Parallel Session 1: Nuclear Physics

Studying Hadrons with Electron Beams

6th edition of the biennial African School of Fundamental Physics and Applications

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Outline

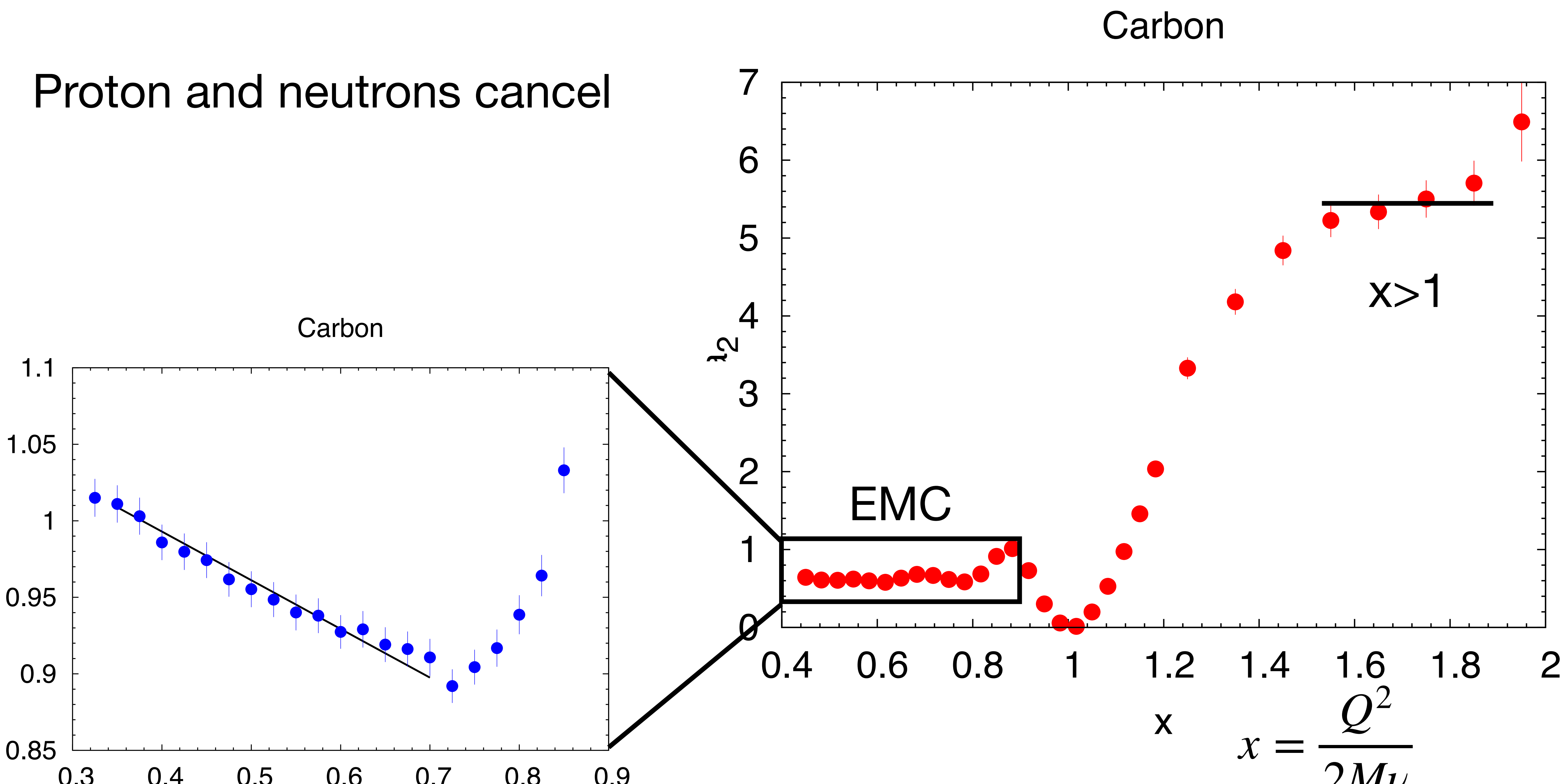
Introduction: what are we trying to learn?
Introduction to electron scattering
Form factors
Deep inelastic scattering
New insights about the nucleus
Exotic spectroscopy

The Nucleus

DIS on Nuclei: The EMC Effect and x>1

$$R = \frac{\sigma_{carbon}/12}{\sigma_{deutrium}/2}$$ ⟵ very weakly bound

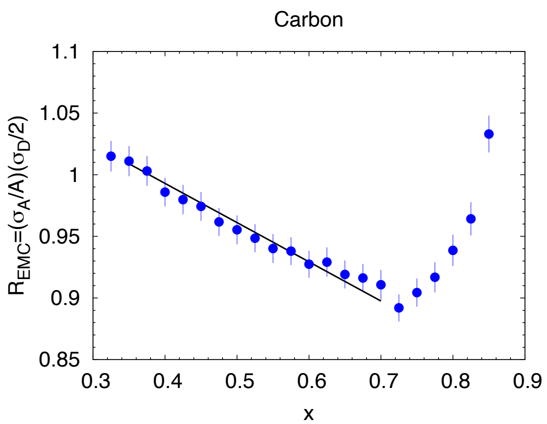
Proton and neutrons cancel



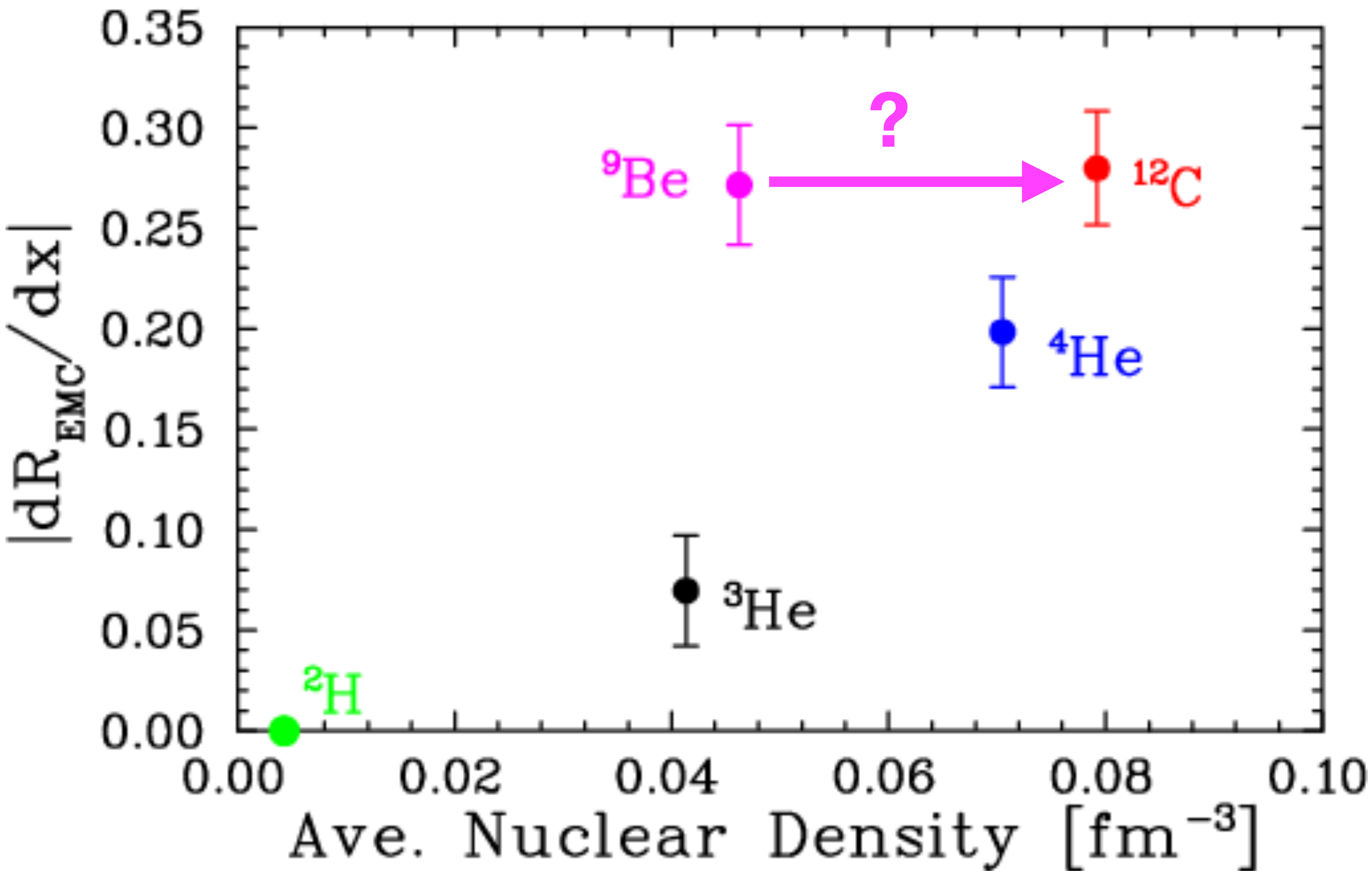
$$x = \frac{Q^2}{2M\nu}$$

The EMC Effect

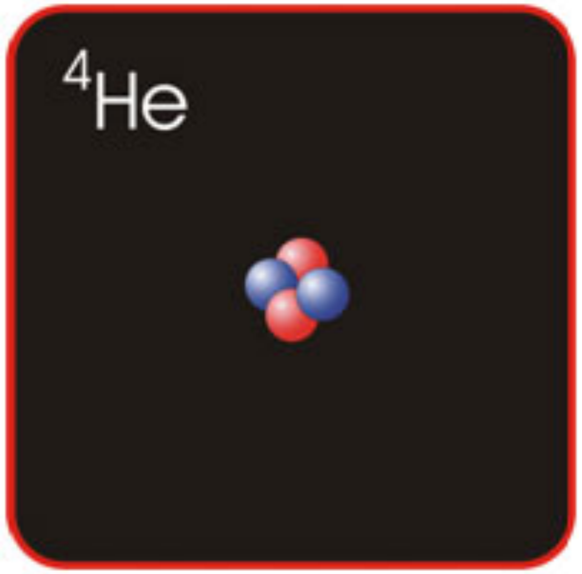
EMC effect scales with average nuclear density

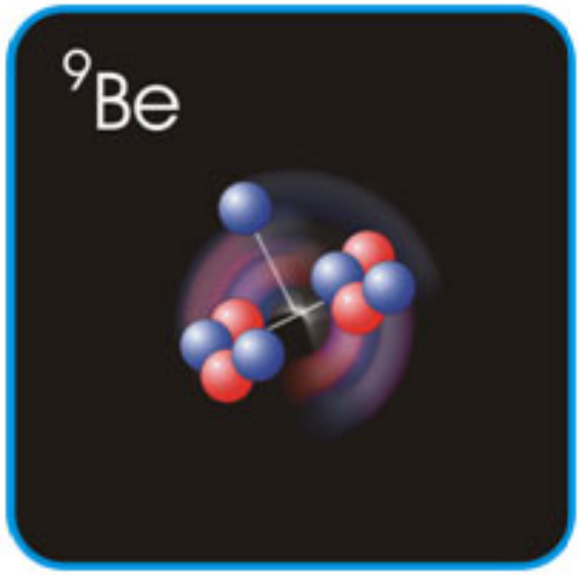


dR/dx = slope of line fit to A/D ratio over region x=0.3 to 0.7



C. Seely, A. Daniel, et al, PRL 103, 202301 (2009)

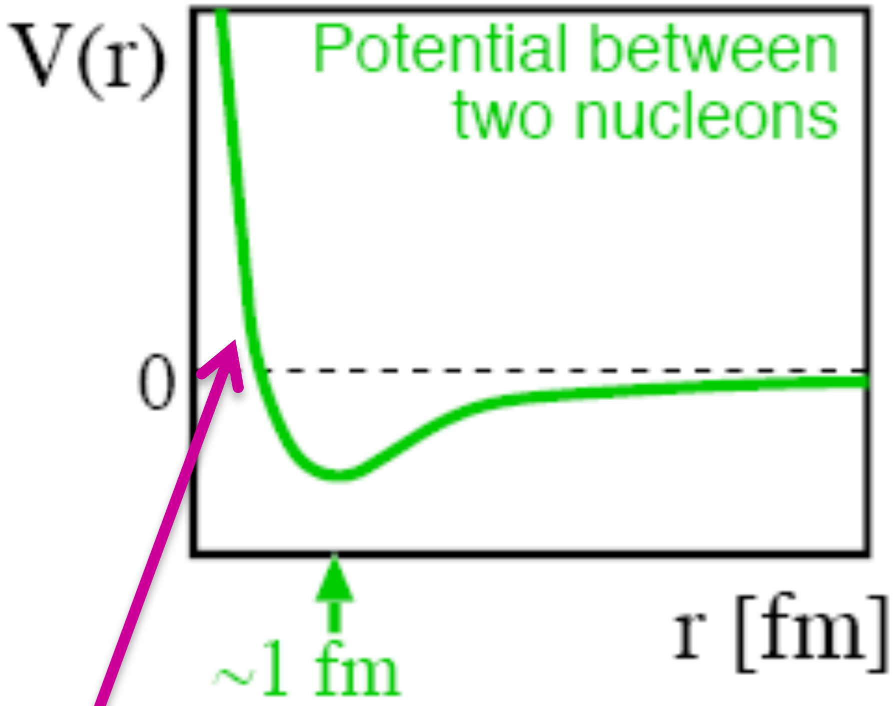




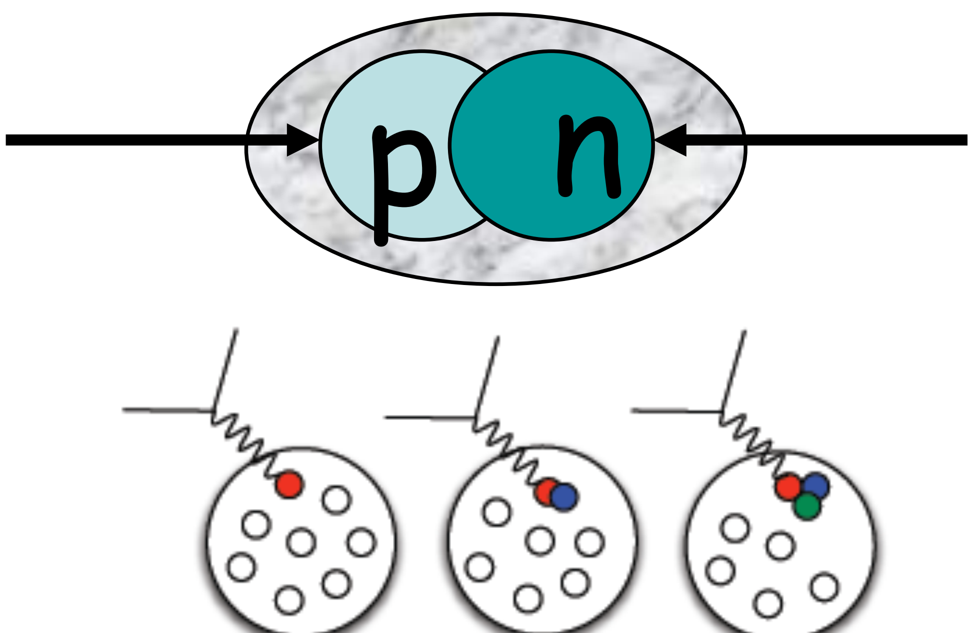
^{9}Be = 2α clusters + “extra” neutron

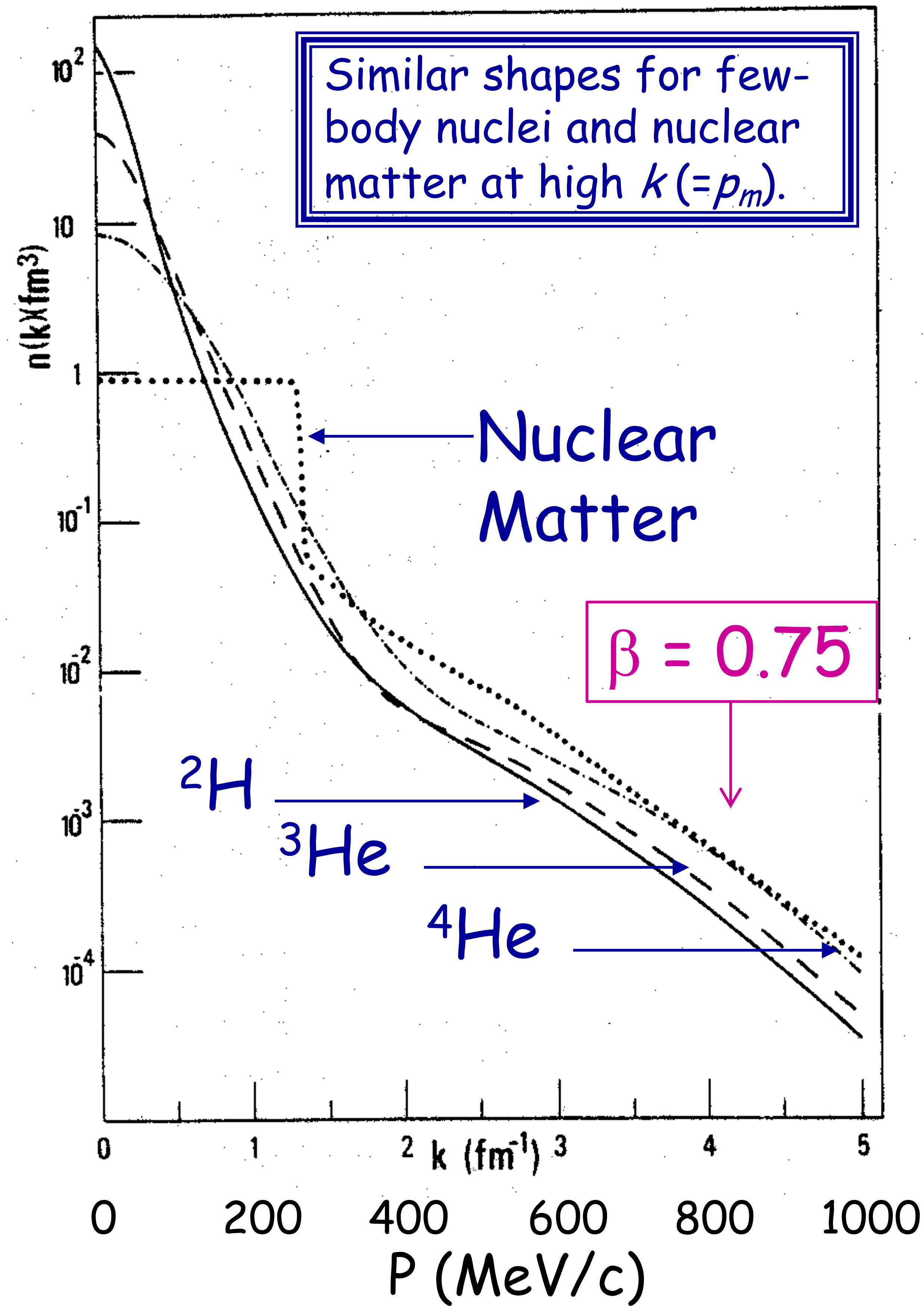
Suggests EMC effect depends on local nuclear environment

Short Range Correlations



Short-range repulsive core gives rise to high proton momenta

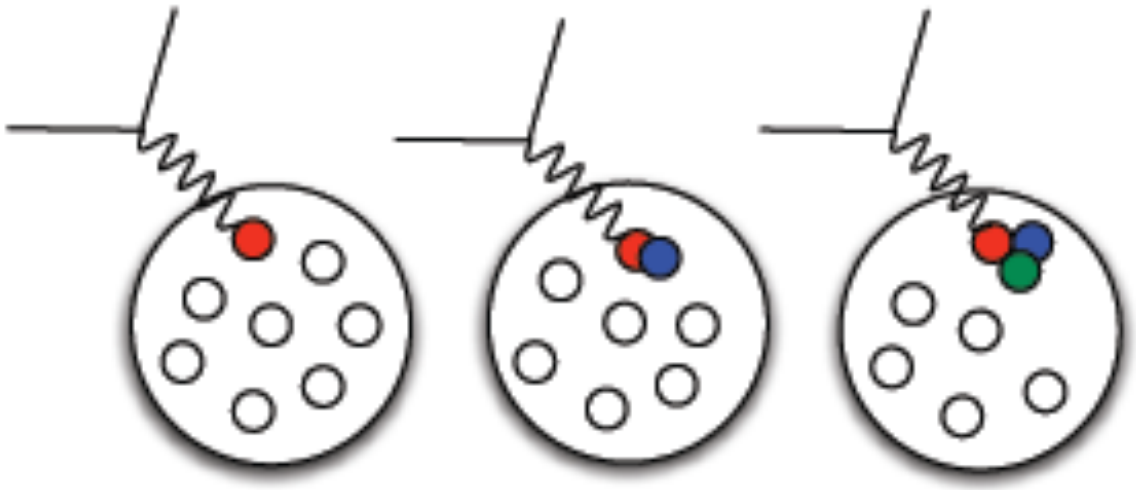




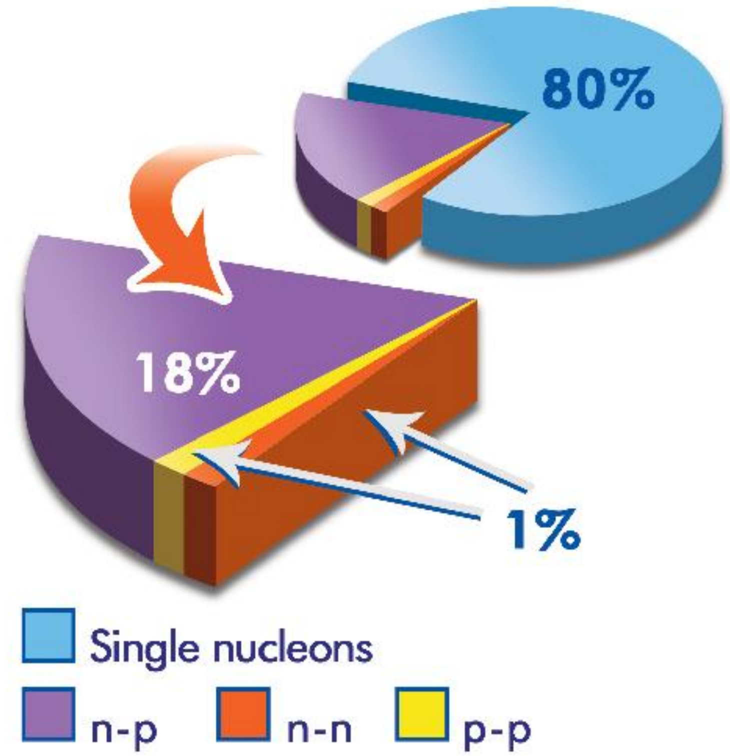
Exclusive Varification

$A(e,e')X$, $A = {}^3He, {}^4He, {}^{12}C, {}^{56}Fe$

$Q^2/2M\nu \rightarrow$



$A(e,e'pN)X$, $A = {}^{12}C$



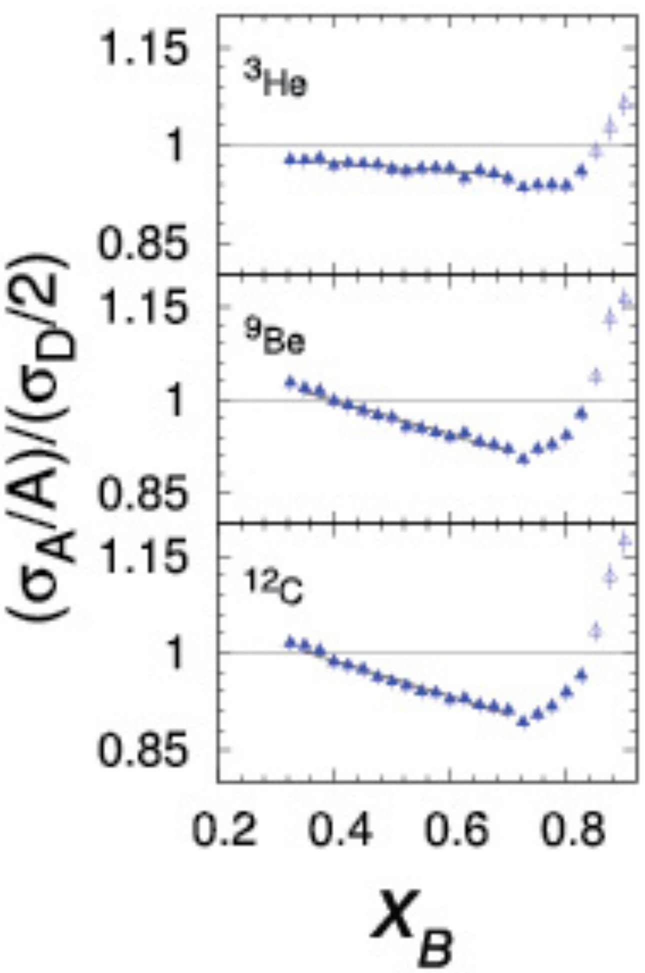
Measured Composition (%)

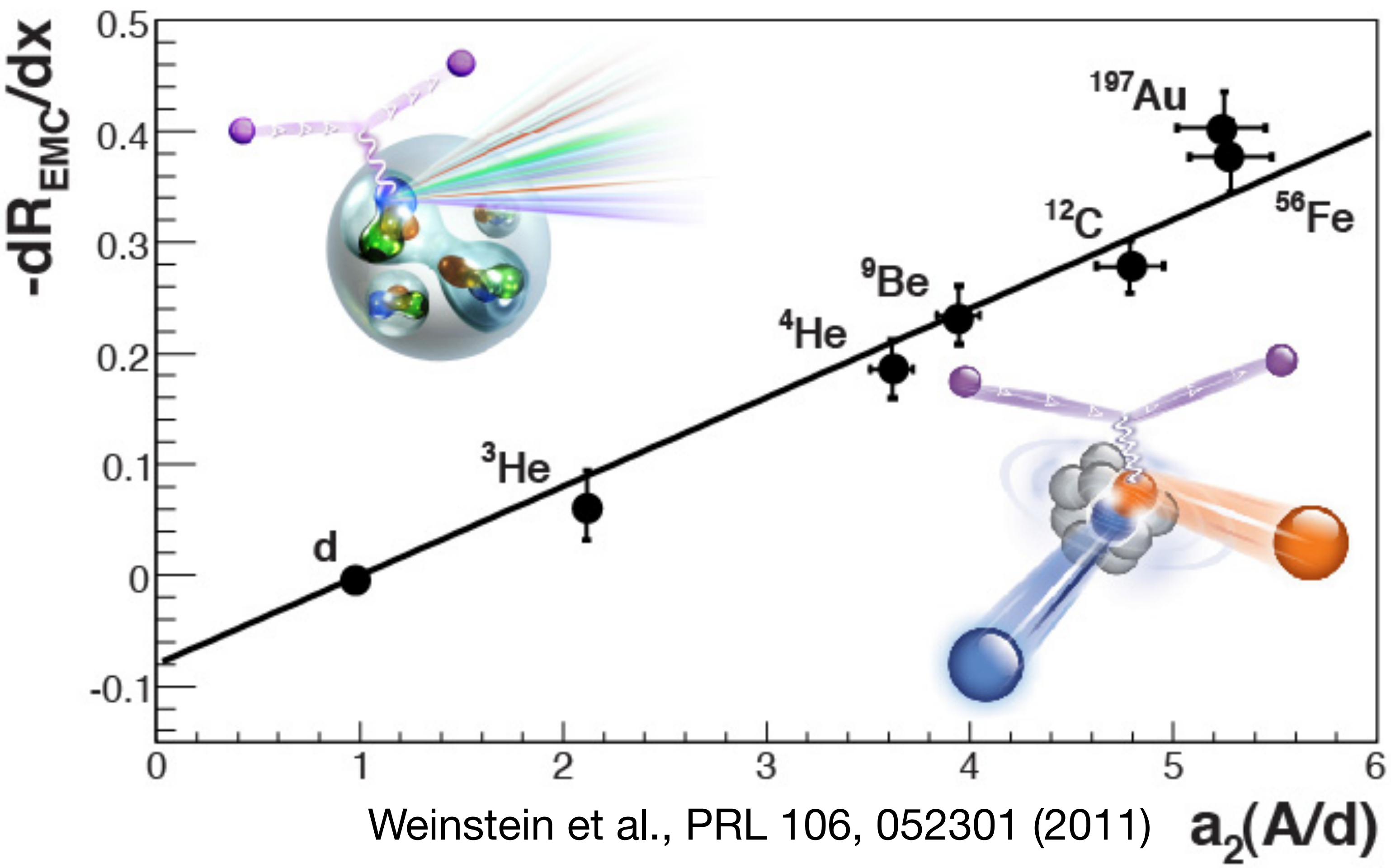
	1N state	2N SRC
^2H	96 ± 0.7	4.0 ± 0.7
^3He	92 ± 1.6	8.0 ± 1.6
^4He	86 ± 3.3	15.4 ± 3.3
^{12}C	80 ± 4.1	19.3 ± 4.1
^{56}Fe	76 ± 4.7	23.0 ± 4.7

Proton-neutron rate is ~20 x proton-proton rate →
two nucleons close together are almost always a p-n pair!
Expected to be due to (**short-range) tensor correlations**.

DIS on Nuclei: The EMC Effect and x>1

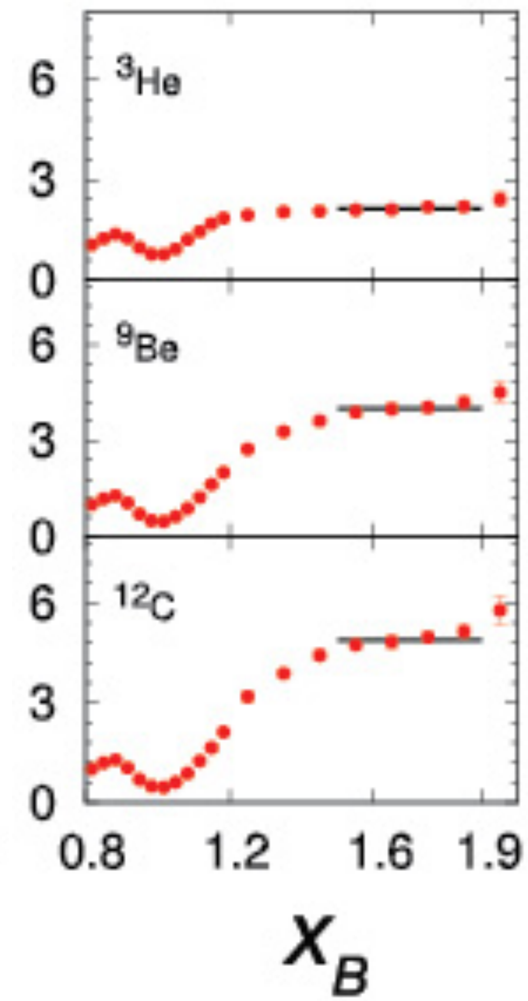
SRC: nucleons see strong repulsive core at short distances
EMC effect: quark momentum in nucleus is altered





Weinstein et al., PRL 106, 052301 (2011)

Fomin et al., PRL 108, 092502 (2012)



Correlation is suggestive of deeper relationship.

How do short range correlations the quark content of nucleon?

Spectroscopy

Constituent Quark Model

Classification scheme for hadrons in terms of “valence quarks” which give rise to the quantum numbers of hadrons.

J^{PC} J- total angular momentum, P-symmetry and C-symmetry

SU(3) flavour “Eightfold way”

Organizes a huge number of hadrons

Symbol	Flavour	Electric charge (e)	Isospin	I_3	Mass Gev/c^2
u	up	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{2}$	≈ 0.33
d	down	$-\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$	≈ 0.33
c	charm	$+\frac{2}{3}$	0	0	≈ 1.5
s	strange	$-\frac{1}{3}$	0	0	≈ 0.5
t	top	$+\frac{2}{3}$	0	0	≈ 172
b	bottom	$-\frac{1}{3}$	0	0	≈ 4.5

Baryon	Quark content	Spin	Isospin	I_3	Mass Mev/c^2
p	uud	$\frac{1}{2}$	$\frac{1}{2}$	$+\frac{1}{2}$	938
n	udd	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	940
Δ^{++}	uuu	$\frac{3}{2}$	$\frac{3}{2}$	$+\frac{3}{2}$	1230
Δ^{+}	uud	$\frac{3}{2}$	$\frac{3}{2}$	$+\frac{1}{2}$	1230
Δ^{0}	udd	$\frac{3}{2}$	$\frac{3}{2}$	$-\frac{1}{2}$	1230
Δ^{-}	ddd	$\frac{3}{2}$	$\frac{3}{2}$	$-\frac{3}{2}$	1230

Meson	Quark content	Spin	Isospin	I_3	Mass Mev/c^2
π^{+}	$u\bar{d}$	0	1	+1	140
π^{0}	$\frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$	0	1	0	135
π^{-}	$d\bar{u}$	0	1	−1	140
ρ^{+}	$u\bar{d}$	1	1	+1	770
ρ^{0}	$\frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$	1	1	0	770
ρ^{-}	$d\bar{u}$	1	1	−1	770
ω	$\frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right)$	1	0	0	782

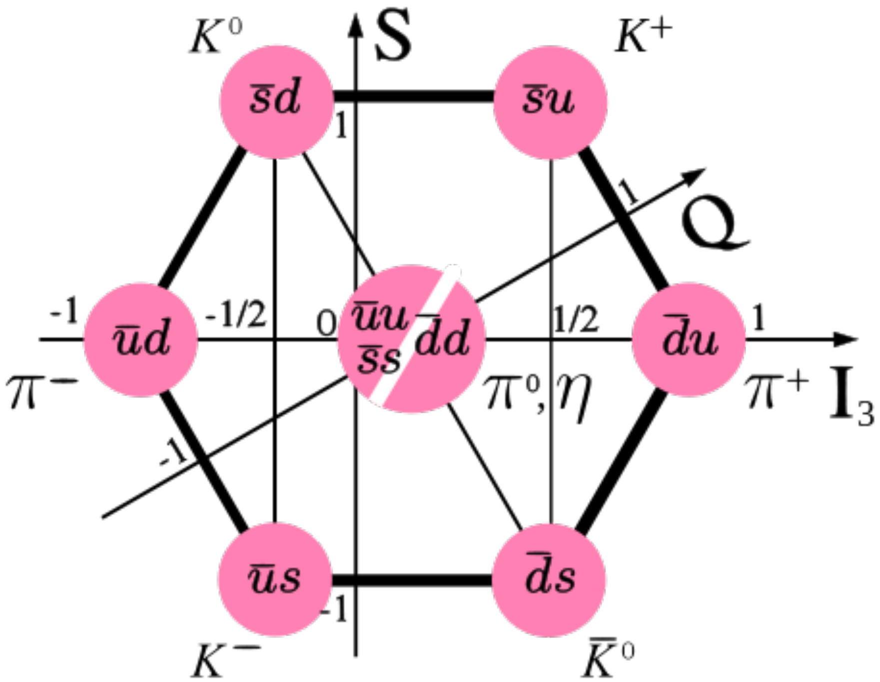
Baryon	Quark content	Spin	Isospin	I_3	Mass Mev/c^2
Σ^+	uus	$\frac{1}{2}$	1	$+1$	1189
Σ^0	uds	$\frac{1}{2}$	1	0	1193
Σ^-	dds	$\frac{1}{2}$	1	-1	1189
Ξ^0	uss	$\frac{1}{2}$	$\frac{1}{2}$	$+\frac{1}{2}$	1314
Ξ^-	dss	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1321
Λ	uds	$\frac{1}{2}$	0	0	1115
Σ^{*+}	uus	$\frac{3}{2}$	1	$+1$	1385
Σ^{*0}	uds	$\frac{3}{2}$	1	0	1385
Σ^{*-}	dds	$\frac{3}{2}$	1	-1	1385
Ξ^{*0}	uss	$\frac{3}{2}$	$\frac{1}{2}$	$+\frac{1}{2}$	1530
Ξ^{*-}	dss	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	1530
Ω^-	sss	$\frac{3}{2}$	0	0	1672

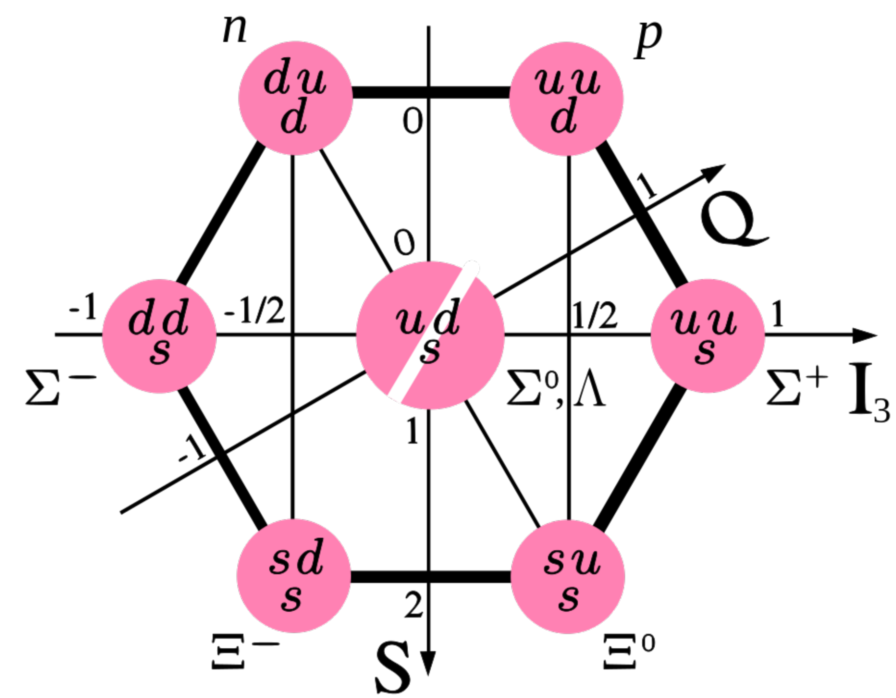
Mesons

Ancient Greek μέσον (méson, “middle”)

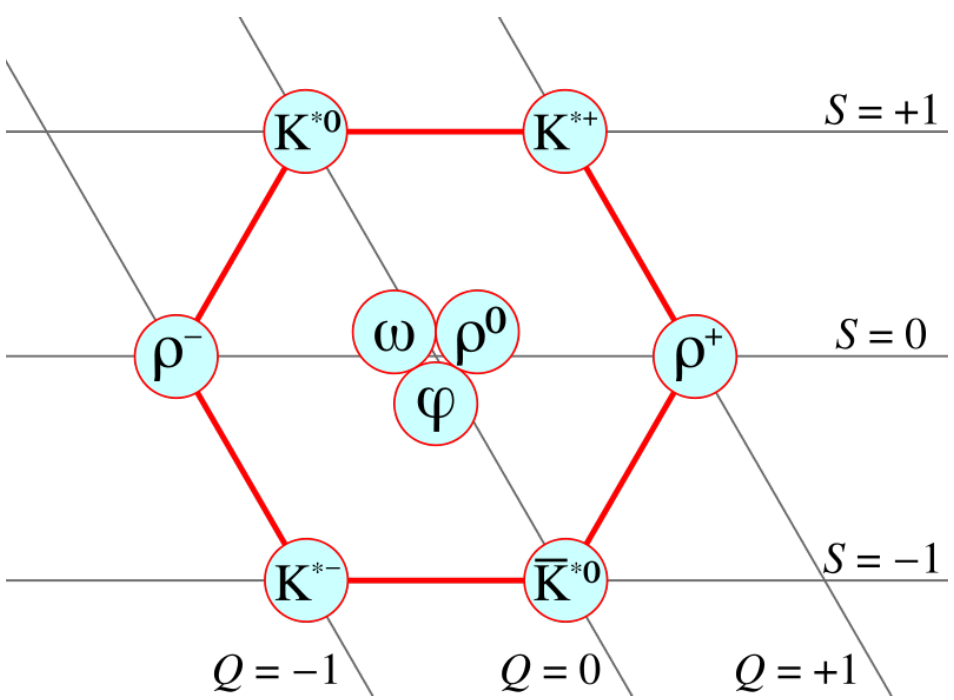
Baryons

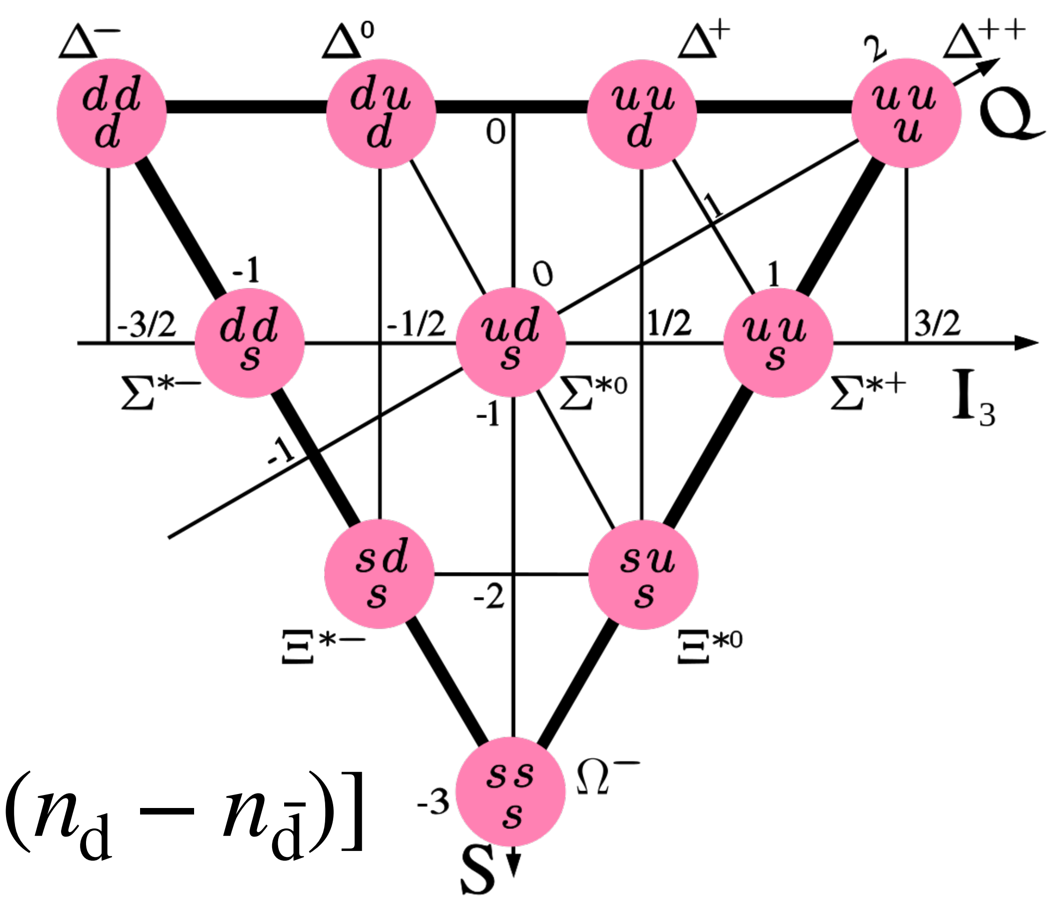
Greek word for "heavy" (βαρύς, barýs)



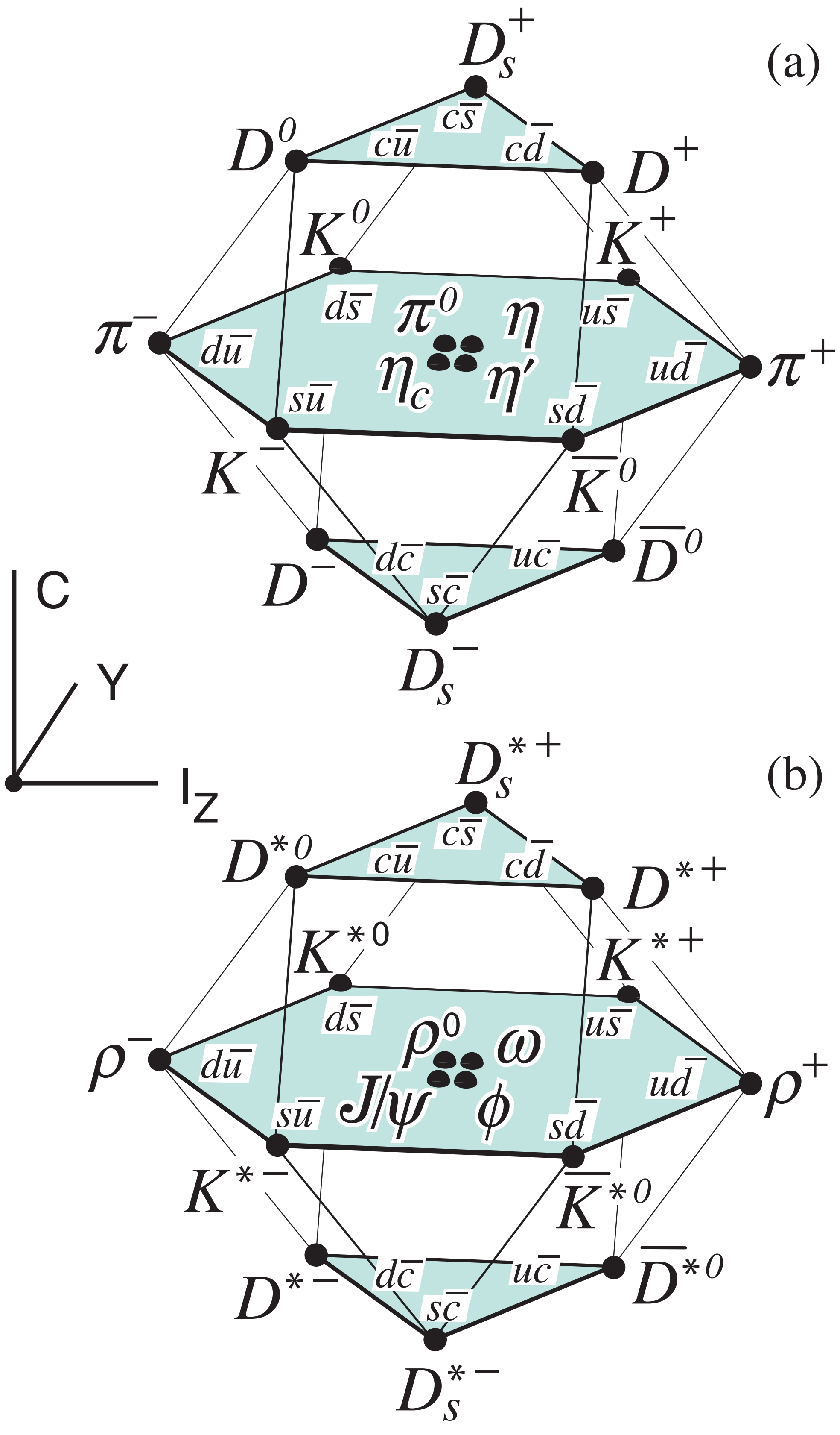


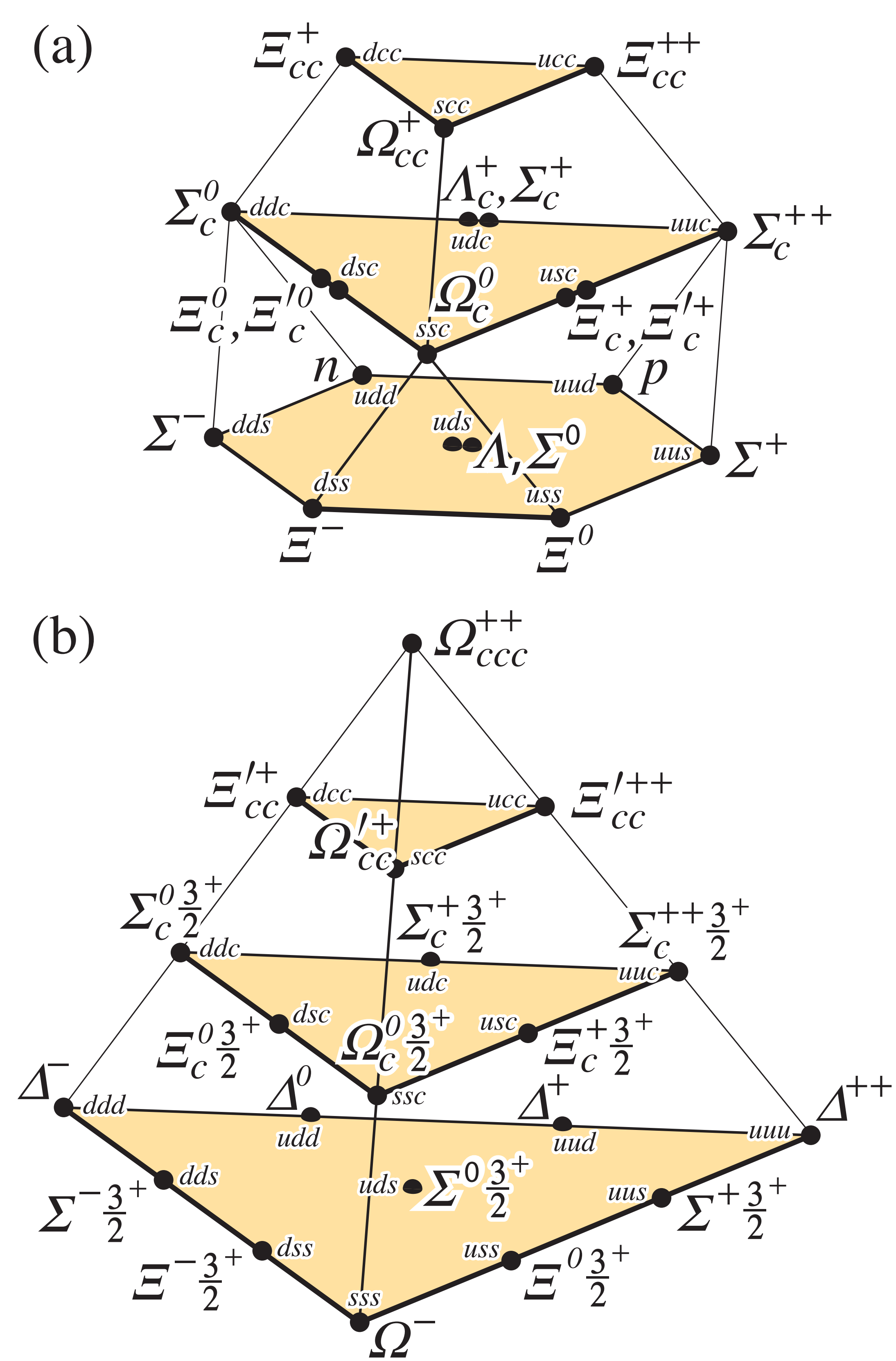
$$Q = I_3 + \frac{1}{2}(B + S)$$





$$I_3 = \frac{1}{2}[(n_\mathrm{u} - n_{\bar{\mathrm{u}}}) - (n_\mathrm{d} - n_{\bar{\mathrm{d}}})]$$

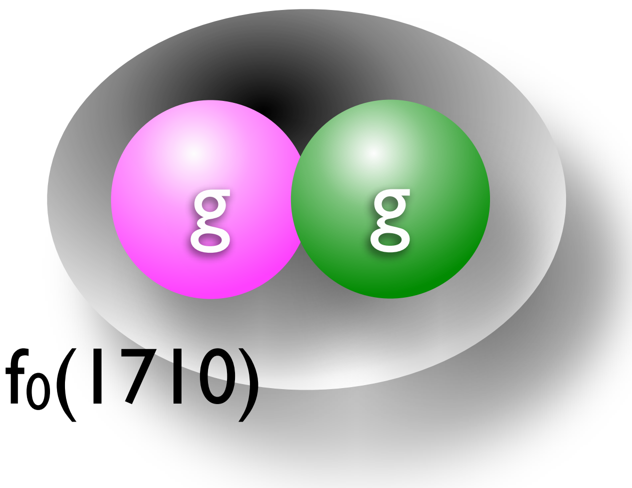

(a)
(b)
C
Y
I Z
D+ s
D0
D+
K0
K+
π−
π+
π0
η
ηc
η′
K−
K 0
D−
D 0
D− s
D*+ s
D*0
D*+
K*0
K*+
ρ−
ρ+
ρ0
ω
J/ψ
φ
K*−
K*0
D*−
D*0
D*− s


(a)
(b)
Ξ+ cc
Ξ++ cc
Ω+ cc
Λ+ c, Σ+ c
Σ0 c
Σ++ c
Ω0 c
Ξ0 c, Ξ′0 c
Ξ+ c, Ξ′+ c
n
p
Σ−
Σ+
Λ, Σ0
Ξ−
Ξ0
Ω++ ccc
Ξ′+ cc
Ξ′++ cc
Ω′+ cc
Δ−
Δ0
Δ+
Δ++
Ω−

Exotic Hadrons

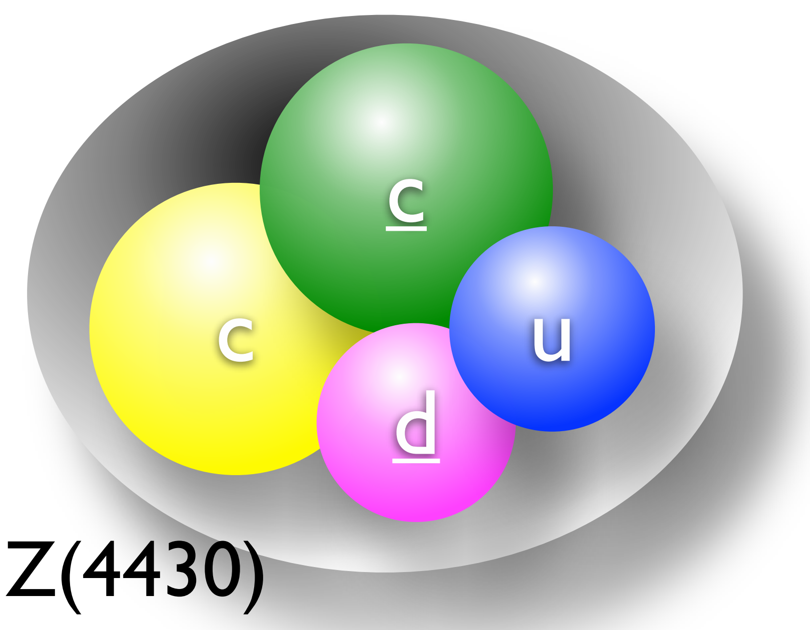
Why don't we find other color-singlets?
If they exist: what are their properties?
Why are they so rare?

glueball



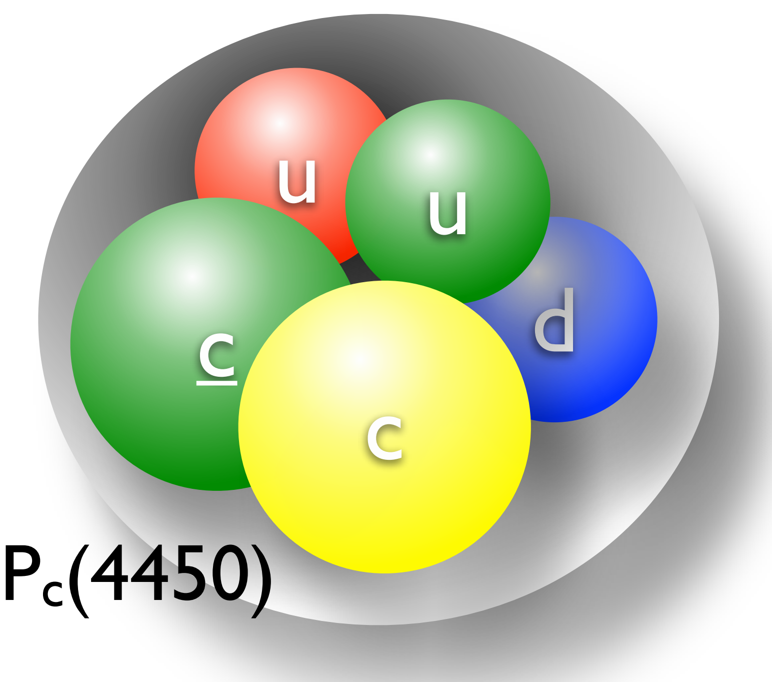
$f_0(1710)$

tetra-quark



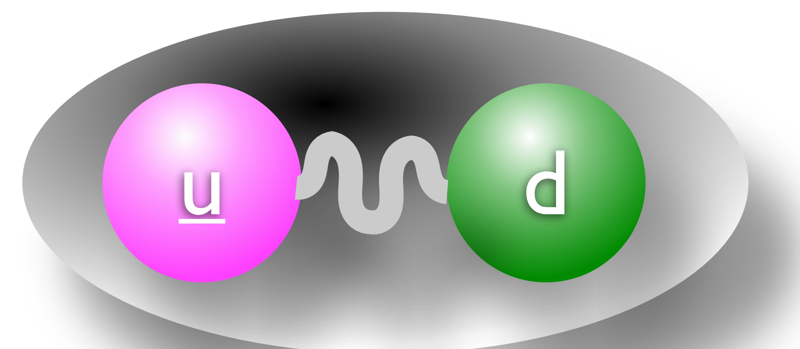
Z(4430)

penta-quark

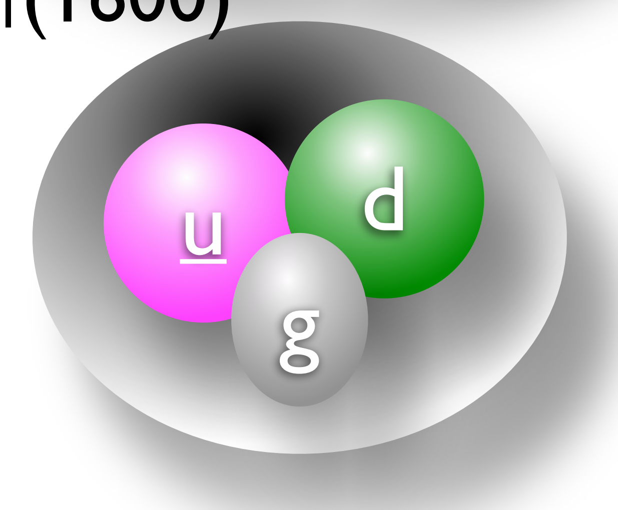


$P_c(4450)$

hybrid meson



$\pi_1(1600)$



Evidence for resonant behavior
PRL 112 (2014) 222002

PRL 115, 072001 (2015)

Meson Quantum Numbers

Mesons have well defined quantum numbers:
total spin J, parity P, and C-parity C represented as J^{PC}

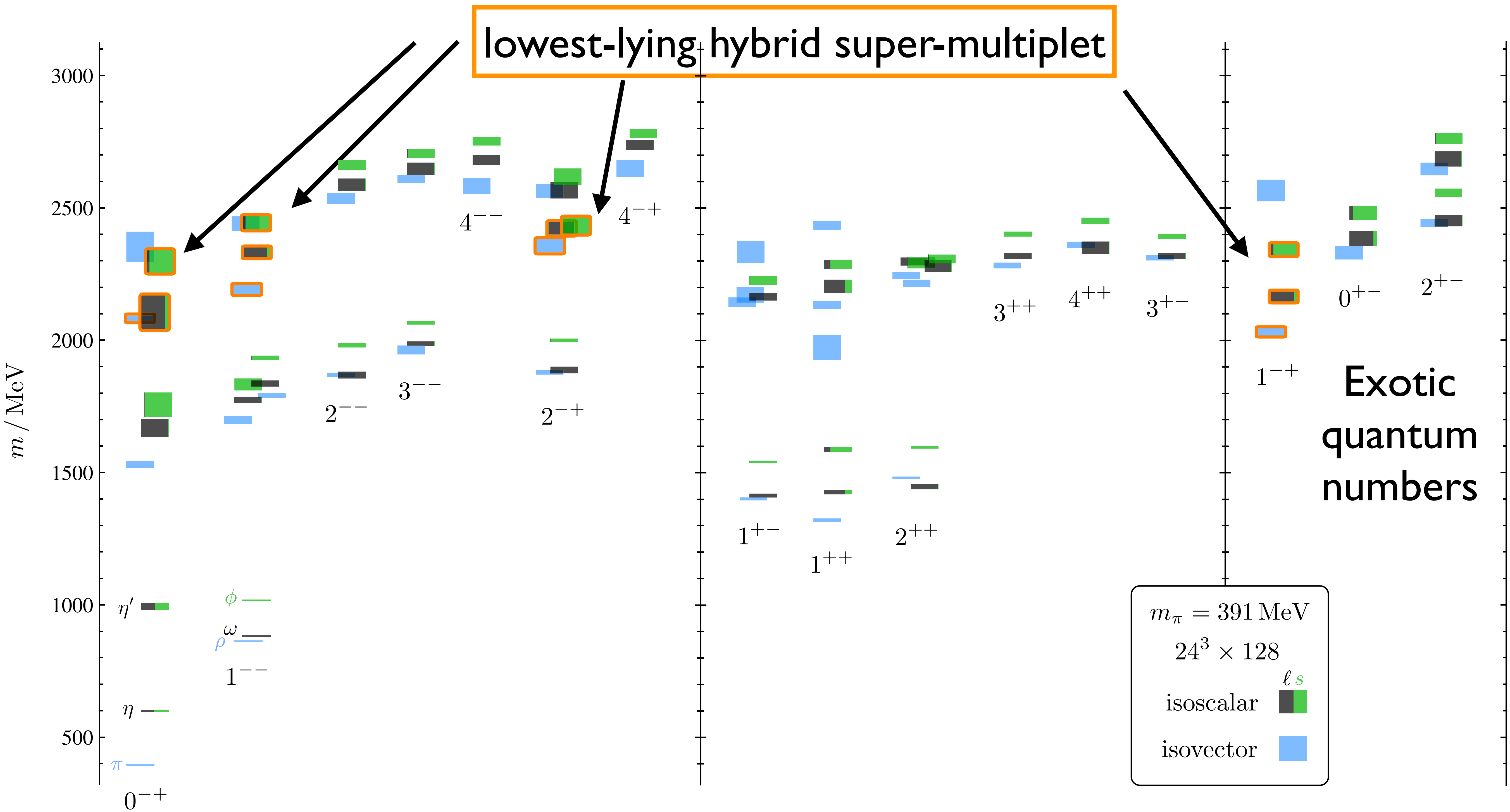
$$P(q\bar{q}) = (-1)^{L+1}$$ mirror

$$C(q\bar{q}) = (-1)^{L+S}$$ particle—anti-particle exchange

S	L	J	P	C	J^{PC}	Mesons				Type
0	0	0	$-$	$+$	0^{-+}	π	η	η'	K	pseudoscaler
1	0	1	$-$	$-$	1^{--}	ρ	ω	ϕ	K^*	vector
0	1	1	$+$	$-$	1^{+-}	b_1	h_1	h'_1	K_1	axial vector
1	1	0	$+$	$+$	0^{++}	a_0	f_0	f'_0	K^*_0	scaler
1	1	1	$+$	$+$	1^{++}	a_1	f_1	f'_1	K^*_1	axial vector
1	1	2	$+$	$+$	2^{++}	a_2	f_2	f'_2	K^*_2	tensor

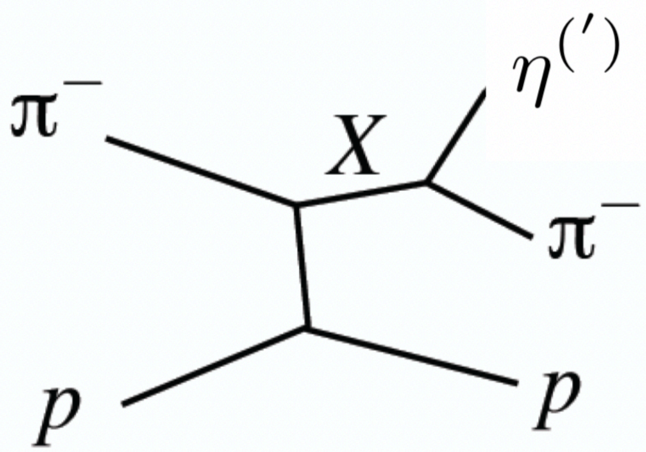
explicitly exotic quantum numbers $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

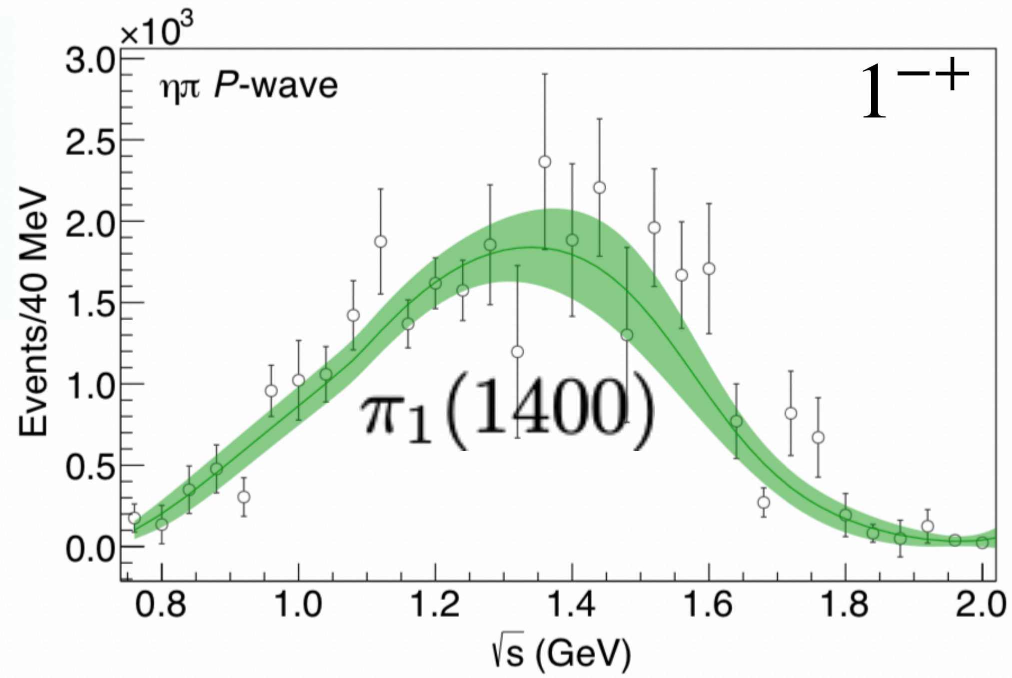
Light Quark Mesons from Lattice

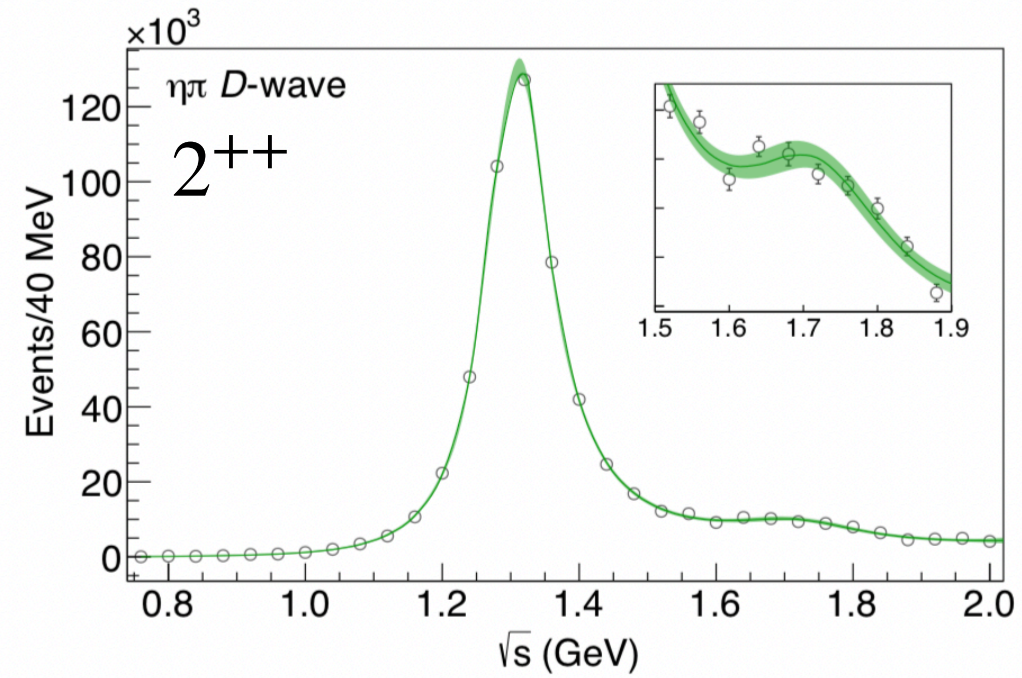


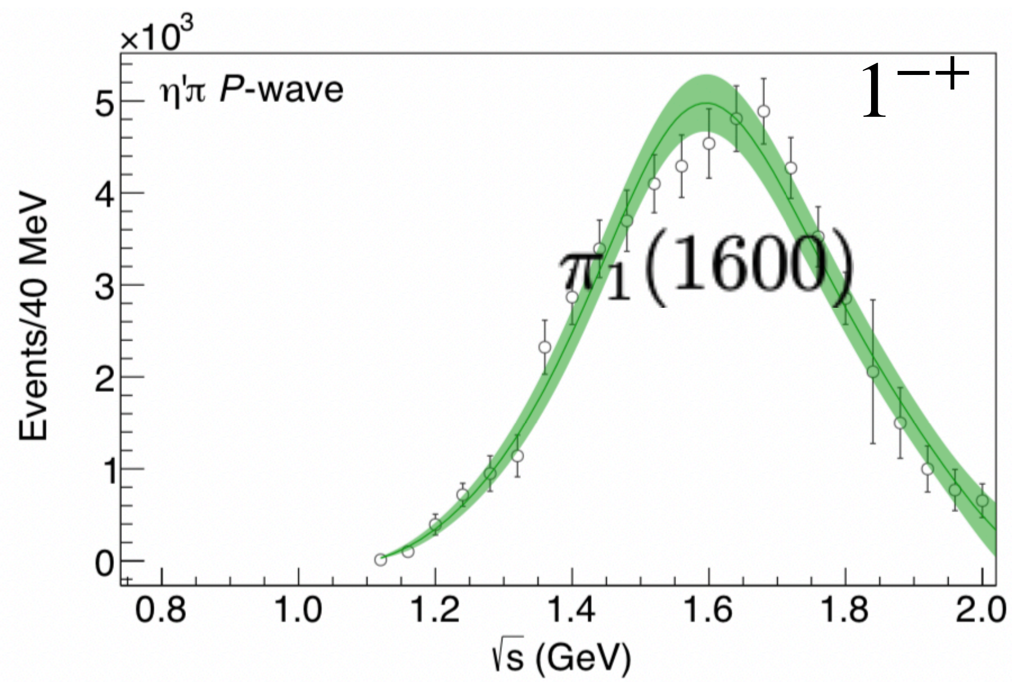
Dudek et al. PRD 88 (2013) 094505

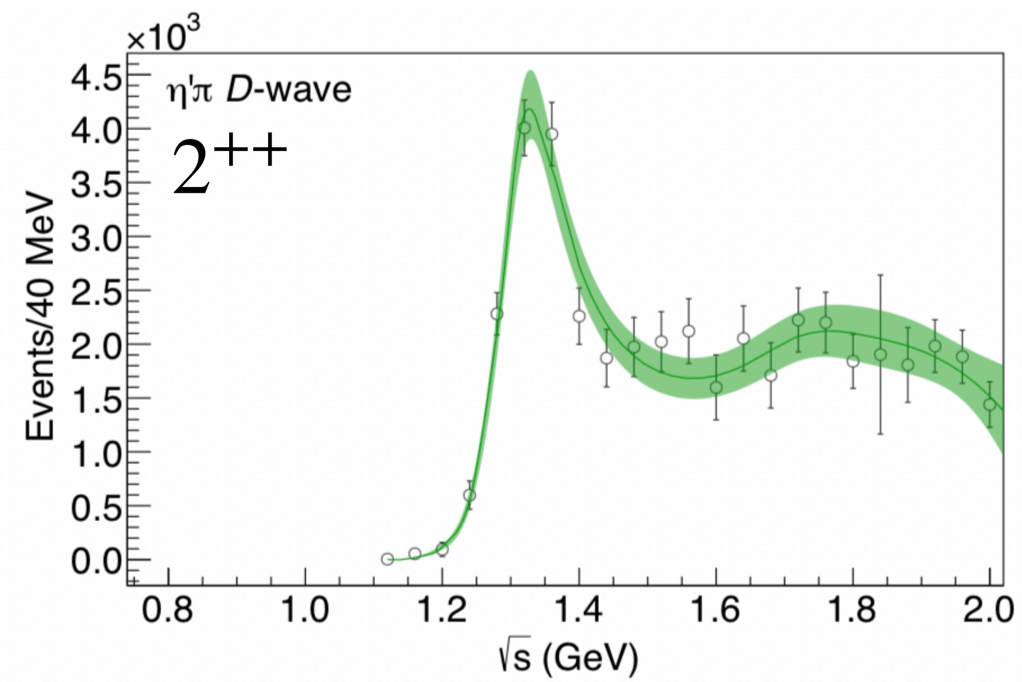
$\eta\pi / \eta'\pi$ spectroscopy





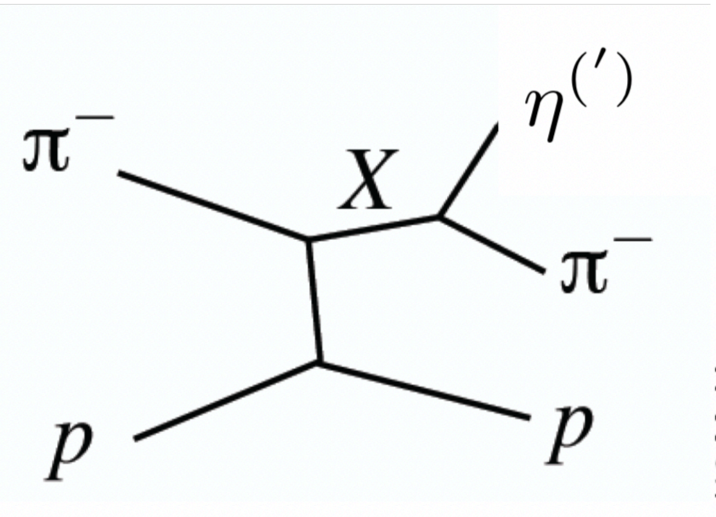




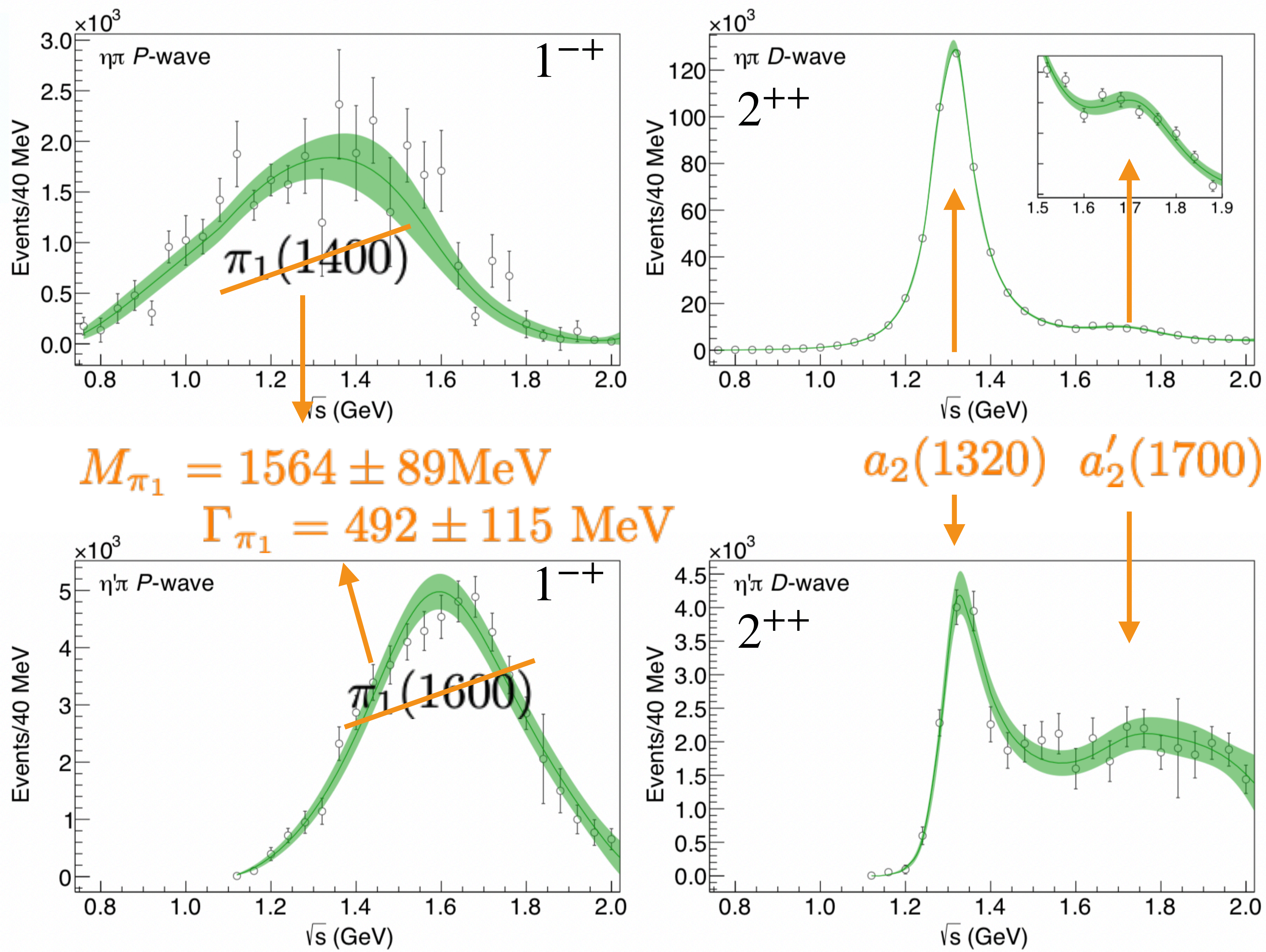


COMPASS:
PLB 740 (2015) 303
JPAC:
PRL 122 (2019) 042002

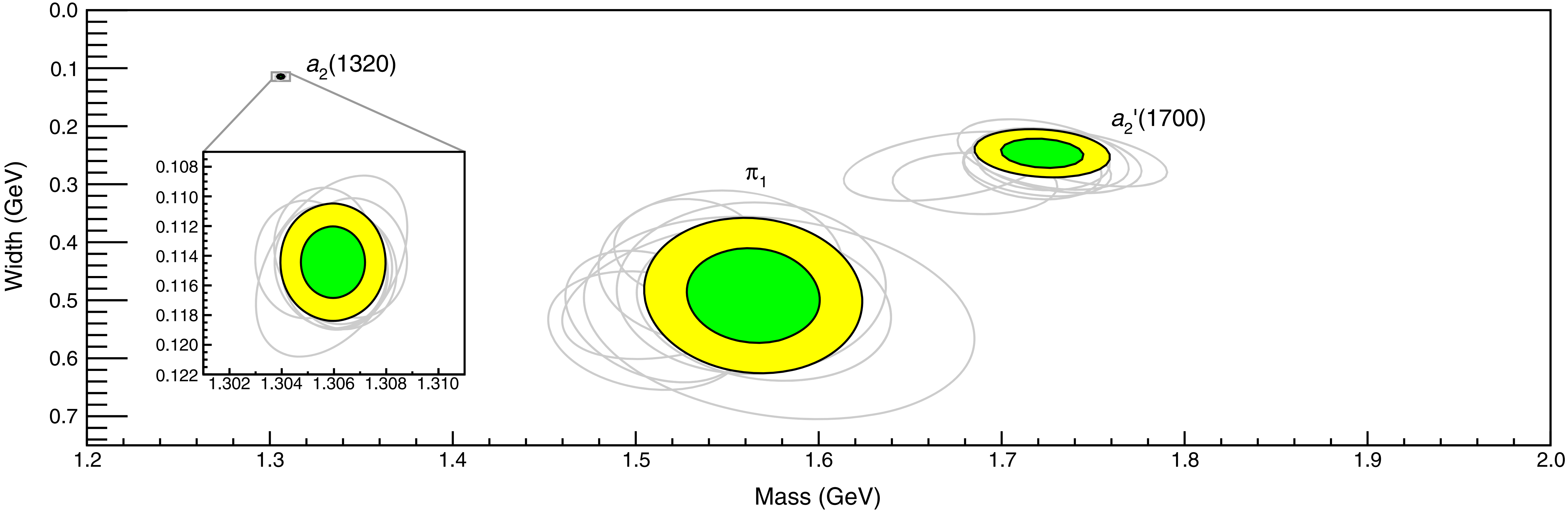
$\eta\pi / \eta'\pi$ spectroscopy



coupled channel fit to ηπ and η'π determine pole positions for a_2, a_2', and exotic π_1



COMPASS:
PLB 740 (2015) 303
JPAC:
PRL 122 (2019) 042002

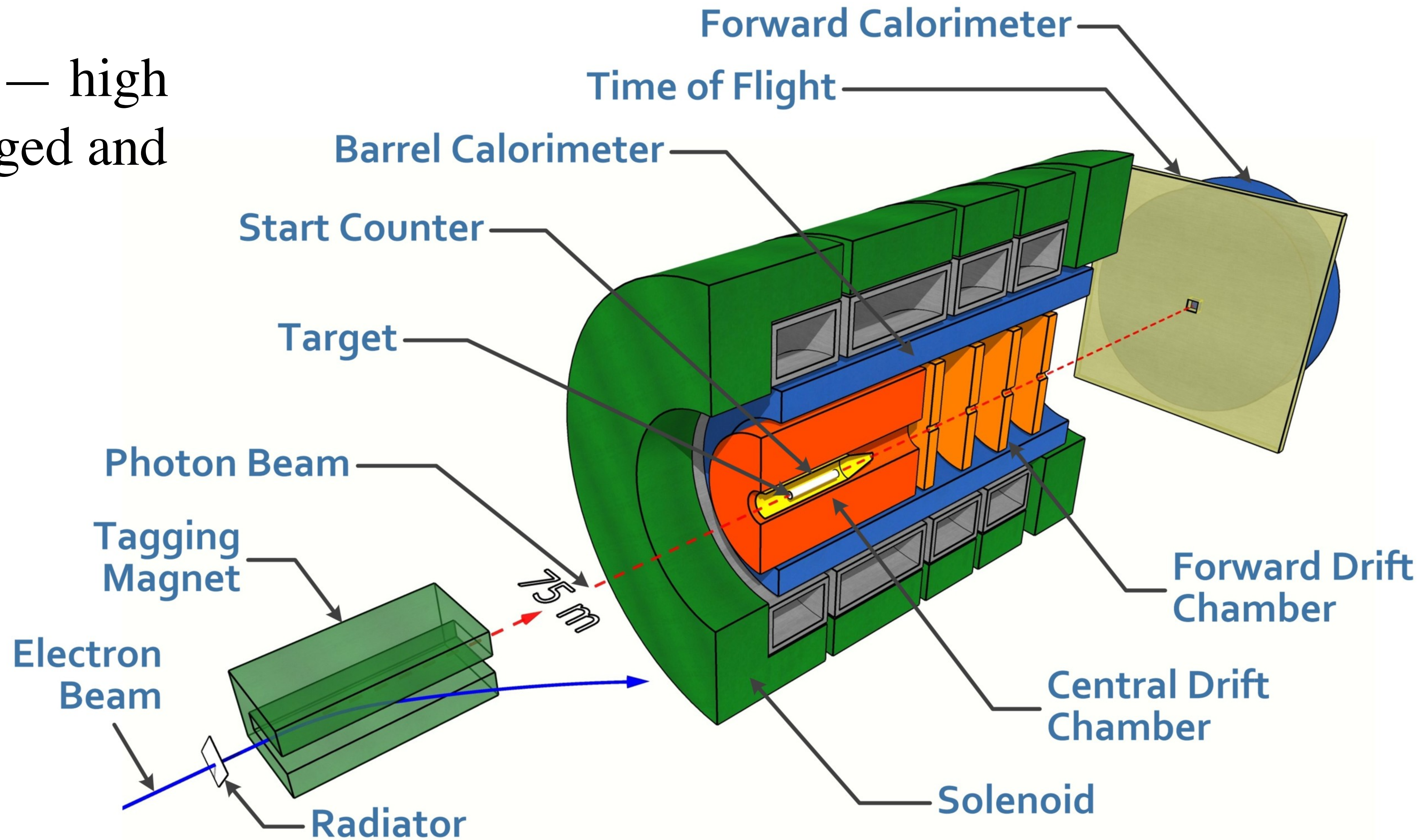


0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Width (GeV)
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
Mass (GeV)
a2(1320)
π1
a2'(1700)
0.108
0.110
0.112
0.114
0.116
0.118
0.120
0.122
1.302
1.304
1.306
1.308
1.310

Experiment and Detector

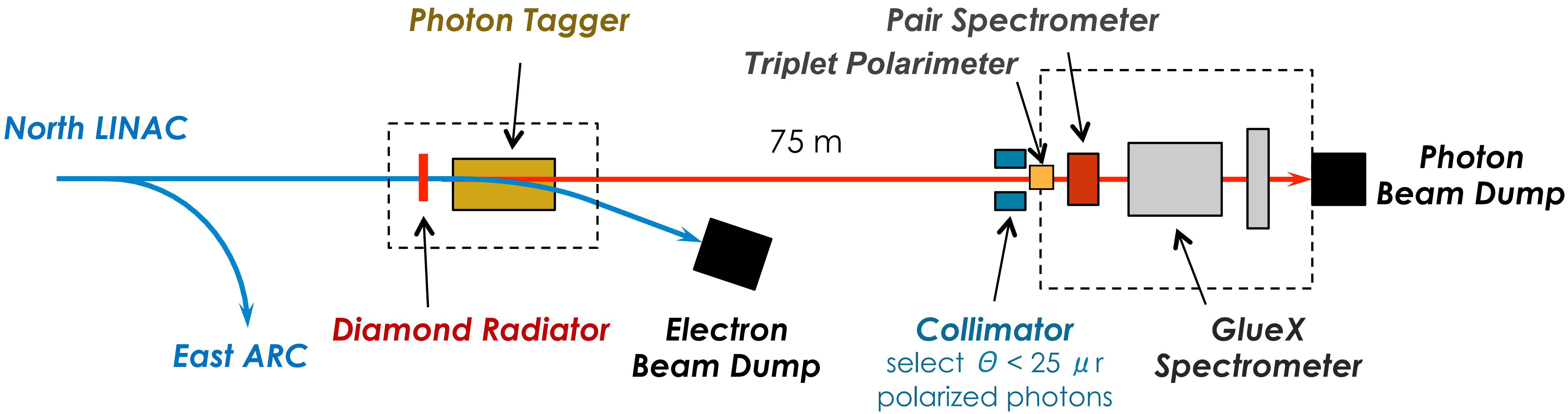
Hall D at Jefferson Lab

Linearly polarized photon beam
Proton target
Hermetic detector — high efficiency for charged and neutral particles



[Nucl. Instrum. & Meth. A987, 164807 (2021)]

Photon Beamline

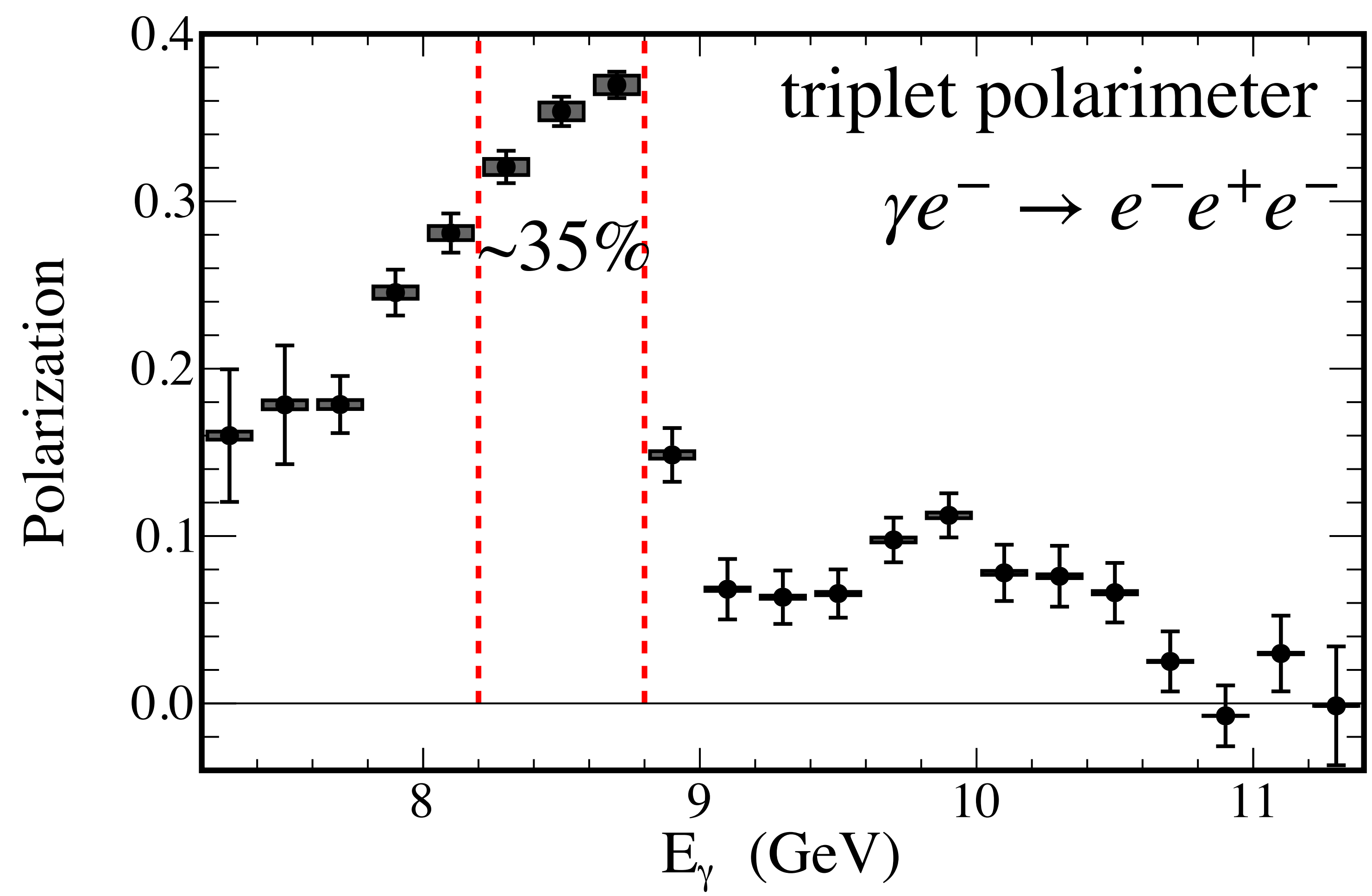


~12 GeV electrons from CEBAF

Coherent bremsstrahlung on thin diamond wafer

Linearly polarized in coherent peak ~35%

Tagged photon energy



GlueX phase 1 tagged luminosity

8.2 - 8.8 GeV 125 pb^{-1}

6.0 - 11.6 GeV 440 pb^{-1}

Summary

Electron scattering is a versatile and powerful experimental technique

It continues to provide new insights in nucleon structure and nuclear structure and the spectroscopy of strongly interacting systems.