Facets of the strong interaction

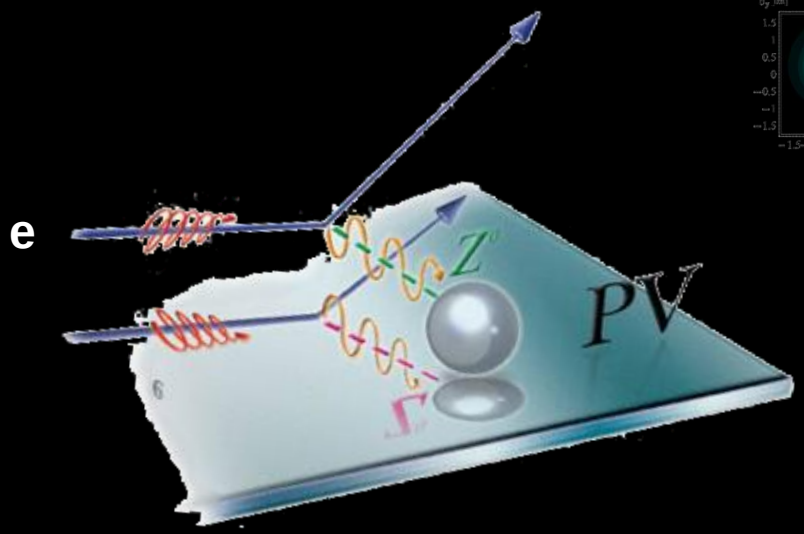
Hirschegg 2012

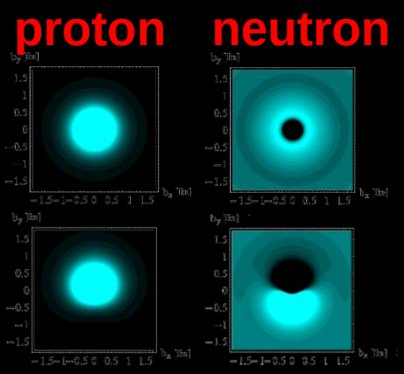
Michael Pennington
Jefferson Lab

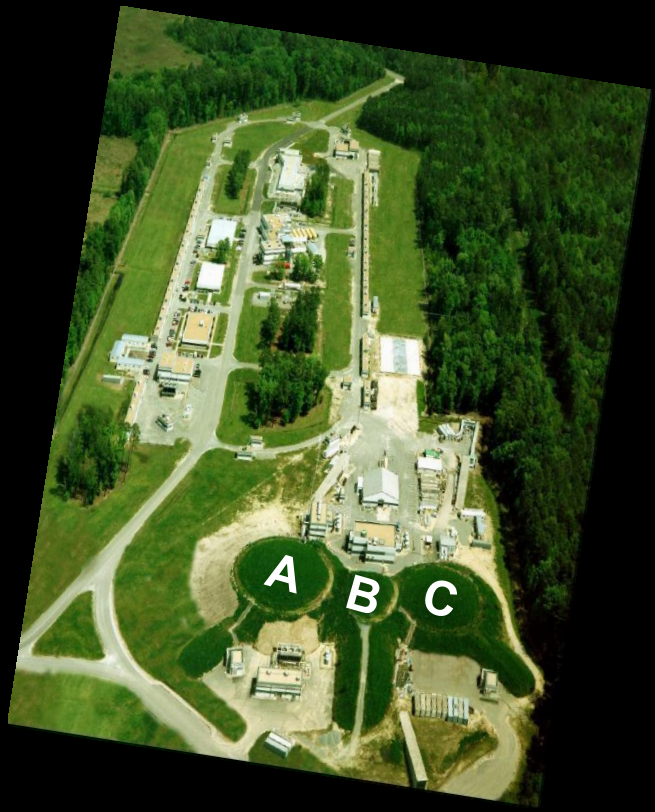

Glimpsing colour
in a world of black & white
Hirschegg 2012


Glimpsing colour
in a world of black & white

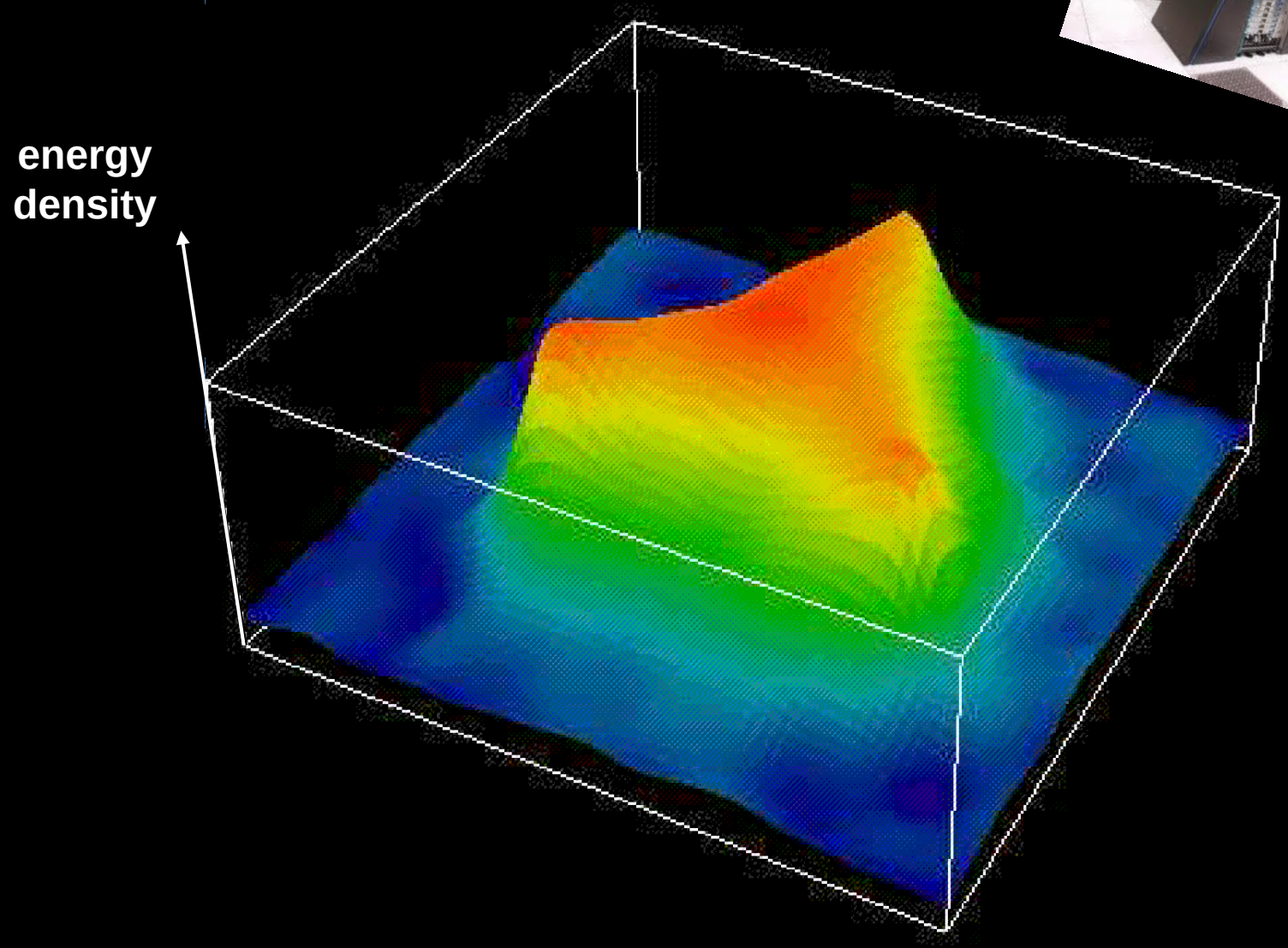
Glimpsing colour in a world of black & white



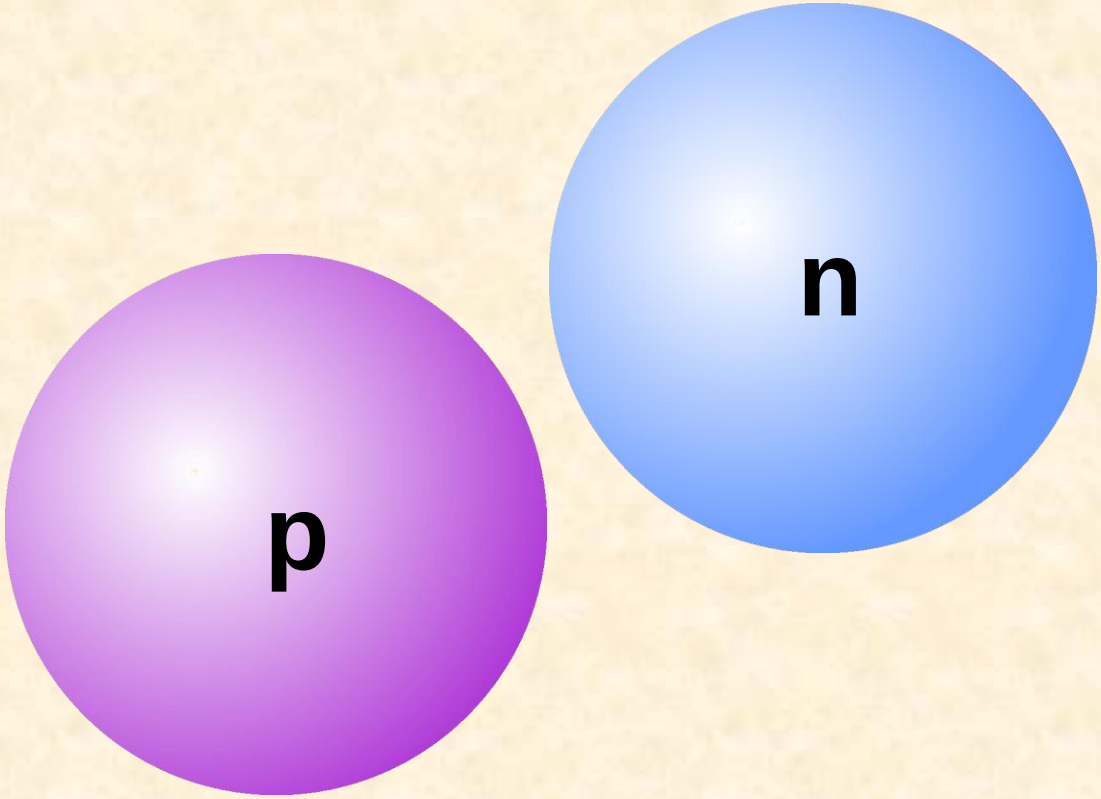




Colour Forces

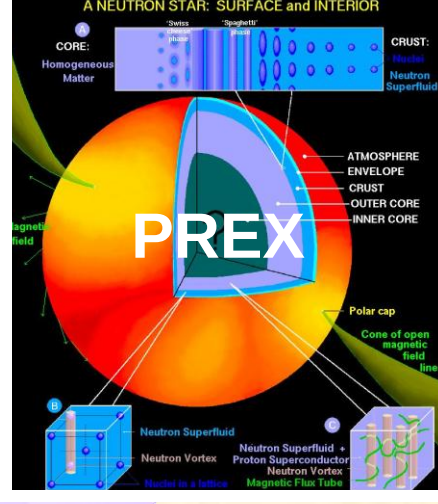


Jefferson Lab
Exploring the Nature of Matter



Jefferson Lab

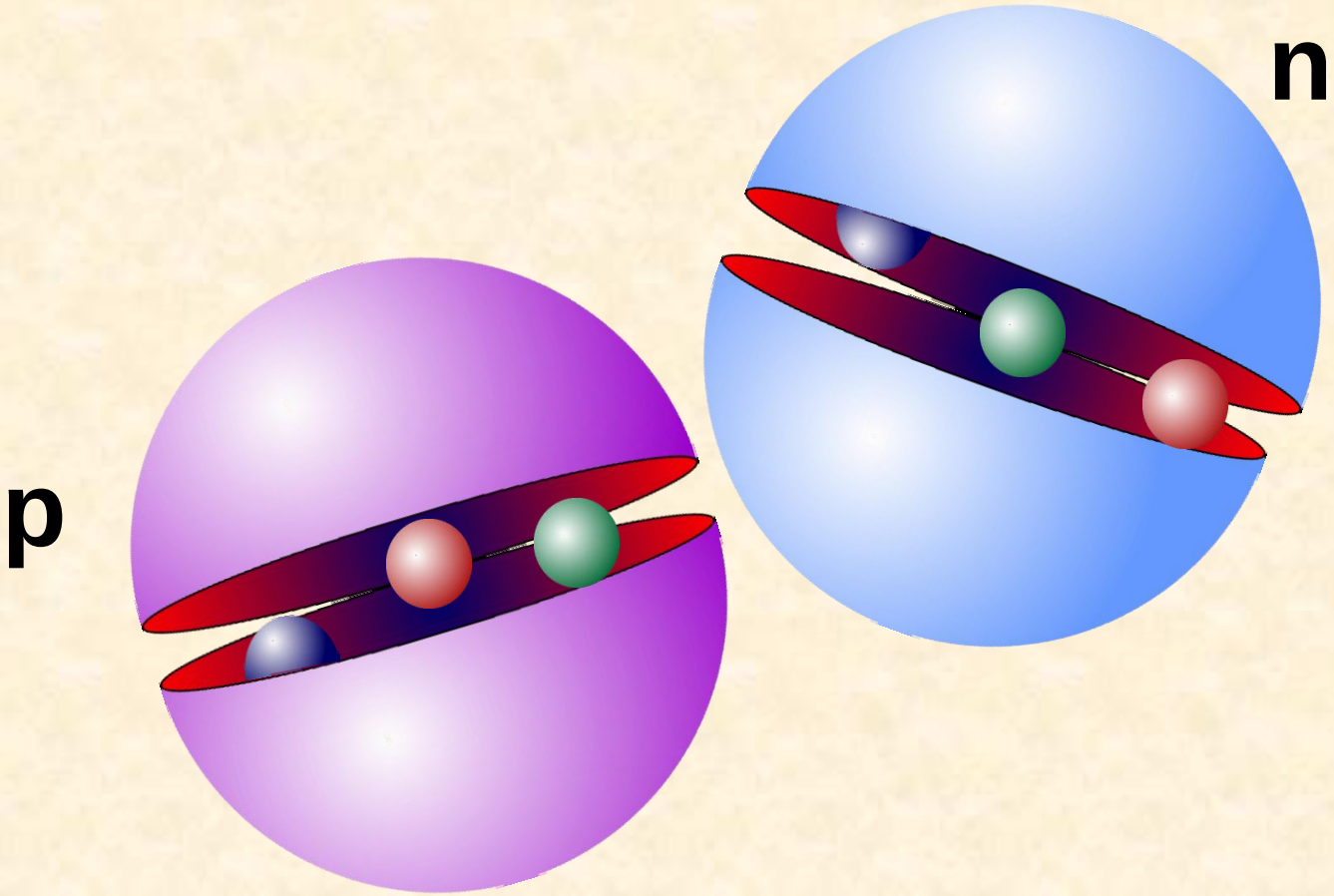
Exploring the Nature of Matter



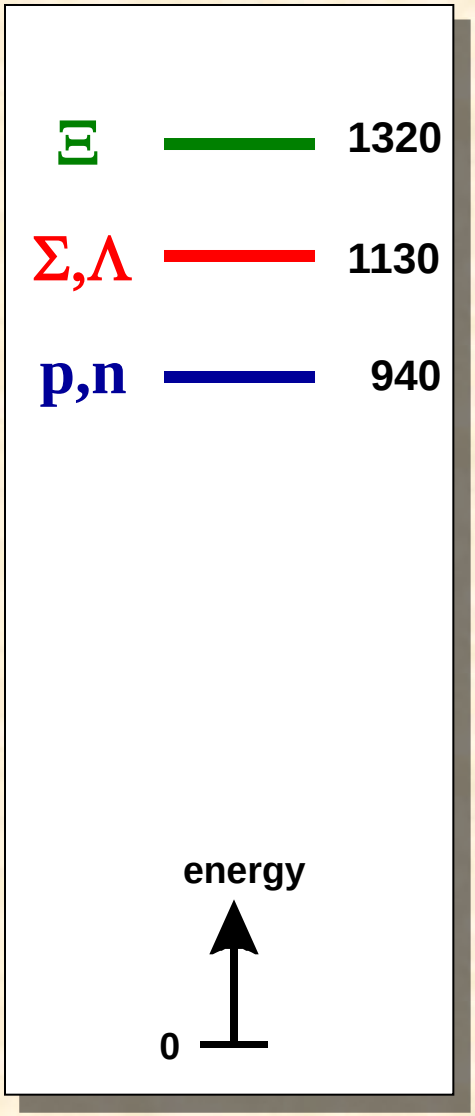
n

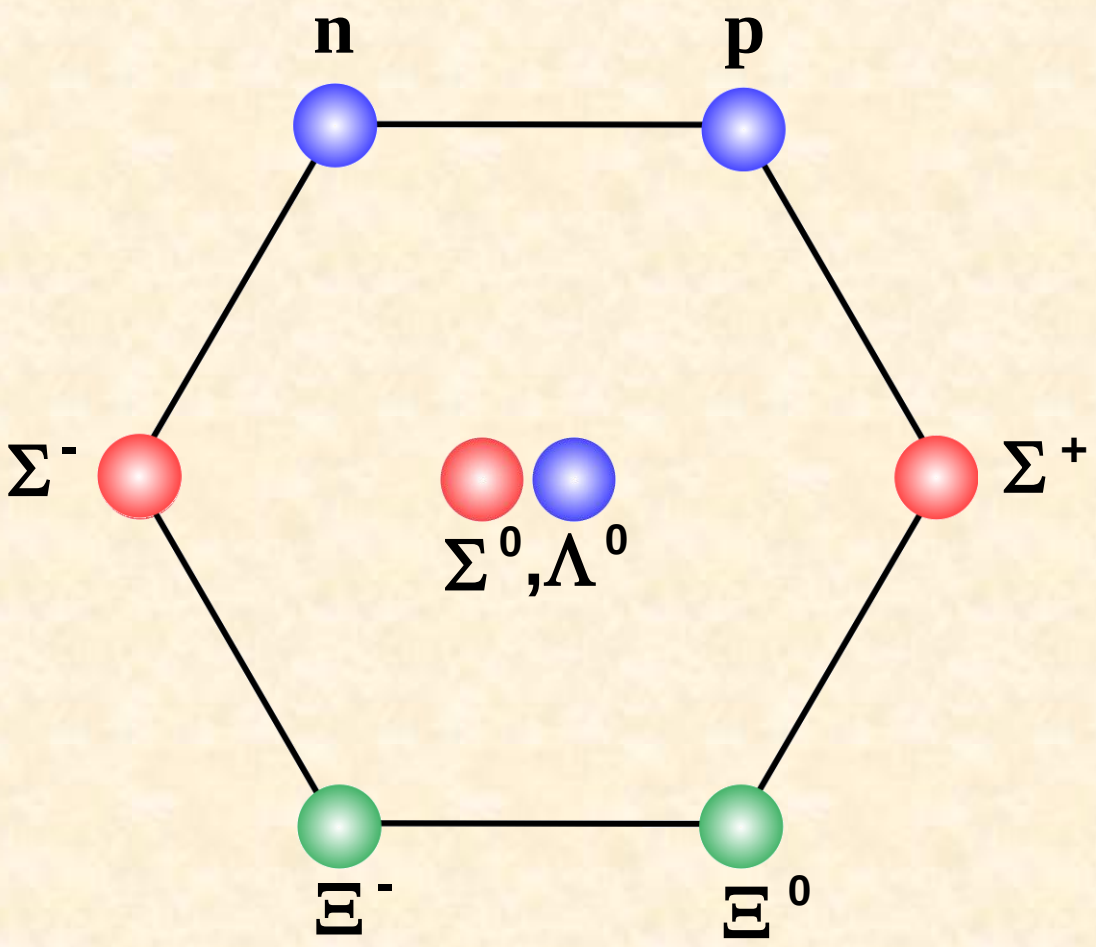
p

Jefferson Lab
Exploring the Nature of Matter



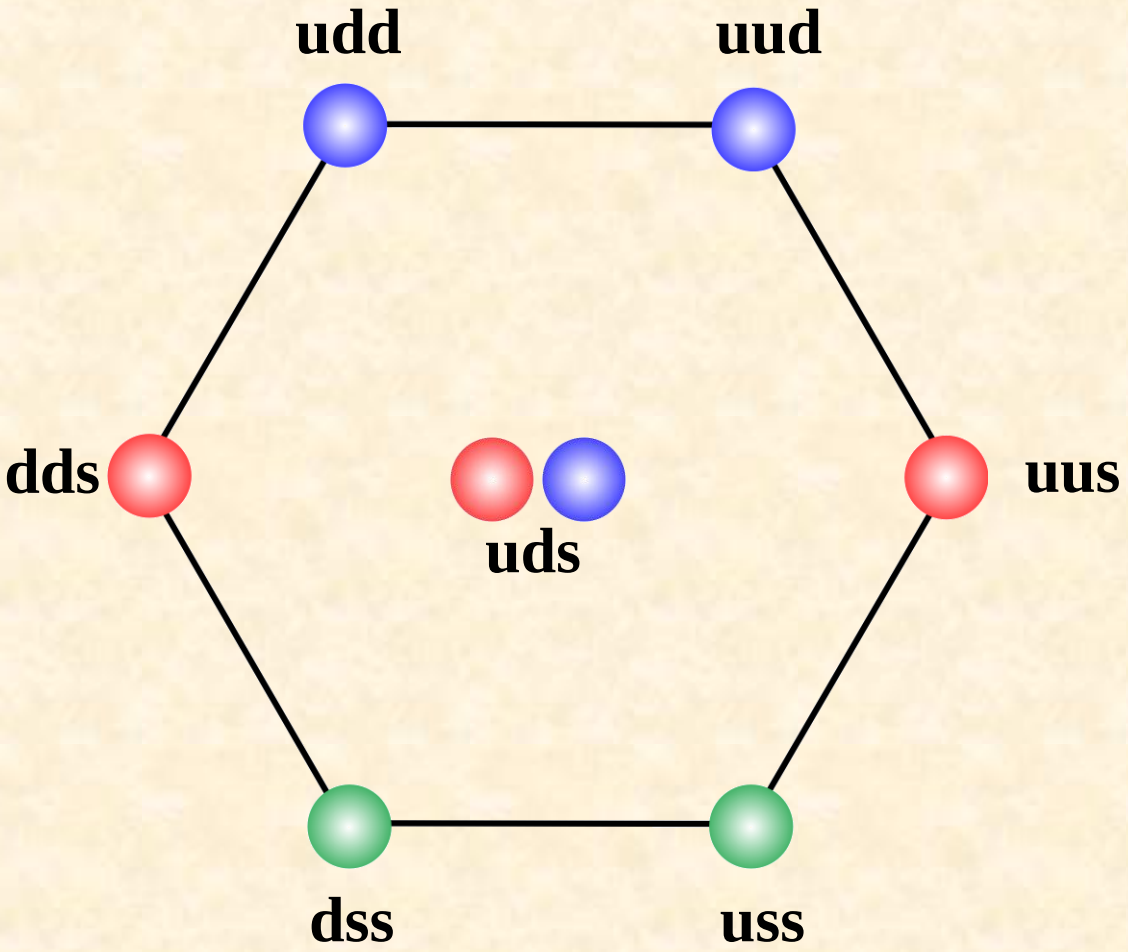
Baryon octet

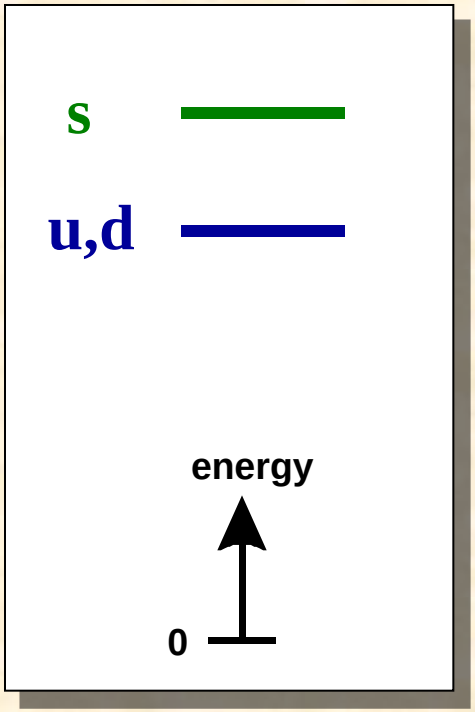




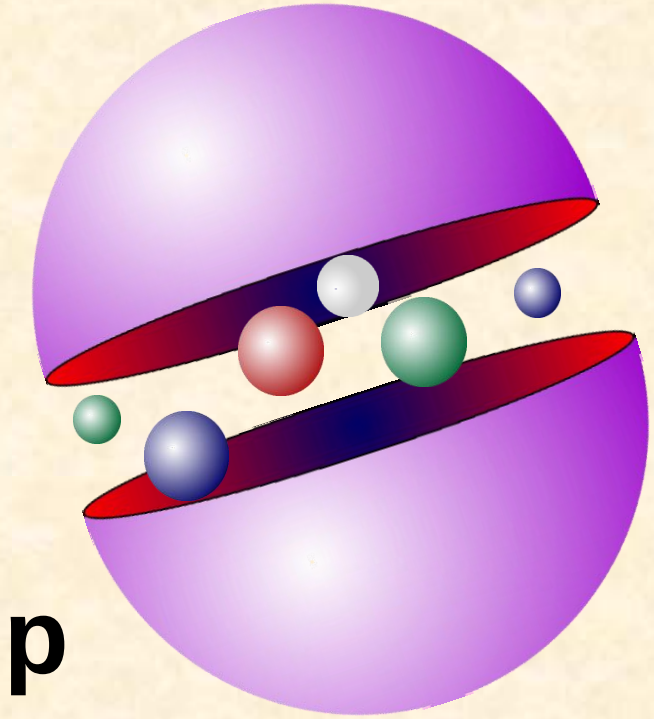
Ground States

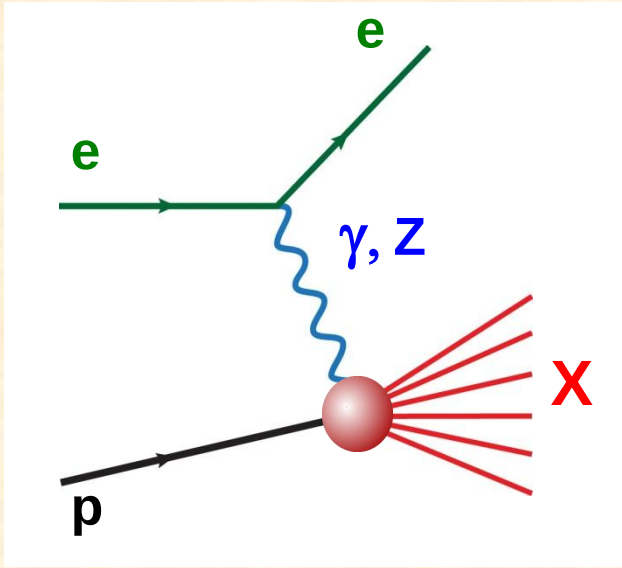
Baryon octet





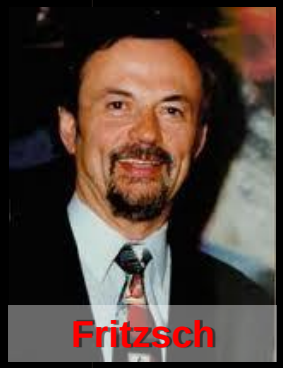
Deep inelastic scattering

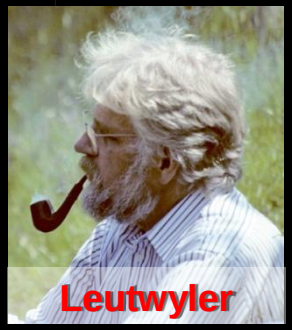


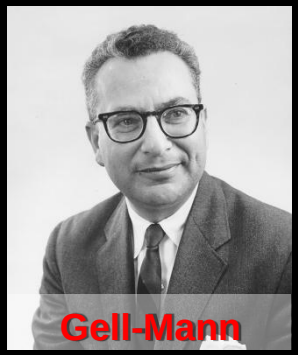


QCD

1971


Fritzsch

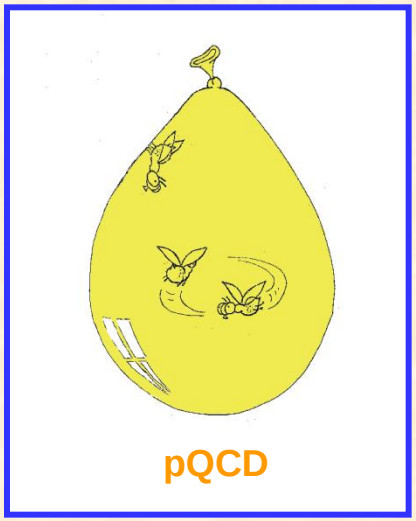

Leutwyler

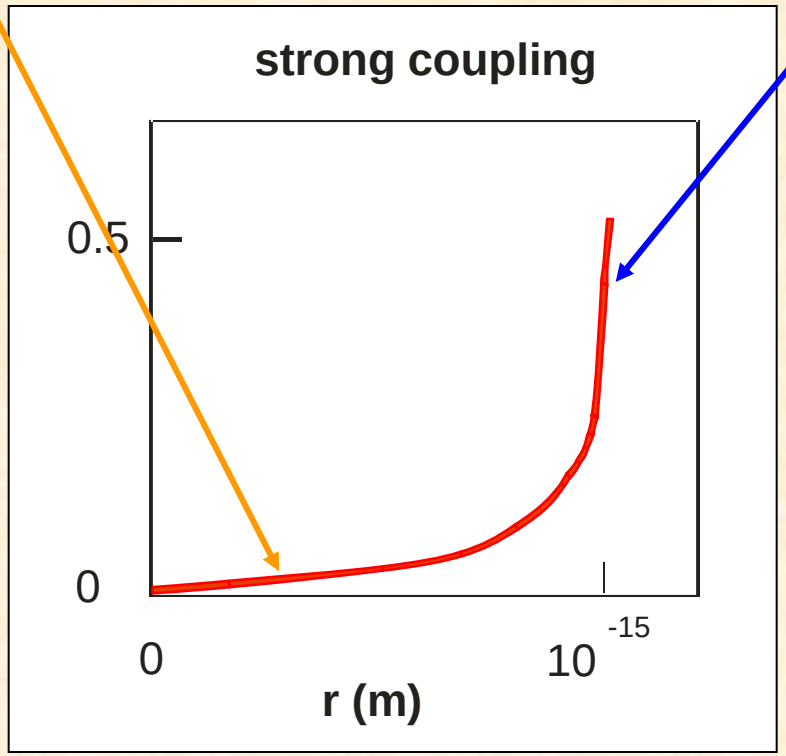

Gell-Mann

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

QCD

asymptotic freedom





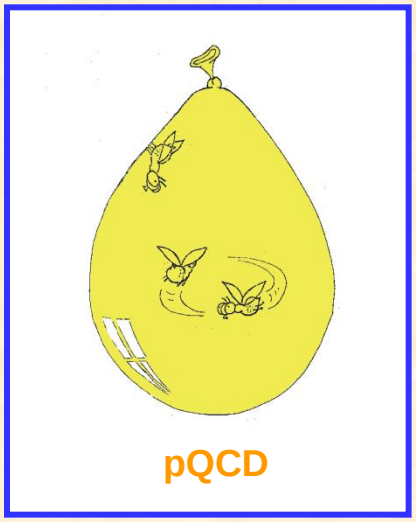
confinement

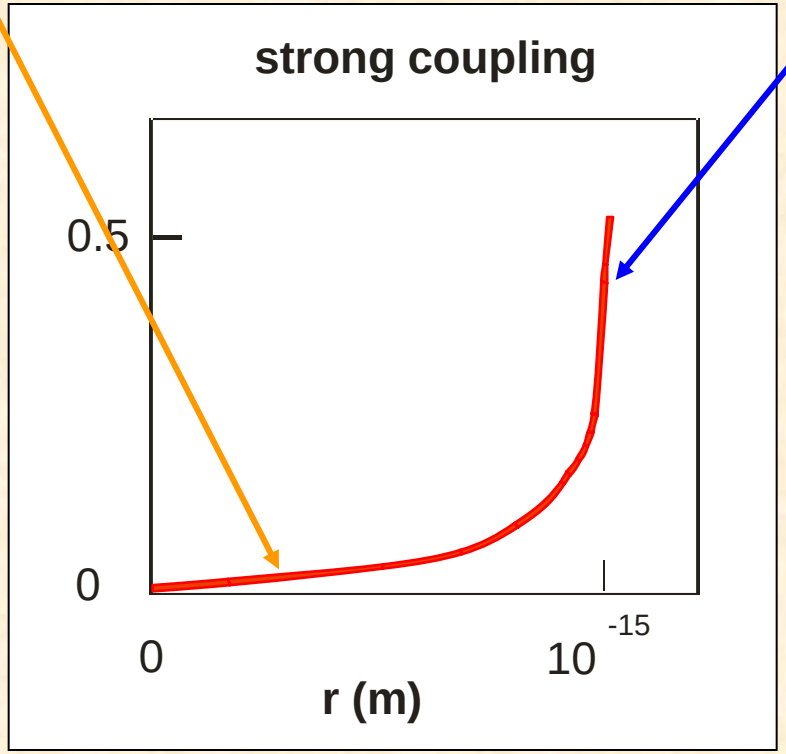

Politzer

QCD

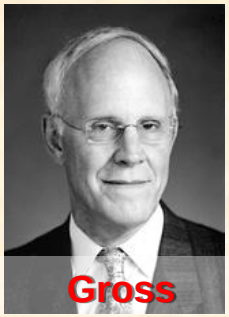
asymptotic freedom

confinement

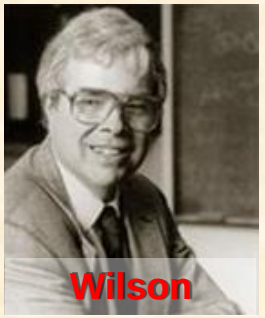

pQCD



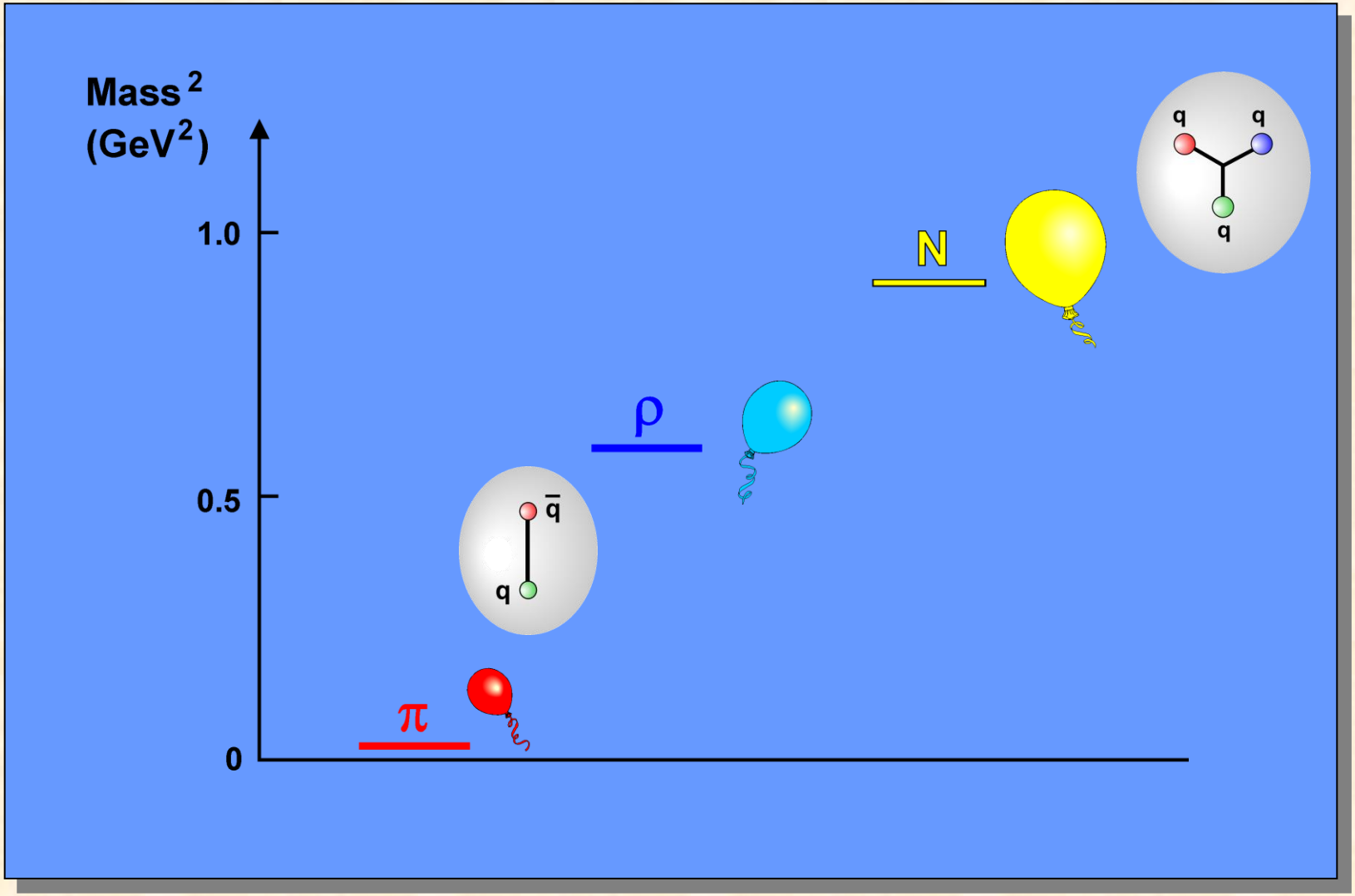

strong QCD

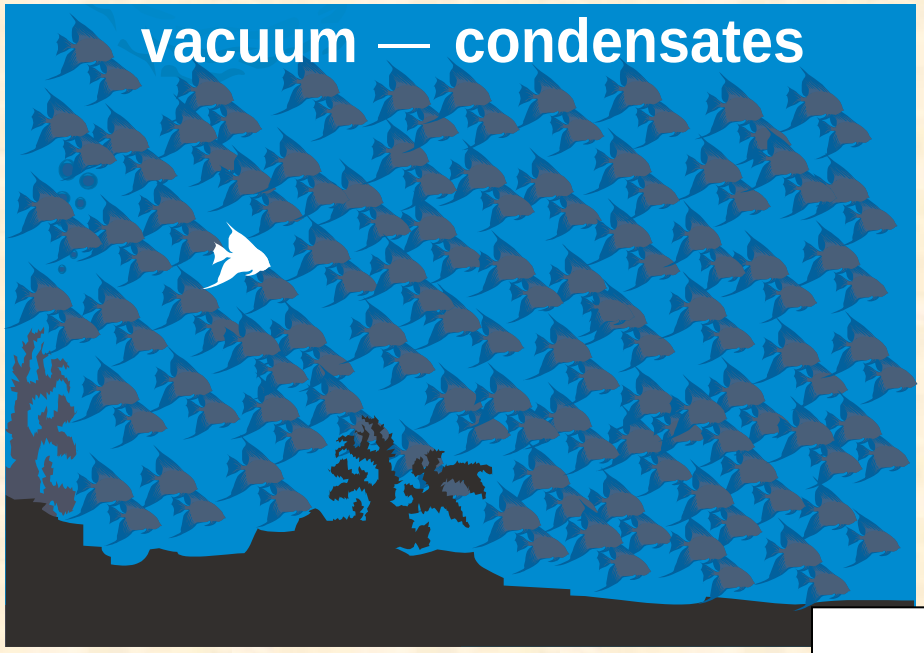

Gross

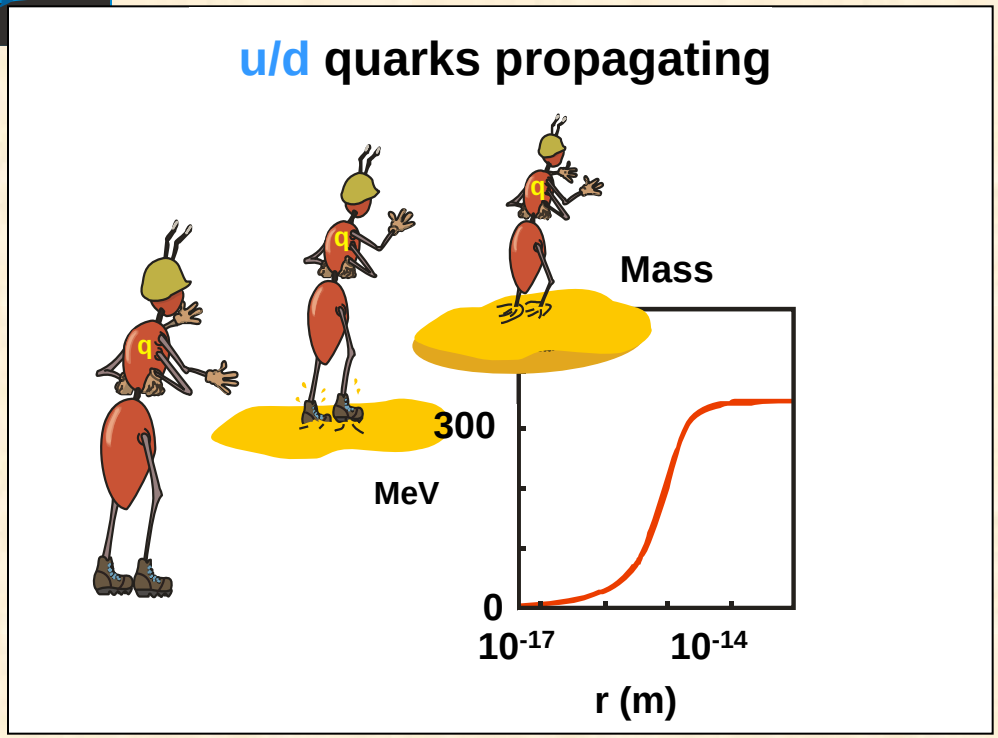

Wilczek


Wilson

Hadron masses [2]

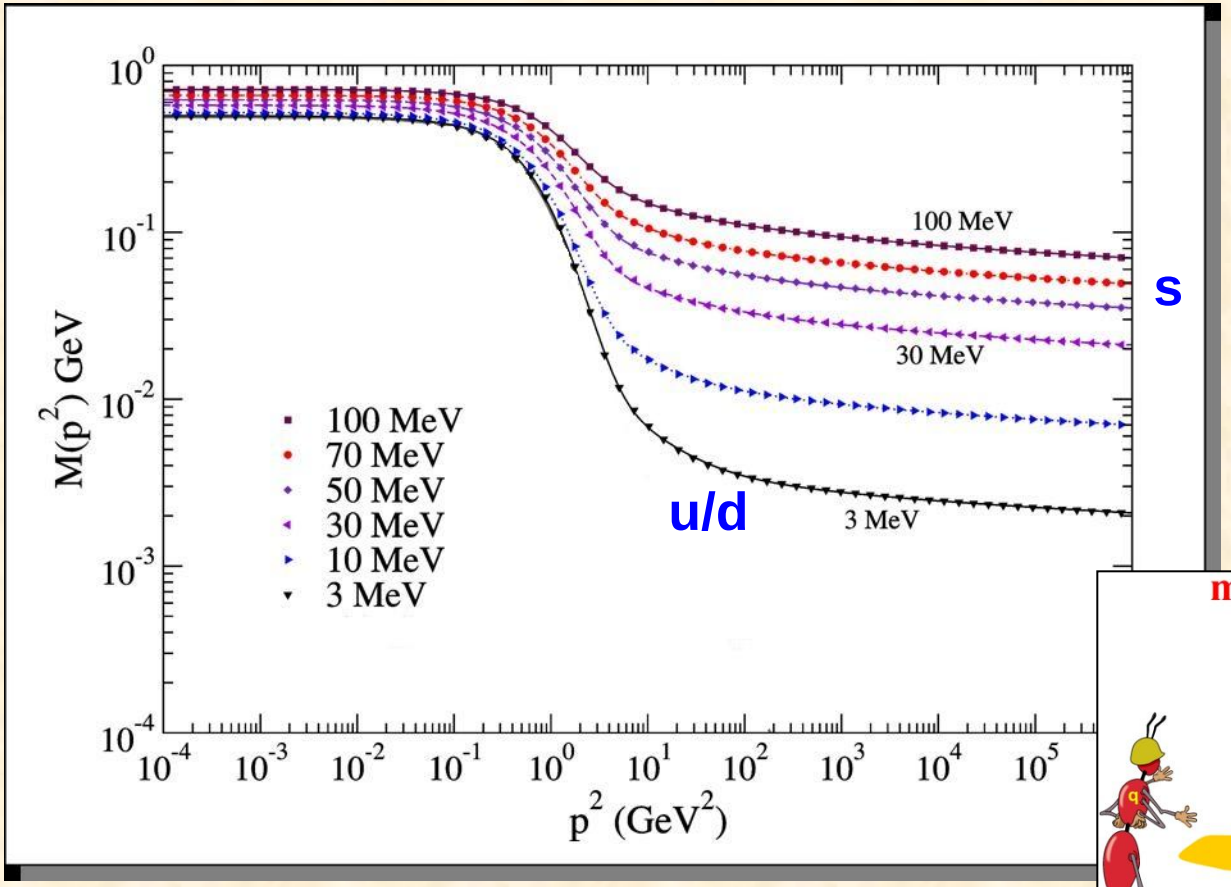



vacuum — condensates

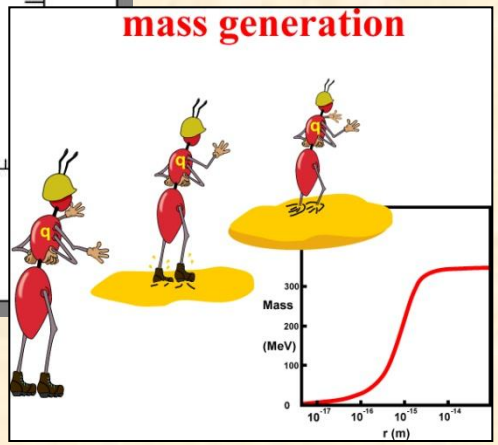

u/d quarks propagating
q
q
q
Mass
300
MeV
0
10-17
10-14
r (m)

Quark mass function

$\alpha_s > 1 \Longrightarrow \chi SB$

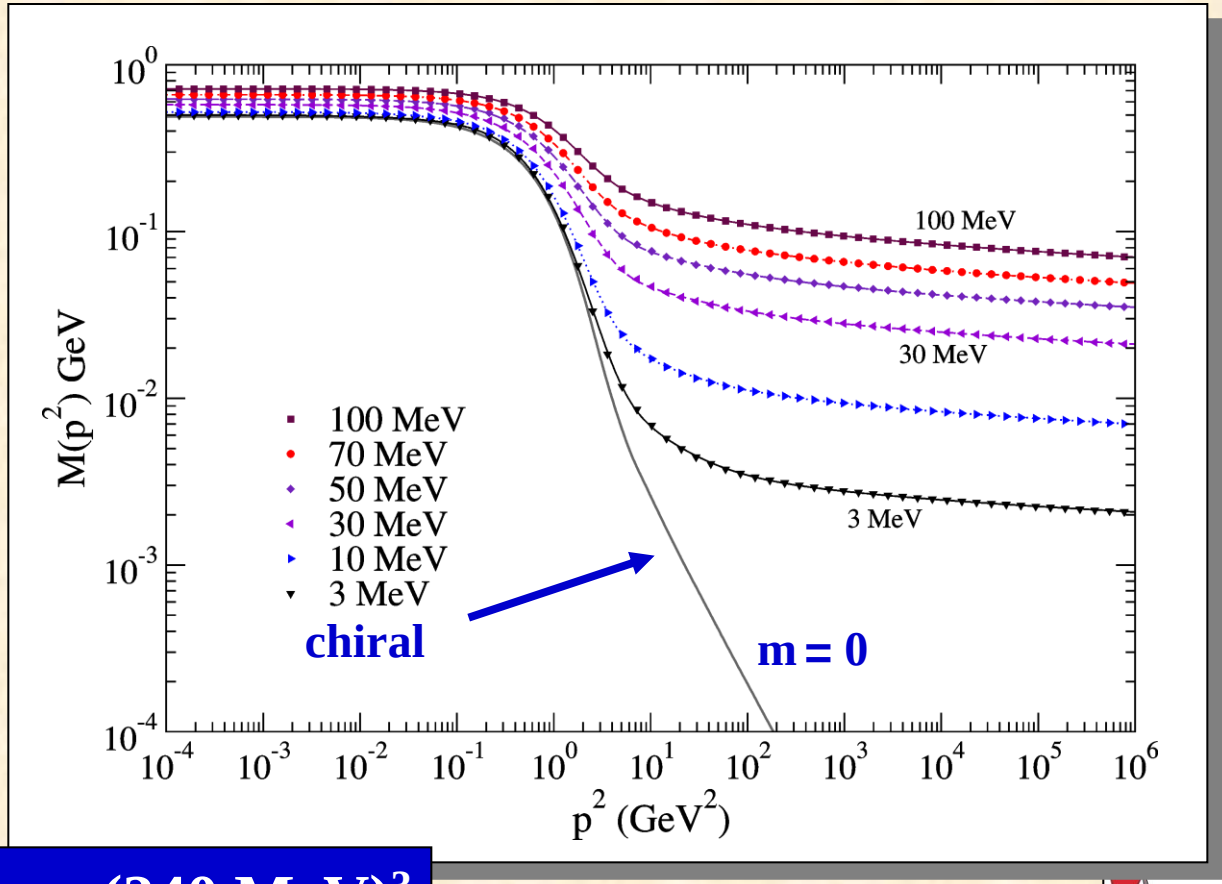


Williams, Fischer, P

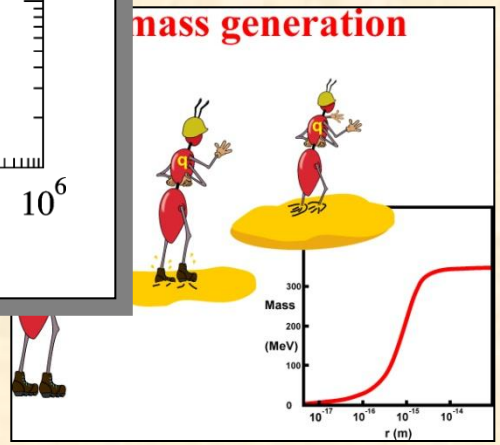


Quark mass function

$\alpha_s > 1 \Longrightarrow \chi SB$



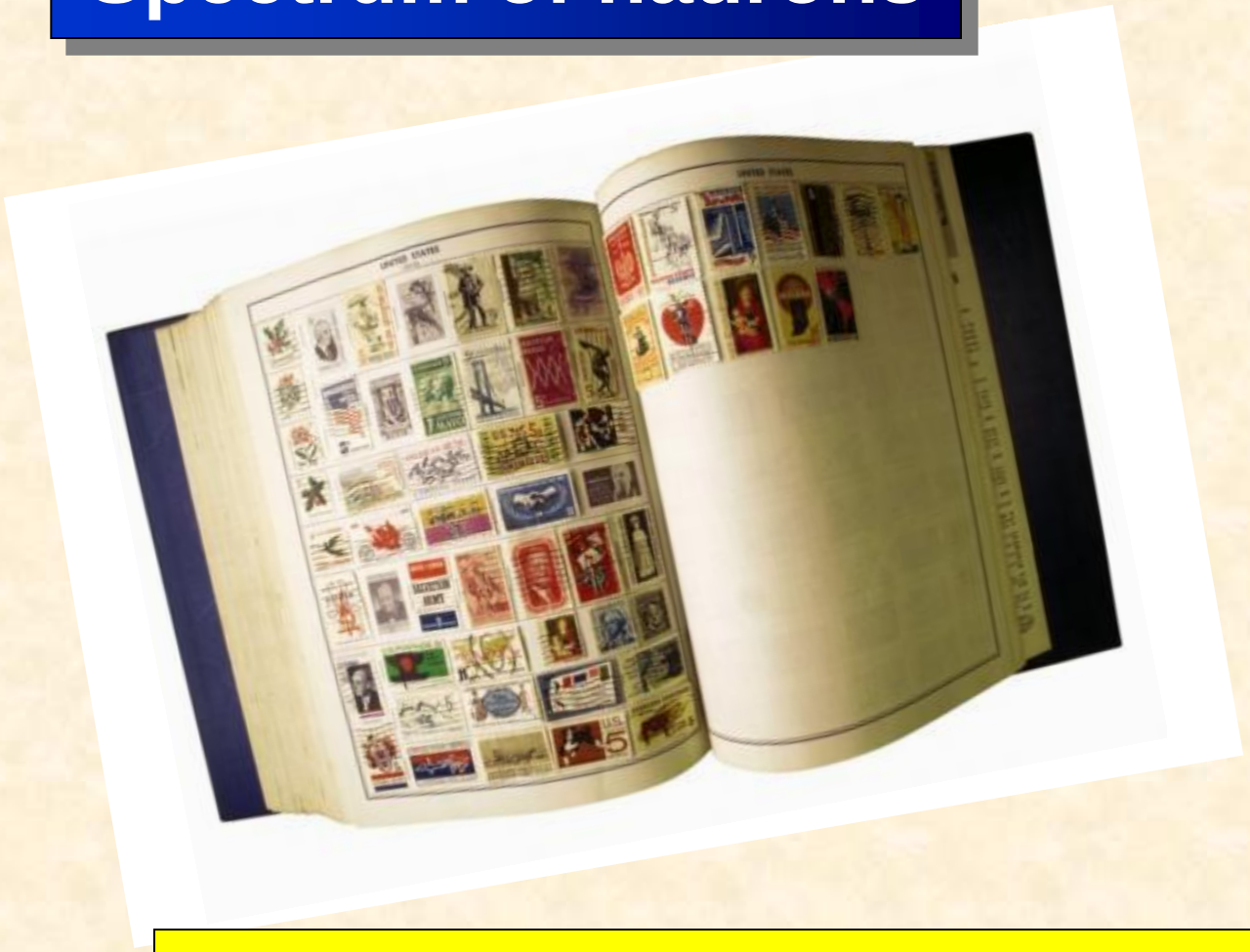
Williams, Fischer, P



$< \bar{q}q >_0 \sim -(240\ \text{MeV})^3$

Bhagwat & Tandy/ Roberts *et al.*

Spectrum of hadrons



Rutherford:

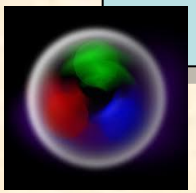
"Science is either physics or stamp-collecting"

colour wave-functions

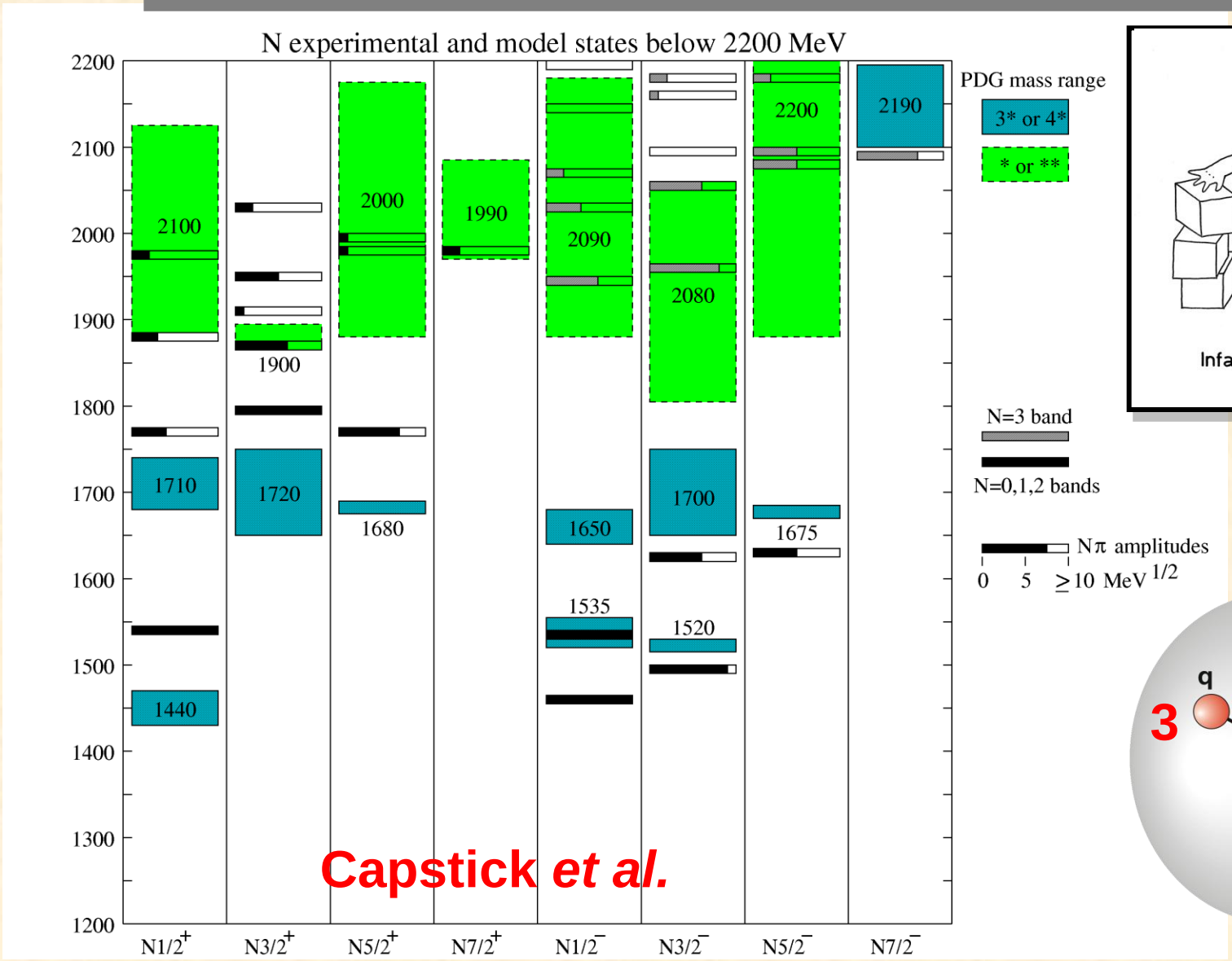
$$\pi^+ = \frac{1}{\sqrt{N_c}} \left[u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right]$$

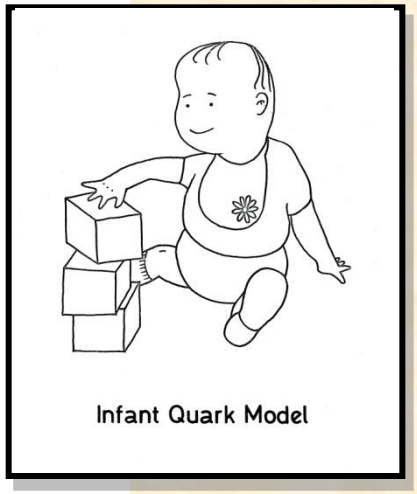
$N_c = 3$

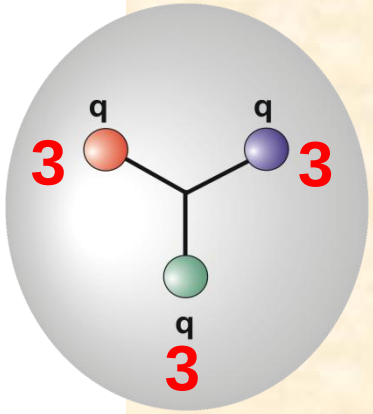
$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud - uud - uud - uud \right]$$



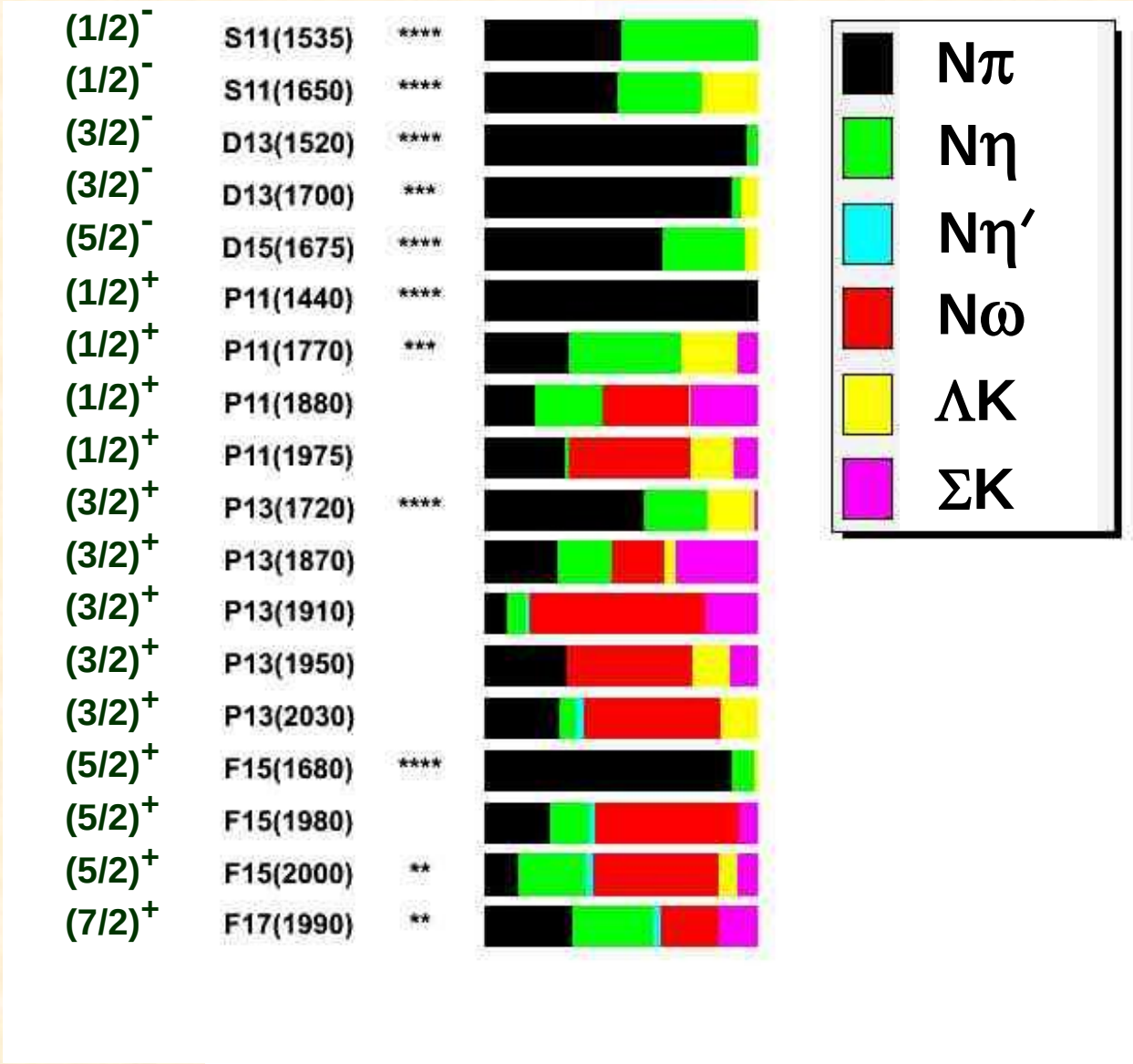
Nucleon model states (πN couplings)



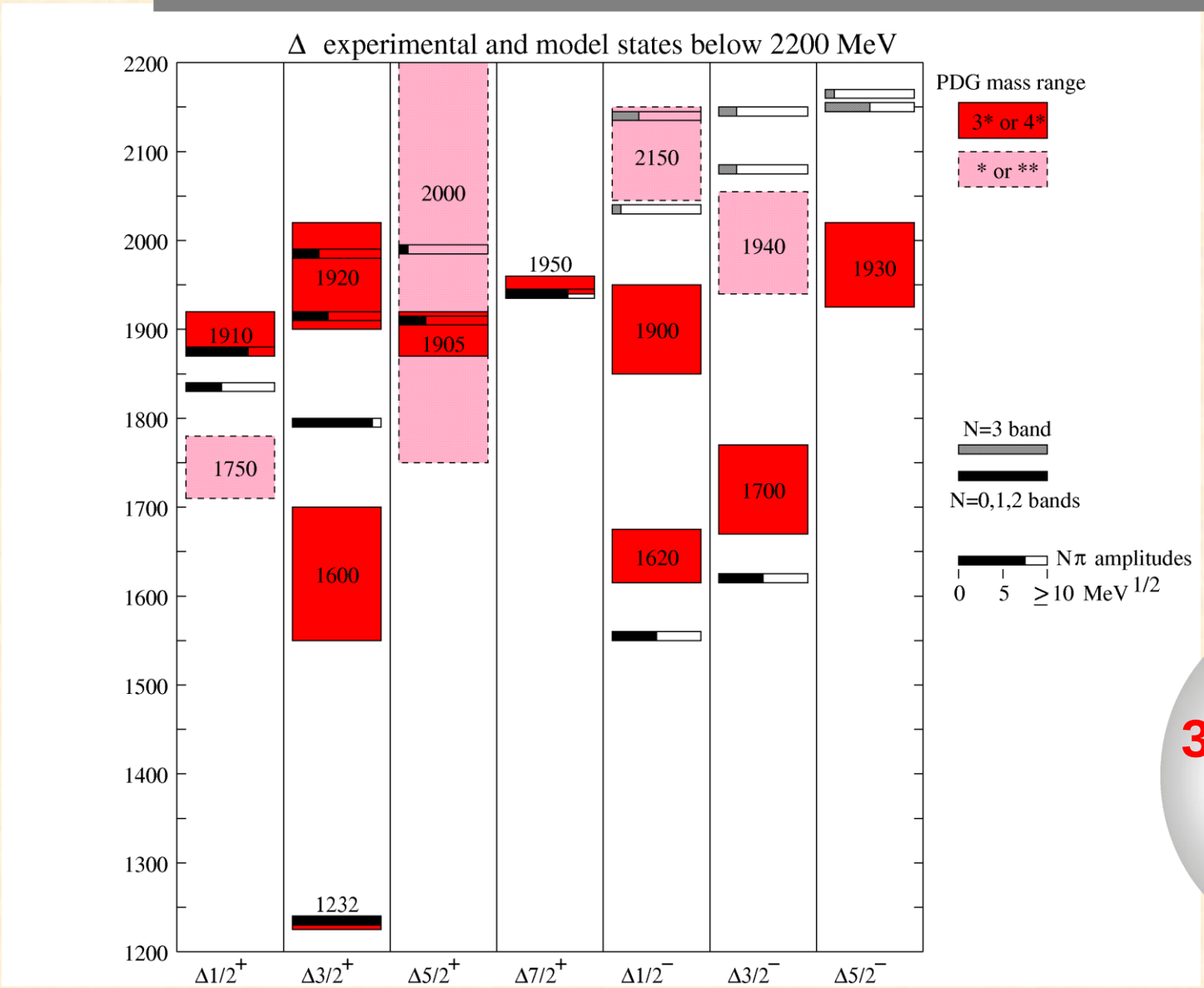


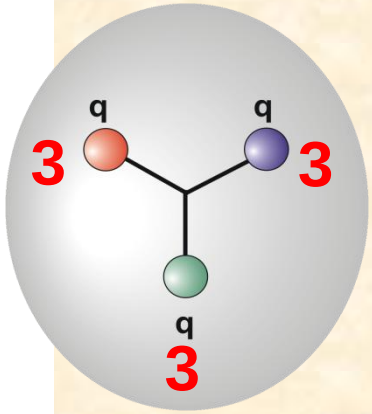


search all channels: not just πN

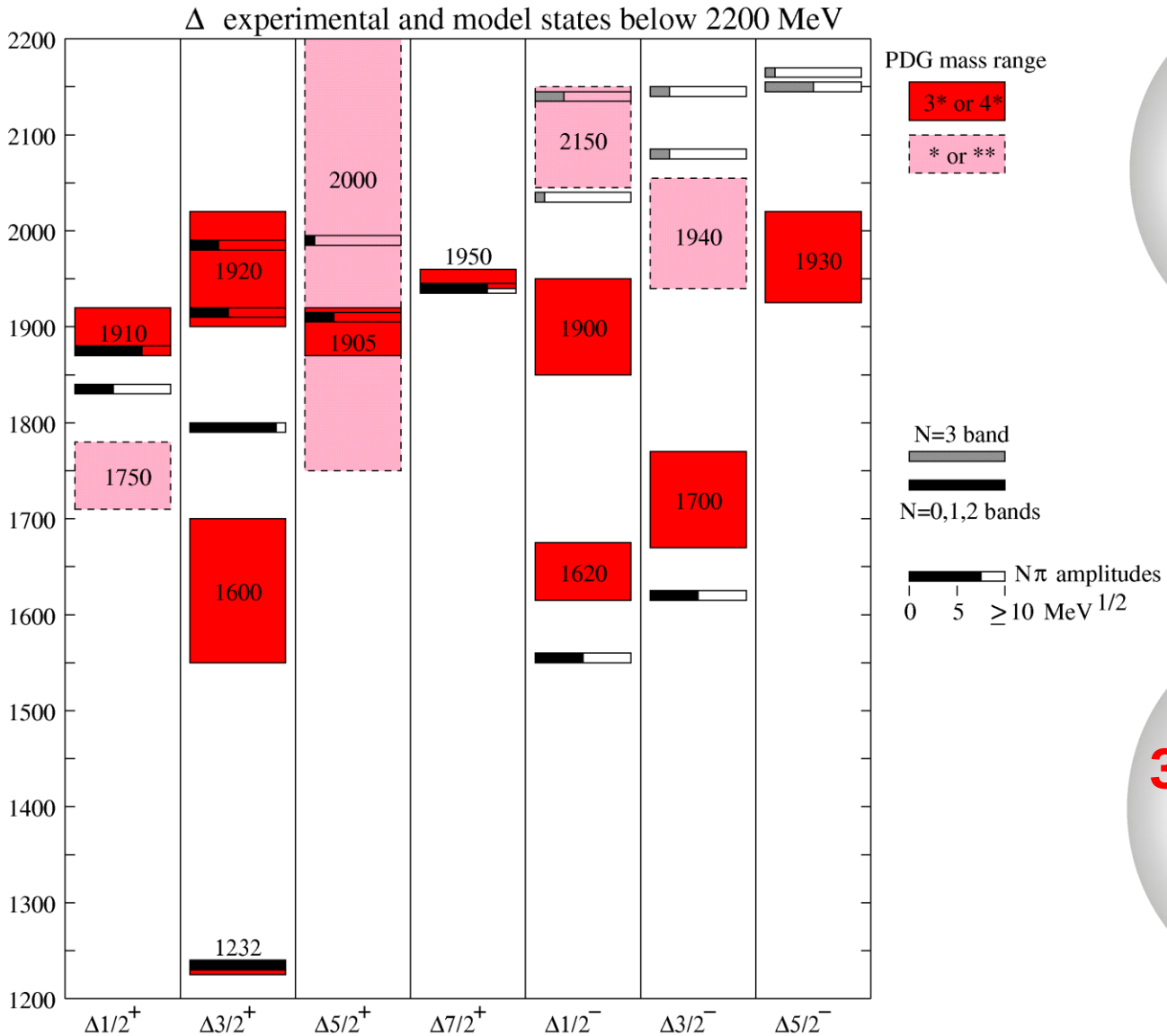


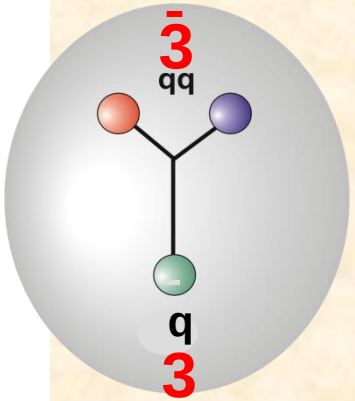
Δ model states (πN couplings)

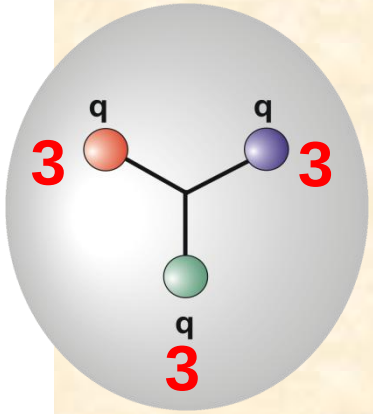




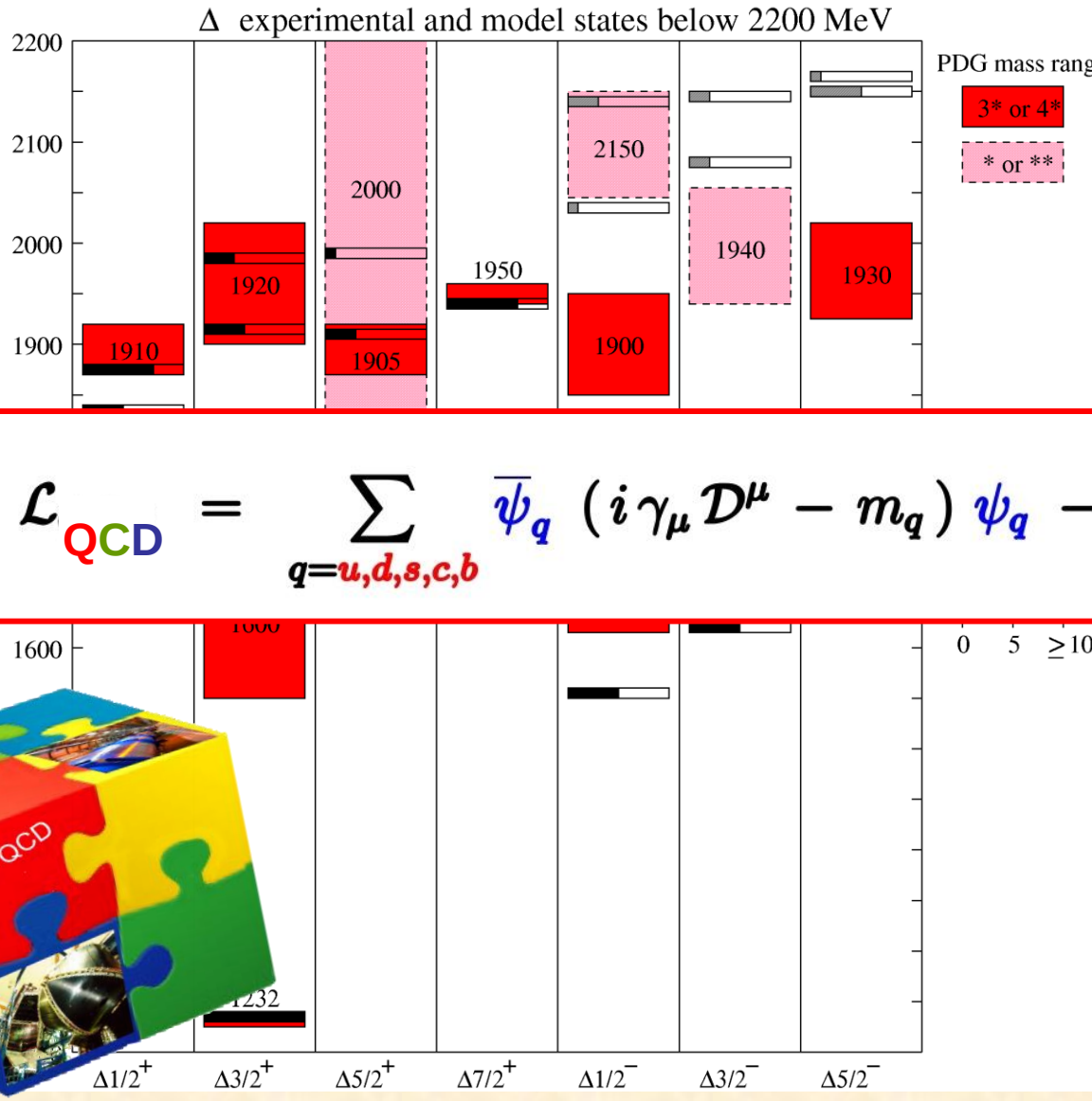
Δ model states (πN couplings)

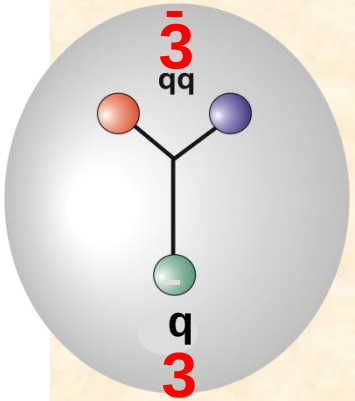




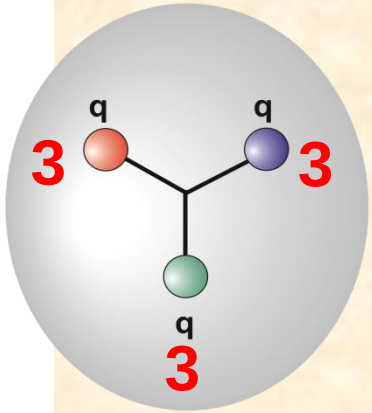


Δ model states (πN couplings)



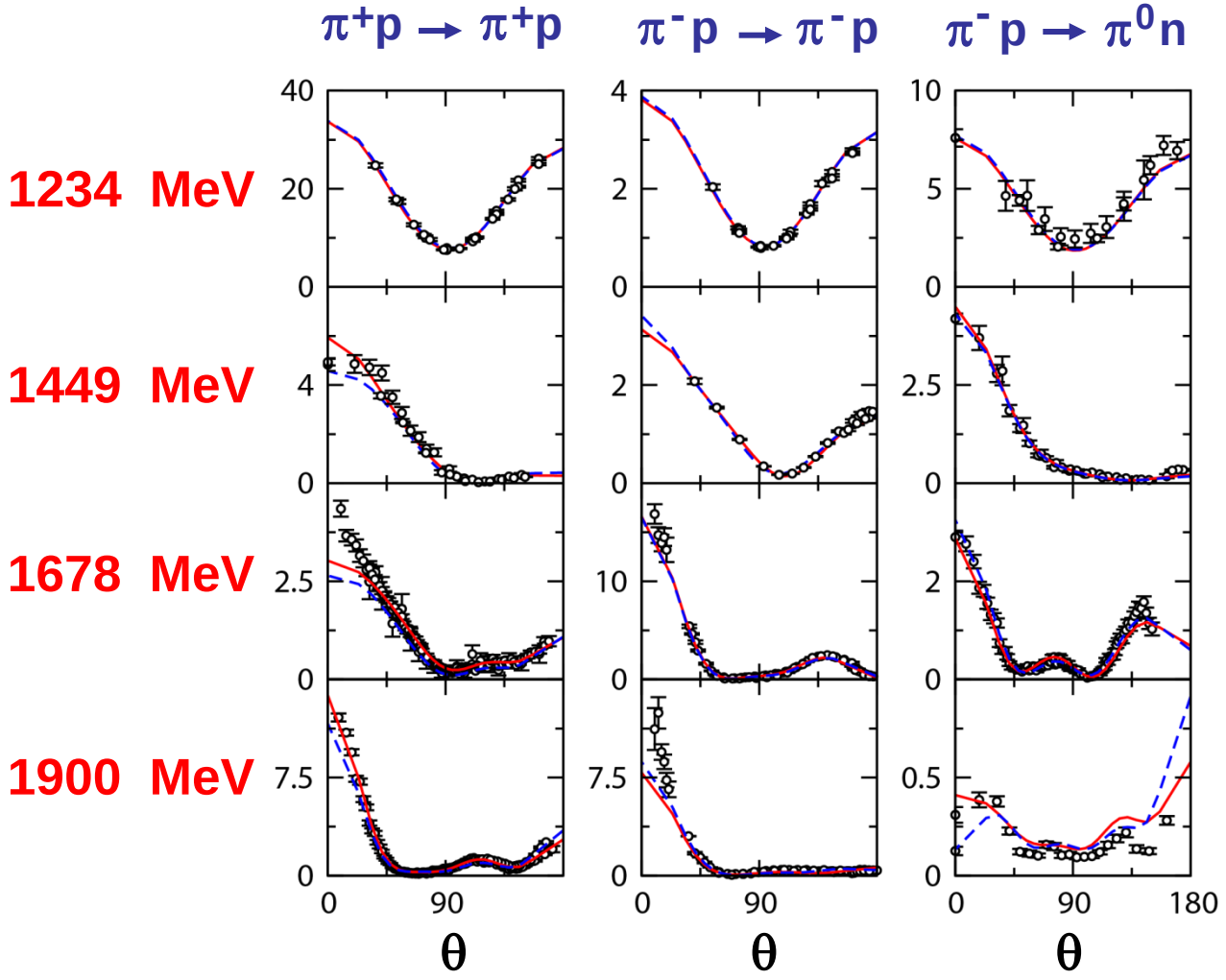


$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$



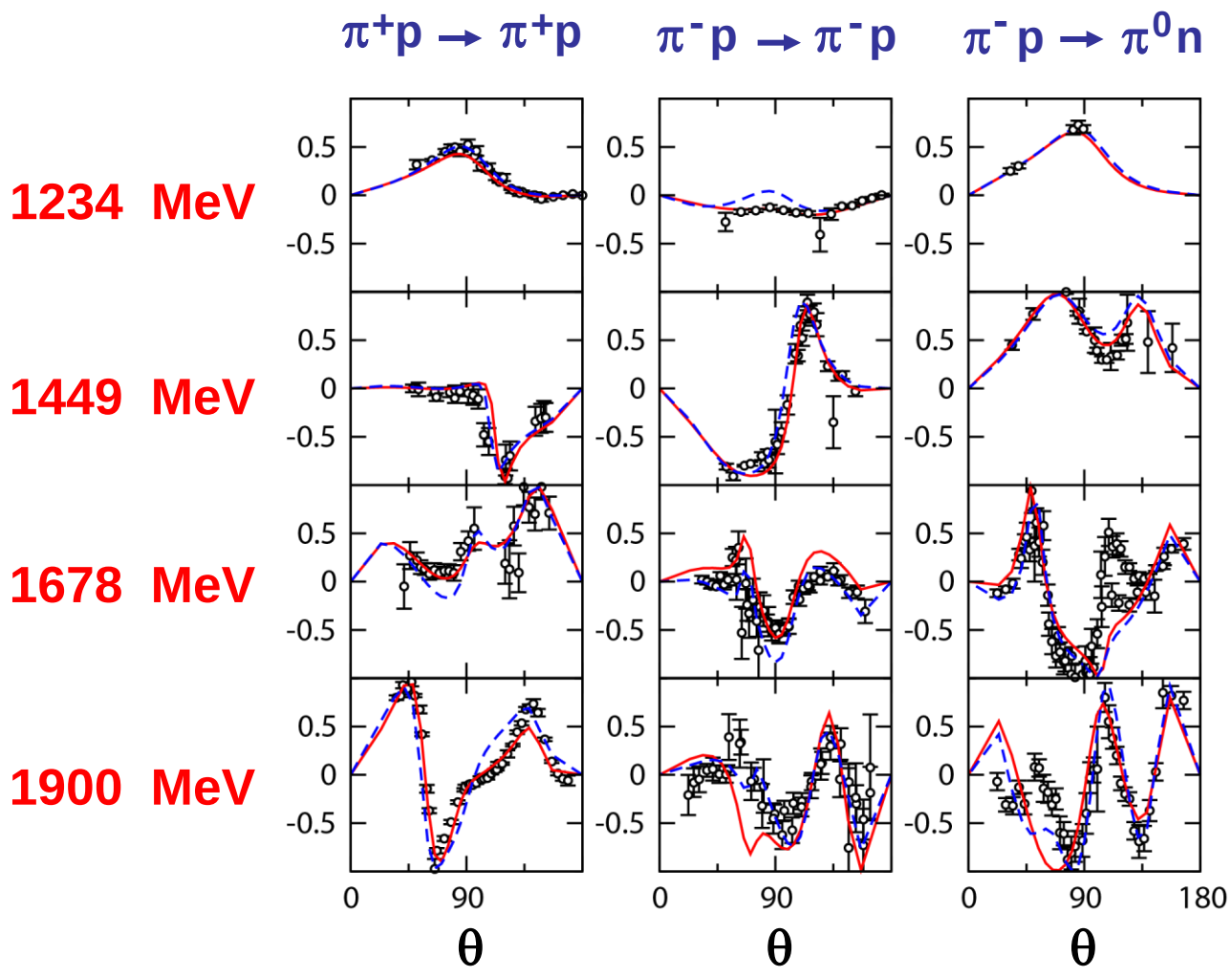
$\pi N \longrightarrow \pi N$ scattering

$d\sigma/d\Omega$

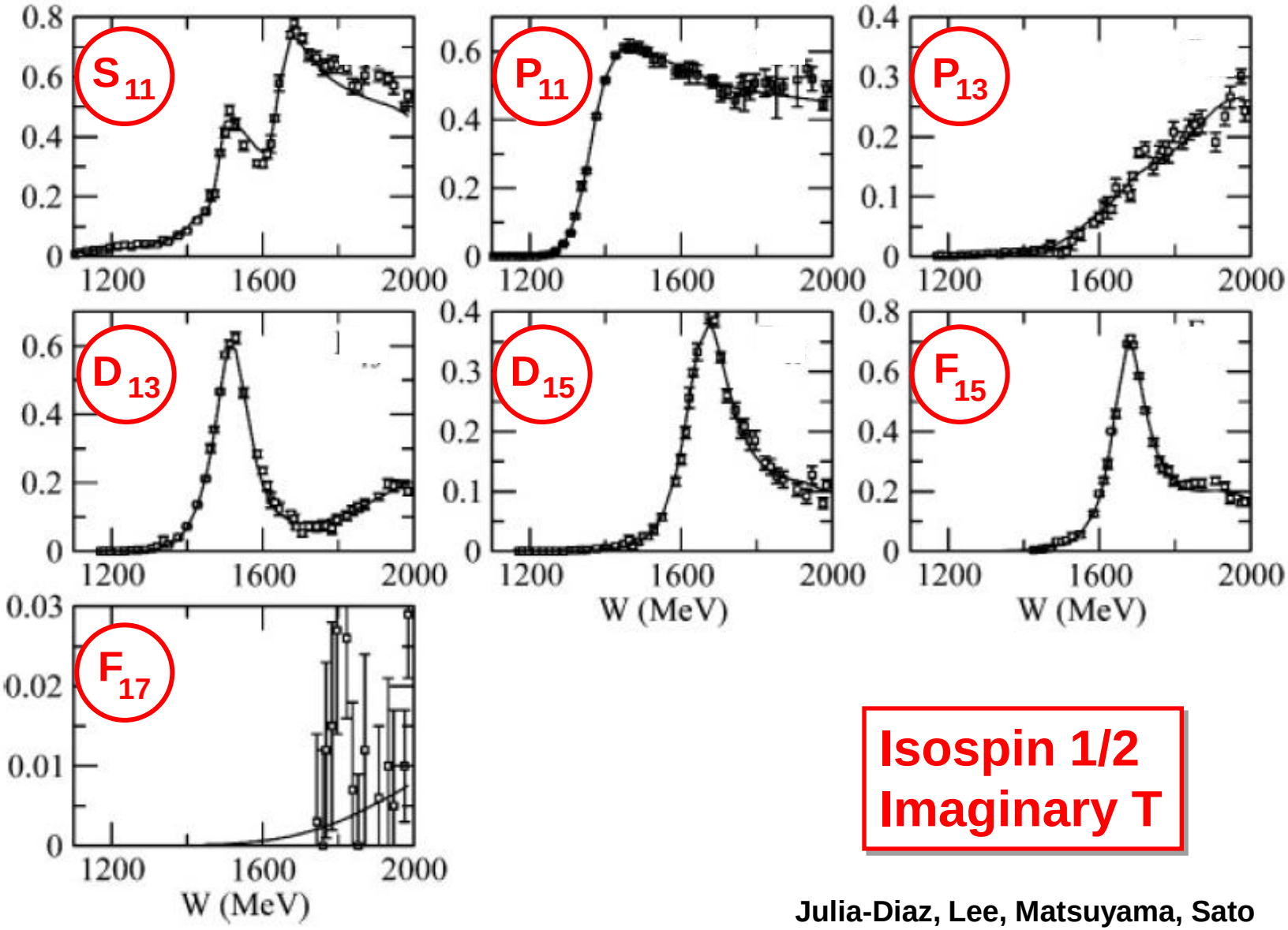


$\pi N \longrightarrow \pi N$ scattering

P



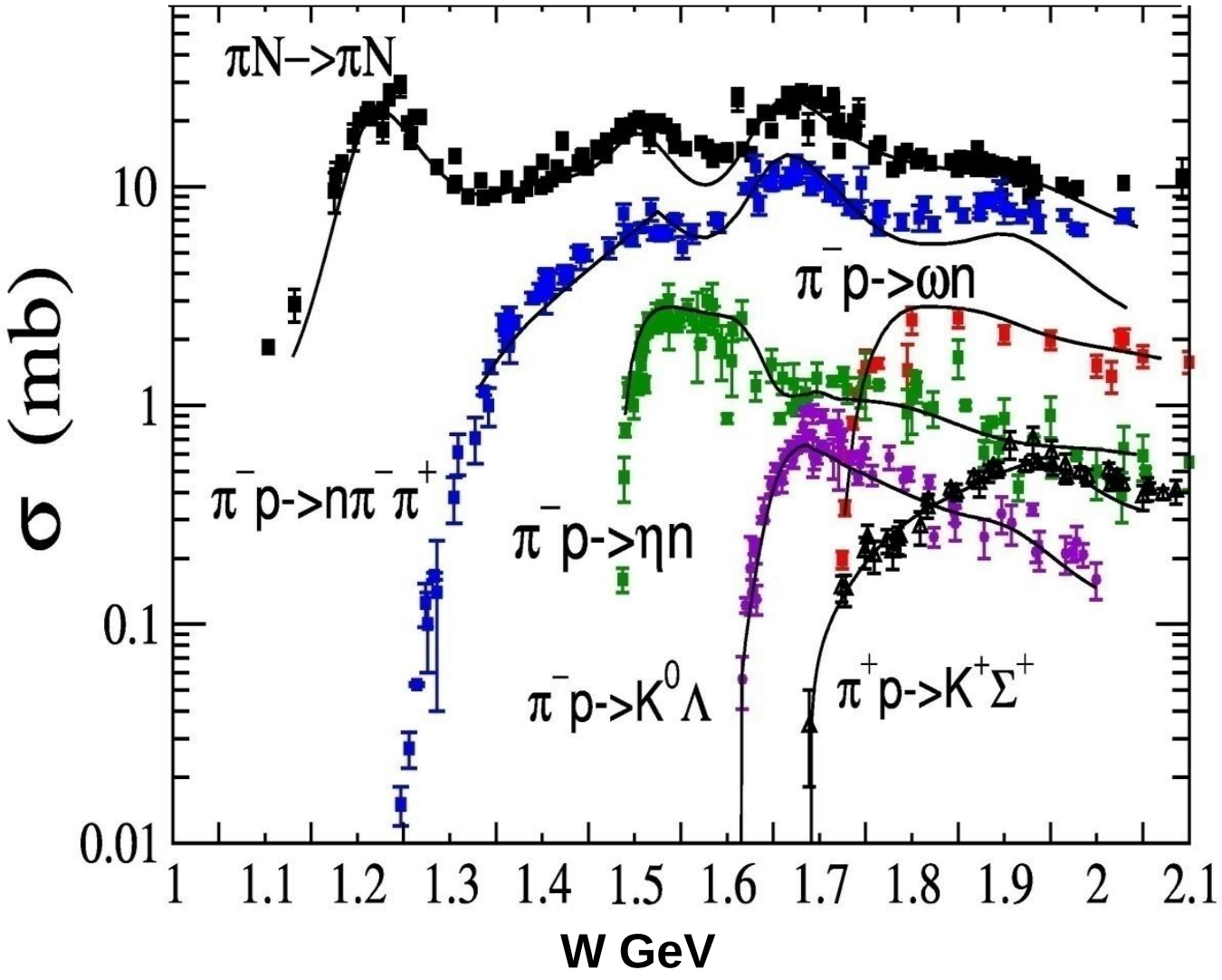
πN amplitudes



Isospin 1/2
Imaginary T

Julia-Diaz, Lee, Matsuyama, Sato

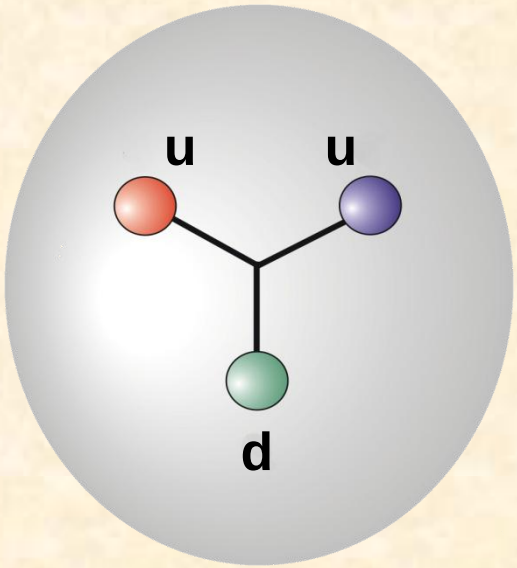
πN exclusive channels



Δ(1232) colour wave-function

$N_c = 3$

$$\Delta^+ = \frac{1}{\sqrt{6}} [\, uud + uud + uud - uud - uud - uud \,]$$



Δ(1232) colour wave-function

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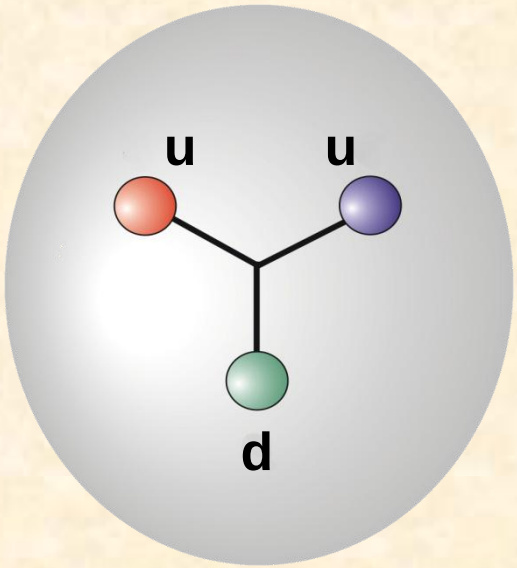
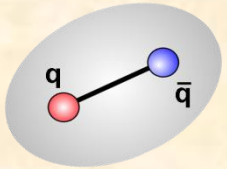
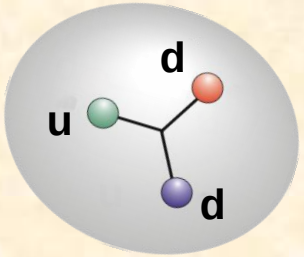




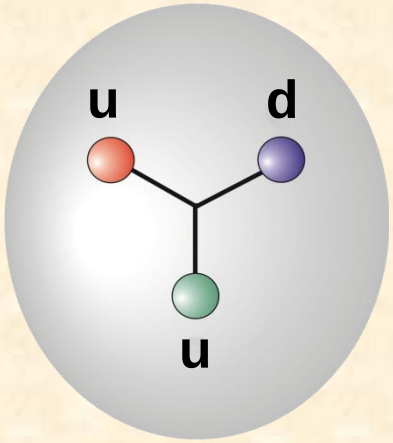
π

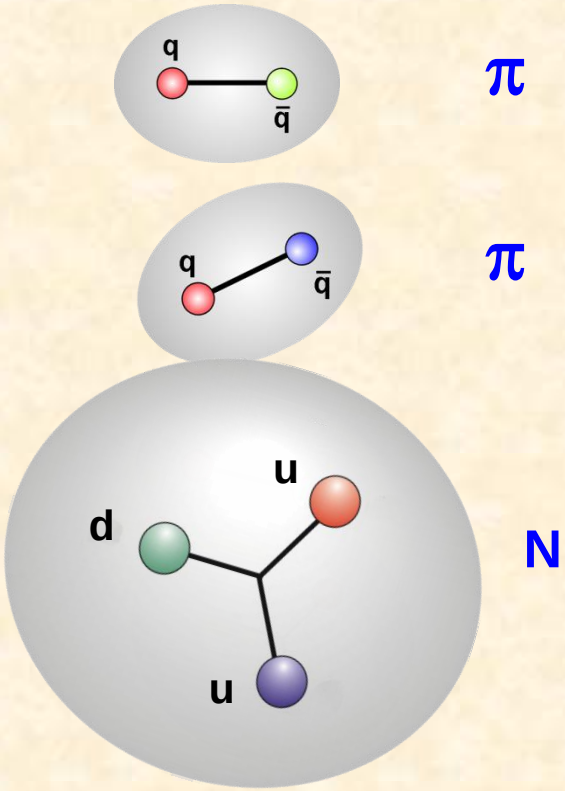


N

N*(1xxx)

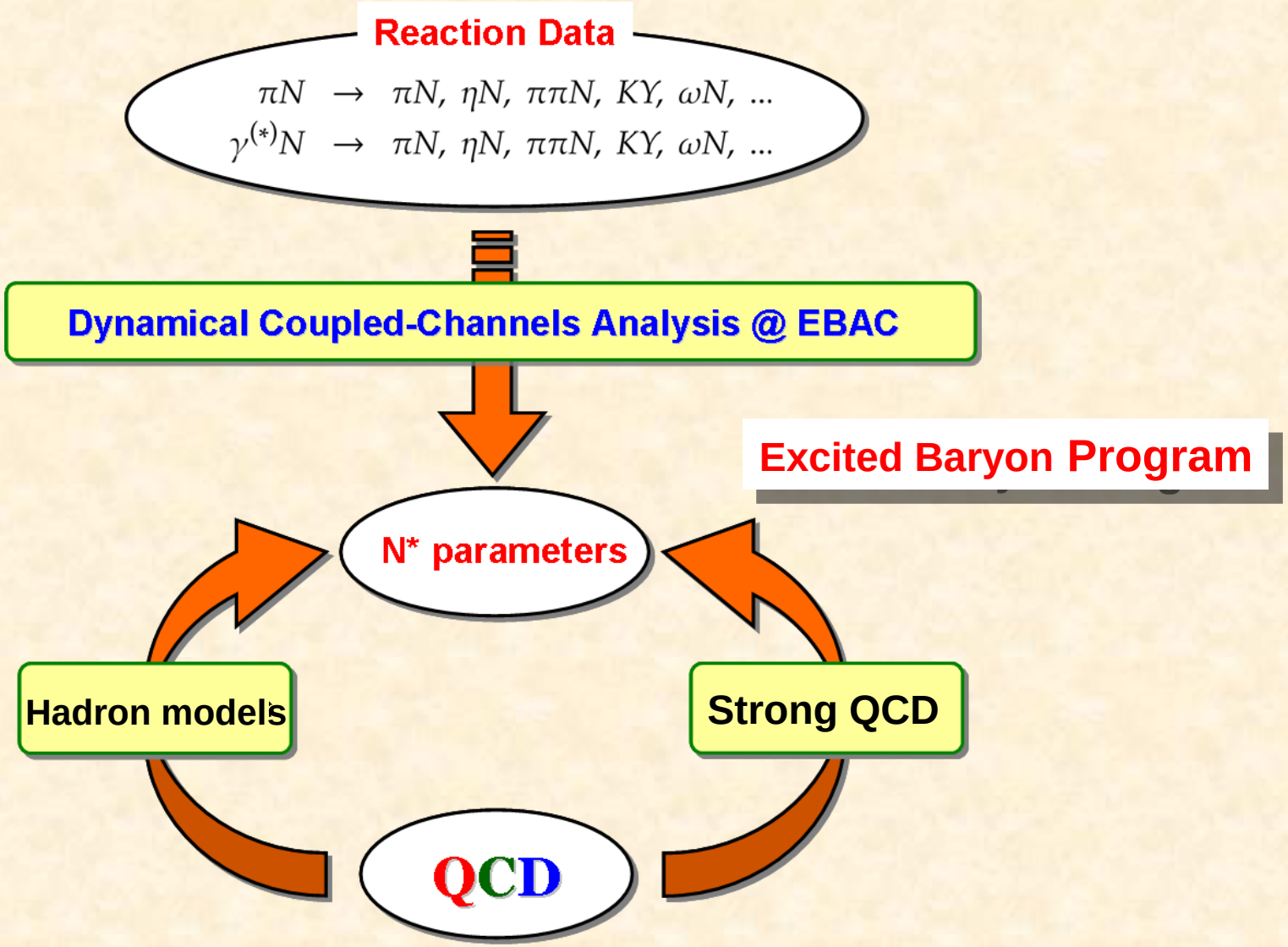
?



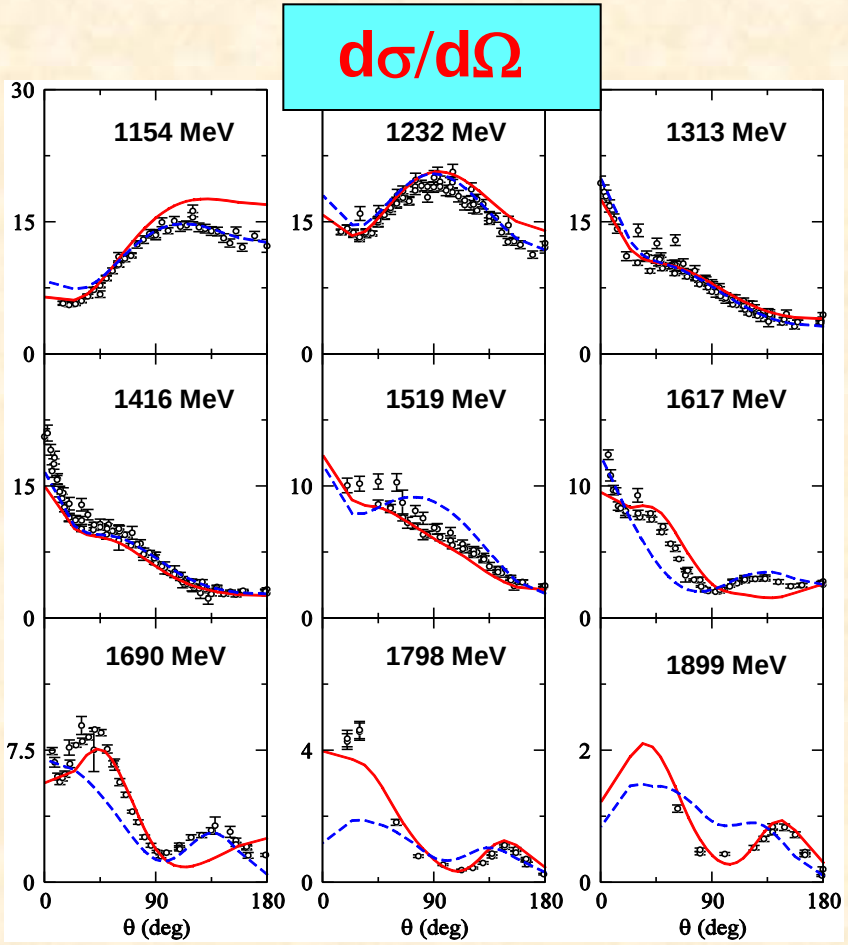


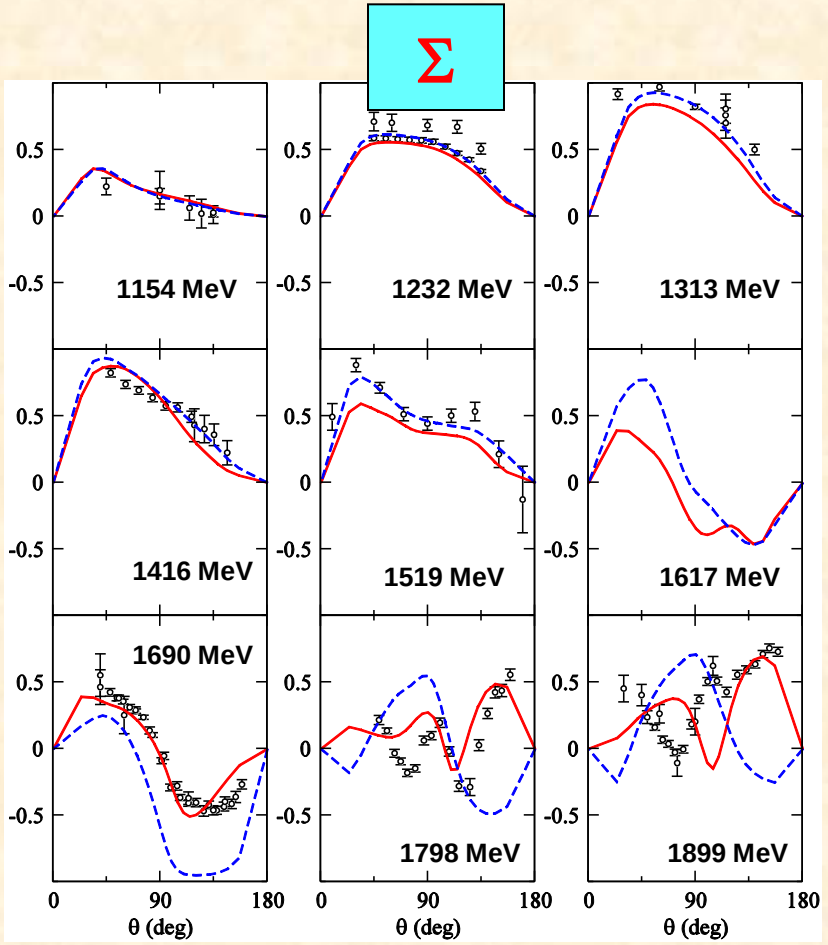

Coupled channels
Coupled channels

Properties of Excited Baryons



pion photoproduction: $\gamma p \longrightarrow \pi^+ n$





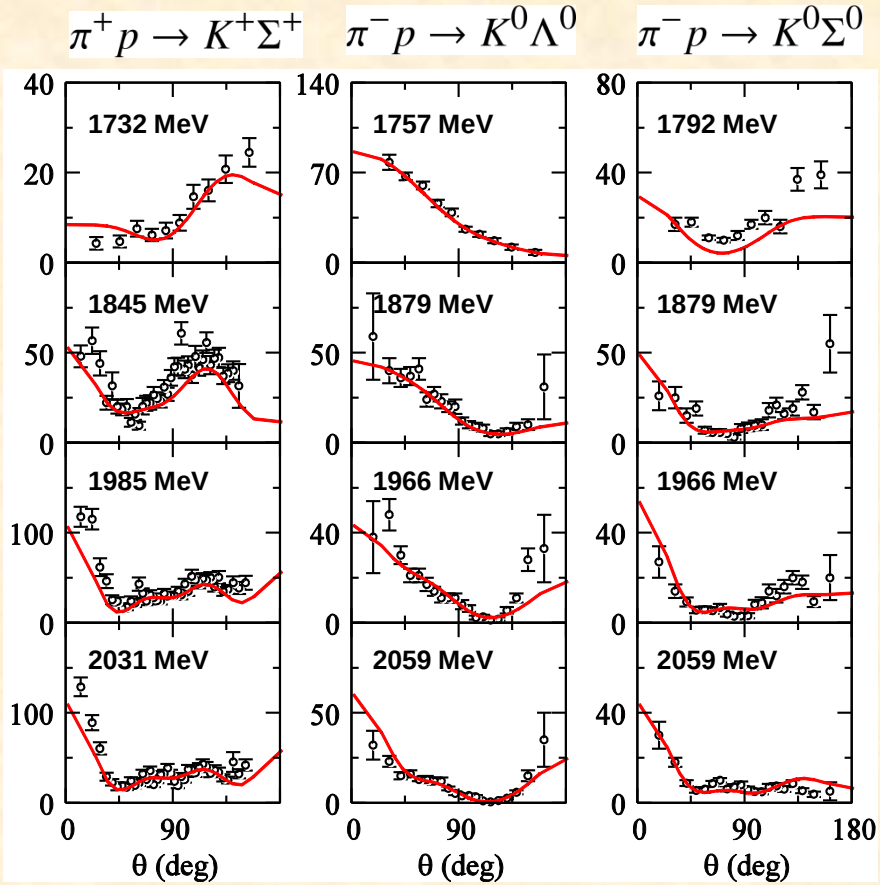
Current model
(full combined analysis

Previous model (fitted to γN → πN data ***up to 1.6 GeV***)

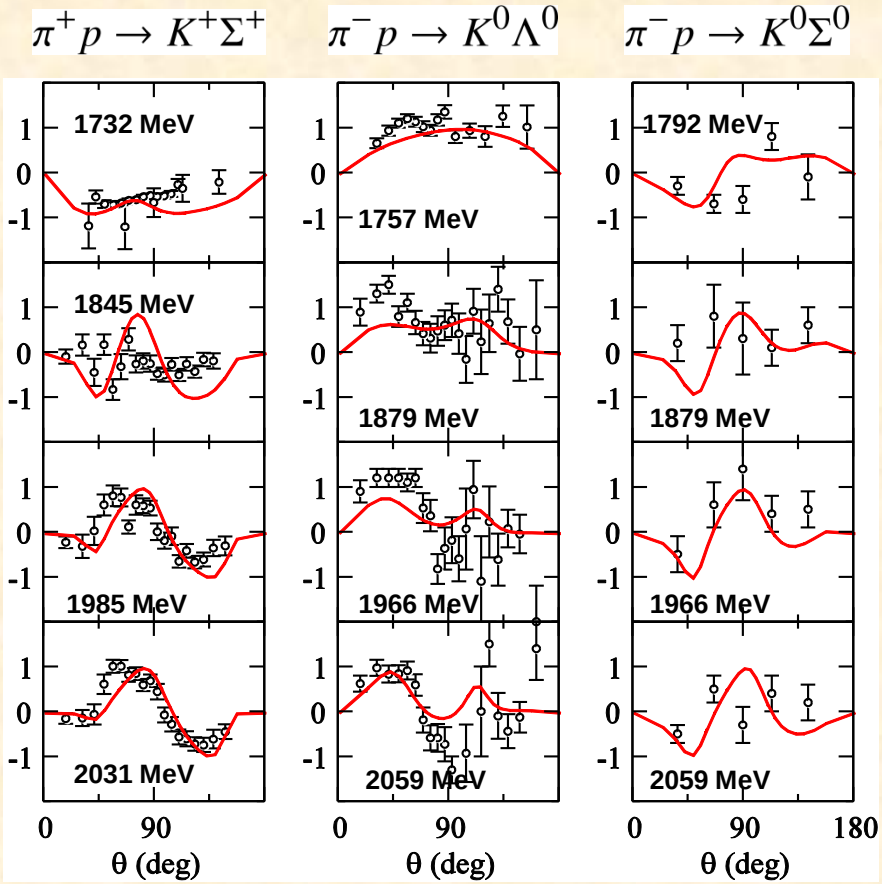
Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki

$\pi N \longrightarrow K\Lambda$

$d\sigma/d\Omega$



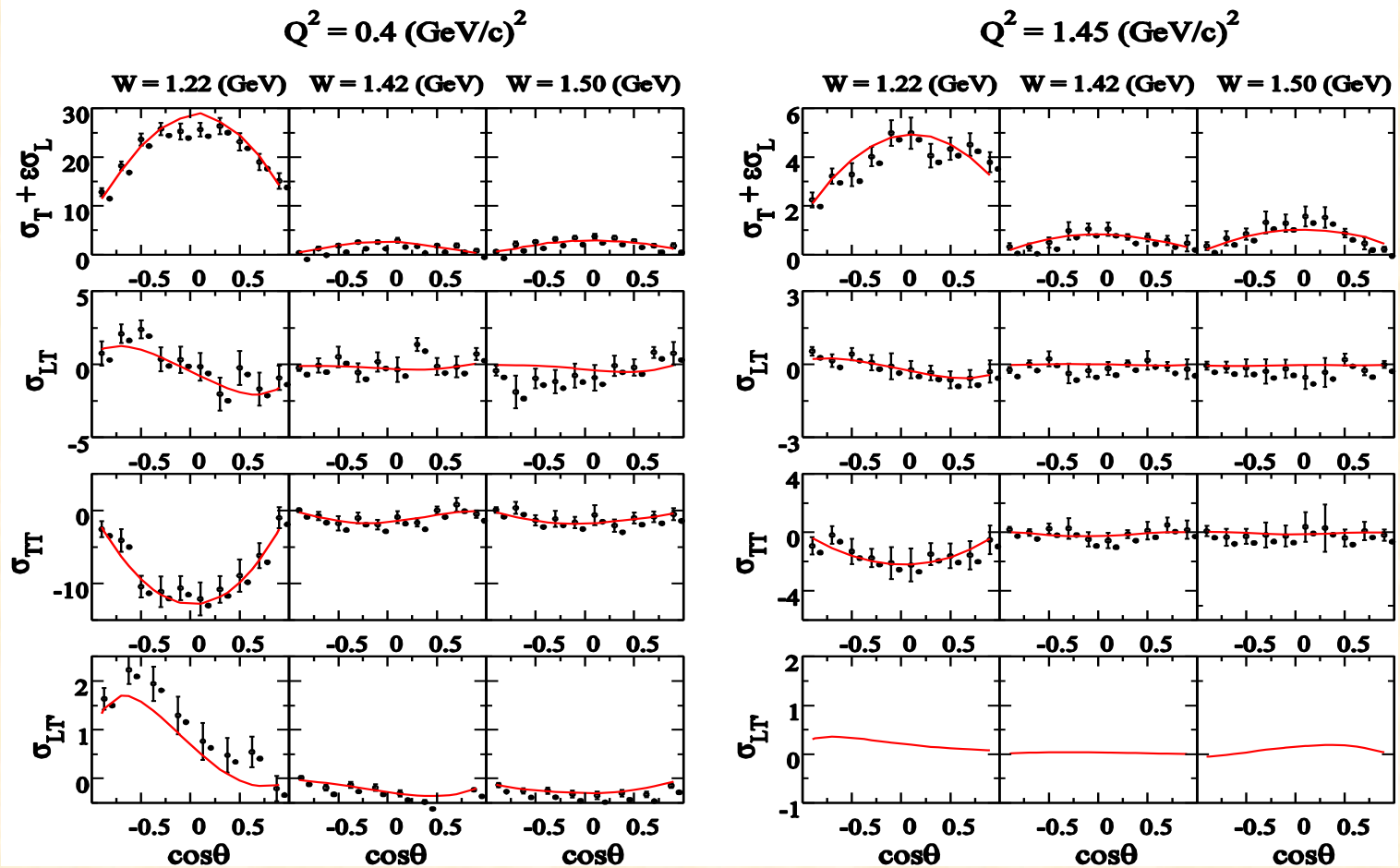
P



pion electroproduction: $ep \longrightarrow e'\pi^0 p$

Fit to the structure function data (~ 20000) from CLAS

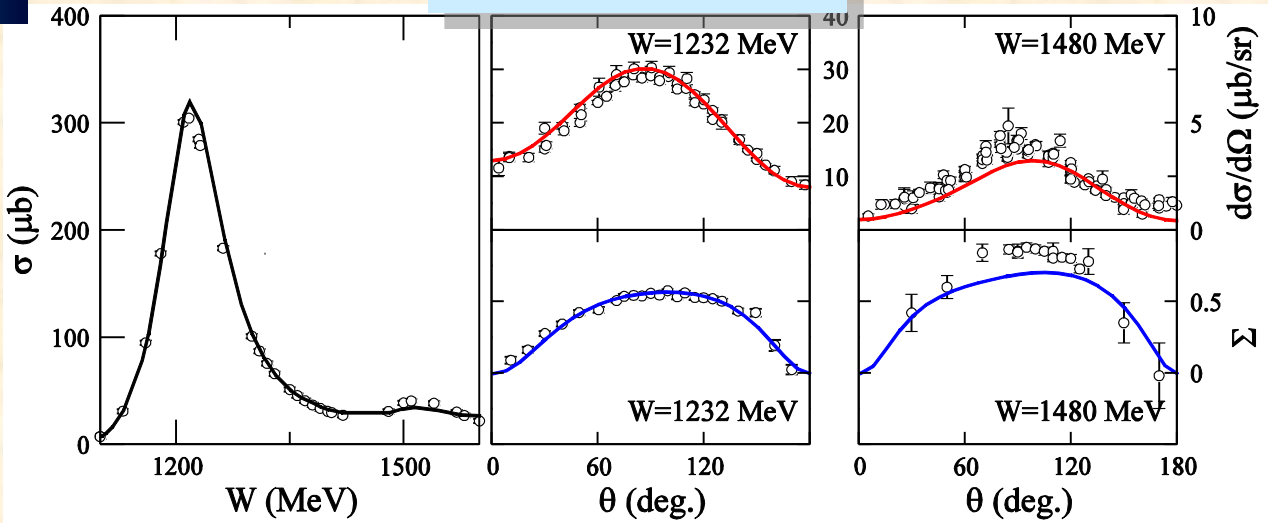
$Q^2 > 0$

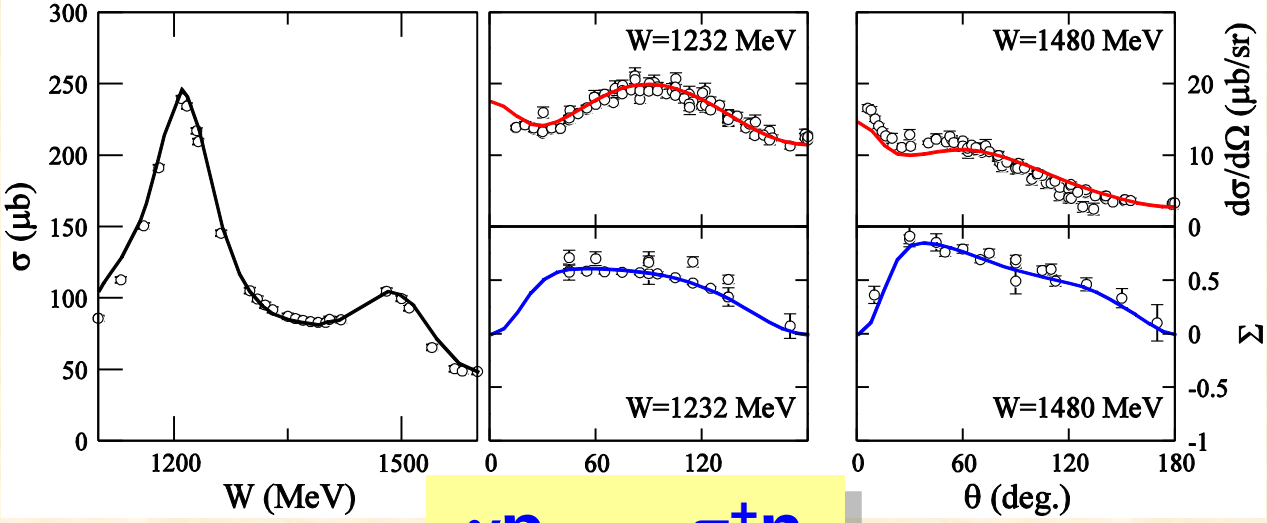


Julia-Diaz, Kamano, Lee, Matsuyama, Sato, Suzuki

EBAC

$\gamma p \rightarrow \pi^0 p$





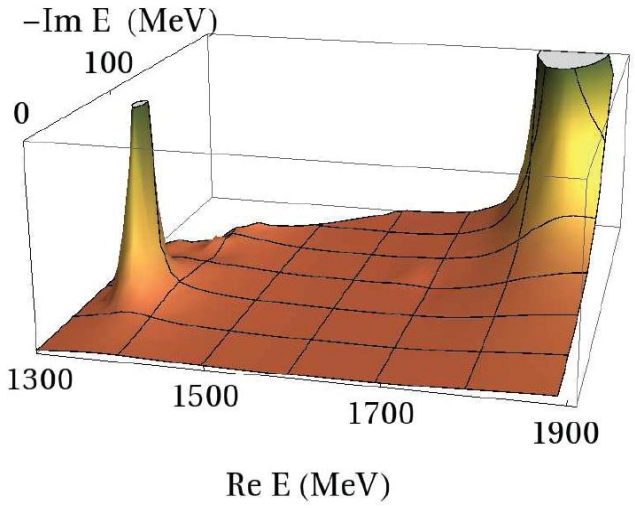
$\gamma p \rightarrow \pi^+ n$

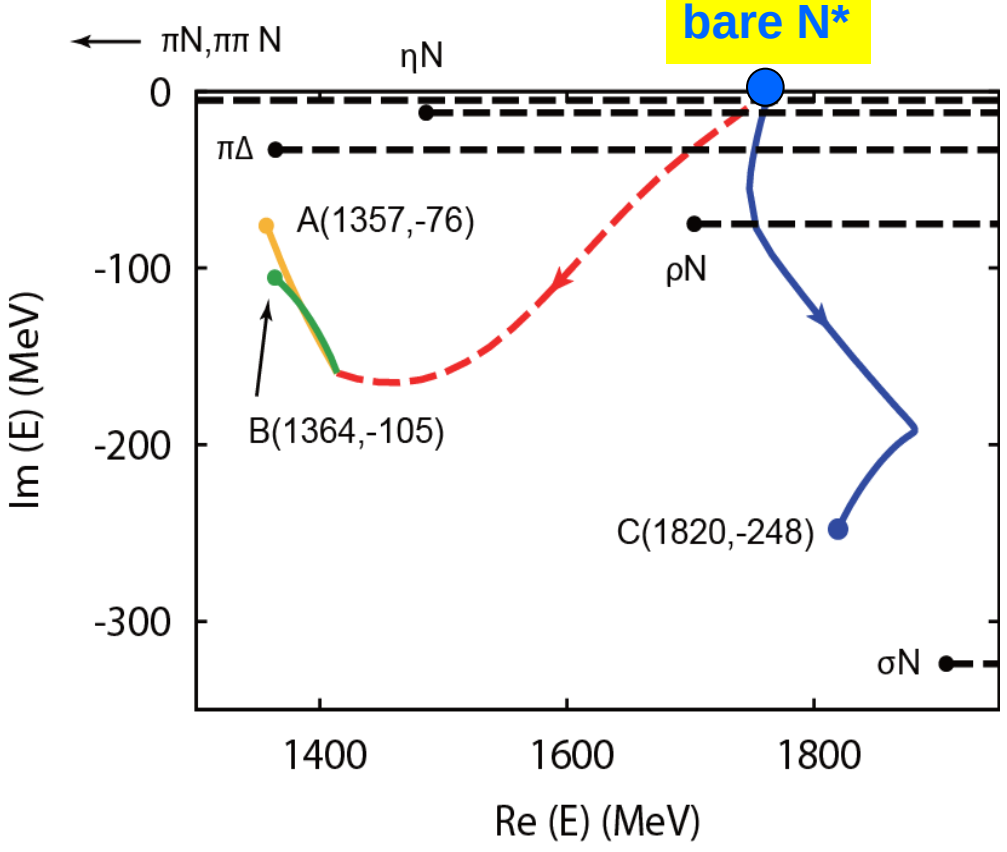
Kamano et al.

$P_{11}(1360)$, $P_{11}(1820)$

EBAC

Suzuki et al.

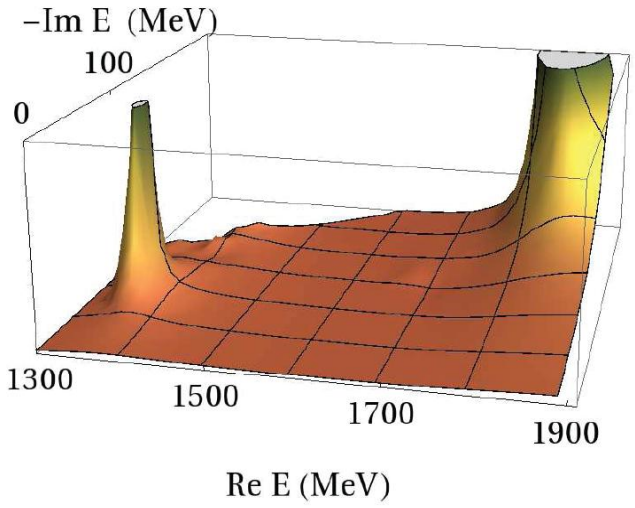


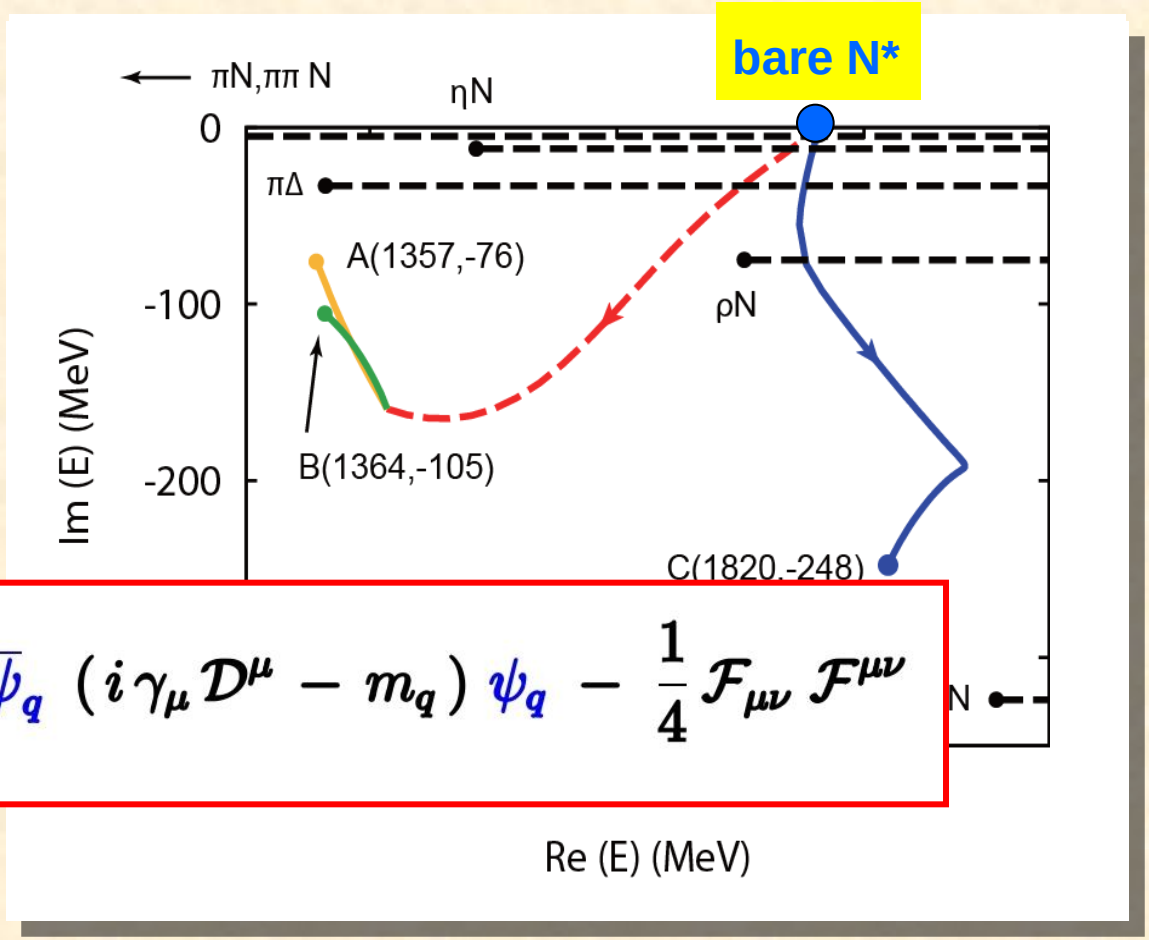


$P_{11}(1360)$, $P_{11}(1820)$

EBAC

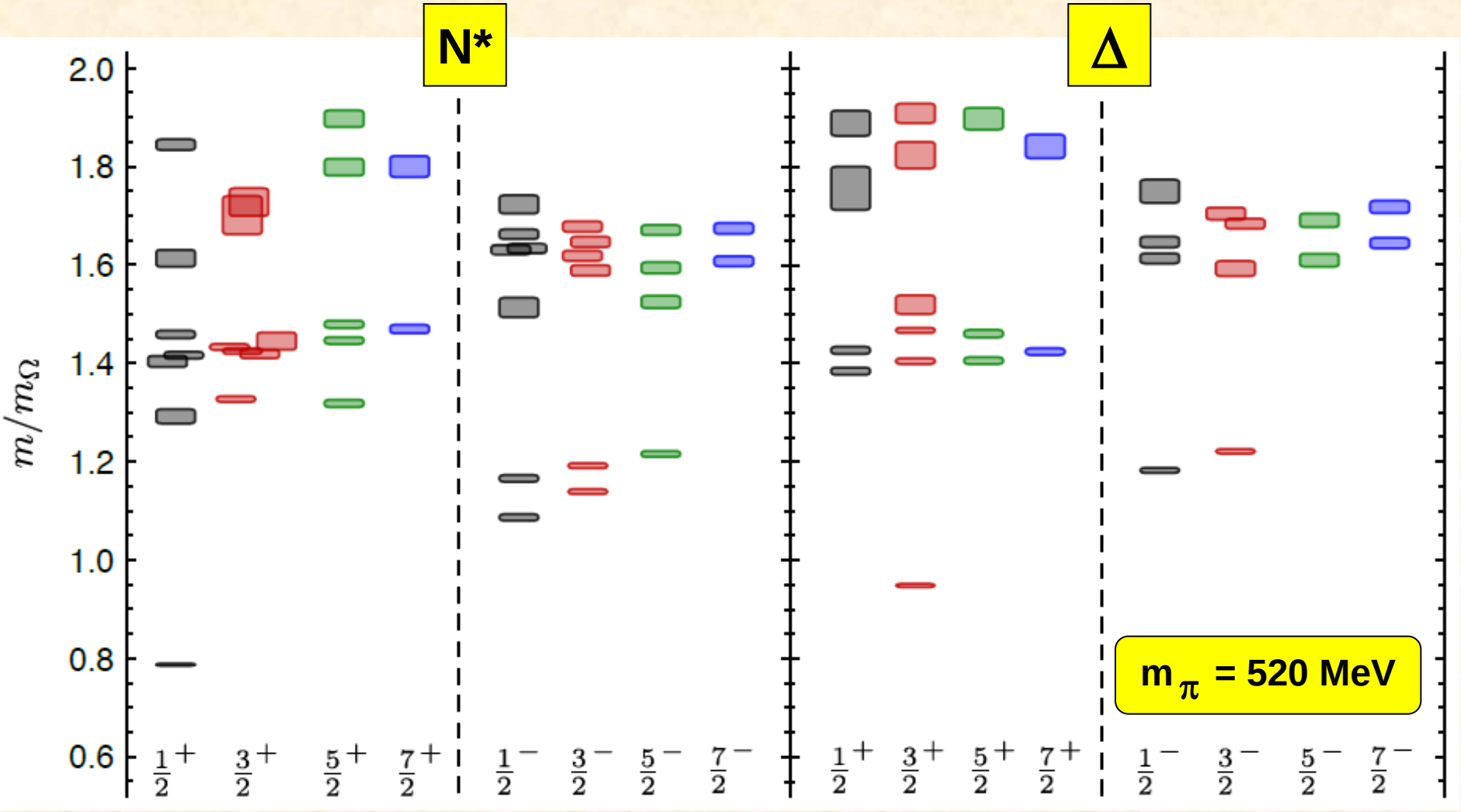
Suzuki et al.





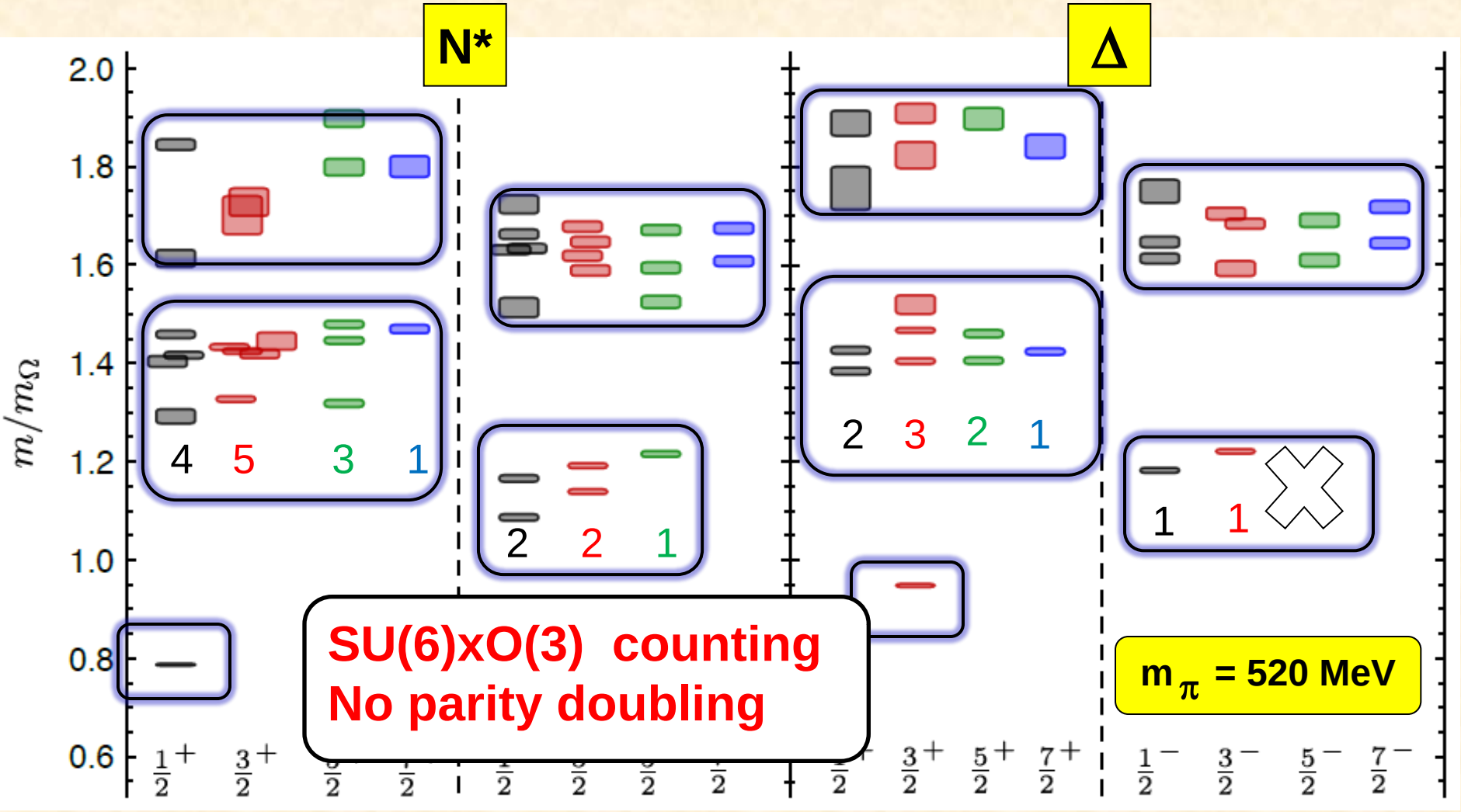
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$

Spin identified N* and Δ states



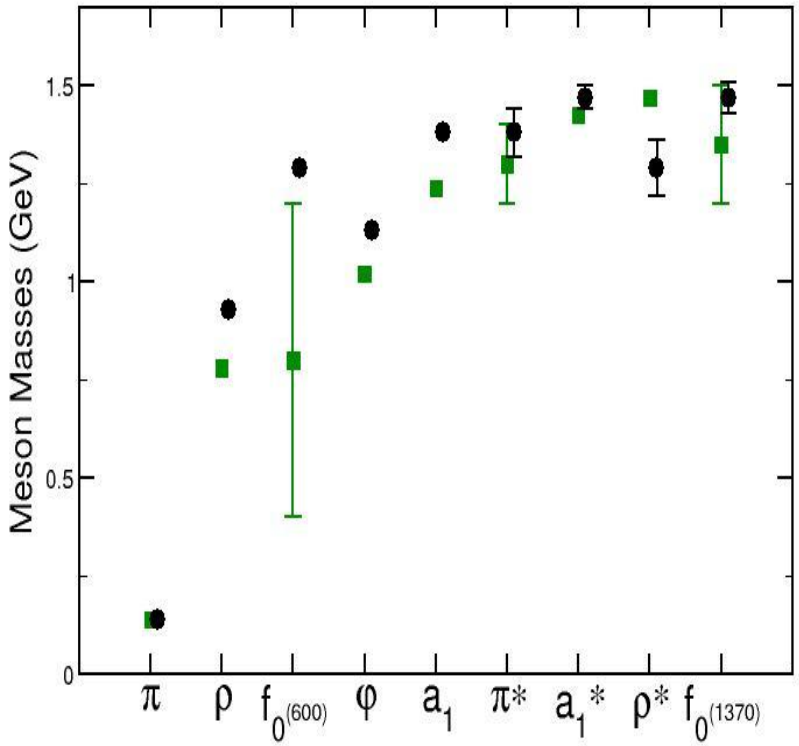
Edwards, Dudek, Wallace & Richards

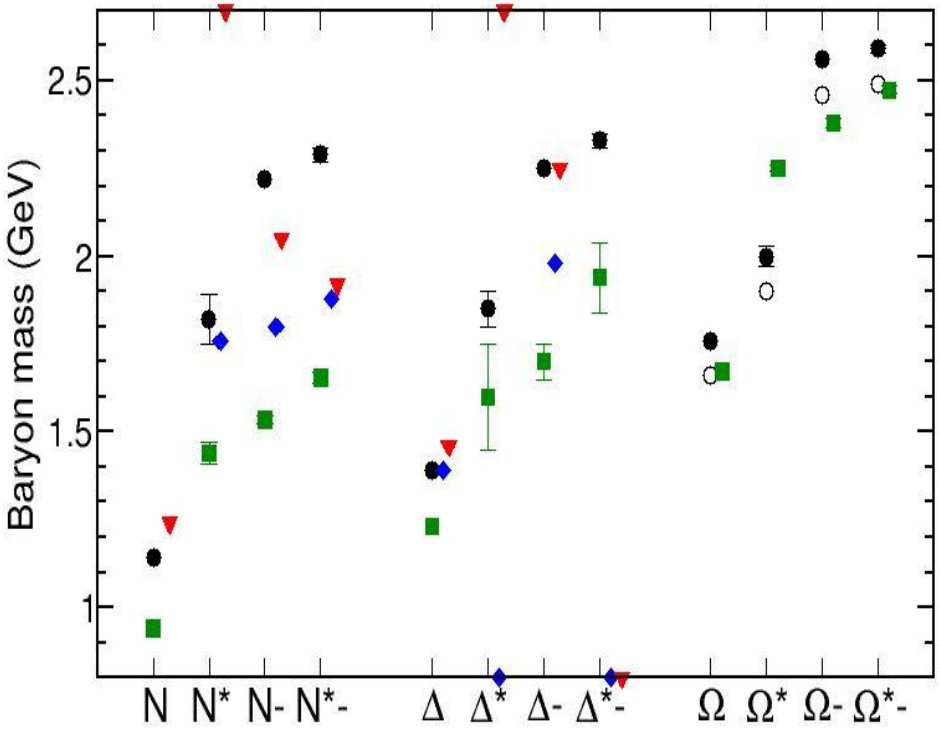
Spin identified N* and Δ states

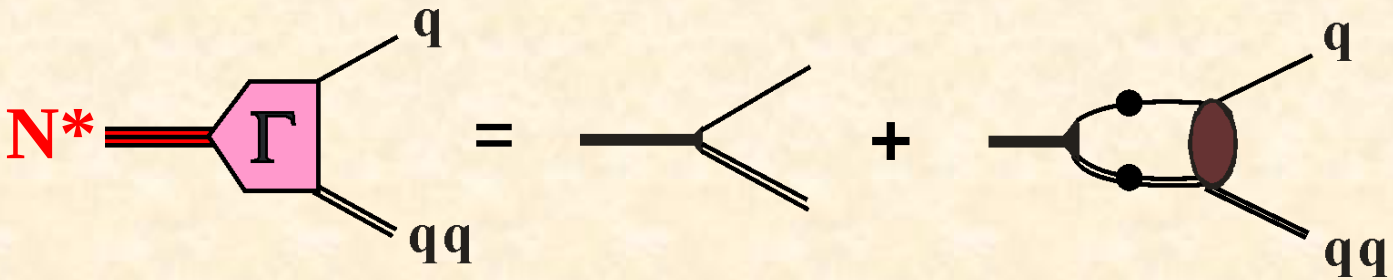


Edwards, Dudek, Wallace & Richards

Hadron Spectrum in ANL BS model



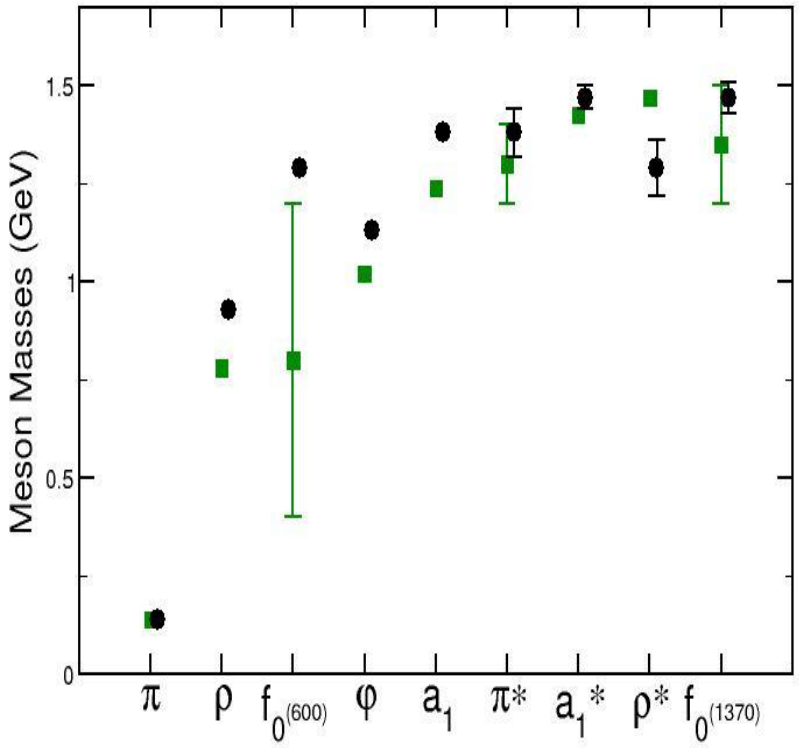


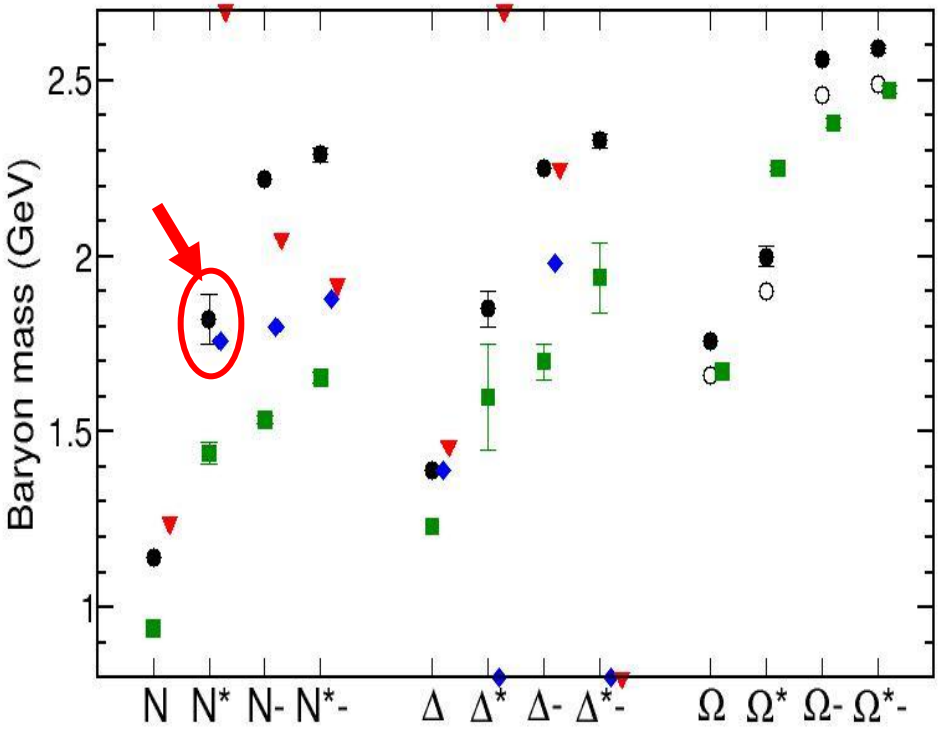


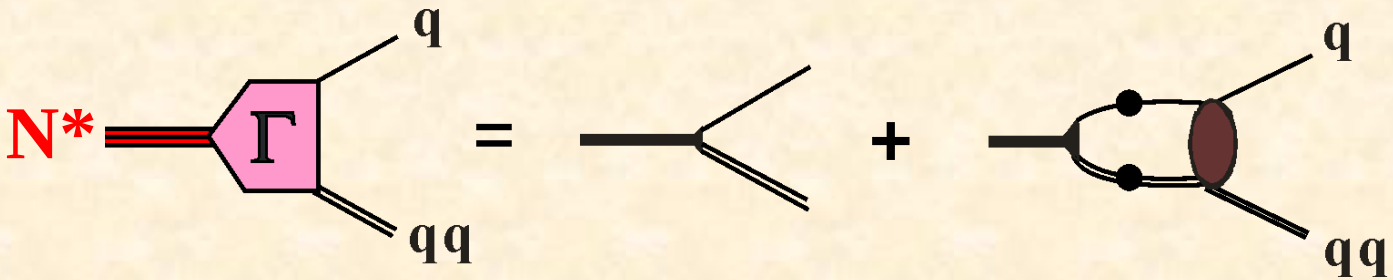
Legend:

- Particle Data Group
- H.L.L. Roberts *et al.*
- EBAC
- Jülich

Hadron Spectrum in ANL BS model



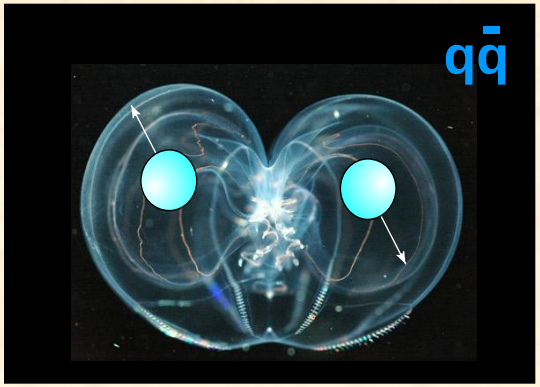


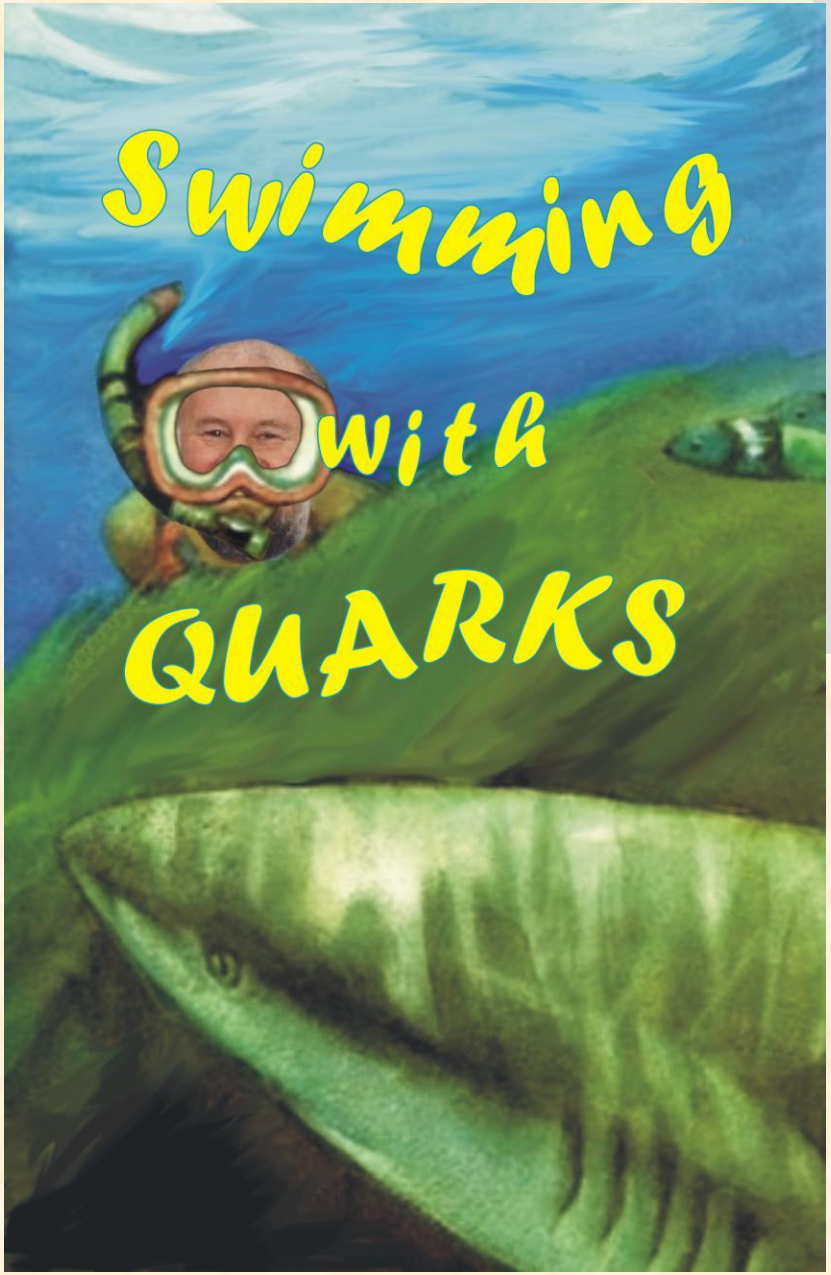


Legend:

- Particle Data Group
- H.L.L. Roberts *et al.*
- EBAC
- Jülich


qqq

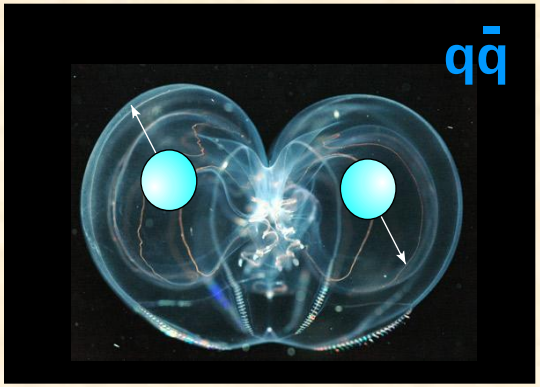

qq̄

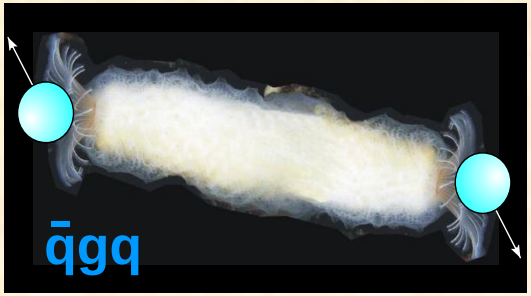

Swimming
with
QUARKS


qqq


q̄
q̄
q
q

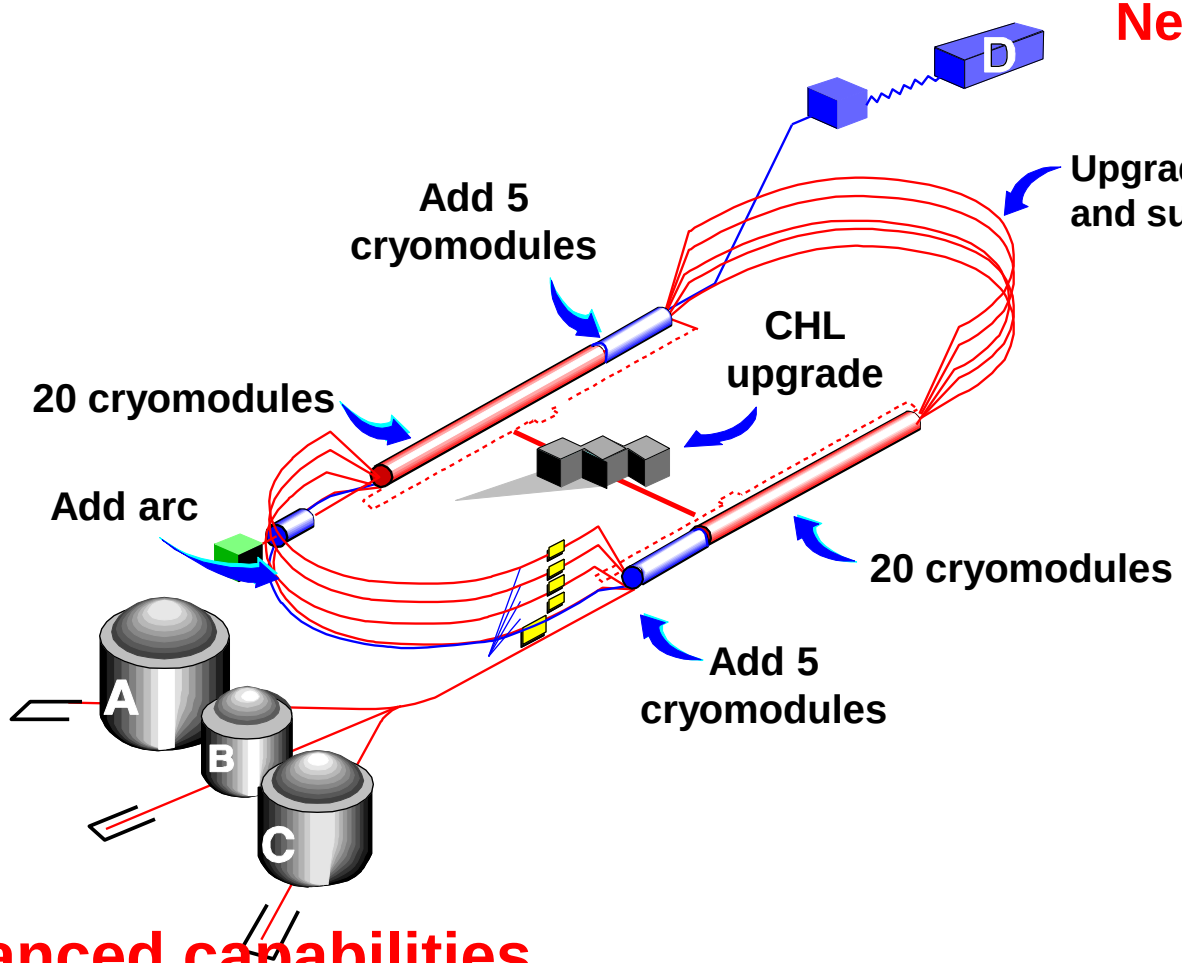

gg


qq̄


q̄gq

Jefferson Lab 12 GeV upgrade

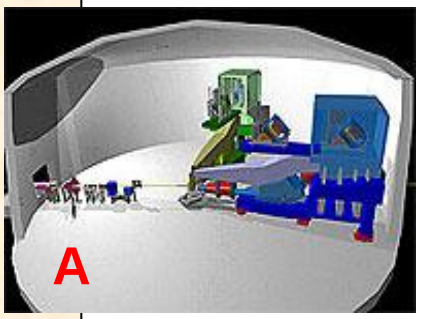
Exploring the Nature of Matter

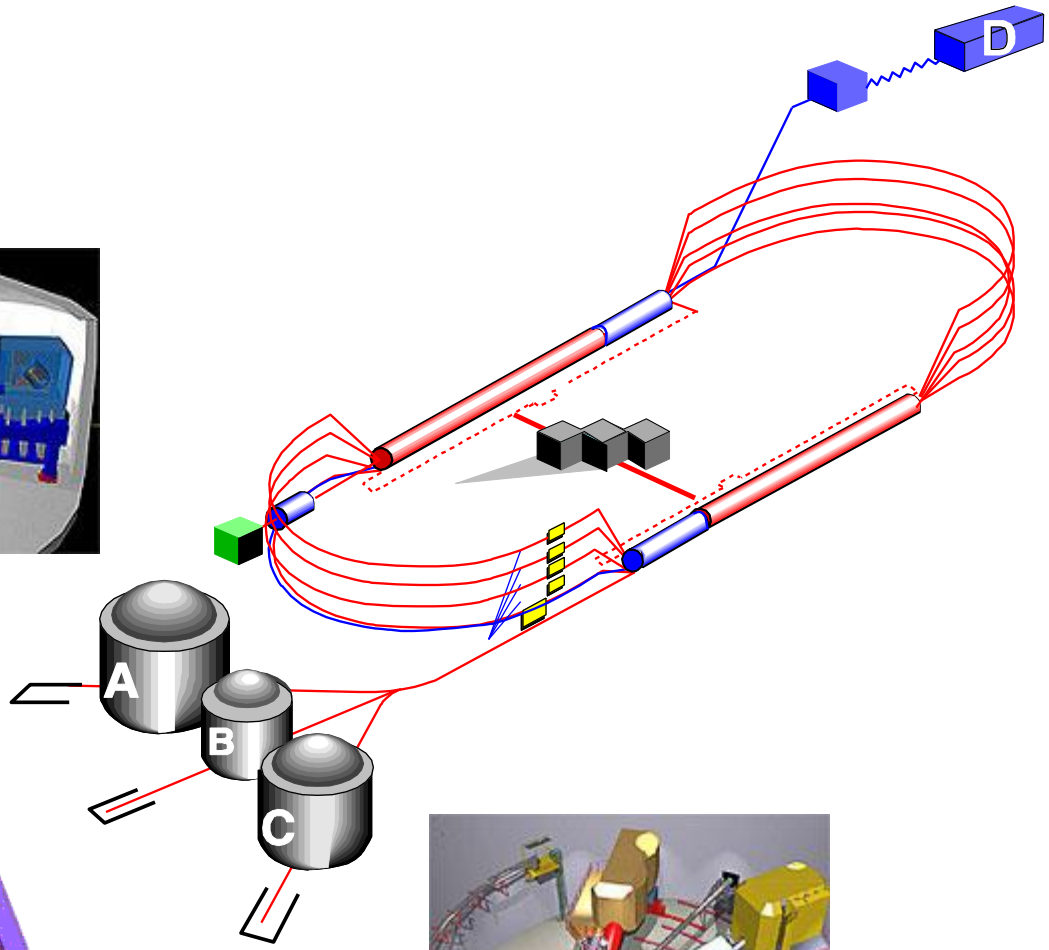


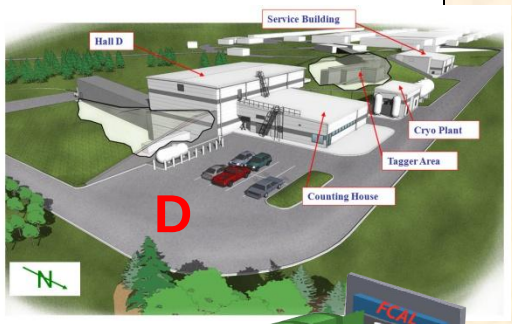
Enhanced capabilities in existing Halls

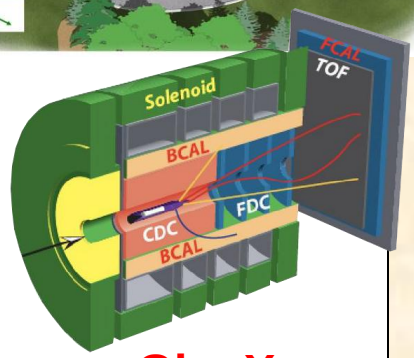
Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter

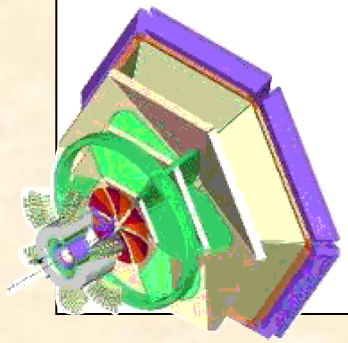




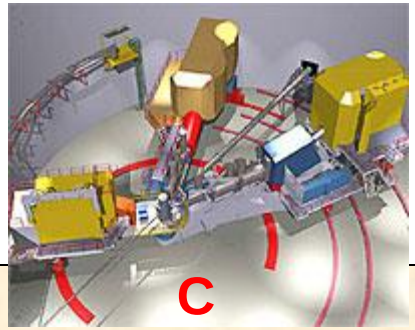




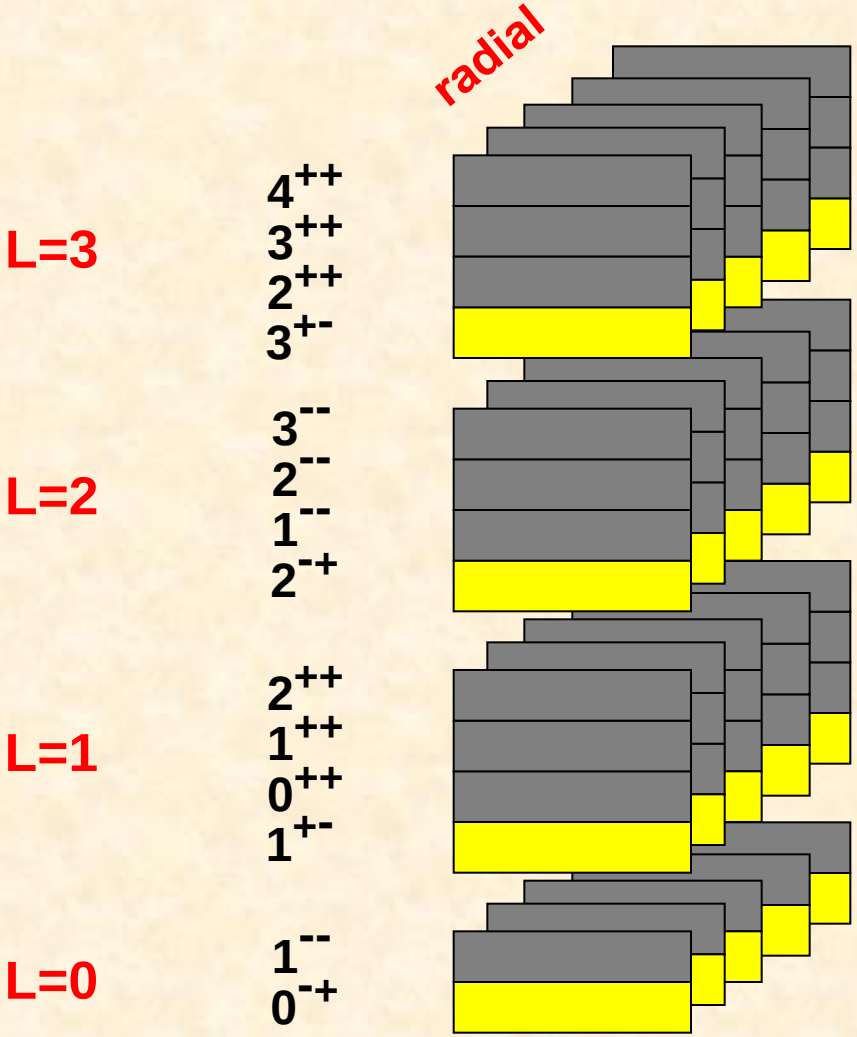
GlueX



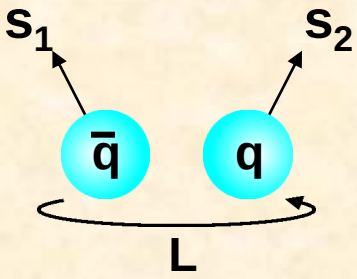
B CLAS12



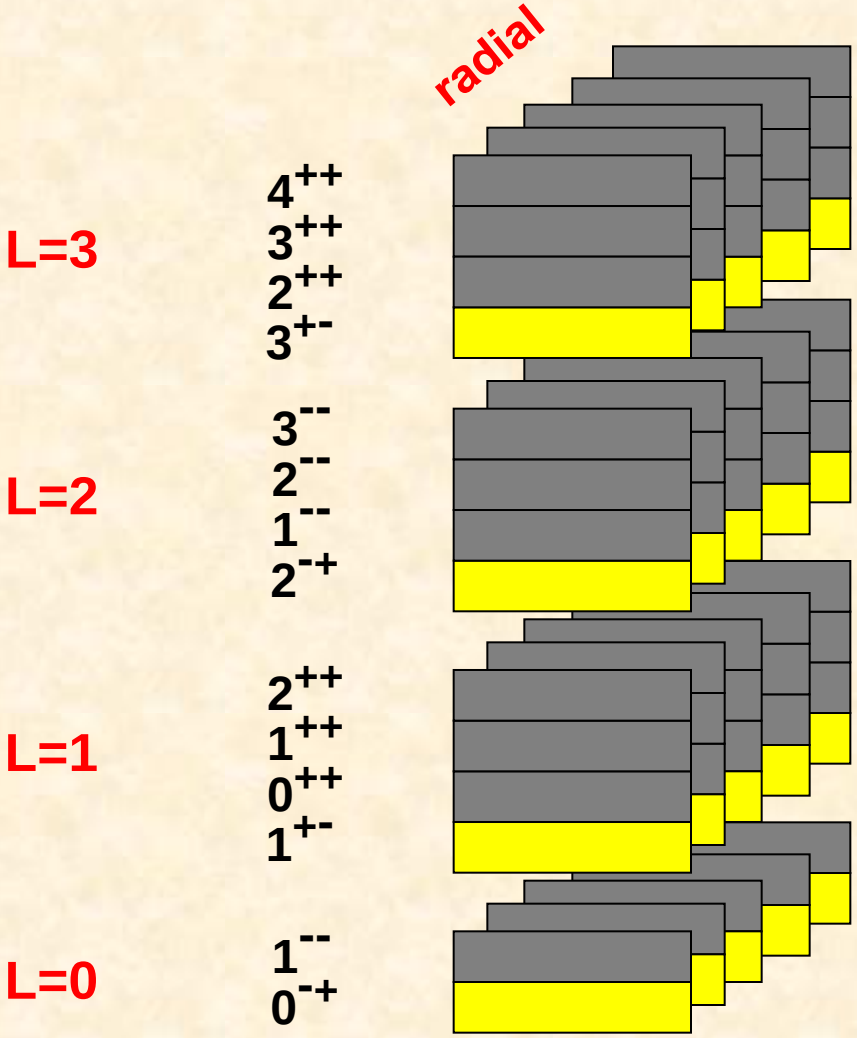
Meson spectrum



S = 0, 1



Meson spectrum



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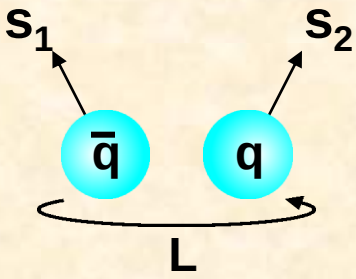
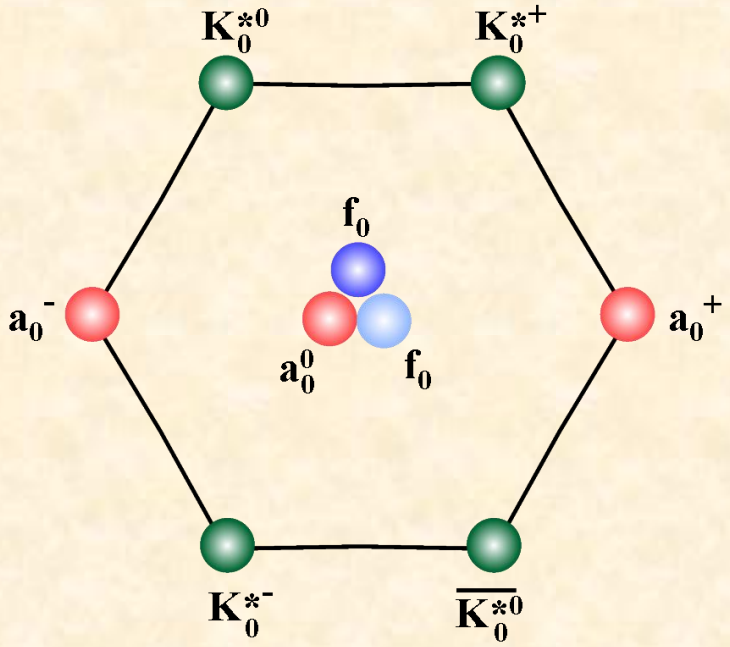
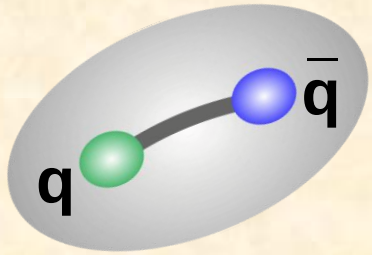


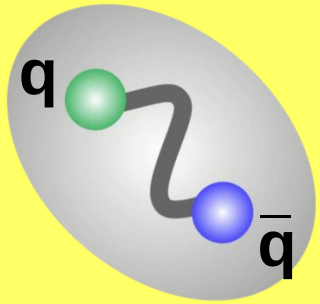


allowed J^{PC}

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



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

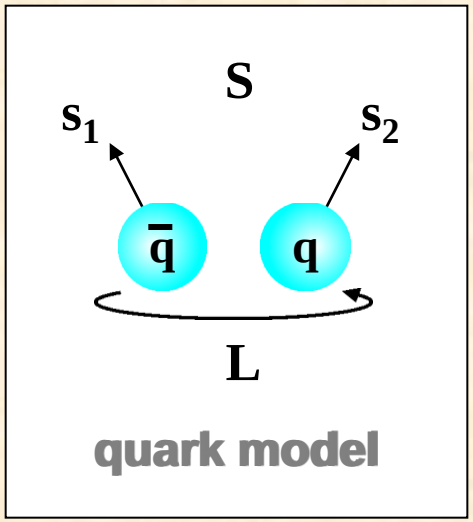


Mesons: J^{PC} quantum numbers

0^{++} 0^{+-} 0^{-+} 0^{--}

1^{++} 1^{+-} 1^{-+} 1^{--}

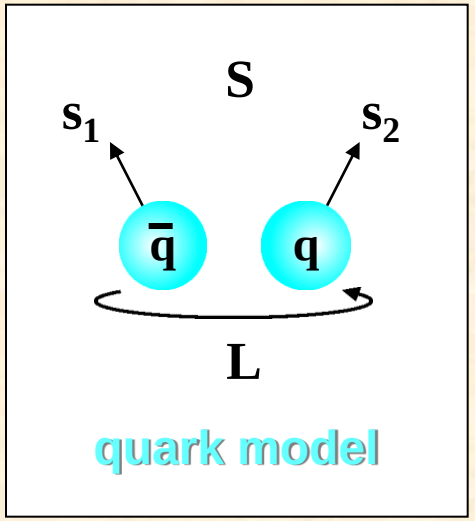
non $\bar{q}q$

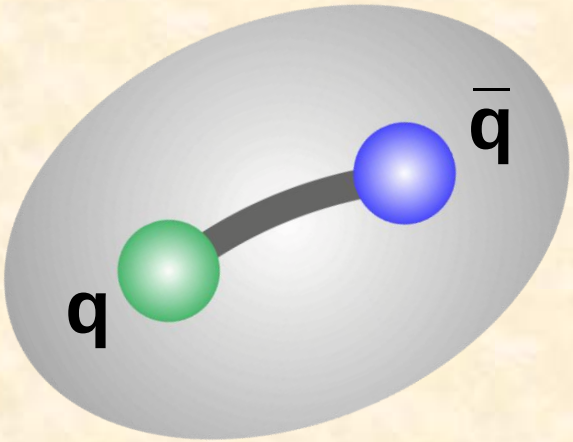


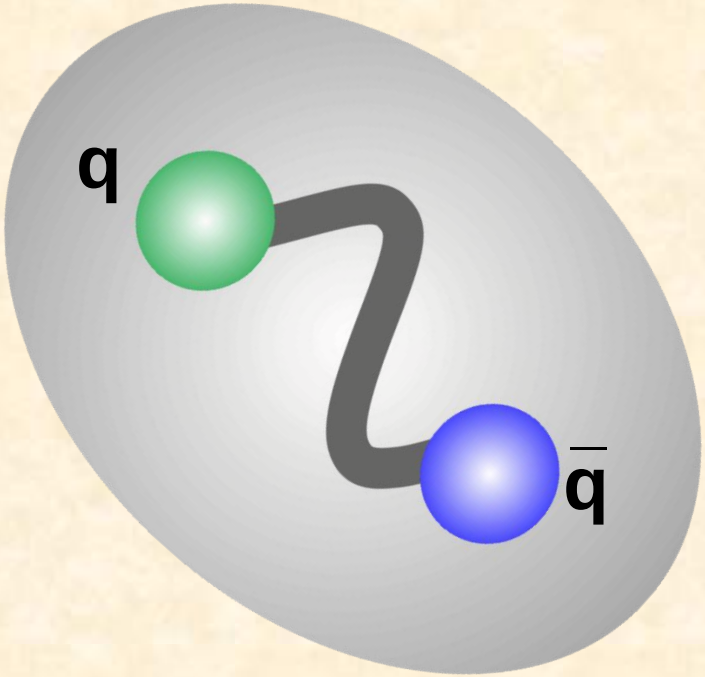
2^{++} 2^{+-} 2^{-+} 2^{--}

. . . .

Calculating Exotic Mesons





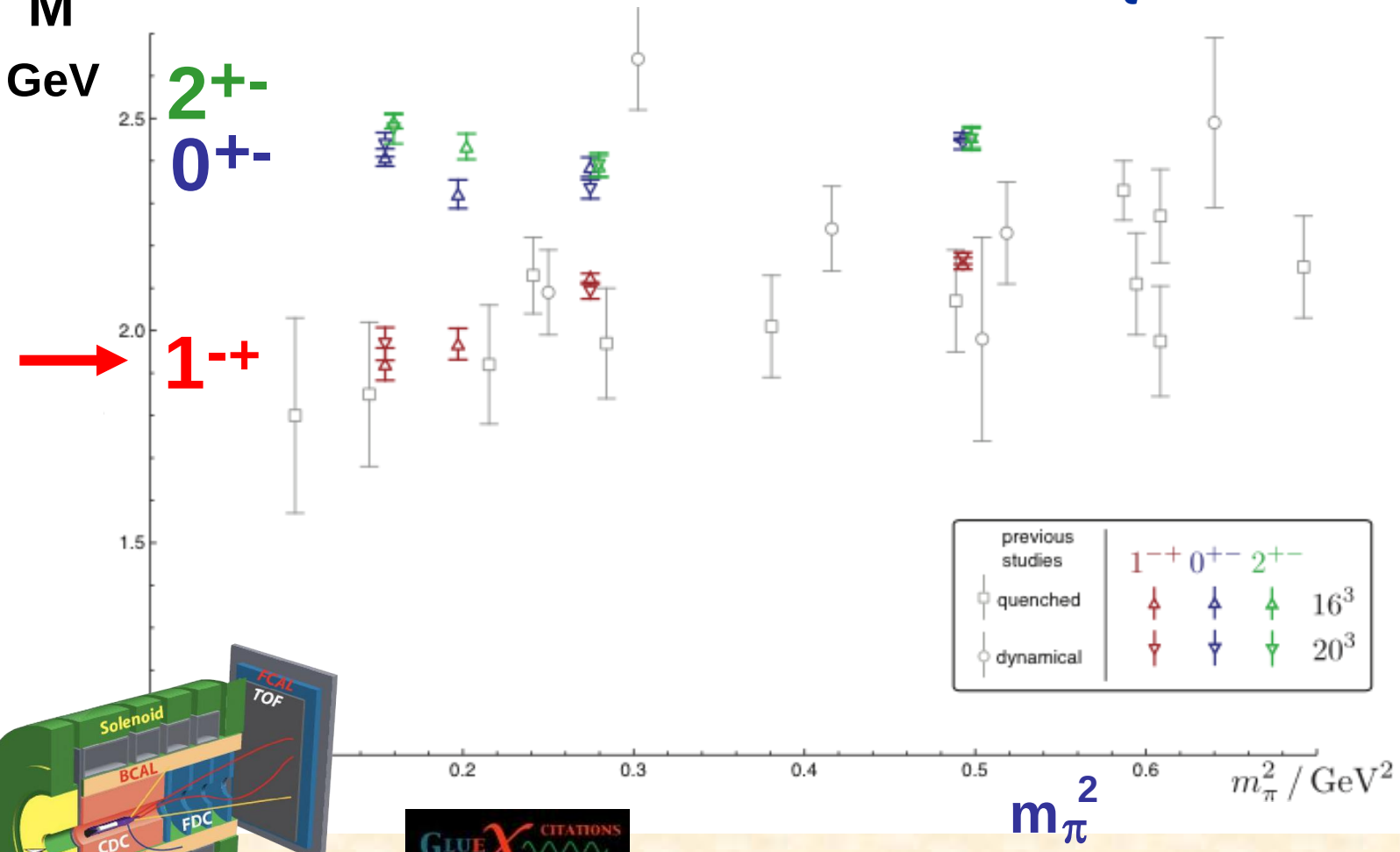


Lattice Game Show

Lattice Game Show

Isovector Meson Spectrum

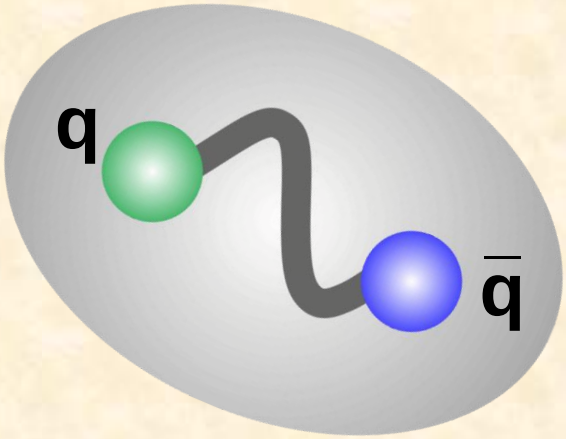
States with Exotic Quantum Numbers

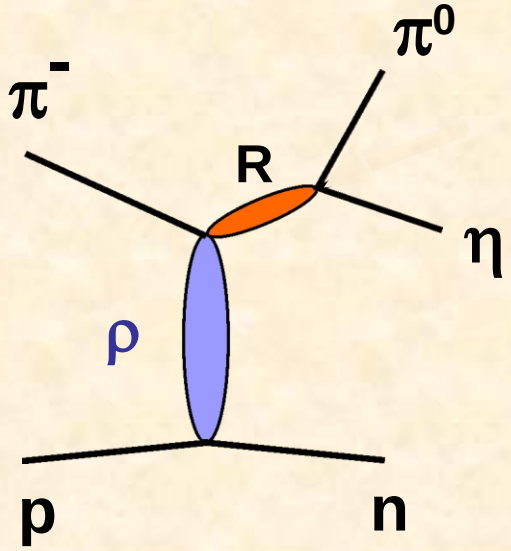


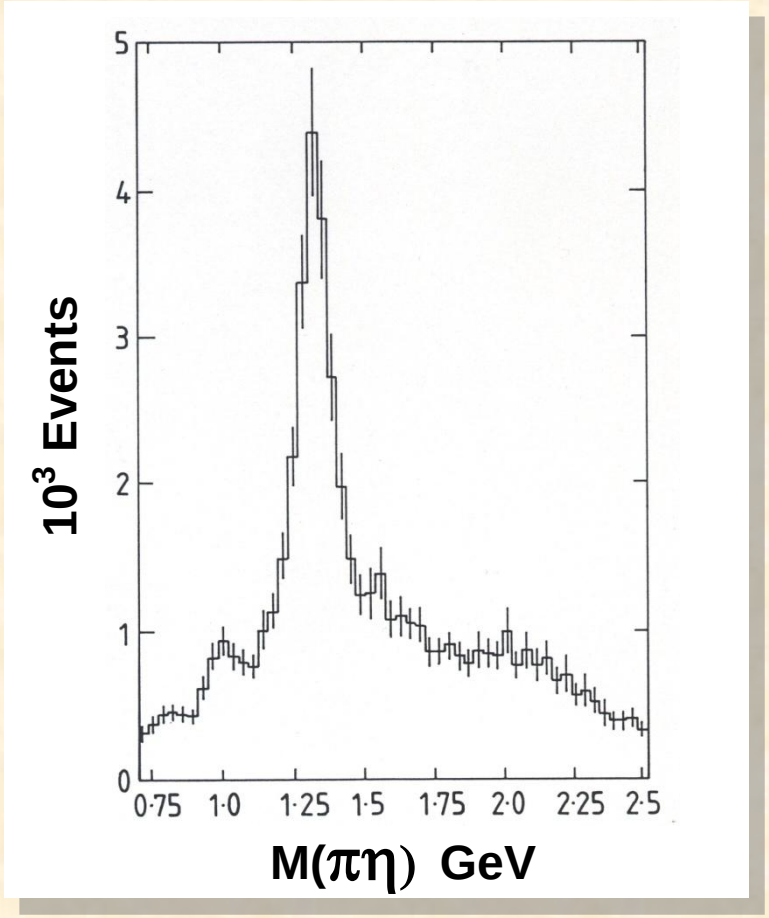
GlueX Collaborations Experiment
Hall D@JLab

Dudek et al.

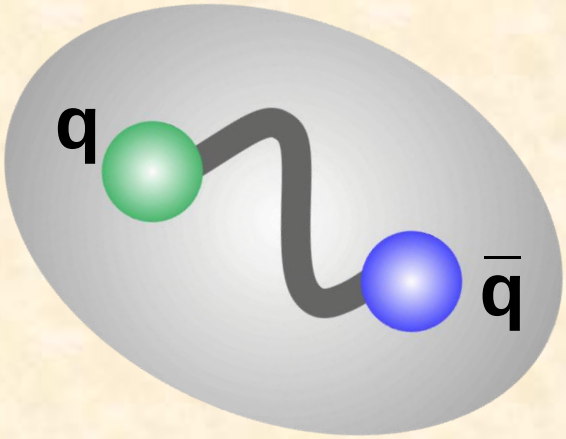
GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$

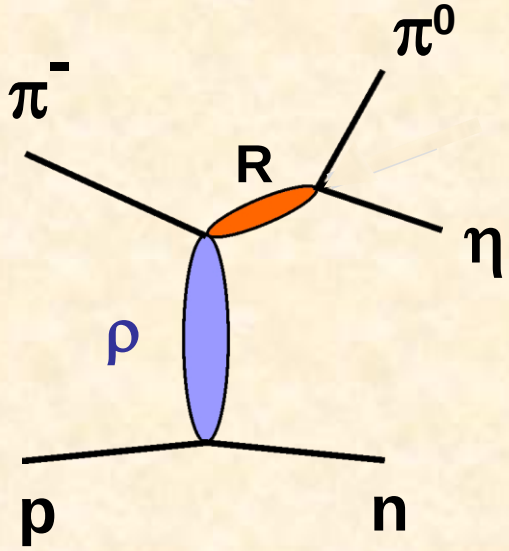


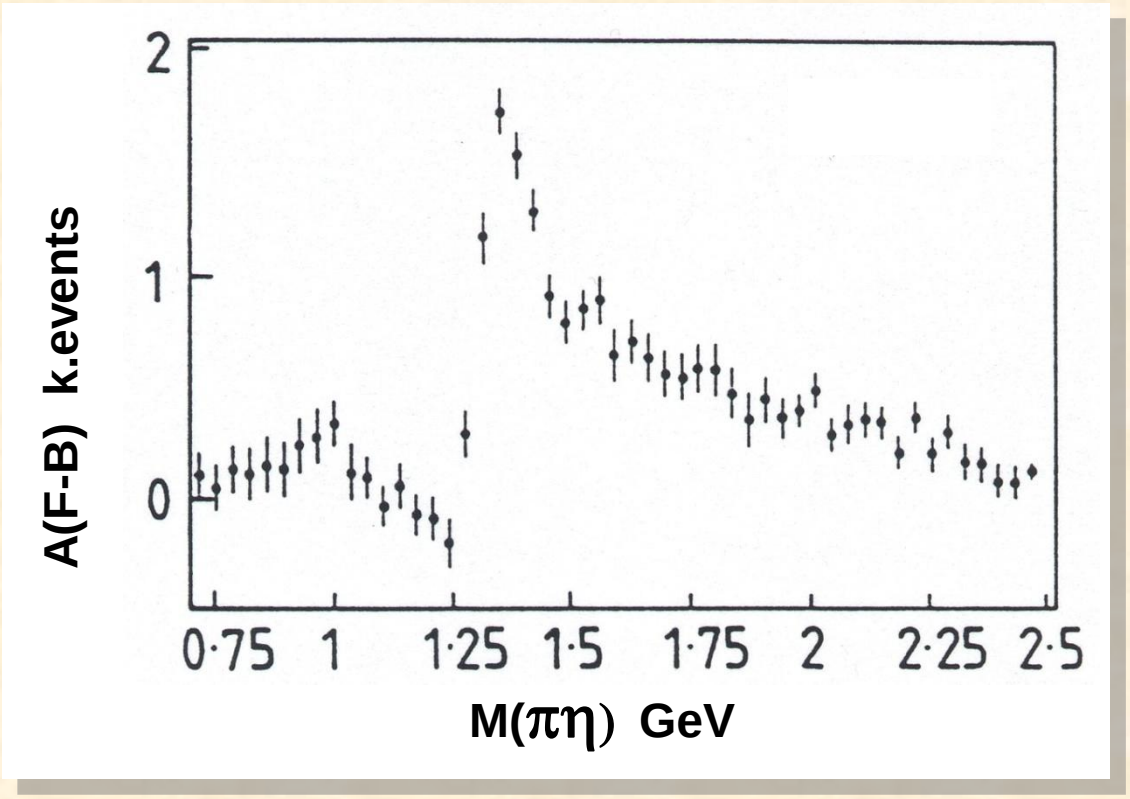




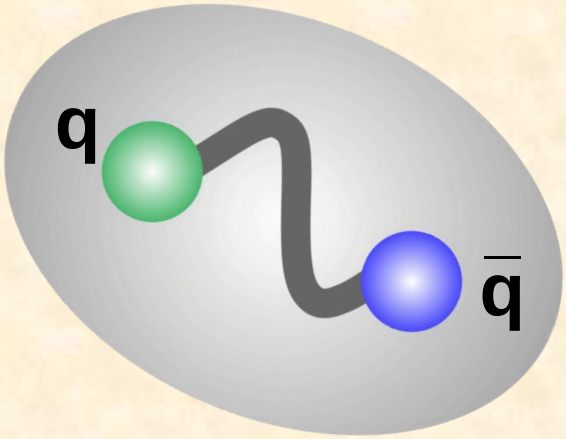
GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$

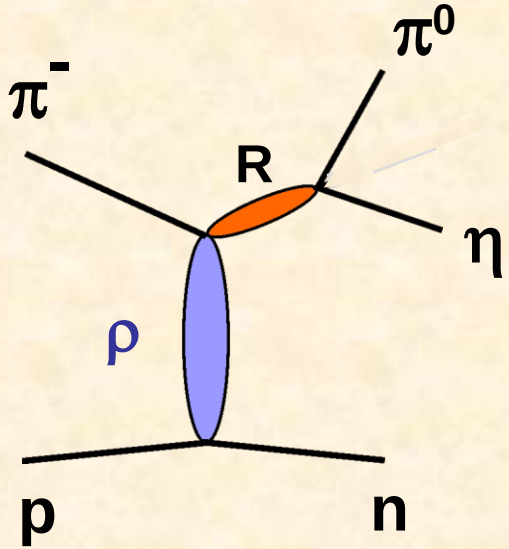




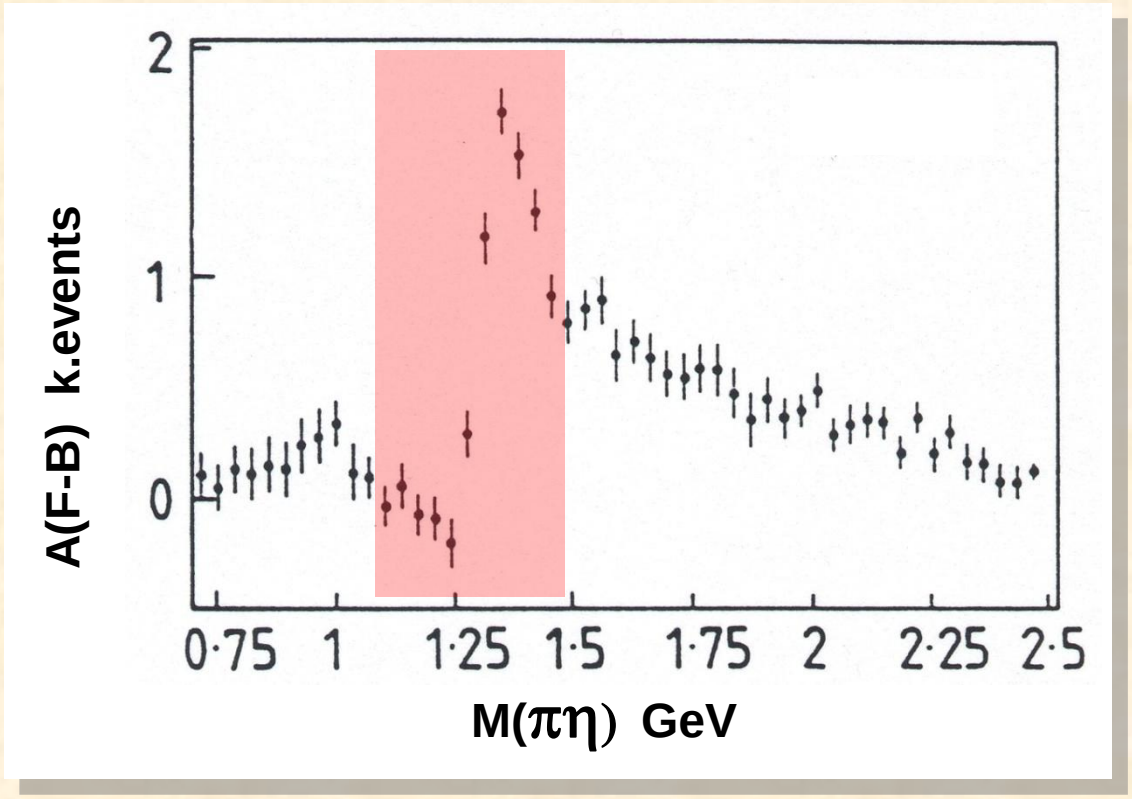


GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$

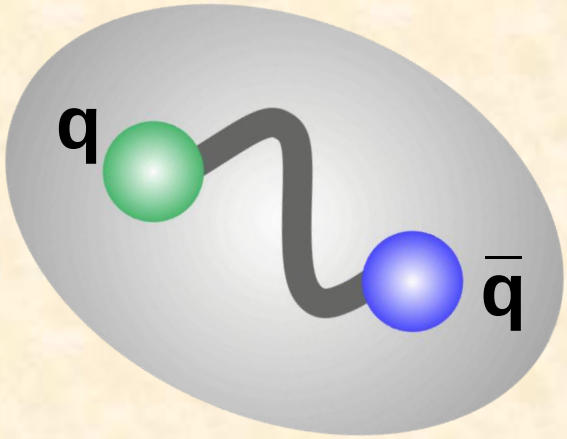


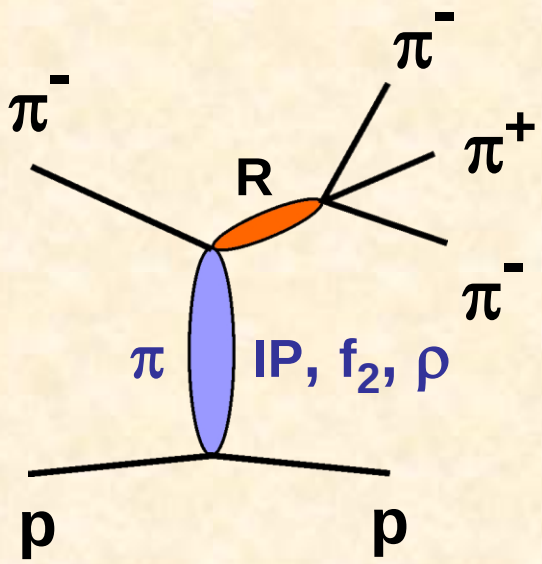


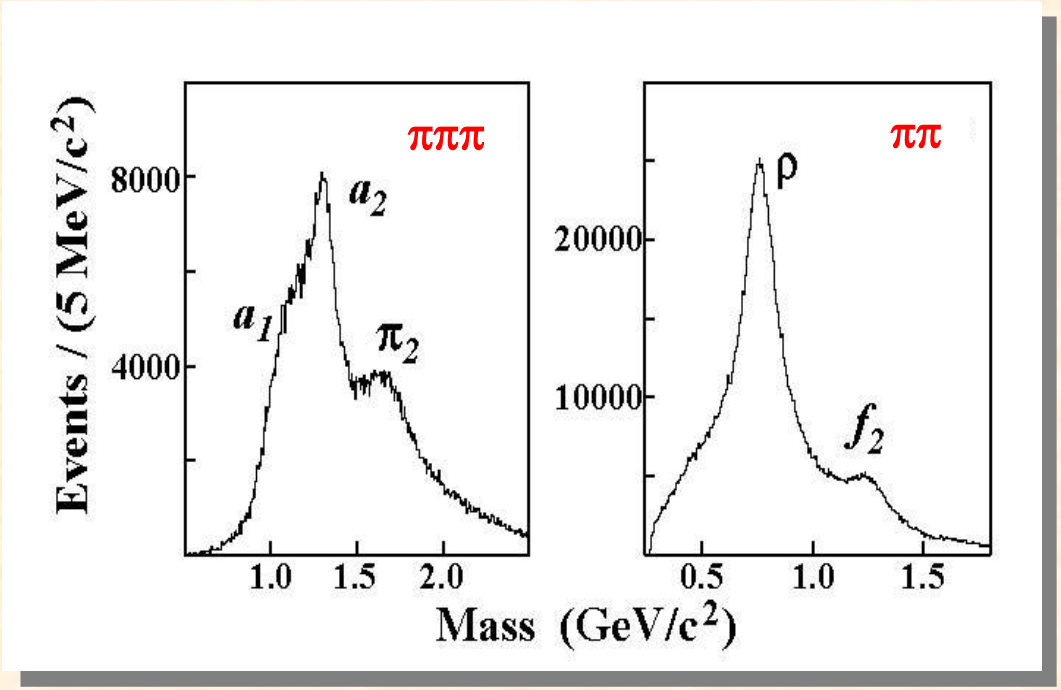
1^{-+}



BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$



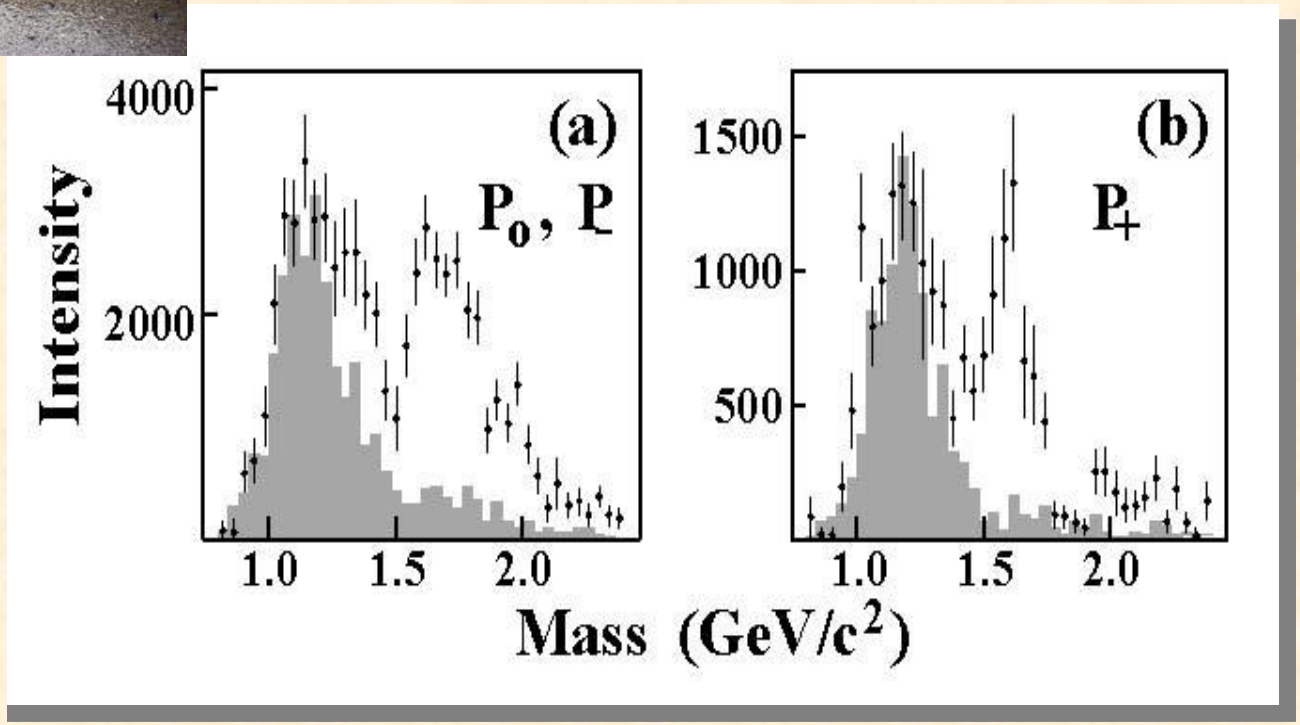




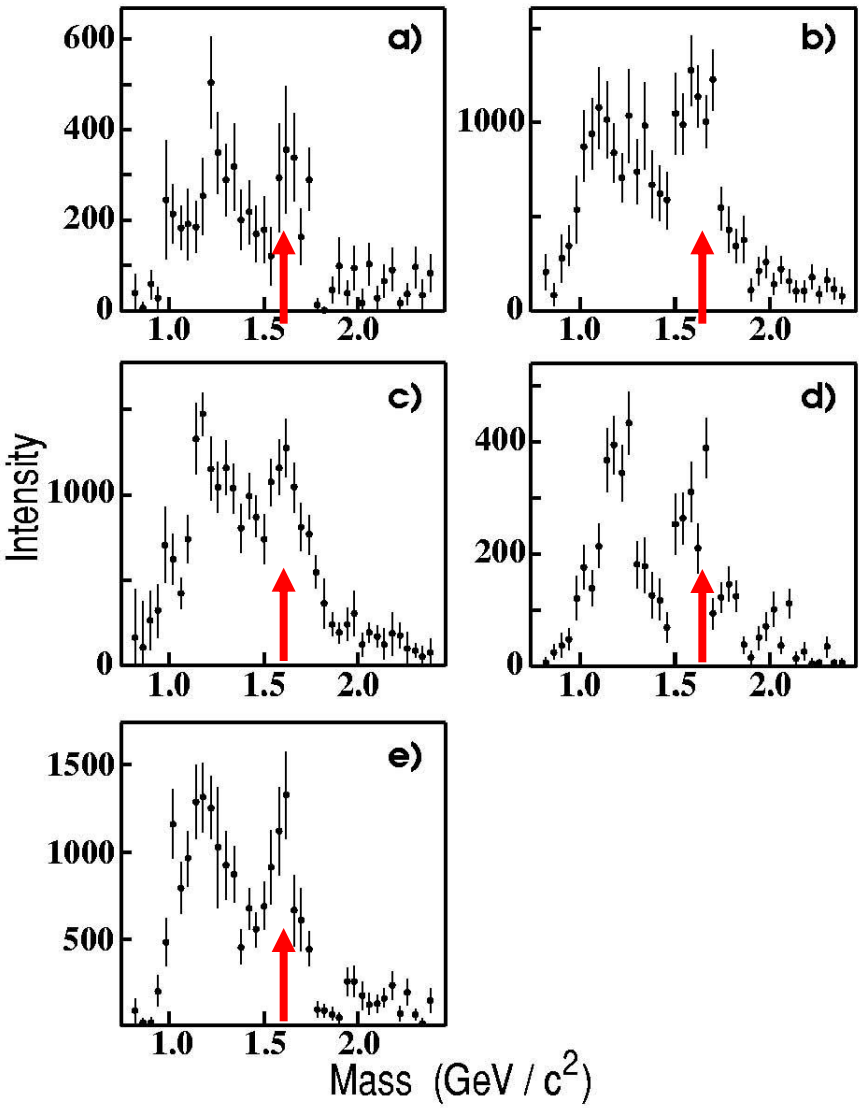
250k events

BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

Monte Carlo
with NO 1^{-+}



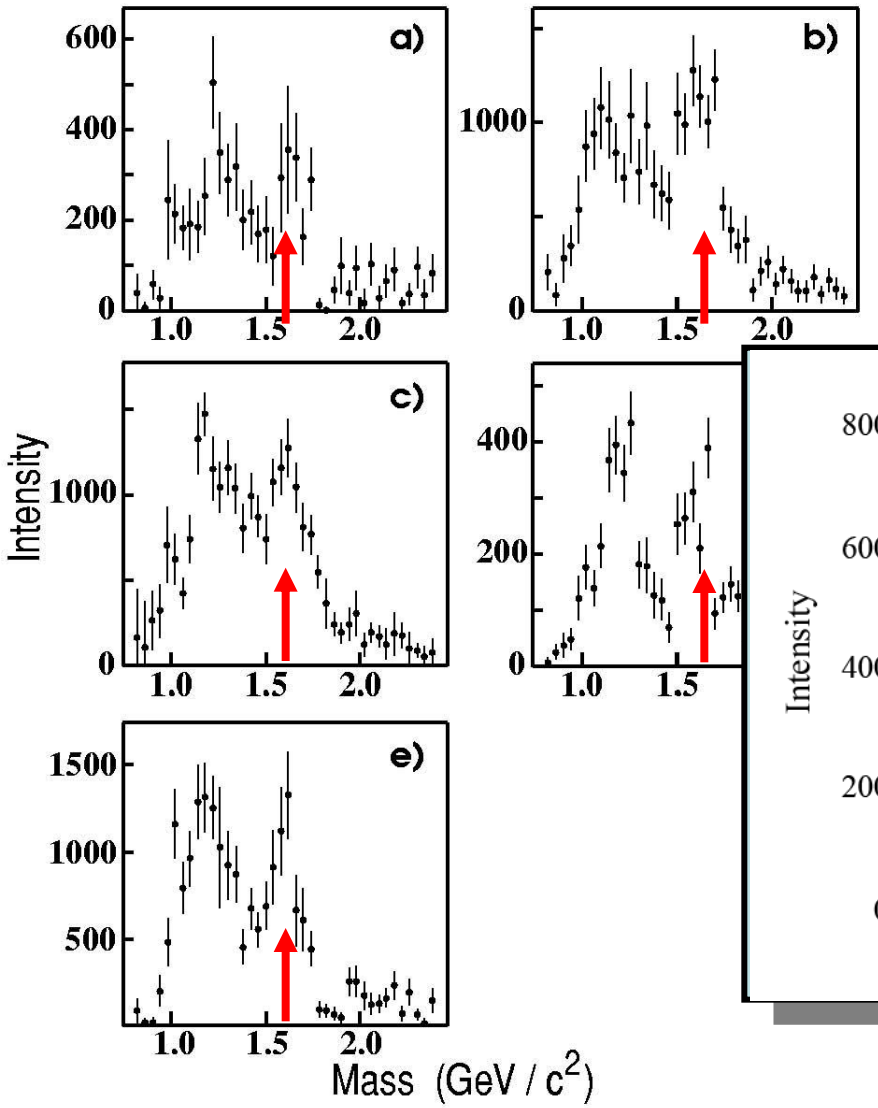
BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

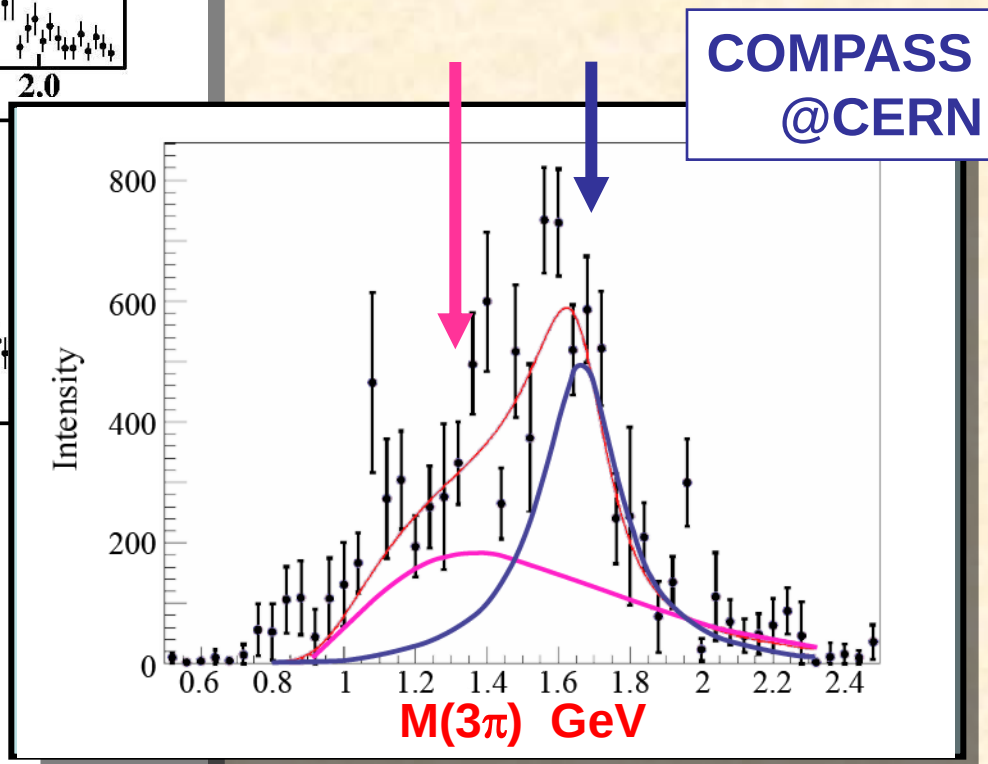


variation of 1^{-+} with 0^{++}

Chung et al.

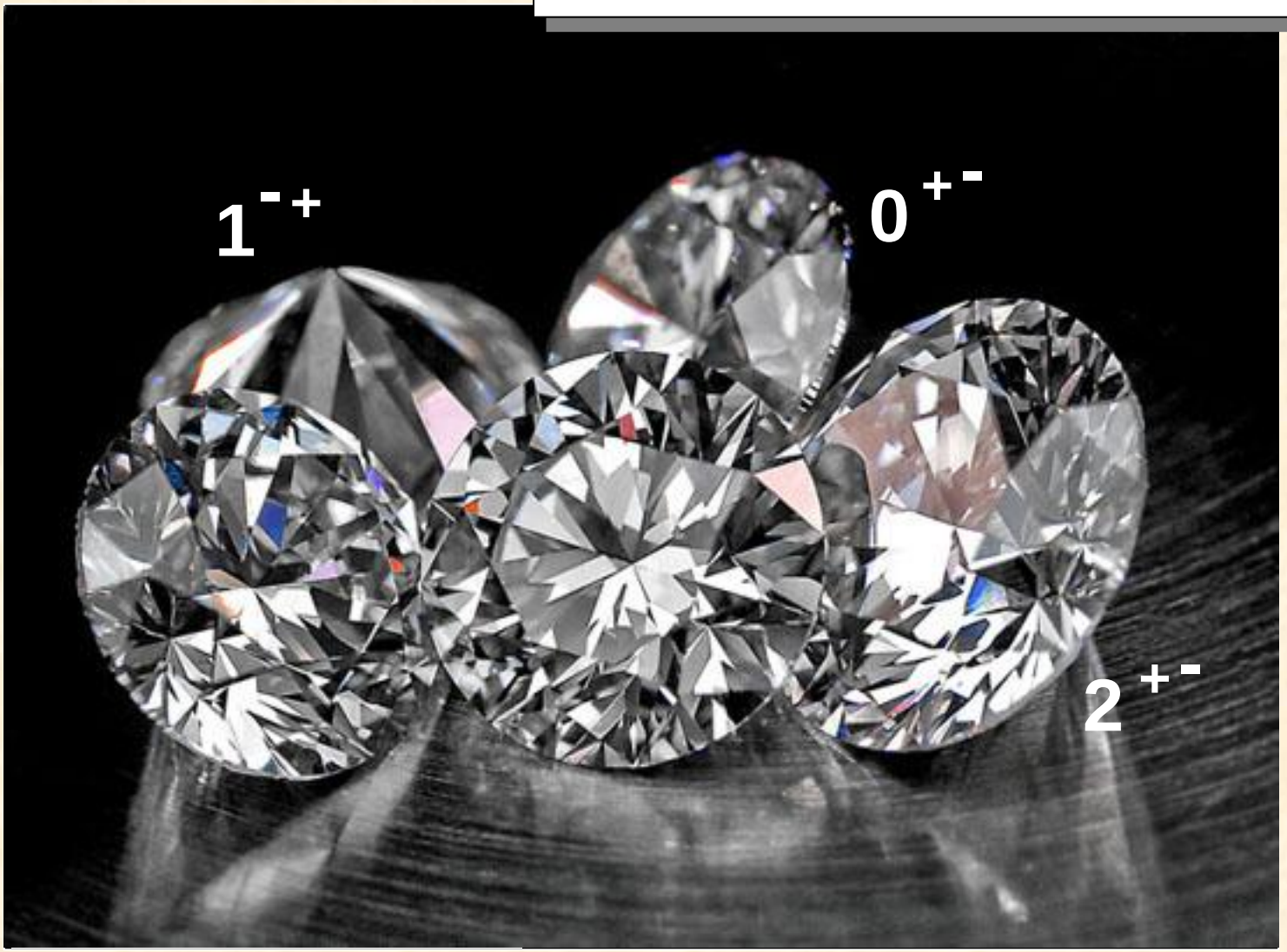
BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$



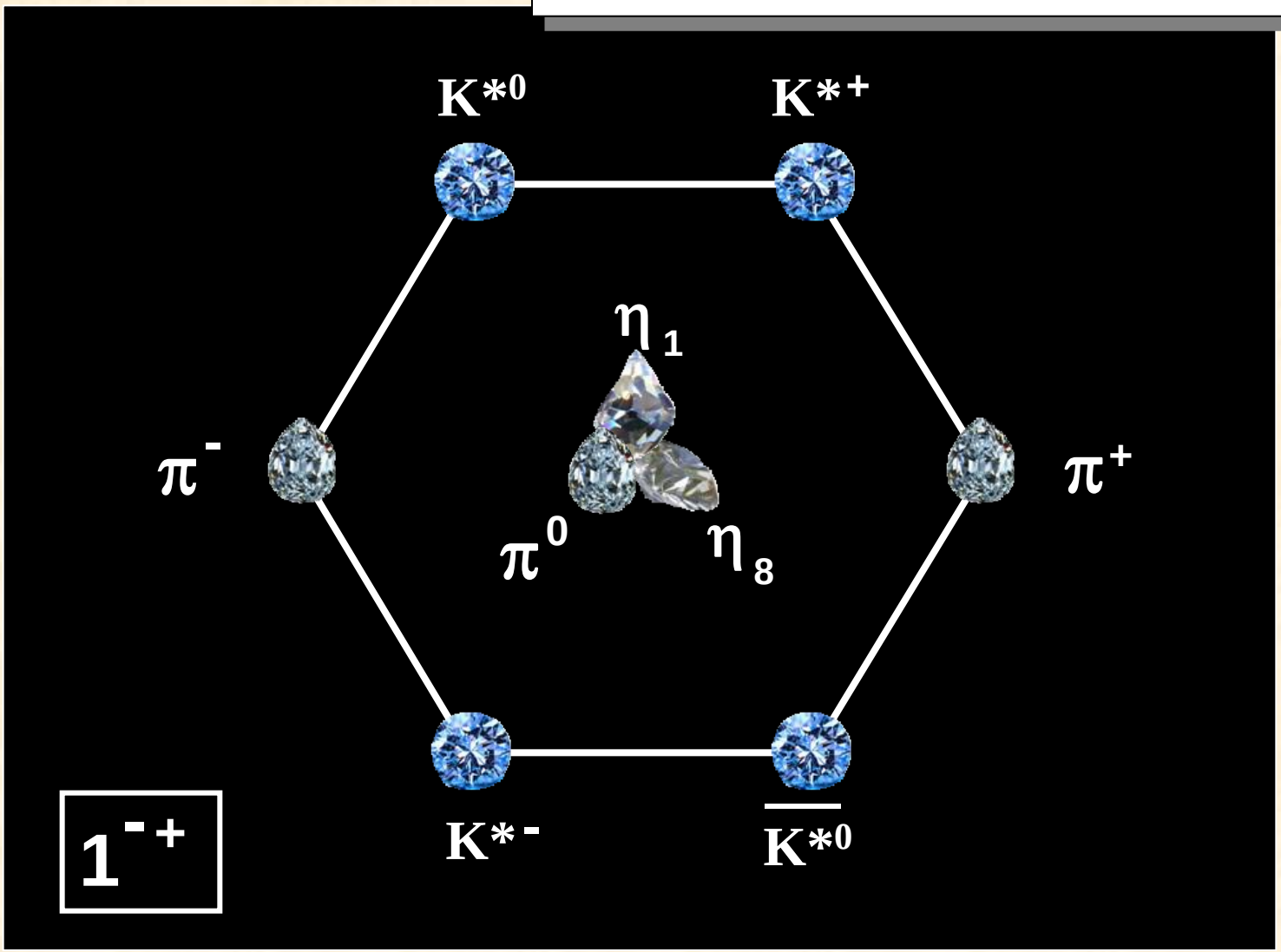


Chung et al.

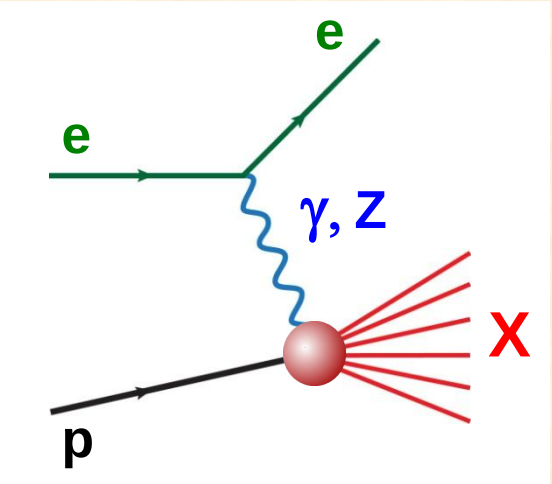
Precision analysis tools

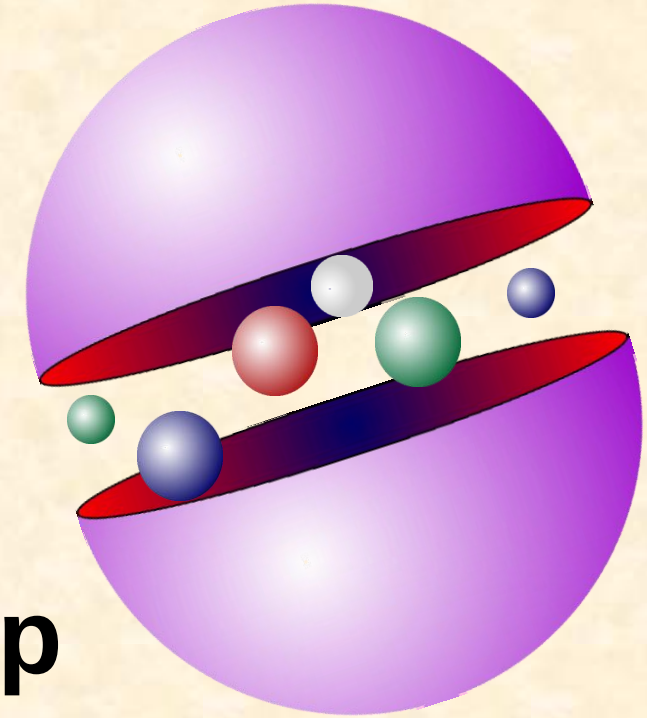


Precision analysis tools

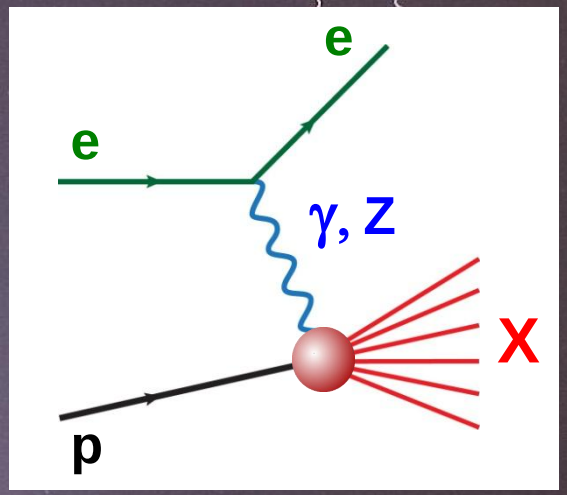


probing excited baryons

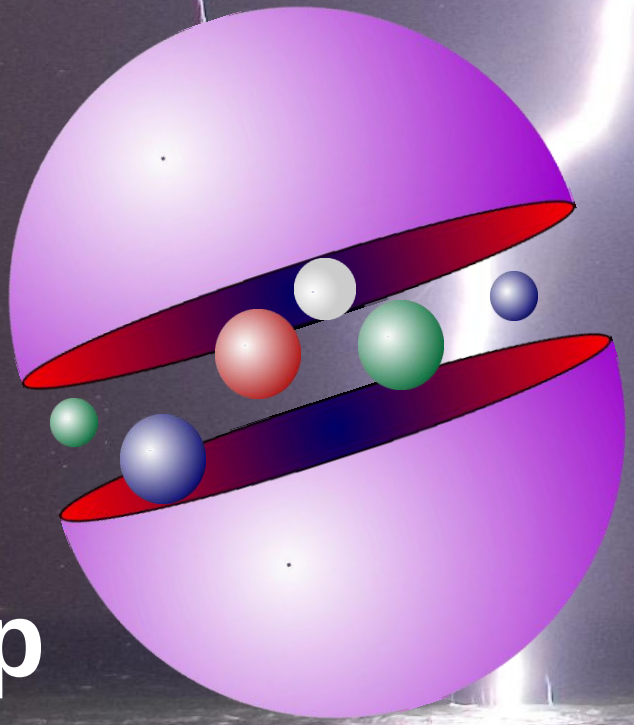




Jefferson Lab
Exploring the Nature of Matter



X = N*



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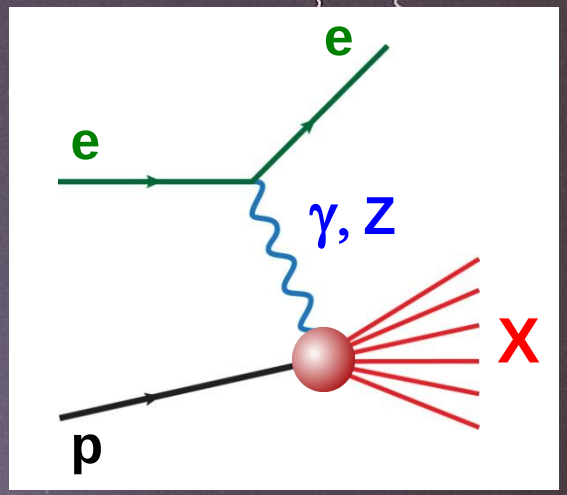
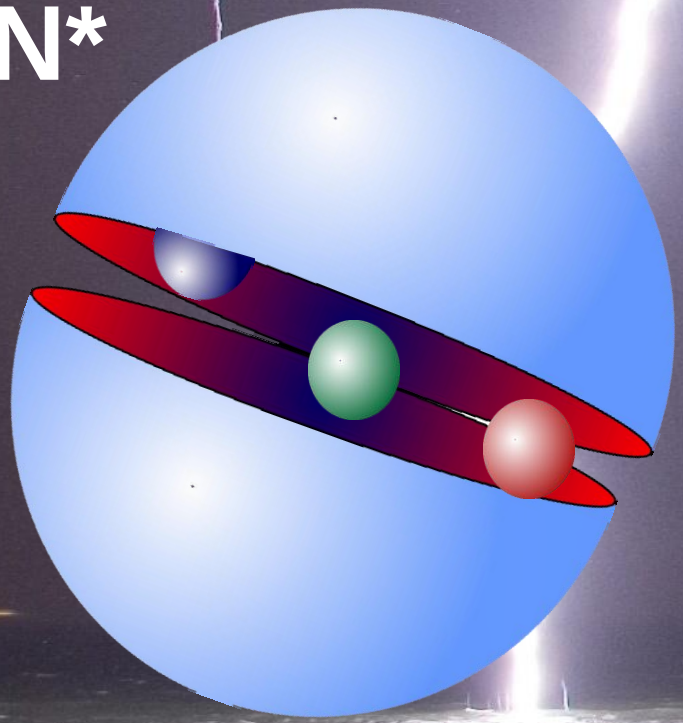
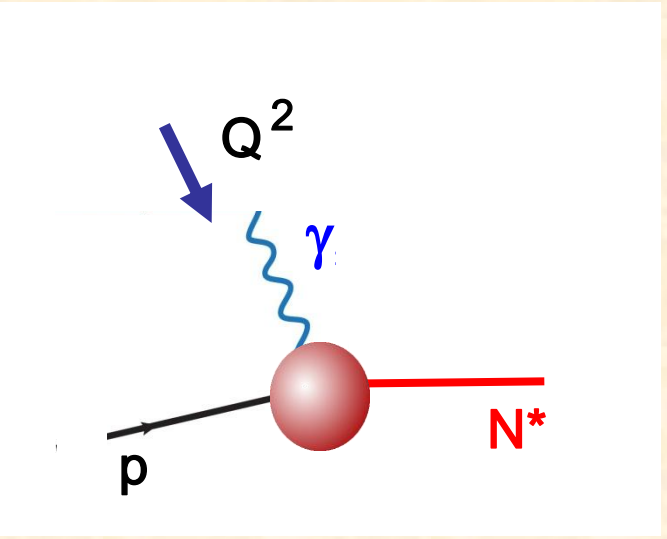


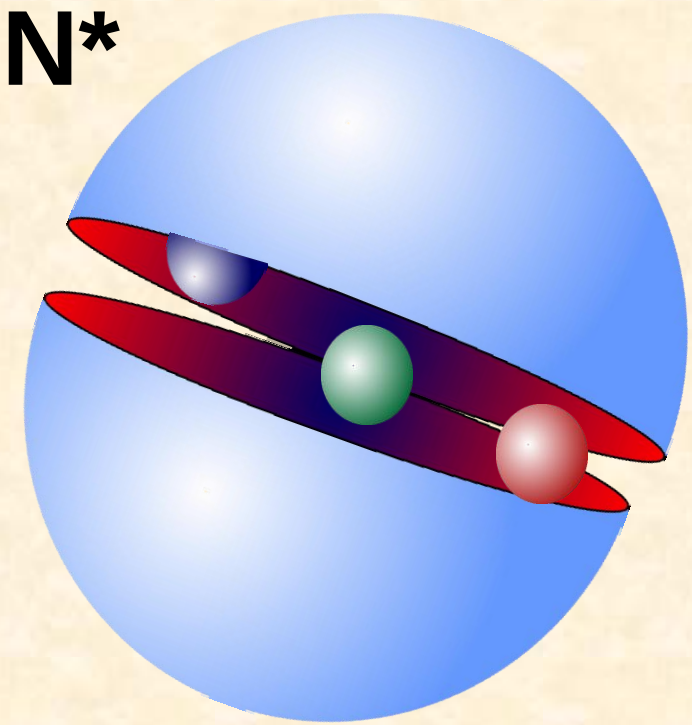
X = N*

N*

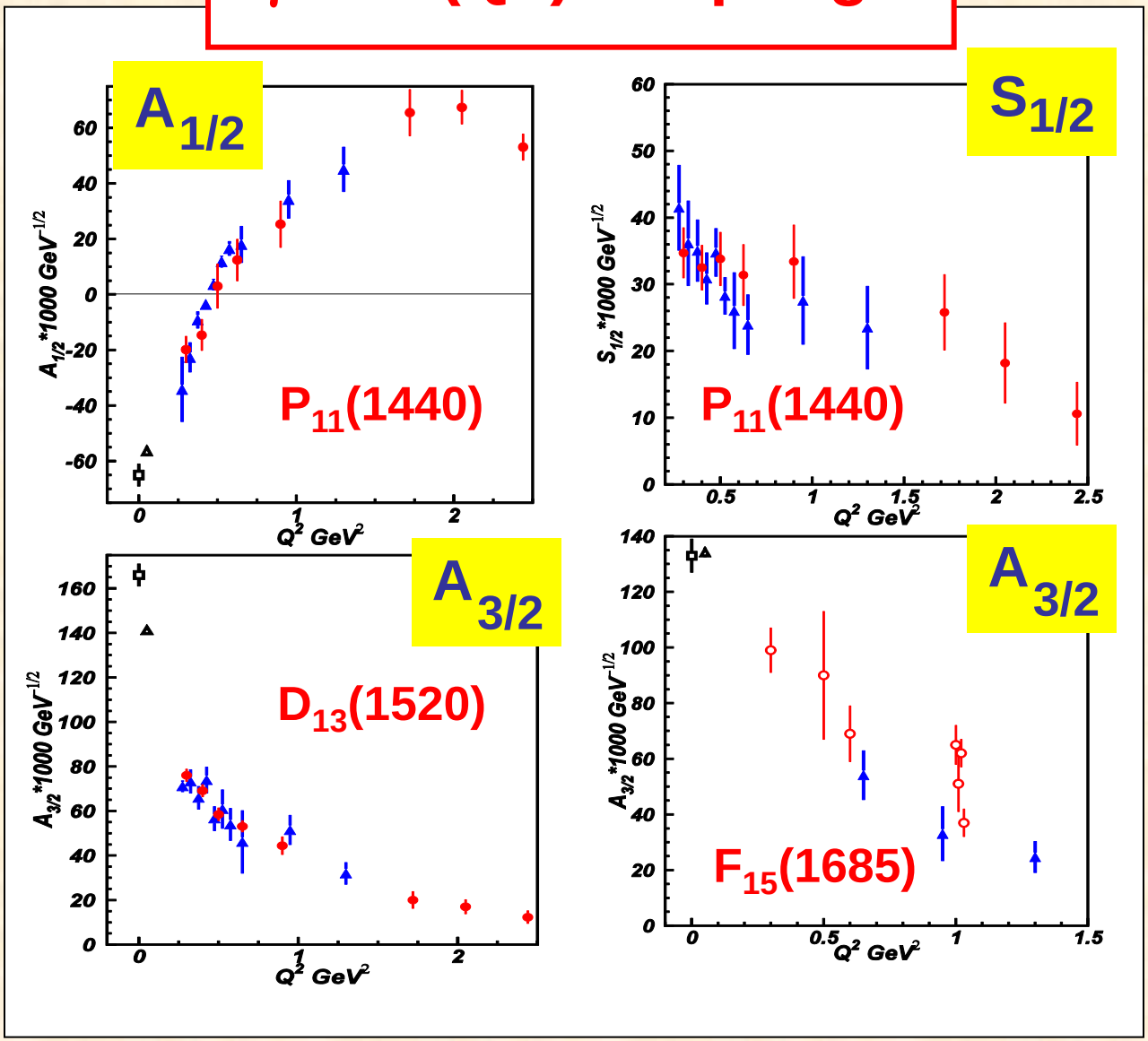


Nucleon Resonance Structure in Exclusive Electroproduction at High Photon Virtualities with the CLAS 12 Detector Workshop





$\gamma^*NN^*(Q^2)$ couplings



Nππ CLAS preliminary.

Nπ Aznauryan et al.

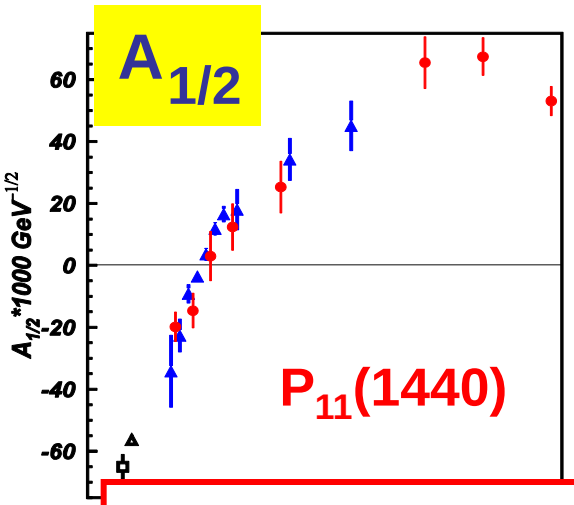
Burkert et al

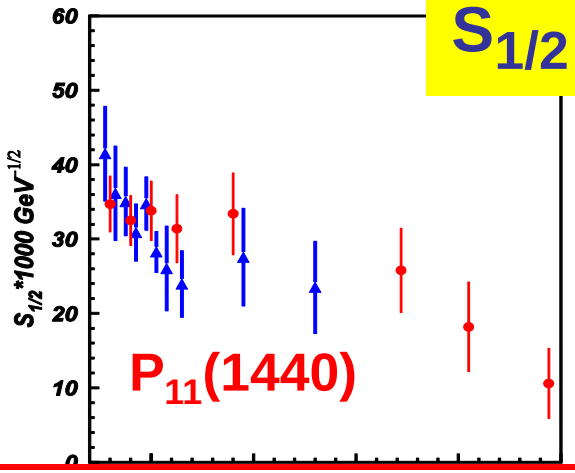
Nπ $Q^2 = 0$ Dugger et al.

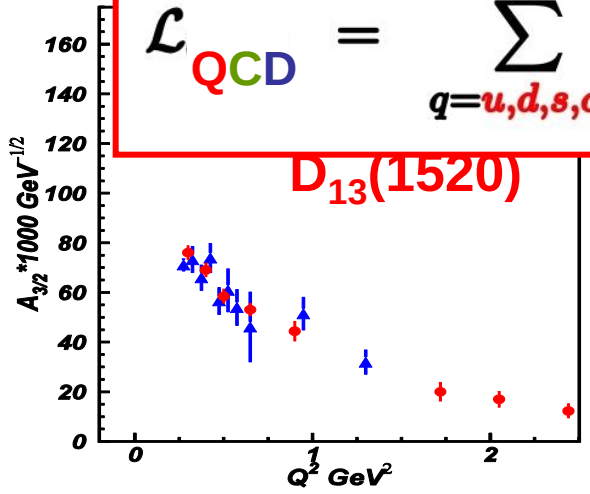
Good *agreement* between *Nπ and Nππ channels.*

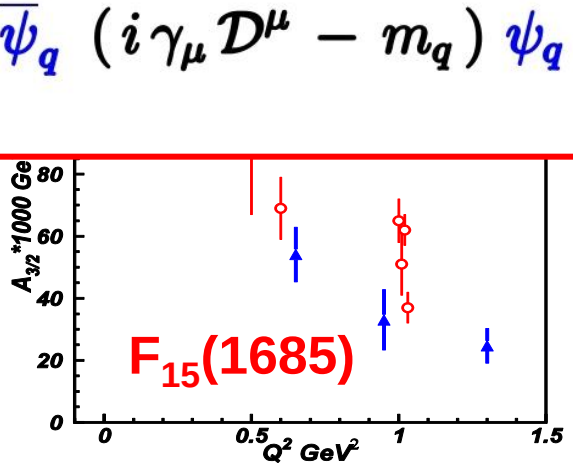
Mokeev

$\gamma^*NN^*(Q^2)$ couplings

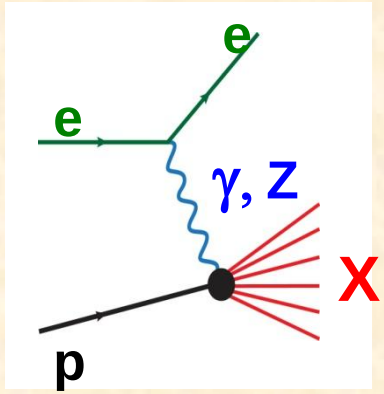








$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$



Nππ CLAS preliminary.

an et al.

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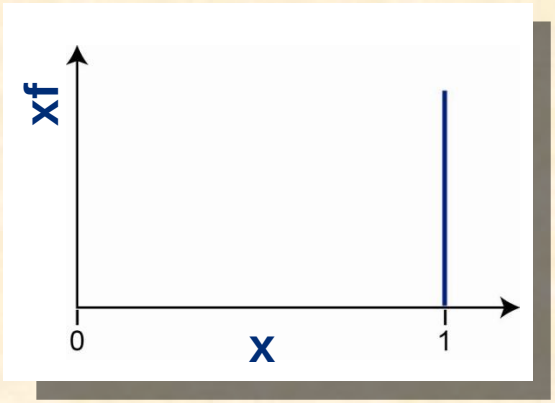
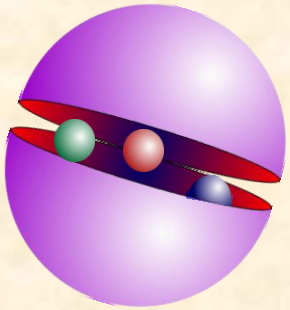
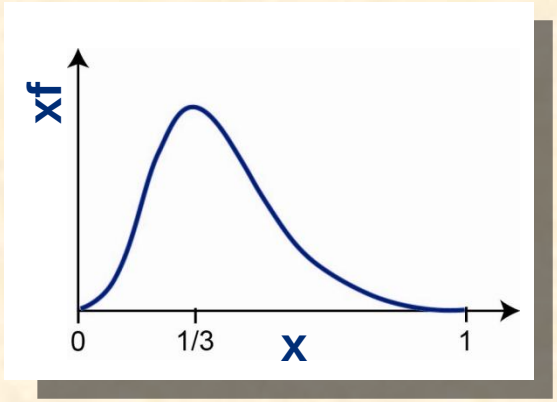
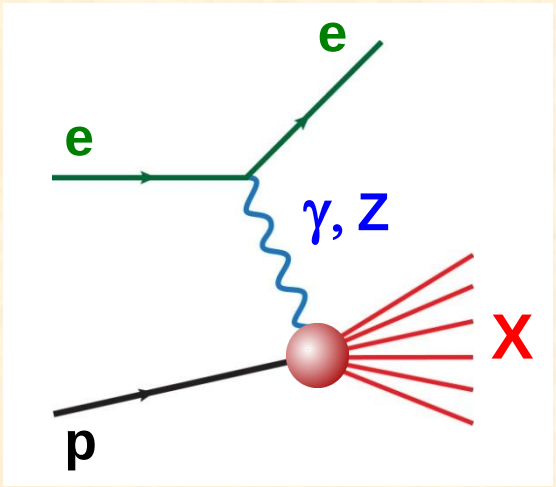
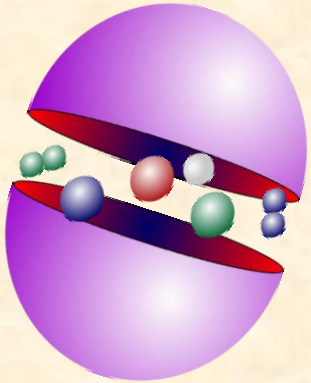
parton structure of the nucleon

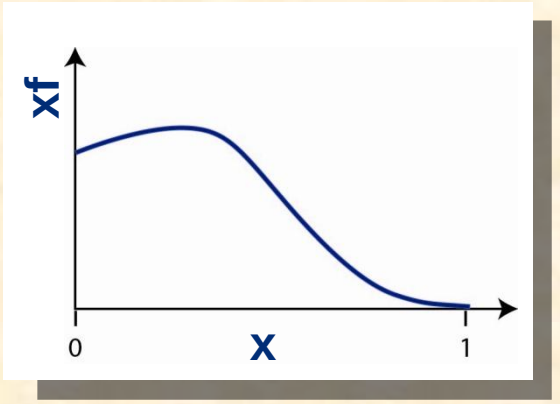




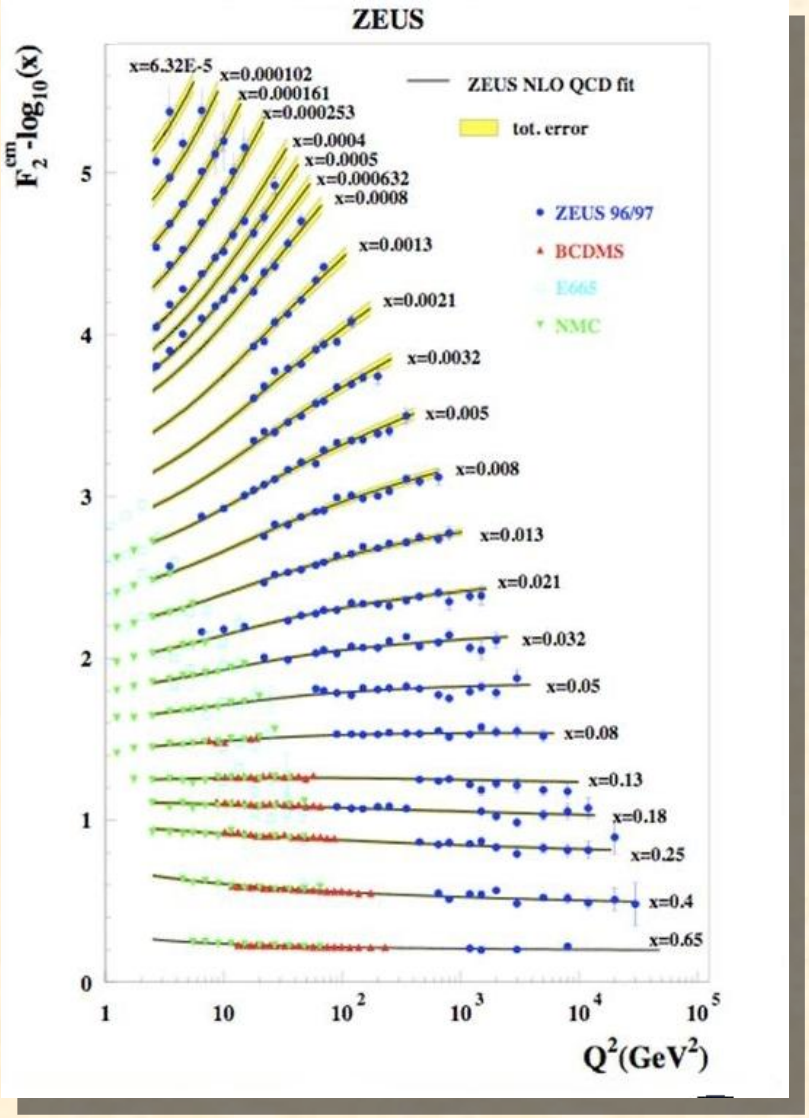


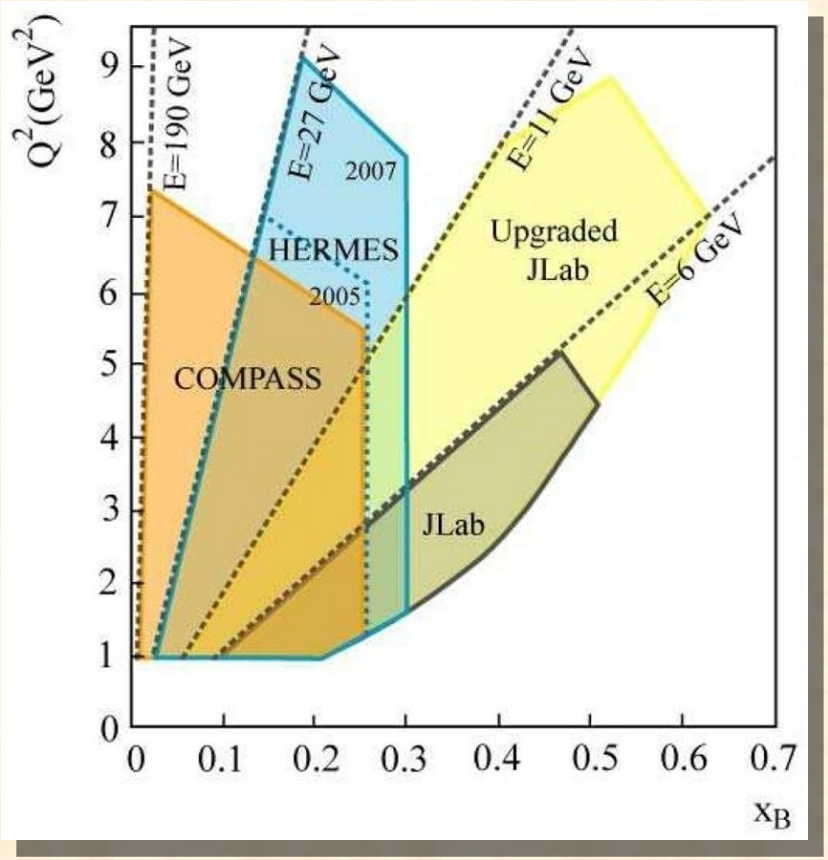




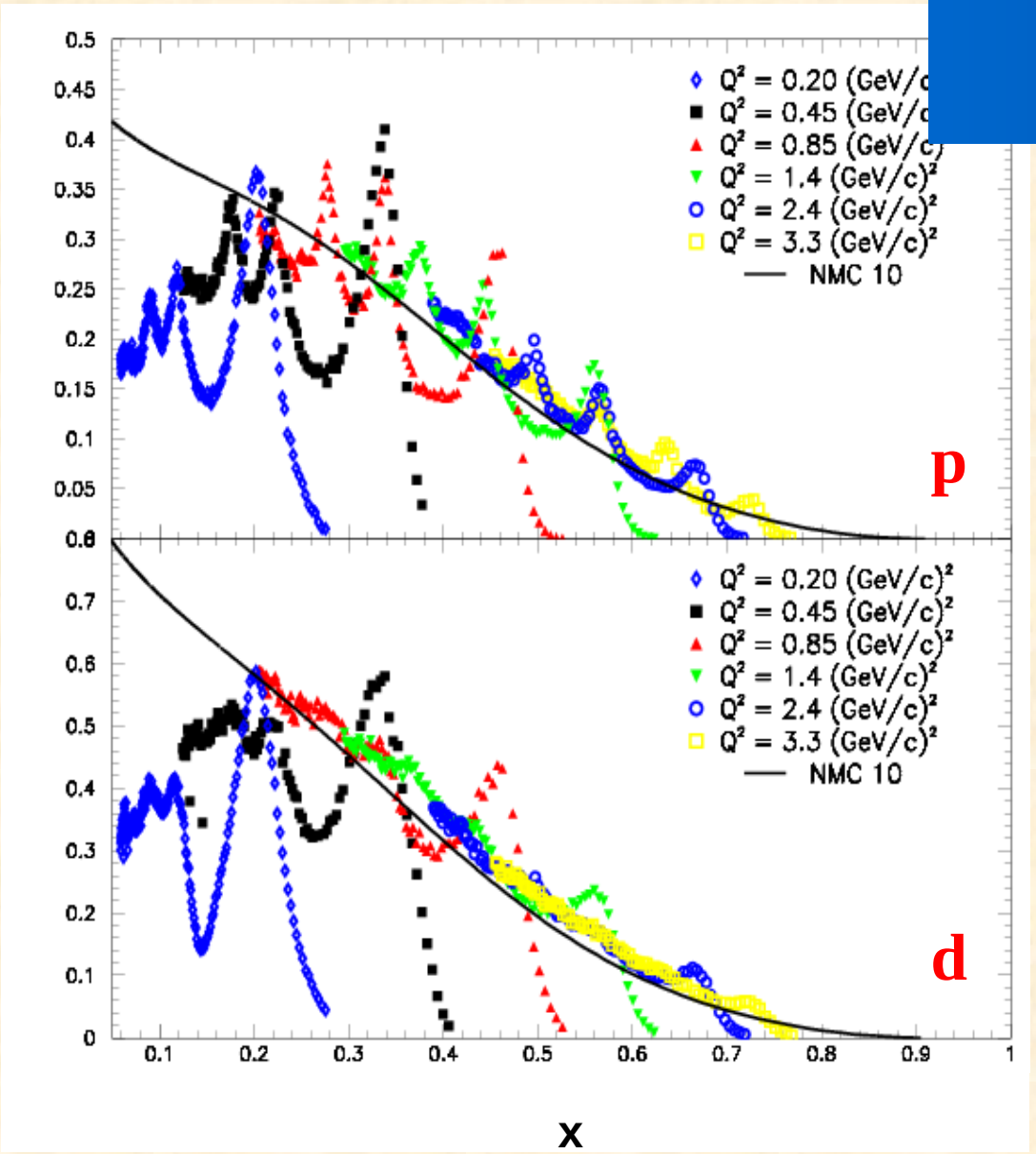


Parton Distribution Functions



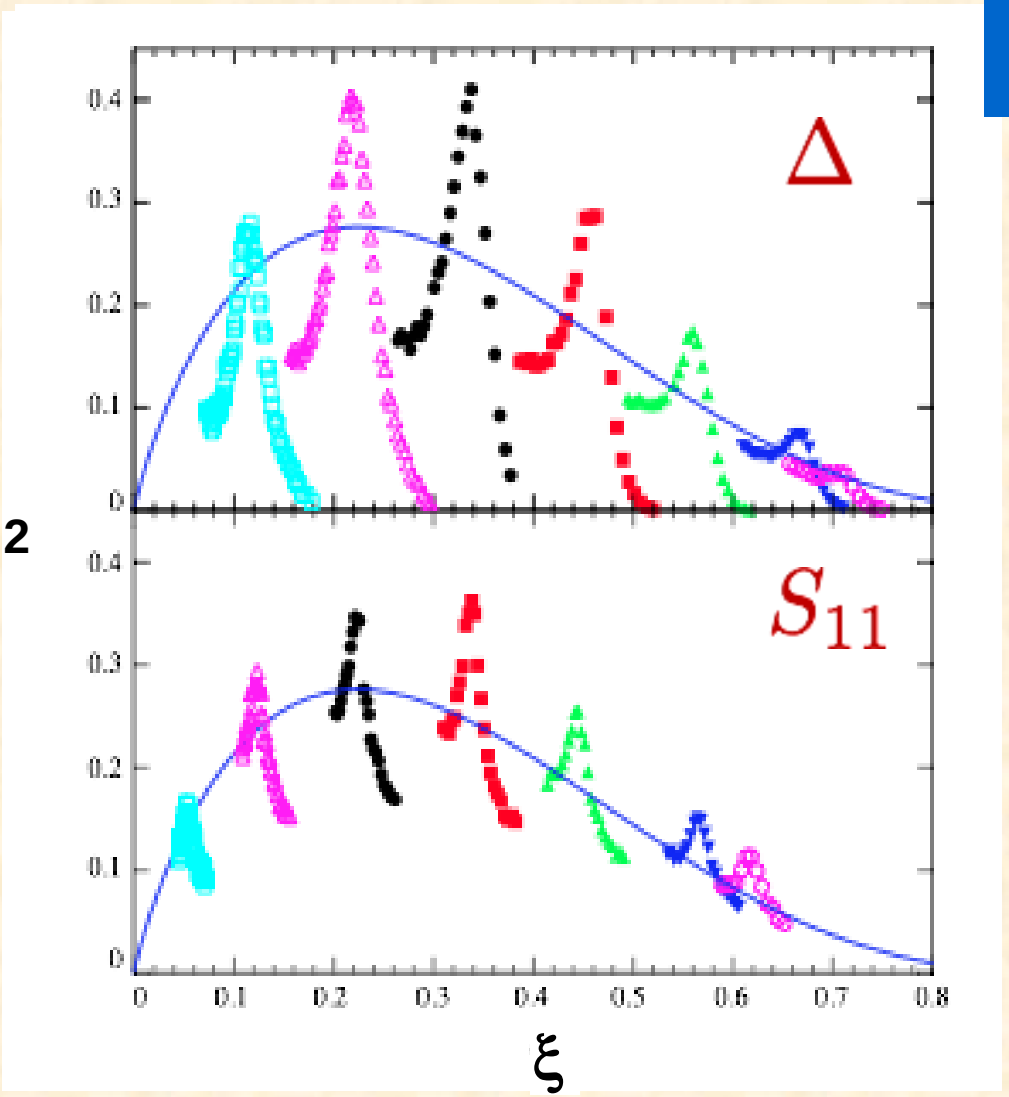


quark-hadron duality



Niculescu et al ’00

quark-hadron duality

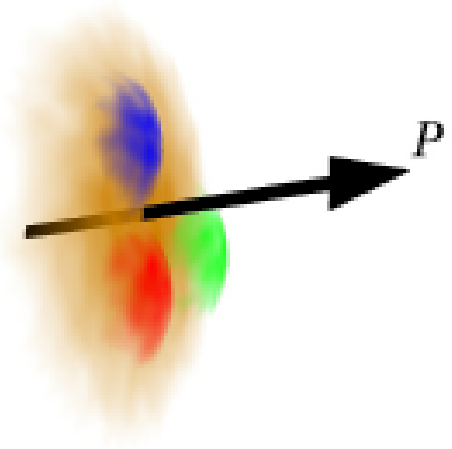


Nachtmann scaling variable

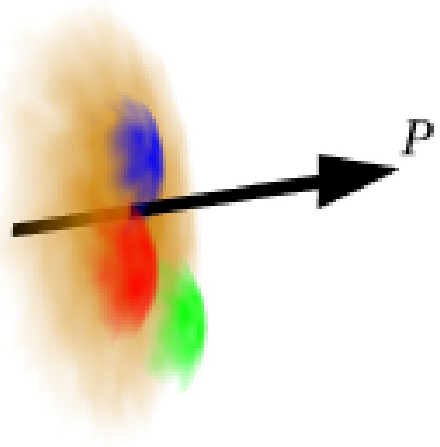
$$\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$$

Niculescu et al ’00

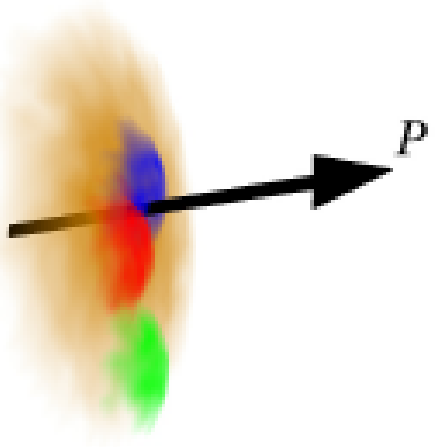
Parton densities



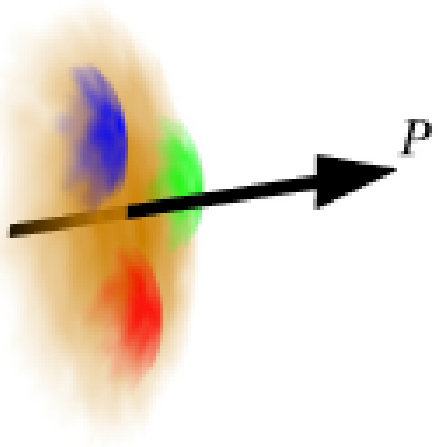
Parton densities



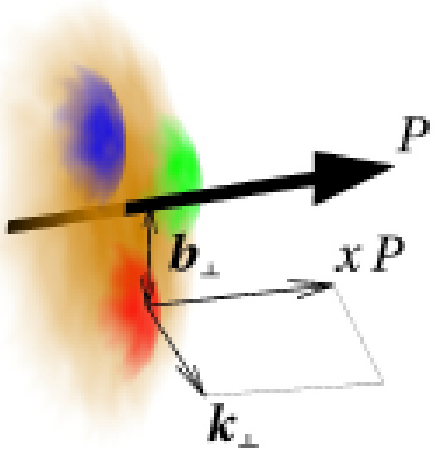
Parton densities



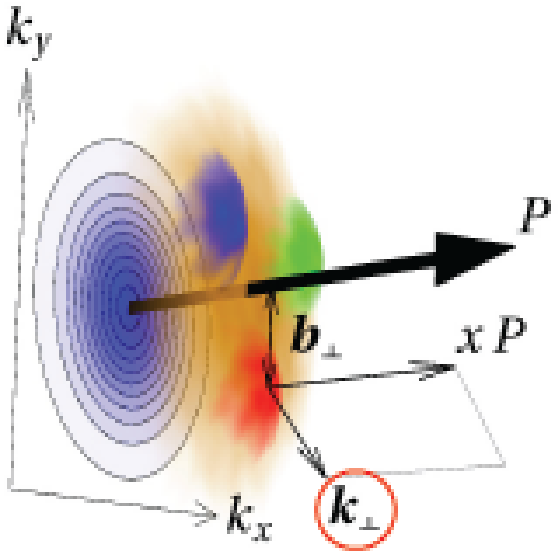
Parton densities



Parton densities

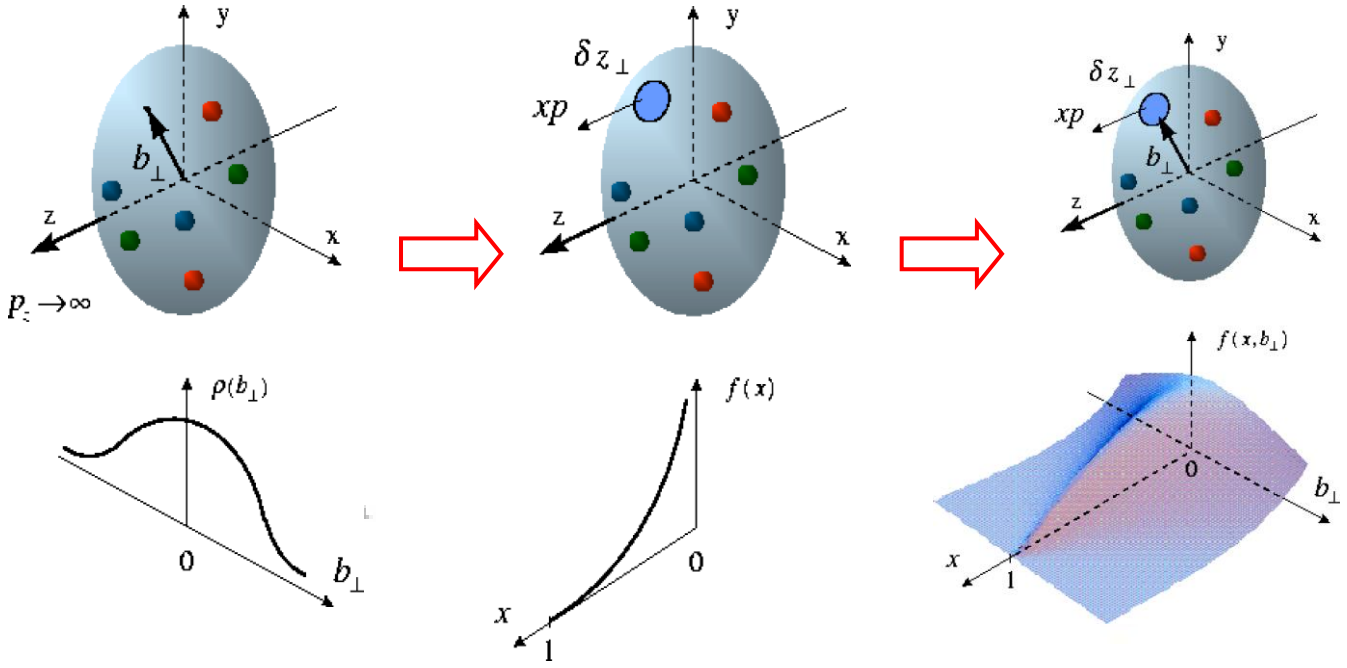


Parton densities



- x (longitudinal momentum fraction) $\Rightarrow$ **PDFs**
- $x, b_\perp$ (impact parameter) $\Rightarrow$ **GPDs**
- $x, k_\perp$ (intrinsic transverse momentum) $\Rightarrow$ **TMDs**

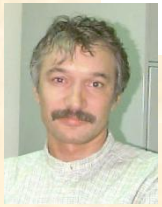
Internal Landscape of the Hadron



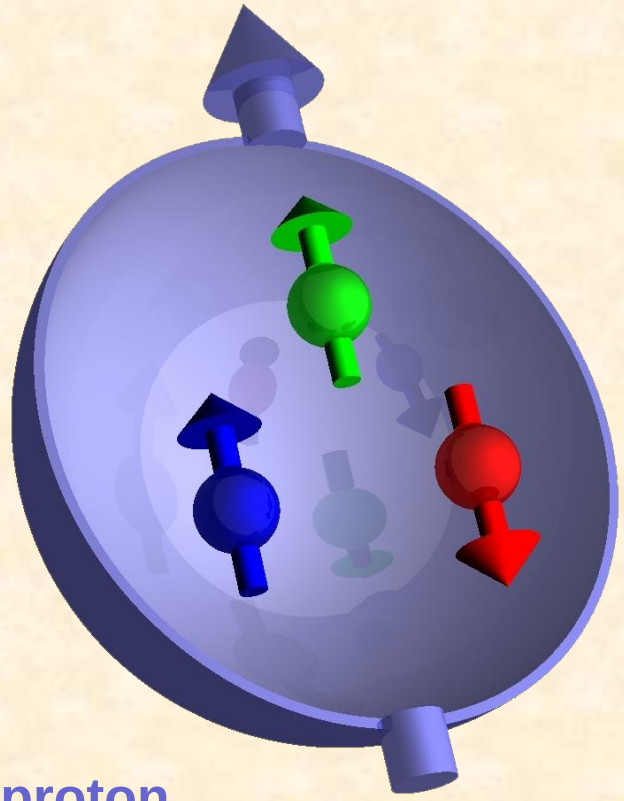
Form Factors
transverse quark distribution in Coordinate space

Structure Functions
longitudinal quark distribution in momentum space

GPDs
Fully-correlated quark distribution in both coordinate and momentum space



Internal Landscape of the Hadron



proton

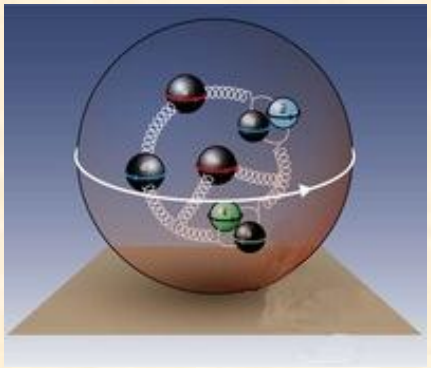
Spatial

Momentum

Flavor

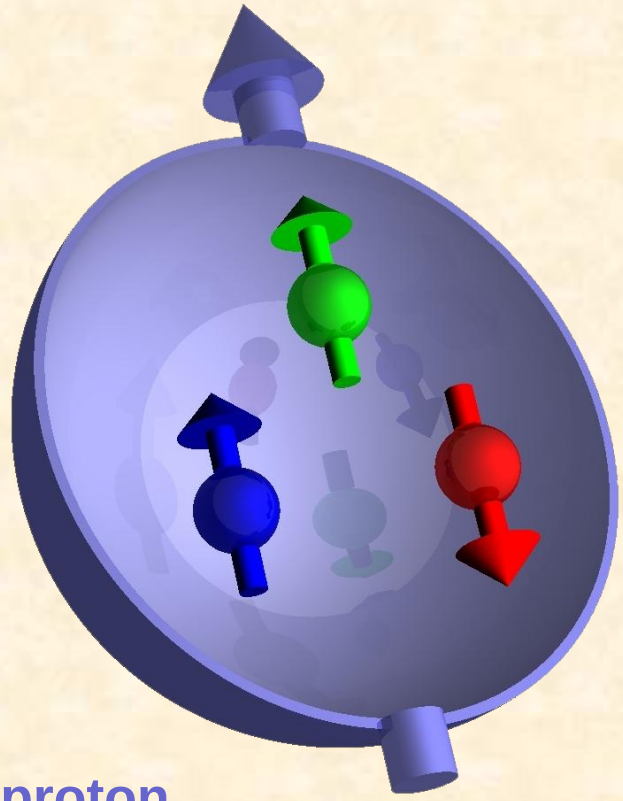
Angular momentum

Parton Distribution Functions

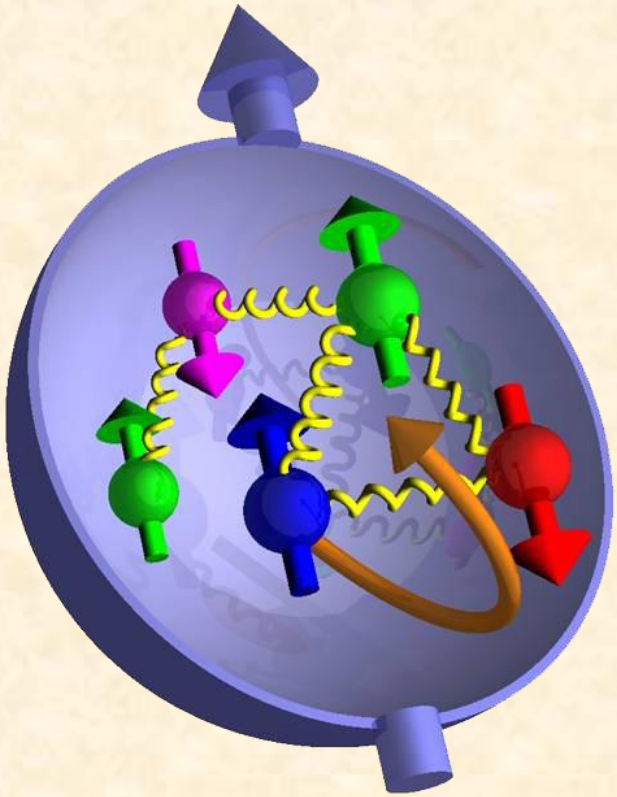


Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

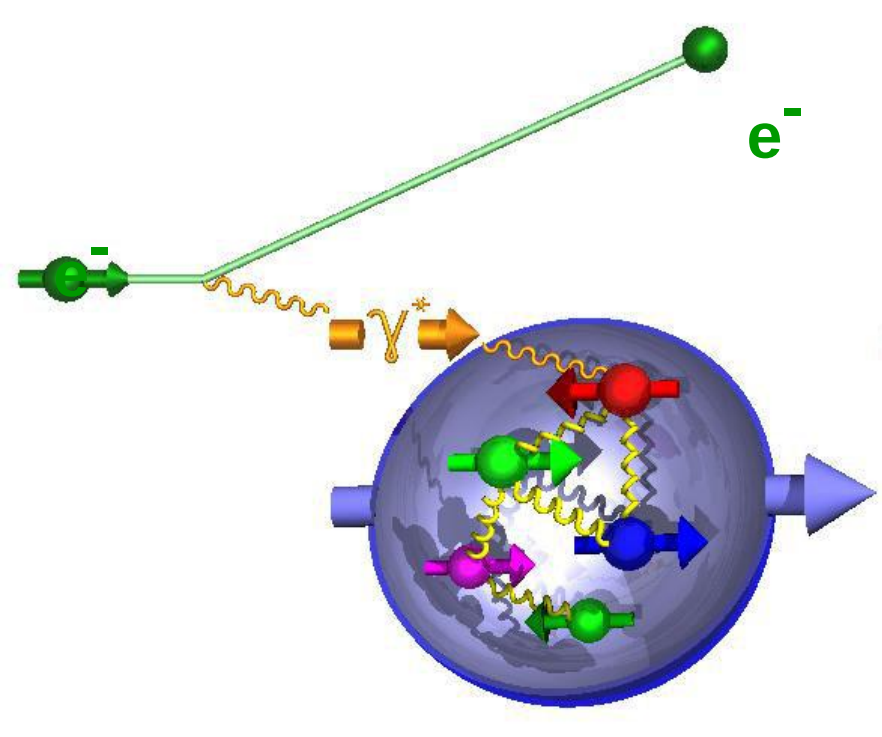
Spin of the proton

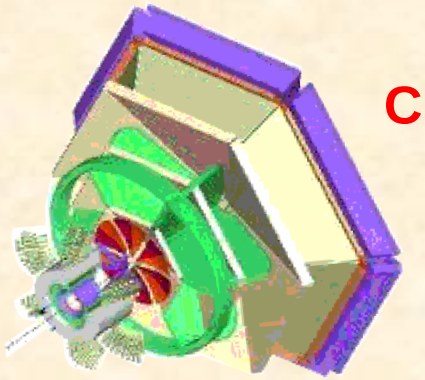


proton

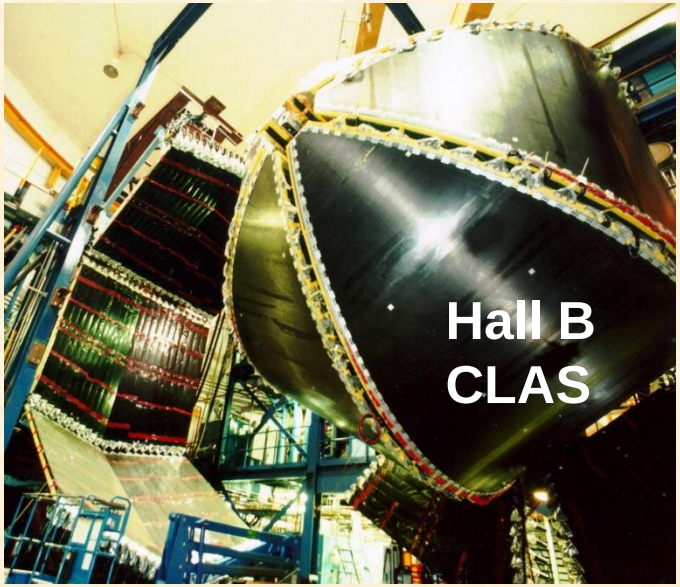


Semi-Inclusive Deep Inelastic Scattering

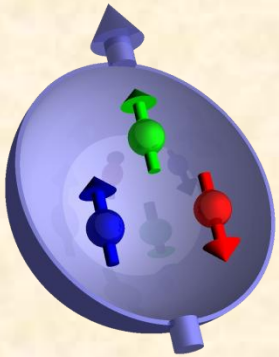




CLAS12

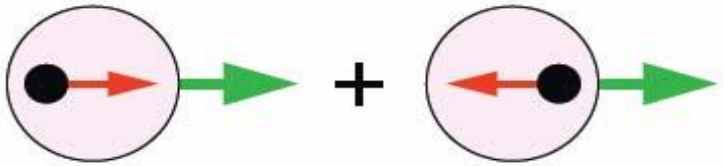


Spin of the proton

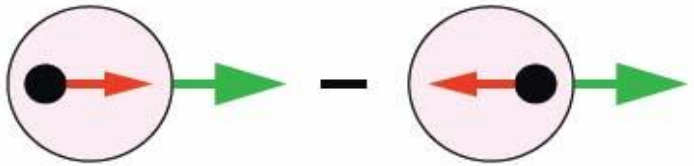


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$



$$\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$



$$\Delta\Sigma \equiv \int dx\ (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x))$$

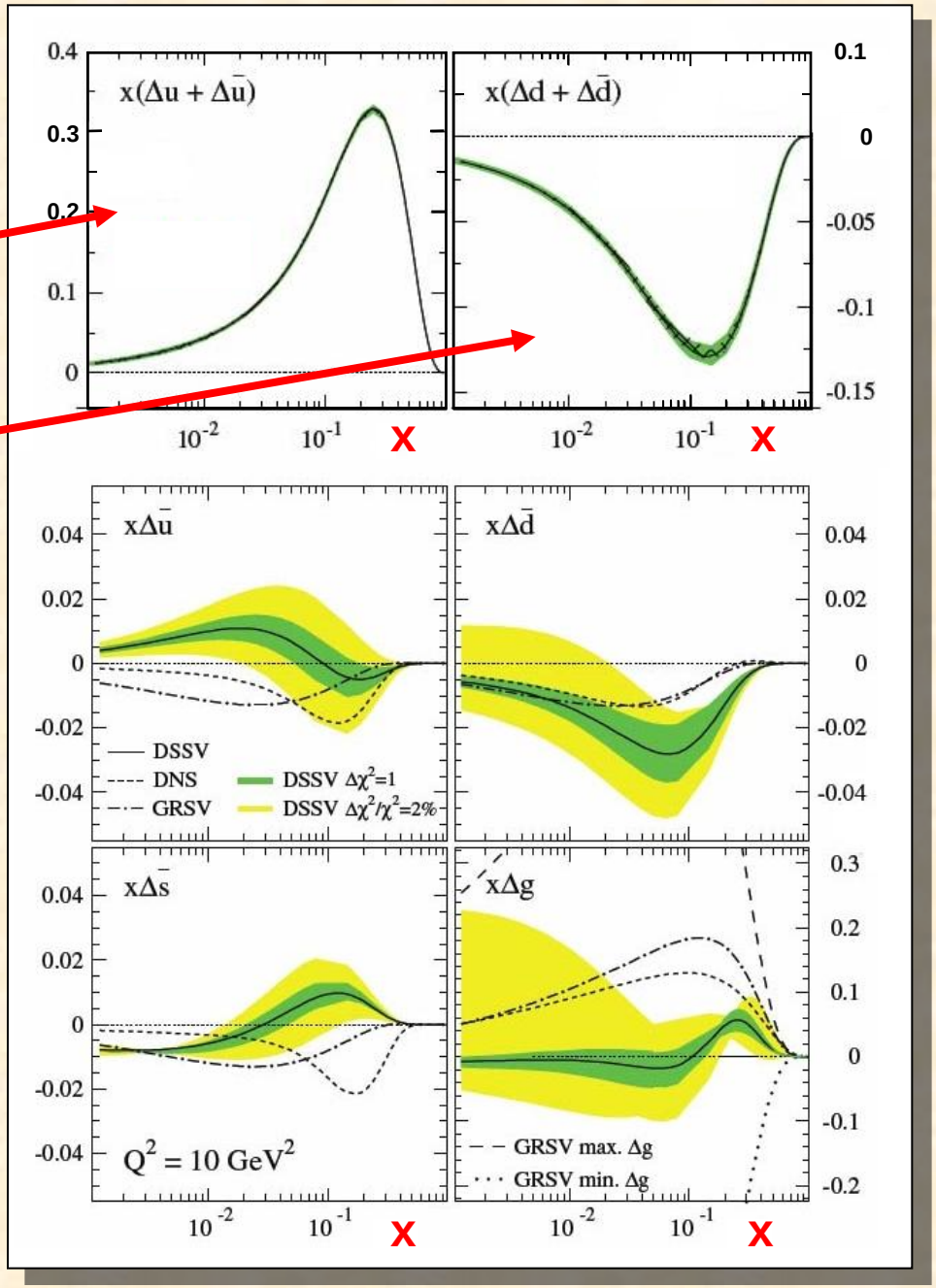
~ 20%

evolves with Q^2 : here $Q^2 > 5\ \mathrm{GeV}^2$

Spin of the proton

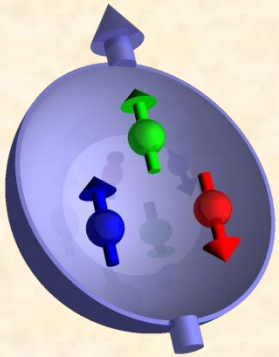
$$\int dx\, \Delta(u + \bar{u}) = +0.81$$

$$\int dx\, \Delta(d + \bar{d}) = -0.46$$



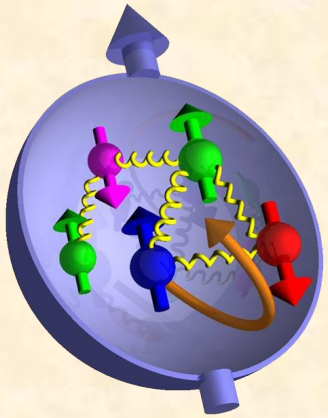
	meas: x > .001	extrap: all x	error
$\Delta\Sigma$	0.37	**0.24**	+0.04 –0.06
$\Delta\bar{u}$	0.03	**0.04**	±0.06
$\Delta\bar{d}$	–0.09	**–0.12**	±0.09
Δs	–0.01	**–0.06**	±0.03
ΔG	0.01	**–0.08**	+0.7 –0.3

Spin of the proton



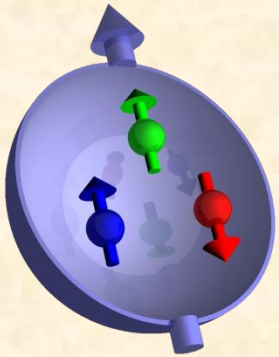
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta G \equiv \int dx\, \Delta g(x)$$

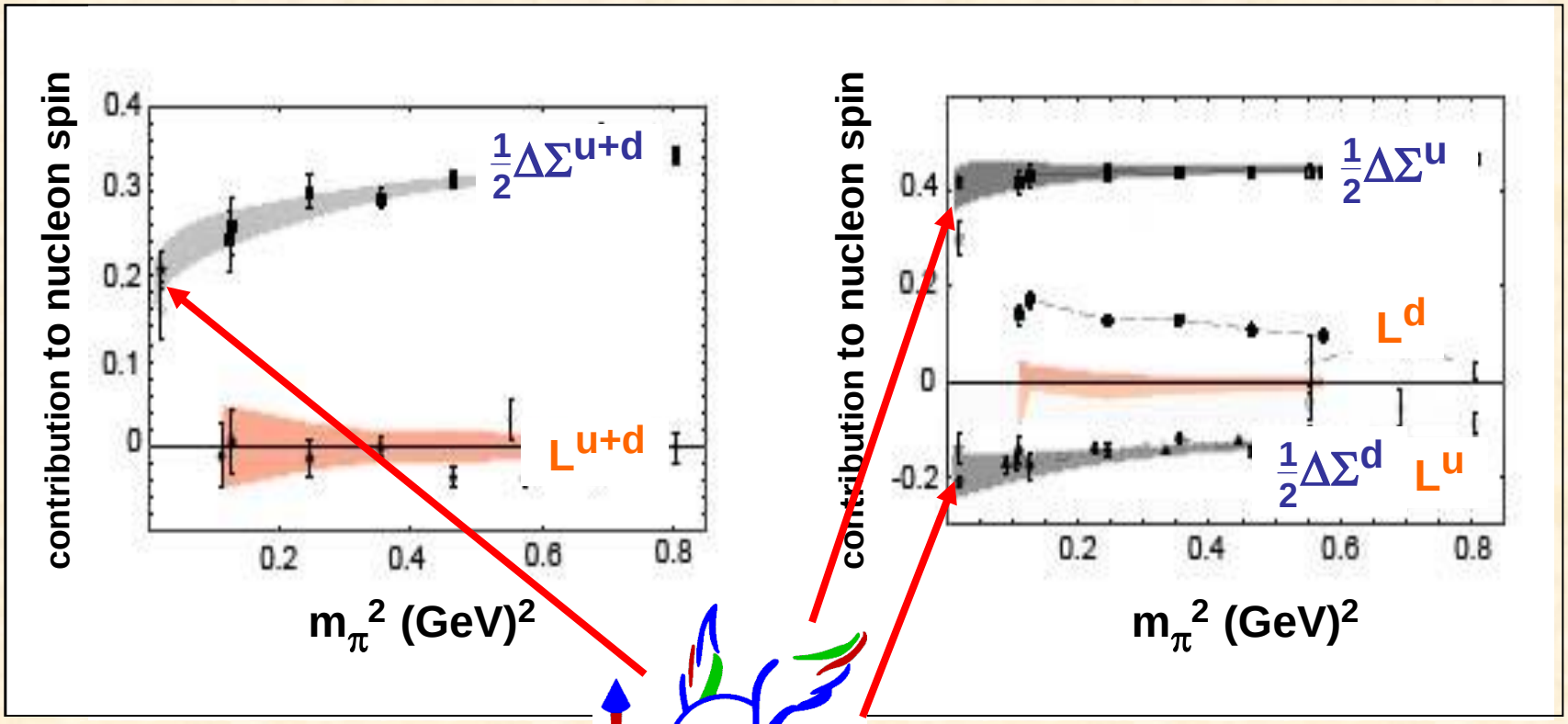


$$L_z \equiv L_q + L_g$$

Spin of the proton: Lattice v Experiment



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



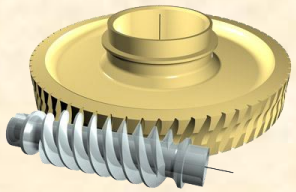
LHPC, Haegler *et al.*

hermes

No disconnected contributions

Transverse Momentum Distributions

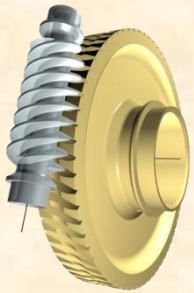
nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

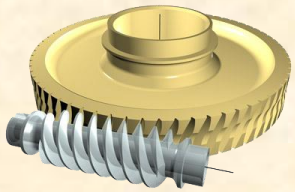


at leading twist

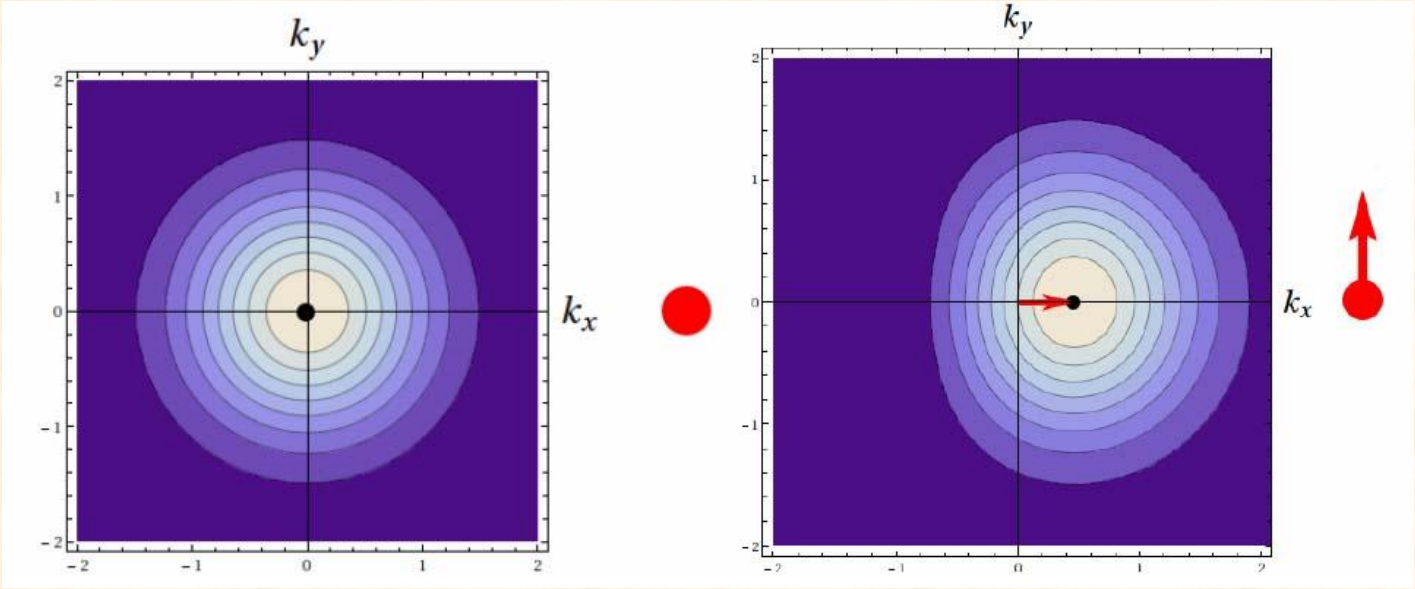
Transverse Momentum Distributions

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity, $h_{1T}^\perp$ pretzelosity

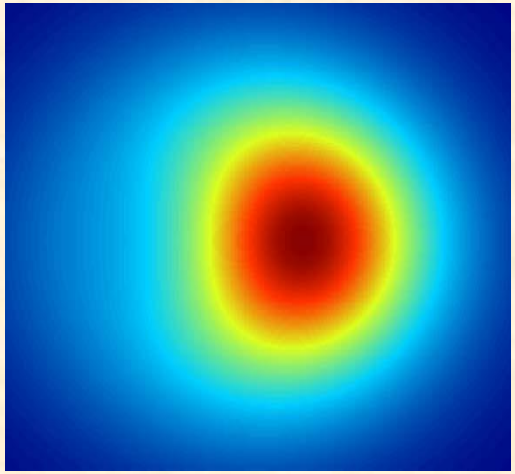


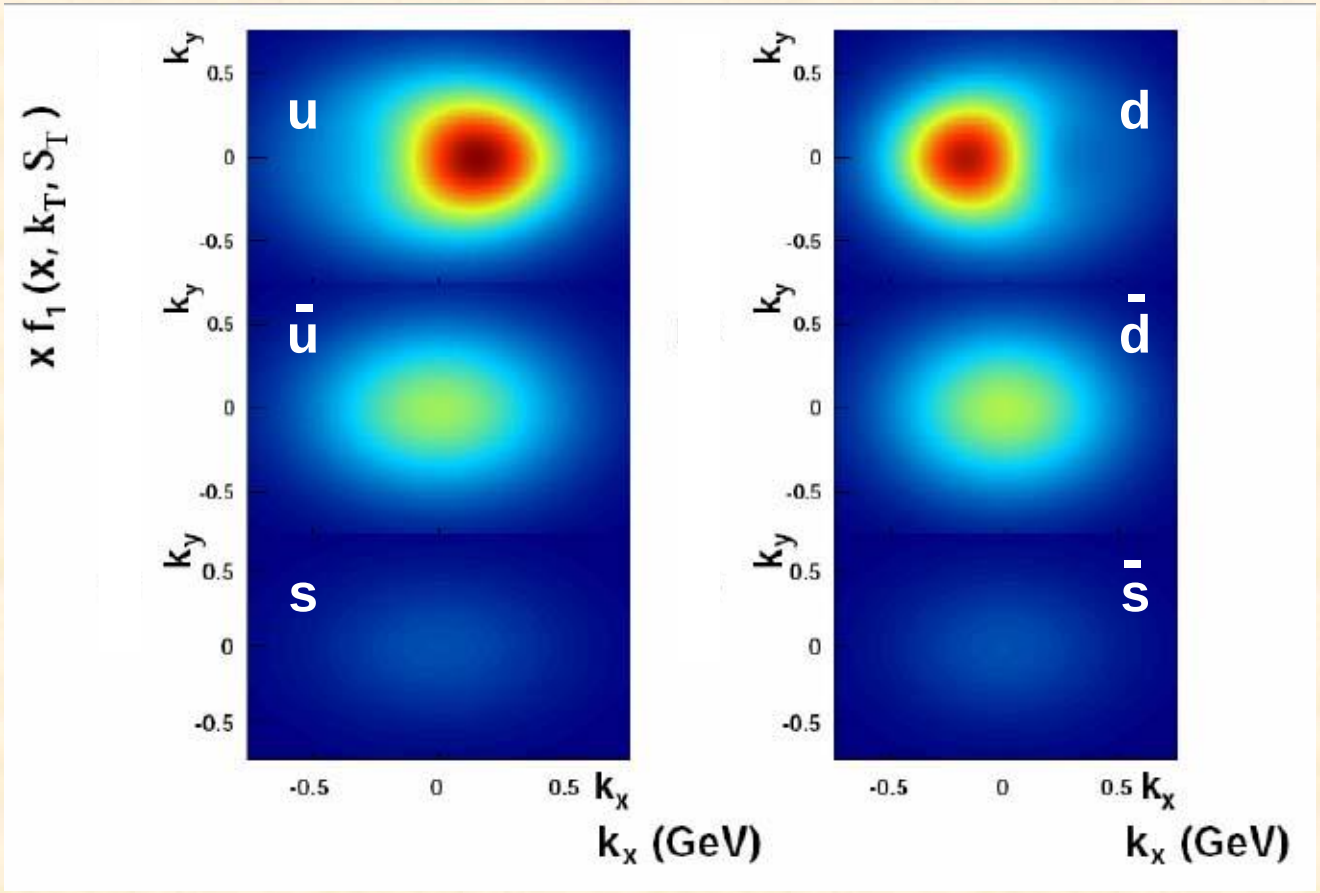


$f\,(\,x,\,z,\,Q^2,\,p_T\,)$

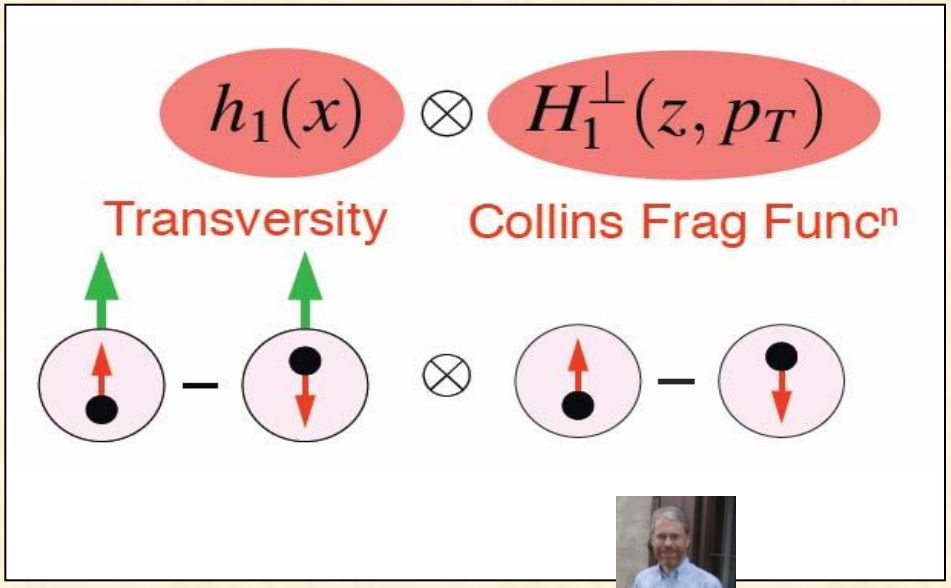


experiment

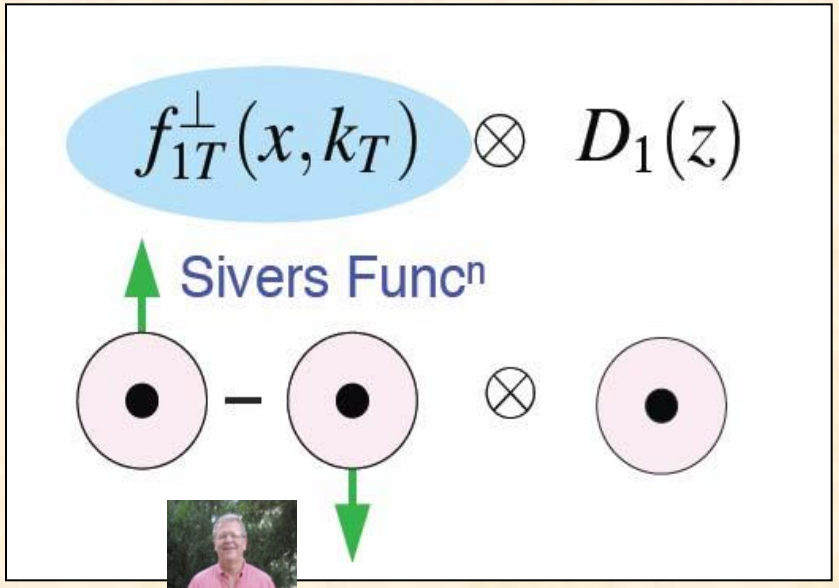


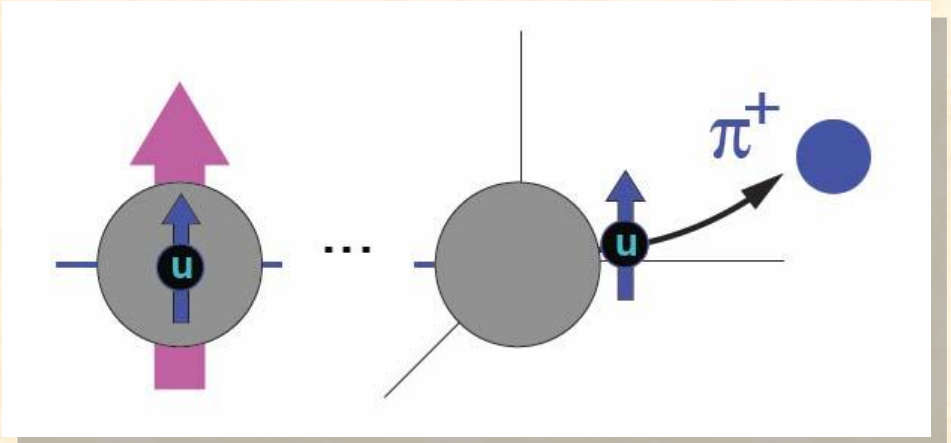

x f1 (x, kT, ST)
u
ū
s
d
d̄
s̄
ky
kx
0.5
0
-0.5
kx (GeV)

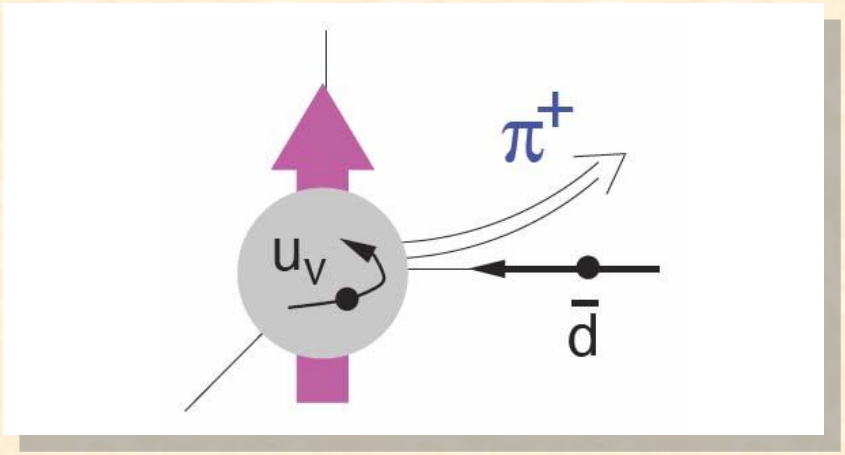
Collins Frag Fn



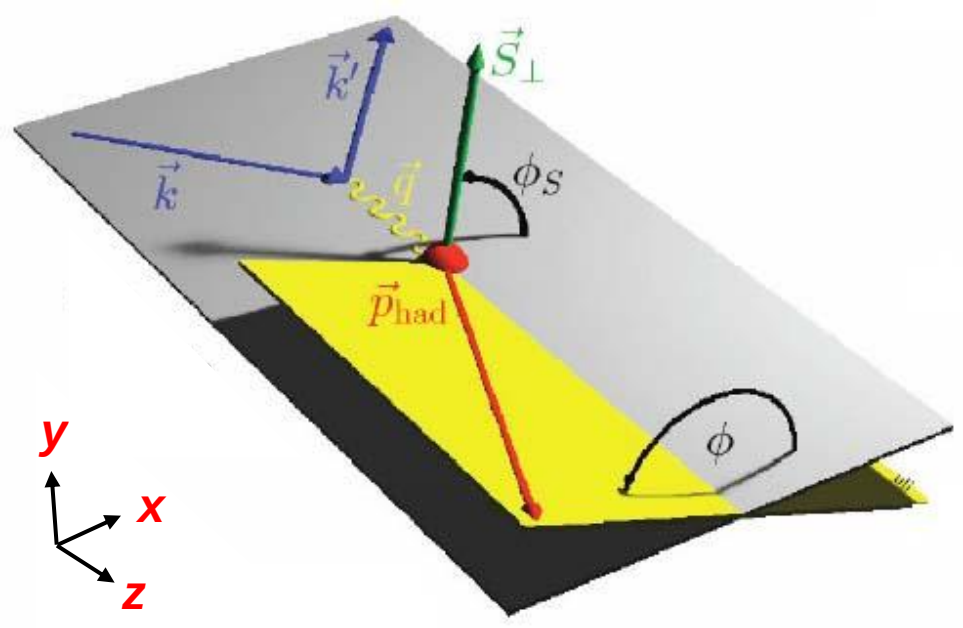
Sivers Dist Fn







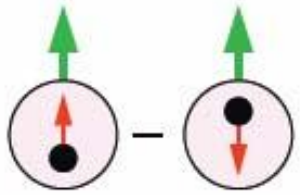
π electroproduction with transverse target

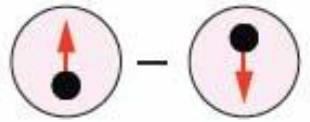


- $(\phi_h^l - \phi_S^l)$ = angle of pion relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l)$ = angle of pion relative to **final** quark spin

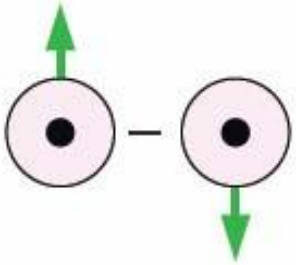
π electroproduction with transverse target

$$\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1 = \quad - \quad \otimes H_1^\perp = \quad -$$

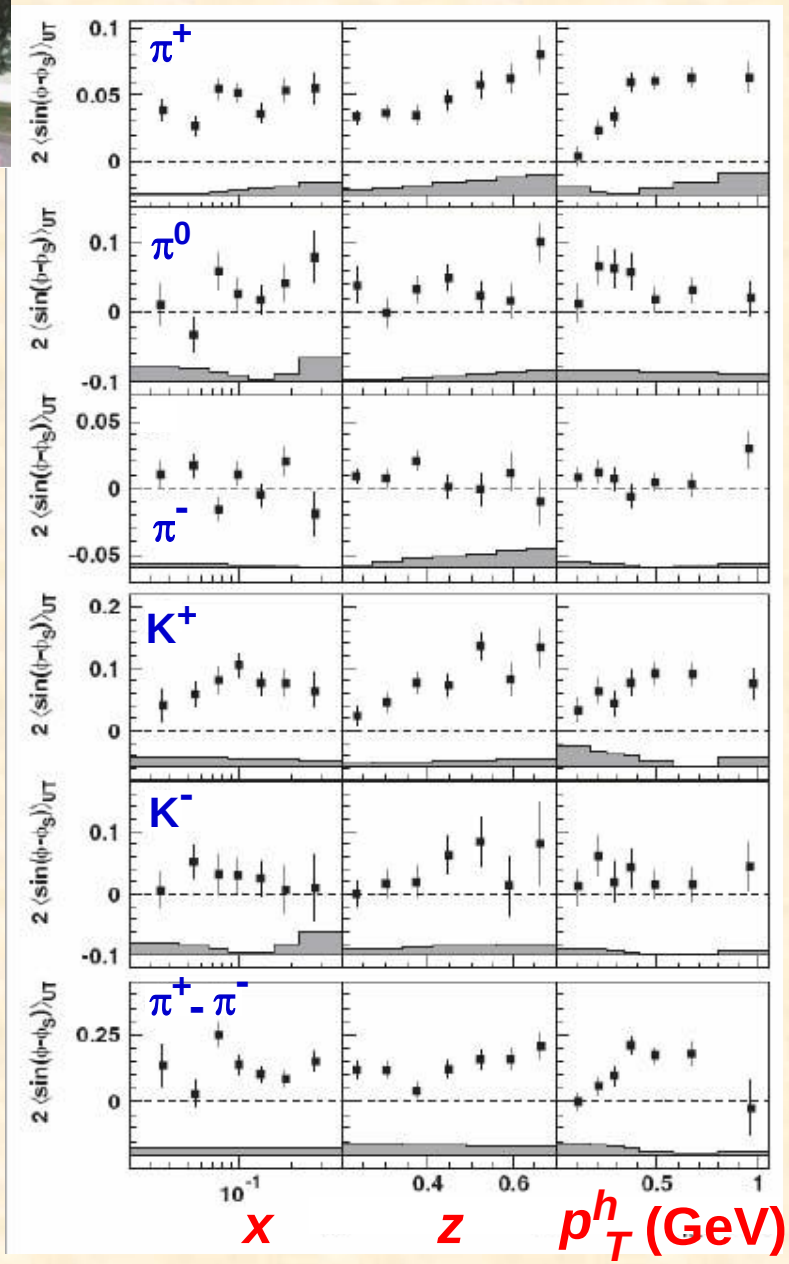


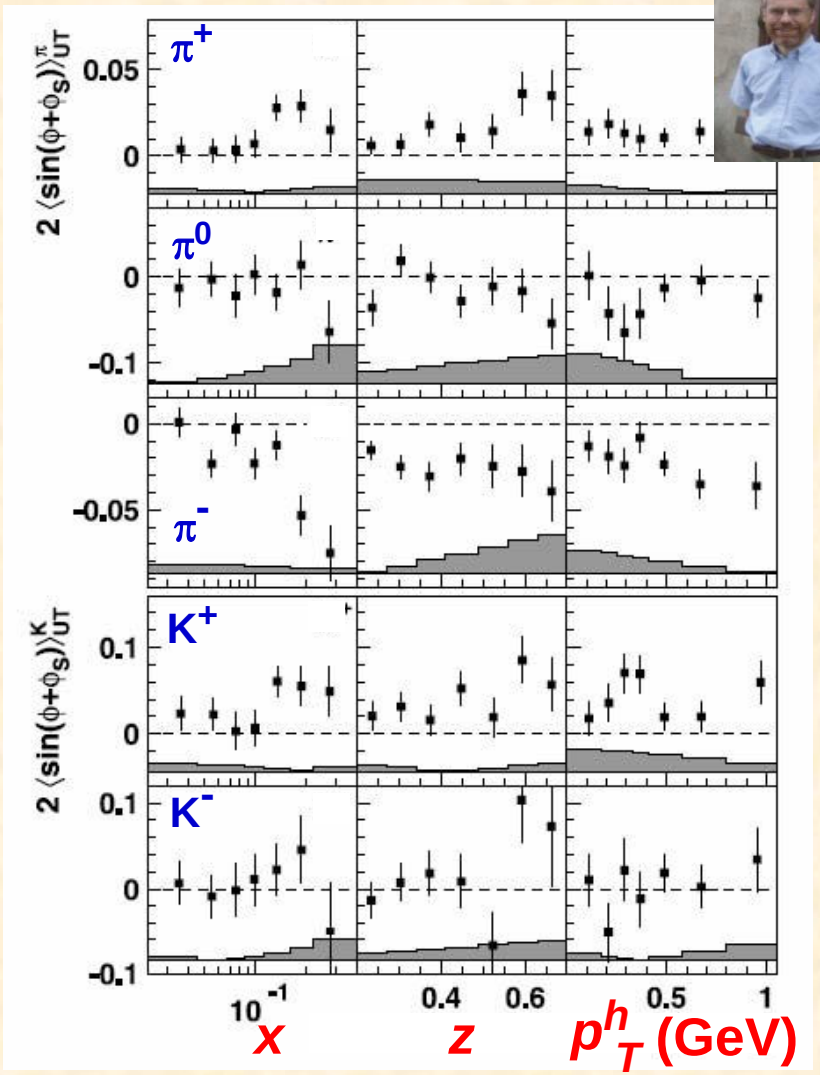


$$\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp = \quad - \quad \otimes D_1 =$$



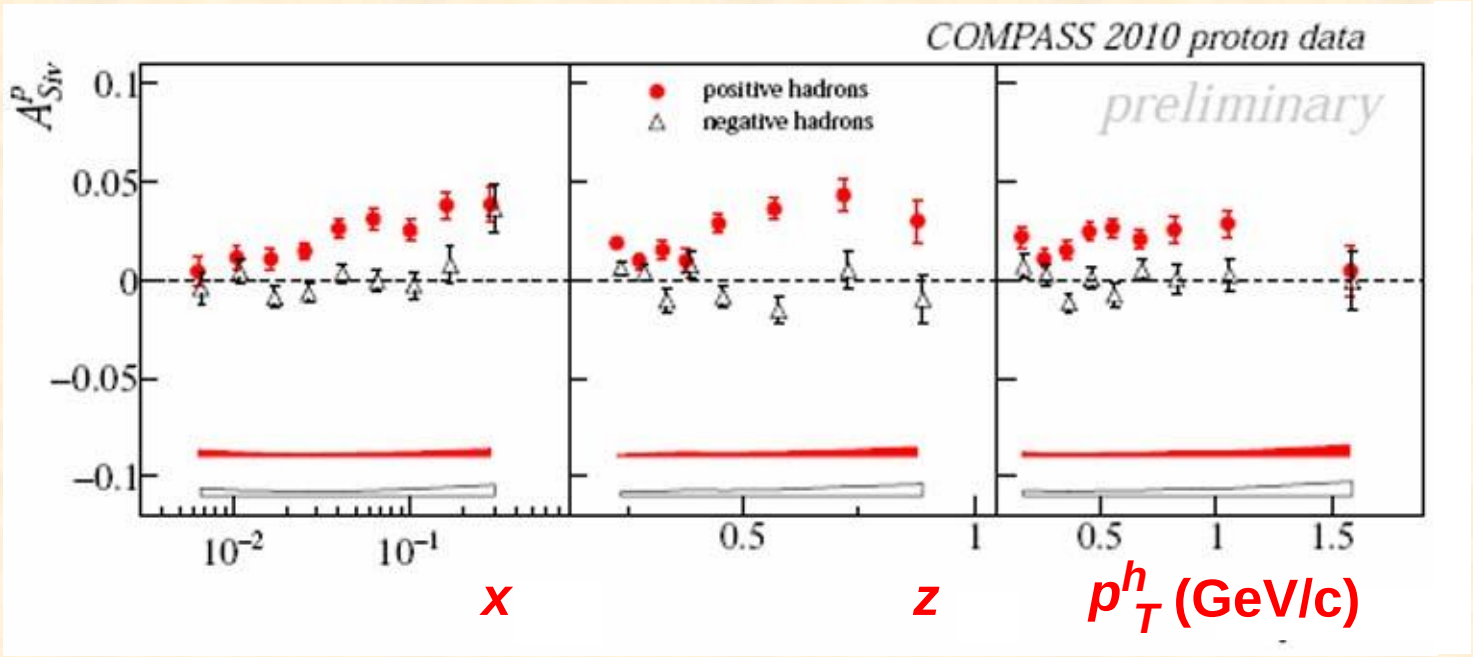
- $(\phi_h^l - \phi_S^l)$ = angle of pion relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l)$ = angle of pion relative to **final** quark spin

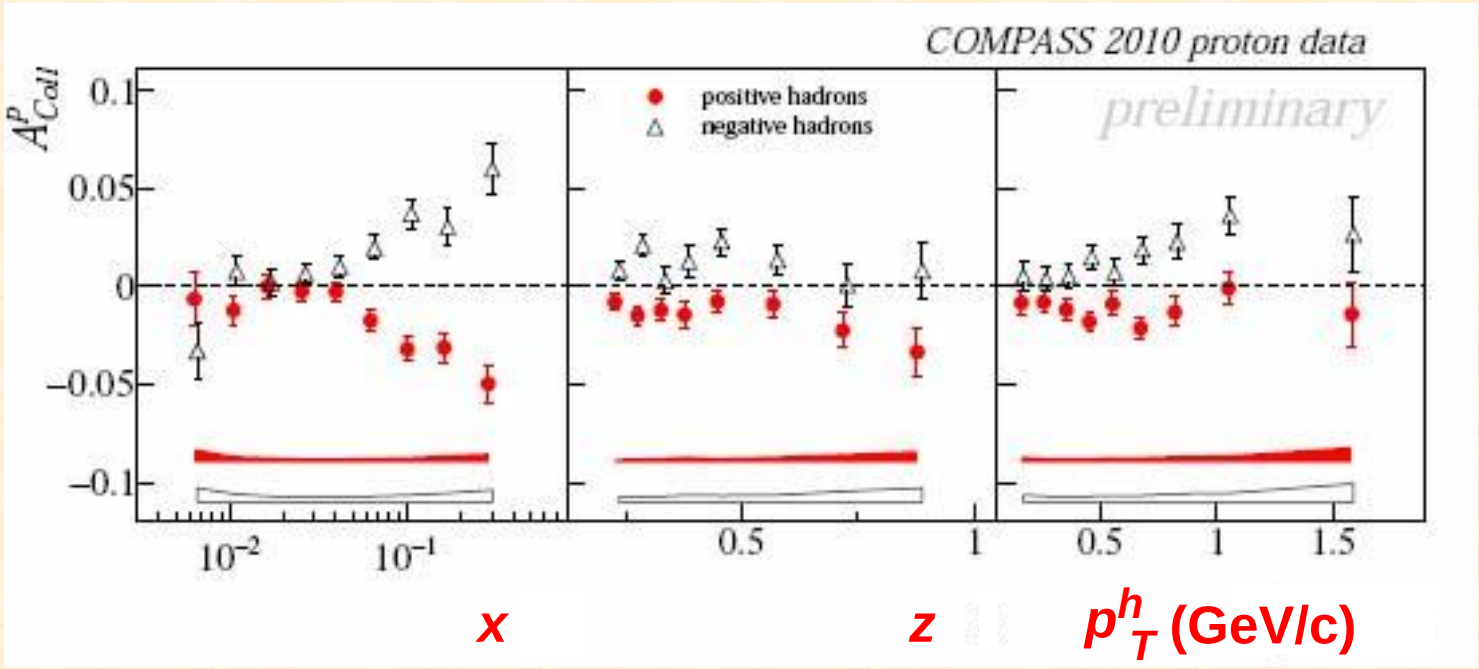




hermes

P_{Lab}
27.5 GeV

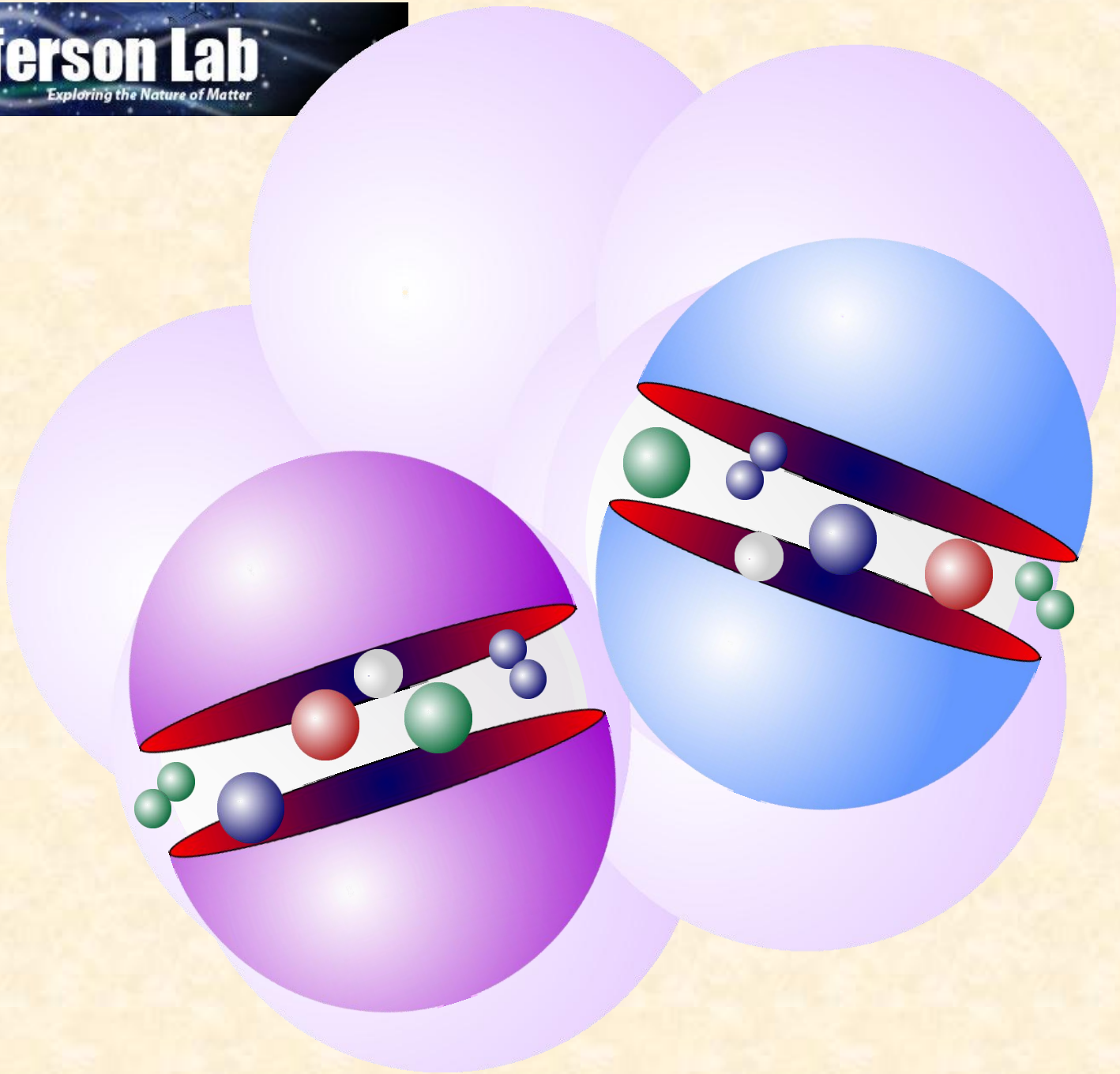

COMPASS 2010 proton data
preliminary
positive hadrons
negative hadrons
A^P_{Siv}
0.1
0.05
0
−0.05
−0.1
10^{-2}
10^{-1}
0.5
1
0.5
1
1.5
x
z
p^h_T (GeV/c)


COMPASS 2010 proton data
preliminary
positive hadrons
negative hadrons
A^P_{Coll}
0.1
0.05
0
−0.05
−0.1
10^{-2}
10^{-1}
0.5
1
0.5
1
1.5
x
z
p^h_T (GeV/c)

P_{Lab} 160 GeV

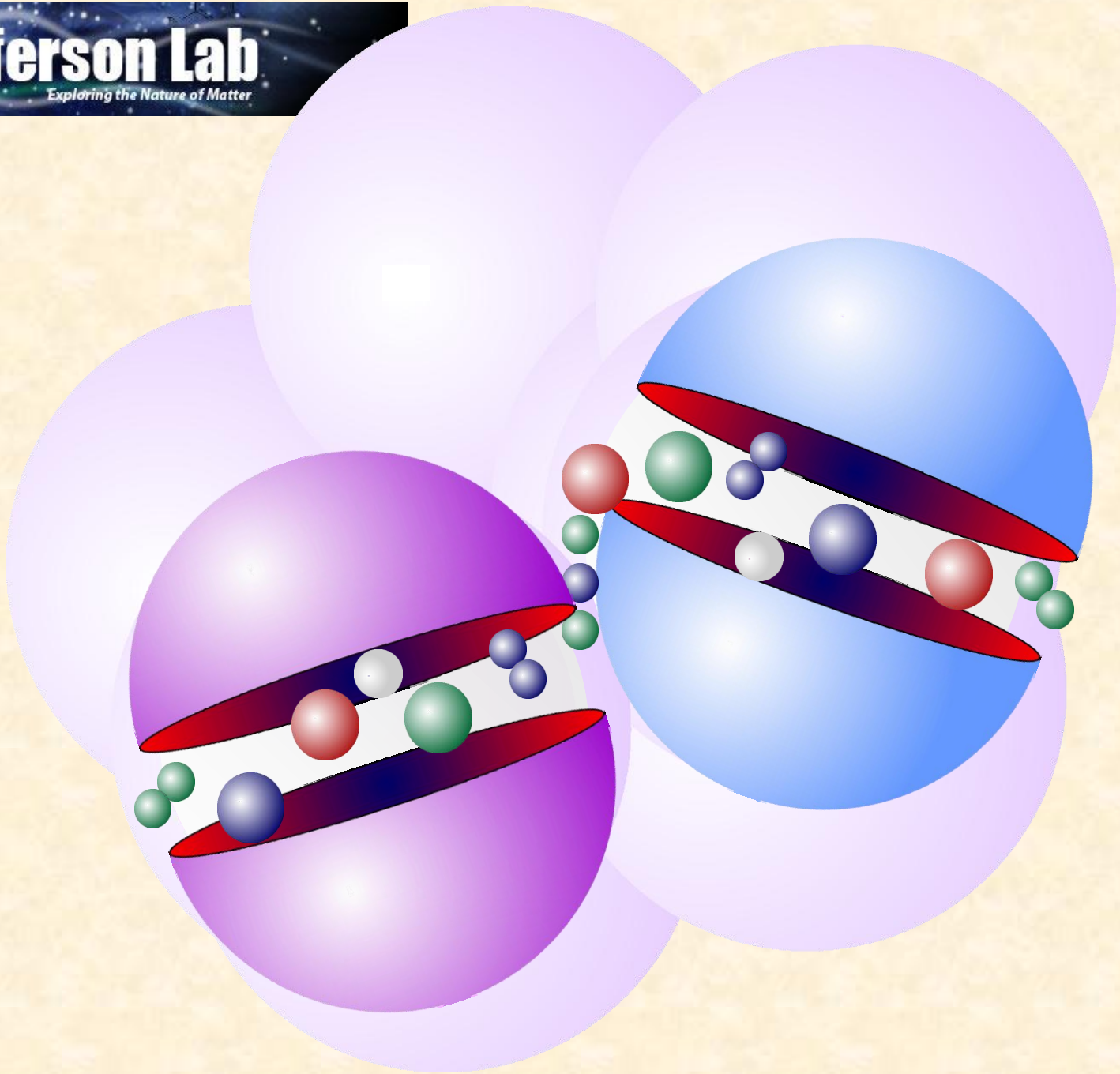
Jefferson Lab

Exploring the Nature of Matter

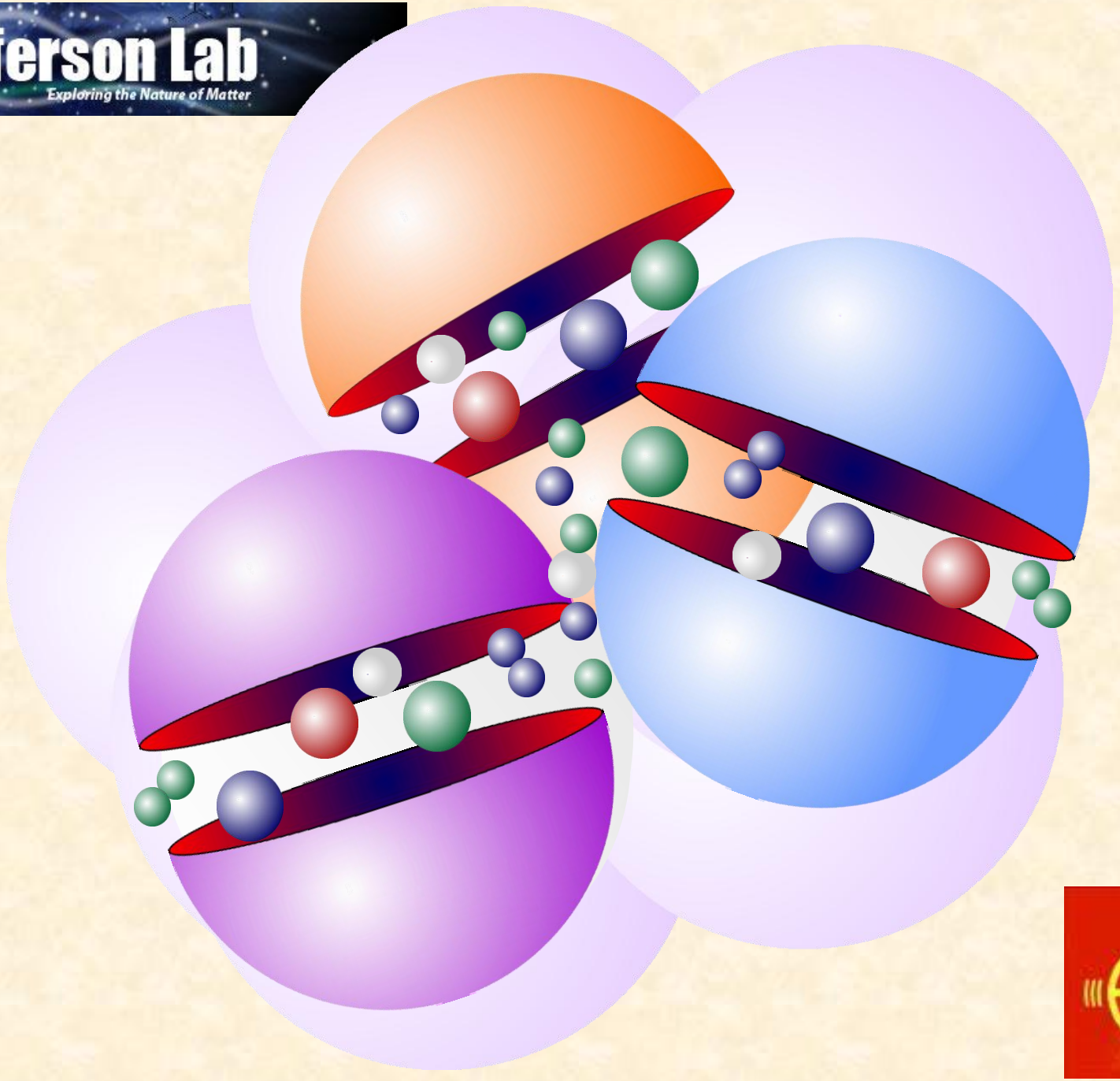


Jefferson Lab

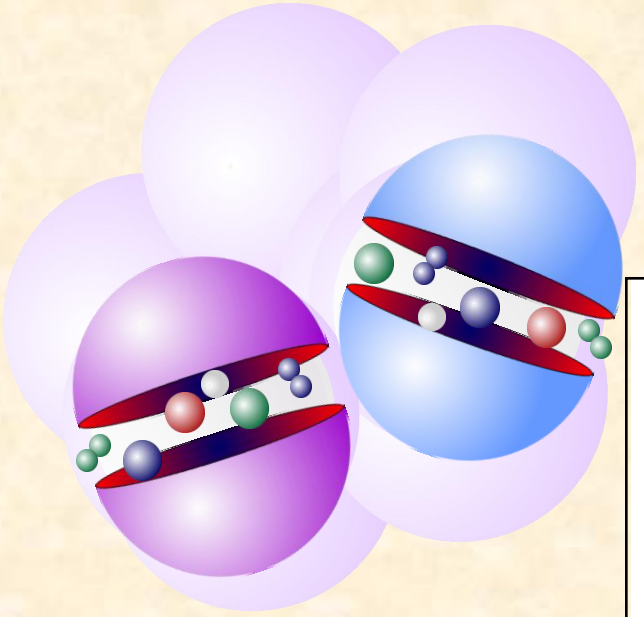
Exploring the Nature of Matter

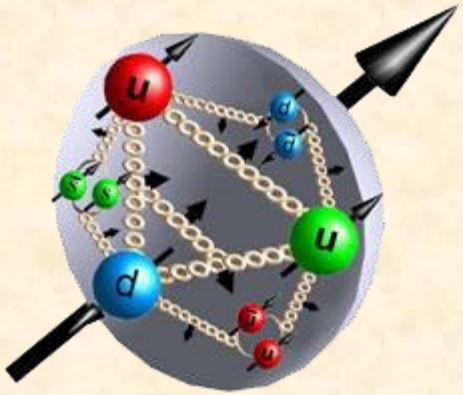


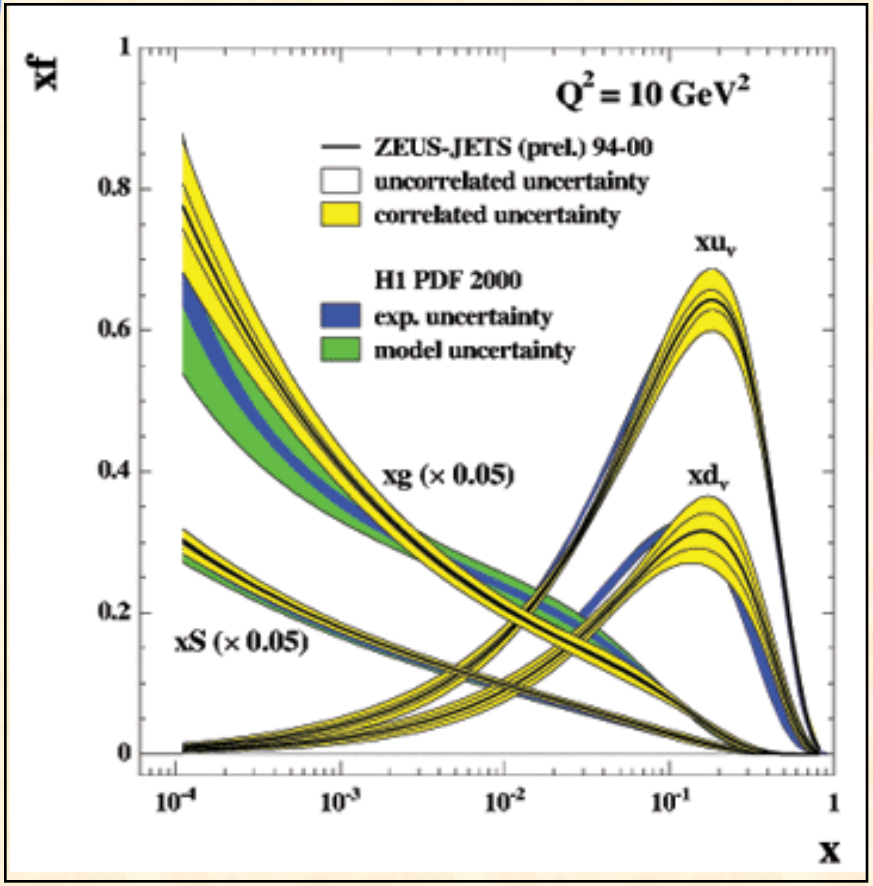
Jefferson Lab
Exploring the Nature of Matter



Electron Ion Collider







New states of matter

Color glass Condensate?


Glimpsing colour
in a world of black & white

Skiing with QUARKS