High Energy Behavior of Light Meson Photoproduction with CLAS & Quark Counting Rule

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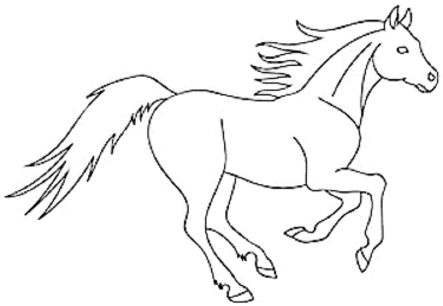
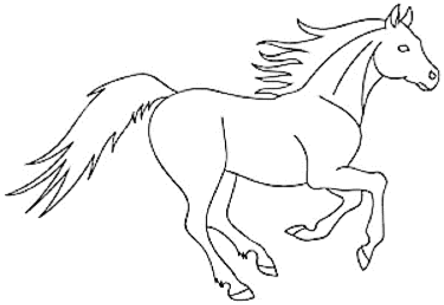
arXiv:2102.03633

[*] Supported by DE-SC0016583

Outline



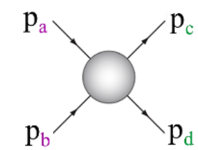
- Quark Counting Rule for hadrons
- Quark Counting Rule for meson photoproduction
- CLAS light meson photoproduction measurements off nucleon
- Point-like nature of photon in γN interaction
- Sudakov form factor
- Light meson photoproduction off nucleon from CLAS
- CLAS data: Partial evaluation
- GlueX differential cross sections for η photoproduction
- Wide angle exclusive photoproduction of π^0 mesons @ Hall C
- Summary



QCR for Hadrons

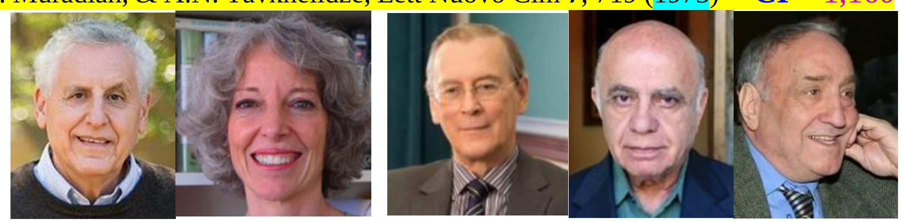
- Binary reactions in **QCD** with large momentum transfer involve *quark* & *gluon* exchanges between colliding particles.

- **QCR** of *Brodsky-Farrar* & *Matveev-Muradyan-Tavkhelidze (1973)* has 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** = 1,865

V.A. Matveev, R.M. Muradian, & A.N. Tavkhelidze, Lett Nuovo Cim **7**, 719 (1973) **CI**= 1,160



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

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

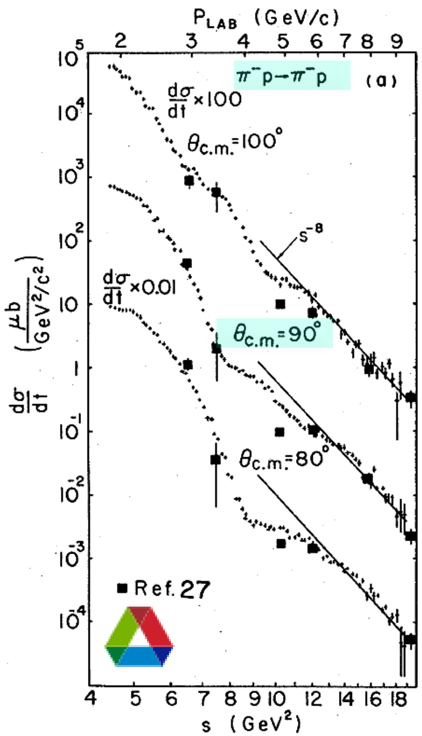
where n is number of constituents: $(n - 2) = (n_a + n_b) + (n_c + n_d) - 2$

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

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

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

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



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

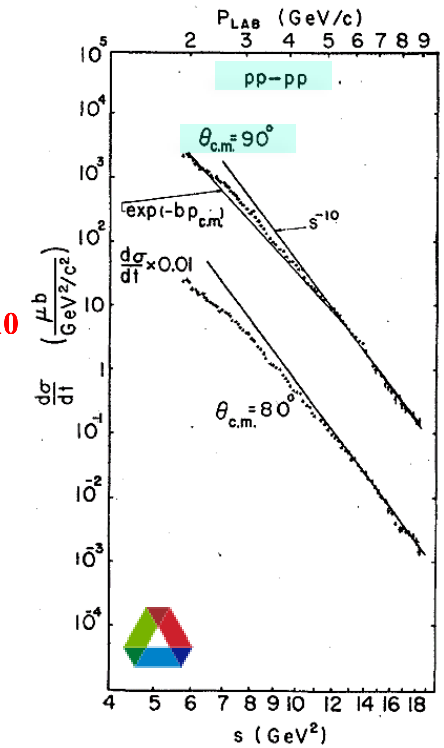
$(n-2) = (2+3) + (2+3) - 2 = 8$

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

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

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

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



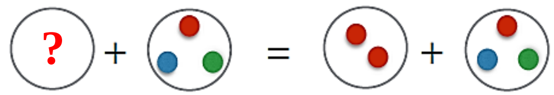
K.A. Jenkins *et al*. Phys Rev D **21**, 2445 (1980)

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		

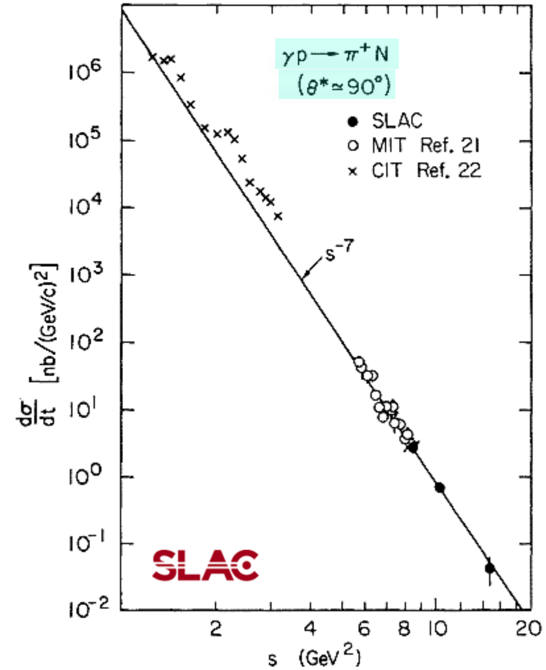
D. Sivers, Ann Phys (NY) **90**, 71 (1975)

QCR for Meson Photoproduction

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



$$(\mathbf{n} - \mathbf{2}) = (\mathbf{?} + \mathbf{3}) + (\mathbf{2} + \mathbf{3}) - \mathbf{2} = \mathbf{?}$$

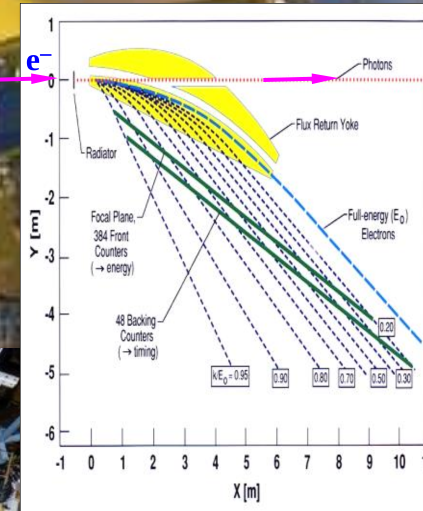


R.L. Anderson *et al.* Phys Rev D **14**, 679 (1976)

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

CEBAF Large Acceptance Spectrometer 1997-2012

Bremsstrahlung Photon Tagger
384 E & 61 T Counters

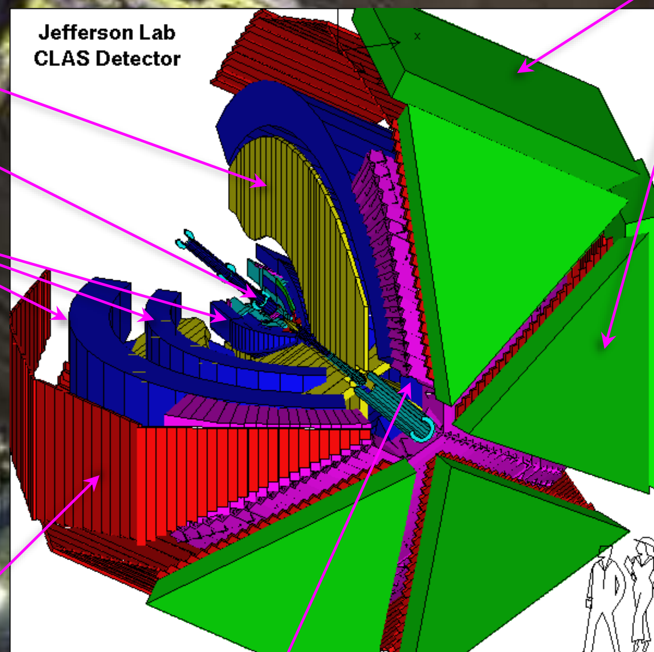


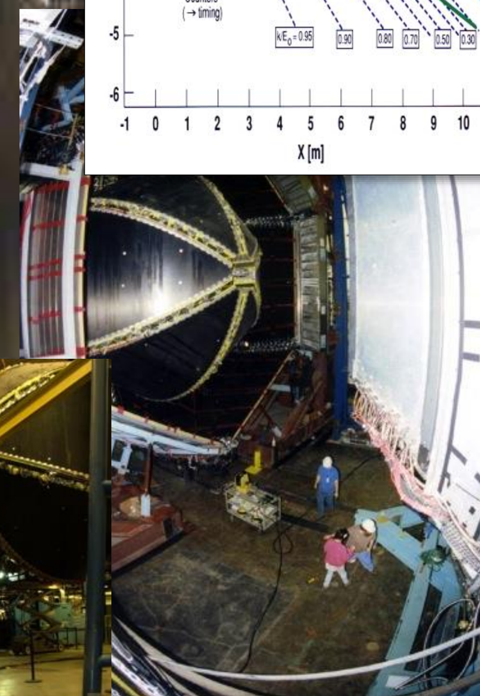
Electromagnetic Calorimeters
Lead/Scintillator, 1296 PMTs

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.

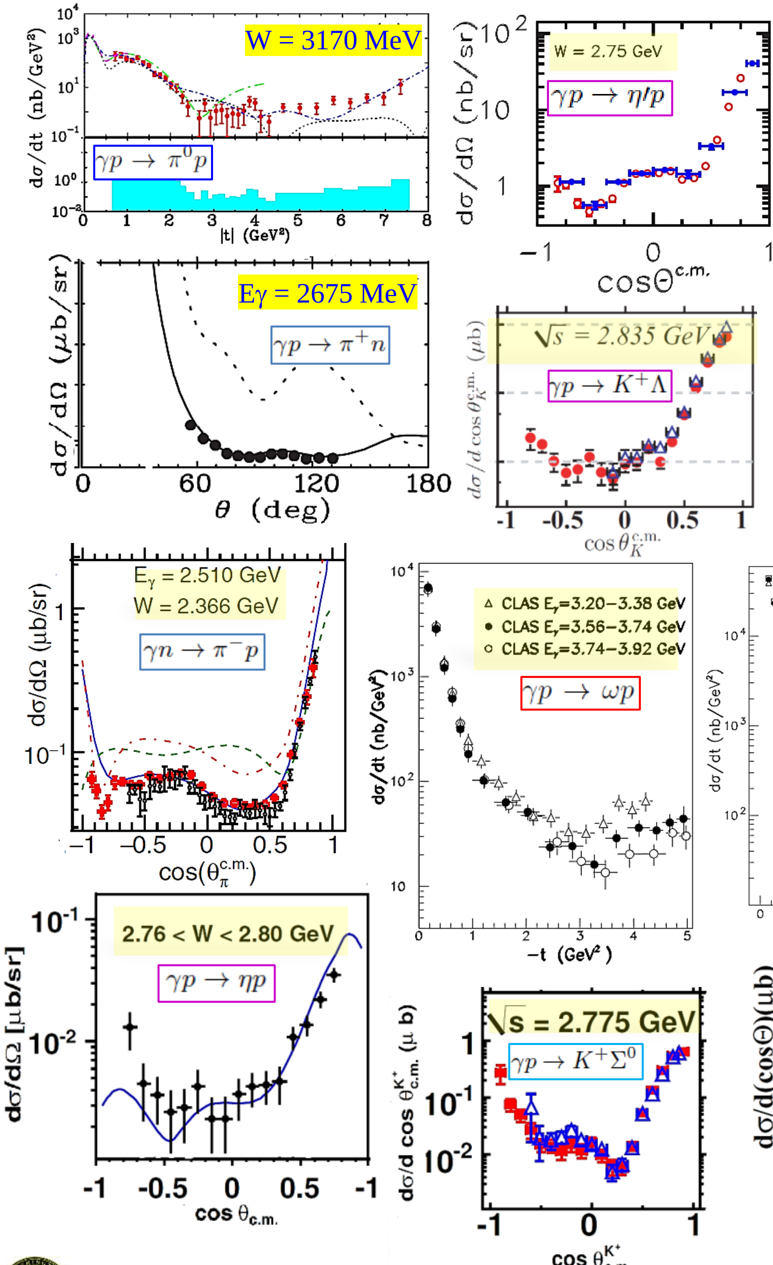
Reaction	Ref.	Reaction	Ref.
$\gamma p \to \pi^0 p$	2018, 2007	$\gamma p \to K^+\Sigma^0$	2010, 2006, 2004
$\gamma p \to \pi^+ n$	2009	$\gamma p \to K^+\Lambda(1450)$	2013
$\gamma n \to \pi^- p$	2017, 2009	$\gamma p \to K^+\Lambda(1520)$	2021, 2013
$\gamma p \to \eta p$	2020, 2009, 2002	$\gamma p \to K^+\Sigma(1385)^0$	2013
$\gamma p \to \eta\prime p$	2016, 2009, 2006	$\gamma p \to K(892)^+\Lambda$	2013
$\gamma p \to \omega p$	2009, 2003	$\gamma p \to K(892)^+\Sigma^0$	2013
$\gamma p \to \rho^0 p$	2001	$\gamma p \to K(892)^0\Sigma^+$	2007
$\gamma p \to \phi p$	2014	$\gamma p \to f_1(1285)p$	2016
$\gamma p \to K^+\Lambda$	2010, 2006, 2004		

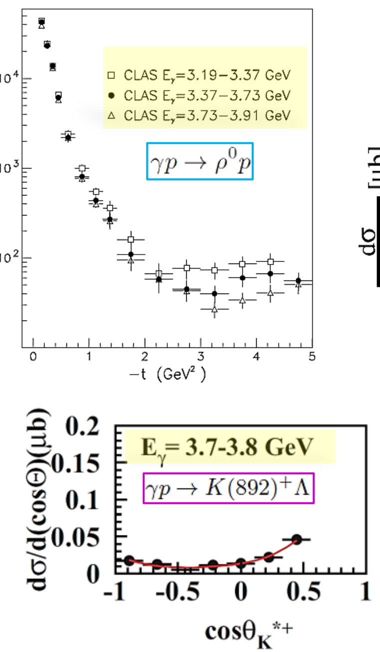
24 papers [2001 – 2021]
CI = 1,937

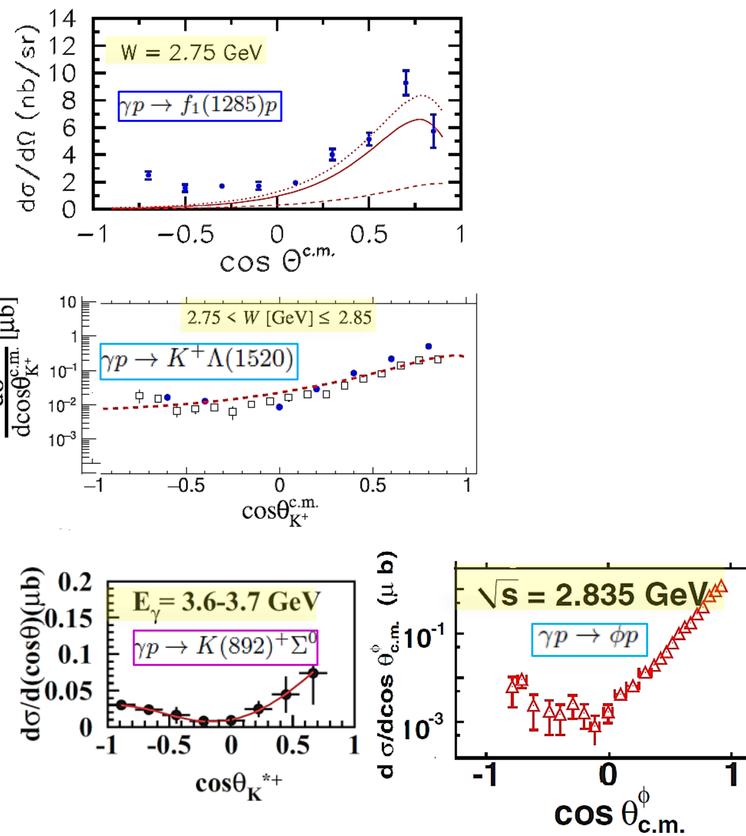
- There is *unique* opportunity to **bridge** ***resonance*** & ***high-energy*** regions, in particular, that encompassing region in which ***Regge*** theory is applicable, & evaluate ***QCR*** phenomenology with differential cross sections above resonance energies.

CLAS Differential Cross Sections @ Large s

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

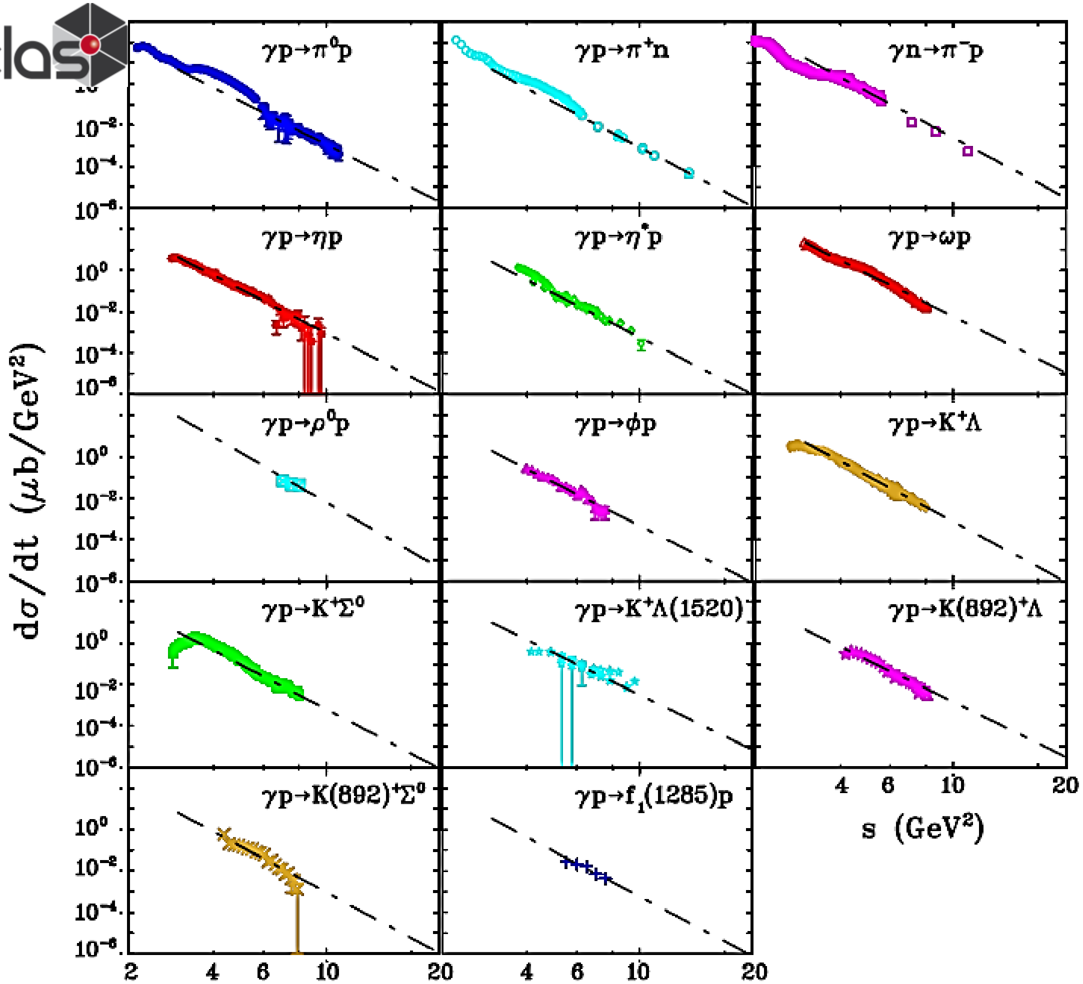






Power Factor (n-2) for Light Meson Photoproduction off Nucleon from CLAS

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



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

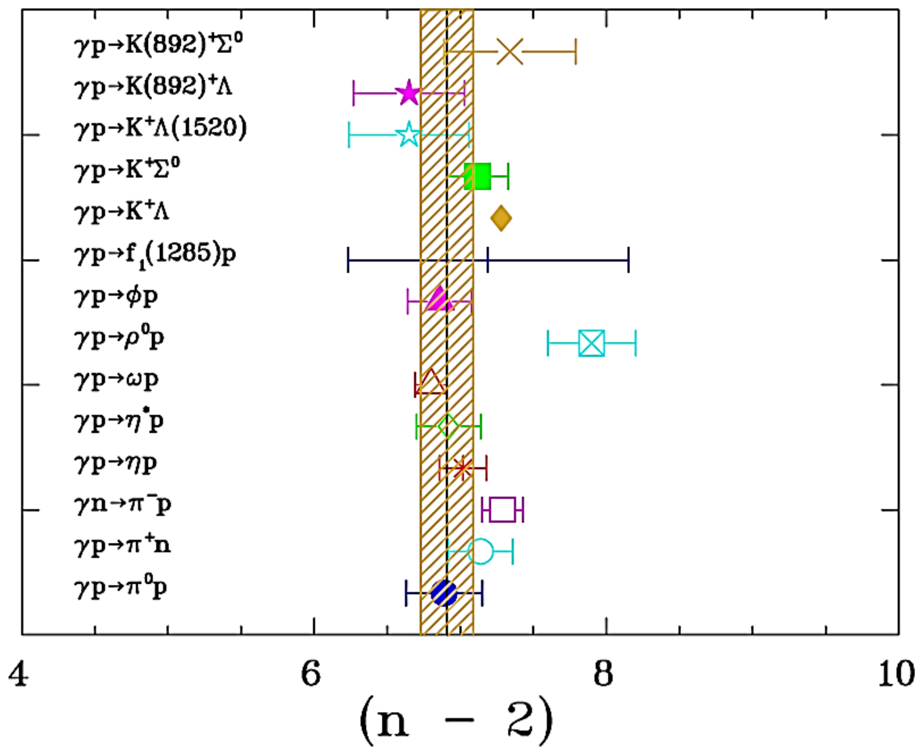
Reaction	s (GeV^2)	$\|t\|$ (GeV^2)	(n−2)	Ref.
$\gamma p \to \pi^0 p$	5.9–11.1	2.1–4.7	6.89±0.26	[17]
$\gamma p \to \pi^+ n$	6.3–14.9	2.3–6.6	7.14±0.22	[8, 11, 27]
$\gamma n \to \pi^- p$	4.0–11.3	0.2–4.6	7.29±0.14	[11, 28]
$\gamma p \to \eta p$	3.2– 9.6	0.6–3.8	7.02±0.16	[29]
$\gamma p \to \eta' p$	4.2– 9.3	0.8–2.6	6.92±0.22	[30, 33, 34]
$\gamma p \to \omega p$	3.5– 8.1	0.3–2.9	6.80±0.11	[12, 35]
$\gamma p \to \rho^0 p$	7.0– 8.0	2.3–2.9	7.9±0.3[a]	[10]
$\gamma p \to \phi p$	4.0– 7.5	0.6–2.4	6.86±0.22	[36]
$\gamma p \to K^+\Lambda$	4.0– 8.0	0.3–2.9	7.28±0.06	[38]
$\gamma p \to K^+\Sigma^0$	5.2– 8.0	0.3–2.8	7.12±0.21	[41]
$\gamma p \to K^+\Lambda(1520)$	4.8– 9.0	0.9–3.2	6.65±0.41	[42, 43]
$\gamma p \to K(892)^+\Lambda$	4.2– 8.1	0.7–2.6	6.65±0.38	[44]
$\gamma p \to K(892)^+\Sigma^0$	4.3– 7.9	0.7–2.4	7.34±0.45	[44]
$\gamma p \to f_1(1285)p$	6.0– 7.6	1.2–2.0	7.19±0.96	[33]

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

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



$<(n-2)> = 6.91 \pm 0.18$

- Thanks to point-like nature of photon, 90^0 cross section or $ds/dt(s) \propto s^{-7}$.

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 form factor.

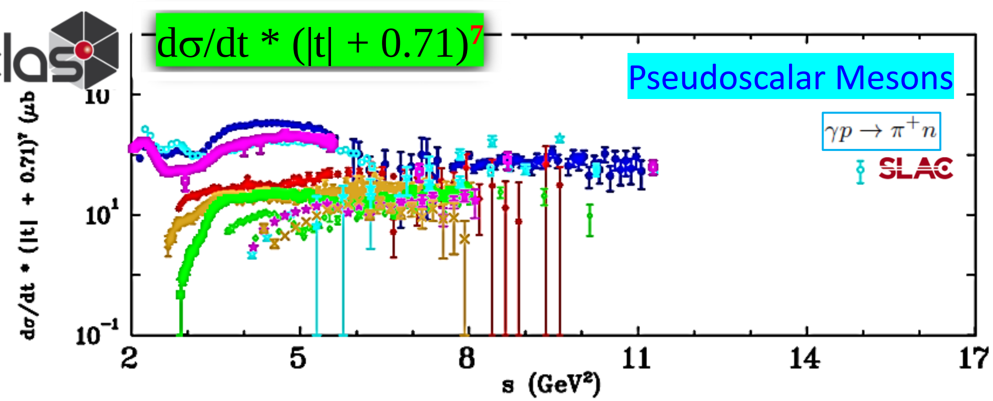
- It is very improbable that two ensembles of constituents can get strong transverse kick & radiate no gluons.
- Of course, probability of new gluon emission is suppressed by QCD coupling constant α_s, but simultaneously it can be enhanced by large $ln^2 s$.
- *Probability* not to emit any additional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

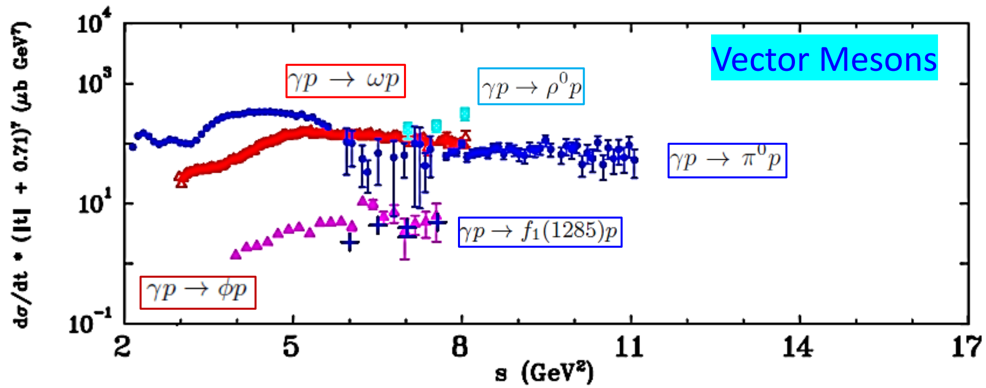
- Theoretically was shown in [G.R. Farrar, G.F. Sterman, & H. Zhang, Phys Rev Lett **62**, 2229 (1989)] that due to *point-like* nature of *photon*, Sudakov form factor is absent in case of large angle meson photoproduction.
- Thus, our phenomenological result confirms QCR in processes where there is no Sudakov correction.

Light Meson Photoproduction off Nucleon from CLAS

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

- Let us reframe **$d\sigma/dt(s)$** $\rightarrow$ **$d\sigma/dt(s) * [s^3/G(t)^2]$.**
- Proton dipole form factor **$G(t)$** = **$1 / (1 + |t|/0.71)^2$** describes all four-momentum dependencies of both electric & magnetic form factors of proton quite well.
- Then, we expect **$d\sigma/dt(s)$** ∞ **$G(t)^2 / s^3$**.
- It appears natural to introduce similar "infrared cutoff" @ lower ***s*** as well & to replace **$1/s^3$** by **$1/(|t| + 0.71)^3$**.



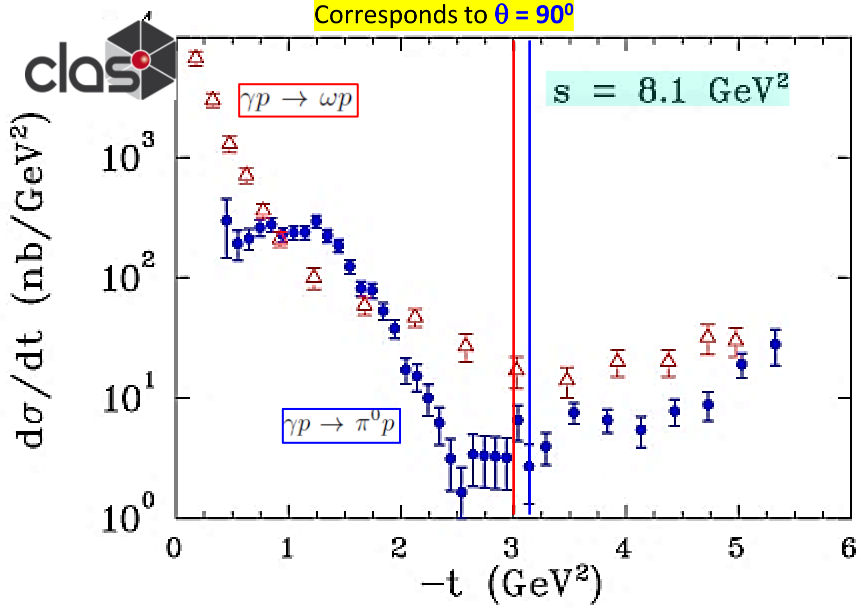


- Accuracy & dispersion of data is better seen here than on pg. **9**.
- It demonstrates possible role of "infrared cutoff".

- When only 90^0 production angle data are selected, all cross sections @ higher values of ***s*** reach same level as well as all other meson production data, except ϕ & f_1, which lie significantly below other mesons plateau @ higher energies.

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

Corresponds to $\theta = 90^0$



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

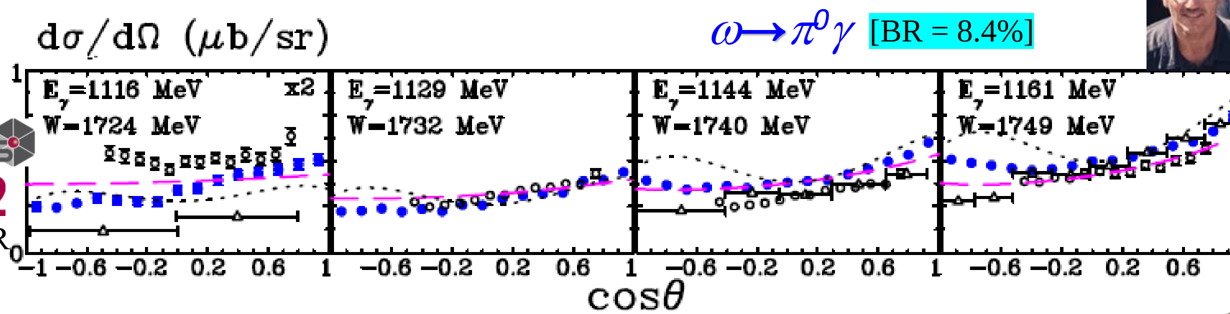
M. Kunkel *et al.* Phys Rev C **98**, 015207 (2018)

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

CLAS Data: Partial Evaluation

Decay	Meson	(n–2)	s (GeV^2)	Reference
	ρ^0	7.9 ± 0.3	7.0 – 8.0	M. Battaglieri *et al*. Phys Rev Lett **87**, 172002 (2001)
	$K^+\Lambda$	7.1 ± 0.1	5.0 – 8.5	R. Schumacher & M. Sargsian, Phys Rev C **83**, 025207 (2011)
	$K^+\Lambda$	7	6.3 – 8.1	B. Dey, Phys Rev D **90**, 014013 (2014)
	$K^+\Sigma$	7	6.3 – 8.1	B. Dey, Phys Rev D **90**, 014013 (2014)
	η'	7	6.3 – 7.8	B. Dey, Phys Rev D **90**, 014013 (2014)
	η	12.7 ± 1.2	6.4 – 7.8	B. Dey, Phys Rev D **90**, 014013 (2014)
	ϕ	12.3 ± 0.6	6.3 – 8.1	B. Dey, Phys Rev D **90**, 014013 (2014)
$\omega \to \pi^+\pi^-\pi^0$	ω	9.4 ± 0.1	6.3 – 8.1	B. Dey, Phys Rev D 90, 014013 (2014)
$\omega \to \pi^+\pi^-\pi^0$	ω	9.08 ± 0.11	5 – 8	T. Reed *et al*. arXiv: 2005.13067
$\omega \to \pi^+\pi^-\pi^0$	ω	7.2 ± 0.7	7.1 – 8.1	M. Battaglieri *et al*. Phys Rev Lett **90**, 022002 (2003)
$\omega \to \pi^+\pi^-\pi^0$ [BR = 89.3%]	ω	6.80 ± 0.11	3.5 – 8.1	M.J. Amaryan *et al*, arXiv:2102.03633

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

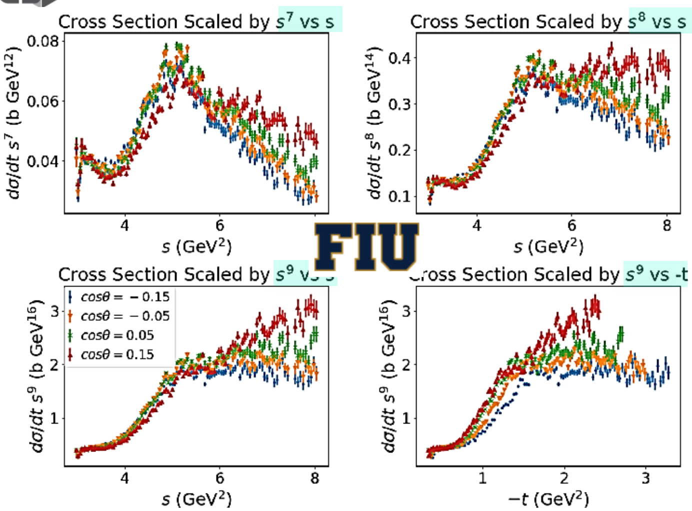


M. Williams *et al*. Phys Rev C **80**, 065208 (2009) — clas

IIS *et al*. Phys Rev C **91**, 045207 (2015) — A2

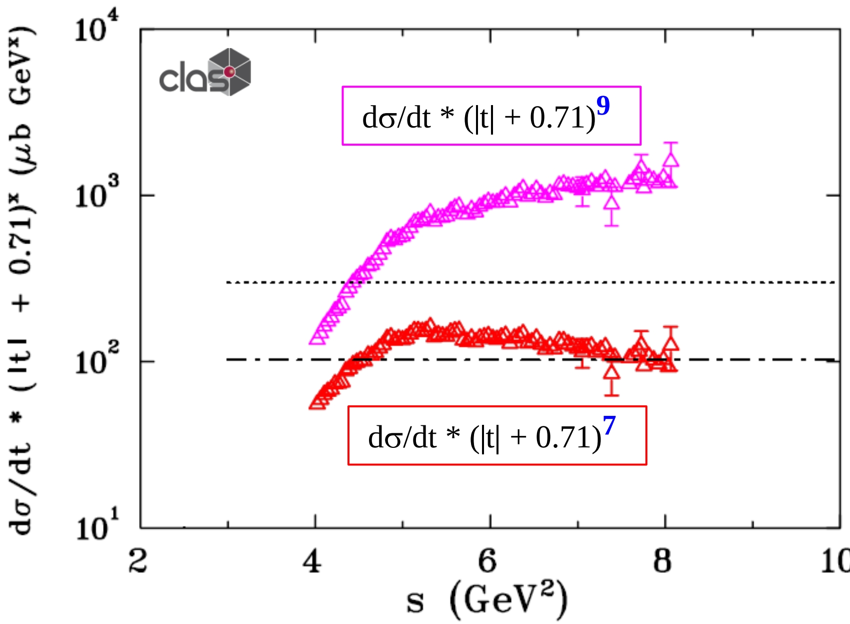
J. Barth *et al*. Eur Phys J A **18**, 117 (2003) — SAPHIR

CLAS Data: Partial Evaluation



T. Reed, C. Leon, F. Vera, L. Guo, & B. Raue, arXiv: 2005.13067

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

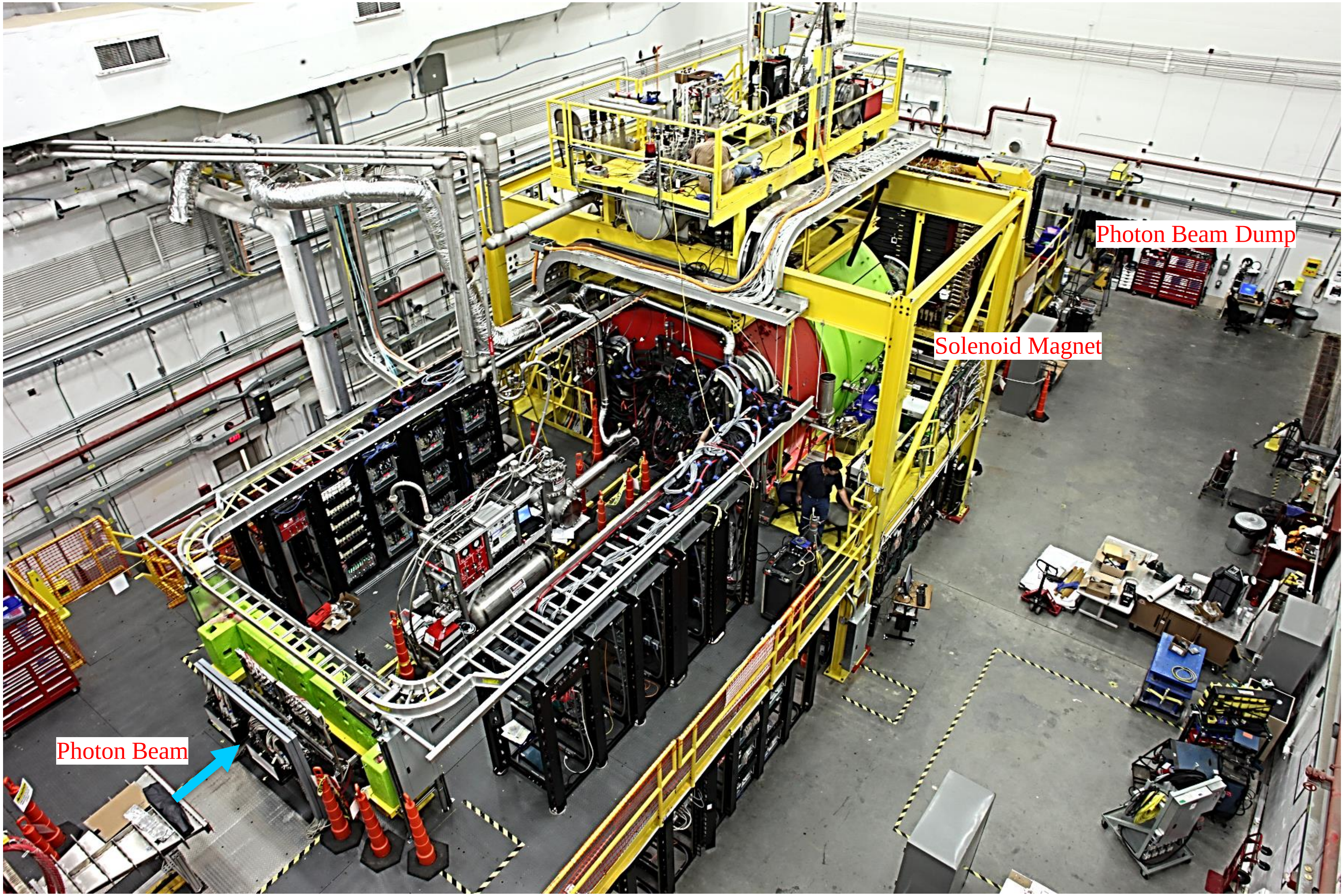


M.J. Amaryan, W.J. Briscoe, M.G. Ryskin, & IIS, arXiv:2102.03633

M. Williams *et al*. Phys Rev C **80**, 065208 (2009)
M. Battaglieri *et al*. Phys Rev Lett **90**, 022002 (2003)

- It looks that for large s > **5** – **6** GeV^2 both '**–7**' & '**–9**' are not good.
- Best will be something like '**–8**'.

- However, accounting for lower s power '**–7**' is better.

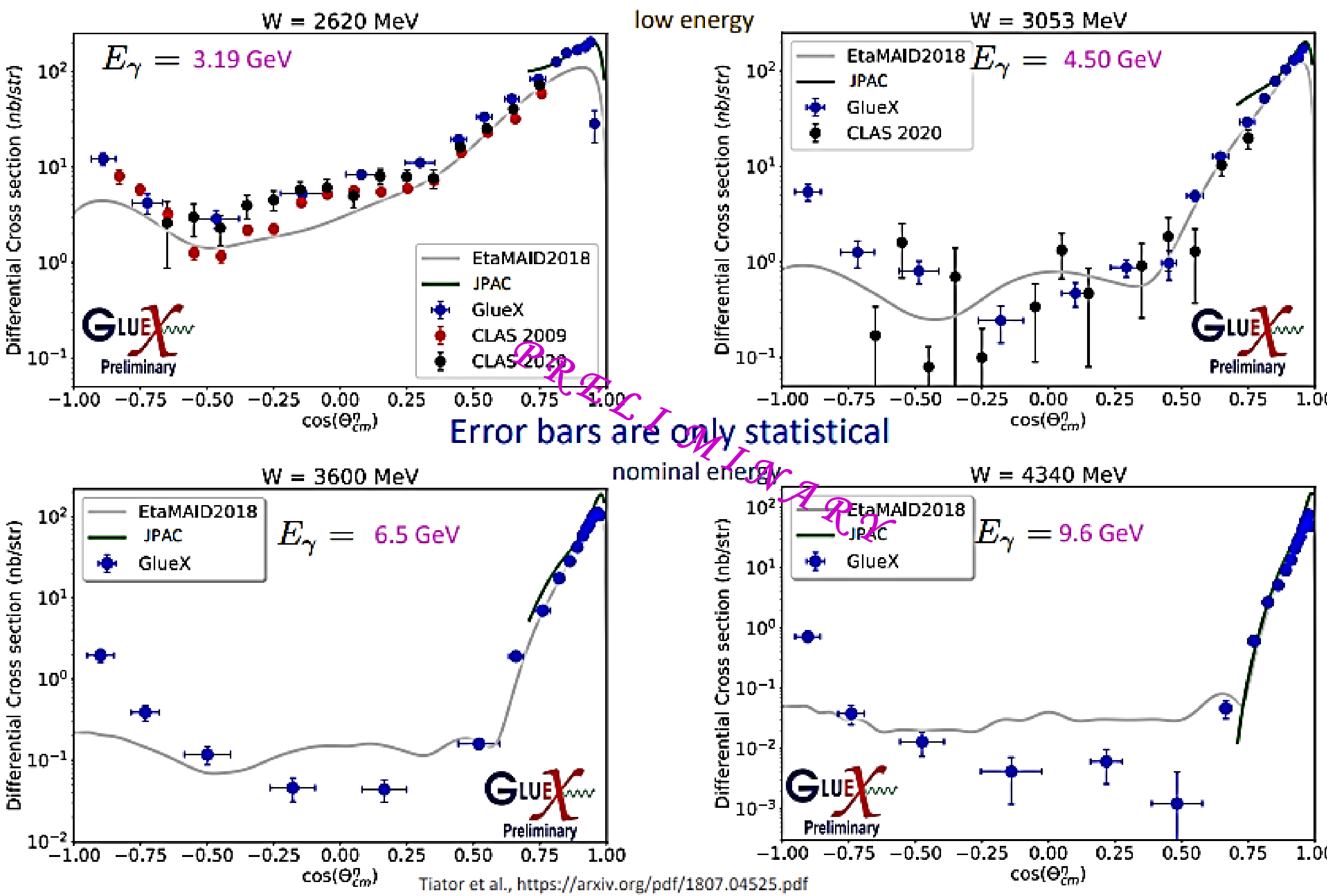


Photon Beam Dump
Solenoid Magnet
Photon Beam

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

s =12.6 – 21.9 GeV^2

low energy



Error bars are only statistical

nominal energy

Tiator et al., https://arxiv.org/pdf/1807.04525.pdf

http://cgl.soic.indiana.edu/jpac/EtaPhot.php, Nys et al., PhysRevD.95.034014, 2017

Williams et al., Physical Review C, 80(4):045213

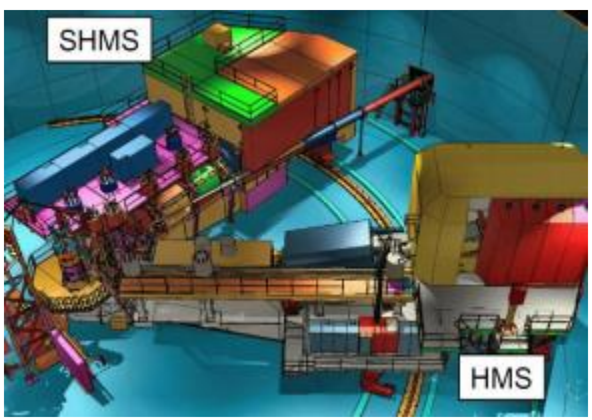
Hu et al., https://arxiv.org/abs/2006.01361

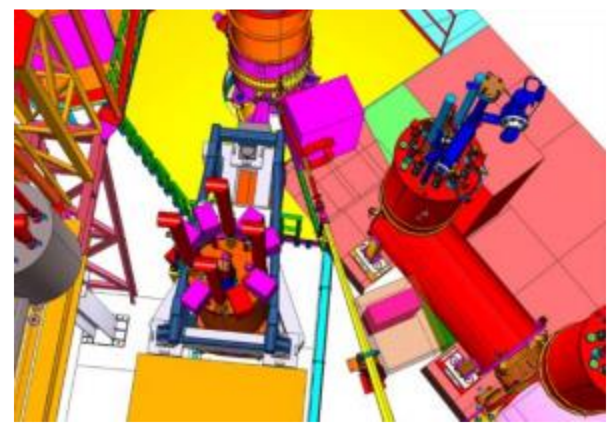
FIU FLORIDA INTERNATIONAL UNIVERSITY

6

Mahmoud Kamel

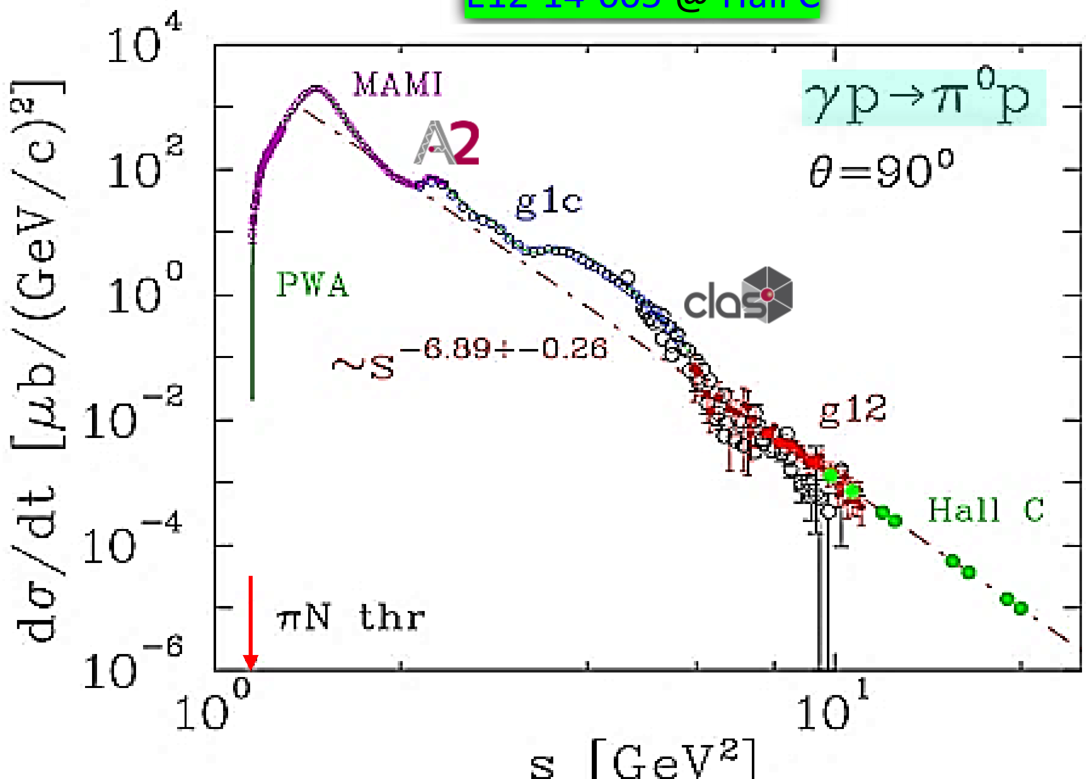
Courtesy of Mahmoud Kamel, DNP2020


SHMS
HMS



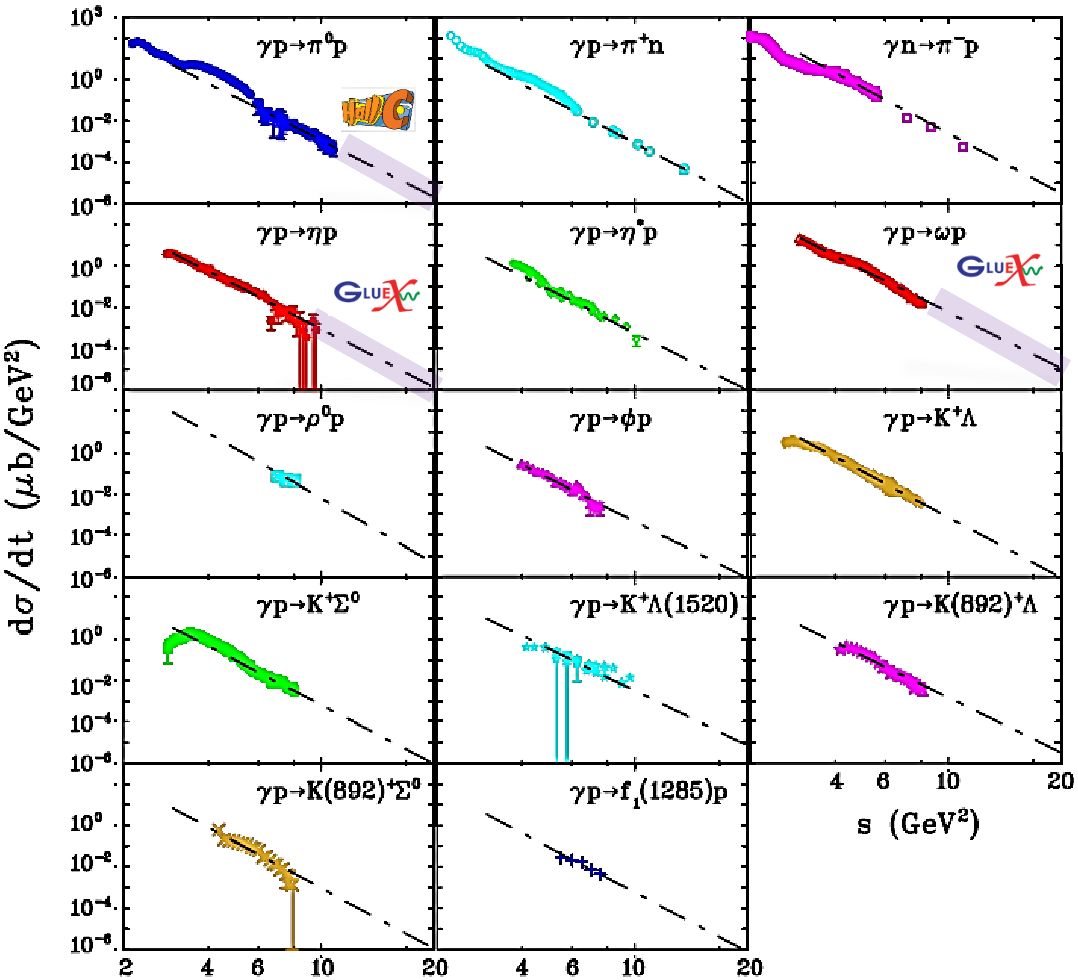
Wide Angle Exclusive Photoproduction of π^0 Mesons

E12-14-005 @ Hall C



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.

Expectation for Power Factor for Light Meson Photoproduction off Nucleon



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

- 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 form factor.

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

- Obviously, JLab6 program is limited by **s** ~ **11** GeV^2.

- Within JLab12 program, **Hall C** (π^0 may come), GlueX (η & ω are coming), & CLAS12 can extend measurements up to **s** ~ **21** GeV^2.