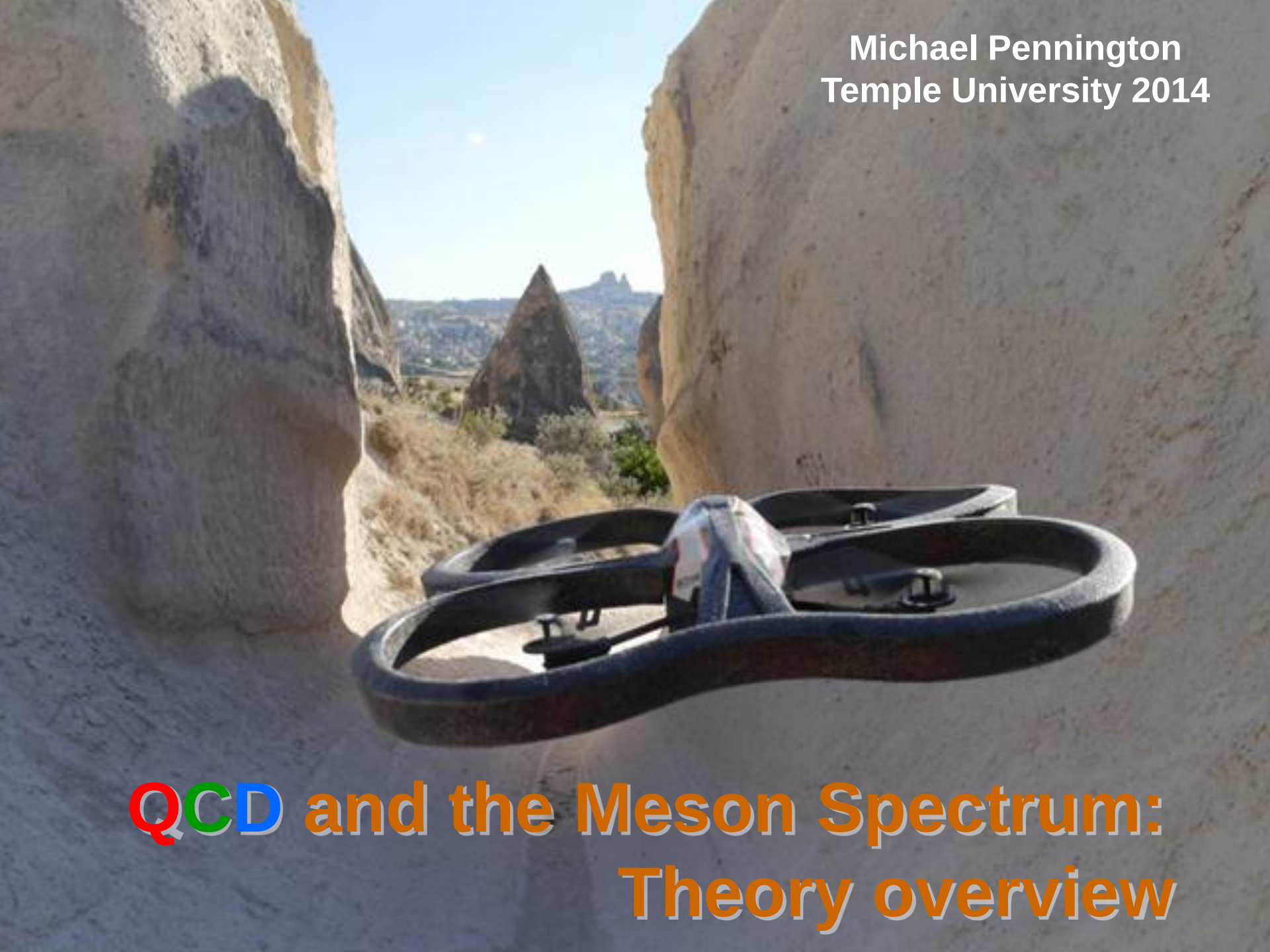
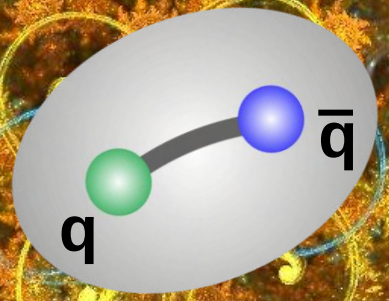


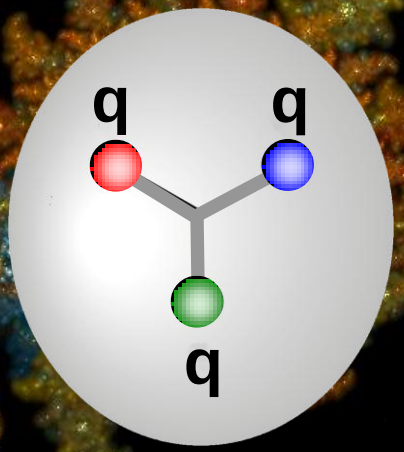
Michael Pennington
Temple University 2014

QCD and the Meson Spectrum: Theory overview

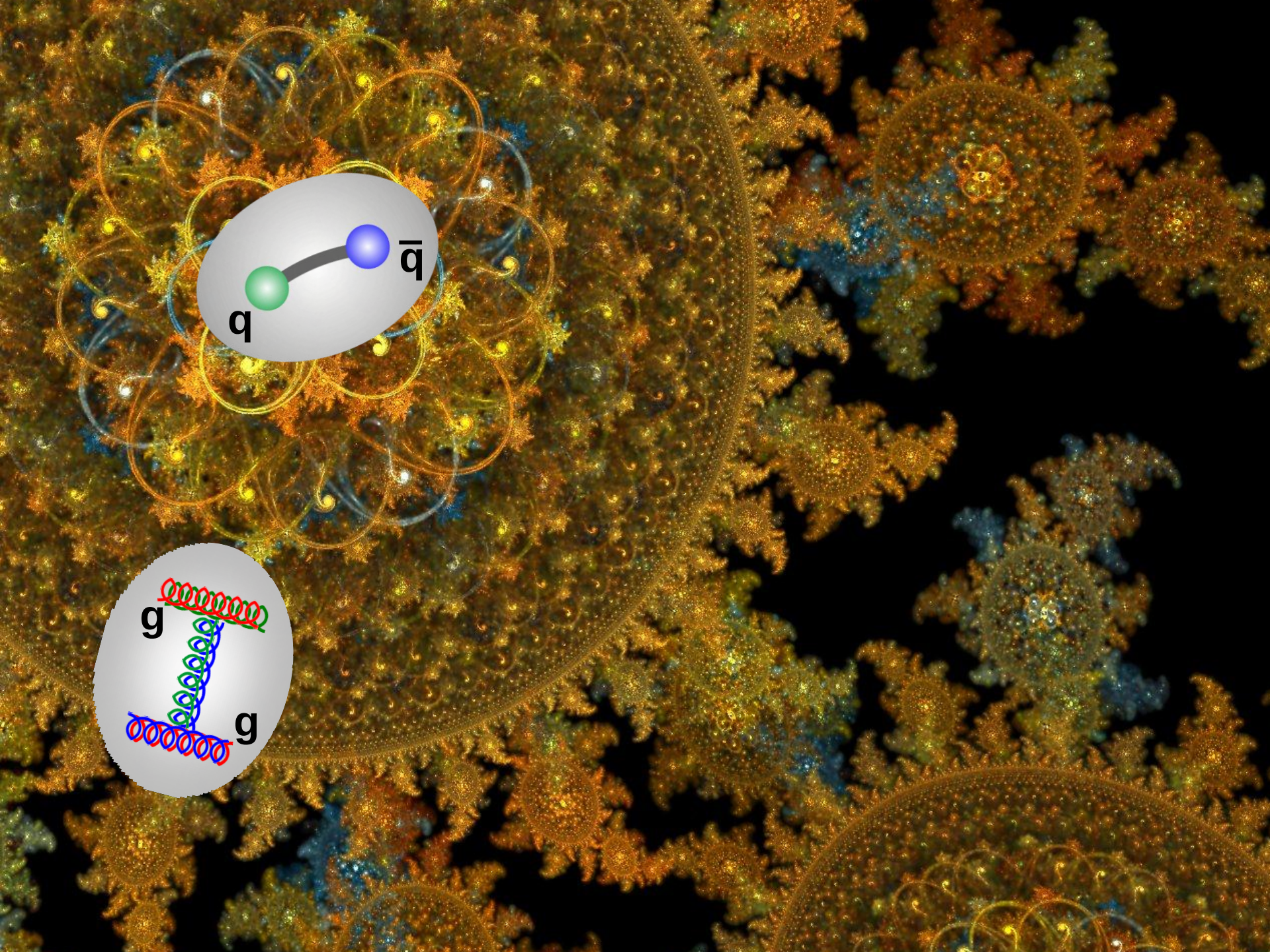
understanding
the spectrum of hadrons

to reveal the workings
of strong coupling QCD





$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q}\,(\,i\gamma_\mu D^\mu - m_q\,)\,q \;-\; \frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}$$


q̄
q
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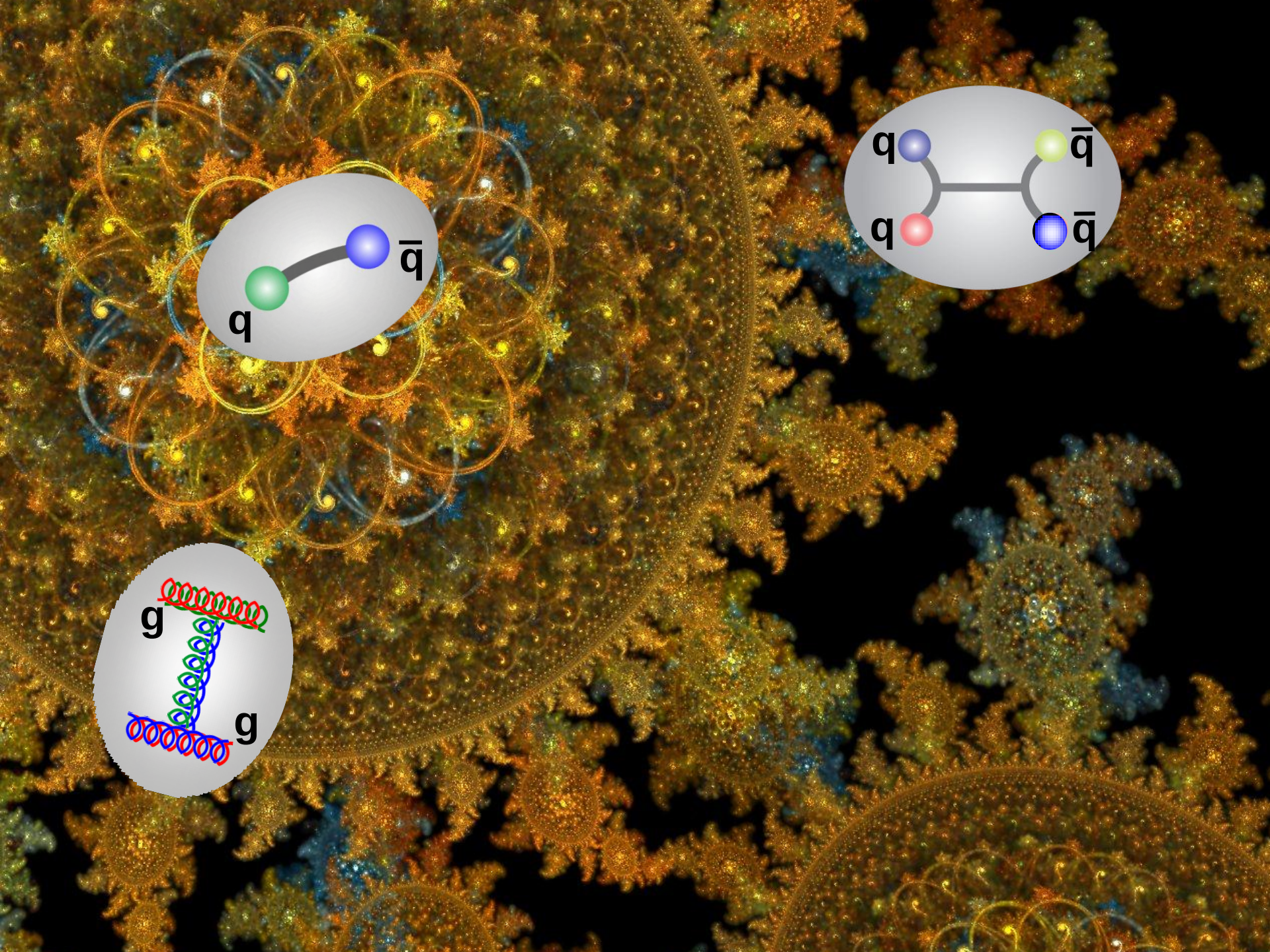
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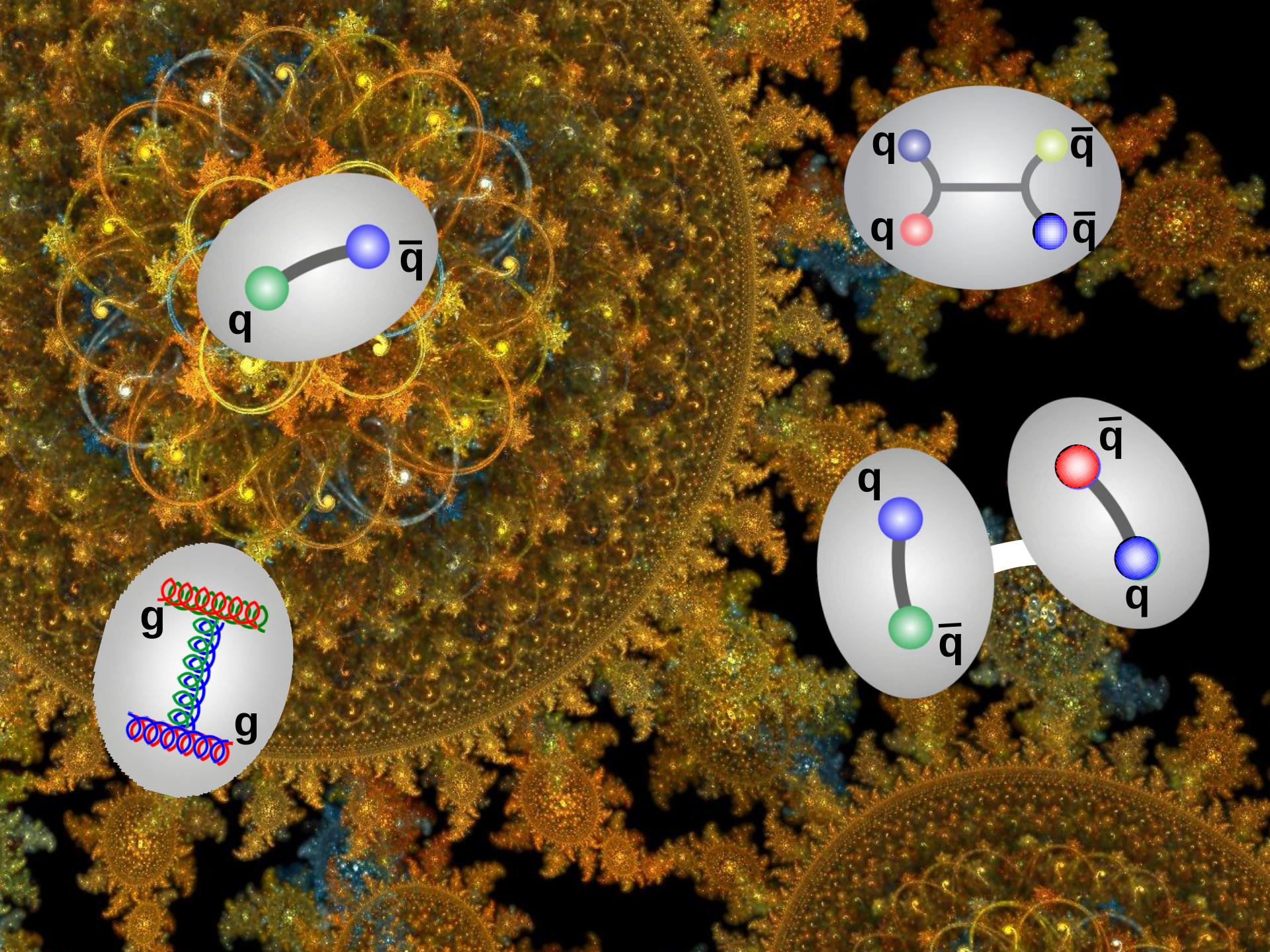
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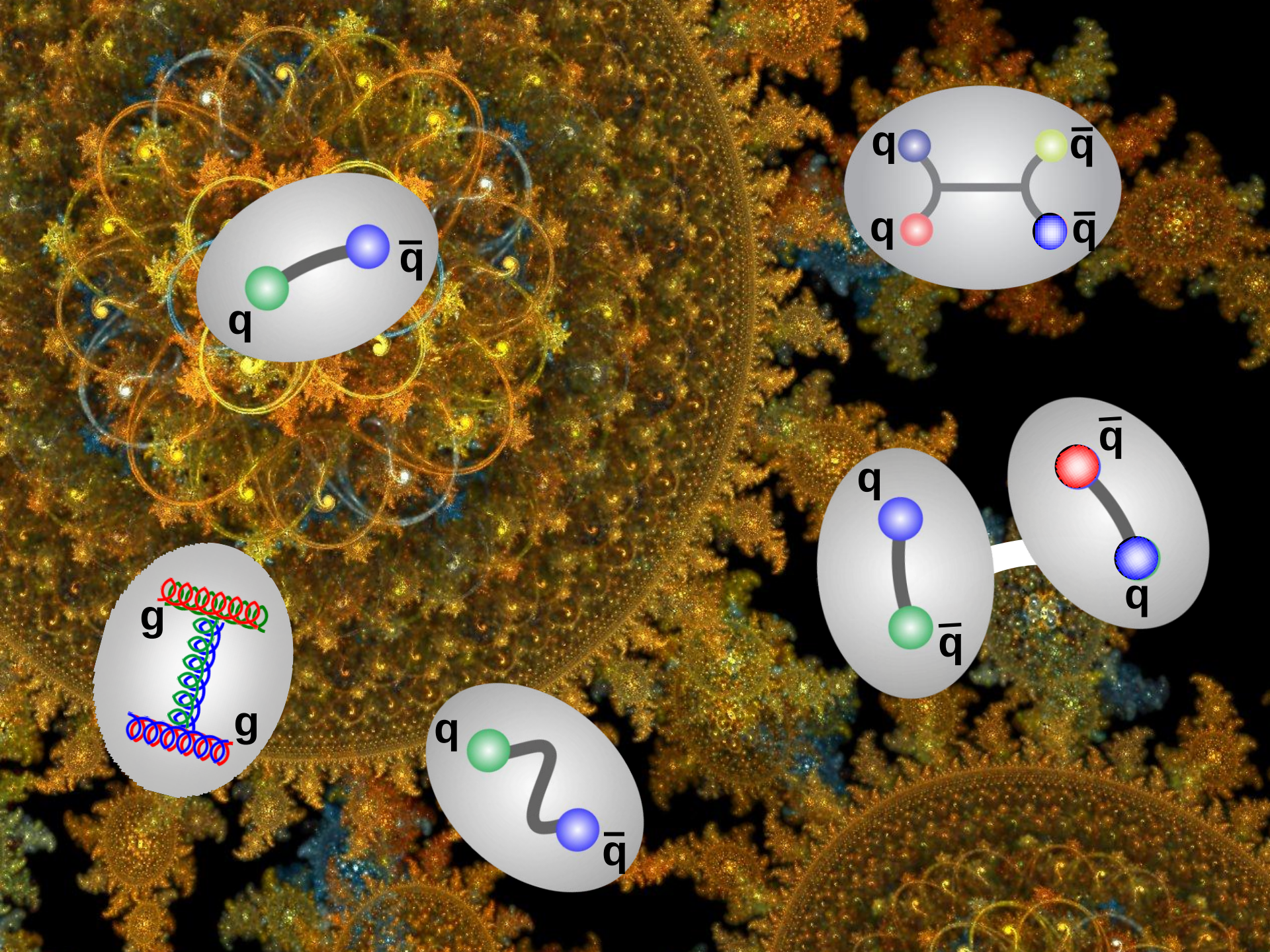
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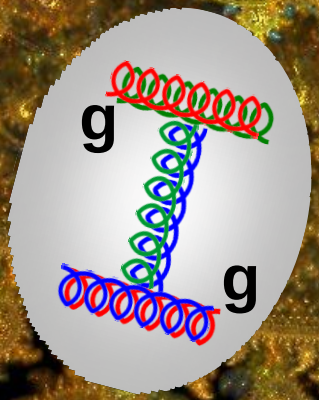
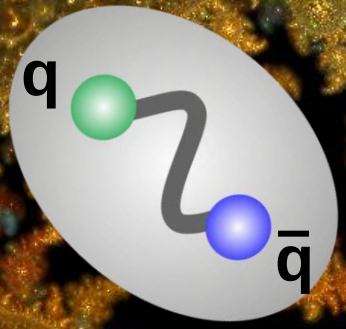
LONG RANGE PLAN: next decade

Definitive discovery of gluonic excitations

i.e. states where glue builds their J^{PC}





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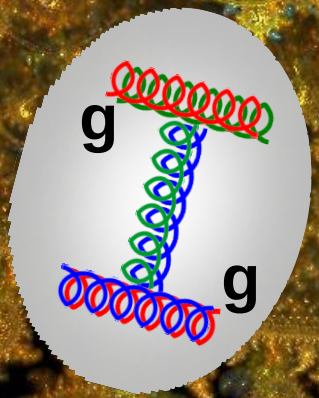
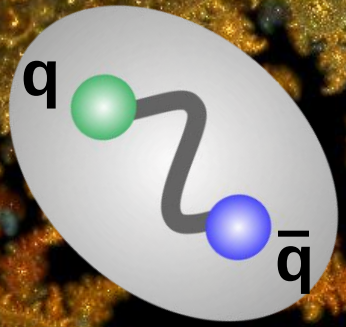
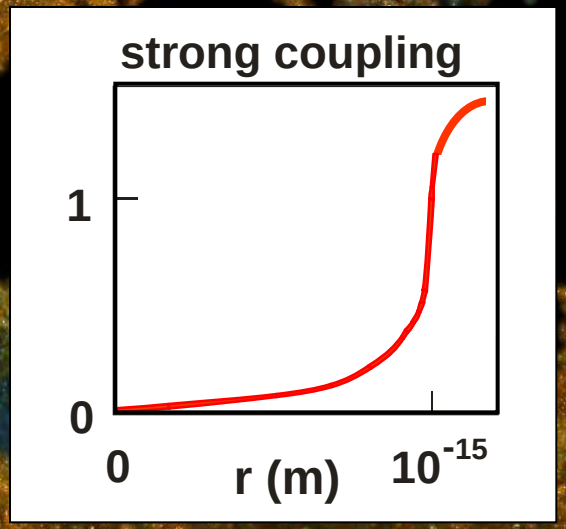


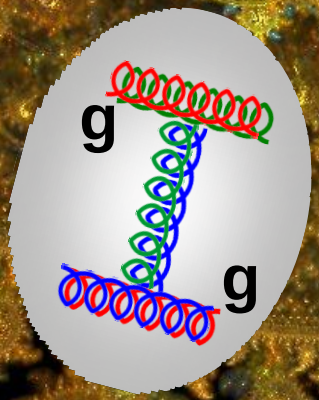


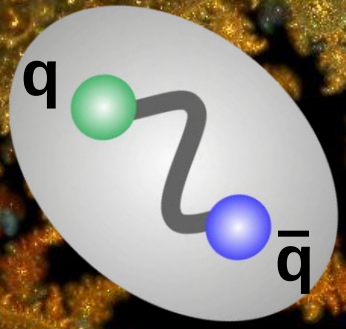


LONG RANGE PLAN: next decade

Synergy of experiment, theory and phenomenology essential

i.e. this is NOT bump-hunting, but the search for poles





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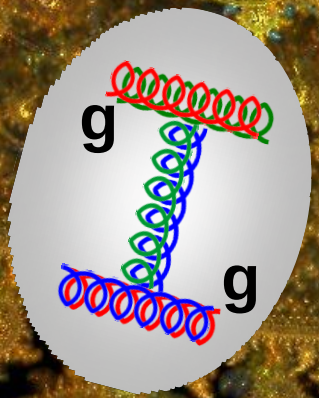

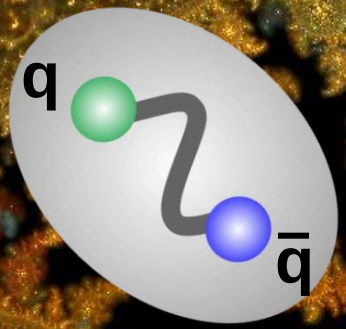

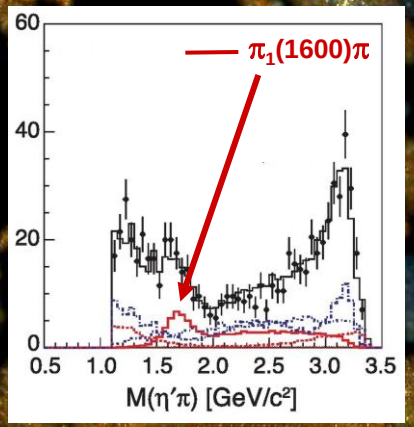

LONG RANGE PLAN: next decade

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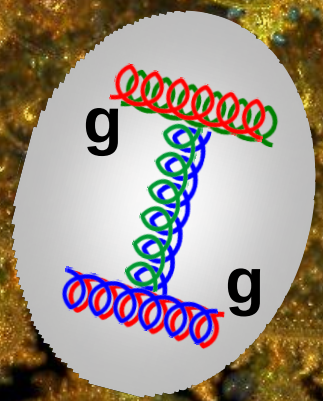
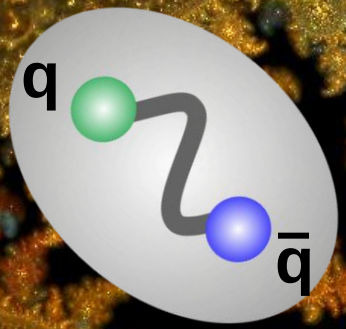
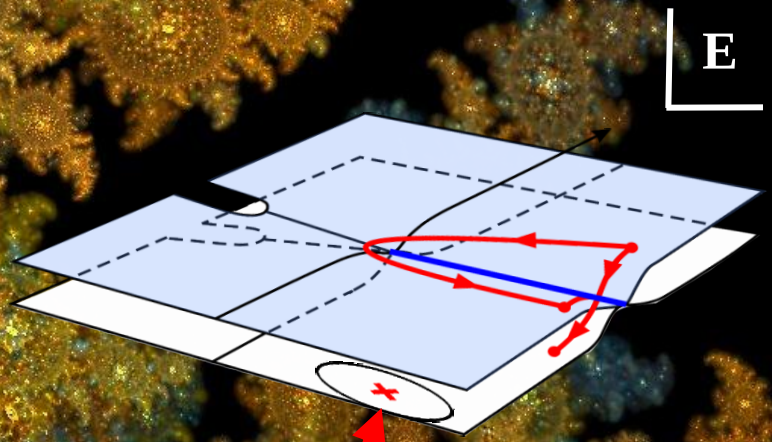






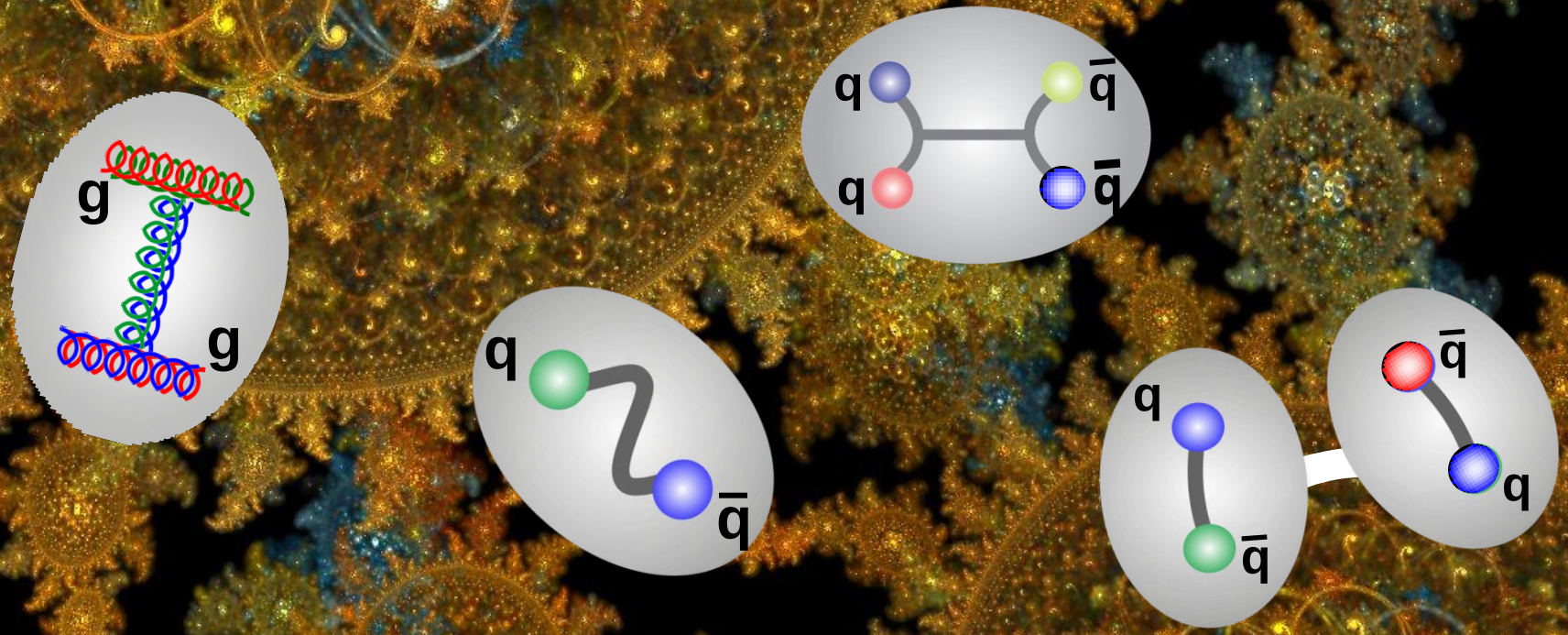
resonance pole

Dispersive analytic continuation

LONG RANGE PLAN: next decade

Robust Amplitude Analyses of data

i.e. must build in S-Matrix constraints and
state-of-the-art knowledge of reaction dynamics



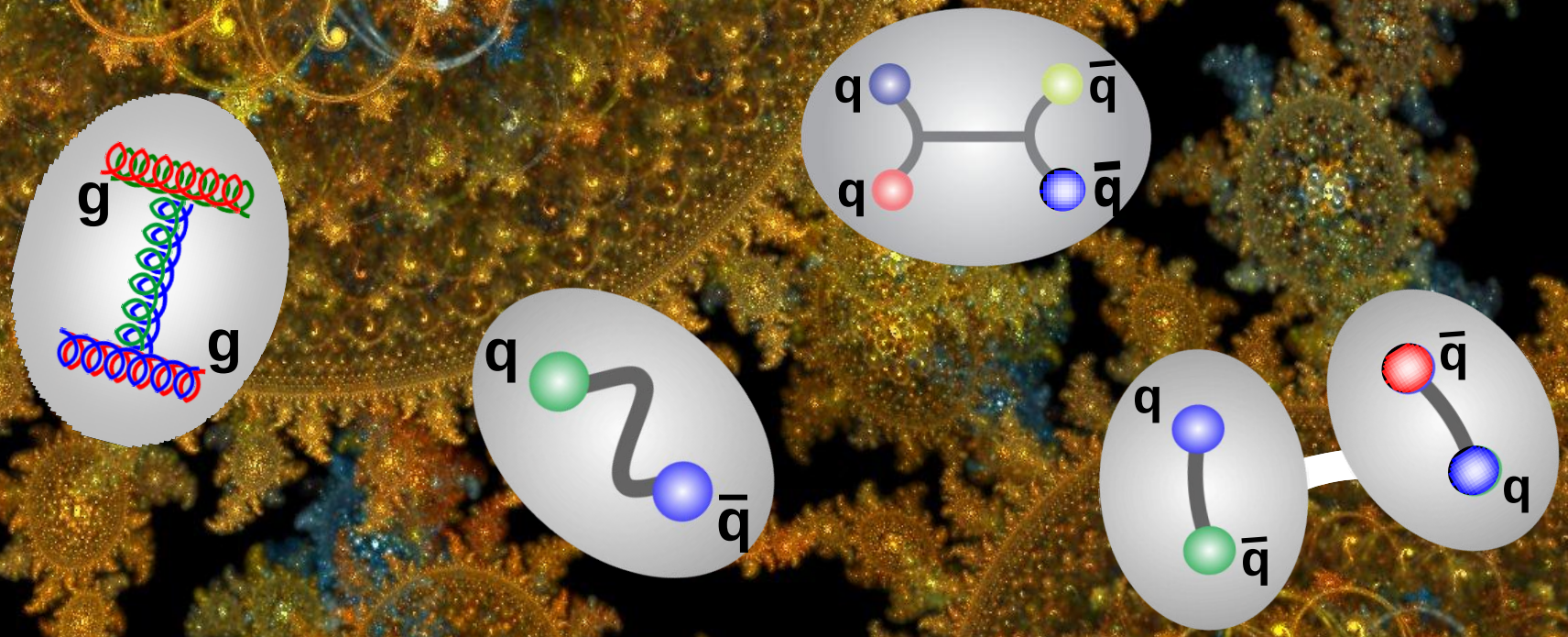
LONG RANGE PLAN: next decade

Interpretations require :

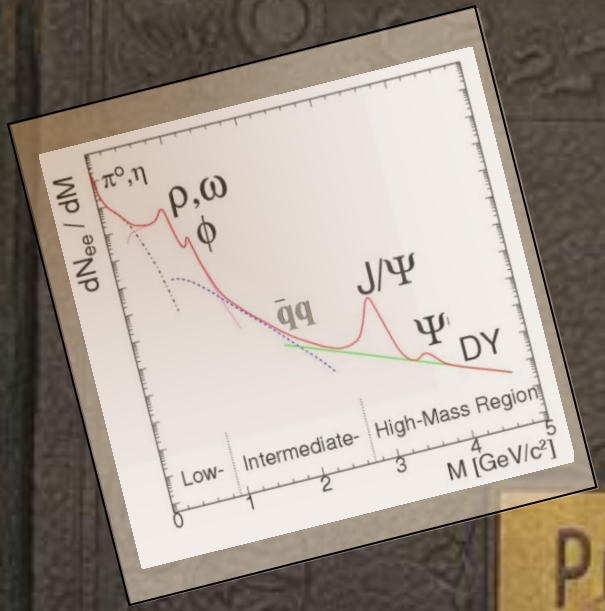
QCD calculations in the continuum and on the lattice

QCD-inspired models of confinement

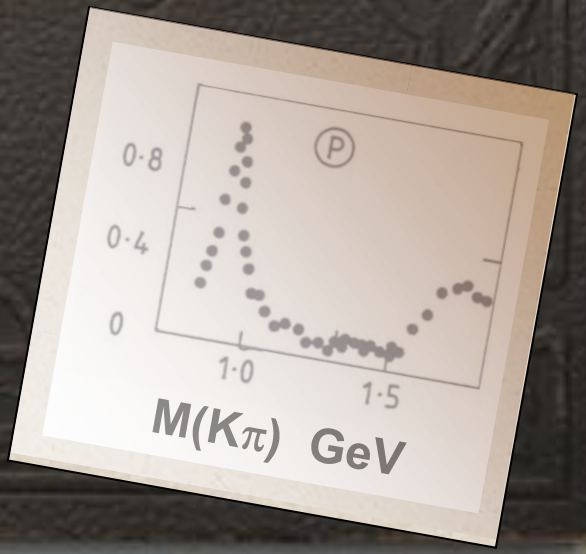
decays essential to brief life of a hadron



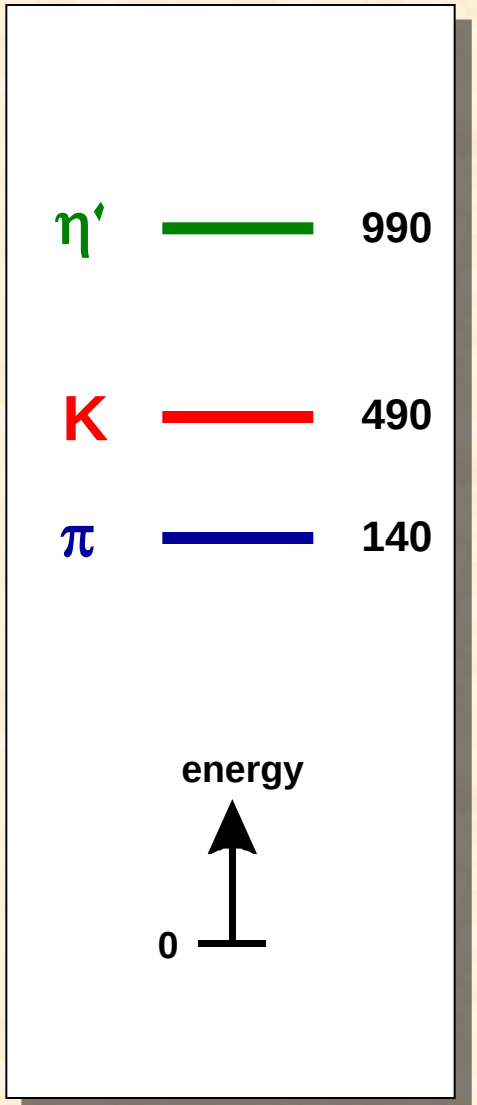
History

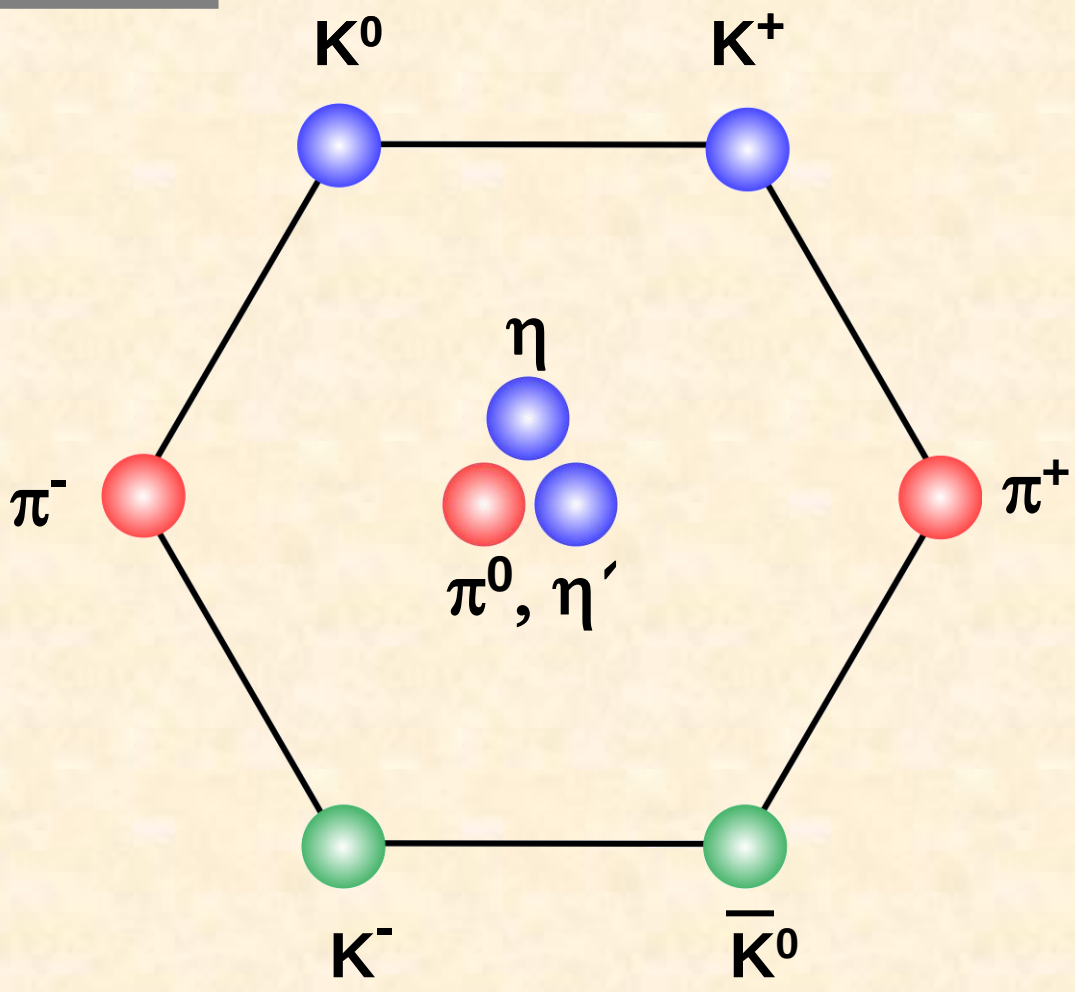


PHOTOGRAPHS



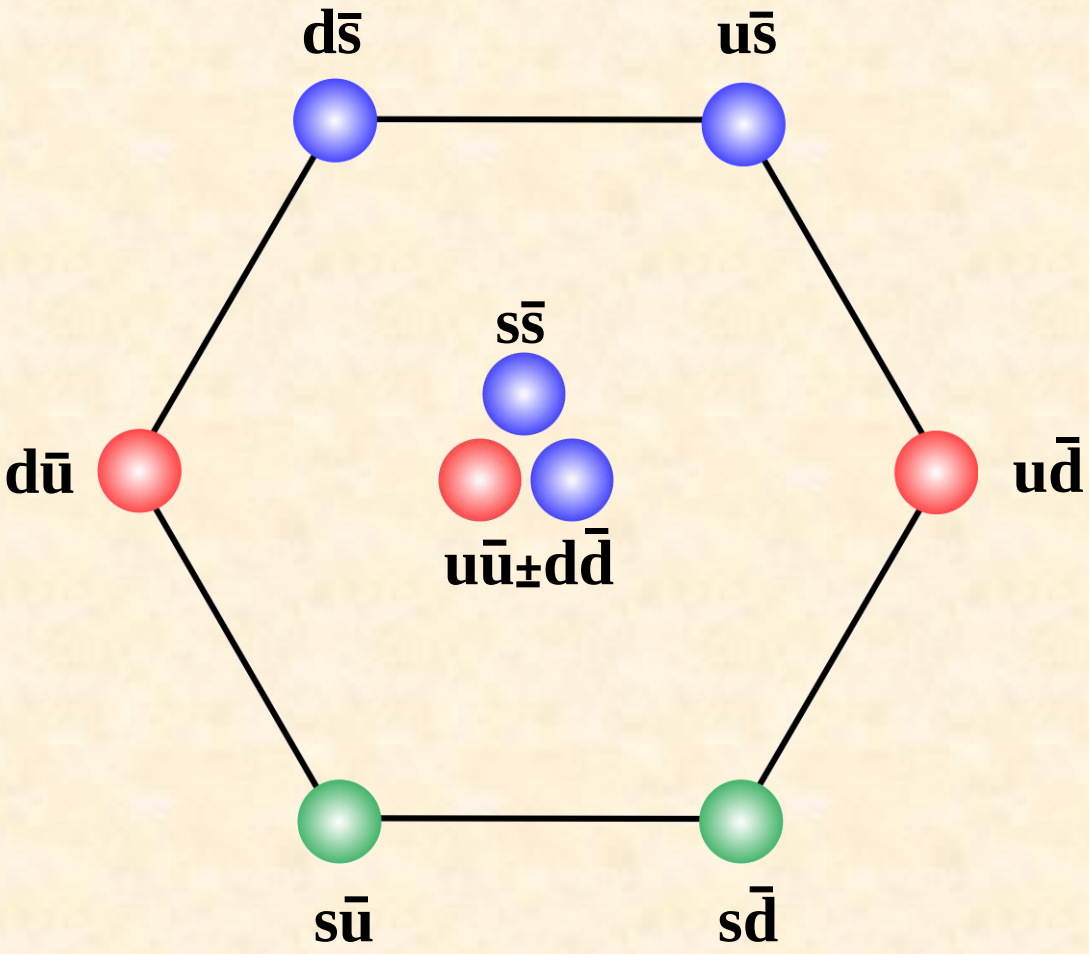
Meson nonet

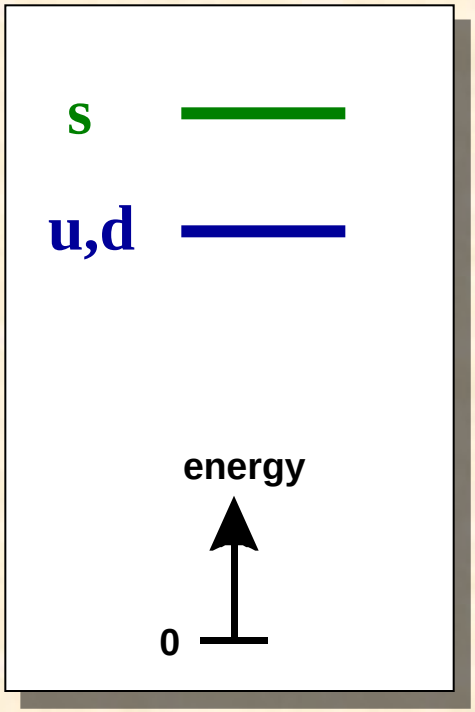




Ground States

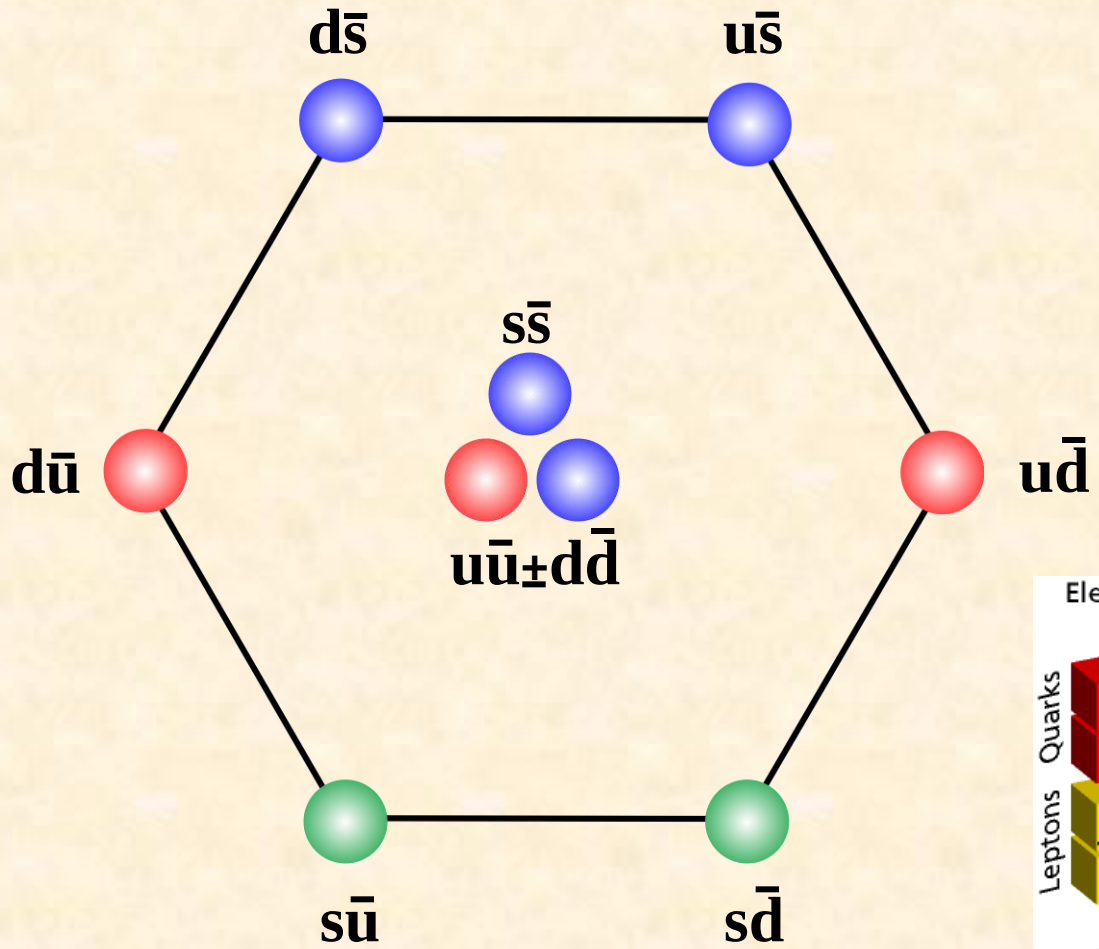
Meson nonet

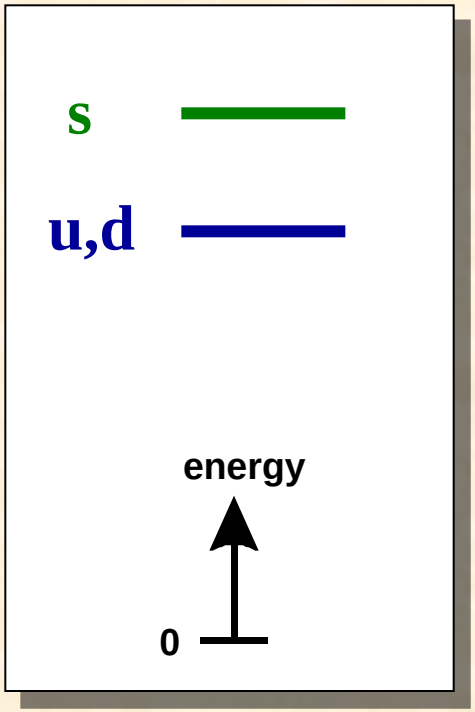


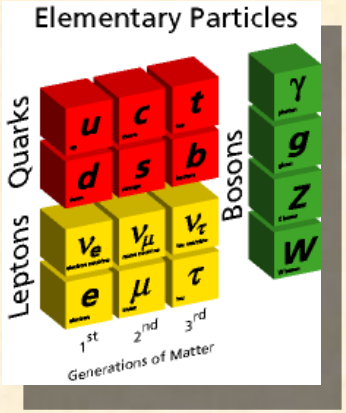


Ground States

Meson nonet

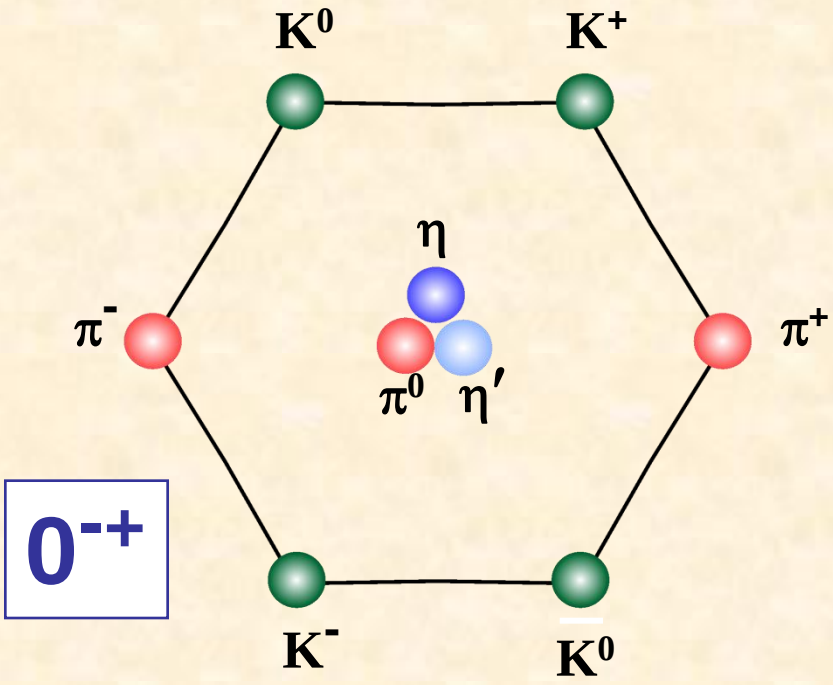




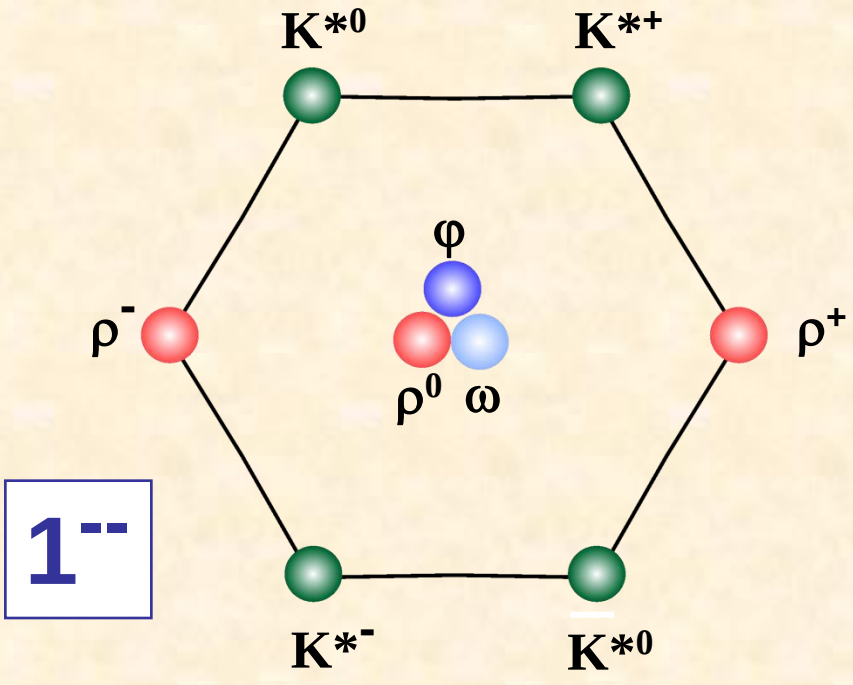


Ground States

Meson spectrum

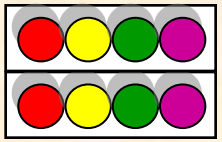


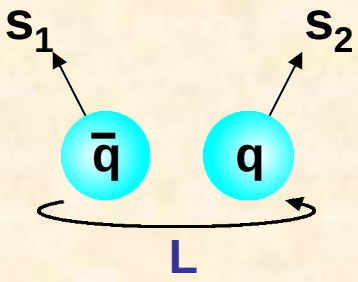
0^{-+}



1^{--}

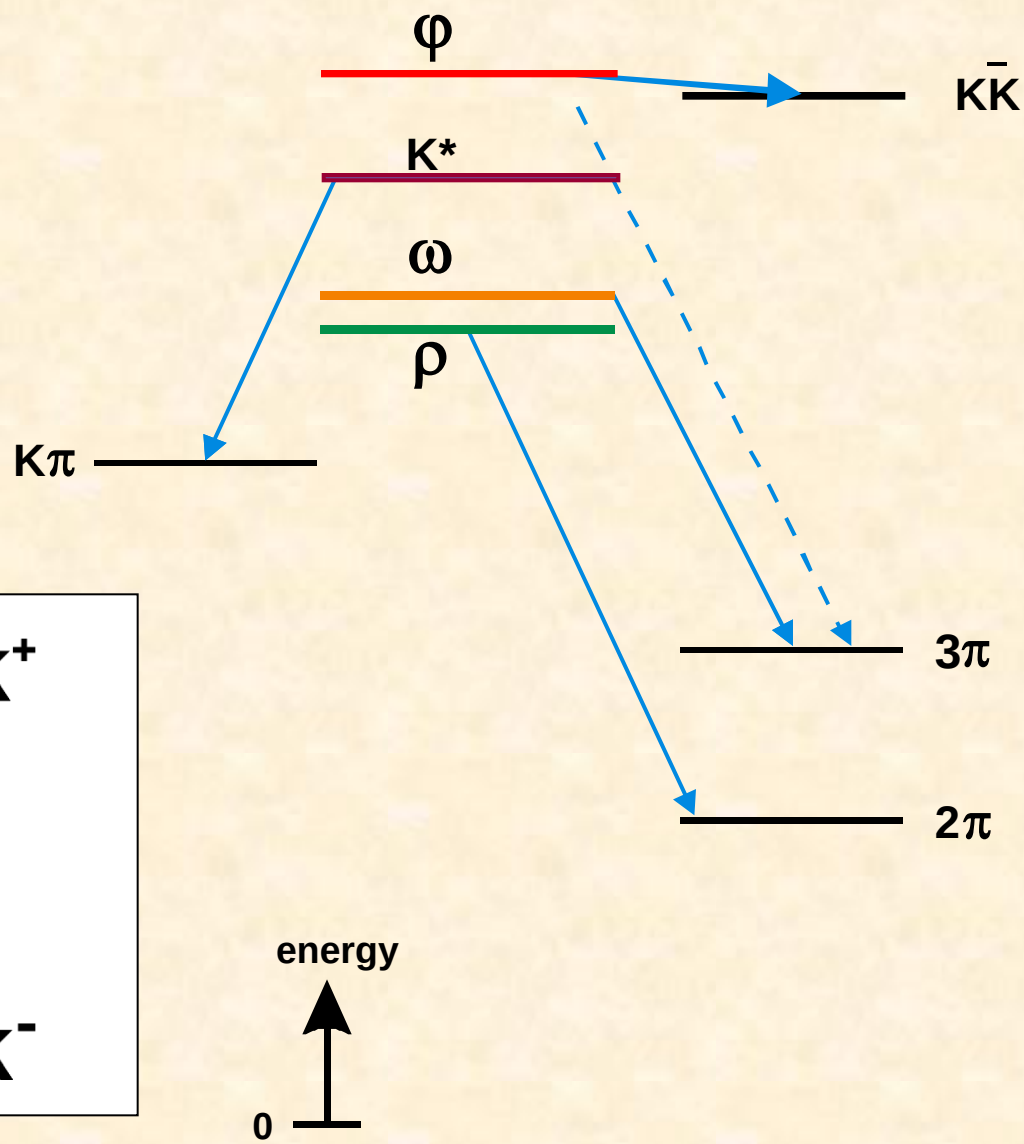
$L=0$ 1^{--} 0^{-+}

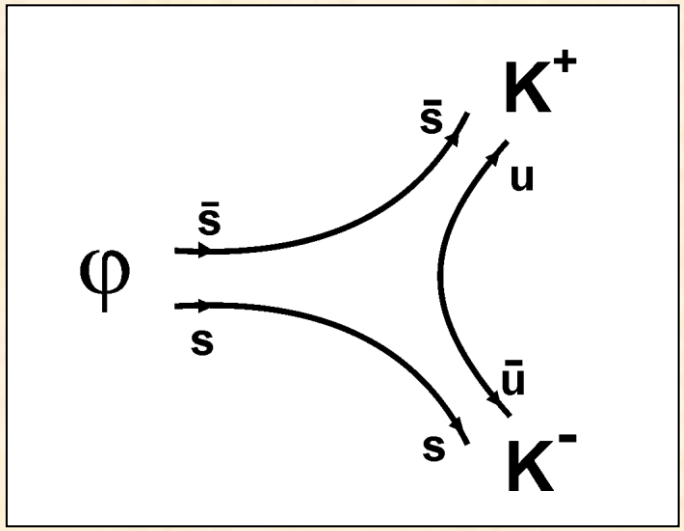




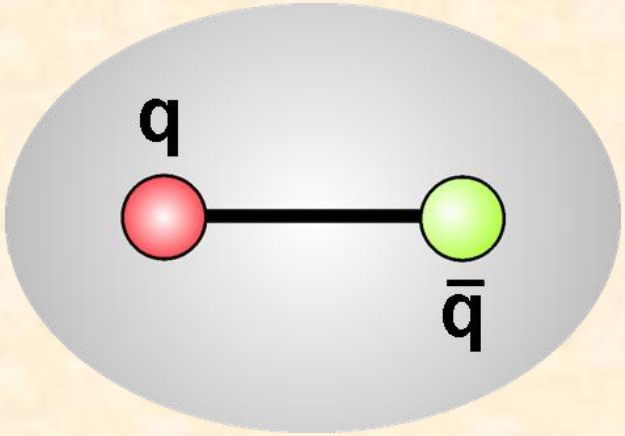
$S = 0, 1$

Vector decays

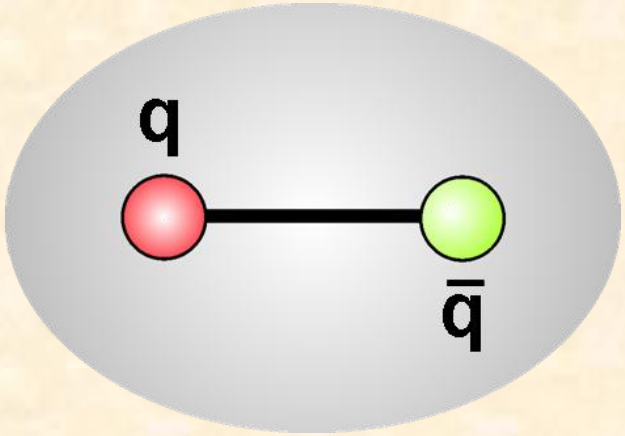


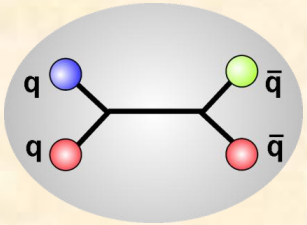


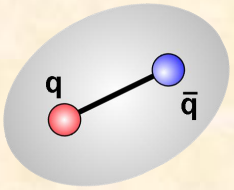
ρ(770)



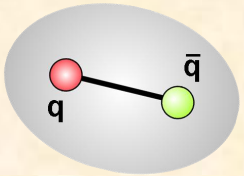
ρ(770)



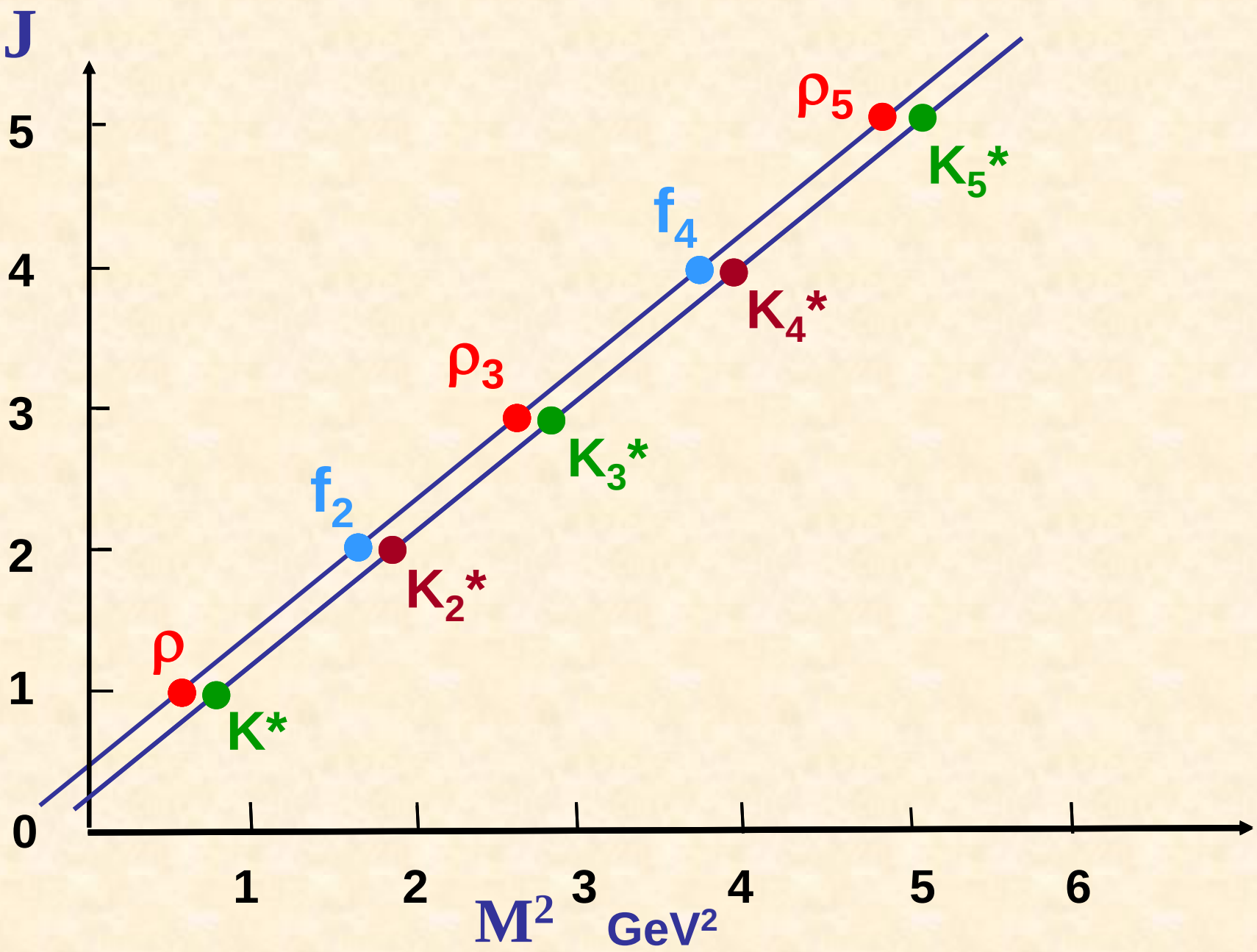




π^+



π^-


J
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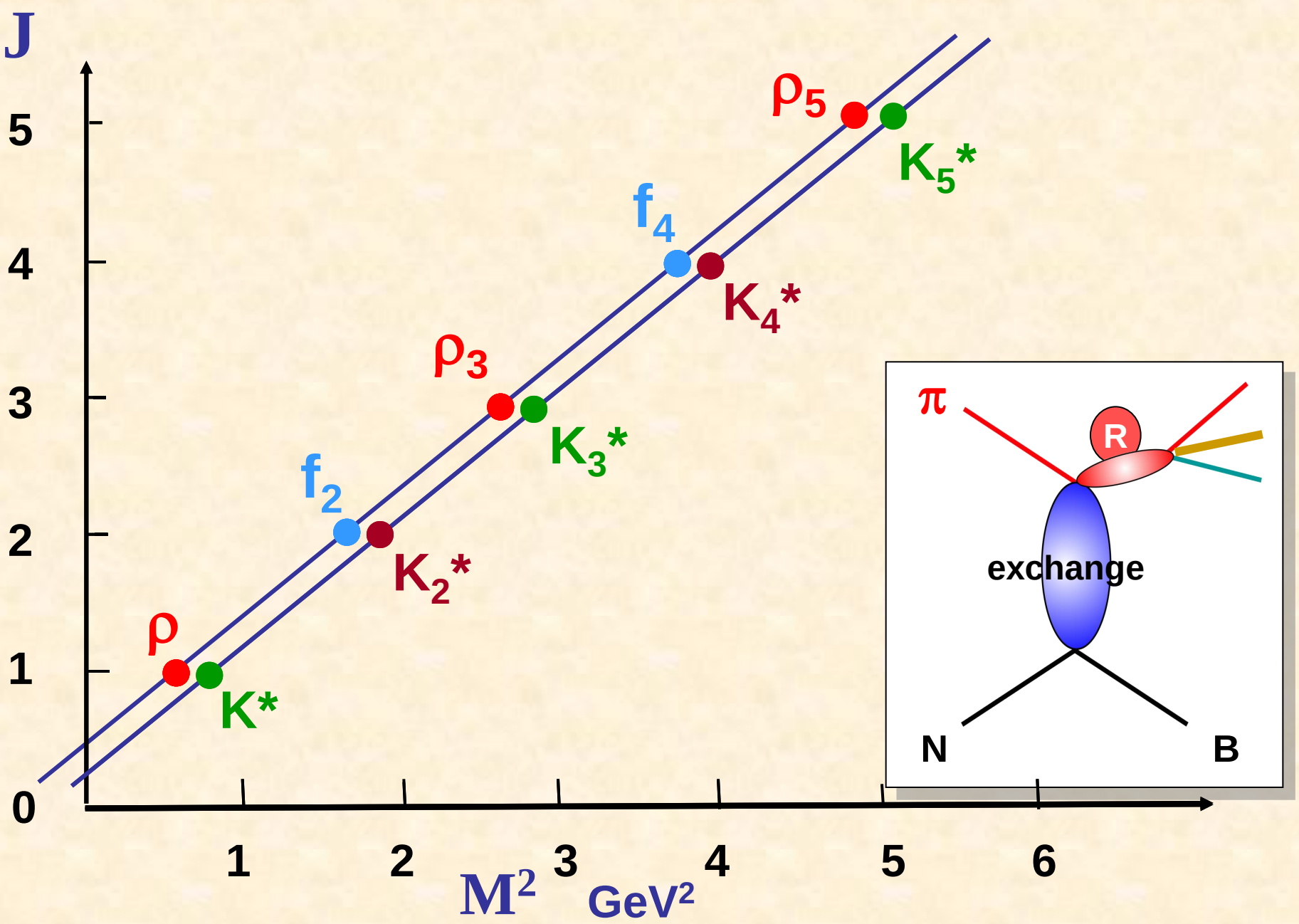
M2 GeV2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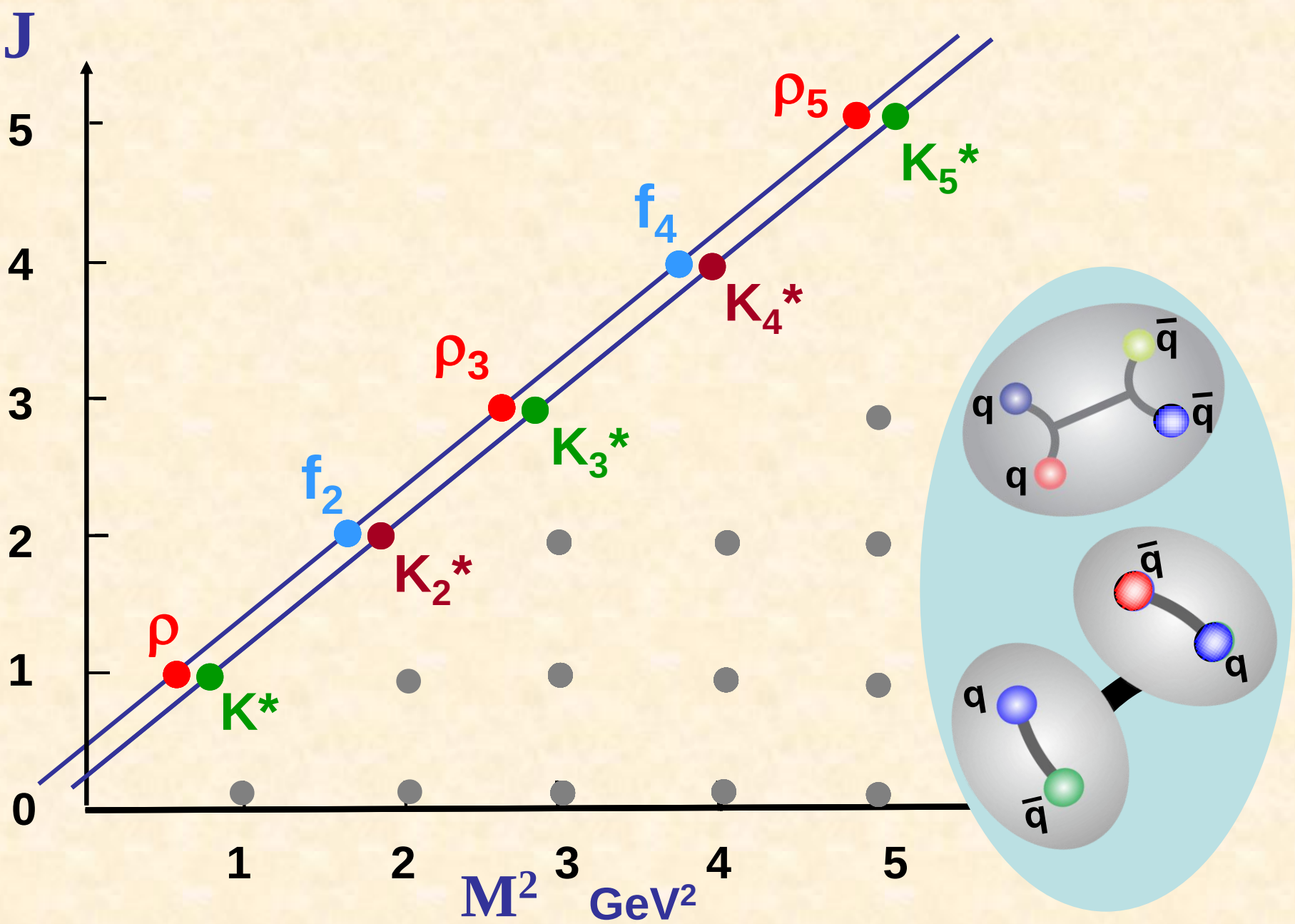
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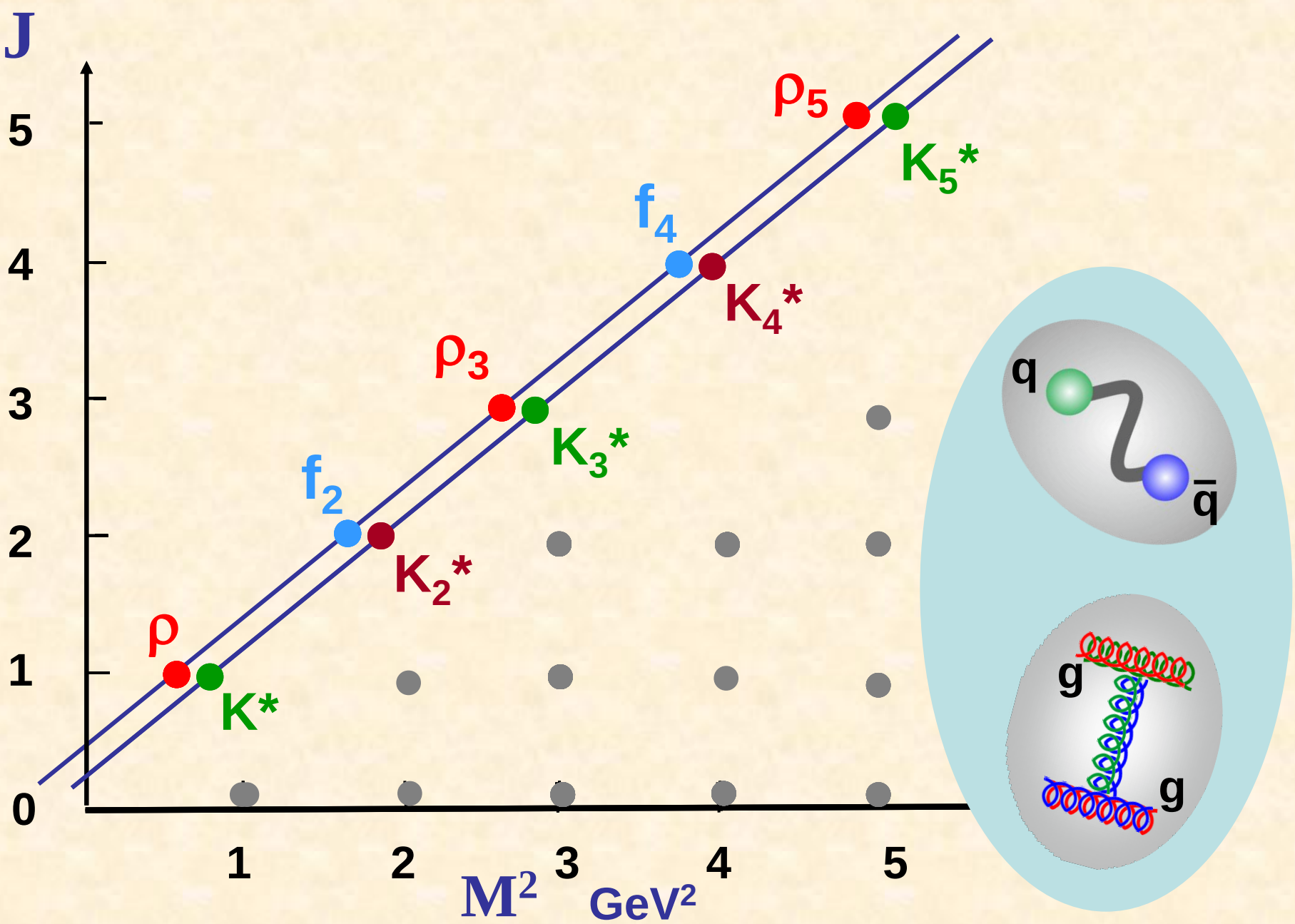
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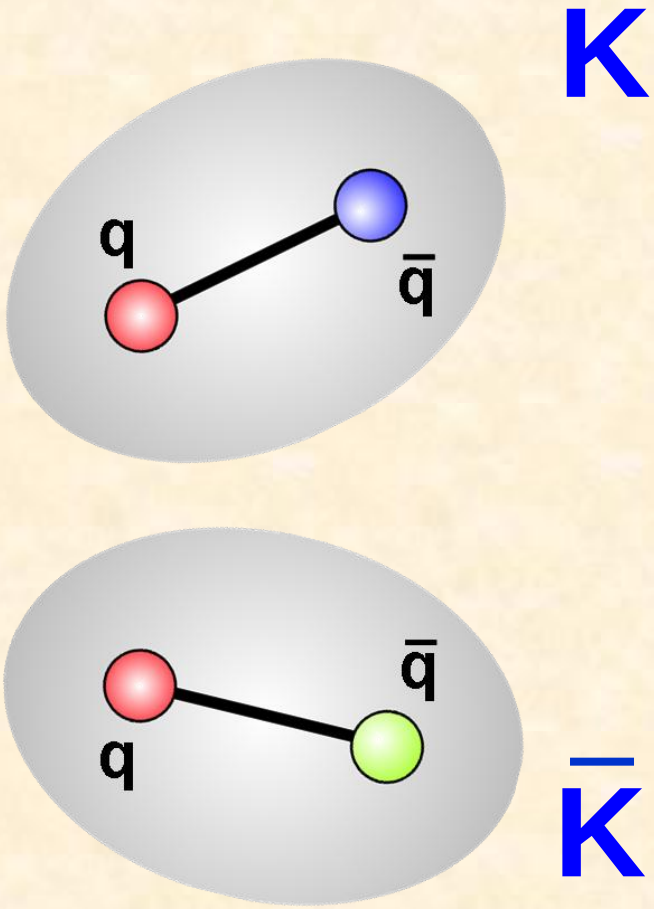
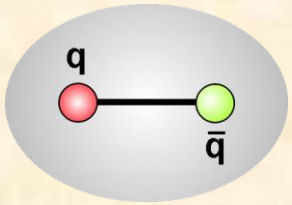
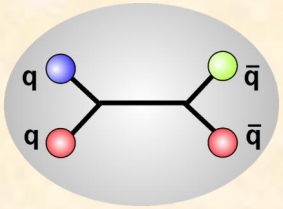
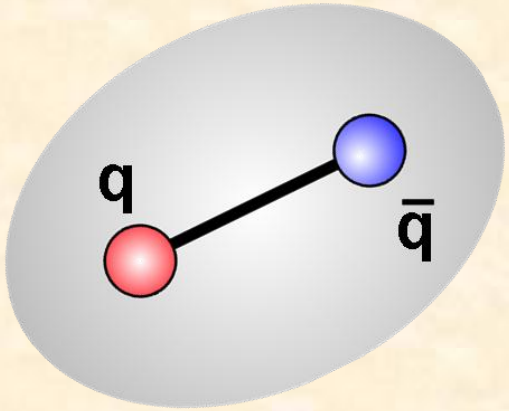
$f_0(980)$



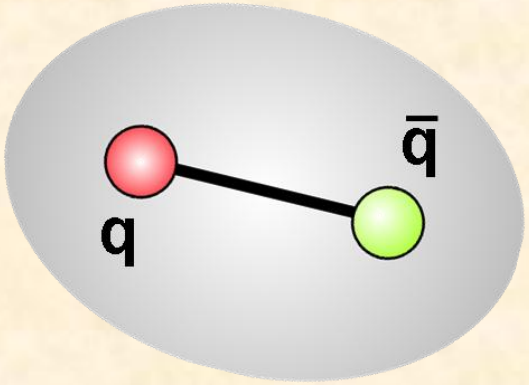
$f_0(980)$







K



$\bar{K}$

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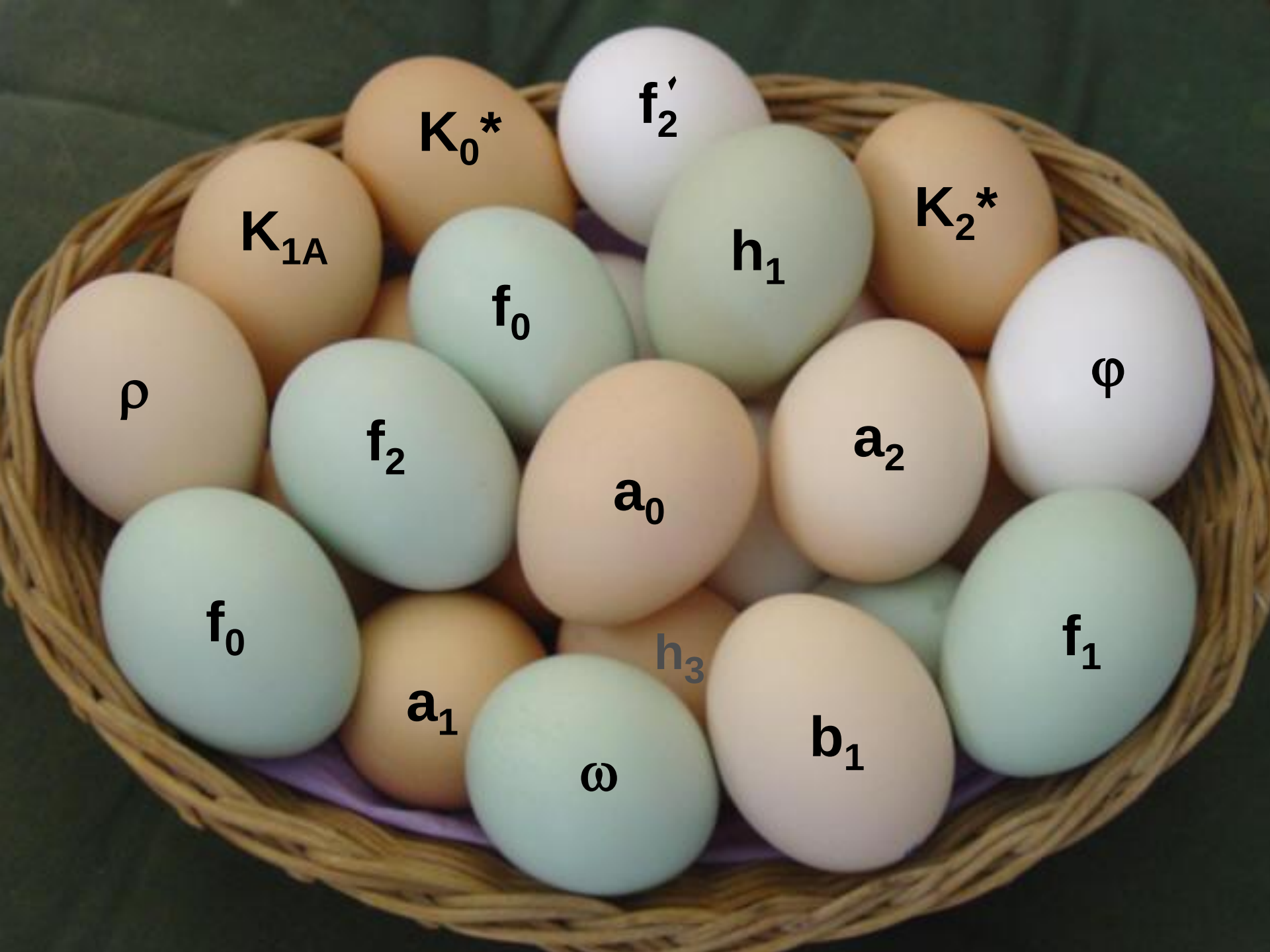
K_0^*
f_2'
K_{1A}
h_1
K_2^*
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f_2
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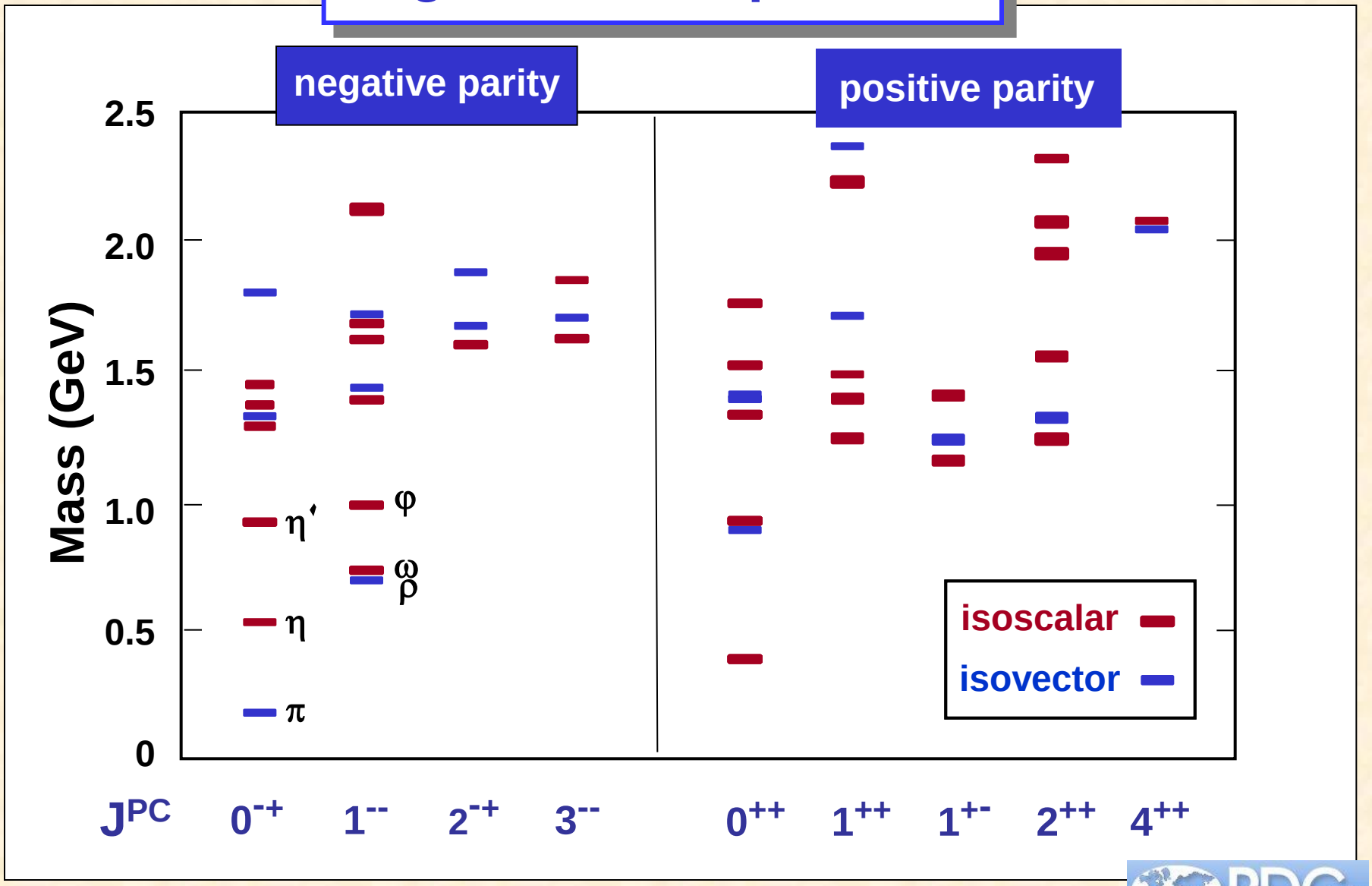
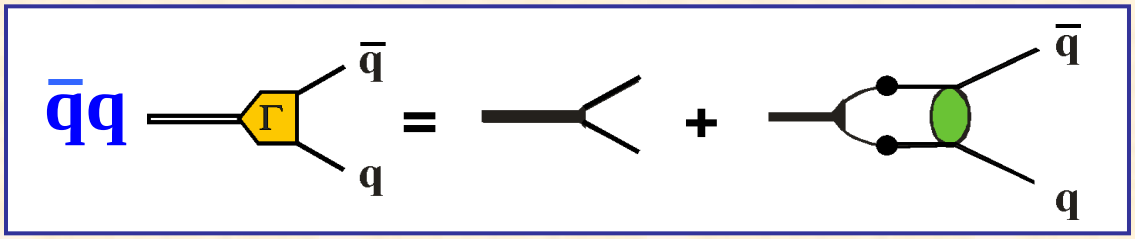
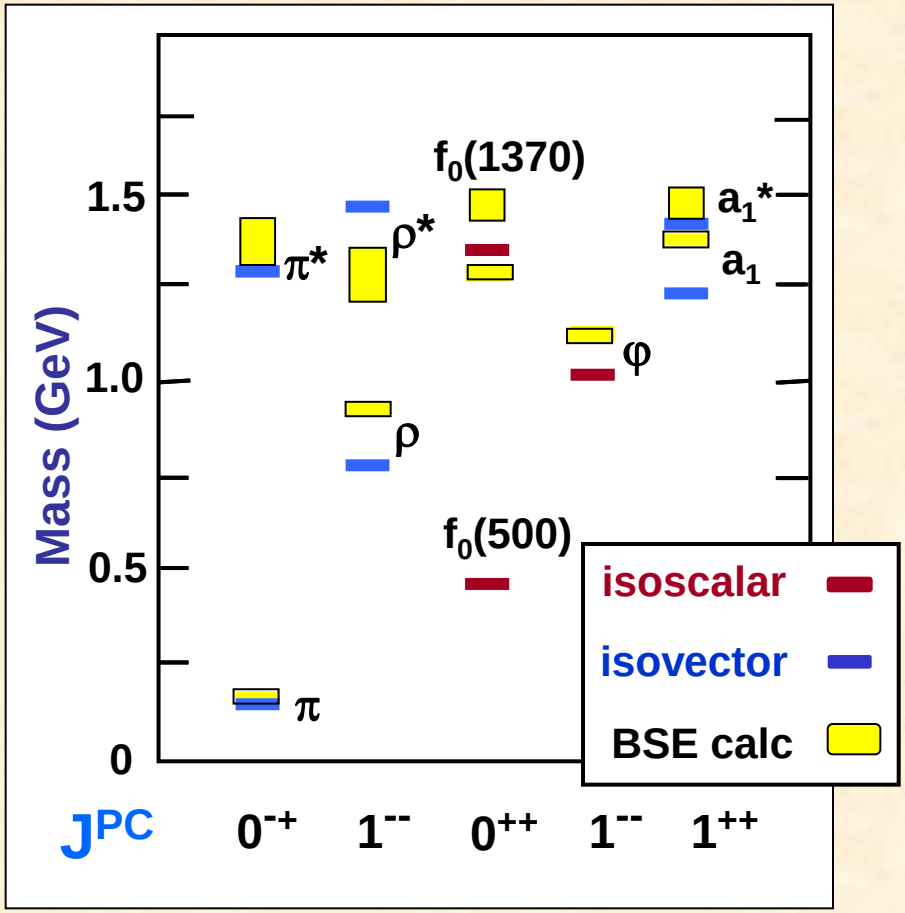
a_0
f_0
f_1
h_3
a_1
b_1
ω

Light Meson Spectrum



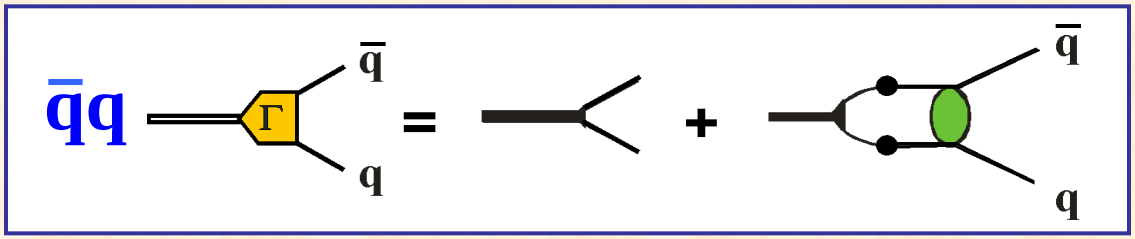
ANL/KSU Bound State comps.



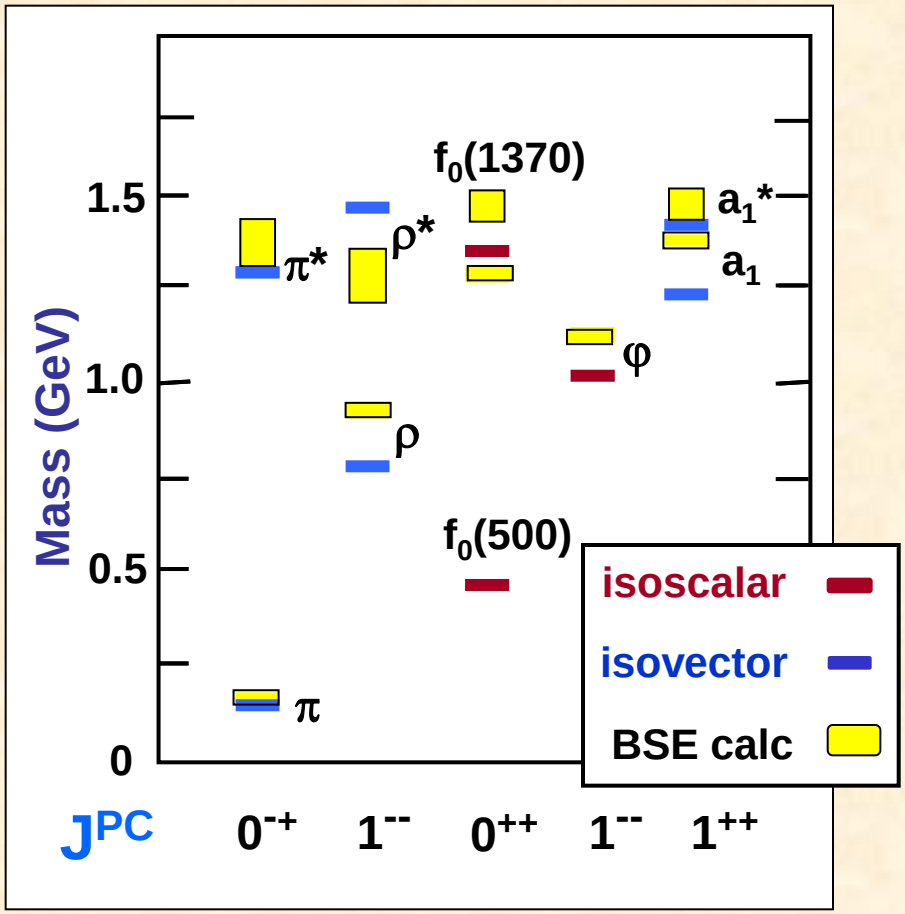


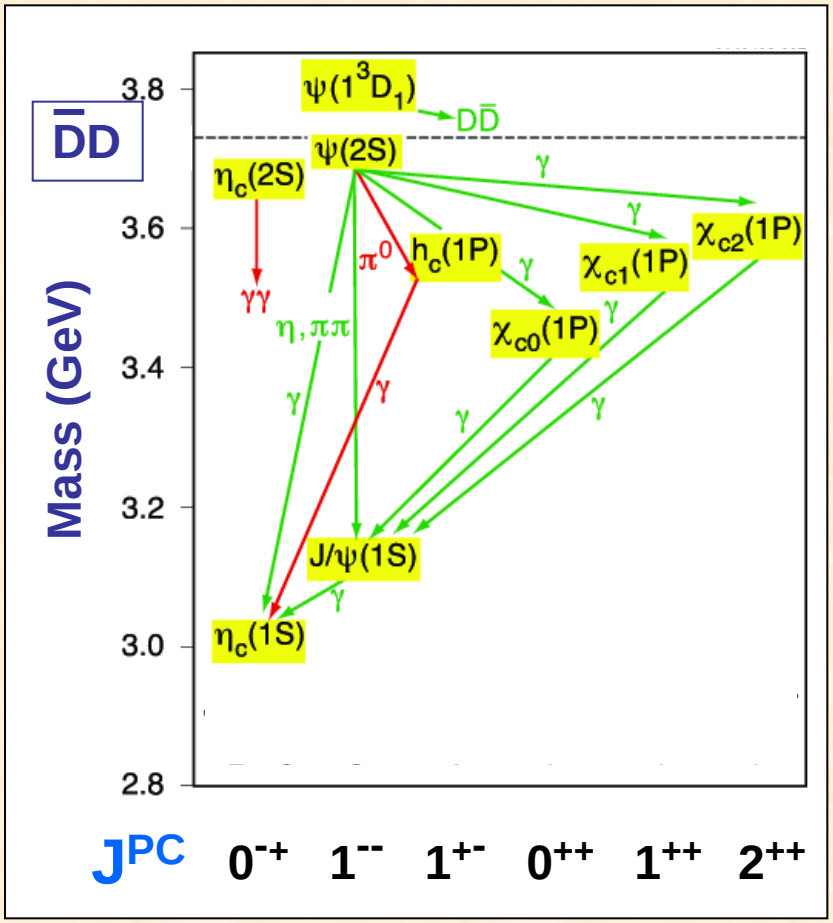
ANL/KSU Bound State comps.

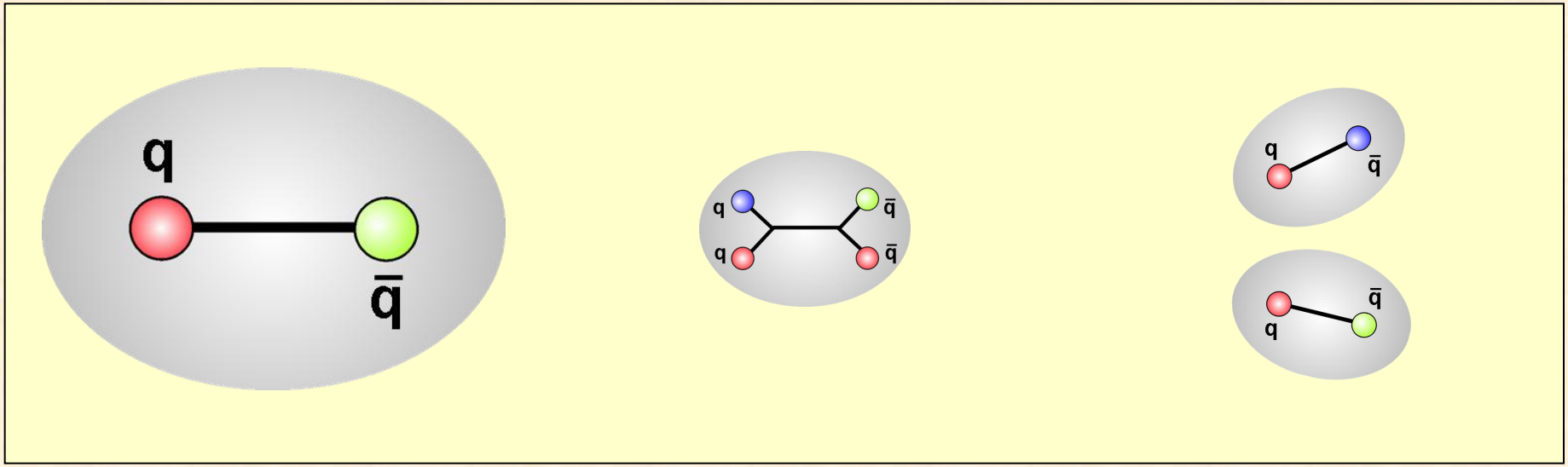
$\bar{c}c$ bound states



potential models






q
q̄
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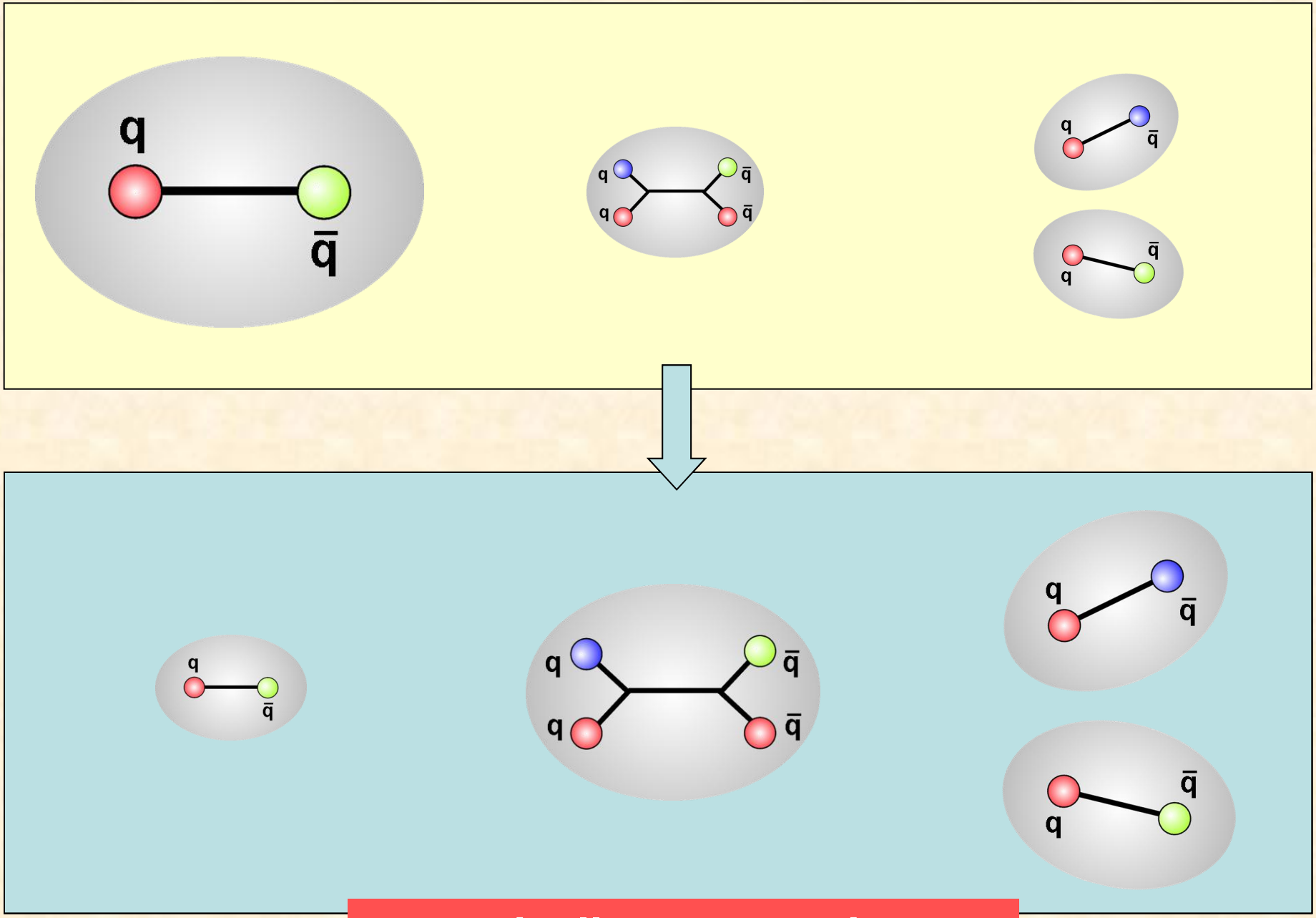
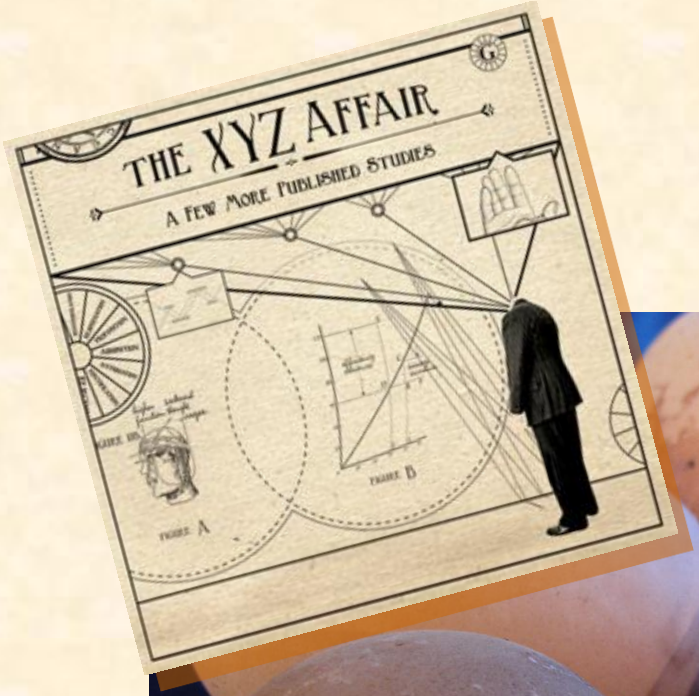
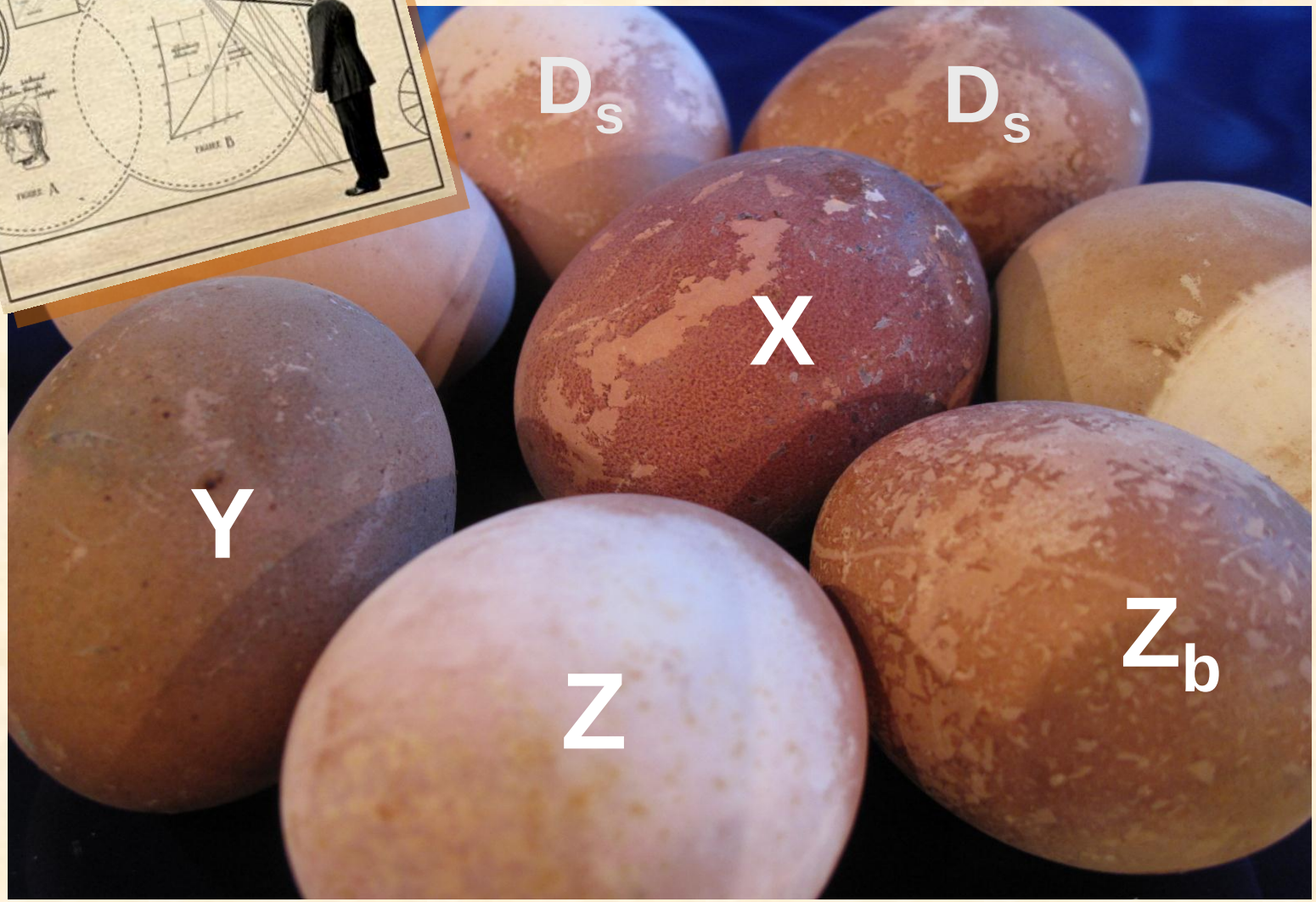


Dynamically generated states

Current Issues

THE XYZ AFFAIR



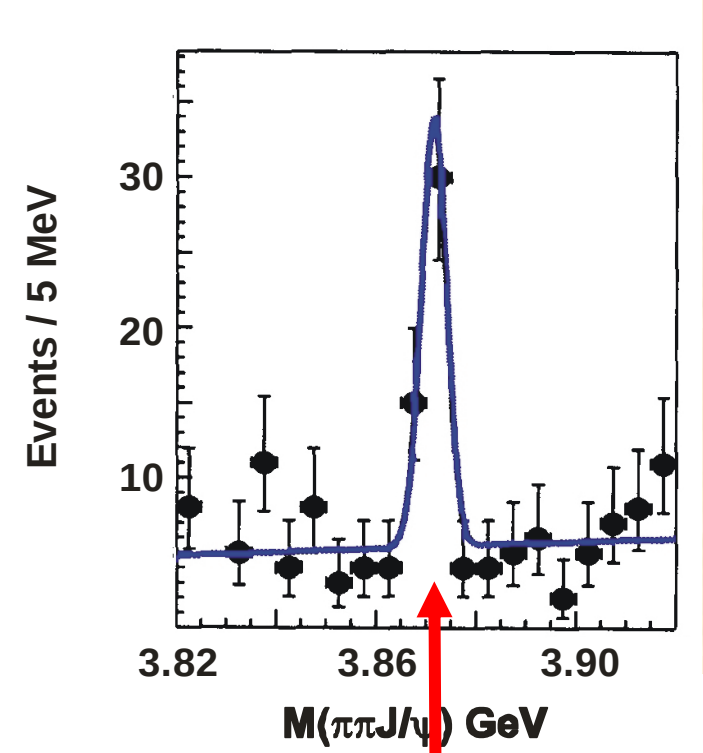


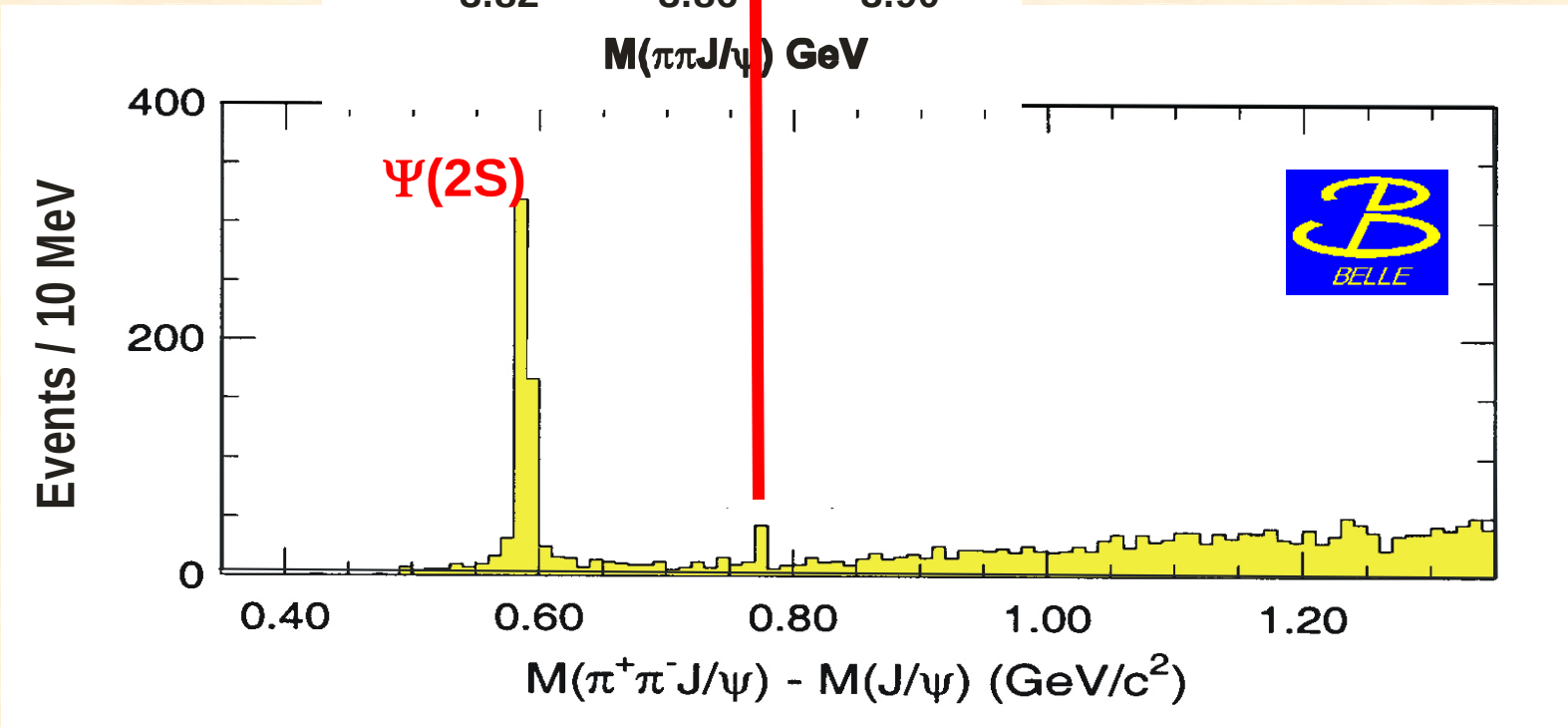
X(3872)

304M B's

$B \rightarrow KX$

$X \rightarrow \pi^+\pi^- J/\psi$



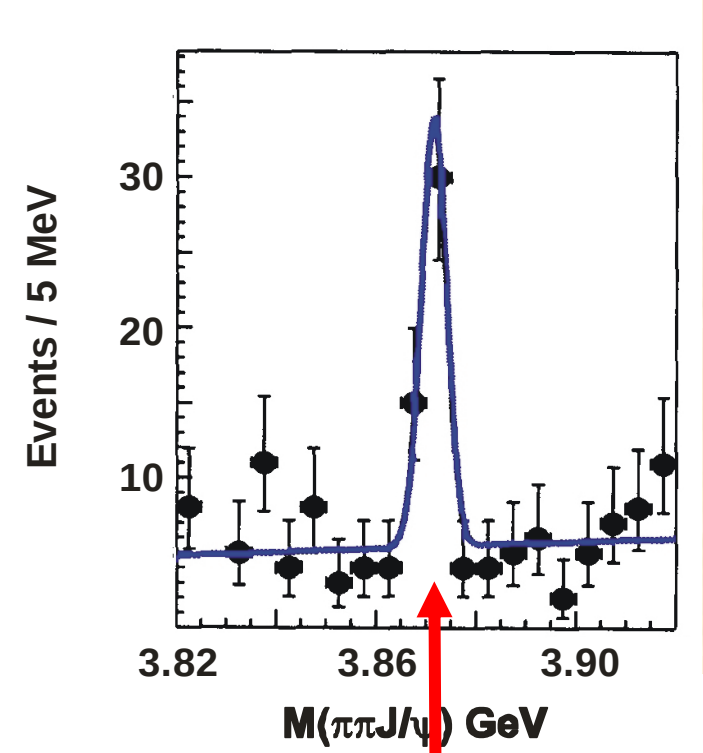


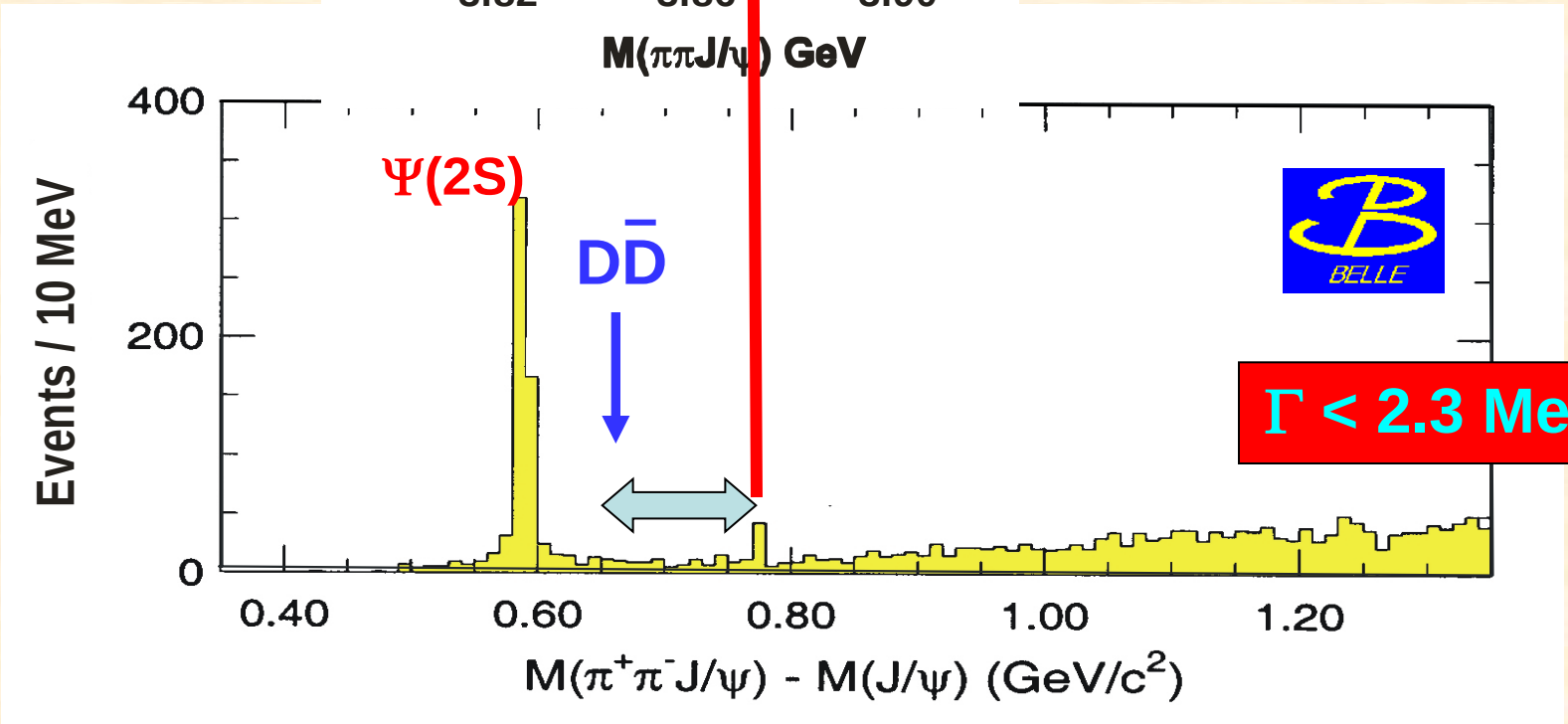
X(3872)

304M B's

$B \rightarrow KX$

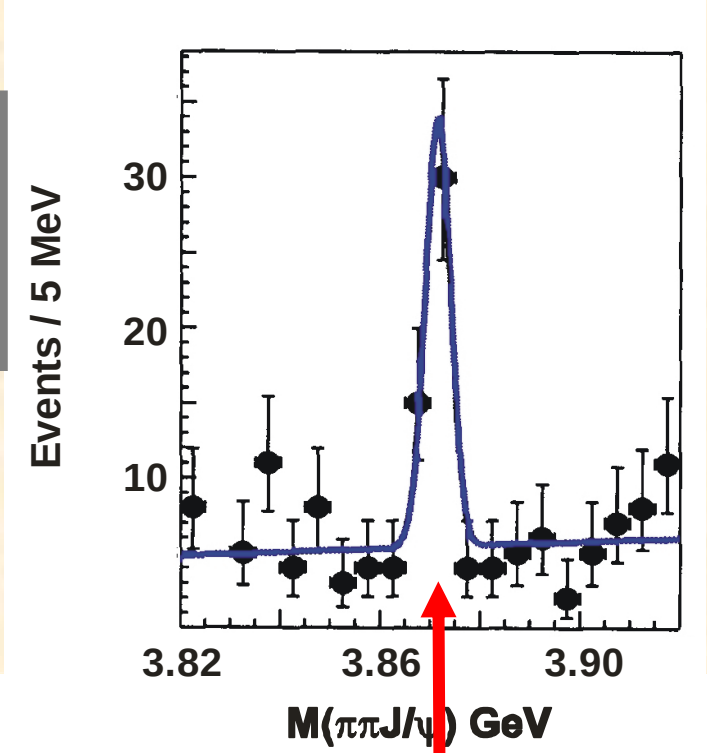
$X \rightarrow \pi^+\pi^- J/\psi$





X(3872)

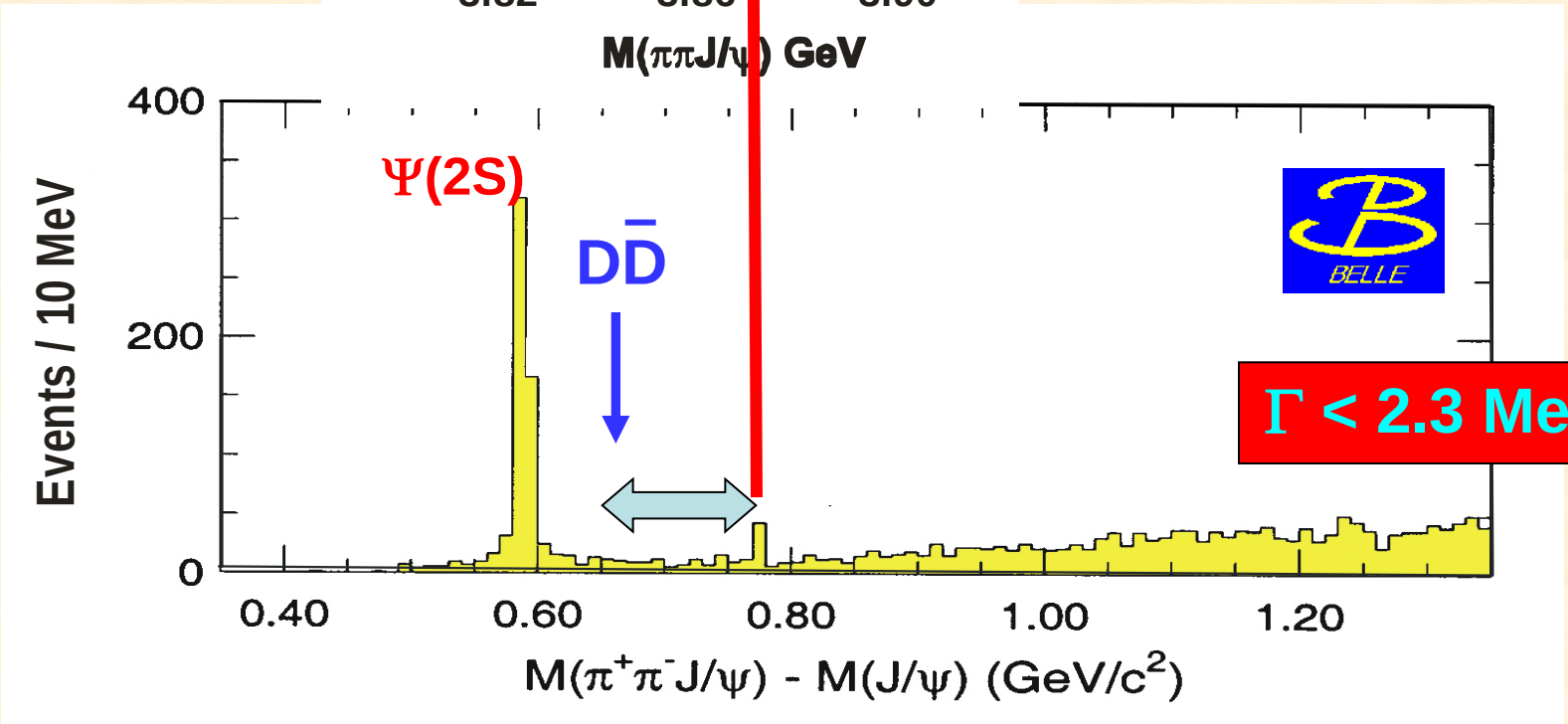
$J^{PC} = 1^{++}$ LHCb



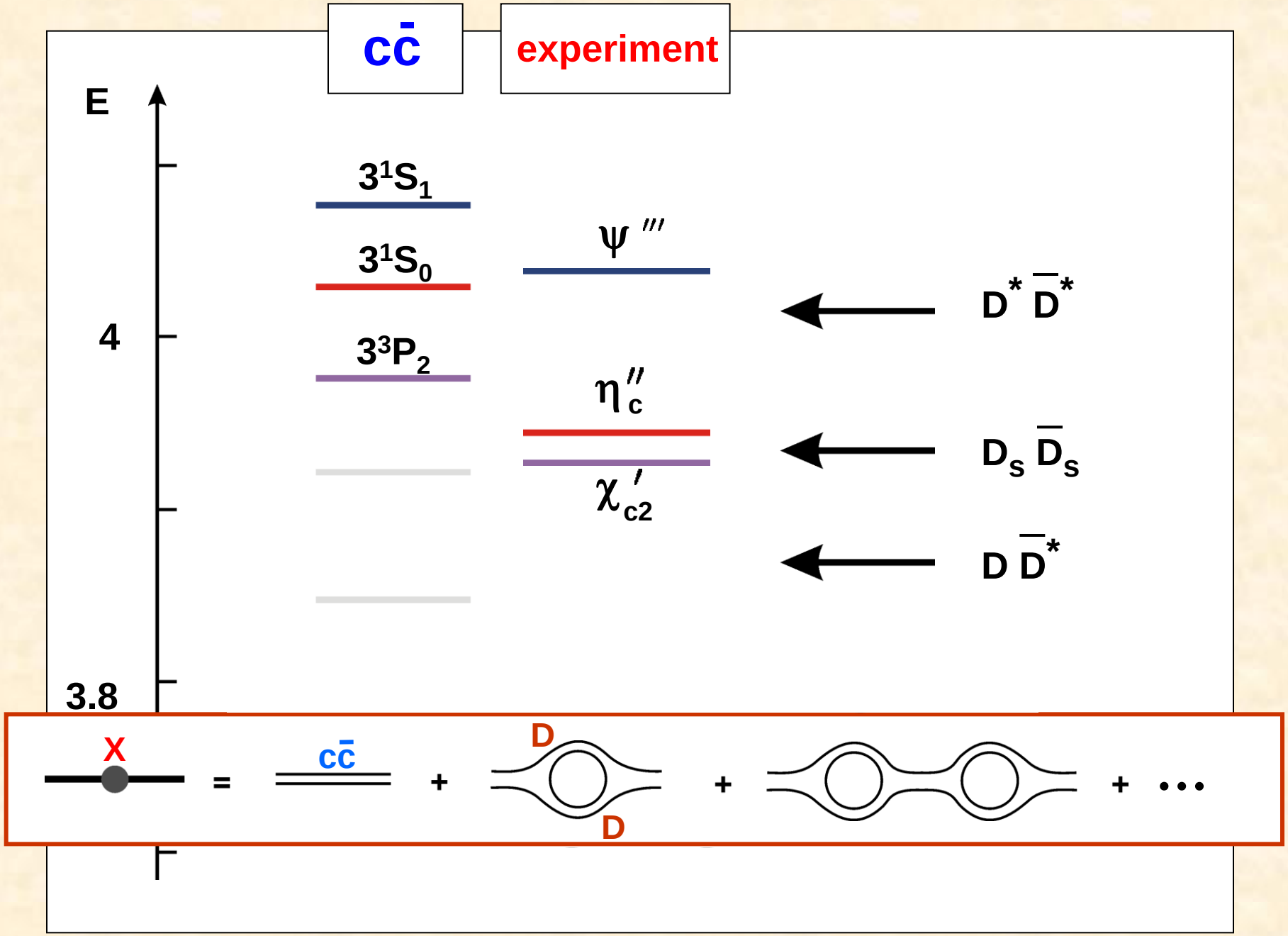
304M B's

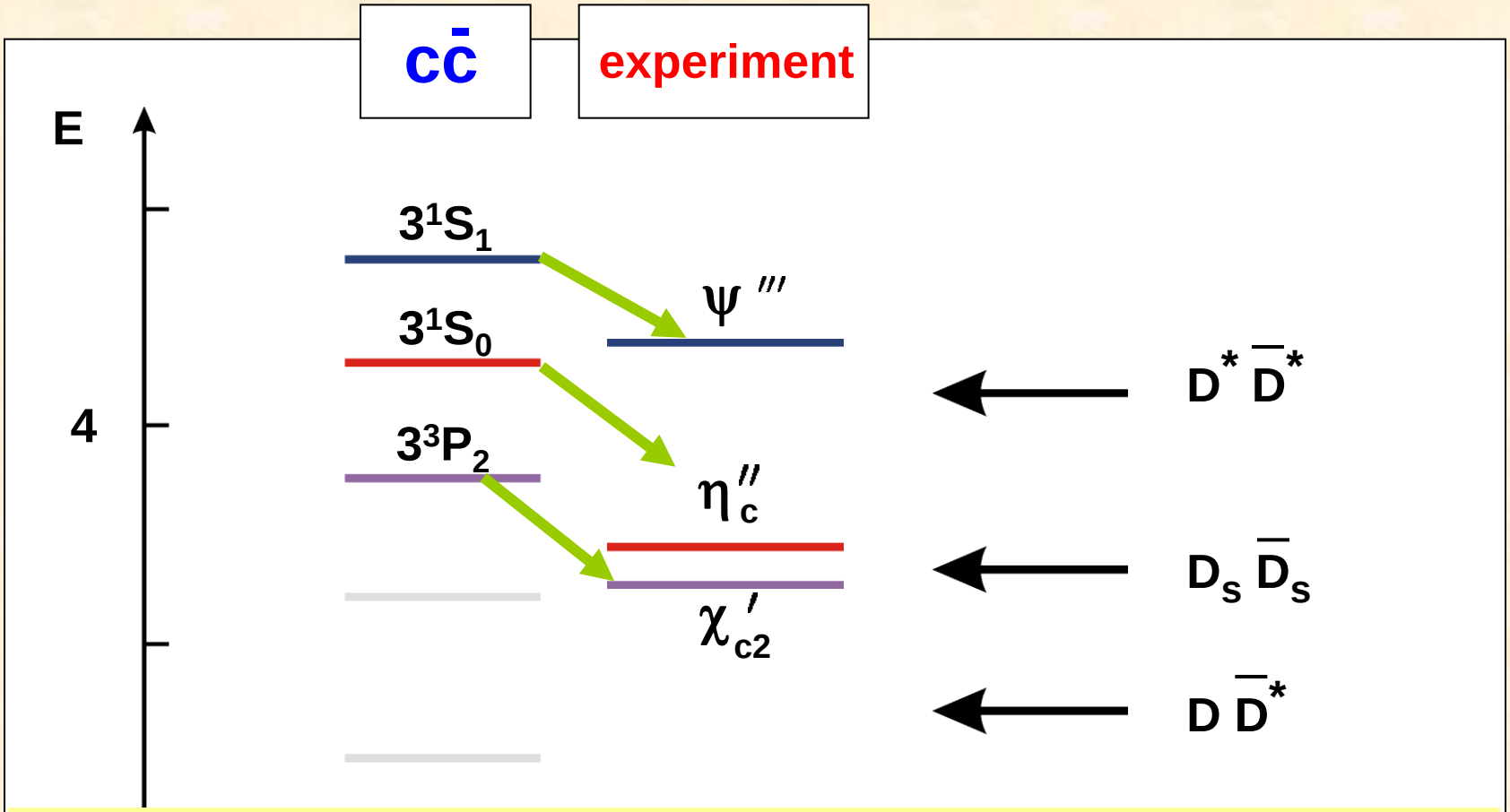
$B \to KX$

$X \to \pi^+\pi^- J/\psi$

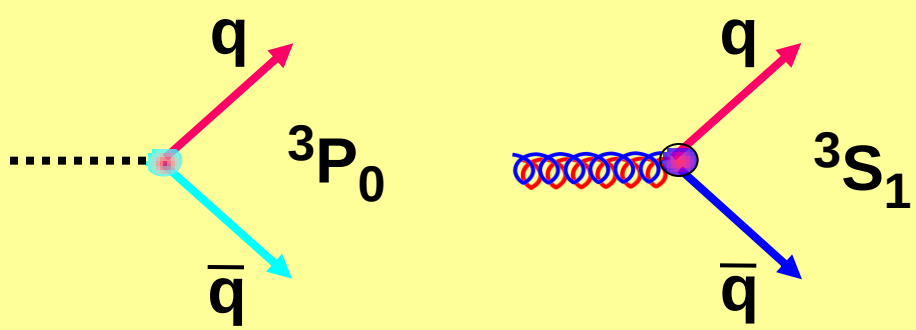


$\Gamma < 2.3$ MeV

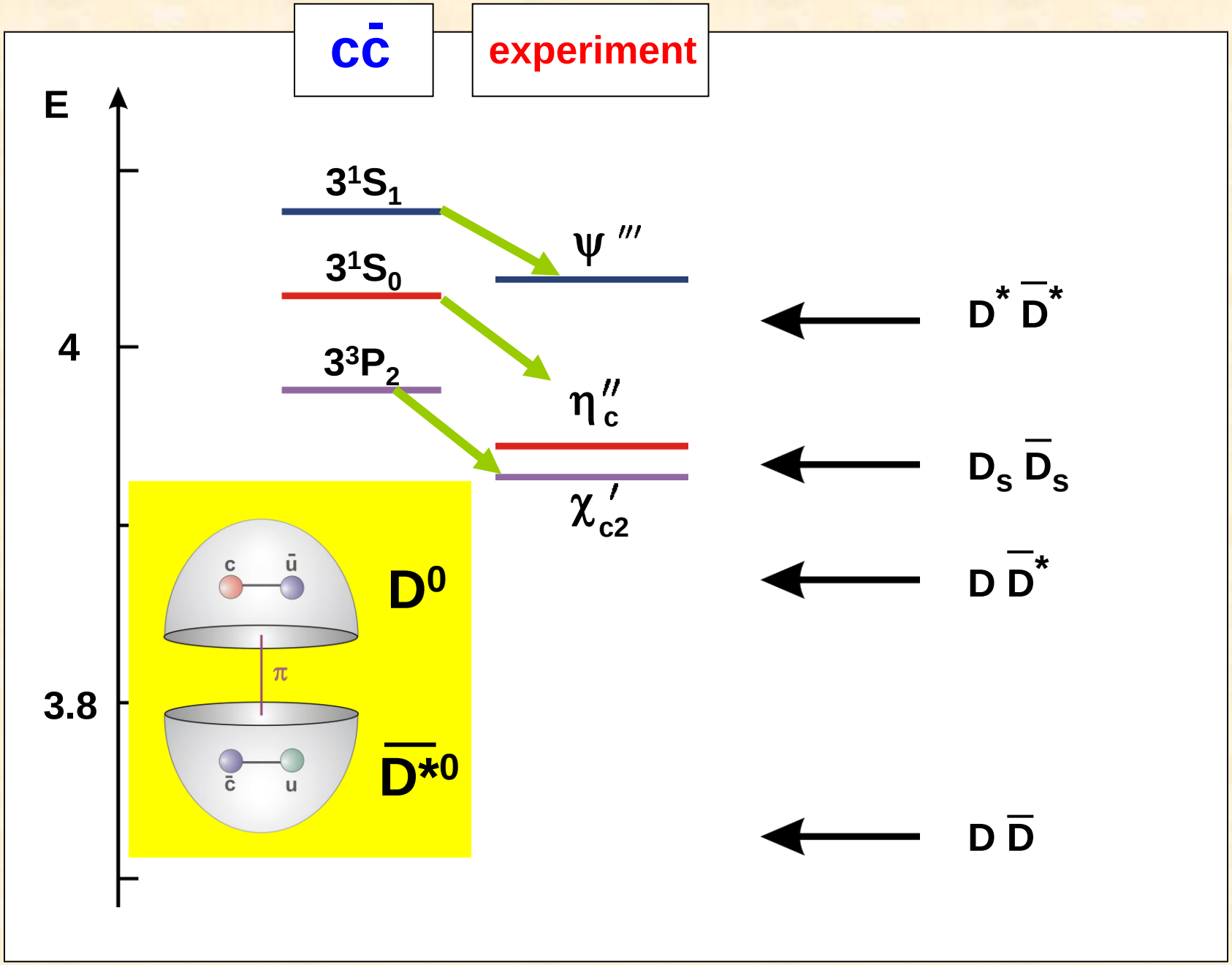

$c\bar{c}$
experiment
E
3^1S_1
3^1S_0
3^3P_2
ψ'''
η_c''
χ_{c2}'
$D^*\bar{D}^*$
$D_s\bar{D}_s$
$D\bar{D}^*$
4
3.8
X
=
$c\bar{c}$
+
D
D
+
+ • • •



Modeling decays

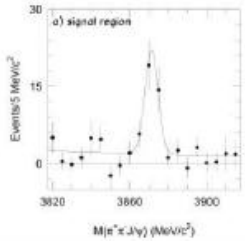


make consistent with chiral dynamics

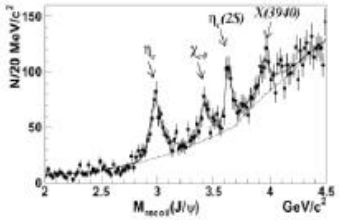

$c\bar{c}$
experiment
E
4
3.8
3^1S_1
3^1S_0
3^3P_2
ψ'''
η_c''
χ_{c2}'
$D^* \bar{D}^*$
$D_s \bar{D}_s$
$D \bar{D}^*$
$D \bar{D}$
c
$\bar{u}$
π
$\bar{c}$
u
D^0
$\bar{D}^{*0}$

XYZ states

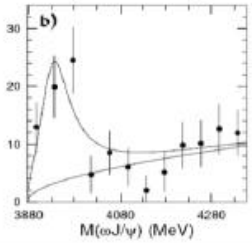
X(3872)
PRL 91,262001 (2003)



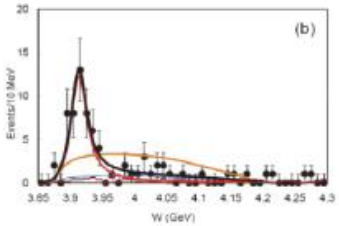
X(3940)
PRL 98,082001 (2007)



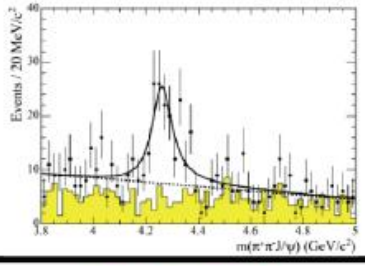
Y(3940)
PRL 94,182002 (2005)



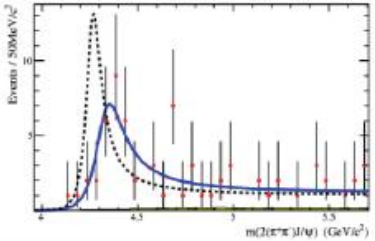
X(3915)
PRL 104,092001 (2010)



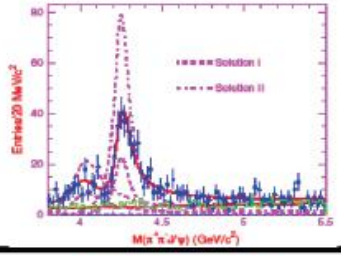
Y(4260)
PRL 95,142001 (2005)



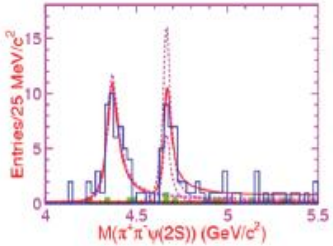
Y(4350)
PRL 98,212001 (2007)



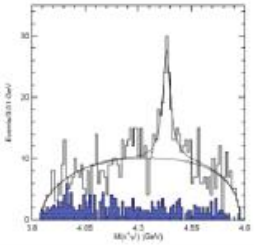
Y(4008)
PRL 99,182004 (2007)



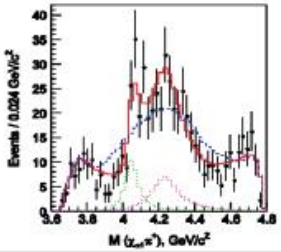
Y(4660)
PRL 99,142002 (2007)



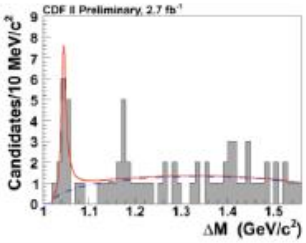
$Z^-(4430)$
PRL 100,142001 (2008)



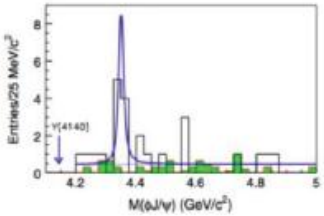
Z_1^-/Z_2^-
PRD 78,072004 (2008)



Y(4140)
PRL 102,242002 (2009)

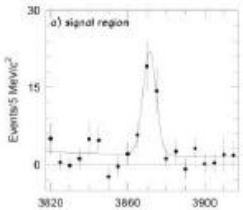


X(4350)
PRL 104,112004 (2010)

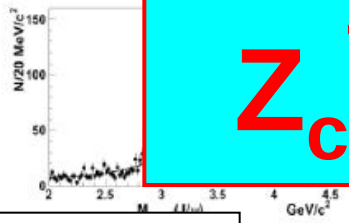


XYZ states

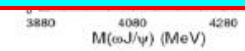
X(3872)
PRL 91,262001 (2003)



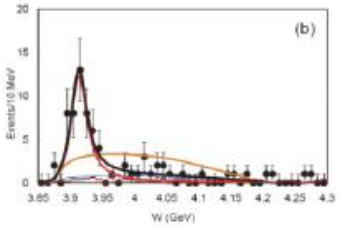
X(3940)
PRL 98,082001 (2007)



Y(3940)
PRL 94,182002 (2005)

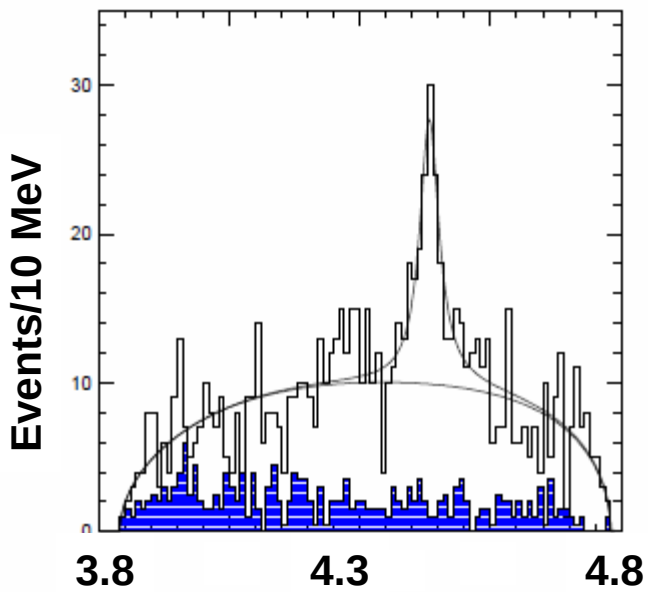


X(3915)
PRL 104,092001 (2010)

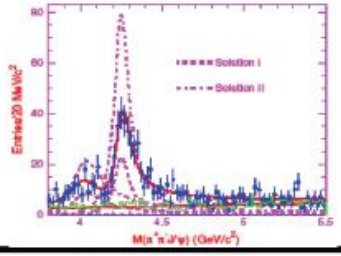


$Z_c^{\pm}(4430)$

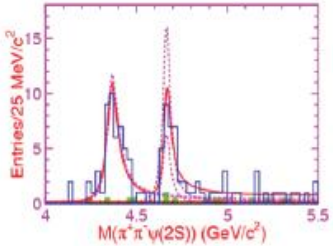
$B \longrightarrow K\pi^{\pm}\psi'$



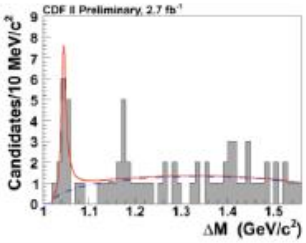
Y(4008)
PRL 99,182004 (2007)



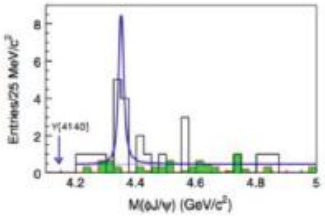
Y(4660)
PRL 99,142002 (2007)



Y(4140)
PRL 102,242002 (2009)



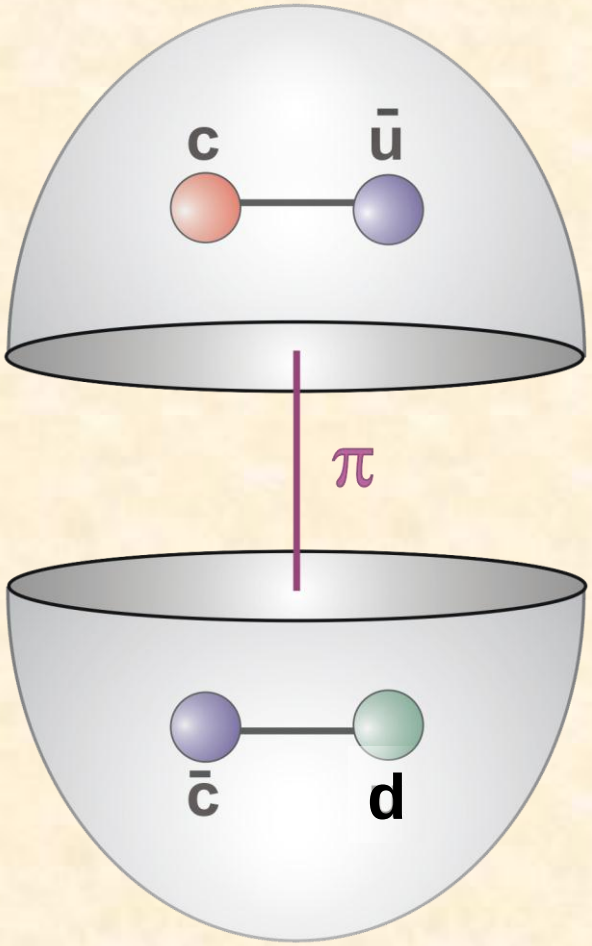
X(4350)
PRL 104,112004 (2010)



BELLE

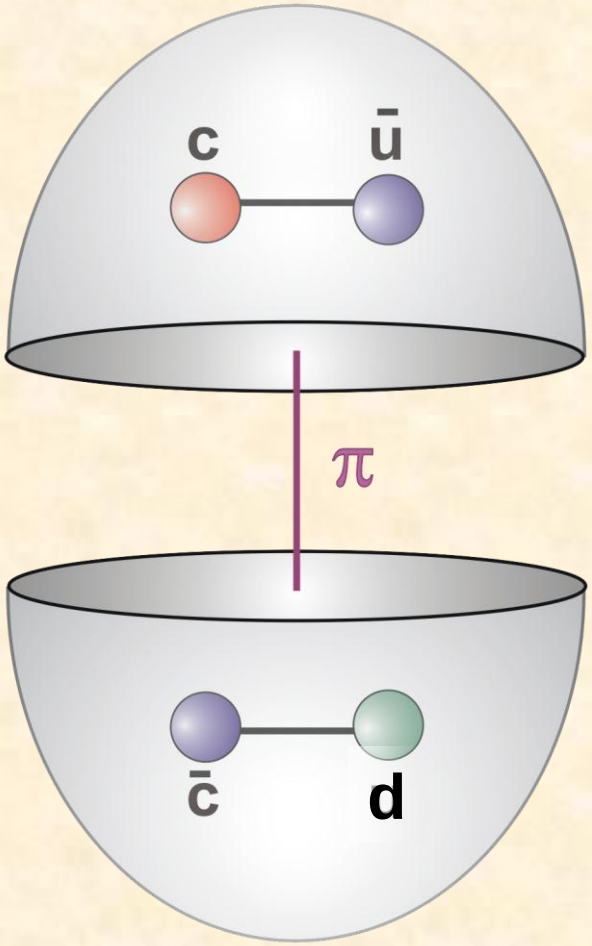
Z_c^-

molecule

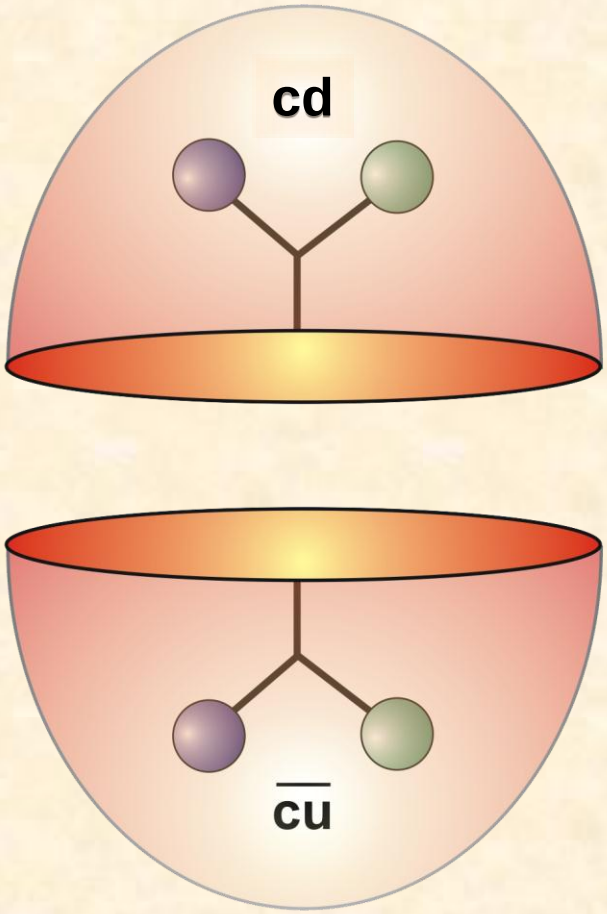


Z_c^-

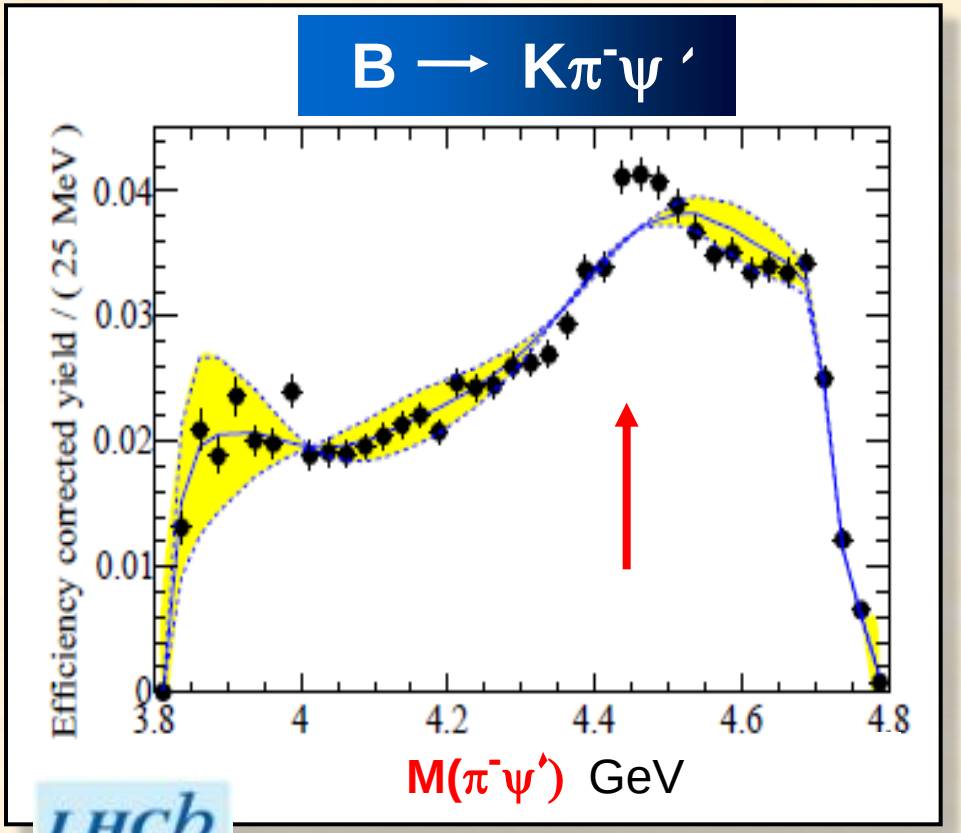
molecule

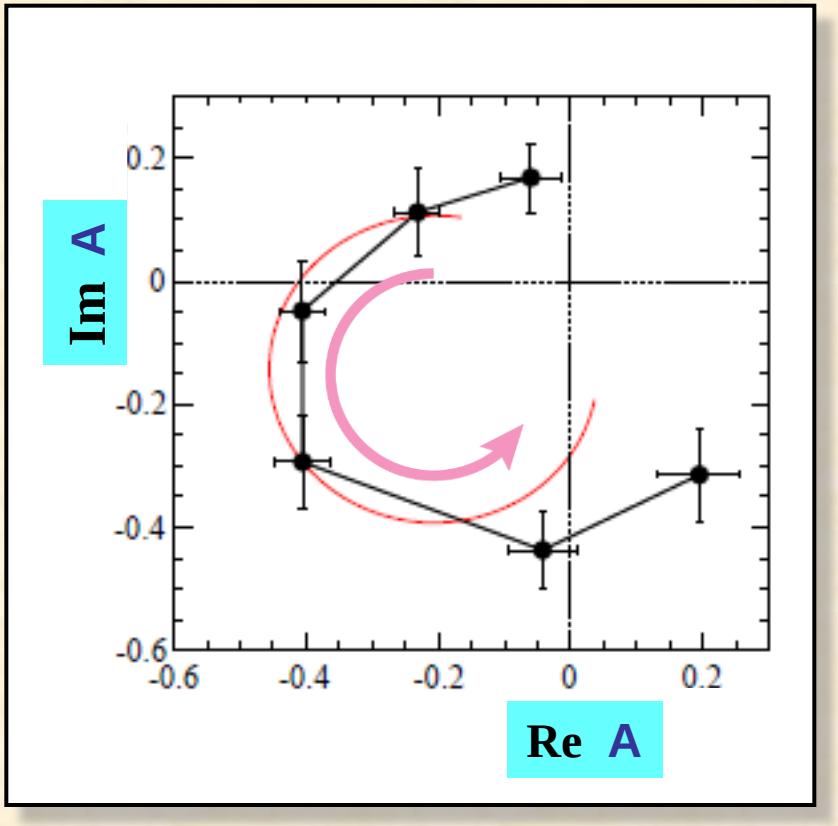


tetraquark

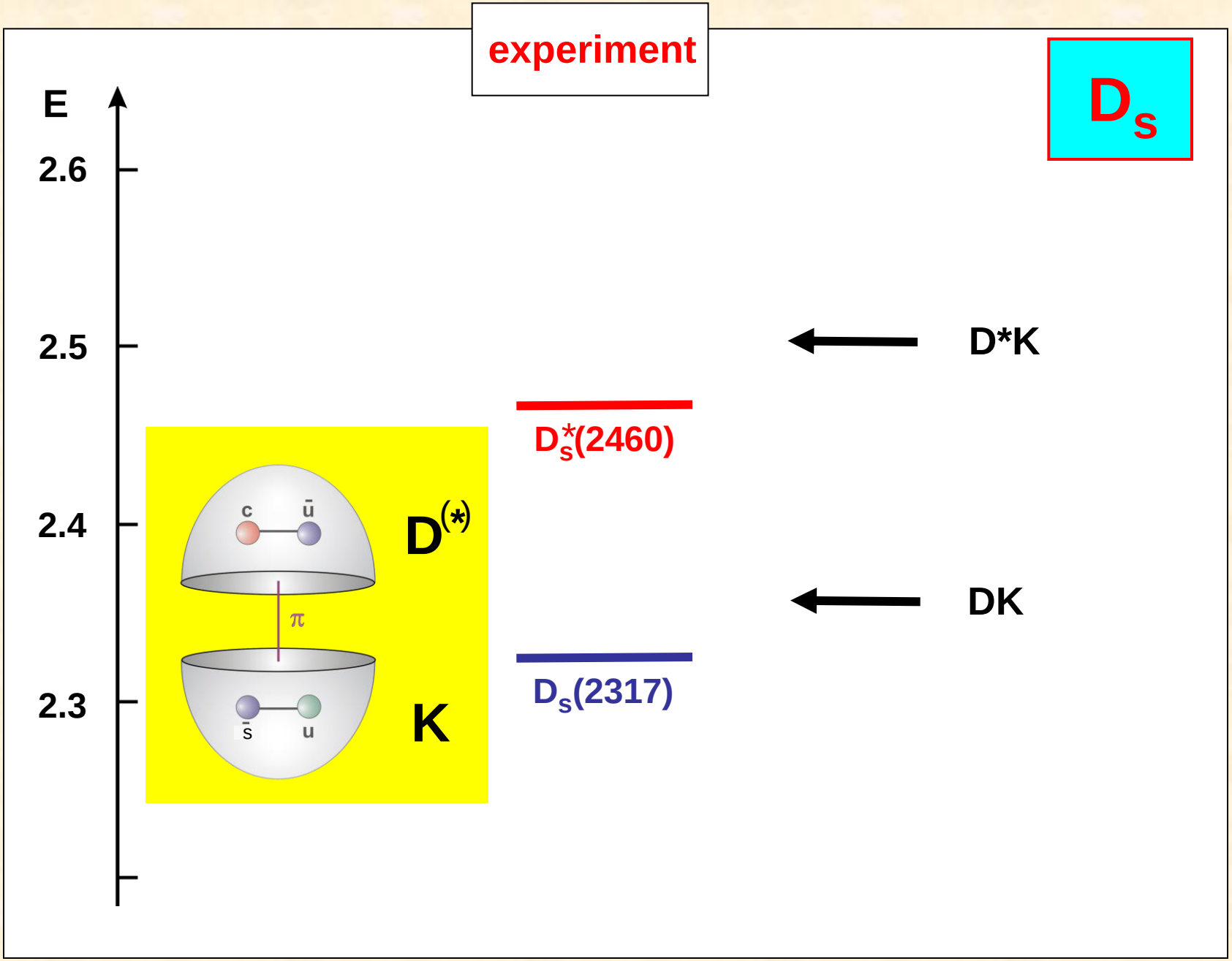


$Z_c^-(4430)$



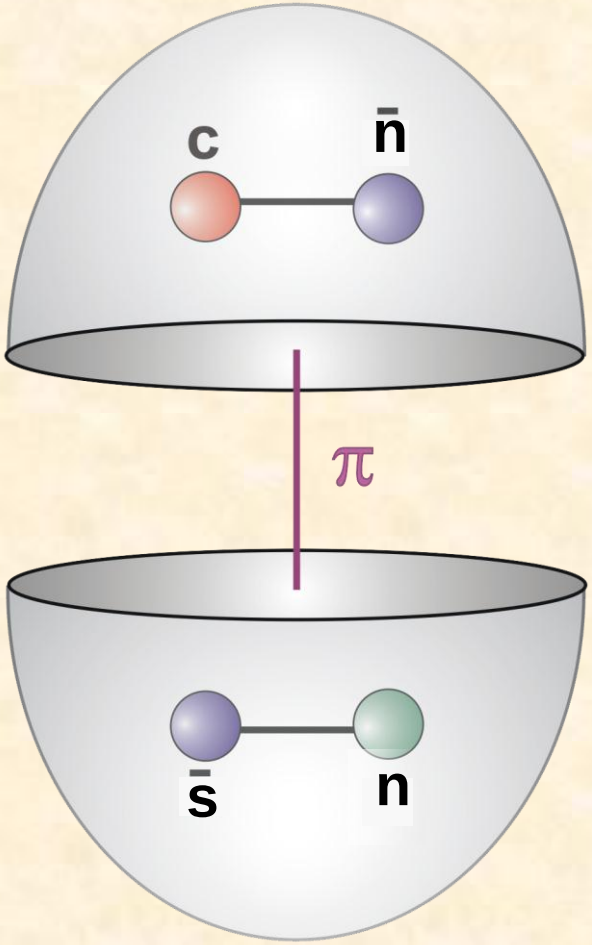


Essential to confirm all such states with robust analyses

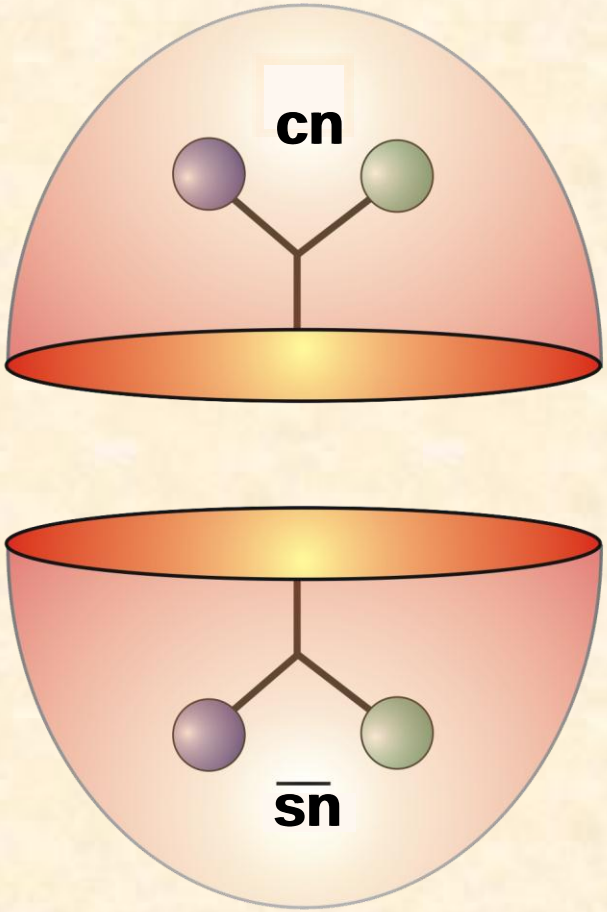

experiment
D_s
E
2.6
2.5
2.4
2.3
D*K
DK
$D_s^*(2460)$
$D_s(2317)$
c
ū
π
s̄
u
$D^{(*)}$
K

$D_s^{(*)+}$

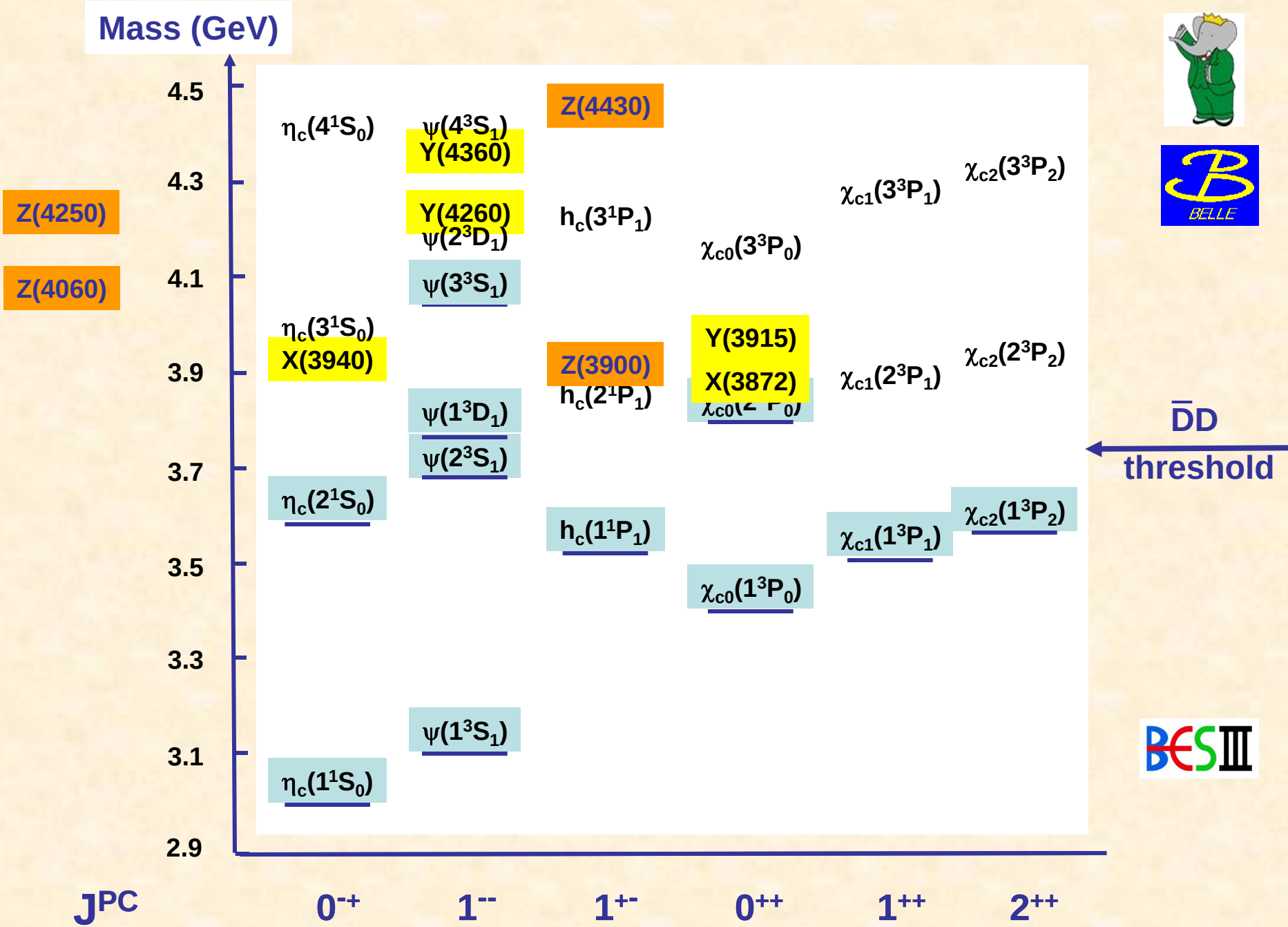
molecule

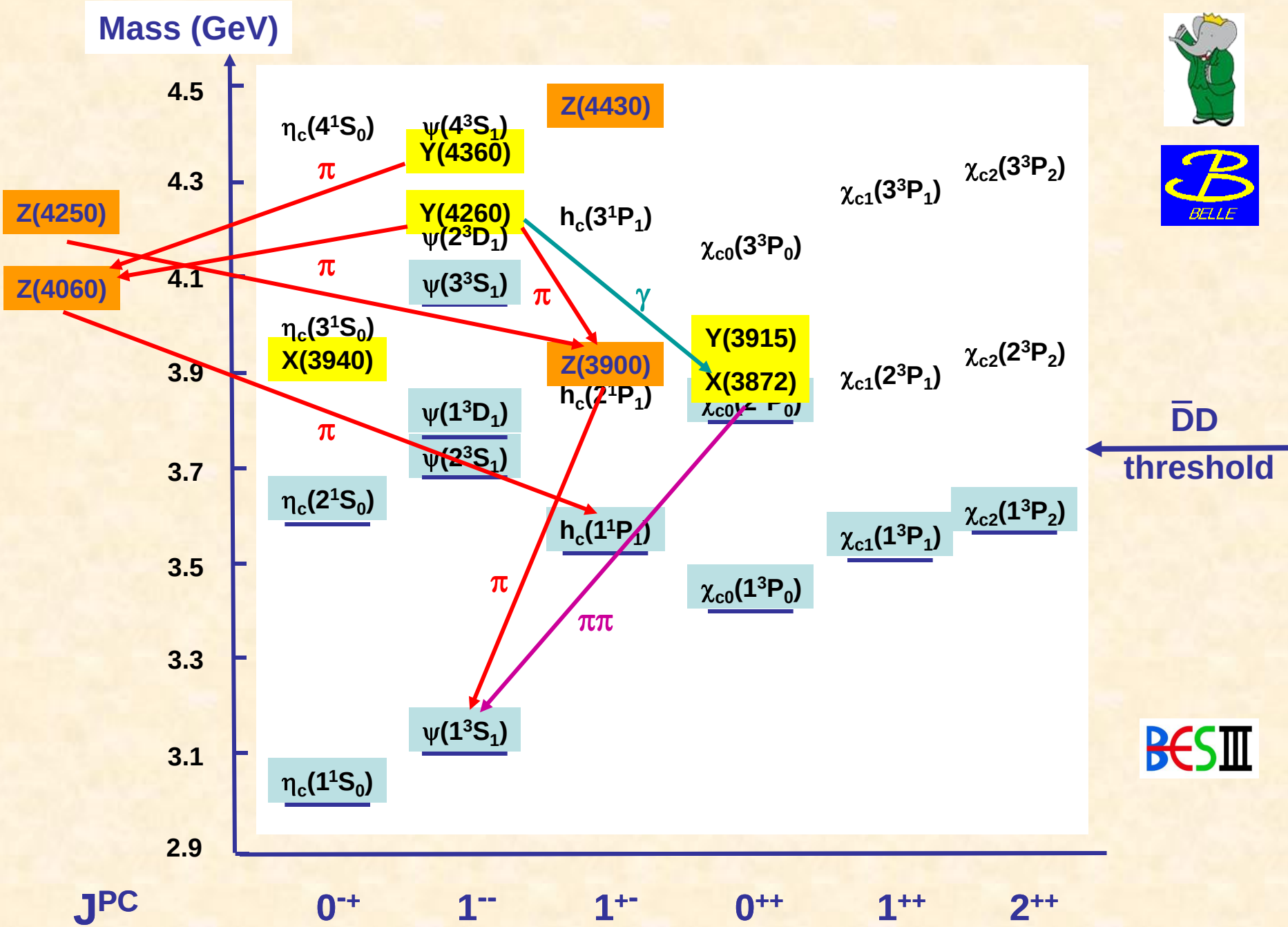


tetraquark



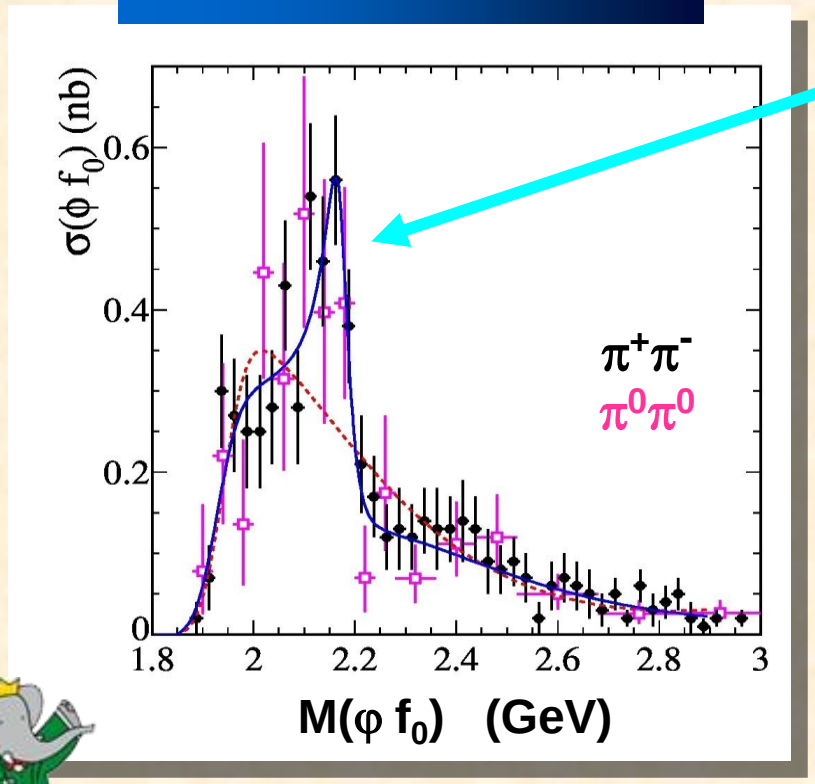
n = u, d


Mass (GeV)
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
Z(4250)
Z(4060)
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
Y(4360)
Z(4430)
$\chi_{c2}(3^3P_2)$
$\chi_{c1}(3^3P_1)$
Y(4260)
$\psi(2^3D_1)$
$h_c(3^1P_1)$
$\chi_{c0}(3^3P_0)$
$\psi(3^3S_1)$
$\eta_c(3^1S_0)$
X(3940)
Z(3900)
Y(3915)
X(3872)
$\chi_{c2}(2^3P_2)$
$\chi_{c1}(2^3P_1)$
$h_c(2^1P_1)$
$\psi(1^3D_1)$
$\psi(2^3S_1)$
$\bar{D}D$
threshold
$\eta_c(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c1}(1^3P_1)$
$\chi_{c0}(1^3P_0)$
$\psi(1^3S_1)$
$\eta_c(1^1S_0)$
J^{PC}
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
BELLE
BESIII

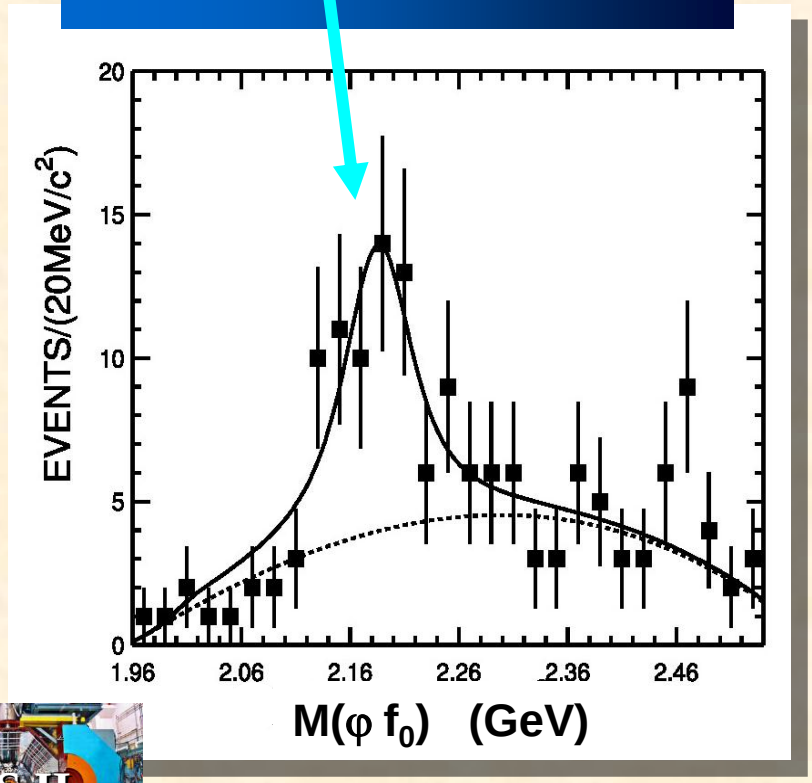

Mass (GeV)
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
Z(4430)
Z(4250)
Z(4060)
Y(4360)
Y(4260)
Z(3900)
Y(3915)
X(3872)
X(3940)
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
$\psi(2^3D_1)$
$\psi(3^3S_1)$
$\eta_c(3^1S_0)$
$\psi(1^3D_1)$
$\psi(2^3S_1)$
$\eta_c(2^1S_0)$
$\psi(1^3S_1)$
$\eta_c(1^1S_0)$
$h_c(3^1P_1)$
$h_c(2^1P_1)$
$h_c(1^1P_1)$
$\chi_{c0}(3^3P_0)$
$\chi_{c0}(2^3P_0)$
$\chi_{c0}(1^3P_0)$
$\chi_{c1}(3^3P_1)$
$\chi_{c1}(2^3P_1)$
$\chi_{c1}(1^3P_1)$
$\chi_{c2}(3^3P_2)$
$\chi_{c2}(2^3P_2)$
$\chi_{c2}(1^3P_2)$
π
γ
$\pi\pi$
$\bar{D}D$ threshold
J^{PC}
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
BELLE
BESIII

$e^+e^- \longrightarrow \gamma_{ISR}\ (\varphi\ f_0)$

Y (2175)



$J/\Psi \longrightarrow \eta\ (\varphi\ f_0)$

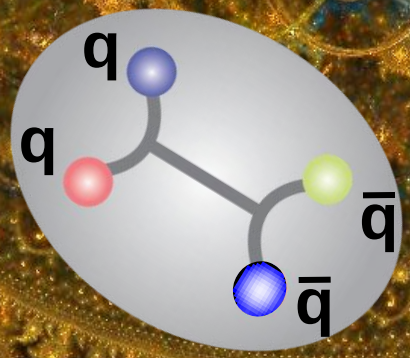


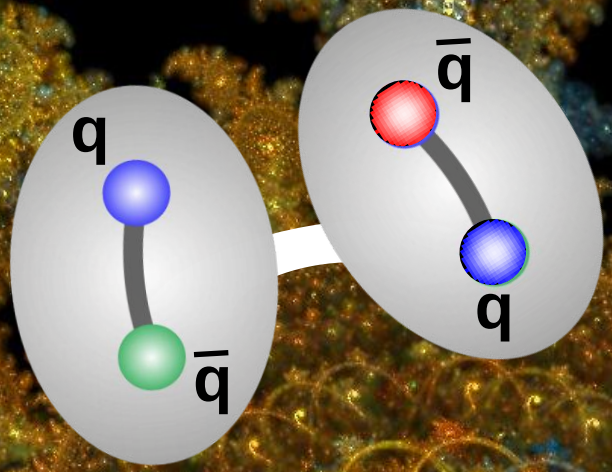
strangeonium sector too?

LONG RANGE PLAN: next decade

Distinguishing compositions

i.e. ranges of forces → scattering lengths to binding channels, and/or poles in complex energy plane



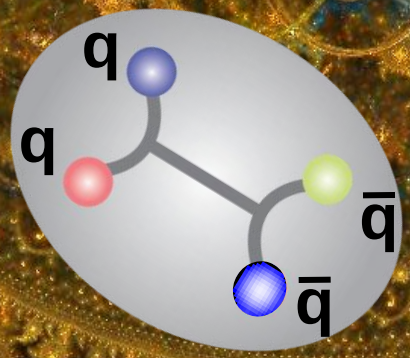


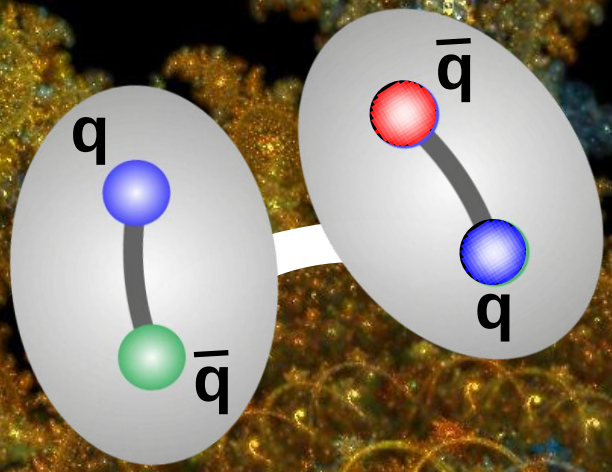
LONG RANGE PLAN: next decade

Distinguishing compositions

i.e. ranges of forces → scattering lengths to binding channels, and/or poles in complex energy plane

analytic continuation
(with chiral constraints when appropriate)





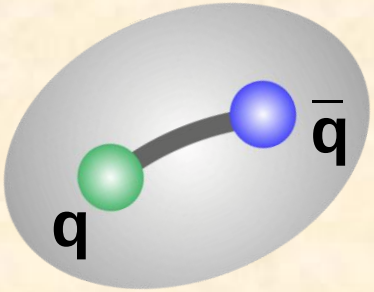
Prospects

meson spectrum

allowed J^{PC}

0^{--}	0^{-+}	0^{+-}	0^{++}
1^{--}	1^{-+}	1^{+-}	1^{++}
2^{--}	2^{-+}	2^{+-}	2^{++}
3^{--}	3^{-+}	3^{+-}	3^{++}
4^{--}	4^{-+}	4^{+-}	4^{++}

...



meson spectrum

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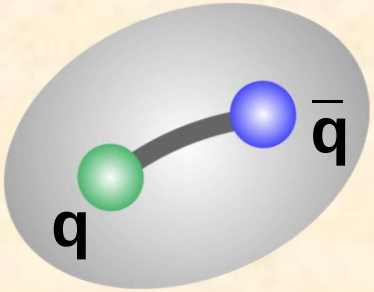
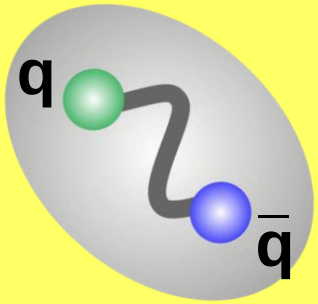
3^{--}	3^{-+}	3^{+-}	3^{++}
4^{--}	4^{-+}	4^{+-}	4^{++}

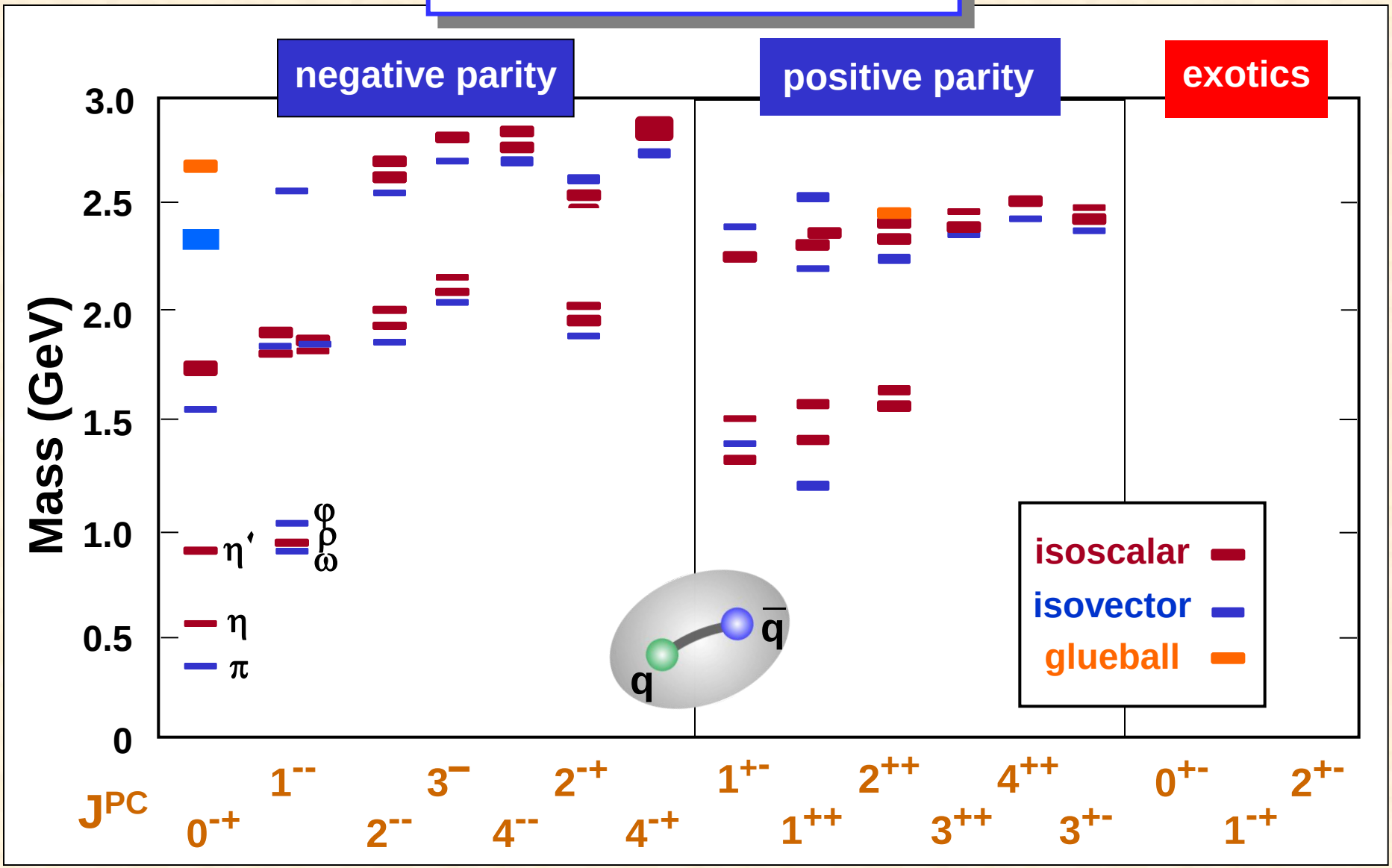
...



$J^{PC} \rightarrow$ not $\bar{q}q$



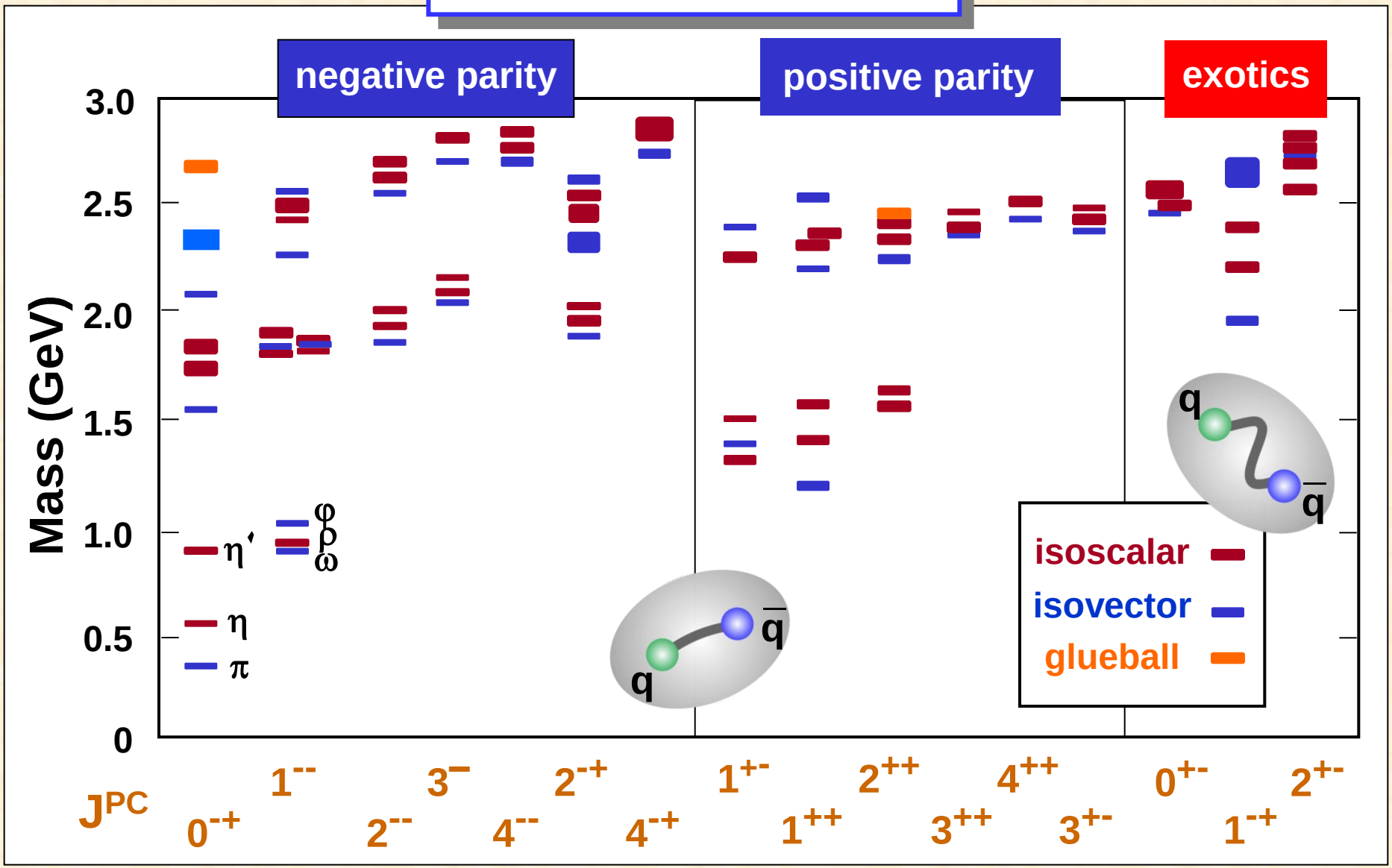
Meson spectrum



Dudek *et al*

m_π = 396 MeV

Meson spectrum



Dudek *et al*

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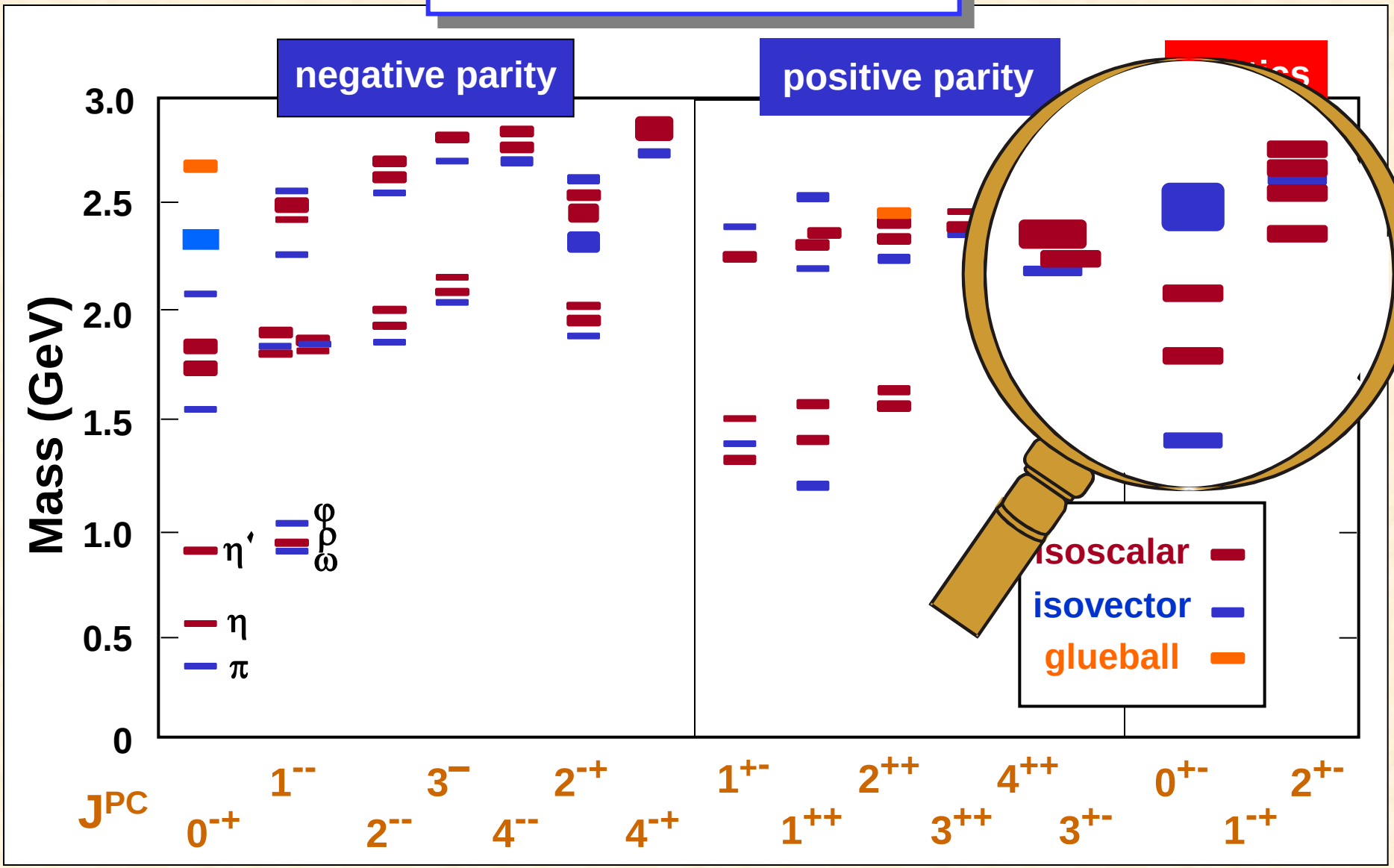
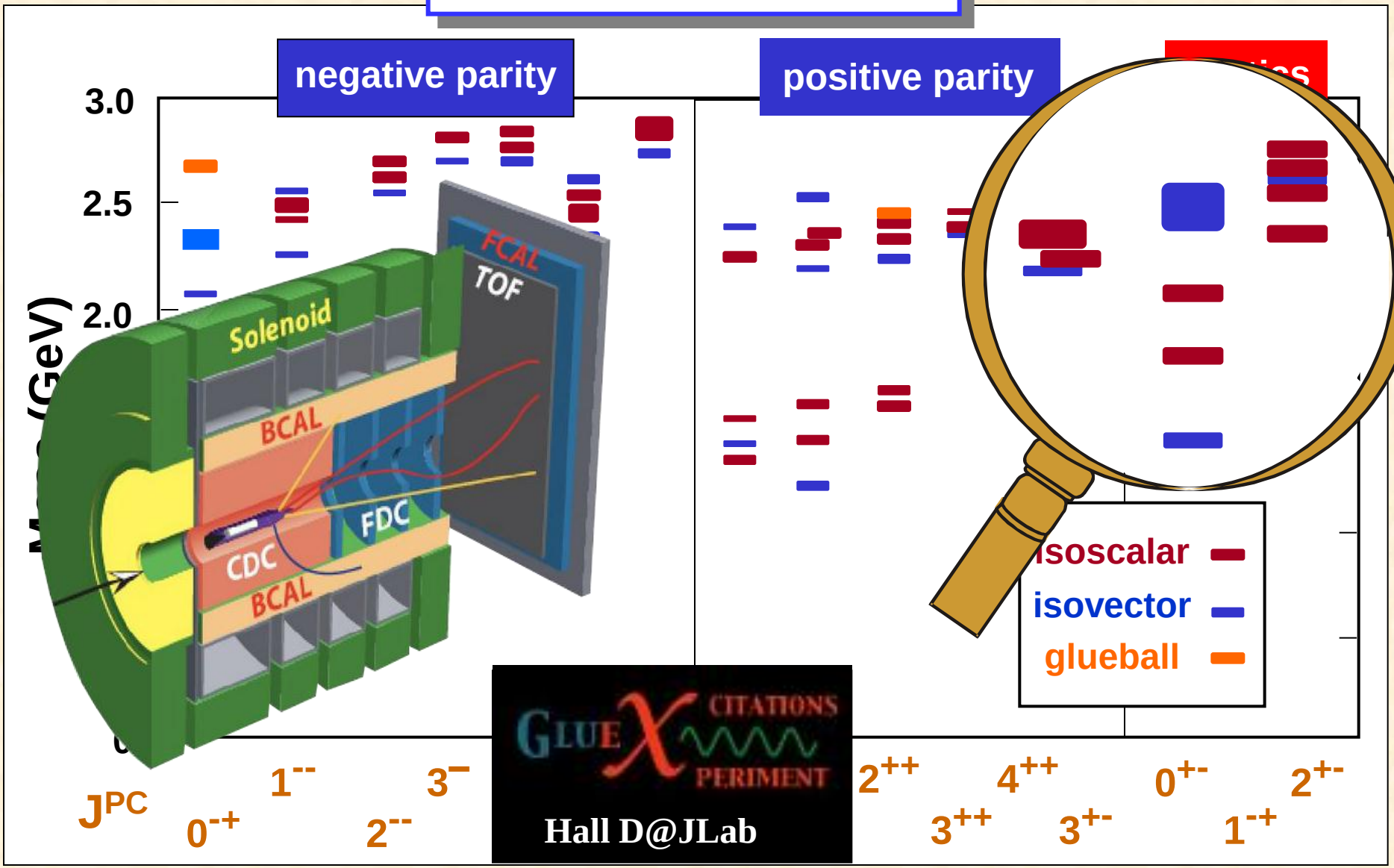
Meson spectrum



Dudek *et al*

m_π = 396 MeV

Meson spectrum

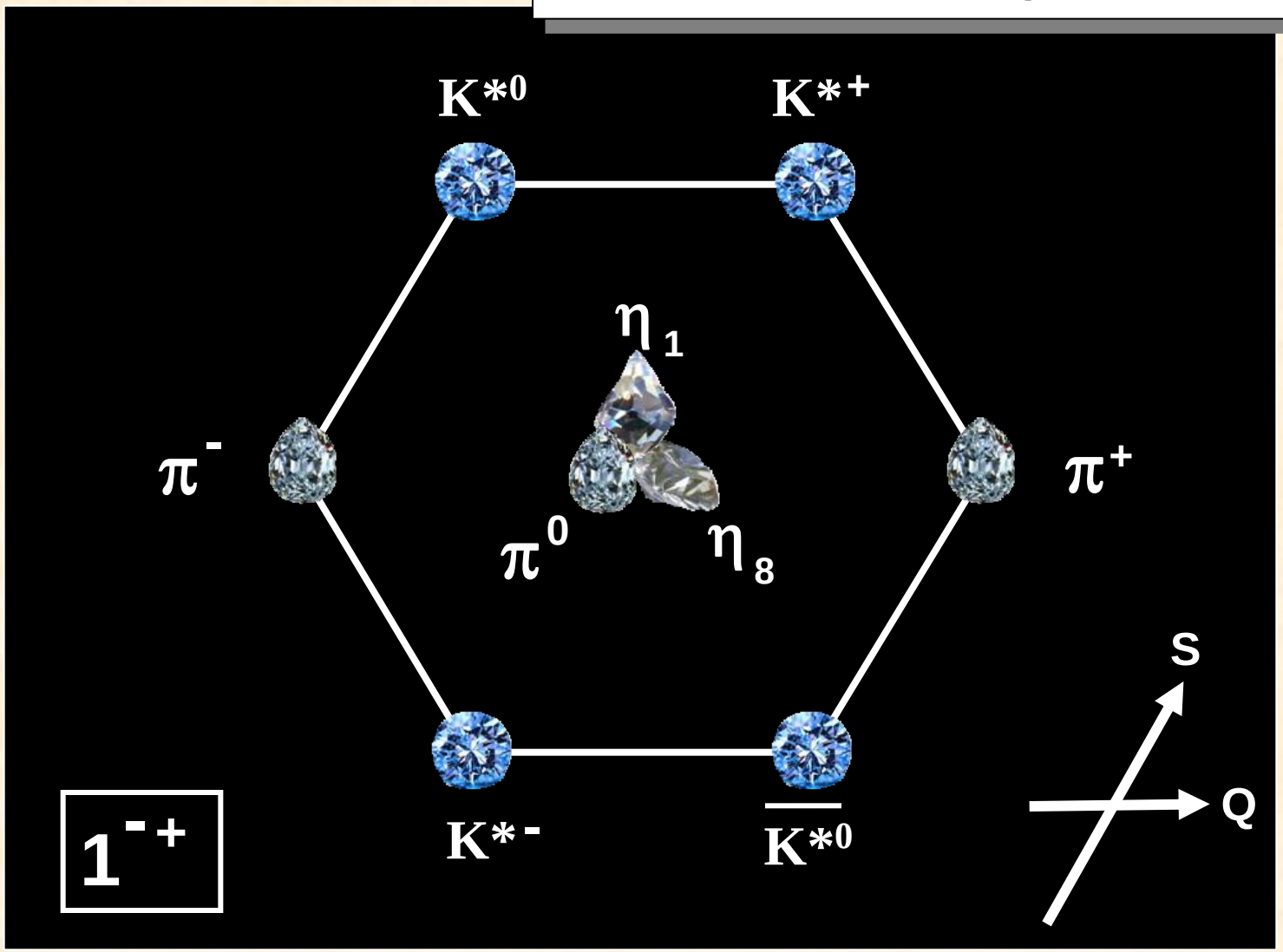


Dudek *et al*

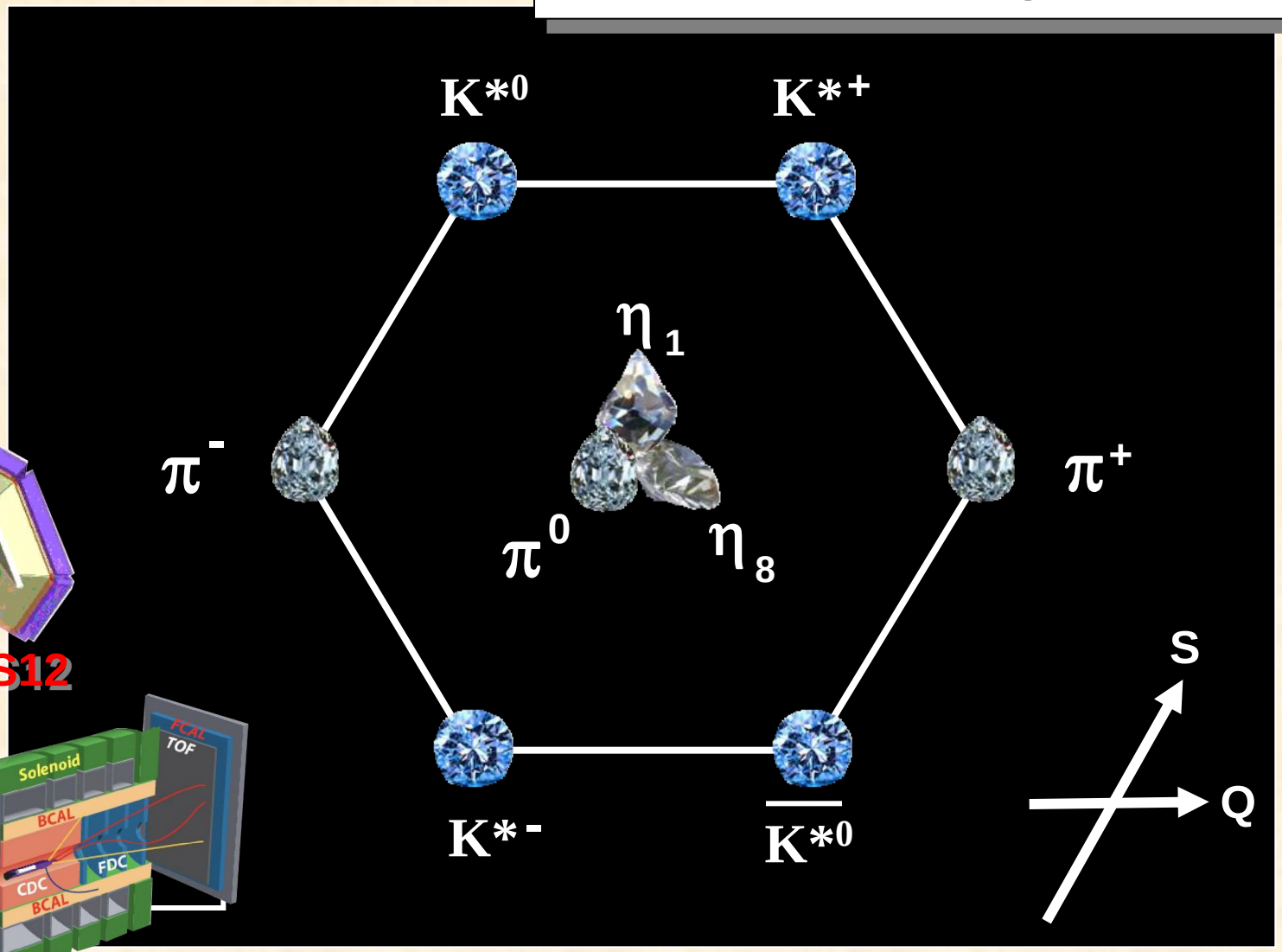
m_π = 396 MeV

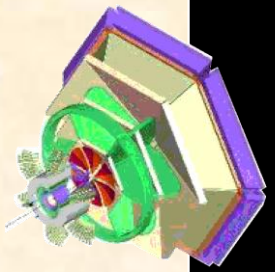
Precision analysis tools

Precision analysis tools

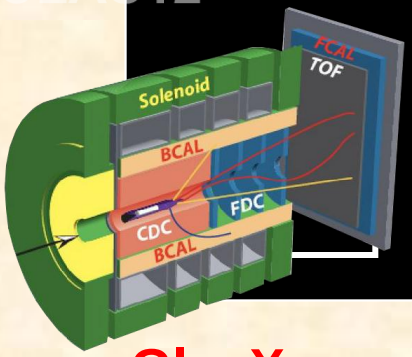


Precision analysis tools



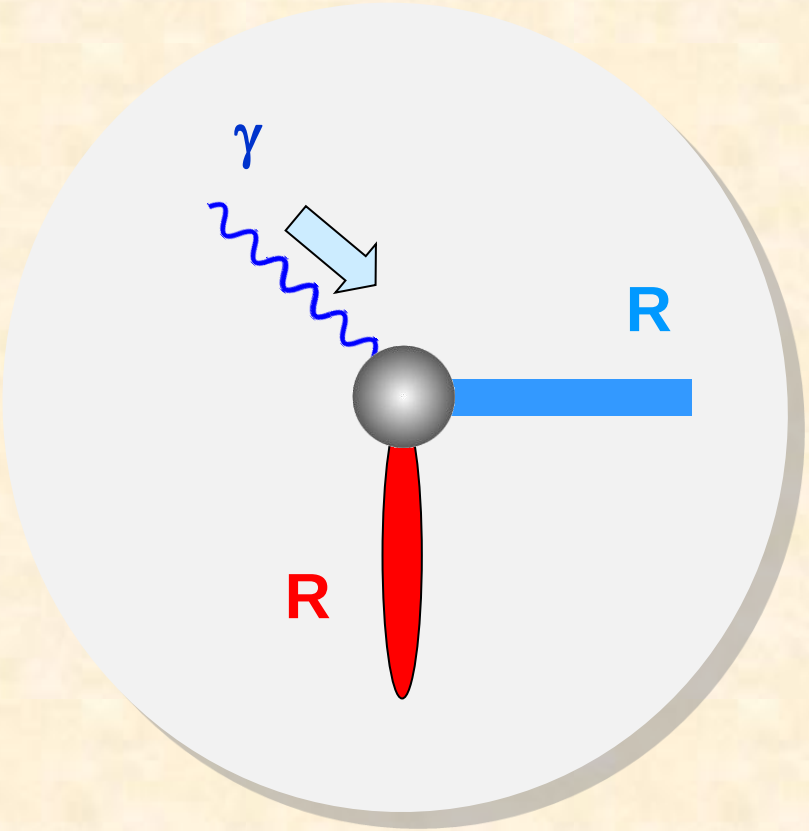


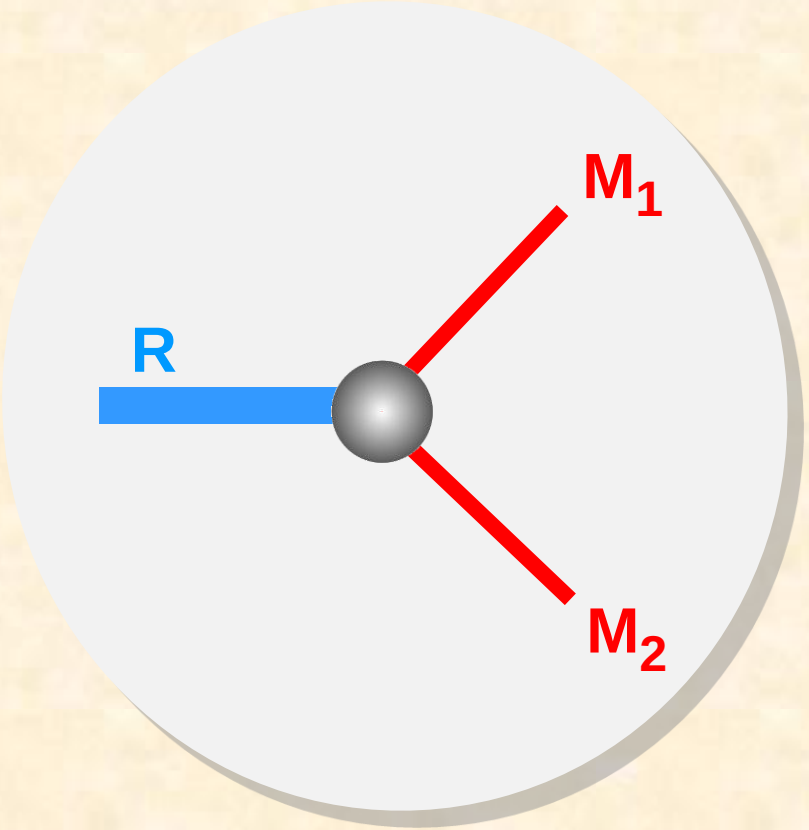
CLAS12



GlueX

Calculating on the lattice



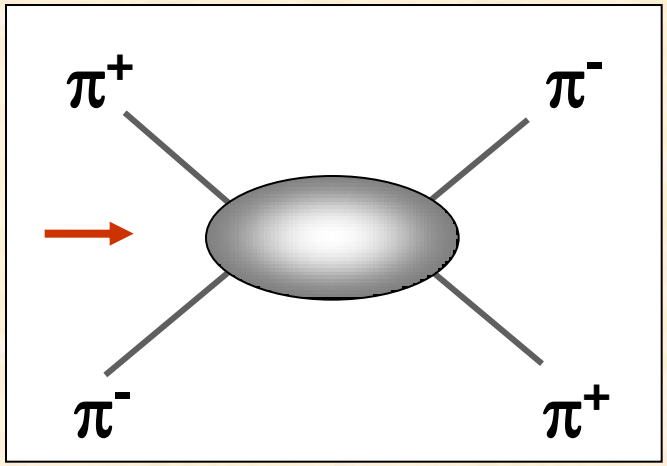


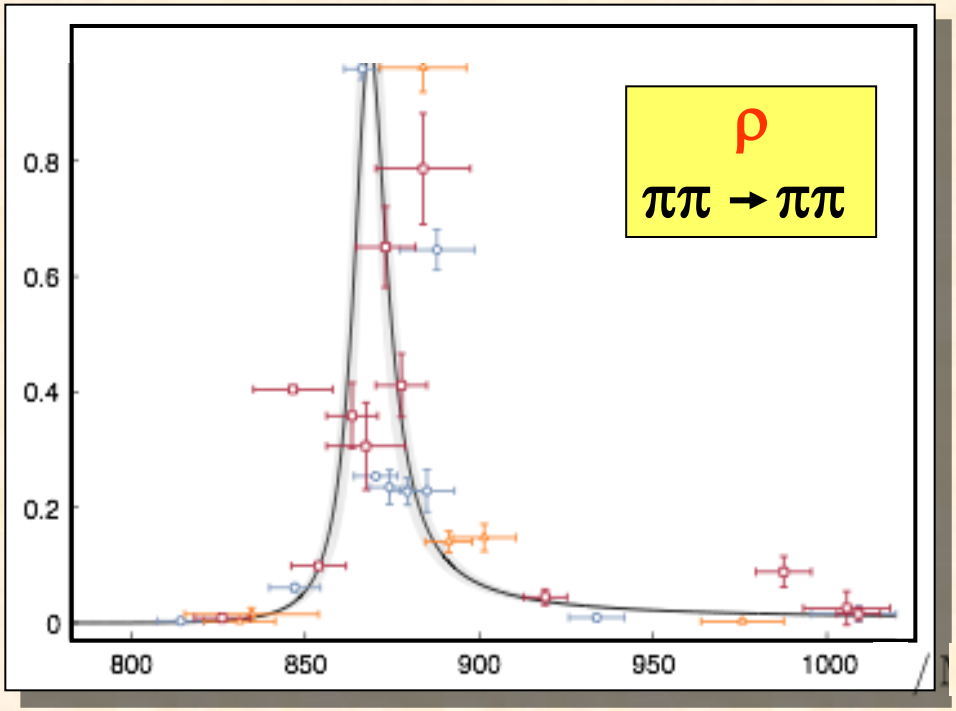
e.g. $\gamma\, \pi_R \rightarrow \pi_1$

e.g. $\pi_1 \rightarrow \rho\, \pi$

normalize photoproduction cross-sections

Scattering on the lattice



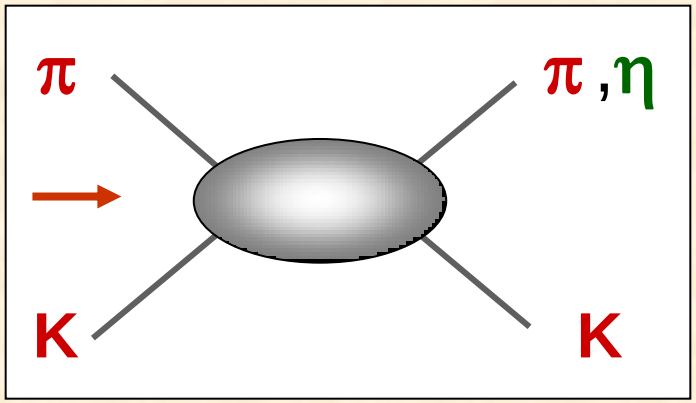


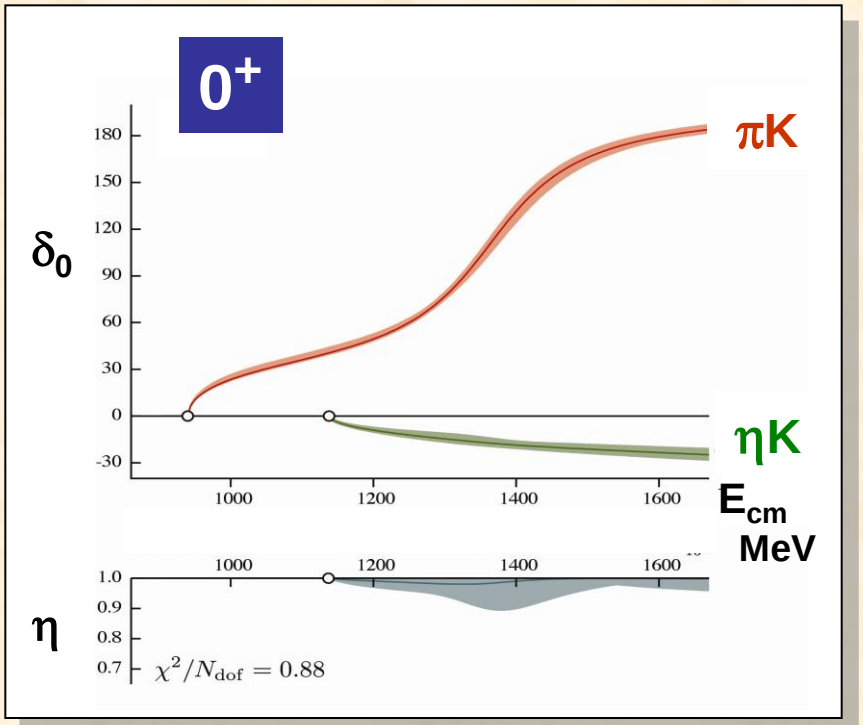
E (MeV)

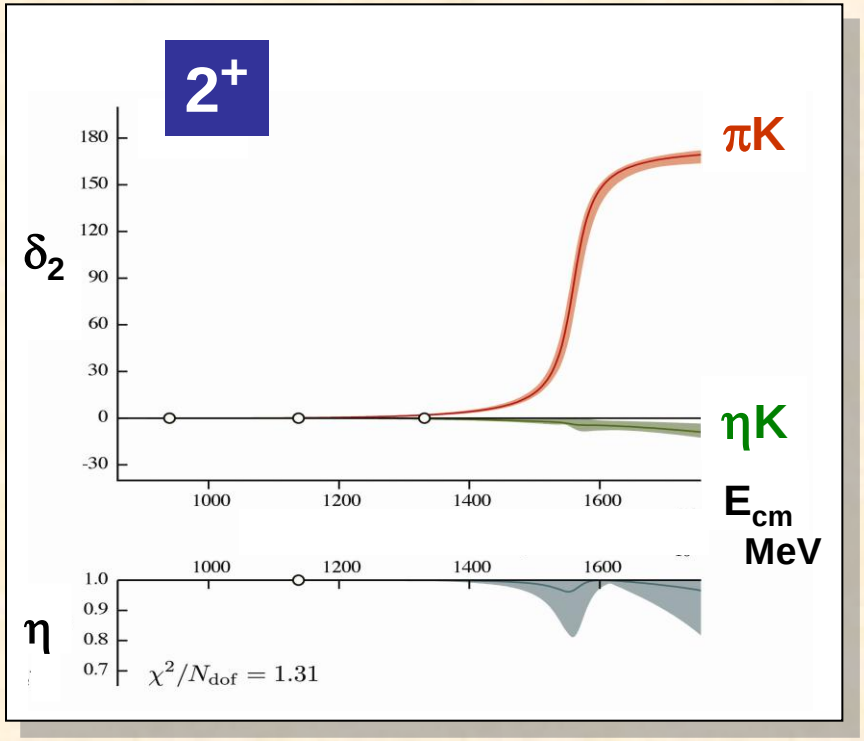
m_π = 396 MeV

Hadron Spectrum Collaboration

Scattering on the lattice



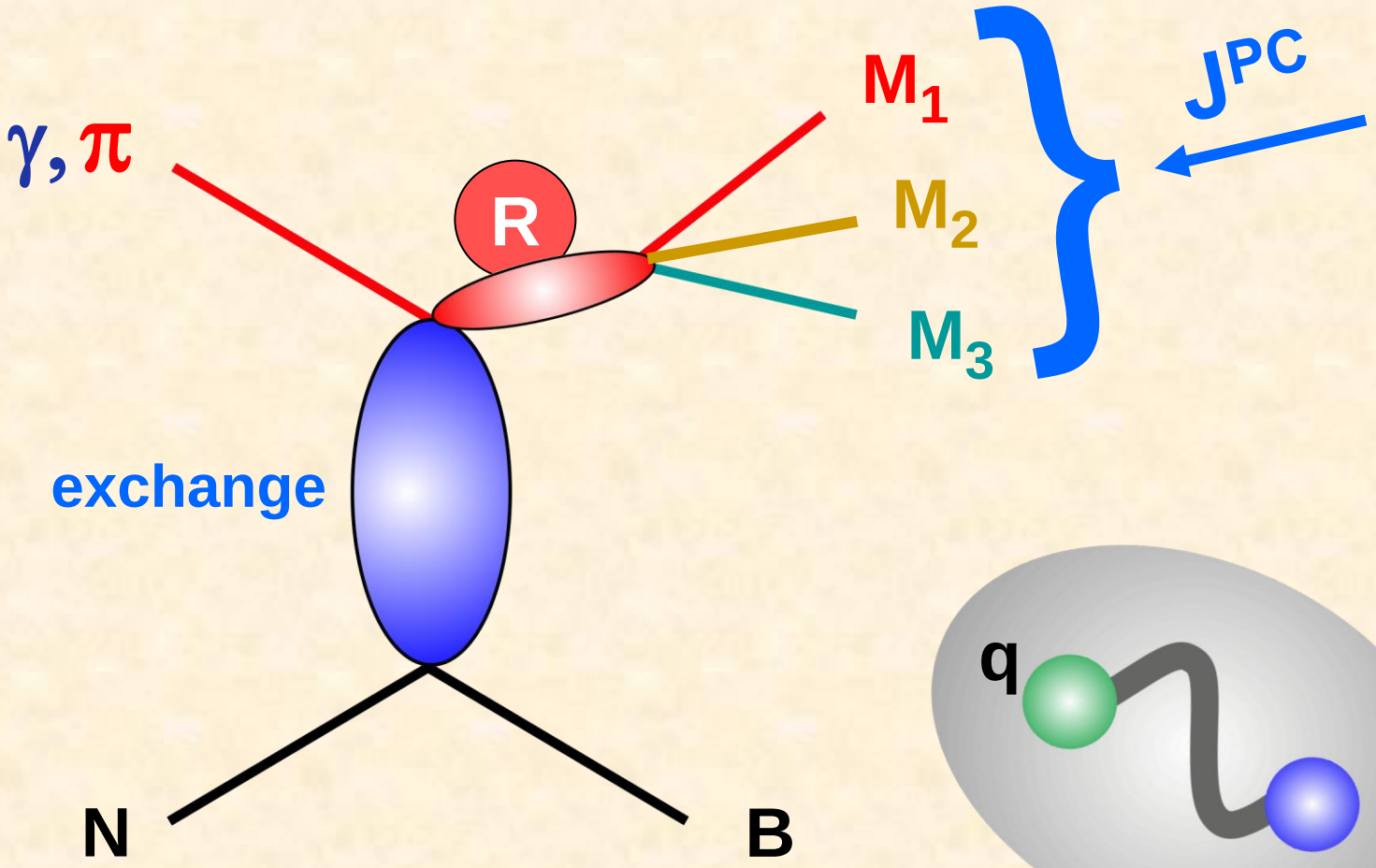


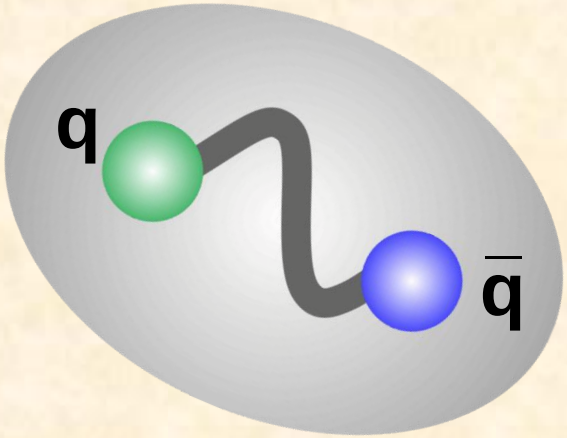


m_π = 396 MeV

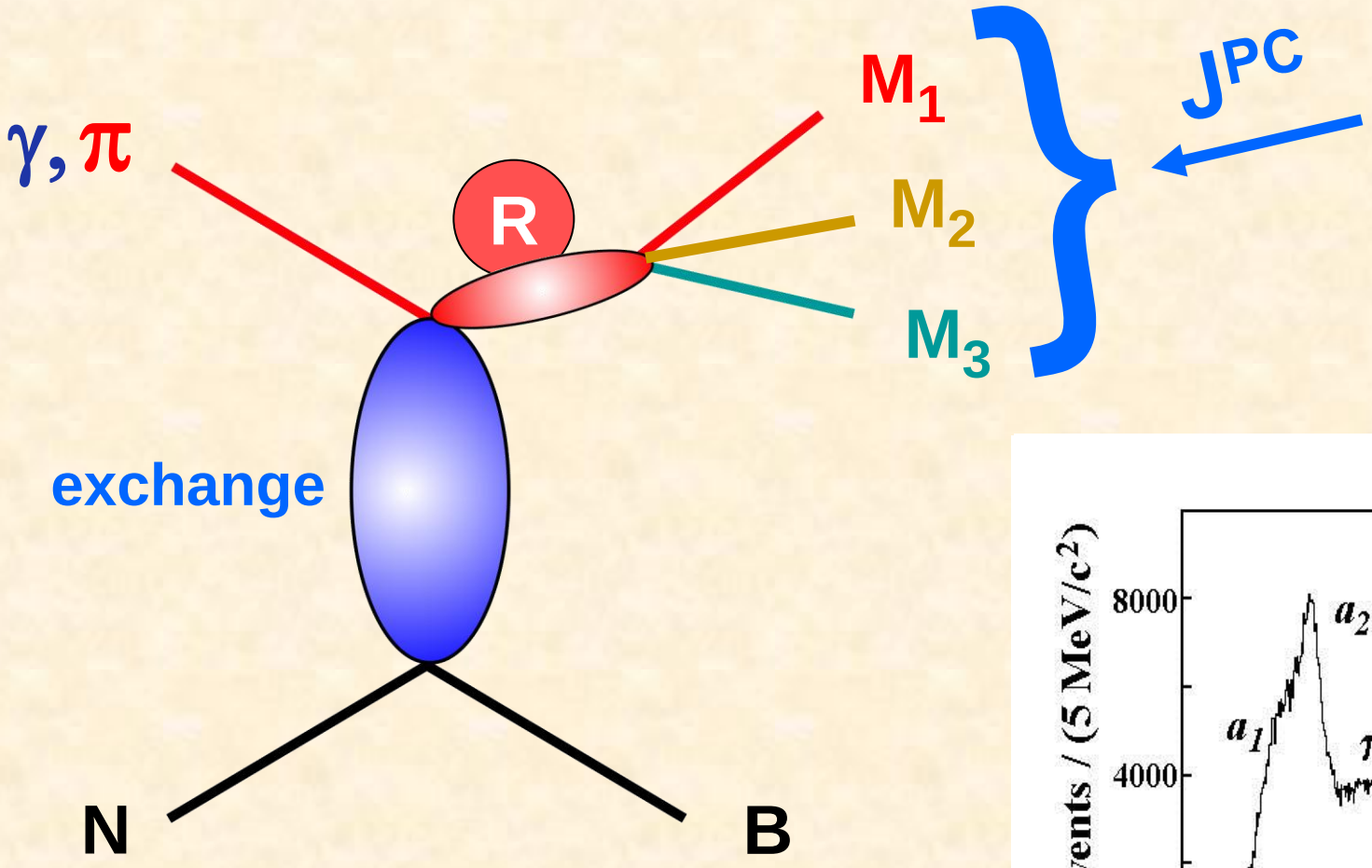
Dudek, Edwards, Thomas, Wilson

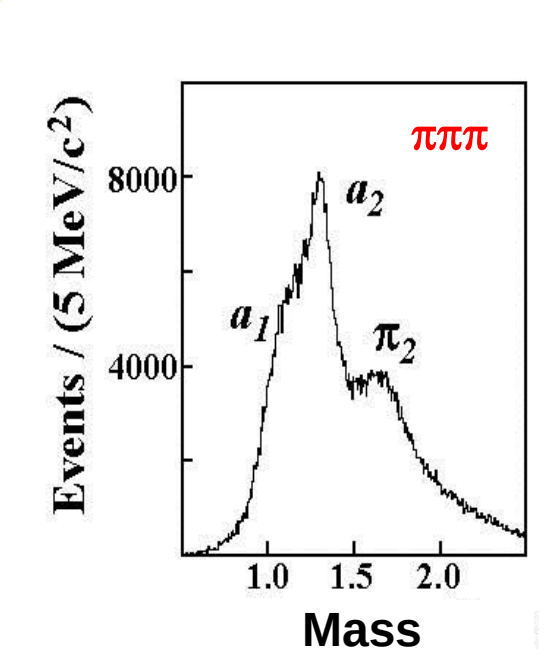
Amplitude Analysis





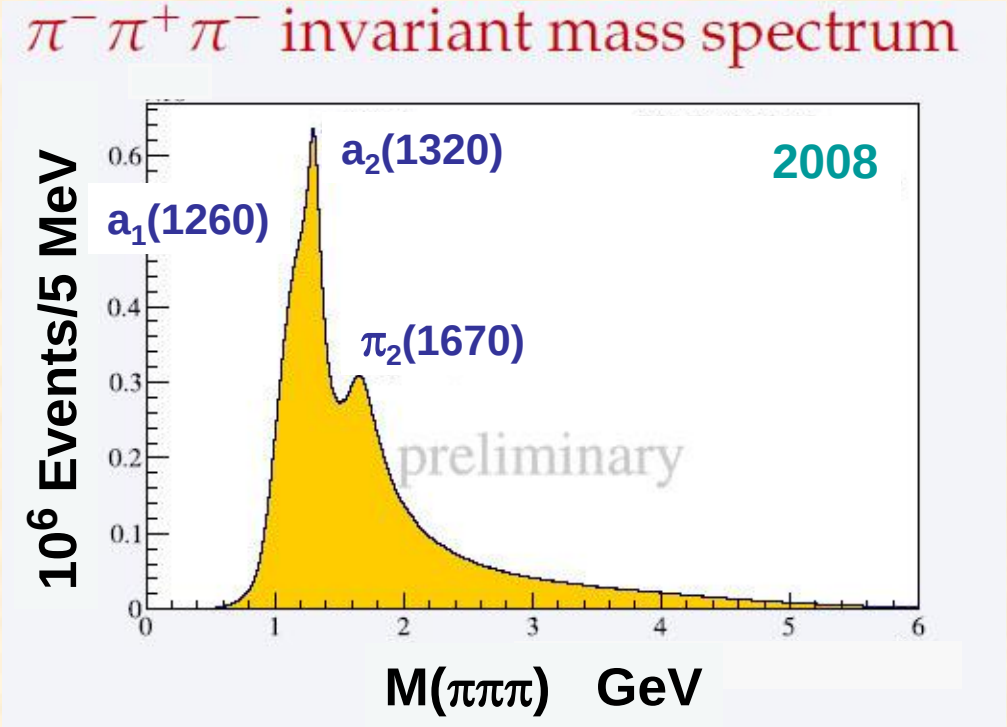
Amplitude Analysis

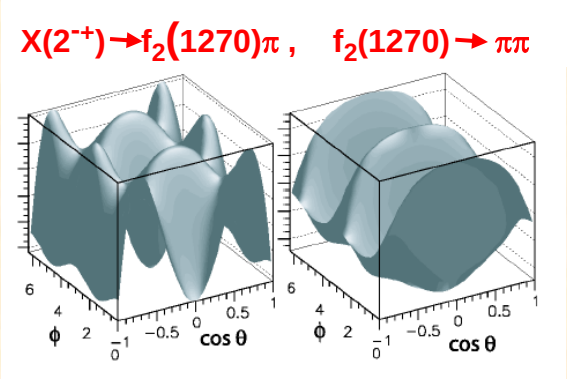




hadron as well as photon beams are crucial: CERN, J-PARC, FAIR….

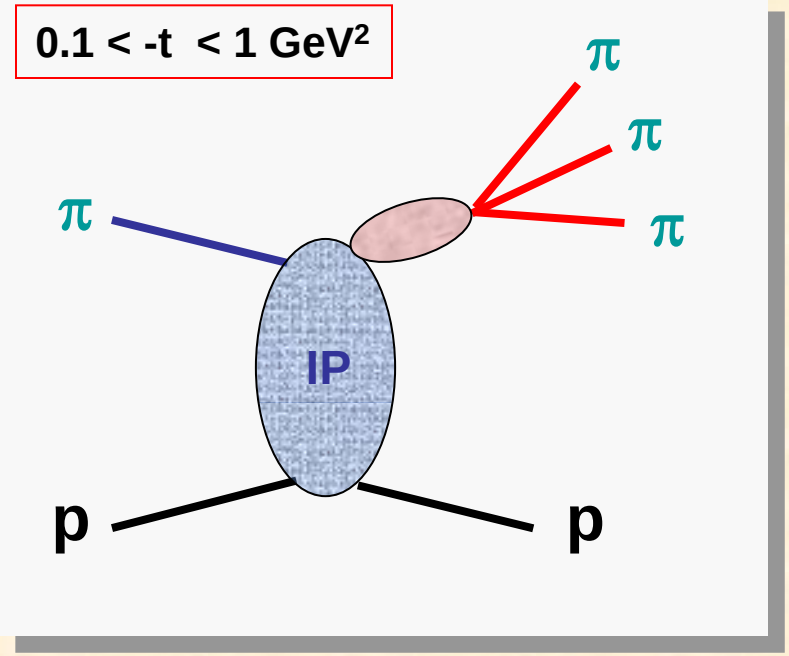
COMPASS @ CERN



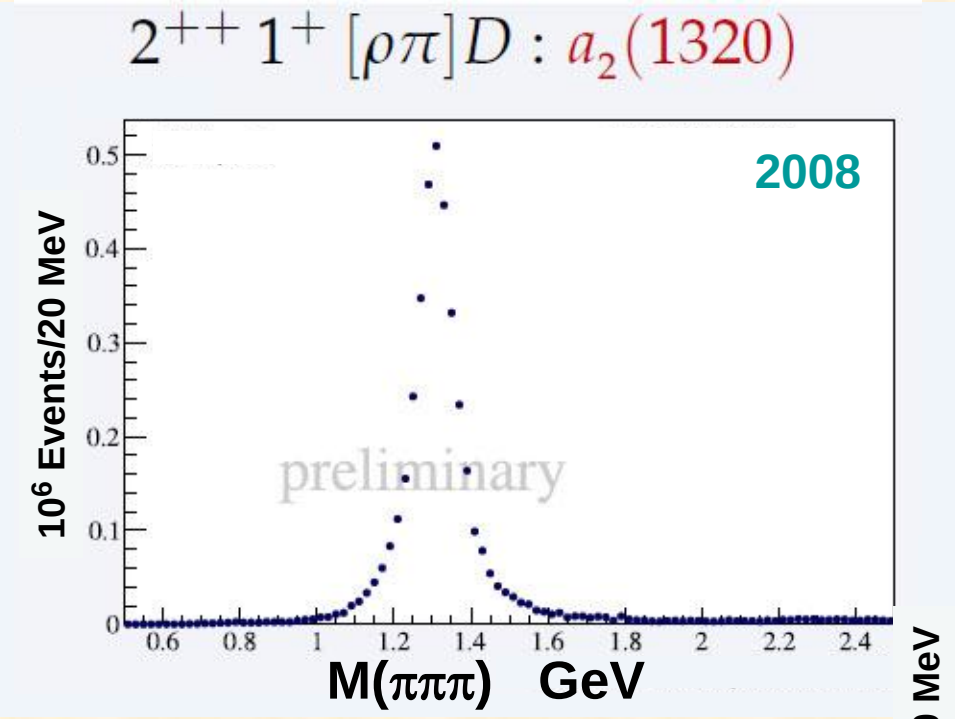


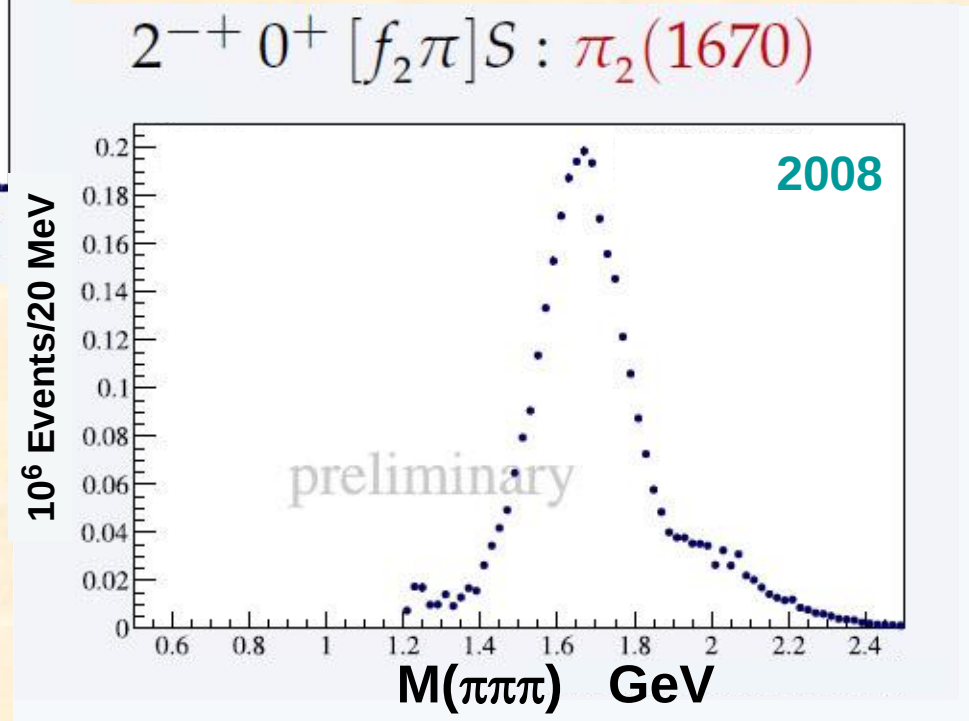
192 GeV beam **96M 3π events**

$\pi^- p \longrightarrow \pi^-\pi^+\pi^- p$



COMPASS @ CERN



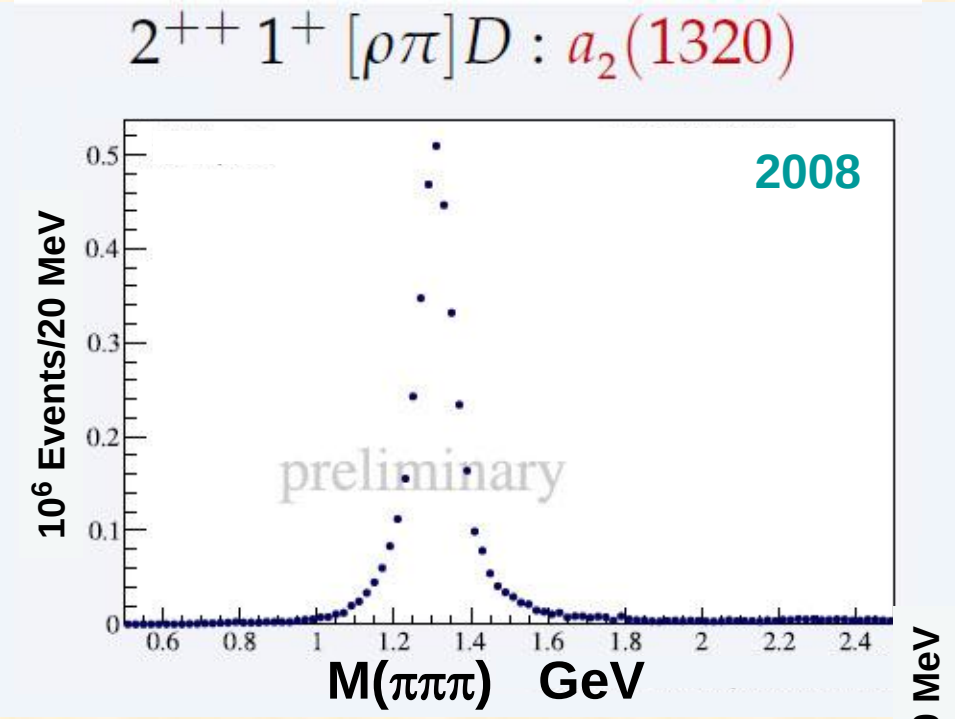


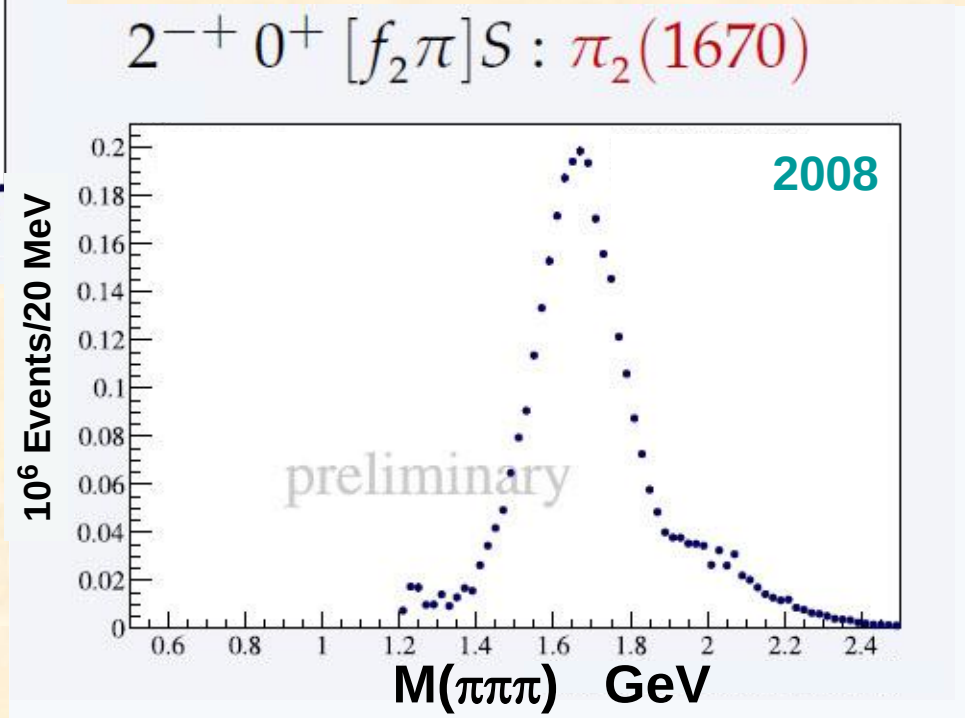
PWA: 2 of 88 waves

COMPASS @ CERN

Robust 1^{-+} results awaited

impact of limiting number of waves





PWA: 2 of 88 waves

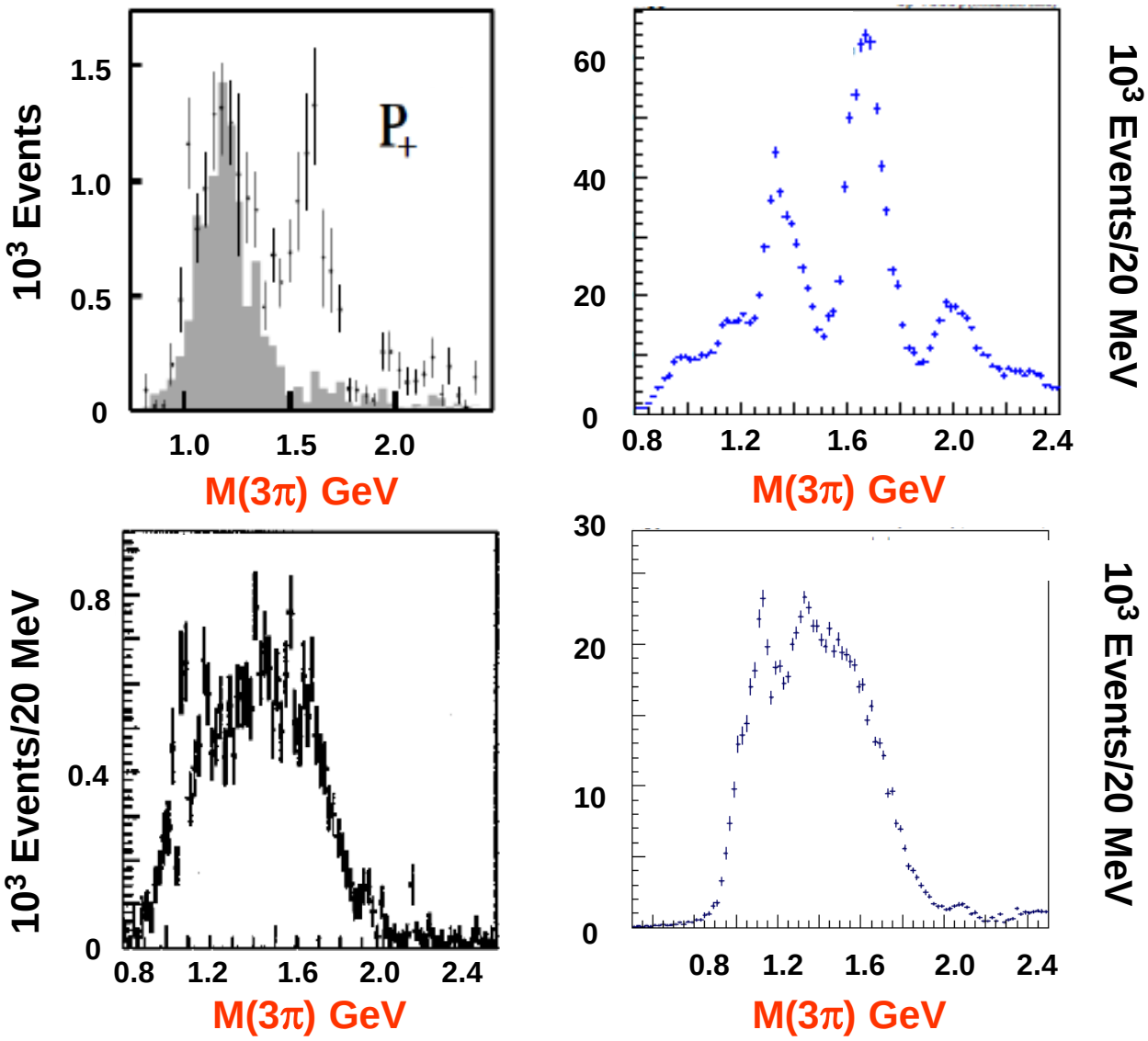
P-wave $\rho\pi$ 1^{-+}

BNL-E852-I
21 waves

COMPASS
21 waves

VES
42 waves

COMPASS
44 waves



- **essential to eliminate partial wave truncation**

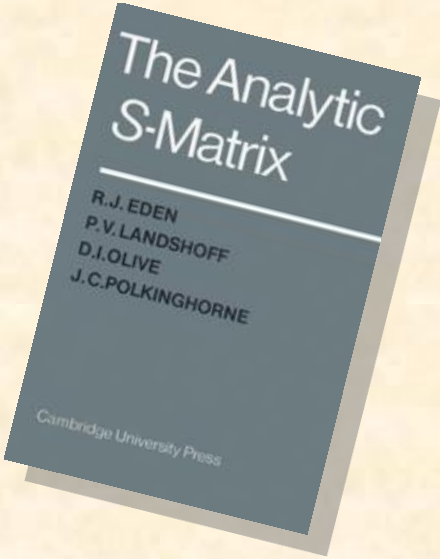
S-MATRIX RELOADED

Weapons:
analyticity
unitarity
S-MATRIX
RELOADED
The Analytic
S-Matrix
R.J. EDEN
P.V. LANDSHOFF
D.I. OLIVE
J.C. POLKINGHORNE
Cambridge University Press

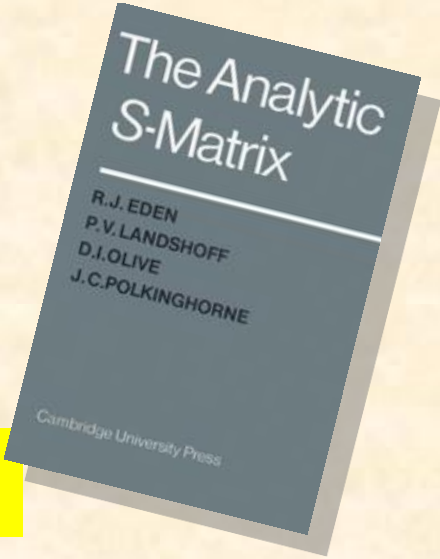
Outstanding theory issues

- **Techniques of Amplitude Analysis**

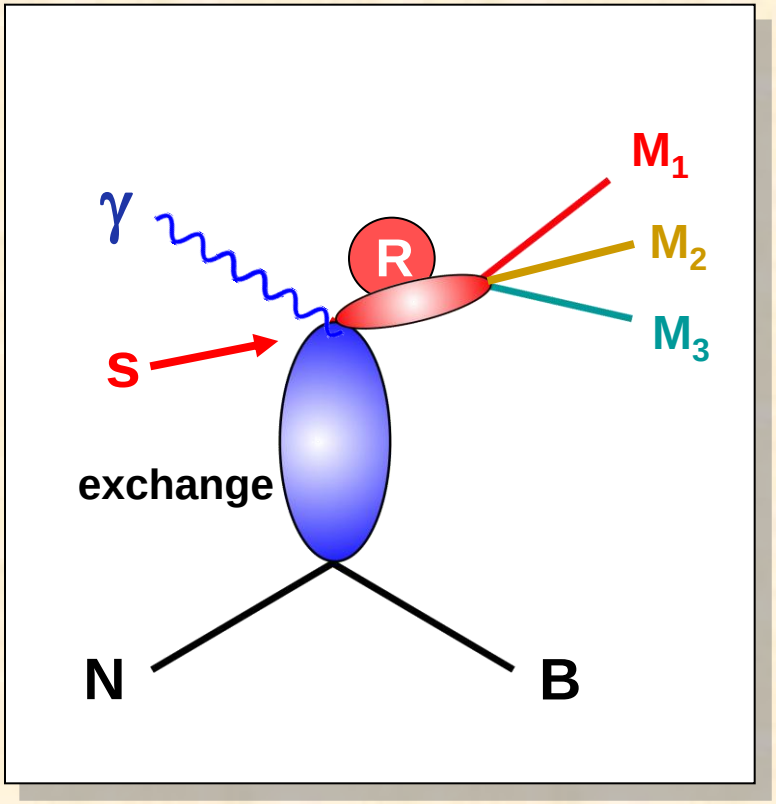
synergy with scattering on the lattice



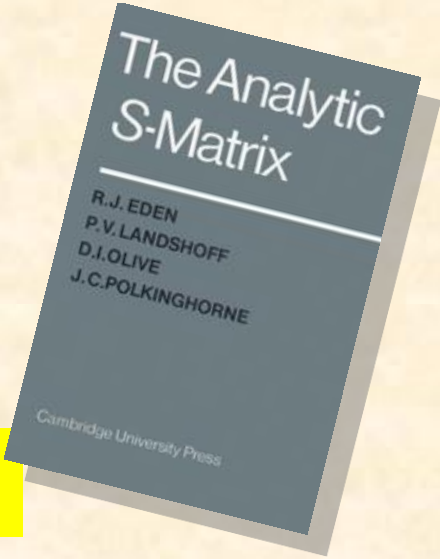
Outstanding theory issues



- Techniques of **Amplitude Analysis**
- **Understand reaction mechanisms**



Outstanding theory issues



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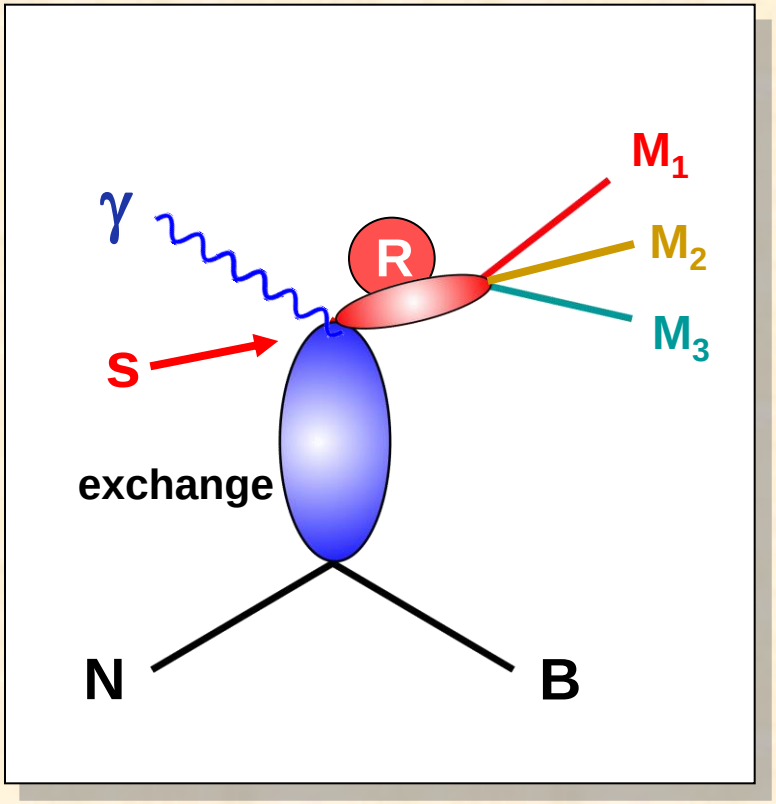
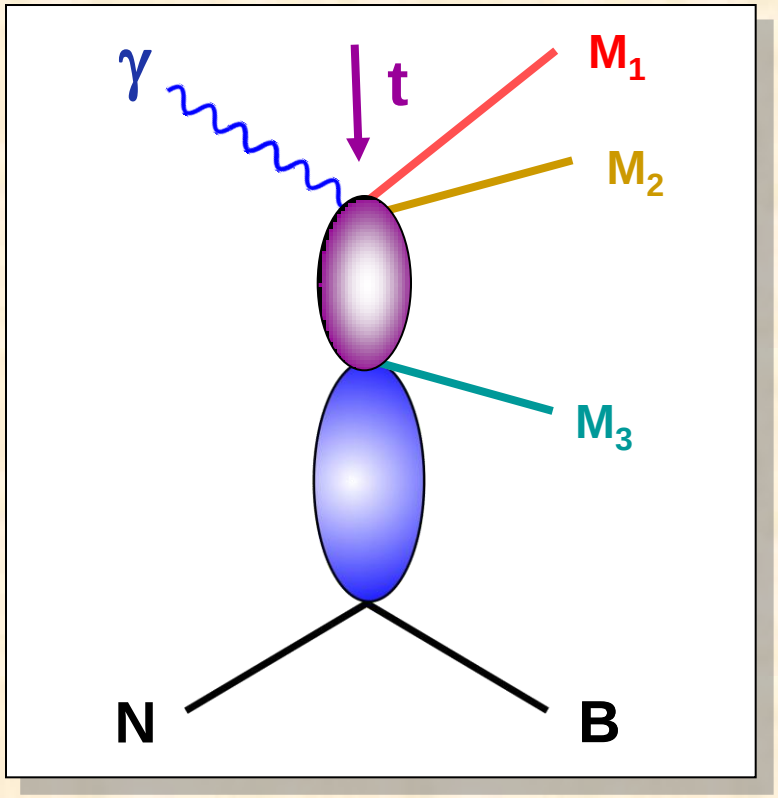
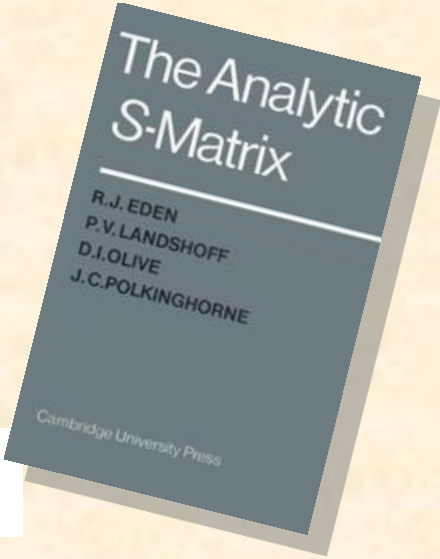
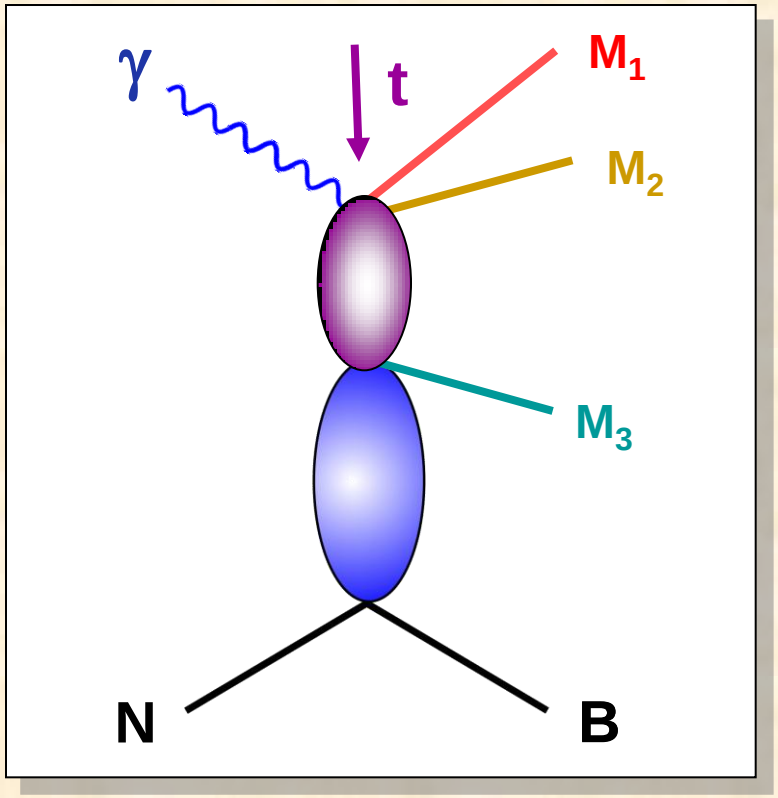




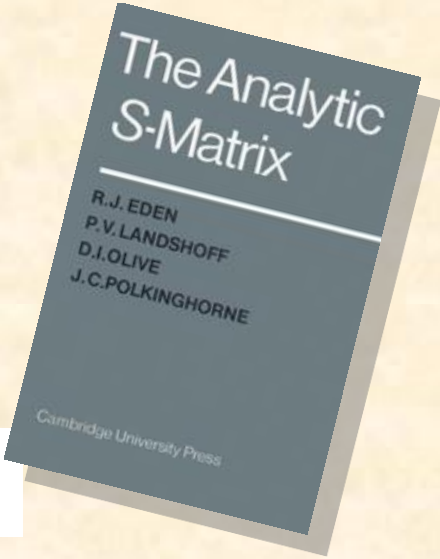
Outstanding theory issues



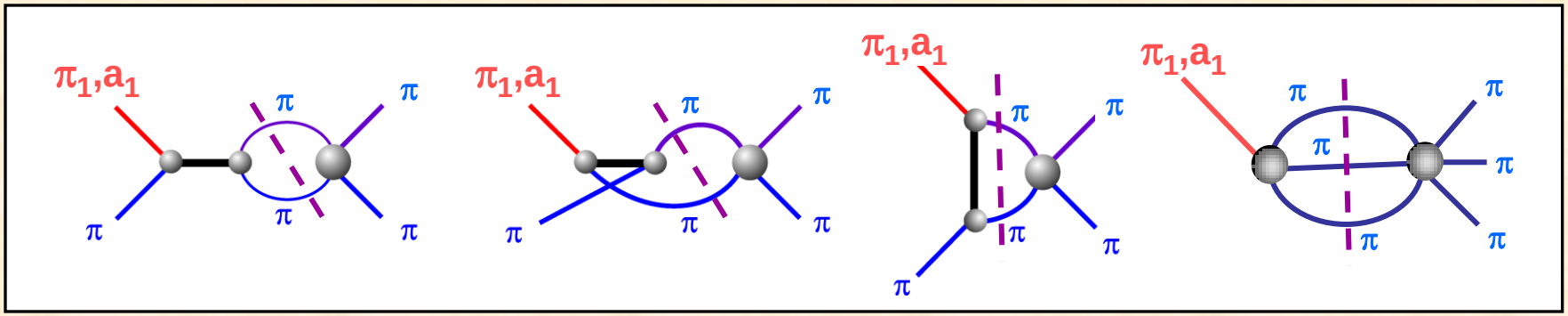
- Techniques of **Amplitude Analysis**
- Understand reaction mechanisms
- **Crossing:** eliminates partial wave truncation



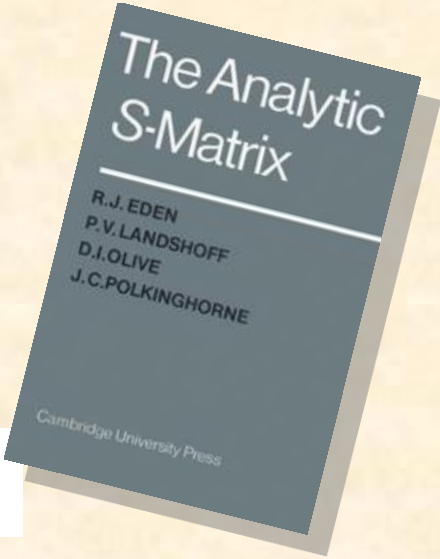
Outstanding theory issues



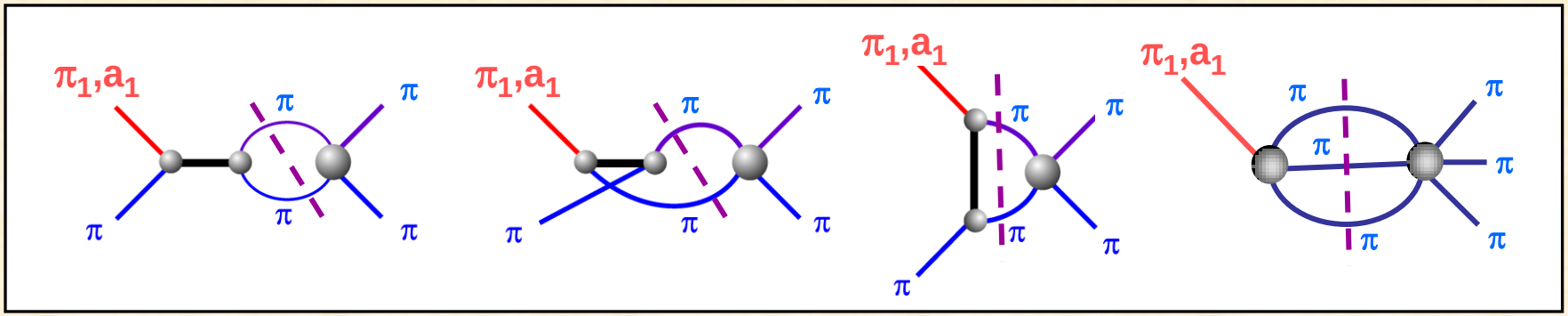
- Techniques of **Amplitude Analysis**
- Understand reaction mechanisms
- Unitarity and final state interactions

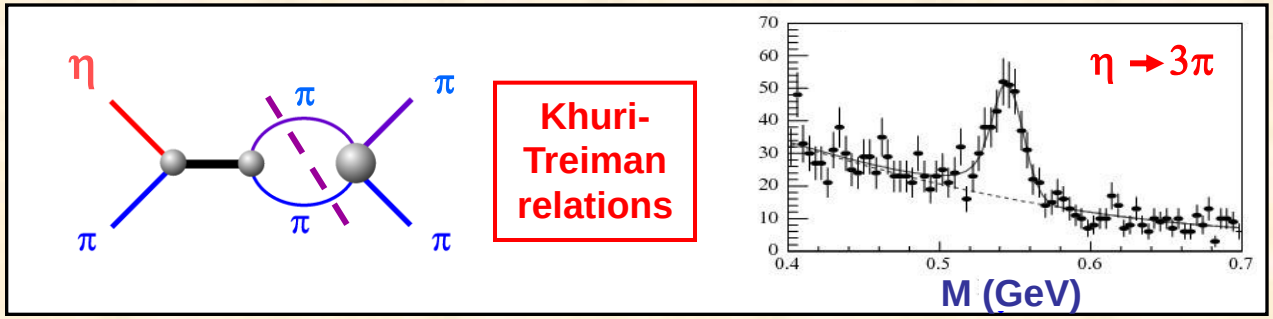


Outstanding theory issues

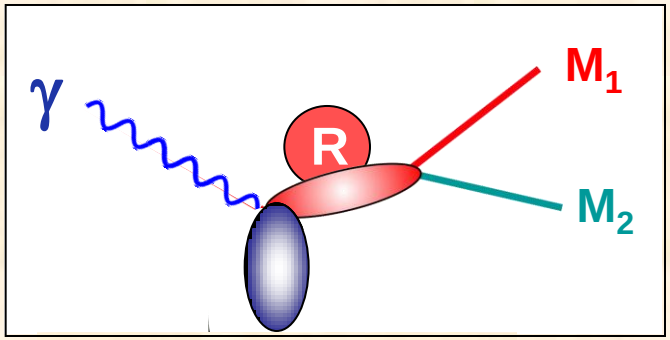


- **Techniques of Amplitude Analysis**
- **Understand reaction mechanisms**
- **Unitarity and final state interactions**



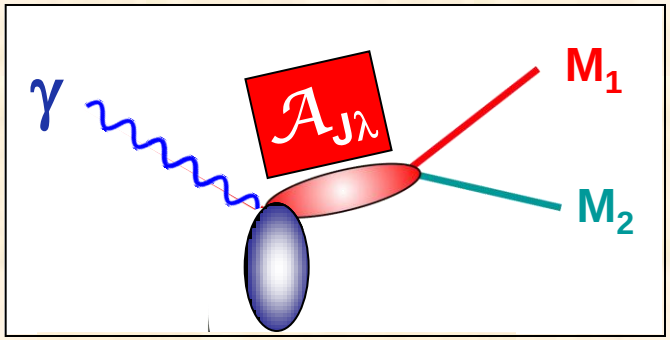


Model Analyses



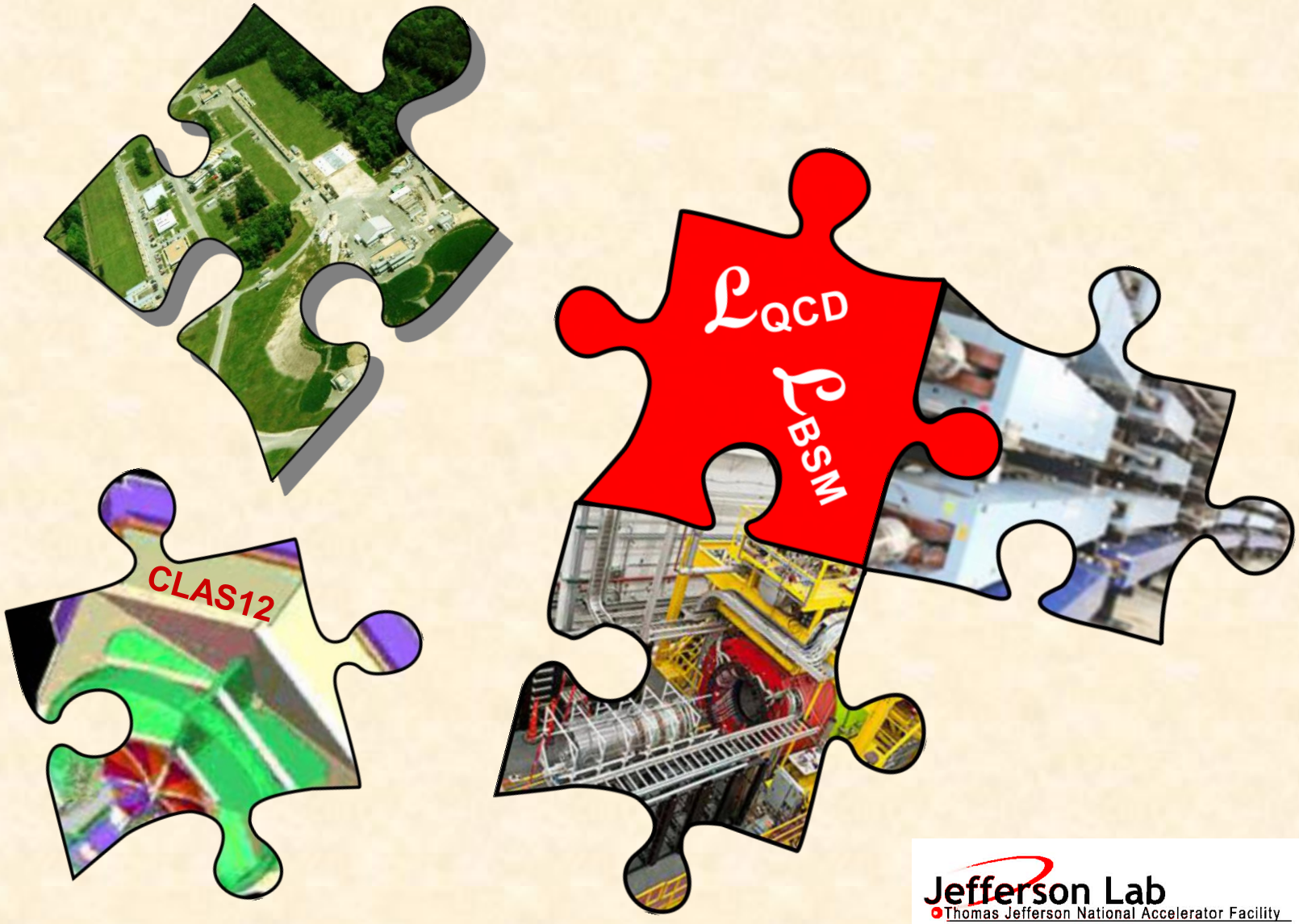
- **Isobar Model**

Model-independent Analyses



- **Beyond the Isobar**

JLab Physics Analysis Center program

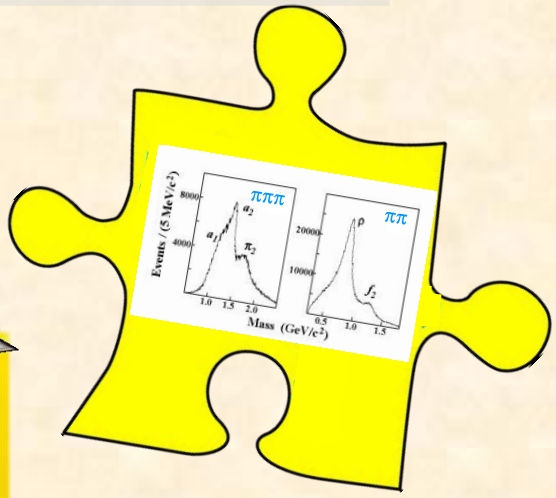


Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

JLab Physics Analysis Center program

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON DC

INDIANA UNIVERSITY
BLOOMINGTON



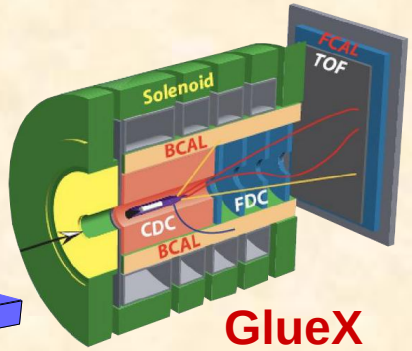
TECHNISCHE UNIVERSITÄT MÜNCHEN

INFN
Sezione di Genova

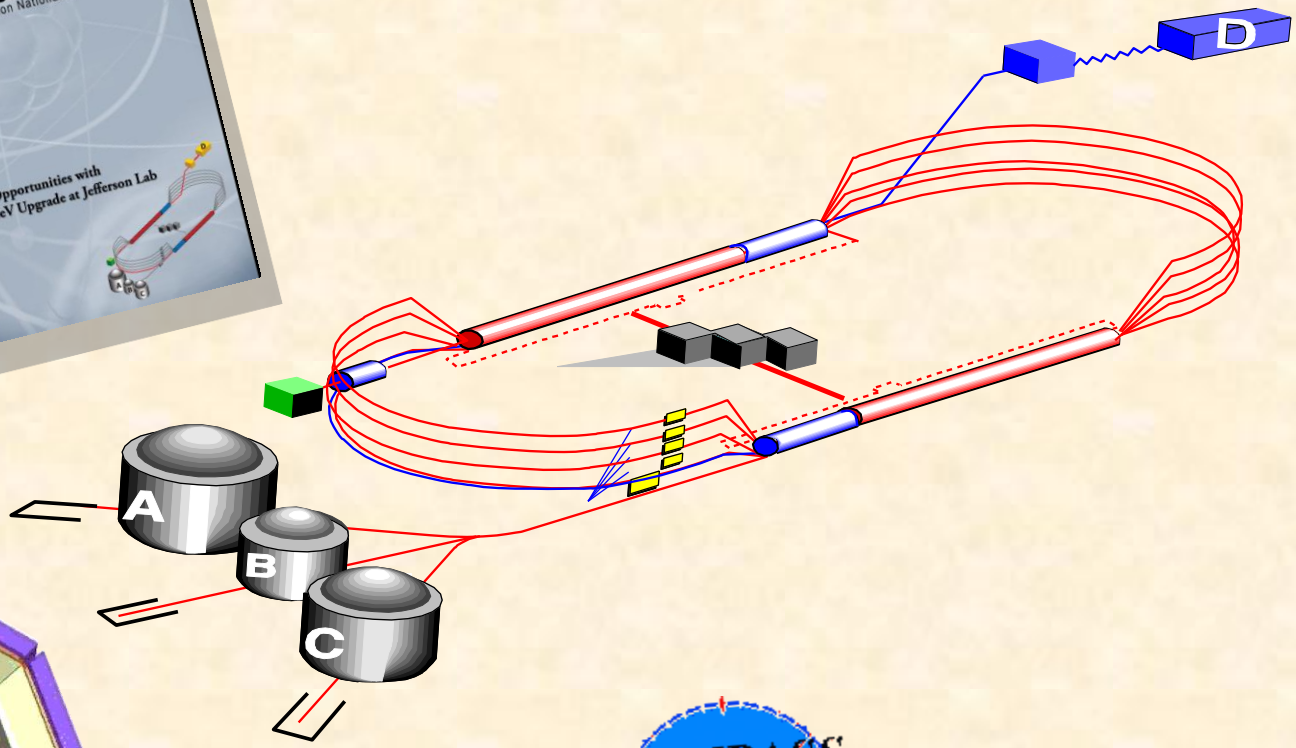
Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

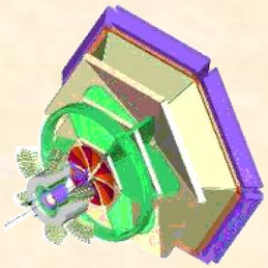
Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter



GlueX





CLAS12

PANDA @ GSI

COMPASS

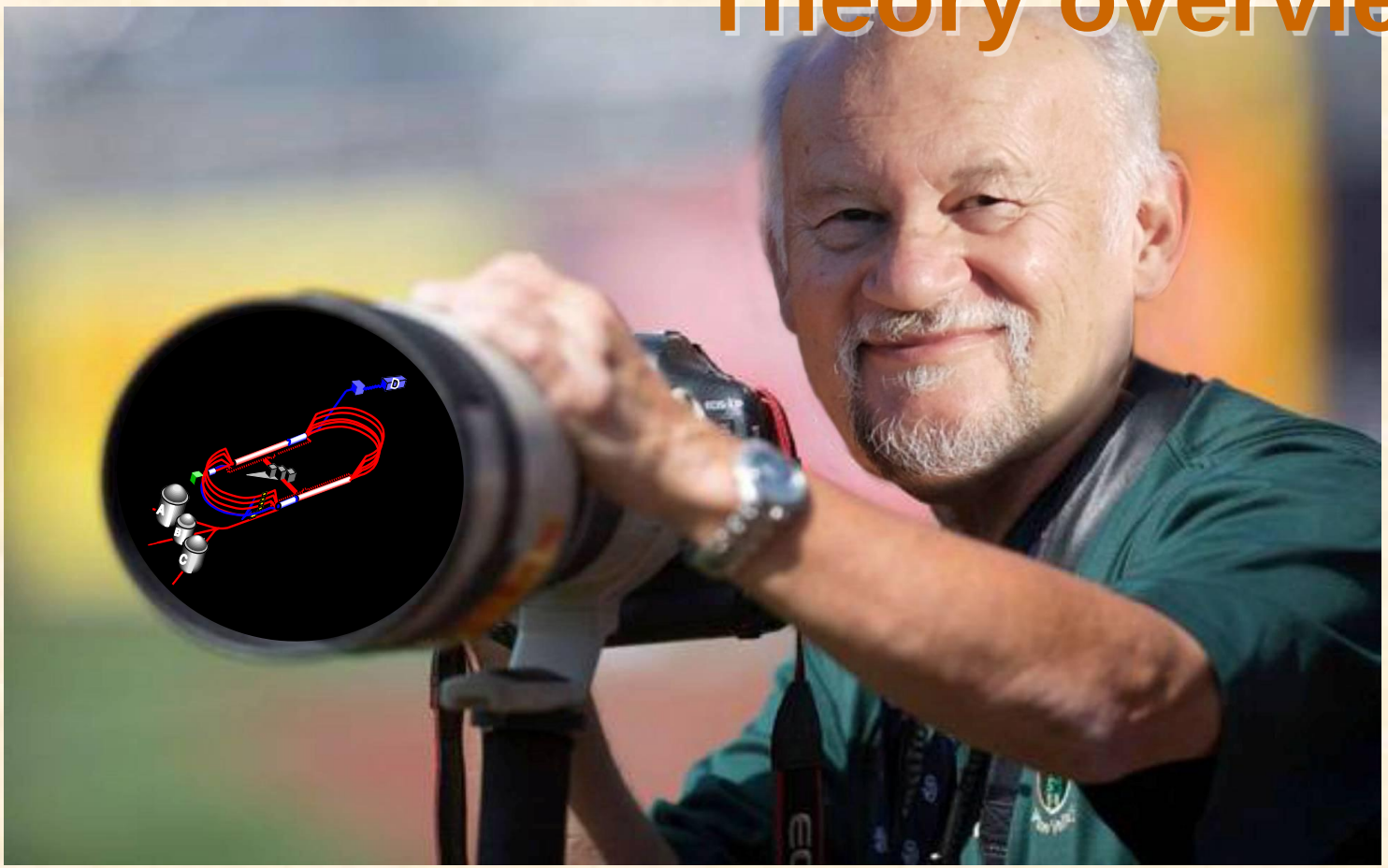
j-PARC

LHCb

BELLE

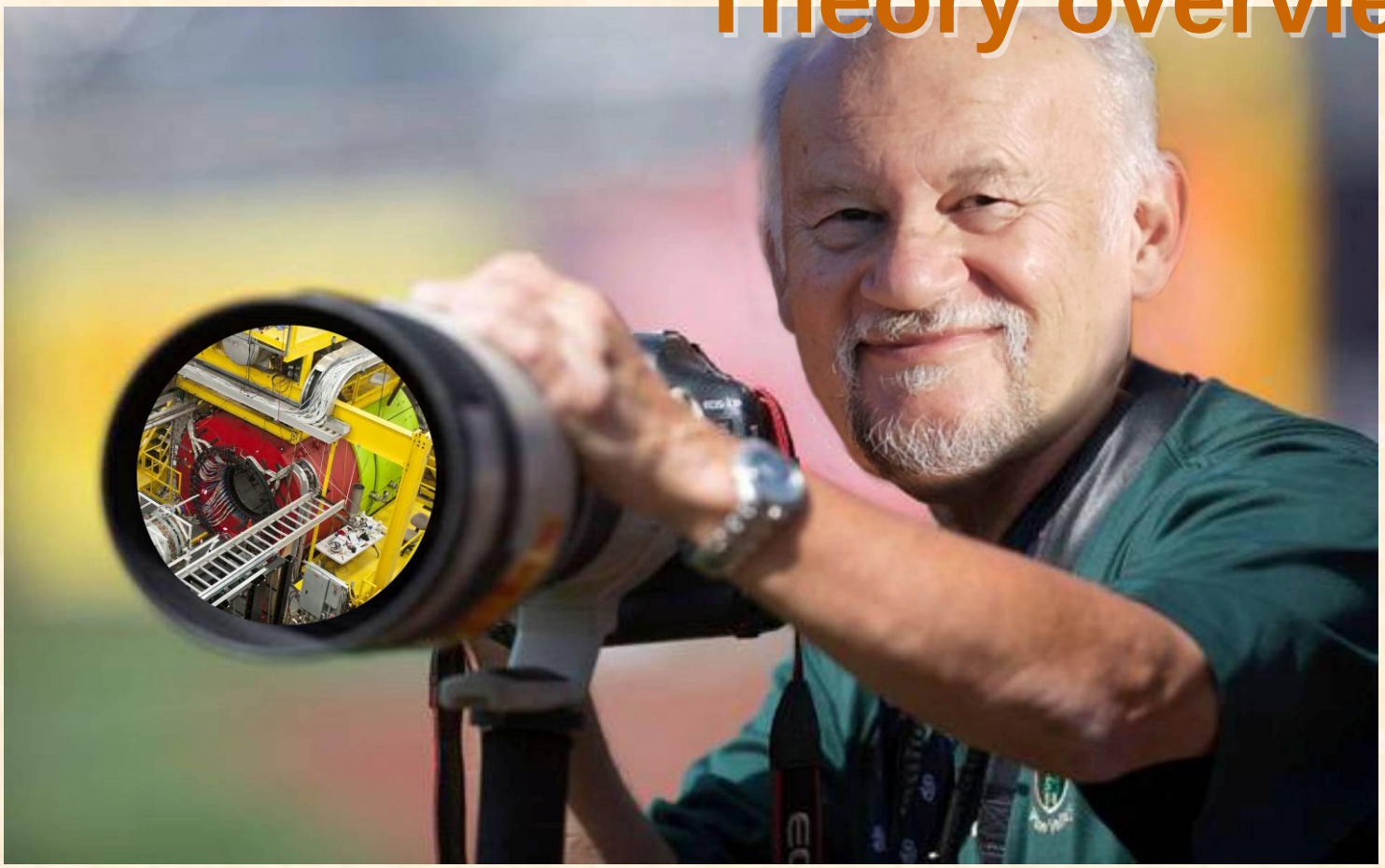
BESIII

QCD and the Meson Spectrum: Theory overview



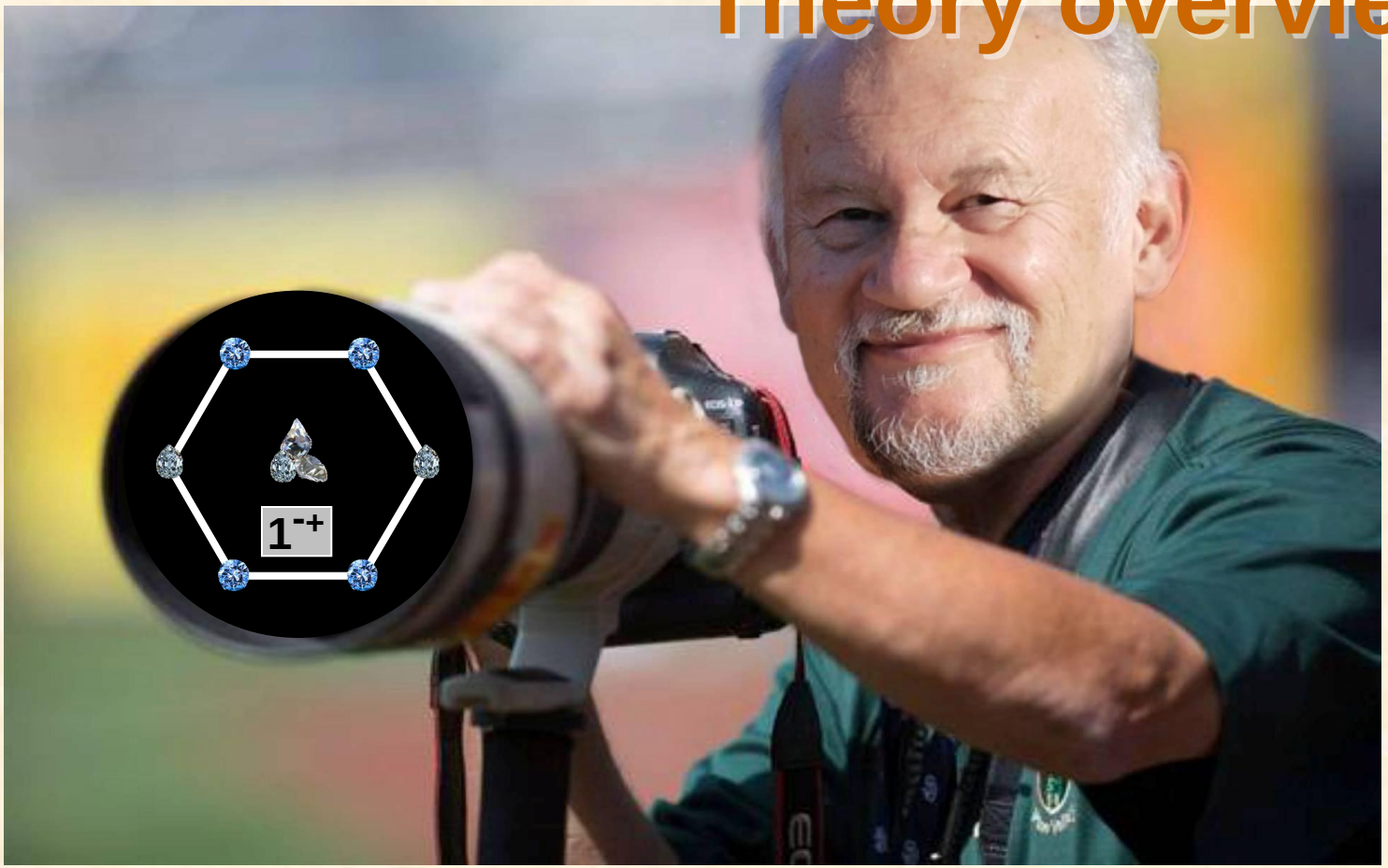
Full operation of 12 GeV CEBAF over a decade imperative

QCD and the Meson Spectrum: Theory overview



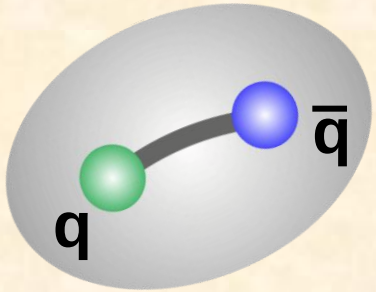
State-of-art detector upgrades essential

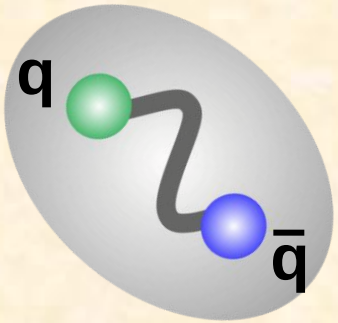
QCD and the Meson Spectrum: Theory overview

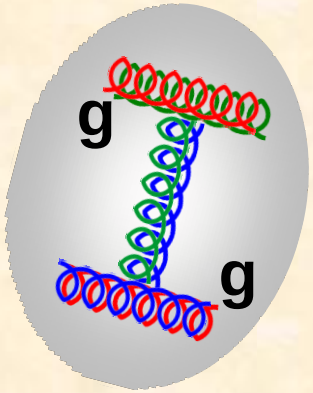


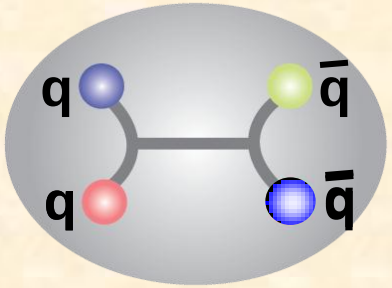
Definitive discovery of gluonic excitations only possible with commensurate theory effort

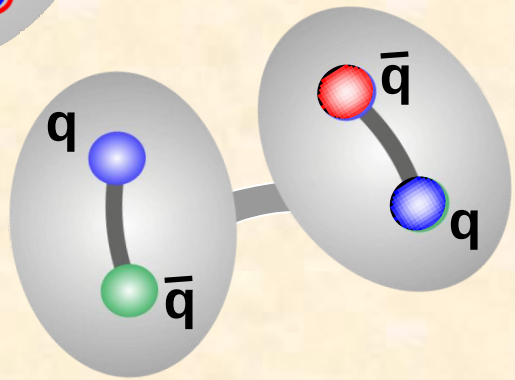
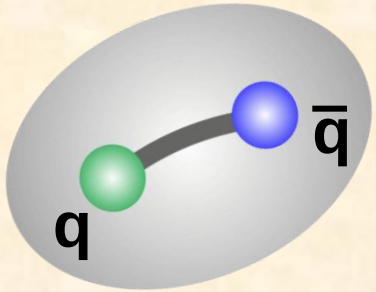
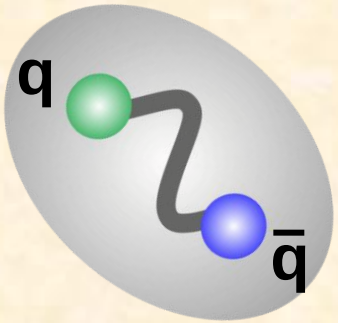
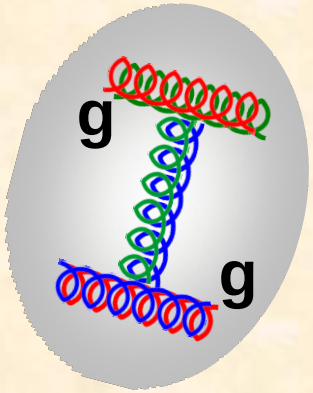
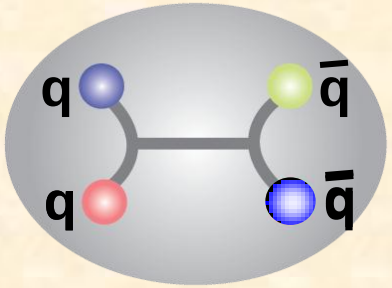
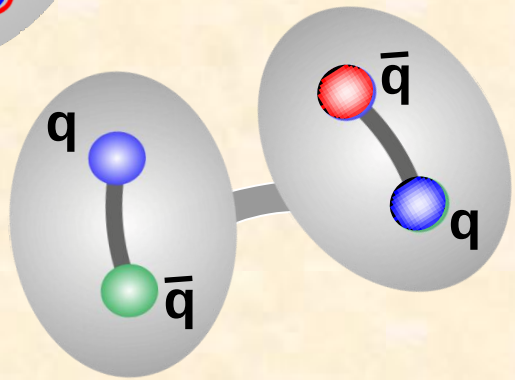
QCD











cool QCD