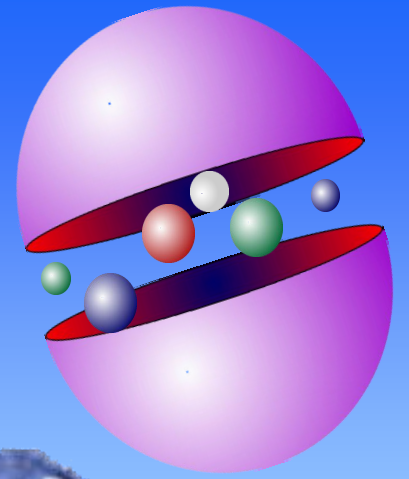




Facets of the strong interaction



Hirschegg 2012



Glimpsing colour in a world of black & white

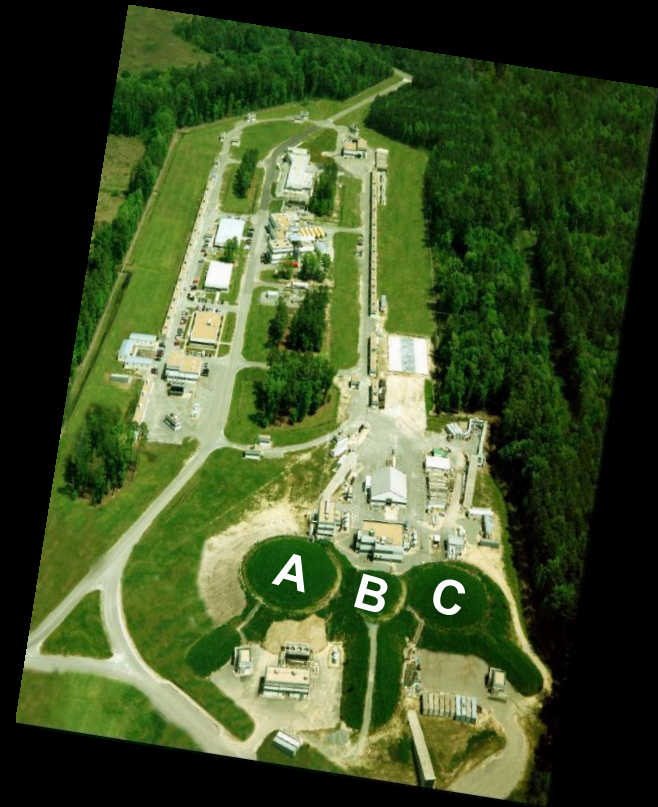
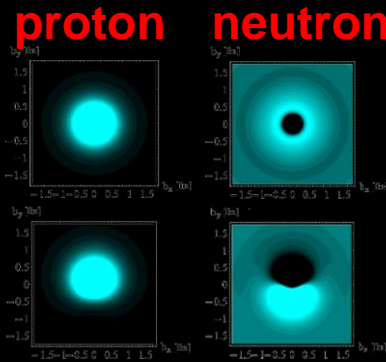
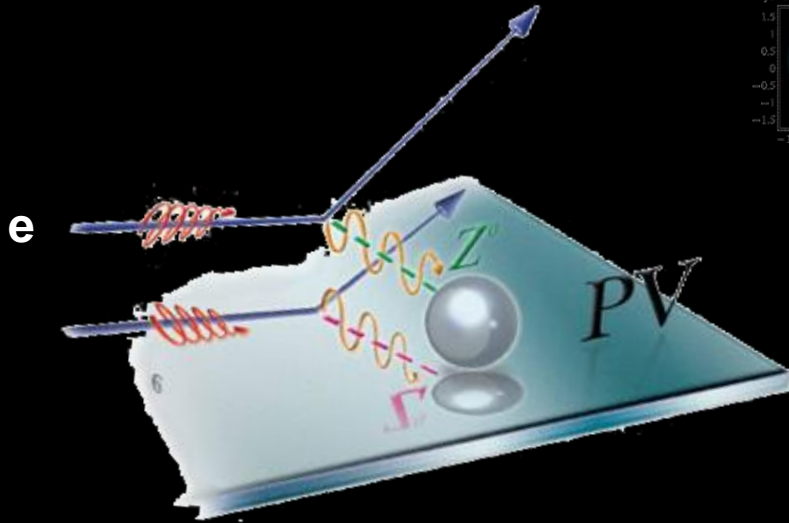
Hirschegg 2012



**Glimpsing colour
in a world of black & white**



Glimpsing colour in a world of black & white

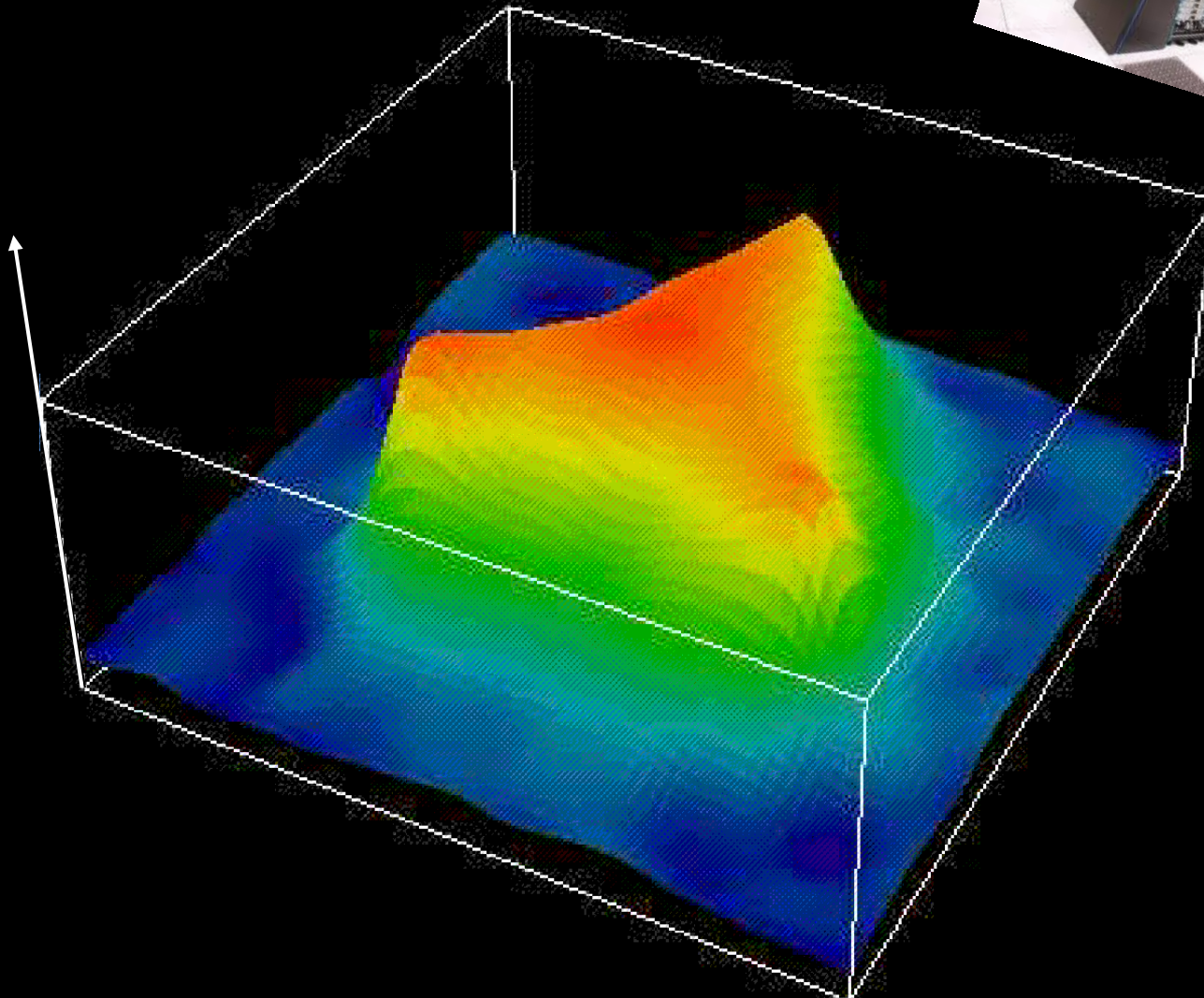


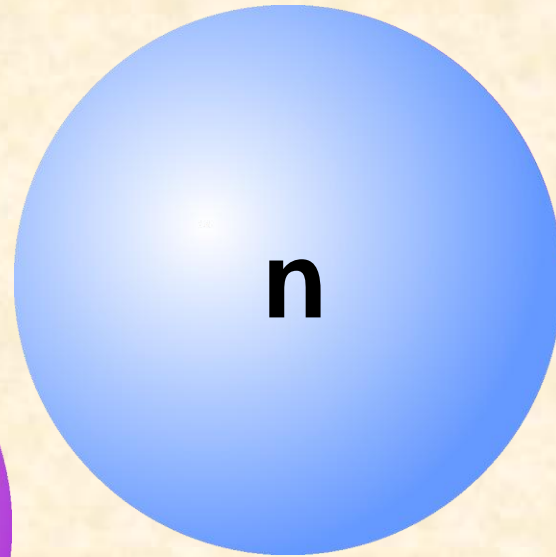
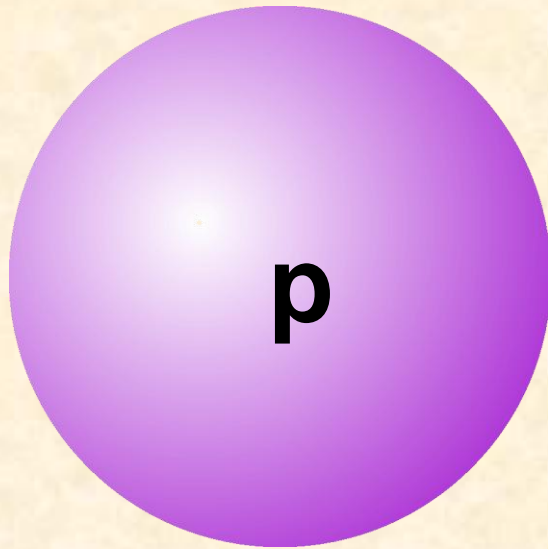
Jefferson Science Associates, LLC
a SURA/CSC Company

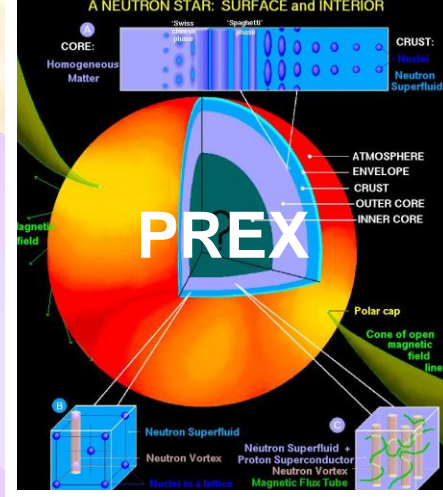
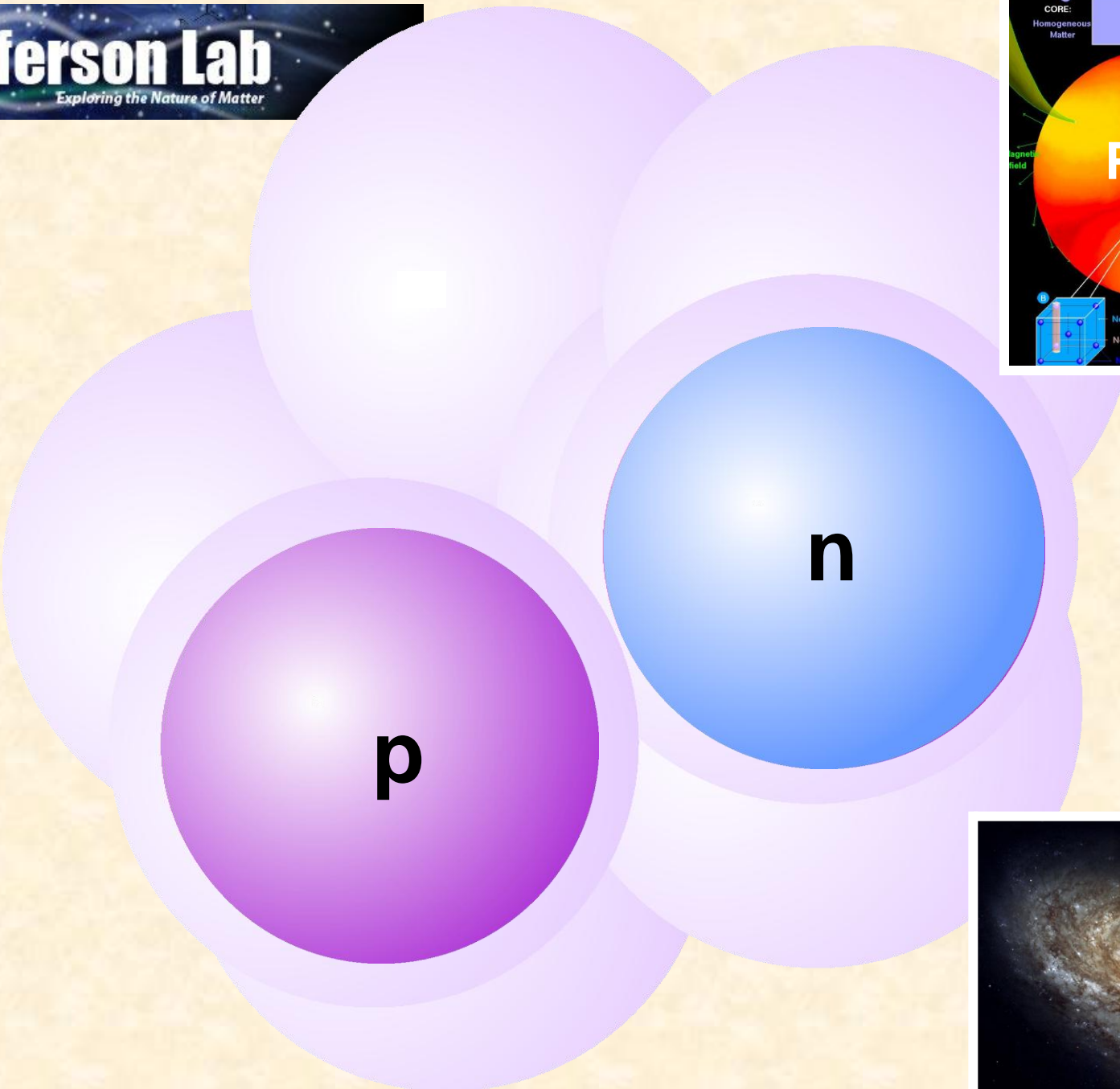
Colour Forces

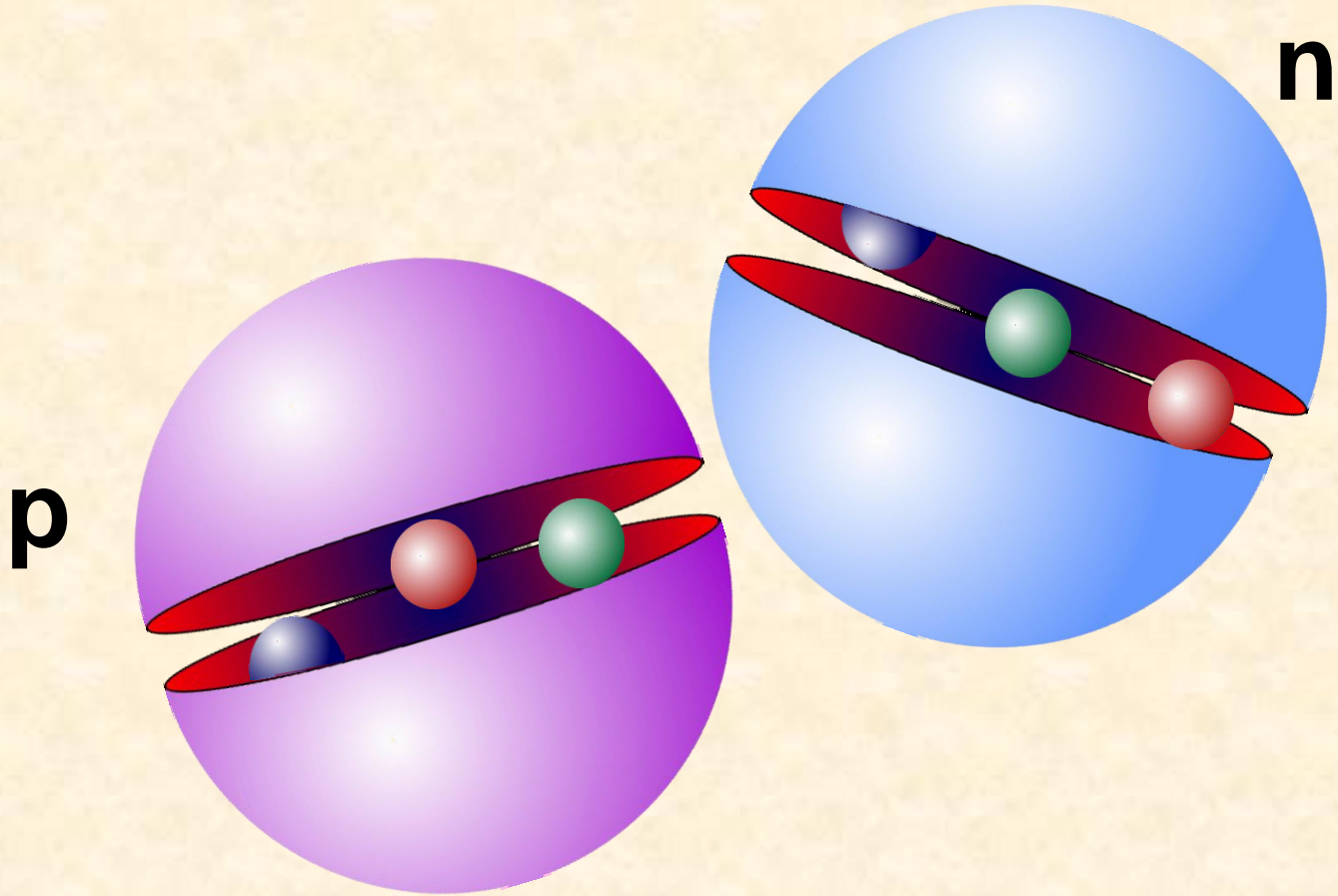


energy
density

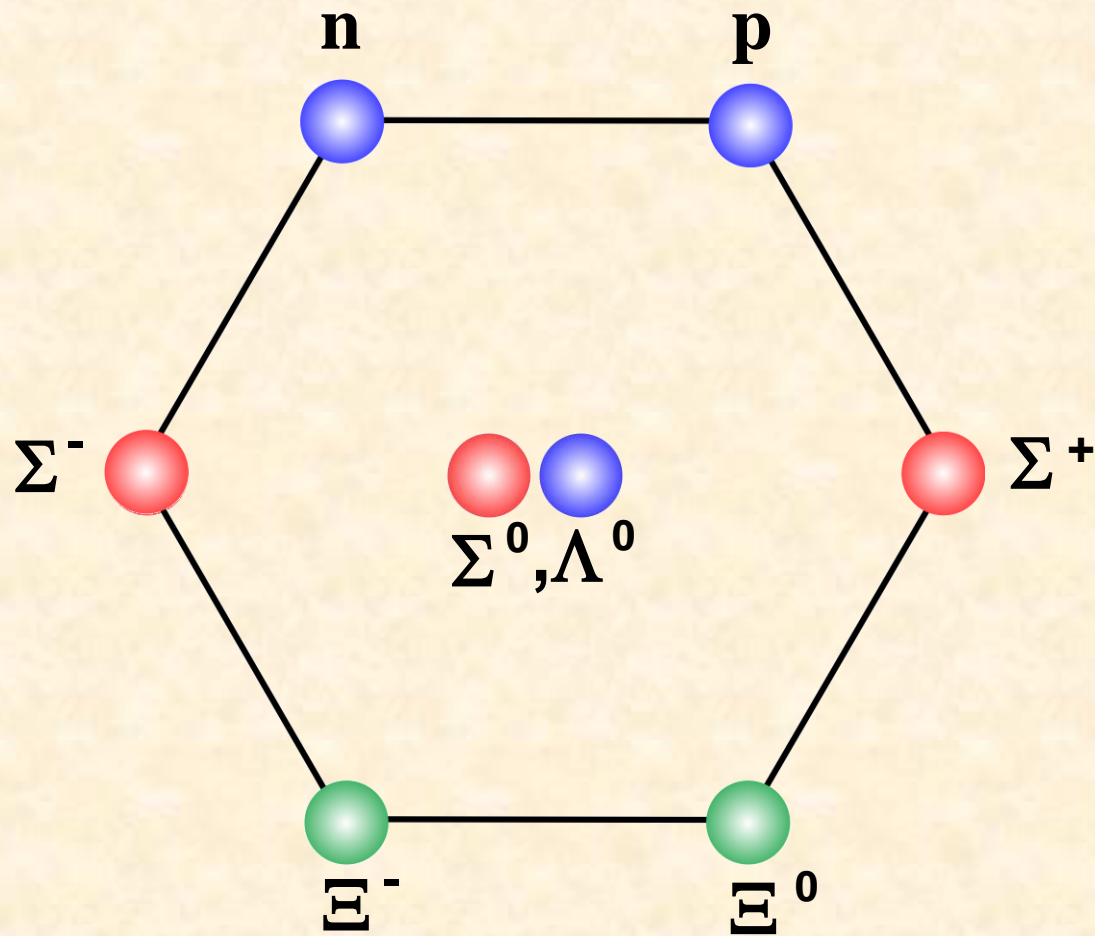




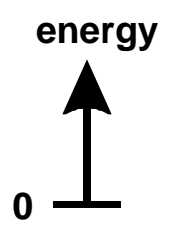




Baryon octet

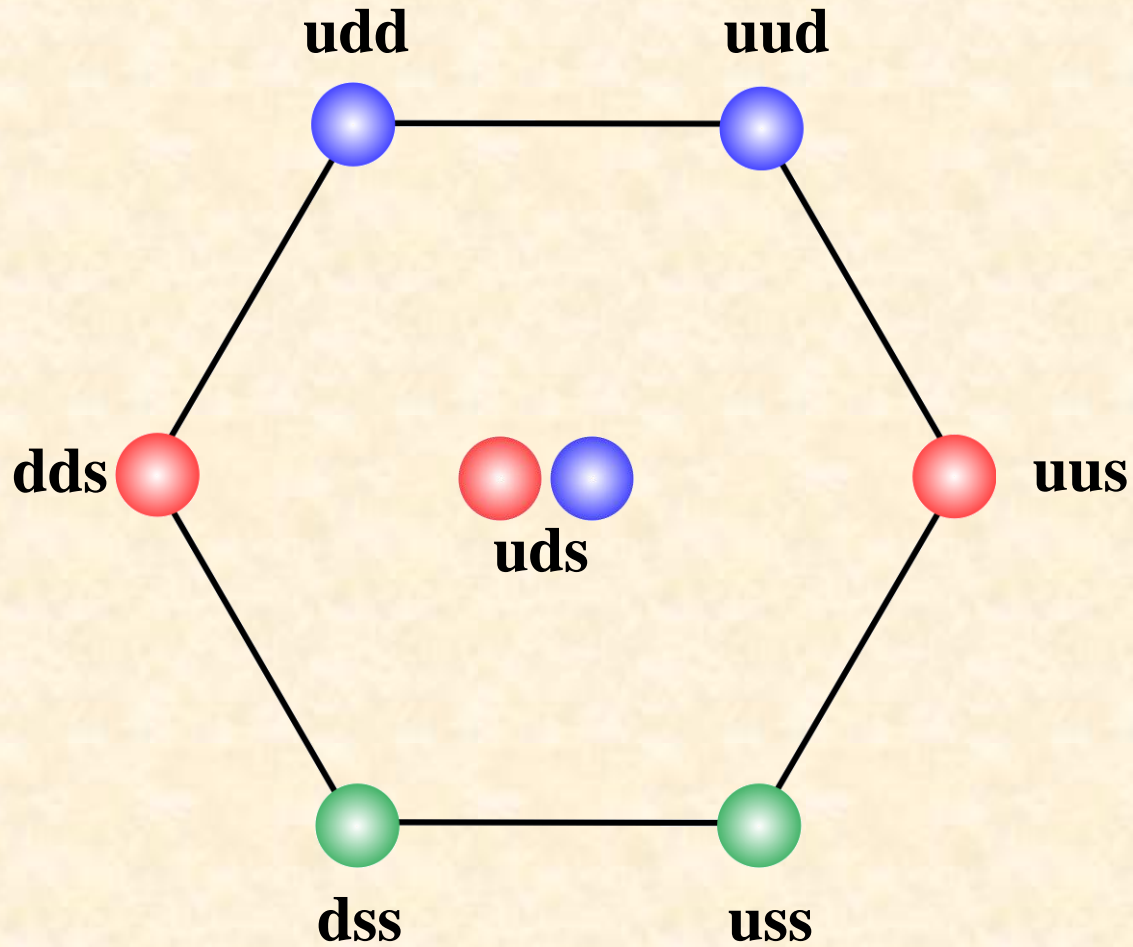


Ξ	—	1320
Σ, Λ	—	1130
p, n	—	940

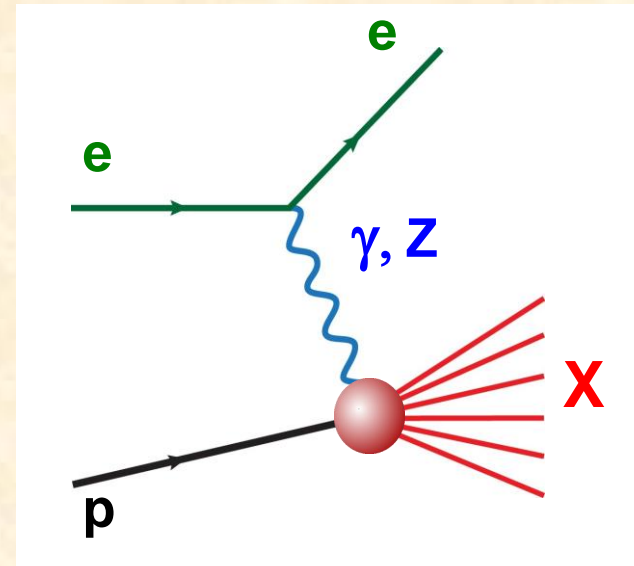
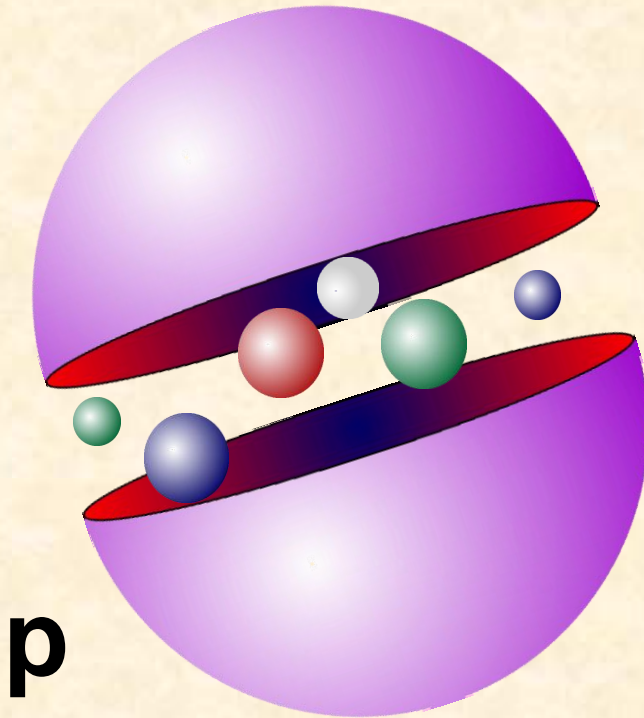


Ground States

Baryon octet



Deep inelastic scattering

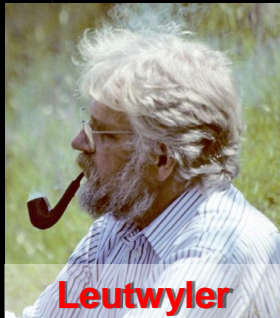


QCD

1971



Fritzsche



Leutwyler

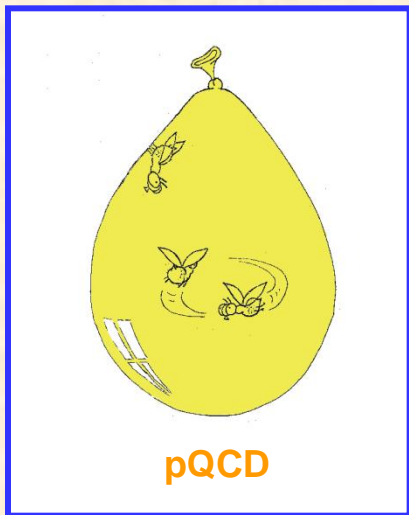


Gell-Mann

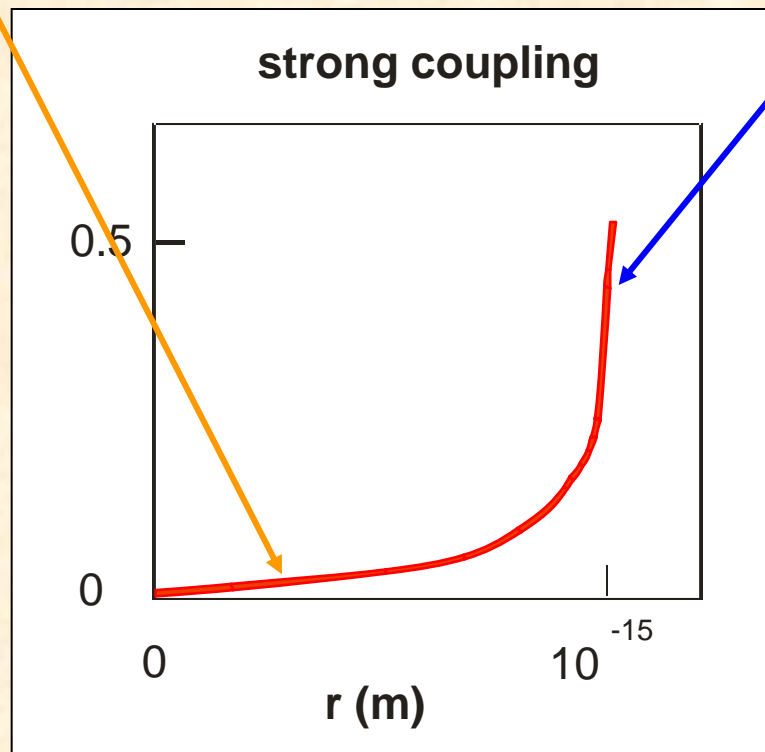
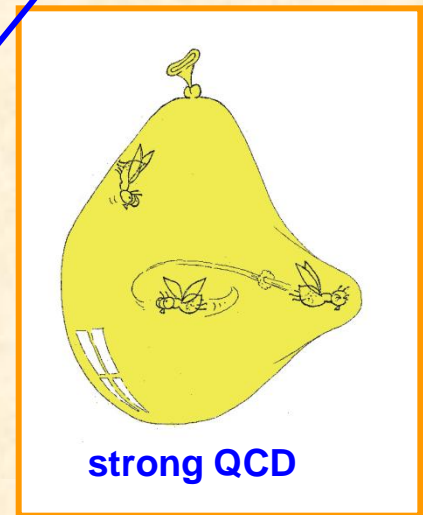
$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b} \bar{q} (i\gamma_{\mu} D^{\mu} - m_q) q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

QCD

asymptotic freedom



confinement



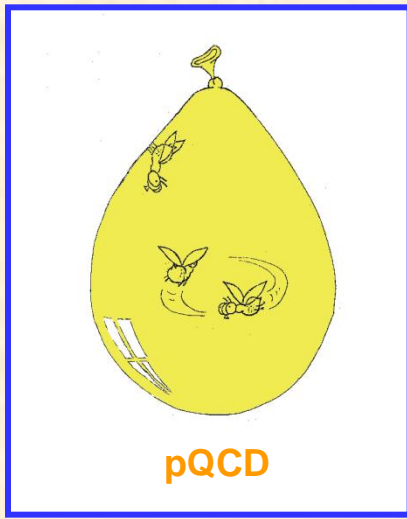


Politzer

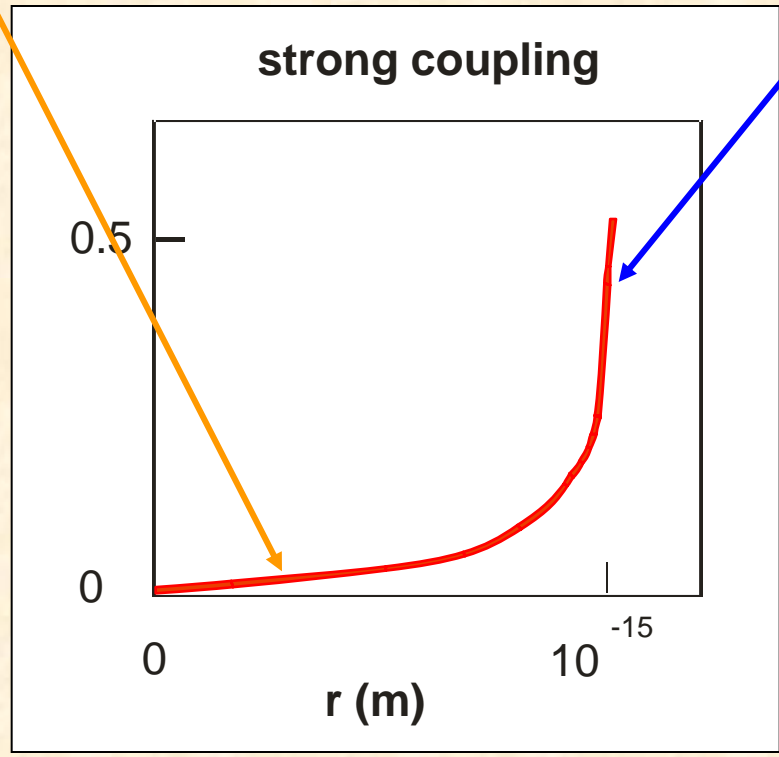
QCD

asymptotic freedom

confinement



pQCD



strong QCD



Gross



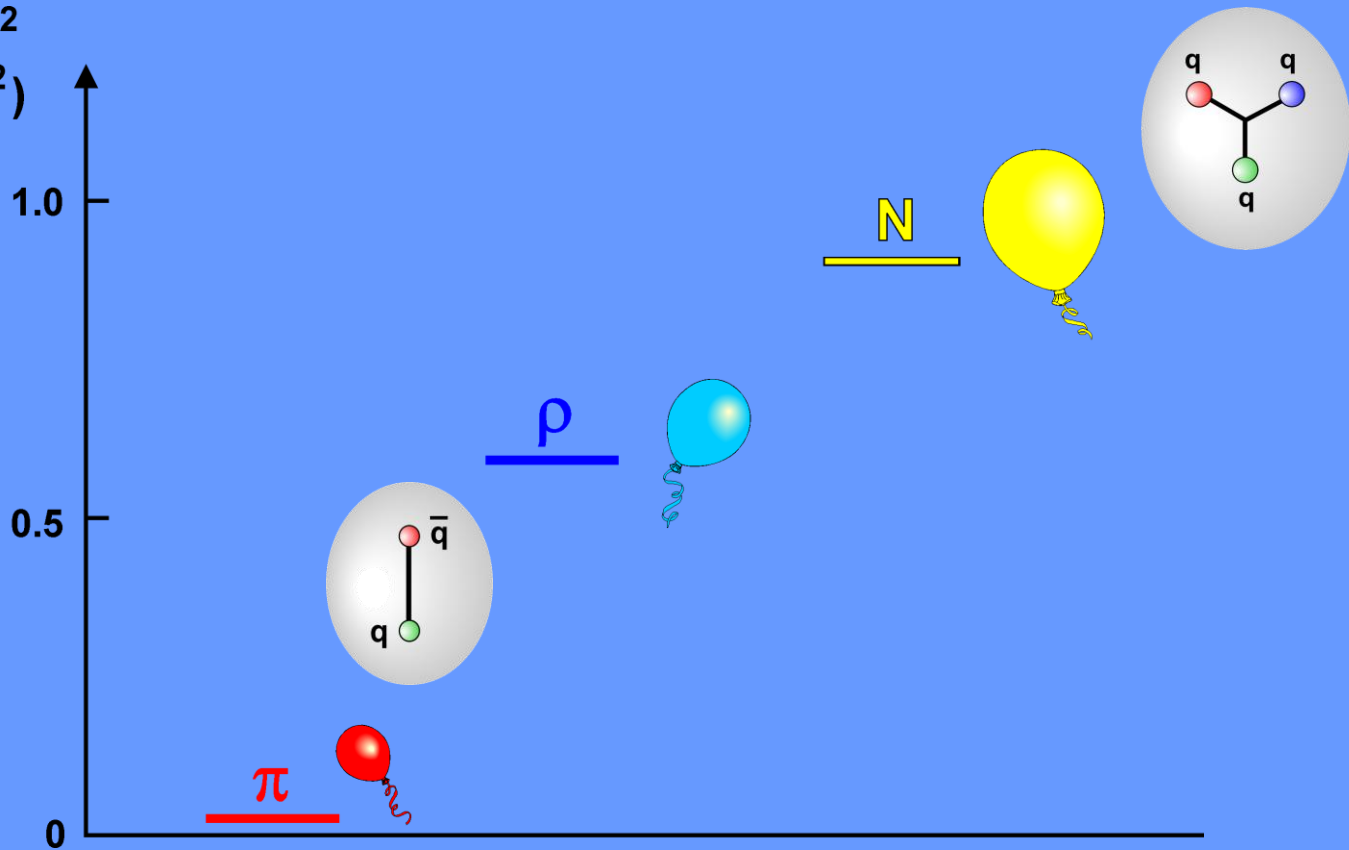
Wilczek



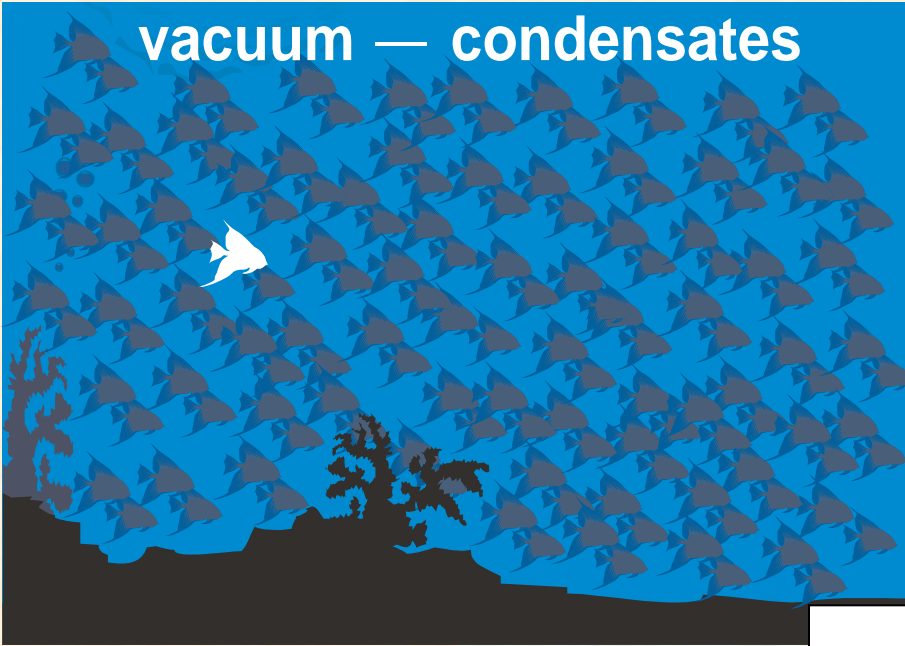
Wilson

Hadron masses ²

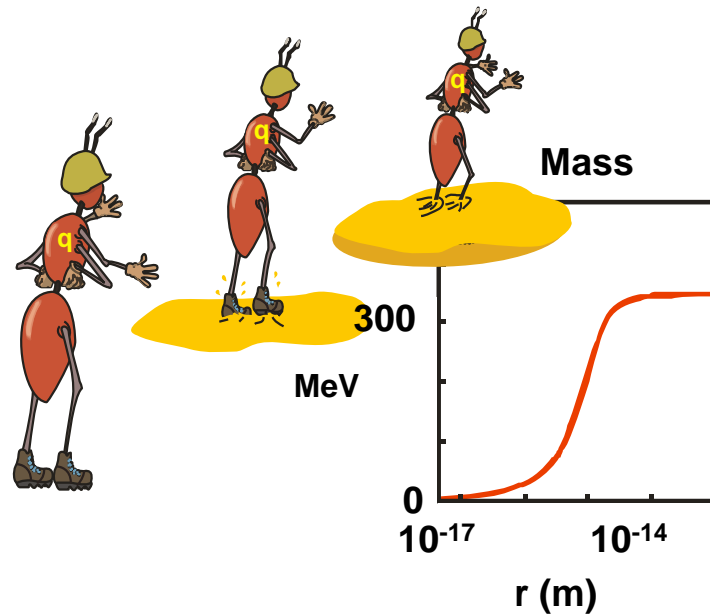
Mass²
(GeV²)



vacuum — condensates



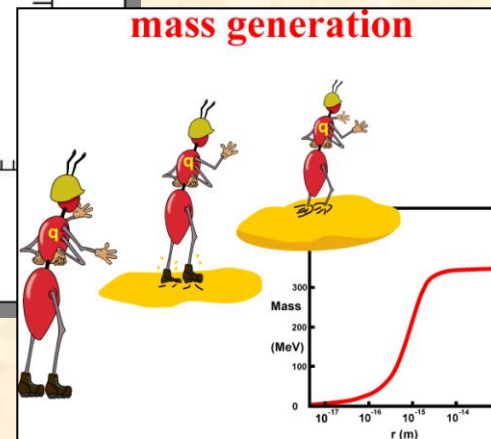
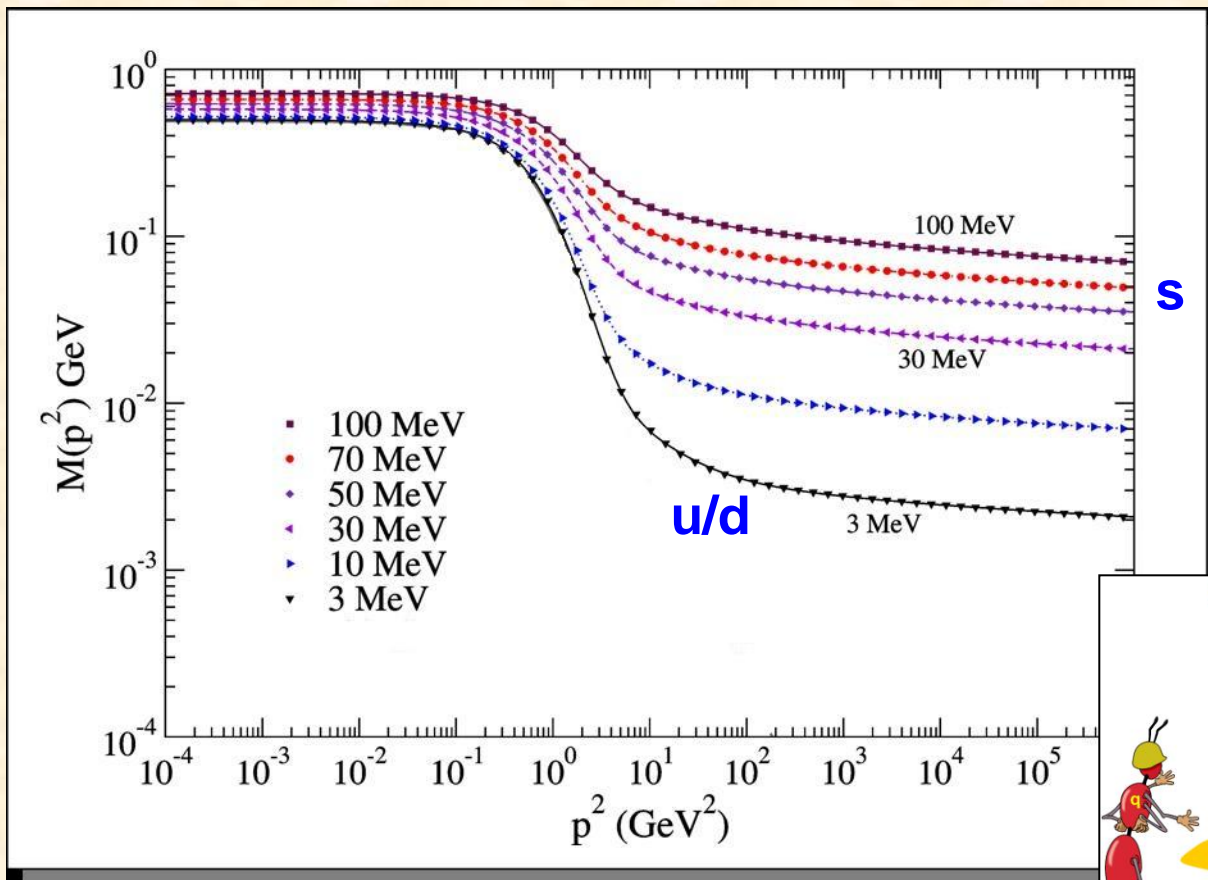
u/d quarks propagating



Quark mass function

$$\alpha_s > 1 \implies \chi\text{SB}$$

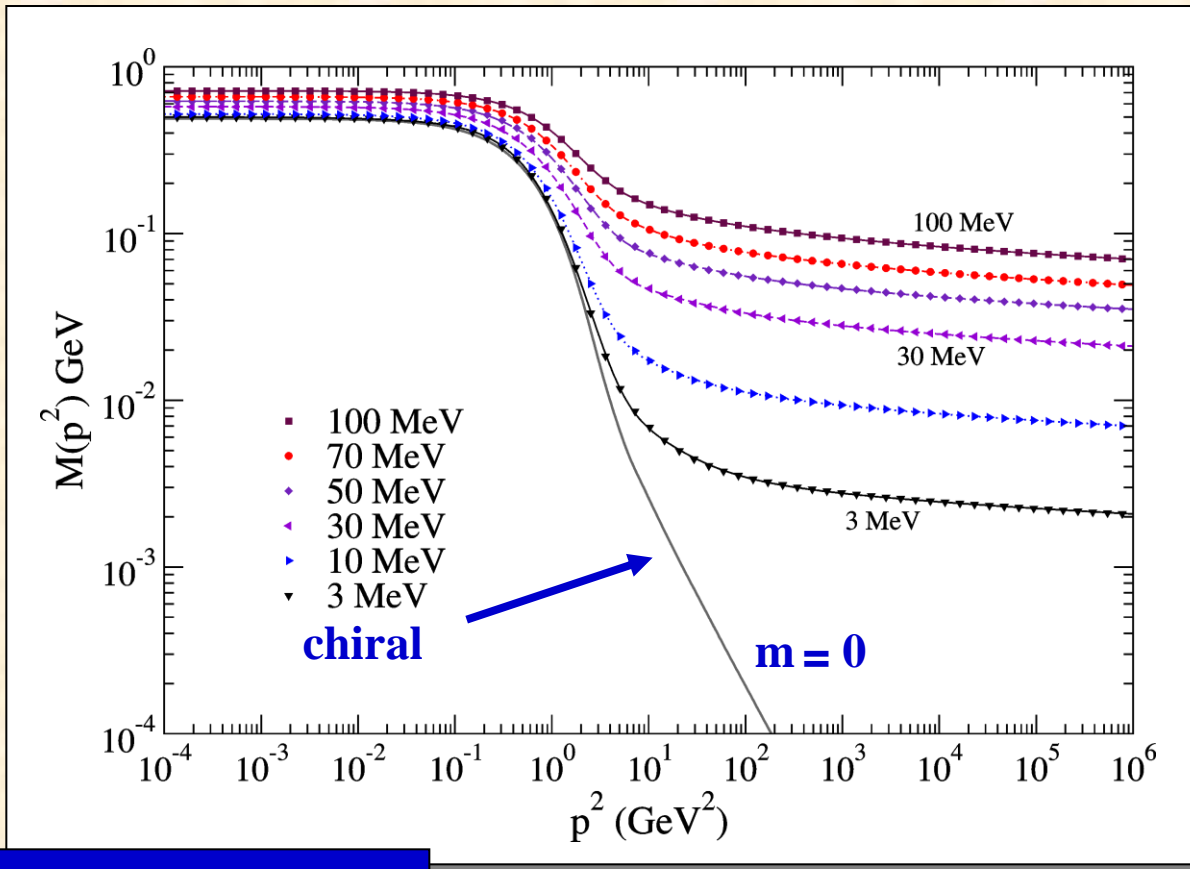
Williams,
Fischer,
P



Quark mass function

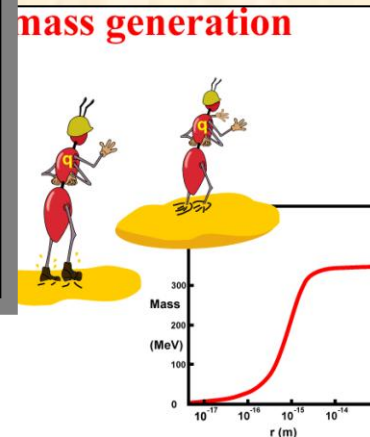
$$\alpha_s > 1 \implies \chi\text{SB}$$

Williams,
Fischer,
P



$$\langle \bar{q}q \rangle_0 \sim - (240 \text{ MeV})^3$$

Bhagwat & Tandy/ Roberts *et al.*



Spectrum of hadrons



Rutherford:

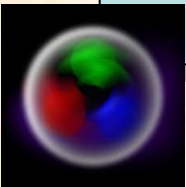
“Science is either physics or stamp-collecting”

colour wave-functions

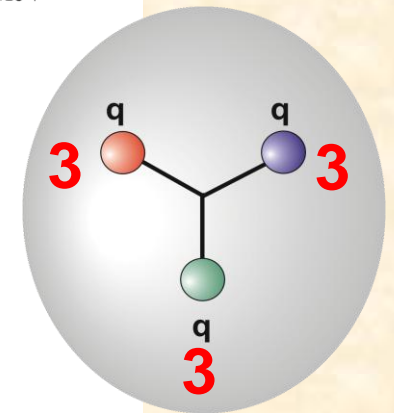
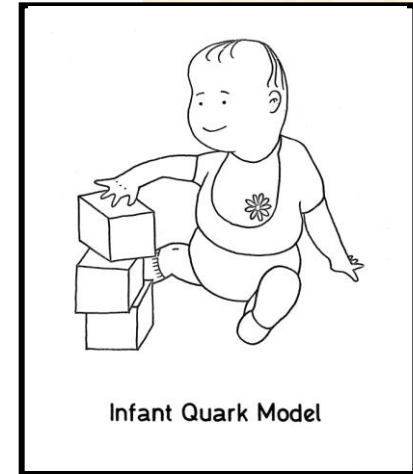
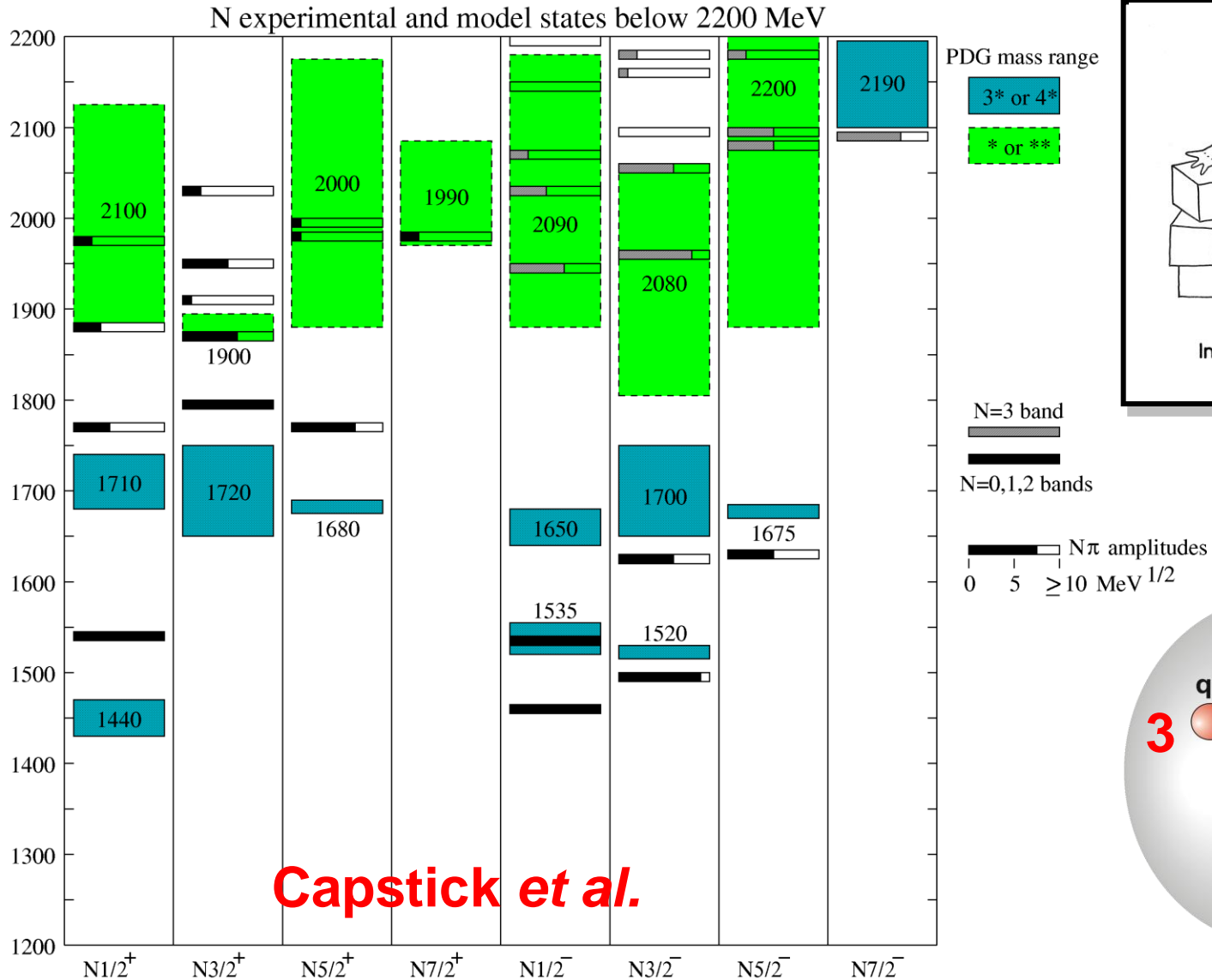
$$\pi^+ = \frac{1}{\sqrt{N_c}} [u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \dots]$$

$$N_c = 3$$

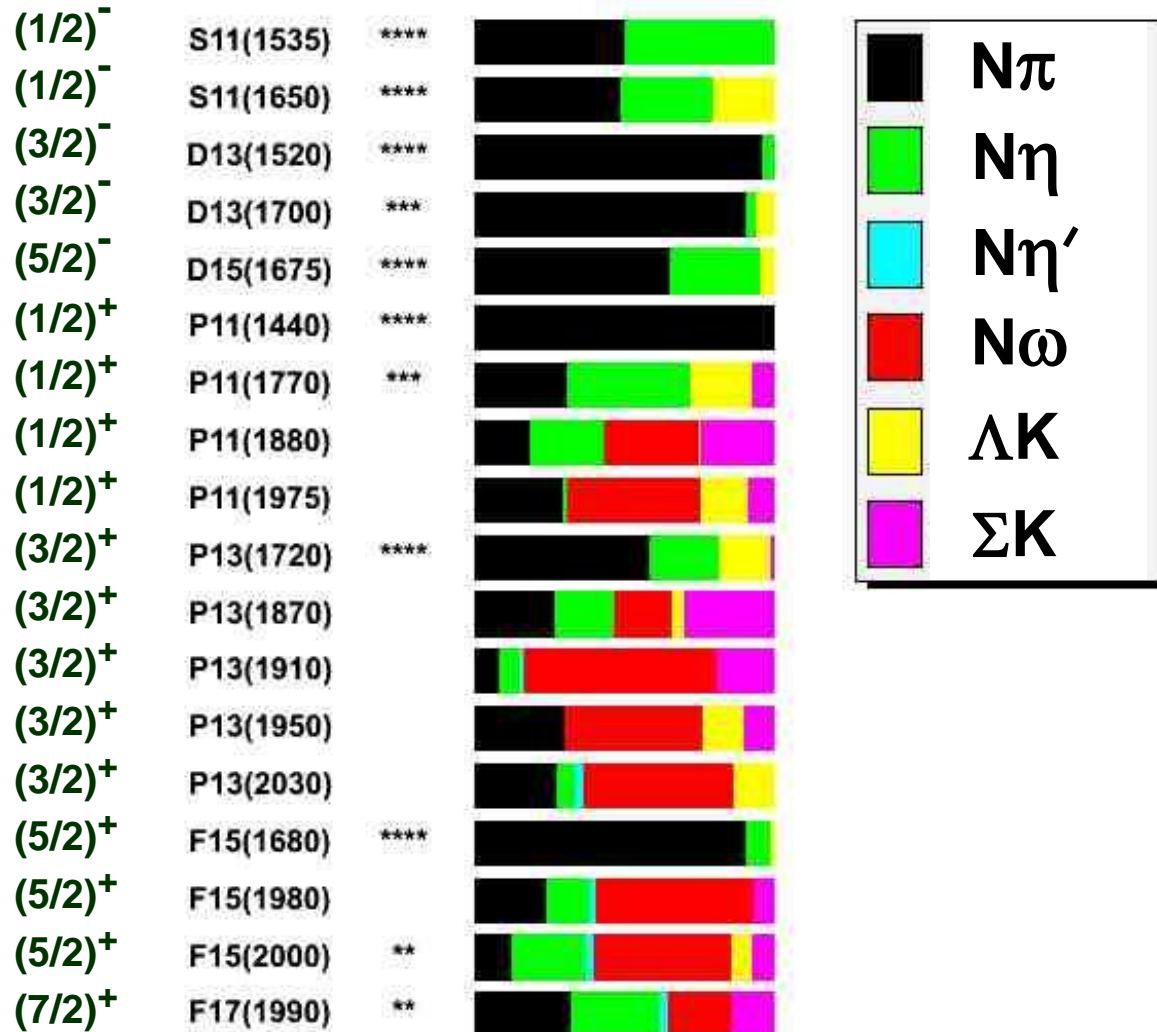
$$p = \frac{1}{\sqrt{6}} [uud + uud + uud \\ - uud - uud - uud]$$



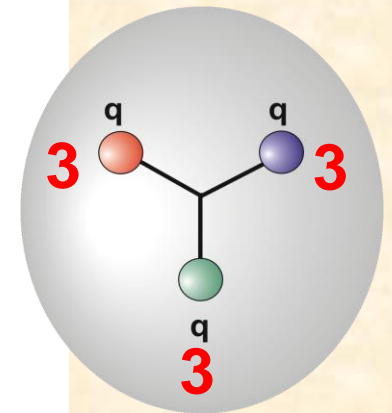
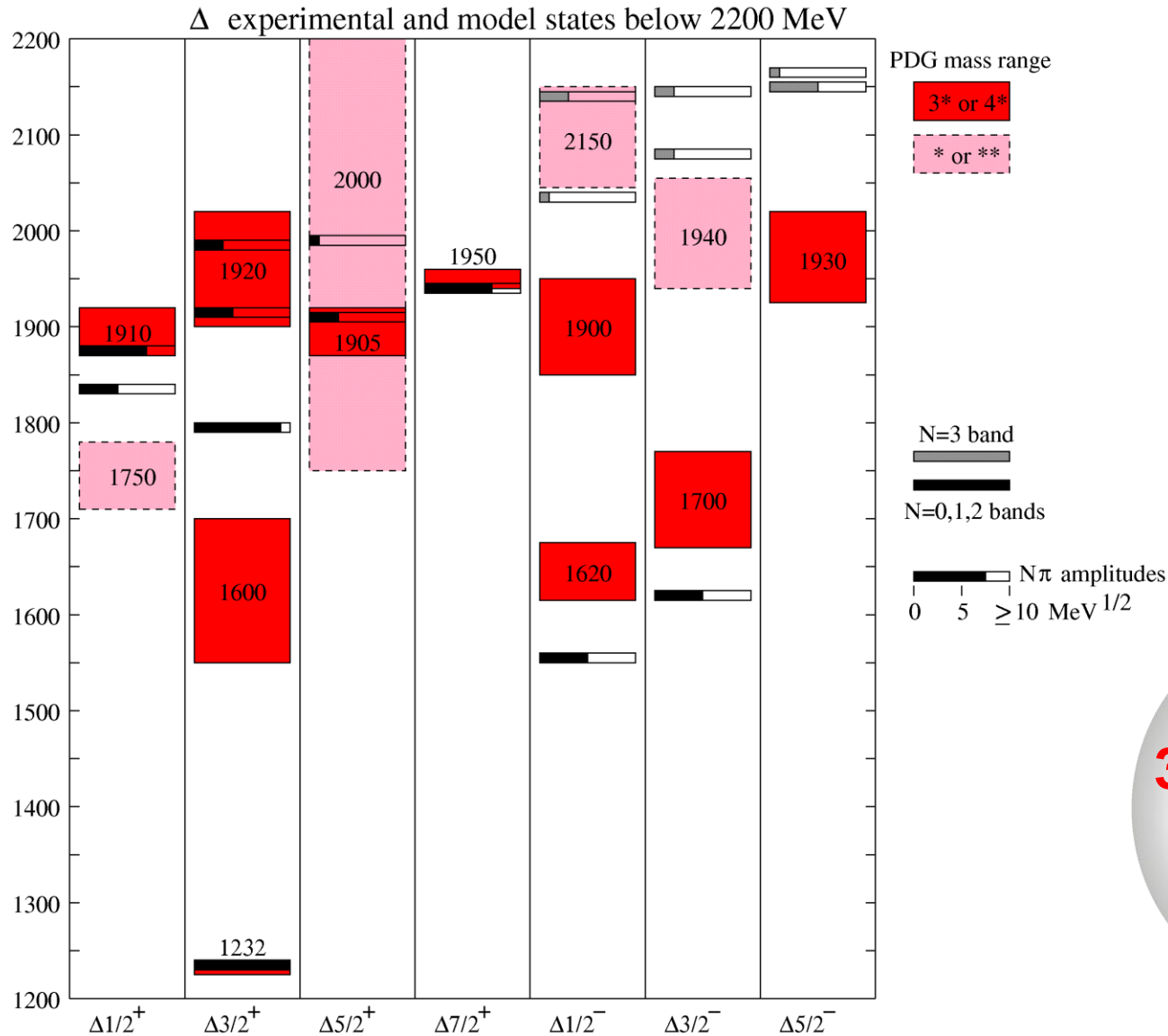
Nucleon model states (πN couplings)



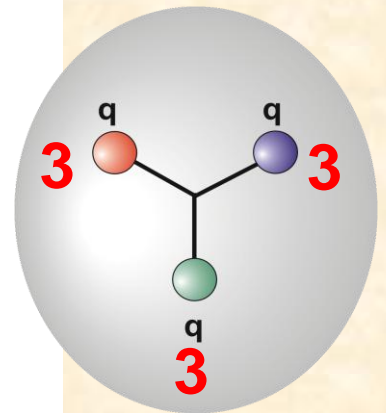
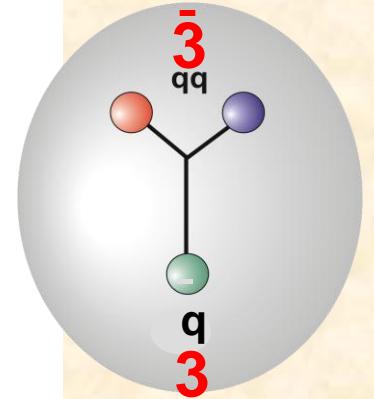
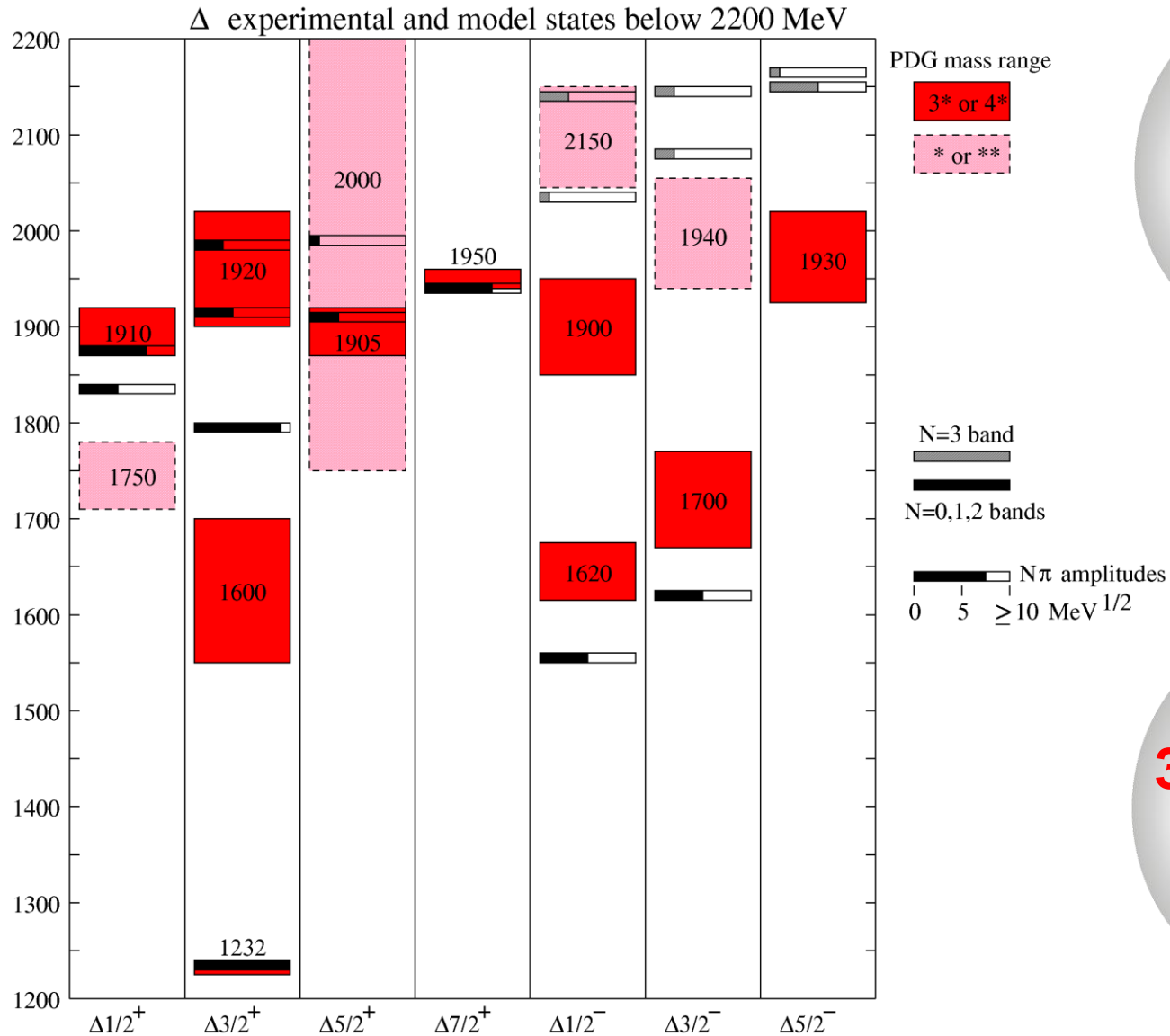
search all channels: not just πN



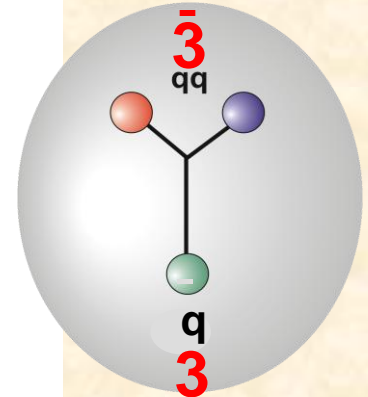
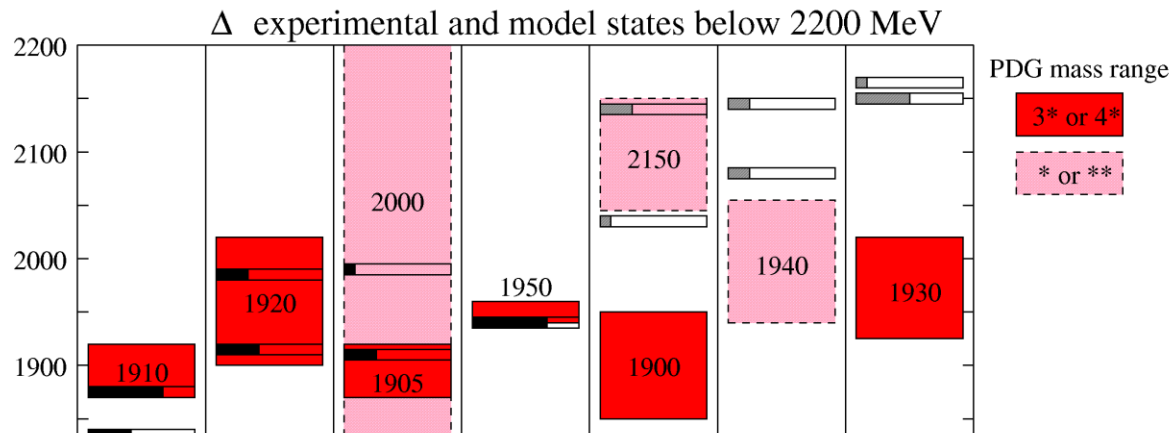
Δ model states (πN couplings)



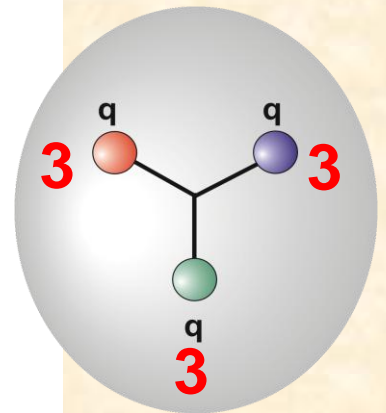
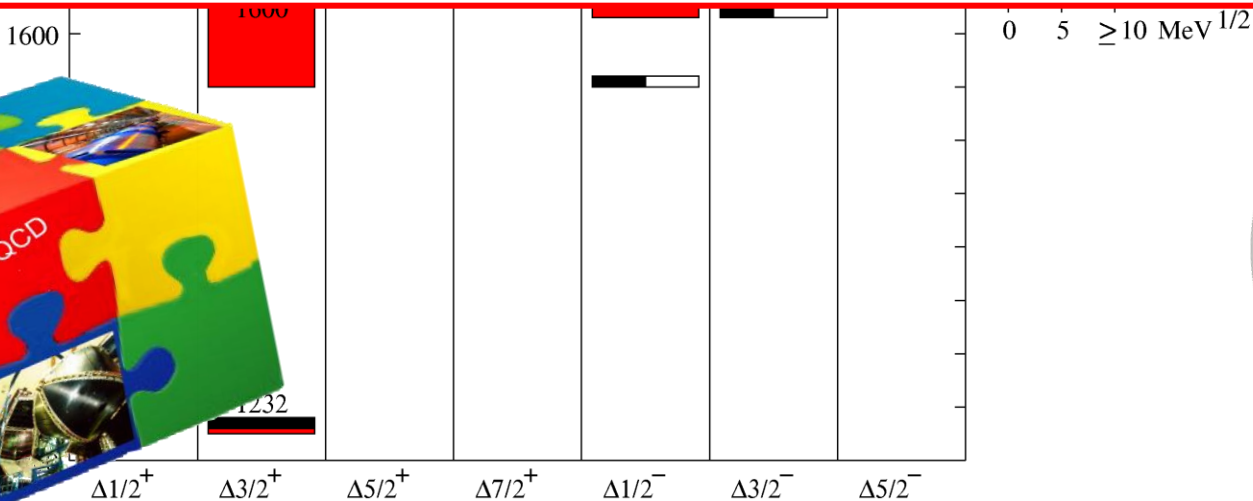
Δ model states (πN couplings)



Δ model states (πN couplings)

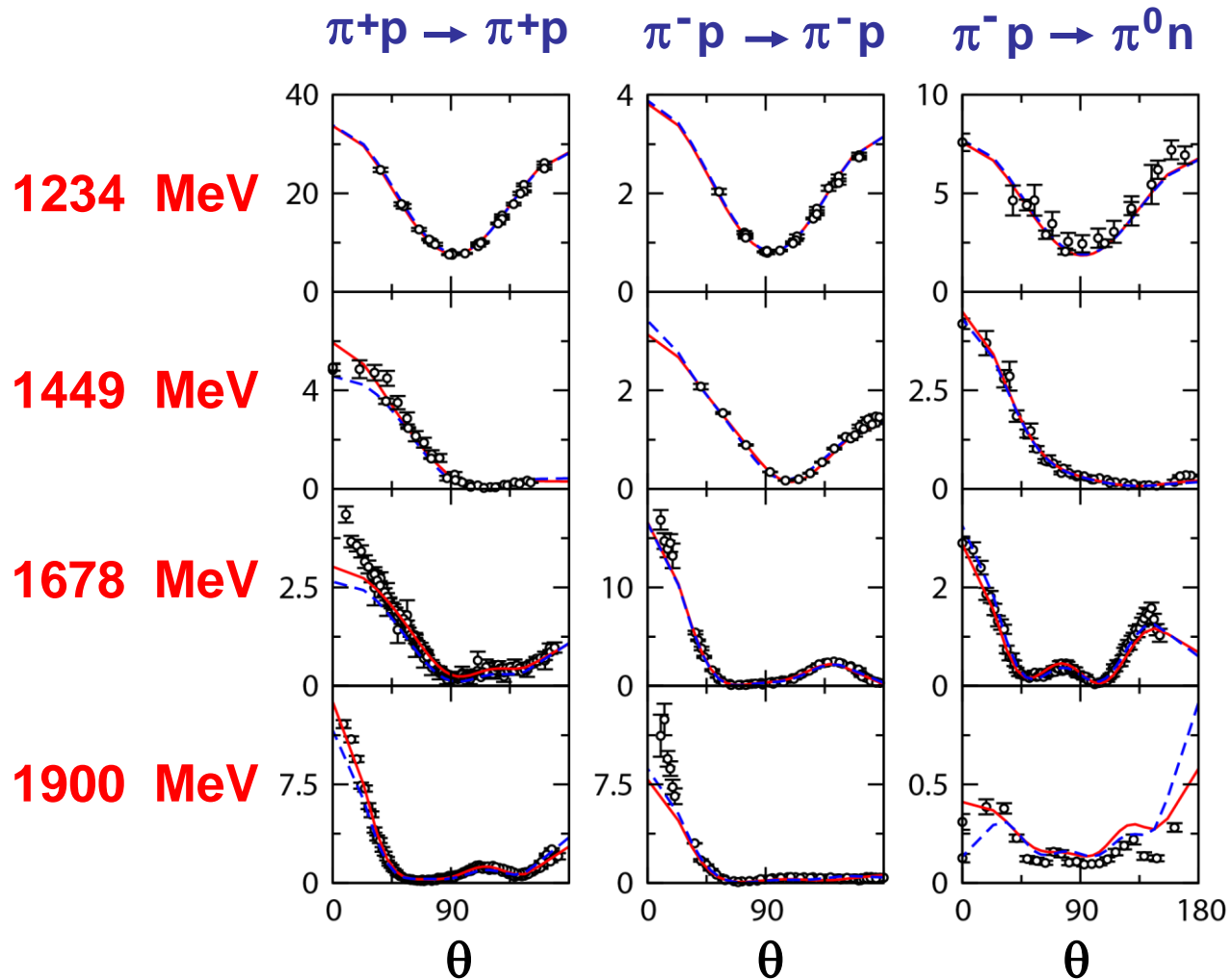


$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b} \bar{\psi}_q (i \gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$



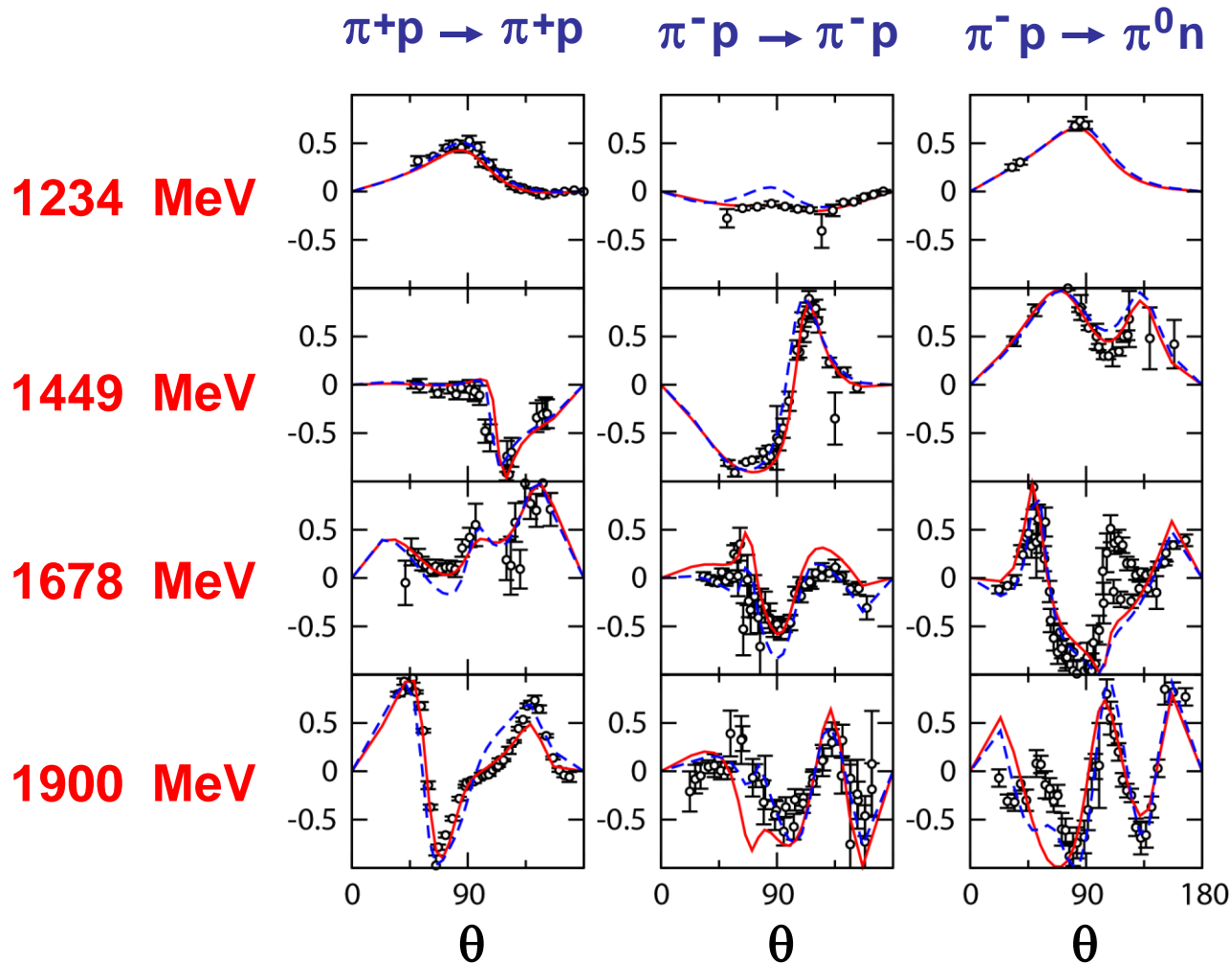
$\pi N \rightarrow \pi N$ scattering

$d\sigma/d\Omega$

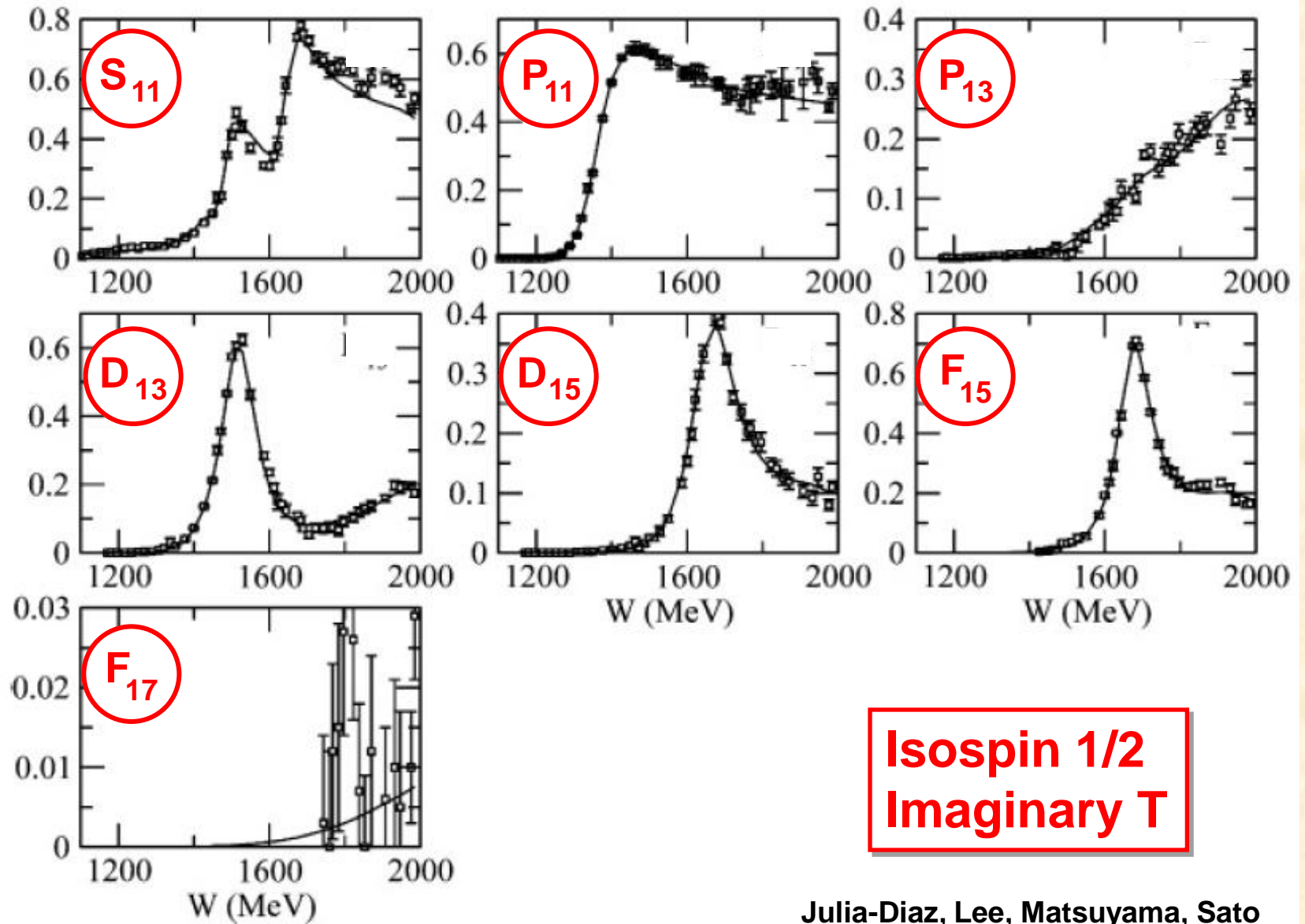


$\pi N \rightarrow \pi N$ scattering

P

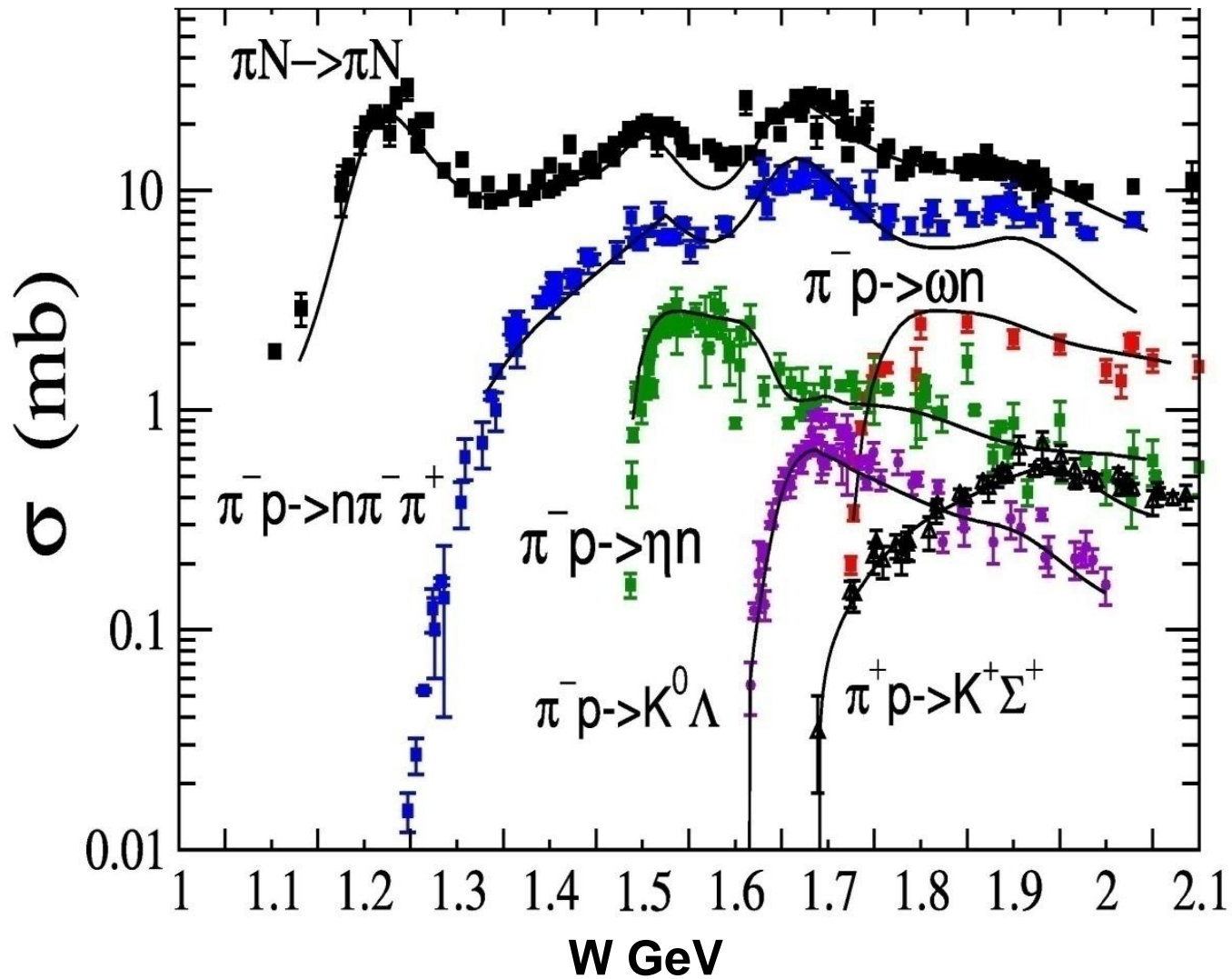


πN amplitudes



Isospin 1/2
Imaginary T

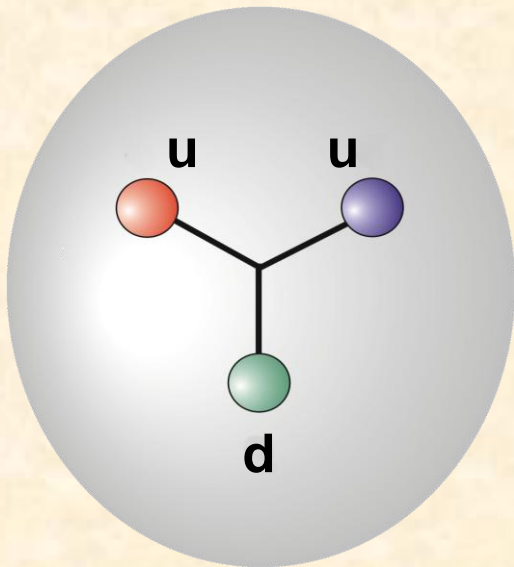
πN exclusive channels



$\Delta(1232)$ colour wave-function

$$N_c = 3$$

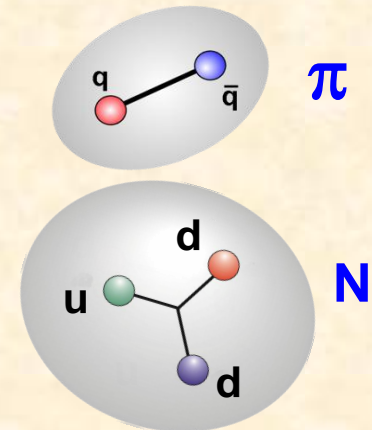
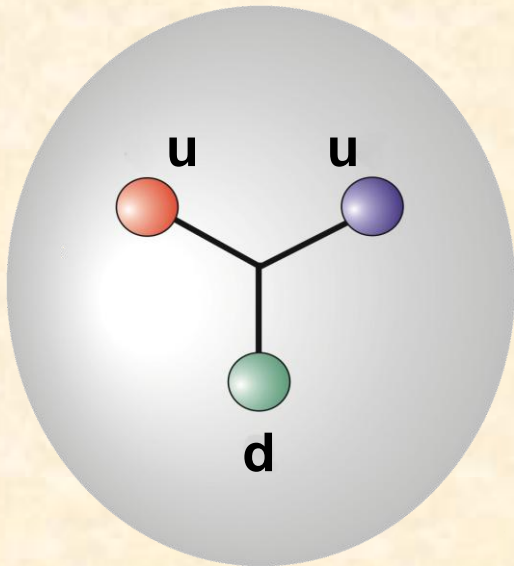
$$\Delta^+ = \frac{1}{\sqrt{6}} \left[\begin{aligned} & \text{uud} + \text{uud} + \text{uud} \\ & - \text{uud} - \text{uud} - \text{uud} \end{aligned} \right]$$



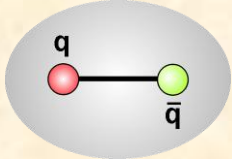
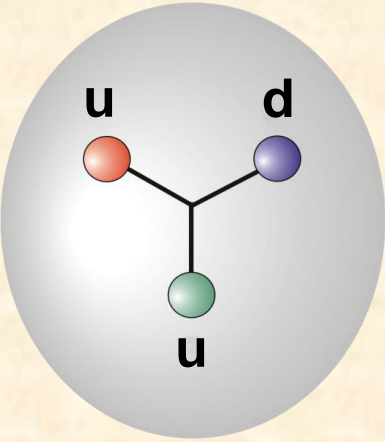
$\Delta(1232)$ colour wave-function

$$N_c = 3$$

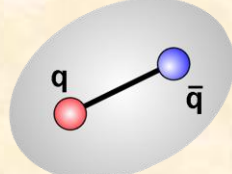
$$\Delta^+ = \frac{1}{\sqrt{6}} \left[\begin{aligned} &uud + uud + uud \\ &- uud - uud - uud \end{aligned} \right]$$



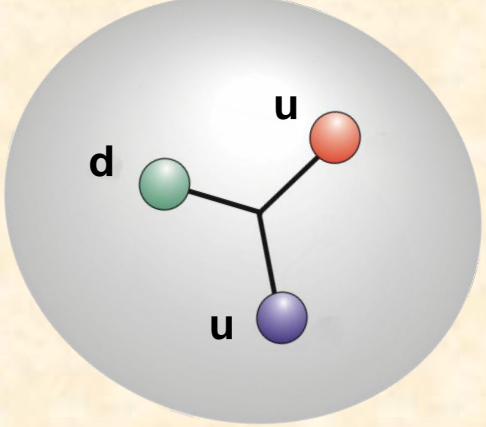
$N^*(1xxx)$



π



π



N

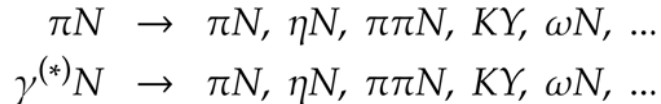
Coupled channels



Coupled channels

Properties of Excited Baryons

Reaction Data



Dynamical Coupled-Channels Analysis @ EBAC

Excited Baryon Program

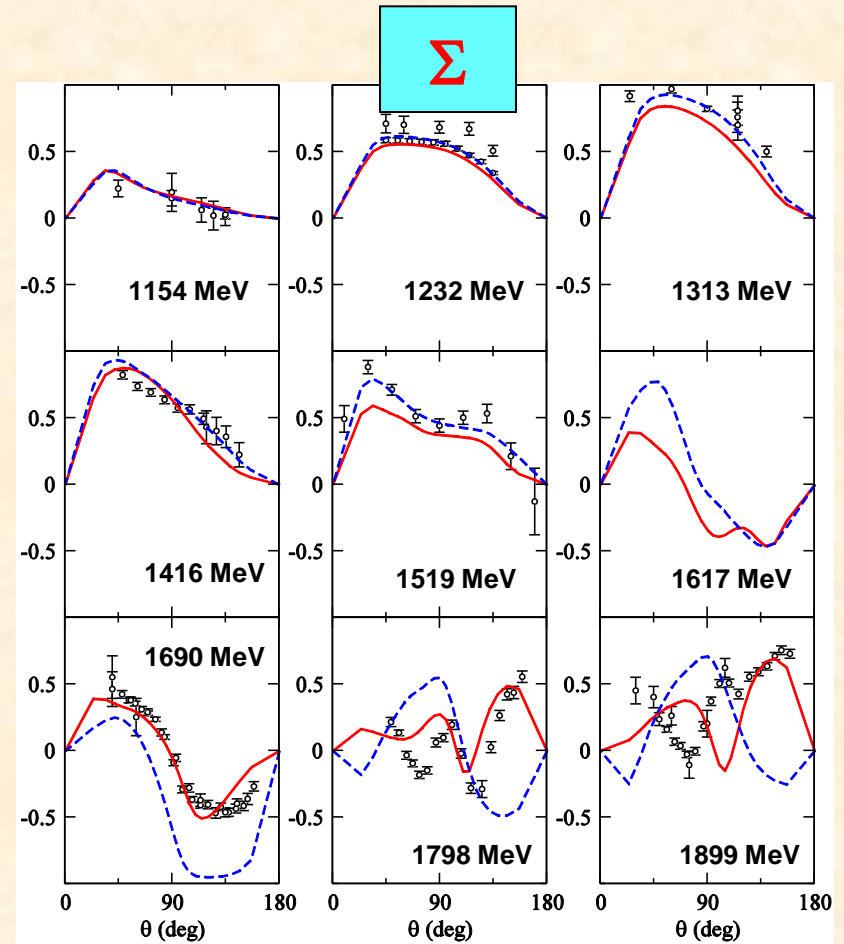
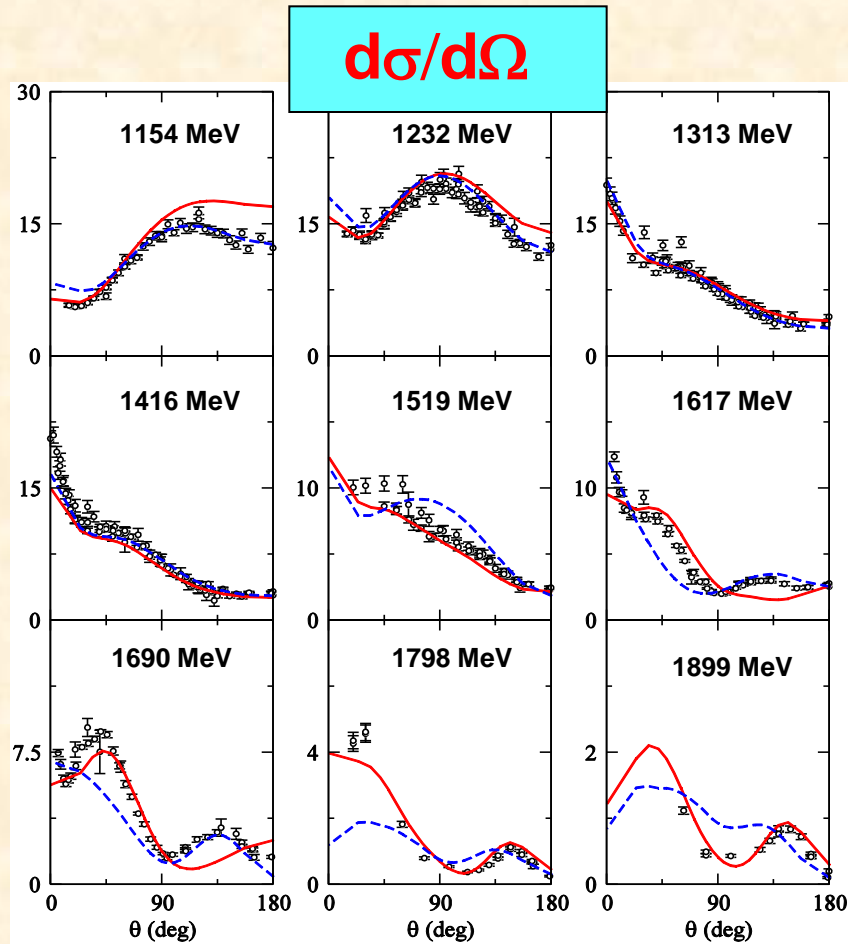
N* parameters

Hadron models

Strong QCD

QCD

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



— Current model
(full combined analysis)

- - - Previous model (fitted to $\gamma N \rightarrow \pi N$ data **up to 1.6 GeV**)

$\pi N \rightarrow K \Lambda$

$d\sigma/d\Omega$

P

$\pi^+ p \rightarrow K^+ \Sigma^+$

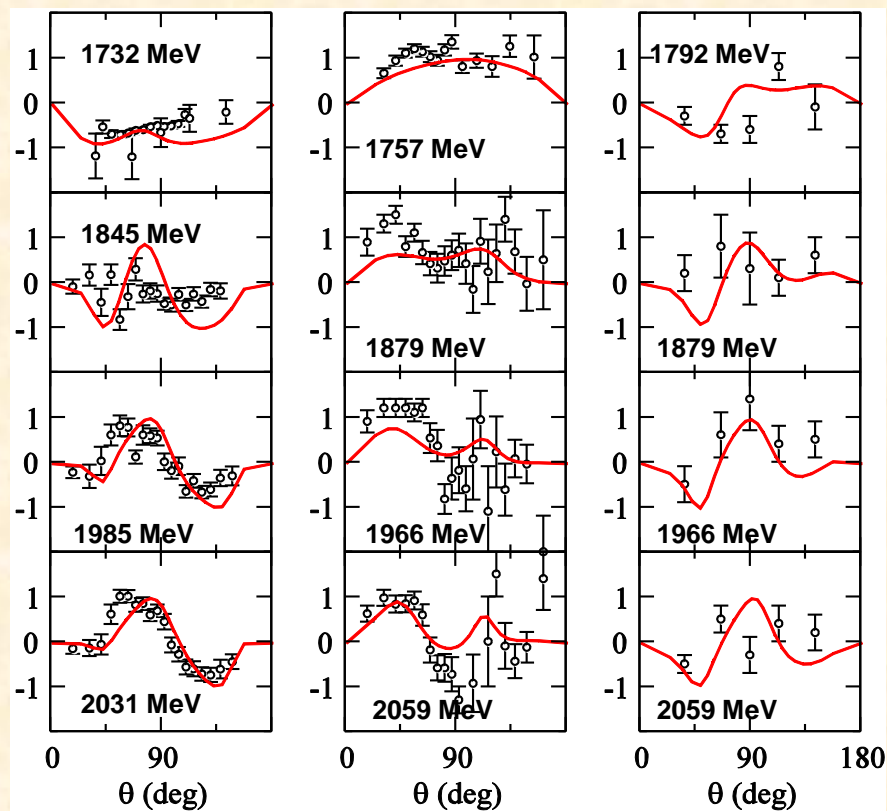
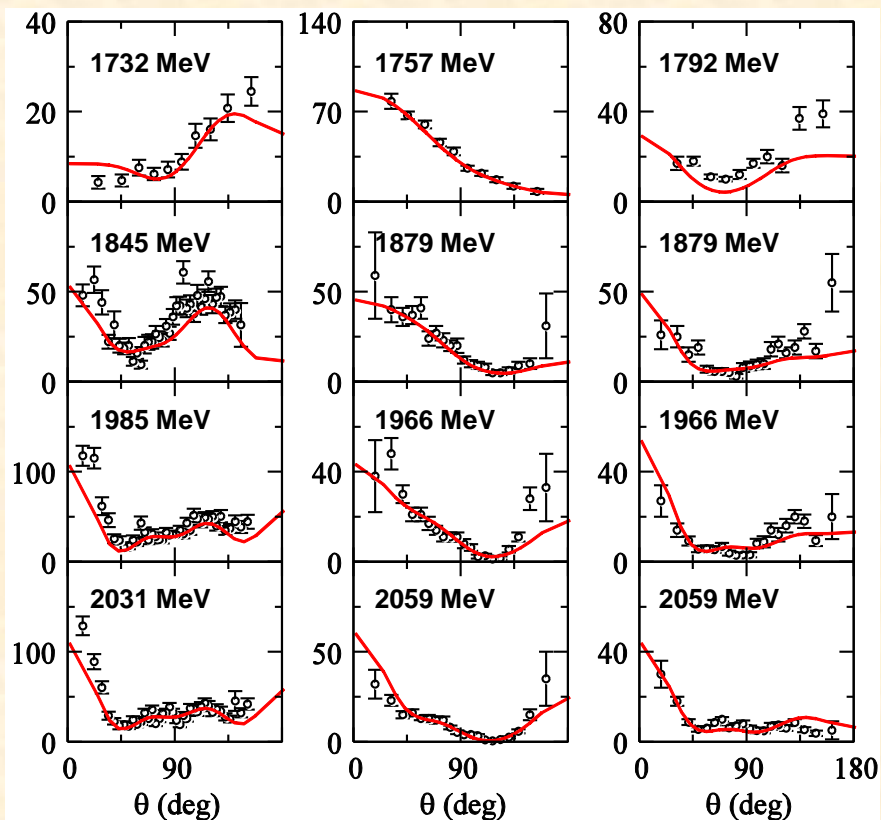
$\pi^- p \rightarrow K^0 \Lambda^0$

$\pi^- p \rightarrow K^0 \Sigma^0$

$\pi^+ p \rightarrow K^+ \Sigma^+$

$\pi^- p \rightarrow K^0 \Lambda^0$

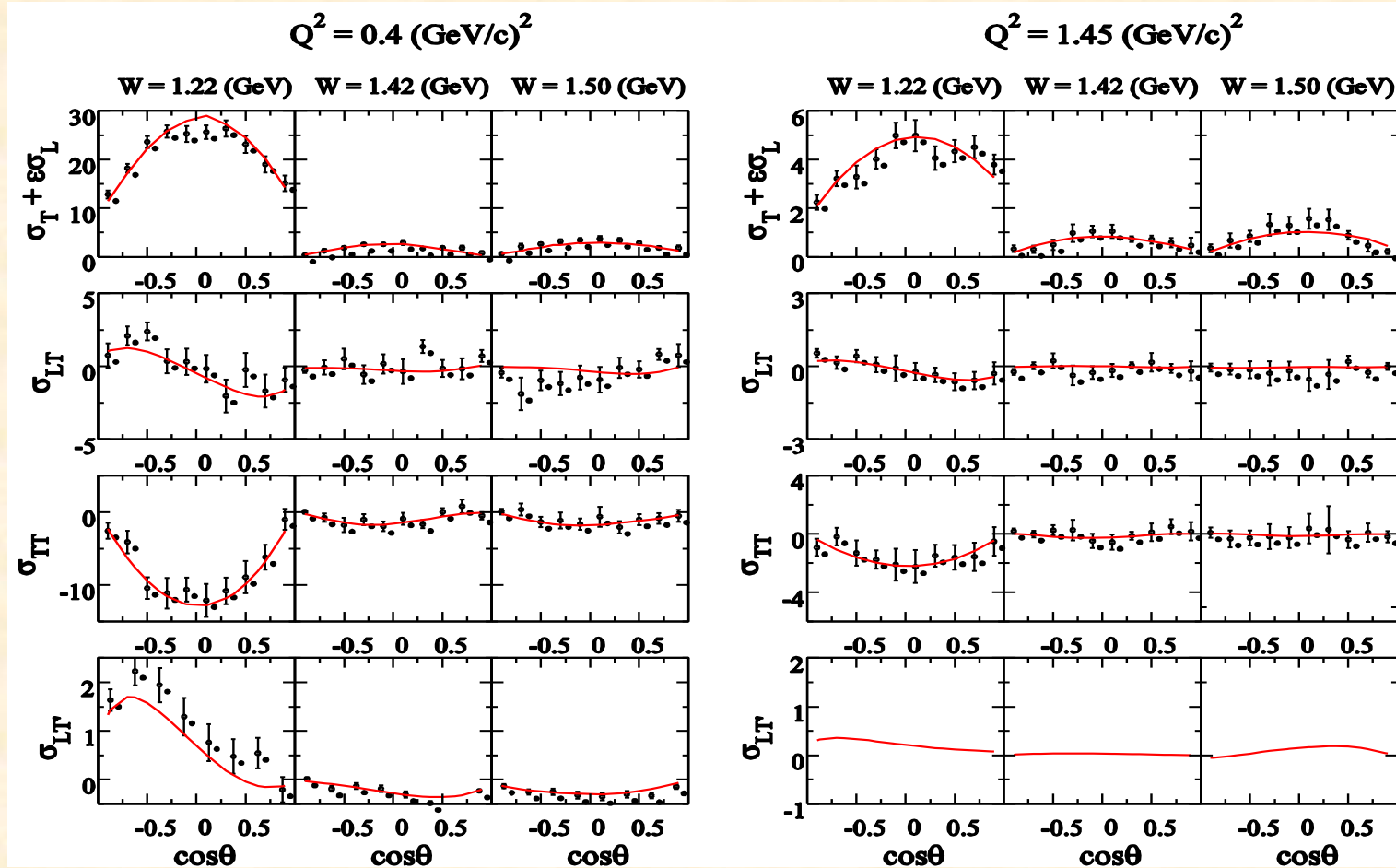
$\pi^- p \rightarrow K^0 \Sigma^0$



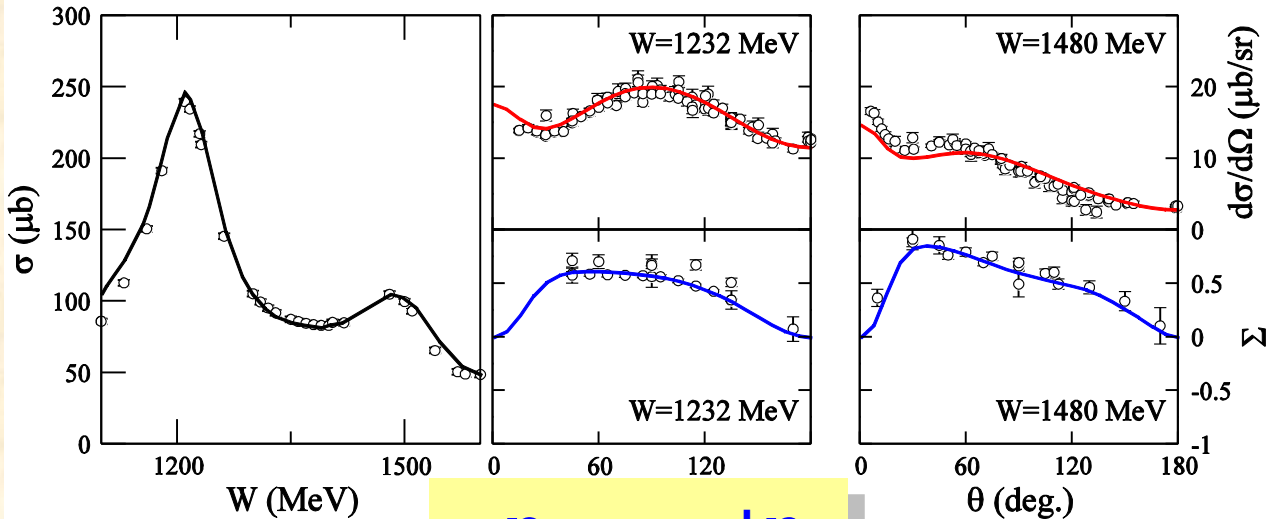
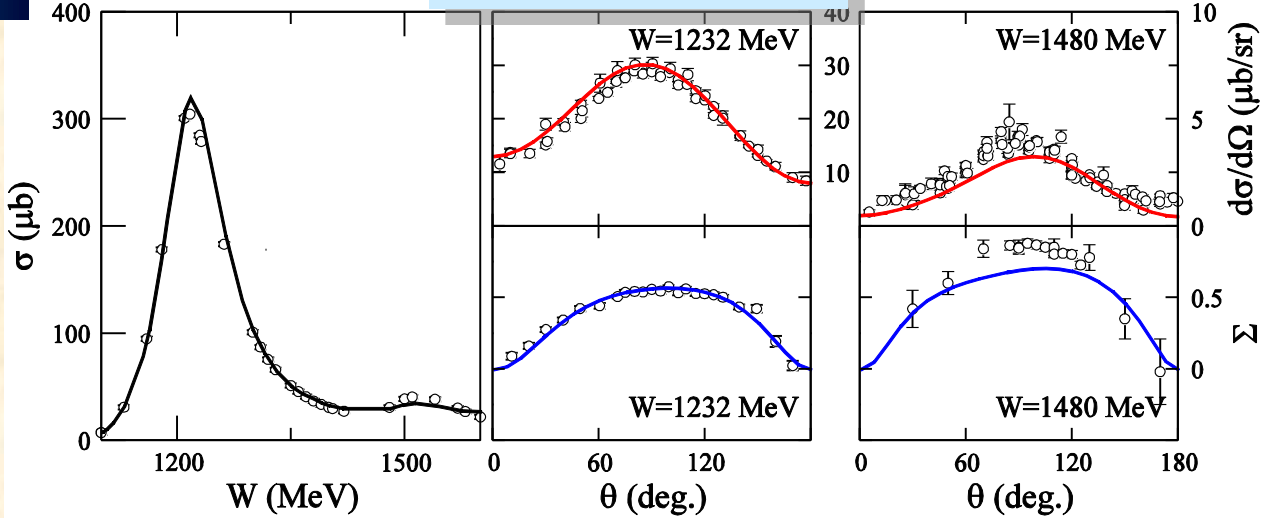
pion electroproduction: $ep \rightarrow e'\pi^0 p$

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

$$Q^2 > 0$$



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

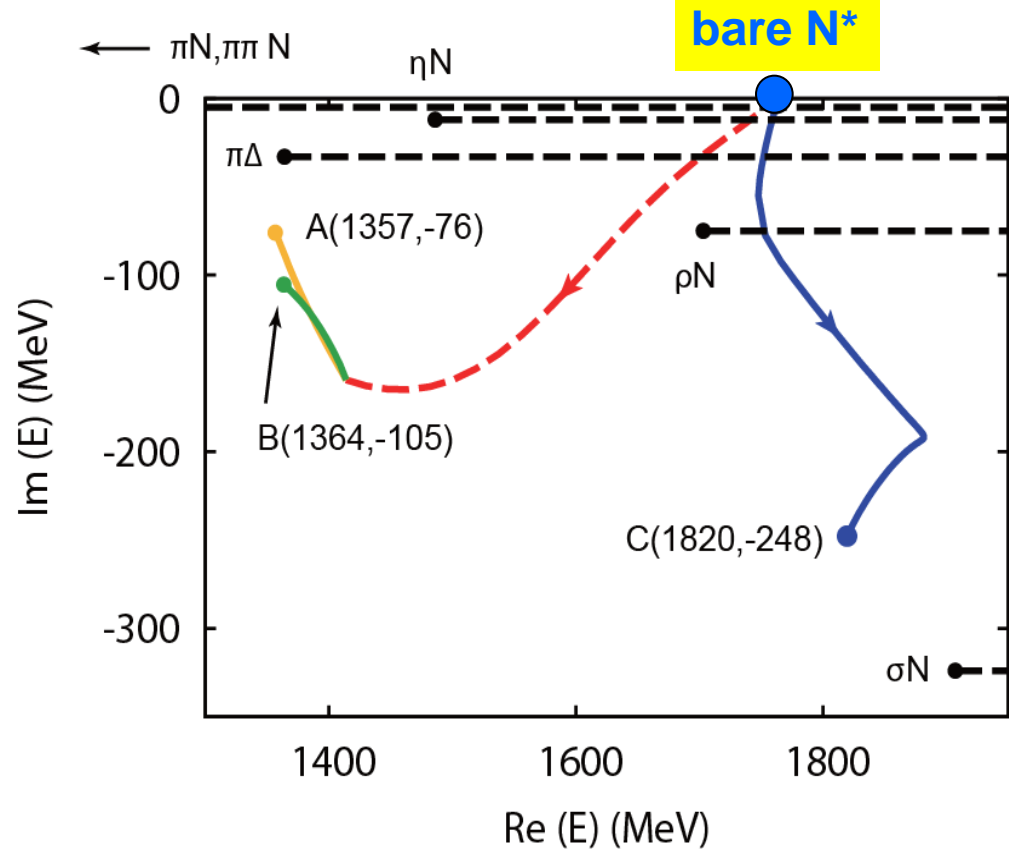
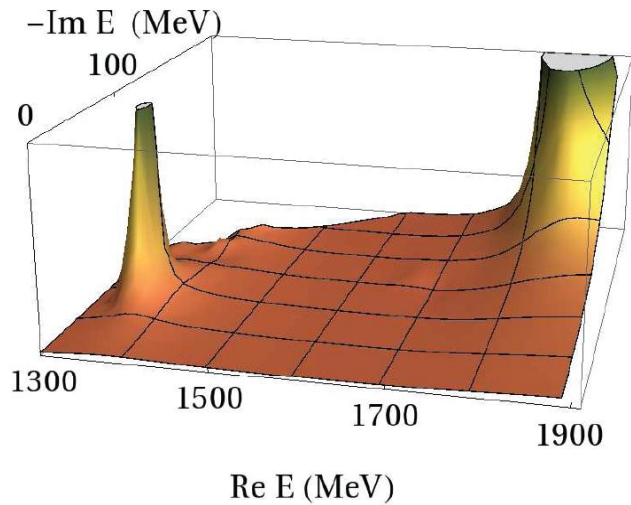


$\gamma p \rightarrow \pi^+ n$

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

EBAC

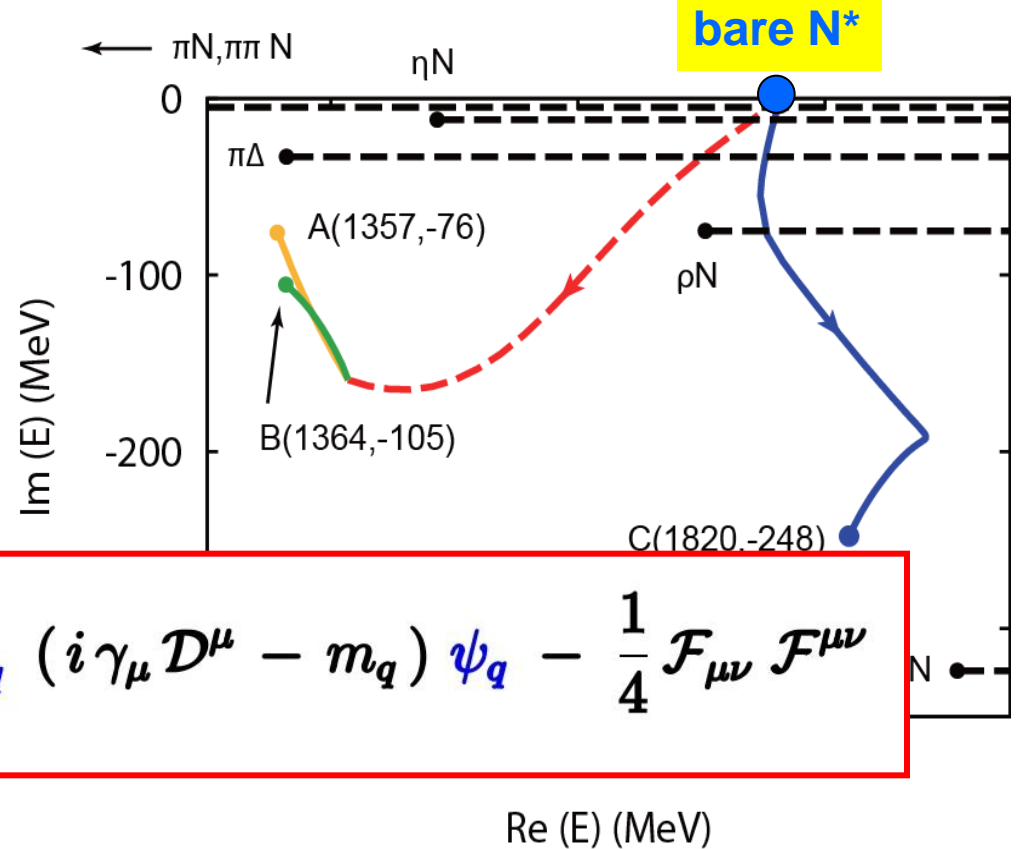
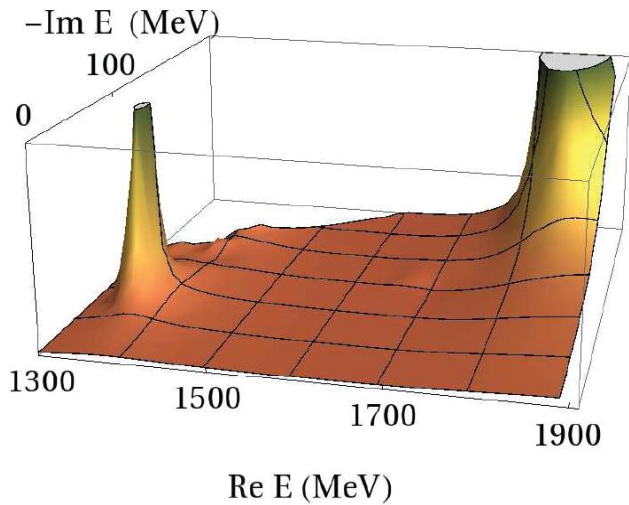
Suzuki et al.



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

EBAC

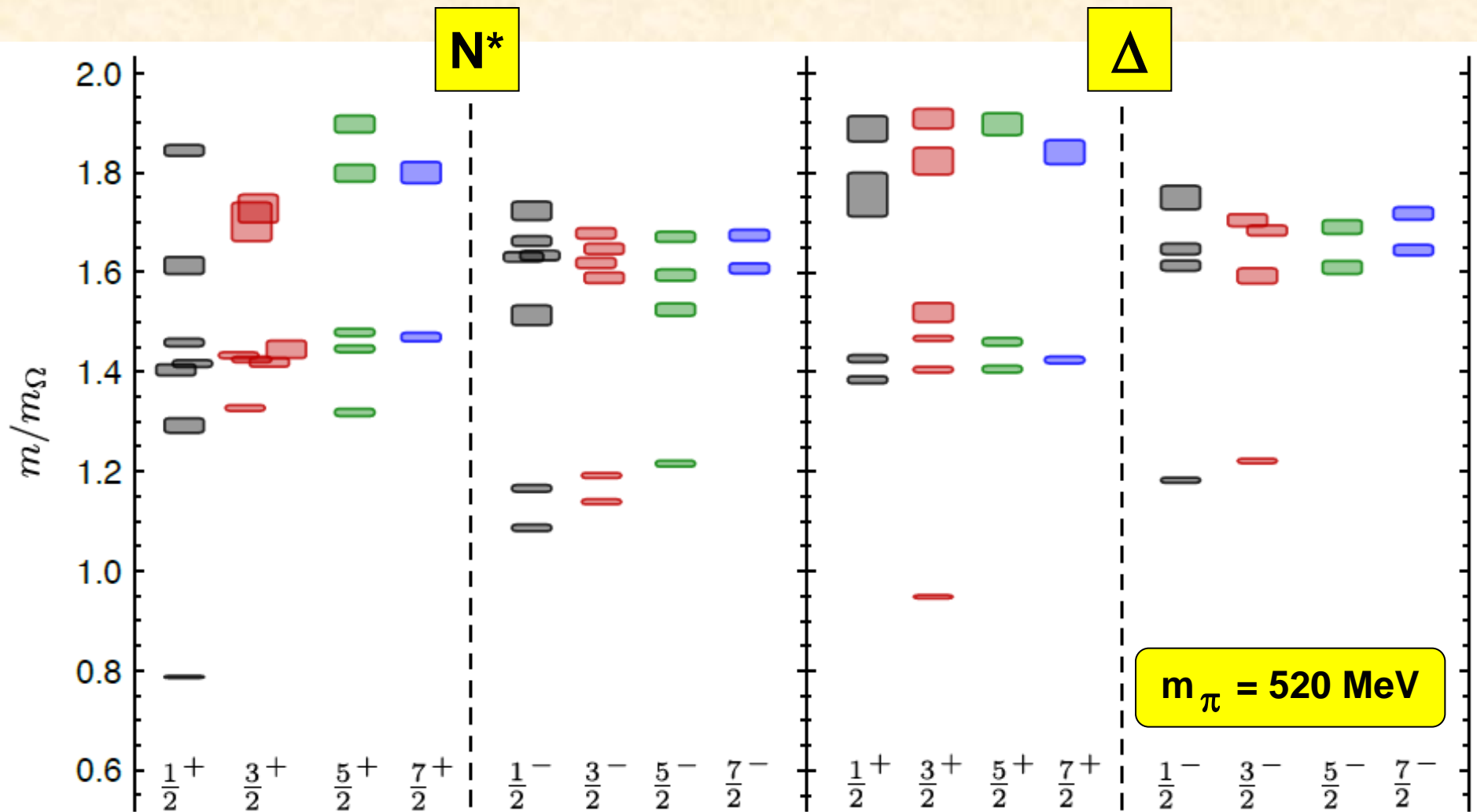
Suzuki et al.



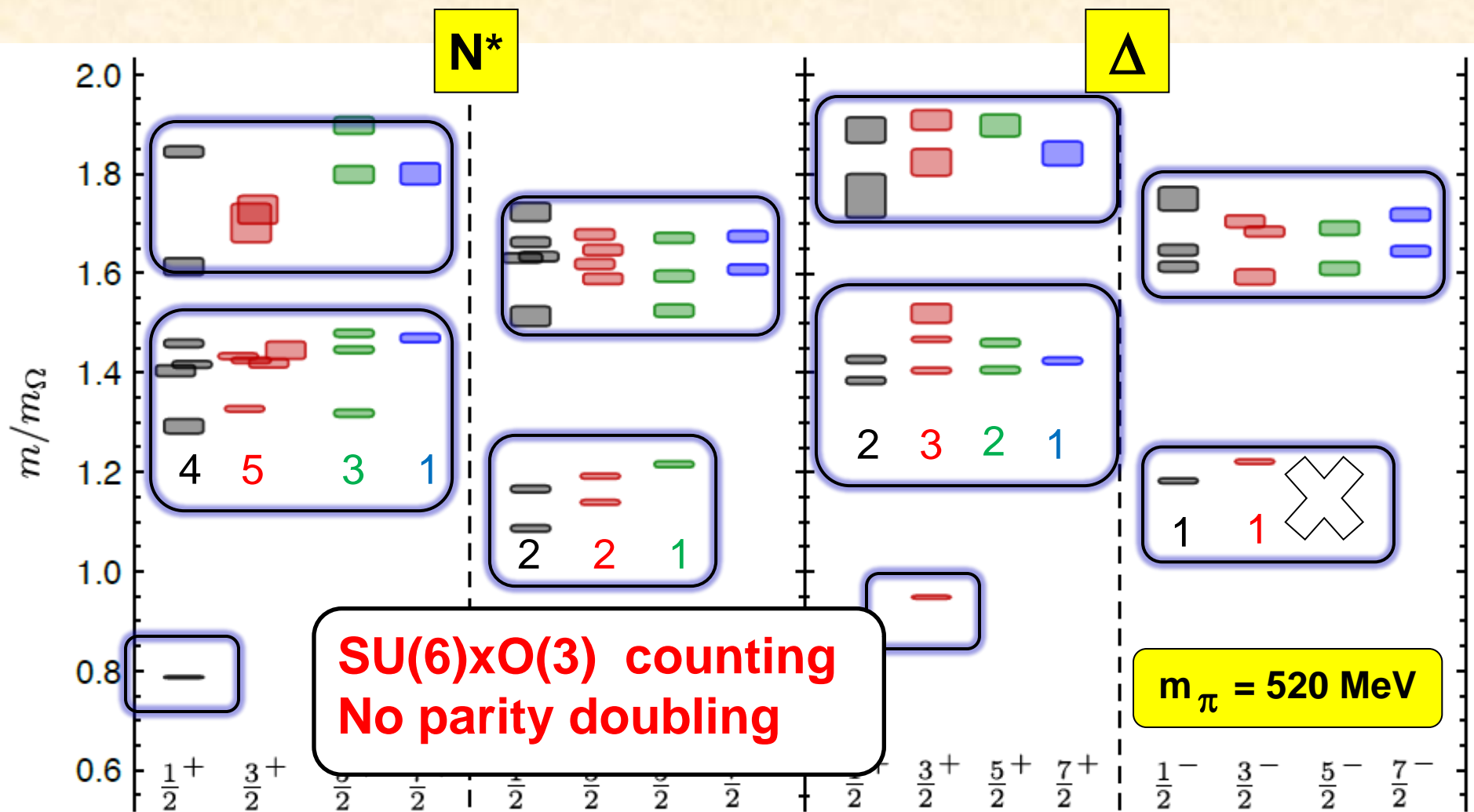
$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b} \bar{\psi}_q (i \gamma_\mu D^\mu - m_q) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$

Re (E) (MeV)

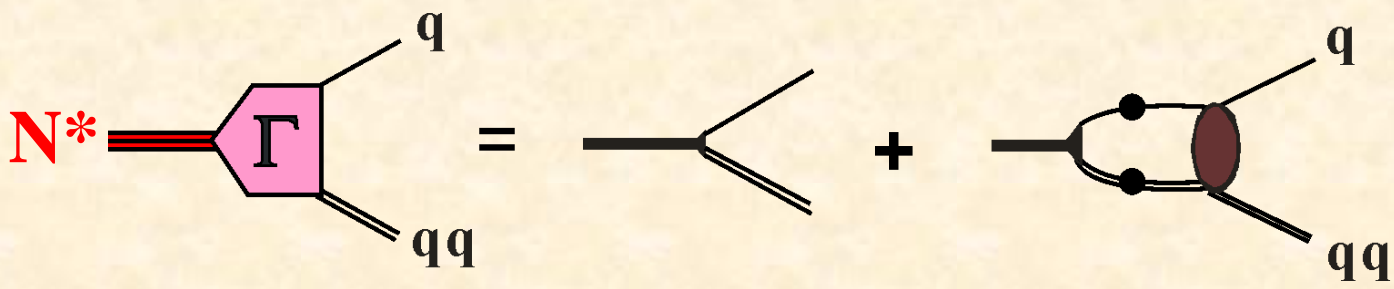
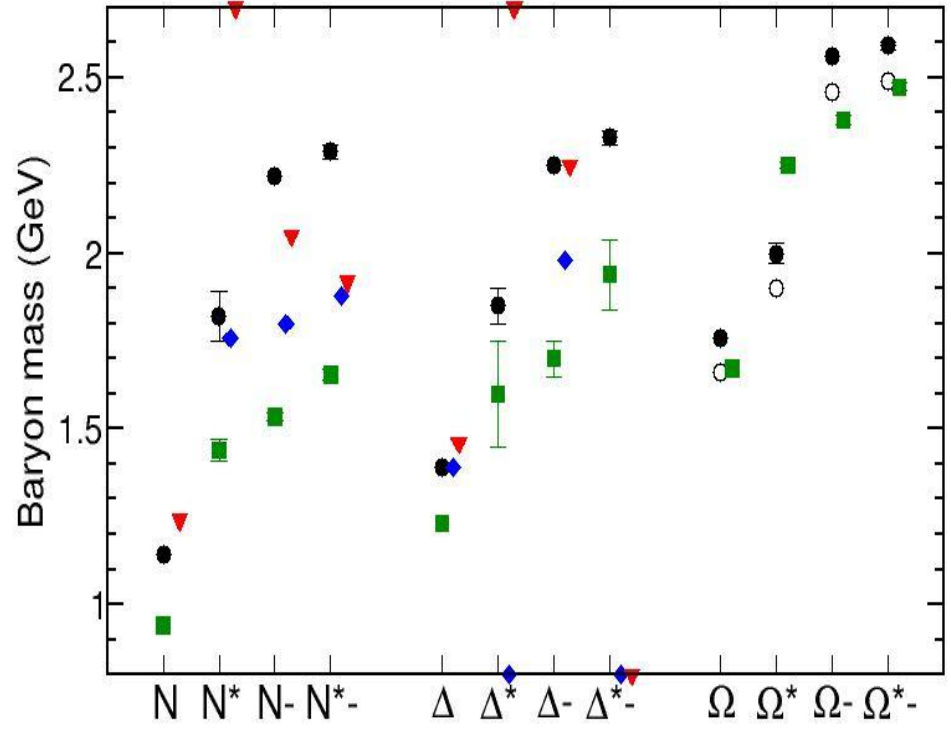
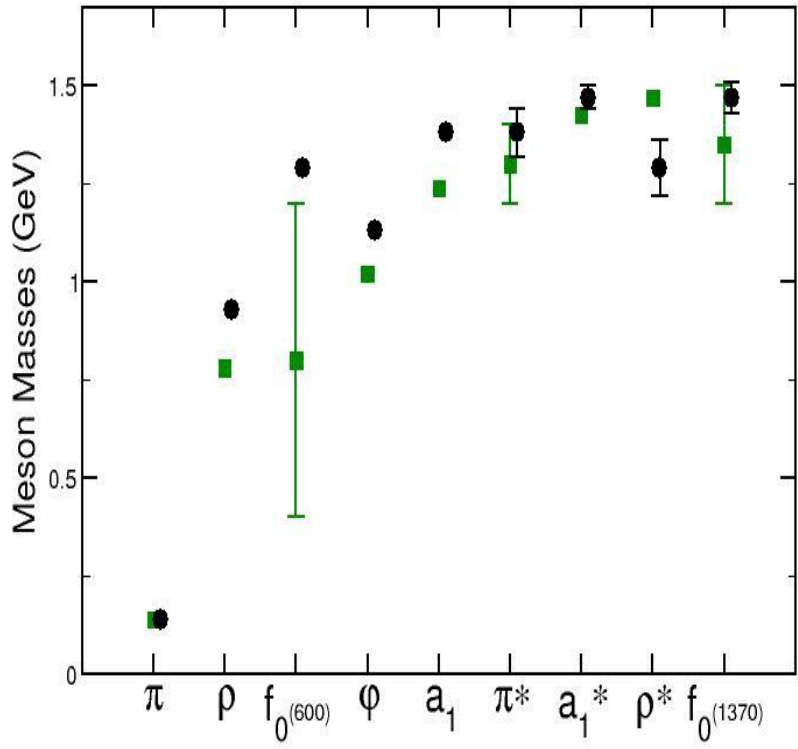
Spin identified N^* and Δ states



Spin identified N^* and Δ states

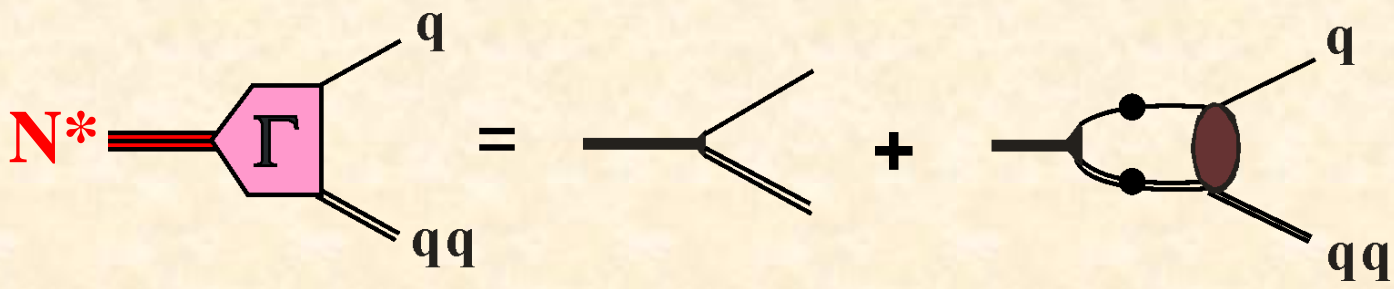
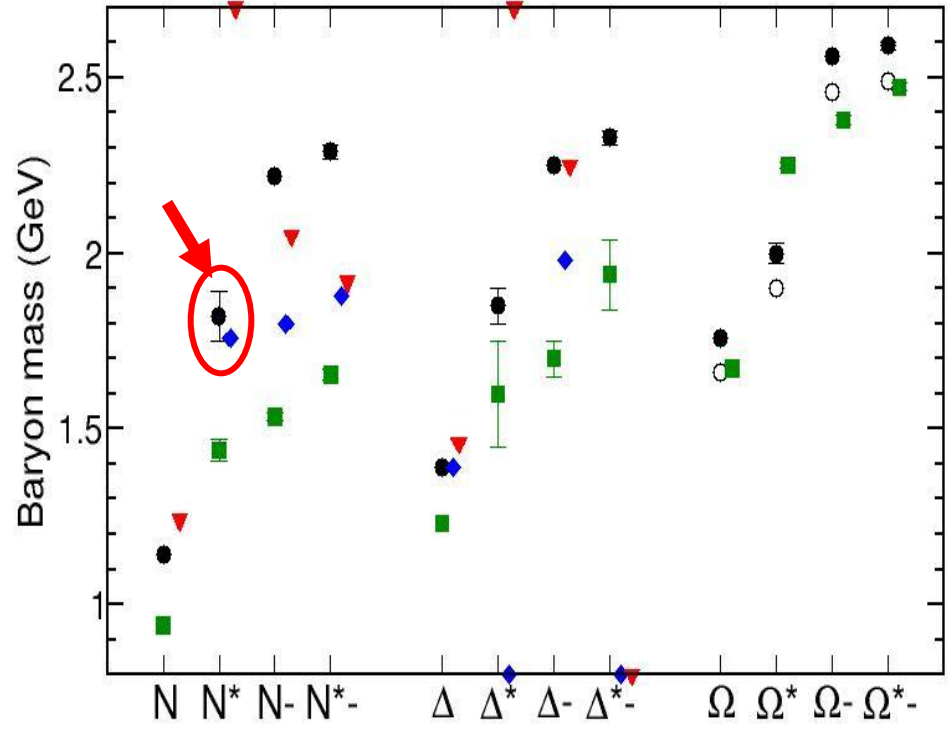
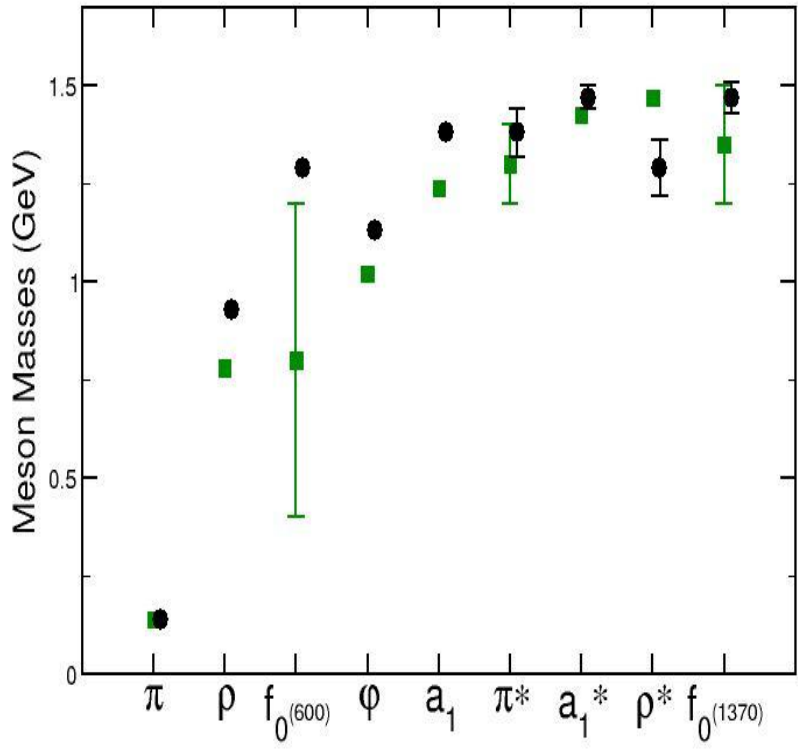


Hadron Spectrum in ANL BS model

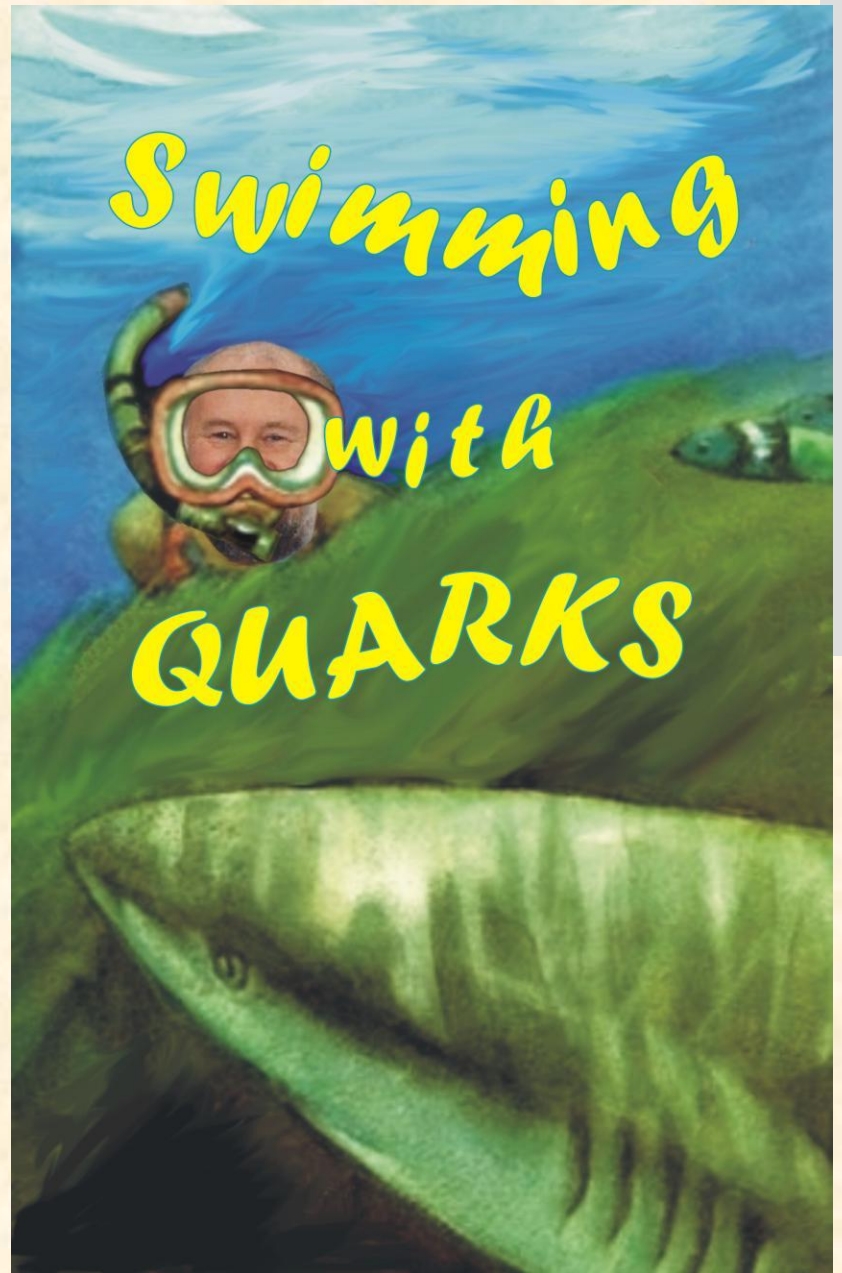
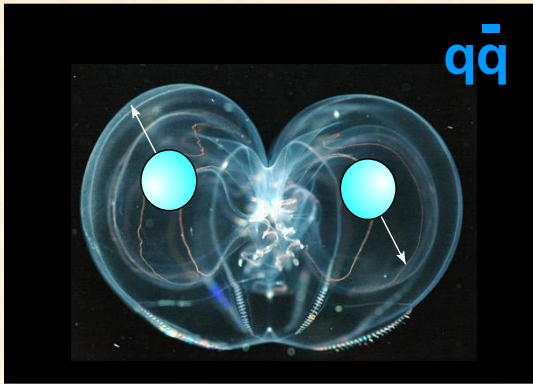


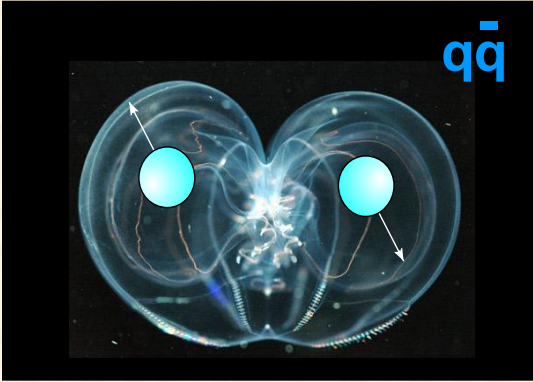
- Legend:**
- Particle Data Group
 - H.L.L. Roberts *et al.*
 - ◆ EBAC
 - ▼ Jülich

Hadron Spectrum in ANL BS model



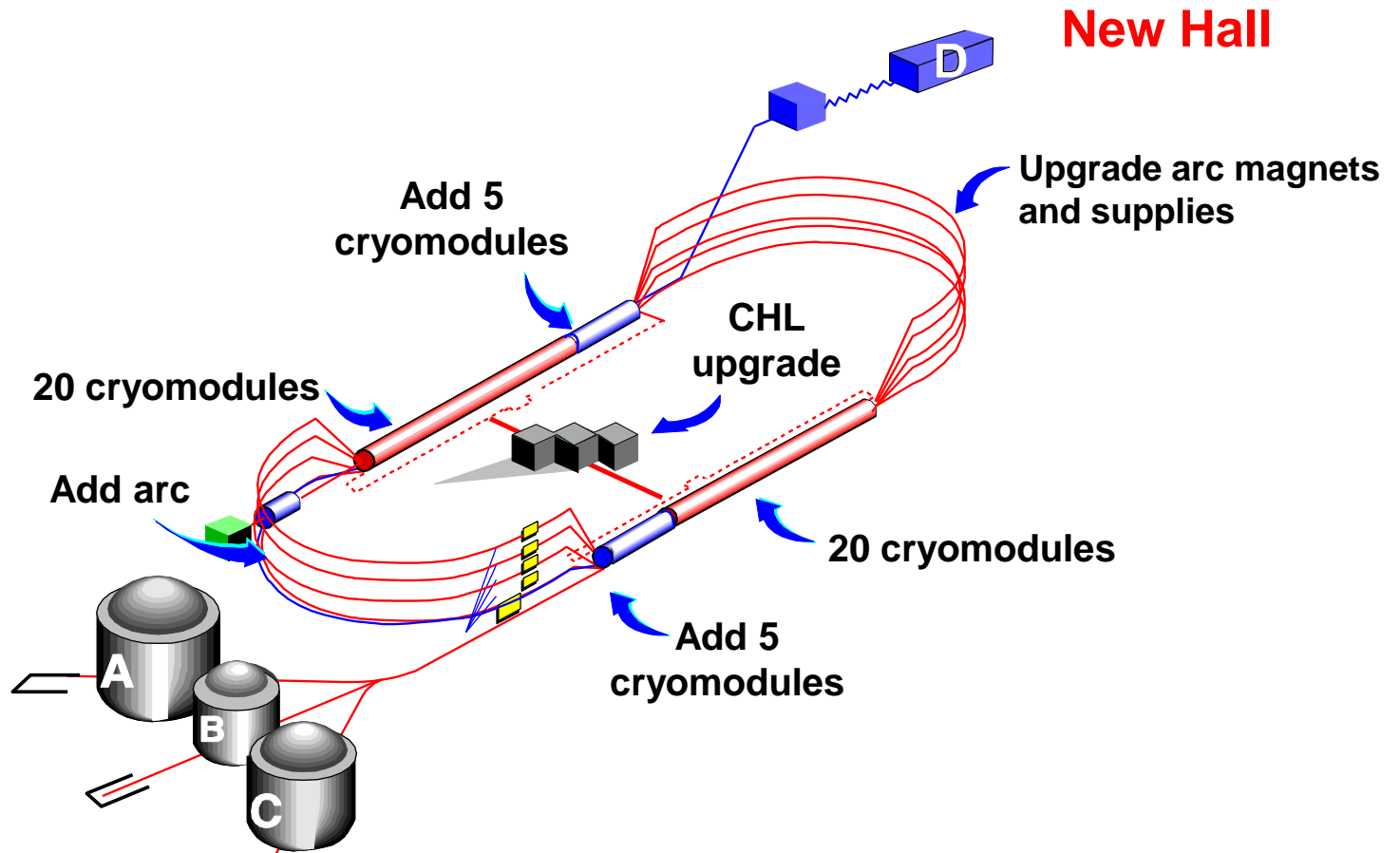
- Legend:**
- Particle Data Group
 - H.L.L. Roberts *et al.*
 - ◆ EBAC
 - ▼ Jülich





Jefferson Lab 12 GeV upgrade

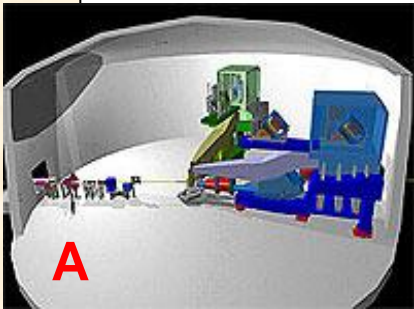
Exploring the Nature of Matter



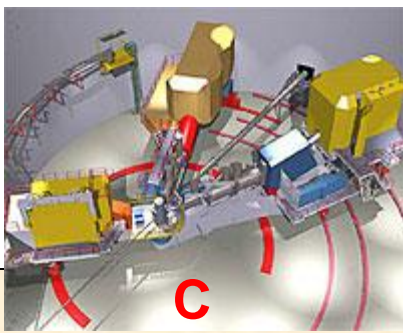
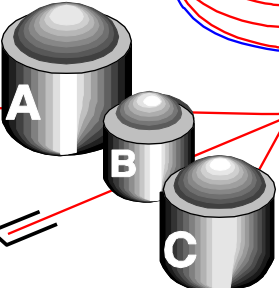
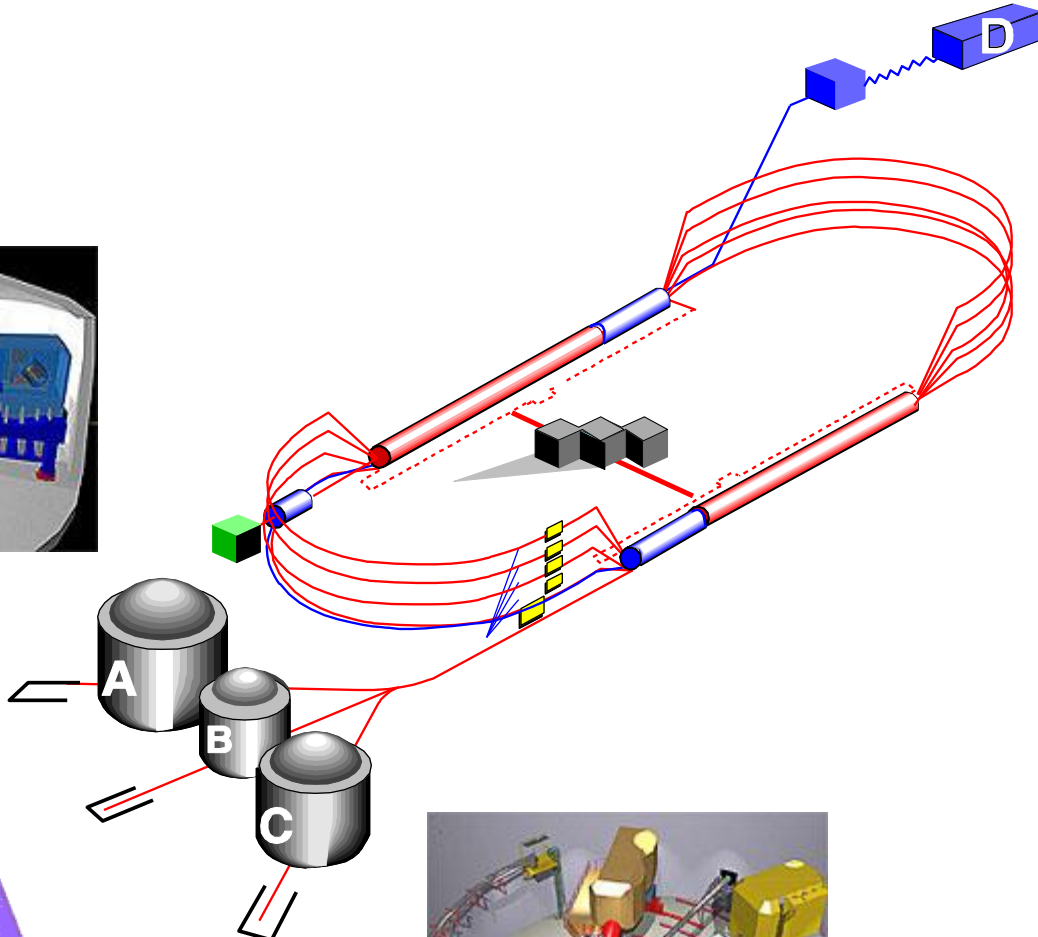
**Enhanced capabilities
in existing Halls**

Jefferson Lab 12 GeV upgrade

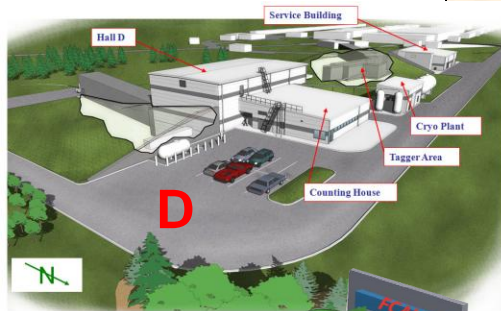
Exploring the Nature of Matter



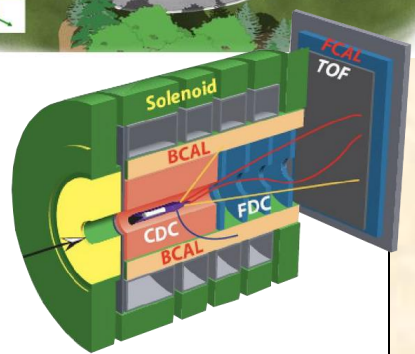
A



C



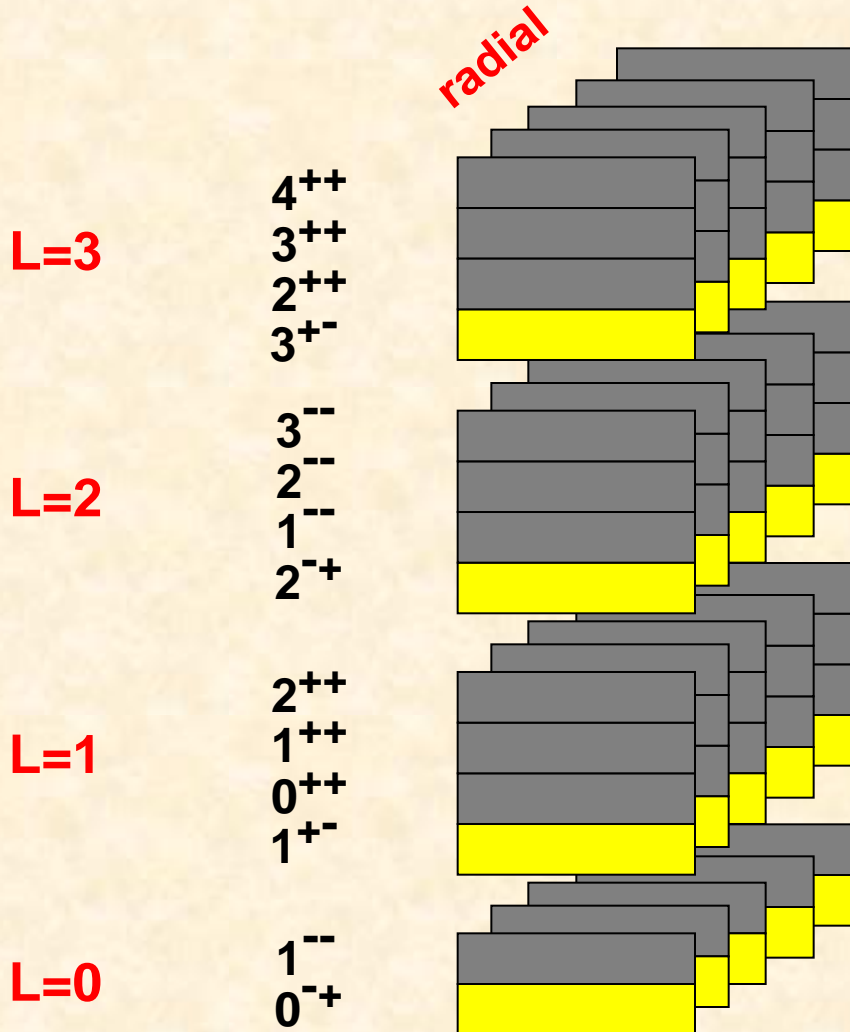
D



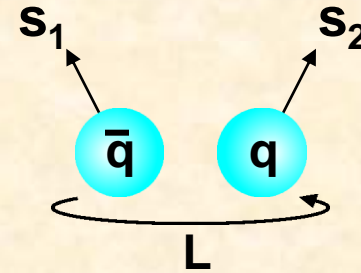
GlueX

B CLAS12

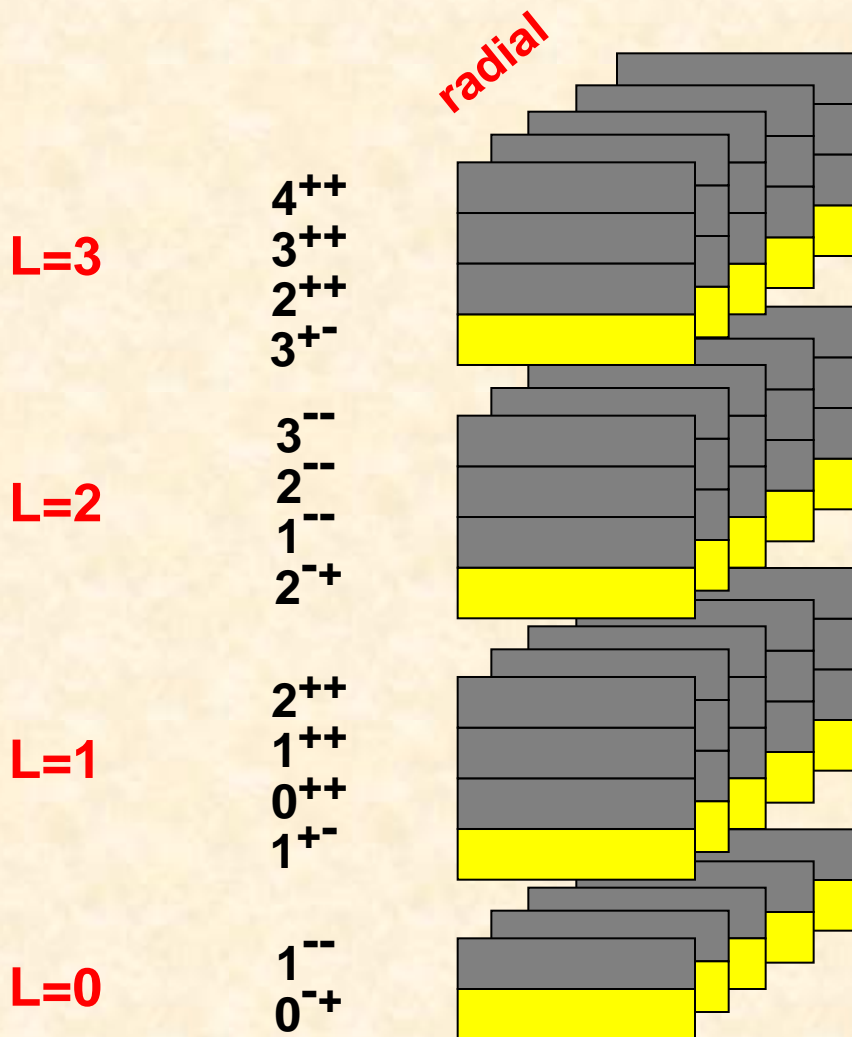
Meson spectrum



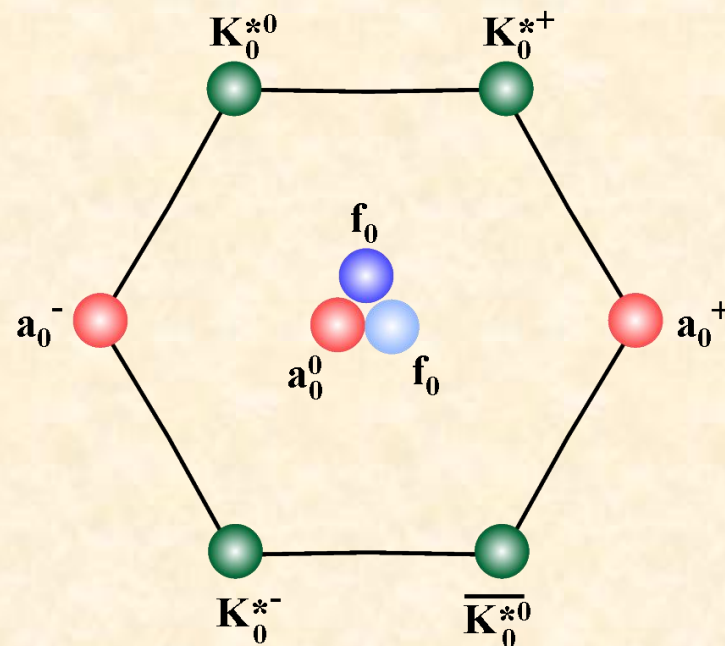
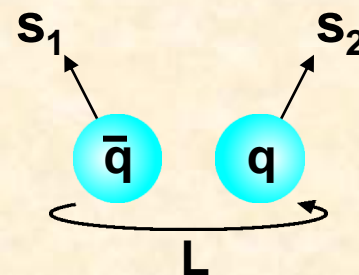
$$S = 0, 1$$



Meson spectrum



$$S = 0, 1$$



allowed J^{PC}

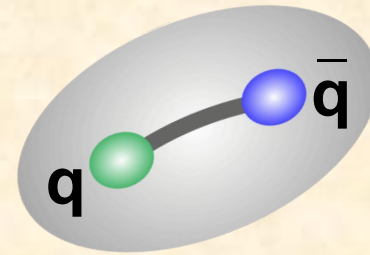
0^{--} 0^{-+} 0^{+-} 0^{++}

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

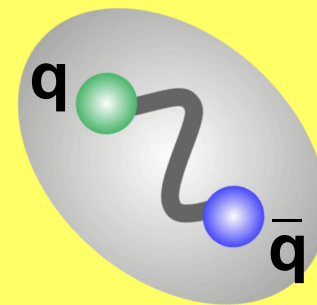
2^{--} 2^{-+} 2^{+-} 2^{++}

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

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



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



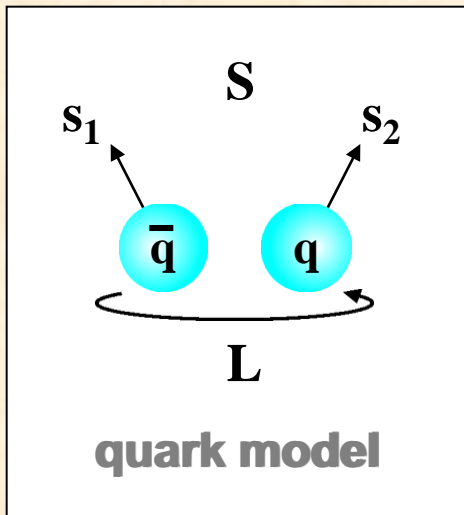
Mesons: J^{PC} quantum numbers

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

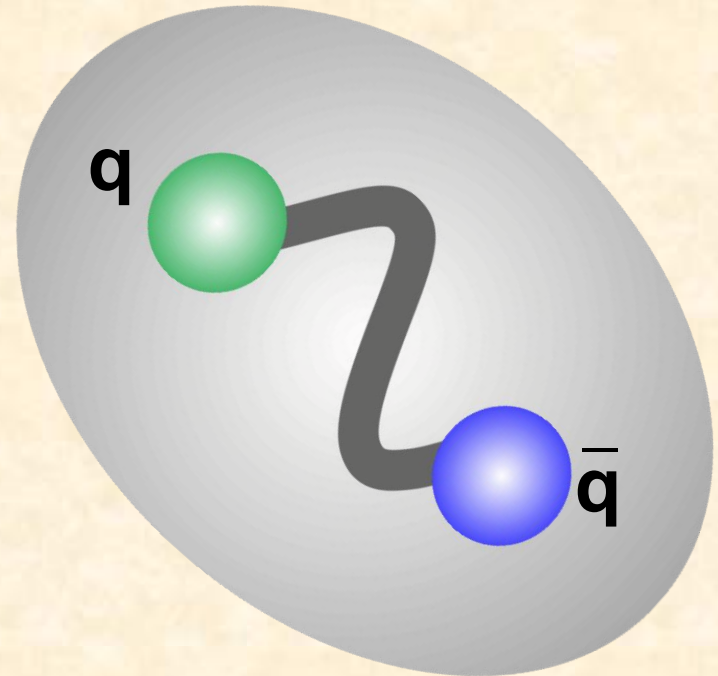
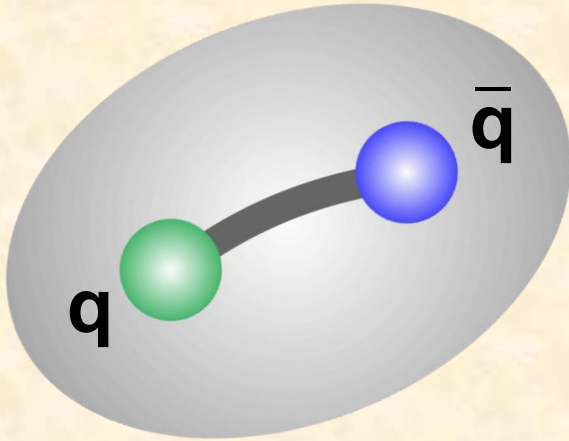
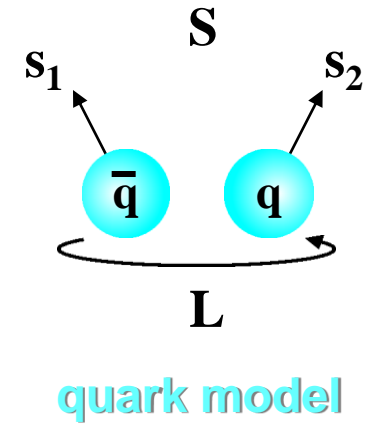
1^{++} 1^{+-} 1^{-+} 1^{--}

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

...



Calculating Exotic Mesons



Lattice Game Show

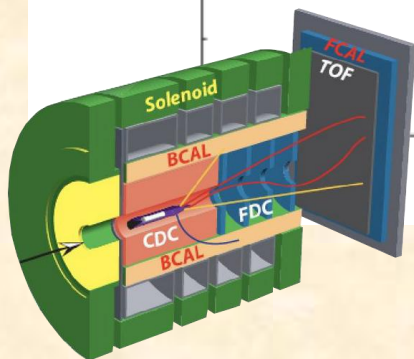
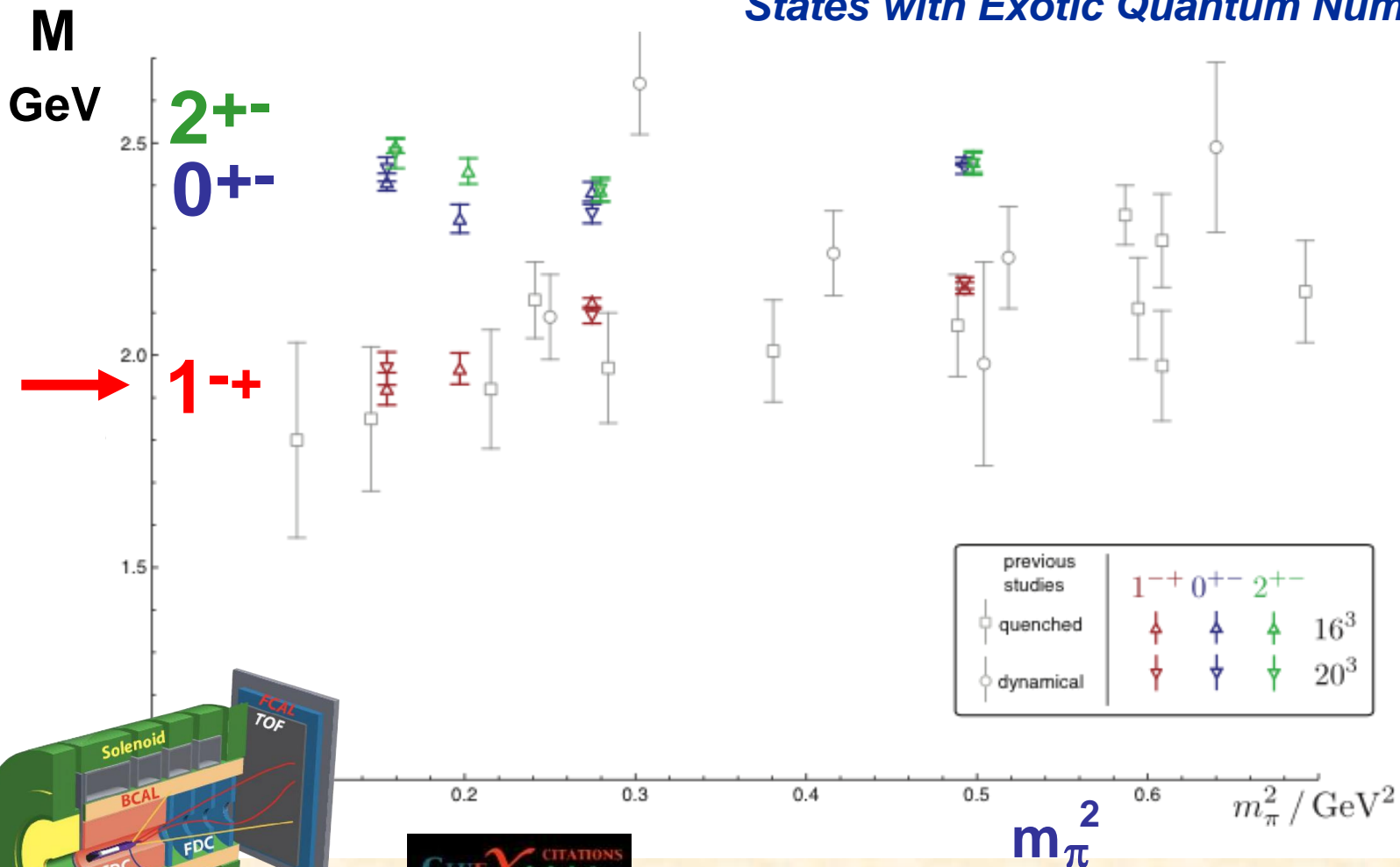


Lattice Game Show

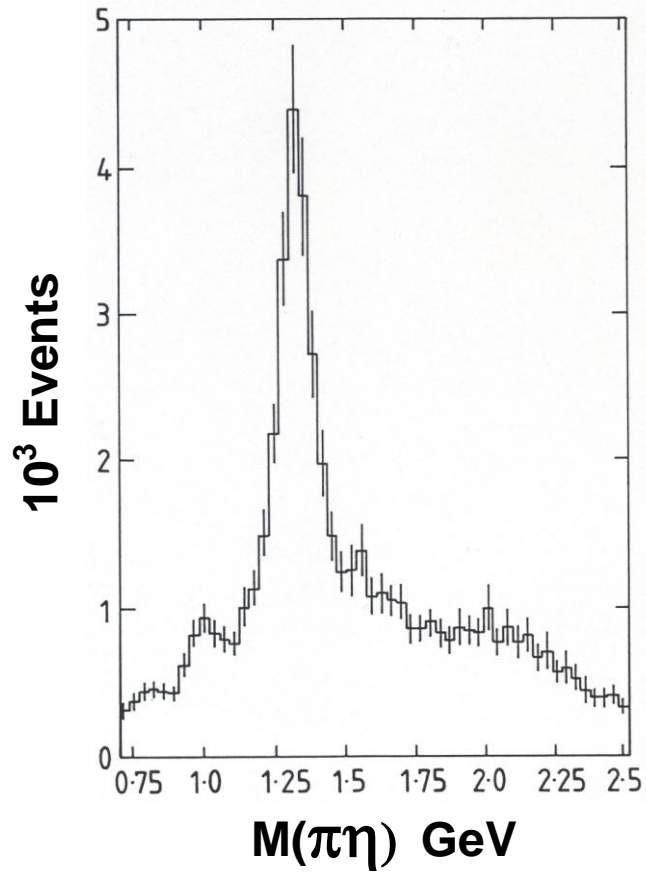
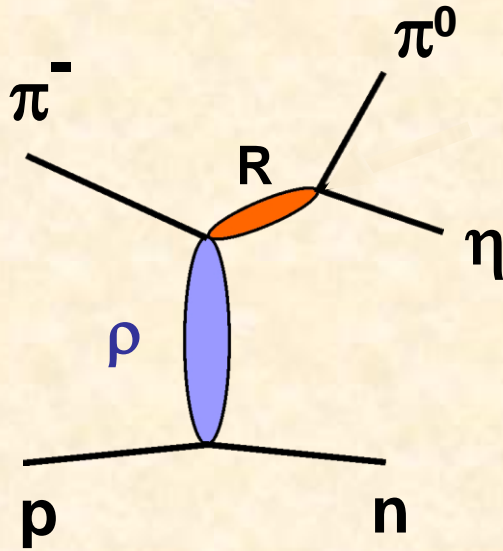
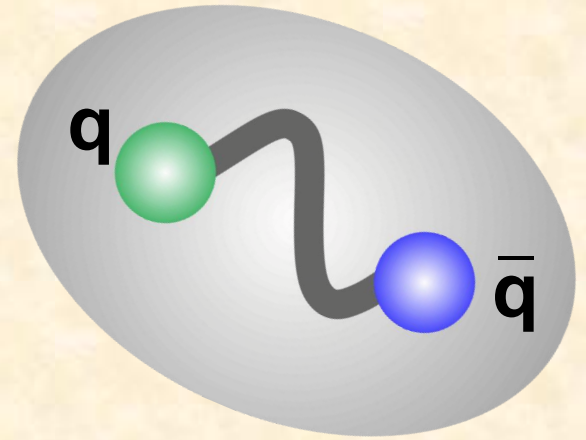


Isvector Meson Spectrum

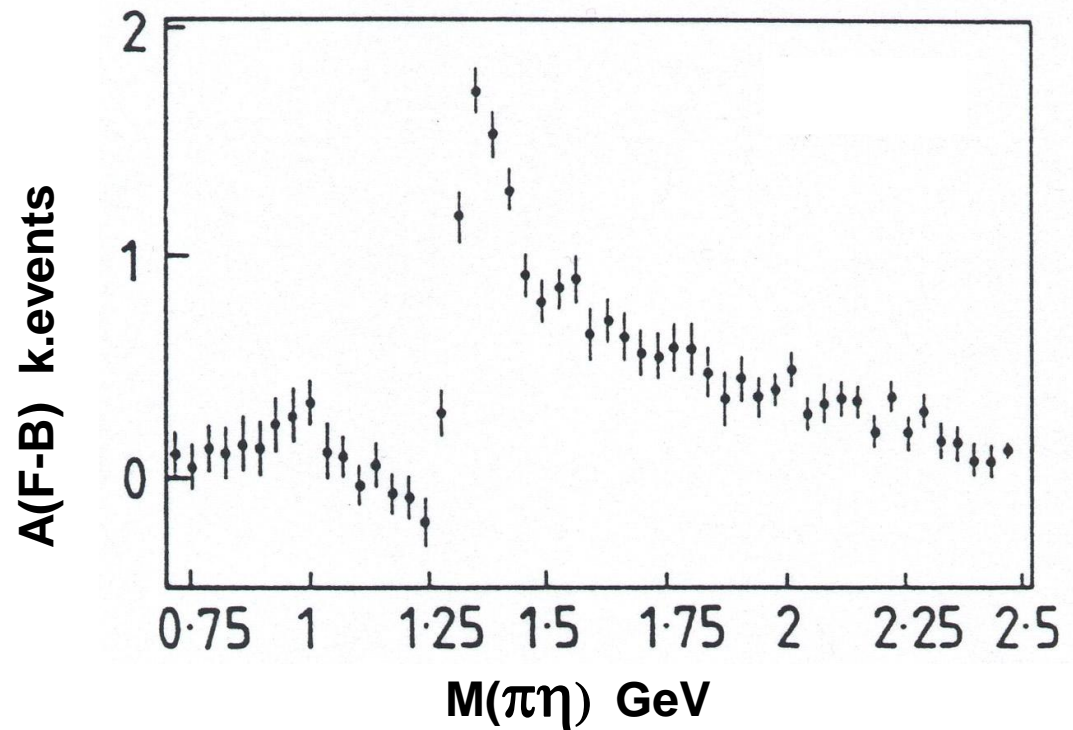
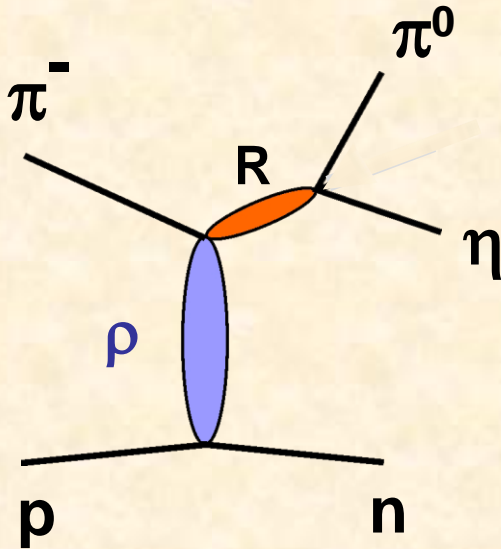
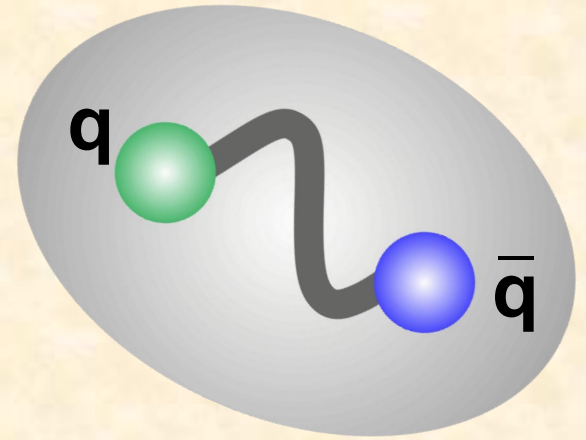
States with Exotic Quantum Numbers



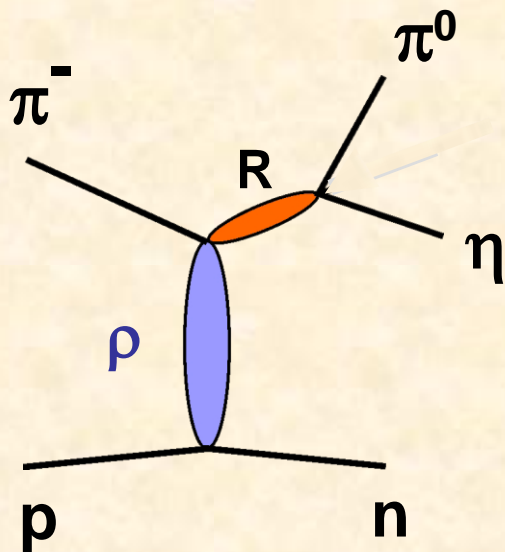
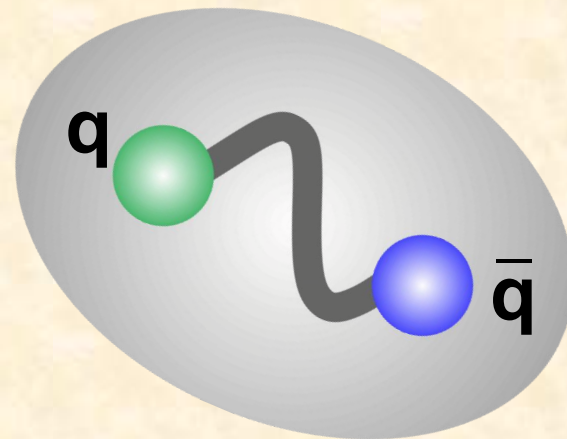
GAMS: $\pi^- p \rightarrow \pi^0 \eta n$



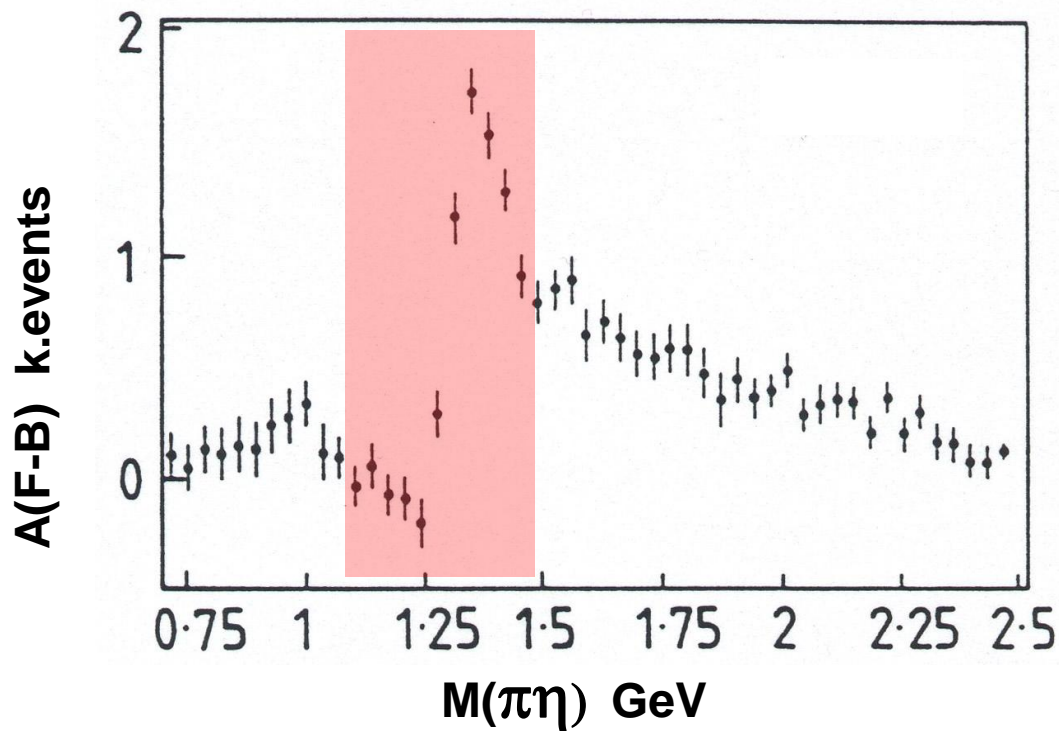
GAMS: $\pi^- p \rightarrow \pi^0 \eta n$



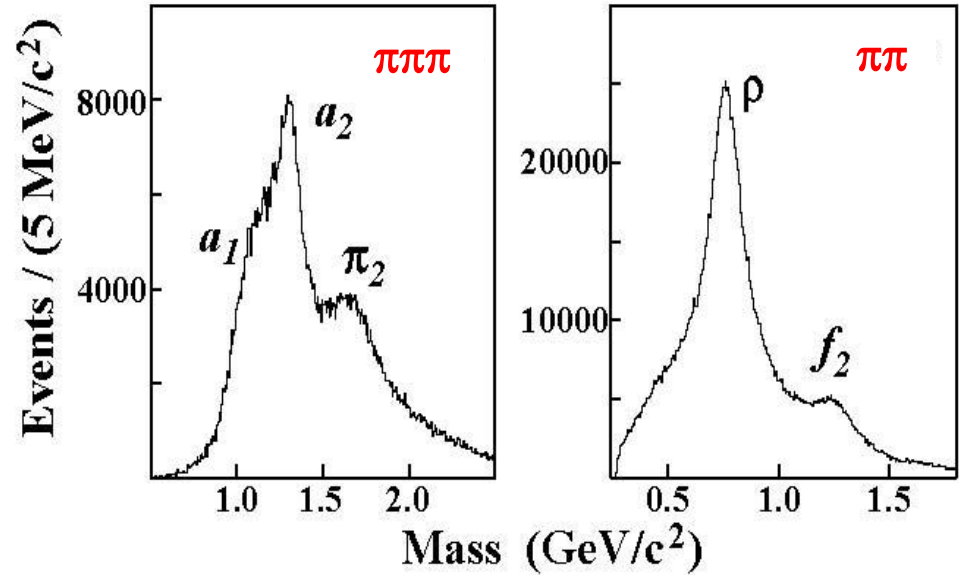
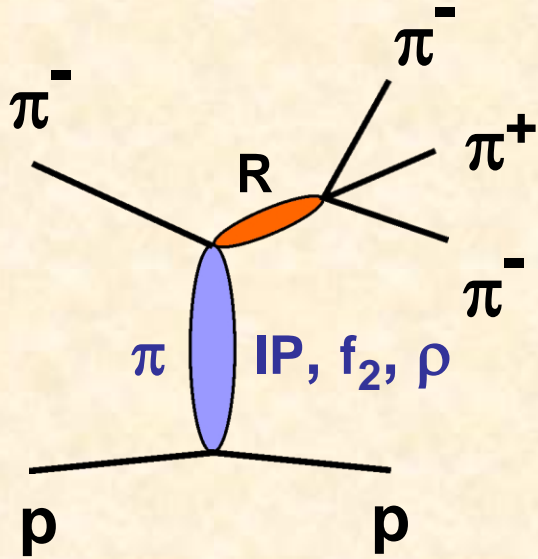
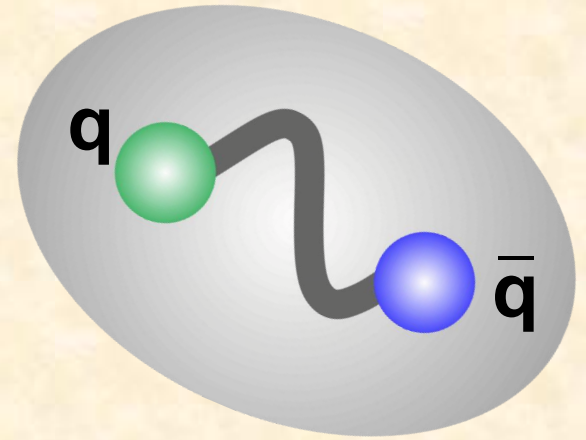
GAMS: $\pi^- p \rightarrow \pi^0 \eta n$



1^{-+}



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

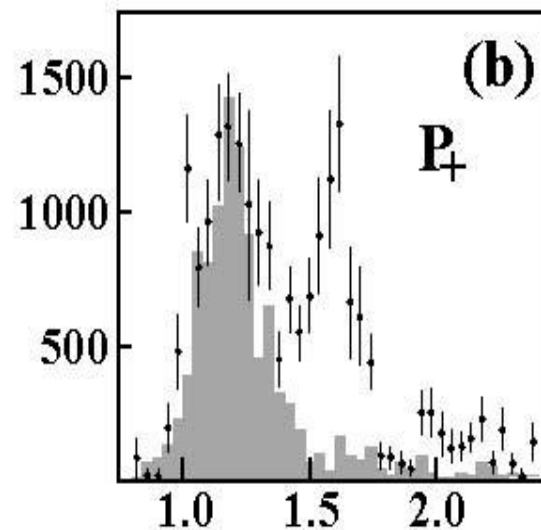
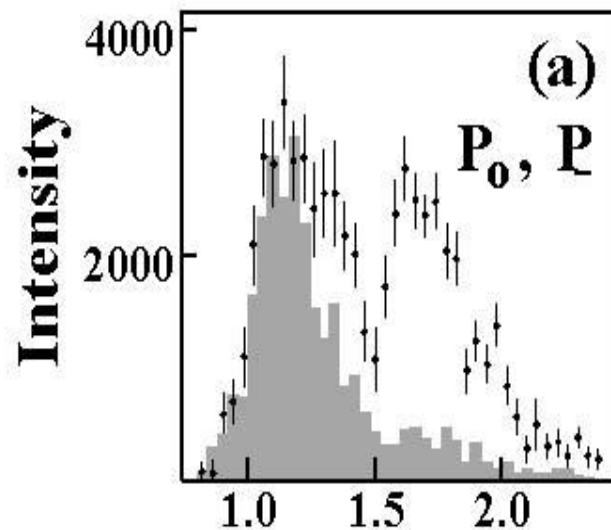


250k events

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

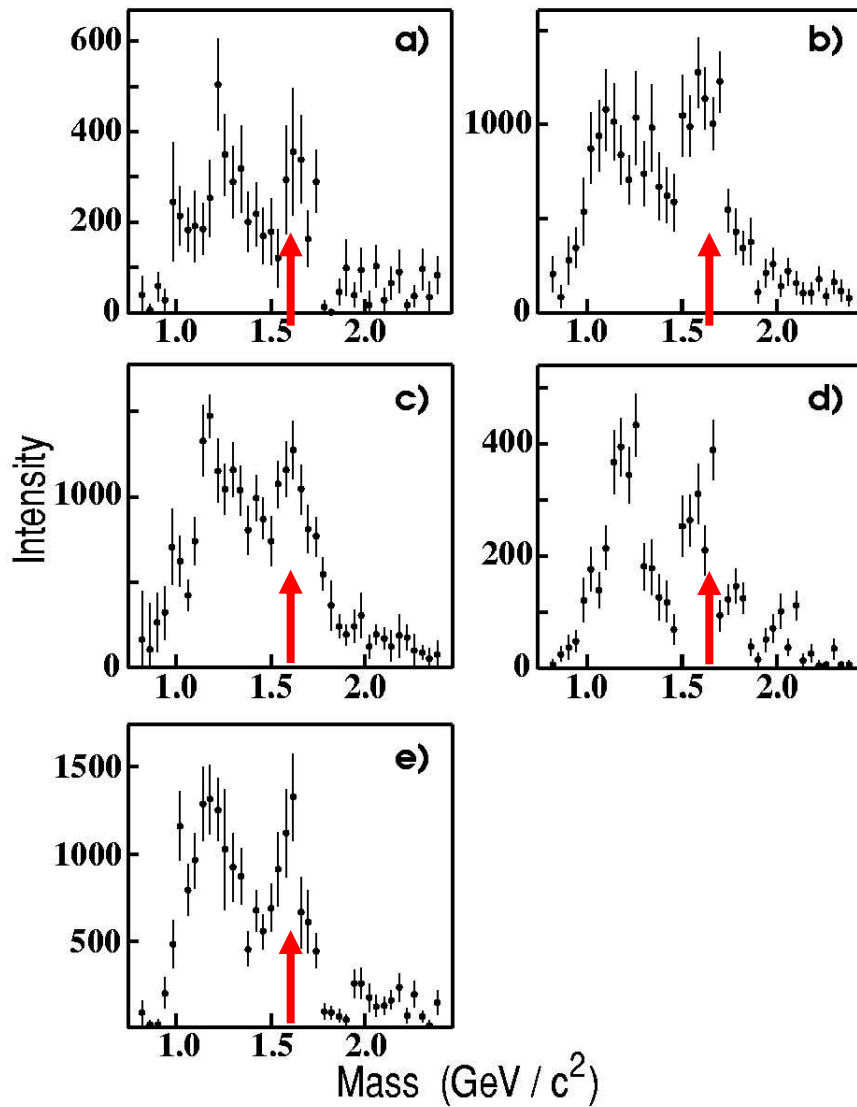


Monte Carlo
with **NO** 1^{++}



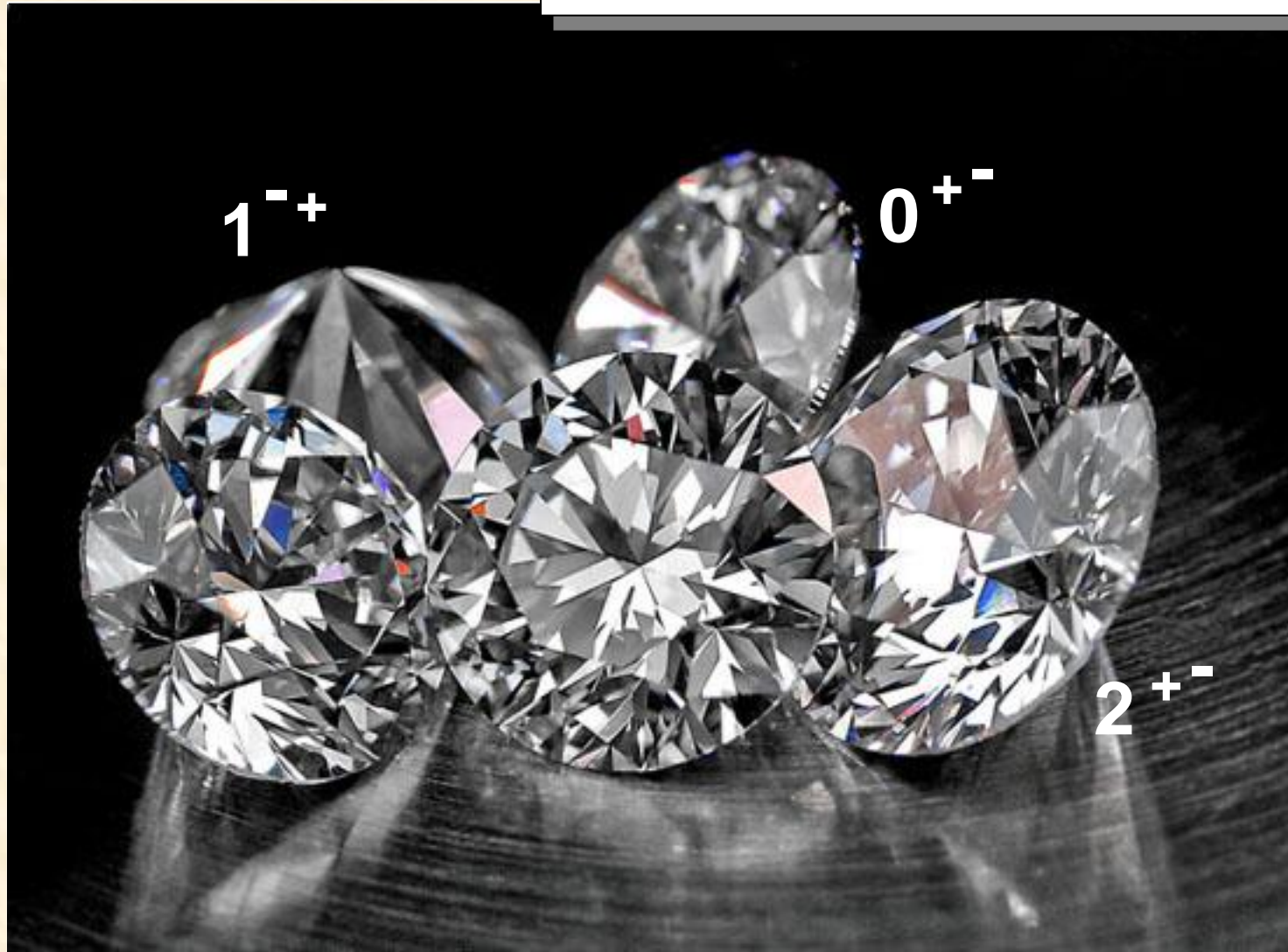
Mass (GeV/c^2)

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

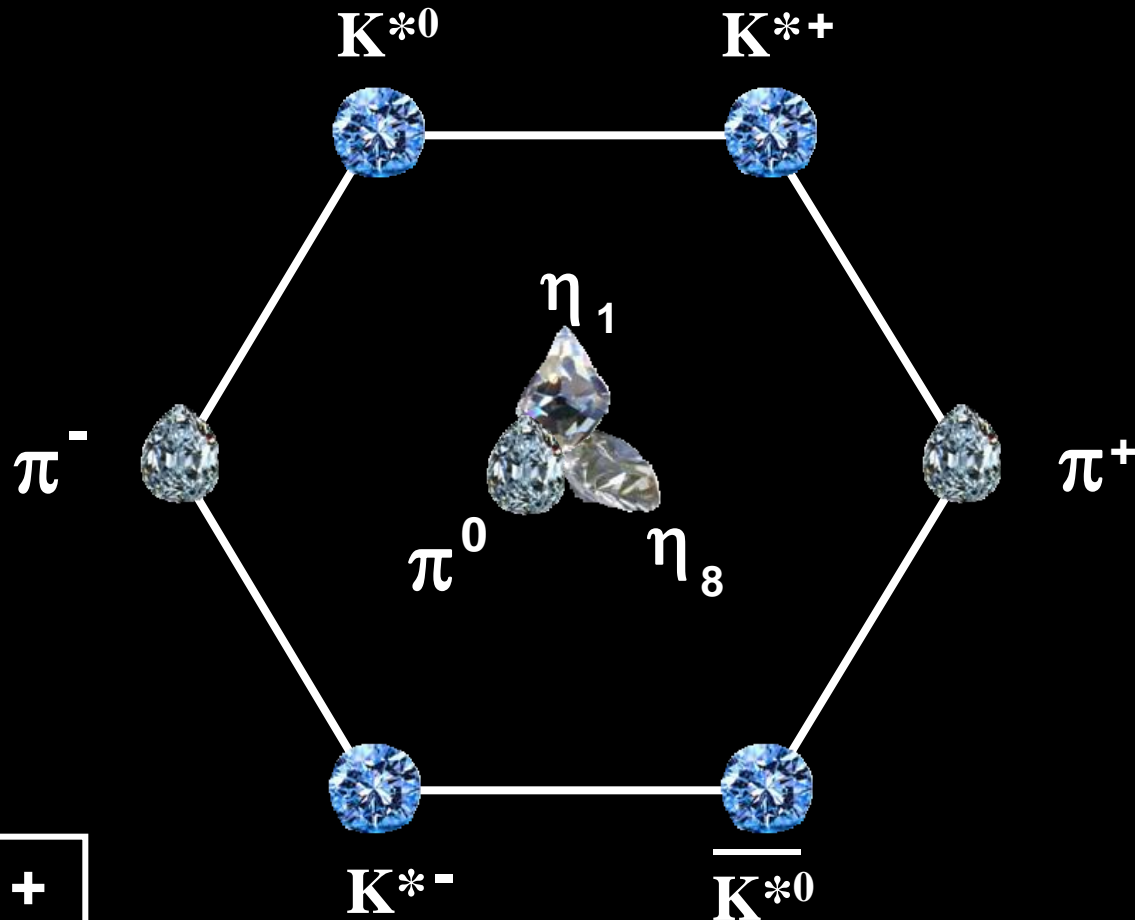


variation of 1^{-+} with 0^{++}

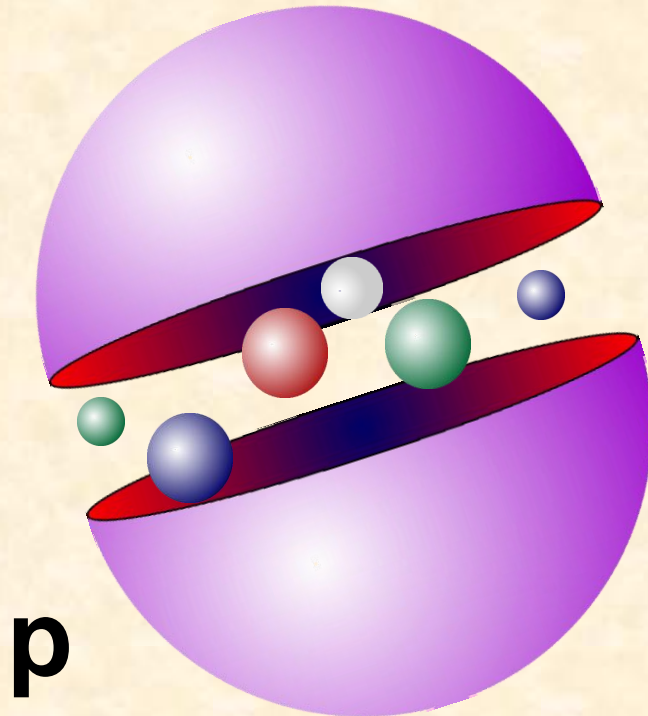
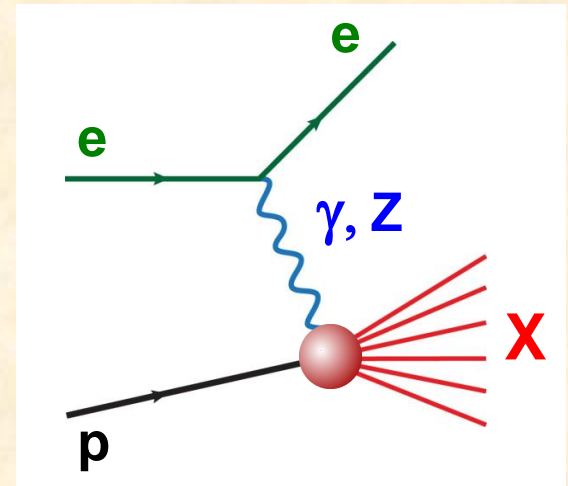
Precision analysis tools

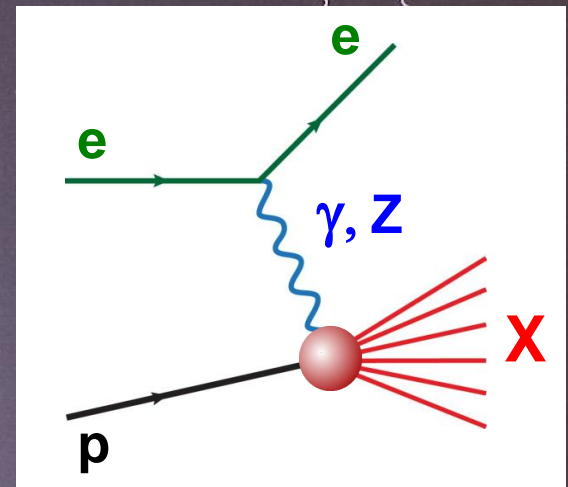
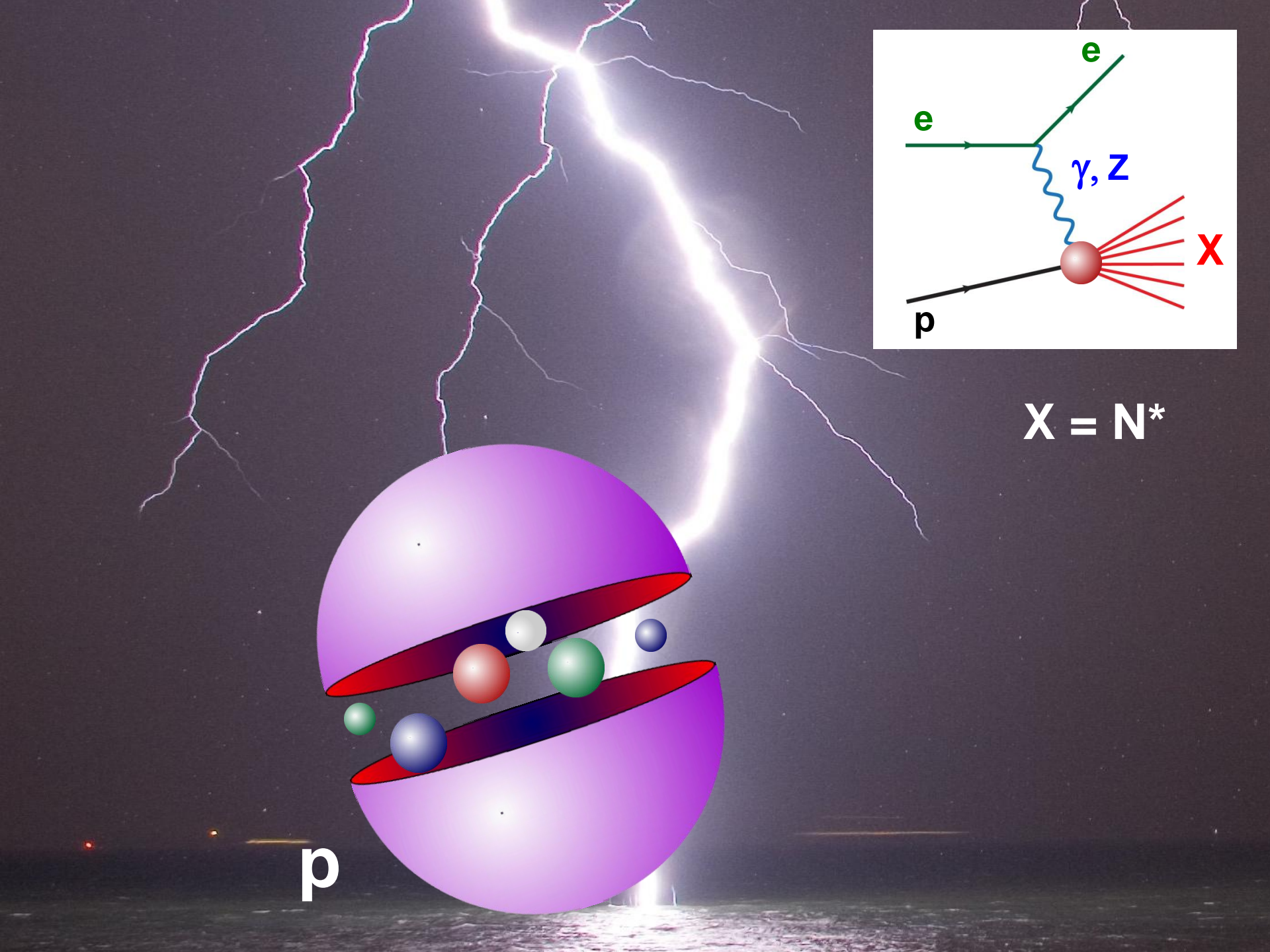


Precision analysis tools

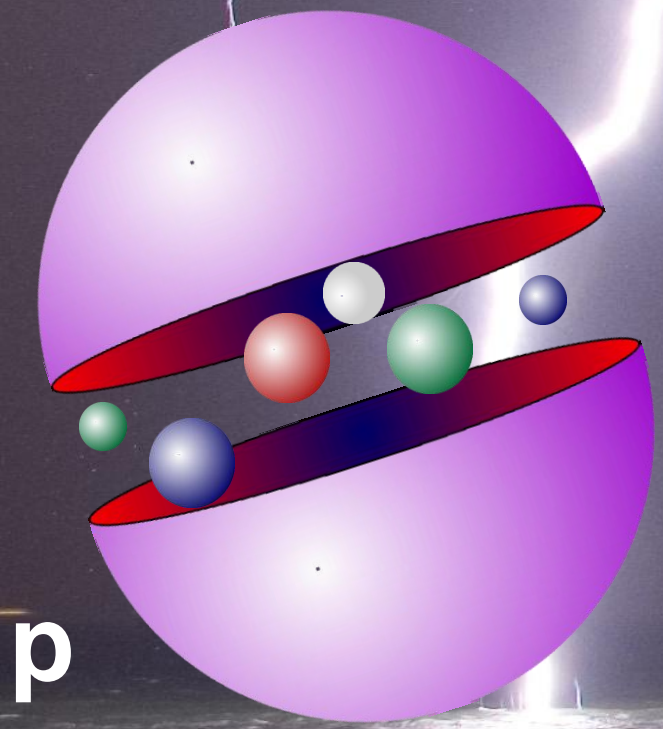


probing excited baryons

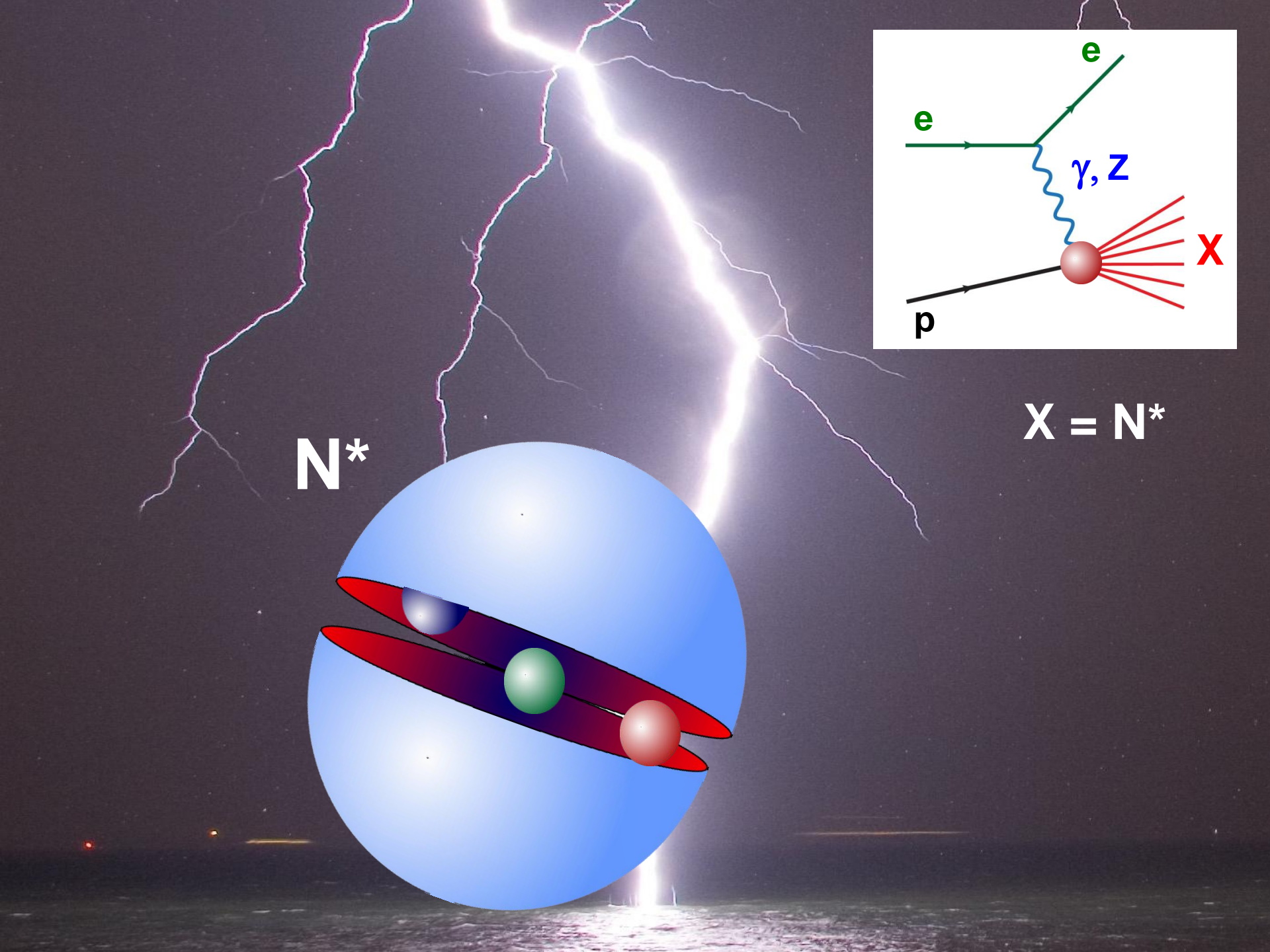




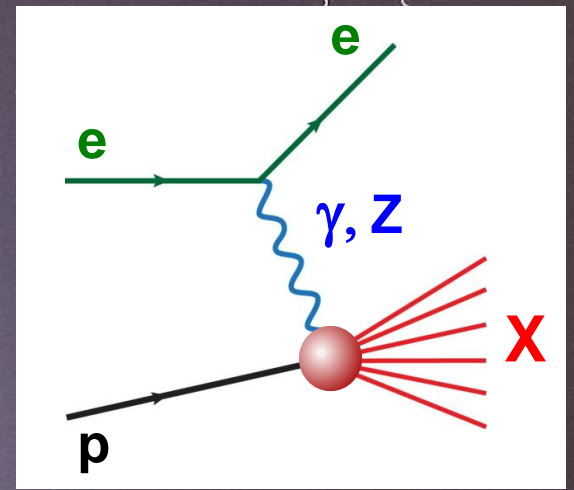
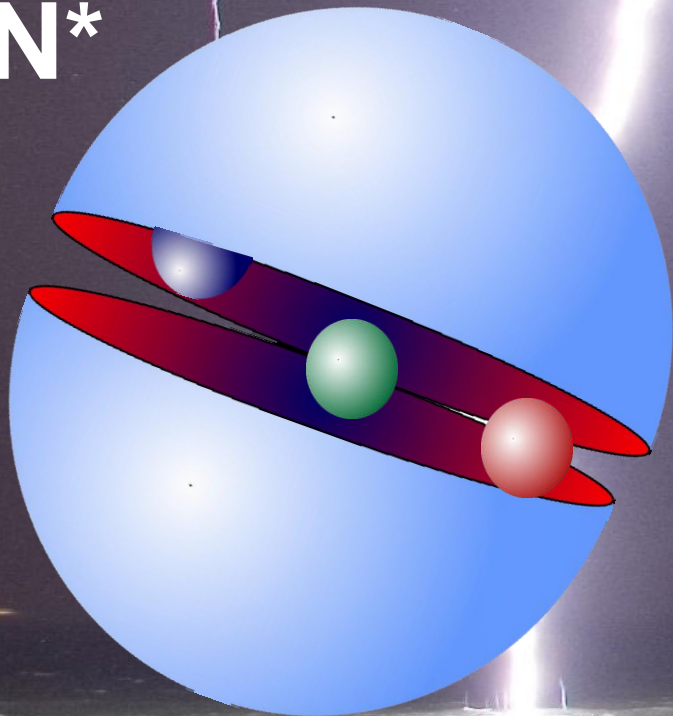
$X = N^*$



p

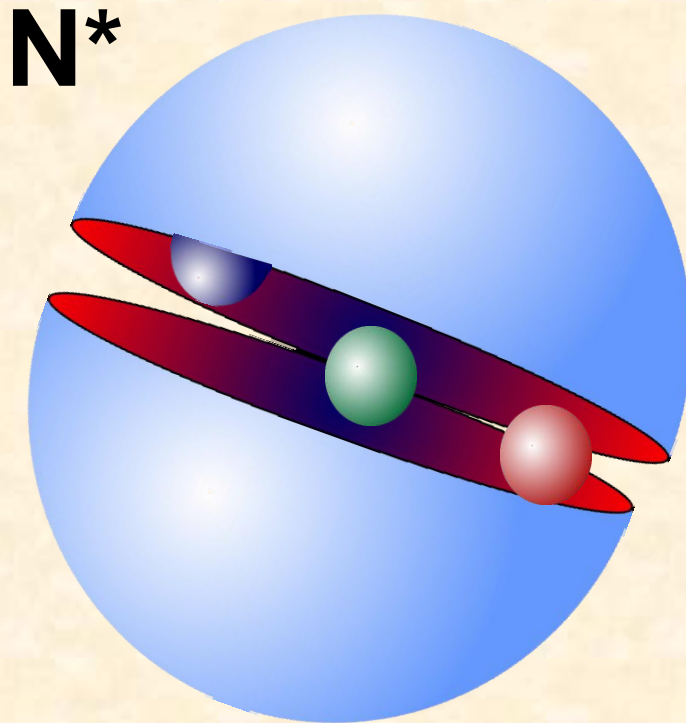
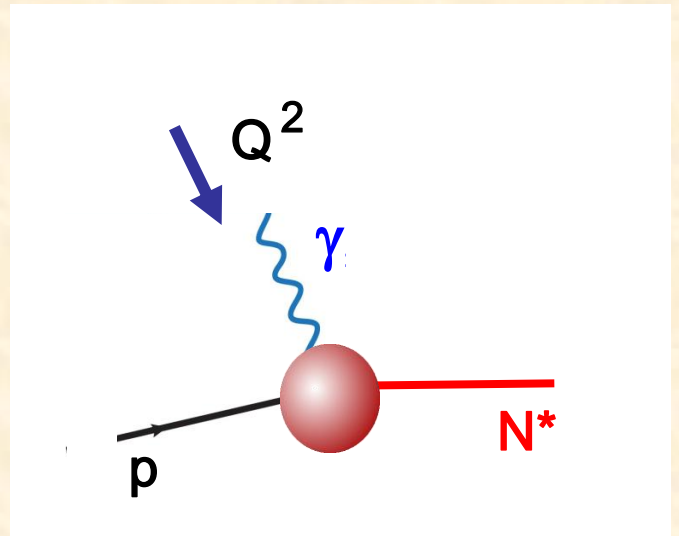


N^*

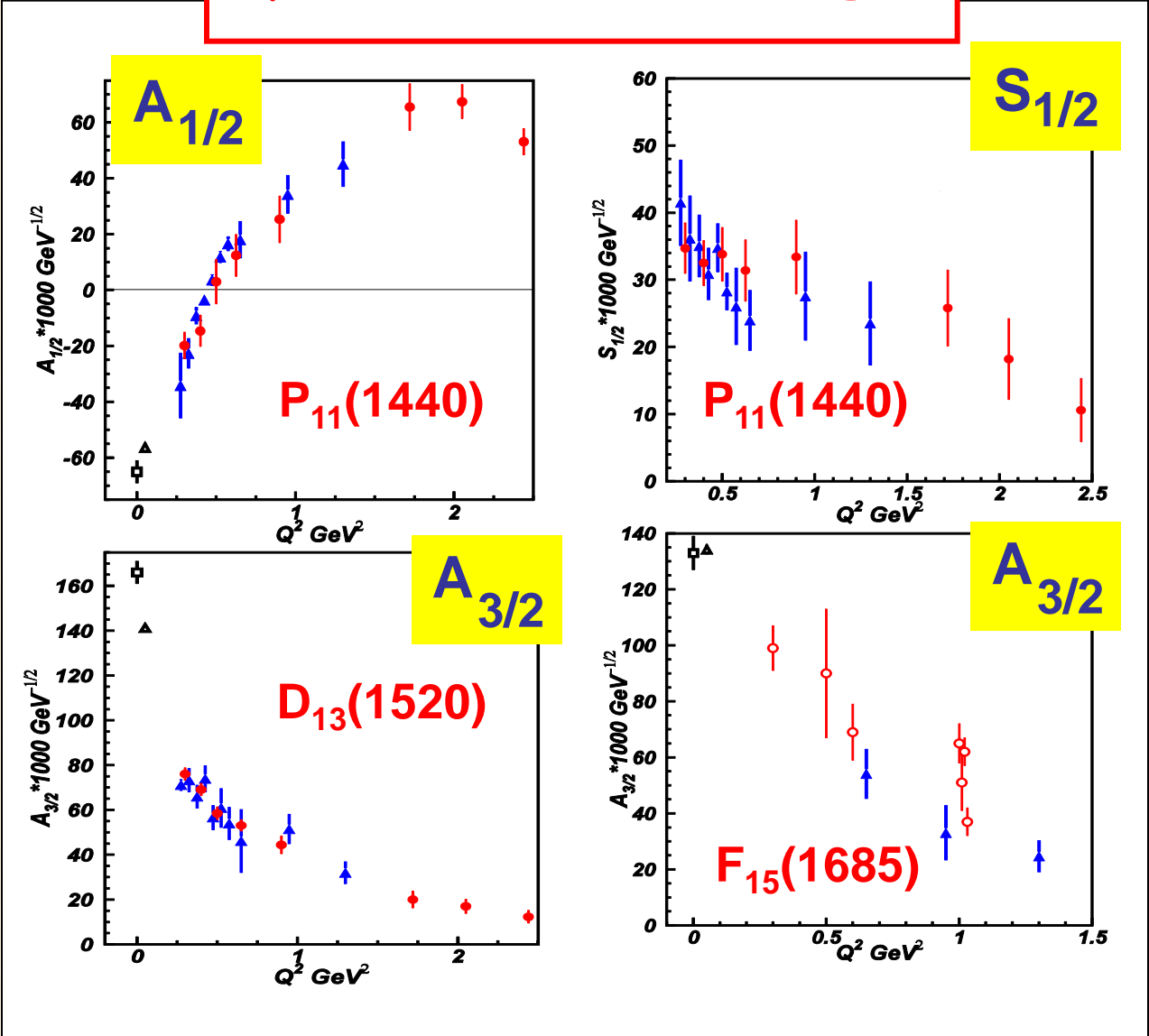


$X = N^*$

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



γ*NN*(Q²) couplings

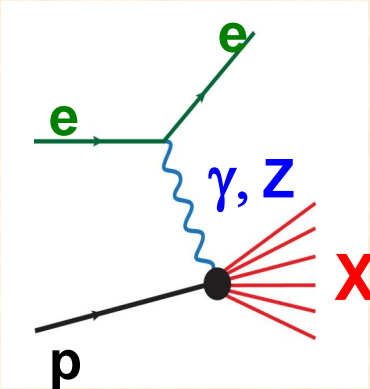


- ▲ $N\pi\pi$ CLAS preliminary.
- $N\pi$ Aznauryan et al.
- Burkert et al.
- ▲ $N\pi$ $Q^2 = 0$ Dugger et al.

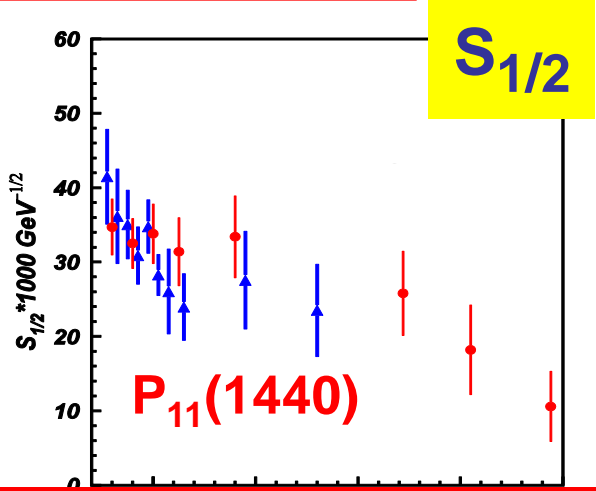
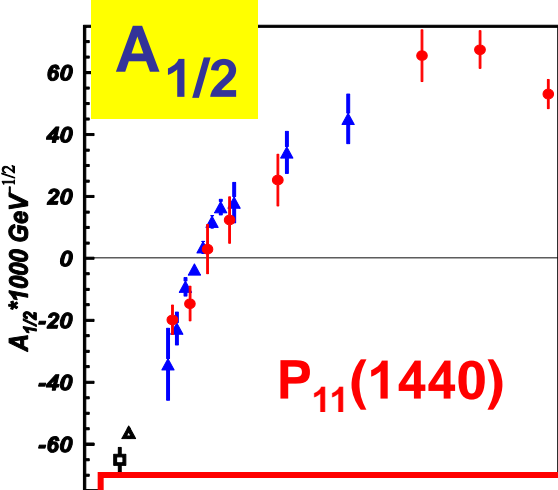
Good agreement between $N\pi$ and $N\pi\pi$ channels.

Mokeepv

γ*NN*(Q²) couplings

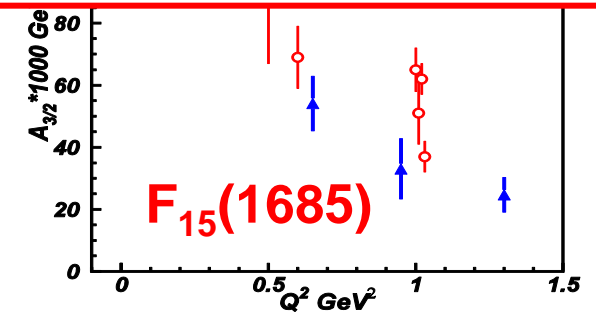
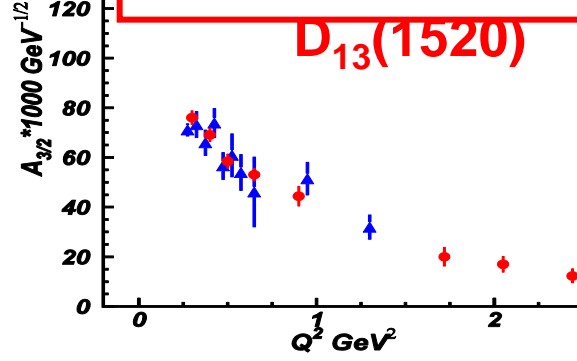


▲ Nπ CLAS preliminary.



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

an et al.

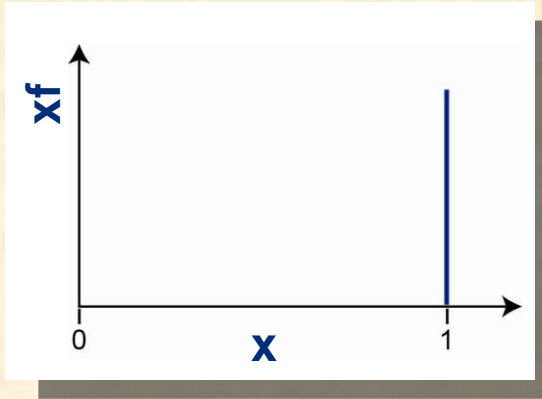


○ Burkert et al

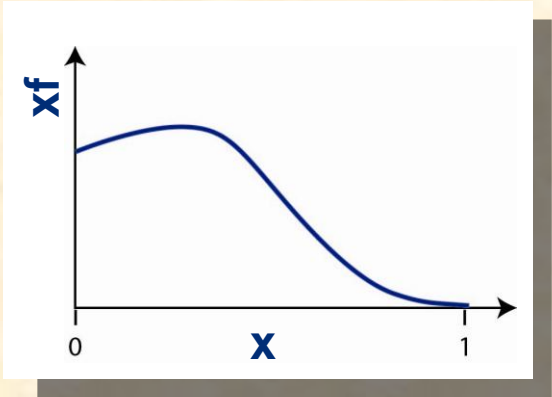
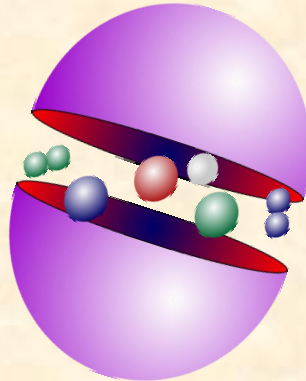
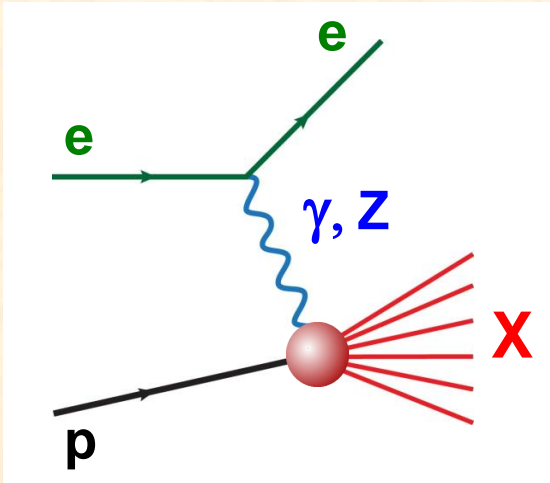
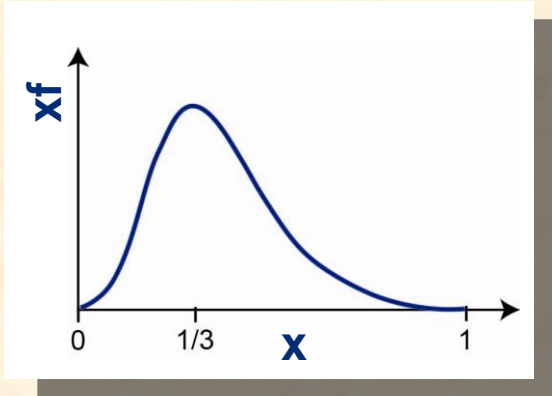
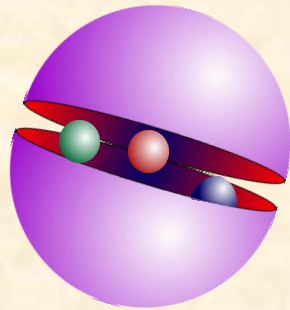
▲ Nπ Q² = 0
Dugger et al.

Good agreement between Nπ and Nππ channels.

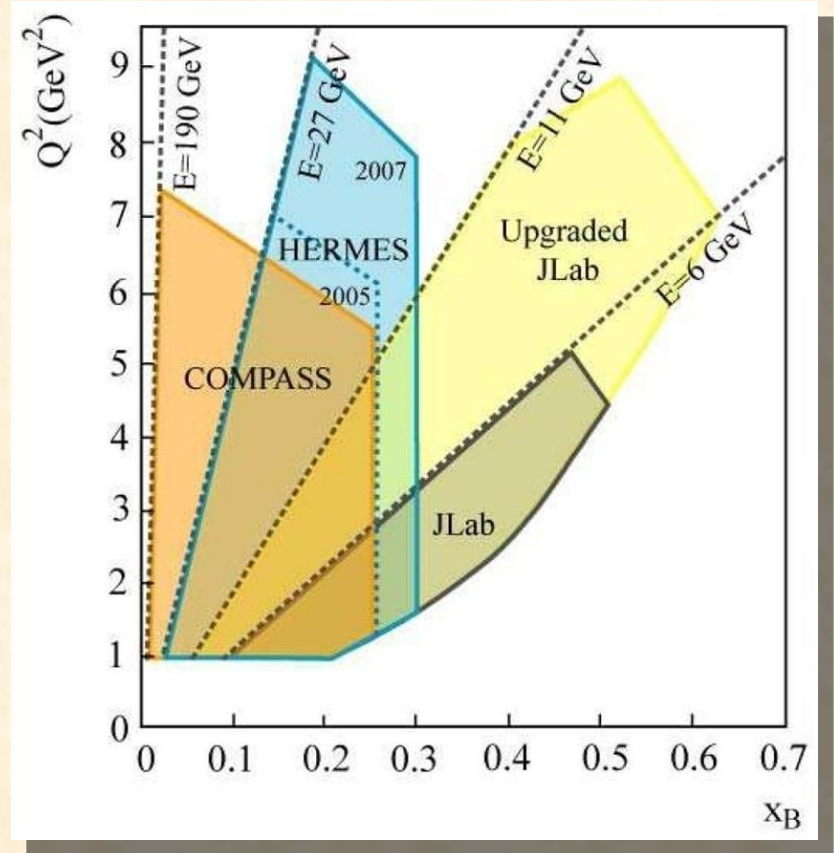
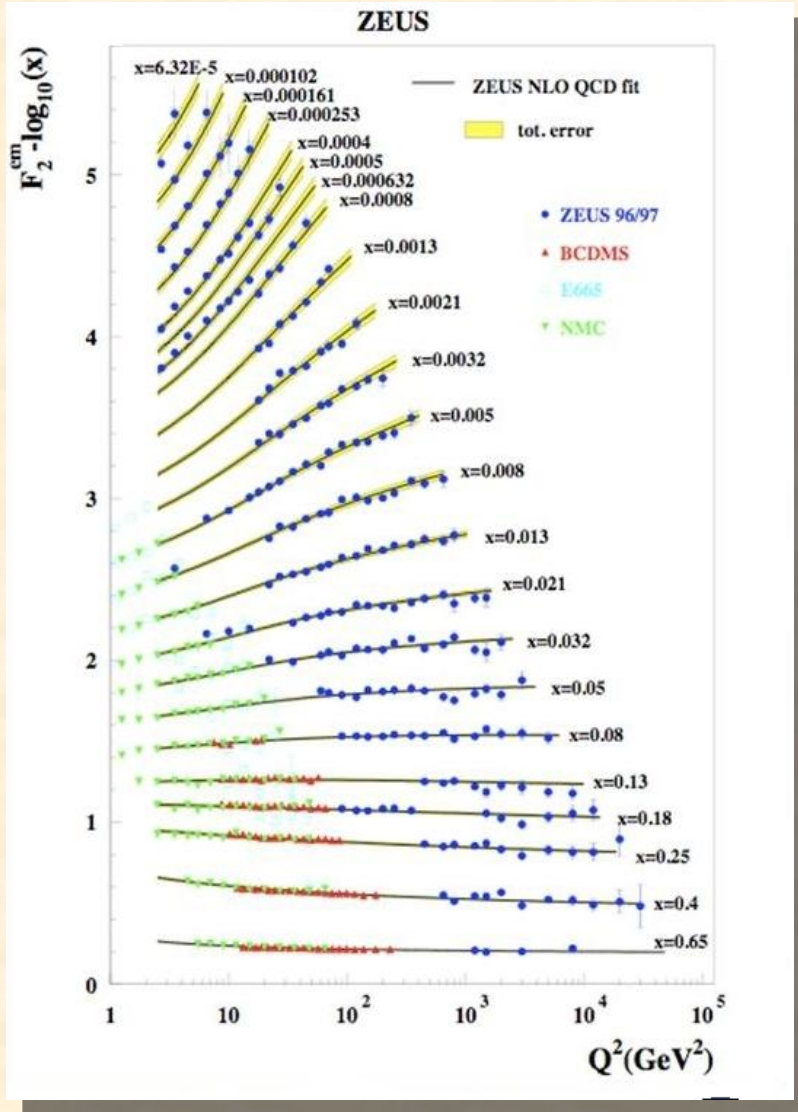
Moakeev



parton structure of the nucleon

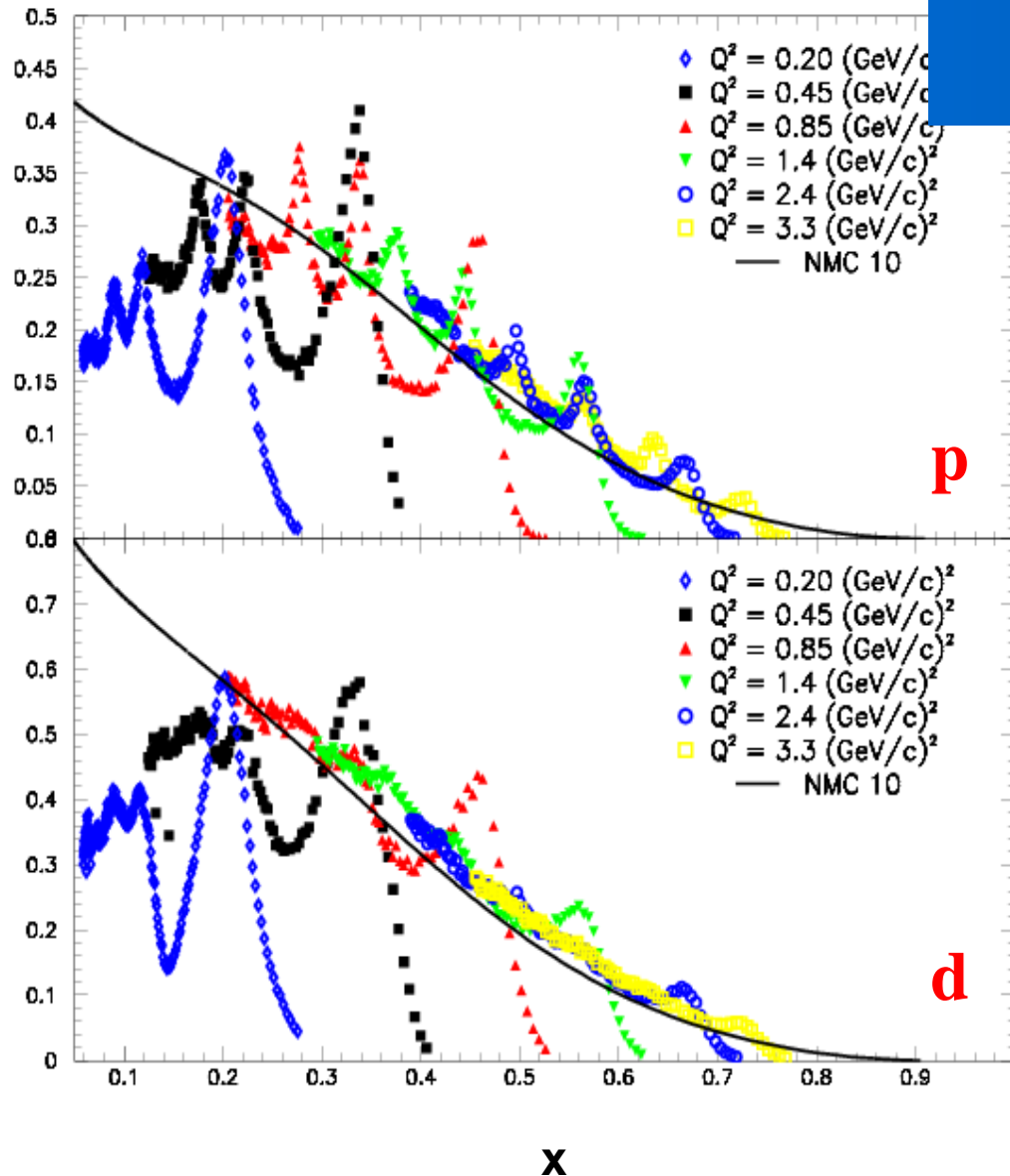


Parton Distribution Functions

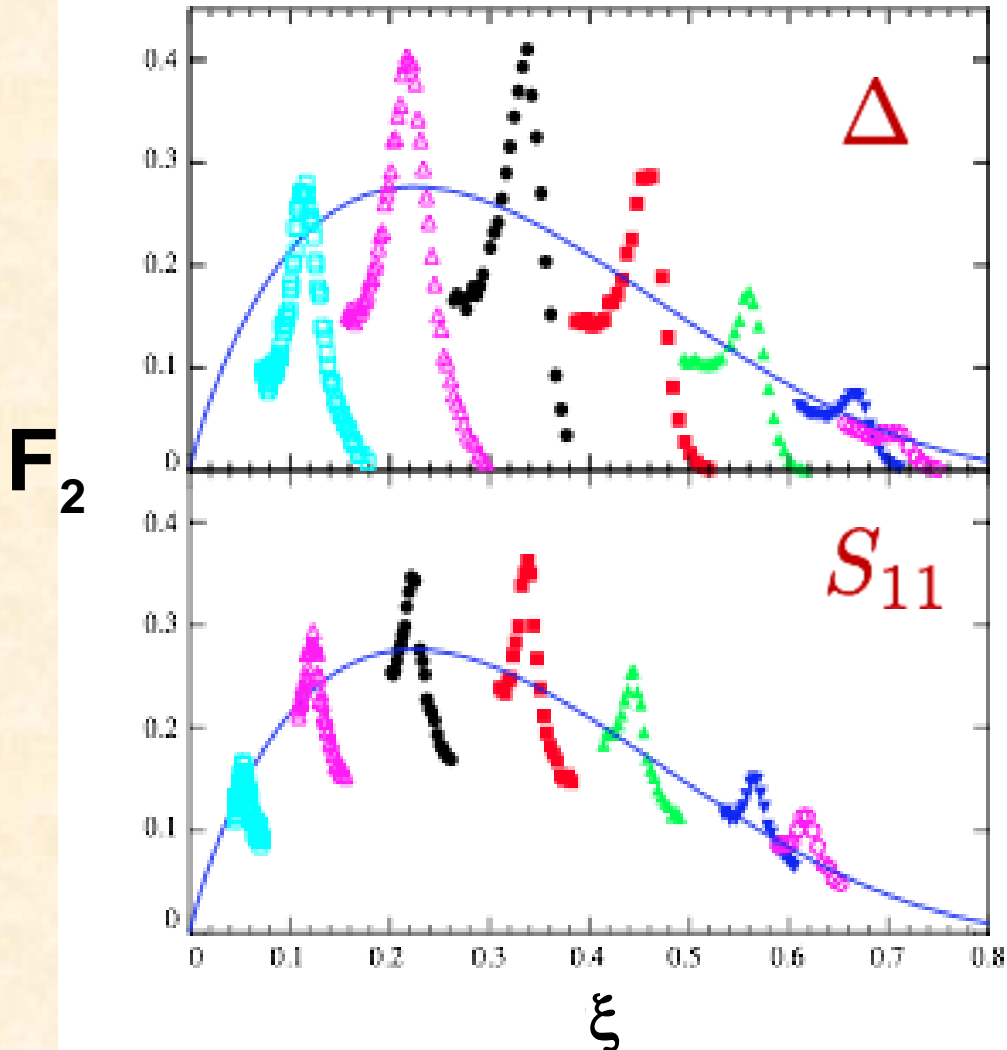


quark-hadron duality

F_2



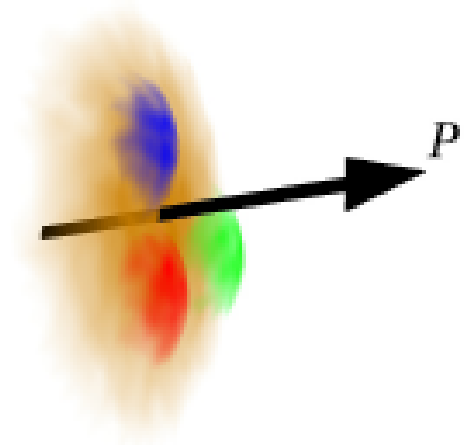
quark-hadron duality



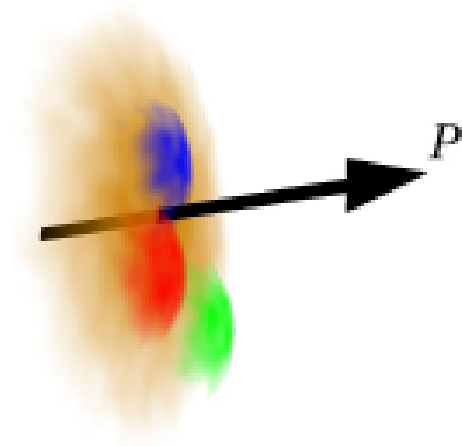
Nachtmann scaling variable

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

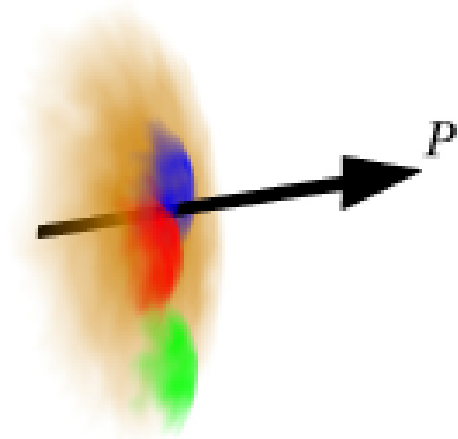
Parton densities



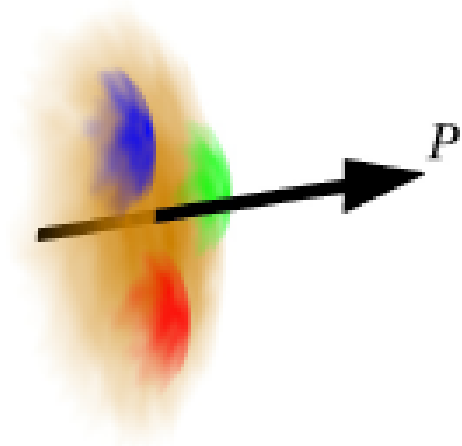
Parton densities



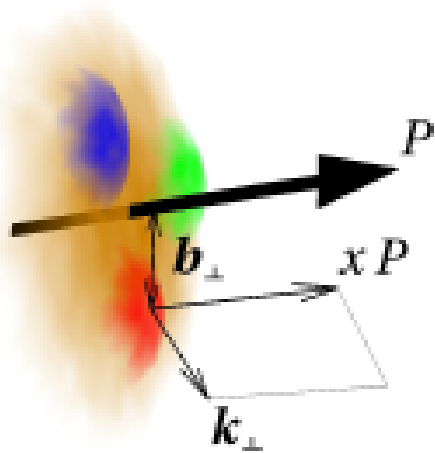
Parton densities



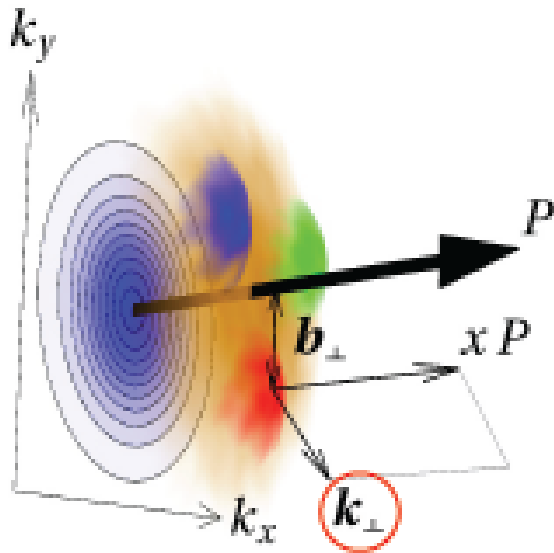
Parton densities



Parton densities

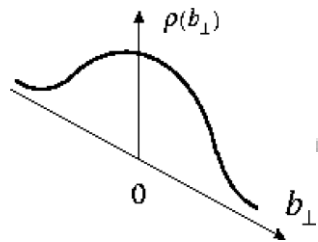
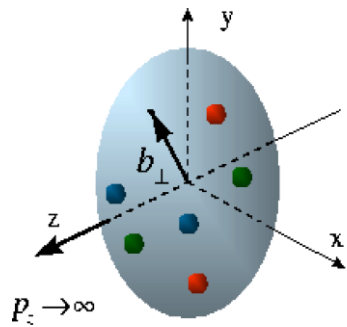


Parton densities

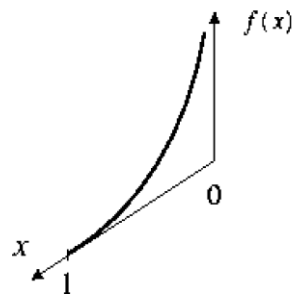
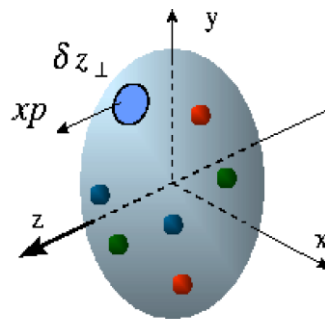


- x (longitudinal momentum fraction) \Rightarrow **PDFs**
- x, b_{\perp} (impact parameter) \Rightarrow **GPDs**
- x, k_{\perp} (intrinsic transverse momentum) \Rightarrow **TMDs**

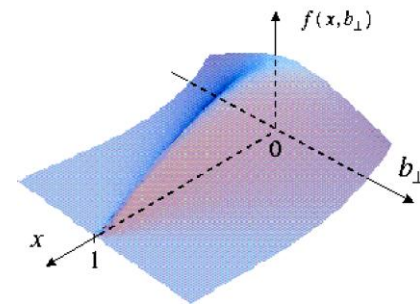
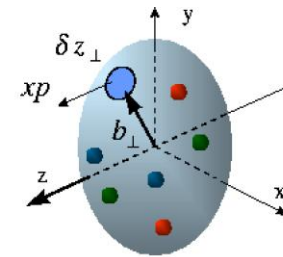
Internal Landscape of the Hadron



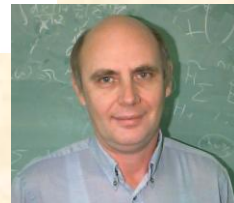
Form Factors
transverse quark
distribution in
Coordinate space



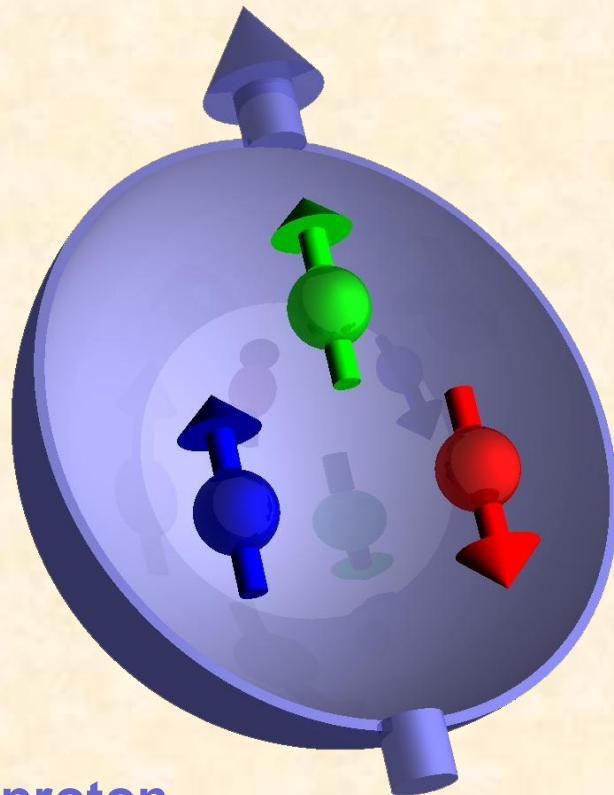
Structure Functions
longitudinal
quark distribution
in momentum space



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



Internal Landscape of the Hadron



proton

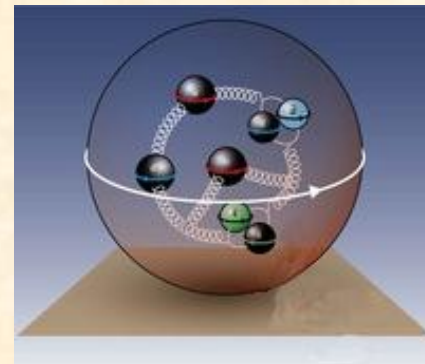
Spatial

Momentum

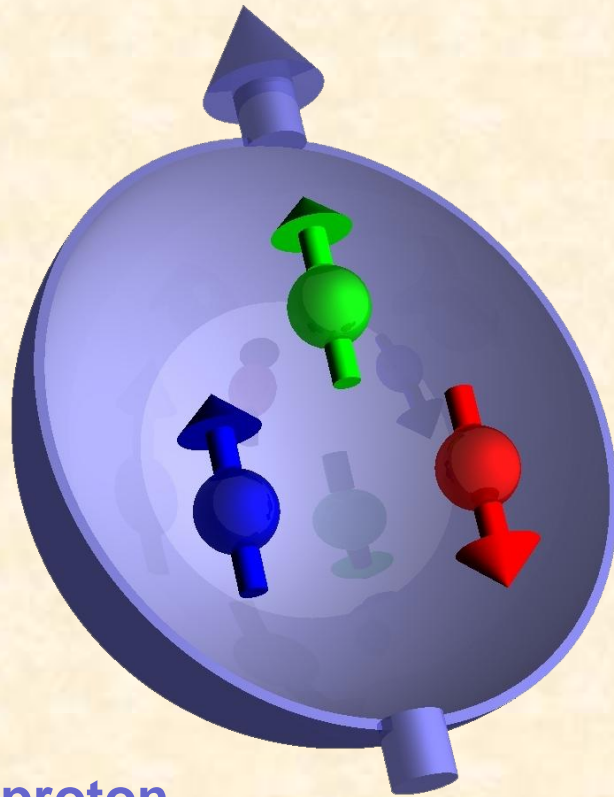
Flavor

Angular momentum

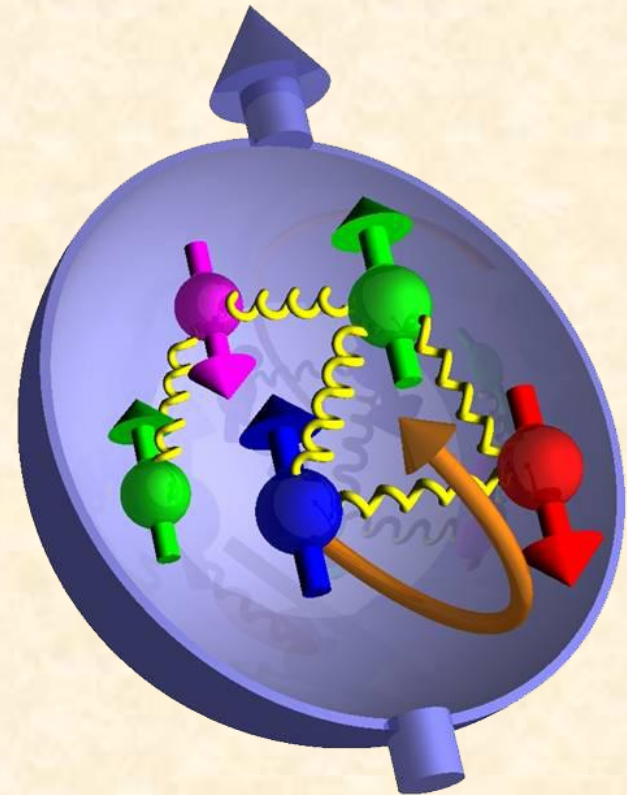
Parton Distribution Functions



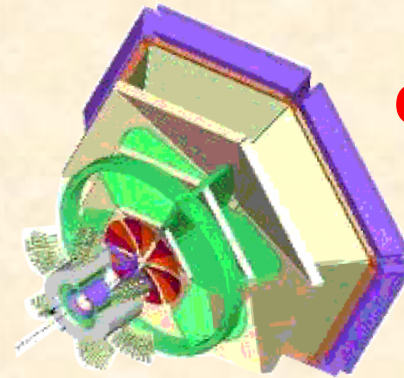
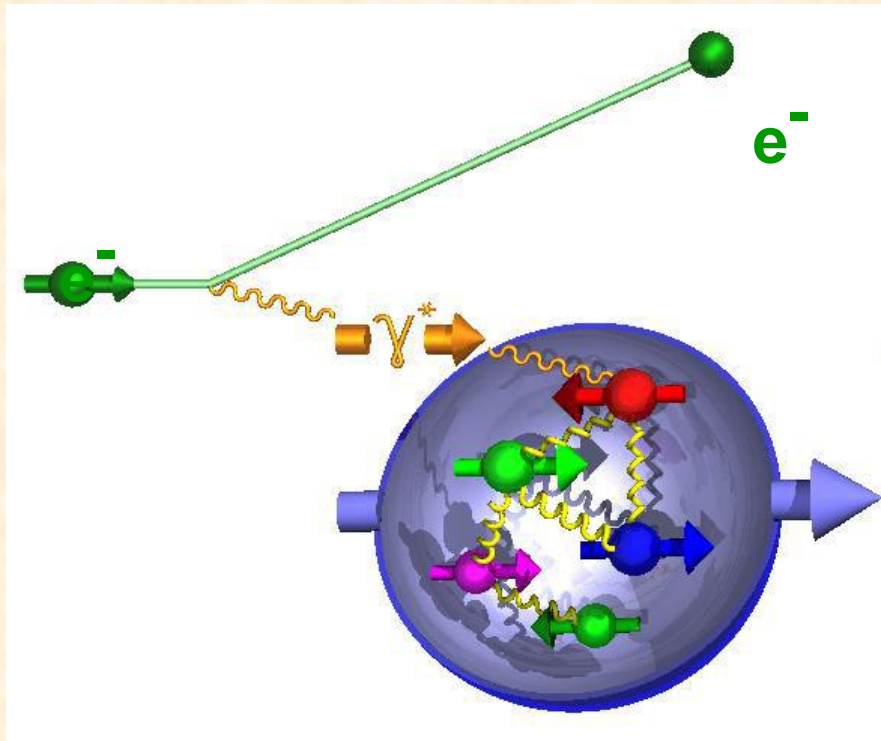
Spin of the proton



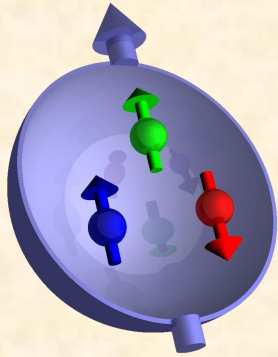
proton



Semi-Inclusive Deep Inelastic Scattering

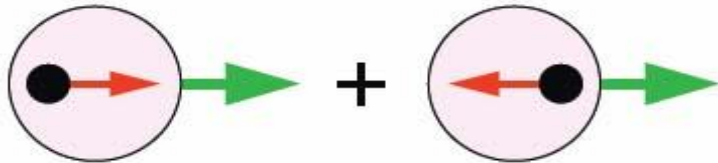


Spin of the proton

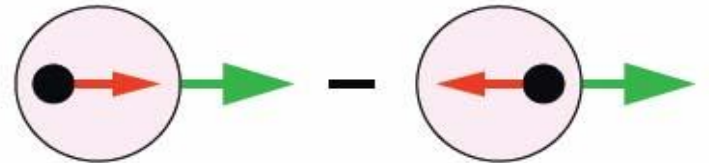


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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



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



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

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

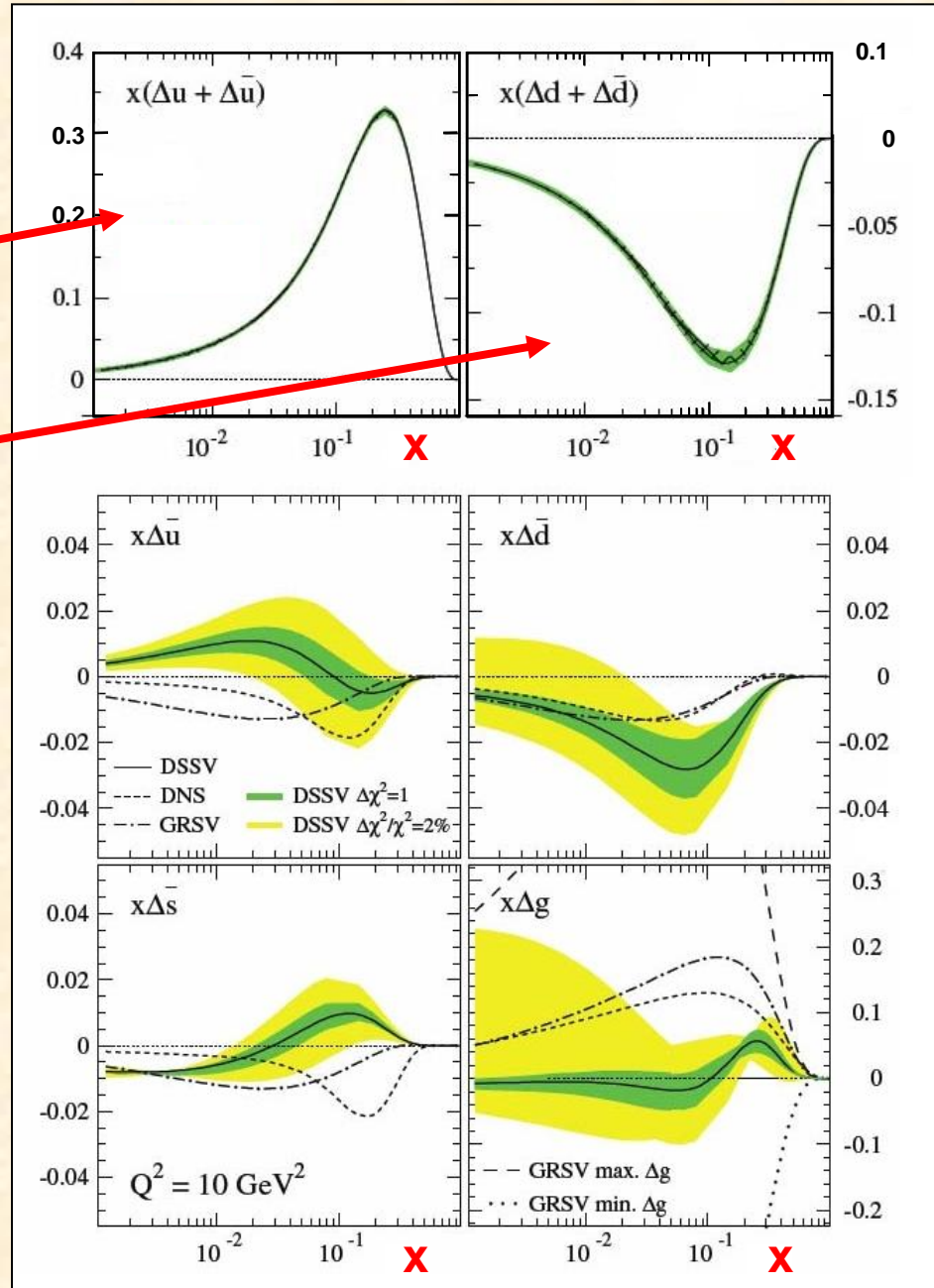
$\sim 20\%$

Spin of the proton

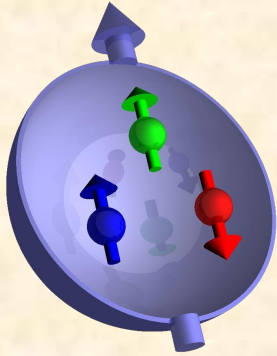
$$\int dx \Delta(u + \bar{u}) = +0.81$$

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

	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



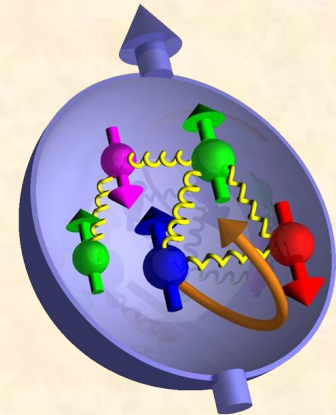
Spin of the proton



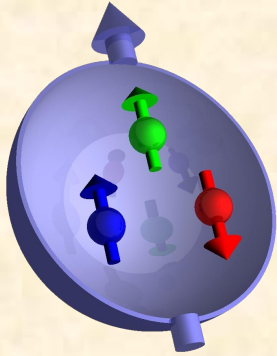
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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

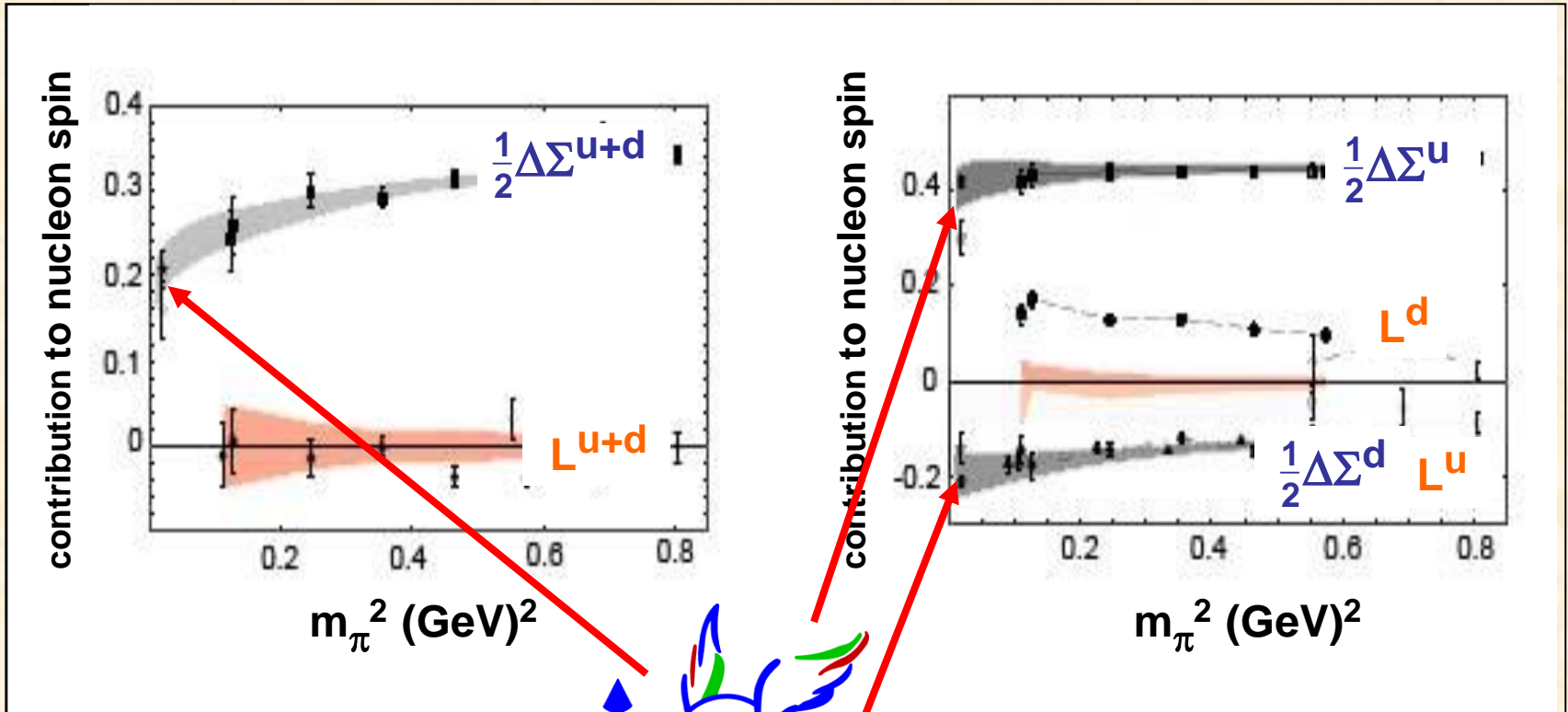
$$L_z \equiv L_q + L_g$$



Spin of the proton: Lattice v Experiment



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



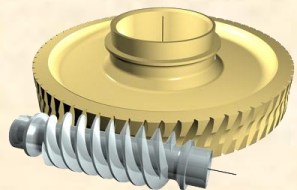
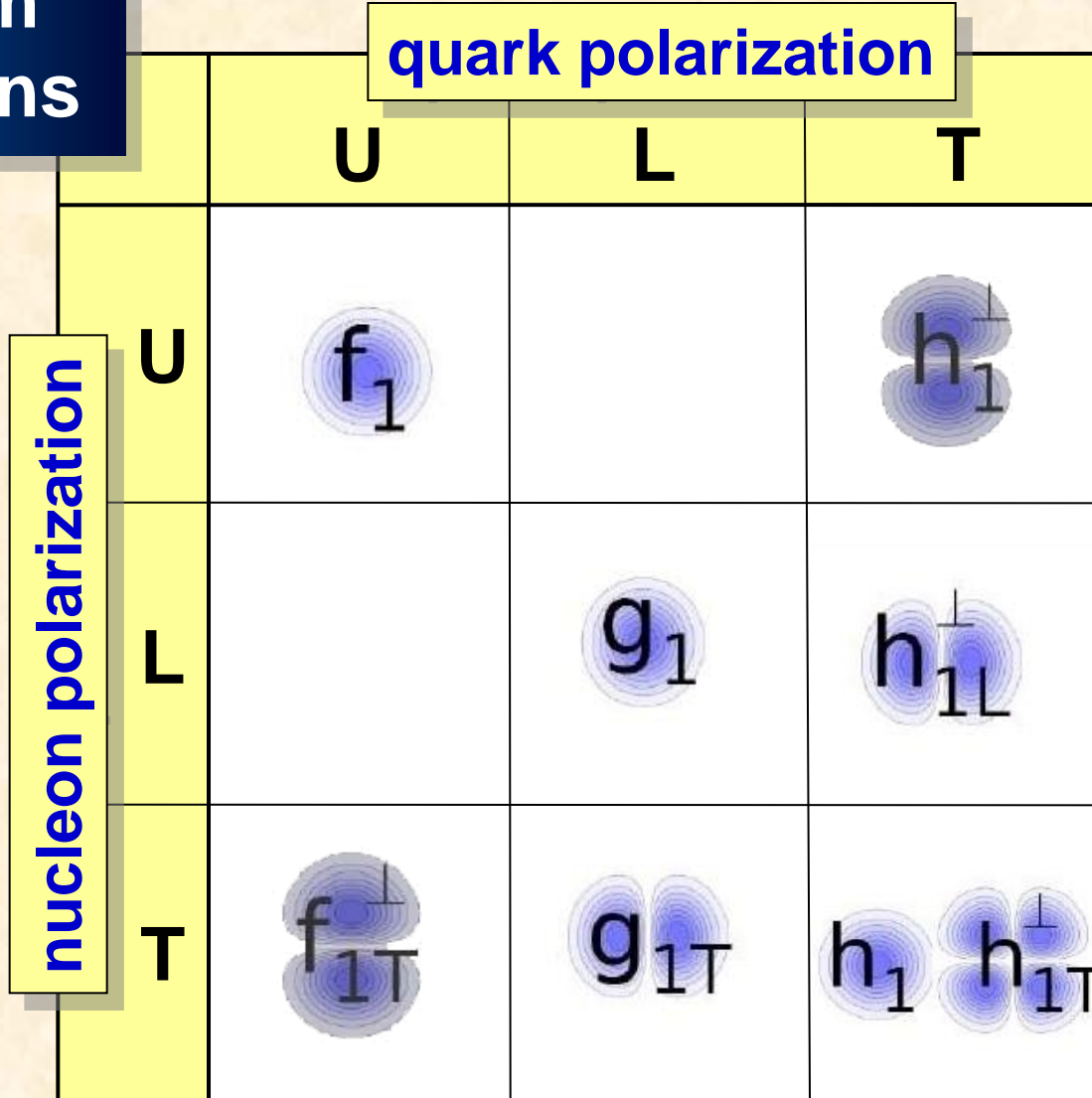
LHPC, Haegler *et al.*



No disconnected contributions

Transverse Momentum Distributions

quark polarization

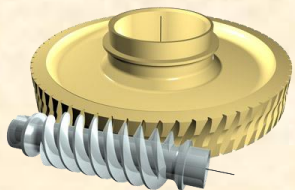
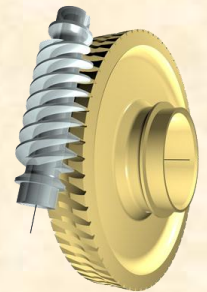


at leading twist

Transverse Momentum Distributions

quark polarization

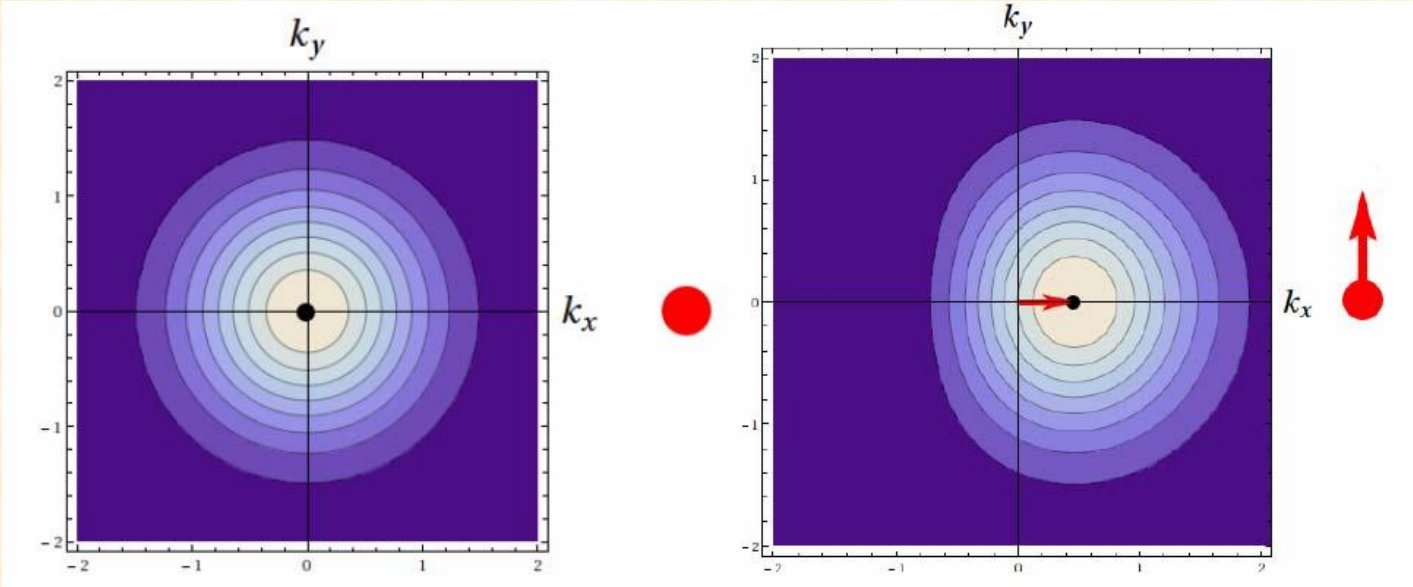
		quark polarization		
		U	L	T
nucleon polarization	U	f_1		h_1 Boer-Mulders
	L		g_1 helicity	h_{1L} worm-gear
	T	f_{1T} Sivers	g_{1T} worm-gear	h_{1T} pretzelosity



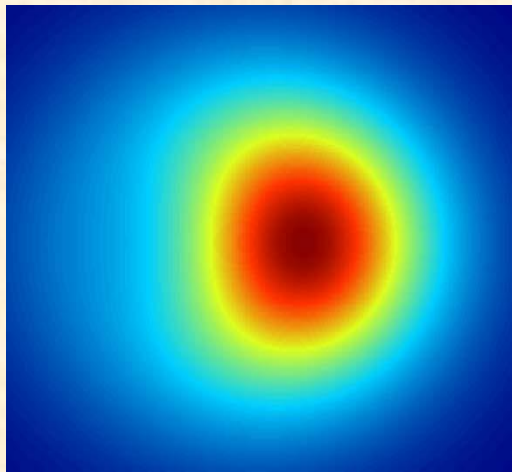
transversity

pretzelosity

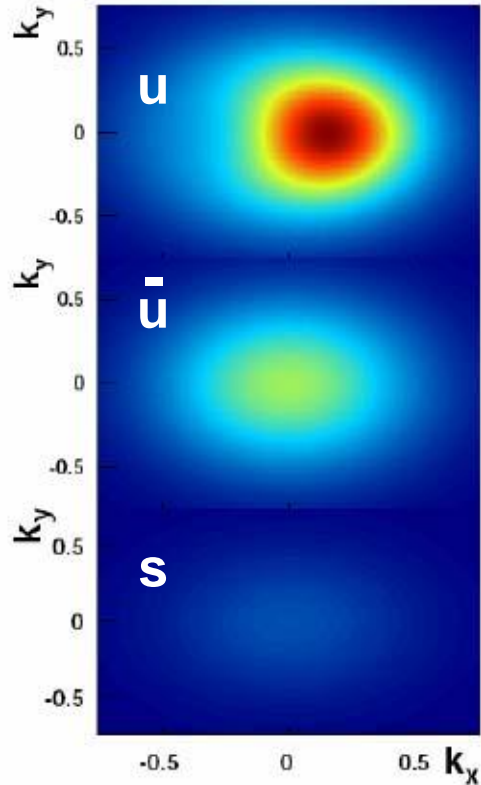
$$f(x, z, Q^2, p_T)$$



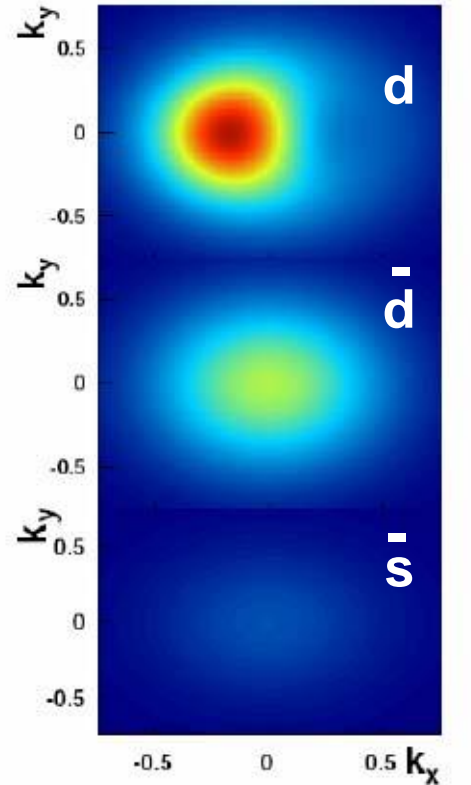
experiment



$\times f_1(x, k_T, S_T)$



k_x (GeV)



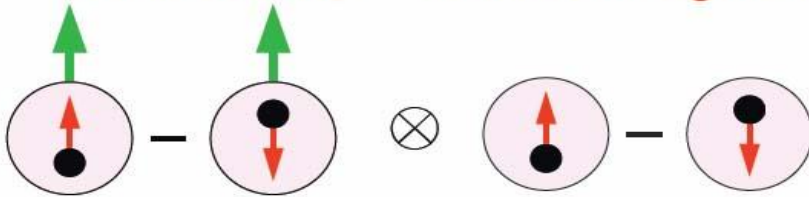
k_x (GeV)

Collins Frag Fn

$$h_1(x) \otimes H_1^\perp(z, p_T)$$

Transversity

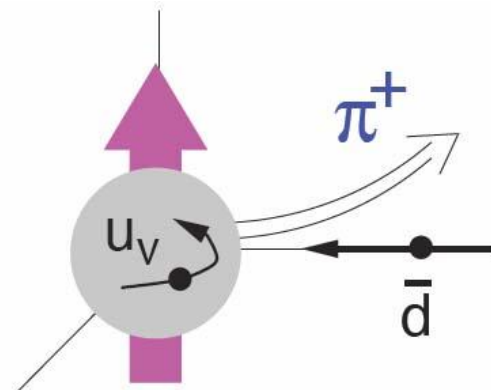
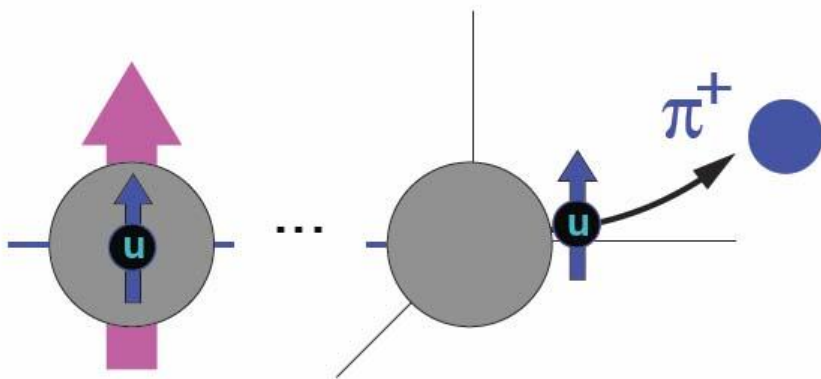
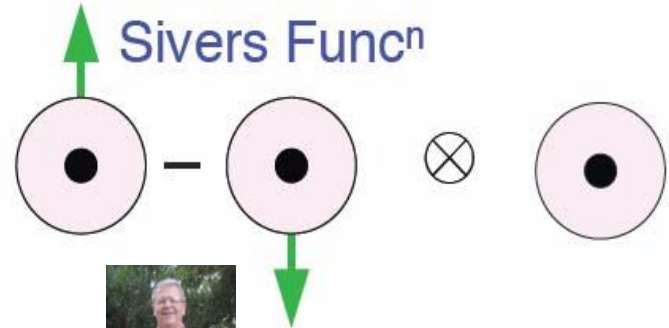
Collins Frag Funcⁿ



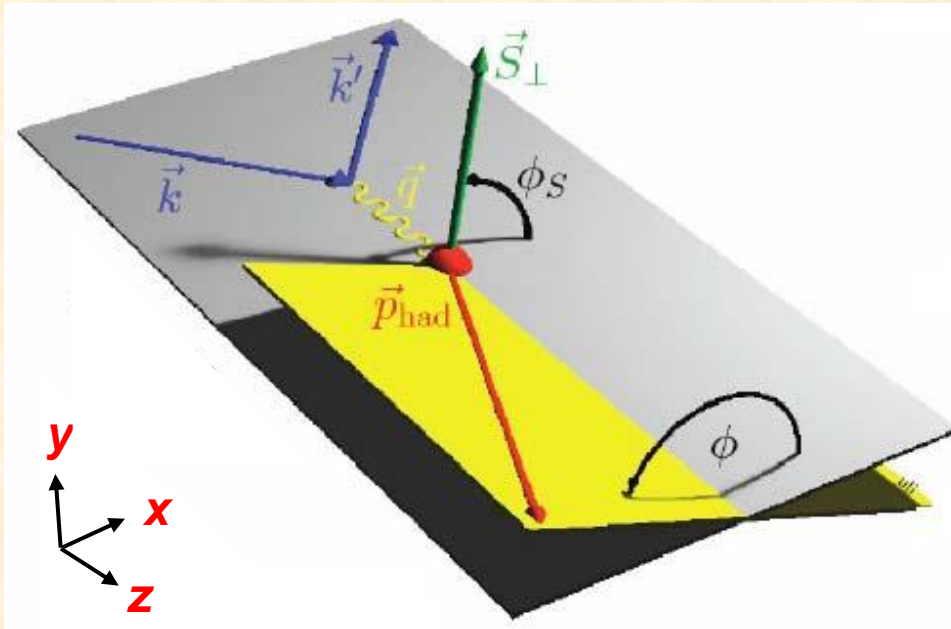
Sivers Dist Fn

$$f_{1T}^\perp(x, k_T) \otimes D_1(z)$$

Sivers Funcⁿ



π electroproduction with transverse target



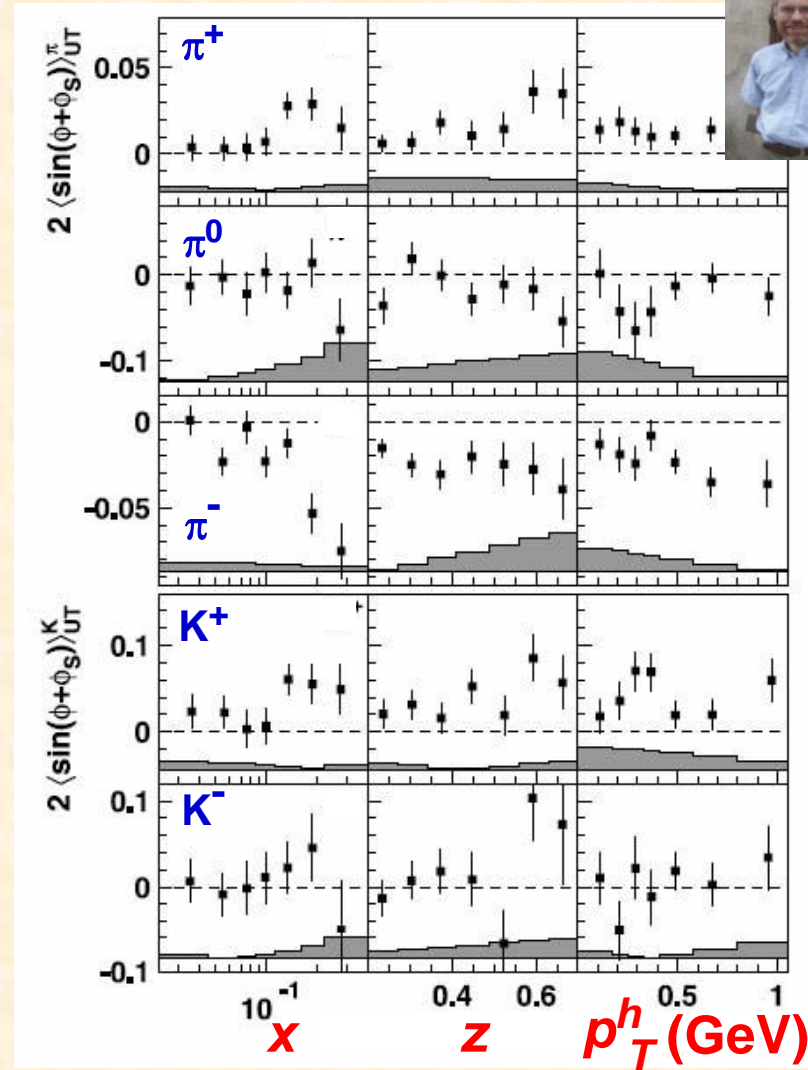
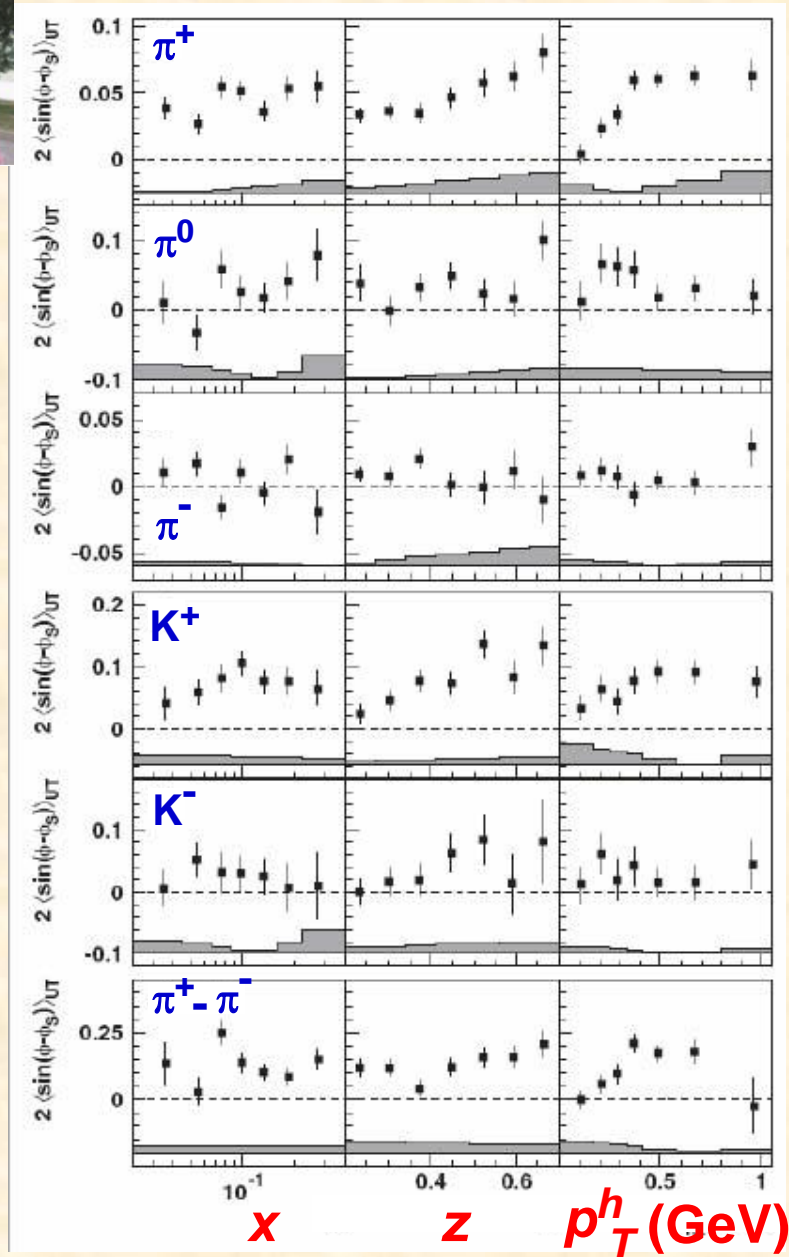
- $(\phi_h^l - \phi_S^l) =$ angle of pion relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l) =$ angle of pion relative to **final** quark spin

π electroproduction with transverse target

$$\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1 = \begin{array}{c} \uparrow \\ \circ \\ \uparrow \\ \bullet \end{array} - \begin{array}{c} \uparrow \\ \circ \\ \downarrow \\ \bullet \end{array} \otimes H_1^\perp = \begin{array}{c} \uparrow \\ \circ \\ \bullet \end{array} - \begin{array}{c} \bullet \\ \circ \\ \downarrow \end{array}$$

$$\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp = \begin{array}{c} \uparrow \\ \circ \\ \bullet \end{array} - \begin{array}{c} \bullet \\ \circ \\ \downarrow \end{array} \otimes D_1 = \begin{array}{c} \bullet \\ \circ \\ \bullet \end{array}$$

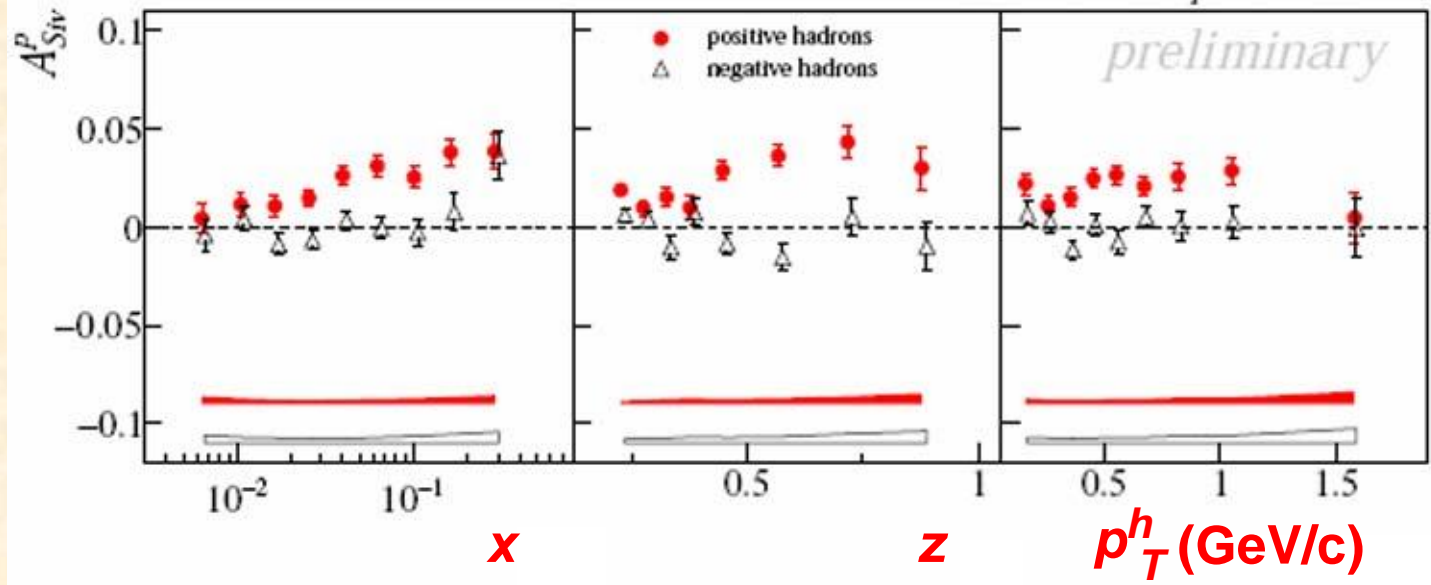
- $(\phi_h^l - \phi_S^l)$ = angle of pion relative to **initial** quark spin
- $(\phi_h^l + \phi_S^l)$ = angle of pion relative to **final** quark spin



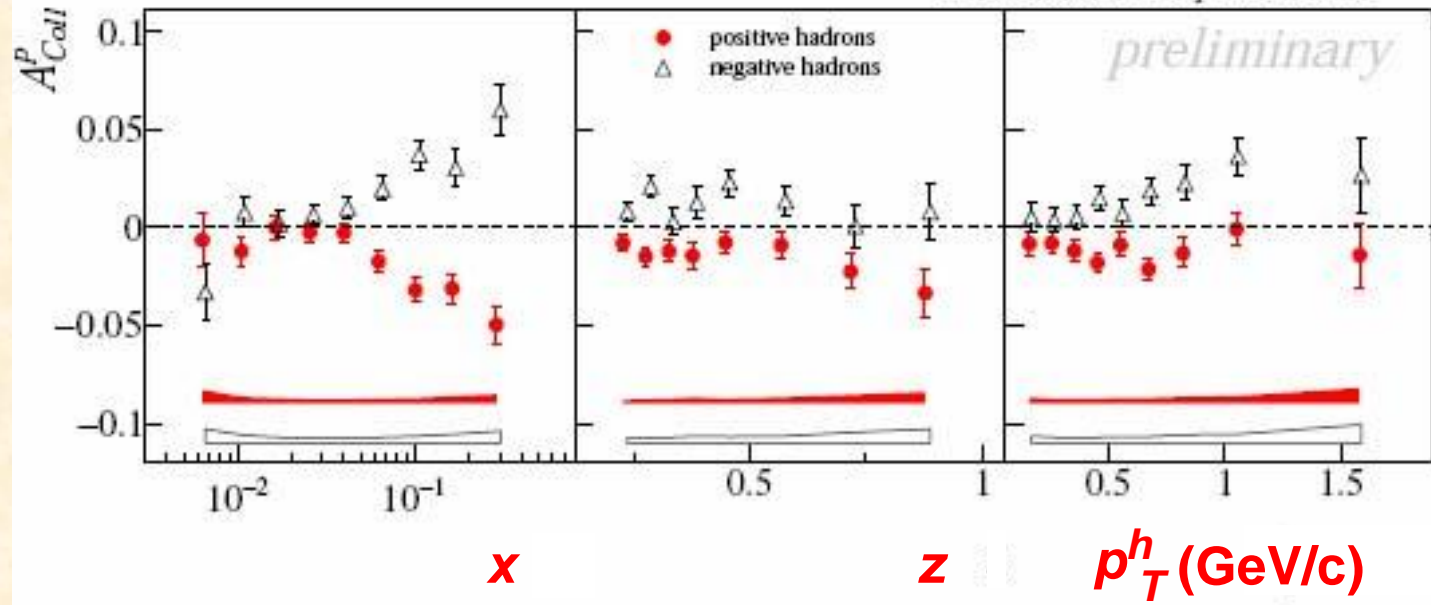
P_{Lab}
27.5 GeV



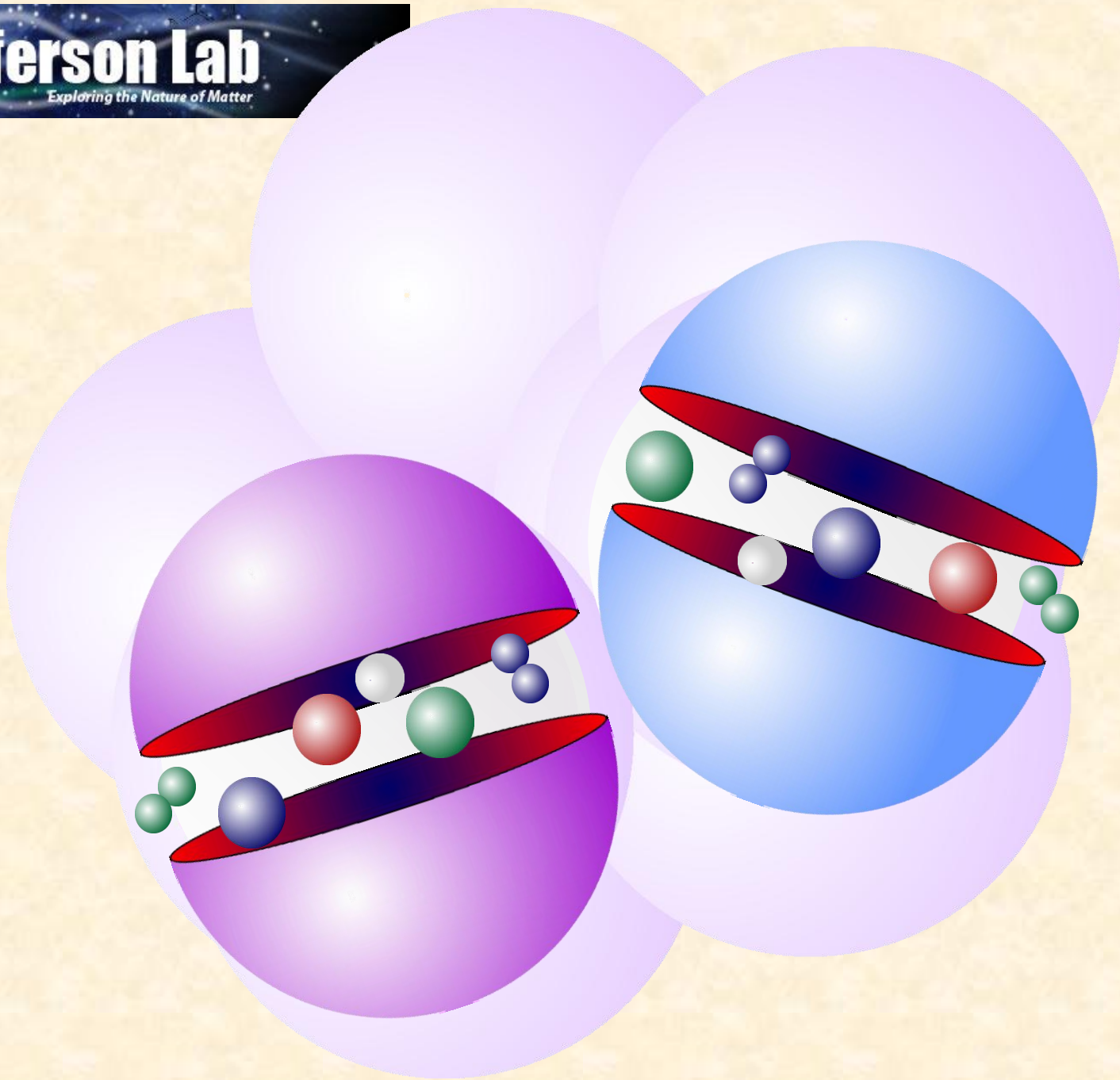
COMPASS 2010 proton data

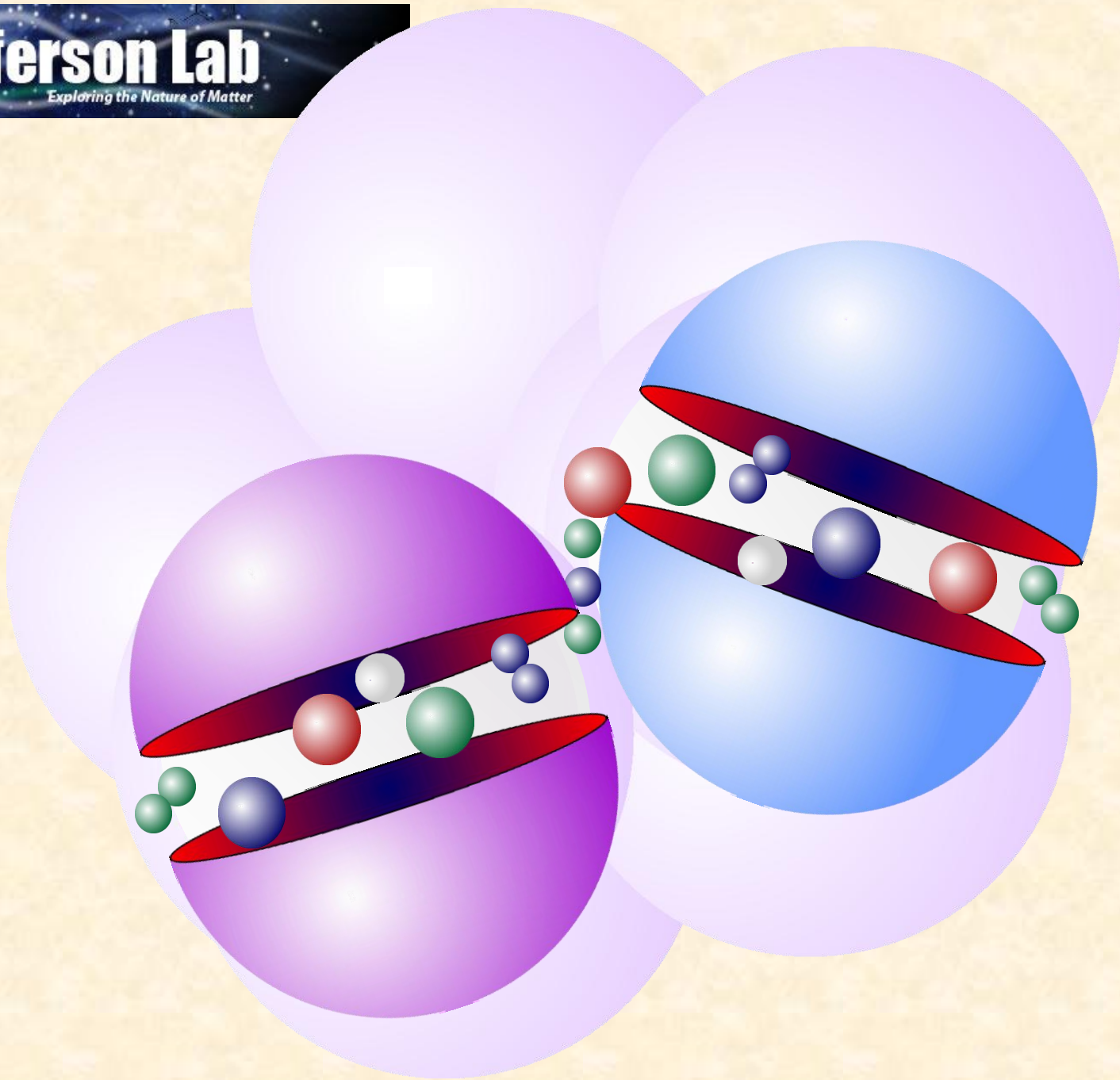


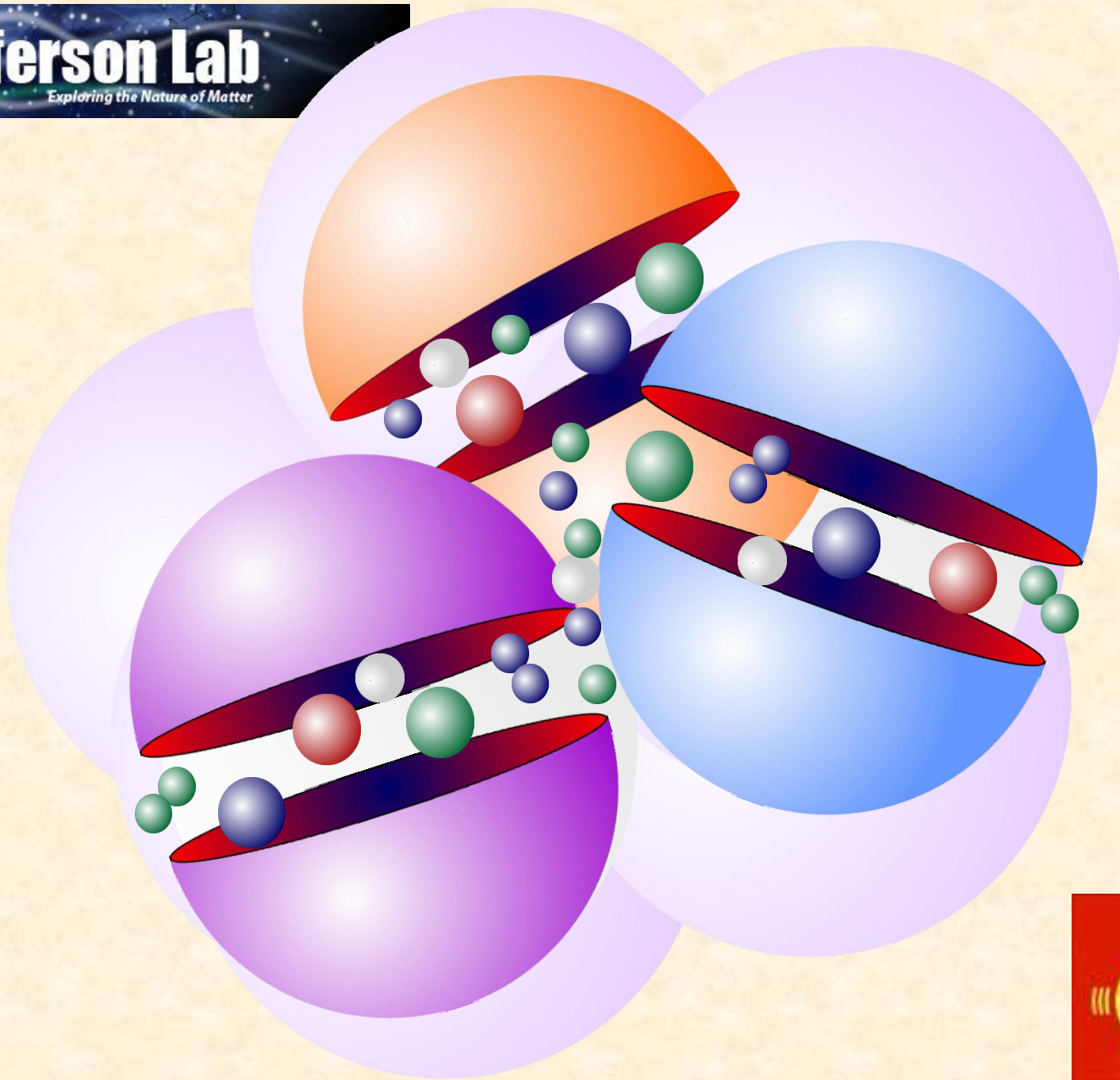
COMPASS 2010 proton data



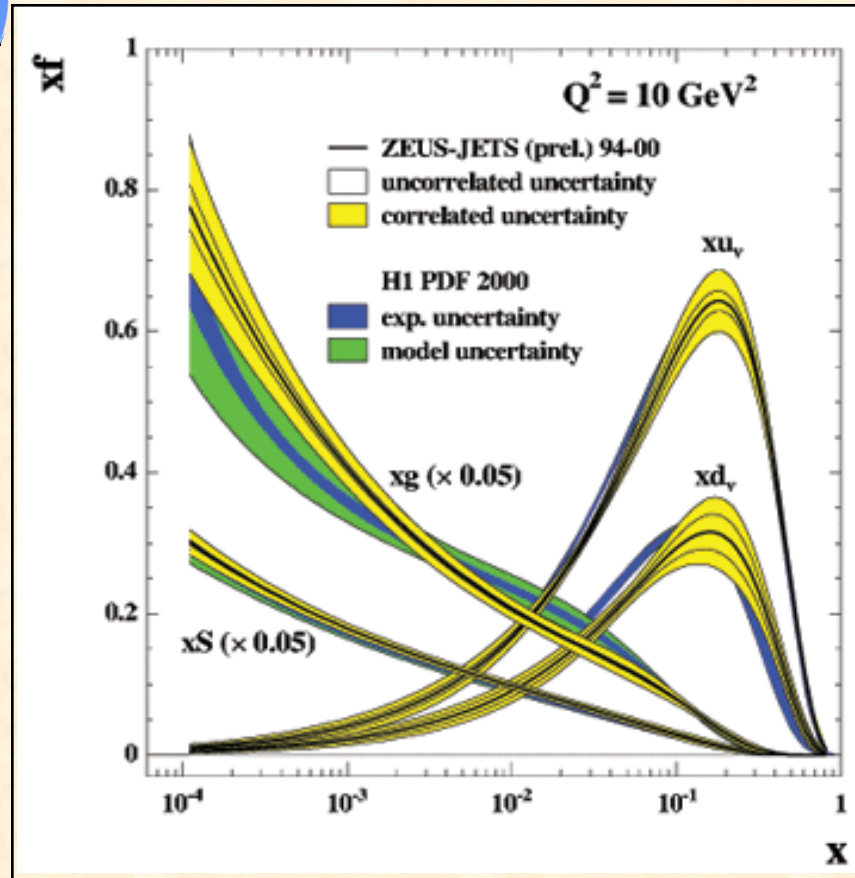
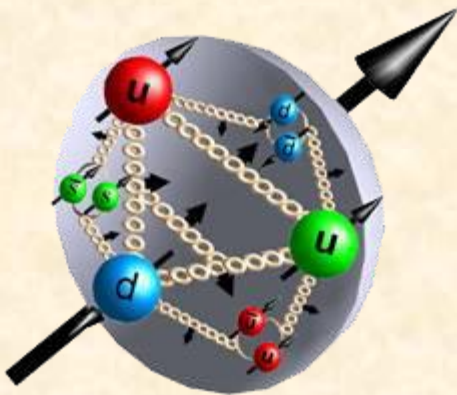
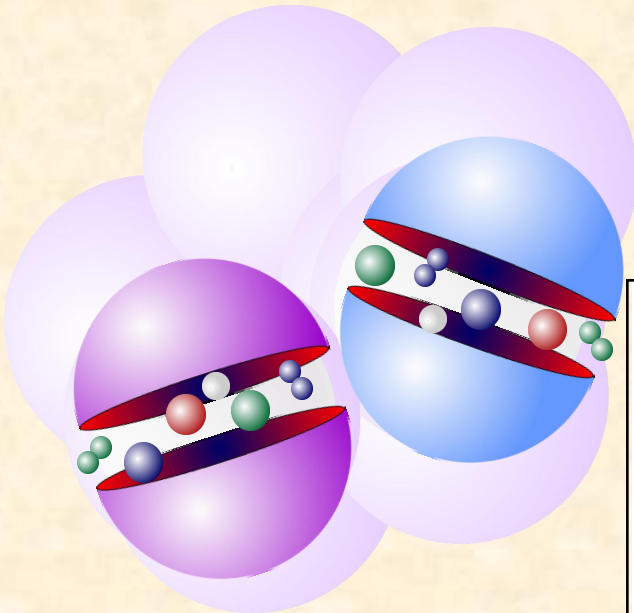
P_{Lab}
160 GeV







Electron Ion Collider



New states
of matter

Color glass
Condensate?



**Glimpsing colour
in a world of black & white**





Skiing

with

QUARKS

