Meson spectroscopy at CLAS

Present and future

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Why hadron spectroscopy?

- Quantitative understanding of quark and gluon confinement
- Reaveling the nature of the mass of the hadrons
- See the QCD degrees of freedom at work
- Validate lattice-QCD predictions

Perturbative

High energy
Small distance

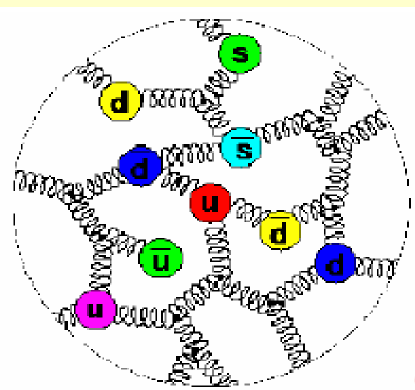
Asymptotic freedom

Transition

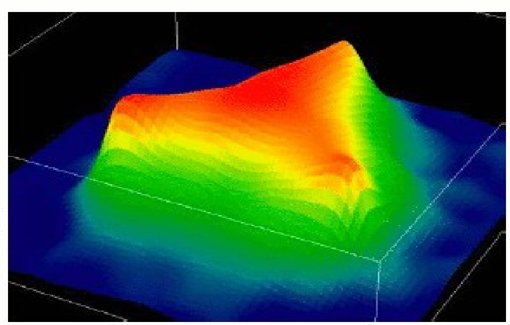
Non- Perturbative

Low energy
Large distance

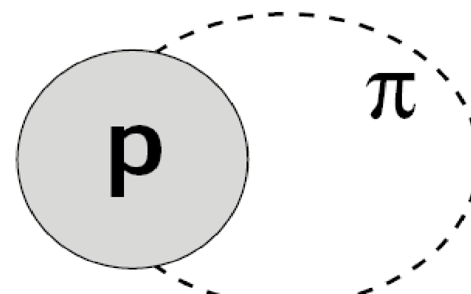
Confinement



pQCD



Effective degrees of freedom (models)



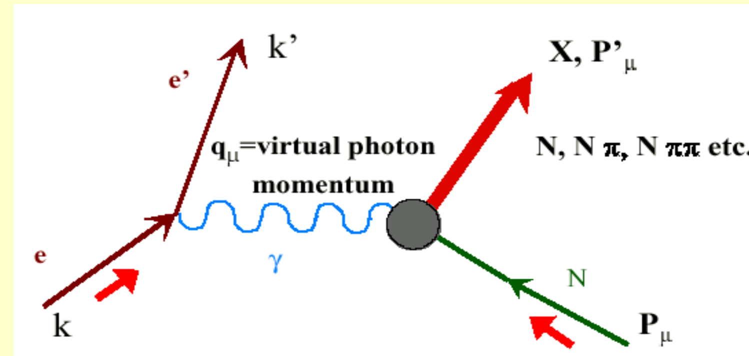
Mesons & Baryons

The tool: electromagnetic interaction

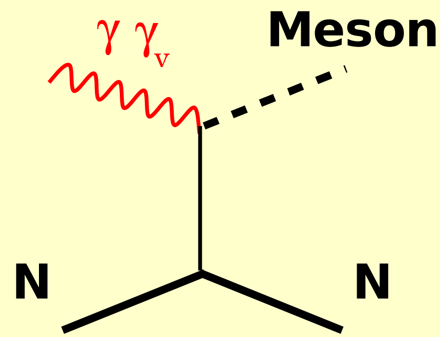
- weaker than strong interactions
- therefore calculable perturbatively
- based on the well-known QED

$-q^{m}q_{m} = Q^2$ = photon virtuality
s = CM total energy
t = momentum transfer

The scattering is normally analyzed in term of the One-Photon-Exchange approximation (OPE)



Hadron spectroscopy



- $q\bar{q}$ system → easier to study
- Indirect coupling to initial particle
- Access to gluonic degrees of freedom
- Access to strong interaction dynamics

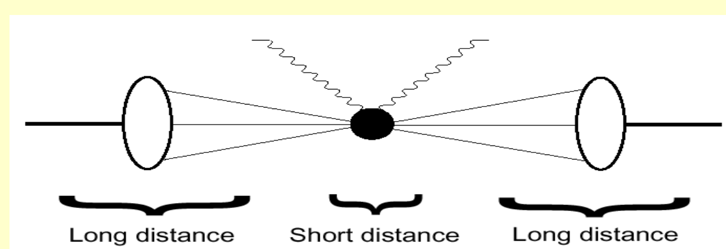
Large momentum transfer

Small impact parameter *b ~ 1/sqrt(t)*
Short interaction time

Large Q^2

High resolving power $\lambda \sim b$
Small observation scale

Short distance (Asymptotic freedom)



Hadron complexity

Elementary Parton scattering

How QCD-partons manifest themself in strong interactions in non-perturbative regime

Dynamic properties of constituent partons

- Vector meson photoproduction at large *-t*
- Vector meson electroproduction at large Q^2

Exclusive electro- and photo- scattering in a wide kinematic range

Beyond the standard quark model

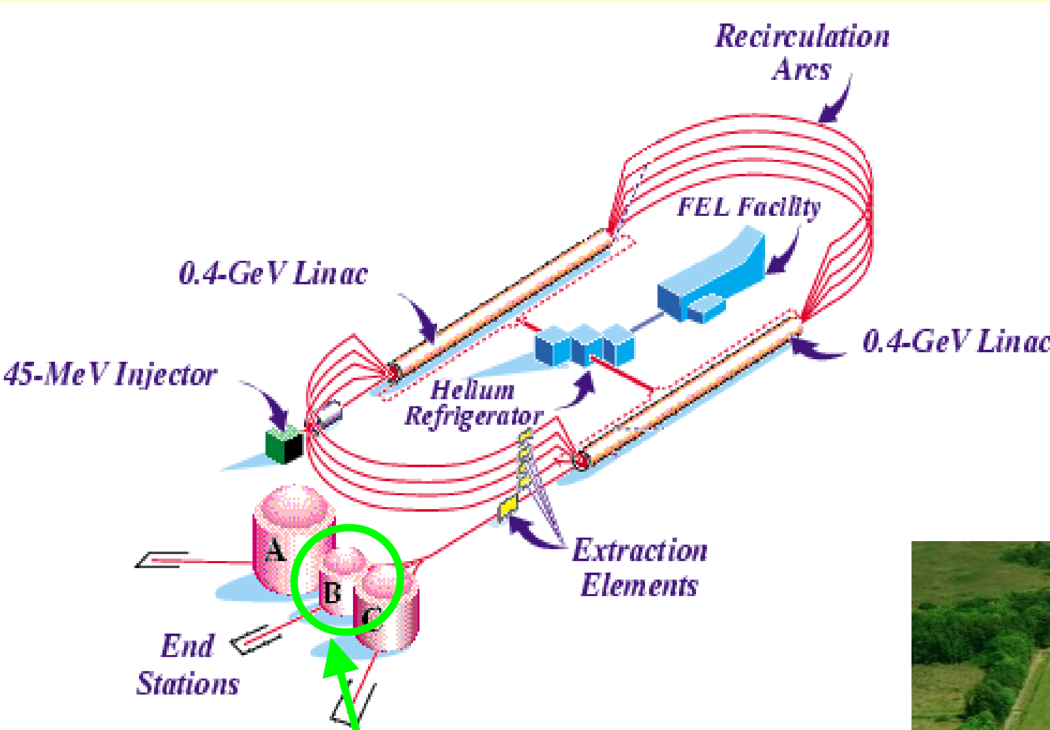
- Pentaquark searches
- Light meson spectroscopy and PWA with CLAS

High statistics, high resolution low energy exclusive measurement

Meson spectroscopy with real photon at JLab-12GeV

- The physics program driving the JLab upgrade at 12 GeV

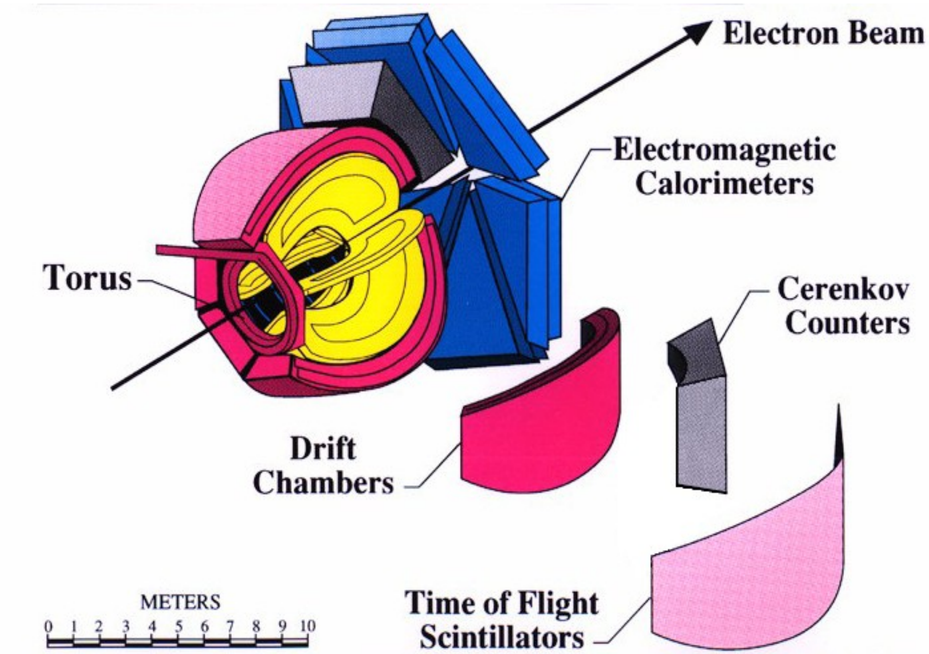
Jefferson Lab

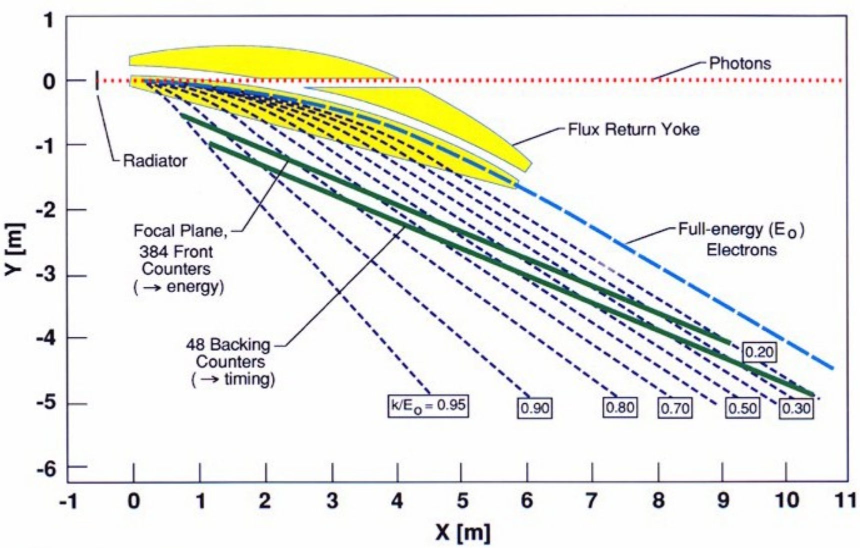


E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam P	~ 80%
E_γ	~ 0.8-5.7 GeV

CLAS

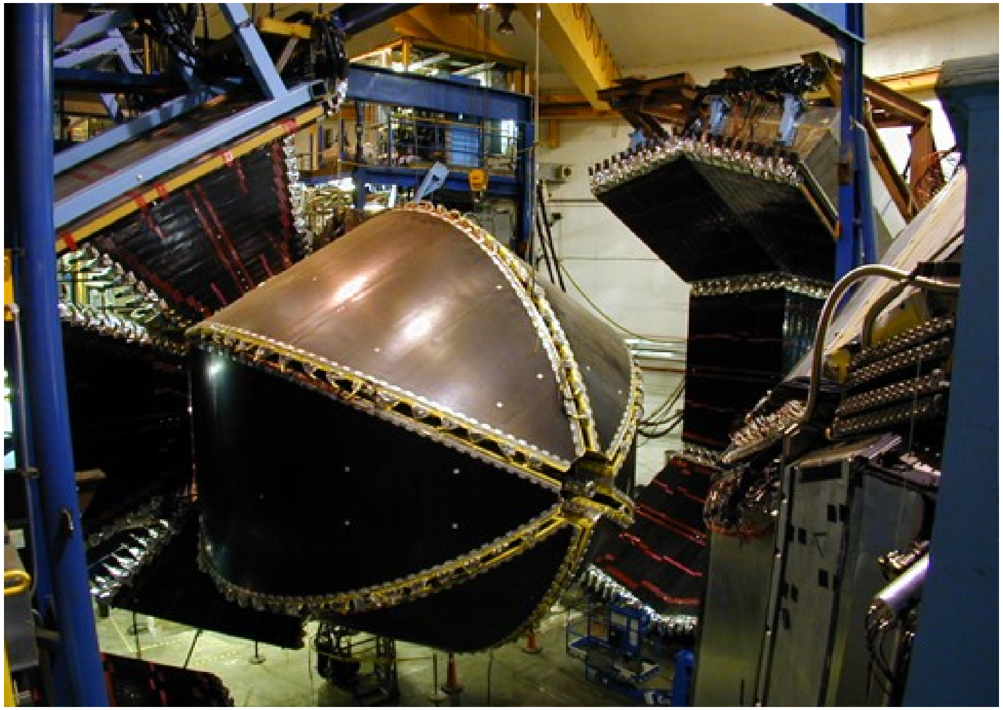
The CEBAF Large Acceptance Spectrometer CLAS



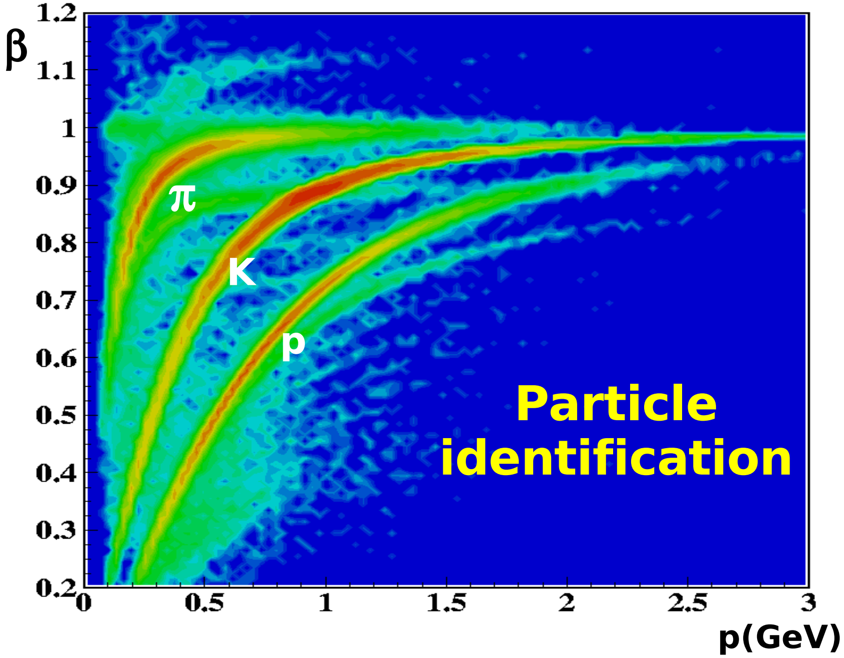


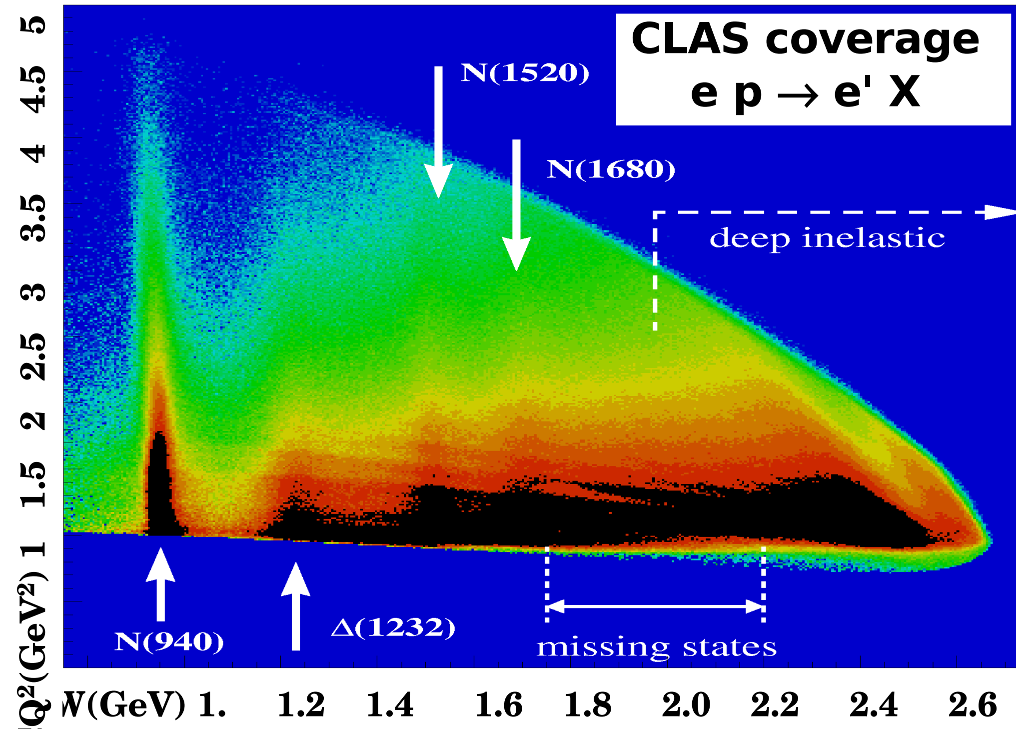
Performance

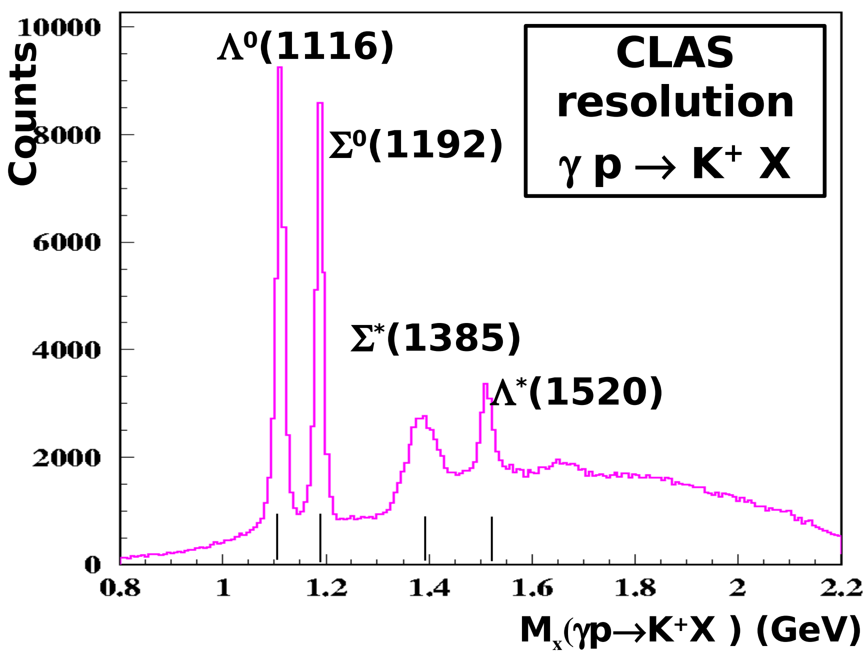
- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- $\int B\, dl = 2.5$ T m
- $\Delta p/p \sim 0.5$-1 %
- $\sim 4\pi$ acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger ($\Delta E_\gamma/E_\gamma \sim 10^{-3}$)

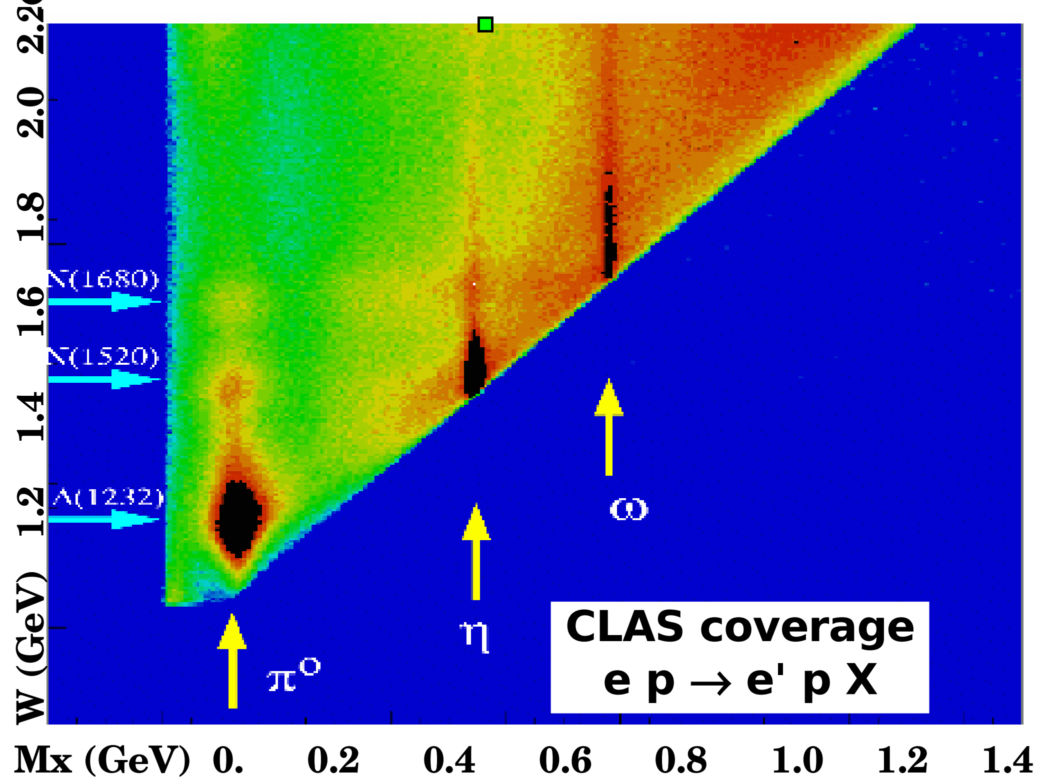


Hadron detection efficiency and kinematic coverage









Why vector mesons (V) electro- photoproduction ?

ρ, ω and φ have the same quantum number as the photon

γ beam ⟷ $q\bar{q}$ beam

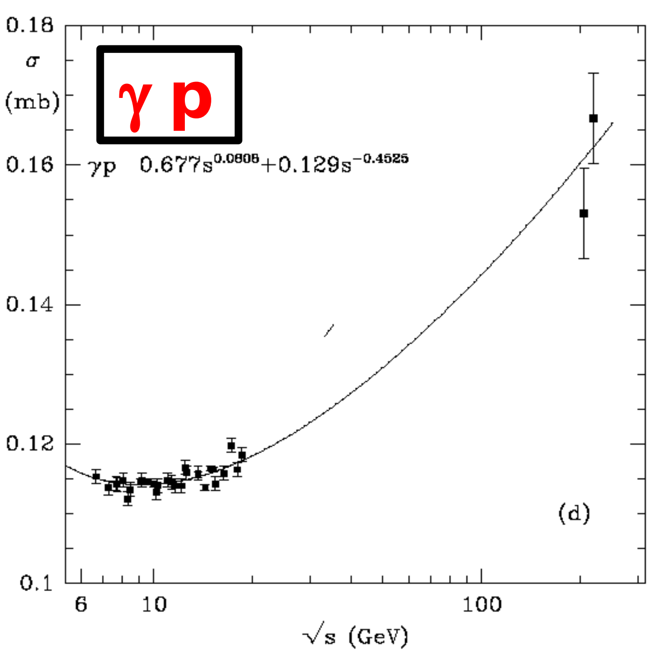
$\gamma \leftrightarrow V$

$$\tau \sim \frac{2E_\gamma}{Q^2+M^2_V}$$

Vector dominance hypothesis

Hadronic scattering ⇔ photoproduction

Total cross section



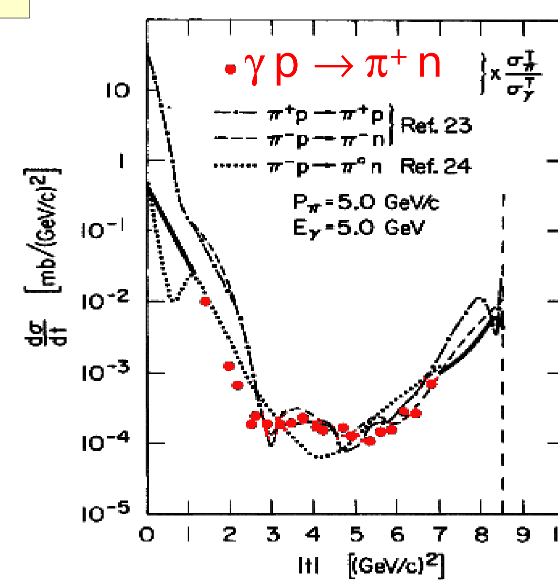
$$\sigma_{tot} = A\,s^{-0.4525} + B\,s^{0.0808}$$

- Simple interpretation in Regge Theory:

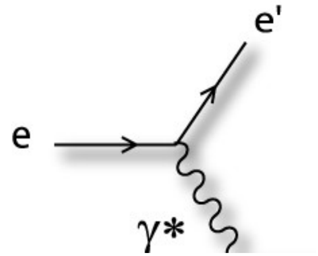
  Pomeron exchange
  +
  reggeon exchange

- forward: *t-channel* exch.
- backward: *u-channel* exch.

Differential x-section at large -t



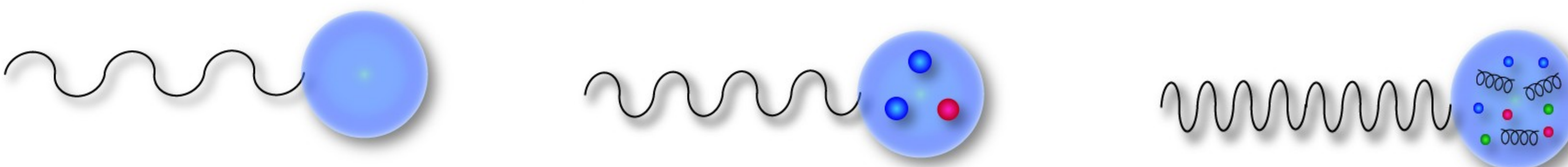
Vector Meson electro-production

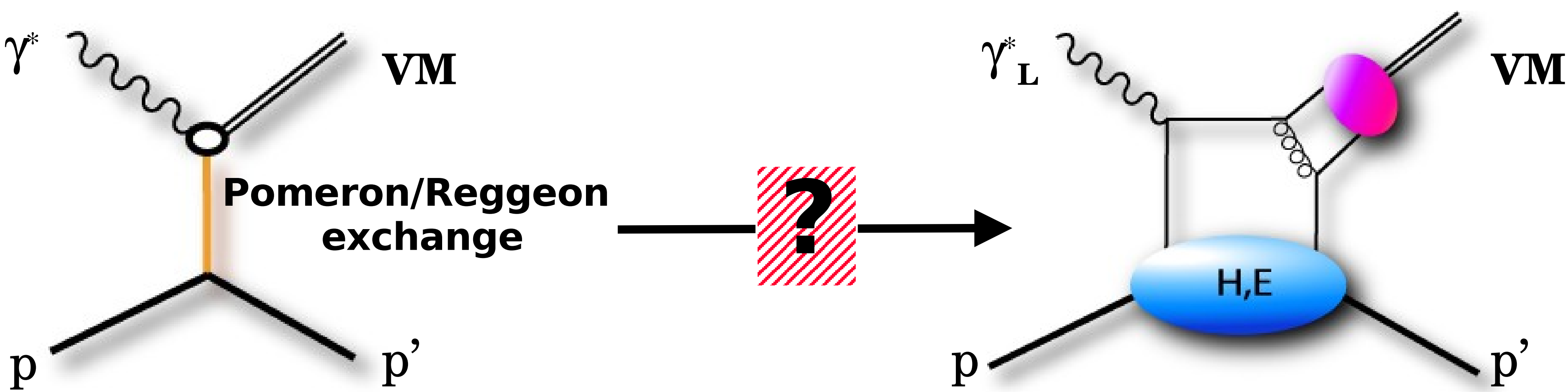


$Q^2 = (e-e')^2$
$= 4E_e E_{e'} \sin^2(\vartheta_{e'}/2)$

- Dynamics fixed at the real-photon point
- Lifetime decreases
  → point-like coupling
- $\lambda \sim 1/Q^2$
  → probes shorter distances

Low Q^2 | **High Q^2**





Vector Meson
γ-production

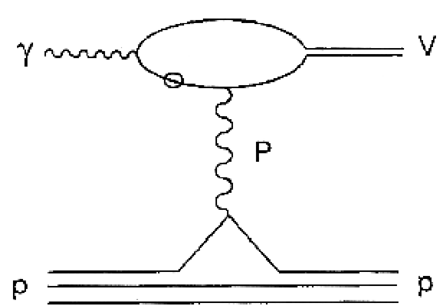
Comparison of different channels

Different qq composition → **Sensitivity to different mechanisms**

Low t

- Vector Dominance
- Diffractive behavior
- Diff xsec~ $\beta e^{-\alpha t}$

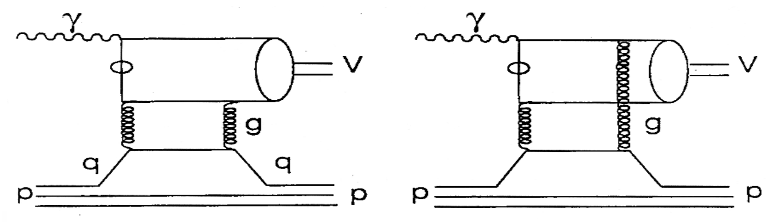
POMERON exchange



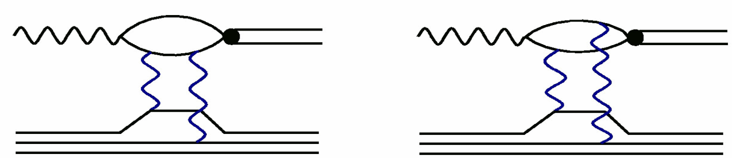
High t

- Small impact parameter
- B ~ *1/sqrt(t)*

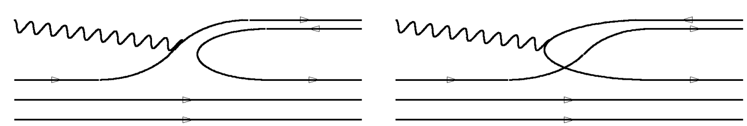
POMERON resolves in 2 gluons



CORRELATIONS between quarks



QUARK EXCHANGE



- **Sensitivity to a possible q-diqark structure** (φ photoproduction)
- **Sensitivity to exchanged quanta structure** (ρ and ω photoproduction)

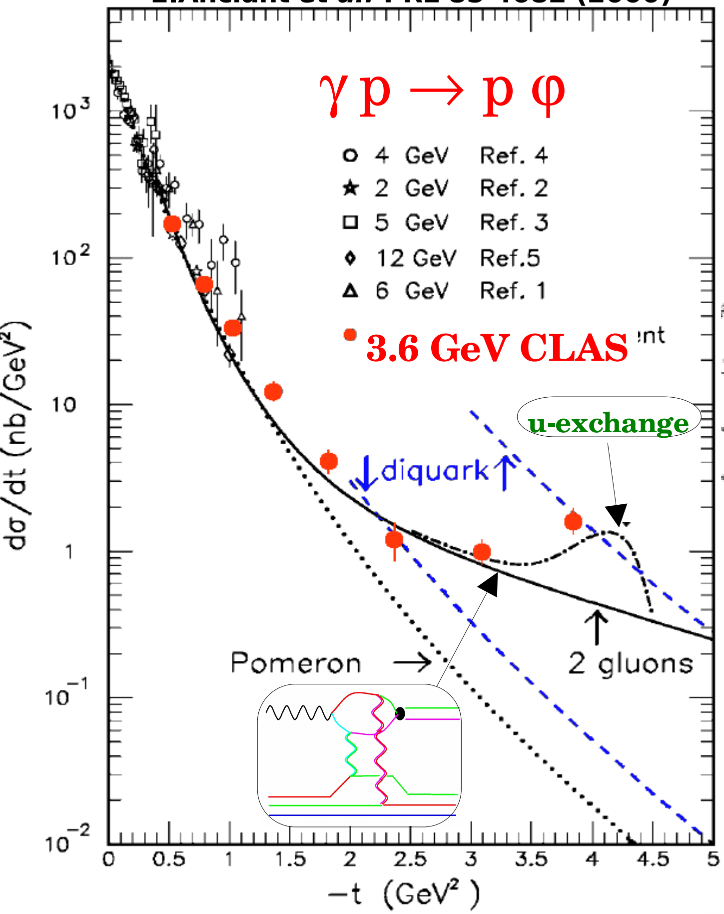
VM photoproduction

F.Cano and J.-M. Laget
Phys.Rev. D65 074022 (2002)

A coherent picture of vector mesons photoproduction

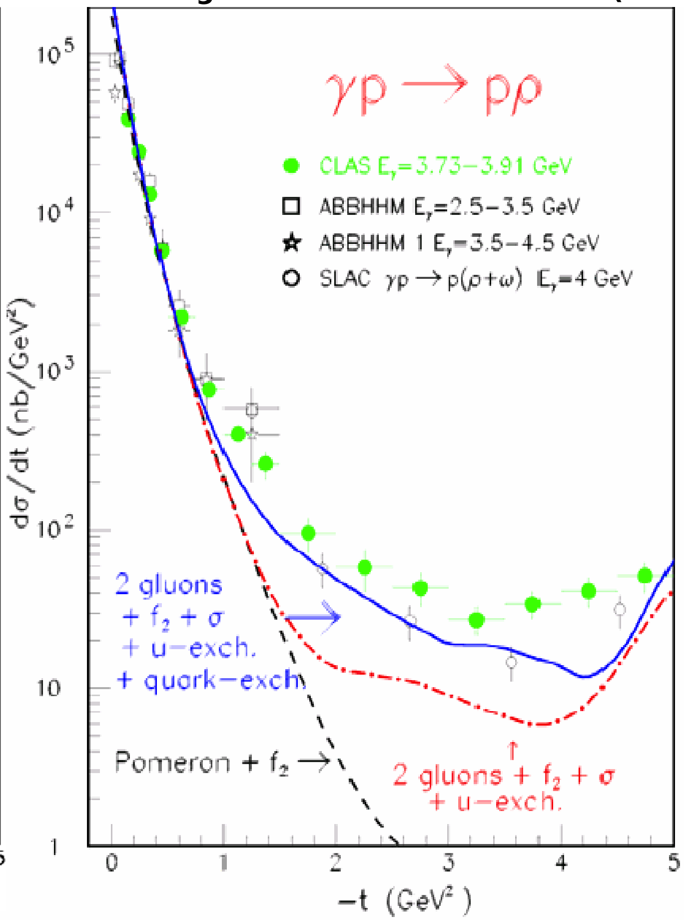
$\gamma p \rightarrow p \varphi \rightarrow p k^+ k^-$

E.Anciant *et al.* PRL 85 4682 (2000)



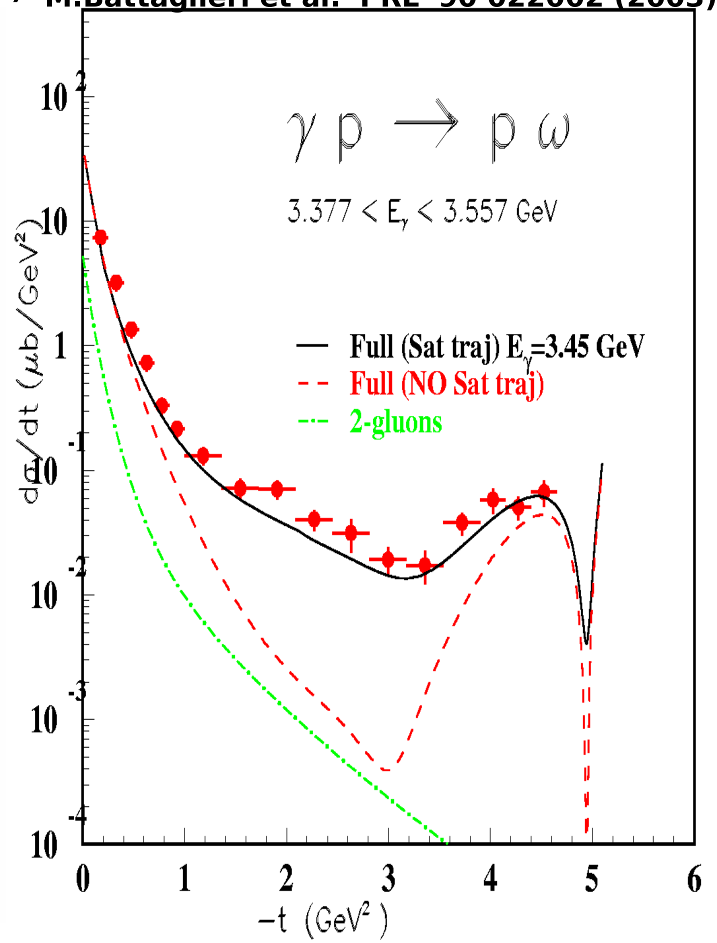
$\gamma p \rightarrow p \rho \rightarrow p \pi^+ \pi^-$

M.Battaglieri et al. PRL 87 172002 (2001)



$\gamma p \rightarrow p \omega \rightarrow p \pi^+ \pi^- \pi^0$

M.Battaglieri et al. PRL 90 022002 (2003)



The φ photoproduction

- POMERON ⇔ 2- gluons
- Nucleon wave function
- Correlations between quarks
- u-exchange around $-t_{max}$

The ρ photoproduction

- P+ f_2+σ exchange at low *-t*
- *Quark-exchange*

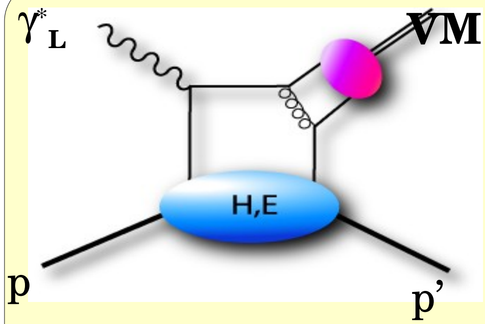
Saturated Regge trajectories

The ω photoproduction

- P+ f_2+ σ + π exch. at low *-t*
- *Quark-exchange*
- No free parameters

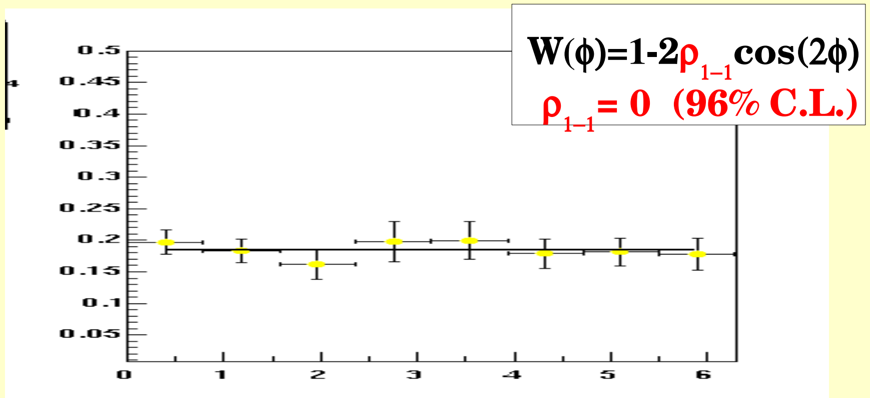
Rho electroproduction

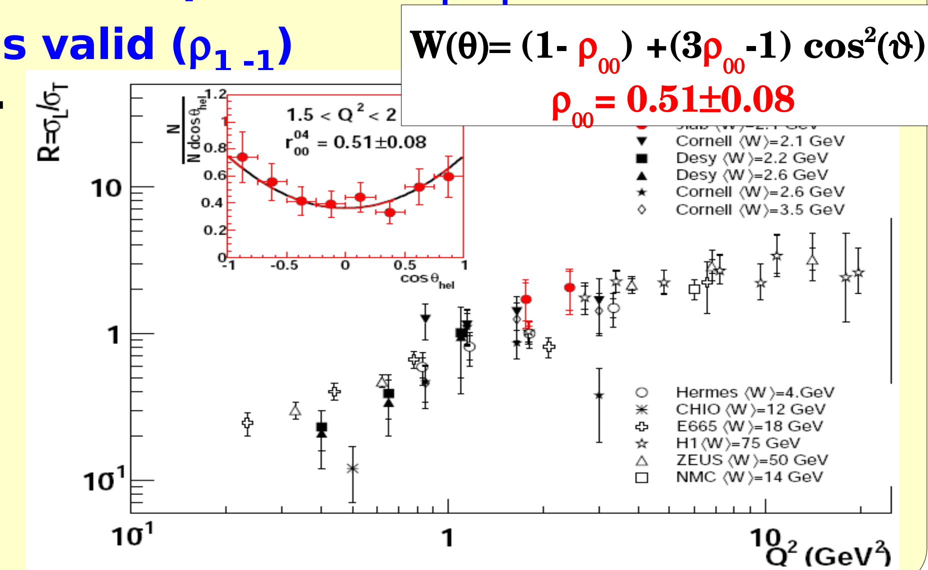
C. Hadjidakis. et al. Phys.Lett.B605:256-264,2005

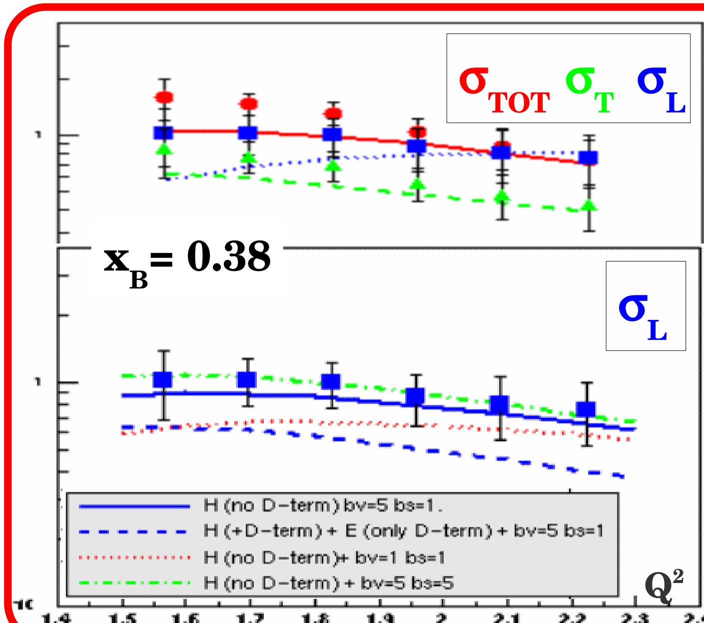


- **Factorization has been proved for longitudinal photons** *(Collins, Frankfurt, Strikman)*
- **Need Longitudinal/Transverse separation (σ_L/σ_T)**
- **From VM decay, if SCHC is valid ($\rho_{1\,-1}$)**

$$R = \sigma_L/\sigma_T = \frac{1}{\varepsilon}\,\frac{\rho_{00}}{1-\rho_{00}}$$







Results:

- **The Transverse cross section is reproduced by the Regge based model (+Q^2 monopole form factor)** *(J.M.Laget F.Cano)*
- **The Longitudinal cross section is reproduced by a GPD based model** *(Vanderhaeghen, Guichon, Guidal)*

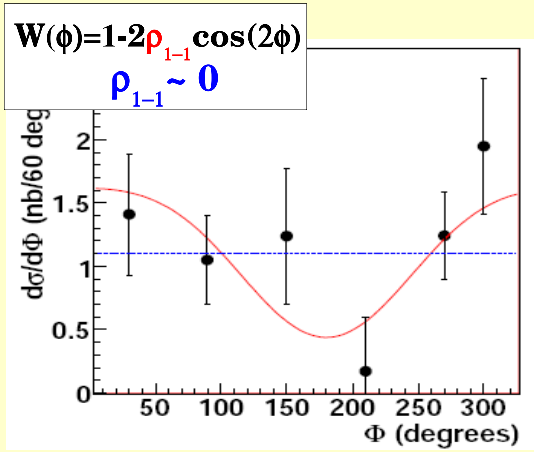
New data are currently under analysis

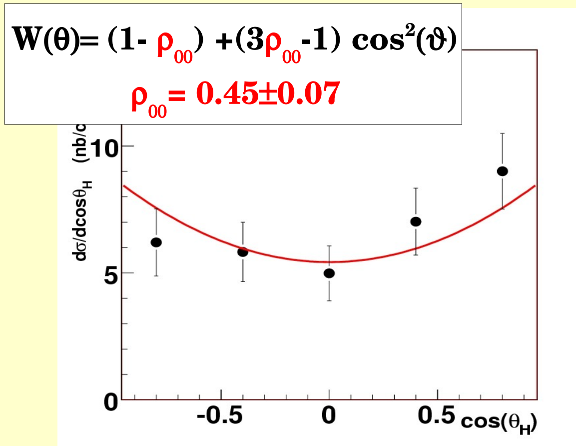
Phi electroproduction

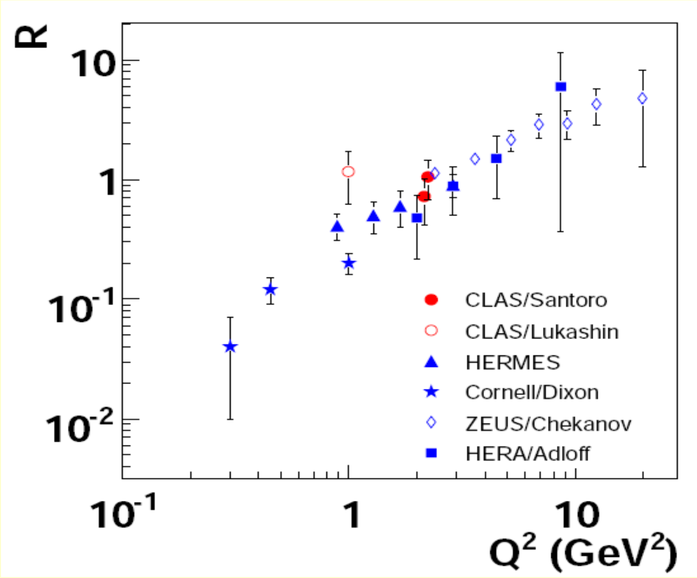
J.Santoro. et al. nucl.ex:0803.3537

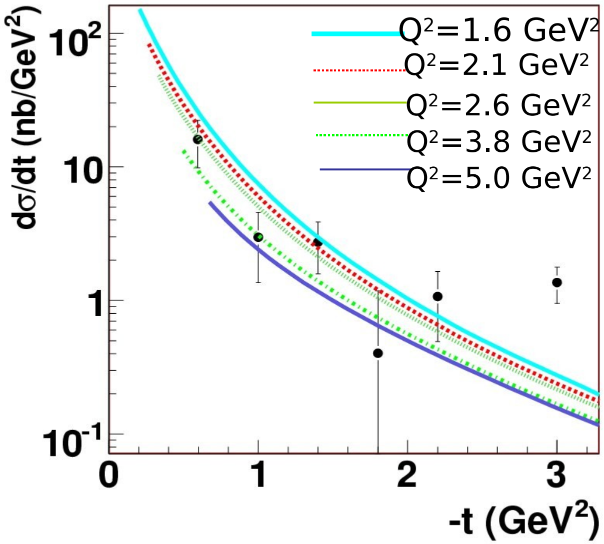
- **Same analysis machinery as for the rho electroproduction**
- **Longitudinal/Transverse separation (σ_L/σ_T)**
- **SCHC valid assumption in this kinematic**

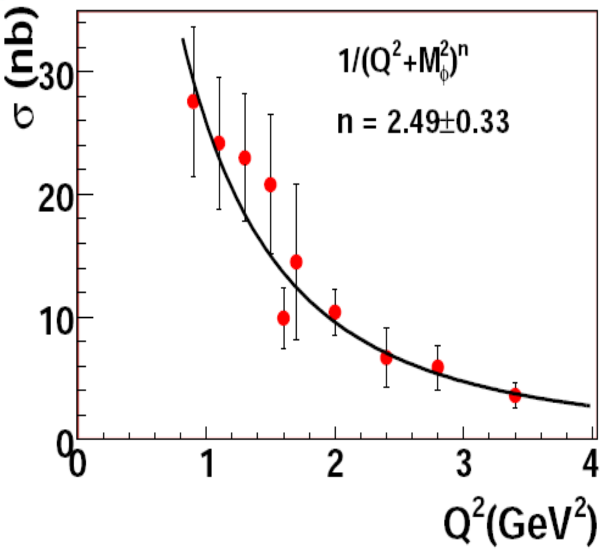
$$R = \sigma_L/\sigma_T = \frac{1}{\varepsilon}\,\frac{\rho_{00}}{1-\rho_{00}}$$











Results:

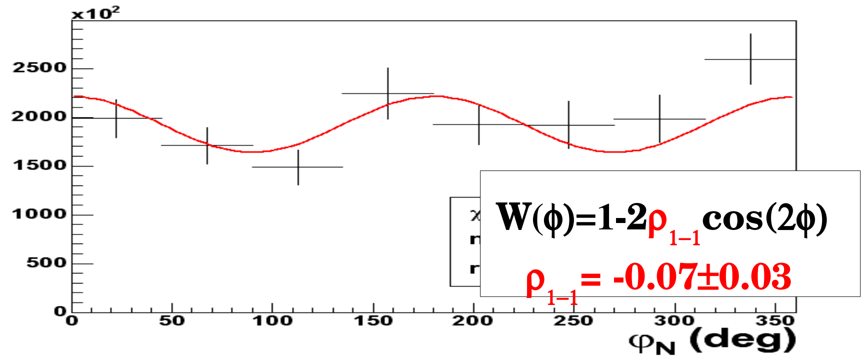
- **VMD predicts Q^2 behavior (n=2)**
- **$R=\sigma_L/\sigma_T=\sim 0.85$**
- **Sensitivity to gluon GPD's**
- **Good agreement with the 2-gluon exchange model used for photoproduction**

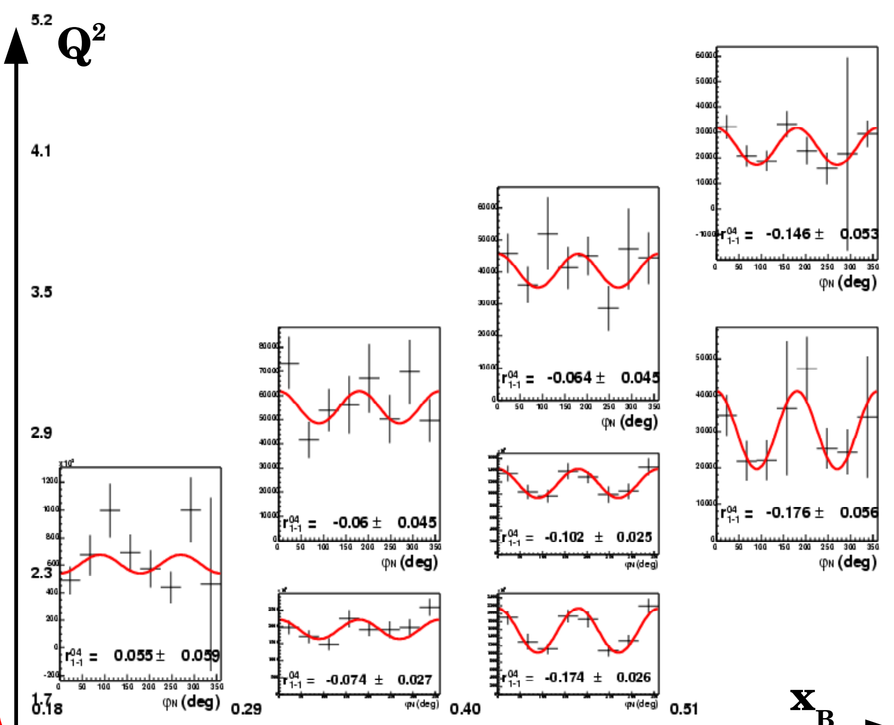
Omega electroproduction (High -t,W,Q^2)

L.Morand et al. Eur.Phys.J.A24:445-458,2005.

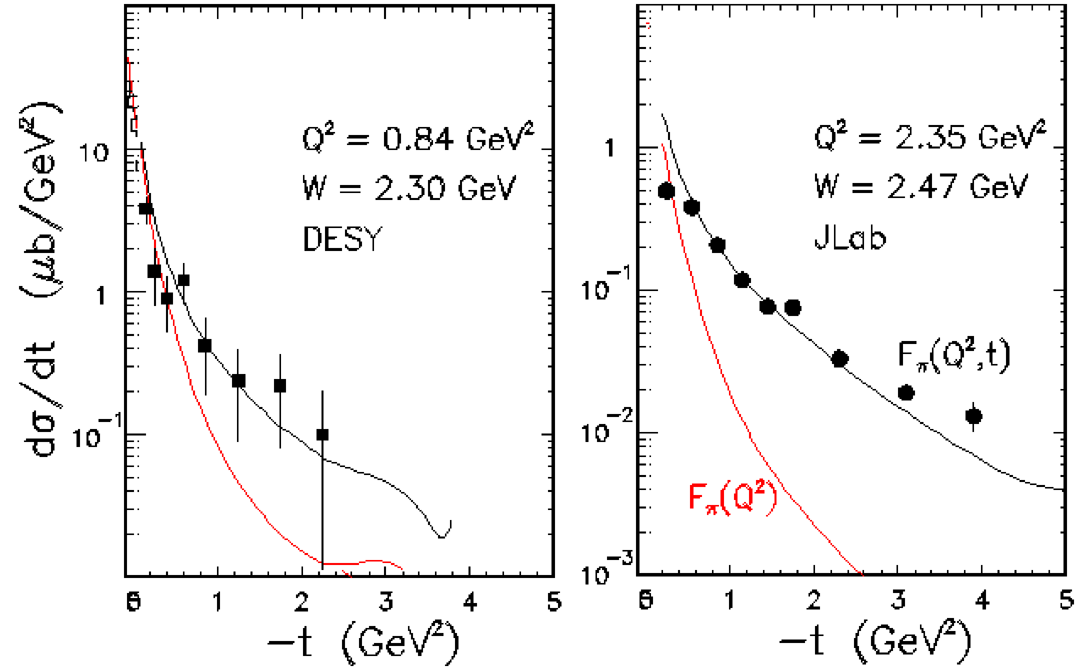
Angular decay distribution

- **Results show $\rho_{1-1} \neq 0$**
- **SCHC <u>not valid</u> in this Q^2 range**





Differential cross section



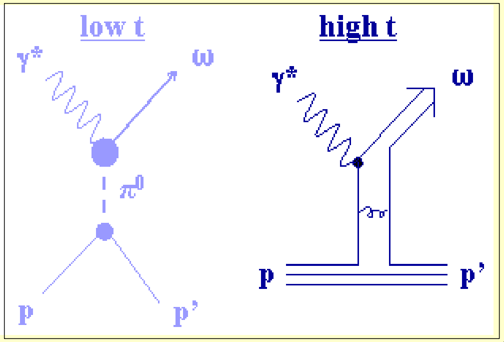
- **Regge approach valid at large *-t* and Q^2**
- **π-exchange still dominant in this Q^2 range**

Low *-t*

- **Hadronic form factor**
- **$d\sigma/dt \sim 1/(Q^2 + \Lambda_0^2)$**

High *-t*

- **Coupling to point-like objects (partons)**
- **$d\sigma/dt \sim$ *flat***



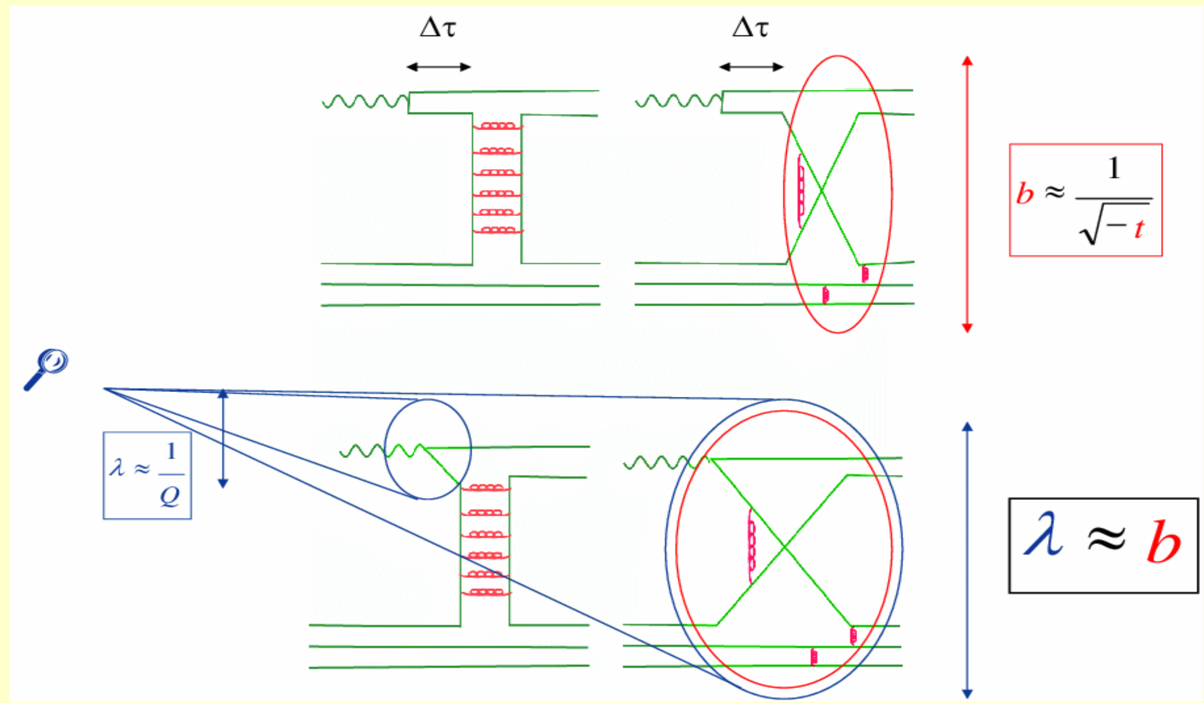
The space time structure of hard scattering process

J.M. Laget Phys.Rev.D70:054023,2004

Two scales:
***-t* and Q^2**

Low Q^2

High Q^2



Low t

High t

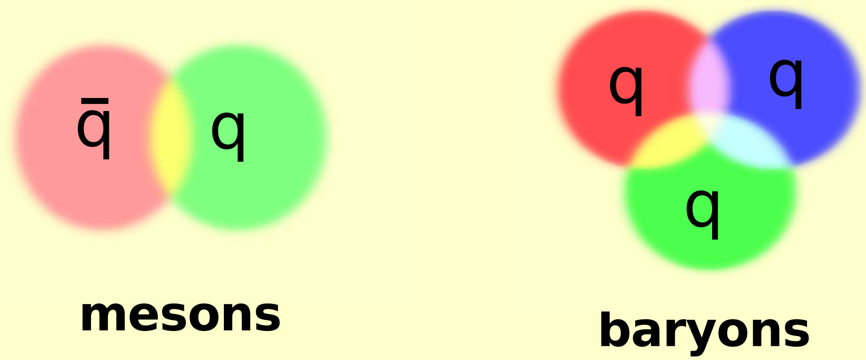
Non perturbative partonic regime

Effective partonic degree of freedom

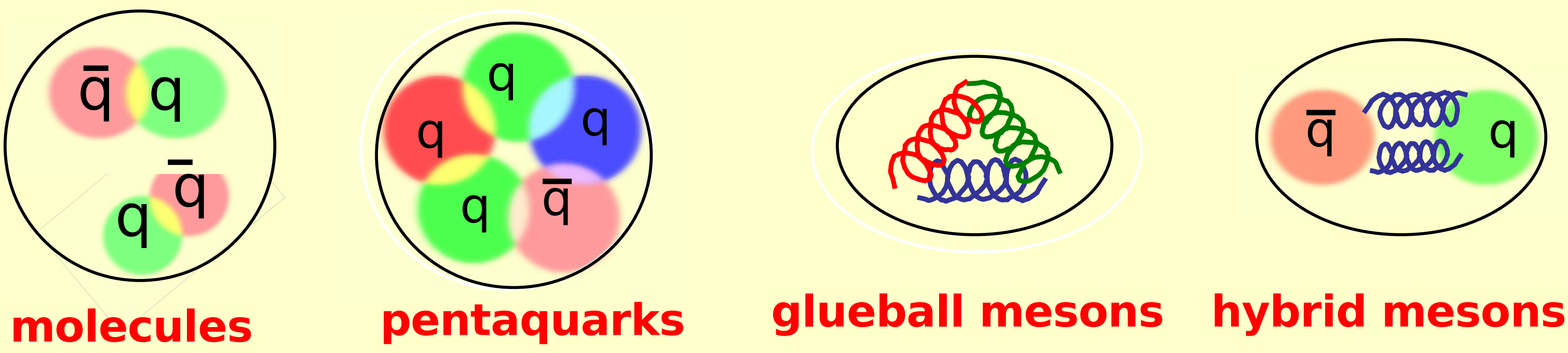
- **Regge quanta exchange in terms of QCD fields**
  pomeron exchange ⇔ 2-gluon exchange
  reggeon exchange ⇔ quark exchange
- **Dressed gluon and constituent quark propagators: from Lattice**
- **GPD-based interpretation is still in progress**

Beyond the quark model: hybrids and exotics

Quarks are confined inside colorless hadrons
they combine to 'neutralize' color force



Other quark-gluon configuration can give colorless objects



QCD does not prohibit such states
but not yet unambiguously observed

The pentaquark

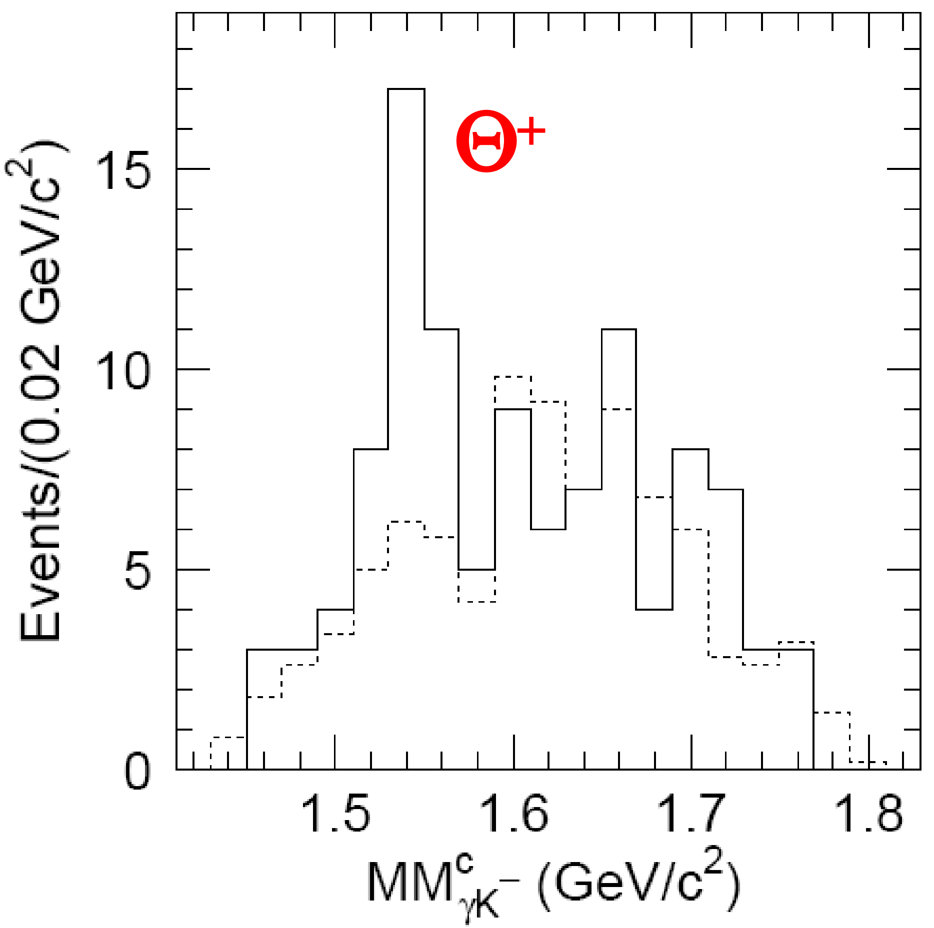
Θ^+

I, S^P = 0, $1/2^+$
Strangeness = +1
Mass ~ 1.530 MeV
Γ ~ 15 MeV

- First clear evidence of exotic configurations (light and narrow)
- New kind of particle will influence our understanding of baryons structure
- 5-quark states are predicted in many theoretical models
- Many experiments with different probes and targets in many different labs aimed to reproduce the initial finding

LEPS @ Spring-8 (Osaka)

T. Nakano et al. Phys. Rev. Lett. 91 012002, 2003



The pentaquark

JLab experiments

- New high statistics, high precision, photoproduction experiment on both proton and deuteron target

- Results for reactions

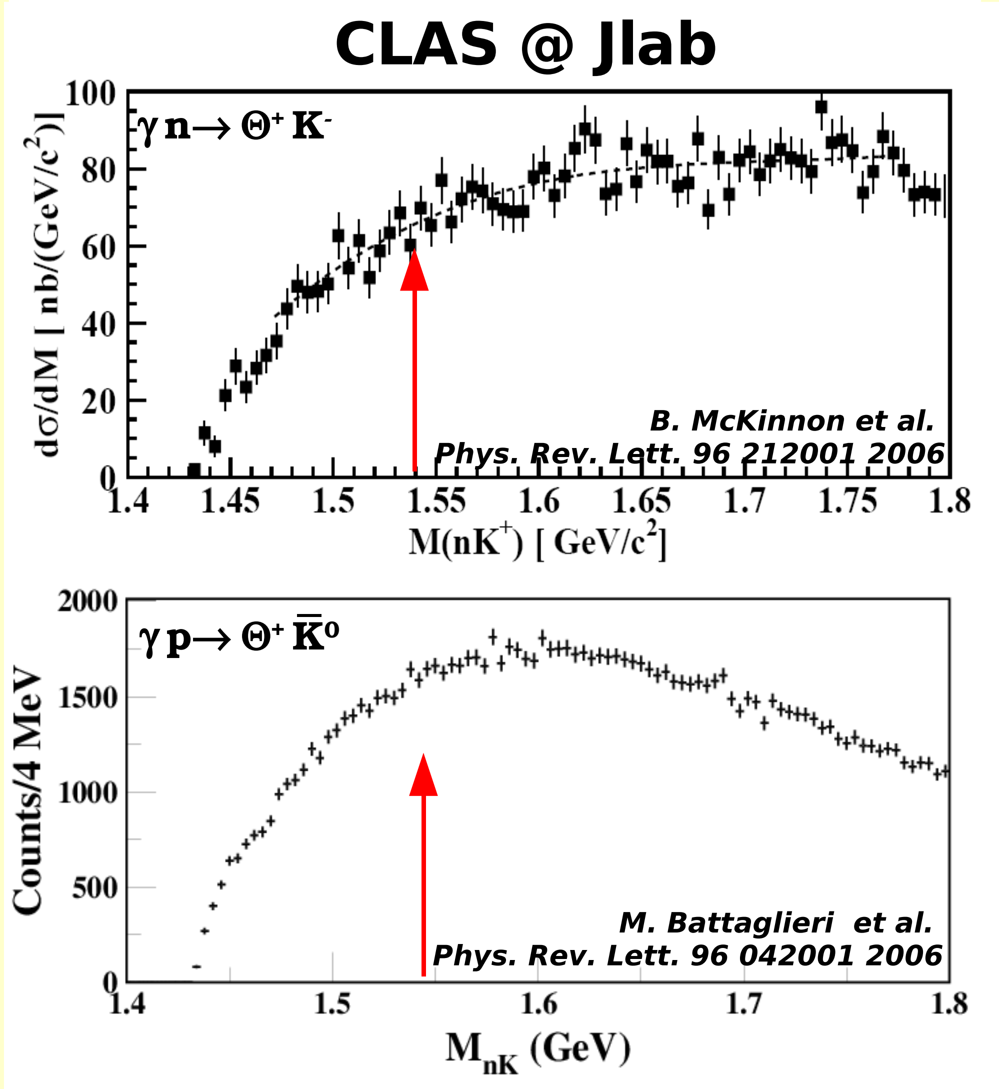
  $\gamma p \rightarrow \Theta^+ \bar{K}^0$ ($\Theta^+ \rightarrow nK^+$ and $\Theta^+ \rightarrow pK^0$)

  $\gamma n \rightarrow \Theta^+ K^-$

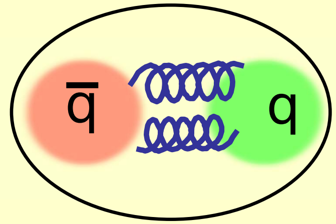
show no indication of a narrow resonance

- An upper limit of 0.75nb (3.0nb) was set for Θ^+ production on proton (neutron)

JLab showed its discovery potential!



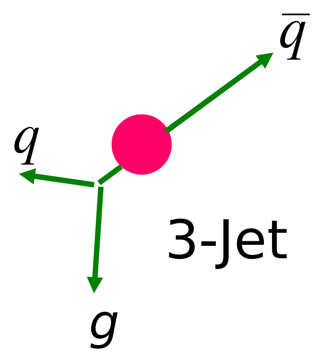
Meson spectroscopy with photons at JLab



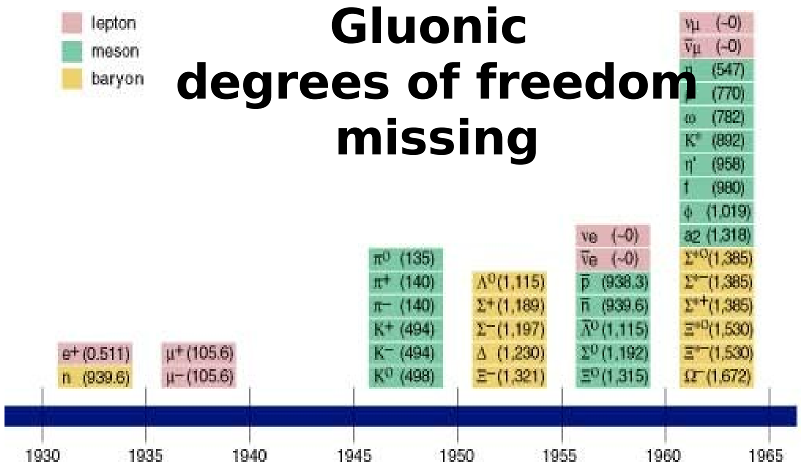
hybrid mesons

☆ **Understanding gluonic excitations of mesons and the origin of confinement**

Gluon jets observed at high energy



Gluonic degrees of freedom missing



Spectroscopy

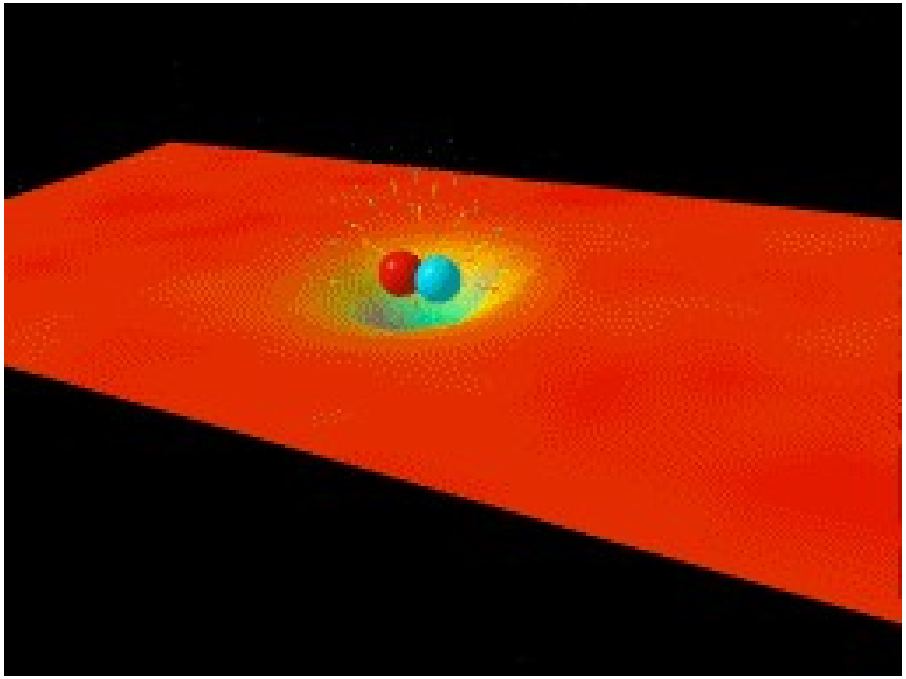
one of the most important issue in hadron physics and main motivation for the JLab 12 GeV upgrade (GlueX program in Hall-D)

Meson spectroscopy with photons at JLab

Indications from Lattice-QCD simulations

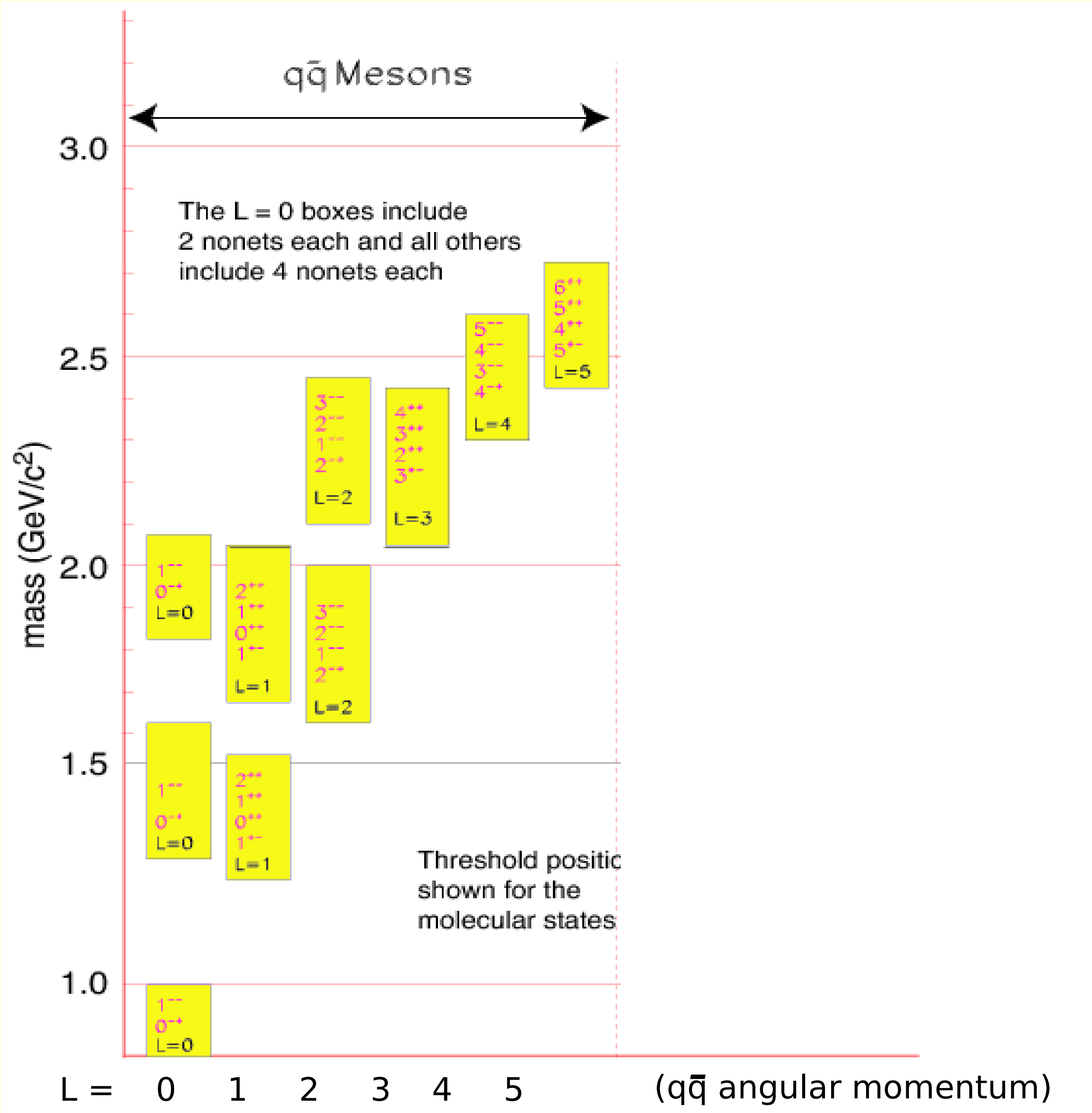
1) Linear potential between quarks is behind the confinement

2) Self-interacting gluons forms a string-like flux tube



How do we look for gluonic degrees of freedom in the real world?

Meson spectroscopy with photons at JLab



Meson map

Hybrid mesons and glueballs mass range:

1.4 GeV - 3.0 GeV

(5 GeV < E_γ <12 GeV)

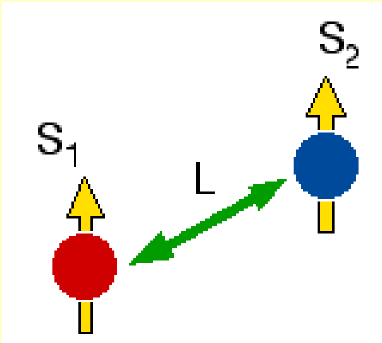
Lattice-QCD predictions for the lowest hybrid states

0^{++} 1.6 GeV

1^{-+} 1.9 GeV

Meson spectroscopy with photons at JLab

☆ **Search for mesons with 'exotic' quantum numbers (not compatible with quark-model)**

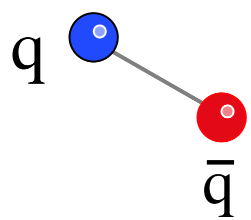


$S=S_1+S_2$ $J= L+S$ $P = (-1)^{L+1}$ $C= (-1)^{L+S}$

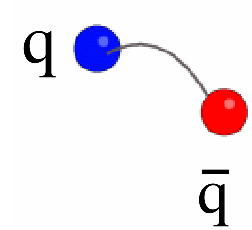
Not-allowed: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \ldots$

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states

Normal meson:
flux tube in ground state
m=0
$CP=(-1)^{S+1}$

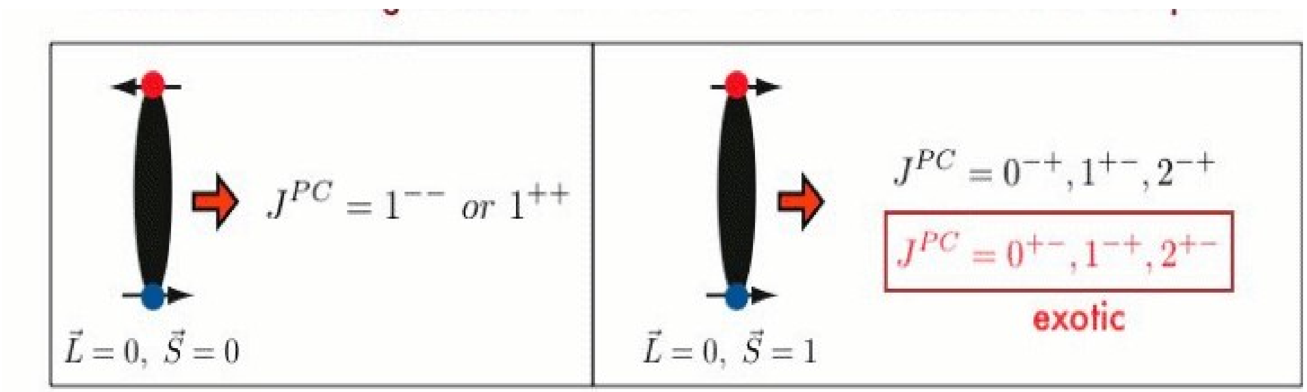


Hybrid meson:
flux tube in excited state
m=1
$CP=(-1)^{S}$



Flux tube
J^{PC} $1^{-+}, 1^{+-}$

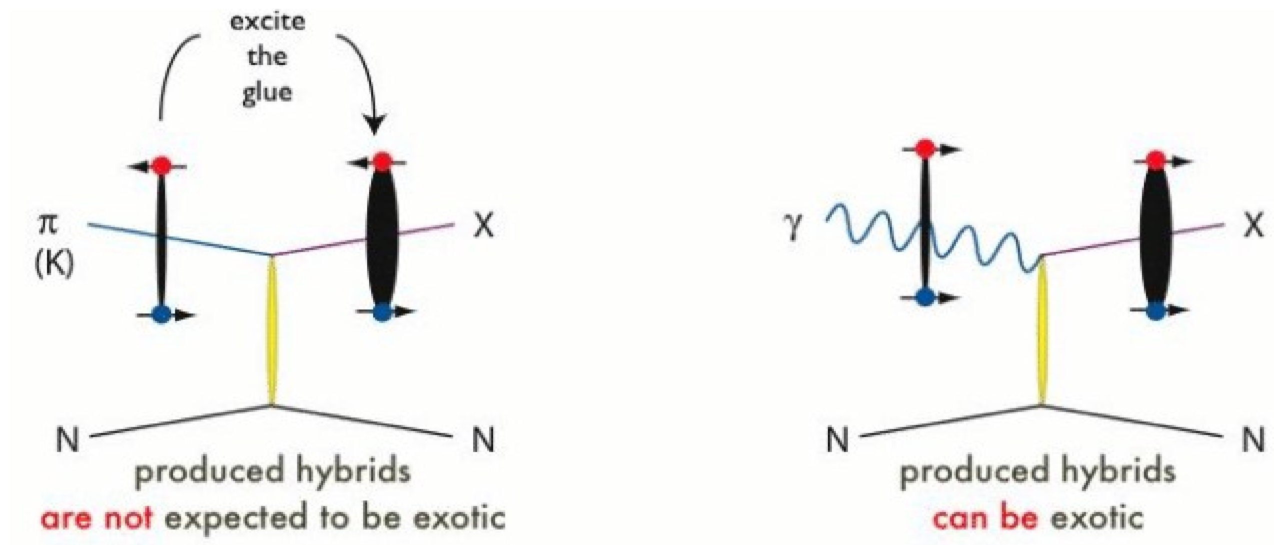
Combine excited glue quantum number with those of the quarks



Meson spectroscopy with photons at JLab

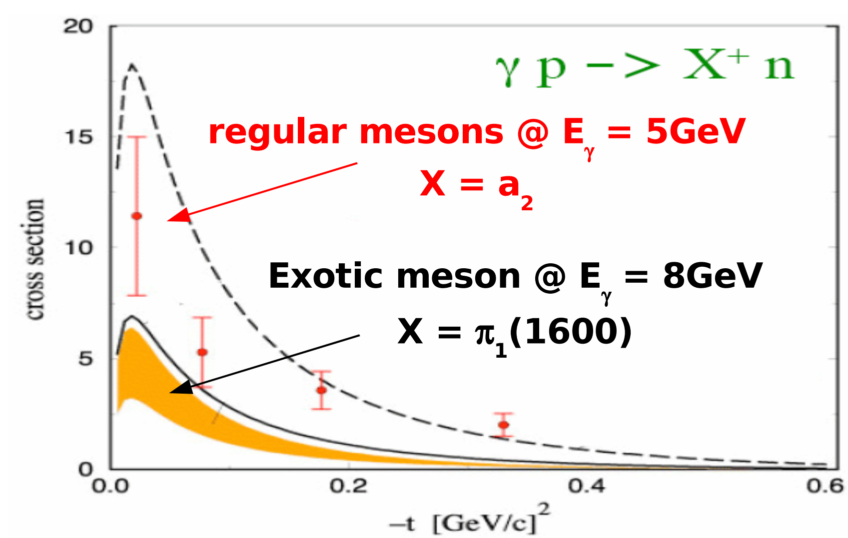
Why photoproduction?

- **Photoproduction: exotic J^{PC} are more likely produced by S=1 probe**



- **Production rate for exotics is expected comparable as for regular mesons**

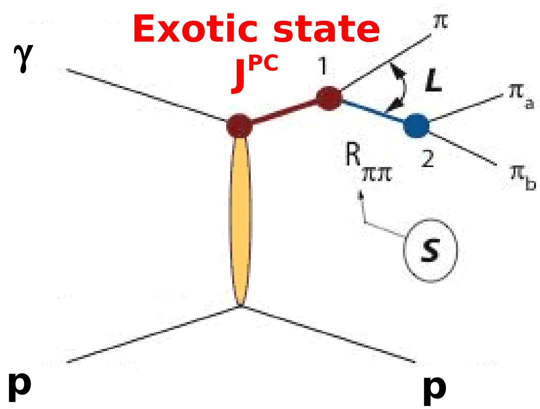
Few data (so far) but expected similar production rate as regular mesons

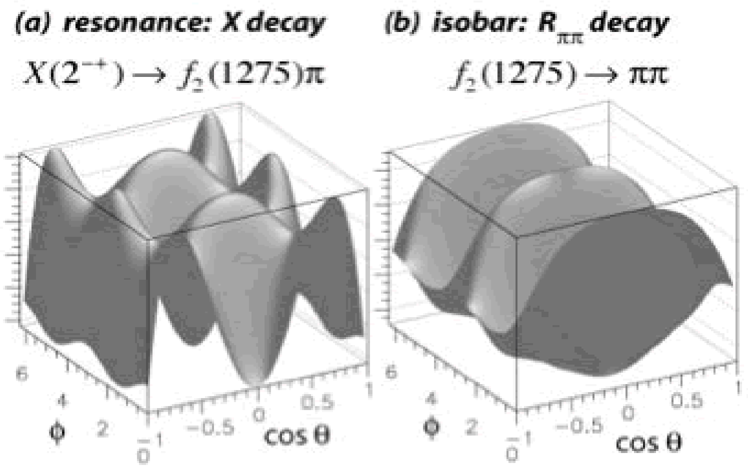


Partial Wave Analysis

1) the isobar model

e.g. 3π system





Does the PWA work with photo-production data?

Use the PWA machinery on CLAS data

2) Moments+Dispersion relations

e.g. 2π system

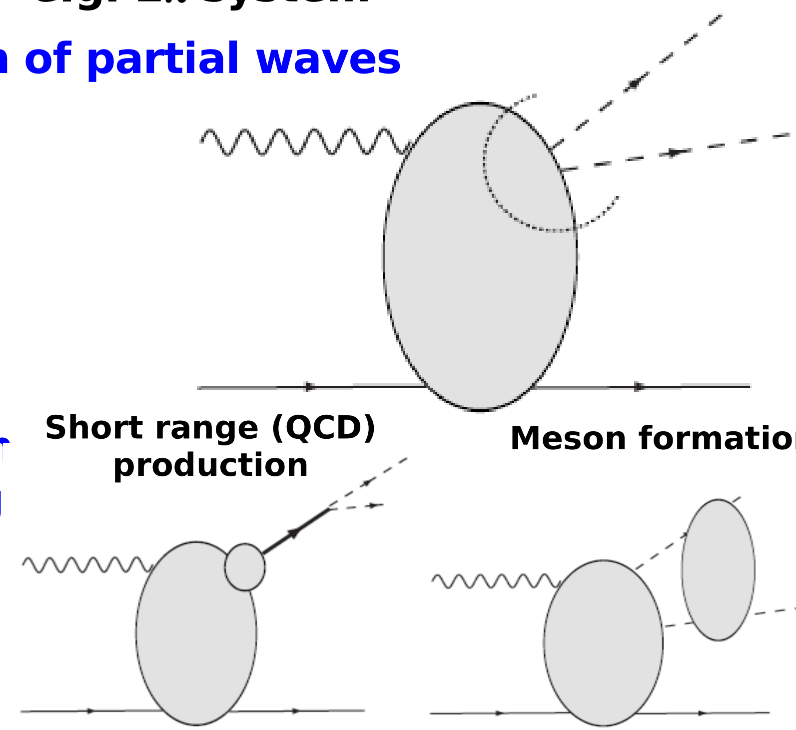
1) Moments of the angular distribution in term of partial waves

$$\langle Y_{\lambda\mu}\rangle(E_\gamma, t, M) = \frac{1}{\sqrt{4\pi}} \int d\Omega_\pi \frac{d\sigma}{dtdMd\Omega_\pi} Y_{\lambda\mu}(\Omega_\pi)$$

$$\langle Y_{00}\rangle = N\left[|S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2\right]$$

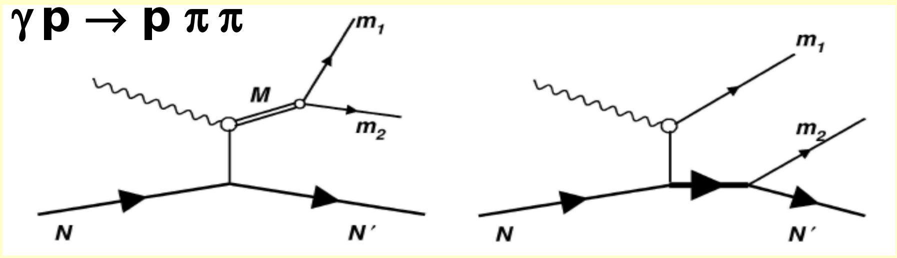
2) Parametrize partial waves in term of known ππ phase shift and unknown coefficients using Dispersion Relations

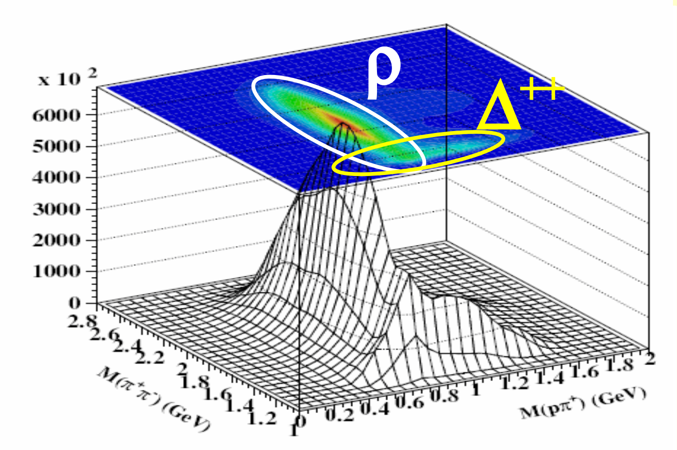
3) Derive partial wave cross sections to compare with models



Coherent meson production on nuclei

☆ Eliminate *s-channel* resonance background





☆ Simplify PWA: S=I=0 target acts as spin and parity filter for final state mesons

☆ Production cross section expected ~ $e^{-bt}|A\,F_A(t)|^2 \to$ low *-t* kinematic

Detection of recoiling nucleus:
- low *-t* (p~0.2-0.5 GeV)
- thin (gas) target (~10^{-3} g/cm^2)

Photon beam:
- small size
- high flux

quasi-real photoproduction Hall-B

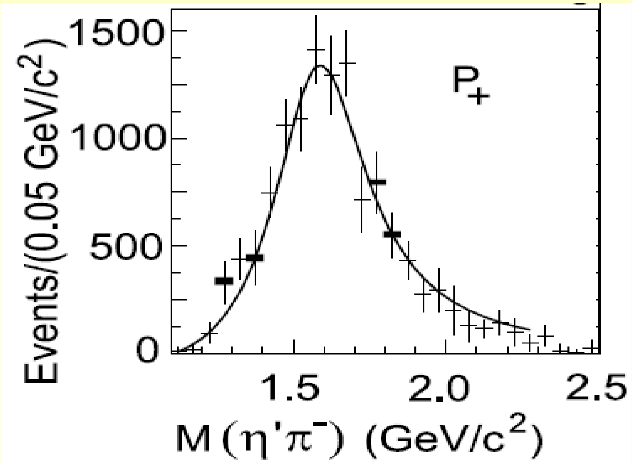
Meson spectroscopy on ^{4}He

$\gamma\, ^4He \to\, ^4He\, \pi^0 \eta$ $\gamma\, ^4He \to\, ^4He\, \pi^0 \eta'$

☆ Strongest evidence of $J^{PC}=1^{-+}$ $\pi_1(1400)$ exotic meson $\pi^- p \to n\eta\pi^0$ in E852-Brookhaven

☆ Search for a resonance in P-wave in $\pi^0\eta$ and $\pi^0\eta'$

☆ Known (non-exotic) resonances can be used as a benchmark (e.g. $J^{PC}=2^{++}$ $a_2(1232)$)



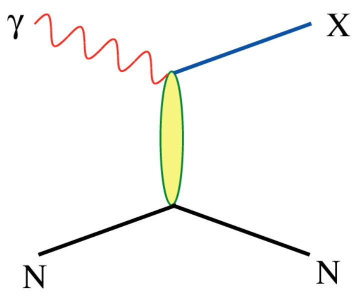
Meson spectroscopy with photons at JLab-12GeV

The photon beam

- With a 12 GeV electron beam only few choices:
  1) Bremsstrahlung
  2) Quasi-real electro-production

- Tagger (initial photon energy) is required to add 'production' information to decay

- Linear polarization is useful to simplify the PWA and essential to isolate the nature of the t-channel exchange

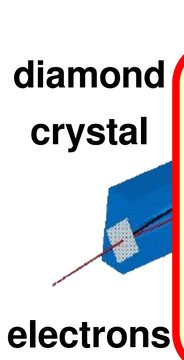


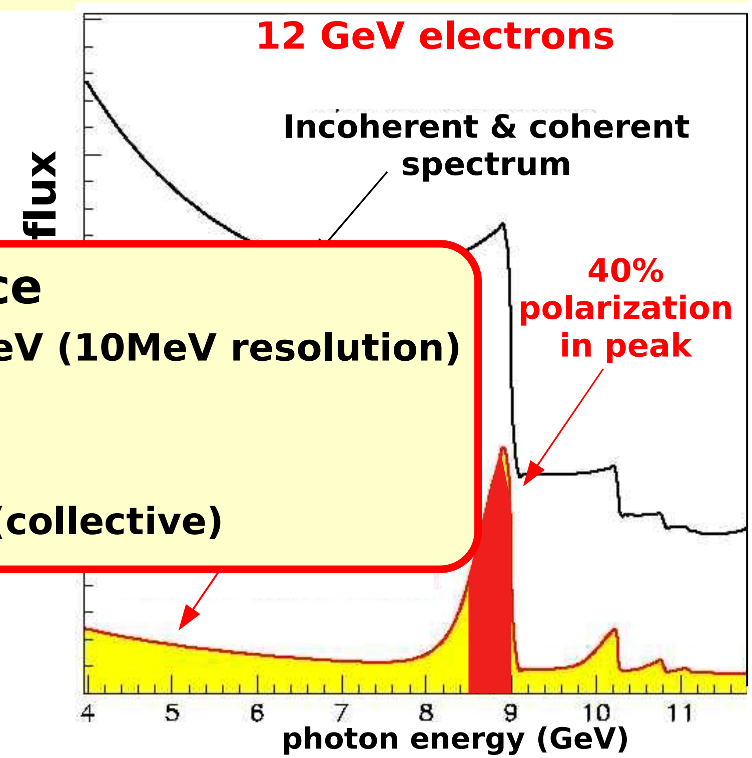
- Essential to isolate production mechanisms (M)
- Polarization acts as a J^{PC} filter if M is known
- Linear polarization separates natural and unnatural parity exchange

Hall-D and Hall-B will host real photon beam!

Meson spectroscopy with photons at JLab-12GeV

Coherent tagged Bremsstrahlung
Hall-D





Performance

- (0.5 - 0.95) $E_{beam} \rightarrow 6 < E_\gamma < 11$ GeV (10MeV resolution)
- Photon Flux ~ 10^7 - 10^8 γ/s
- 30cm LH target $\rightarrow$ L ~ 10^{31} $cm^{-2}s^{-1}$
- Linear polarization ~ 50% - 15% (collective)

Quasi-real electroproduction at very Low Q^2
Hall-B

$E_{scattered}$	1 - 4 GeV
θ	0.5^o - 1.2^o
ϕ	0^o - 360^o
ν	7 - 10 GeV
Q^2	0.003 - 0.029 GeV^2
W	3.9 - 4.6 GeV
x_{Bj}	0.0001 - 0.002

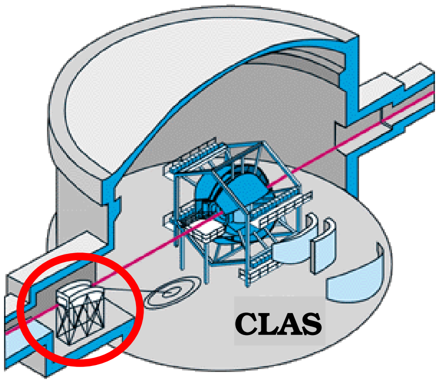
Performance

- $7 < E_\gamma < 10$ GeV
- 5cm LH target $\rightarrow$ L ~10^{34} $cm^{-2}s^{-1}$
- Linear polarization ~ 65% - 20% (individual)
- Capability of forward tagging (electron detection)

Real and quasi-real photon beams at JLab-12GeV

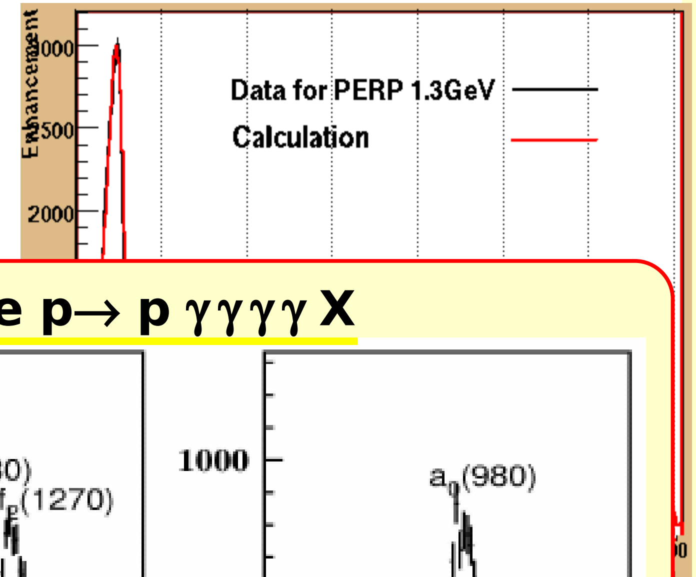
Coherent tagged Bremsstrahlung:well established technique

Hall-B real Bremsstrahlung Photon Tagger

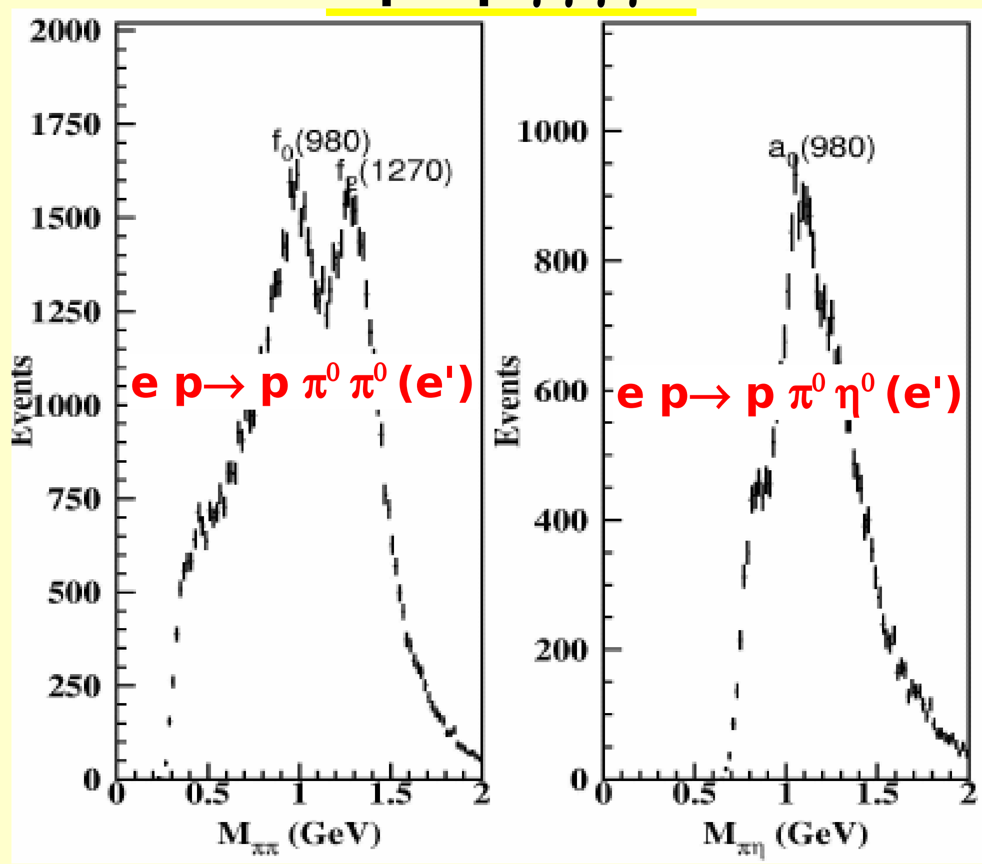


Performance

- E_γ =0.8-5.4 GeV (20% - 95% E_{beam})
- $\Delta E_\gamma/E_\gamma \sim 10^{-3}$ $\Delta t \sim 2$
- Linearly polarize
  (coherent Brems



e p→ p γγγγ X



Quasi-real electroproduction at very Low Q^2

- Test level
- Fake "0^0" electroproduction (no electron in the trigger) from huge collected statistic

Bright meson peaks show up
The technique works!

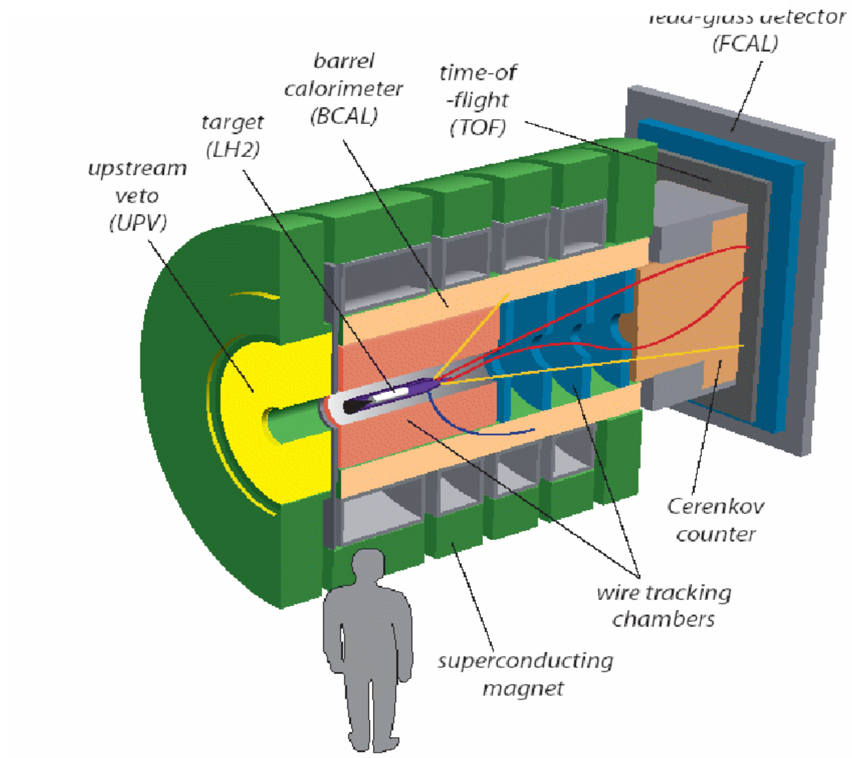
Meson spectroscopy with photons at JLab-12GeV

✯ The Detector

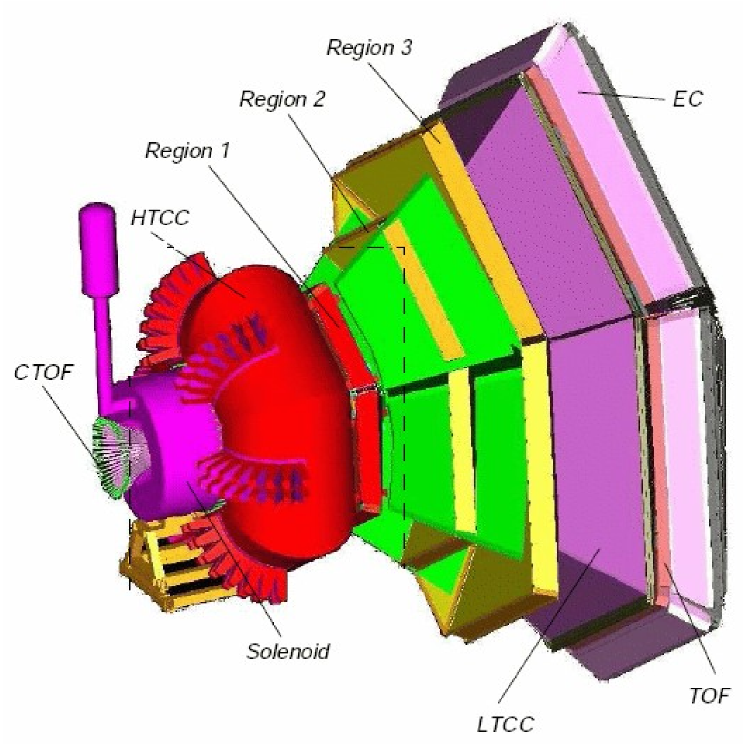
- Determination of J^{PC} of meson states requires Partial Wave Analysis
- Decay and Production of exclusive reactions
- Good acceptance, energy resolution, particle Id

➜ **Hermetic charged/neutral particles detector**

Hall-D - GlueX Detector



Hall-B - CLAS12 Detector



Conclusions

New precise and abundant data from CLAS@Jefferson Lab

Exclusive reactions reveal hadron complexity beyond quark model

Dynamic properties of constituent partons

Interacting partons in meson photoproduction

- **Production mechanisms help to understand confinement**

Beyond the standard quark model

Search for exotic configurations (pentaquarks, S=+1)

- **New high statistics, high precision, low energy measurement show no indication of a narrow resonance setting an upper limit for Θ^+ production**

Meson spectrum investigated in photoproduction

- **PWA (IM and Moments + Dispersion relations) feasible in CLAS**

- **Better understanding of hadrons structure and nuclear dynamics**
- **Progress in understanding confinement in QCD and the role of *constituent quark* and *gluons* to describe the non-perturbative regime**

Near future:
Dedicated detectors and high intensity photon beams at Jlab-12 will make JLab-12 the ideal facility to study hadron spectroscopy