Experimental Tests of QCD Scaling Laws at Large Momentum Transfer in Exclusive Light-Meson Photoproduction

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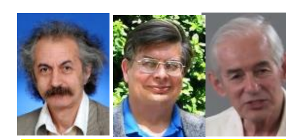
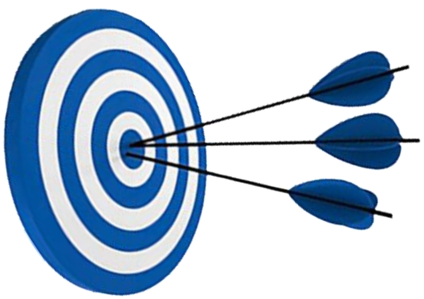


Phys. Rev. C **103**, 055203 (2021)

*) Supported by DE-SC0016583

Outline



- *QCR & Sudakov form factor*
- *Brief tour through CLAS light meson photoproduction experiments*
- *QCR for light meson photoproduction*
- *CLAS data: Partial evaluation*
- *Brief tour through future GlueX & Hall C experiments*
- *Summary*

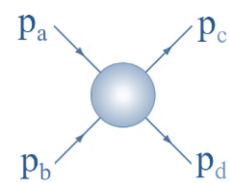
Quark Counting Rule

&

Sudakov FF

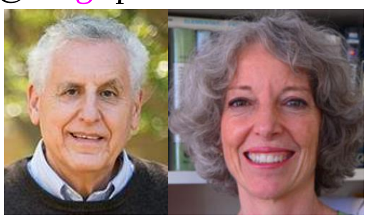
- Binary reactions in ***QCD*** with large momentum transfer involve ***quark*** & ***gluon*** exchanges between colliding particles.

- ***QCR*** of *Brodsky-Farrar* & *Matveev-Muradyan-Tavkhelidze* have simple recipe to predict energy dependence of differential cross sections of two-body reactions



$$a + b \rightarrow c + d$$

@ large *production* or *scattering* angles when t/s is *finite* & is kept *constant*.



S.J. Brodsky & G.R. Farrar, Phys Rev Lett **31**, 1153 (1973) **CI** = 1,932

V.A. Matveev, R.M. Muradian, & A.N. Tavkhelidze, Lett Nuovo Cim **7**, 719 (1973) **CI**= 1,186

- **Fixed angle** (90^0) for *production* or *scattering* behavior for exclusive processes is expected to be

$$d\sigma/dt(s) \propto s^{-(n-2)}$$

where n is number of constituents: $(n - 2) = (n_a + n_b) + (n_c + n_d) - 2$

$$s + t + u = m_a^2 + m_b^2 + m_c^2 + m_d^2$$

- **Condition is** large s with large $|t|$ & $|u|$ => optimal angle $\theta = 90^0$

- Recall that in order to provide *exclusivity* of *hard* scattering, we must balance *large transferred momentum* between all *quarks* in *hadron*.

- This means that in order to get maximum contribution, we must consider *Fock* components of hadron wave function with *minimum number* of *quarks*.
  - Moreover, these *quarks* should be close to each other.
  - Small ***q***-***q*** separation provides possibility to better balance momenta between *quarks*.

- These **two** conditions are based elements of *QCR* expression $d\sigma/dt(s) \infty s^{-(n-2)}$
  - In *Matveev-Muradian-Tavkhelidze* approach, authors considered just probability to find *quarks* sufficiently close to each other.
  - In *Brodsky-Farrar* approach, balance of *quark* momenta was reached via exchanged of additional *gluon* between *quarks*. Since virtuality of this *gluon* is large it means that again we consider configuration with short-range ***q***-***q*** configuration.

Sudakov Form Factor

Hard processes are those in which momentum transfer, Q, is substantial with respect to **QCD** scale, $Q > \Lambda_{QCD} \simeq 220\ MeV$
In this regime, strong coupling constant, α_s, is perturbative.
In contrast, non-perturbative effects in soft emission requires complicated techniques (*e.g.*, showering).

- *QCR* accounts for minimum numbers of elementary *hard processes* needed to provide large momentum transfer to *hadron*.

Yu.L. Dokshitzer, D.I. Diakonov, & S.I. Troian, Phys. Rep. **58**, 269 (1980)
Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller, & S.I. Troian, *Basics of Perturbative* QCD, Edition Frontieres (Singapore, 1991)

- @ very large energies, this *QCR* is modified by so-called Sudakov *FF*.

- It is very improbable that two ensembles of constituents can get strong transverse kick & radiate no *gluons*.
- Of course, probability of new *gluon* emission is suppressed by *QCD* coupling constant α_s, but simultaneously it can be enhanced by large $\ln^2 s$.
- *Probability* not to emit any additional *gluons* is called Sudakov *FF*.

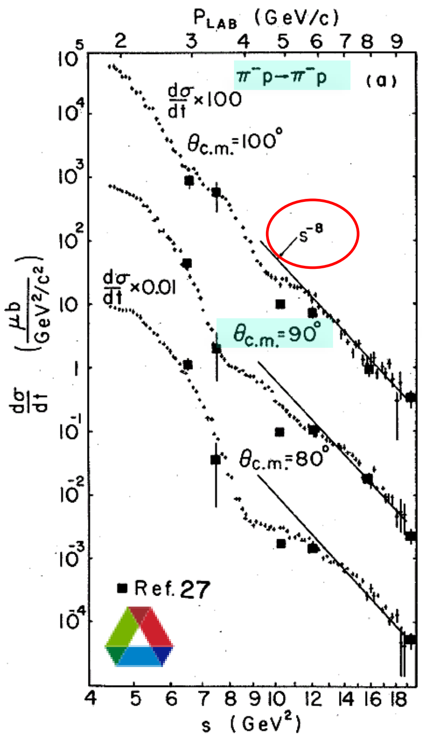
- For very large s, we expect that cross section of large angle *hadron*-*hadron* scattering should fall with s faster than *QCR* prediction.

- In *hadron* case, Sudakov *FF* works as was theoretically shown [J. Botts & G. F. Sterman, Phys Lett B **224**, 201 (1989)]

- Theoretically was shown in [G.R. Farrar, G.F. Sterman, & H. Zhang, Phys Rev Lett **62**, 2229 (1989)] that due to *point-like* nature of *photon*, Sudakov *FF* is ***absent*** in case of *large angle* meson photoproduction.

$$d\sigma/dt(s) \propto s^{-(n-2)}$$

- For *hadron*-*proton* interaction, ***QCR*** works well, where hadron is ***pion***, ***kaon***, ***proton***, or ***antiproton***.



$$\pi + p \longrightarrow \pi + p$$

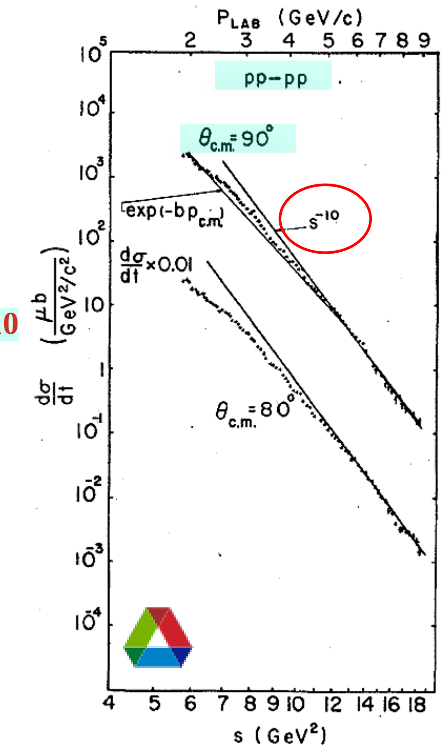
$(n-2) = (2+3) + (2+3) - 2 = 8$

$$d\sigma/dt(s) \propto s^{-8}$$

$$p + p \longrightarrow p + p$$

$(n-2) = (3+3) + (3+3) - 2 = 10$

$$d\sigma/dt(s) \propto s^{-10}$$



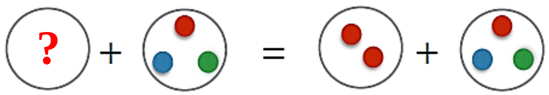
K.A. Jenkins *et al*. Phys Rev D **21**, 2445 (1980)

Process	Constituent power	Experimental power	Range $\sqrt{s}$
$\gamma N \to \pi^+ N$	7	7.3 ± 0.3 [54]	2.8–3.8
$K_L{}^0 p \to K_L{}^0 p$	8	8.5 ± 1.4 [56]	2.2–3.4
$\bar{K}_0 p \to \pi^+ \Lambda$	8	7.4 ± 1.4 [56]	2.0–4.0
$\bar{K}_0 p \to \pi^+ \Sigma^0$	8	8.1 ± 1.4 [56]	2.3–3.4
$K^+ p \to K^+ p$	8	7 ± 1 [55]	2.0–3.6
$\pi^- p \to \pi^- p$	8	8 ± 1 [57]	2.0–4.1
$\pi^+ p \to \pi^+ p$	8	7 ± 1 [55]	2.0–3.5
$pp \to pp$	10	9.7 ± 0.5	(2.5–6.1)
$\bar{p}p \to \bar{p}p$	10		

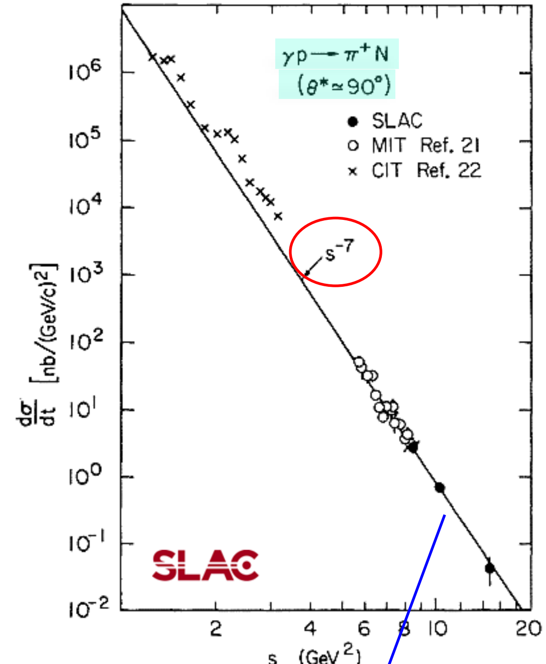
D. Sivers, Ann Phys (NY) **90**, 71 (1975)

QCR for Meson Photoproduction

$$\gamma + p \longrightarrow \mathcal{M} + \mathcal{B}$$



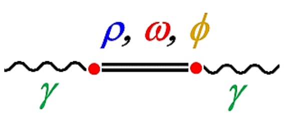
$$(n-2) = (? + 3) + (2+3) - 2 = ?$$



R.L. Anderson *et al*. Phys Rev D **14**, 679 (1976)

?

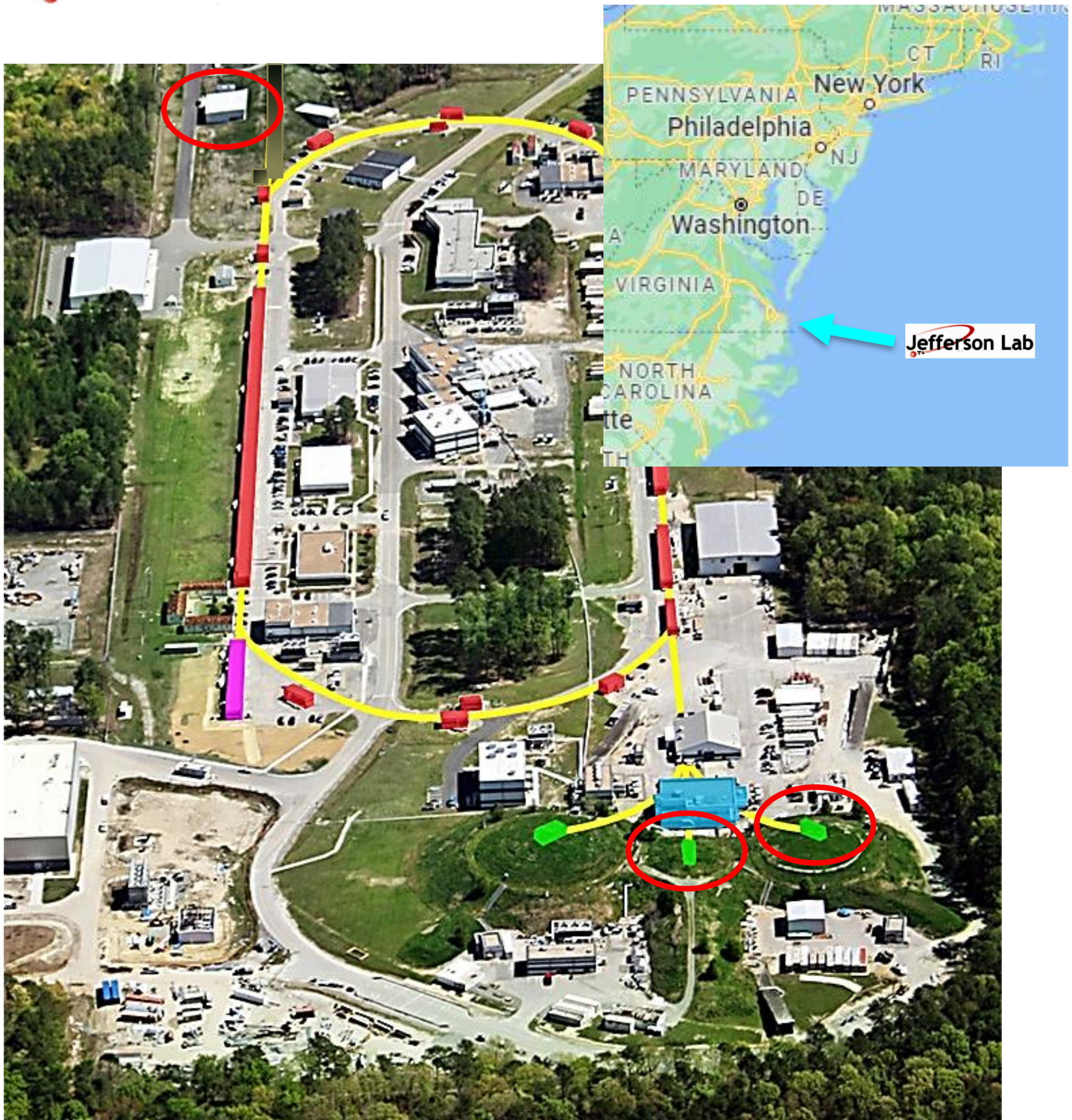
- There are ***three*** options of how one can consider ***photon*** in *γN* interaction:
  - No constituents ($n_\gamma = 0$) & $d\sigma/dt(s) \propto s^{-6}$.
  - Photon is point-like particle which participated in strong interaction ($n_\gamma = 1$) & $d\sigma/dt(s) \propto s^{-7}$.
  - There is *q*-bar-*q* configuration which participated in interaction ($n_\gamma = 2$) & $d\sigma/dt(s) \propto s^{-8}$.



In *VMD*, ***real photon*** can *fluctuate* into *virtual* ***vector meson***, which subsequently scatters off target proton.

Brief Tour through CLAS Light Meson Photoproduction Experiments

Jefferson Lab *Continuous Electron Beam Accelerator Facility* in *2022*



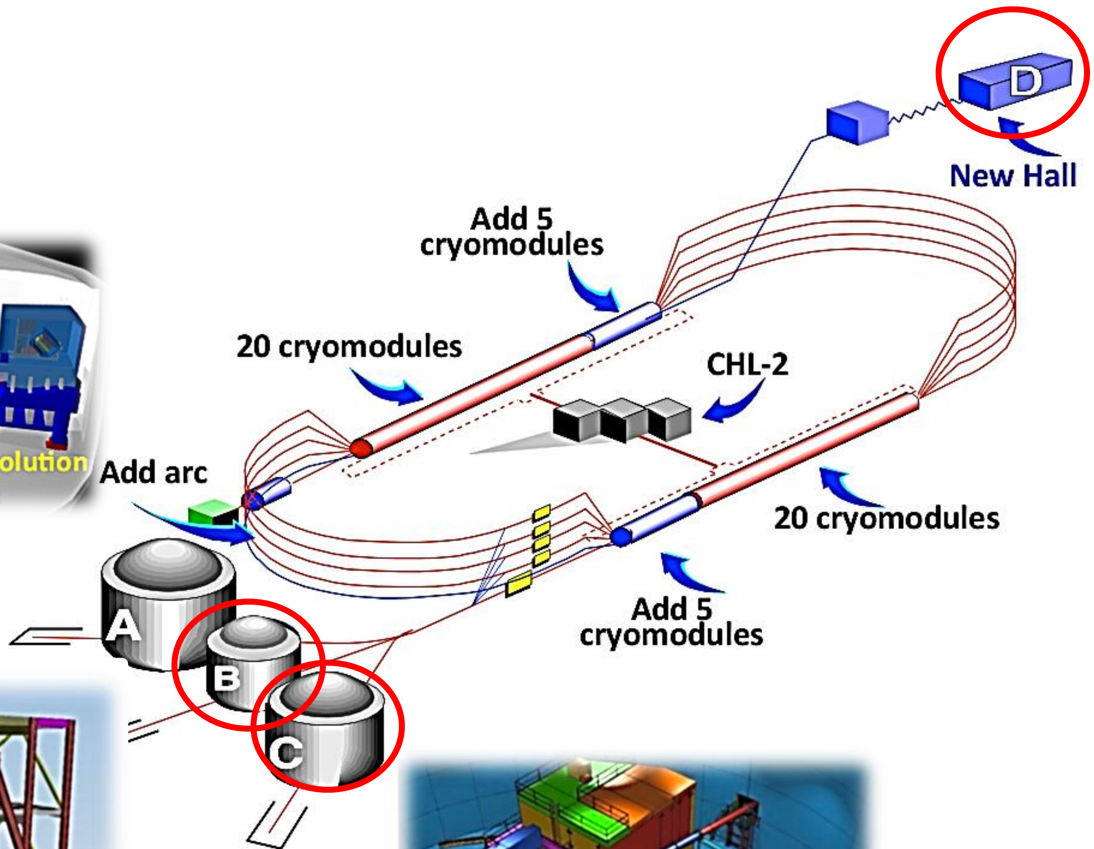
1995 – 2012…
Energy 0.4 – 6.0 GeV
- 200 μA, polarization 85%
- Simultaneous delivery 3 halls

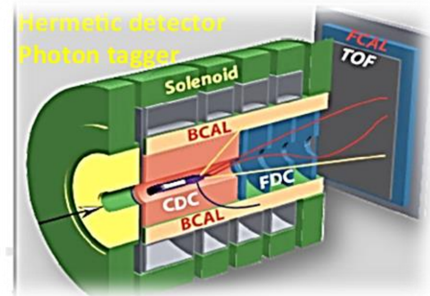
- 500+ PhDs completed
- On average 22 US PhDs per year, roughly 25-30% of US PhDs in nuclear physics
- 1530 users in FY16, ~1/3 international from 37 countries

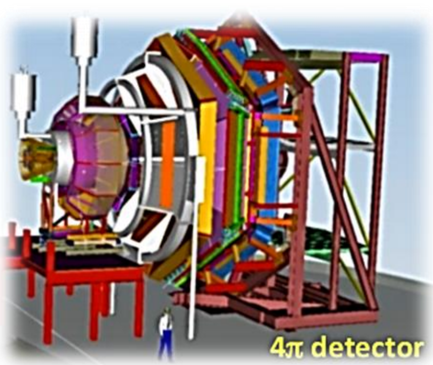
~2016 – …..
Energy 0.4 – 12.0 GeV
- 150 μA, polarization ~85%
- Simultaneous delivery 4 Halls
- FY18: First try simultaneous delivery to **4** Halls – A, B, C, D

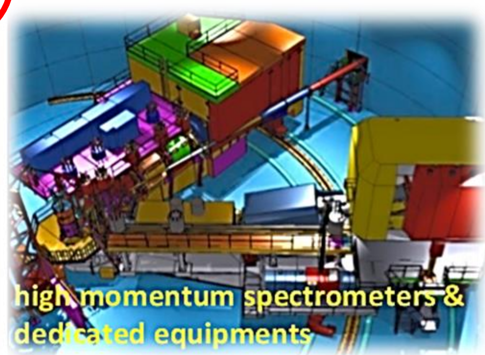
Courtesy of Thia Keppel, 2017

What is Jefferson Lab *After?*







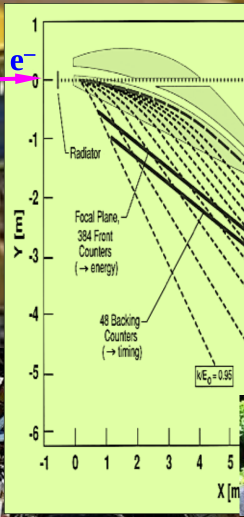


***Beam Power:** 1MW*
***Beam Current:** 90 μA*
***Max Pass energy:** 2.2 GeV*
***Max Enery Hall A-C:** 10.9 GeV*
- ***Max Energy Hall D:** 12 GeV*

Courtesy of Thia Keppel, 2017

CEBAF Large Acceptance Spectrometer 1997-2012

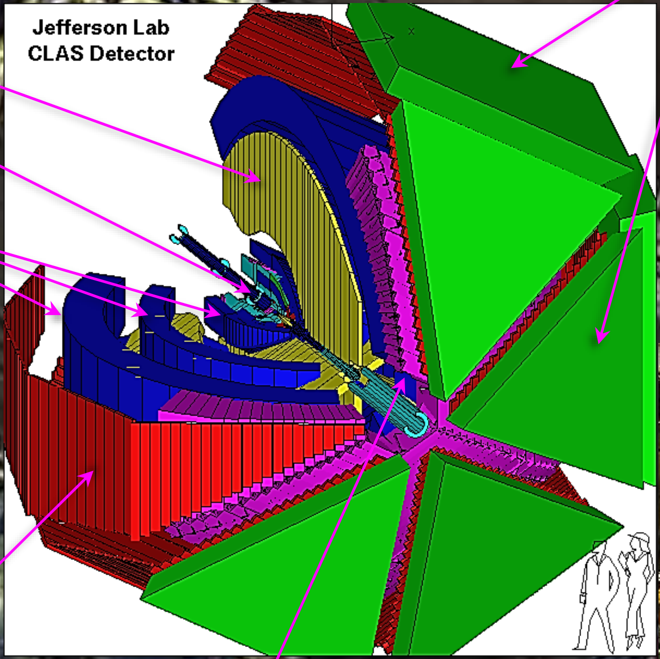
Bremsstrahlung Photon Tagger
384 E & 61 T Counters



Torus Magnet
6 Superconducting Coils

Electromagnetic Calorimeters
Lead/Scintillator, 1296 PMTs

Target + Start Counter



Drift Chambers
35,000 cells

Time-of-Flight Counters
Plastic Scintillators, 684 PMTs

Gas Cherenkov Counters
e/π separation, 256 PMTs

B.A. Mecking *et al*. Nucl Inst Meth A **503**, 513 (2003)

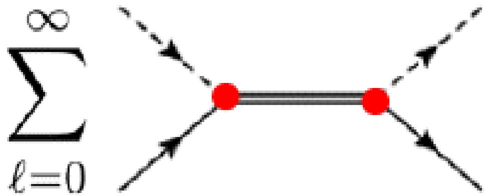
CLAS Light Meson Photoproduction Measurements off Nucleon

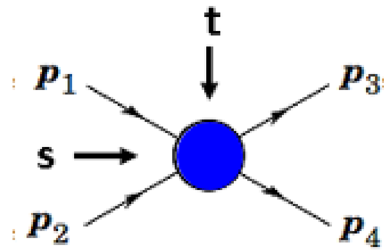
- **Two decades** of **JLab6** *Era* has ended leaving in its wake **plethora** of cross section measurements for light meson photoproduction off nucleon. Most of them by clas **Collaboration** & $s < 11$ GeV^2.

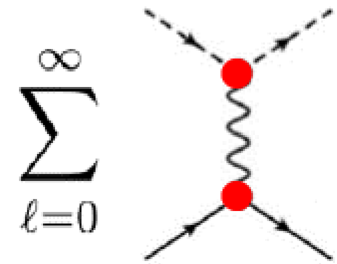
26 paper [**2001 – 2021**] with **CI** > **2000**

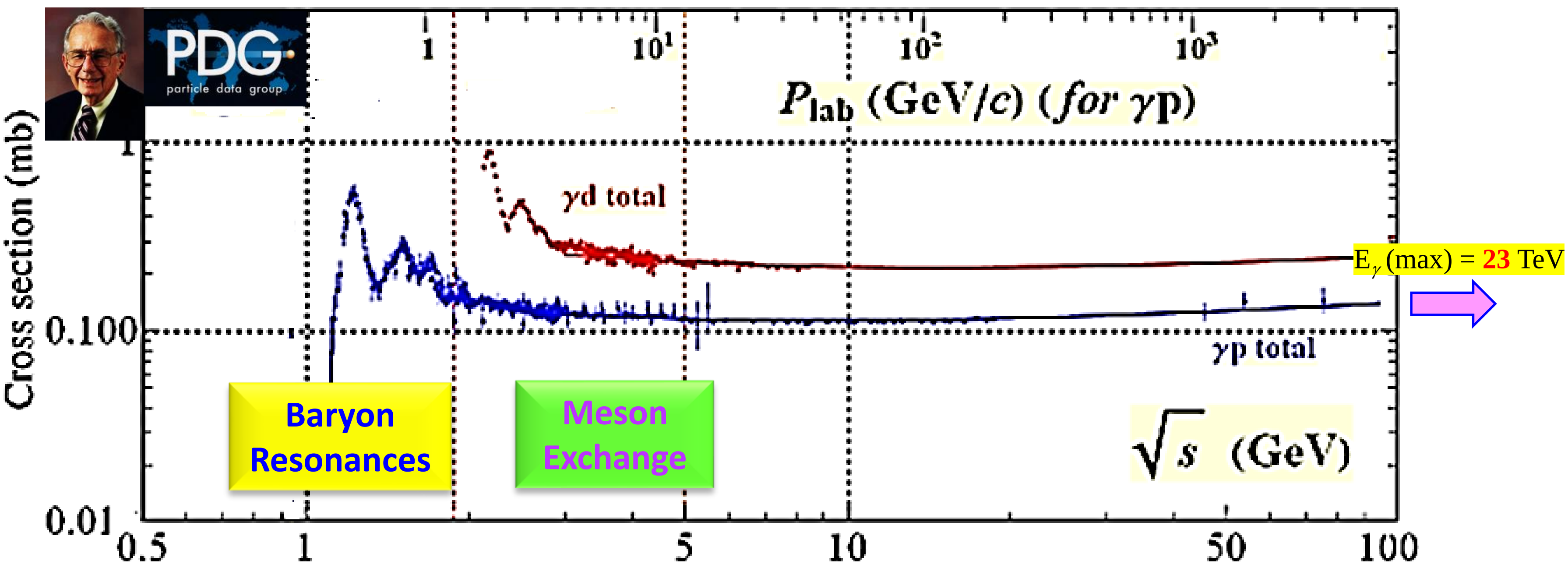
- There is *unique* opportunity to ***bridge*** ***resonance*** & ***high-energy*** regions that encompassing region in which ***Regge*** theory is applicable, & evaluate ***QCR*** phenomenology with differential cross sections above resonance energies.

Low- & High-Energy Dynamics for Meson Photoproduction









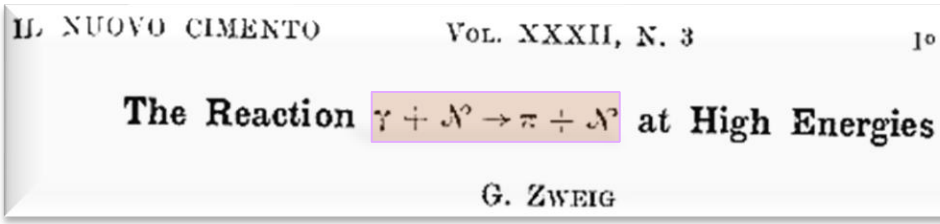
Jefferson Lab → clas

GlueX

CLAS12

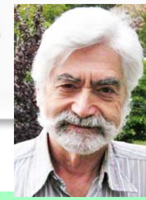
Regge Pole Model

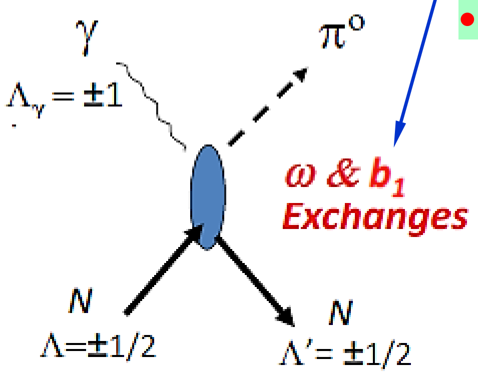
with Regge-cut corrections


IL NUOVO CIMENTO Vol. XXXII, N. 3 1° Maggio 1964

The Reaction $\gamma + \mathcal{N} \to \pi + \mathcal{N}$ at High Energies

G. Zweig





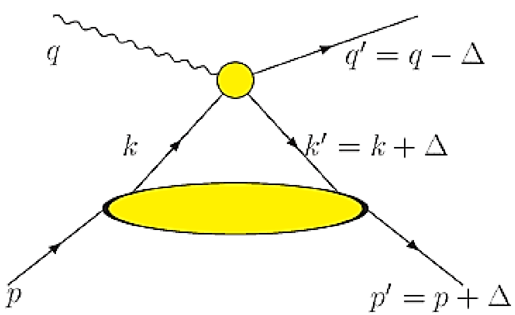
- There were no b_1 mesons back to **1964**.

- **Regge cut** amplitudes are incorporated into some models & are interpreted as re-scattering of on-shell *meson*-*nucleon* amplitudes.
- ω-exchange is dominant in π^0 photoproduction. That is unique case in ***meson photoproductions*** – **single** trajectory.

Handbag Model

with twist-3 contribution

H.W. Huang & P. Kroll, Eur Phys J C **17**, 423 (2000)

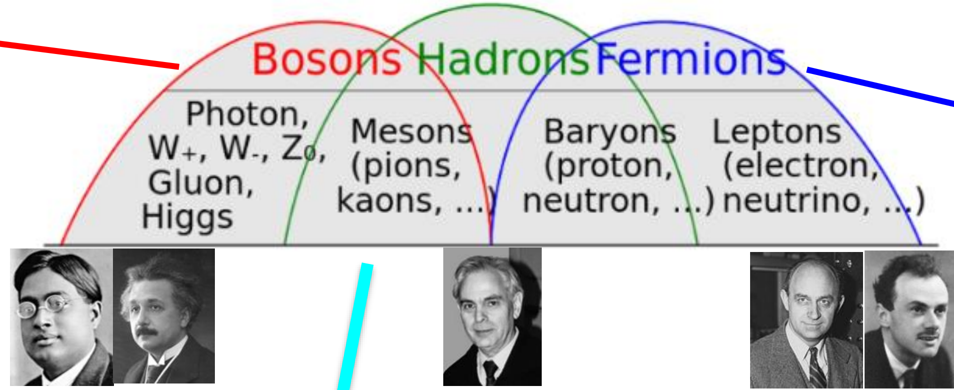


- Reaction is factorized into **two** parts:
  - One *quark* from incoming & one from outgoing nucleon participate in hard sub-process, which is calculable using **pQCD**.
  - Soft part consists of all other ***partons*** that are spectators & can be described in terms of **GPD**s.

QCR for Light Meson Photoproduction

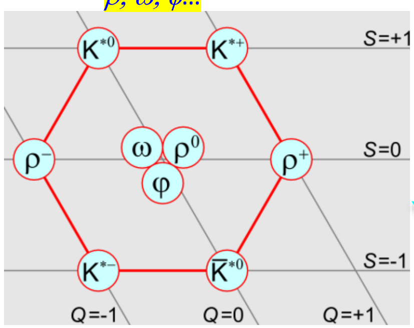
Breakthrough

BE statistics applies only to particles not limited to single occupancy of same state – that is, particles that do not obey *Pauli* exclusion principle restrictions. Such particles have integer values of spin & are named **bosons**.



FD statistics applies to identical & indistinguishable particles with half-integer spin (1/2, 3/2, *etc*.), called **fermions**, in thermodynamic equilibrium.

ρ, ω, ϕ...



Orbital Angular Momentum

Spin

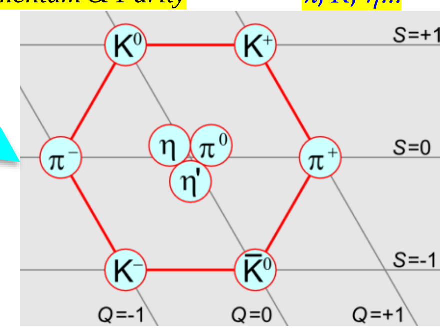
Total Angular Momentum & Parity

π, K, η...

SU(3)

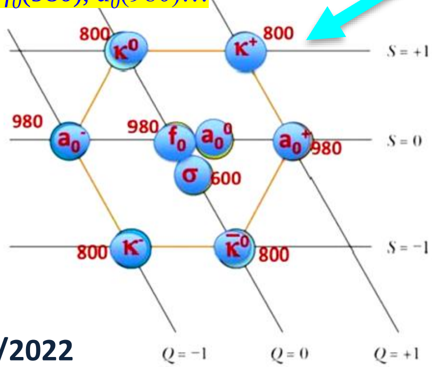
Type of Meson	S	L	J^P
Pseudoscalar	0	0	0^-
Pseudovector	0, 1	1	1^+
Vector	1	0, 2	1^-
Scalar	1	1	0^+
Tensor	1	1, 3	2^+

b_1, h_1...



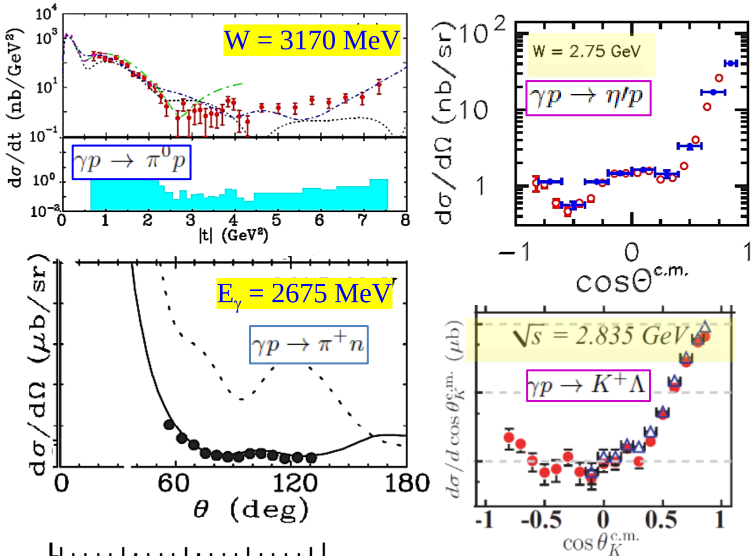
ρ(770), *f_2*(1270)…

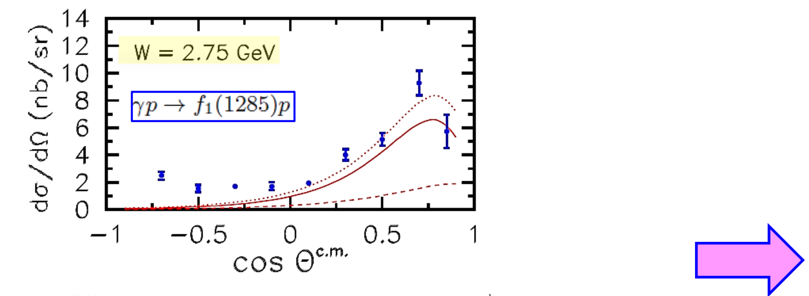
f_0(500), *f_0*(980), *a_0*(980)…

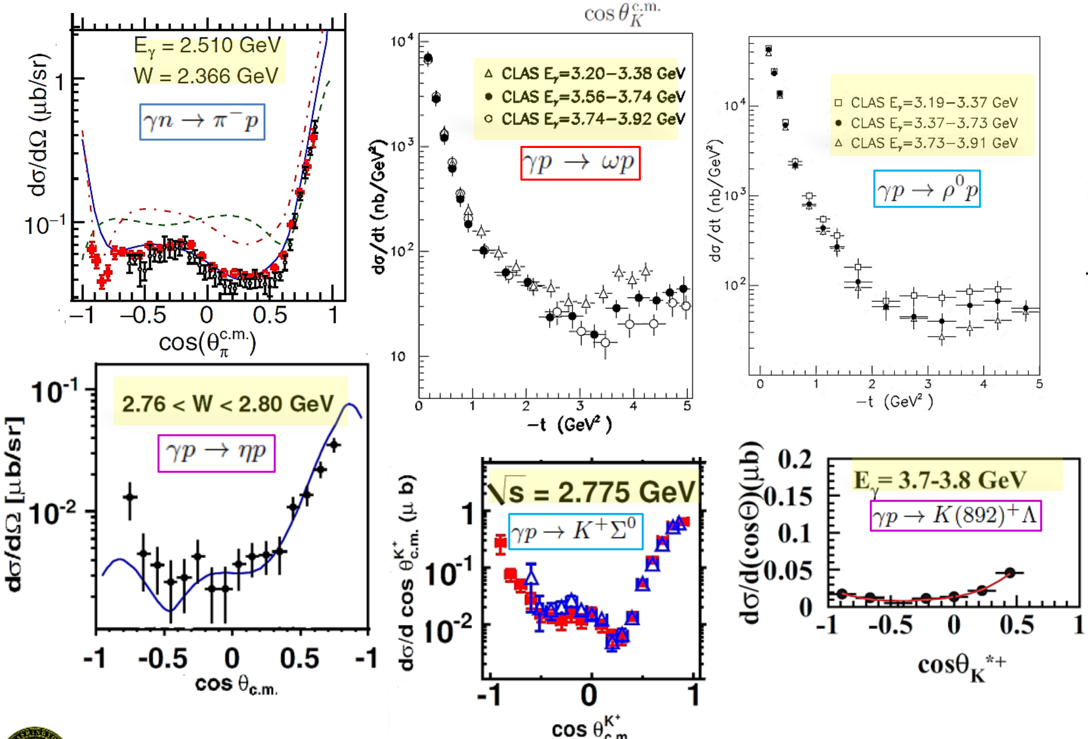


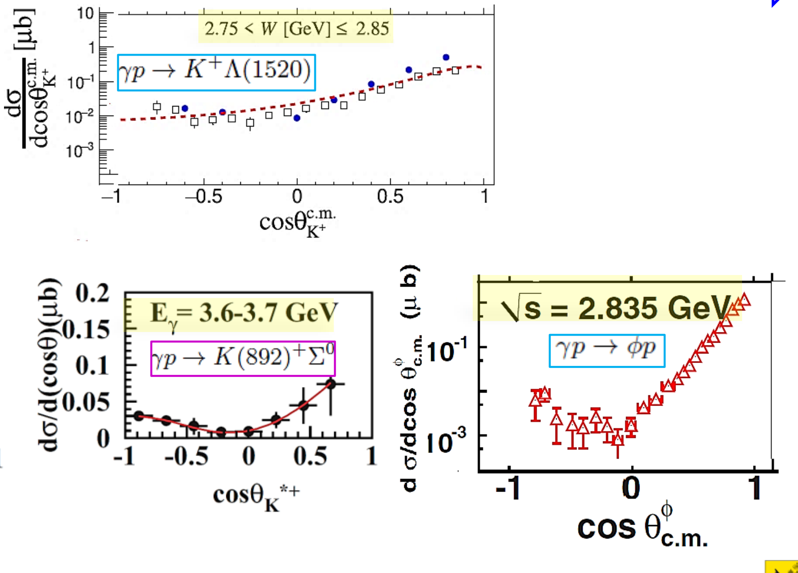
clas *Differential Cross Sections* @ *Large s*

- Cross sections for *light meson photoproduction* off nucleon @ **90^0** is very small.
- It may cause problem for best-fit analysis. ⚠





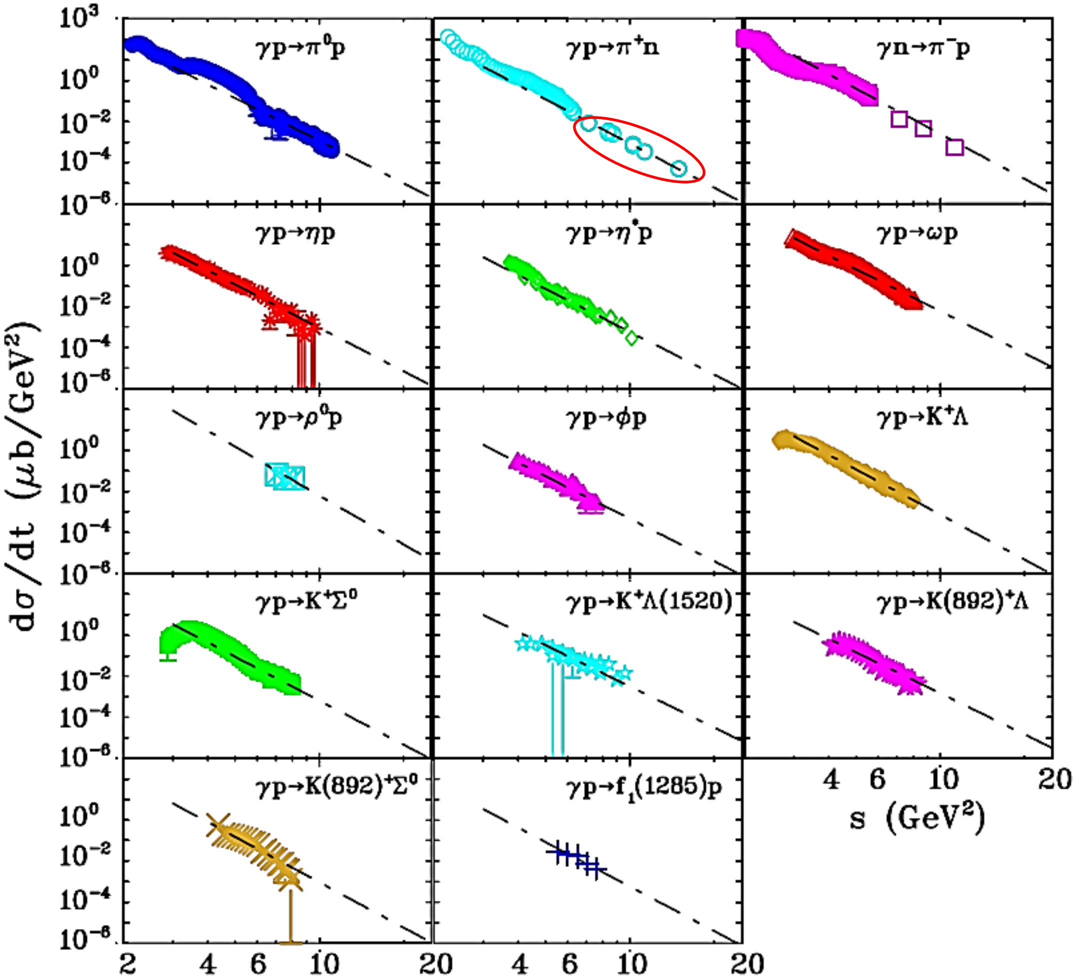




Light Meson Photoproduction off Nucleon from clas

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, Phys. Rev. C **103**, 055203 (2021)

$d\sigma/dt(s) \propto s^{-(n-2)}$ $\theta = 90^0$ $s < 11$ GeV^2



Power Factor for Light Meson Photoproduction off Nucleon from clas

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, Phys. Rev. C **103**, 055203 (2021)

$d\sigma/dt(s) \propto s^{-(n-2)}$

$s < 11$ GeV^2

	Reaction	s (GeV^2)	$\lvert t\rvert$ (GeV^2)	(n–2)	Ref.
Pseudoscalar Mesons	$\gamma p \to \pi^0 p$	5.9–11.1	2.1–4.7	6.89±0.26	[21]
	$\gamma p \to \pi^+ n$	6.3–14.9	2.3–6.6	7.14±0.22	[12, 15, 29]
	$\gamma n \to \pi^- p$	4.0–11.3	0.2–4.6	7.29±0.14	[15, 30]
	$\gamma p \to \eta p$	3.2– 9.6	0.6–3.8	7.02±0.16	[31]
	$\gamma p \to \eta' p$	4.2– 9.3	0.8–2.6	6.92±0.22	[32–34]
	$\gamma p \to K^+\Lambda$	4.0– 8.0	0.3–2.9	7.28±0.06	[37]
	$\gamma p \to K^+\Sigma^0$	5.2– 8.0	0.3–2.8	7.12±0.21	[38]
	$\gamma p \to K^+\Lambda(1520)$	4.8– 7.8	0.9–3.2	6.65±0.41	[39, 40]
Vector Mesons	$\gamma p \to \omega p$	3.5– 8.1	0.3–2.9	6.80±0.11	[16, 35]
	$\gamma p \to \omega p$	5.0– 8.1	0.3–2.9	8.80±0.06[a]	[16, 35]
	$\gamma p \to \rho^0 p$	7.0– 8.0	2.3–2.9	7.9±0.3[b]	[14]
	$\gamma p \to \phi p$	4.0– 7.5	0.6–2.4	6.86±0.22	[36]
	$\gamma p \to K(892)^+\Lambda$	4.2– 8.1	0.7–2.6	6.65±0.38	[41]
	$\gamma p \to K(892)^+\Sigma^0$	4.3– 7.9	0.7–2.4	7.34±0.45	[41]
	$\gamma p \to f_1(1285)p$	6.0– 7.6	1.2–2.0	7.19±0.96	[33]

For π^+, we added ***Hall A*** & SLAC data

} There is sensitivity to ***s*** range.

For ρ^0, result came from PRL2001

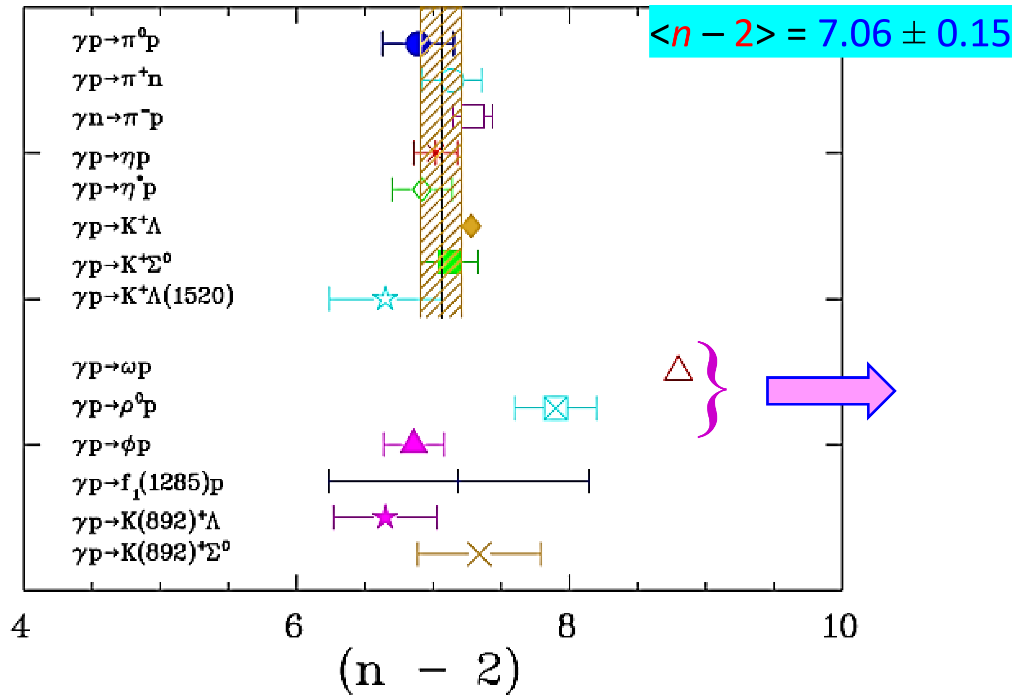
Point-like Nature of Photon in γN Interaction

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, Phys. Rev. C **103**, 055203 (2021)

$d\sigma/dt(s) \propto s^{-(n-2)}$

Pseudoscalar Mesons

Vector Mesons



No gluon emitted

- Thanks to **point-like nature** of **photon** in high energy large angle scattering.
- Thus, our phenomenological result confirms *QCR* in processes where there is no Sudakov correction.

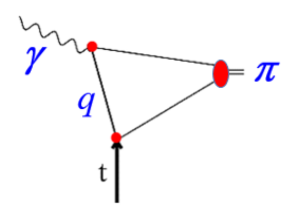
Power Factor for ω & ρ Photoproduction off Nucleon

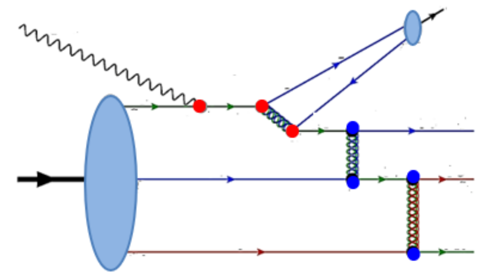
- Due to *vector* nature of ω & ρ mesons in order to form spin part of corresponding wave function, we must ***violate*** *s-channel helicity conservation*.
  - Vertex does not flip *quark* spin ($q_R \rightarrow q_L$ transition is suppressed by power of s)

J. Ballam *et al*, Phys Rev Lett **24**, 960 (1970)

- Therefore, we must expect additional suppression of **90^0** high energy photoproduction.

- For case of ω & ρ mesons:
  - Without *s-channel helicity non-conservation*, expected $n_\gamma = 1$ & $(n - 2) = 7$
  - Accounting for *helicity non-conservation*, expected $n_\gamma = 2$ & $(n - 2) = 8$
  - Accounting for *helicity non-conservation*, expected $n_\gamma = 3$ & $(n - 2) = 9$





- Thus, one can say that observed energy dependence of ω & ρ cross section behavior @ larger s is consistent with *QCR*.

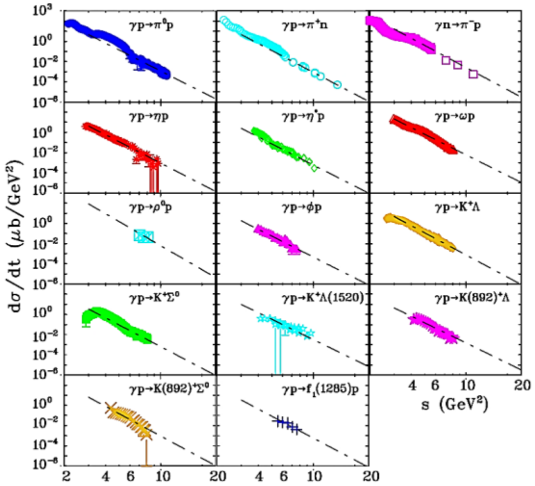
CLAS Data:
Partial Evaluation

Light Meson Photoproduction off Nucleon from clas

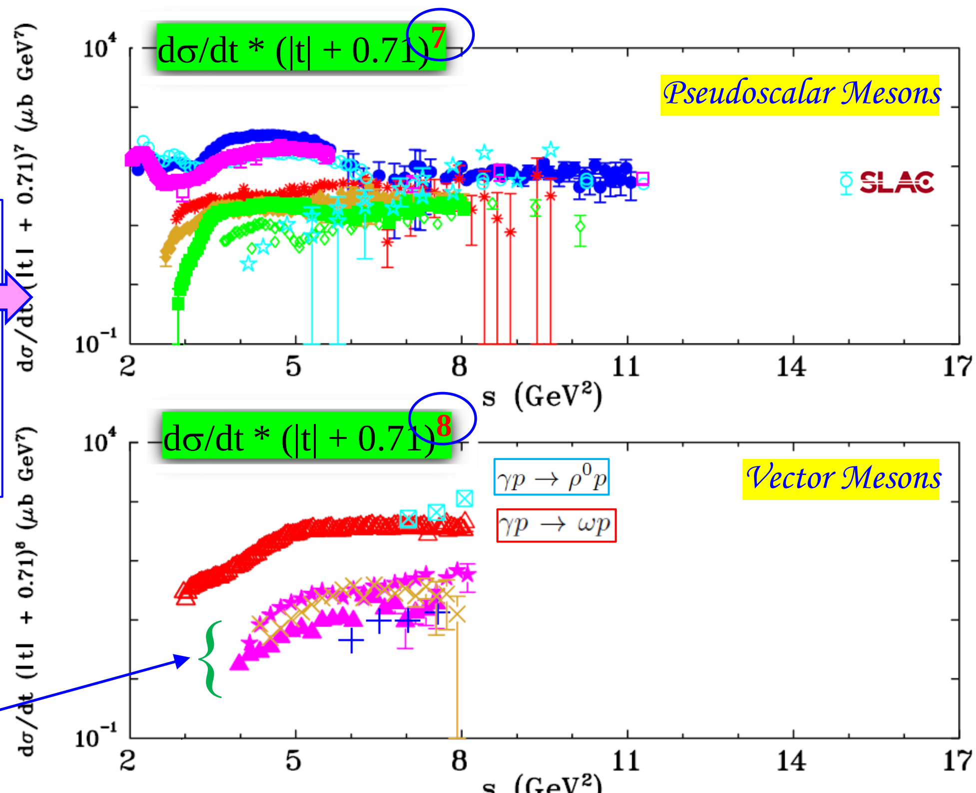
- Since we consider not very large ***s***, we must discuss possible power corrections to *QCR*.
- Unfortunately, corresponding power corrections are closely related to *nonPerturbative* structure of incoming hadrons.
- Therefore, we evaluate possible role of power corrections based on well known dipole behavior of proton QED *FF*,

$$G(t) = 1 / (1 - t/0.71)^2$$

which describes all four-momentum dependencies of both ***electric*** & ***magnetic*** *FF*s of proton quite well, where constant **0.71 GeV^2** determines scale of correction in comparison with asymptotic behavior **$G(t) = 1/t^2$**.



- Accuracy & dispersion of data is better seen here.
- It demonstrates possible role of "infrared cutoff" **(t – 0.71)** in this energy interval.



- ***ϕ***, ***f$_1$*(1285)**, & ***K*(892)$^+$** cross sections are close to each other & lie significantly below other mesons plateau.
- It may indicate common mechanism of their production.

CLAS ω Data: Partial Evaluation

$\omega \to \pi^+ \pi^- \pi^0$

[BR = 89.3%]

(n–2)	s (GeV^2)	Reference
7.2 ± 0.7	7.1 – 8.1	M. Battaglieri *et al*. PRL **90**, 022002 (2003)
9.4 ± 0.1	6.3 – 8.1	B. Dey, PRD 90, 014013 (2014)
9.08 ± 0.11	5 – 8	T. Reed *et al*. arXiv: 2005.13067
6.80 ± 0.11	3.5 – 8.1	M.J. Amaryan *et al*, PRC **103**, 055203 (2021)
8.80 ± 0.06	5.0 – 8.1	M.J. Amaryan *et al*, PRC **103**, 055203 (2021)

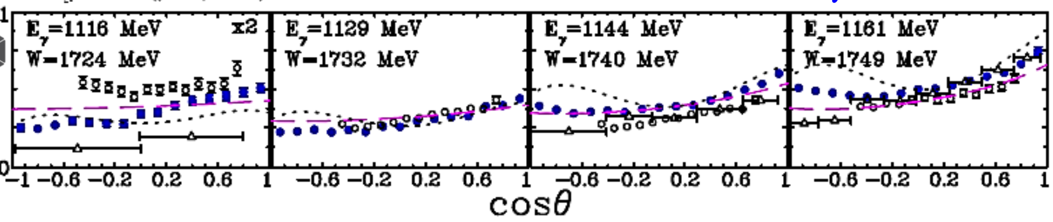



$\omega \to \pi^0 \gamma$ [BR = 8.4%]

M. Williams *et al*. Phys Rev C **80**, 065208 (2009)

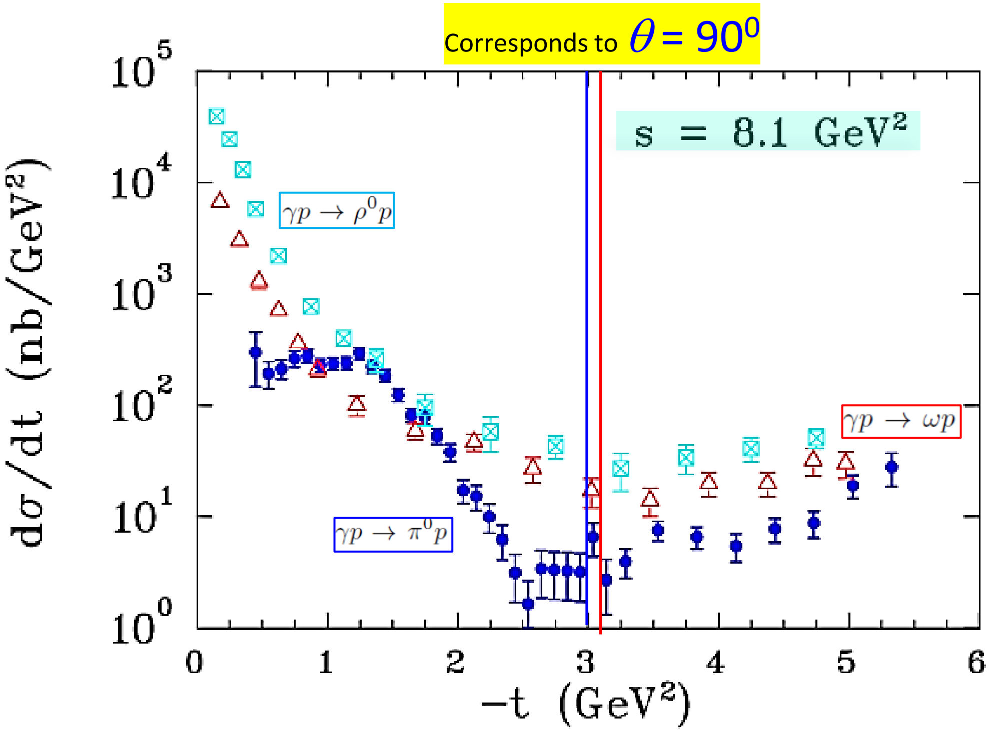
IIS *et al*. Phys Rev C **91**, 045207 (2015)

J. Barth *et al*. Eur Phys J A **18**, 117 (2003)



Light Meson Photoproduction off Nucleon from clas

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, Phys. Rev. C **103**, 055203 (2021)



M. Battaglieri *et al*. Phys Rev Lett **87**, 172002 (2001)

M. Battaglieri *et al*. Phys Rev Lett **90**, 022002 (2003)

M. Kunkel *et al*. Phys Rev C **98**, 015207 (2018)

- For lower values of $|t|$, dσ/dt of ω & ρ^0 photoproduction is order of magnitude higher than that of π^0, for higher values of $|t|$, ω & ρ^0 photoproduction dσ/dt is little bit higher.
- dσ/dt(t) for light meson photoproduction off nucleon @ $\mathbf{90^0}$ is *minimal*.

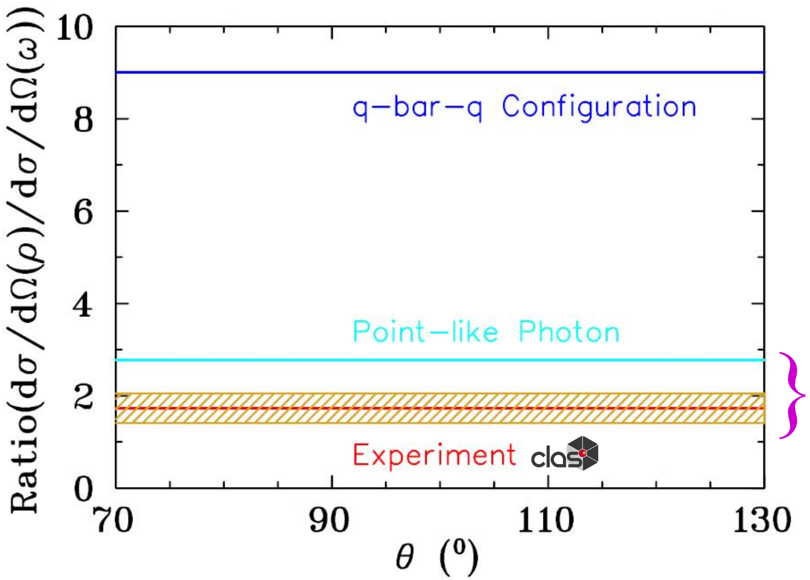
- We evaluate light mesons photoproduction & **it was not evident** whether in this situation photon acts like *q-bar-q* pair (*VDM* contribution) or *point-like* object.
  - Vertex is quark electric charged \times wave function.
  - Cross section is ~ (vertex)^2.

    $|\rho^0\rangle = |uu\rangle - |dd\rangle \Rightarrow$ vertex$(\gamma+\rho)$ = 2/3 – (–1/3) = 1

    $|\omega\rangle = |uu\rangle + |dd\rangle \Rightarrow$ vertex$(\gamma+\omega)$ = 2/3 + (–1/3) = 1/3

    Ratio is $(1/(1/3))^2$ = **9**
  - Analogous calculation & accounting for proton wave function.

    Ratio is $(5/3)^2$ = **2.8**



M. Battaglieri *et al*. Phys Rev Lett **87**, 172002 (2001)
M. Battaglieri *et al*. Phys Rev Lett **90**, 022002 (2003)

Brief Tour through
Future
GlueX & Hall C Experiments

Expectation for Power Factor for Light Meson Photoproduction off Nucleon

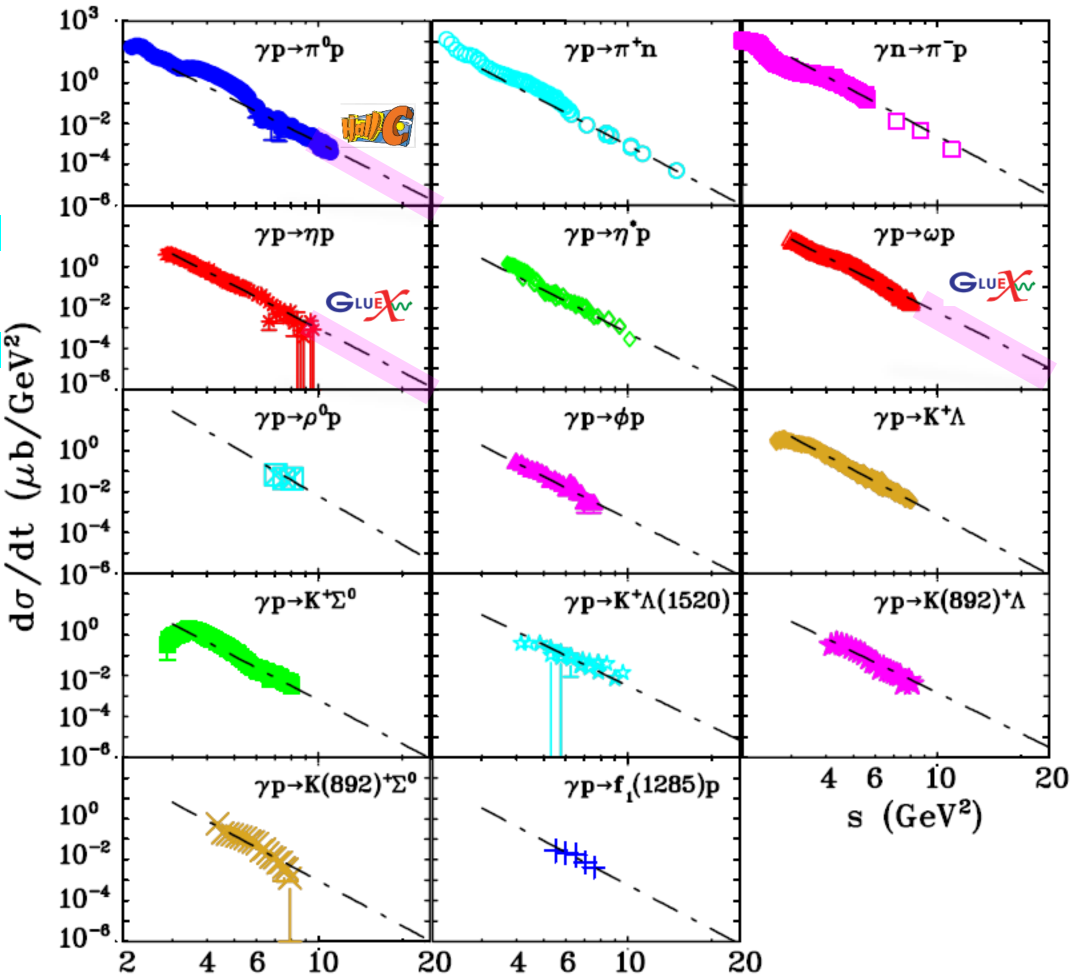
- From s = **11** GeV^2 to s = **21** GeV^2, $d\sigma/dt(90^0)$ drops down by factor of **10^4**.

$\eta \to \gamma\gamma$ [BR = 39.4%]

$\eta \to \pi^0\pi^0\pi^0$ [BR = 32.7%]

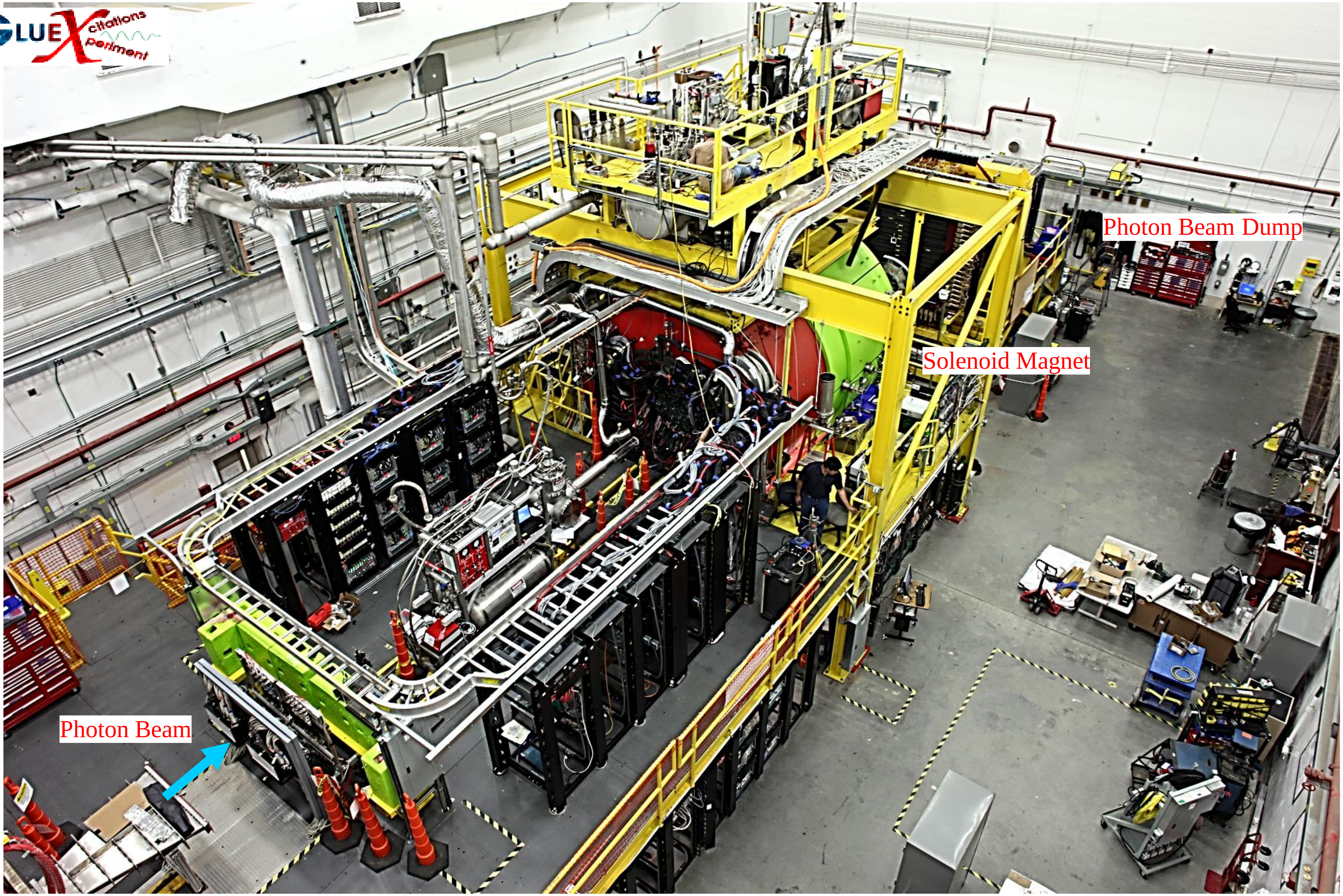
$\eta \to \pi^+\pi^-\pi^0$ [BR = 22.9%]

$\eta \to \pi^+\pi^-\gamma$ [BR = 4.2%]



$\omega \to \pi^+\pi^-\pi^0$ [BR = 89.3%]

$\omega \to \pi^0\gamma$ [BR = 8.4%]

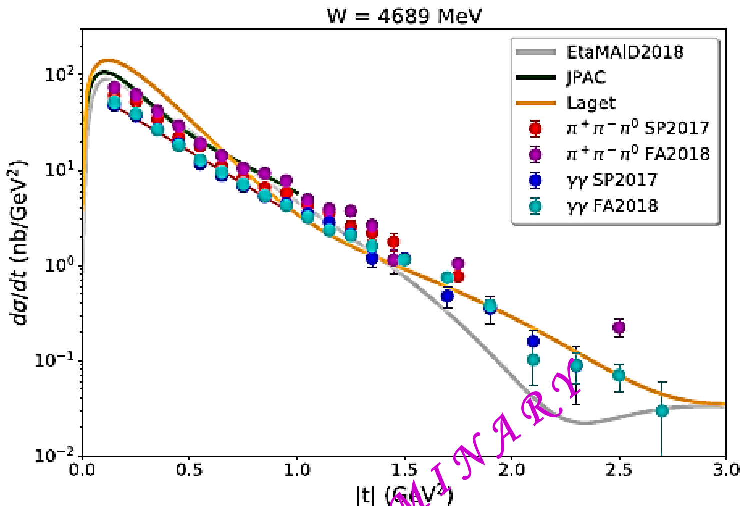


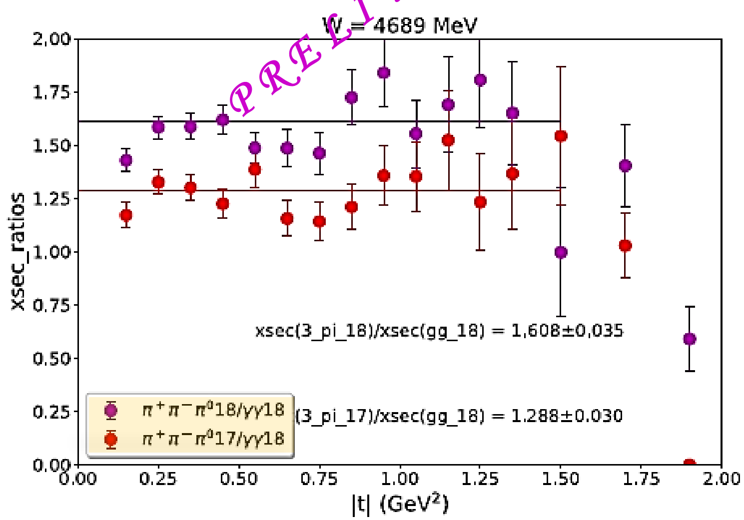
GlueX Statistics: above 8.2 GeV

Spring 2016: 10 pb^{-1}
Spring 2017: 58 pb^{-1}

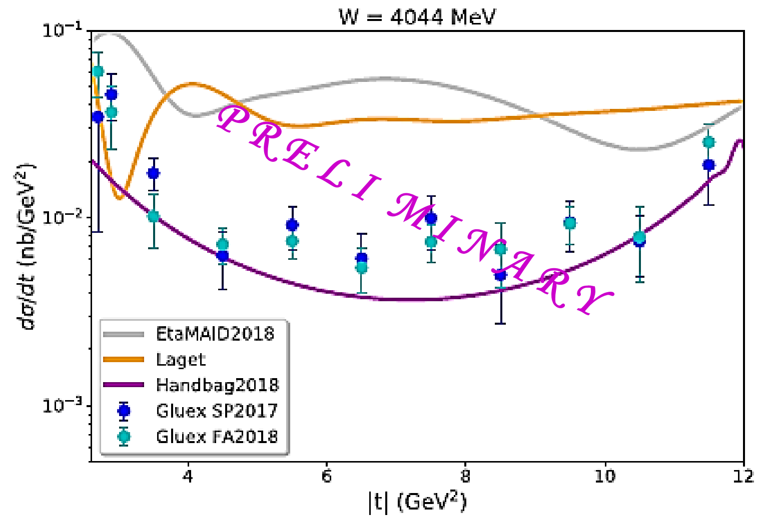
25% of total statistics (2016-2018) up to date.

GlueX Differential Cross Sections for $\gamma p \to \eta p$





s = 12.6 – 21.9 GeV^2

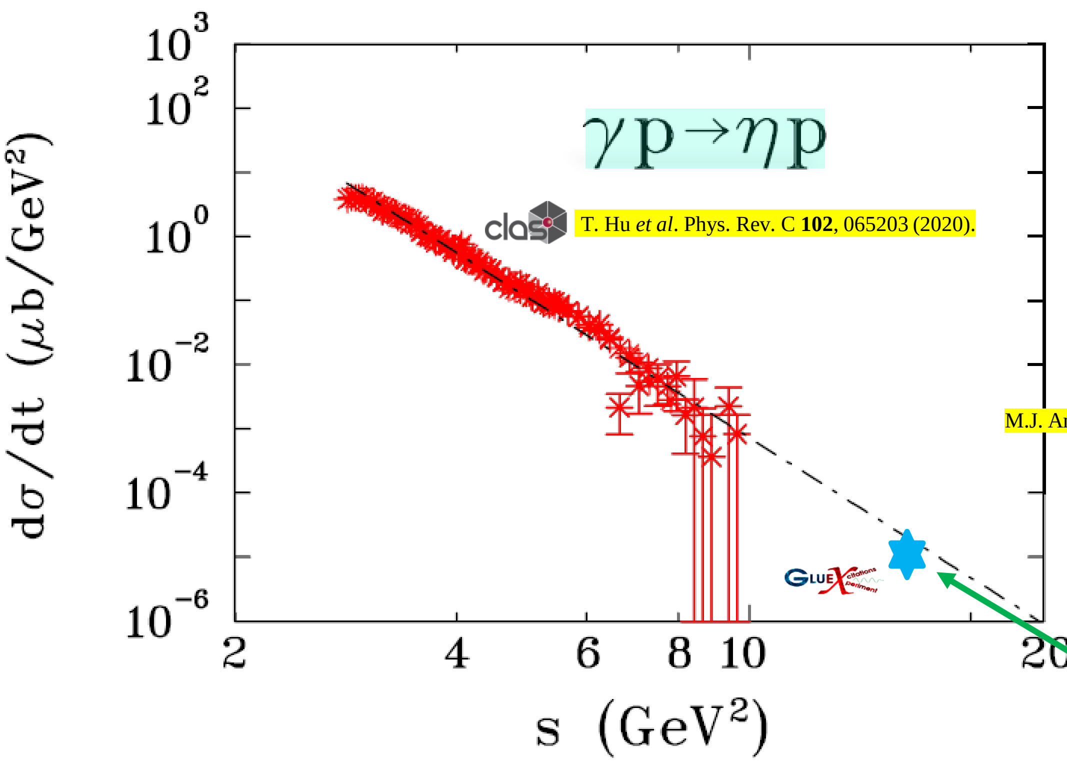


Courtesy of Mahmoud Kamel, GHP2021

GlueX Preliminary Results @ 90^0

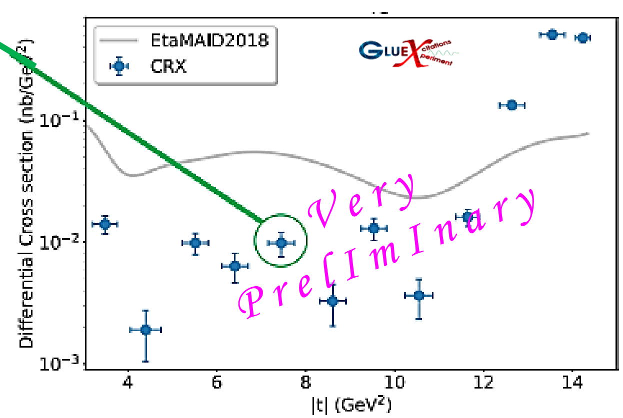
$$d\sigma/dt(s) \propto s^{-(n-2)}$$

Collab	(n-2)
clas	7.01 ± 0.16
clas & GlueX	7.25 ± 0.13



M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, Phys. Rev. C **103**, 055203 (2021)

20 events @ **s** = 16.3 GeV^2
|t| = **7.15** GeV^2

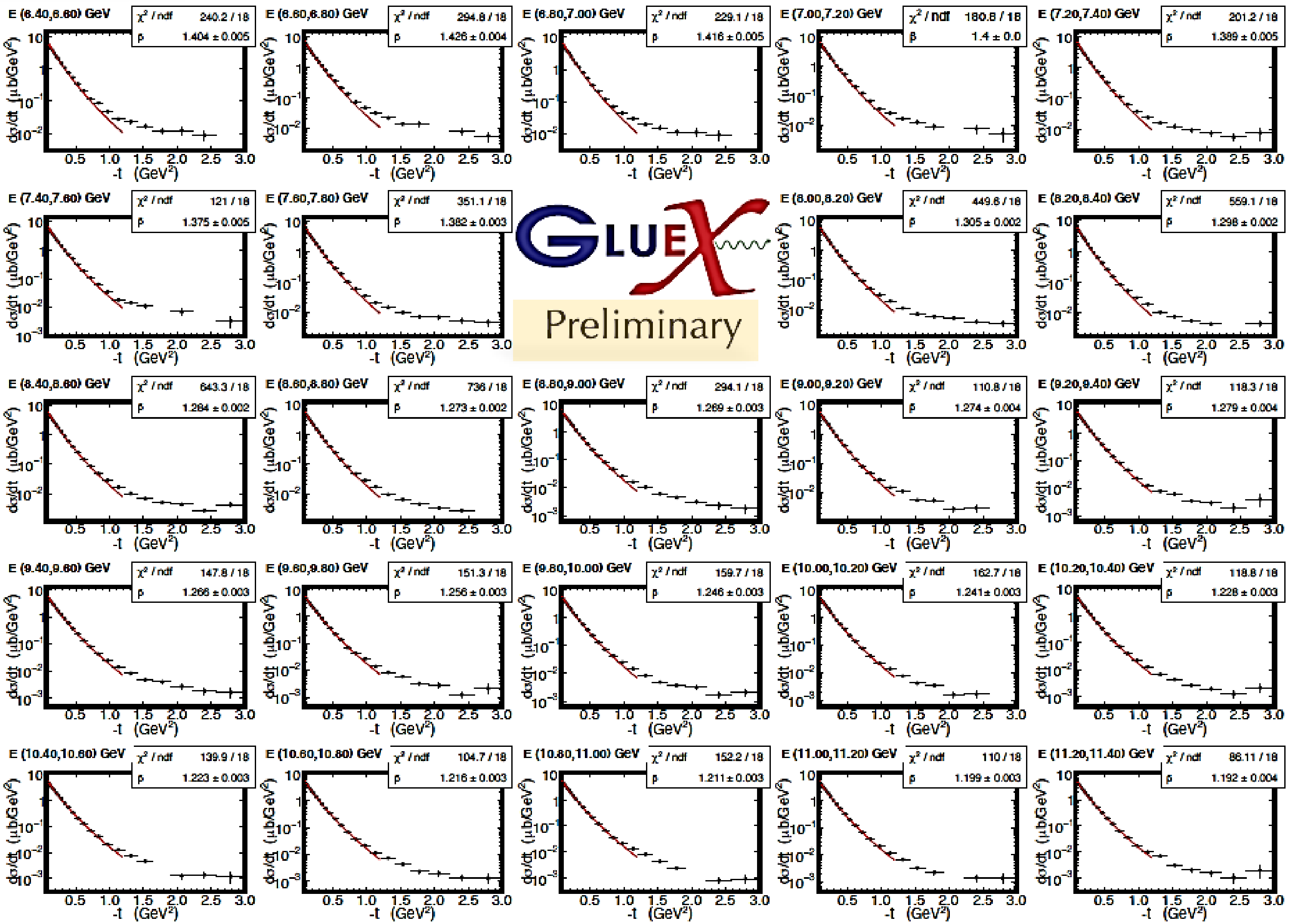


Courtesy of Mahmoud Kamel
GlueX Collab. Meeting, Feb 2021

Differential Cross Sections for $\gamma p \rightarrow \omega p$

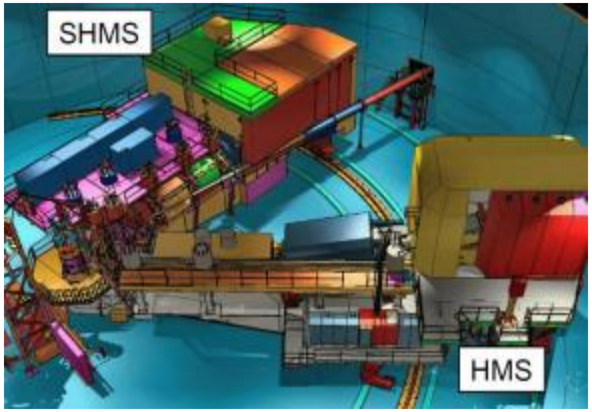
s = 6.5 – 22.6 GeV^2

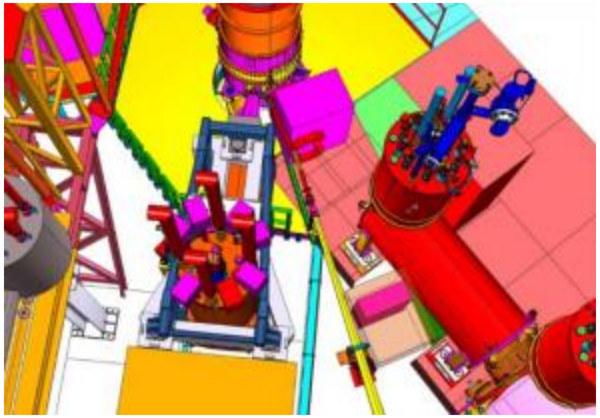
Stamp plots, $\omega \rightarrow \pi^+\pi^-\pi^0$, 50% of GlueX phase 1



Jefferson Lab Mark Dalton APS Topical Group on Hadronic Physics 13 April 2021

Courtesy of Mark Dalton, GHP2021

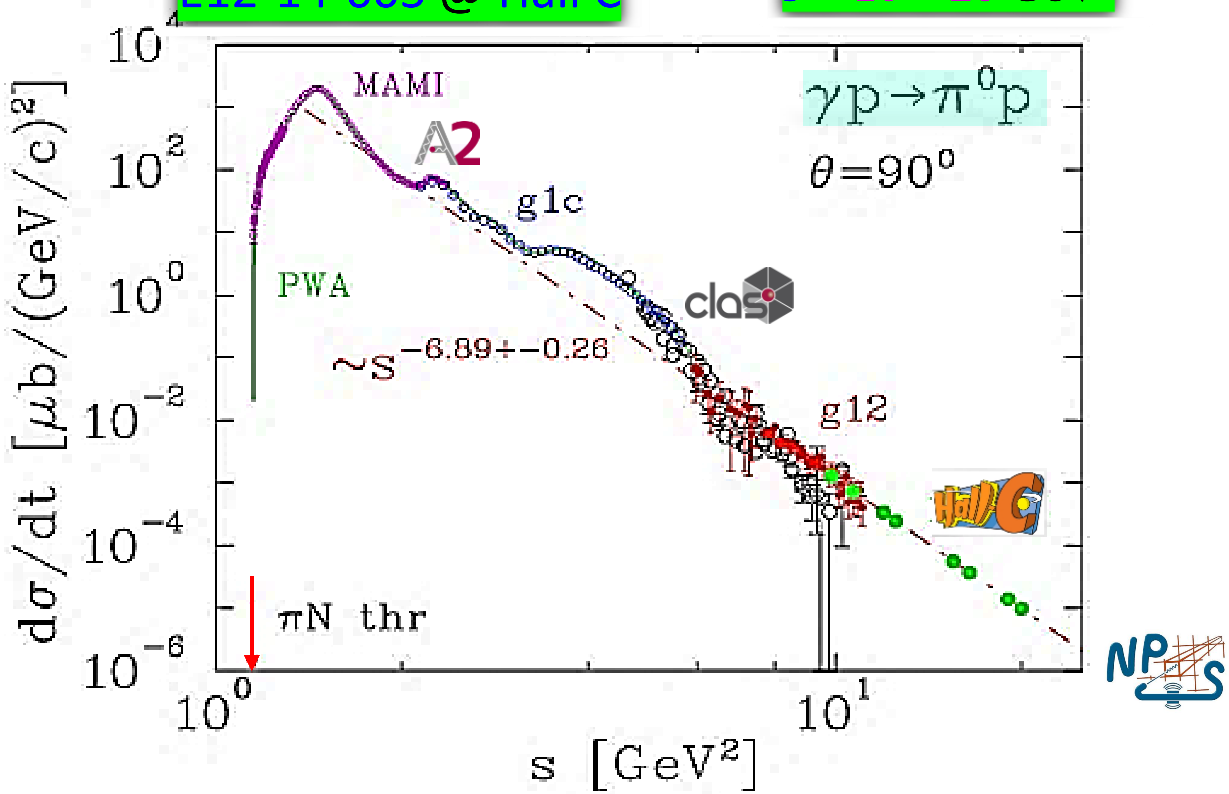

SHMS
HMS



Wide Angle Exclusive Photoproduction of π^0 Mesons

E12-14-005 @ Hall C

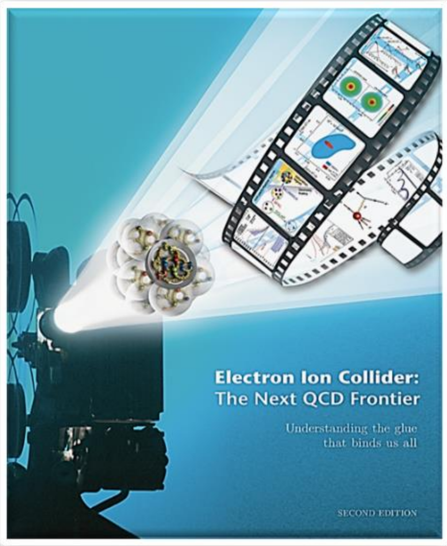
s = 10 – 20 GeV^2

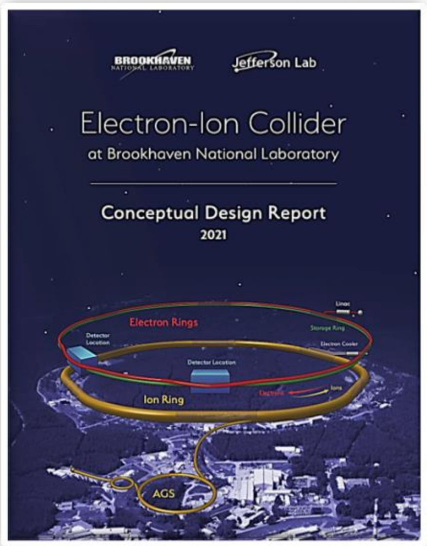


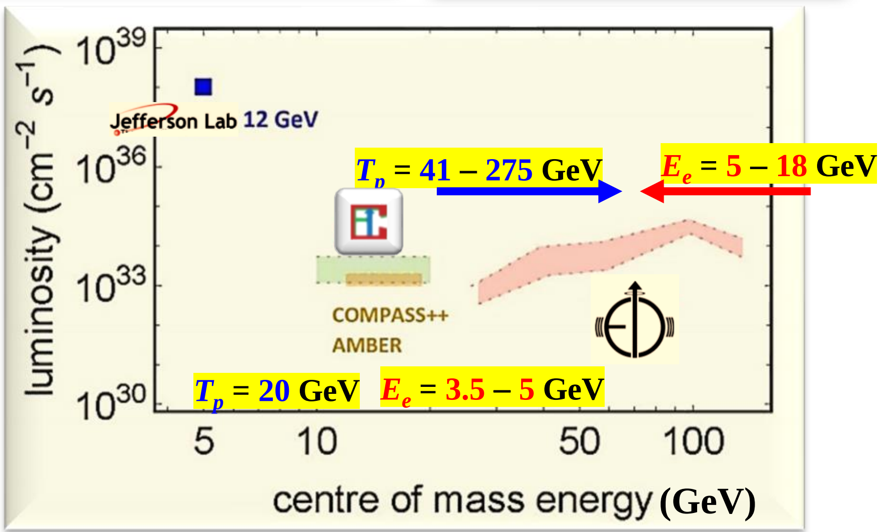
Wide angle exclusive photoproduction of π^0 mesons,
Spokespersons: D. Dutta, H. Gao, S. Sirca, M. Amaryan, M. Kunkel, & IIS [RCS and NPS Collaborations], JLab Proposal **E12-14-005**.

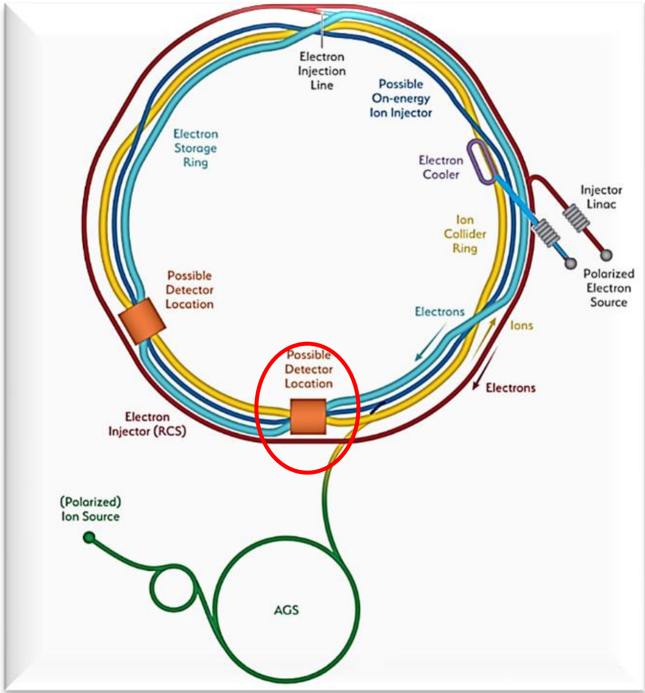
The US Electron Ion Collider

- New tool for precision *QCD* in 2030's



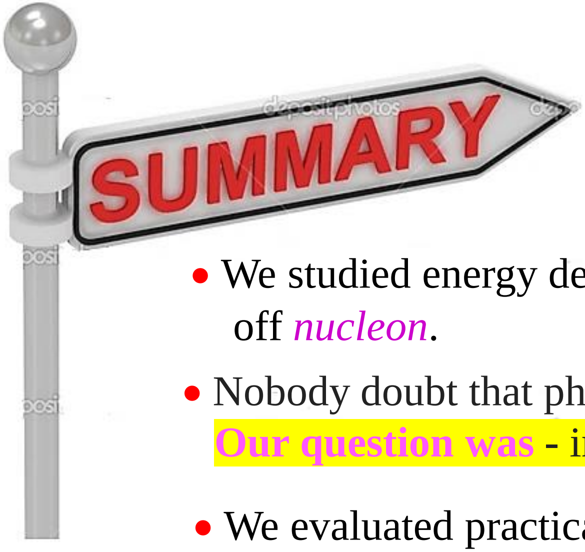






Hadron Storage Ring
Electron Storage Ring
Electron Injector Synchrotron
Possible on-energy Hadron injector ring
Hadron injector complex

Summary



- We studied energy dependence of 90^0 ***pseudoscalar*** & ***vector*** *meson photoproduction* off *nucleon*.
- Nobody doubt that photon is *point-like* particle.
  Our question was - in what form photon participates in high energy large angle scattering.
- We evaluated practically all available experimental data obtained by CLAS Collaboration over more than last **two** decades & compare results with *QCR* predictions.

- We found that one can consider *photon* in γN interaction as point-like particle.
- We emphasized that in case of photoproduction, *QCR* prediction does not affected by Sudakov *FF*.

- Obviously, JLab6 program is limited by $s \simeq 11$ GeV^2.
- Within JLab12 program, Hall C (π^0 will come), GlueX (η & ω are coming), & CLAS can extend measurements up to $s \simeq 21$ GeV^2.