Hadrons, QCD and Confinement

Adam Szczepaniak
Indiana University
Jefferson Lab

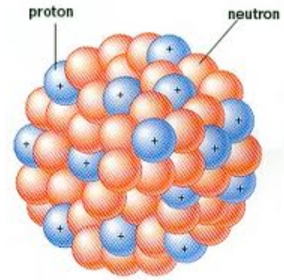
Hadrons as laboratory of strong QCD

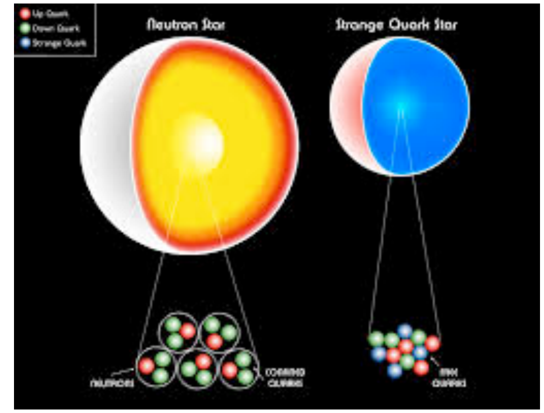
Expectations and phenomenology

Challenges and opportunities

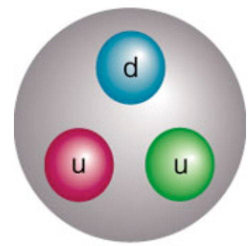
Why is QCD special ?

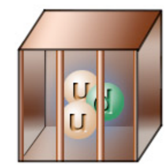
✓ A single theory is responsible for phenomena at distance scales of the order of 10^{-15}m as well as of the order 10^{4}m.



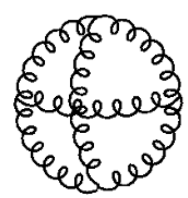


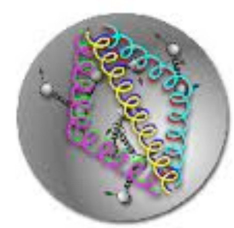
✓ It builds from objects (quarks and gluons) that do not exist in a common sense. >90% mass comes from interactions!

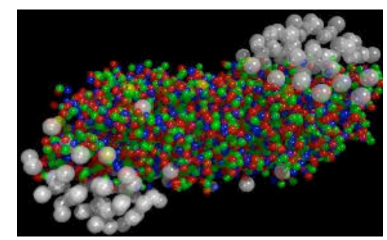




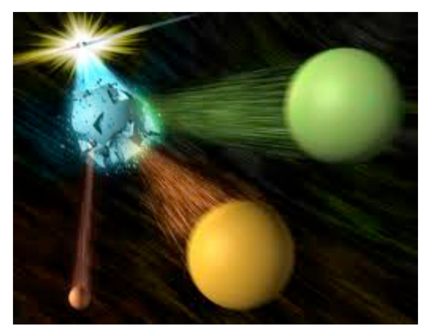
✓ Predicts existence of exotic matter, e.g. made from radiation (glueballs,hybrids) or novel plasmas.



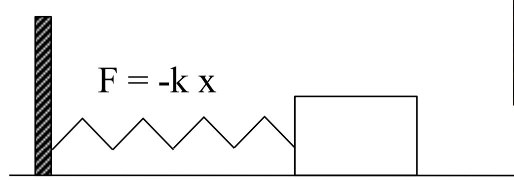




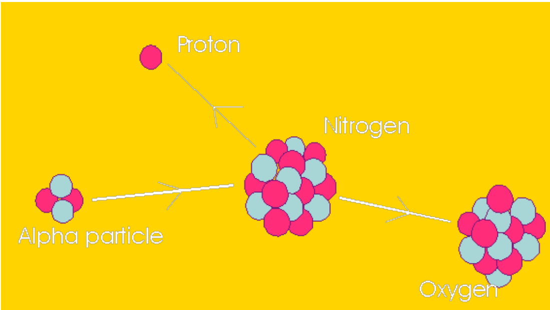
✓ A possible template for physics beyond the Standard Model



✓ It is challenging !



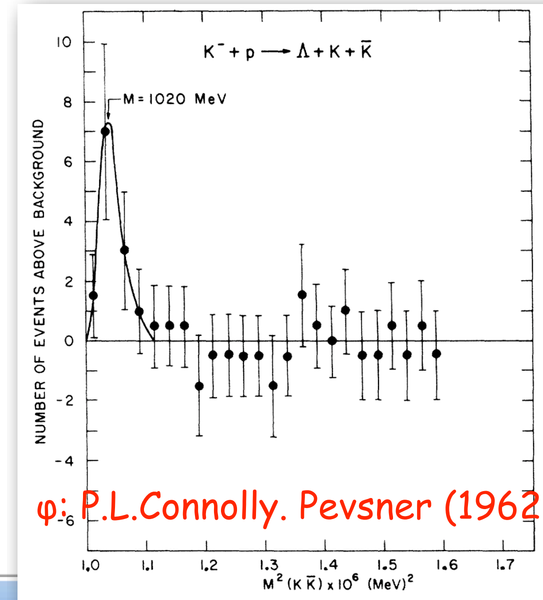
This talk is about Hadrons: strongly interacting particles

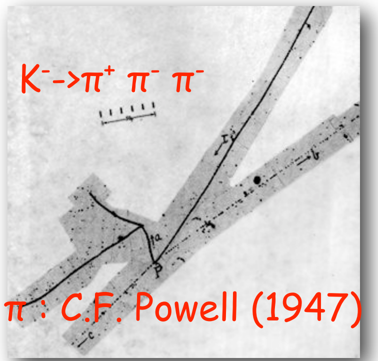


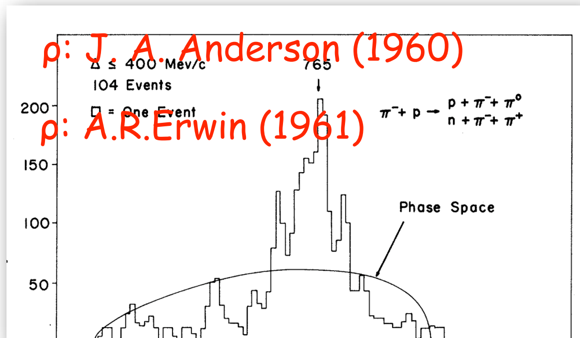
1909/1911 Rutherford/Geiger/Marsden discover the nucleus

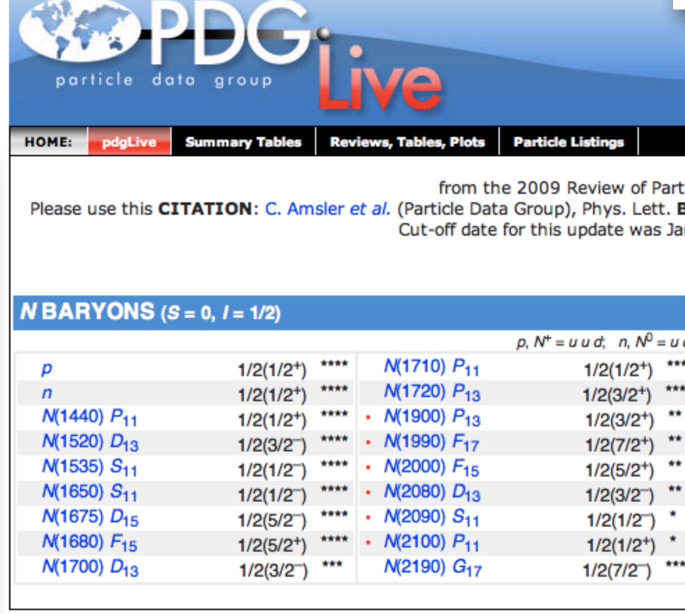
1919 Rutherford discovers the proton

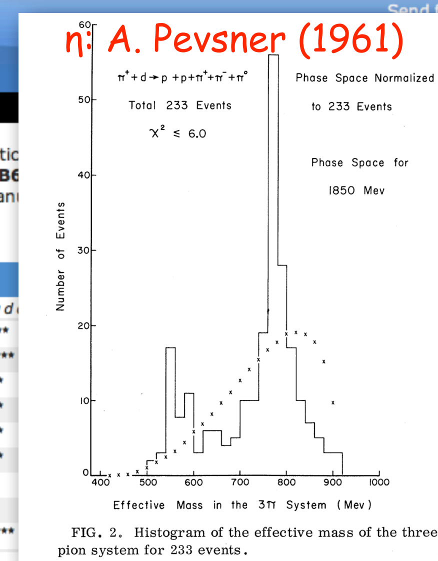
1932 Chadwick discovers the neutron

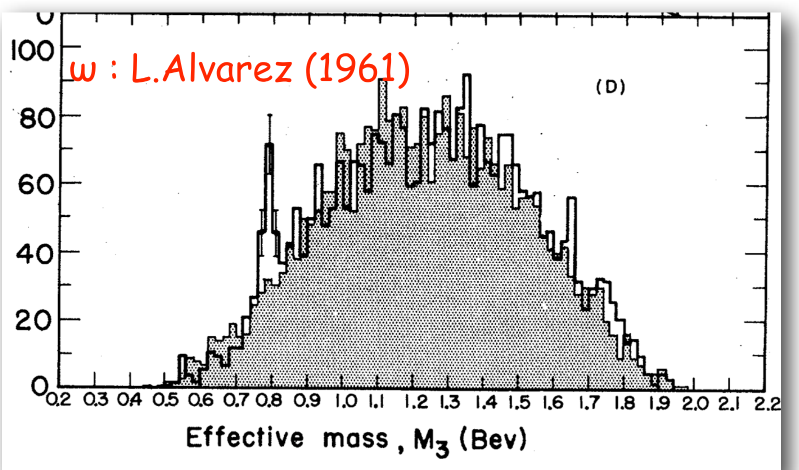


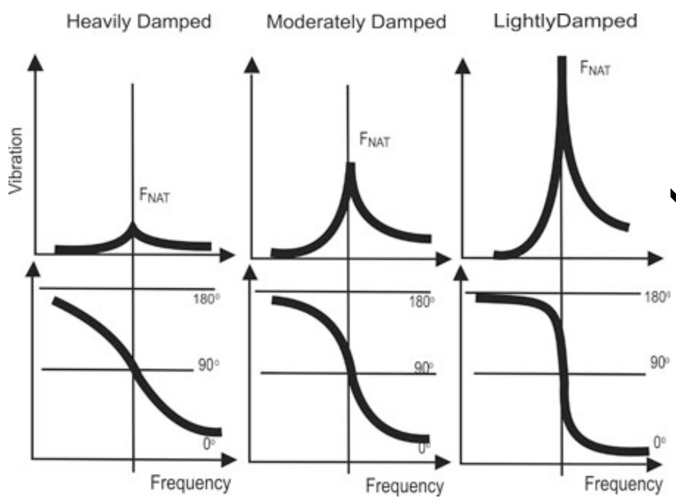






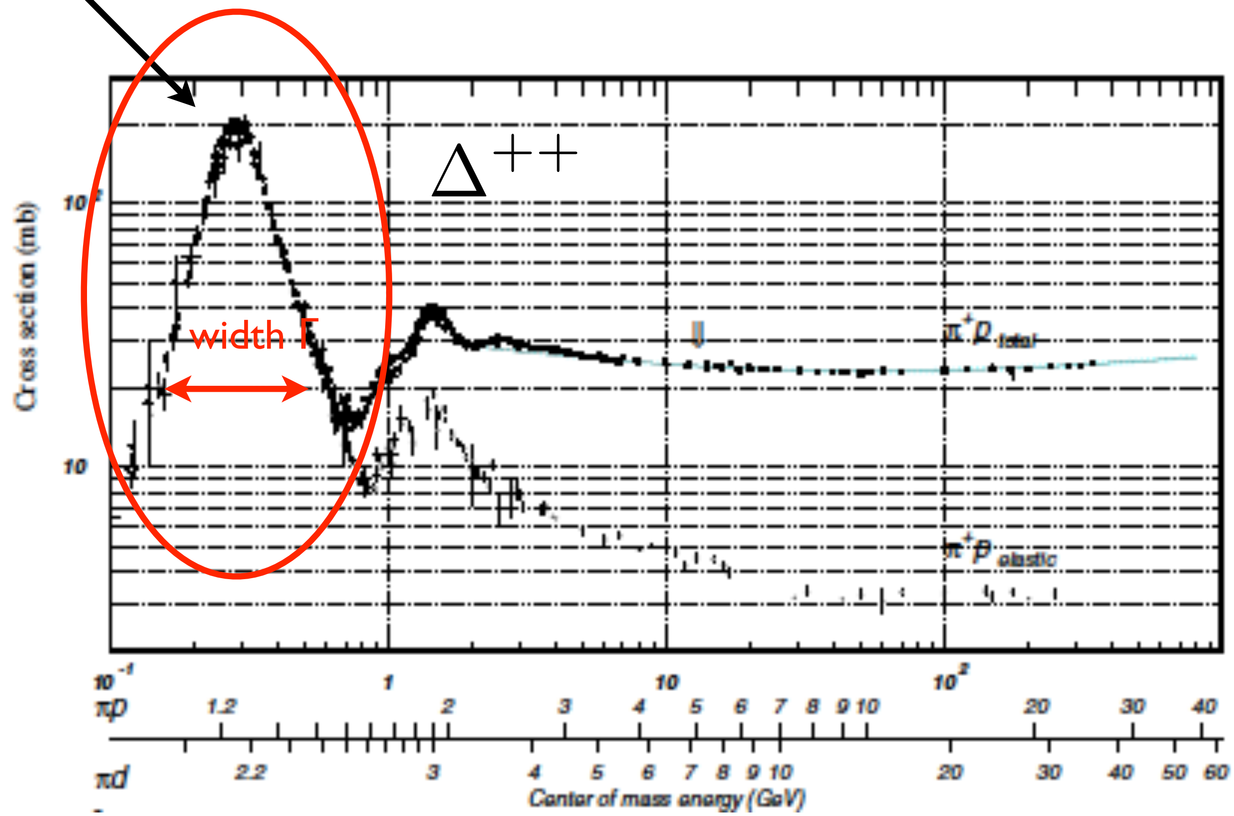






peak in intensity
(cross section)

In 1952, E. Fermi and collaborators measured the cross section for $\pi^+ p \to \pi^+ p$ and found it steeply raising.

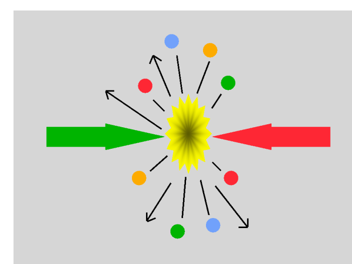


180⁰ phase change
in the amplitude

mass ~ 30% above proton

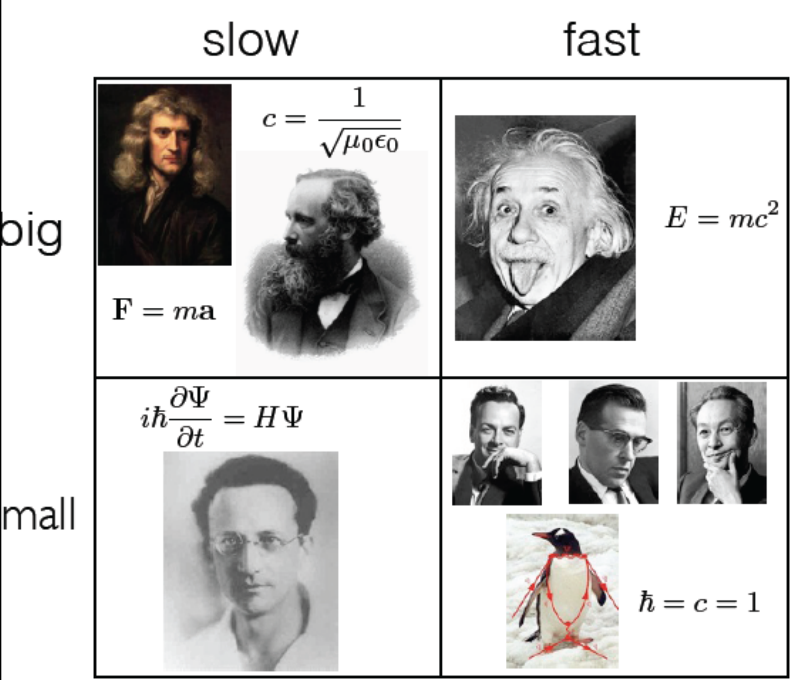
lifetime ~ 4.5 x 10^{-24} s

width ~ lifetime^{-1} = 150 MeV



It is difficult to “picture” what’s going on inside hadrons

we are lacking intuition about:



small world (10^{-15}m)

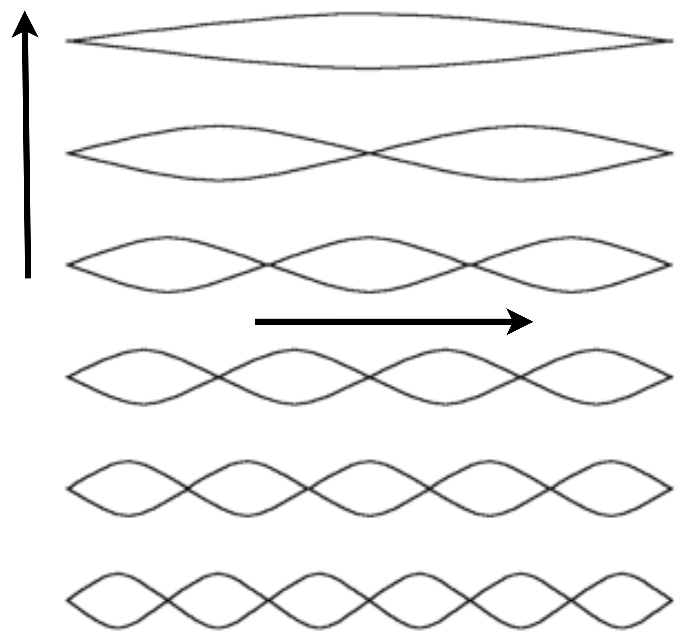
of fast (v~c) particles

exerting ~1T forces !!!

How to think about the constituents of hadrons: quarks and gluons?

In relativistic quantum mechanics (QFT) particles are emergent phenomena

“excitation of the ether” → field



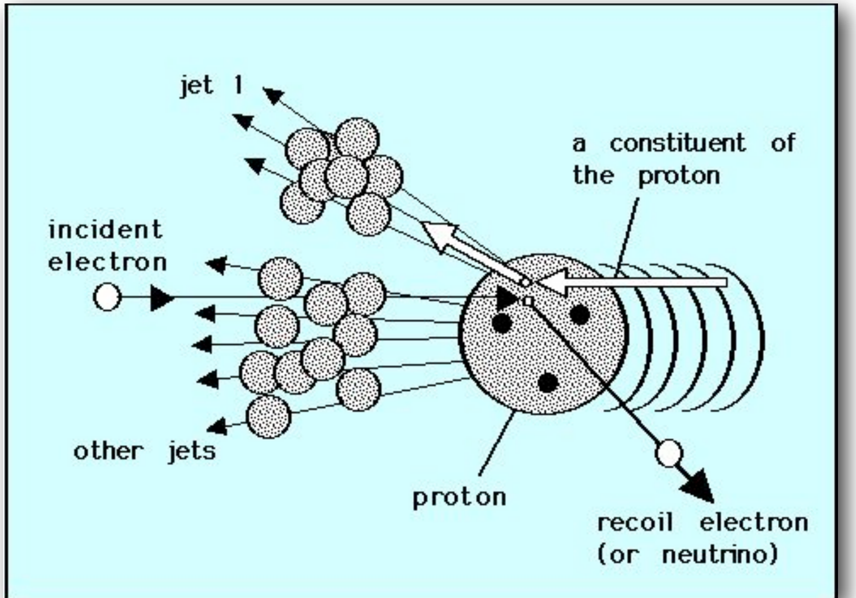
collective motion → particle

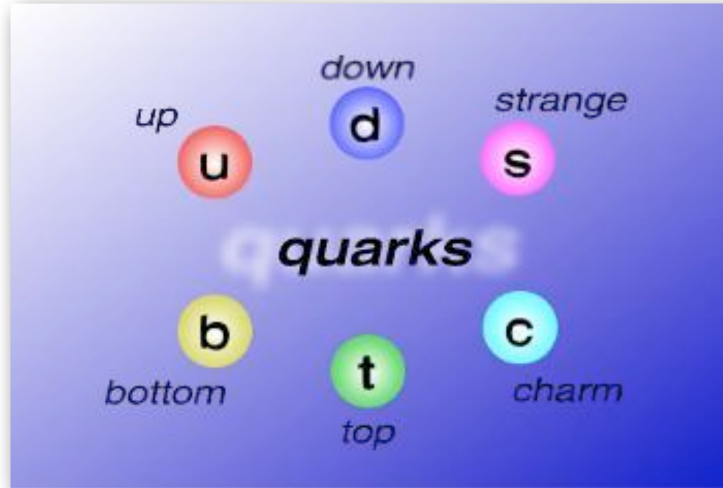
$H = H_{c.h.o} =$ coupled harmonic oscillators

“bare” particles : eigenstates of c.h.o.

“Bare (free)” particles of QCD: quarks and gluons

e.g. as seen in high energy collisions





x8 combinations

analogous to 8 (color) x 6 (flavor) copies of QED

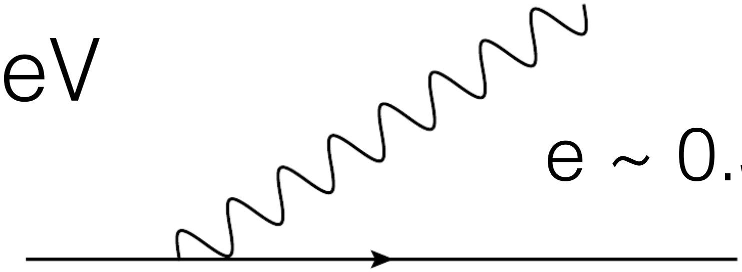
quark → electron

gluon → photon

If interactions are weak (e.g. QED) than "bare particle" ~ observed particle

$$H_{QED} = H_{c.h.o.} + eV$$

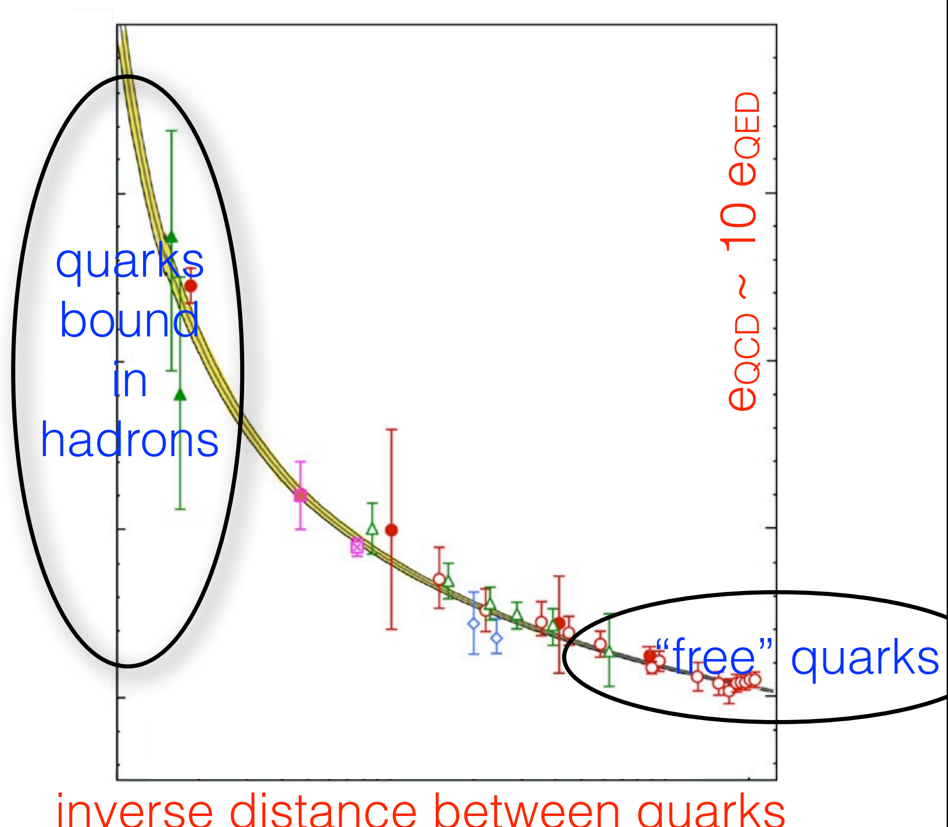
$e \sim 0.3$

|electron> =  +  + $O(e^2)$

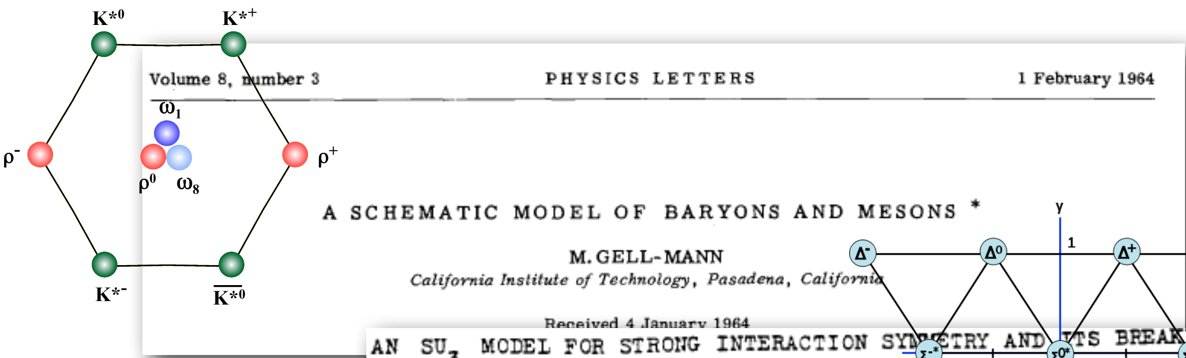
|bare electron> eV|bare electron>

but in QCD e > 1

the nature of physical quarks and gluons remains a mystery



old (but still surprisingly adequate) description of quarks in hadrons : quark model

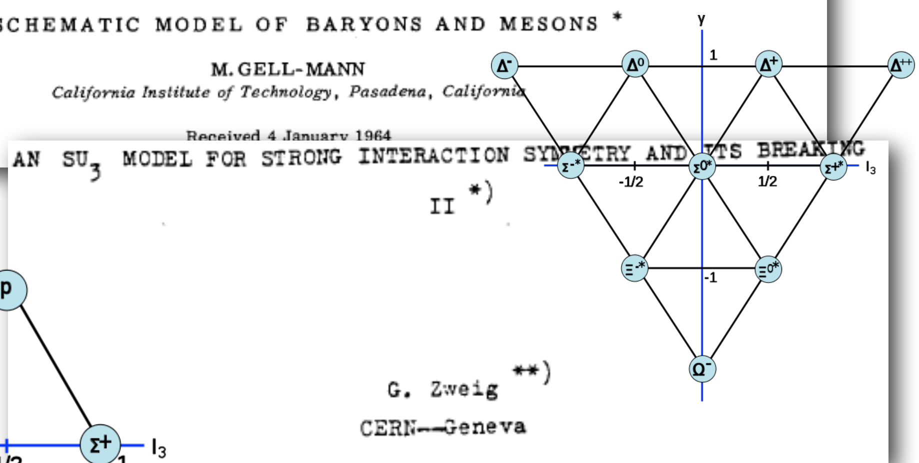


Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

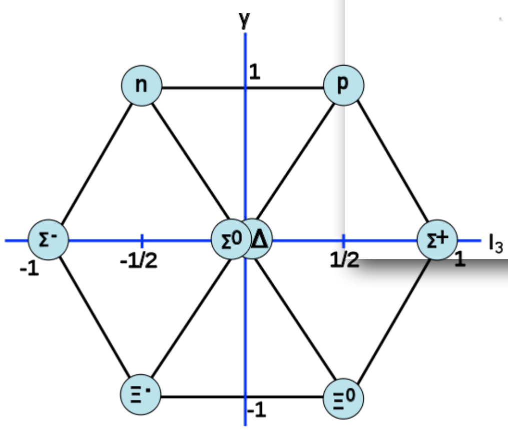
Received 4 January 1964

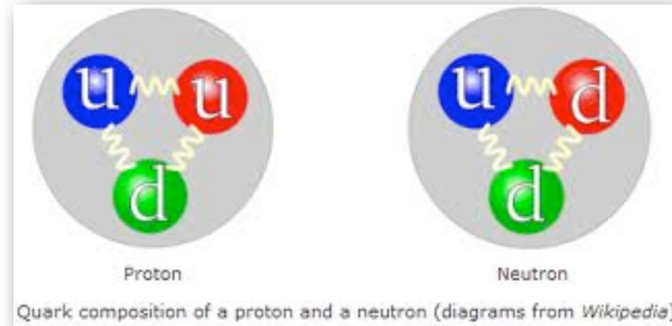


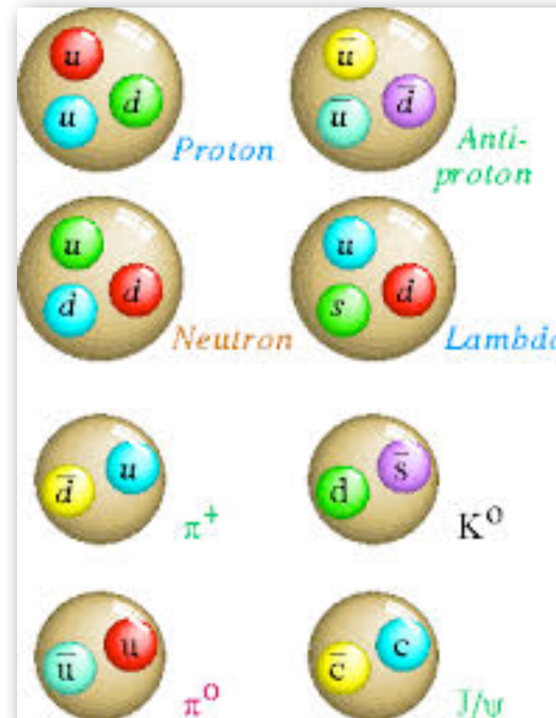
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig **)
CERN - Geneva







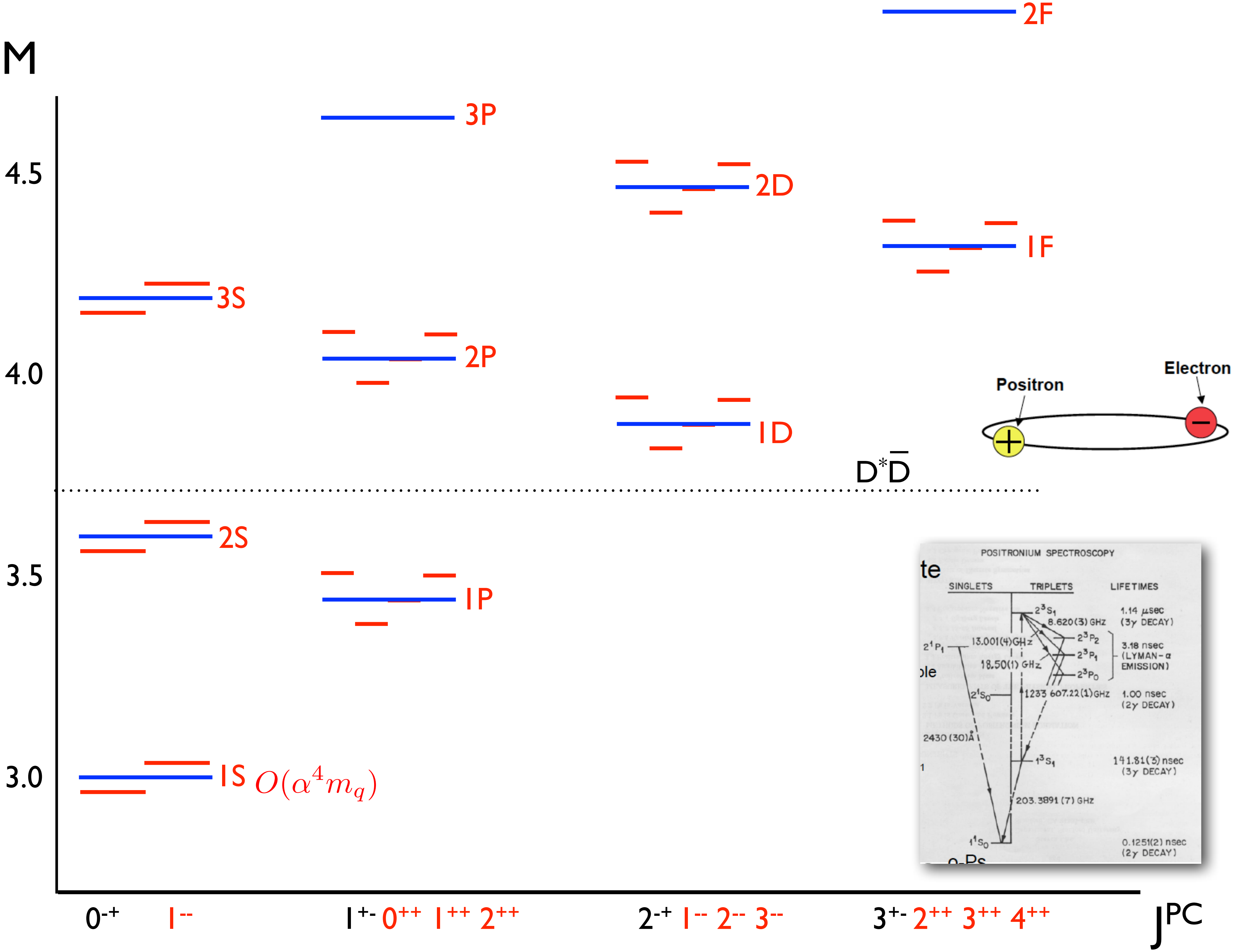
$c\bar{d} = D$

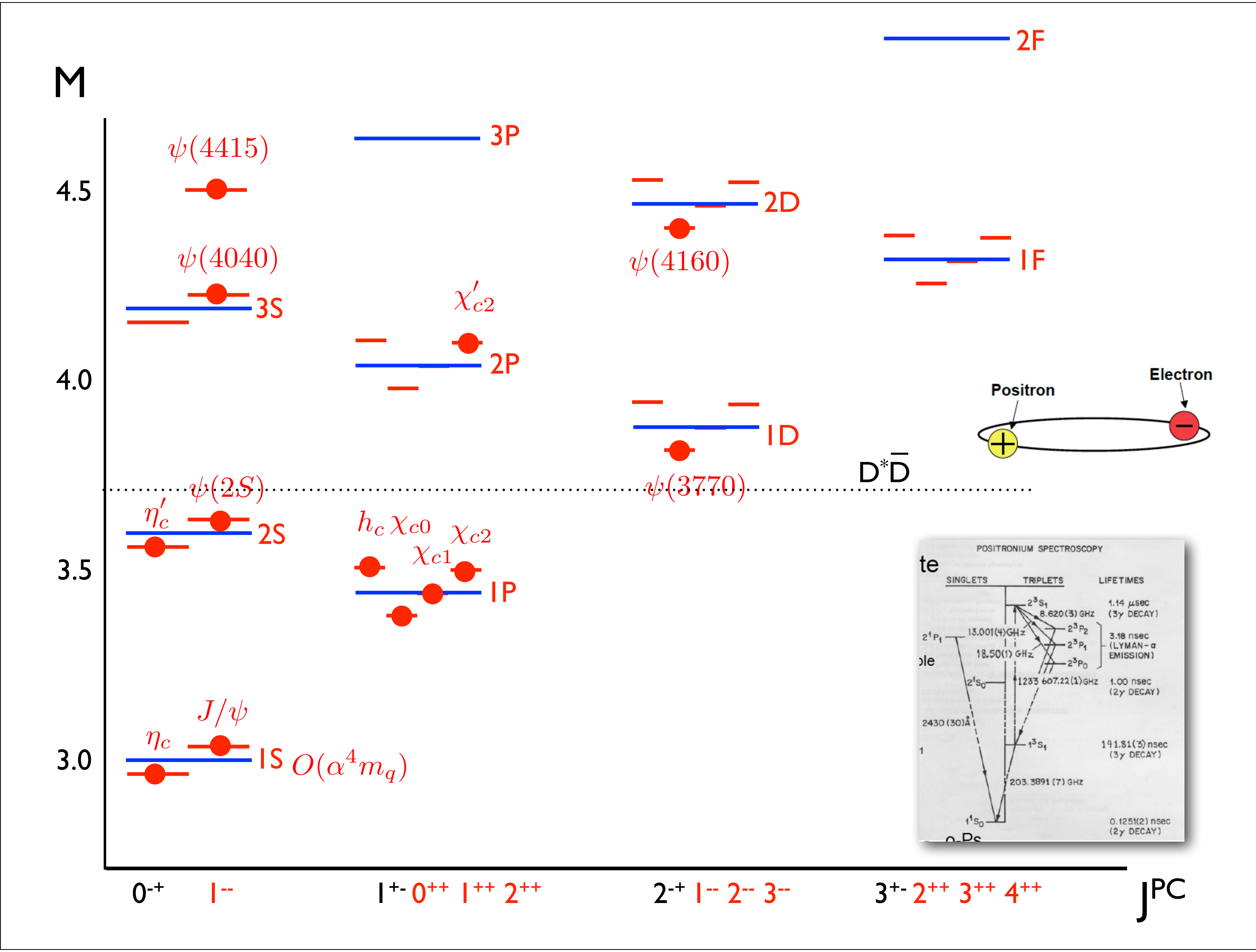
$c\bar{c} = J/\psi$

$u\bar{b} = B$

$b\bar{b} = \Upsilon$

physical quarks appear to move in a kind of "mean, gluonic field"


M
4.5
4.0
3.5
3.0
3P
2F
2D
1F
3S
2P
1D
Positron
Electron
$D^*\bar{D}$
2S
1P
1S $O(\alpha^4 m_q)$
POSITRONIUM SPECTROSCOPY
SINGLETS
TRIPLETS
LIFETIMES
2^3S_1
8.620(3) GHz
1.14 μsec (3γ DECAY)
13.001(4)GHz
2^3P_2
2^1P_1
2^3P_1
3.18 nsec (LYMAN-α EMISSION)
18.50(1) GHz
2^3P_0
2^1S_0
1233 607.22(1)GHz
1.00 nsec (2γ DECAY)
2430 (30)Å
1^3S_1
141.81(3) nsec (3γ DECAY)
203.3891 (7) GHz
1^1S_0
0.1251(2) nsec (2γ DECAY)
0^{-+} 1^{--}
1^{+-} 0^{++} 1^{++} 2^{++}
2^{-+} 1^{--} 2^{--} 3^{--}
3^{+-} 2^{++} 3^{++} 4^{++}
J^{PC}

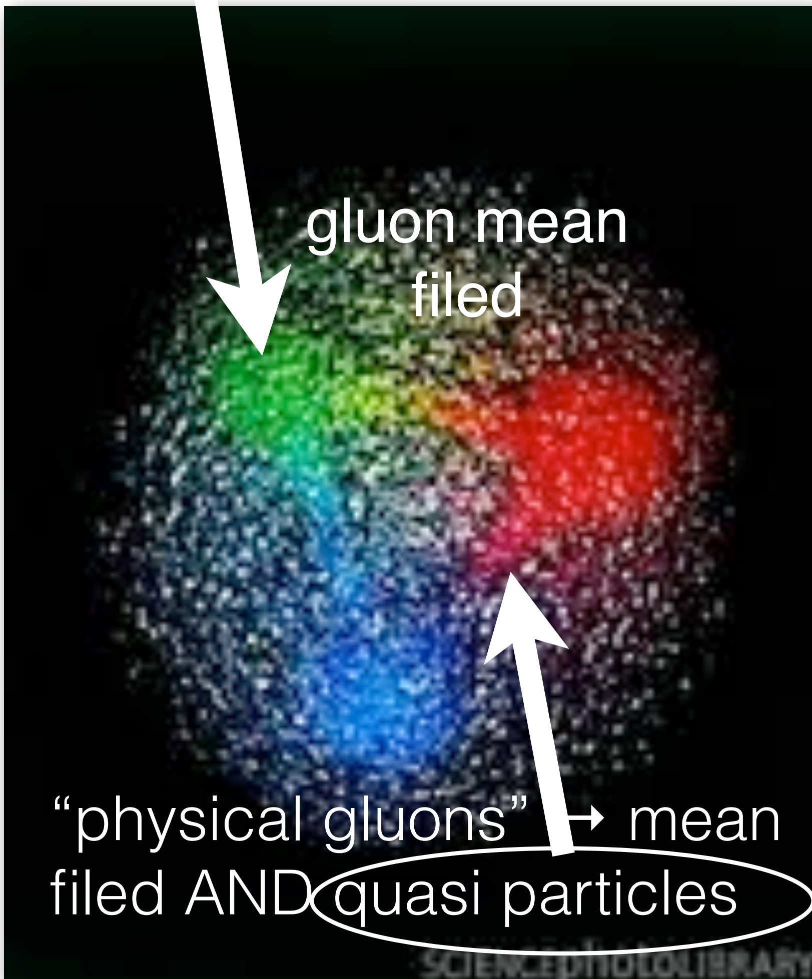


M
4.5
4.0
3.5
3.0
$\psi(4415)$
$\psi(4040)$
3S
$\psi(2S)$
η_c'
2S
J/ψ
η_c
1S $O(\alpha^4 m_q)$
3P
χ_{c2}'
2P
h_c χ_{c0}
χ_{c1}
χ_{c2}
1P
2D
$\psi(4160)$
1D
$\psi(3770)$
$D^*\bar{D}$
2F
1F
Positron
Electron
POSITRONIUM SPECTROSCOPY
SINGLETS
TRIPLETS
LIFETIMES
0^{-+} 1^{--}
1^{+-} 0^{++} 1^{++} 2^{++}
2^{-+} 1^{--} 2^{--} 3^{--}
3^{+-} 2^{++} 3^{++} 4^{++}
J^{PC}

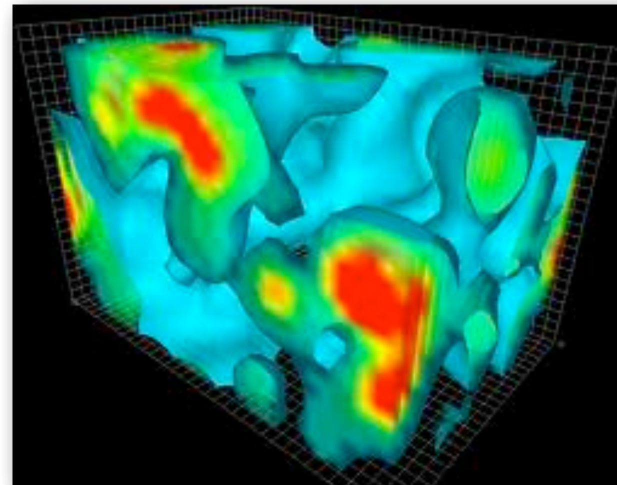
Plausible scenario: $H_{QCD} = H_{c.h.o.} +$ non-linear

finite energy, localized solutions:
solitons (monopoles, vortices , ...)

“physical quarks” →
quasi particles in gluon mean filed



The QCD vacuum is not empty. Rather it contains quantum fluctuations in the gluon field at all scales. (Image: University of Adelaide)



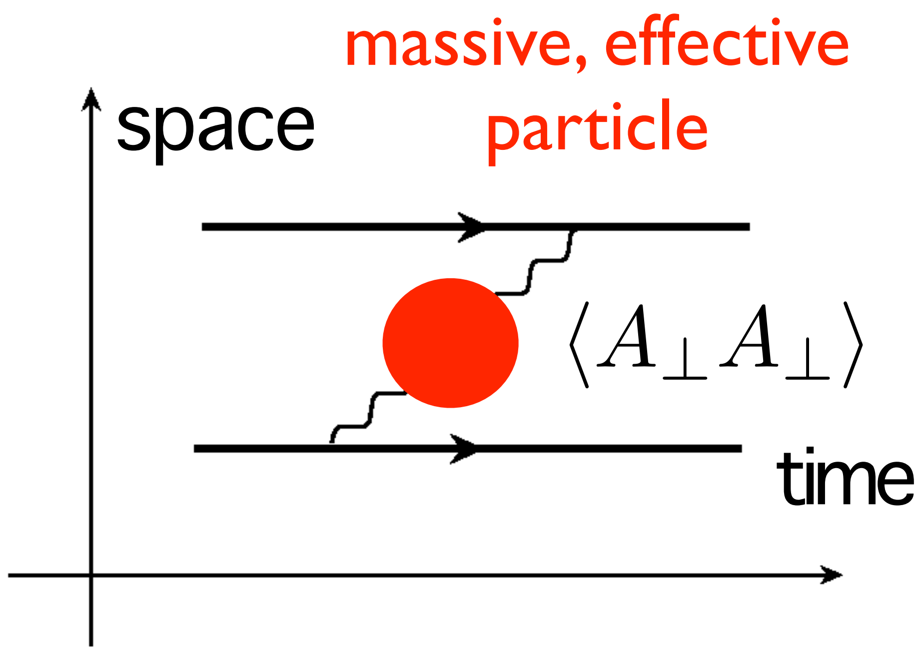
Monopoles have been long speculated to be candidate gluon filed configurations responsible for confinement

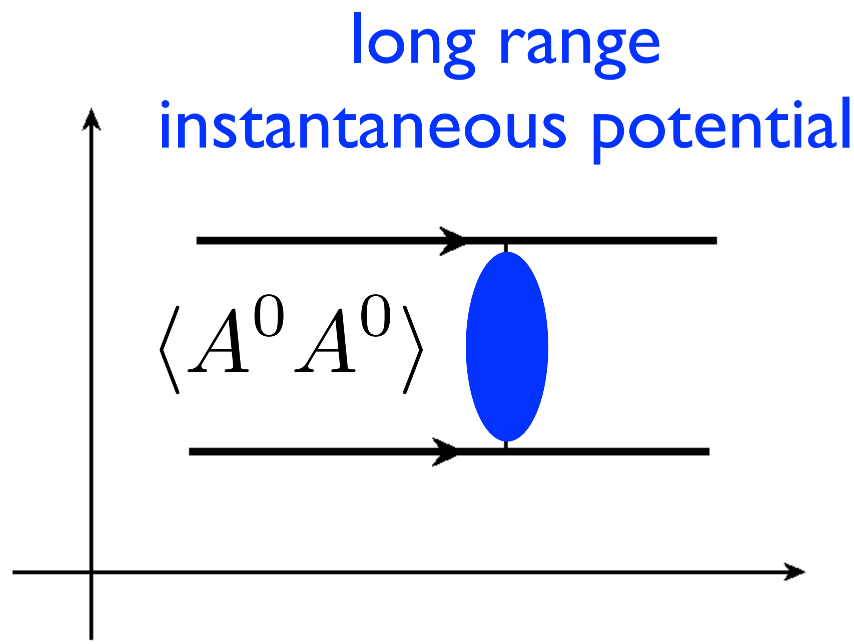
Dual role of gluons

(all gluons are equal but some are more equal than others)

provide confinement => monopole condensate

are confined => constituent gluons

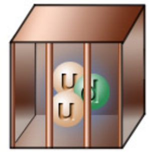




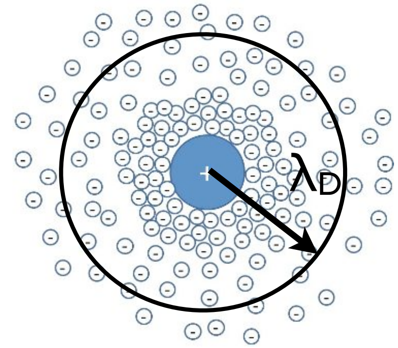
"constituent gluon" of large effective mass

confined potential between external sources emerges through interactions with chromo-magnetic condensate

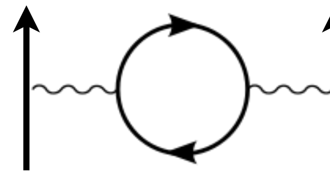
Confinement in QCD



e.g. absence of isolated quarks applies to both screening and confinement



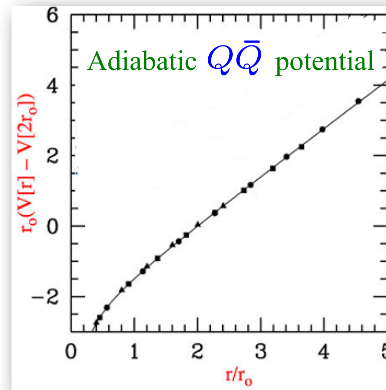
condensate (i.e. electrons in metal)



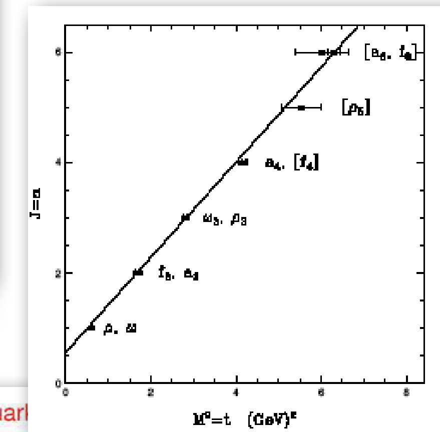
$$-\frac{e^2}{r} \rightarrow -\frac{e^2}{r}e^{-r/\lambda_D}$$

- absence of isolated quarks

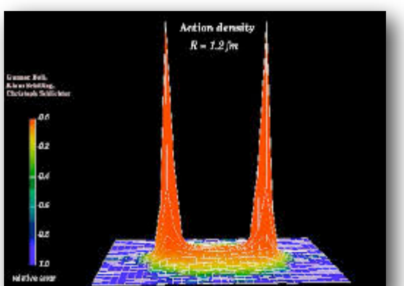
In absence of an order parameter we have to content with properties of confinement:

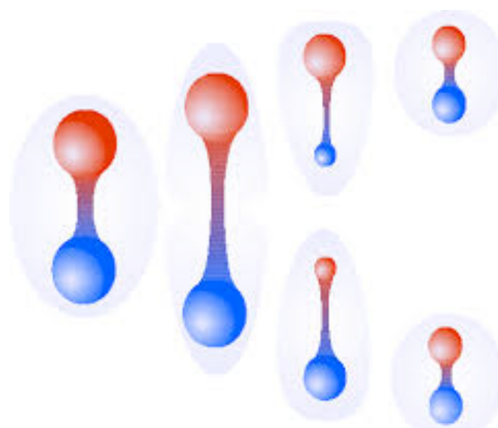


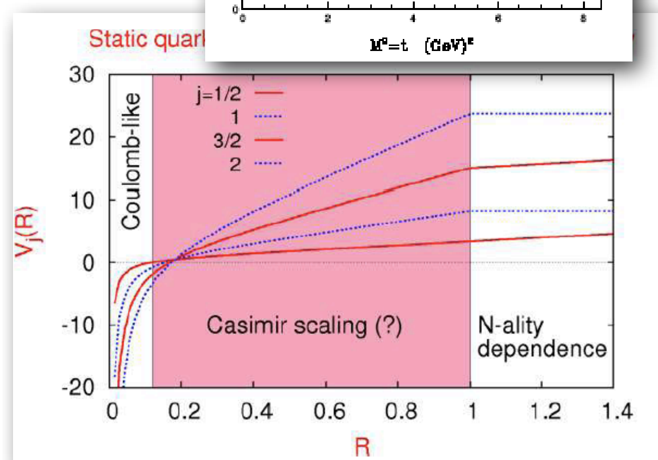
$r_0 = 0.5$ fm



- linearly rising potential
- Regge trajectories
- Casimir and N-ality scaling
- string behavior

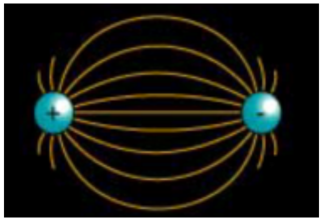






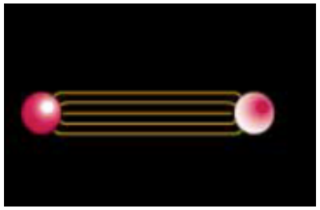
Monopole confinement scenario

in “empty vacuum”



Type-II supper conductor

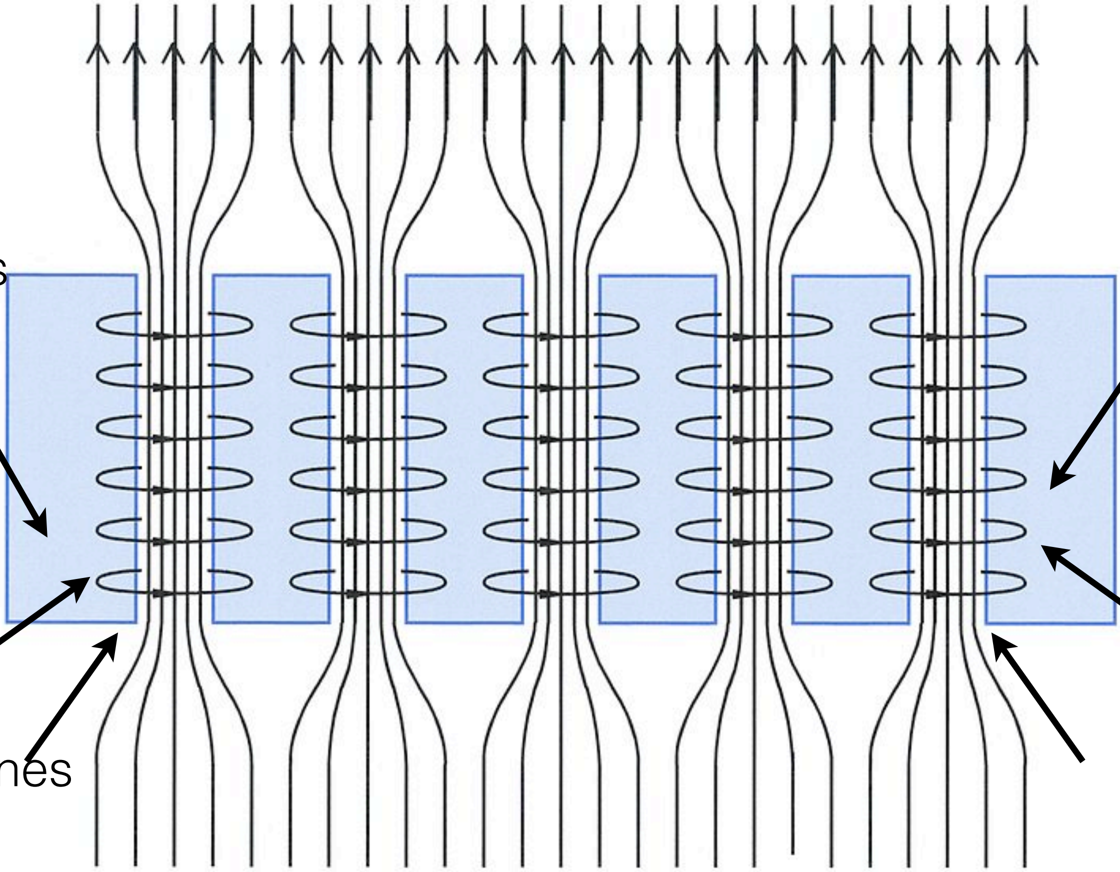
in “magnetic condensate”



Dual Type-II supper conductor

QED

QCD



condensate of electric charges

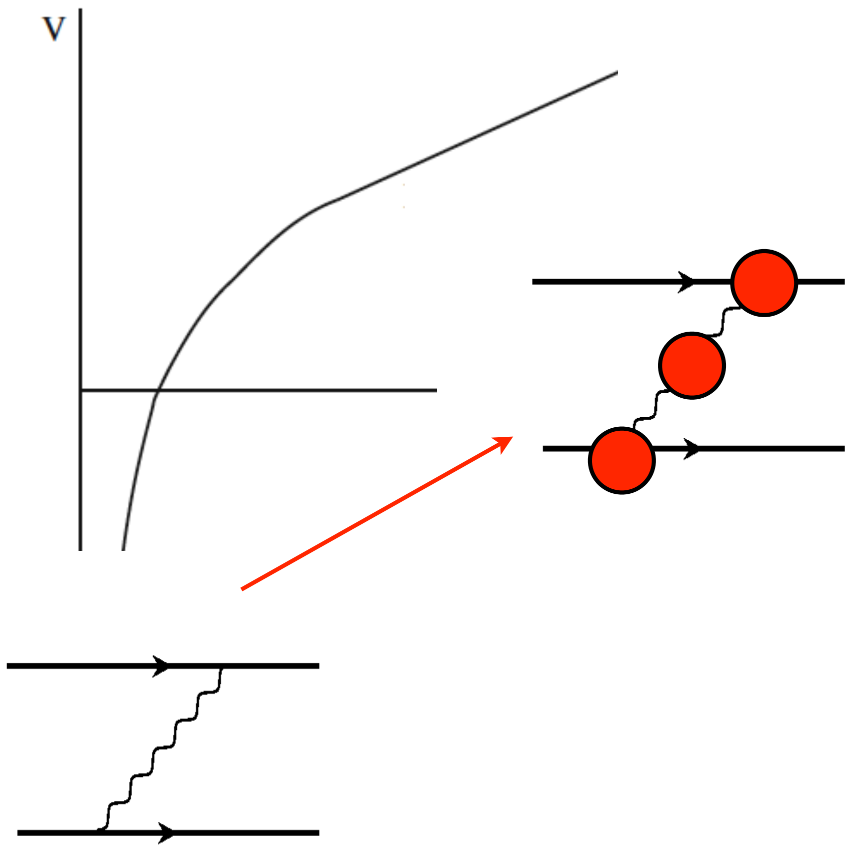
electric current screens magnetic lines

condensate of magnetic charges

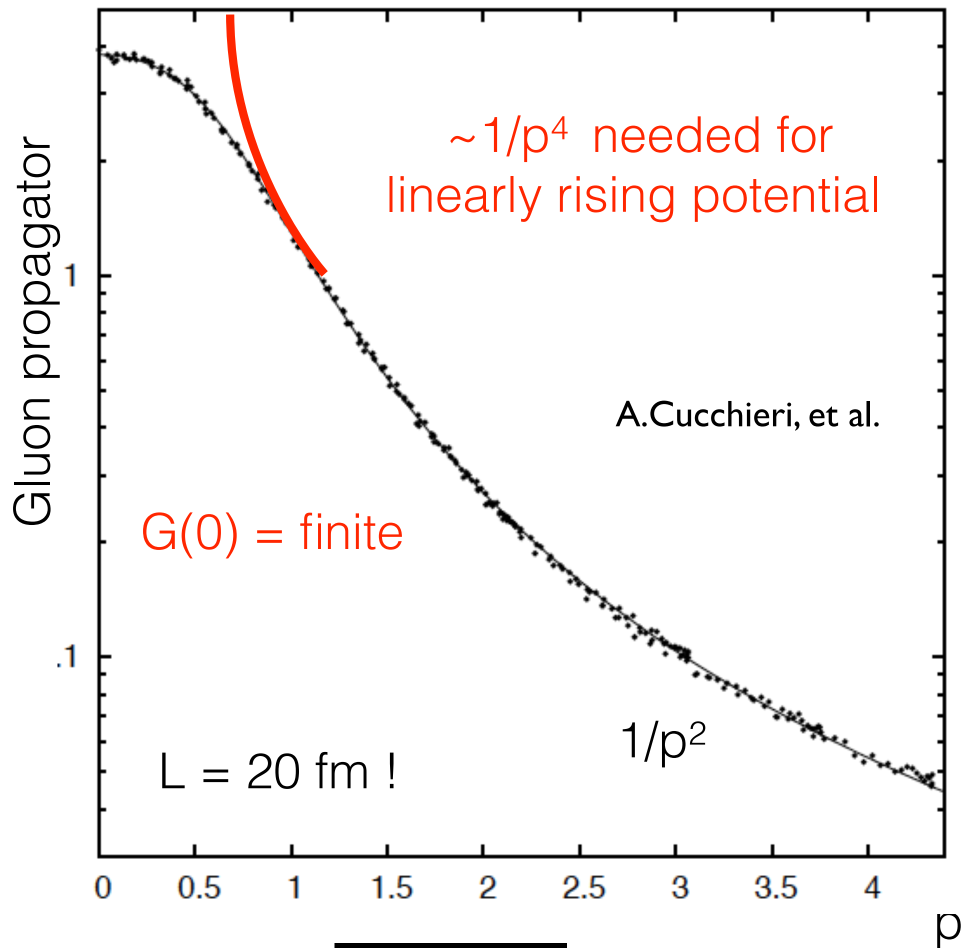
magnetic current screens electric lines

Early ideas about the origin of confinement

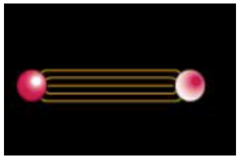
"One-gluon" exchange



Landau gauge
gluon propagator



Not compatible with current understanding (in terms of condensation of chromo-magnetic charges)



Spectroscopy of Hadrons can teach us about "workings" of QCD

1. Hadrons with gluon excitations (confinement)

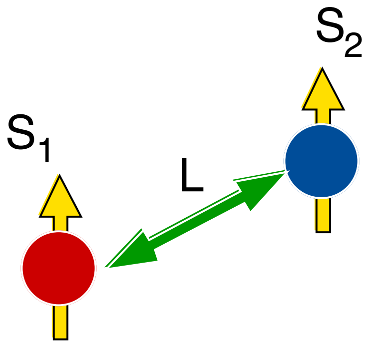
2. Hadron molecules (residual forces)

the rest of this talk

Theoretical expectations and phenomenological interpretations

Experimental Challenges and opportunities

focus on gluon's role



$S = S_1 + S_2$

$J = L + S$

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

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

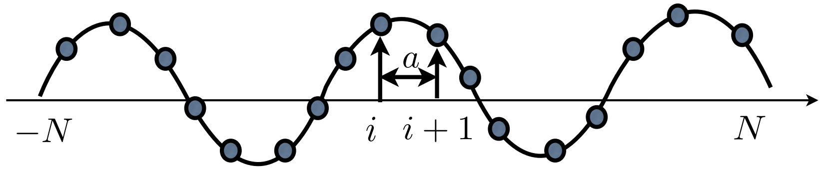
Determine J^{PC} through Partial Wave Analysis

Mesons with $J^{PC} = 0^{--}, 0^{+-}, \underline{1^{-+}}, 2^{+-}$: Exotic Quantum Numbers

π_1

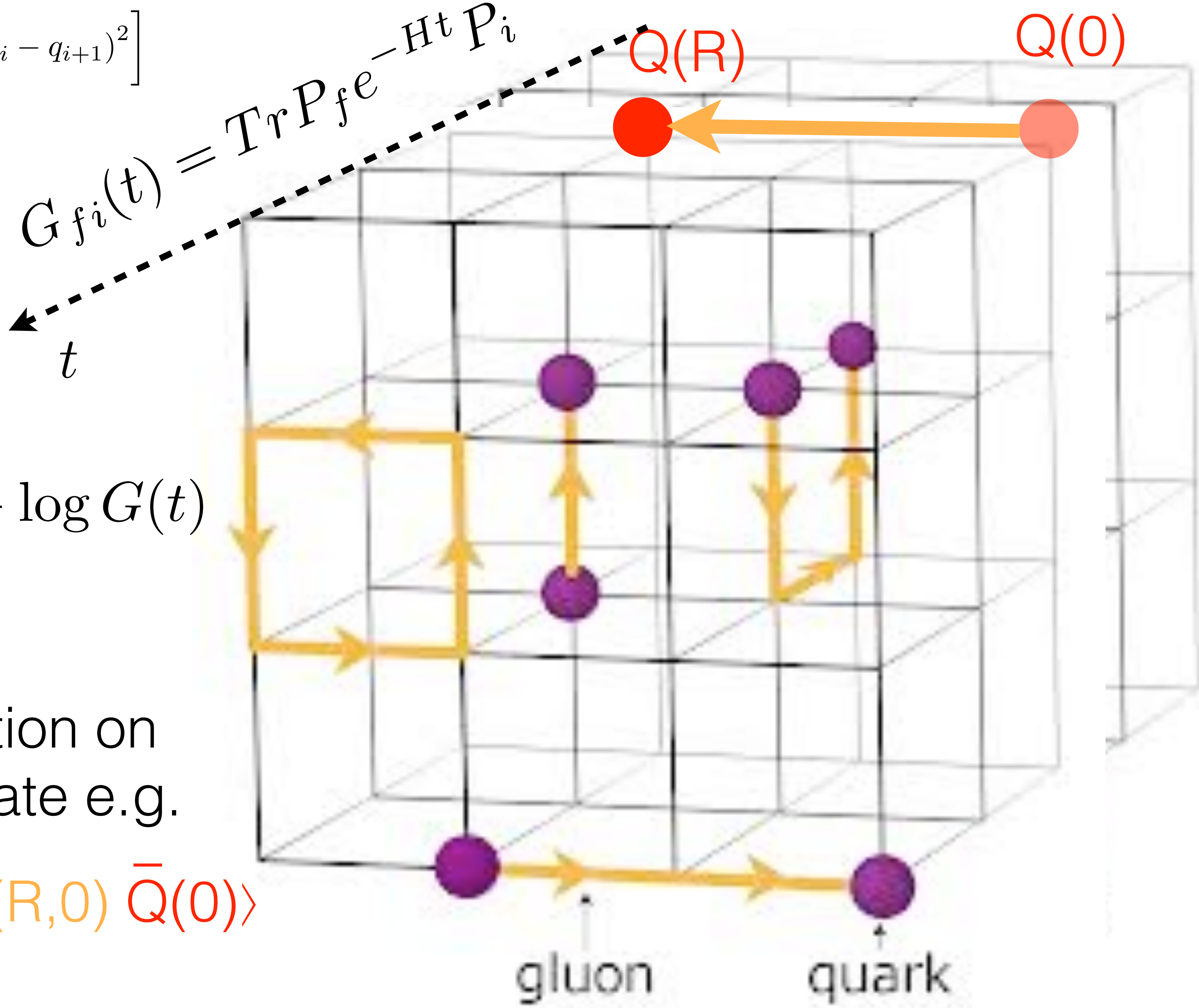
Expected to have very similar properties to ordinary $Q\bar{Q}$ mesons

Lattice QCD



$$H = \frac{1}{2} a \sum_i \left[p_i^2 + \frac{1}{a^2} (q_i - q_{i+1})^2 \right]$$

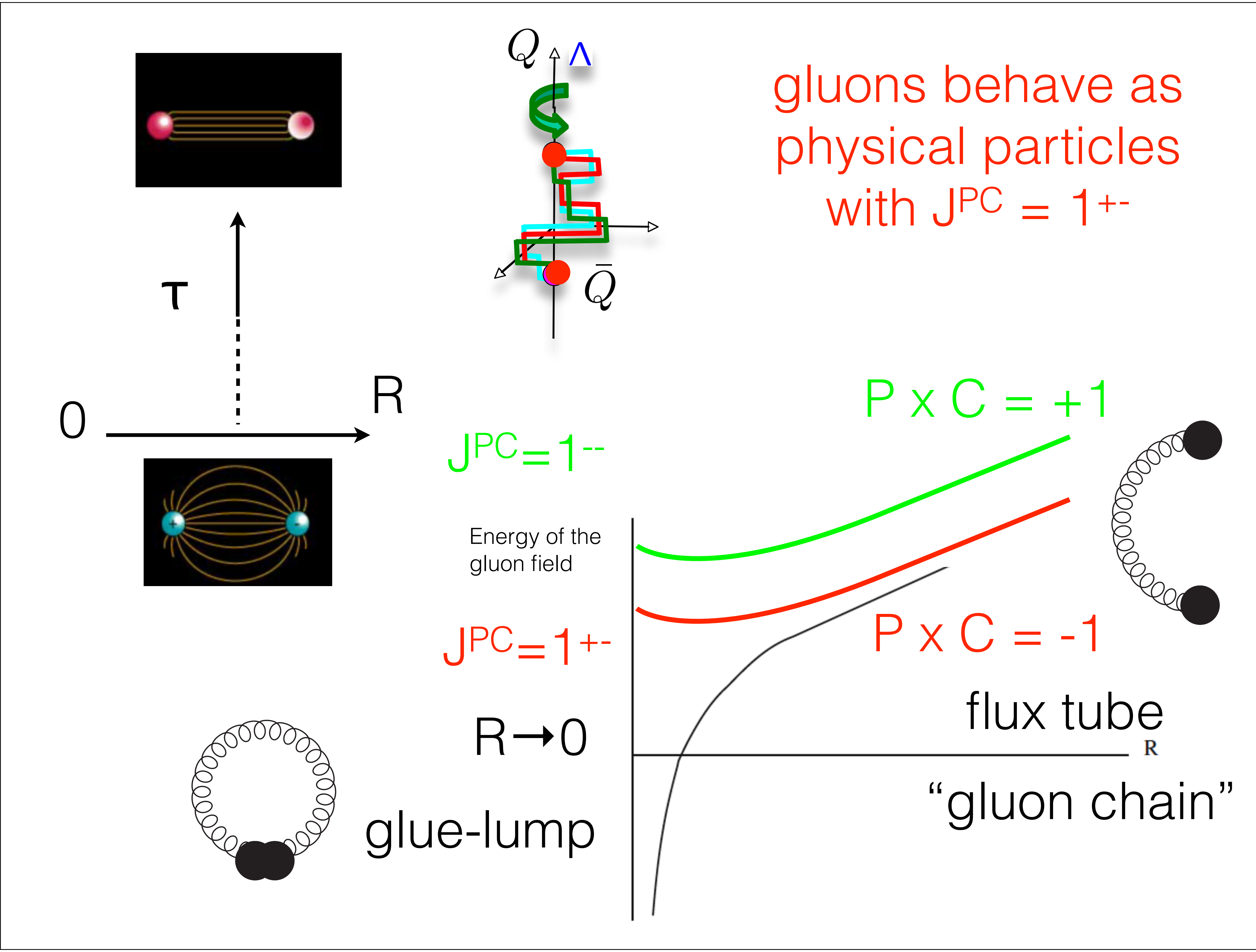
$$G_{fi}(t) = Tr P_f e^{-Ht} P_i$$



$$E = - \lim_{t \to \infty} \frac{1}{t} \log G(t)$$

$P_{i,f}$ → projection on initial/final state e.g.

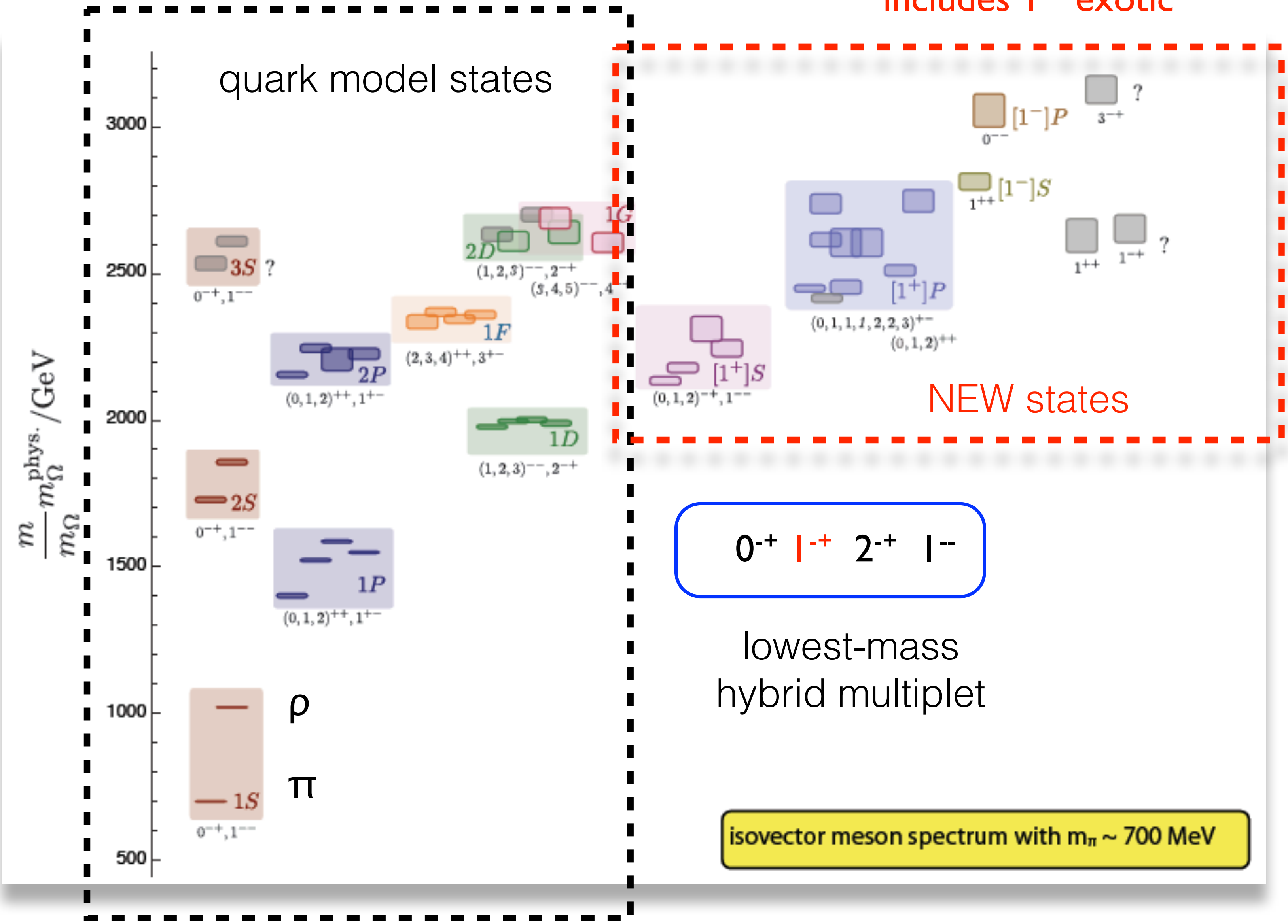
$|Q(R)$ Gluons(R,0) $\bar{Q}(0)\rangle$



gluons behave as physical particles with J^PC = 1^+-
Q
Λ
Q̄
τ
0
R
J^PC=1^--
P x C = +1
Energy of the gluon field
J^PC=1^+-
P x C = -1
flux tube
R
R→0
"gluon chain"
glue-lump

new multiplets from lattice

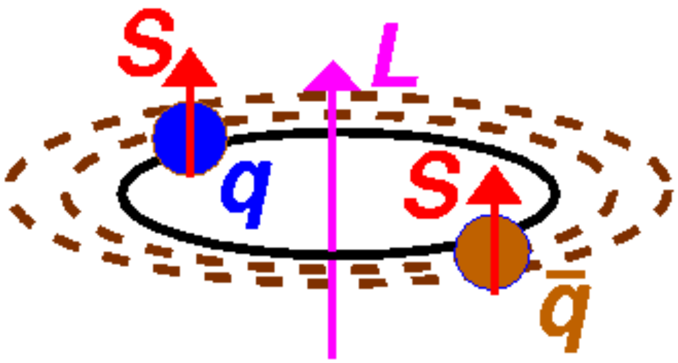
large overlap with
gluonic operators
includes 1^{-+} exotic



same pattern in $s\bar{s}$, $c\bar{c}$

hybrid interpretation of the **Y(4260)**

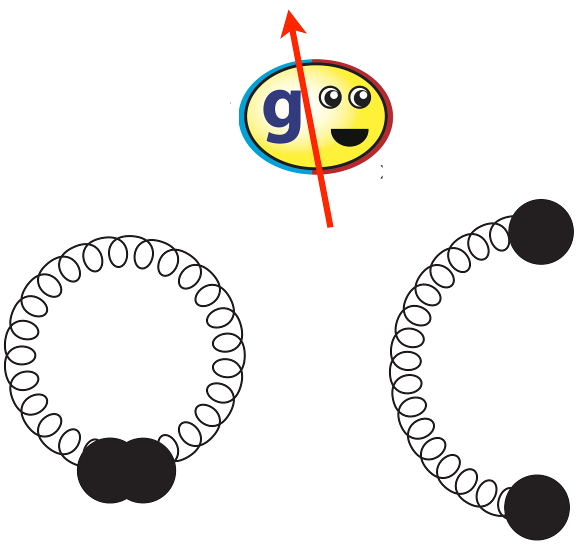
J.Dudek et al. JLab



$$P_{q\bar{q}} = (-1)^{L+1}$$

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

$$J_g^{PC} = 1^{+-}$$



J^PC glue

J^PC QQ̄

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} = \boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

$J^{PC} = 1^{-+}$ is not a $q\bar{q}$ state

exotic quantum numbers

Strong, theoretical evidence (lattice) for gluon filed excitations in hadron spectrum

Phenomenologically, gluons behave as axial vector, quasiparticles $J^{PC}=1^{+-}$

Lowest multiplet of "hybrid mesons" has $J^{PC} = 0^{-+}$, 1^{-+}, 2^{-+}, 1^{--} states

What about other non-quark model possibilities ?
Can these be detected and distinguished ?

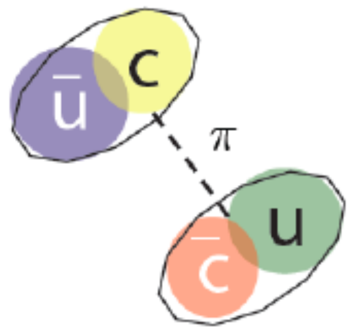
QCD: There are many other possible color singlets.

dibaryon

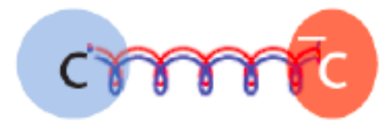
pentaquark

glueball

diquark + di-antiquark

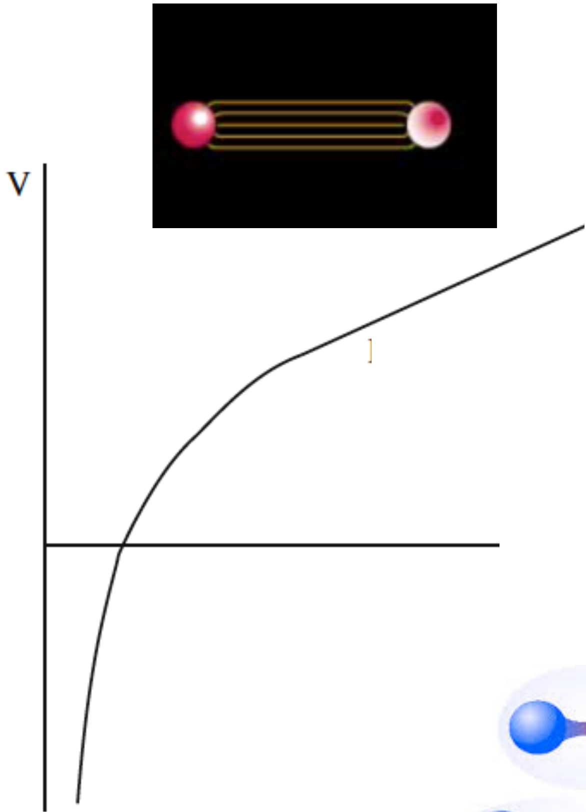


dimeson molecule

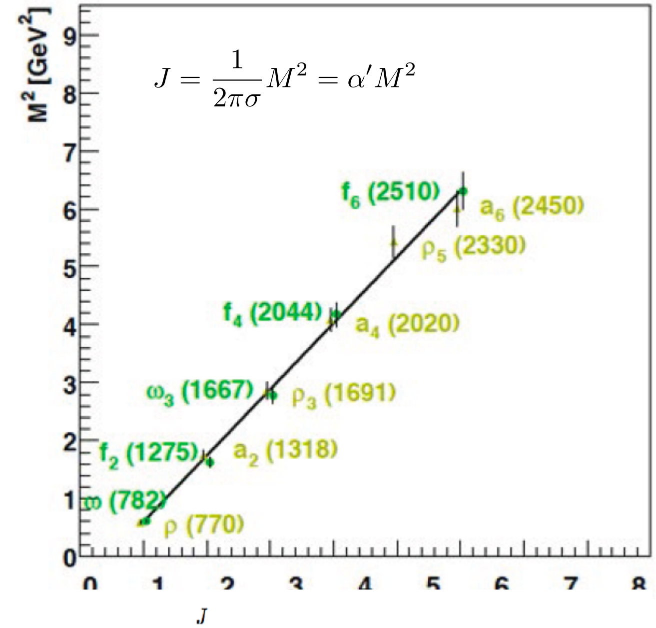


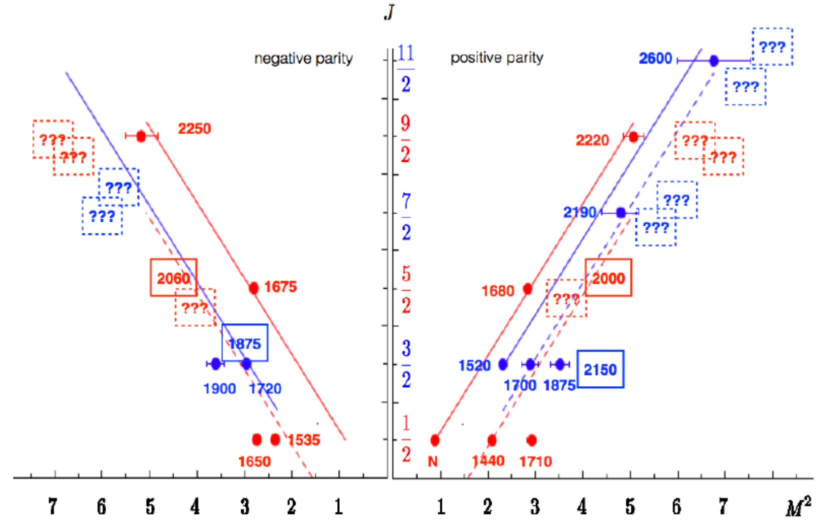
$q\,\bar{q}\,g$ hybrid

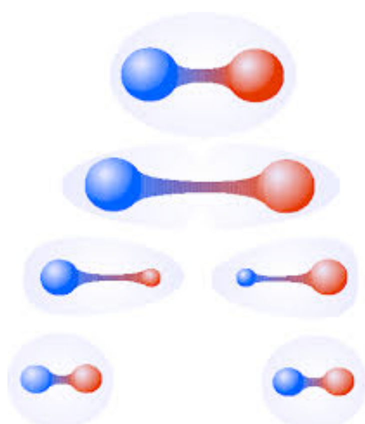
relativistic “spinning stick” : J ~ M²



Normal (quark model hadrons) seem to follow linear Regge trajectories (J vs M²).



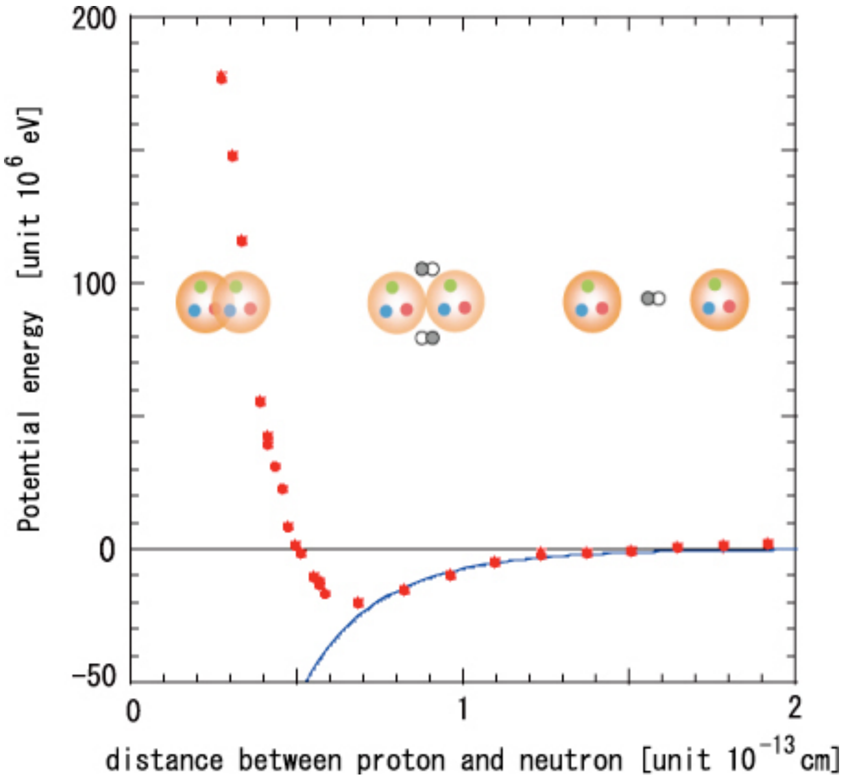


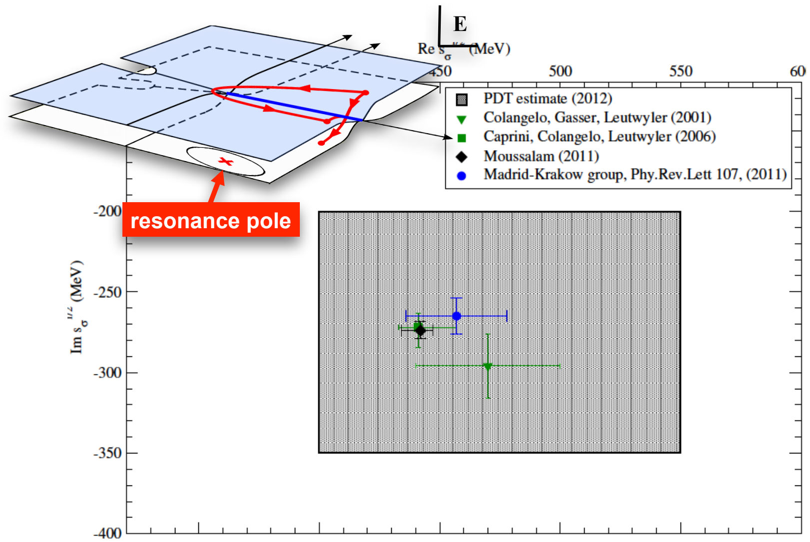


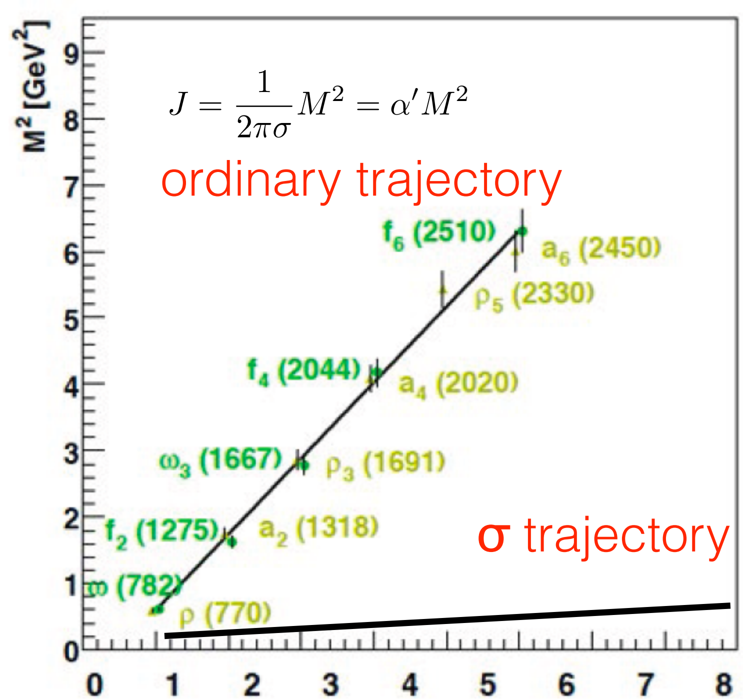
They survive even in presence of open decay channels

But there are known exceptions e.g. **σ** meson

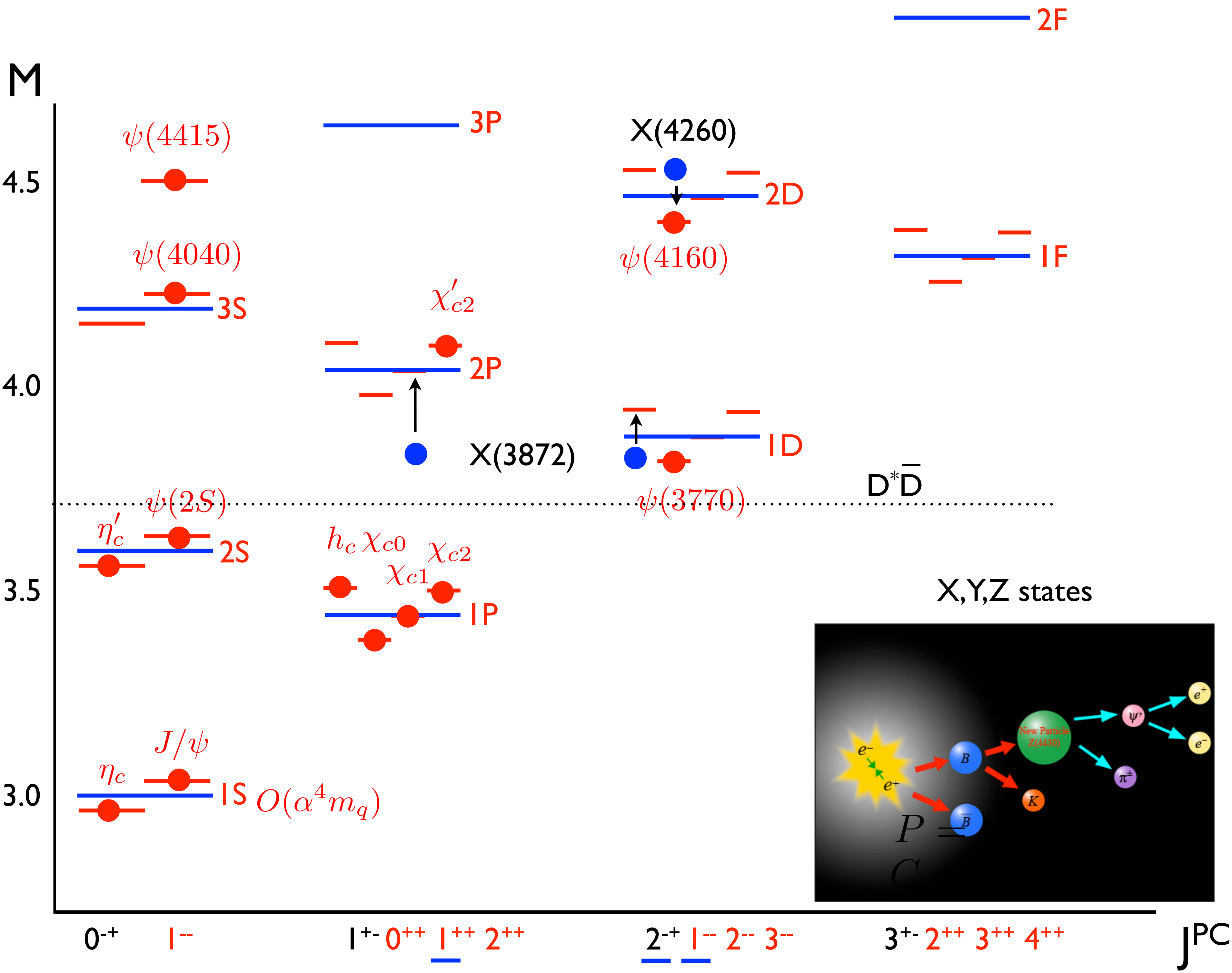
σ meson "medium range NN attraction"





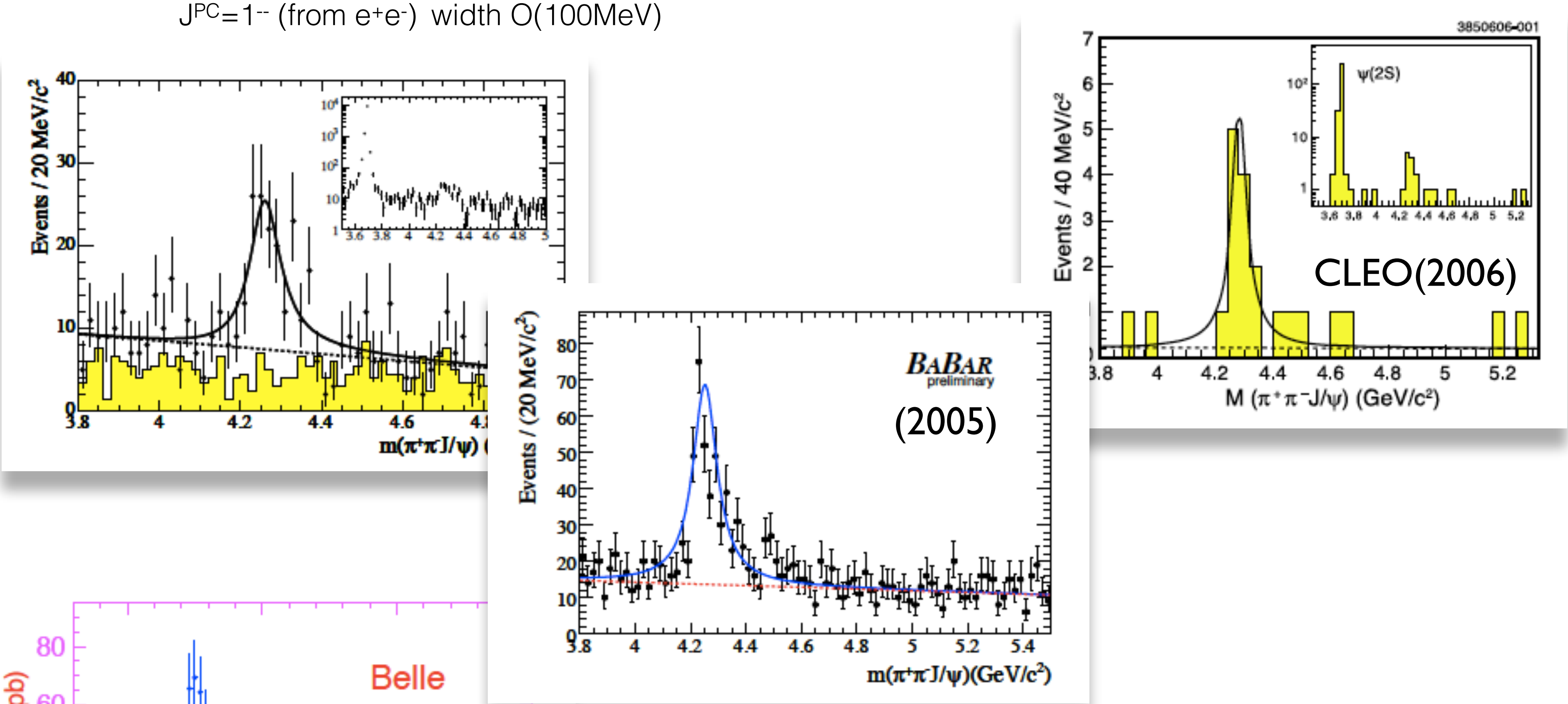


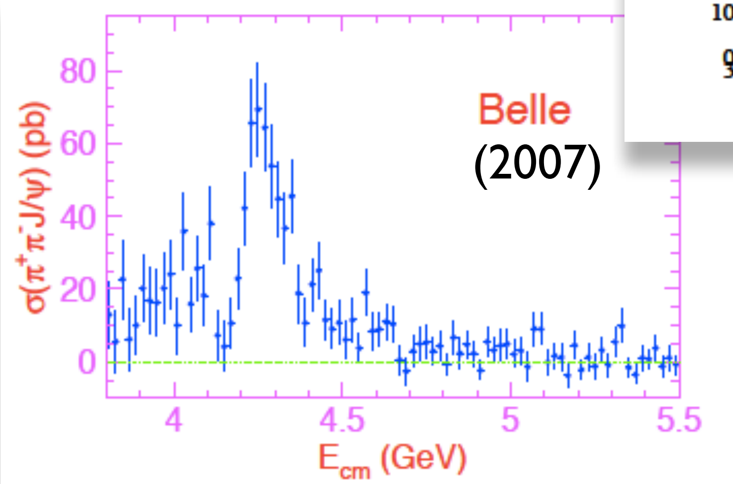
but **σ** meson is not "ordinary"

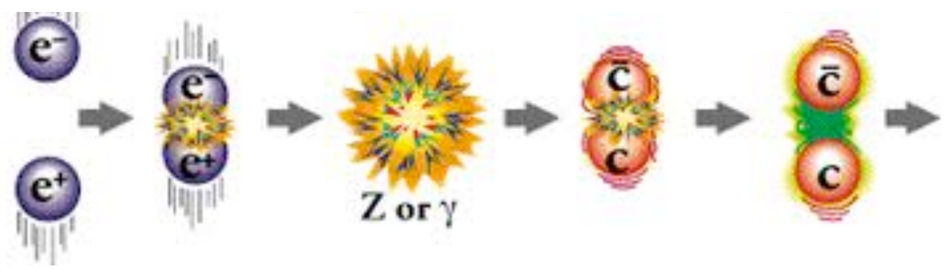


M
4.5
4.0
3.5
3.0
$\psi(4415)$
$\psi(4040)$
3S
$\psi(2S)$
η_c'
2S
J/ψ
η_c
1S
$O(\alpha^4 m_q)$
3P
χ_{c2}'
2P
X(3872)
h_c χ_{c0}
χ_{c2}
χ_{c1}
1P
X(4260)
2D
$\psi(4160)$
1D
$\psi(3770)$
$D^*\bar{D}$
2F
1F
X,Y,Z states
New Particle Z(4430)
e^-
e^+
B
$\bar{B}$
K
ψ'
$\pi^\pm$
e^+
e^-
0^{-+} 1^{--}
1^{+-} 0^{++} 1^{++} 2^{++}
2^{-+} 1^{--} 2^{--} 3^{--}
3^{+-} 2^{++} 3^{++} 4^{++}
J^{PC}

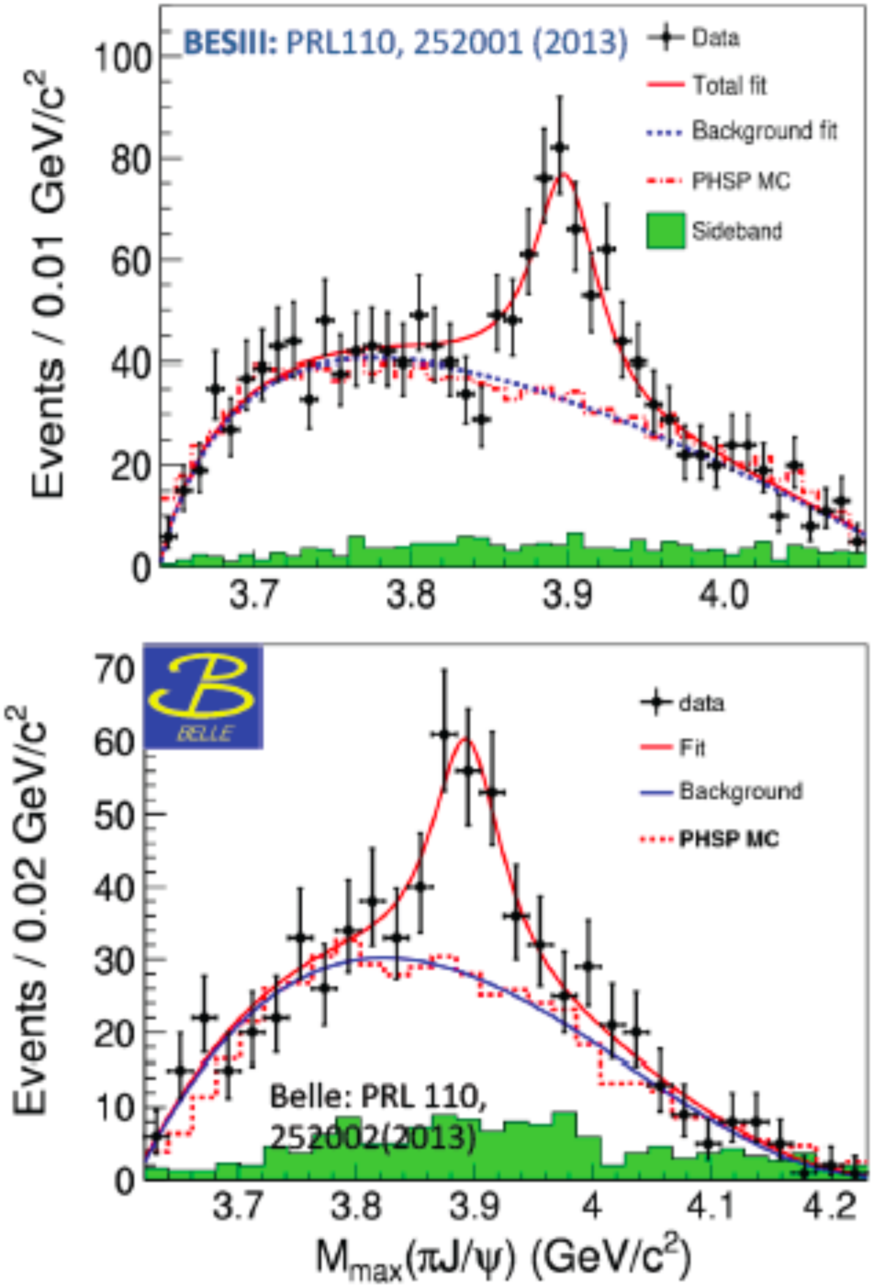
- **Y(4260)** discovered by BaBar in $J/\psi\ \pi^+\pi^-$ (2005) confirmed by CLEO,Belle other modes from BaBar
  $J^{PC}=1^{--}$ (from e^+e^-) width O(100MeV)

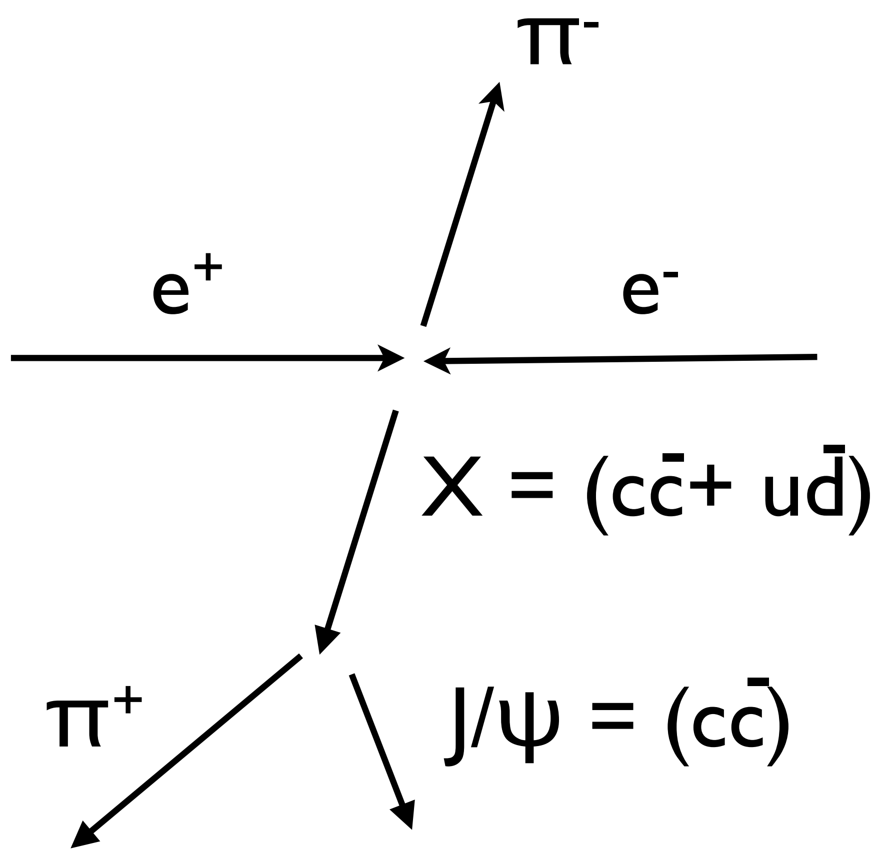






✱ Theory favor: Hybrid

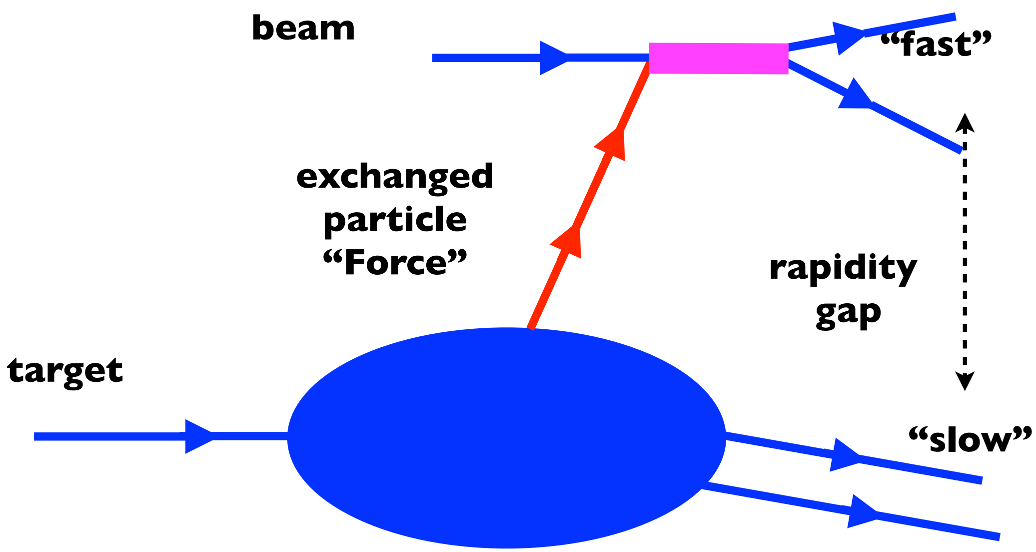

BESIII: PRL110, 252001 (2013)
Data
Total fit
Background fit
PHSP MC
Sideband
Events / 0.01 GeV/c2
100
80
60
40
20
0
3.7
3.8
3.9
4.0
BELLE
data
Fit
Background
PHSP MC
Belle: PRL 110,
252002(2013)
Events / 0.02 GeV/c2
70
60
50
40
30
20
10
0
3.7
3.8
3.9
4
4.1
4.2
Mmax(πJ/ψ) (GeV/c2)


π-
e+
e-
X = (cc̄+ ud̄)
π+
J/ψ = (cc̄)

Hunting for Resonances in fixed target experiments

(ACCMOR,VES,E852,FOCUS,
LASS,OMEGA,...COMPASS,Jlab12)

Resonance, "R" production

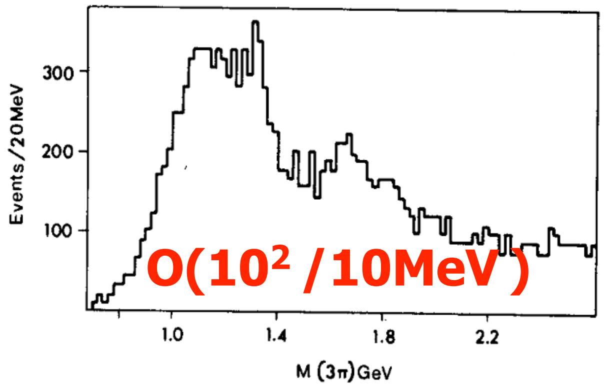


target = photon (JLab)
pion (COMPAS)

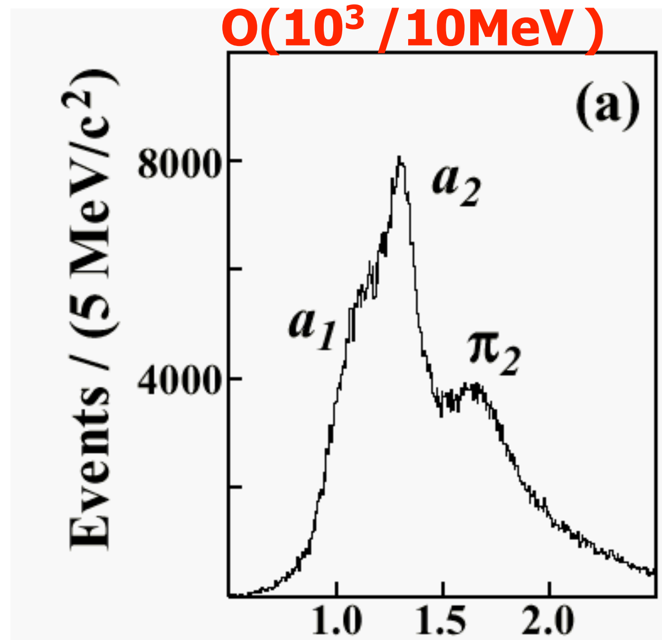
diffractive-dissociation

evolution in statistics $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

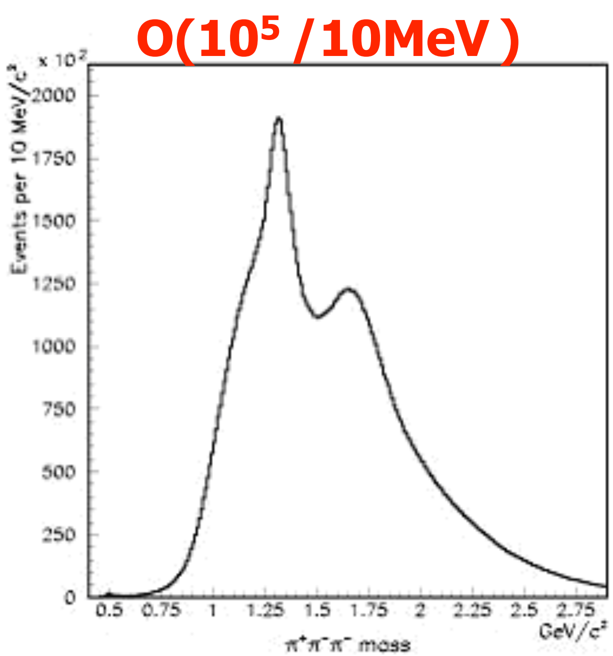
CERN ca. 1970



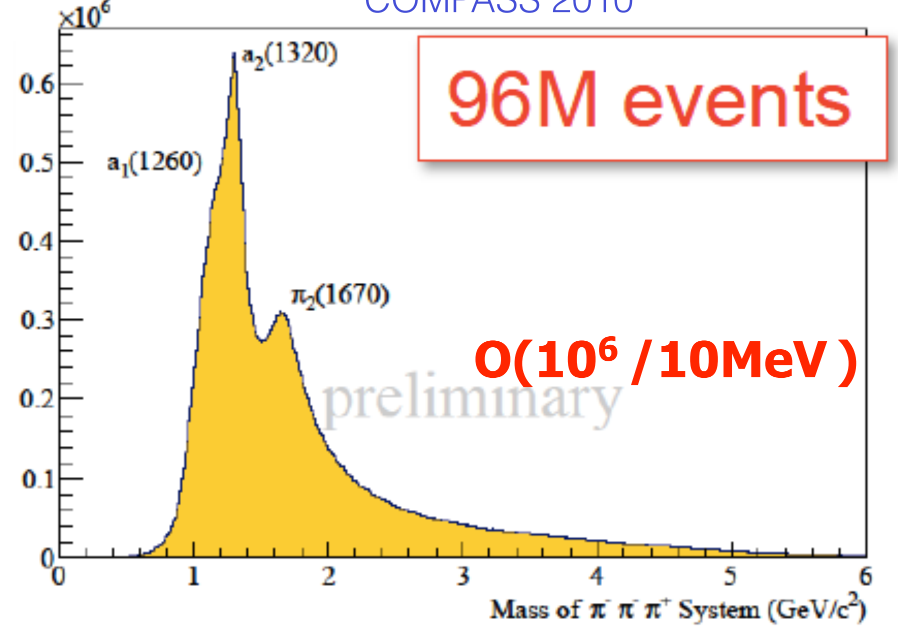
BNL (E852) ca 1995



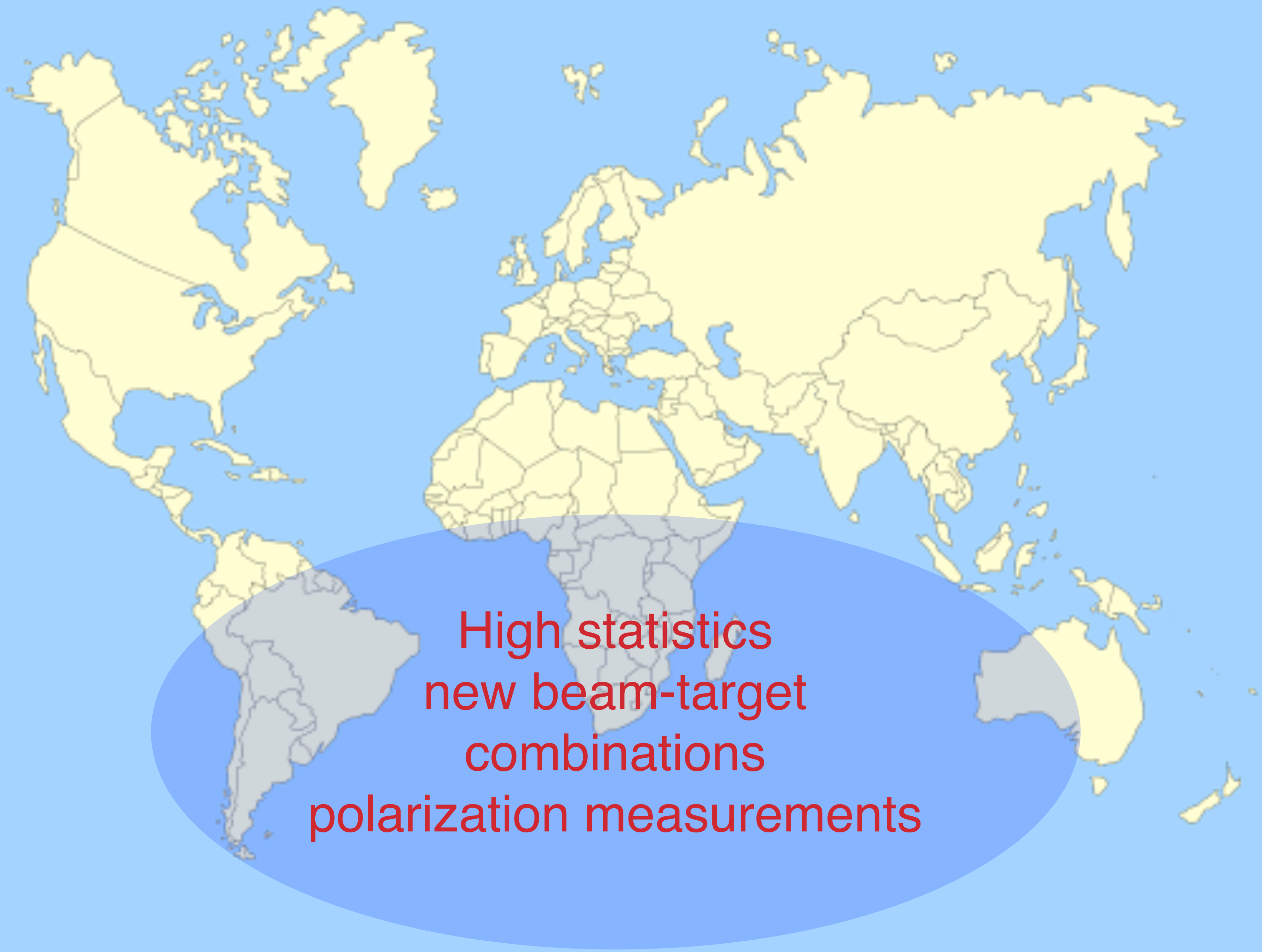
E852 (Full sample)



COMPASS 2010



New opportunities

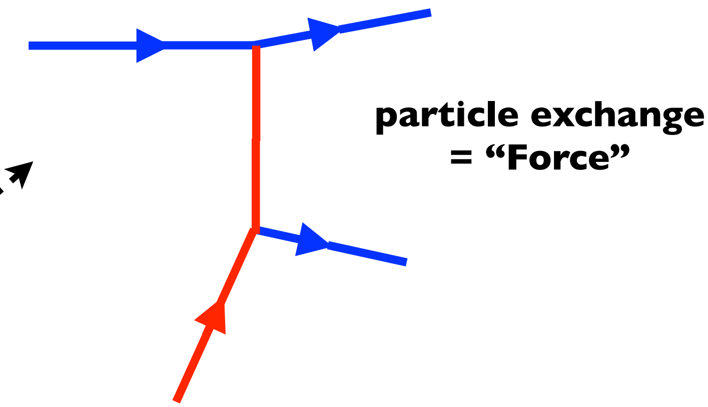


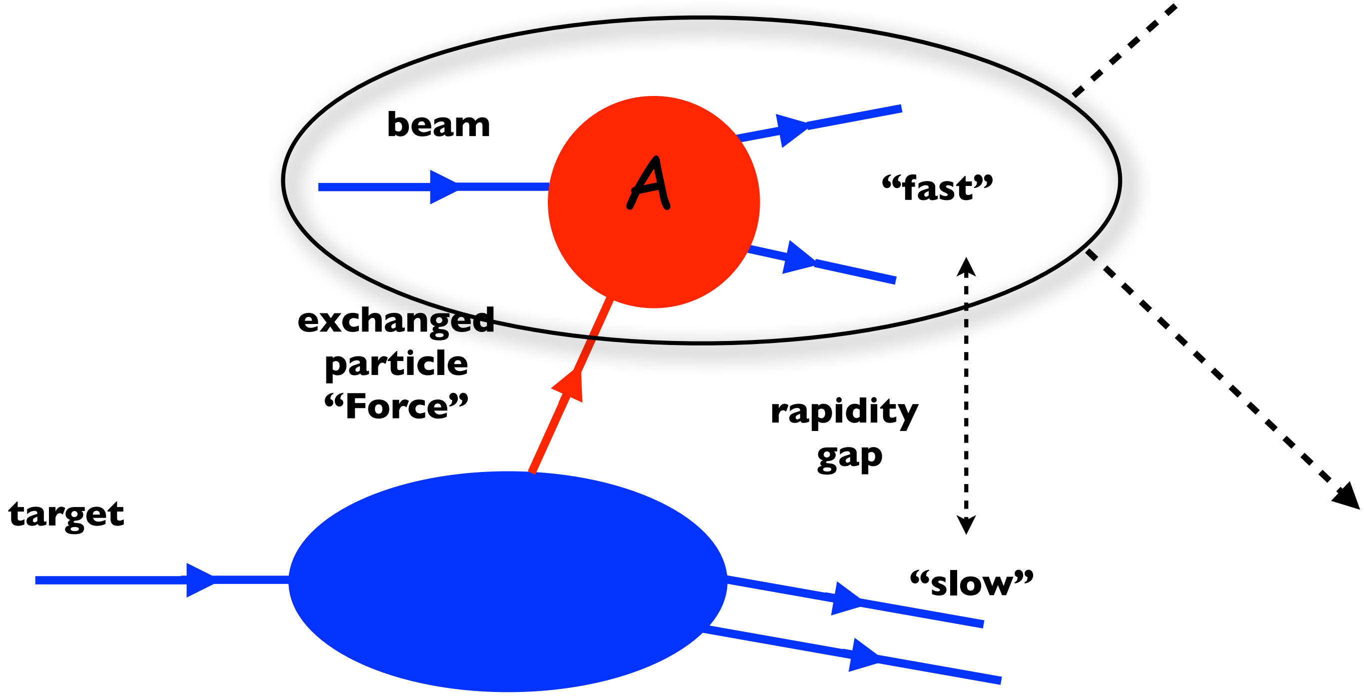
New opportunities

High statistics
new beam-target combinations
polarization measurements

Hunting for Resonances in fixed target experiments

(ACCMOR,VES,E852,FOCUS, LASS,OMEGA,...COMPASS,Jlab12)



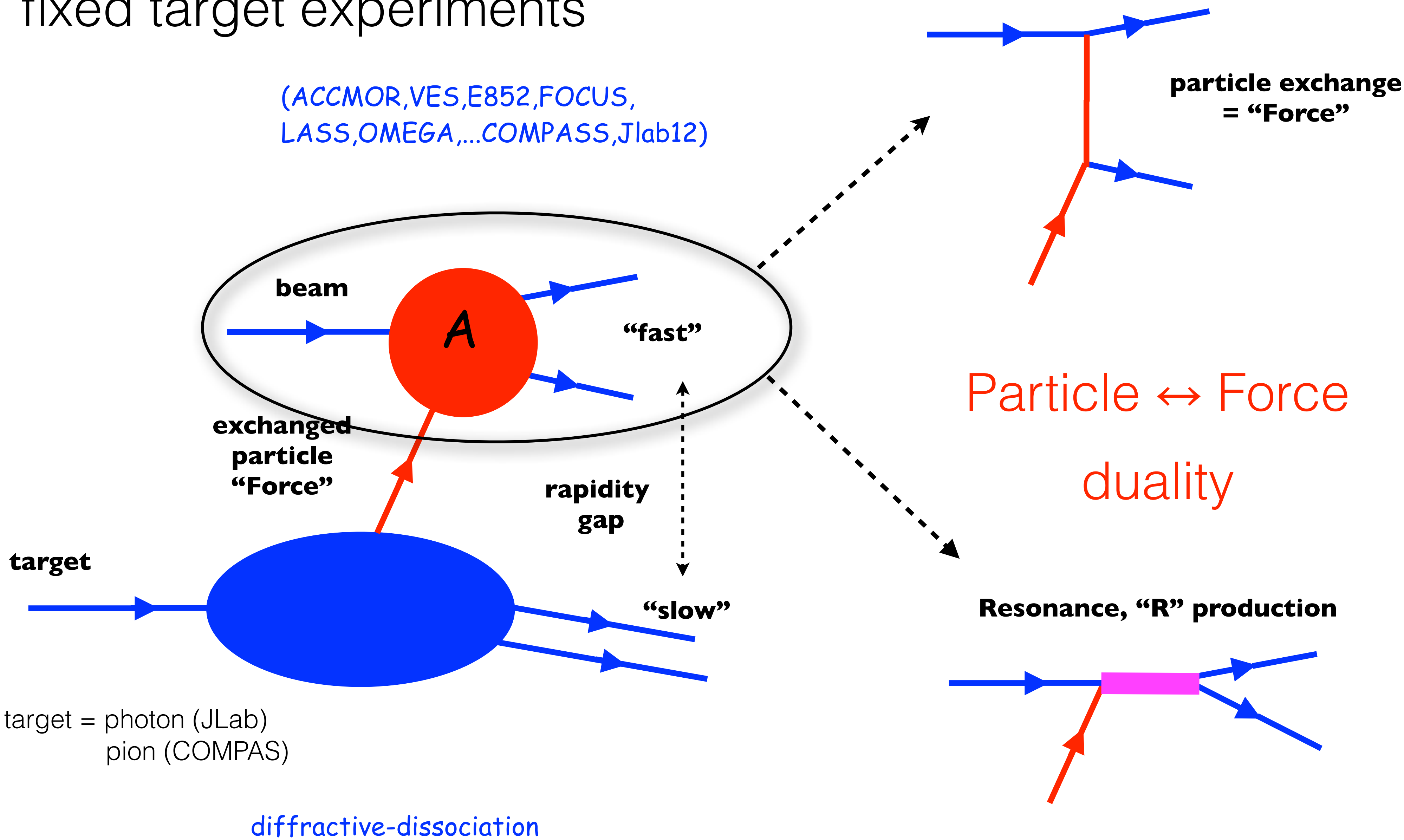


Particle ↔ Force duality

target = photon (JLab)
pion (COMPAS)

diffractive-dissociation

Hunting for Resonances in fixed target experiments



Amplitude analysis: and S-matrix game

"The bootstrap manifesto (1962)"

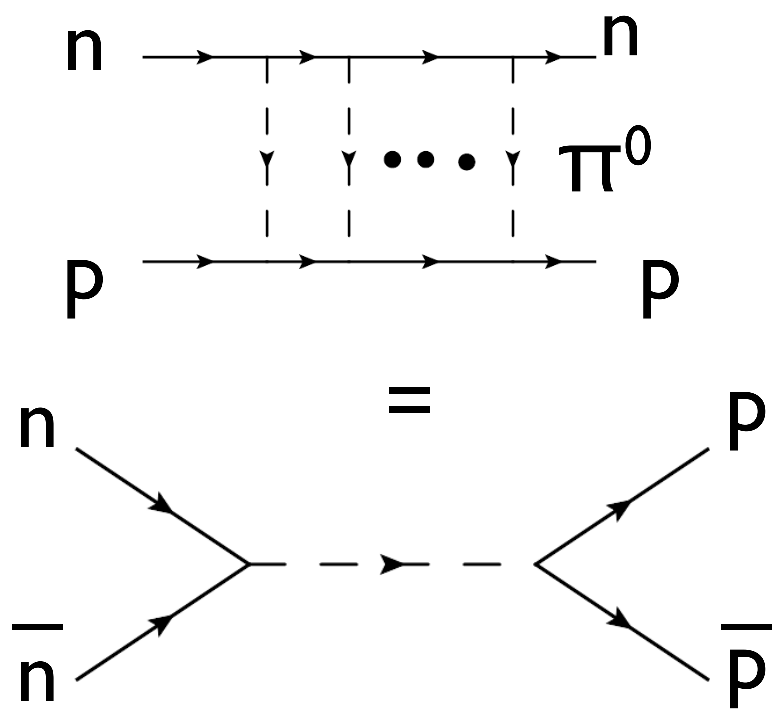
REVIEWS OF MODERN PHYSICS VOLUME 34, NUMBER 3 JULY, 1962

S-Matrix Theory of Strong Interactions without Elementary Particles*†

GEOFFREY F. CHEW
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California

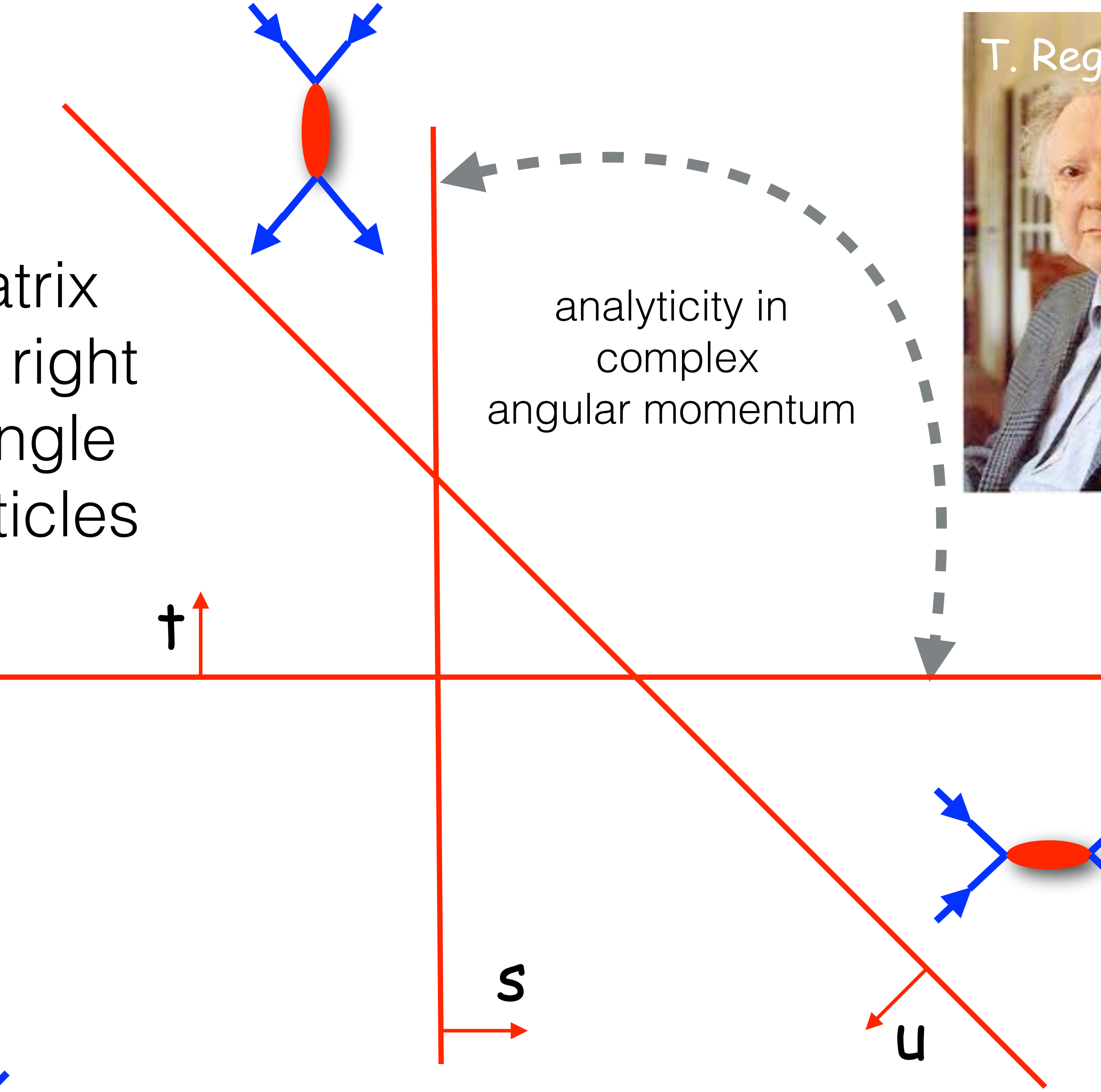
all observed hadrons are made of each other

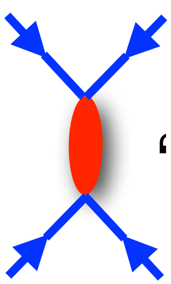
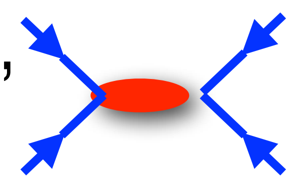
"In this paper I resent an indecently optimistic view of strong interactions theory. My belief is that a major breakthrough has occurred and that within a relatively short period we are going to achieve a depth of understanding of strong interactions that a few years ago I, at least, did not expect to see within my lifetime. …. I am bursting with excitement, as are a number of other theorists in this game."

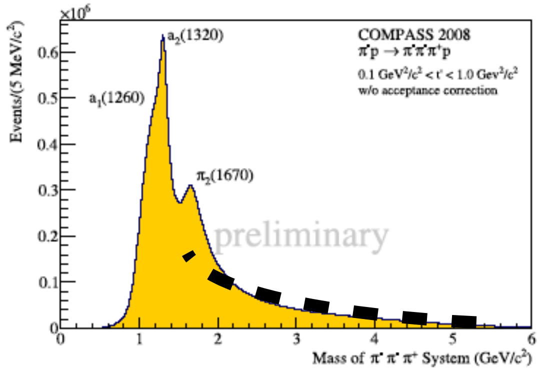


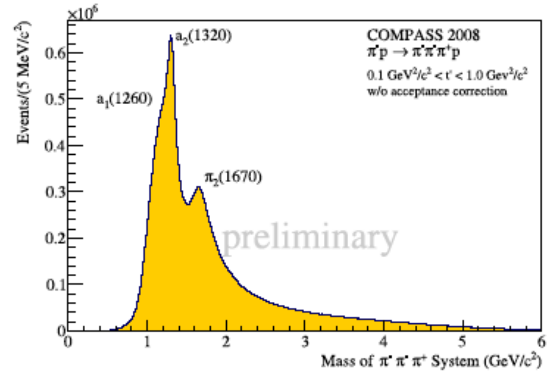
Bootstrap failed to reproduce linear Regge trajectories because QCD does have elementary particles: quarks and gluons

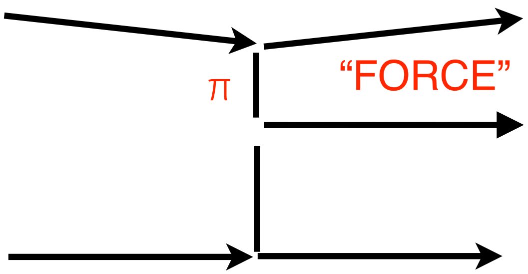
... but the S-matrix theory gives the right tools to disentangle Forces from Particles




“force” <duality>“particle”


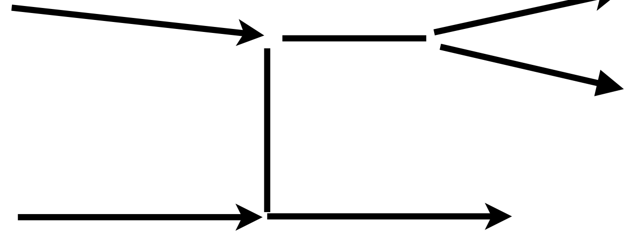


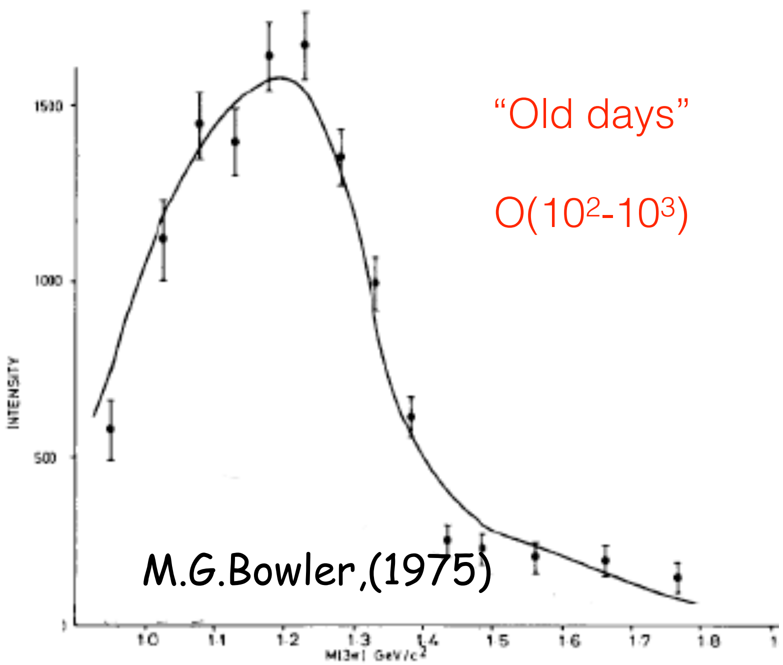




~

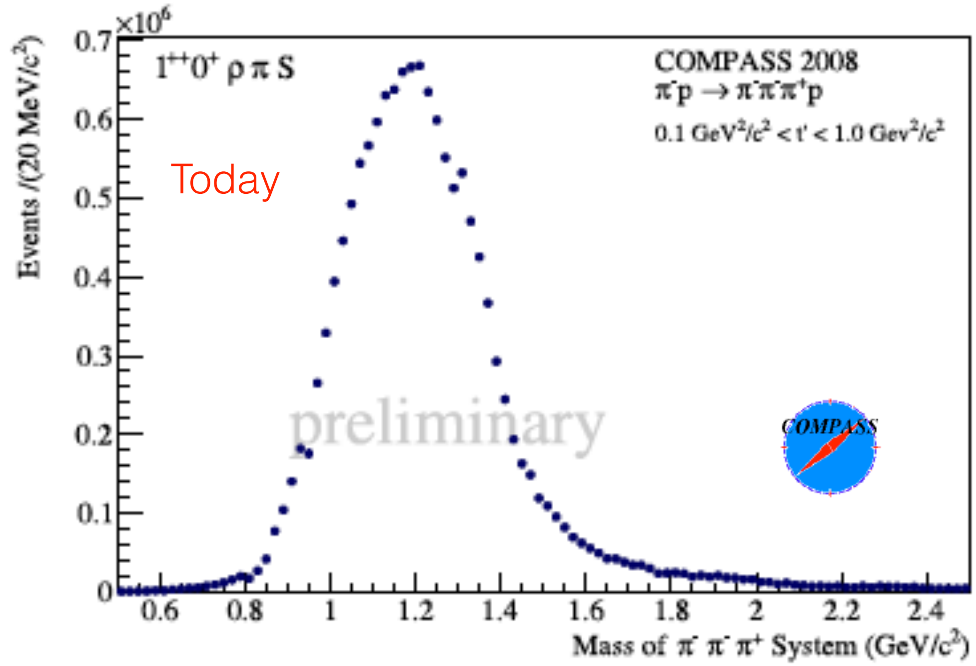
RESONANCE



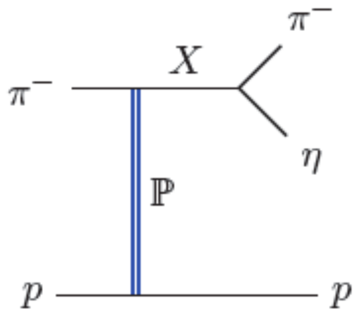


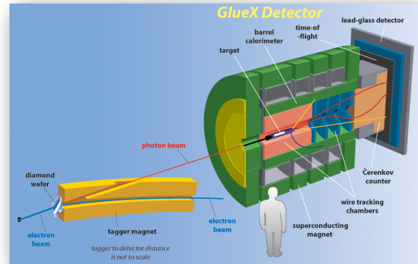
"Old days"

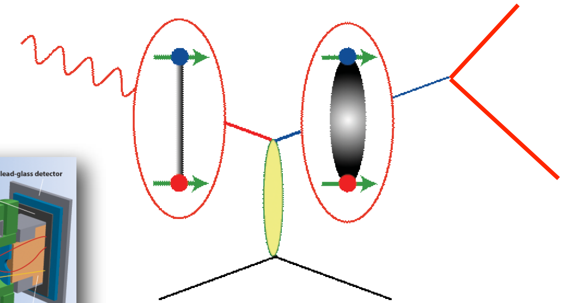
$O(10^2\text{-}10^3)$



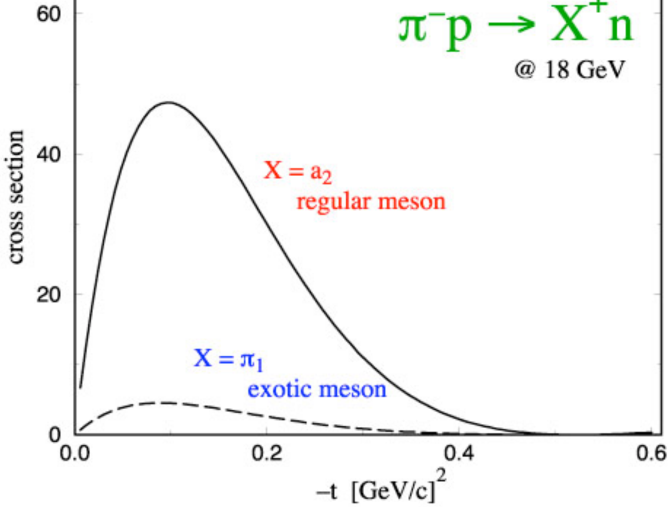
Hunting for $J^{PC}=1^{-+}$ exotic meson



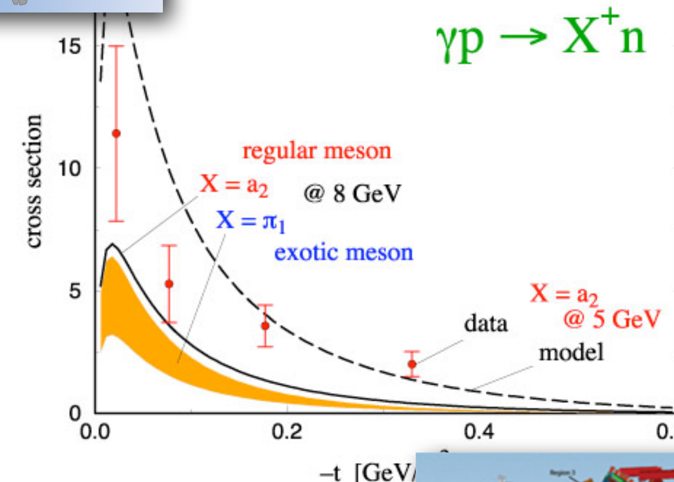


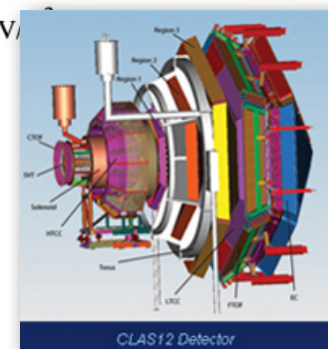


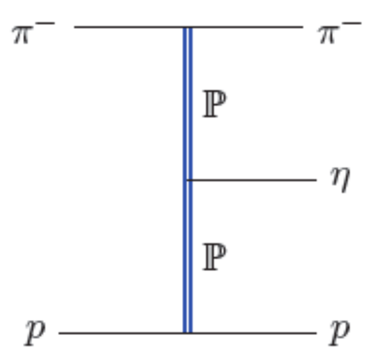
exotic/non-exotic » 0.1

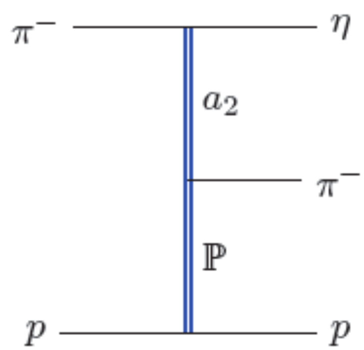


exotic/non-exotic » 1









$\pi^- p \to \eta \pi^- p$

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

search for

$n\bar{n}$ hybrid $\pi_1(1600)$

$\pi^- p \to \eta \pi^0 n$

No consistent B-W interpretation possible but a weak $\eta\pi$ interaction exists and can reproduce the exotic wave

$\pi^- p \to \eta\pi^- p$

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

search for
$n\bar{n}$ hybrid $\pi_1(1600)$

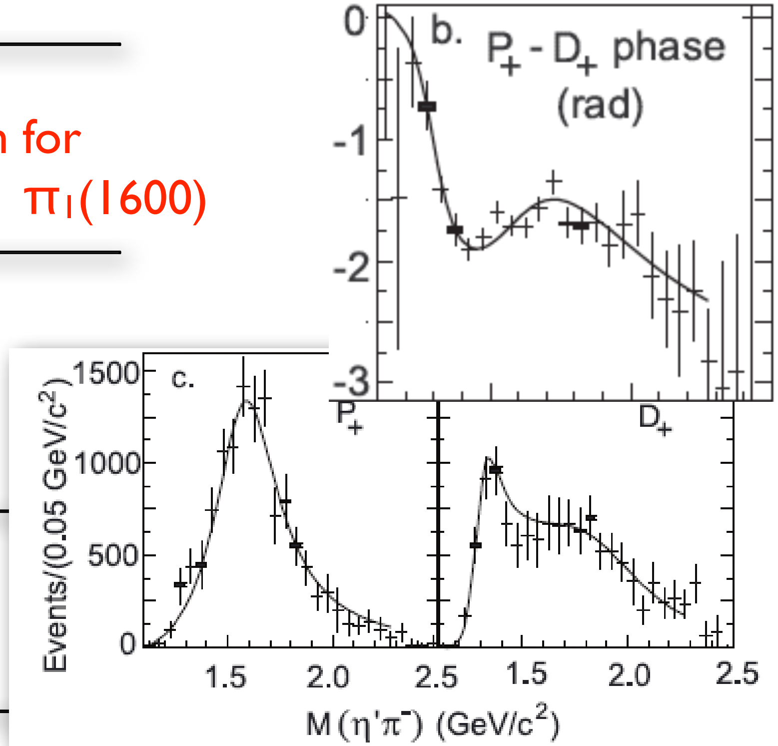
$\pi^- p \to \eta\pi^0 n$

No consistent B-W interpretation possible but a weak $\eta\pi$ interaction exists and can reproduce the exotic wave

$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2



$\pi^- p \to \eta\pi^- p$

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

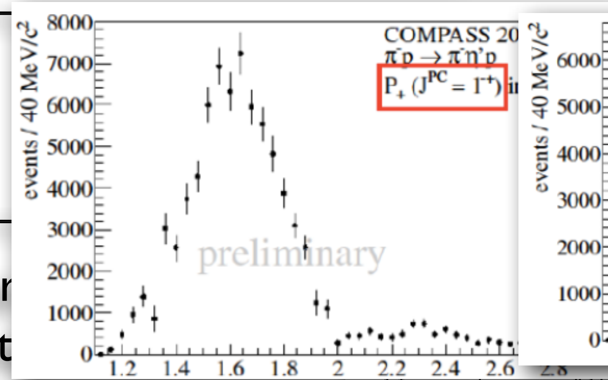
$\pi^- p \to \eta\pi^0 n$

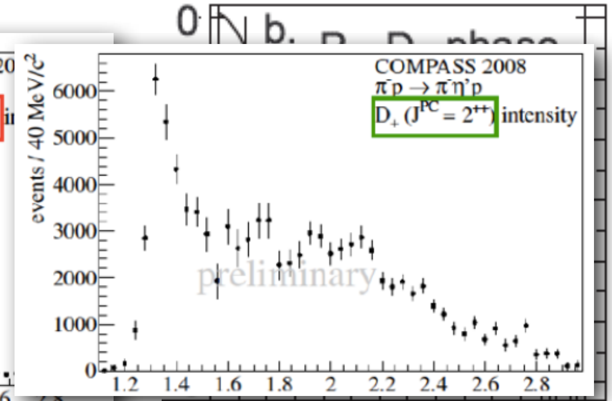
No consistent B-W interpr
possible but a weak ηπ int
exists and can reproduce the exotic wave

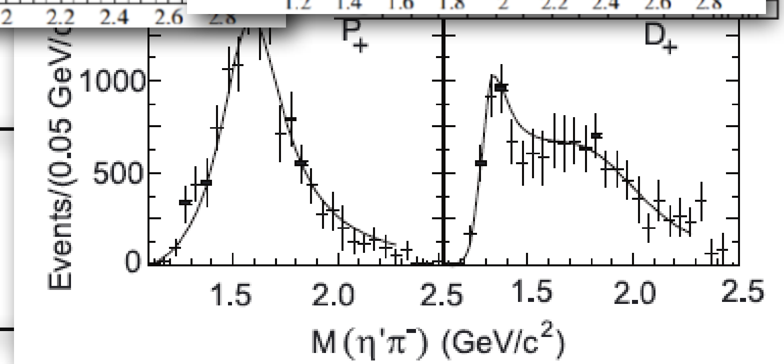
$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2







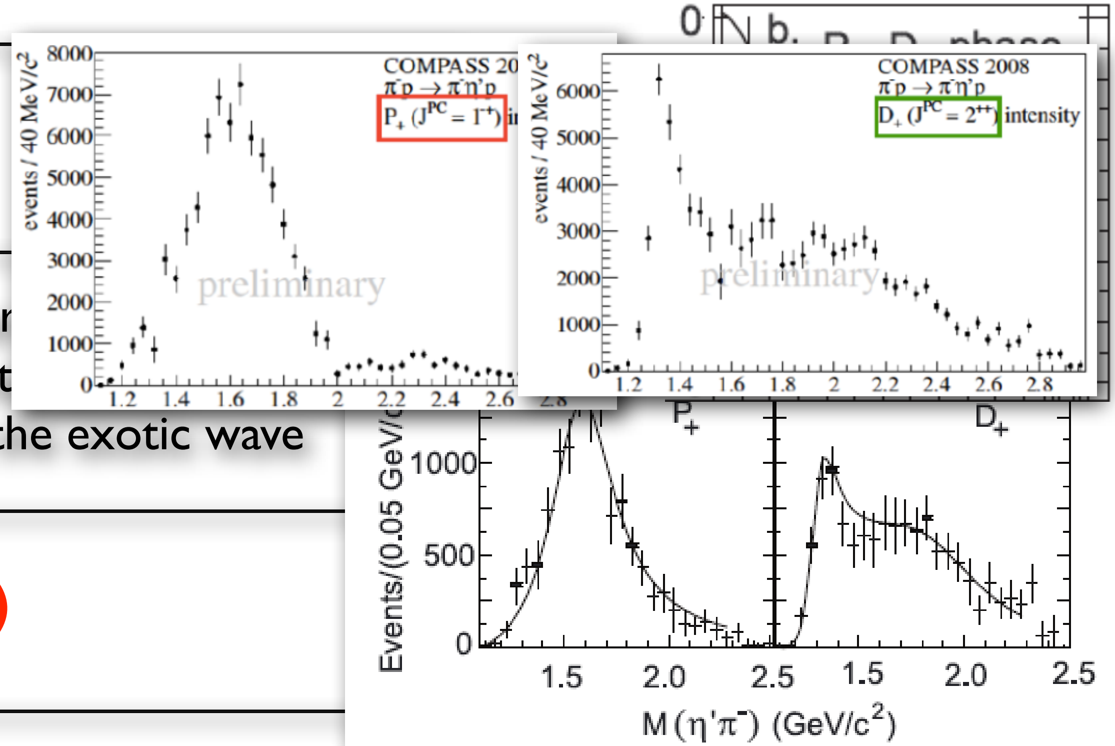
$\pi^- p \to \eta\pi^- p$

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

$\pi^- p \to \eta\pi^0 n$

No consistent B-W interpr possible but a weak ηπ int exists and can reproduce the exotic wave



$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2

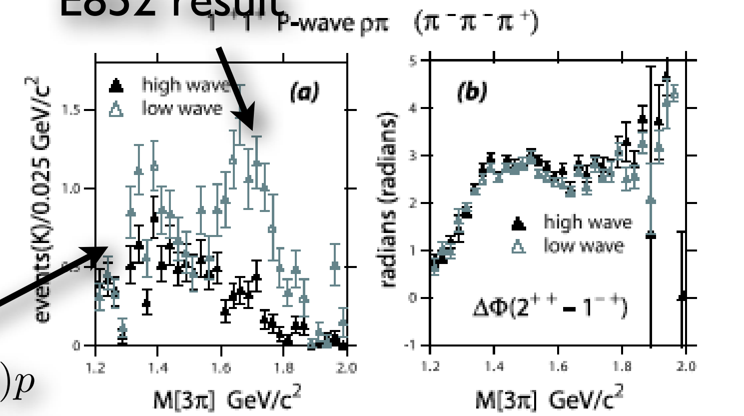
$\pi^- p \to \rho^0\pi^- p$

$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2

$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV / c^2

BNL (E852) yes/no
COMPASS yes

E852 result



$\pi^- p \to \pi_2^-(1600) p$

$\pi_2^- \to \rho^0 \pi^-$

ρ^0

FIG. 25: (a) The $1^{-+}1^+$ P-wave $\rho\pi$ partial wave in the charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA and the low-wave set PWA and (b) the phase difference $\Delta\Phi$ between the 2^{++} and 1^{-+} for the two wave sets.

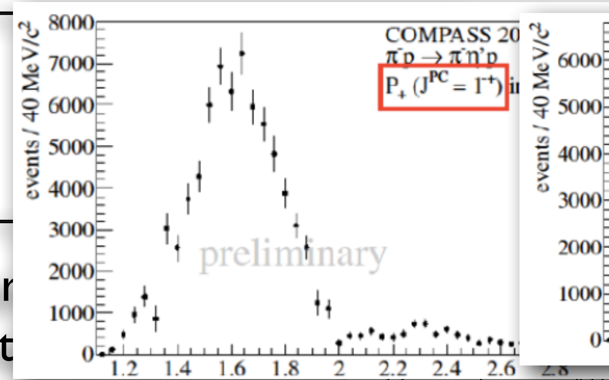
$\pi^- p \to \eta\pi^- p$

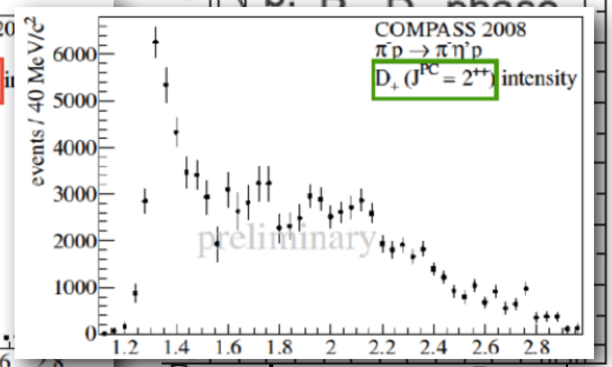
$M = 1370 \pm 16^{+50}_{-30}\ \mathrm{MeV}/c^2$

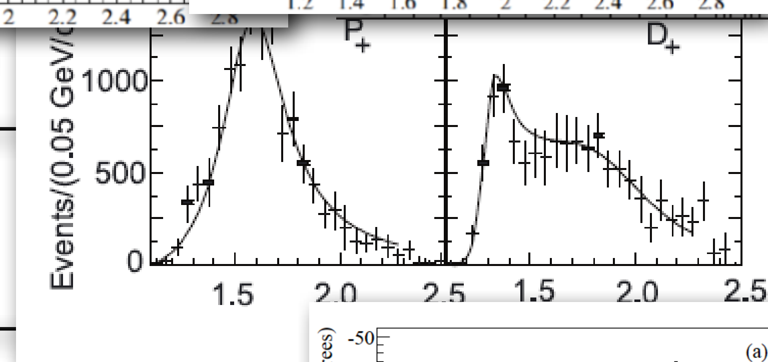
$\Gamma = 385 \pm 40^{+65}_{-105}\ \mathrm{MeV}/c^2$

$\pi^- p \to \eta\pi^0 n$

No consistent B-W interpr
possible but a weak ηπ int
exists and can reproduce the exotic wave







$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}\ \mathrm{MeV}/c^2$

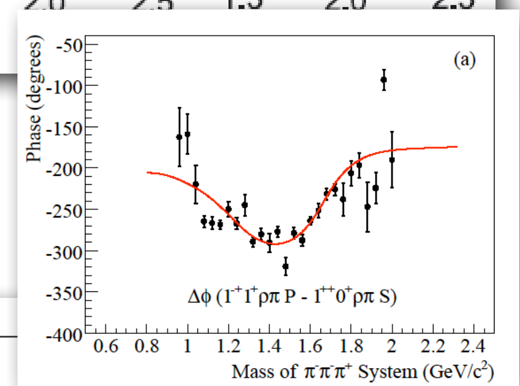
$\Gamma = 340 \pm 40^{+50}_{-50}\ \mathrm{MeV}/c^2$

$\pi^- p \to \rho^0\pi^- p$

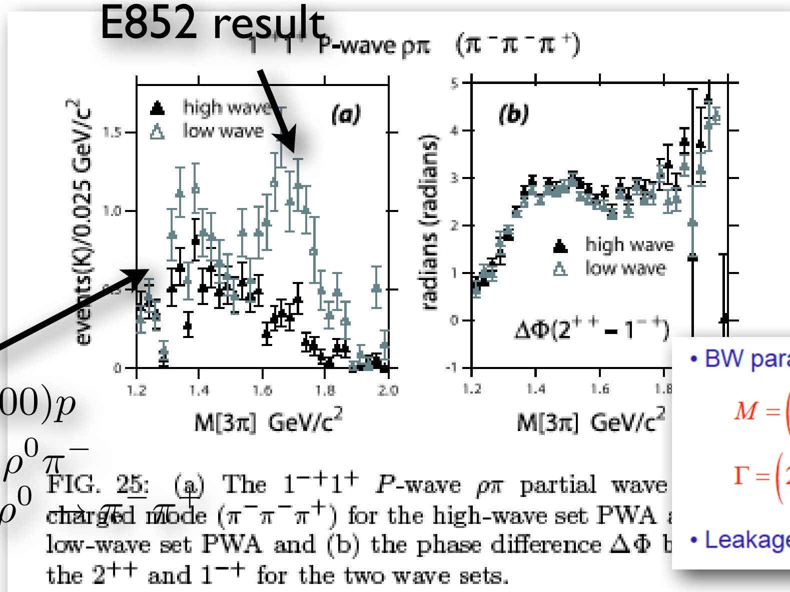
$M = 1593 \pm 8^{+29}_{-47}\ \mathrm{MeV}/c^2$

$\Gamma = 168 \pm 20^{+150}_{-12}\ \mathrm{MeV}/c^2$

BNL (E852) yes/no
COMPASS yes



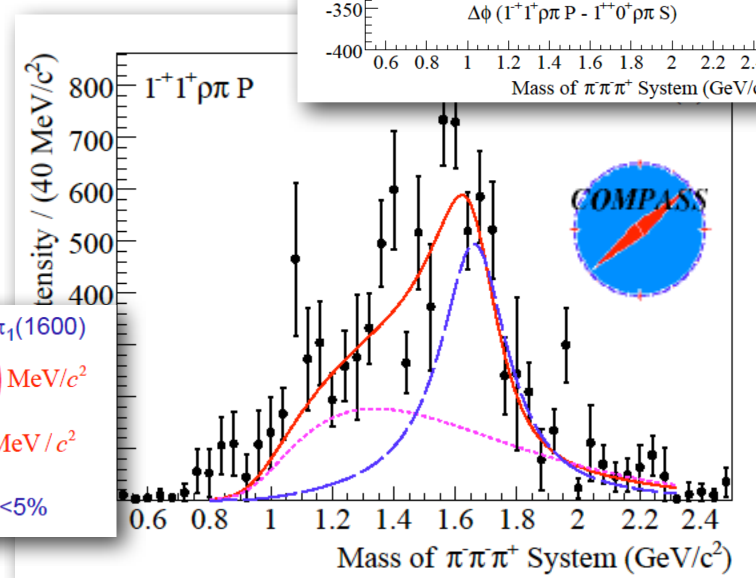
E852 result



$\pi^- p \to \pi_2^-(1600)p$

$\pi_2^- \to \rho^0\pi^-$

ρ^0

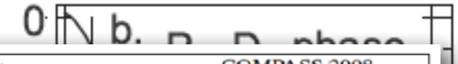


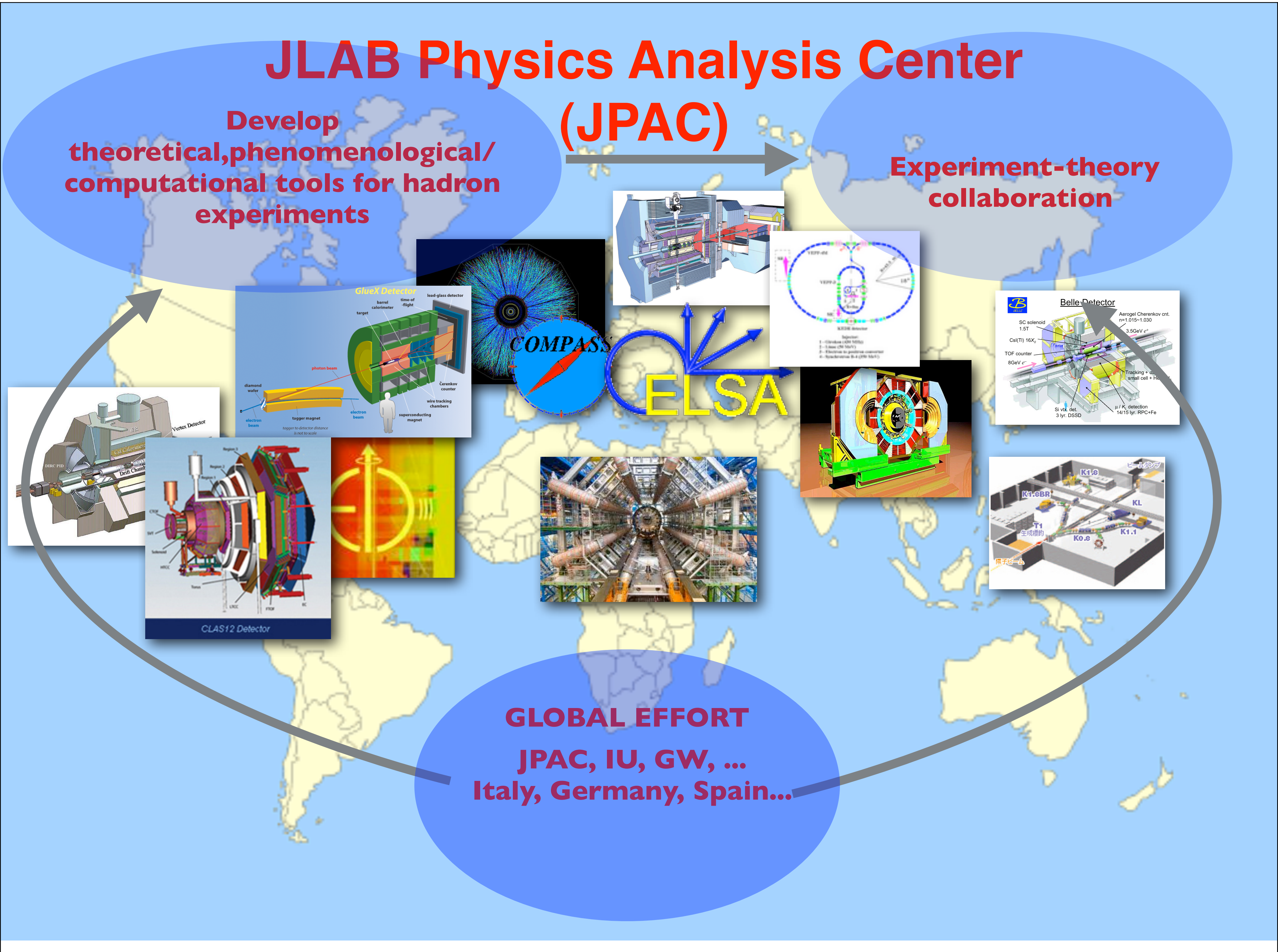
• BW parameters for $\pi_1(1600)$

$M = \left(1660 \pm 10^{+0}_{-64}\right)\ \mathrm{MeV}/c^2$

$\Gamma = \left(269 \pm 21^{+42}_{-64}\right)\ \mathrm{MeV}/c^2$

• Leakage negligible: <5%




JLAB Physics Analysis Center
(JPAC)
Develop theoretical,phenomenological/ computational tools for hadron experiments
Experiment-theory collaboration
GlueX Detector
COMPASS
ELSA
Belle Detector
CLAS12 Detector
GLOBAL EFFORT
JPAC, IU, GW, ...
Italy, Germany, Spain...