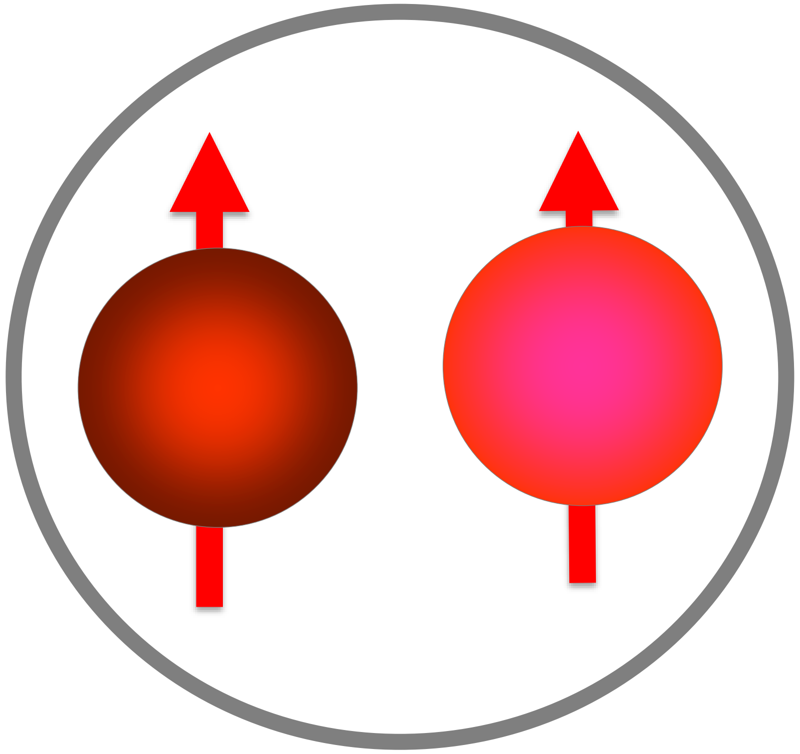
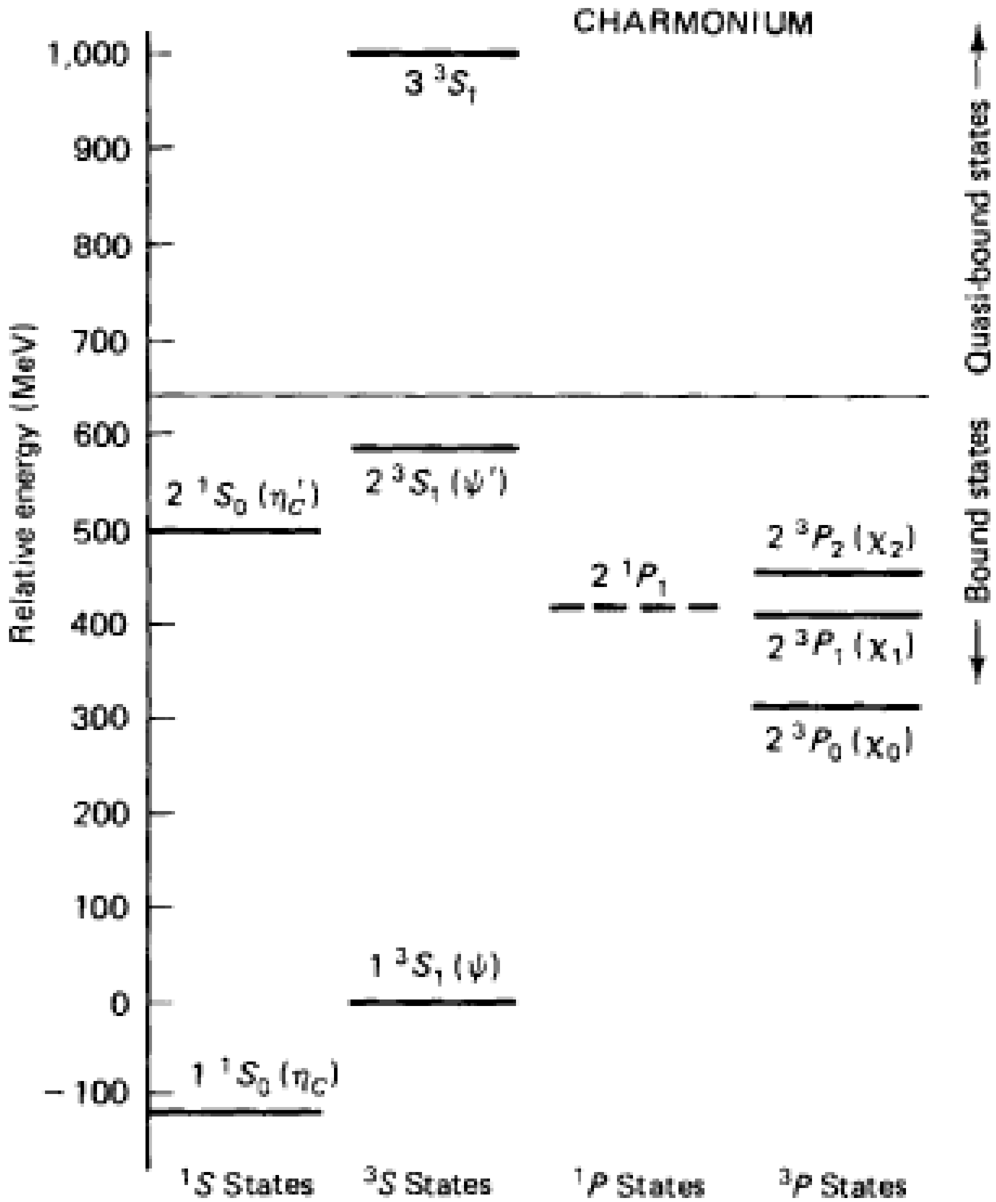


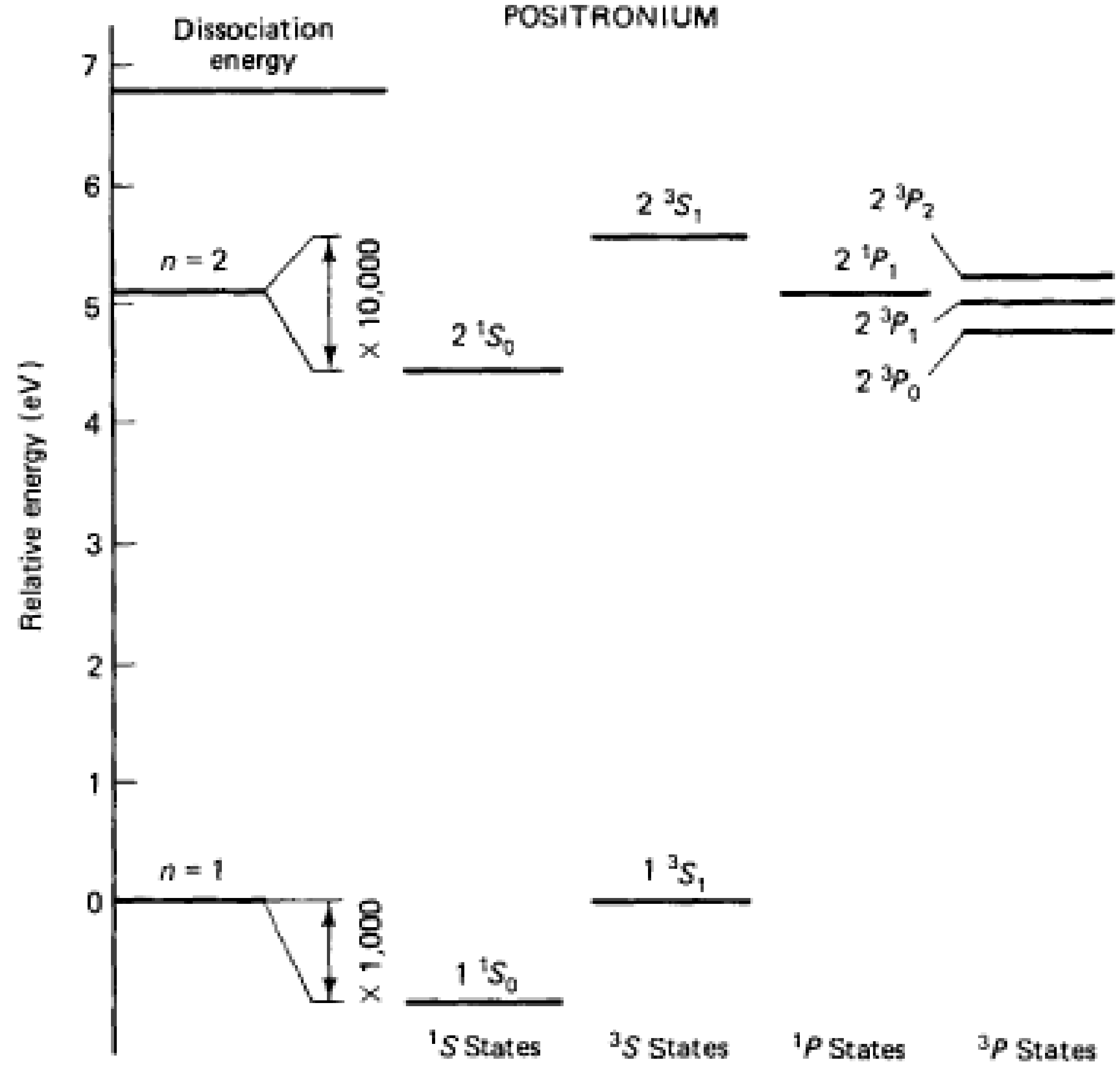


$J^P = 1^-$

- 1^- same quantum numbers as photon
- Easy to produce in e^+e^- collisions
- Best studied states

What is inside?
1) Heavy quarkonia



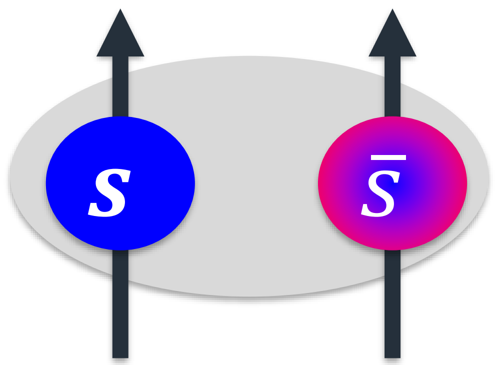


What is inside?
1) Heavy quarkonia

Based on excitation spectra, mesons are

- Made of particle and antiparticle (at least some of them)
- The spectrum of heavy quarkonia and positronium looks identical (besides energy scale)
    - Constituents of mesons are spin $\frac{1}{2}$ particles
    - Interaction between them is mediated by $\mathrm{J}^{\mathrm{P}} = 1^{-}$ particle

ϕ-meson and OZI rule



- $J^{PC} = 1^{--}$, quantum numbers of a photon
- $I = 0$, isoscalar
- Can be easily produced in $e^+e^- \to \phi$
- $M(\phi) = 1020\ MeV$
- $\Gamma(\phi) = 4.2\ MeV$
- $Br\,\frac{\Gamma(\phi\to K\bar{K})}{\Gamma_{tot}(\phi)} = 83\%$

ϕ-meson and OZI rule

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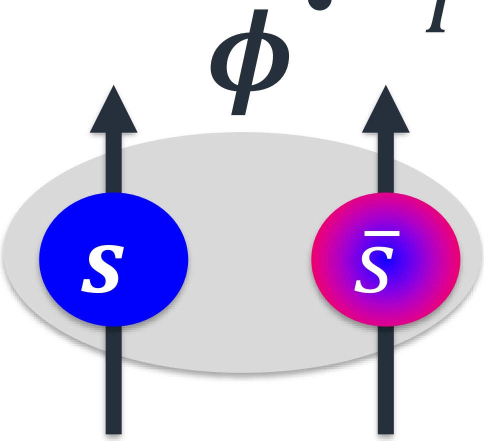
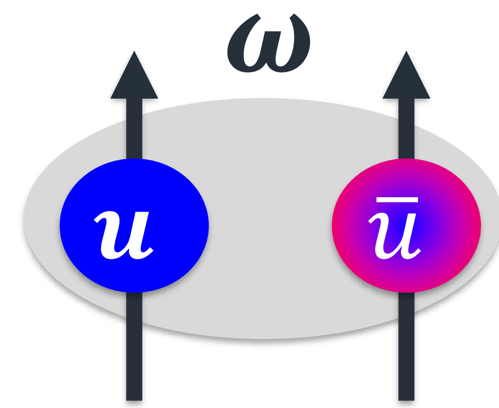
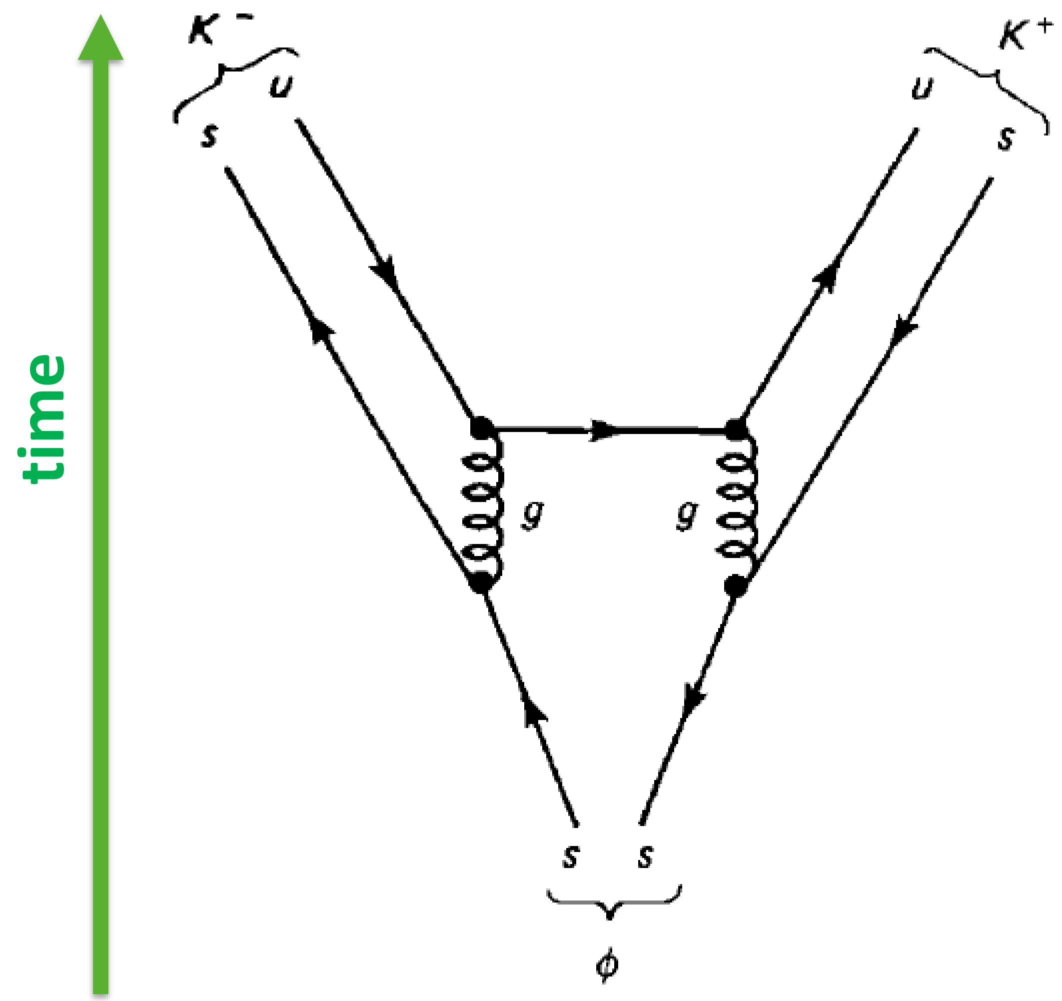


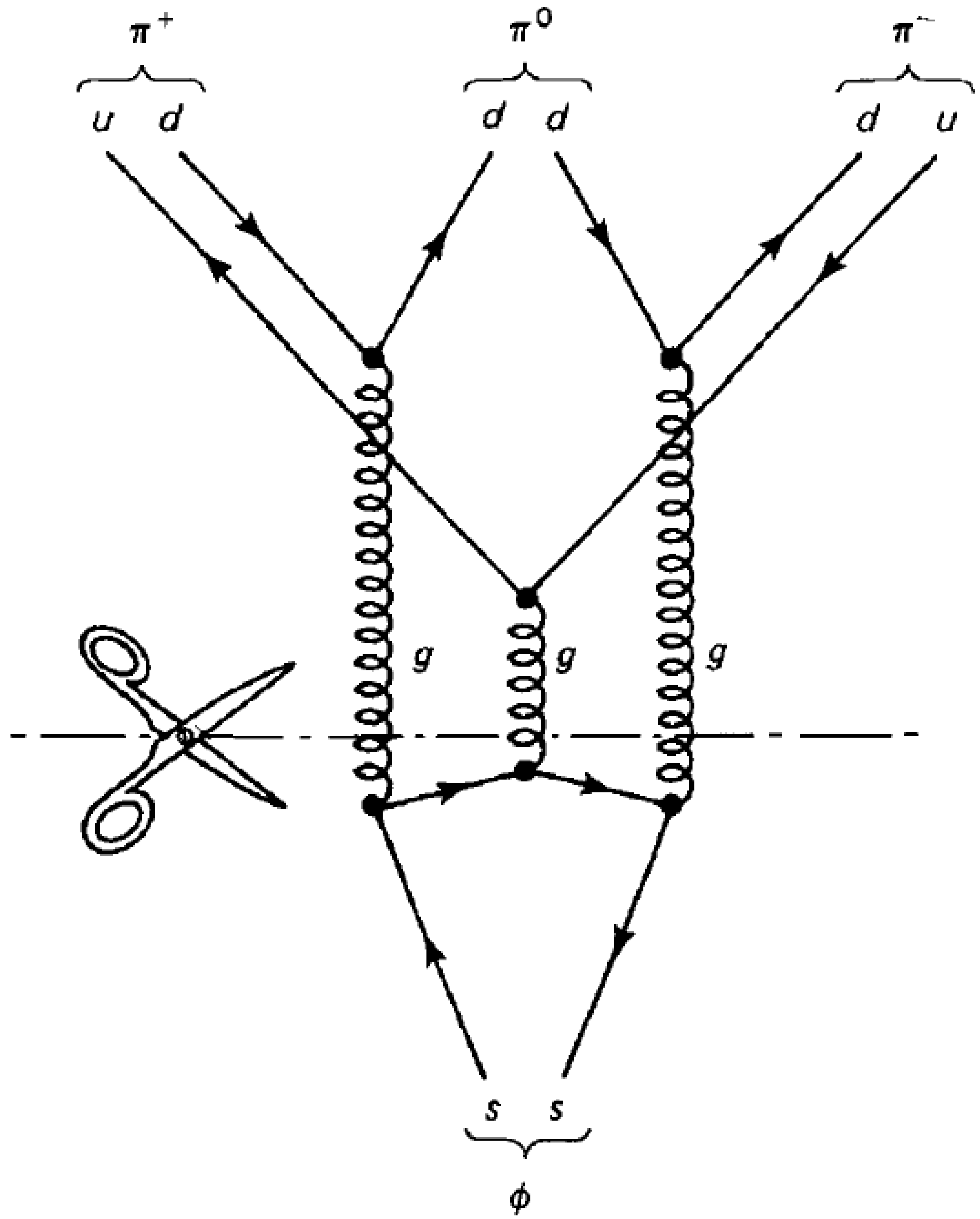


- $M(\phi) = 1020\ MeV$
- $\Gamma(\phi) = 4.2\ MeV$
- $Br\frac{\Gamma(\phi\to K\bar{K})}{\Gamma_{tot}(\phi)} = 83\%$
- $M(\phi) - 2M(K^+) =$
  $=1024 - 2 \cdot 494 = 36\ MeV$
- $Br\frac{\Gamma(\phi\to 3\pi)}{\Gamma_{tot}(\phi)} = 15\%$

- $M(\omega) = 782\ MeV$
- $\Gamma(\omega) = 8.72\ MeV$
- $M(\omega) - 3M(\pi) = 369\ MeV$
- $Br\frac{\Gamma(\omega\to 3\pi)}{\Gamma_{tot}(\omega)} = 89\%$

ϕ-meson and OZI rule



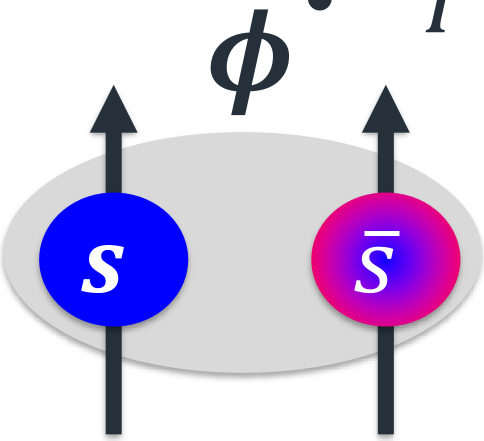


Okuba, Zweig, Iizuka:

The OZI rule: If the diagram can be cut in two by slicing only gluon lines (and not cutting open any external particles), **the process is suppressed**.

J/ψ-meson and OZI rule

- $J^{PC} = 1^{--}$, quantum numbers of a photon
- $I = 0$, isoscalar



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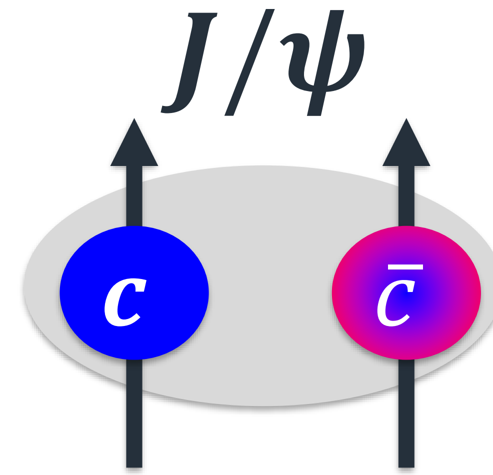
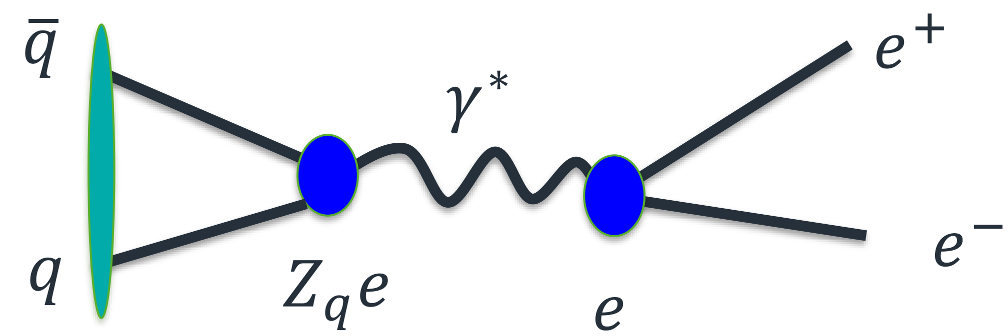
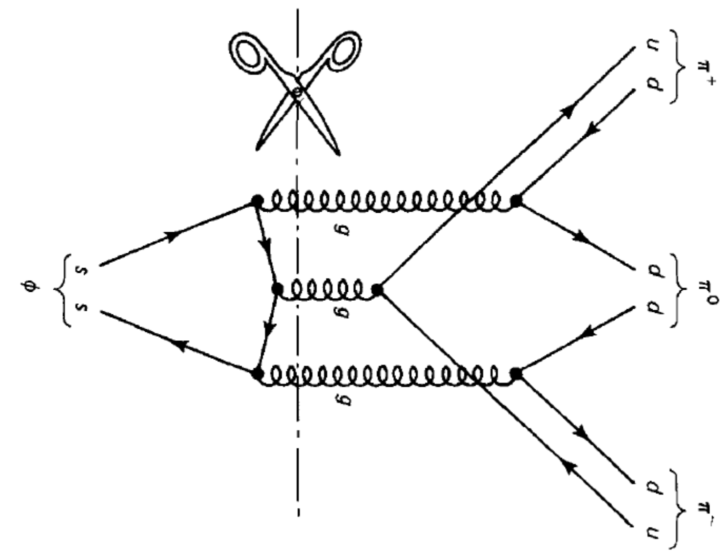


- $M(J/\psi) = 3096\ MeV$
- $\Gamma(J/\psi) = 0.1\ MeV$
- $Br\,\frac{\Gamma(J/\psi\to 2D)}{\Gamma_{tot}(J/\psi)} = \mathbf{0}\%$
- $M(J/\psi) - 2M(D)$
  $= \mathbf{-642}\ MeV$
- $Br\,\frac{\Gamma(J/\psi\to 3\pi)}{\Gamma_{tot}(J/\psi)} = 2\%$

Vector mesons & OZI

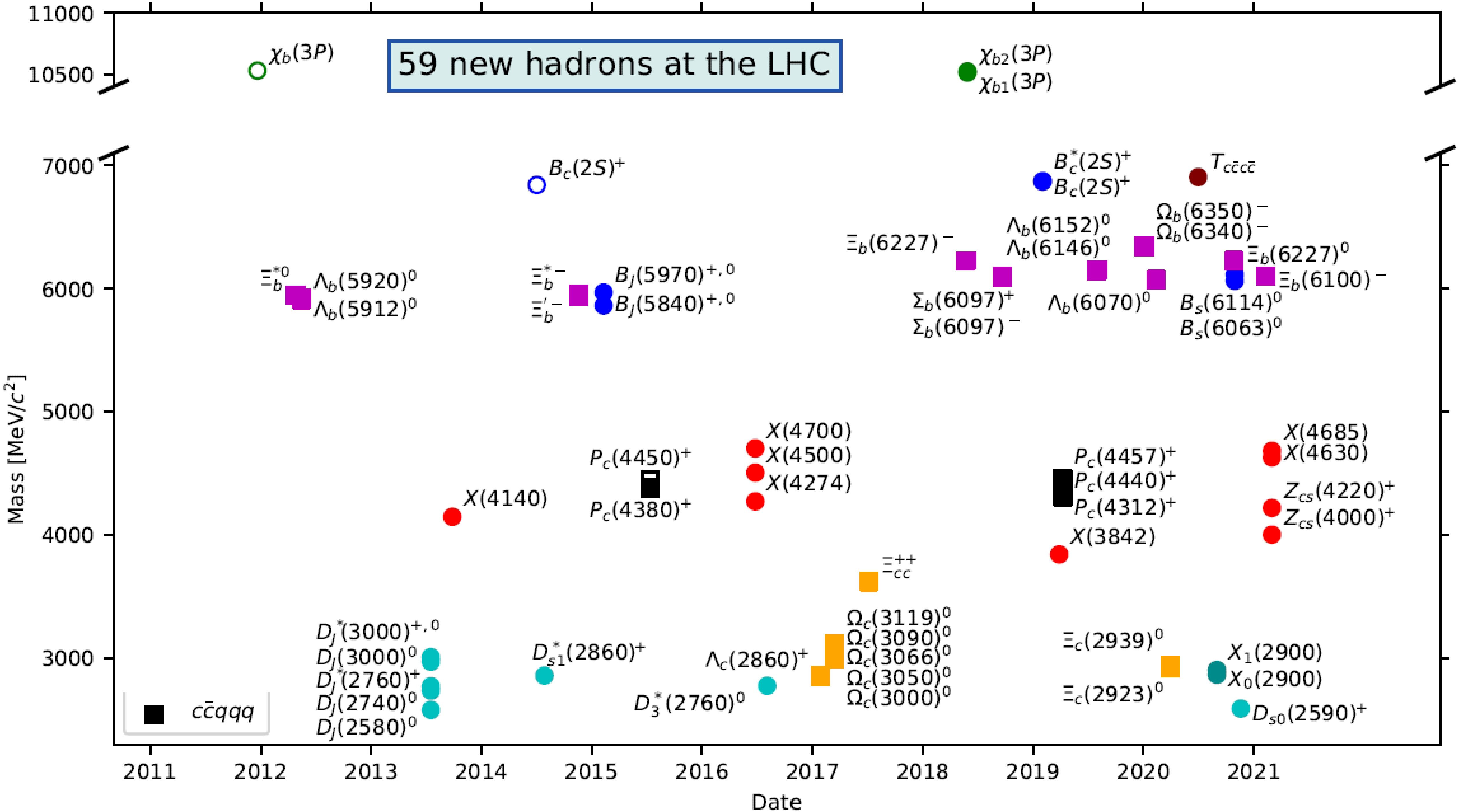




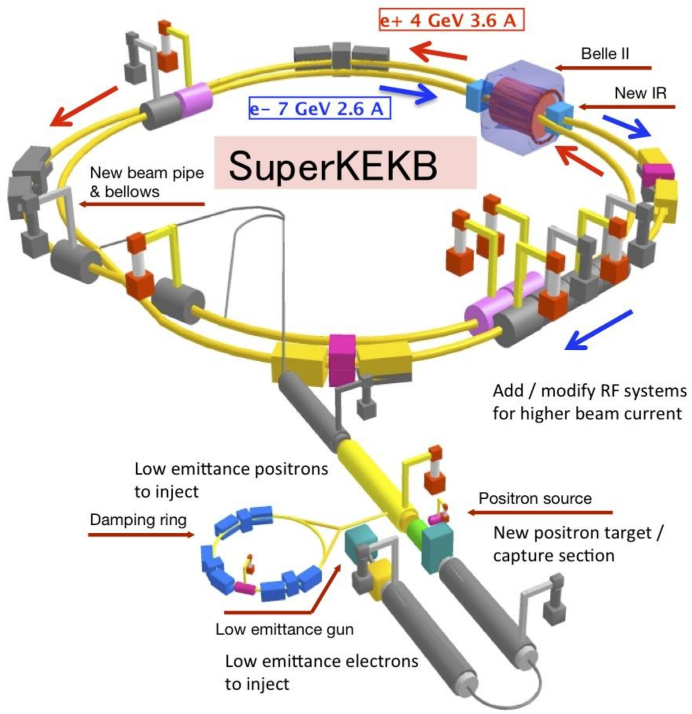
	$\phi(s\bar{s})$ $M = 1.02GeV$	$J/\psi(c\bar{c})$ $M = 3.1GeV$	$\Upsilon(b\bar{b})$ $M = 9.46GeV$
$\Gamma(V \to 3\pi)$	654 keV	1.63keV	$\sim 10^{-6}$keV
$\Gamma(V \to e^+e^-)$	1.27 keV	5.53keV	1.29keV
$\Gamma(V \to \mu^+\mu^-)$	0.05keV	5.13keV	1.34keV
Γ_{tot}	4200keV	92.6keV	54.02keV
“Binding” Energy	+36MeV	-642MeV	-1100MeV

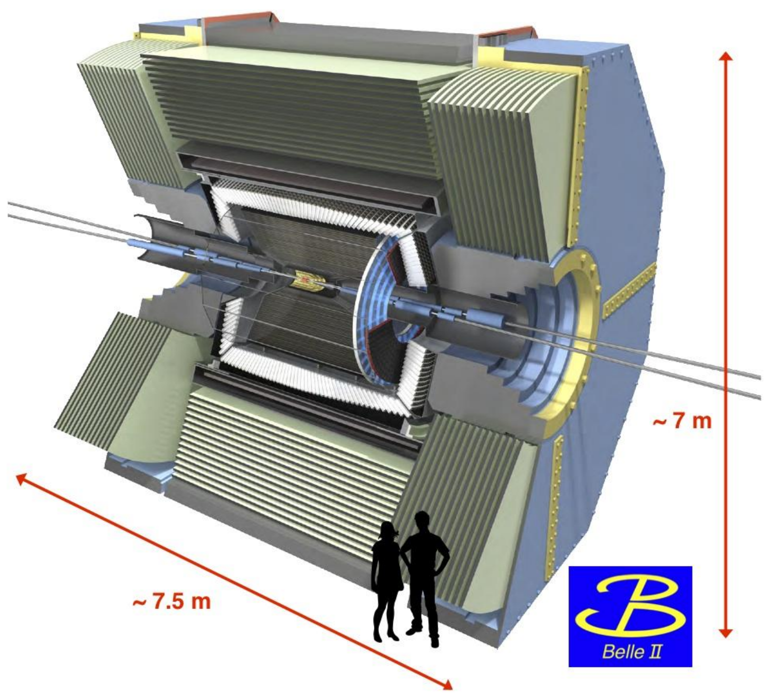
Exotic particles:

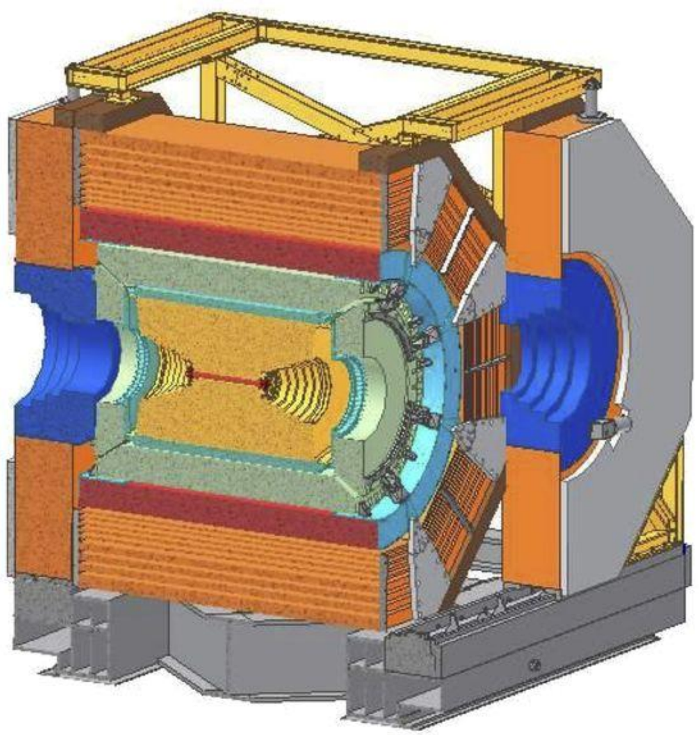
Exotics at LHCb



$Z^+(3900)$ at Belle and BESIII







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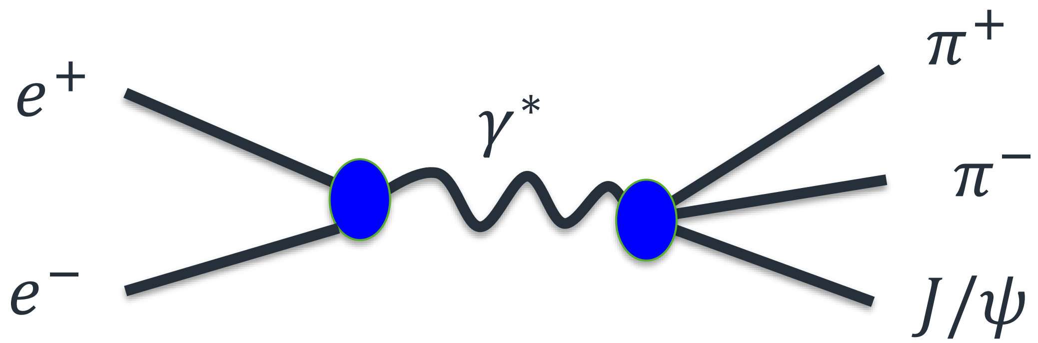
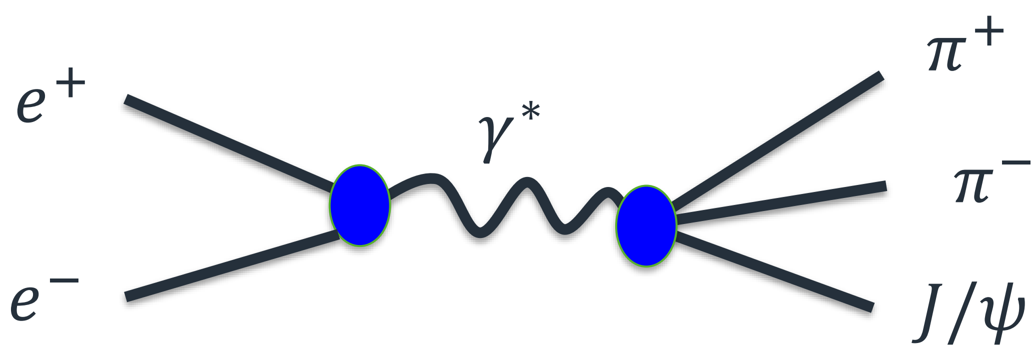
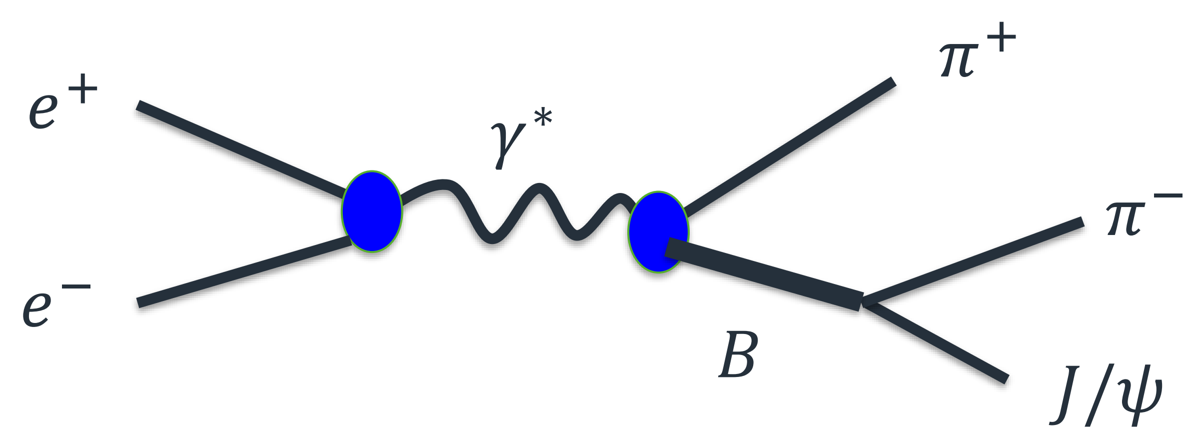
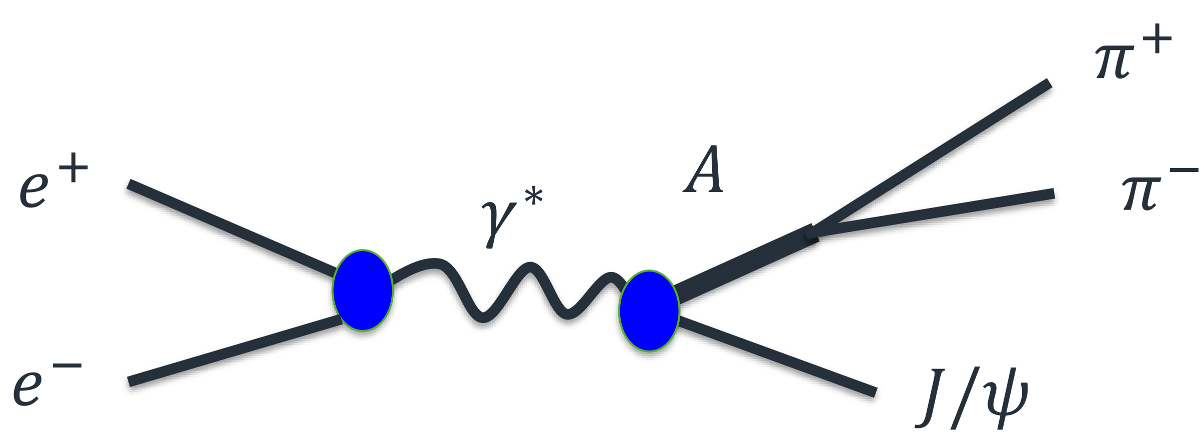
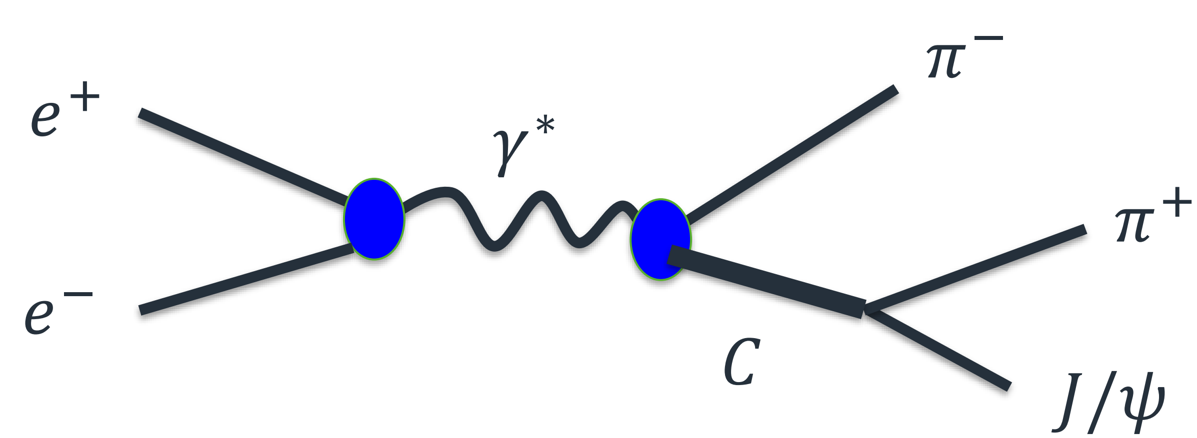


$Z^+(3900)$ at Belle and BESIII

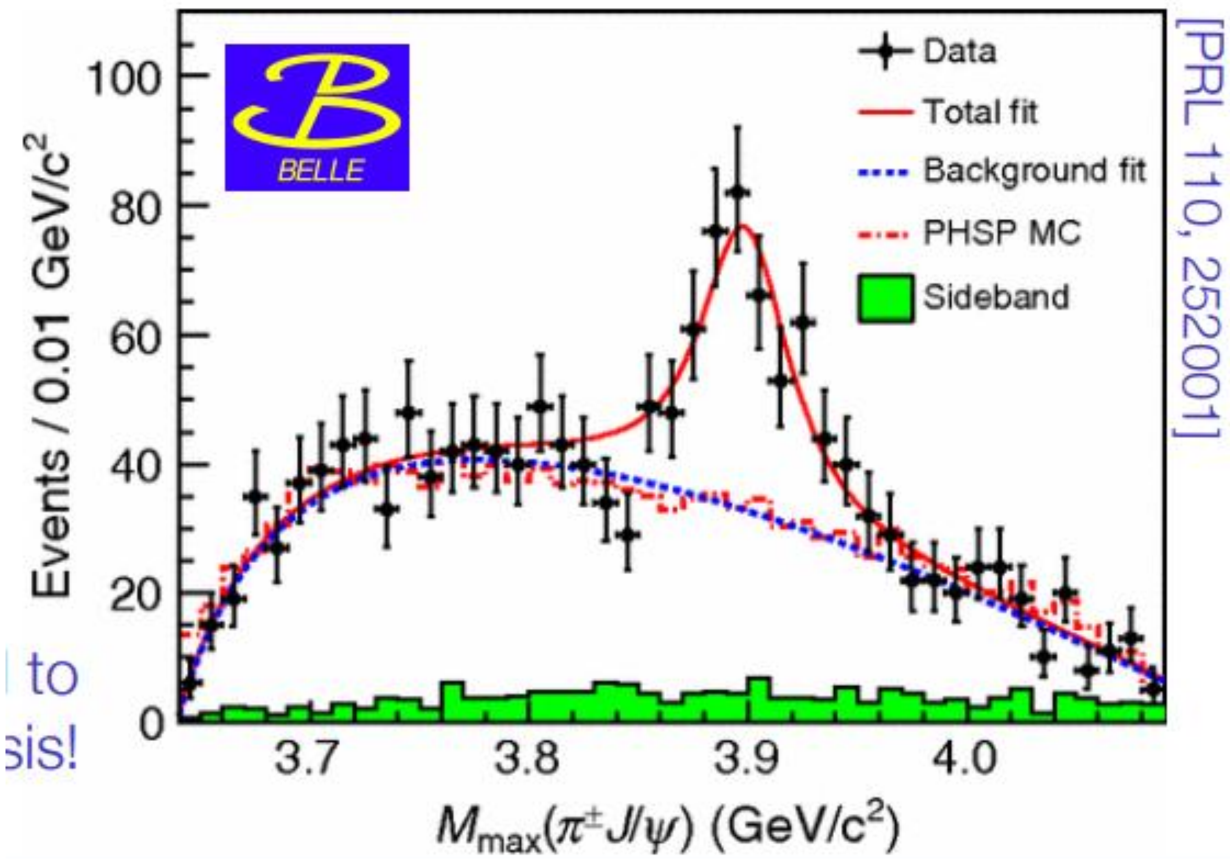


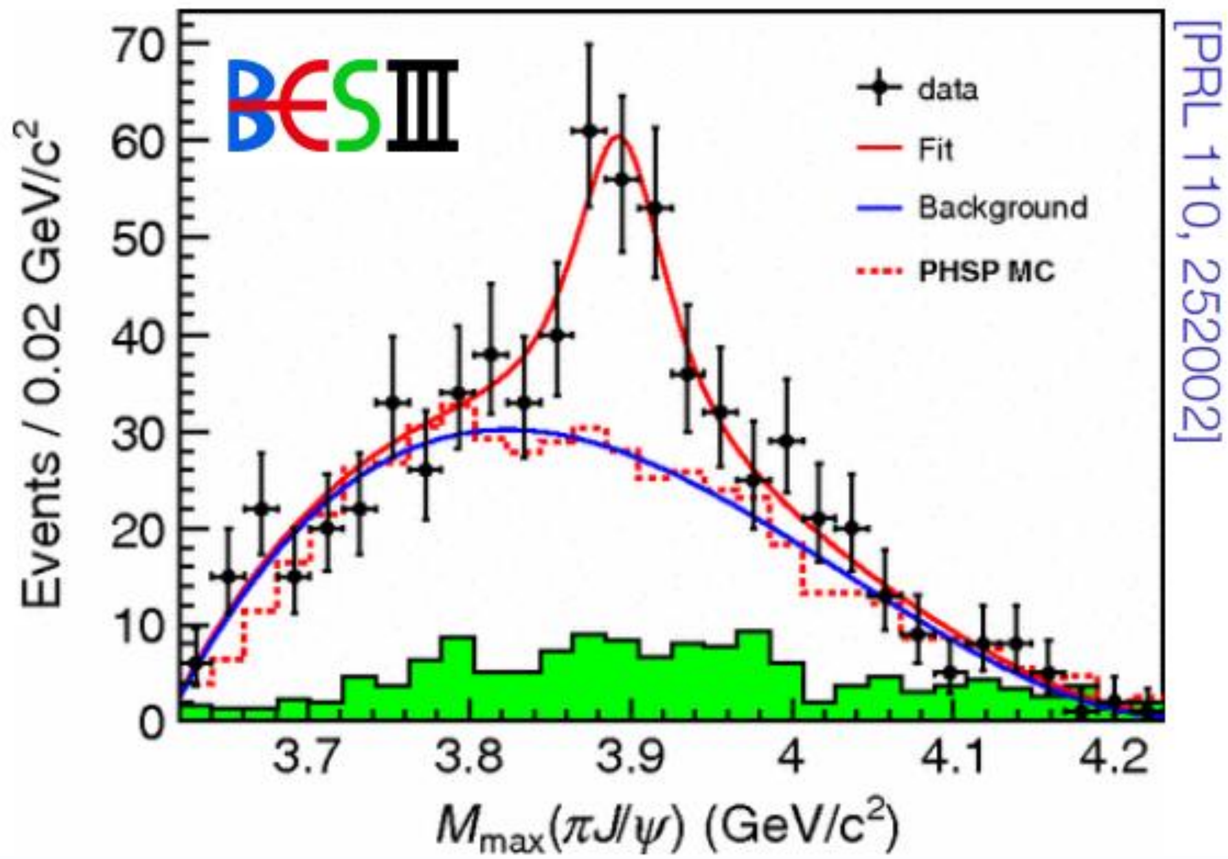






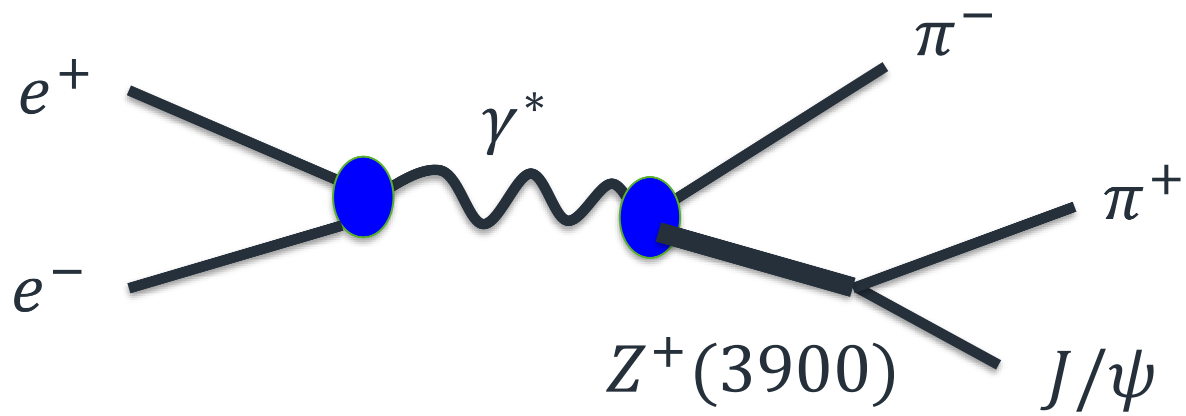
$Z^+(3900)$ at Belle and BESIII





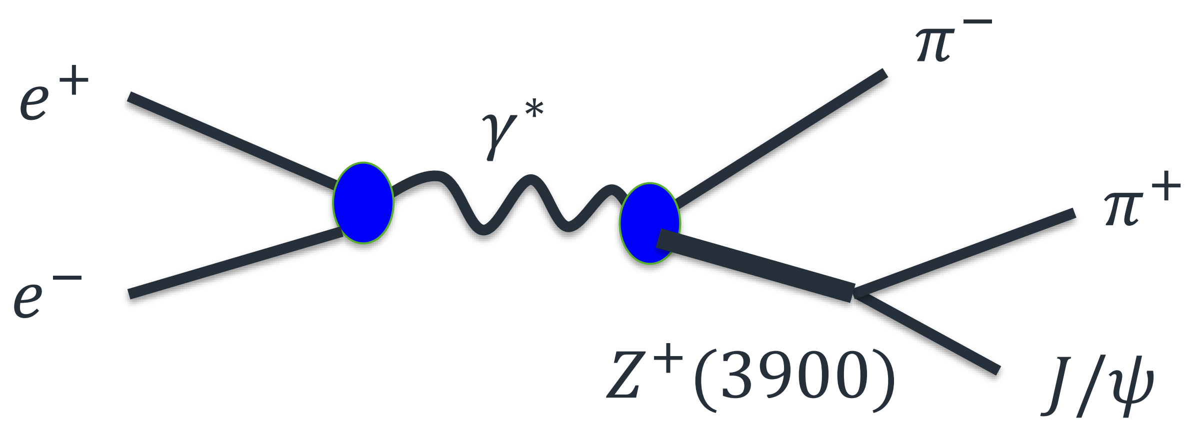
What can we tell about this mysterious particle?

$Z^+(3900)$ at Belle and BESIII



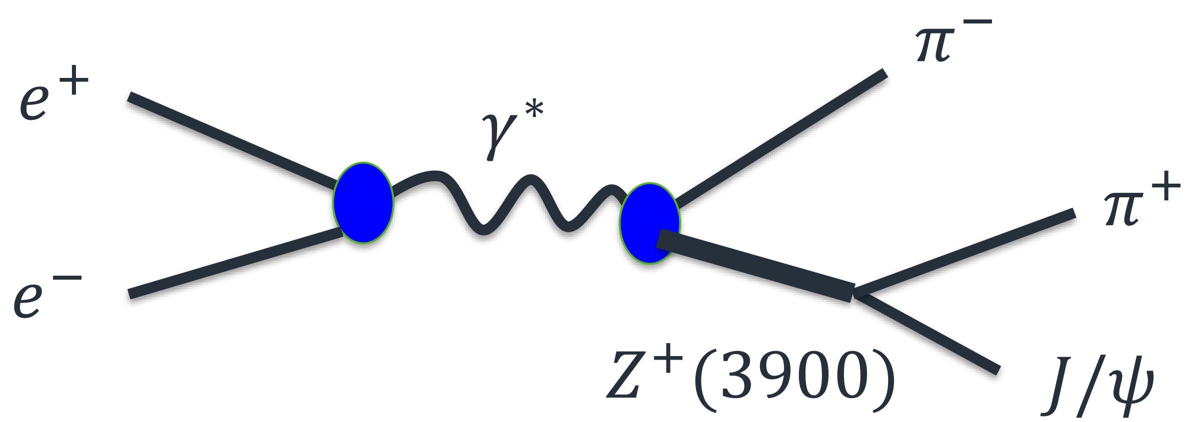
Isospin?

$Z^+(3900)$ at Belle and BESIII



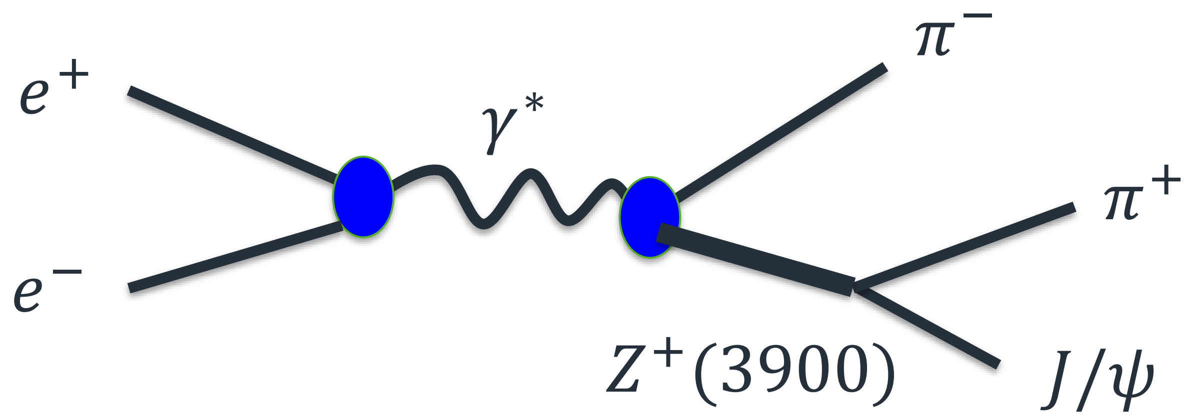
Isospin? : $I(J/\psi)$=0; $I(\pi)$=1 $\Rightarrow \vec{0} + \vec{1} = \vec{1}$ $\begin{pmatrix} Z^+ \\ Z^0 \\ Z^- \end{pmatrix} \rightarrow J/\psi \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$

$Z^+(3900)$ at Belle and BESIII



Isospin $I(Z^+(3900)) = 1$
Quark content?

$Z^+(3900)$ at Belle and BESIII



Isospin $I(Z^+(3900)) = 1$

Quark content: $Z^+(3900) = |c\bar{c}u\bar{d}\rangle$ - minimal allowed quark content

Mass-Width

$\omega(782)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*
8.68±0.13 OUR AVERAGE		

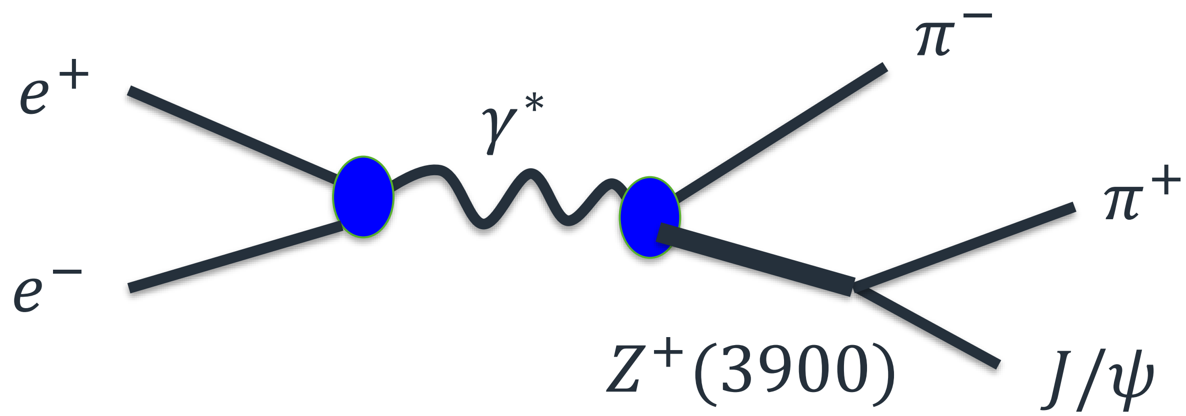
$\omega(1420)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*
290±190 OUR ESTIMATE			

$\omega(1650)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*
315± 35 OUR ESTIMATE			

$Z^+(3900)$ at Belle and BESIII

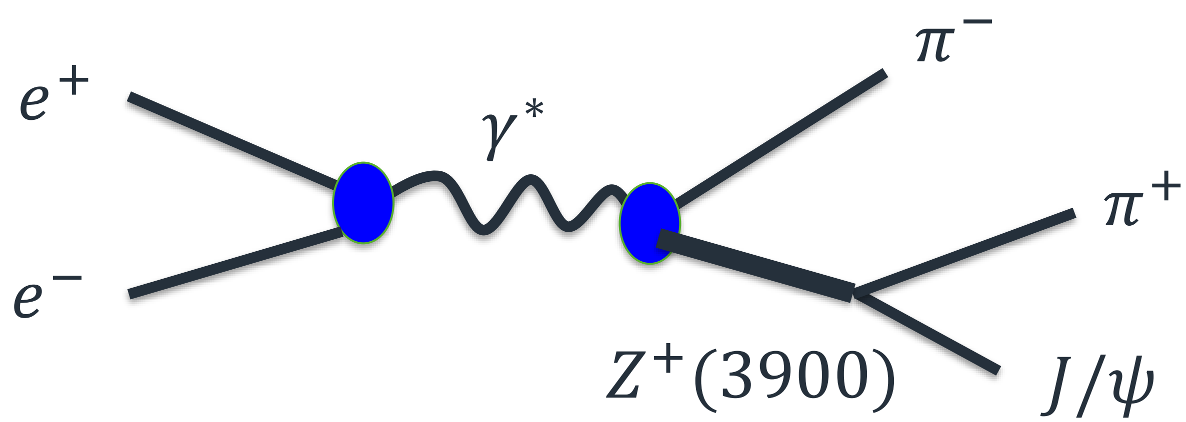


Isospin $I(Z^+(3900)) = 1$

Quark content: $Z^+(3900) = |c\bar{c}u\bar{d}\rangle$ - minimal allowed quark content

Quantum numbers?

$Z^+(3900)$ at Belle and BESIII



Isospin $I(Z^+(3900)) = 1$

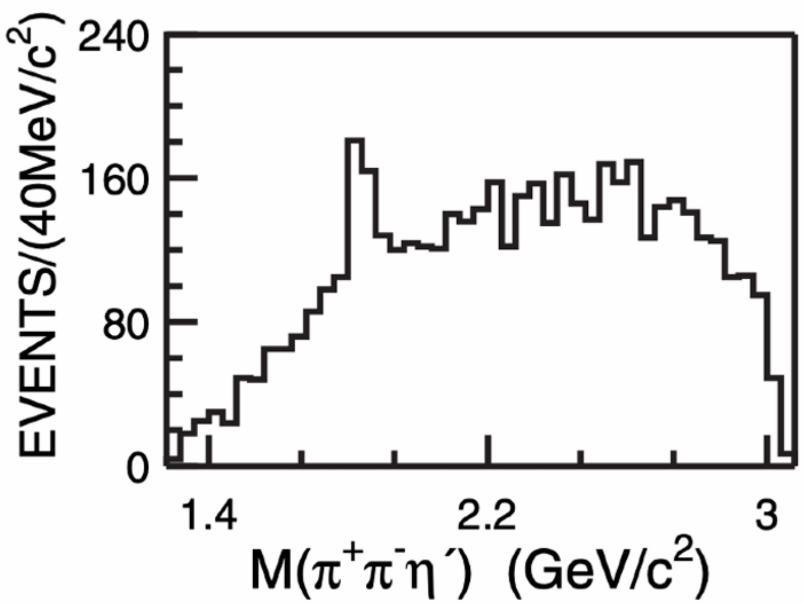
Quark content: $Z^+(3900) = |c\bar{c}u\bar{d}\rangle$ - minimal allowed quark content

Quantum numbers: $J^P(\pi) = 0^-; J^P(J/\psi) = 1^-$

$$L = 0 \rightarrow 1^+$$
$$L = 1 \rightarrow 2^-, 1^-, 0^-$$

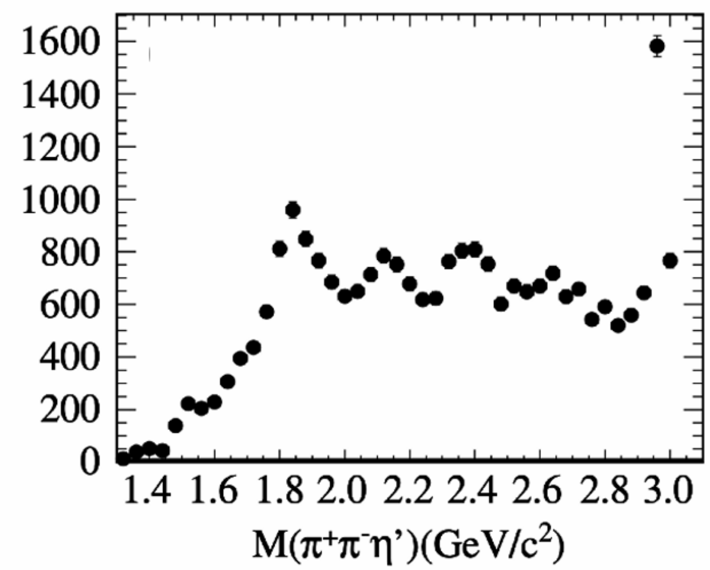
Statistics !!!

58M J/ψ events



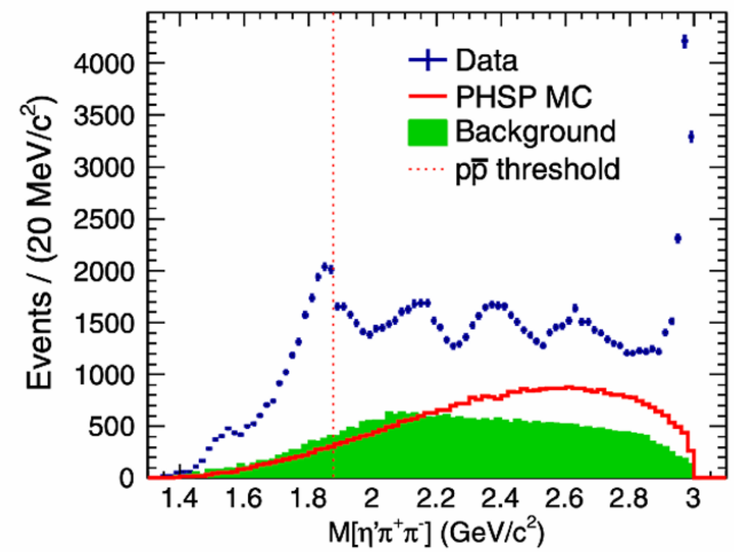
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

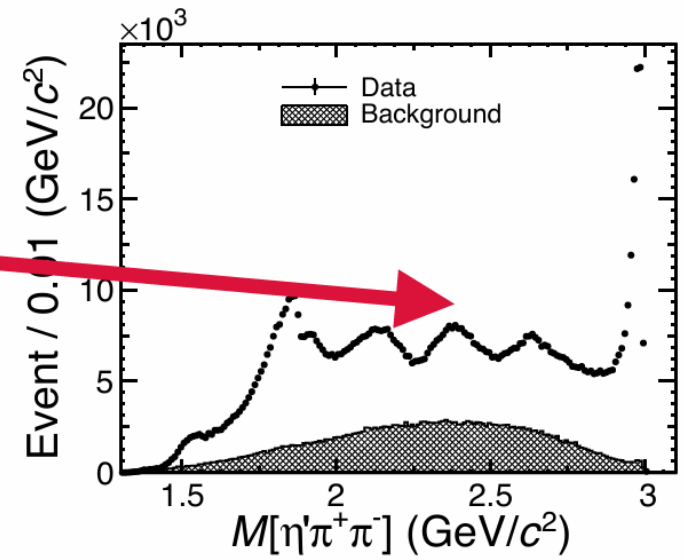
1090M J/ψ events



BESIII, PRL 117, 042002 (2016)

- Spin-parity of $X(2370)$ recently determined to be 0^{-+}!

PRL 132 181901 (2024)



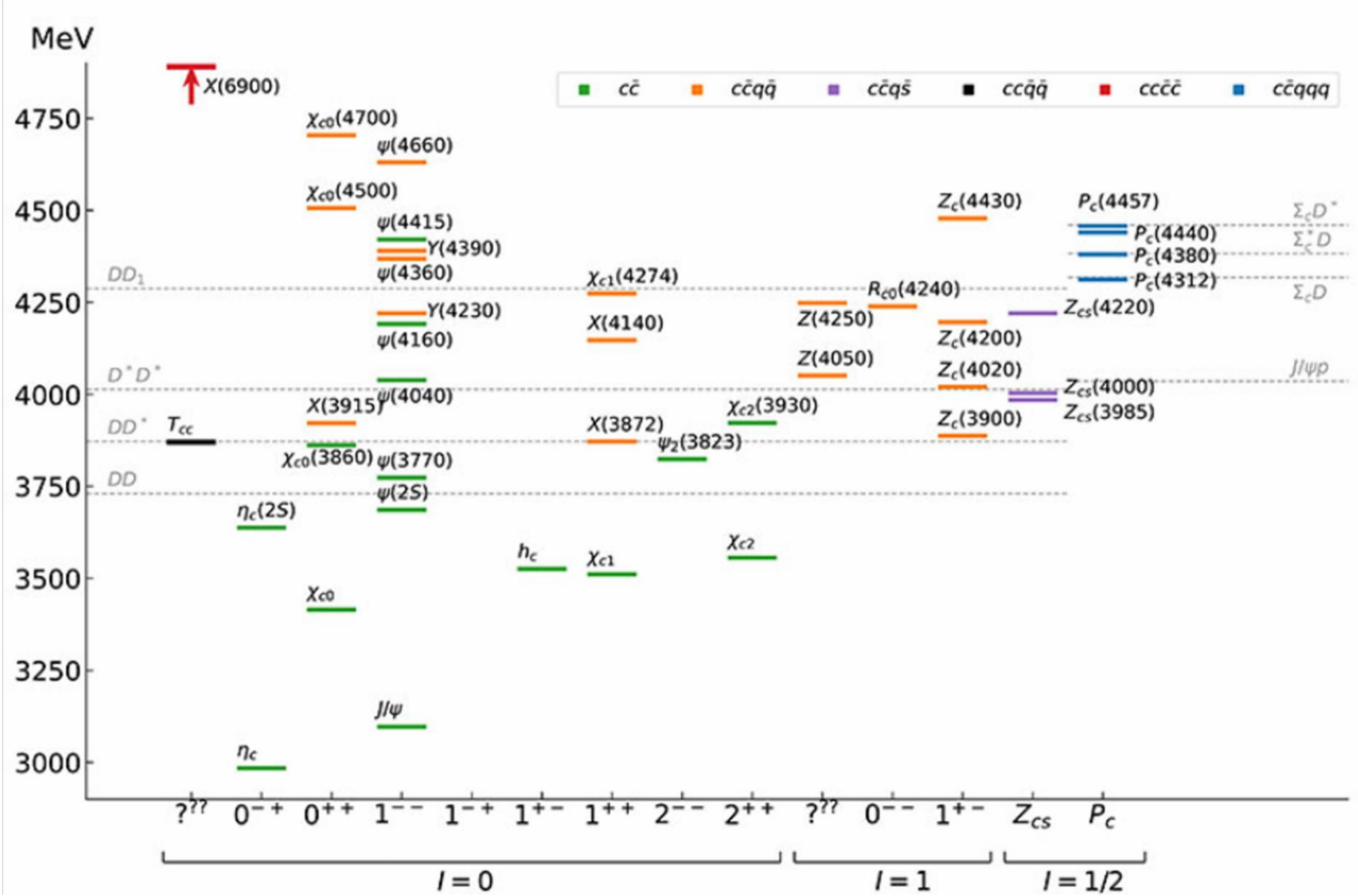
BESIII, PRL 129, 042001 (2022)

10B J/ψ events

Exotics

Above threshold region

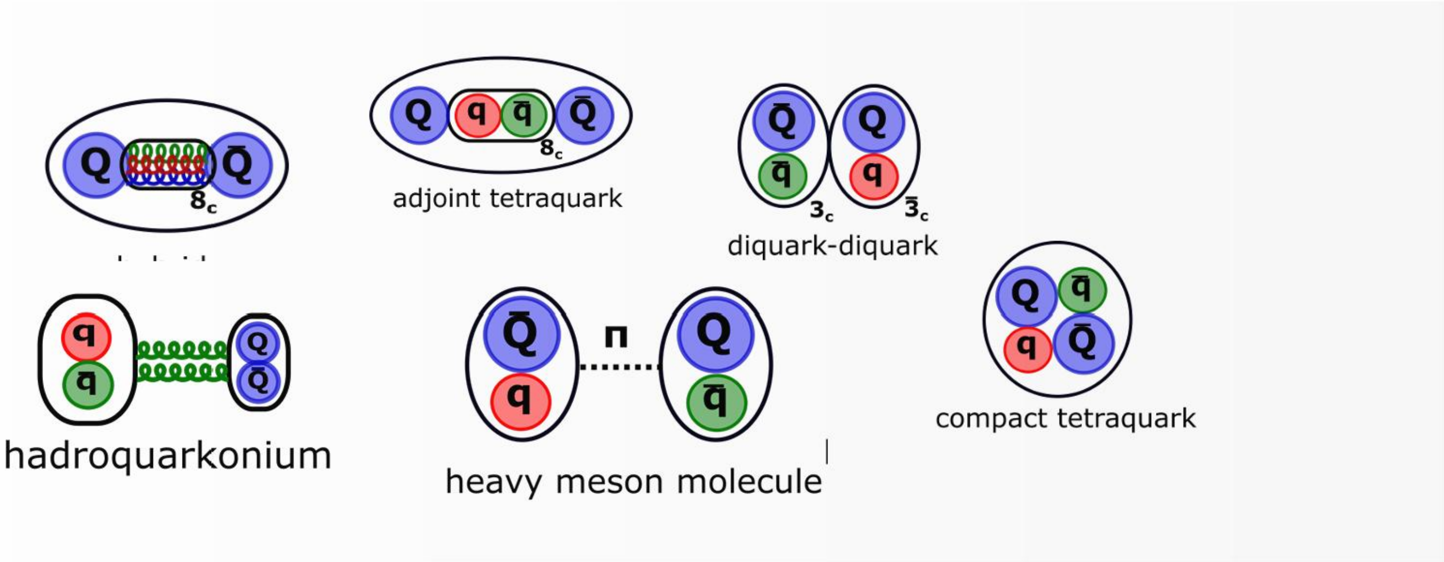
below threshold region

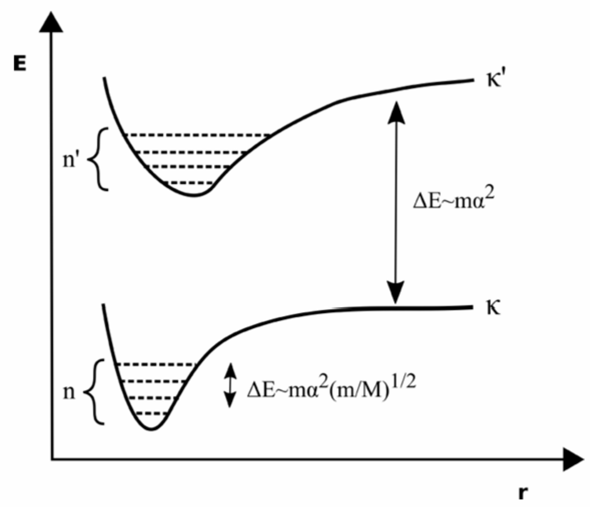


Exotics

Close/above threshold new degrees of freedom like glue and light quarks are nonperturbative part in the binding.

- Multiquark states involve different configurations. Models assume some degrees of freedom in some configurations and a model interaction : molecular model, tetraquark model.. .





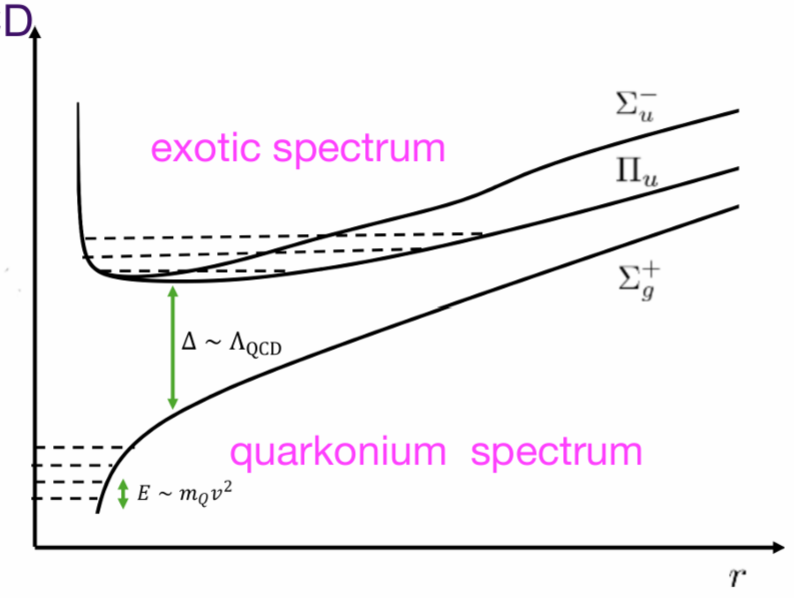
QED — Born Oppenheimer Description QCD

$$\Lambda_{QCD} > mv^2$$

fast (gluons, light quarks) and slow (heavy quarks)

like in molecular physics (fast-electrons, slow nuclei

Braaten PRL 111 (2013) 162003
Braaten Langmack Smith PRD 90 (2014) 014044



Conclusion

- QCD at high energies behaves very similar to QED
  - Asymptotically free quarks
- A lot of states
- A lot of exotics
  - Molecules
  - Tetraquarks

Questions

1. An exotic state X(3872) decays into $J/\psi\rho$ and $J/\psi\omega$ with similar probabilities:
   1. why is it a problem?
   2. Determine quantum numbers of this state for 3 lowest partial wave
   3. What is the quark content of this state.
2. You want to discover charm hybrid made of $\bar{c}cg$
   1. What quantum numbers should it have to avoid misidentification with a regular $c\bar{c}$ state
   2. What decay channel would you foresee for this object.