High Energy Behavior of Light Meson Photoproduction & Quark Counting Rule

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Unfortunately, On-line

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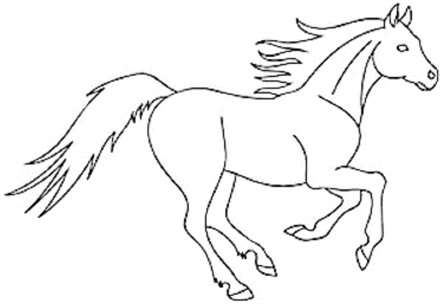
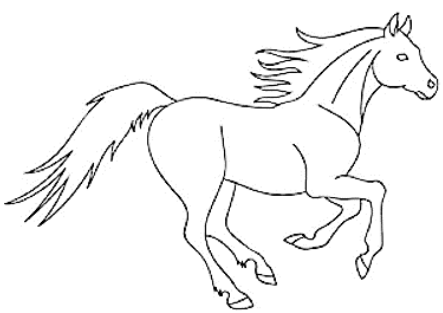
Outline



- *Quark Counting Rule & 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

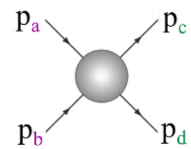
&

Sudakov FF

QCR for Hadrons

- 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



$$a + b \longrightarrow c + d$$

@ 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** = 1,873

V.A. Matveev, R.M. Muradian, & A.N. Tavkhelidze, Lett Nuovo Cim **7**, 719 (1973) **CI**= 1,166

- 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 have to balance *large transferred momentum* between all *quarks* in *hadron*.

- This means that in order to get maximum contribution, we have to 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 $d\sigma/dt(s) \propto s^{-(n-2)}$.
  - 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

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

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

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)

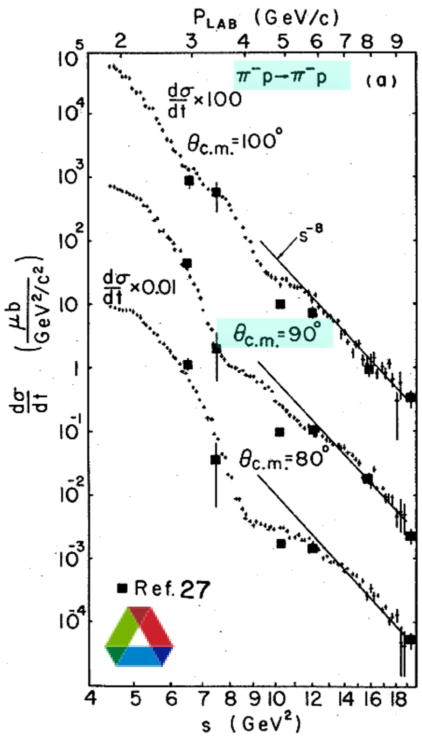
- It is very improbable that two ensembles of constituents can get strong transverse kick & radiate no gluons.
- Of course, probability of new gluon emission is suppressed by *QCD* coupling constant α_s, but simultaneously it can be enhanced by large $ln^2 s$.
- *Probability* not to emit any additional *gluons* is called Sudakov *FF*.
- For very large ***s***, we expect that cross section of large angle *hadron*-*hadron* scattering should fall down with ***s*** faster than *QCR* prediction.

- In *hadron* case, Sudakov *FF* works as was theoretically shown in [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***.



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

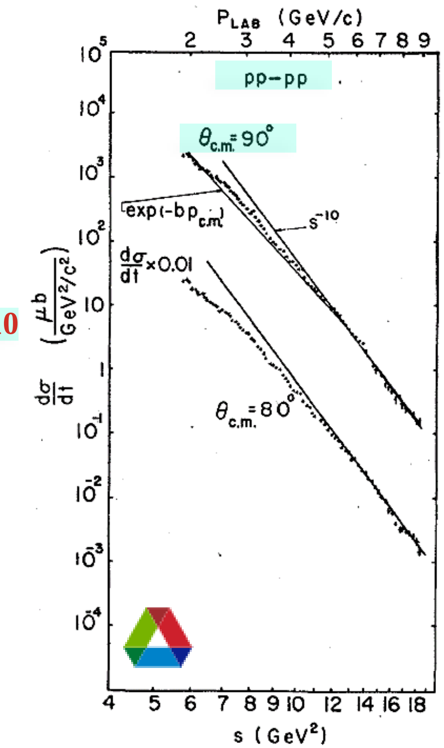
$$(n-2) = (2+3) + (2+3) - 2 = 8$$

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

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

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

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



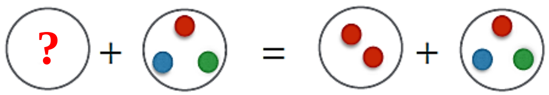
K.A. Jenkins *et al*. Phys Rev D **21**, 2445 (1980)

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		

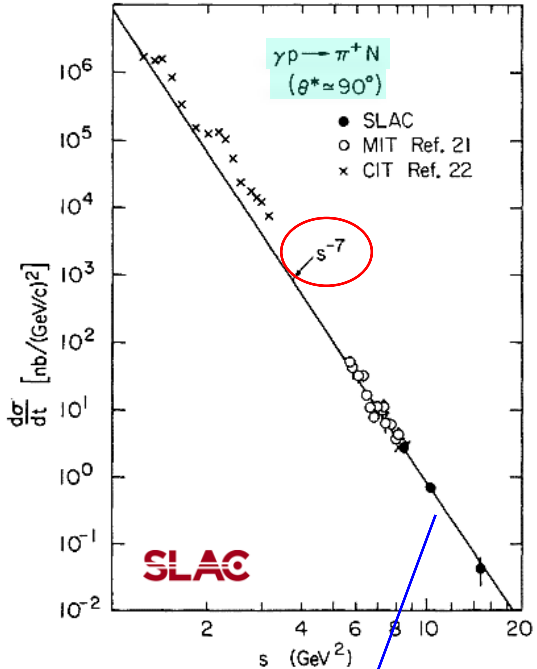
D. Sivers, Ann Phys (NY) **90**, 71 (1975)

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)

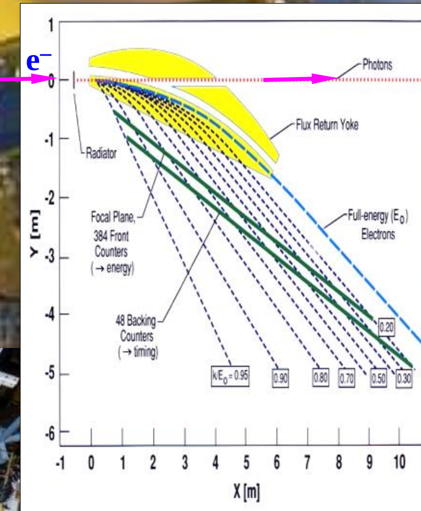
- There are ***three*** options of how one can consider ***photon*** in *γN* interaction:
  - No constituents ($n_\gamma = 0$) & $d\sigma/dt(s) \propto s^{-6}$.
  - Photon is point-like particle which participated in strong interaction ($n_\gamma = 1$) & $d\sigma/dt(s) \propto s^{-7}$.
  - There is *q*-bar-*q*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

?

Brief Tour through CLAS Light Meson Photoproduction Experiments

CEBAF Large Acceptance Spectrometer 1997-2012

Bremsstrahlung Photon Tagger
384 E & 61 T Counters

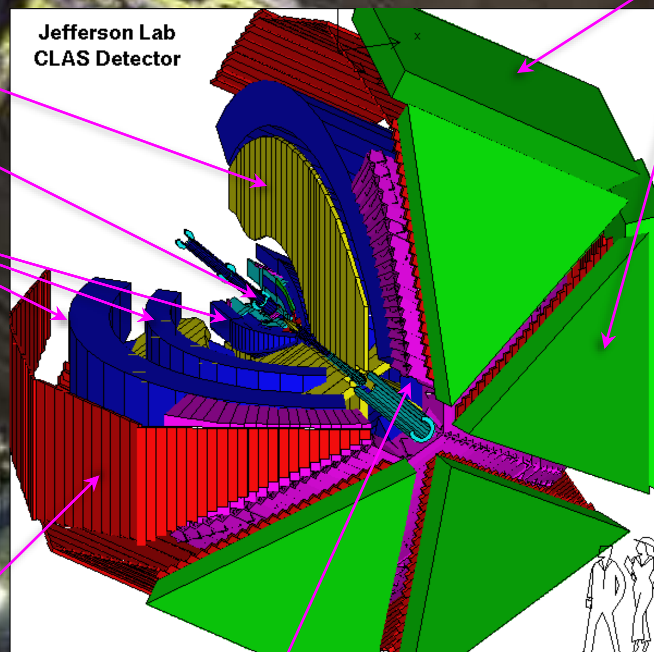


Electromagnetic Calorimeters
Lead/Scintillator, 1296 PMTs

Torus Magnet
6 Superconducting Coils

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

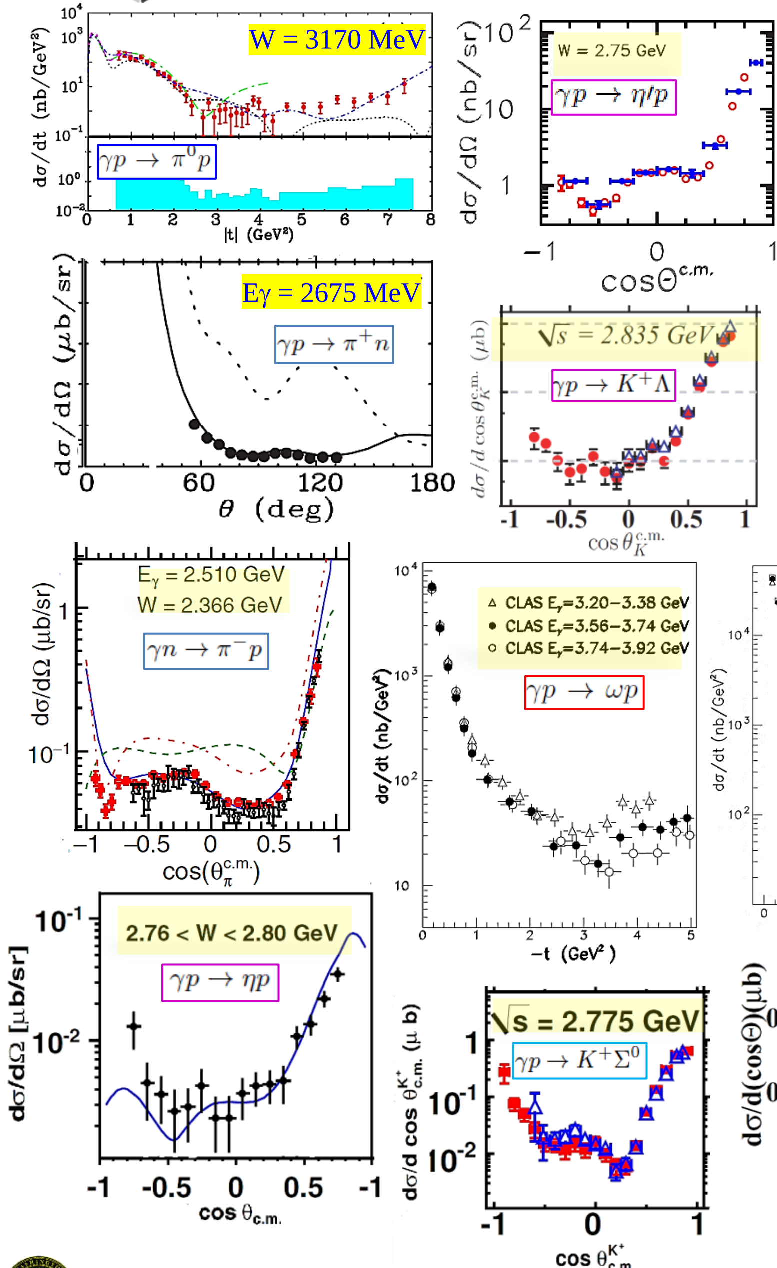
- **Two decades** of **JLab6** *Era* has ended leaving in its wake **plethora** of cross section measurements for light meson photoproduction off nucleon. Most of them by **CLAS Collaboration** & $s < 11$ GeV^2.

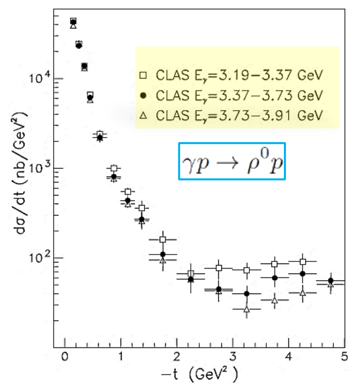
26 paper [**2001 – 2021**] with **CI** $\simeq$ **2000**

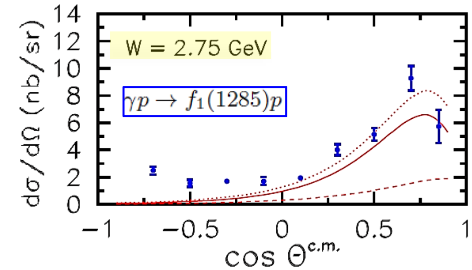
- There is *unique* opportunity to ***bridge*** ***resonance*** & ***high-energy*** regions, in particular, that encompassing region in which ***Regge*** theory is applicable, & evaluate ***QCR*** phenomenology with differential cross sections above resonance energies.

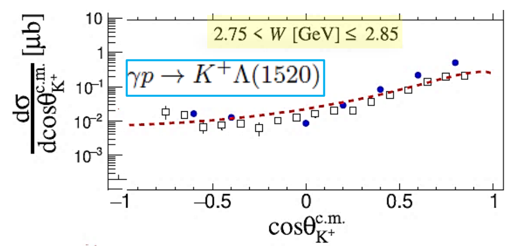
CLAS Differential Cross Sections @ Large s

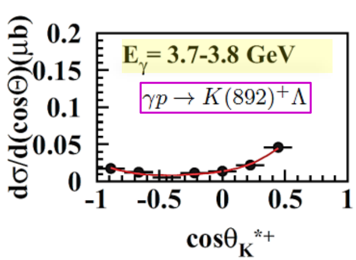
- Cross sections for light meson photoproduction off nucleon @ **90^0** is very small.
- It may cause problem for best-fit analysis.

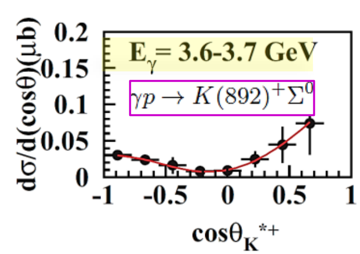


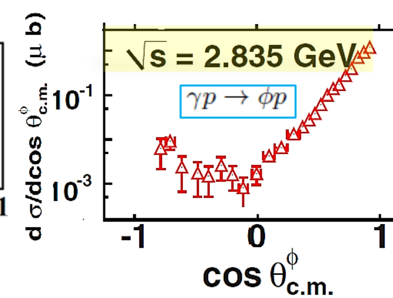












QCR

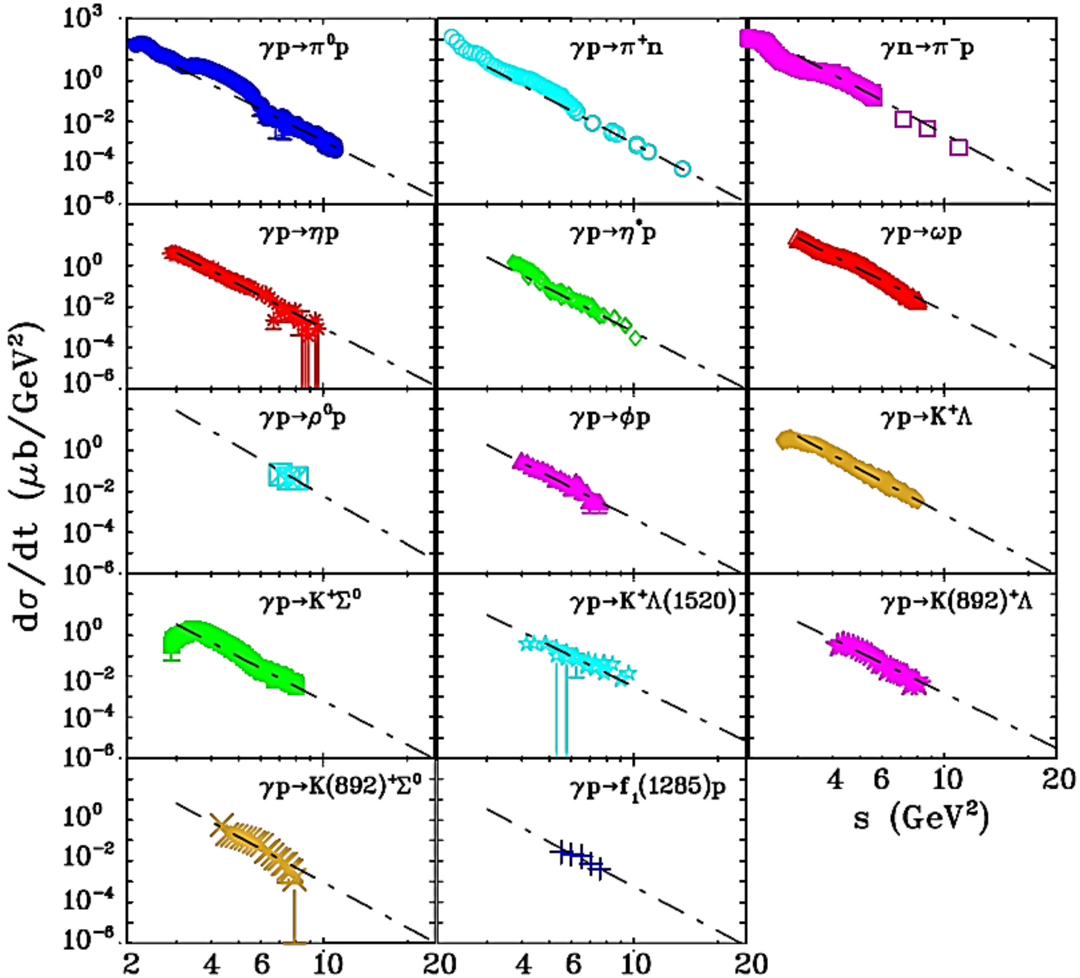
for Light Meson Photoproduction

Power Factor for Light Meson Photoproduction off Nucleon from CLAS

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, arXiv:2102.03633

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

$s < 11$ GeV^2



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Pseudoscalar Mesons

Vector Mesons

Reaction	s (GeV^2)	$\|t\|$ (GeV^2)	(n−2)	Ref.
$\gamma p \to \pi^0 p$	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]
$\gamma p \to \omega p$	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 of analysis.

For ρ^0, result came from PRL2001

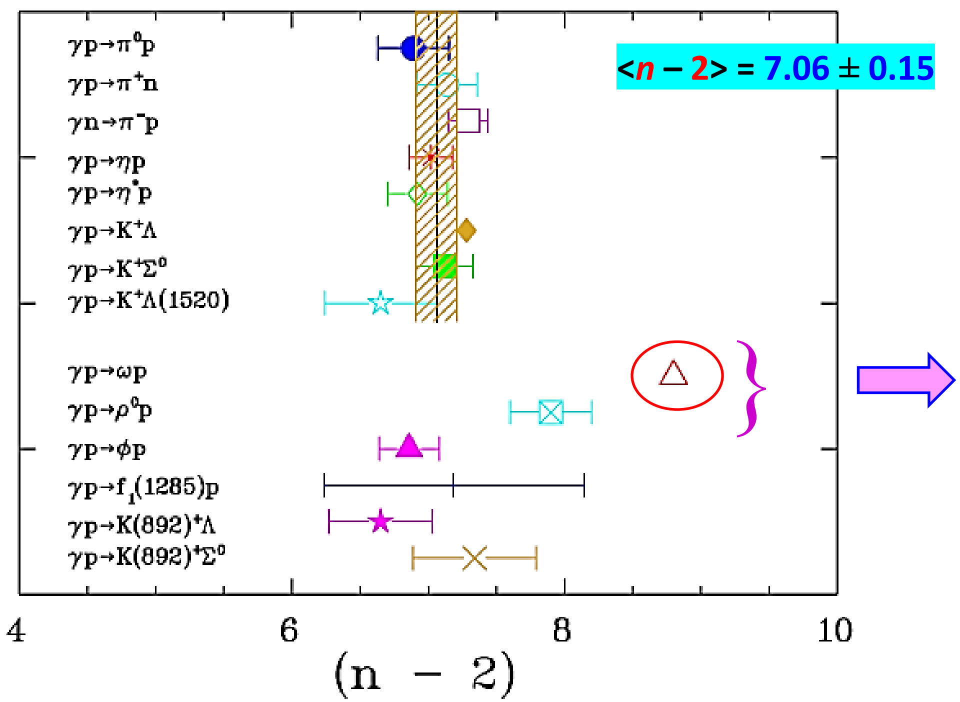
Point-like Nature of Photon in γN Interaction

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, arXiv:2102.03633

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

Pseudoscalar Mesons

Vector Mesons



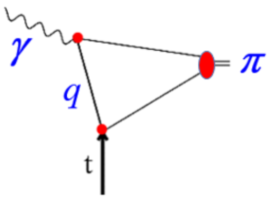
- Thanks to point-like nature of photon in *γN* interaction.
- Thus, our phenomenological result confirms *QCR* in processes where there is no Sudakov correction.

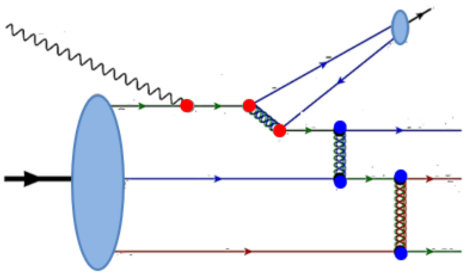
Power Factor for ω & ρ Photoproduction off Nucleon

- Due to *vector* nature of ***ω*** & ***ρ*** mesons in order to form spin part of corresponding wave function, we have to ***violate s-channel helicity conservation***.

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

- For case of ***ω*** & ***ρ*** mesons:
  - Without 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

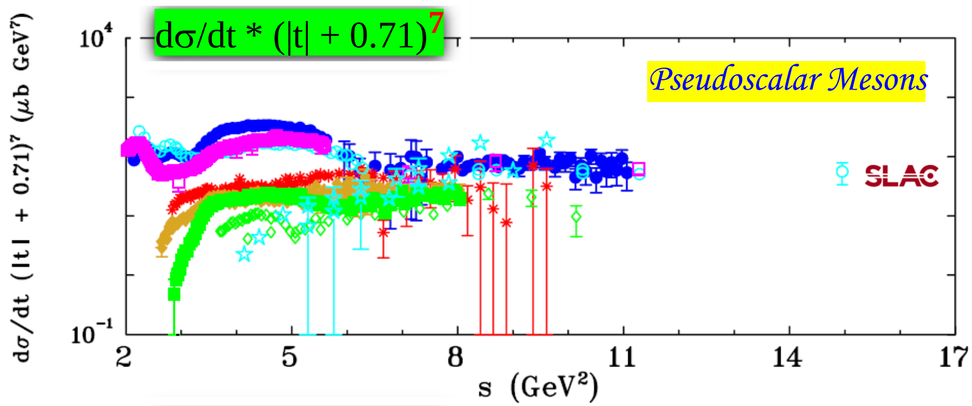
Light Meson Photoproduction off Nucleon from CLAS

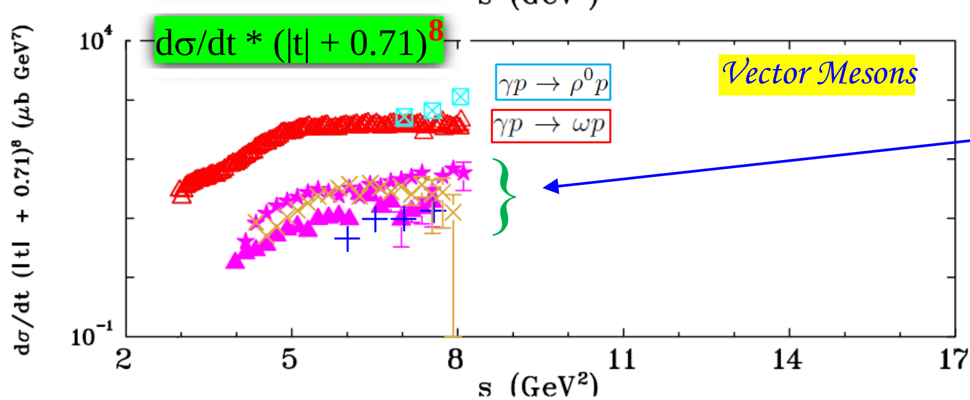
- Accuracy & dispersion of data is better seen here than on pg. **14**.
- It demonstrates possible role of "infrared cutoff" **(t – 0.71)** in this energy interval.

- Since we consider not very large ***s***, we have to discuss possible power corrections to *QCR*.
- Unfortunately, corresponding power corrections are closely related to *nonPerturbative* structure of incoming hadrons.
- Therefore, we evaluate possible role/scale 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 GeV²** determines scale of correction in comparison with asymptotic behavior $G(t) = 1/t^2$.

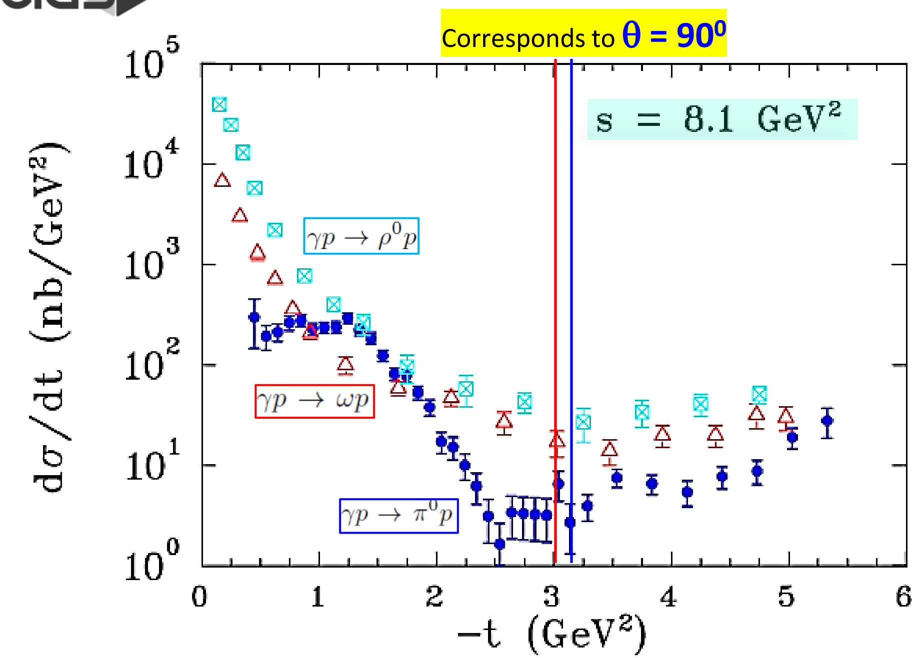




- ϕ, f_1**(1285)**, & ***K*(892)⁺** cross sections are close to each other & lie significantly below other mesons plateau.
- It may indicate common mechanism of their production.

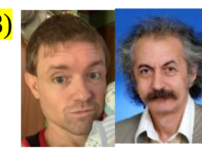
Light Meson Photoproduction off Nucleon from CLAS

M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, arXiv:2102.03633



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

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



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 @ **90⁰** is *minimal*.

CLAS Data: Partial Evaluation

Meson	(n–2)	s (GeV^2)	Reference
ρ^0	7.9 ± 0.3	7.0 – 8.0	M. Battaglieri *et al*. PRL **87**, 172002 (2001)
$K^+\Lambda$	7.1 ± 0.1	5.0 – 8.5	R. Schumacher & M. Sargsian, PRC **83**, 025207 (2011)
$K^+\Lambda$	7	6.3 – 8.1	B. Dey, PRD **90**, 014013 (2014)
$K^+\Sigma$	7	6.3 – 8.1	B. Dey, PRD **90**, 014013 (2014)
η'	7	6.3 – 7.8	B. Dey, PRD **90**, 014013 (2014)
η	12.7 ± 1.2	6.4 – 7.8	B. Dey, PRD **90**, 014013 (2014)
ϕ	12.3 ± 0.6	6.3 – 8.1	B. Dey, PRD **90**, 014013 (2014)
ω	9.4 ± 0.1	6.3 – 8.1	B. Dey, PRD 90, 014013 (2014)
ω	9.08 ± 0.11	5 – 8	T. Reed *et al*. arXiv: 2005.13067
ω	7.2 ± 0.7	7.1 – 8.1	M. Battaglieri *et al*. PRL **90**, 022002 (2003)
ω	6.80 ± 0.11	3.5 – 8.1	M.J. Amaryan *et al*, arXiv:2102.03633
ω	8.80 ± 0.06	5.0 – 8.1	M.J. Amaryan *et al*, arXiv:2102.03633




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

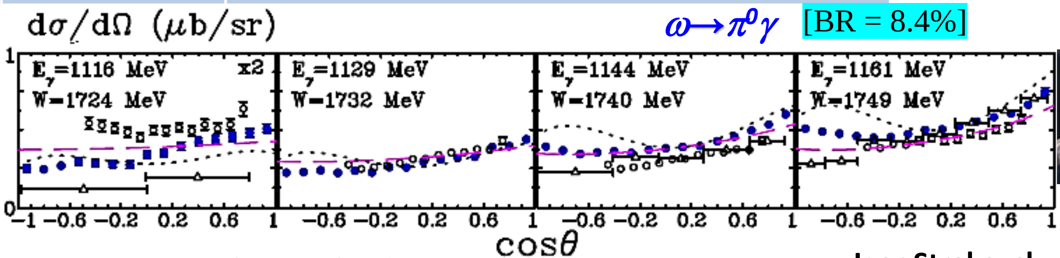
[BR = 89.3%]


$\omega \to \pi^0\gamma$ [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) SAPHIR



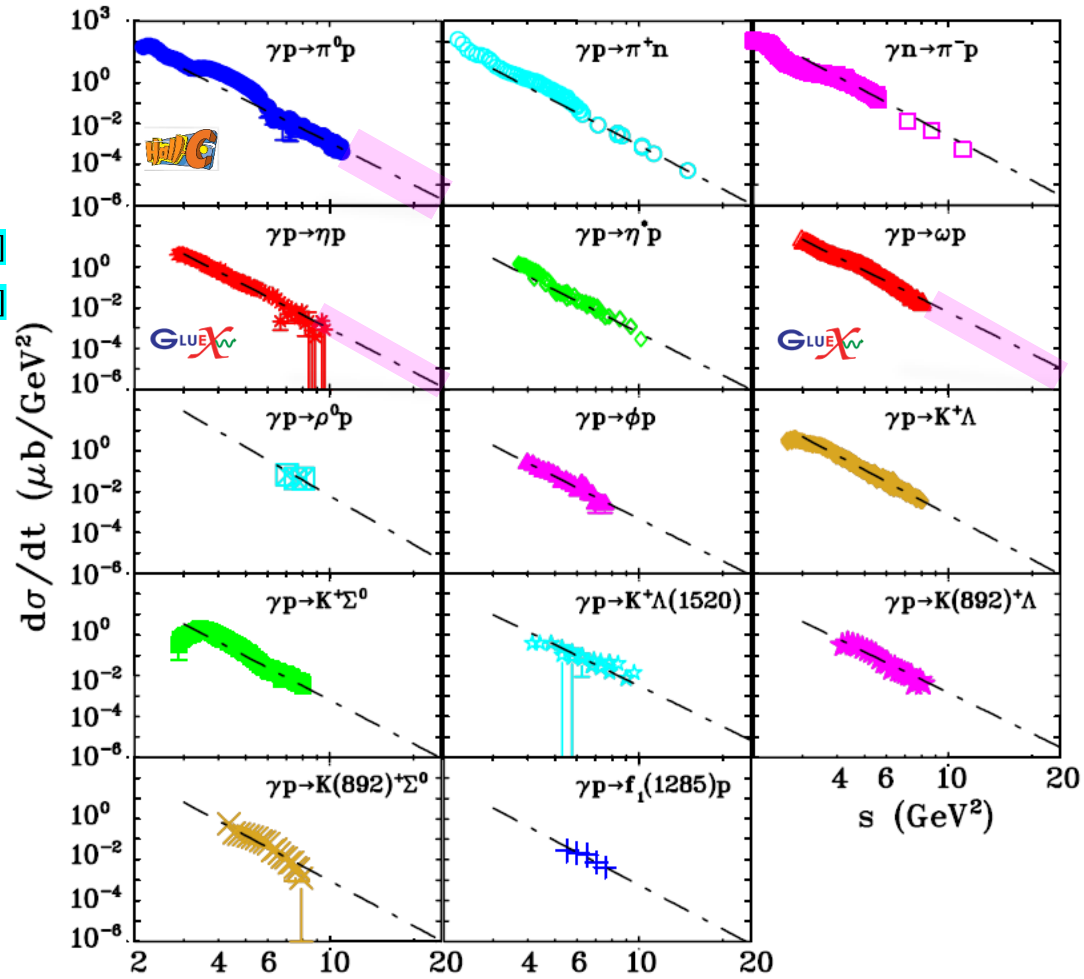
Brief Tour through Future GlueX & Hall C Experiments

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**.

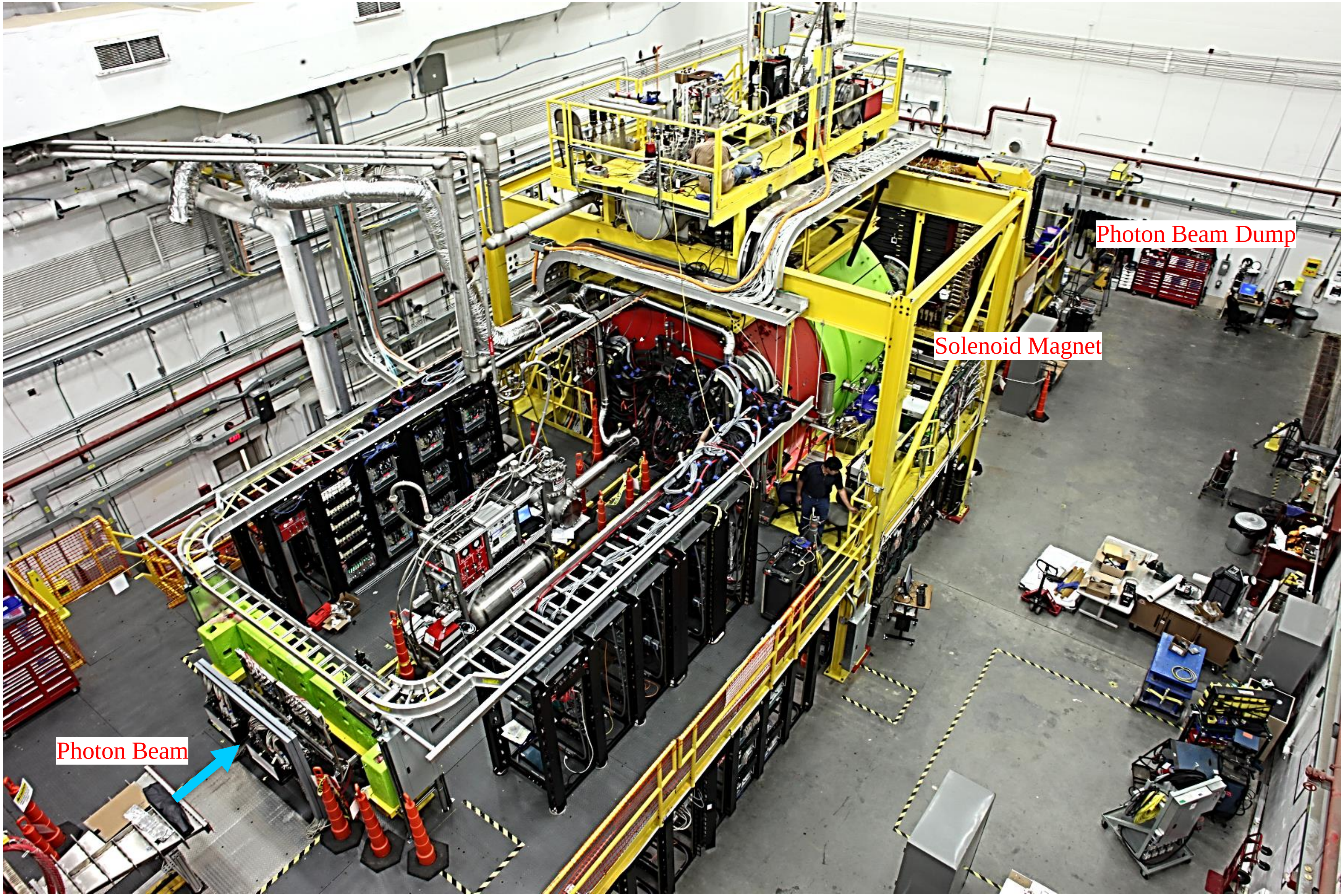
$\eta \to \pi^+ \pi^- \pi^0$ [BR = 22.9%]

$\eta \to \pi^0 \gamma$ [BR = 39.4%]



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

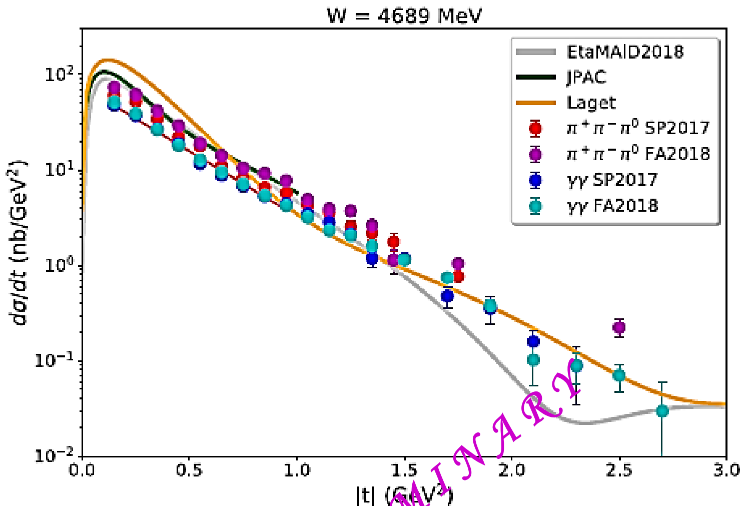
$\omega \to \pi^0 \gamma$ [BR = 8.4%]

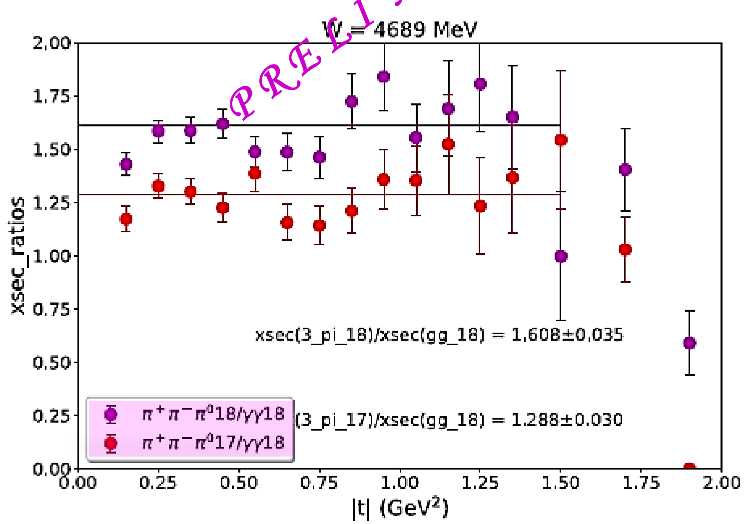


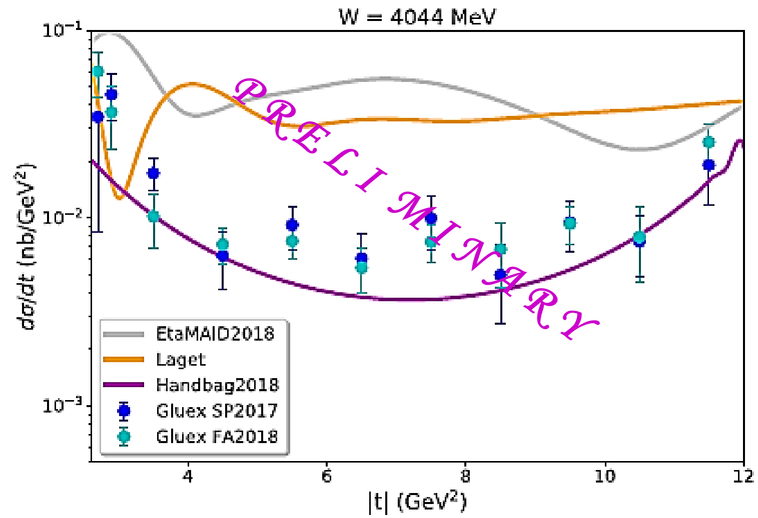
Photon Beam Dump
Solenoid Magnet
Photon Beam

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

s = 12.6 – 21.9 GeV^2





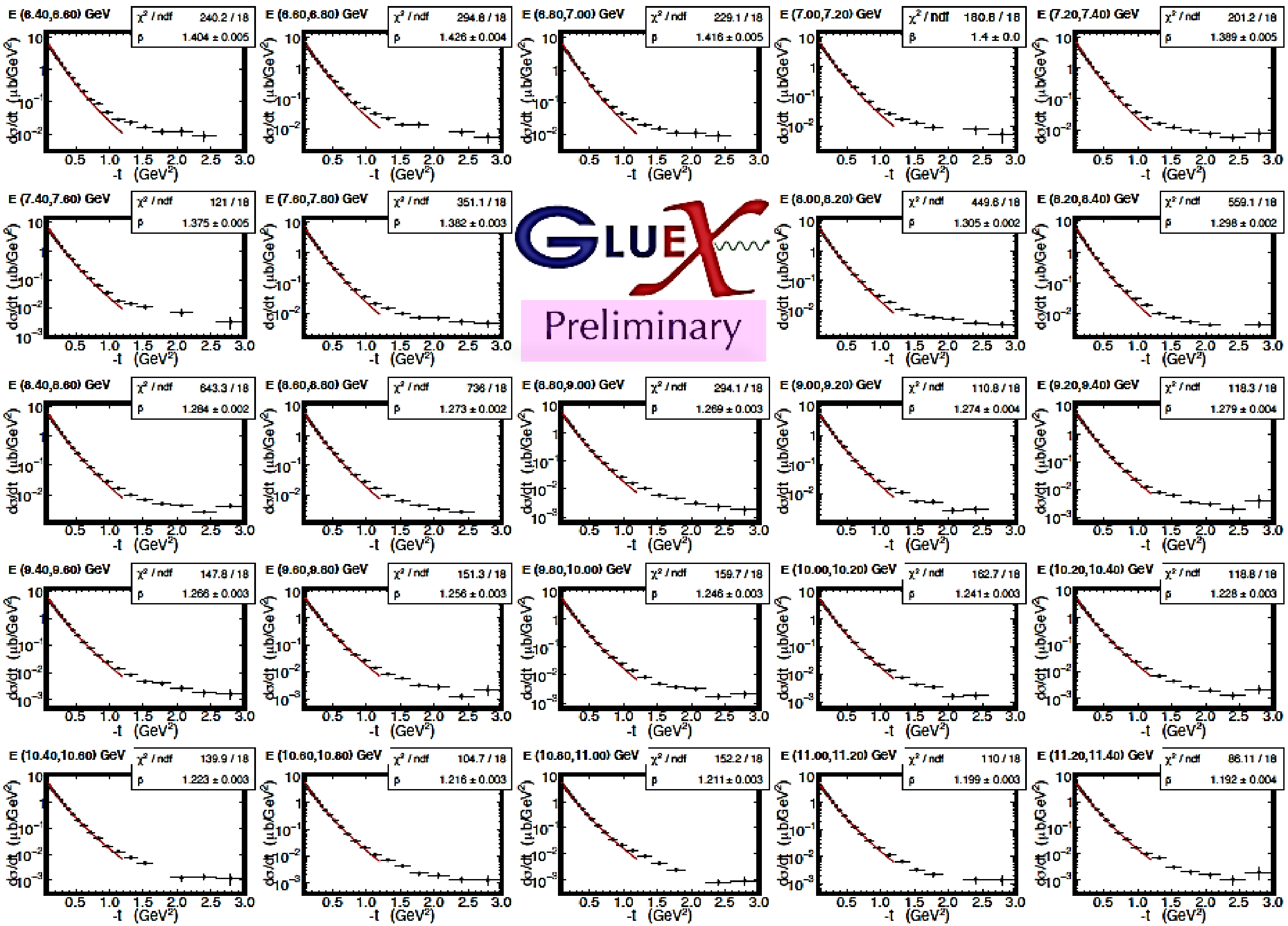


Courtesy of Mahmoud Kamel, GHP2021

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

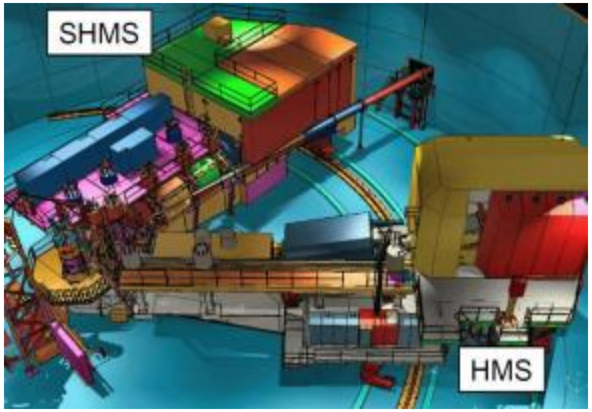
s = 6.5 – 22.6 GeV^2

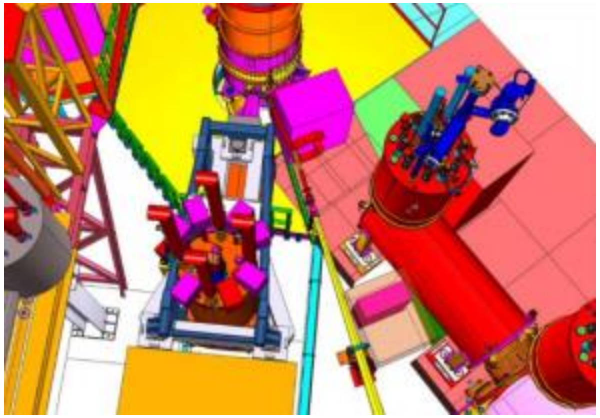
Stamp plots, $\omega \to \pi^+\pi^-\pi^0$, 50% of GlueX phase 1



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

Courtesy of Mark Dalton, GHP2021

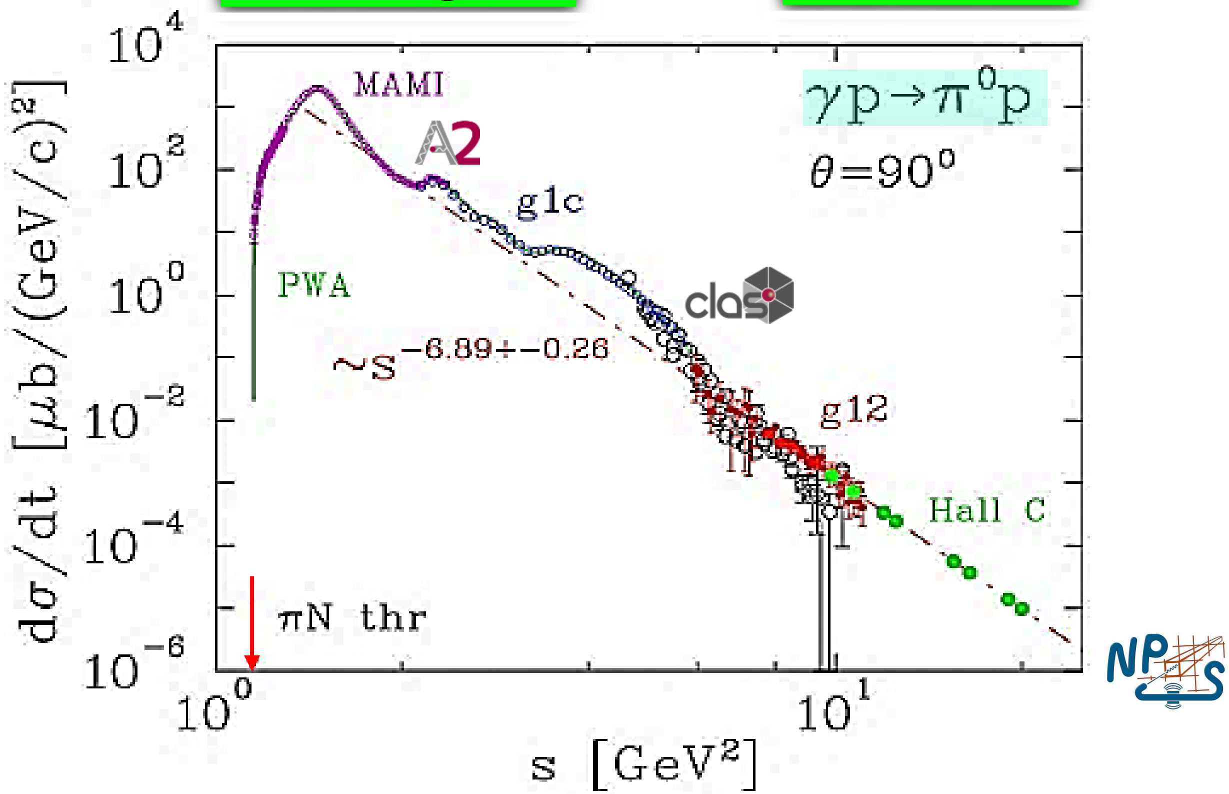

SHMS
HMS



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.

Summary

- We studied energy dependence of **90^0** ***pseudoscalar*** & ***vector*** *meson photoproduction* off *nucleon*.

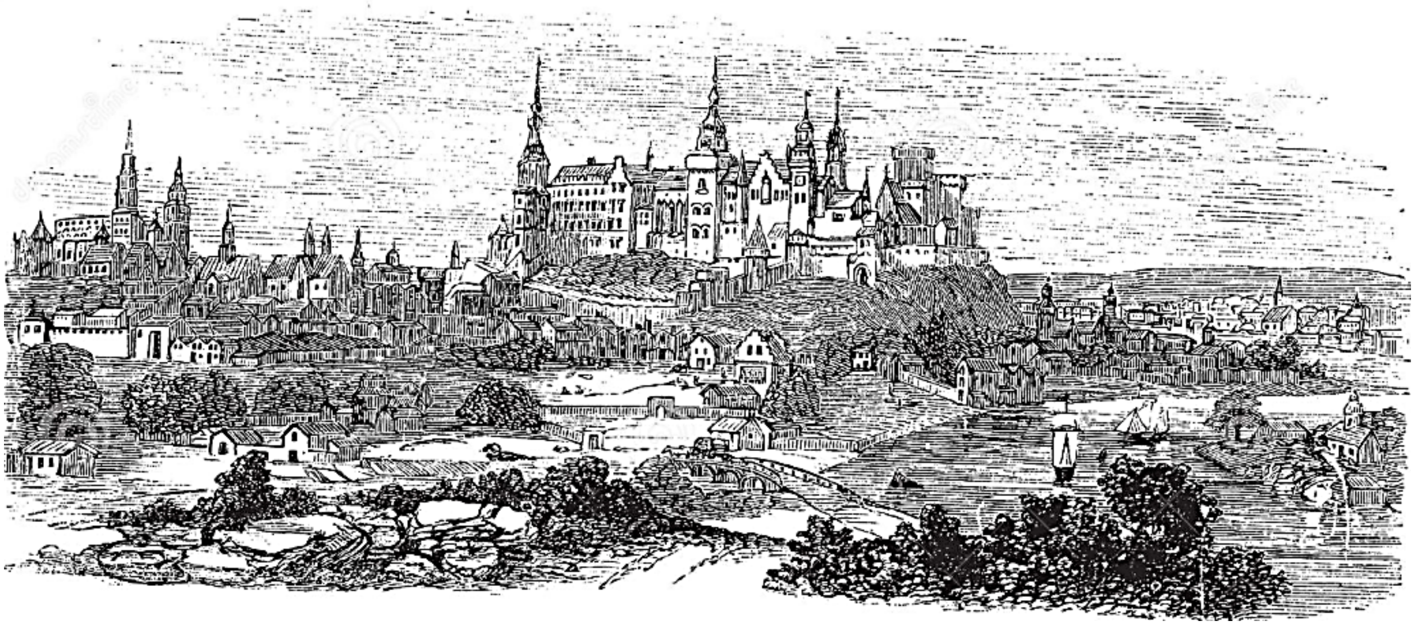
- We evaluated practically all available experimental data obtained by CLAS Collaboration over more than last **two** decades & compare results with *QCR* predictions.

- 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), & CLAS12 can extend measurements up to $s \simeq 21$ GeV^2.



Thanks

Any Question?