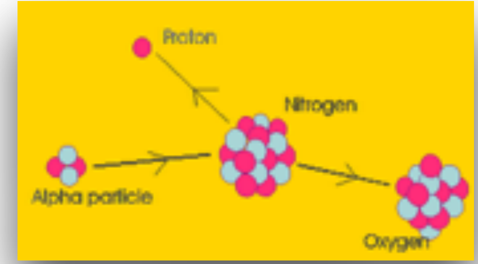
Adam Szczepaniak, Department of Physics Indiana University and Jefferson Lab

New opportunities in hadron spectroscopy

Hadrons a brief history

- 1909/1911 Rutherford/Geiger/Marsden discover the nucleus
- 1919 Rutherford discovers the proton
- 1932 Chadwick discovers the neutron
- 1940 - till now hundreds of resonances discovered (lifetime ~ 10^{-24} s width ~ O(100 MeV)



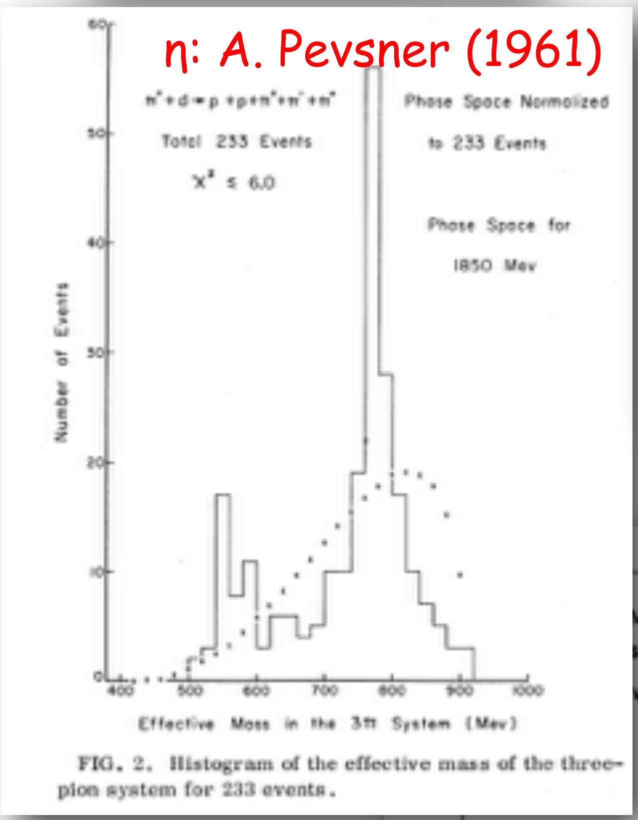
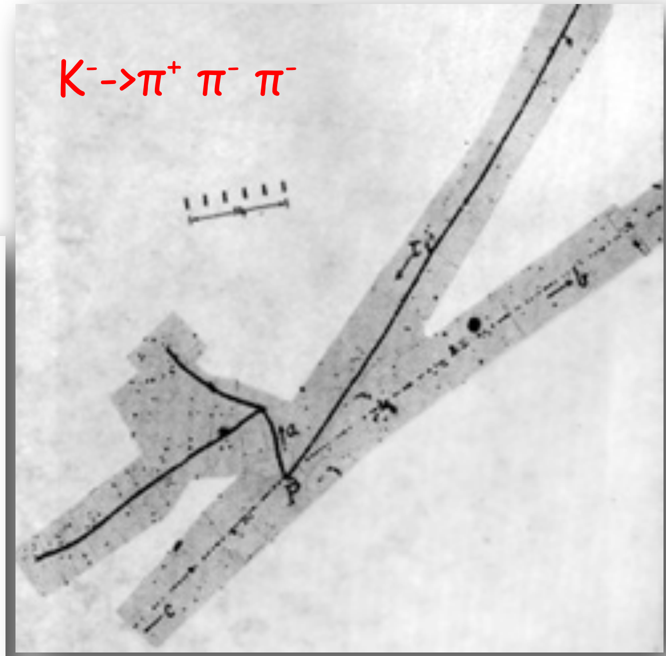
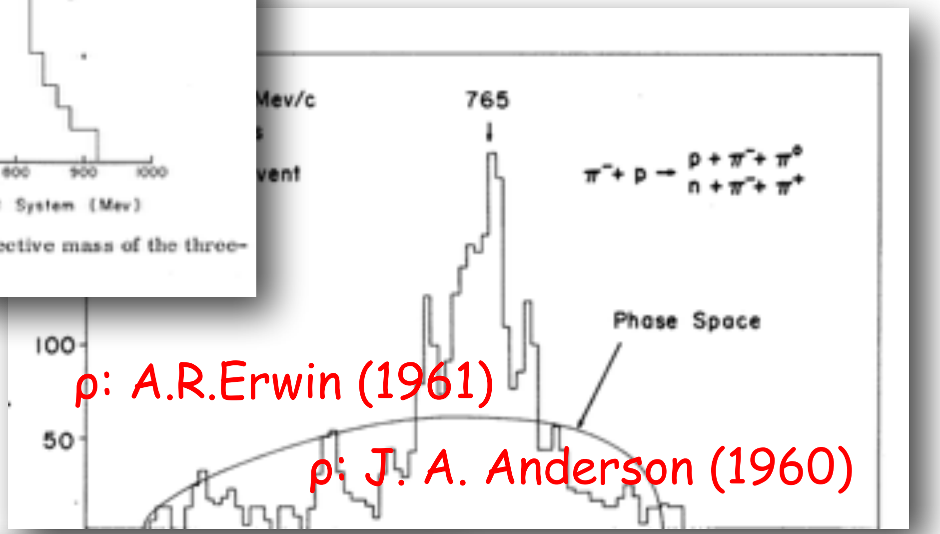
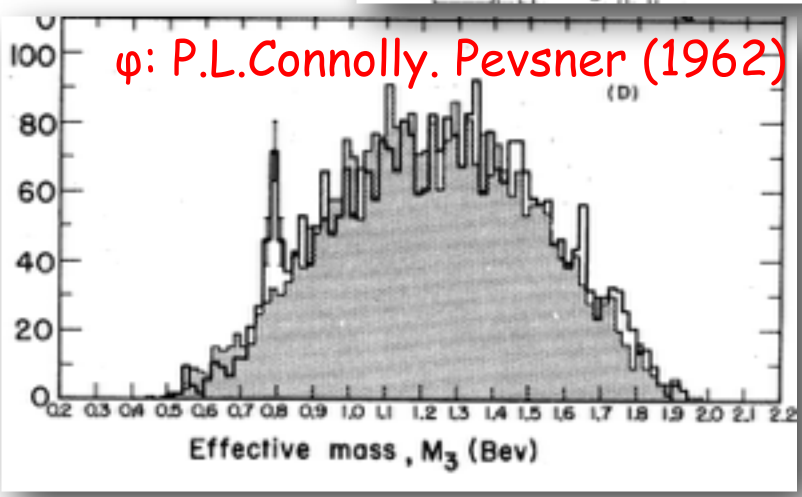


FIG. 2. Histogram of the effective mass of the three-pion system for 233 events.







from the 2009 Review of Particle Physics.
Please use this **CITATION**: C. Amsler et al. (Particle Data Group), Phys. Lett. **B667**, 1 (2008) and 2009 partial update for the 2010 edition.
Cut-off date for this update was January 15, 2009.

back to contents

N BARYONS ($S = 0$, $I = 1/2$)

$p, N^+ = uud$; $n, N^0 = udd$

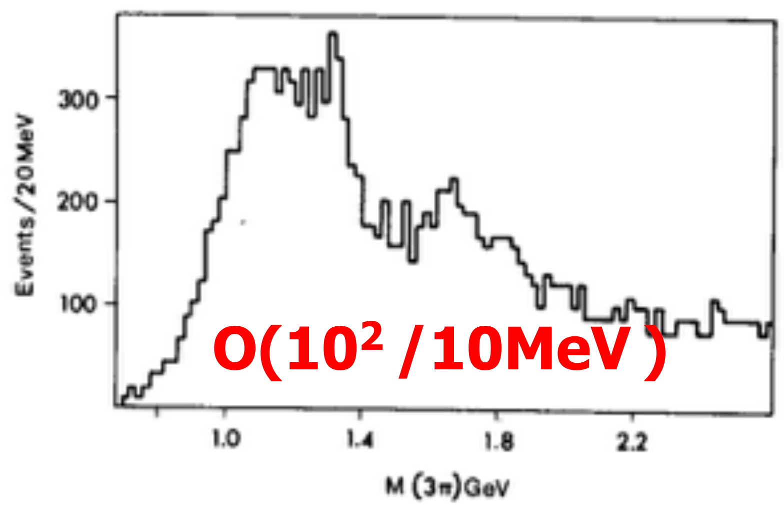
p	1/2(1/2$^+$)	****	$N(1710)\ P_{11}$	1/2(1/2$^+$)	***	• $N(2200)\ D_{15}$	1/2(5/2$^-$)	**
n	1/2(1/2$^+$)	****	$N(1720)\ P_{13}$	1/2(3/2$^+$)	****	$N(2220)\ H_{19}$	1/2(9/2$^+$)	****
$N(1440)\ P_{11}$	1/2(1/2$^+$)	****	• $N(1900)\ P_{13}$	1/2(3/2$^+$)	**	$N(2250)\ G_{19}$	1/2(9/2$^-$)	****
$N(1520)\ D_{13}$	1/2(3/2$^-$)	****	• $N(1990)\ F_{17}$	1/2(7/2$^+$)	**	$N(2600)\ I_{1,11}$	1/2(11/2$^-$)	***
$N(1535)\ S_{11}$	1/2(1/2$^-$)	****	• $N(2000)\ F_{15}$	1/2(5/2$^+$)	**	• $N(2700)\ K_{1,13}$	1/2(13/2$^+$)	**
$N(1650)\ S_{11}$	1/2(1/2$^-$)	****	• $N(2080)\ D_{13}$	1/2(3/2$^-$)	**	• $N(\sim 3000$ Region) Partial-Wave Analyses		
$N(1675)\ D_{15}$	1/2(5/2$^-$)	****	• $N(2090)\ S_{11}$	1/2(1/2$^-$)	*			
$N(1680)\ F_{15}$	1/2(5/2$^+$)	****	• $N(2100)\ P_{11}$	1/2(1/2$^+$)	*	• — OMITTED FROM SUMMARY TABLE		
$N(1700)\ D_{13}$	1/2(3/2$^-$)	***	$N(2190)\ G_{17}$	1/2(7/2$^-$)	****			

Hadron Physics is entering a new area with precision in measurements and theory

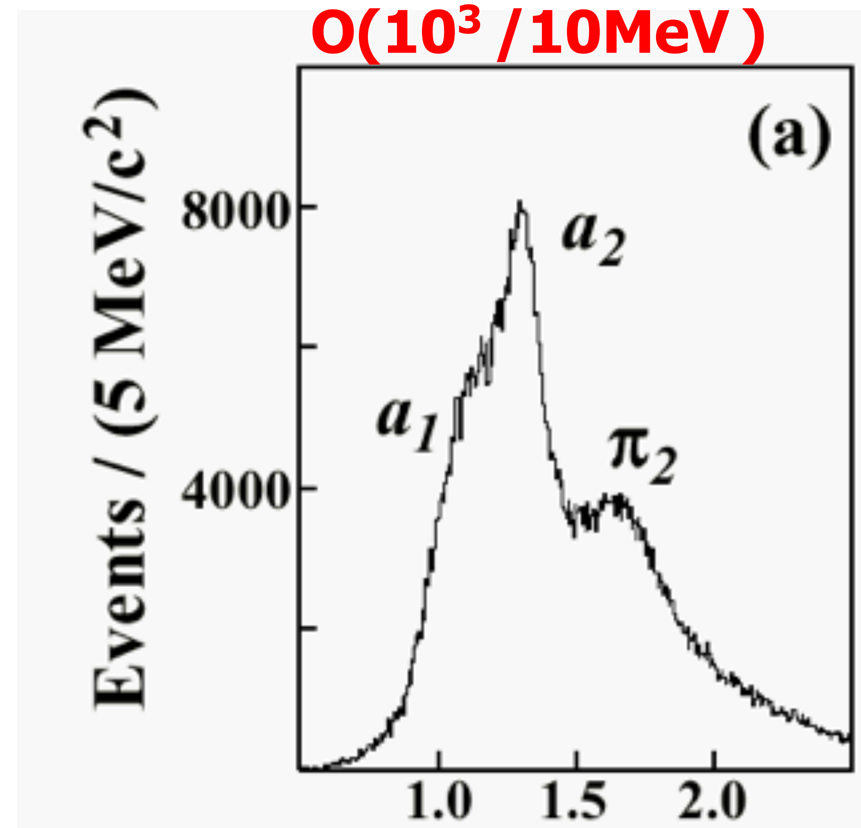
- high statistics
- new beam-target combinations
- polarization measurements
- lattice gauge simulations
- precision reaction amplitude analysis

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

CERN ca. 1970

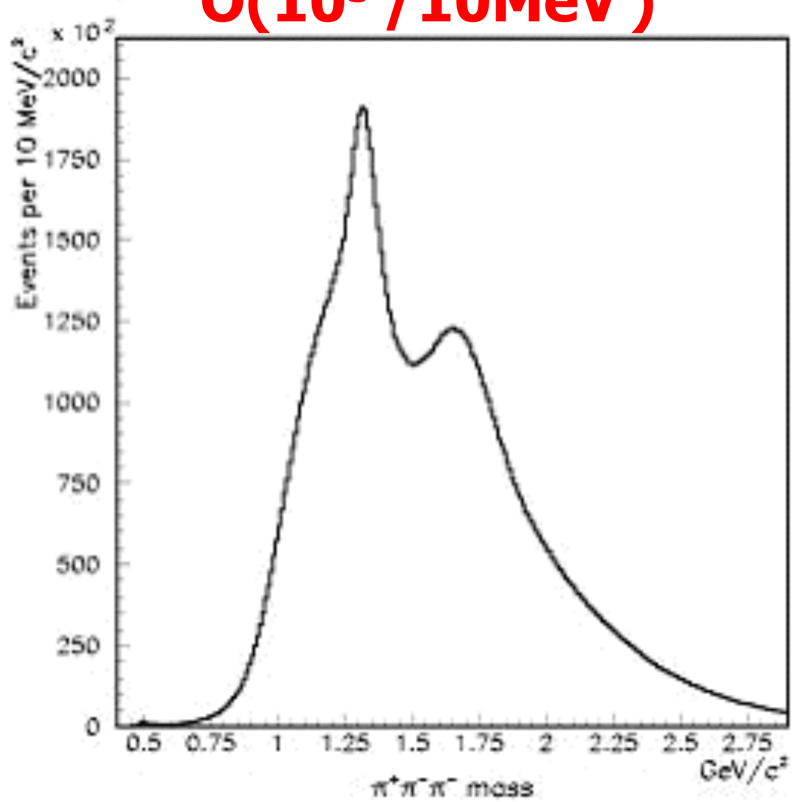


BNL (E852) ca 1995

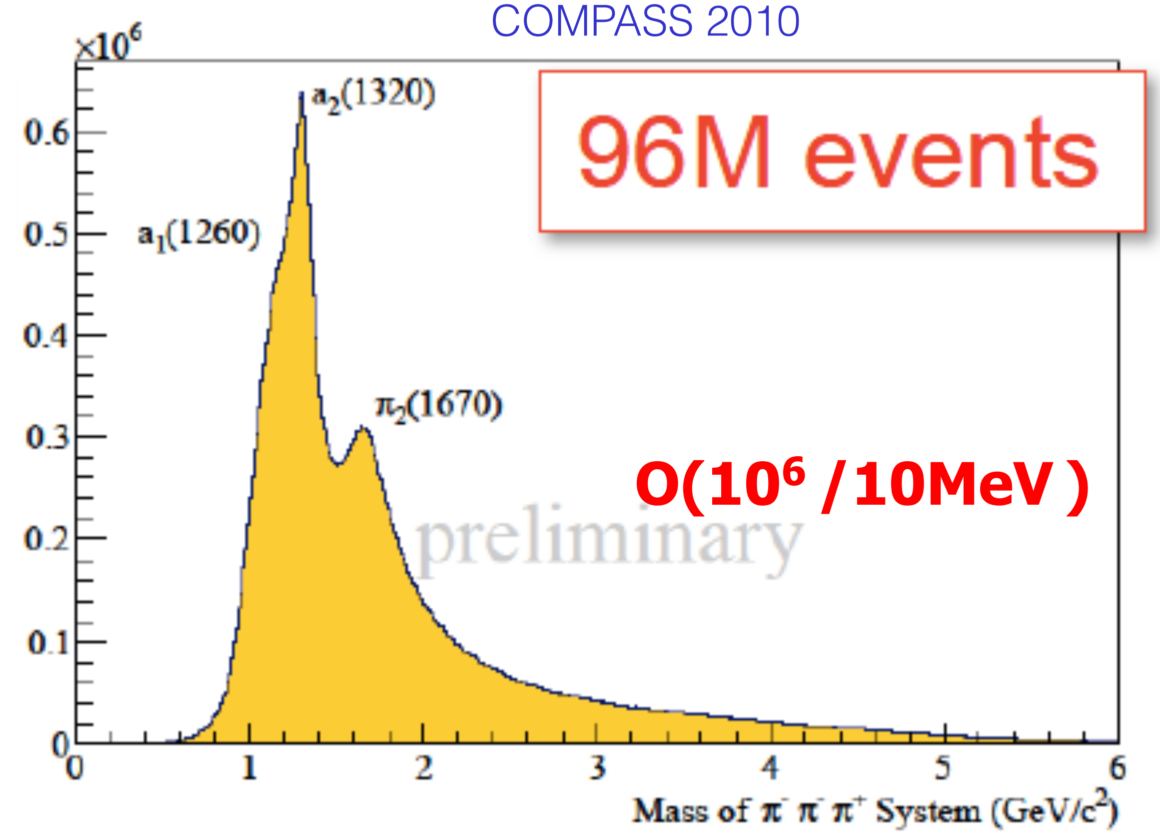


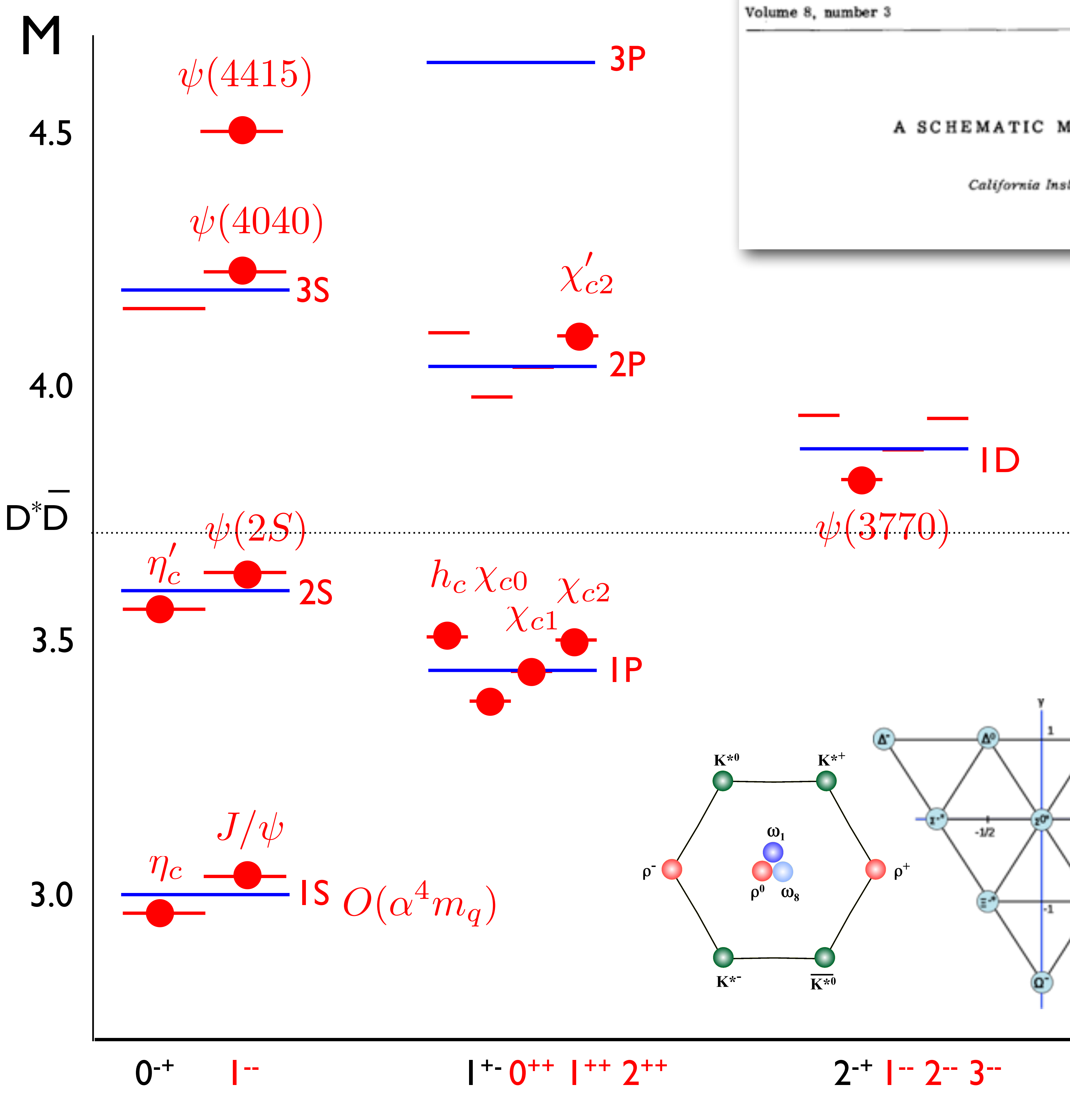
E852 (Full sample)

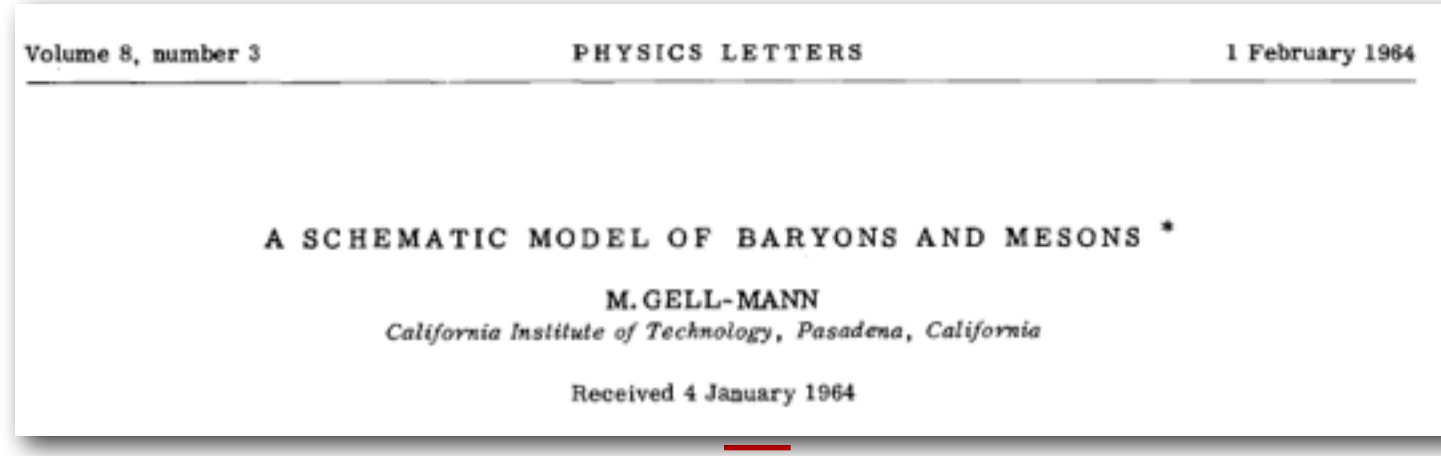
O(10⁵ / 10MeV)



COMPASS 2010





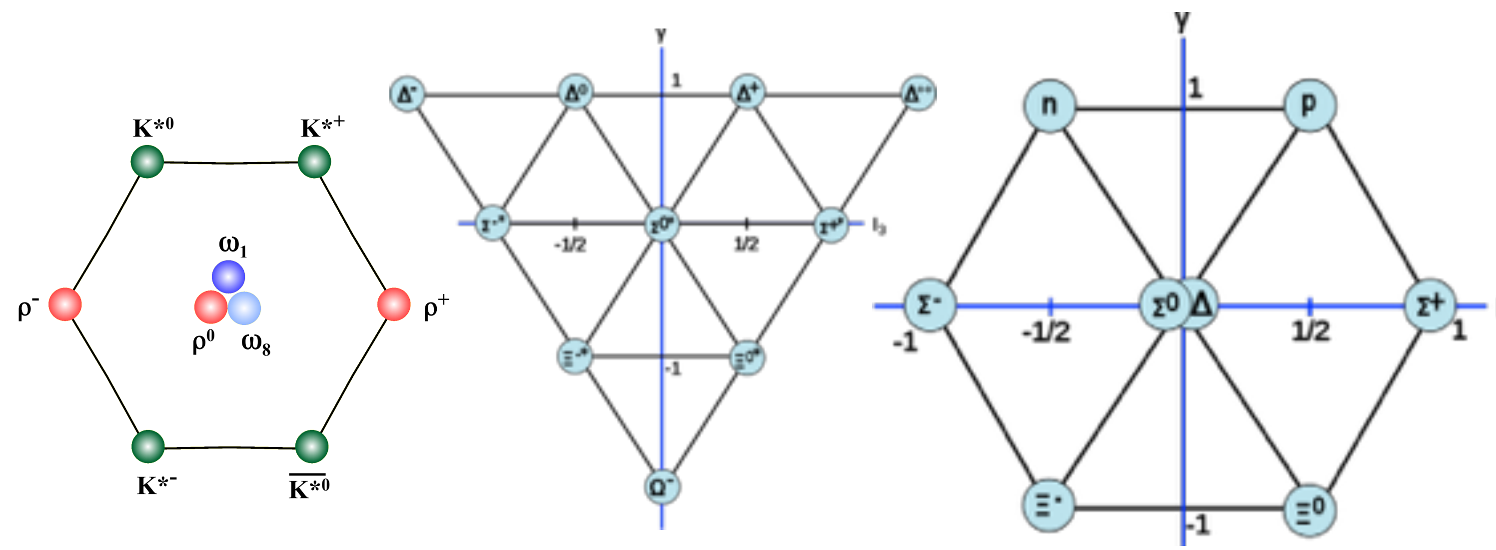

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

From the naive (perturbative) QCD perspective it is hard to understand the origin of the quark model



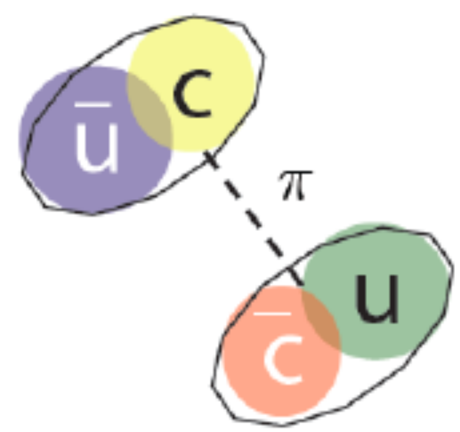
Hadrons beyond quark model

dibaryon

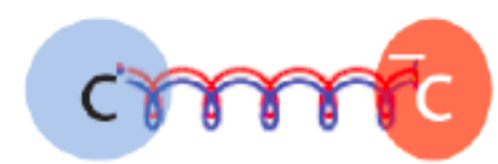
pentaquark

glueball

diquark + di-antiquark



dimeson molecule



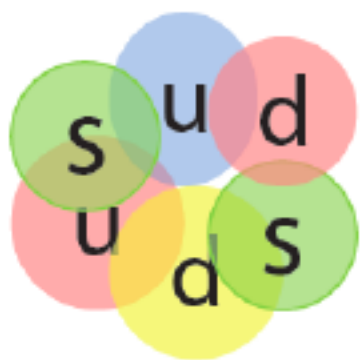
$q\,\bar{q}\,g$ hybrid

It is difficult to “picture” what’s going on inside hadrons when we are lacking intuition about:

small world (10^{-15}m) of fast (v~c) particles exerting ~1T forces !!!

- Do hadrons beyond those predicted by the quark model exist ?
- How to “poke” gluons ?
- How does the inside of the proton look like ?
- Can we actually compute the hadron spectrum and determine their structure from first principles ?

Hadrons beyond quark model

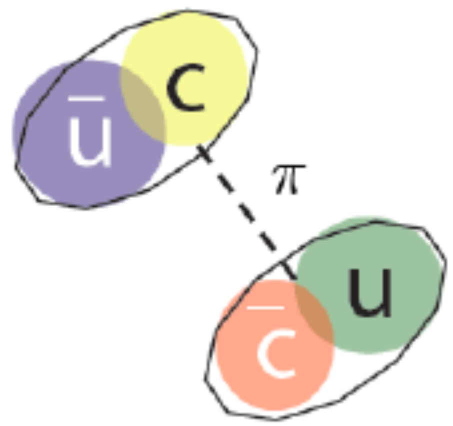


dibaryon

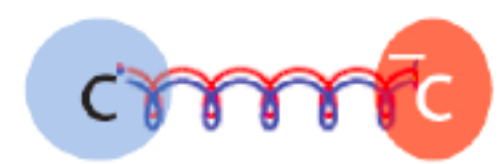
pentaquark

glueball

diquark + di-antiquark

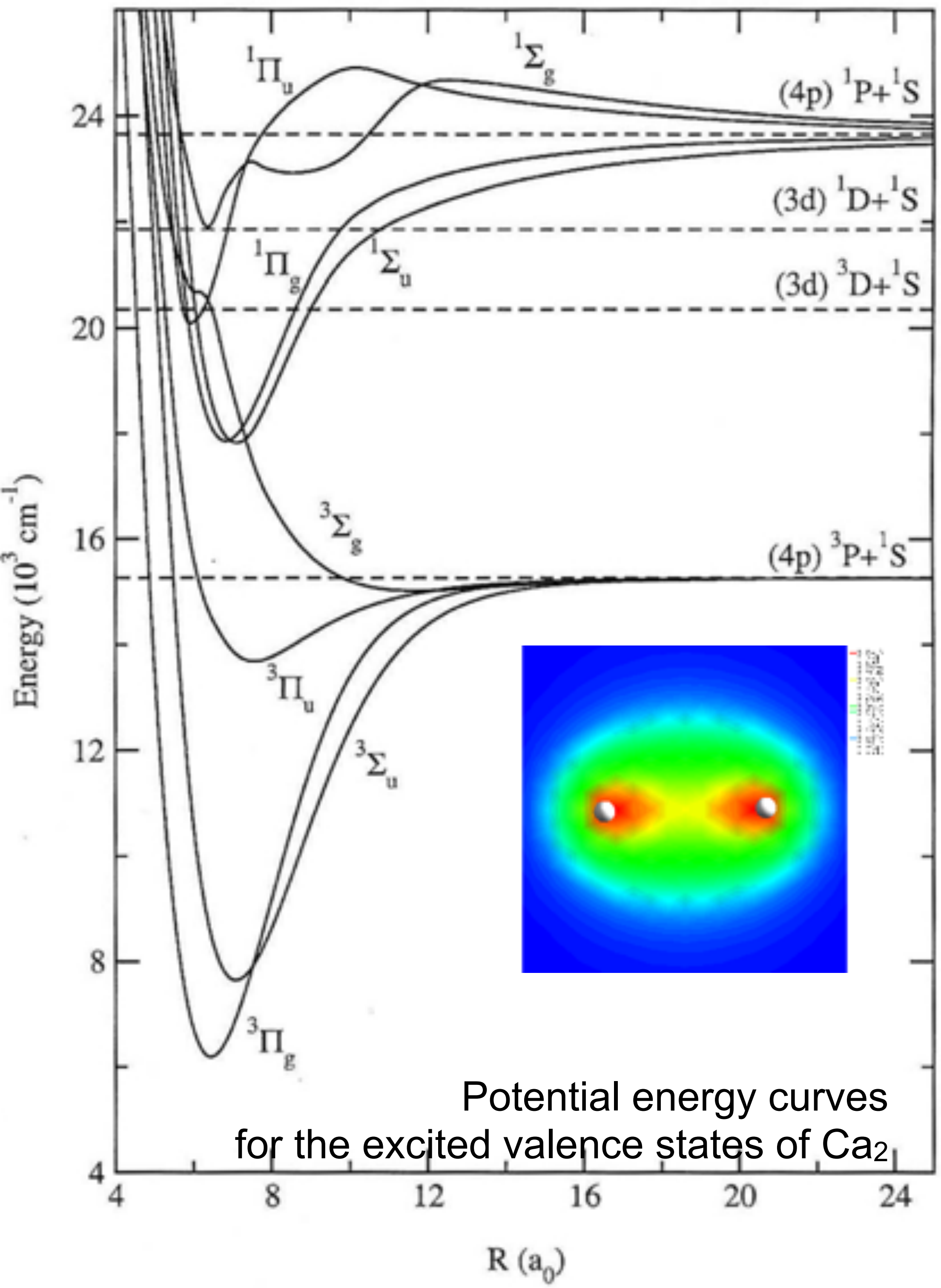


dimeson molecule

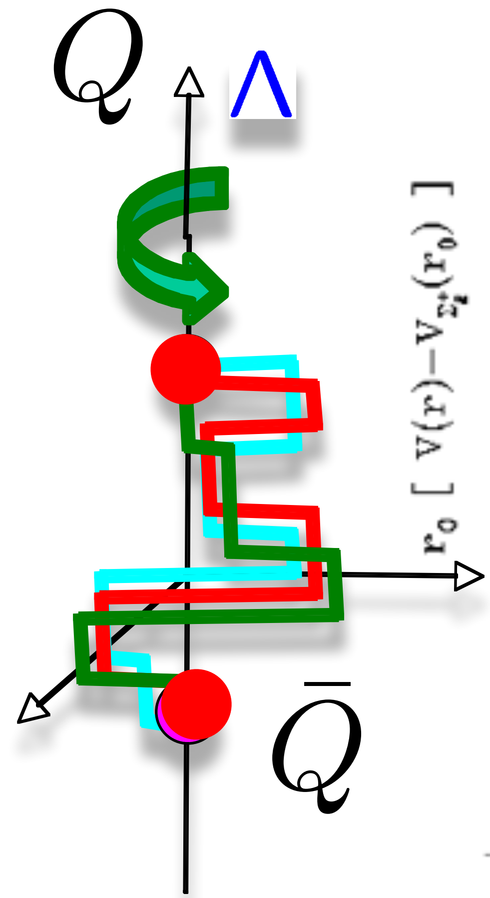


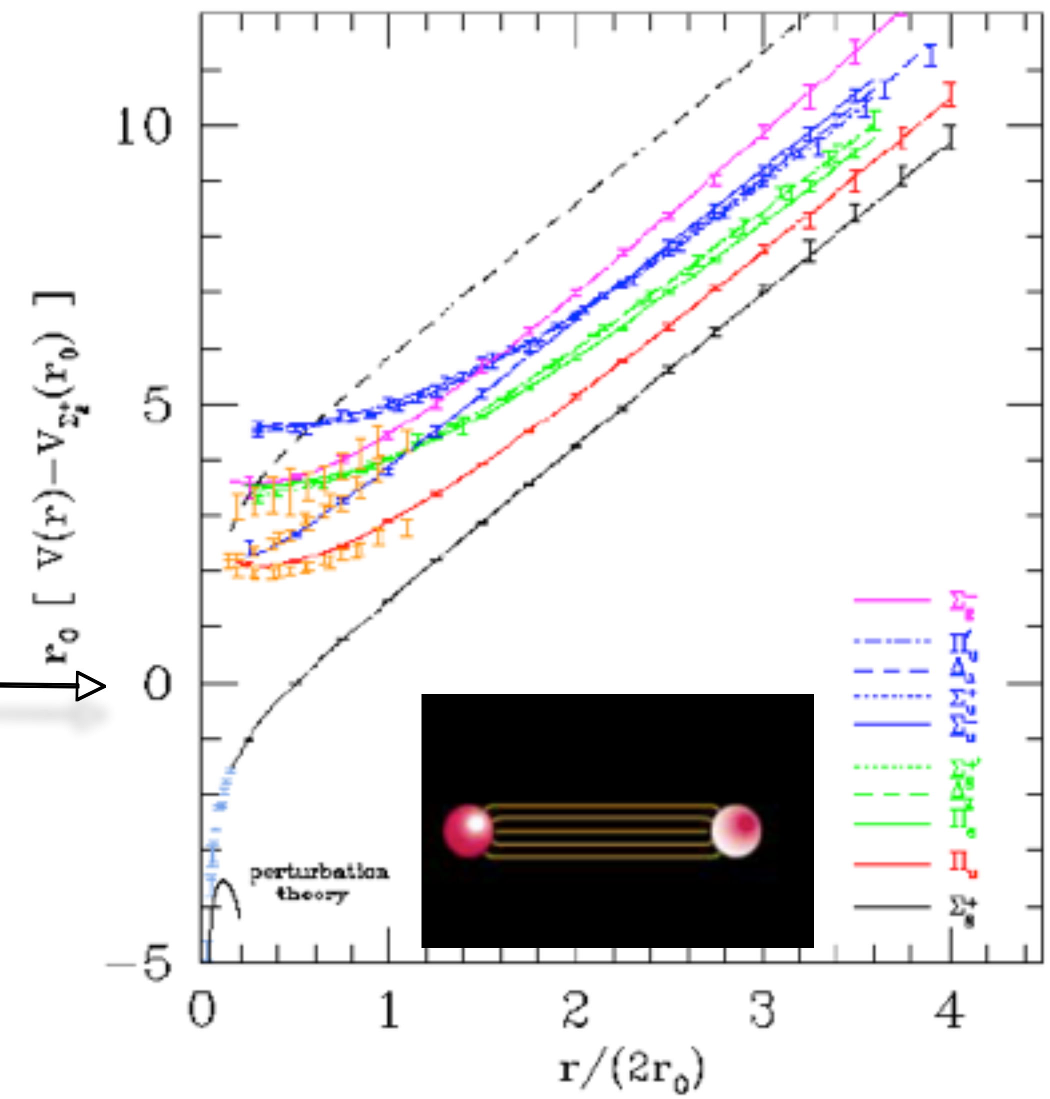
$q\,\bar{q}\,g$ hybrid

Static $Q\bar{Q}$ pair as a diatomic molecule

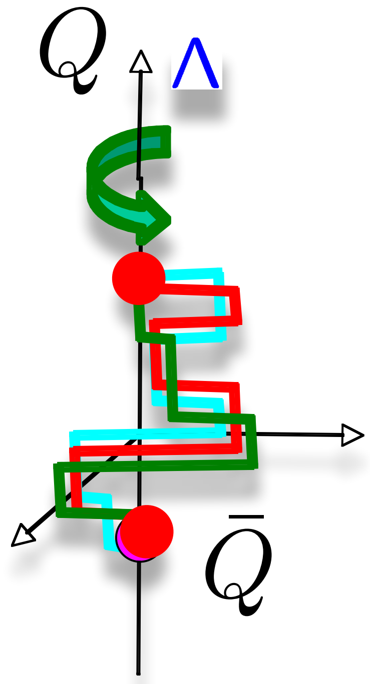


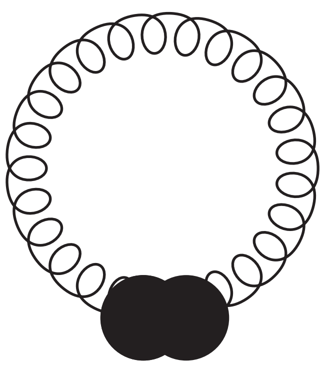
Potential energy curves for the excited valence states of Ca_2

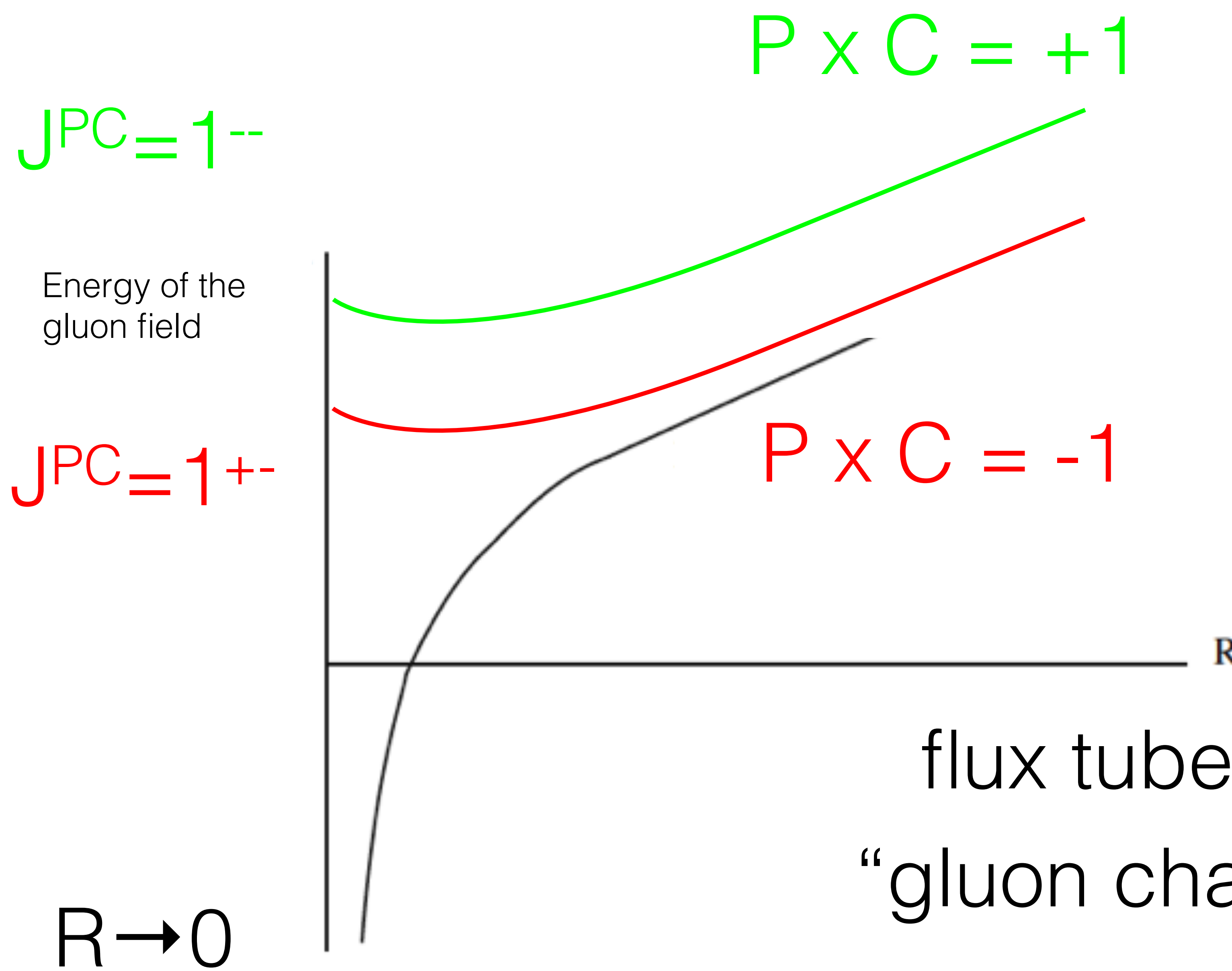


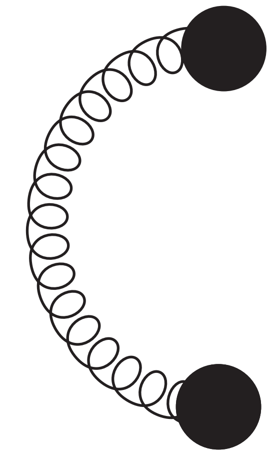


- Excited adiabatic potentials map out distribution of exited gluons





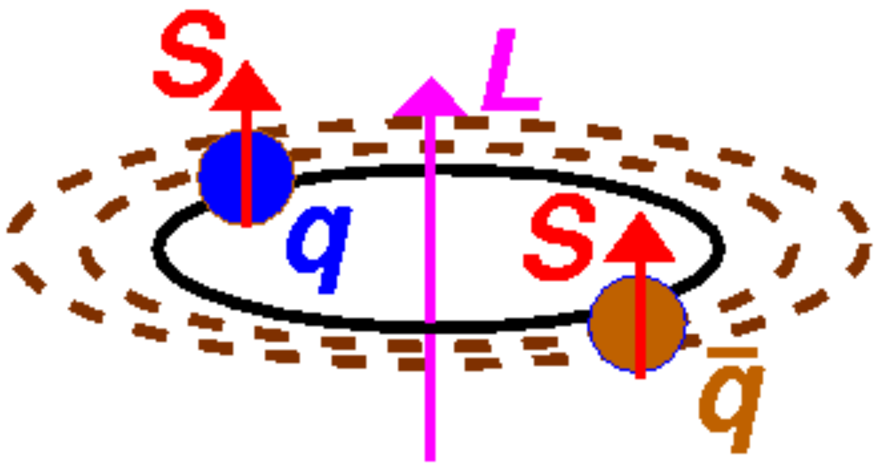




flux tube
“gluon chain”

glue-lump

gluons behave as physical particles with J^{PC} = 1^{+-}



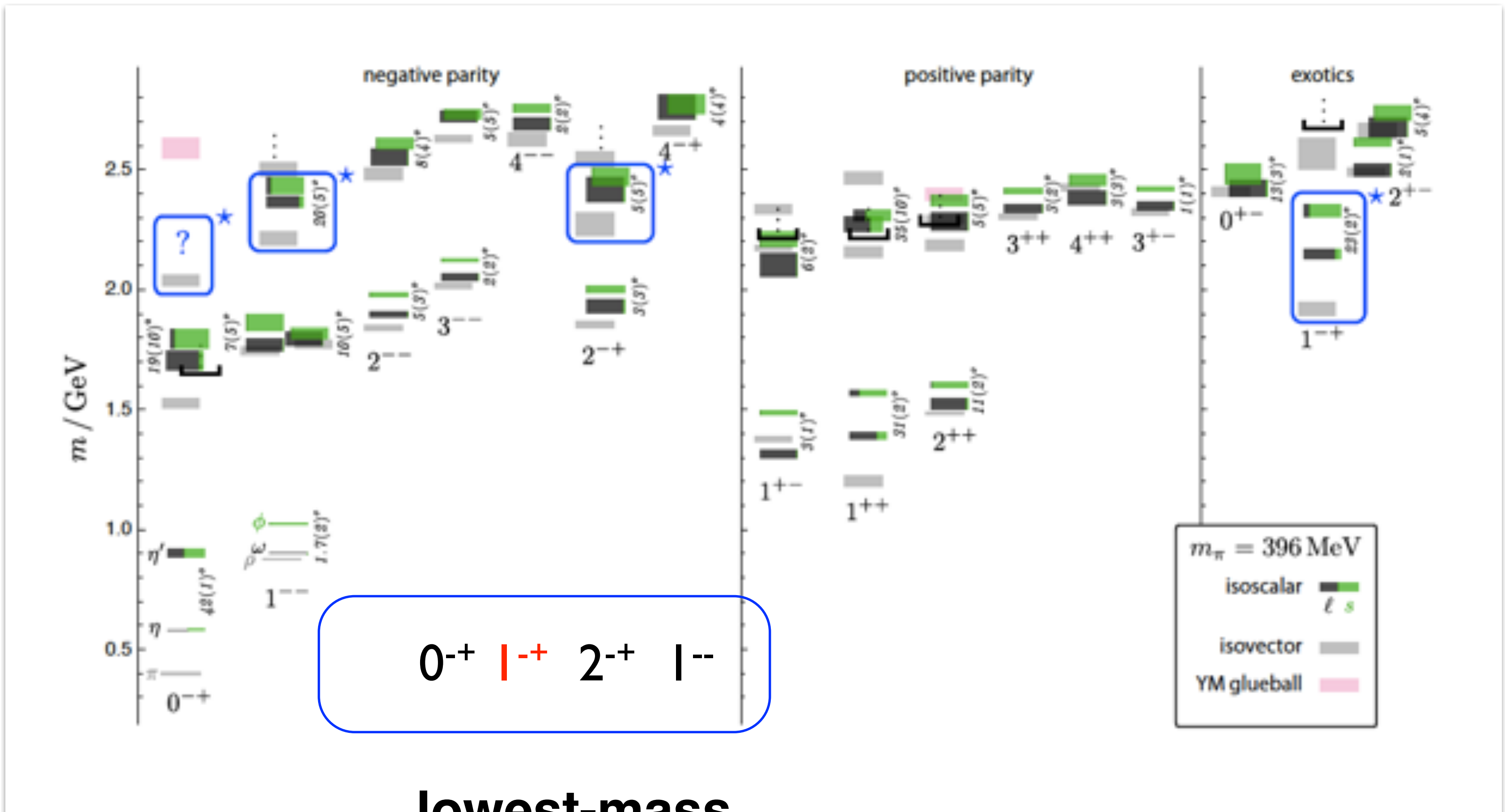
$$P_{q\bar{q}} = (-1)^{L+1}$$
$$C_{q\bar{q}} = (-1)^{L+S}$$

Mesons with
JPC = 0--,0+-,1-+,2+- :
Exotic Quantum Numbers

J^{PC} glue

J^{PC} $Q\bar{Q}$

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



lowest-mass hybrid multiplet

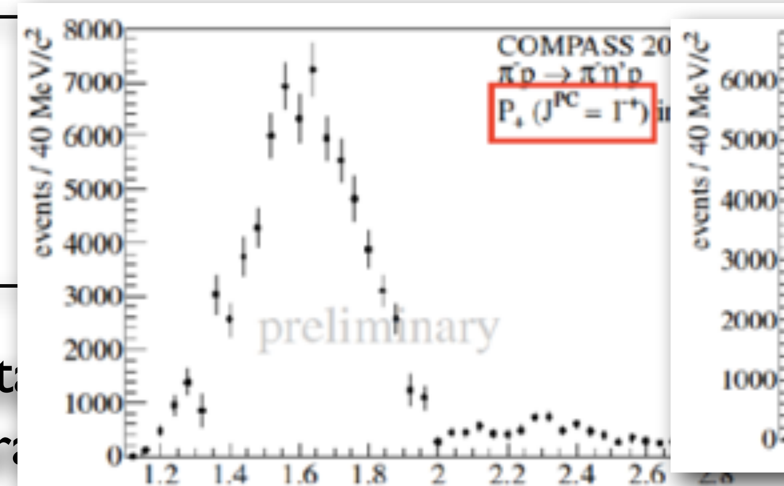
$\pi^- p \rightarrow \eta \pi^- p$

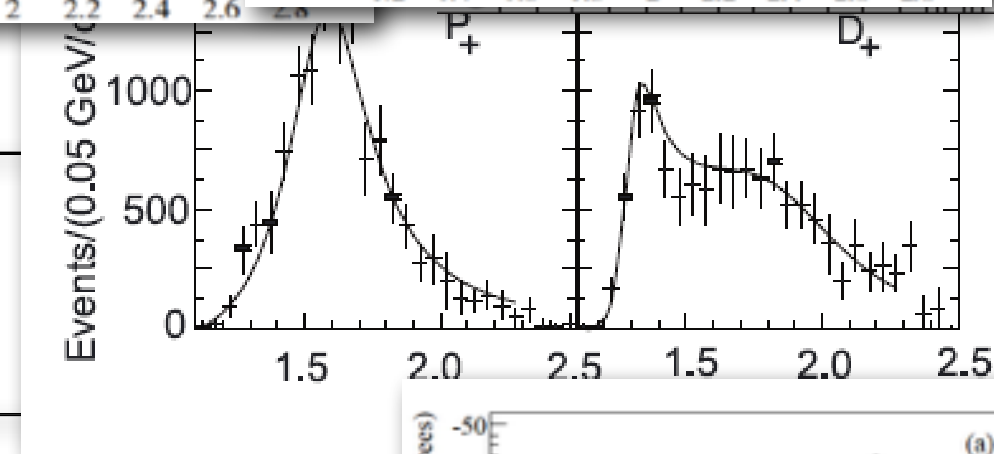
$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

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

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

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





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

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

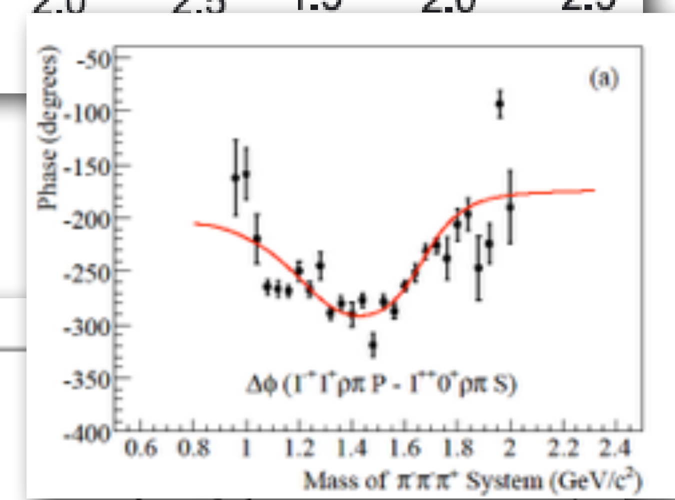
$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2

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

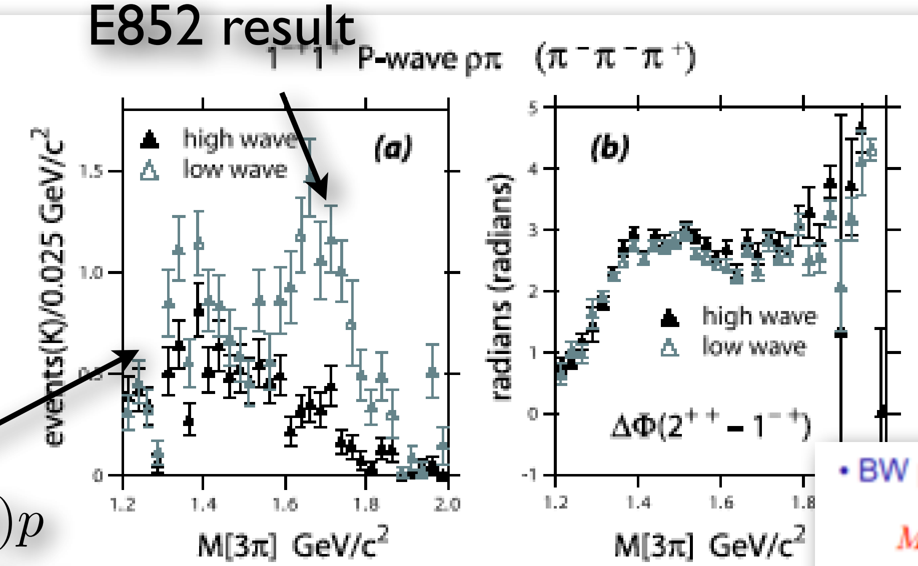
$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2

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

BNL (E852) yes/no
COMPASS yes



E852 result



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

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

ρ^0

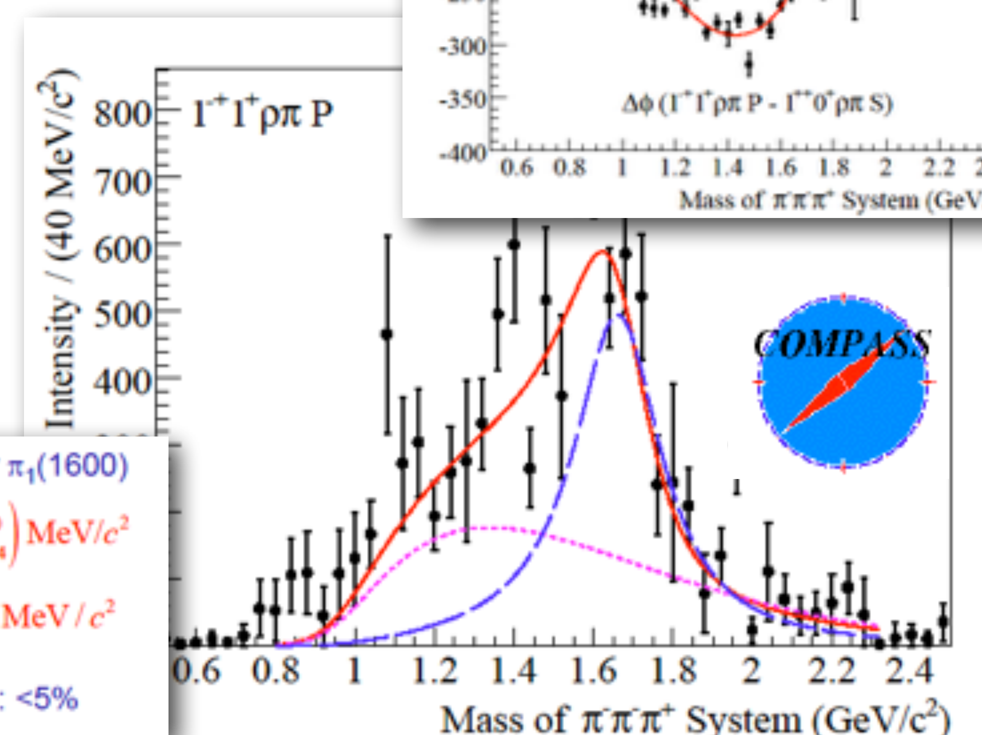
FIG. 25: (a) The $1^{-+}1^{+}$ P-wave $\rho\pi$ partial wave
charged mode $(\pi^-\pi^-\pi^+)$ for the high-wave set PWA a
low-wave set PWA and (b) the phase difference $\Delta\Phi$ b
the 2^{++} and 1^{-+} for the two wave sets.

- BW parameters for $\pi_1(1600)$

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

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

- Leakage negligible: <5%



$\pi^- p \rightarrow \eta \pi^- p$

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

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

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

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

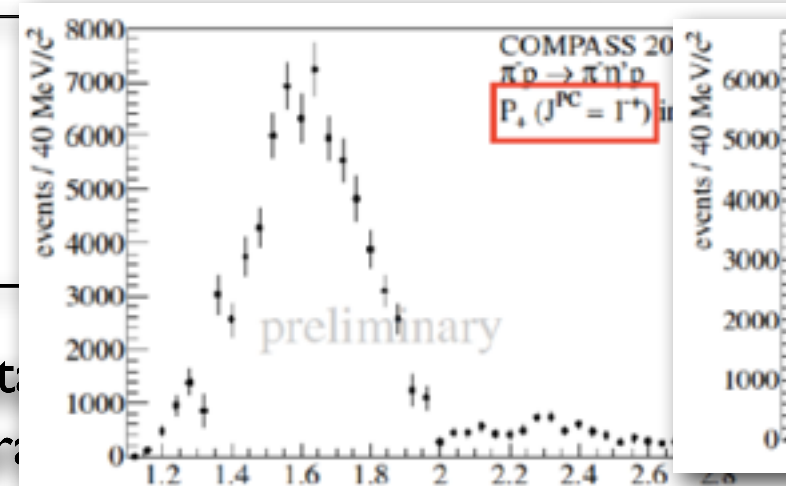
$\pi^- p \rightarrow \eta' \pi^- p$

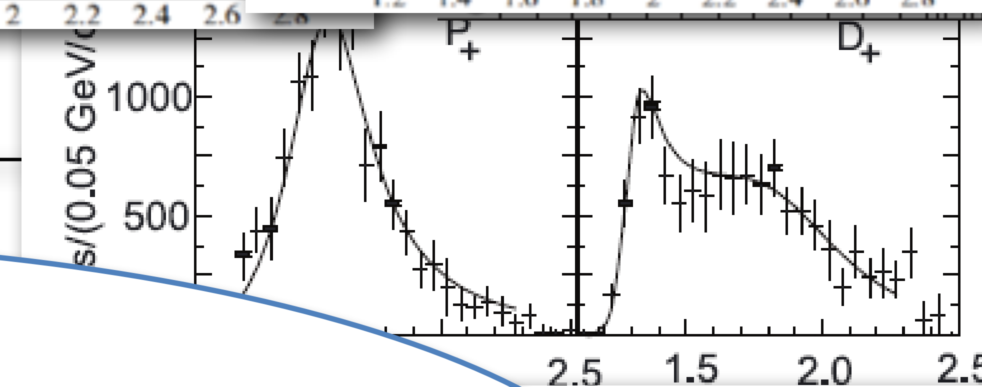
$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

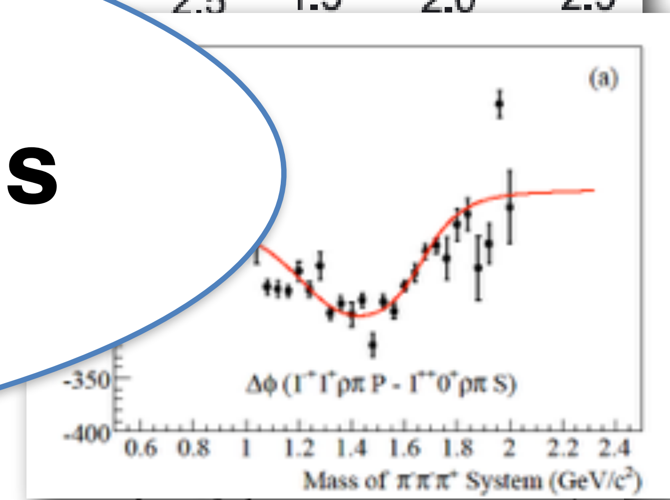
$\Gamma = 34$

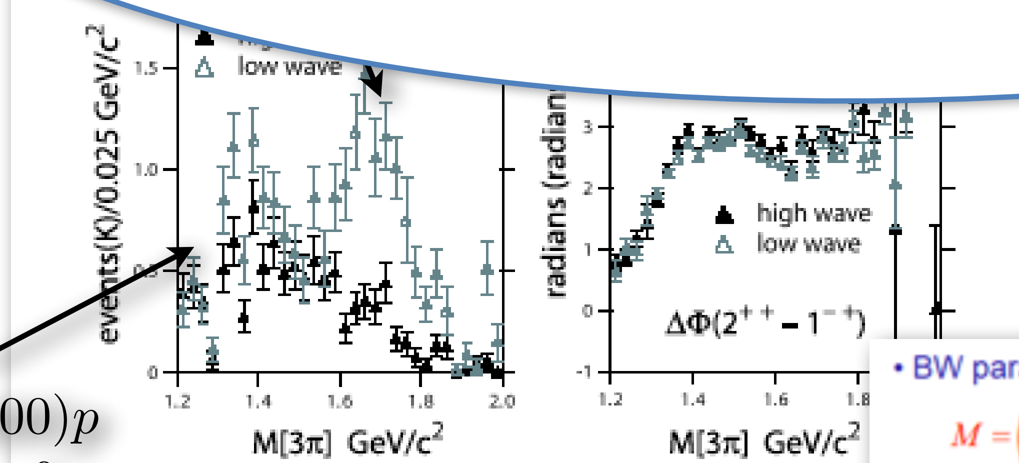
$\pi^- p \rightarrow \rho^0$

Need confirmation/more analysis









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

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

$\rho^0 \rightarrow \pi^- \pi^+$

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

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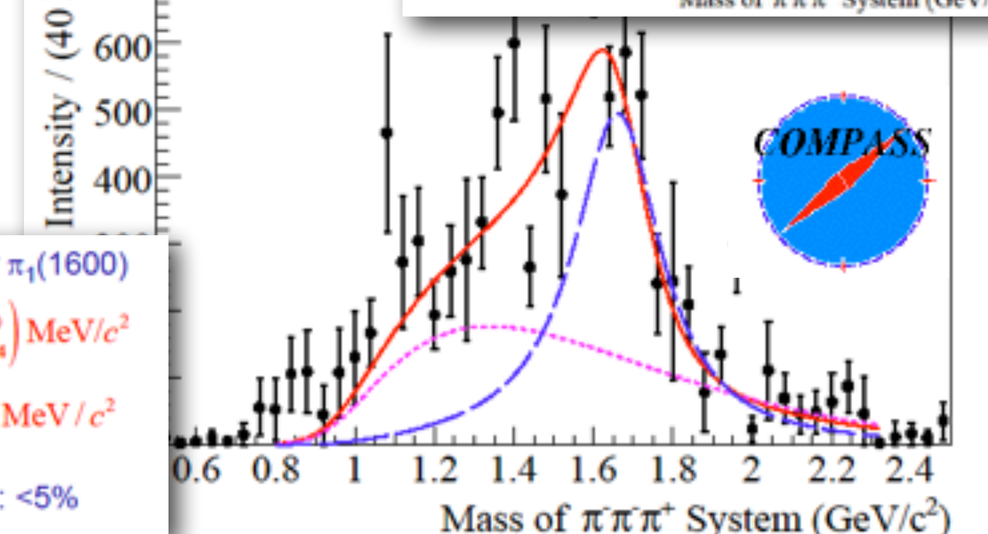
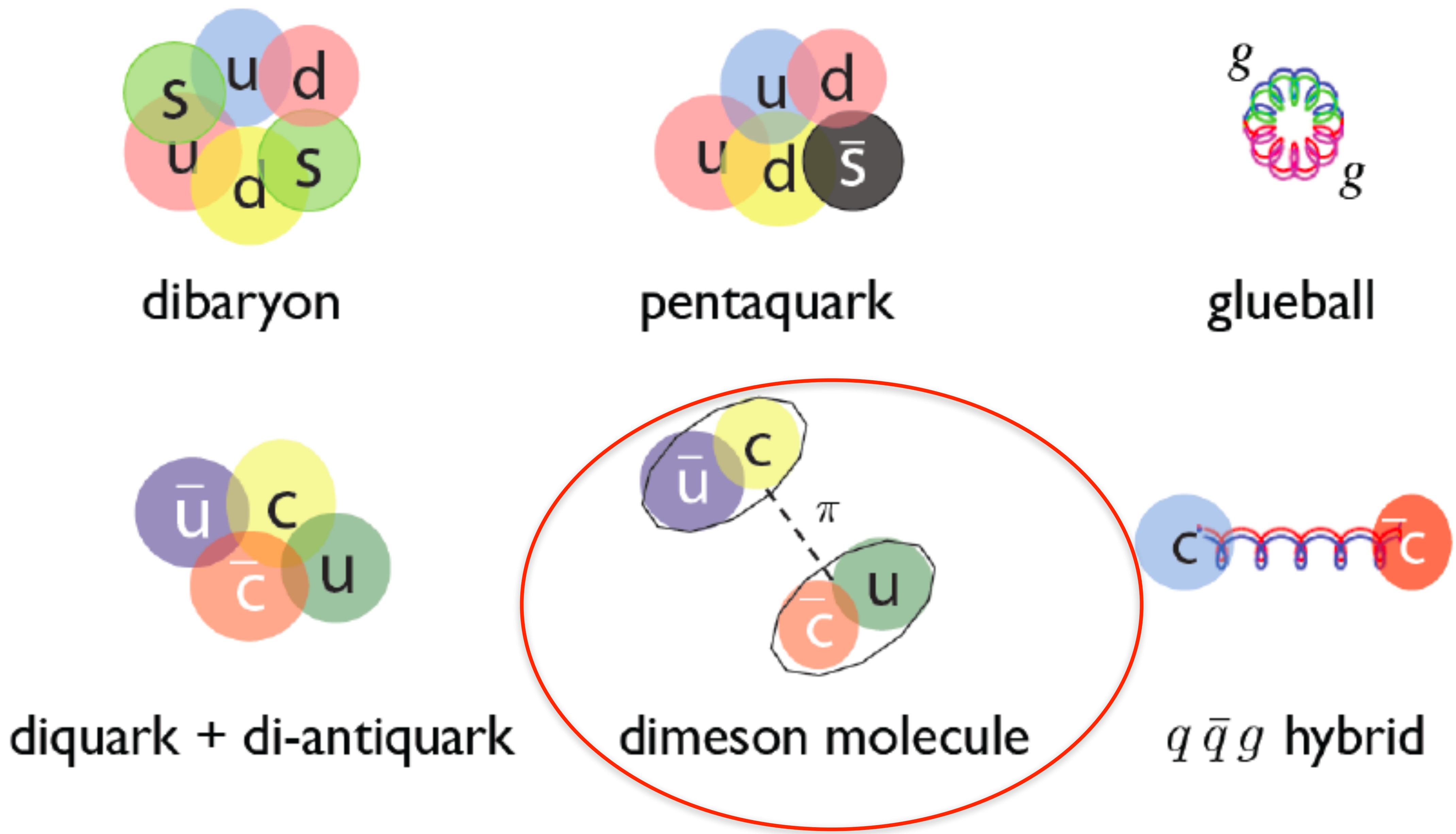
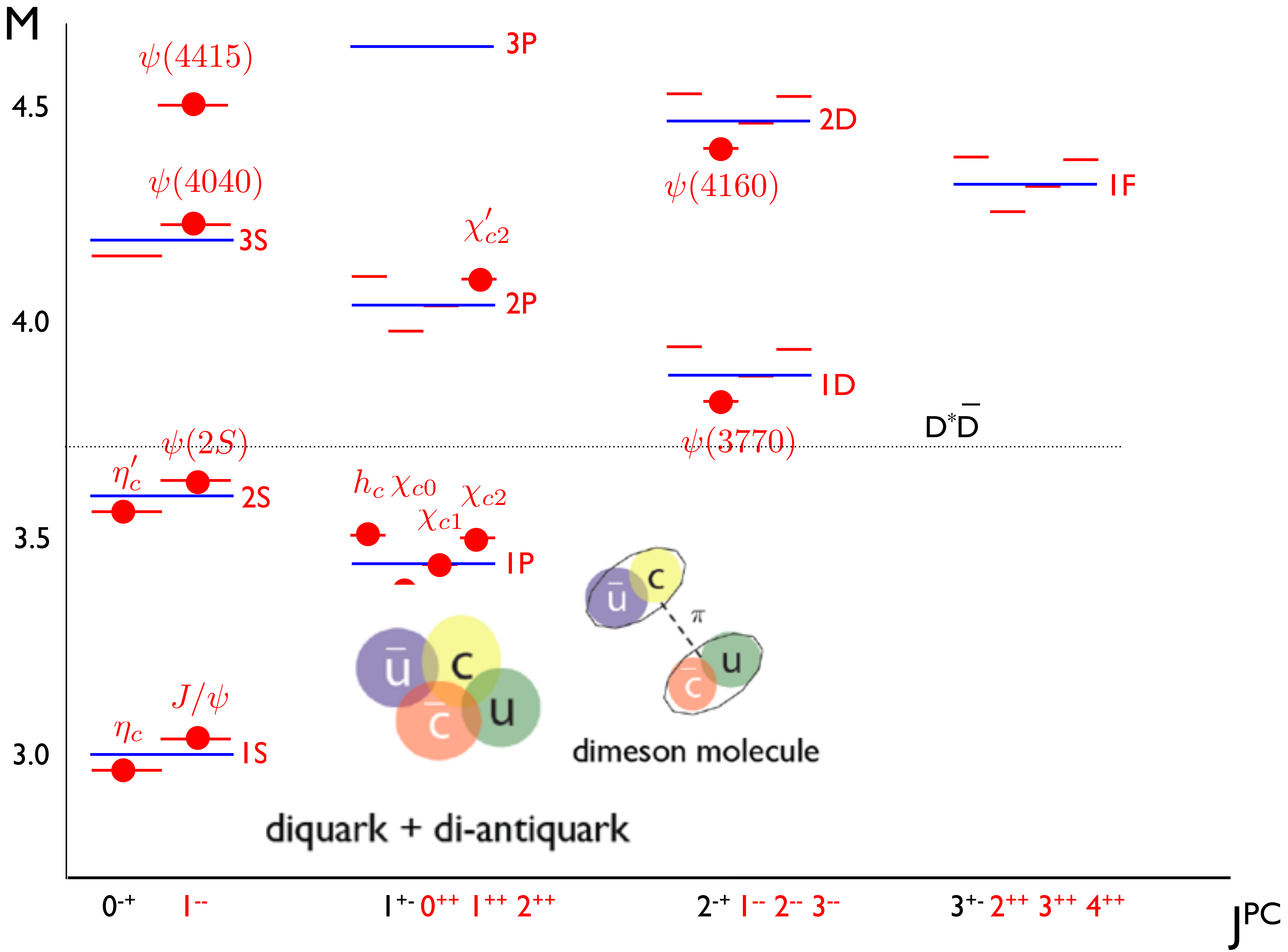
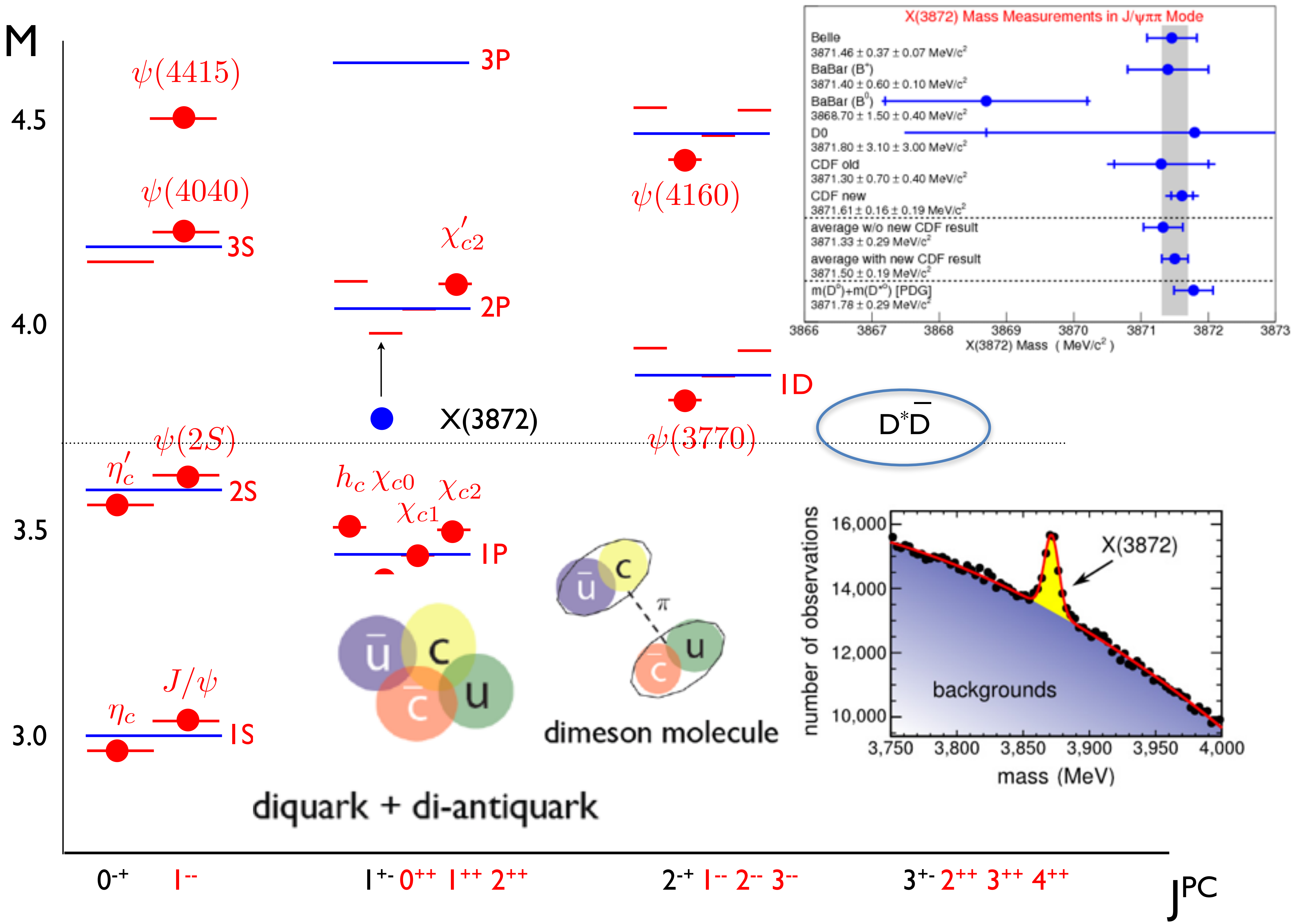


Hadrons beyond quark model



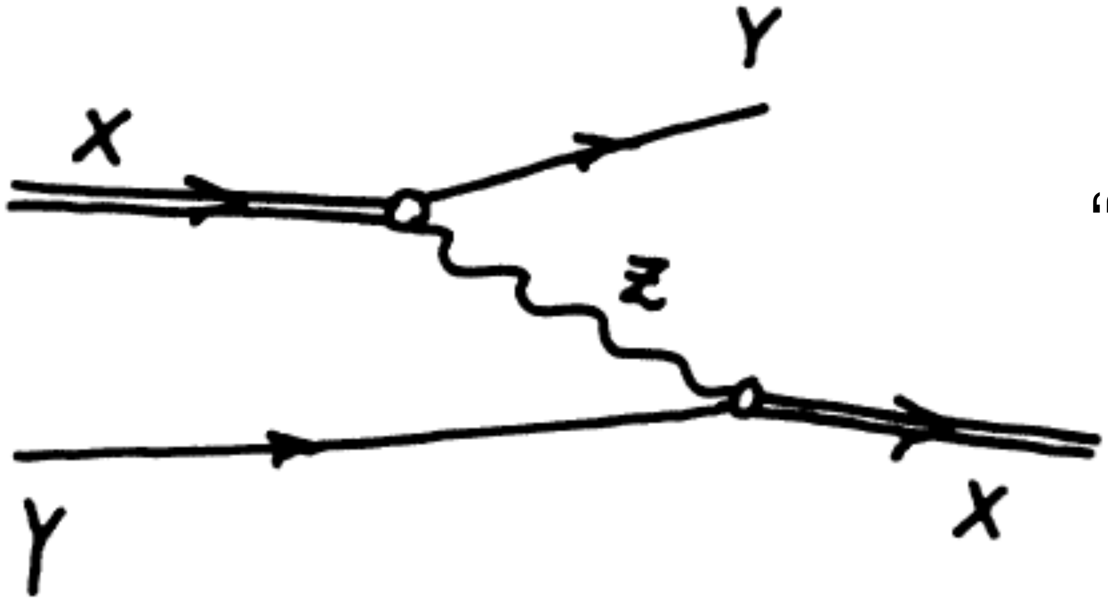

M
4.5
4.0
3.5
3.0
$\psi(4415)$
$\psi(4040)$
3S
$\psi(2S)$
η_c'
2S
J/ψ
η_c
1S
3P
χ_{c2}'
2P
$h_c\ \chi_{c0}$
χ_{c2}
χ_{c1}
1P
2D
$\psi(4160)$
1D
$\psi(3770)$
1F
$D^*\bar{D}$
$\bar{u}$ c
$\bar{c}$ u
dimeson molecule
π
diquark + di-antiquark
0^{-+} 1^{--}
1^{+-} 0^{++} 1^{++} 2^{++}
2^{-+} 1^{--} 2^{--} 3^{--}
3^{+-} 2^{++} 3^{++} 4^{++}
J^{PC}


M
4.5
4.0
3.5
3.0
ψ(4415)
ψ(4040)
3S
ψ(2S)
η′c
2S
J/ψ
ηc
1S
3P
χ′c2
2P
X(3872)
hc χc0
χc1
χc2
1P
ψ(4160)
1D
ψ(3770)
D*D̄
X(3872) Mass Measurements in J/ψππ Mode
Belle
3871.46 ± 0.37 ± 0.07 MeV/c²
BaBar (B⁺)
3871.40 ± 0.60 ± 0.10 MeV/c²
BaBar (B⁰)
3868.70 ± 1.50 ± 0.40 MeV/c²
D0
3871.80 ± 3.10 ± 3.00 MeV/c²
CDF old
3871.30 ± 0.70 ± 0.40 MeV/c²
CDF new
3871.61 ± 0.16 ± 0.19 MeV/c²
average w/o new CDF result
3871.33 ± 0.29 MeV/c²
average with new CDF result
3871.50 ± 0.19 MeV/c²
m(D⁰)+m(D*⁰) [PDG]
3871.78 ± 0.29 MeV/c²
3866 3867 3868 3869 3870 3871 3872 3873
X(3872) Mass (MeV/c²)
number of observations
16,000
14,000
12,000
10,000
X(3872)
backgrounds
3,750 3,800 3,850 3,900 3,950 4,000
mass (MeV)
ū c
c̄ u
π
dimeson molecule
diquark + di-antiquark
0⁻⁺ 1⁻⁻
1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺
2⁻⁺ 1⁻⁻ 2⁻⁻ 3⁻⁻
3⁺⁻ 2⁺⁺ 3⁺⁺ 4⁺⁺
J^PC

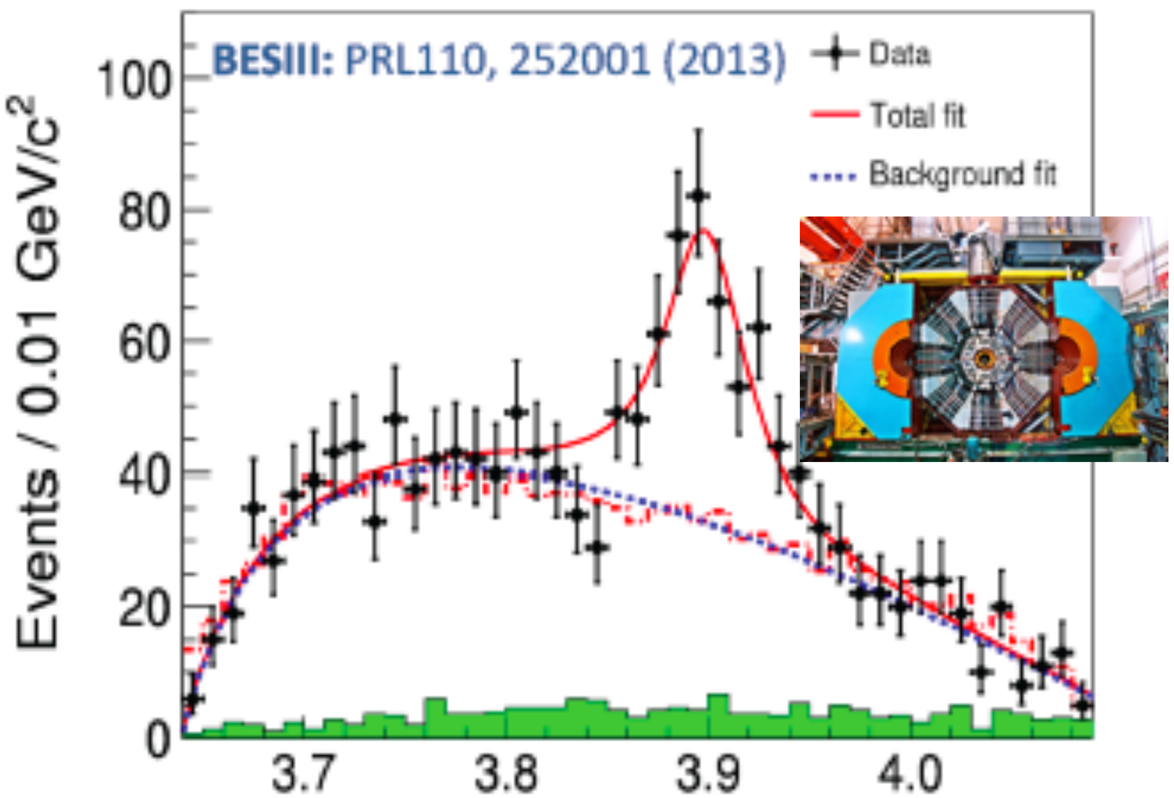
REMARK ON ENERGY PEAKS IN MESON SYSTEMS

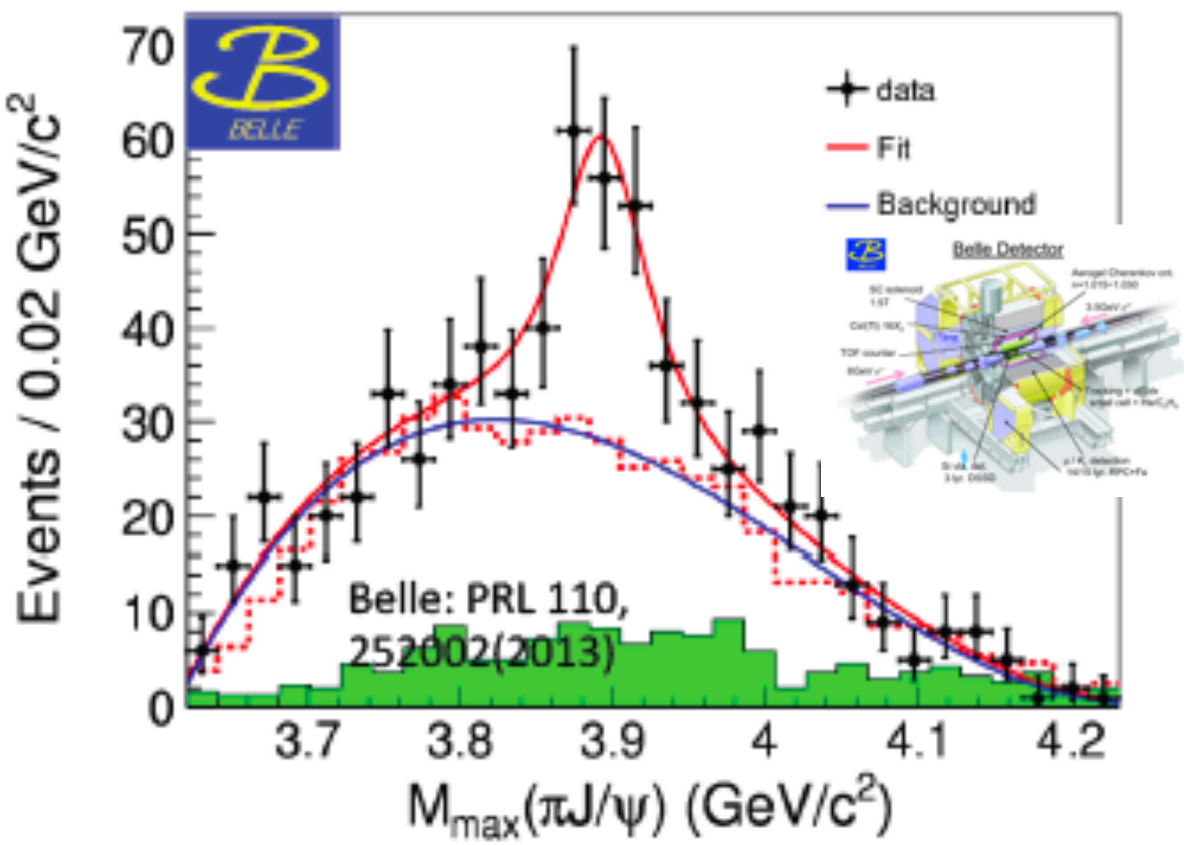
M. Nauenberg A. Pais

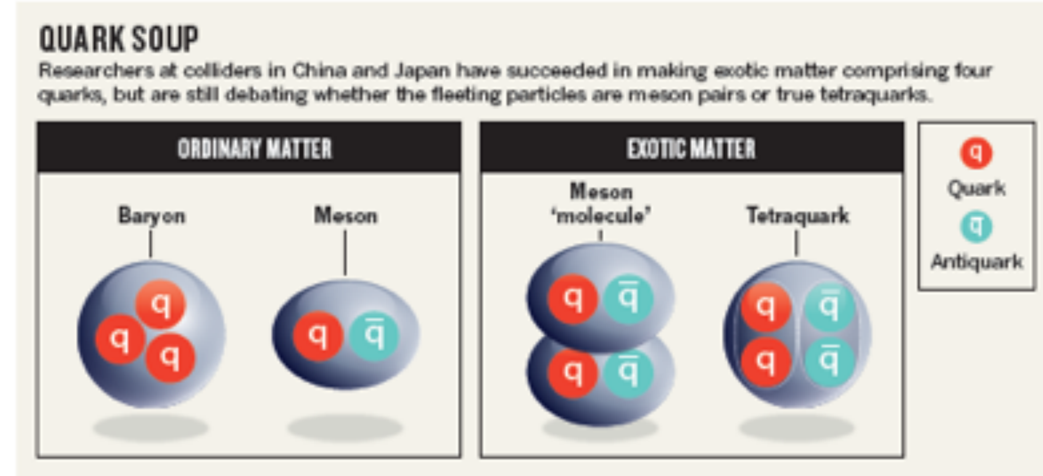
If the width of particle X is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical s causes the peaking effect to which we refer as an (X, Y, Z) peak.



"Peierls mechanism"



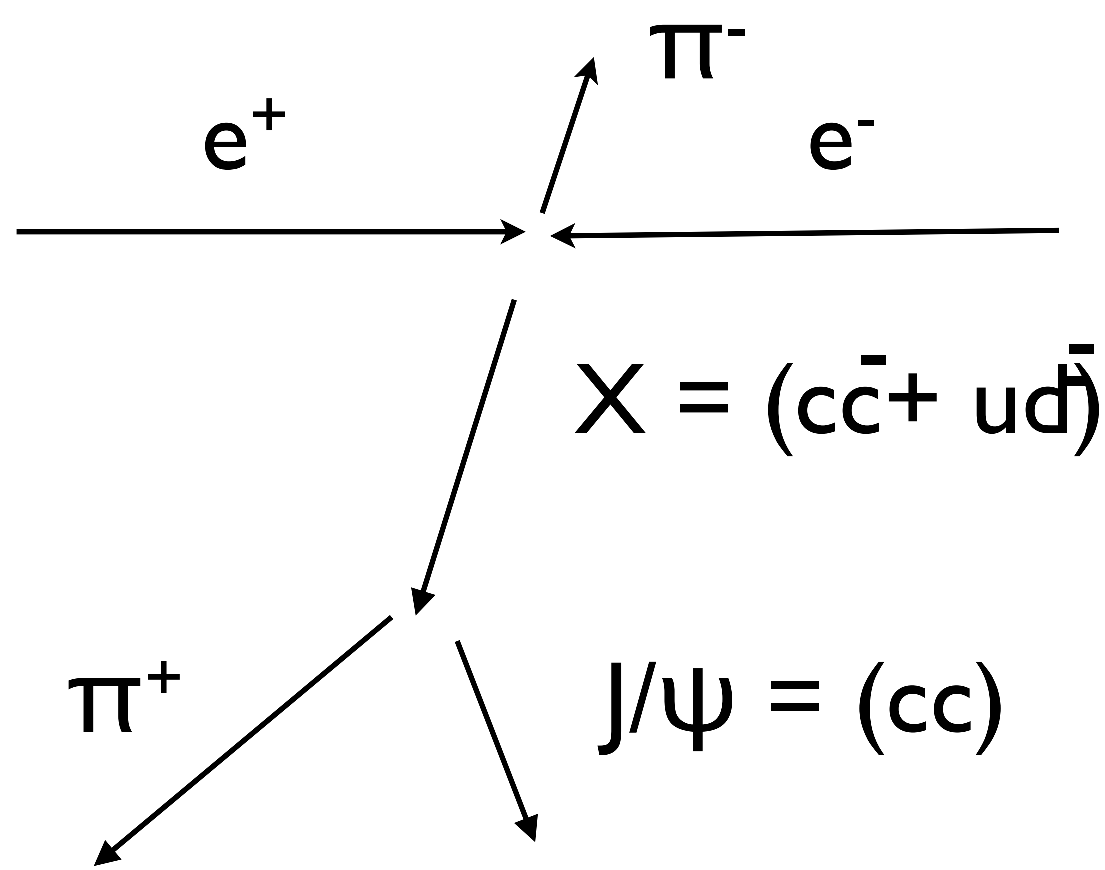




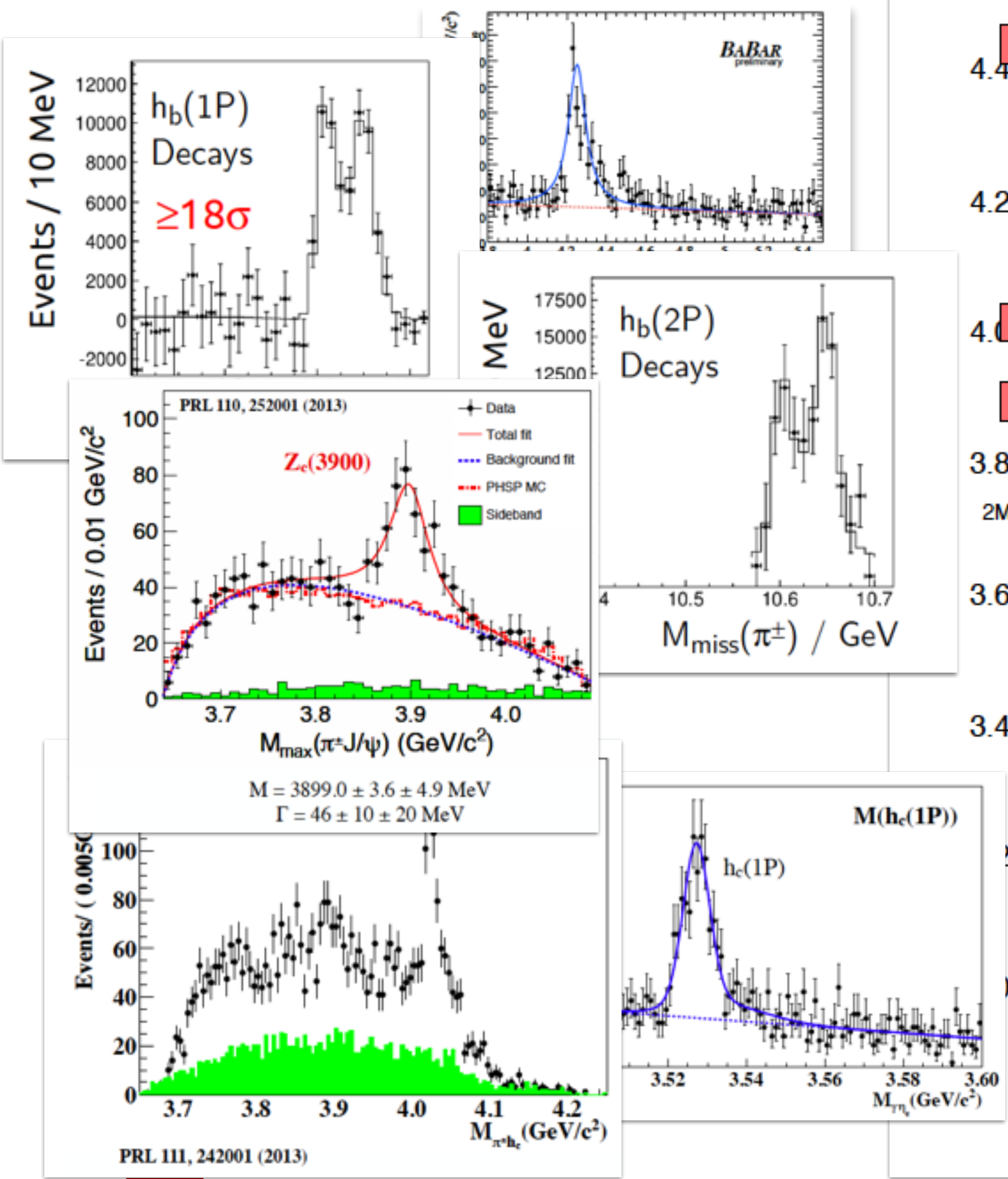
PARTICLE PHYSICS

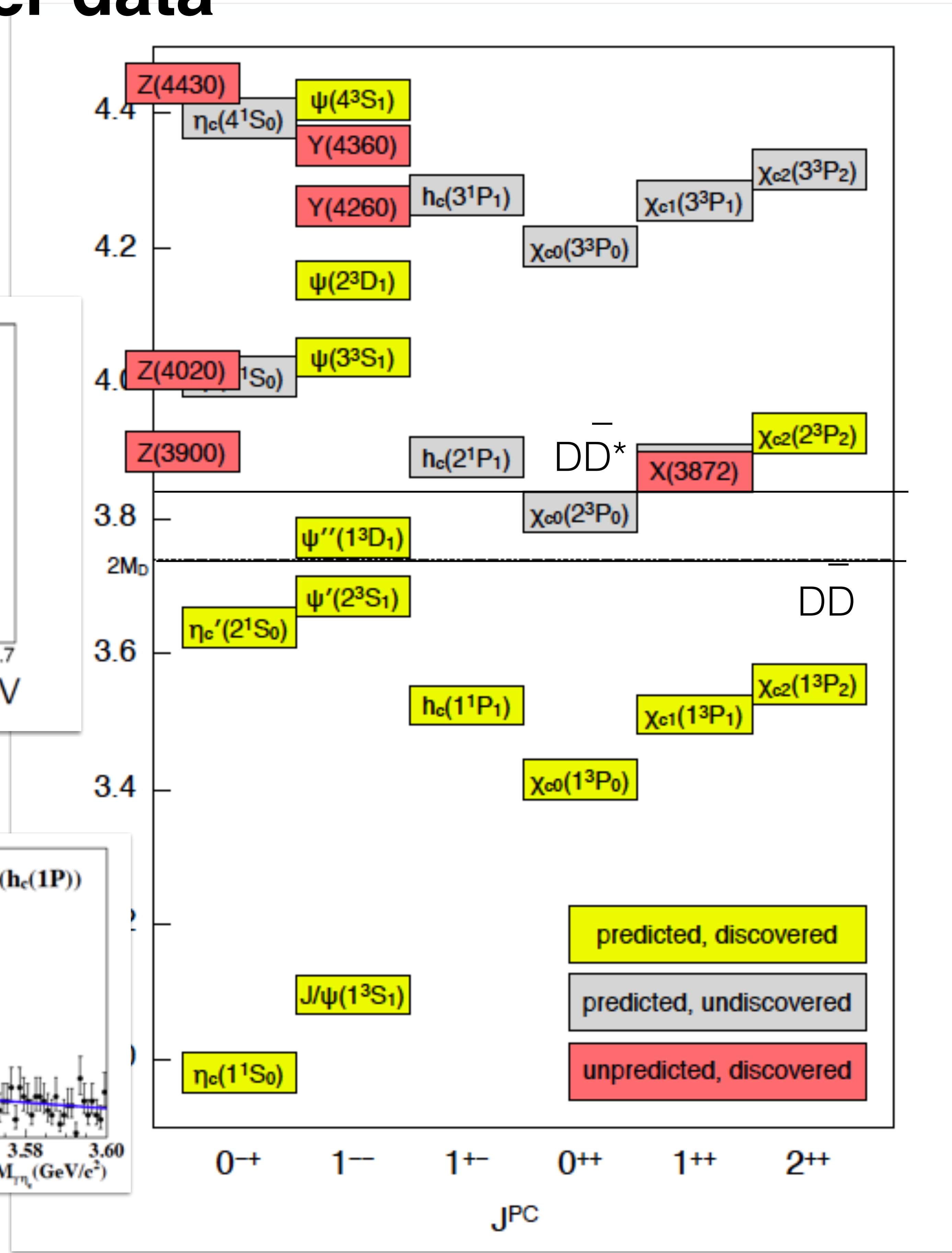
Quark quartet opens fresh vista on matter

First particle containing four quarks is confirmed.

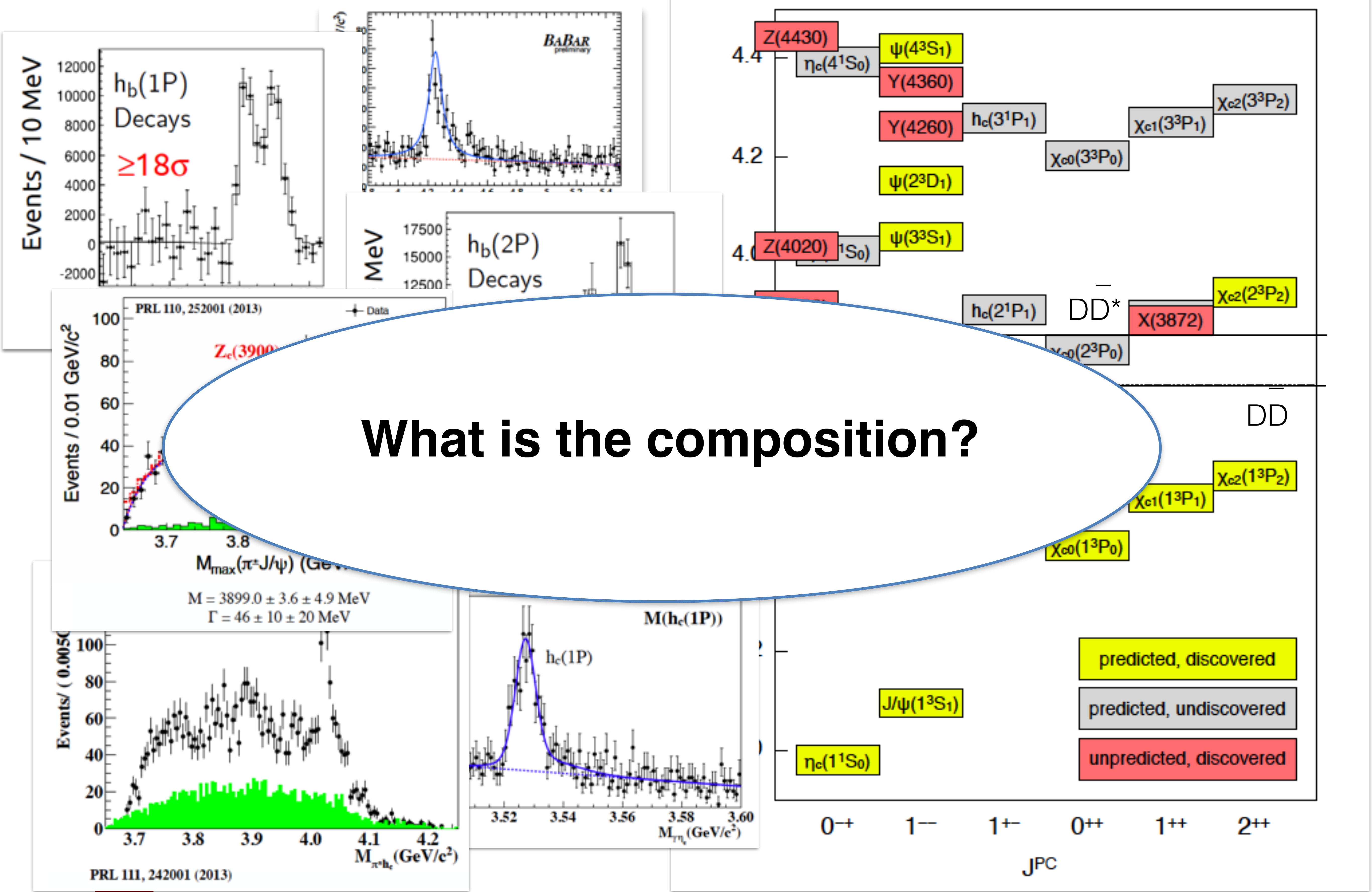


Mainly from e+ e- collider data



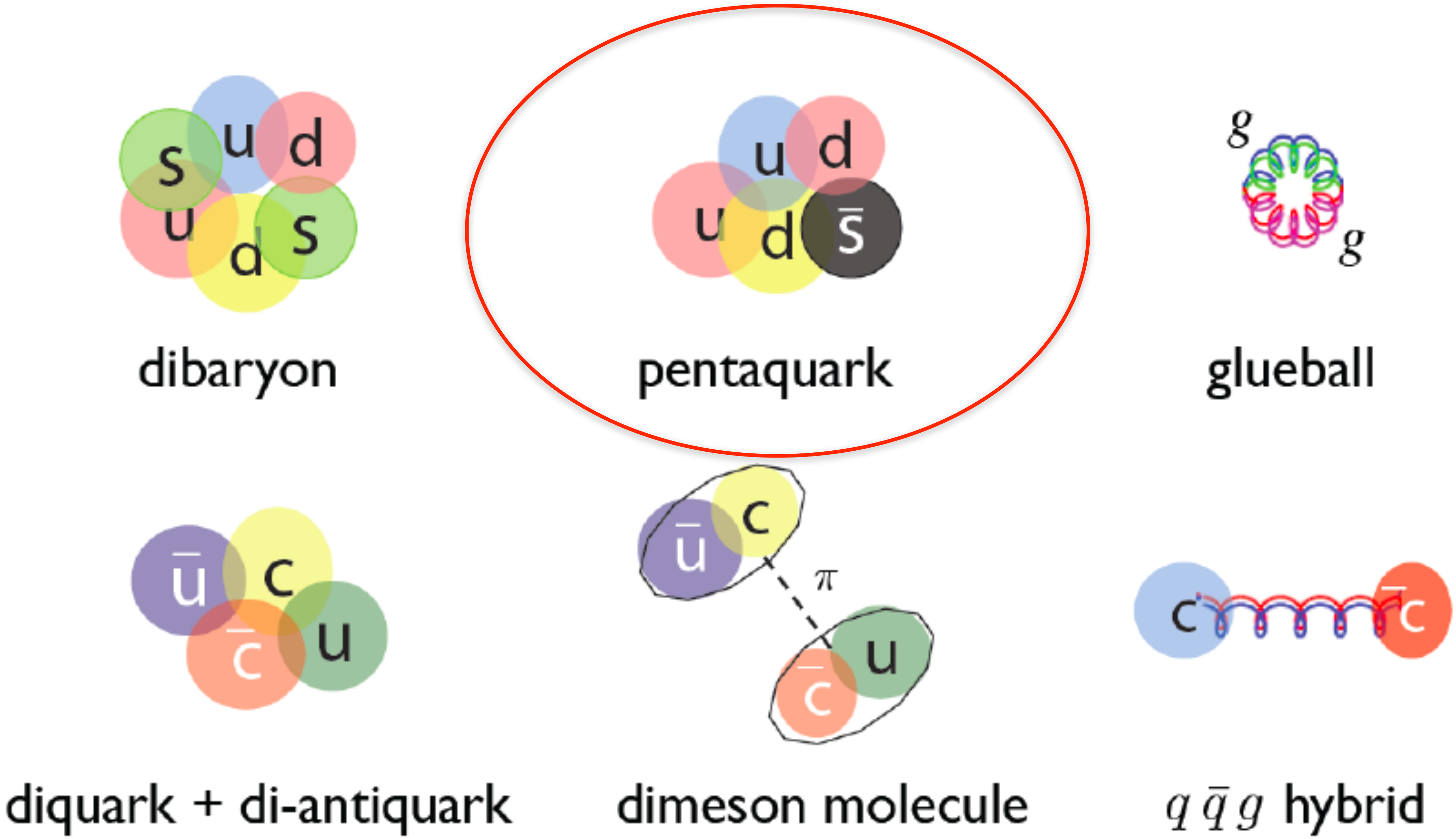


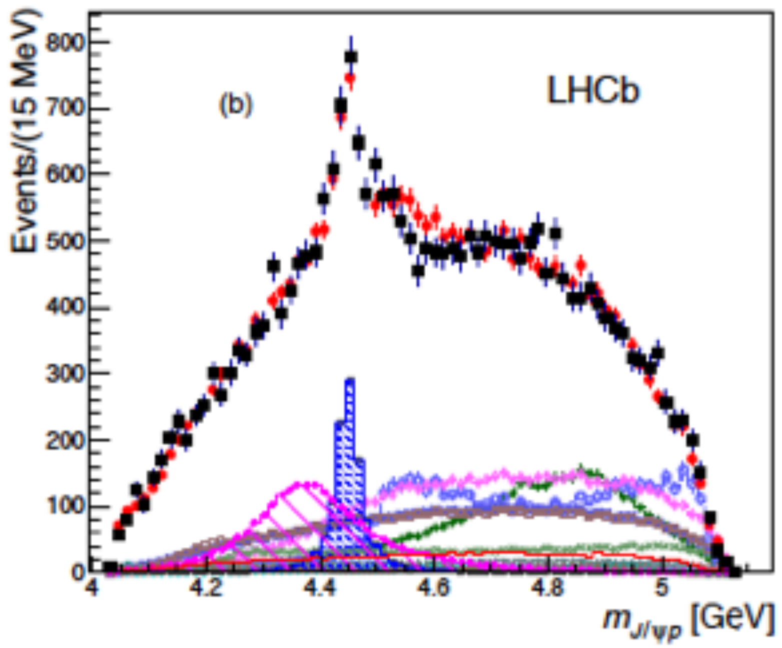
Mainly from e+ e- collider data

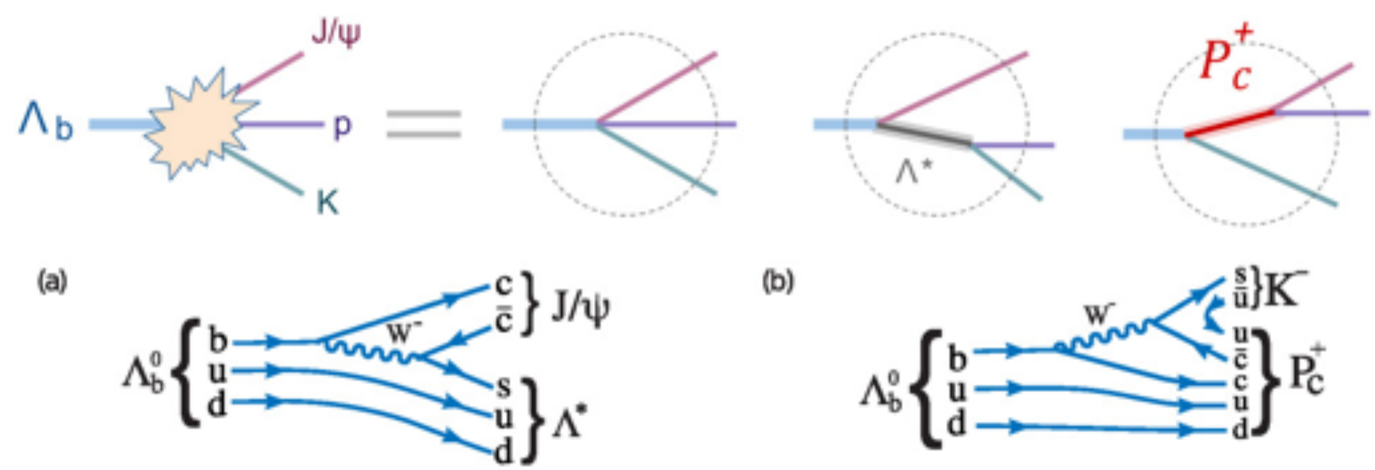


What is the composition?

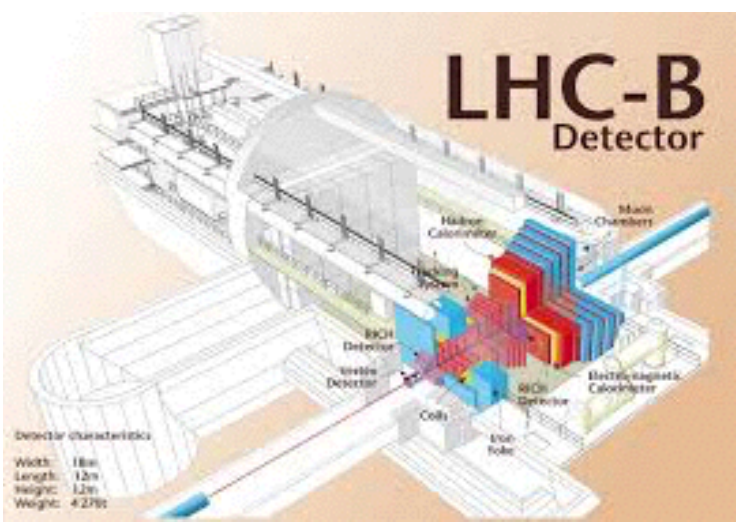
Hadrons beyond quark model

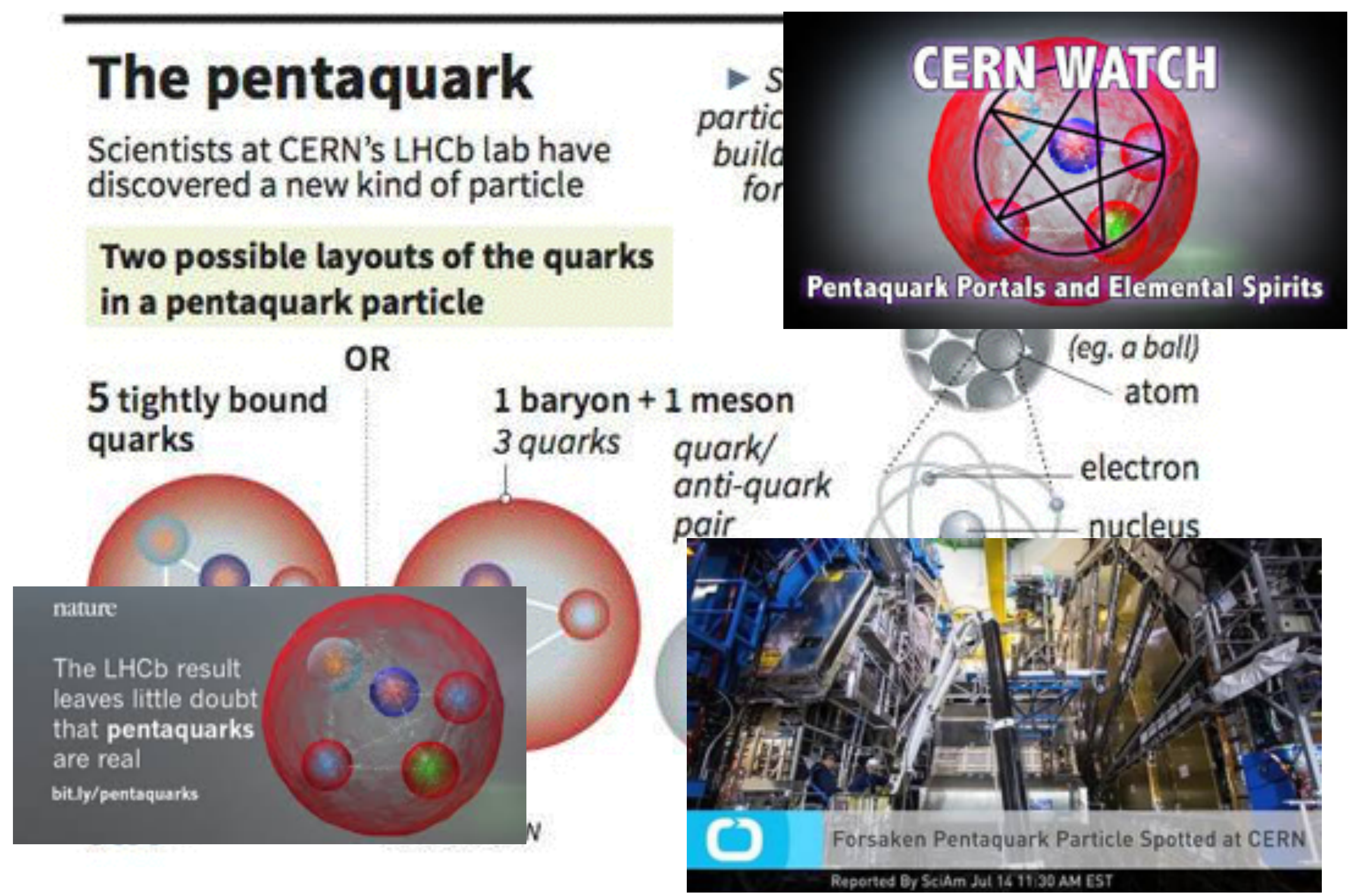


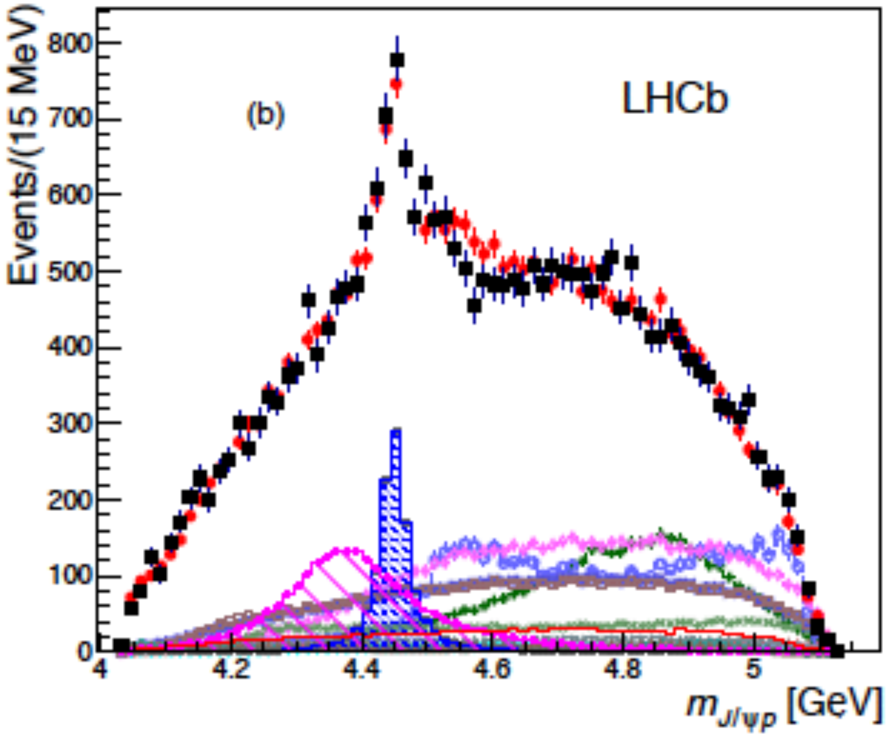

Events/(15 MeV)
(b)
LHCb
$m_{J/\psi p}$ [GeV]

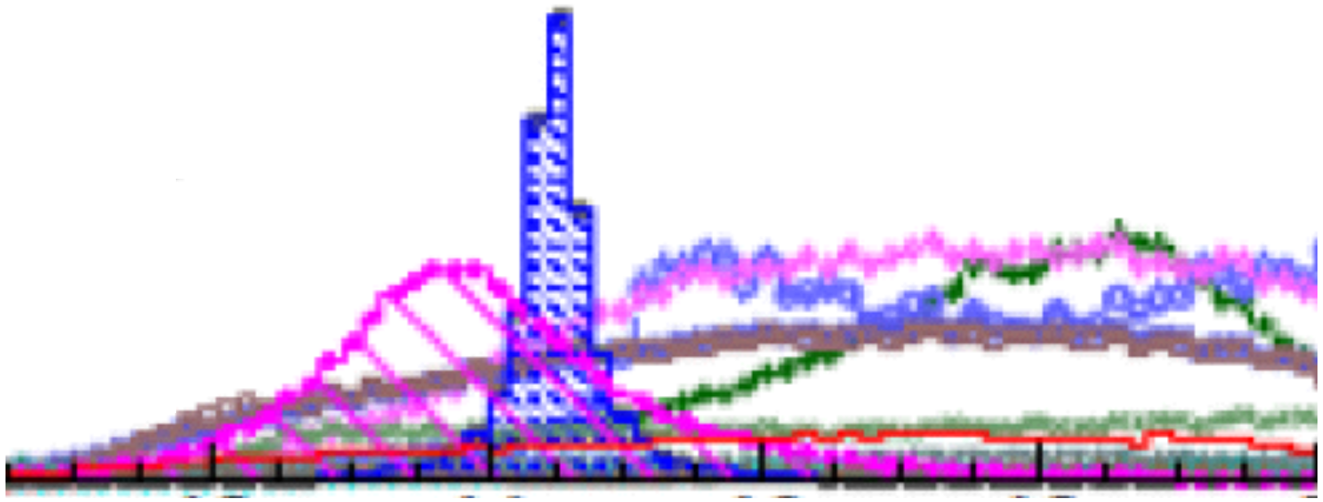

Λ_b
J/ψ
p
K
Λ^*
P_c^+
(a)
(b)
W⁻
J/ψ
Λ^*
K^-
P_c^+


ALICE
CMS
ATLAS
LHCb

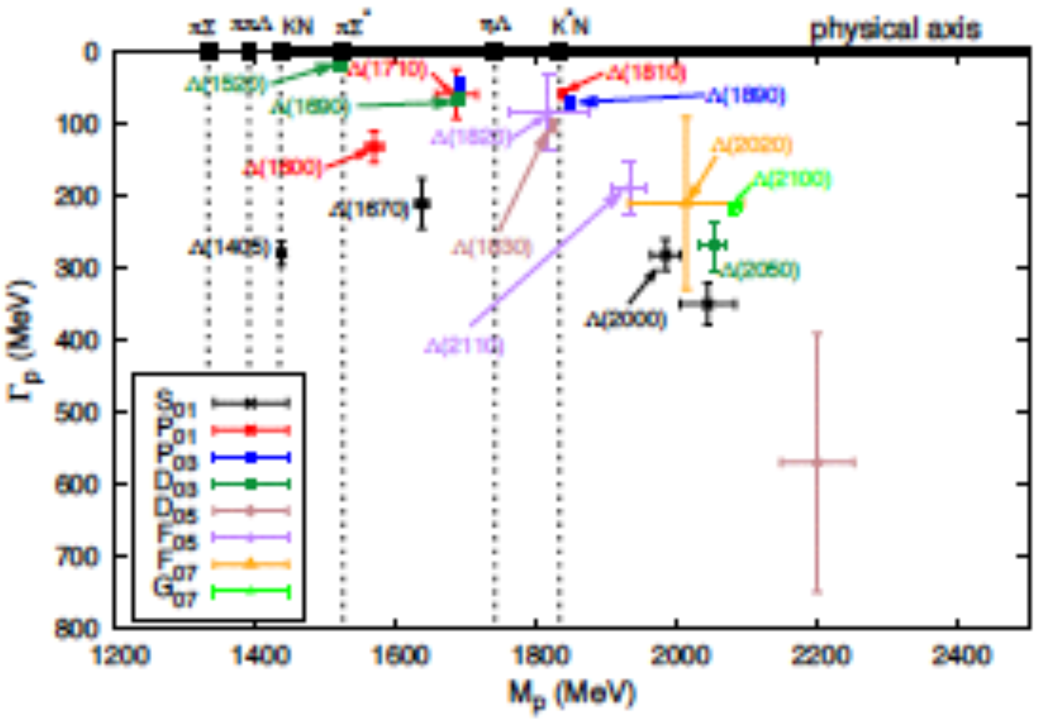

LHC-B
Detector


The pentaquark
Scientists at CERN's LHCb lab have
discovered a new kind of particle
Two possible layouts of the quarks
in a pentaquark particle
OR
5 tightly bound
quarks
1 baryon + 1 meson
3 quarks
quark/
anti-quark
pair
(eg. a ball)
atom
electron
nucleus
CERN WATCH
Pentaquark Portals and Elemental Spirits
nature
The LHCb result
leaves little doubt
that pentaquarks
are real
bit.ly/pentaquarks
Forsaken Pentaquark Particle Spotted at CERN





$$\Lambda_b \to J/\psi + p + K$$



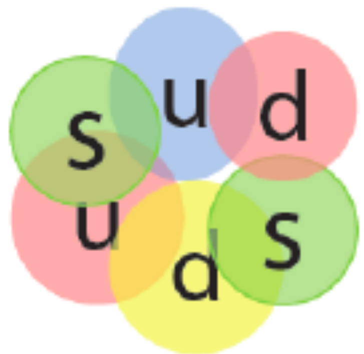
Pentaquark

Λ - resonances

Λ - spectrum is very rich

C.Fernandez-Ramirez, et al. Phys Rev. D93, 034029 (2016)

There may be hadrons that look like …

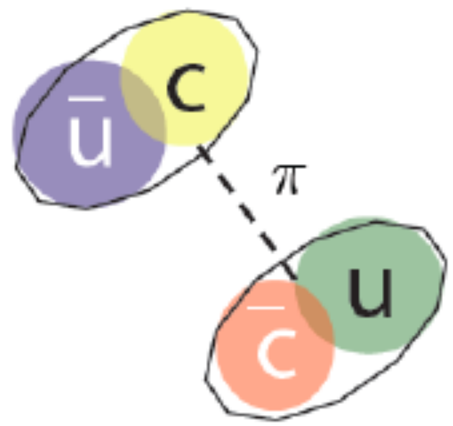


dibaryon

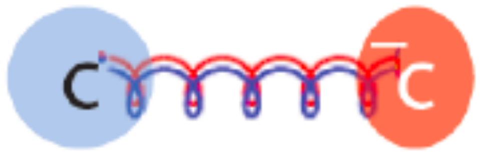
pentaquark

glueball

diquark + di-antiquark



dimeson molecule

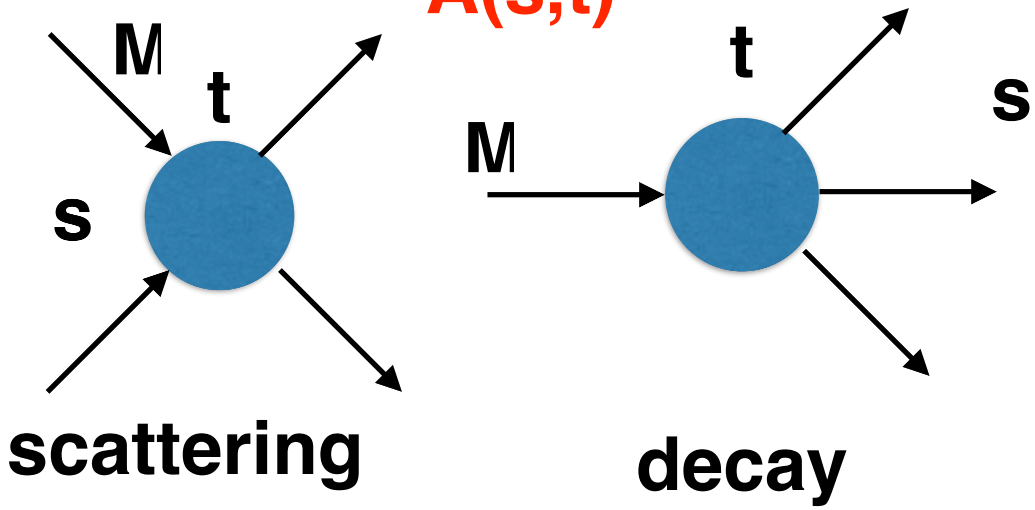


$q\,\bar{q}\,g$ hybrid

…before we know these exist it is necessary to identify resonances in scattering amplitudes

S-matrix principles: Crossing, Analyticity, Unitarity

A(s,t)



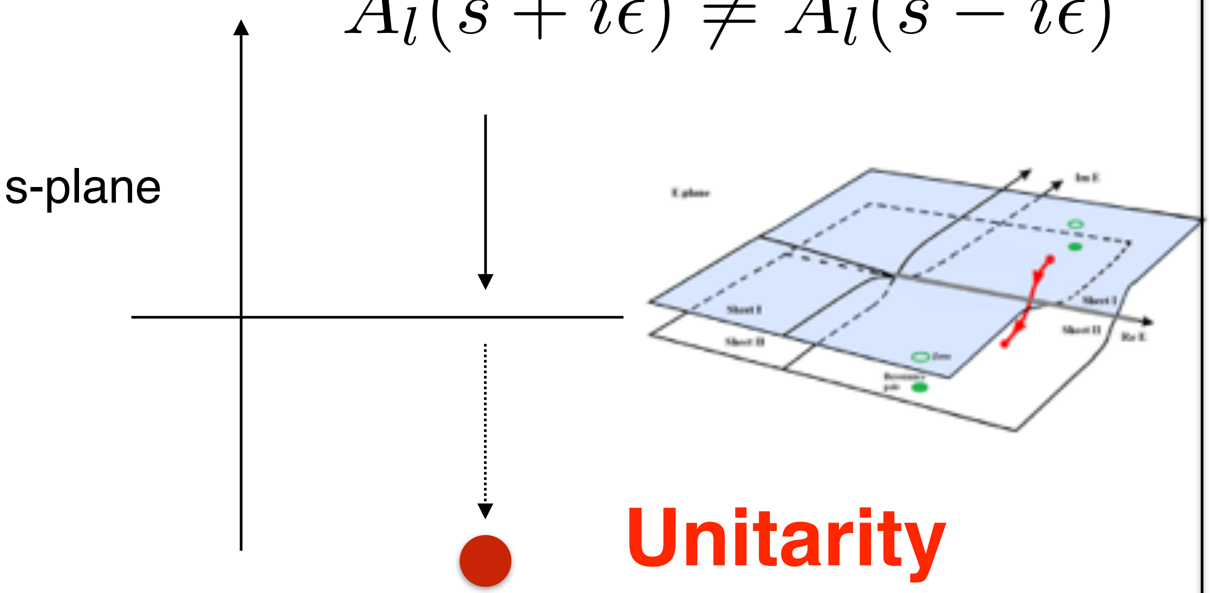
Crossing

$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$

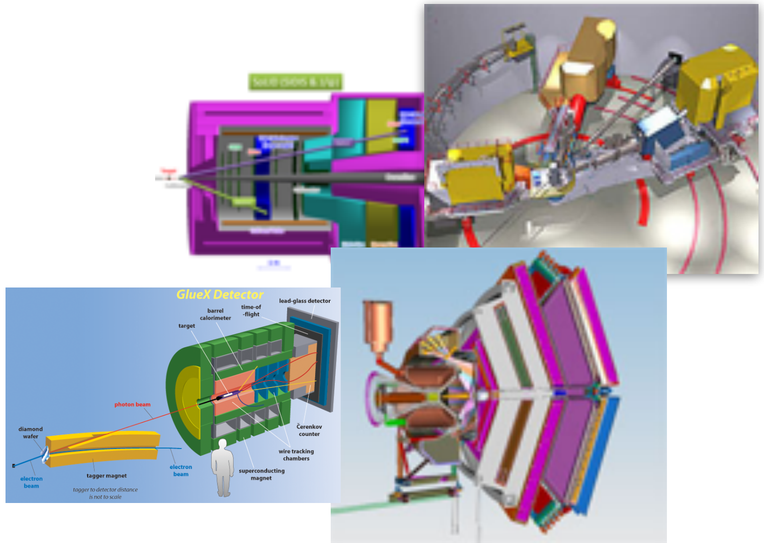


Unitarity

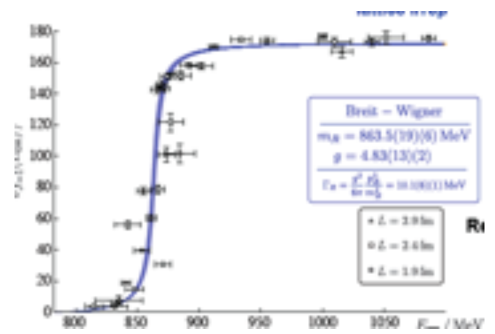
Resonances : bumps/peaks on the real axis (experiment) come from singularities in unphysical sheets

Joint Physics Analysis Center

- Started in the Fall of 2013 to support the extraction of physics results from analysis of experimental data from JLab12 and other accelerator laboratories.

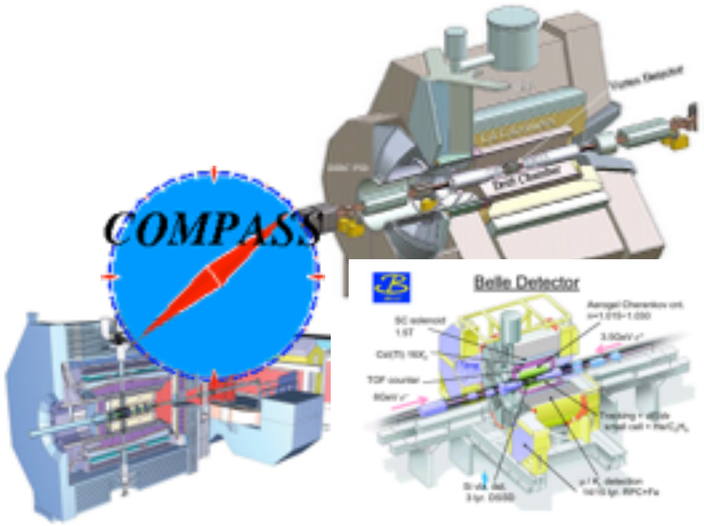


- Work is on theoretical, phenomenological and data analysis tools in close collaboration with theorists and experimentalists worldwide.

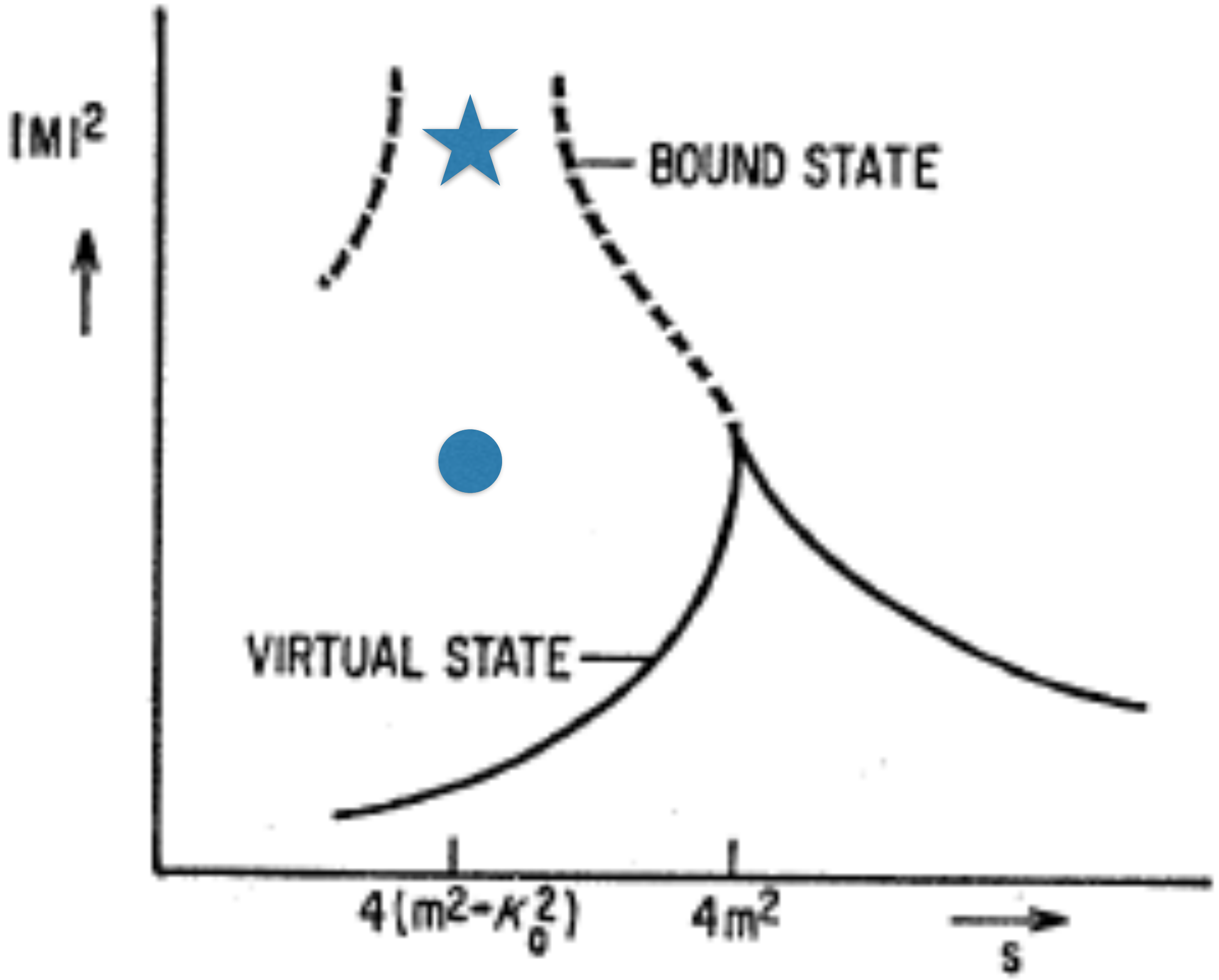


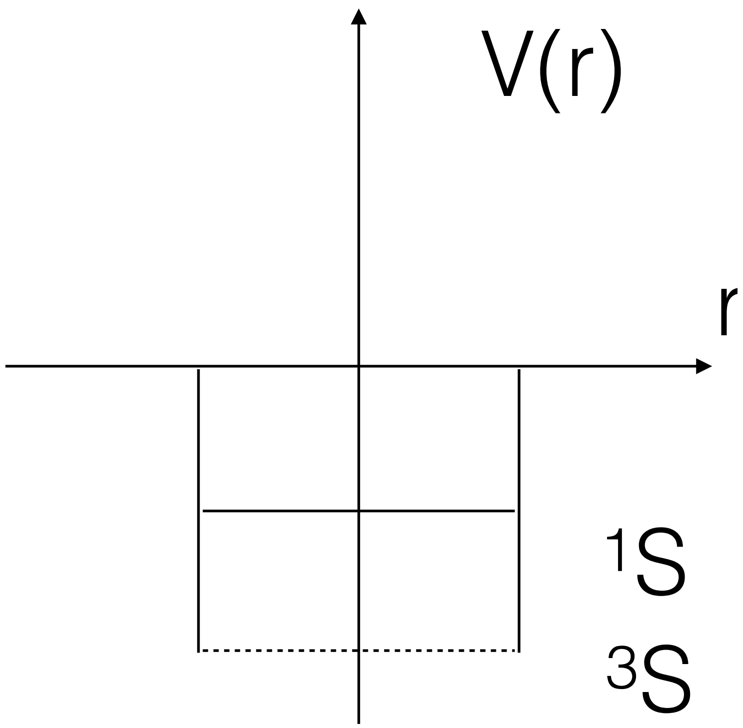
- Successful external 3y review (May 2016).

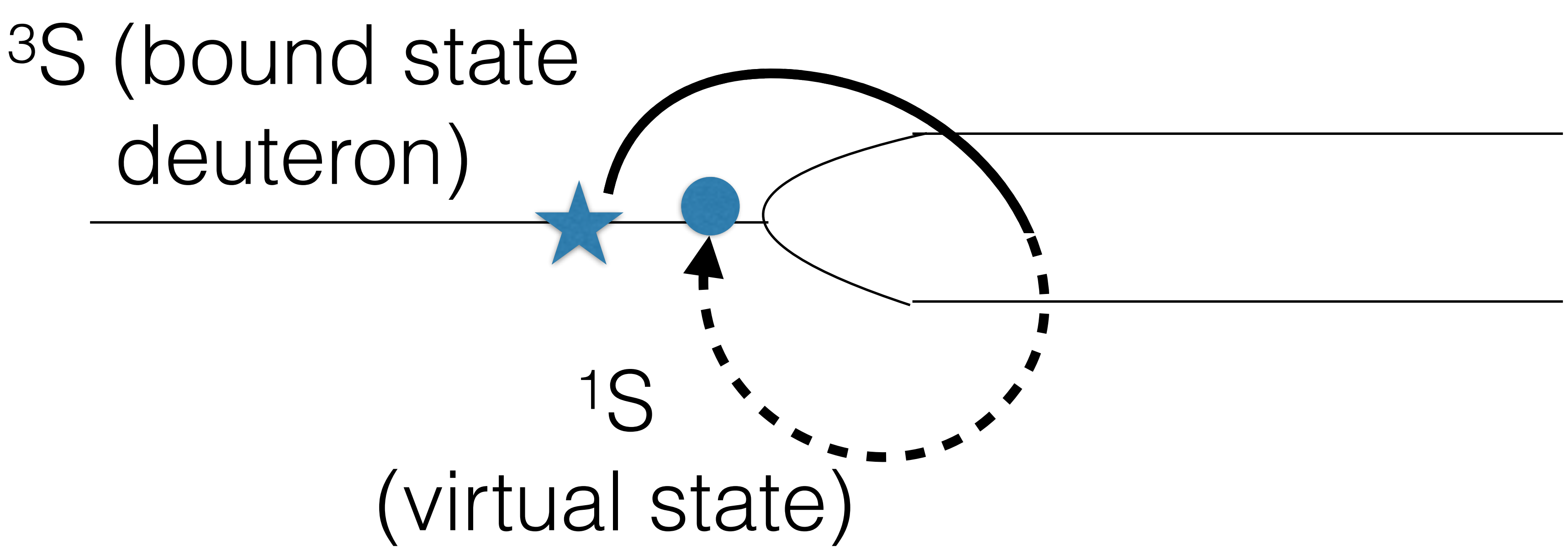
- Average 1paper/month, Over 100 invited talks, ~10 ongoing experimental analyses, novel communication and data preservation tools, workshops, summer schools.



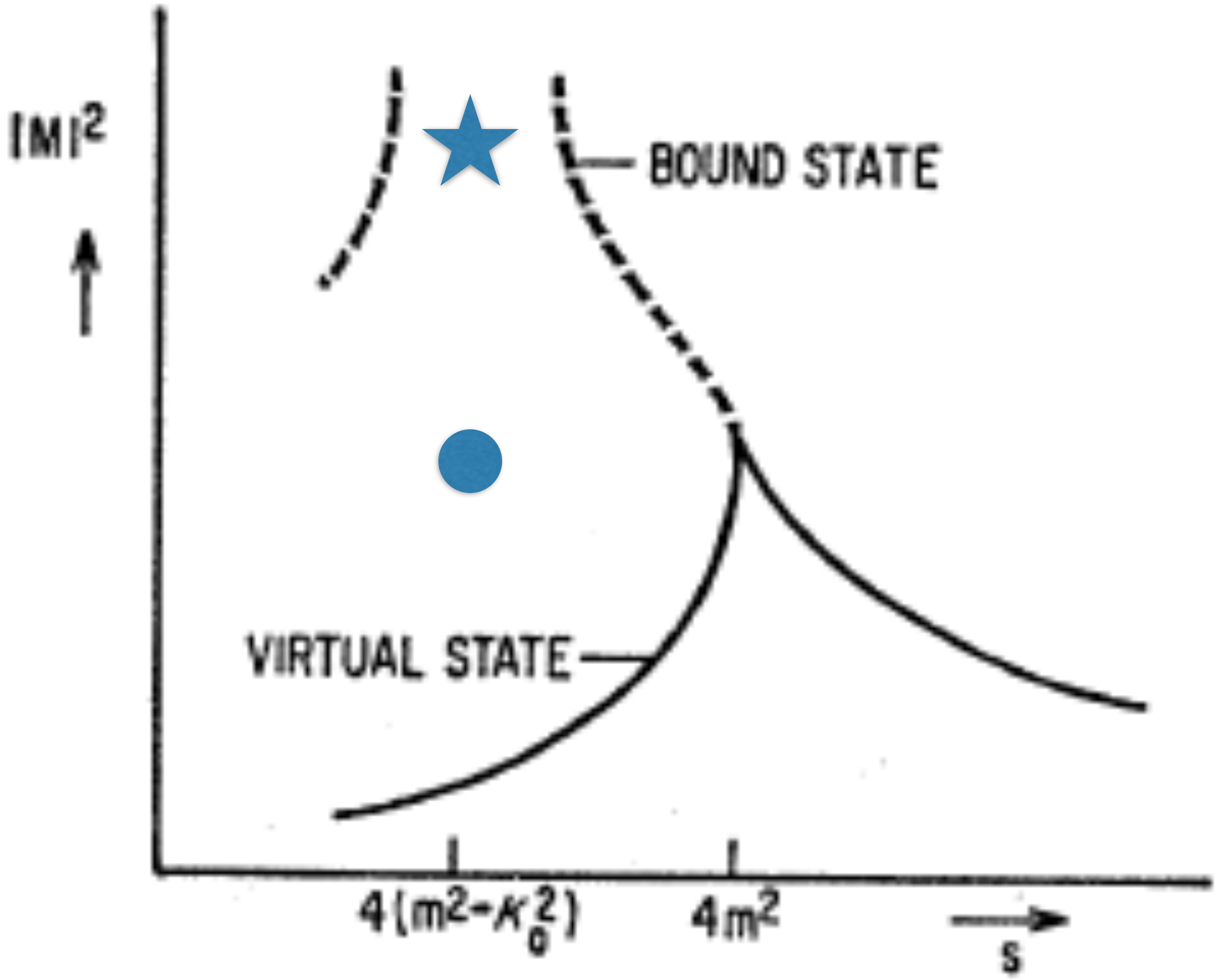
Singularities, is all that matters: poles and cuts

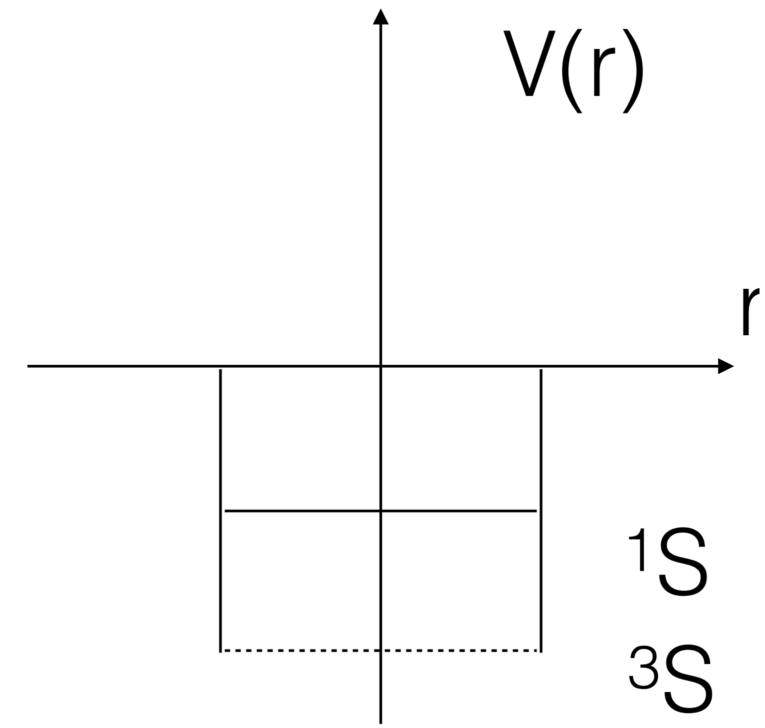


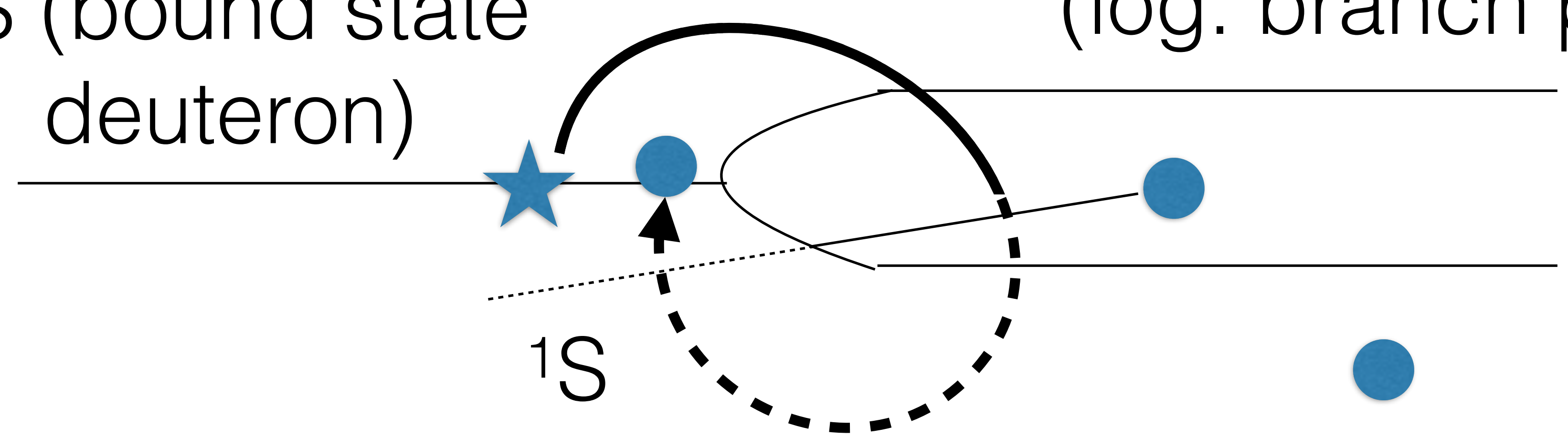


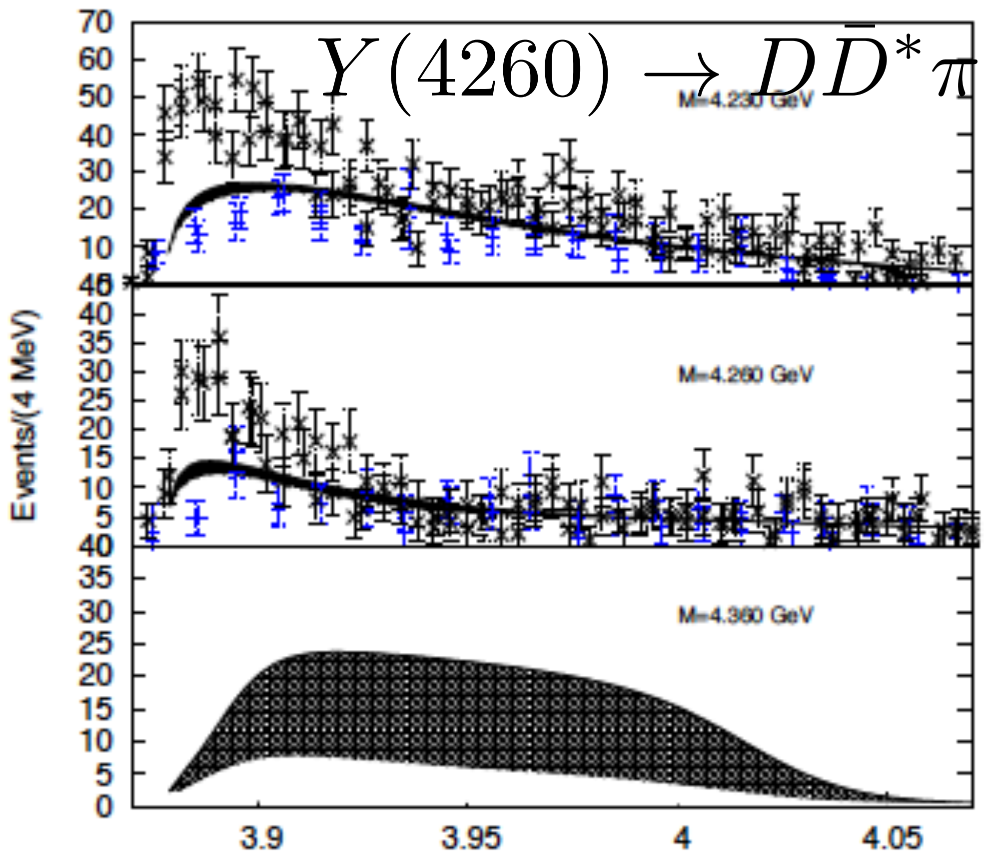


Singularities, is all that matters: poles and cuts

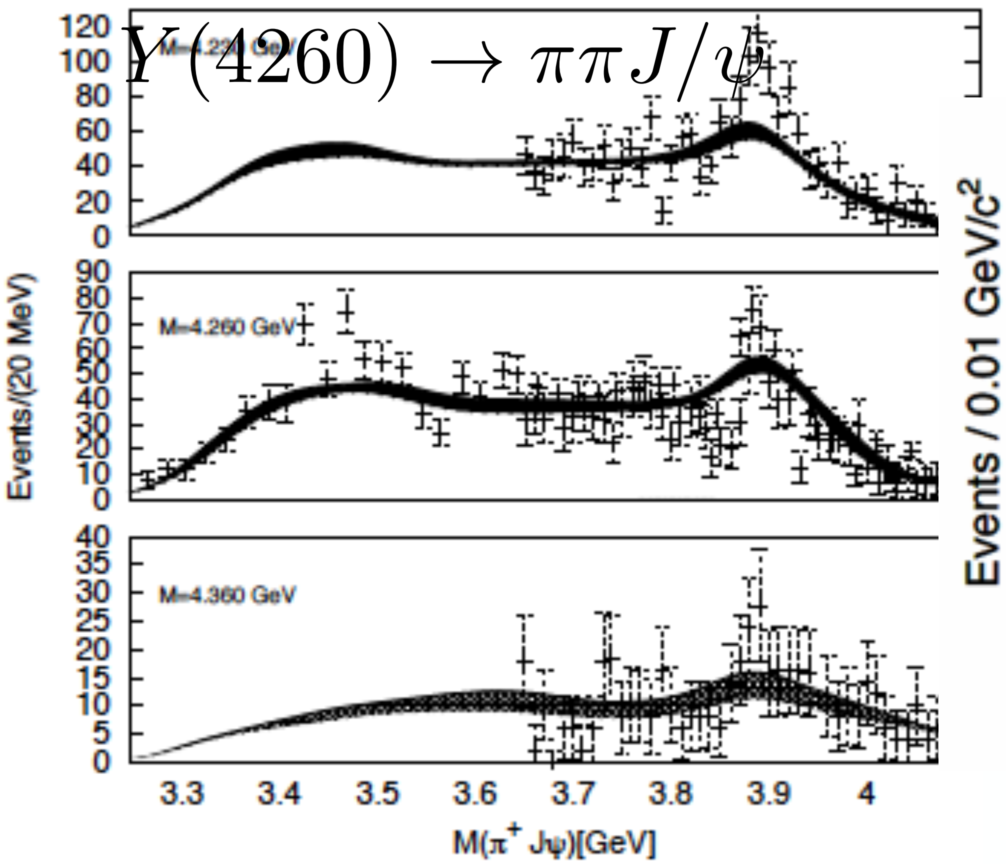




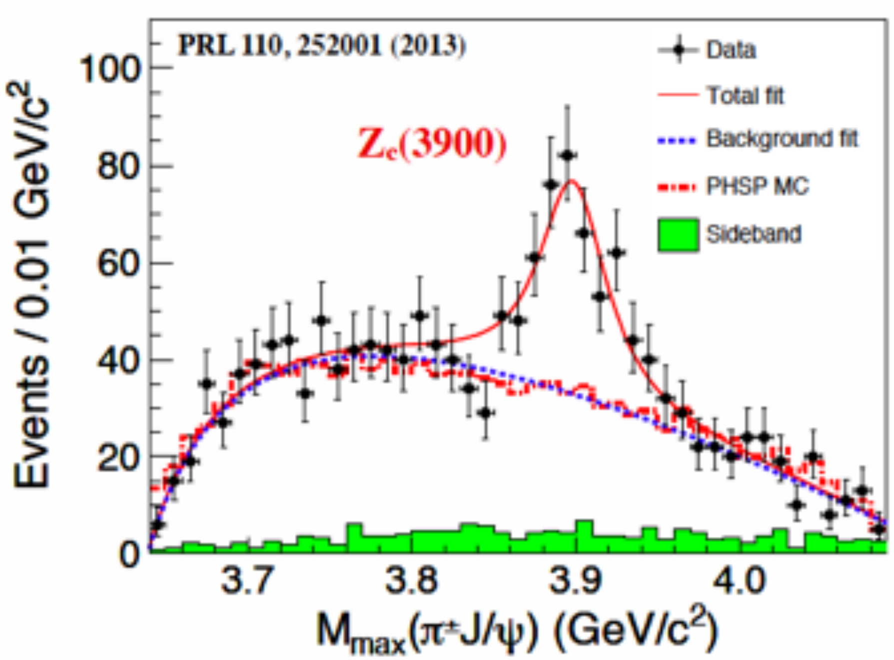




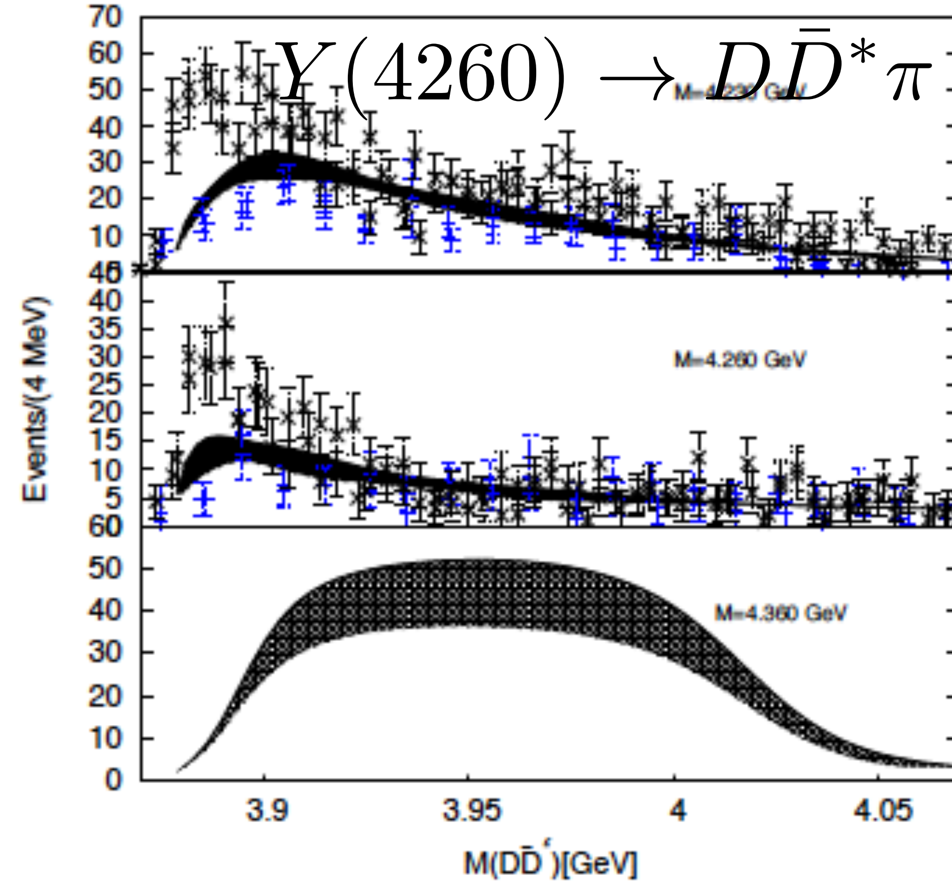
Model I



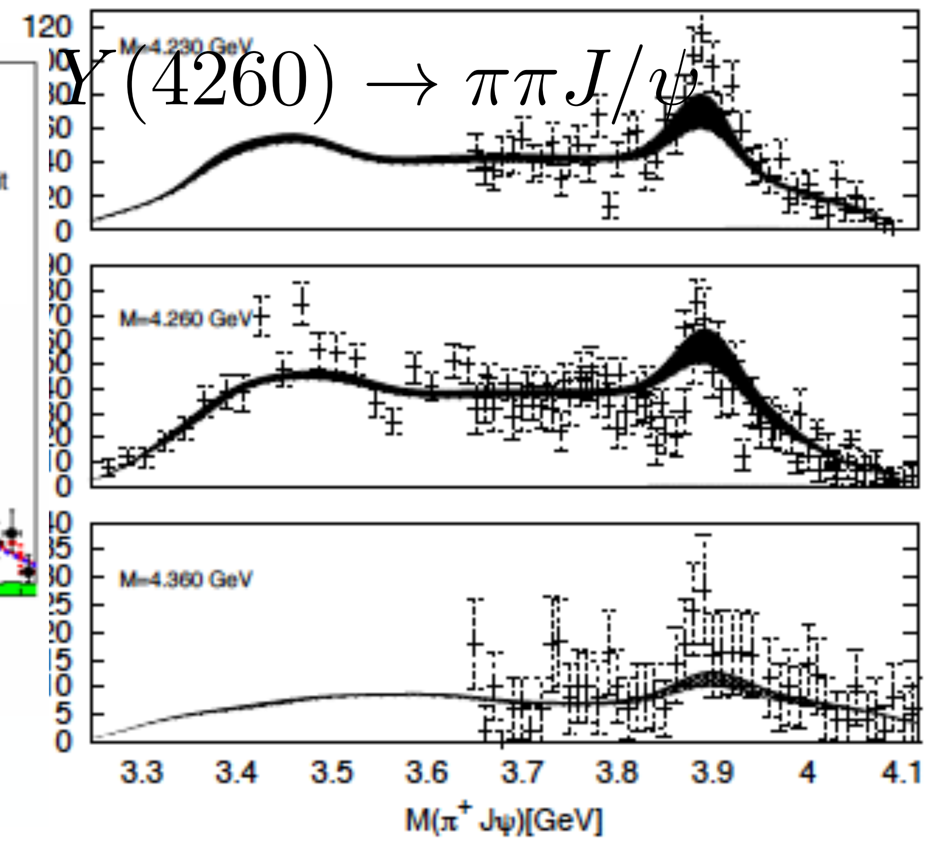
Current data cannot discriminate the dynamical origin of the XYZ peaks



$M = 3899.0 \pm 3.6 \pm 4.9$ MeV
$\Gamma = 46 \pm 10 \pm 20$ MeV



Model II



Perfecting amplitude analysis (light meson decays)

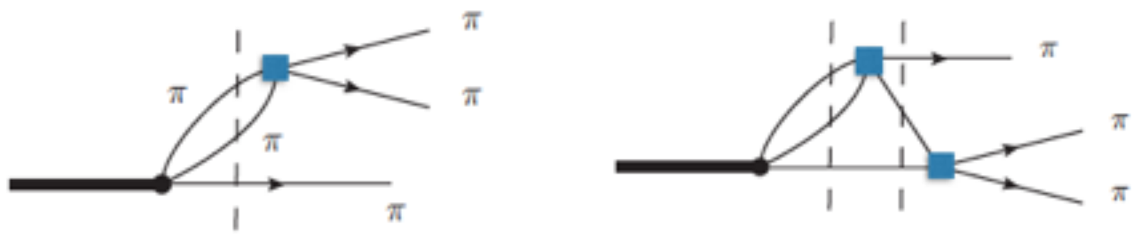
- $\eta \to 3\pi$: Isospin violating decay sensitive to the quark mass difference.

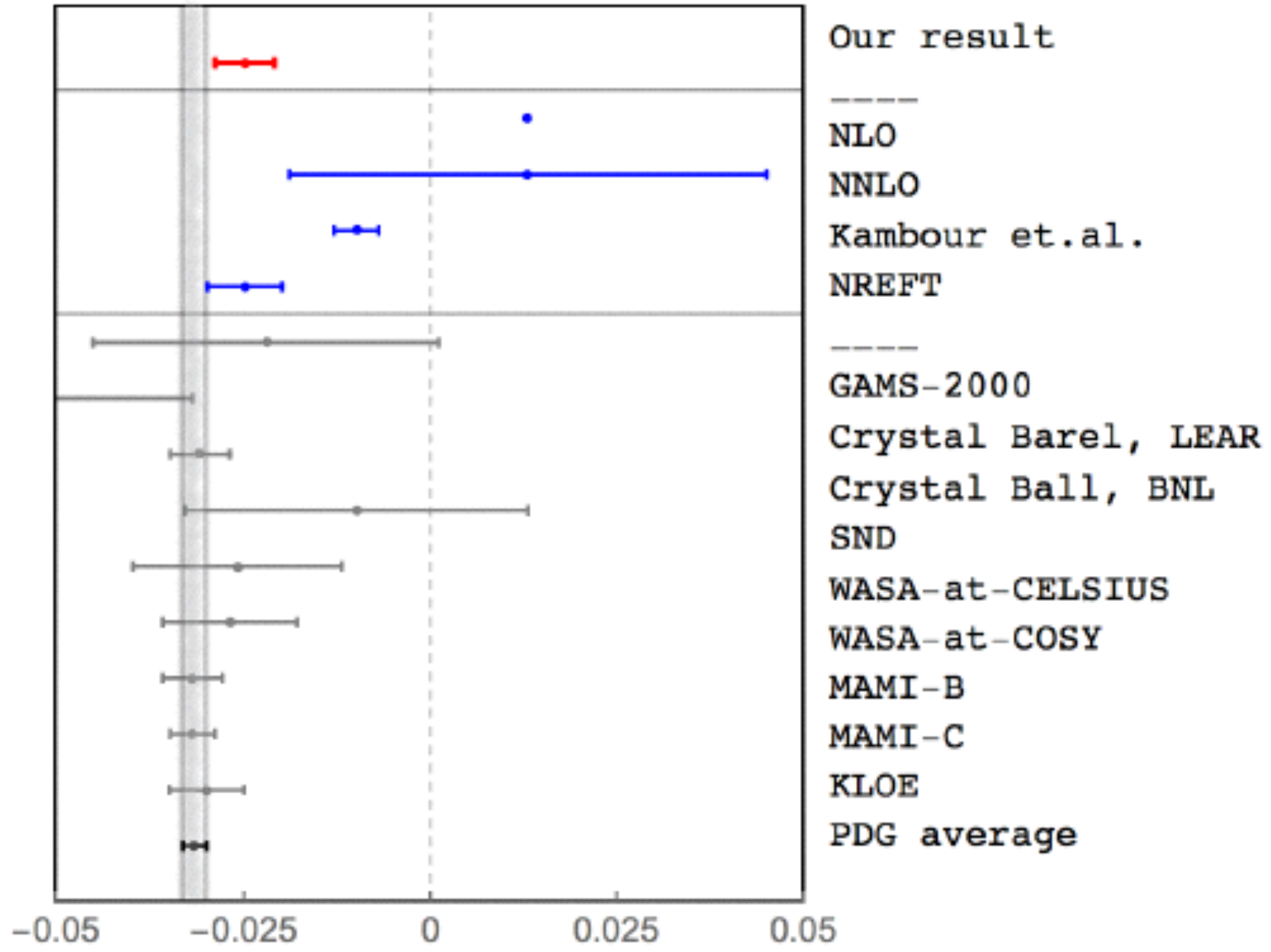
- Slow convergence of ChPT (importance of all-order,f.s.i, effects.

$$\Gamma_{\eta\to\pi^+\pi^-\pi^0} = 66_{[\mathrm{LO}]} + 94_{[\mathrm{NLO}]} + \ldots = 296 \pm 16\,\mathrm{eV}_{[\mathrm{Exp}]}$$

- Slope parameter in neutral decay, a puzzle for ChPT.

$$|A_{\eta\to 3\pi^0}|^2 \propto 1 + 2\alpha z + \ldots$$

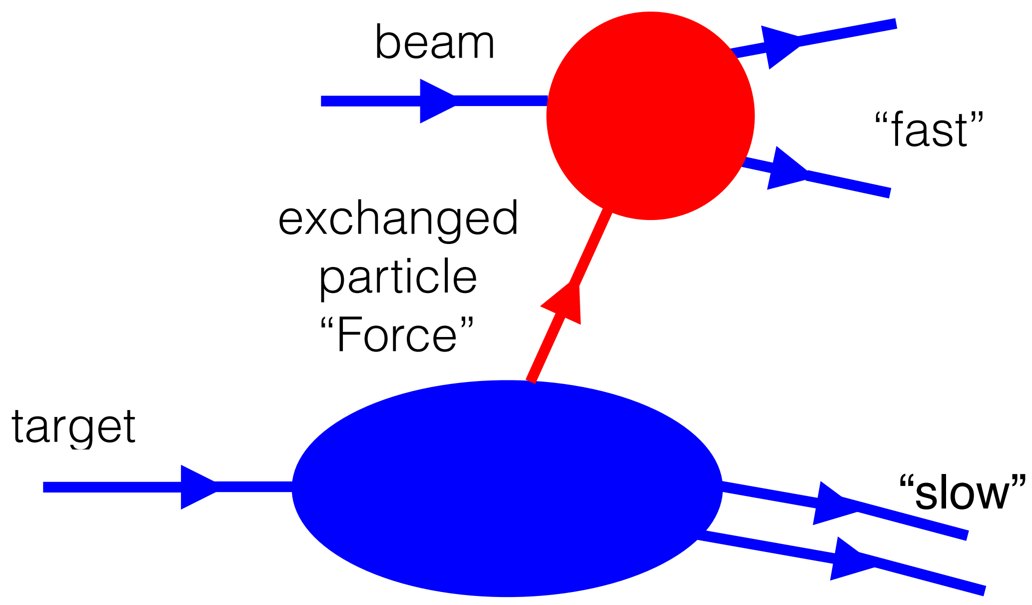




P.Guo, et al. (JPAC), Phys. Rev. D. 92 (2015) 054016

Future analyses for meson spectroscopy

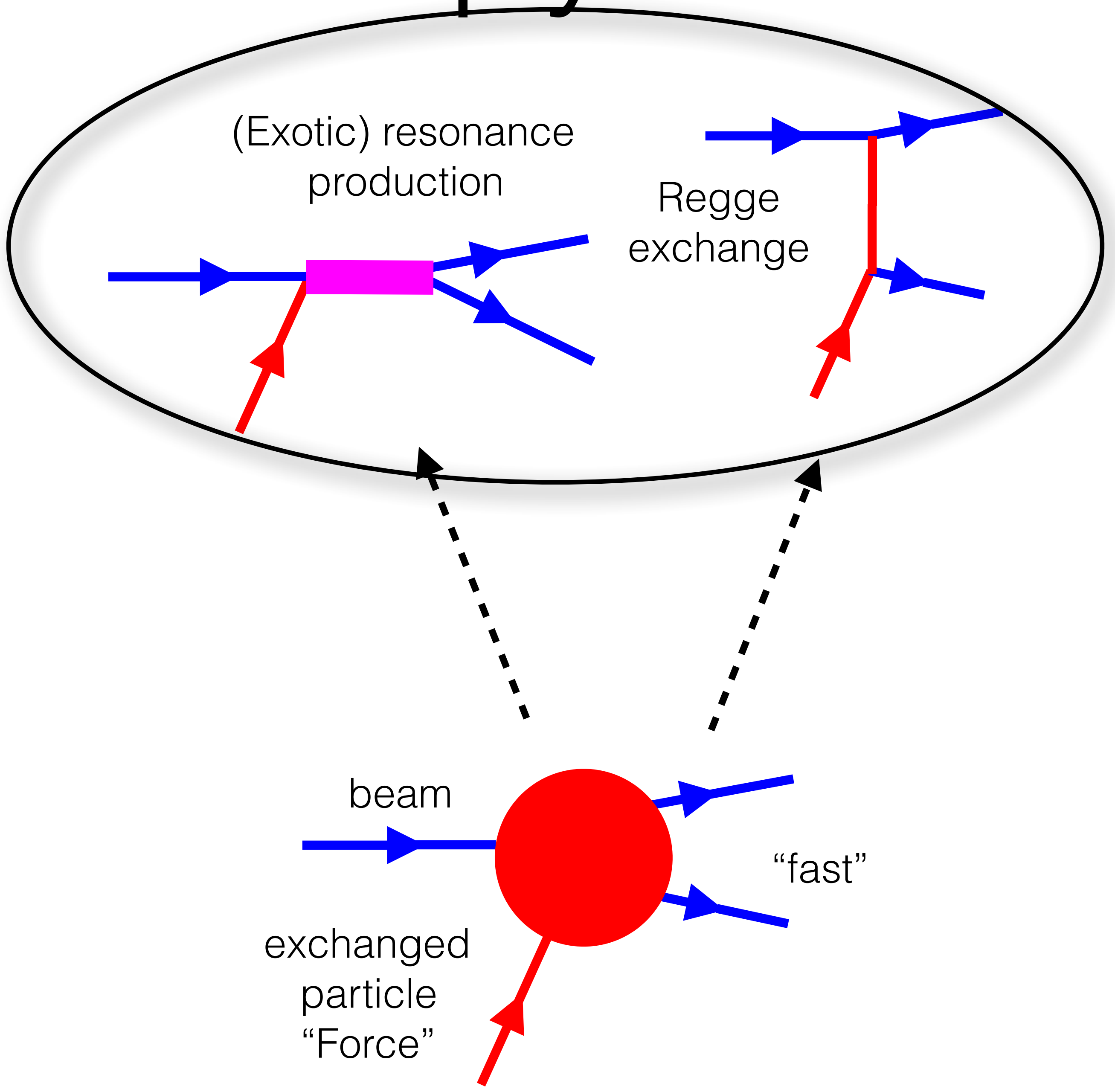
- Complete development of 2-to-2 reactions, establish factorization (and corrections to) of beam-target fragmentation



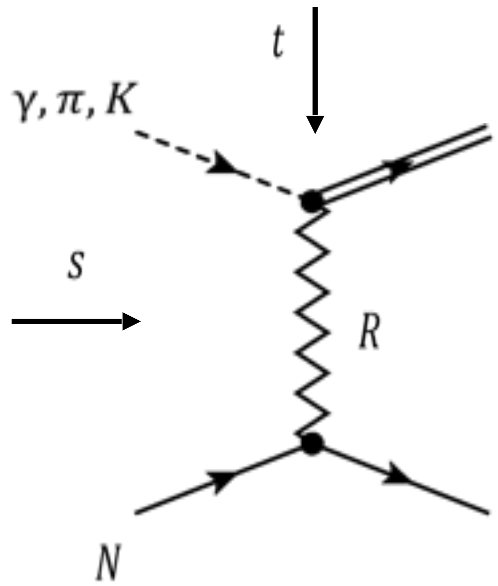
Future analyses for meson spectroscopy

- Complete development of 2-to-2 reactions, establish factorization (and corrections to) of beam-target fragmentation

- Develop analytical constraints to relate resonance production with high energy (Regge) dynamics



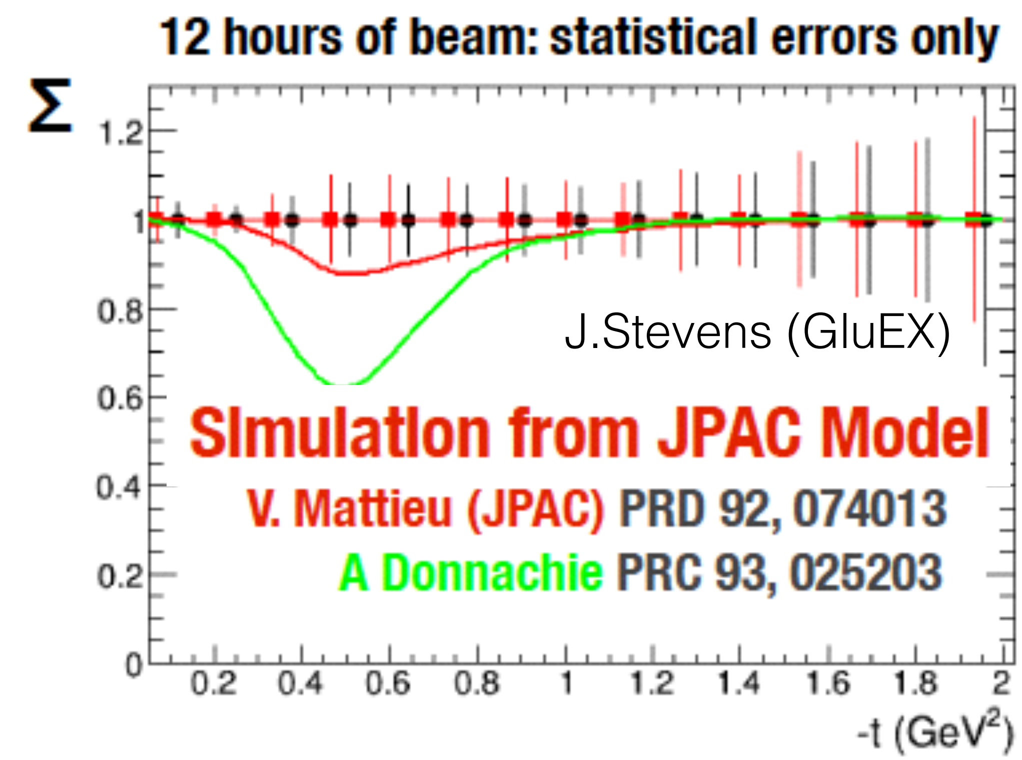
Regge analysis of meson resonance production

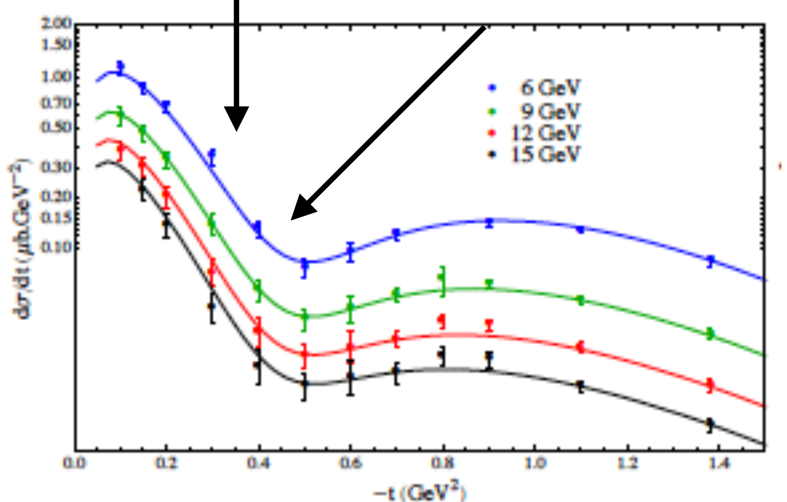


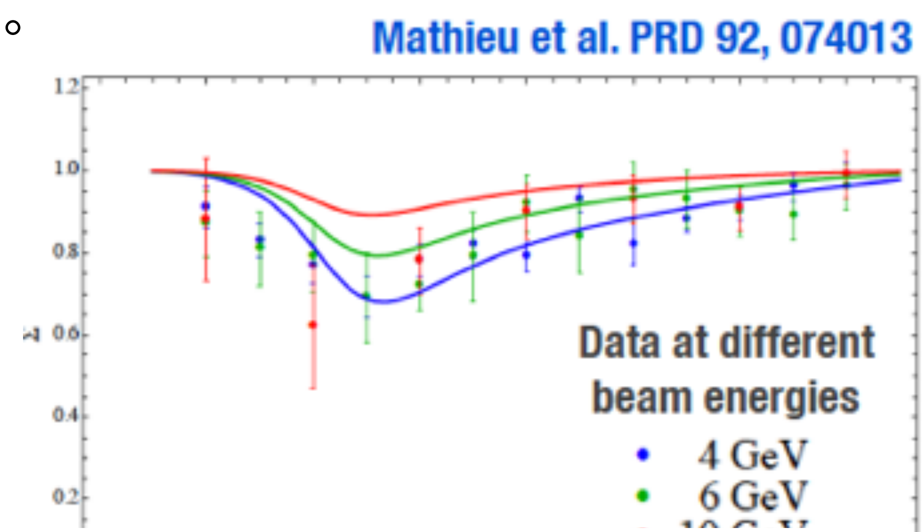
- Key to determine separatioı meson from baryon resonance production

$$H^{(s)}_{\mu_3\mu_4,\mu_2\mu_1} = \frac{V(t)}{\sin \pi\alpha(t)} g_{\mu_3\mu_1}(t) g_{\mu_4\mu_2}(t) \left(\frac{\nu}{-t}\frac{1-\cos\vartheta_s}{2}\right)^{\frac{|\mu_i-\mu_f|}{2}} \left(\frac{1+\cos\vartheta_s}{2}\right)^{\frac{|\mu_i+\mu_f|}{2}}$$

- correction to leading pole (cut)°

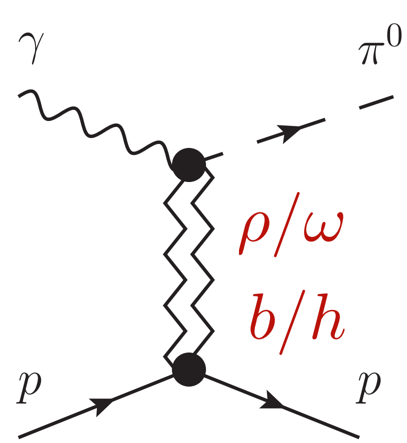






Data collection:

- γ,π,K beams
- 0^-, 1^-, 2^+ peripheral meson production
- Universal data format

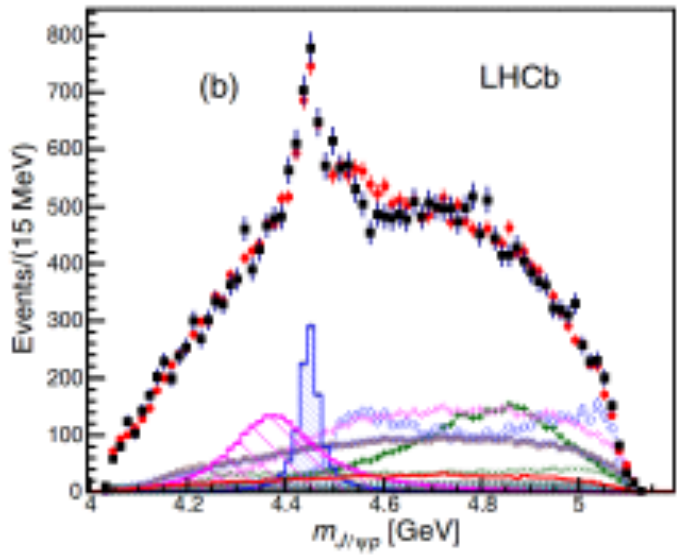


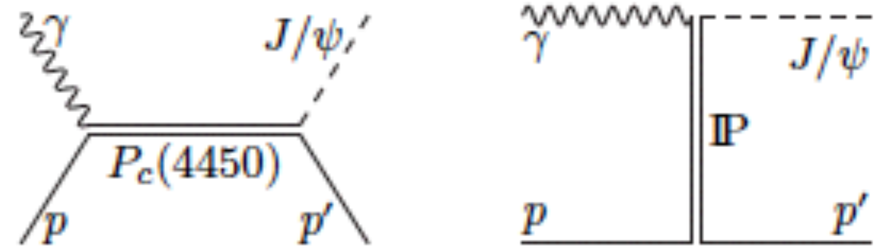
$$\Sigma = \frac{|\omega+\rho|^2 - |h+b|^2}{|\omega+\rho|^2 + |h+b|^2}$$

axial-vector exchanges strength decreases with energy

$P_c(4450)$ in J/ψ photo production

Hall C PAC 44 approved (A*)





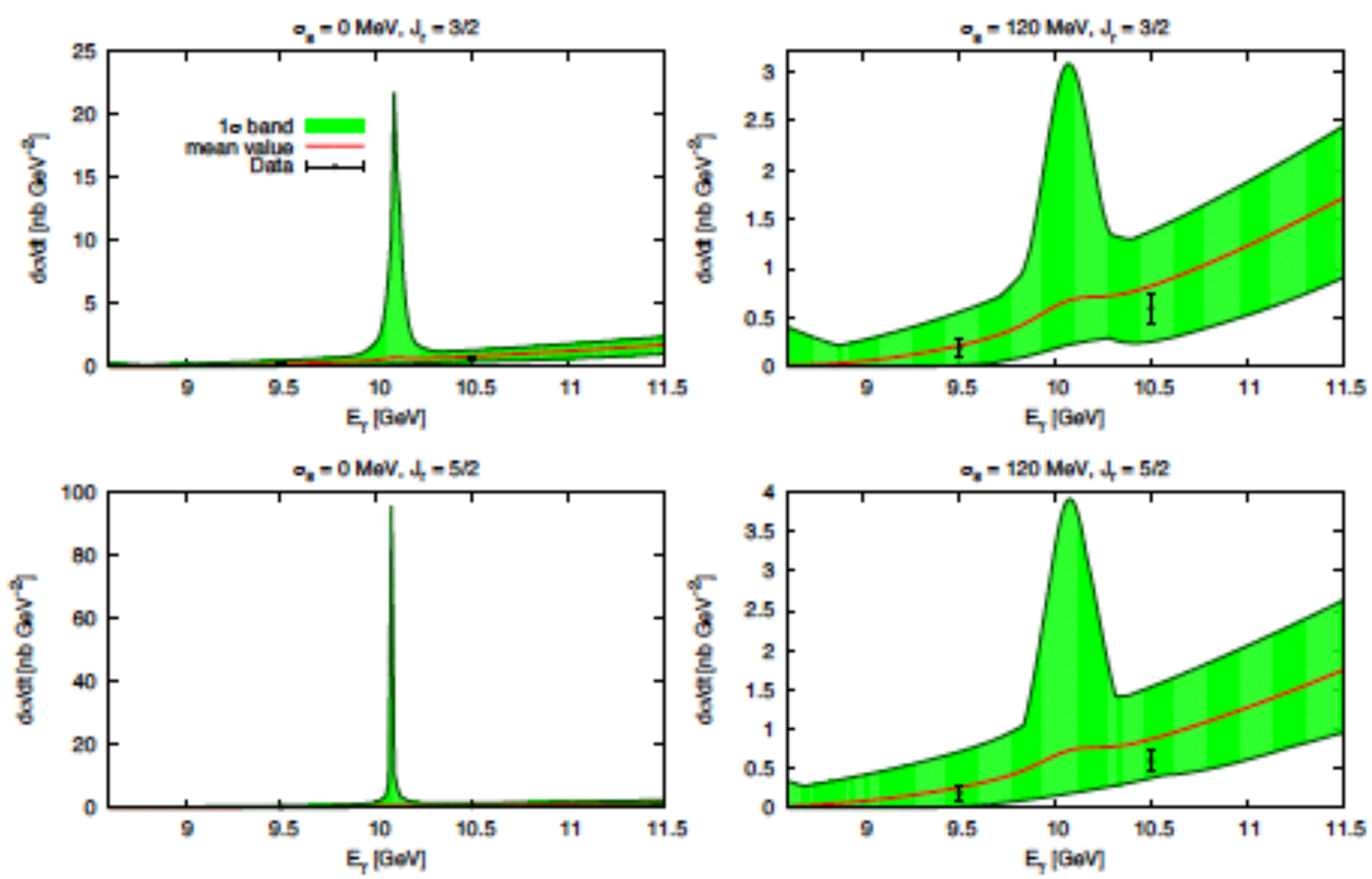
LHCb Collaboration, PRL 115, 072001 (2015)

Fit to data! W from threshold to ~ 300 GeV.

Upper bound for partial decay width!

$$\begin{cases} J_r = 3/2 \Rightarrow 23 - 30\% \\ J_r = 5/2 \Rightarrow 8 - 17\% \end{cases}$$

Also angular distributions and photocouplings studied.

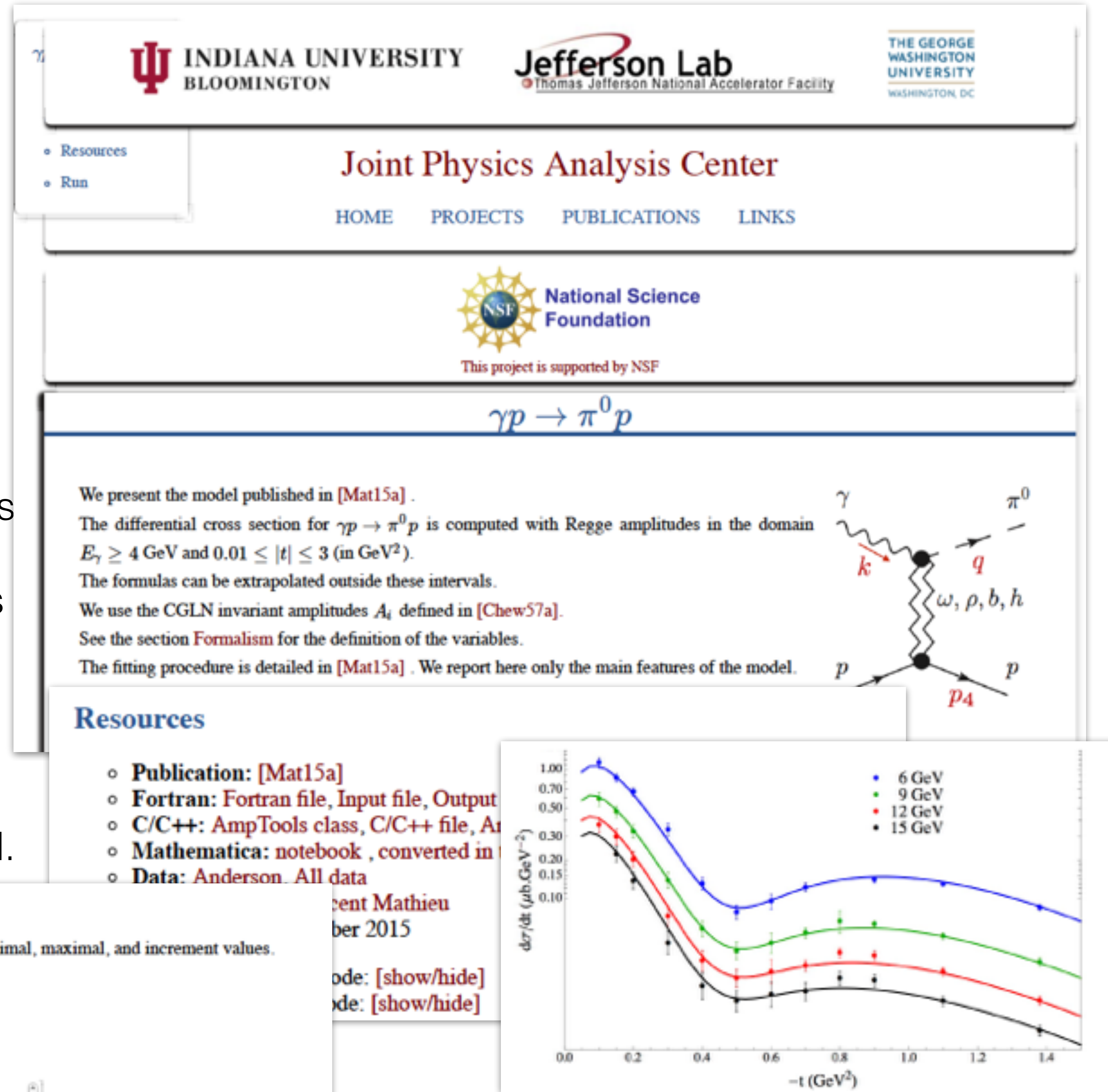


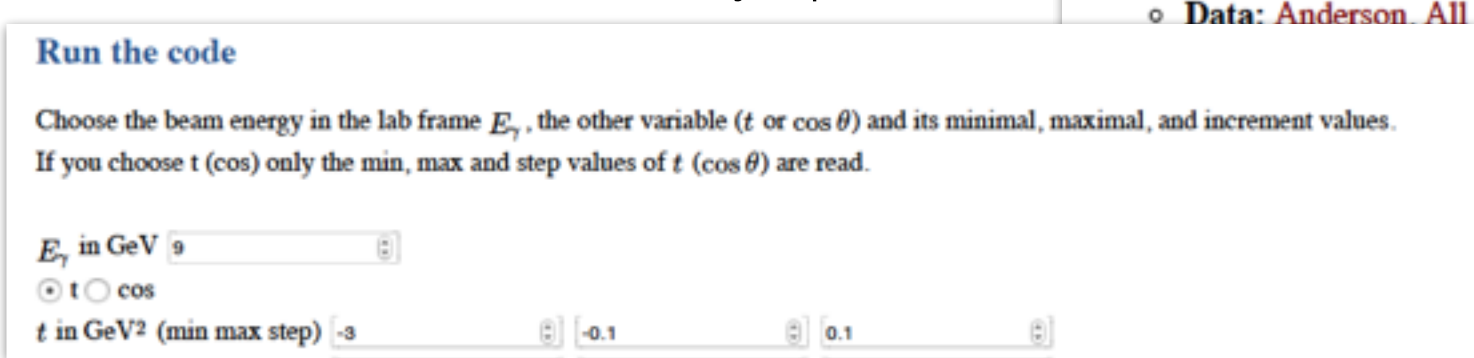
Astrd Blin, et al. (JPAC), Phys.Rev. D94 (2016), 034002

Particle Physics on the Cloud

Example : π^0 photo production (eg. for GlueX/CLAS)

- Interactive portal for analysis of hadron reaction data.
- Collects both new and old theoretical reaction models.
- Includes description of individual reactions, formalism, references, theory, etc.
- Contains source codes and analysis tools. Codes run on/off-line, with variable parameters, display results on-line.
- Ready for MC and data analysis.
- List of reactions constantly updated.





Education of the future generations

- Postdocs:
  - (past) L.Dai (Bonn), I.Danilkin (Mainz), P.Guo (Cal. State U.), C.Fernandez-Ramires (UNAM), D.Schott (Med. Coll. of Wis.)
  - (current) V.Mathieu (IU), I.Lorentz (IU), A.Pilloni, (JLab) V.Pauk (JLab), D.Ronchen (Bonn U.)
- Students:
  - (past) M.Shi (Pekin U.)
  - (current) E.Alexeev (IU), A.Blin (Valencia), B. Hu (GWU), A.Jackura (IU), M.Mikhasenko (Bonn), J.Nis (U. Gent)

- Faculty: M.Doering (GWU), G.Fox (IU), J.T.Londergan (IU),I.Mokeev (JLab), M.Pennington (JLab), E.Passemar (IU), A.Szczepaniak (IU/JLab), R.Workman (GWU)

Summary

- Identification of the nature of the recently discovered exotic hadrons requires close collaboration on many fronts: lattice, reaction dynamics, phenomenology, data science.

- With a number of new experiments coming on line the prospects for finding the answer to the question “How does the Glue bind us all ?” are better then ever.

Hadrons can teach us able the interworking of QCD

- Do hadrons beyond those predicted by the quark model exist ?
- How to “poke” gluons ?
- How does the inside of the proton look like ?
- Can we actually compute the hadron spectrum and determine their structure from first principles ?