Vector Meson Photoproduction at Threshold: from Omega to Upsilon

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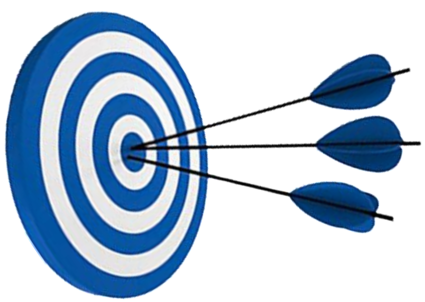
IS, S. Prakhov, Ya. Azimov *et al*, Phys Rev C **91**, 045207 (2015)
IS, D. Epifanov, & L. Pentchev, Phys Rev C **101**, 042201 (2020)
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101**, 045201 (2020)
Meng-Lin Du, V. Baru, Feng-Kun Guo, Ch. Hanhart, U.-G. Meissner, A. Nefediev, & IS, Eur Phys J C **80**, 1053 (2020)
L. Pentchev & IS, Eur Phys J A **57**, 56 (2021)
IS, W.J. Briscoe, L. Pentchev, & A. Schmidt, Phys Rev C **104**, 074028 (2021)
Xiao-Yun Wang, Fancong Zeng, & IS, Phys Rev C **106**, 015202 (2022)

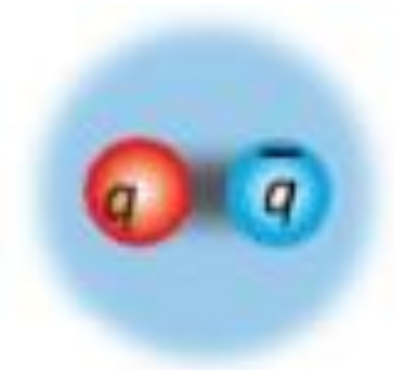
Supported by DE-SC0016583

Outline



- *Vector Meson Zoo*
- *VM – Nucleon SL*
- *Thr Kinematics & EM Properties of VM*
- *VMD Phenomenology*
- *Brief tour through Photoproduction Experiments*
- *VM – Nucleon SLs*
- *Outlook: A View of Future*

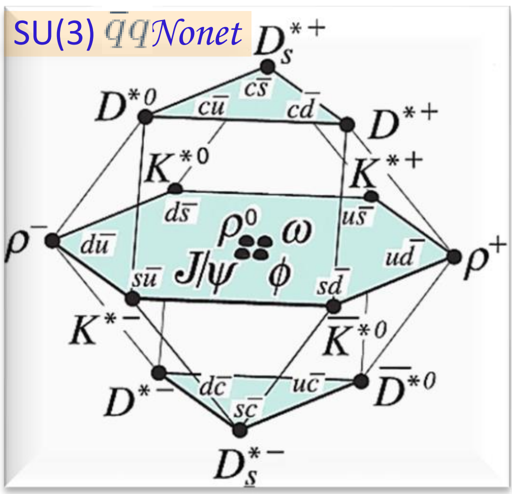
Vector Meson Zoo



Vector Meson Domestic Zoo

- Some *vector mesons* can, compared to other mesons, be measured to very high precision.
- This stems from fact that *vector mesons* have ***same*** quantum numbers as *photon*.

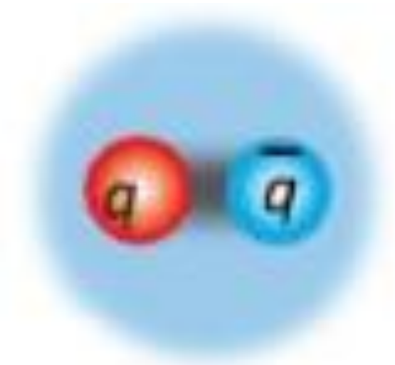
$I^G(J^{PC}) = 0^-(1^{--})$

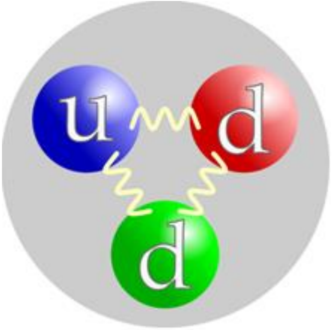


Name (PDG)	Quark Content	Γ (MeV)	
$\rho^+(770)$	$u\bar{d}$	148	
$\rho^0(770)$	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	149	
$\omega(782)$	$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	8.5	
$K^{*+}(892)$	$u\bar{s}$	51	
$K^{*0}(892)$	$d\bar{s}$	47	
$\phi(1020)$	$s\bar{s}$	4.3	
$D^{*+}(2010)$	$c\bar{d}$	0.083	*Open Charm*
$D^{*0}(2007)$	$c\bar{u}$	< 2.1	
$J/\psi(1S)(3097)$	$c\bar{c}$	0.093	*Charmonium*
$\psi'(2S)(3686)$	$c\bar{c}$	0.284	
$\Upsilon(1S)(9460)$	$b\bar{b}$	0.052	*Quarkonium*

- We will focus on **5** ***vector mesons*** from $\bar{q}q$ ***Nonet*** which widths are **narrow** enough to study *meson photoproduction* @ threshold & where data are available.

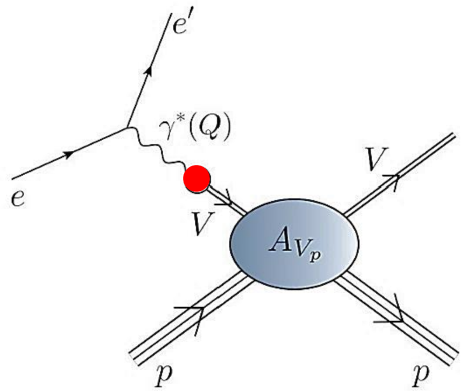
Vector Meson – Nucleon SL



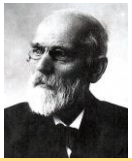


$Vp \rightarrow Vp$

- Don't have *vector meson* beams, so experiments @ modern ***EM***-accelerators attempt to access such interactions via ***EM*** production reactions ***ep→e'Vp***.



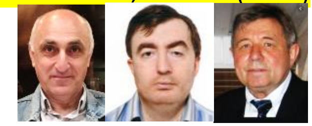
- Interaction of ***heavy*** *vector mesons*, *J/ψ* or *Υ*, with *proton* offers prospects for access to ***QCD van der Waals*** interaction, generated by multiple gluon exchange may relate to observation, *e.g.*, of *hidden-charm* ***5q*** states.



- ***Gluonic van der Waals*** interaction between color singlet hadrons can be described in *QCD* & is equivalent to *EM* interaction between two neutrally charged atoms.

Vector Meson – Nucleon Scattering Length Determination

IS, D. Epifanov, & L. Pentchev, Phys Rev C **101**, 042201 (2020)
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101**, 045201 (2020)



- Small ***positive*** or ***negative*** *VN SL* may indicate weakly ***repulsive*** or ***attractive*** *VN* interaction if there is no *VN* bound state below experimental q_{min}.
- For evaluation of *absolute* value of *VN SL*, we apply *VMD* approach that links near-threshold photoproduction *Xsections* of ***γp→Vp*** & elastic ***Vp→Vp***

$$\frac{d\sigma^{\gamma p\to Vp}}{d\Omega}\Big|_{\rm thr} = \frac{q}{k}\frac{1}{64\pi}|T^{\gamma p\to Vp}|^2 = \frac{q}{k}\cdot\frac{\pi\alpha}{g_V^2}\frac{d\sigma^{Vp\to Vp}}{d\Omega}\Big|_{\rm thr} = \frac{q}{k}\cdot\frac{\pi\alpha}{g_V^2}|\alpha_{Vp}|^2$$

$q \to 0$

k is ***photon*** CM momentum $k = (s - M^2) / 2 s^{1/2}$

q is *vector-meson* CM momentum

$T^{\gamma p\to Vp}$ is the invariant amplitude of *vector-meson* photoproduction

α is fine-structure constant

g_V is *VMD* coupling constant, related to *vector-meson* ***EM*** decay width $\Gamma(V\to e^+e^-)$

$$g_V^2 = \frac{\pi\cdot\alpha^2\cdot m_V}{3\cdot\Gamma(V\to e^+e^-)}$$

- Finally, one can express absolute value of *VN SL* as product of pure ***EM*** *VMD*-motivated kinematic factor

$$B_V^2 = \frac{\alpha\cdot m_V\cdot k}{12\pi\cdot\Gamma(V\to e^+e^-)}$$ ⟸ PDG

& hadronic factor $h_{Vp} = \sqrt{b_1}$

$$\sigma_t(q) = b_1\cdot q + b_3\cdot q^3 + b_5\cdot q^5$$ ⟸ Experiment

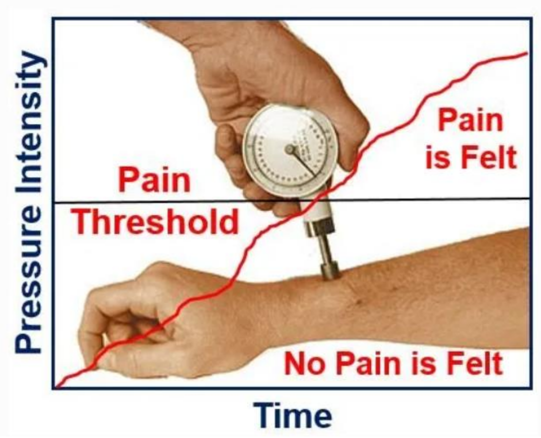
where b_1 came from ***best fit***

that is determined by interplay of strong (*hadronic*) & ***EM*** dynamics as

$$|\alpha_{Vp}| = B_V\cdot h_{Vp}$$

- To ***avoid*** theoretical uncertainties, we did not
  - determine sign of ***SL***,
  - separate **Re** & **Im** parts of ***SL***,
  - extract *spin* **1/2** & **3/2** contributions.

Threshold Kinematics
&
Vector Meson Properties



Kinematics for VM Photoproduction off Proton @ Thresholds & VM EM Properties

VMD coupling constant

$$g_V^2 = \frac{\pi \cdot \alpha^2 \cdot m_V}{3 \cdot \Gamma(V \to e^+e^-)}$$

EM factor

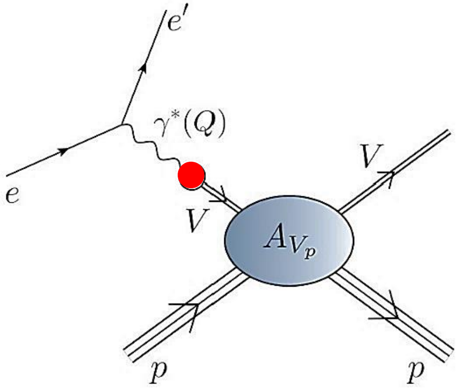
$$B_V^2 = \frac{\alpha \cdot m_V \cdot k}{12\pi \cdot \Gamma(V \to e^+e^-)}$$

PDG particle data group

Vector Meson	m_V	W_{thr}	E_{thr}	k_{thr}	$\Gamma(V \to e^+e^-)$	g_V	B_V
	(MeV)	(MeV)	(MeV)	(MeV/c)	(keV)		(MeV$^{1/2}$)
$\omega(762)$	782.65	1720.9	1109.1	604.7	0.60 ± 0.02	8.53 ± 0.14	390.49 ± 6.35
$\phi(1020)$	1019.461	1957.7	1573.3	754.0	1.27 ± 0.04	6.69 ± 0.10	342.50 ± 5.27
$J/\psi(1S)$	3096.900	4035.2	8207.8	1908.5	5.53 ± 0.10	5.59 ± 0.05	454.92 ± 4.06
$\psi'(2S)$	3686.1	4624.4	10926.7	2217.0	2.29 ± 0.06	9.47 ± 0.12	831.12 ± 108.88
$\Upsilon(1S)$	9460.30	10398.6	57152.9	5156.9	1.340 ± 0.018	19.85 ± 1.21	2654.96 ± 162.15

- *EM* factor B_V for low-lying *vector meson* is close to each other.

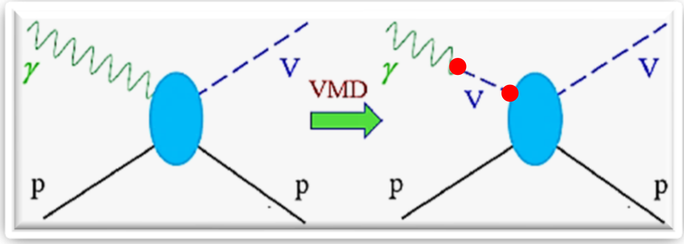
VMD Phenomenology



VMD Model

- *Vector Meson Dominance* model relying on transparent current-field identities
  - M. Gell-Mann & F. Zachariasen, Phys Rev **124**, 953 (1961)
  - J.J. Sakurai, *Currents and Mesons* (The University of Chicago Press, 1969)
  - N.M. Kroll, T.D. Lee, & B. Zumino, Phys. Rev. **157**, 1376 (1967)

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



- *VMD* does not contain *free parameters* & can be used for variety of qualitative estimates of observables in ***vector meson*** photoproductions @ least as first step towards their more extended theoretical studies.

VMD for VN Interaction

- There is no alternative *VMD* to get ***J/ψ p SL*** from meson photoproduction.
  [Possible alternative is to develop sophisticated, nonperturbative reaction theory that can explain *quark+anti-quark* scattering from hadron targets into vector meson final-states.]

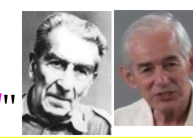
Courtesy of Arkady Vainshtein & Misha Ryskin, July 2020

- To estimate theoretical uncertainty related to *VMD* model, one refer to estimation of cross section of ***J/ψ*** photoproduction in *peripheral model* & found strong energy dependence close to threshold because non-diagonal ***γp→Vp*** & elastic *Vp→Vp* must have larger transfer momenta vs elastic scattering.
  This result in violation of *VMD* by factor of **5**.

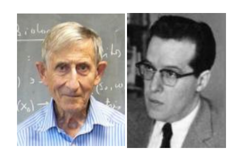
K.G. Boreskov & B.L. Ioffe, Sov J Nucl Phys **25**, 331 (1977)
B.Z. Kopeliovich, I. Schmidt, & M. Siddikov, Phys Rev C **95**, 065203 (2017)

- Color factor for *charmonium* is **1**/**9** while for *open charm* is **8**/**9**.

- Strong suppression in *VN* interaction close to threshold is observed because of $\bar{q}q$ pair in point-like configuration lacks sufficient time to form complete wave function of vector meson;
  that is, proton interacts with "*young*" (undressed) *vector meson* whose size is smaller than that of "*old*" one participating in elastic *Vp→Vp* scattering.



E.L. Feinberg, Sov Phys Usp, **23**, 629 (1980); Courtesy of Misha Ryskin, July 2020



- In recent study, effect of *VMD* assumption was studied in formalism of *Dyson-Schwinger* equations which one can consider as alternative interpretation of "*young age*" effect in another (more formal) language.

Y.Z. Xu, S. Chen, Z.Q. Yao, D. Binosi, Z.F. Cui, & C.D. Roberts, Eur Phys J C **81**, 895 (2021)

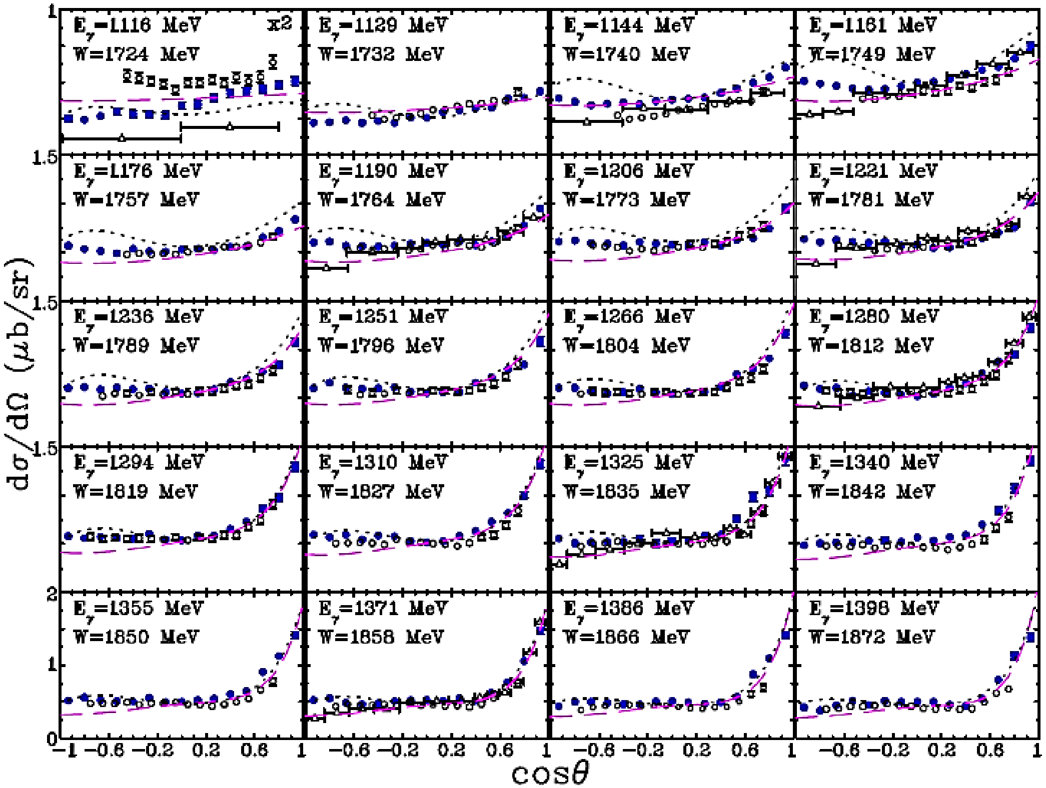
Brief Tour through Photoproduction Experiments

A2 for Omega

$\gamma p \to \omega p \to \pi^0 \gamma p \to 3\gamma p$ Measurements

BR($\omega p \to \pi^0 \gamma$) = 8.4%

IS, S. Prakhov, Ya. Azimov *et al*, Phys Rev C **91**, 045207 (2015)



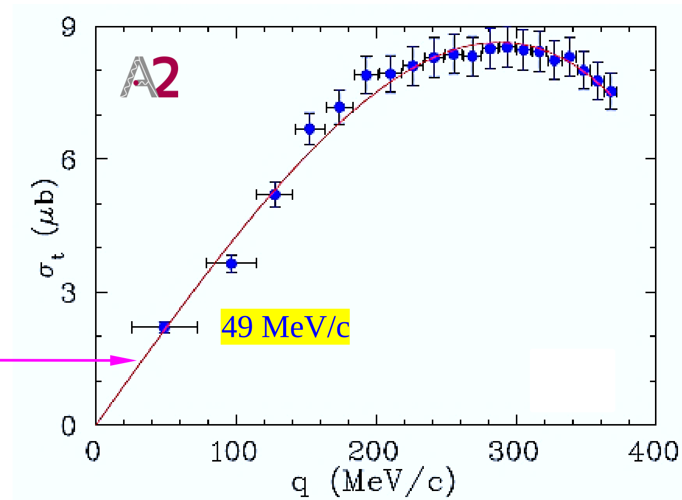
- Full production-angle coverage allows to determine σ_t.
- *Legendre* polynomial extension

$$d\sigma/d\Omega(E_\gamma, \cos\theta) = \sum_{j=0} A_j(E_\gamma)P_j(\cos\theta)$$

confirms σ_t determination

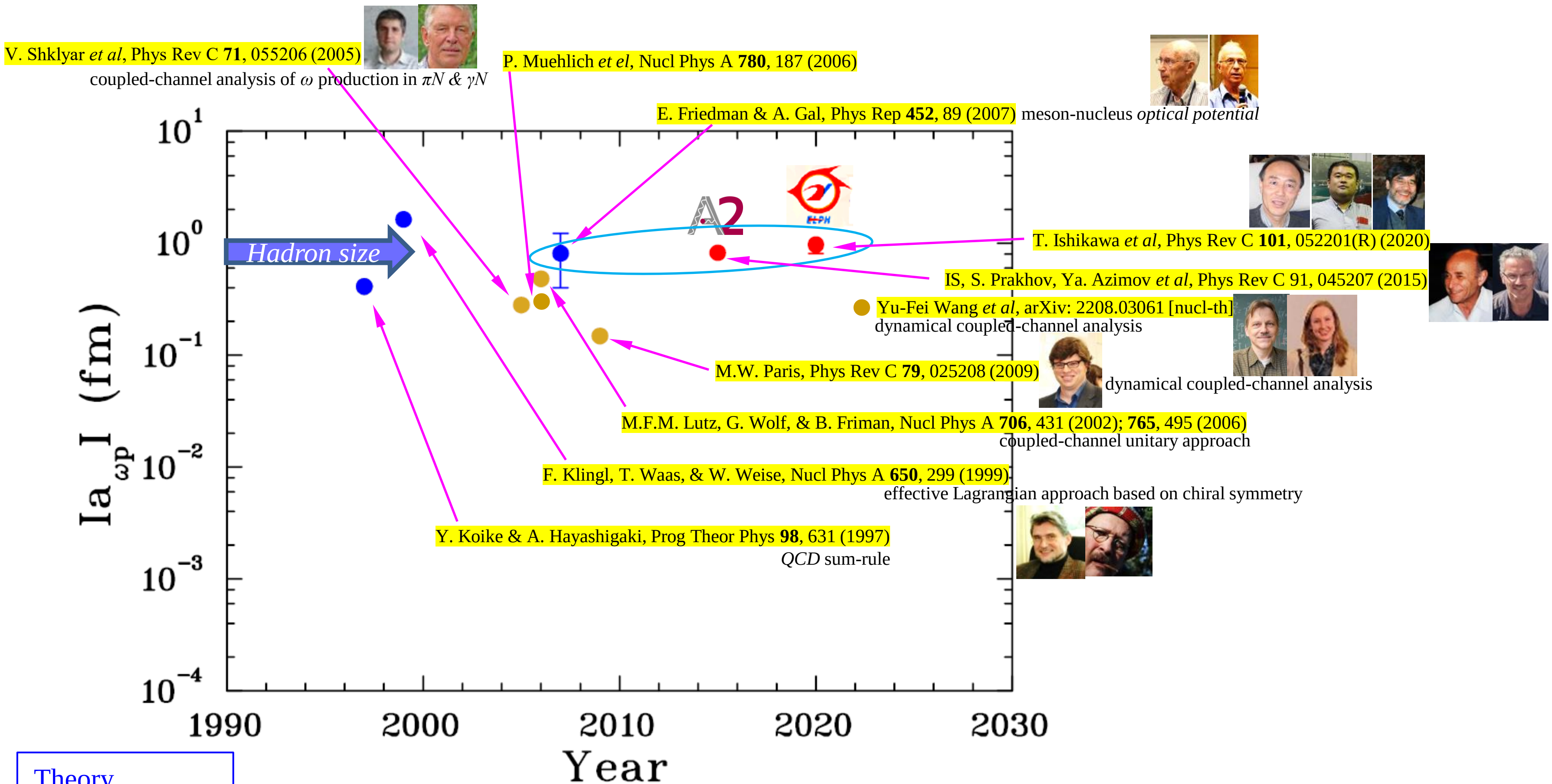
$$\sigma_t = 4\pi A_0(E_\gamma)$$

$$\sigma_t(q) = b_1 \cdot q + b_3 \cdot q^3 + b_5 \cdot q^5$$



What is Known for ωN Scattering Length

- To *avoid* theoretical uncertainties, we did not
  - determine sign of *SL*,
  - separate Re & Im parts of *SL*,
  - extract *spin* 1/2 & 3/2 contributions.

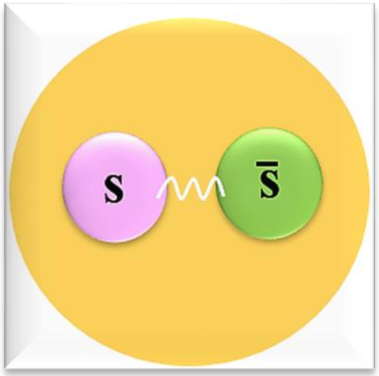


Theory
~~LQCD~~
PWA
Phenomenology

- *ωp SL* agrees with ***size*** of hadron & ***optical*** potential approach.
- A2 & ELPH phenomenological results are larger than ***PWA*** outcomes.

JLab for Phi & J/Psi

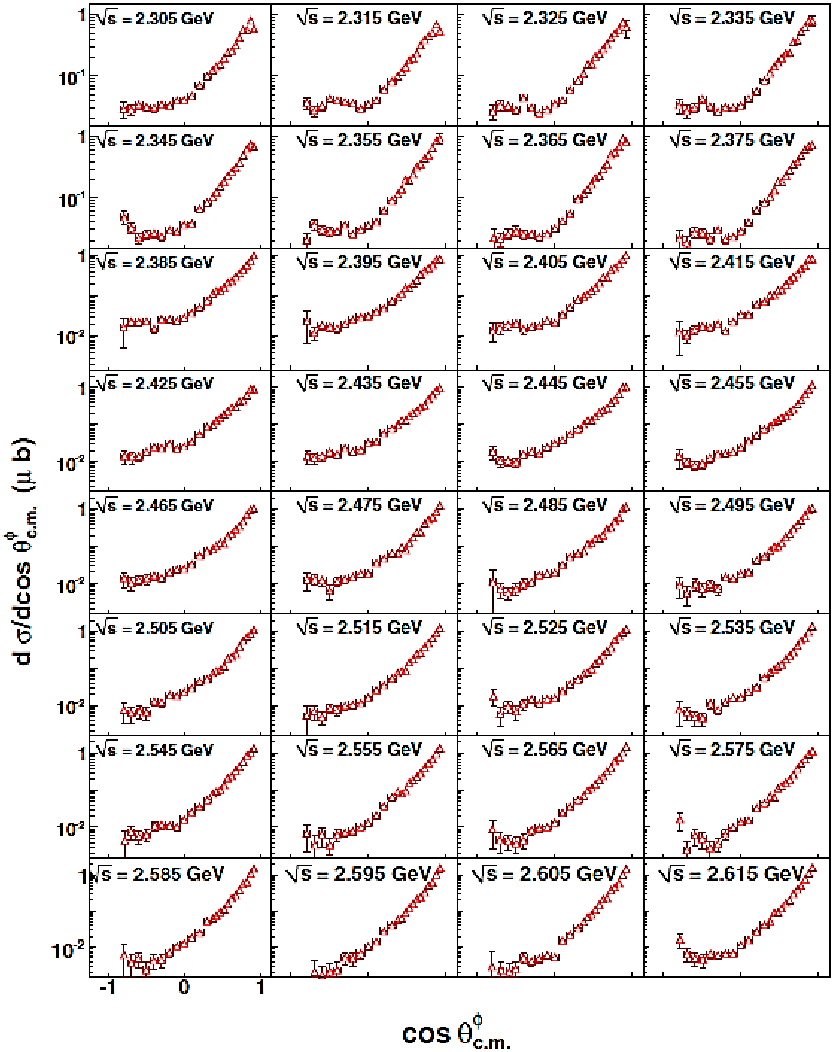
JLab for Phi



$\gamma p \rightarrow \phi p \rightarrow K^+K^-p$ Measurements

BR($\phi p \rightarrow K^+K^-$) = 49.2%

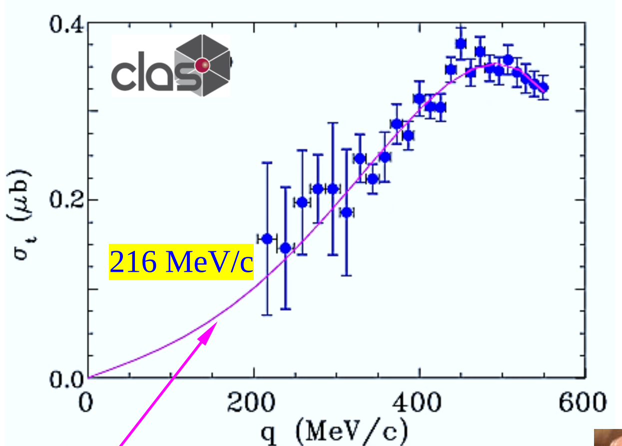
B. Dey *et al*, Phys Rev C **89**, 055208 (2014)



- ***cosθ*** of clas spans from -0.80 to 0.93.
- *Legendre* polynomial extension

$$d\sigma/d\Omega(E_\gamma, \cos\theta) = \sum_{j=0} A_j(E_\gamma)P_j(\cos\theta)$$

is way to determine $\boldsymbol{\sigma_t}$ $\quad \sigma_t = 4\pi A_0(E_\gamma)$

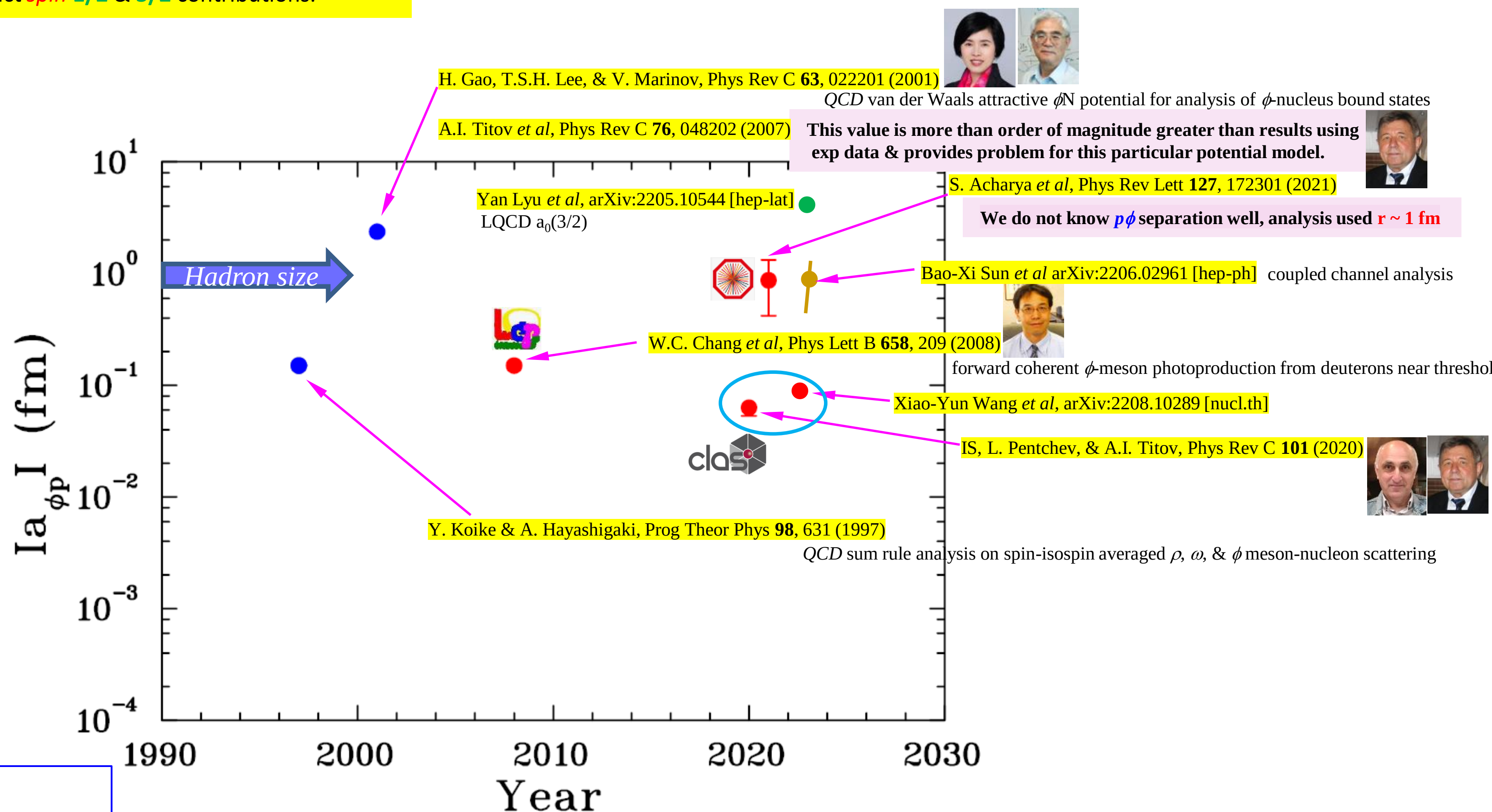


$$\sigma_t(q) = b_1 \cdot q + b_3 \cdot q^3 + b_5 \cdot q^5$$

IS, L. Pentchev, & A.I. Titov, Phys Rev C **101**, 045201 (2020)

What is Known for ϕN Scattering Length

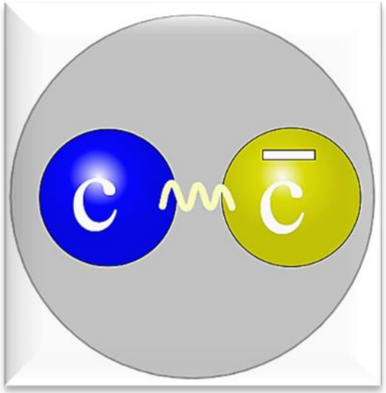
- To *avoid* theoretical uncertainties, we did not
  - determine sign of *SL*,
  - separate Re & Im parts of *SL*,
  - extract *spin* **1/2** & **3/2** contributions.



Theory
LQCD
PWA
Phenomenology

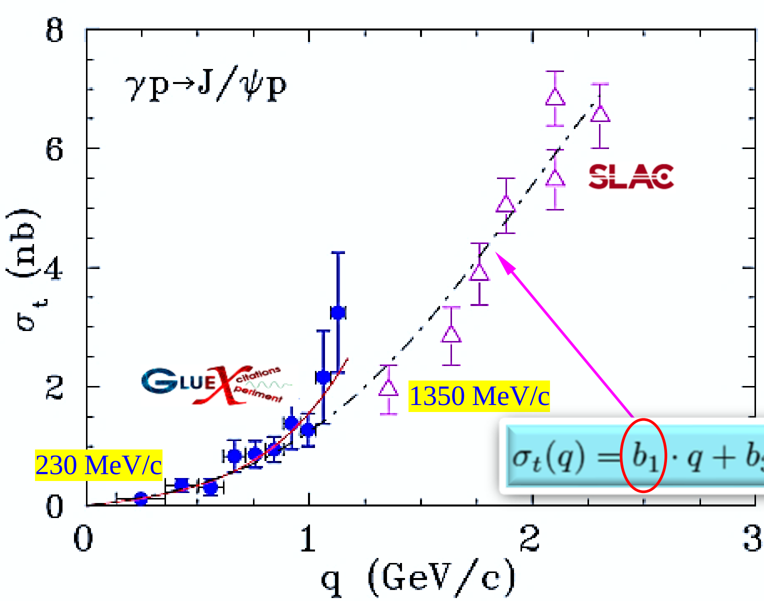
- Our knowledge about ϕp *SL* is limited.

JLab for J/Psi

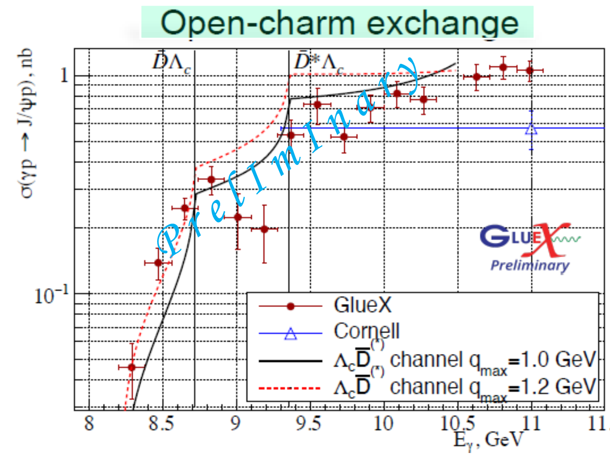


New J/ψ-p Scattering Length

- All previous *theoretical* results (including *potential* approaches & *LQCD* calculations) gave much-much larger *SL*.



$$\sigma_t(q) = b_1 \cdot q + b_3 \cdot q^3 + b_5 \cdot q^5$$



Courtesy of Lubomir Pentchev, September 2022

a_i	GlueX	GlueX & SLAC
a_1 [nb/(GeV/c)]	0.46 ± 0.16	0.53 ± 0.12
a_3 [nb/(GeV/c)^3]	0.83 ± 0.91	0.78 ± 0.16
a_5 [nb/(GeV/c)^5]	0.28 ± 0.87	-0.06 ± 0.03
χ^2/dof	0.67	0.98

- There is ***no** discrepancy* between

GlueX A. Ali *et al*, Phys Rev Lett **123**, 072001 (2019)

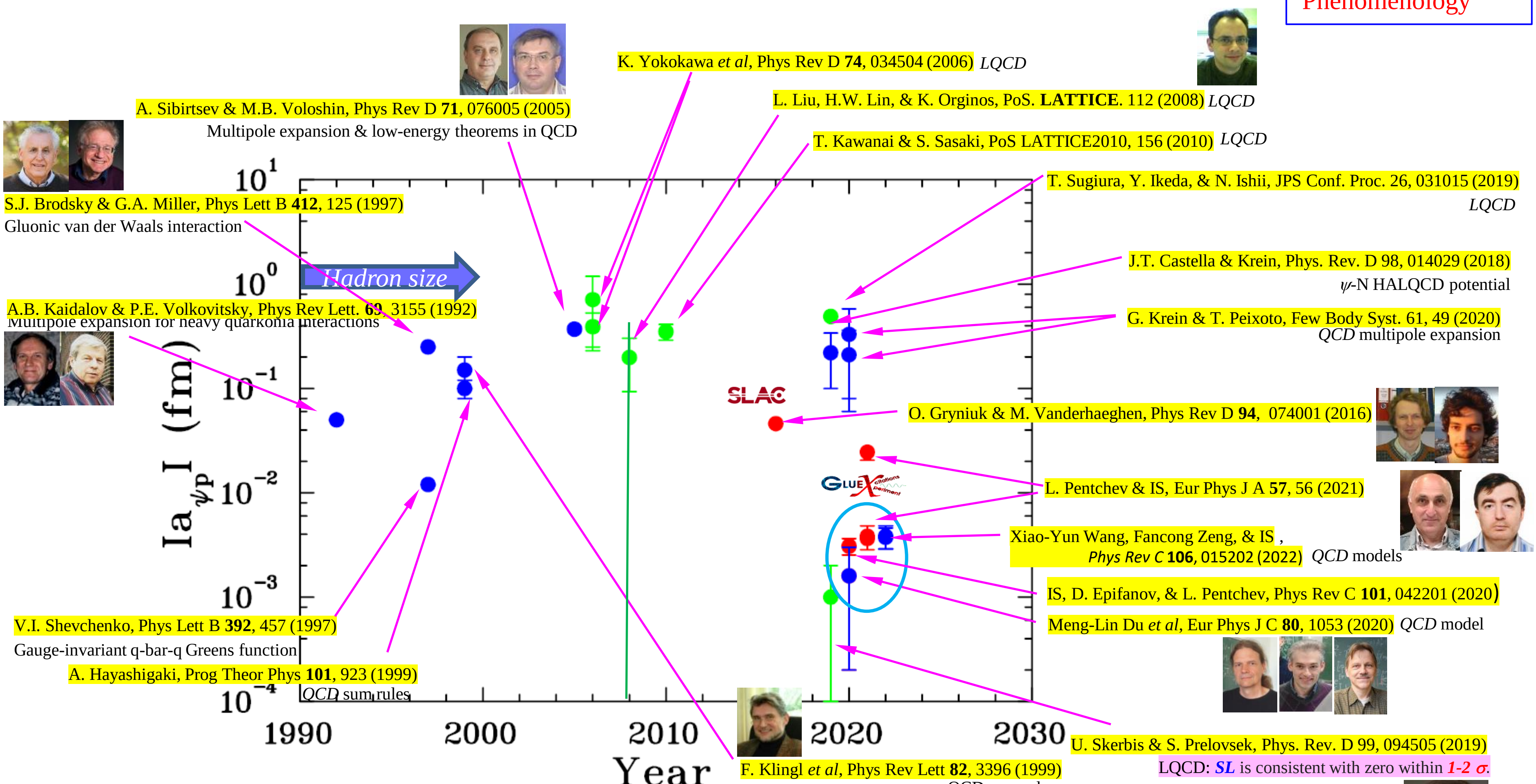
&

SLAC U. Camerini *et al*, Phys Rev Lett **35**, 483 (1975)

What is known for $J/\psi p$ Scattering Length

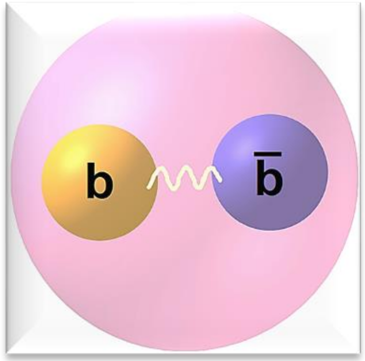
- To *avoid* theoretical uncertainties, we did not
  - determine sign of *SL*,
  - separate Re & Im parts of *SL*,
  - extract *spin* 1/2 & 3/2 contributions.

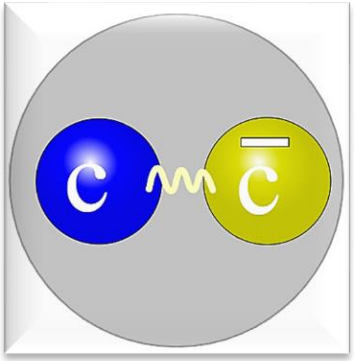
Theory
LQCD
~~PWA~~
Phenomenology



- Our result for $J/\psi p$ *SL* disagrees with theoretical predictions, though it is within wide range of these predictions.
- They do not consider "*young*" meson effect.
- *LQCD* results are still uncertain.

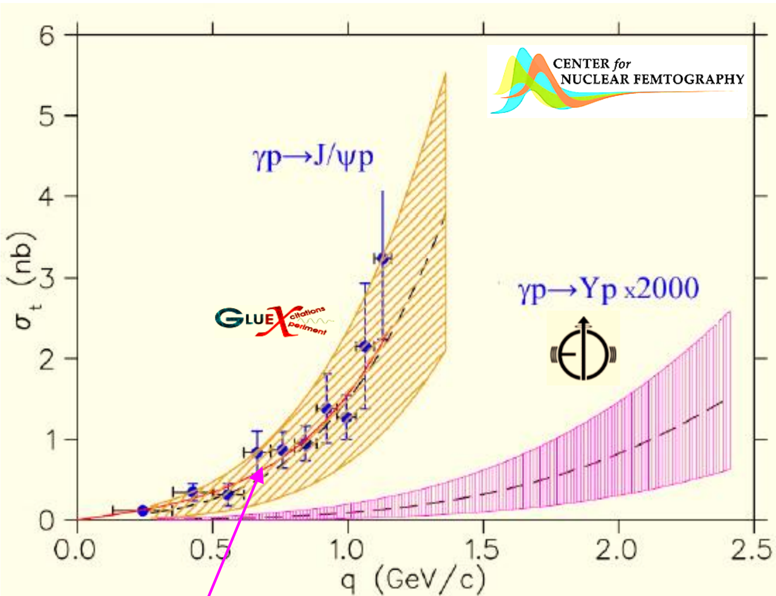
EIC for Upsilon & Psi'





Expectation from

IS, W.J. Briscoe, L. Pentchev, & A. Schmidt, Phys Rev C **104**, 074028 (2021)



- Theoretical fit of GlueX data @ 95% C.L.

- ***QCD*** production amplitude can be factorized in terms of *gluonic generalized parton distributions* (*GPD*) & ***quarkonium*** distribution amplitude on one side & hard *quark-gluon* interaction on other side.

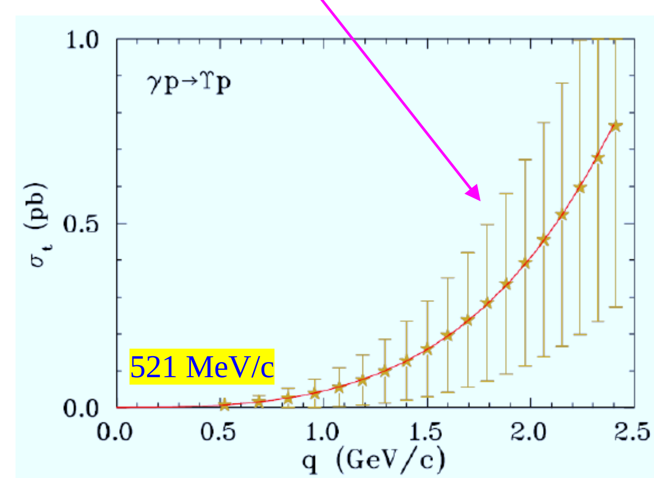
Y. Guo, X. Ji, & Y. Liu, Phys Rev D **103**, 096010 (2021)

- Just *theoretical* uncertainties.
- *Experimental* uncertainties depend on luminosity, detector acceptance, & efficiency.
- One can expect enormous ***Υ*** rate, & uncertainties will be comparatively small.

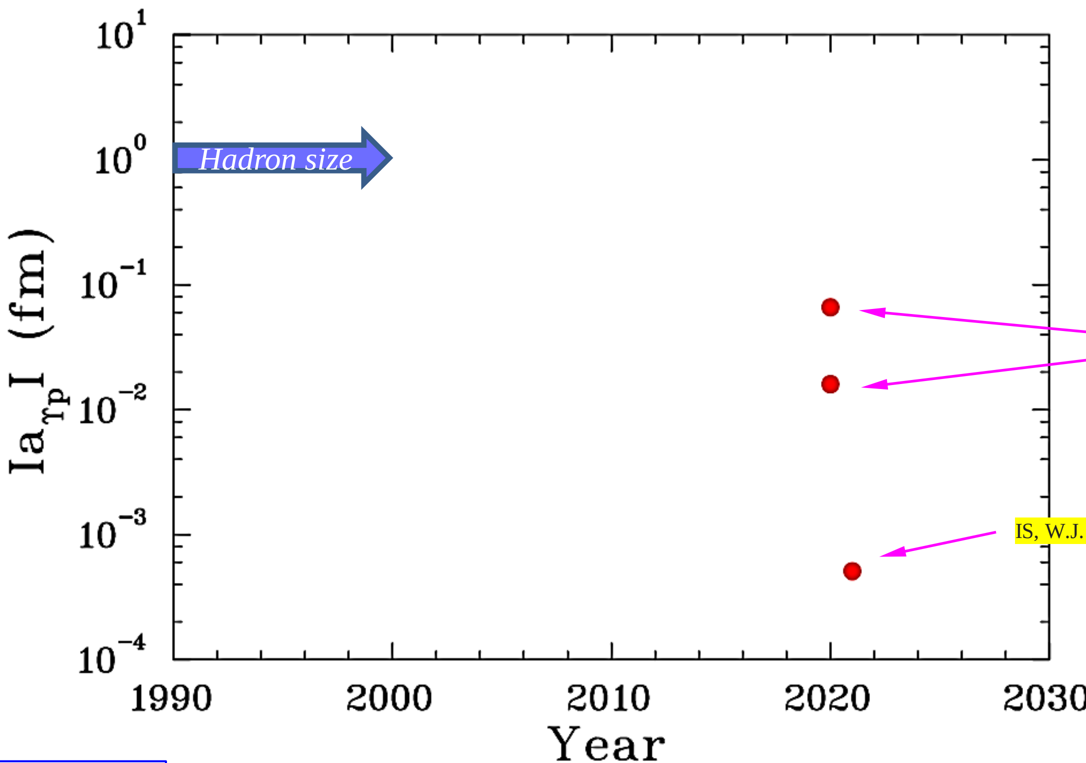
- *Quasi-data* were generated using ***QCD*** approach using detector properties.
- Further optimization of the low-Q^2 taggers may allow even smaller q_{min} to be achieved.

- It was assumed total integrated luminosity of 100 fb^{-1} for photoproduction @ , which corresponds to 116 days of beam with 10^{34} cm^{-2} s^{-1}, for MC calculations.

O. Gryniuk *et al*, Phys Rev D **102**, 014016 (2020)



What may be known for Yp Scattering Length



O. Gryniuk *et al*, Phys Rev D **102**, 014016 (2020)

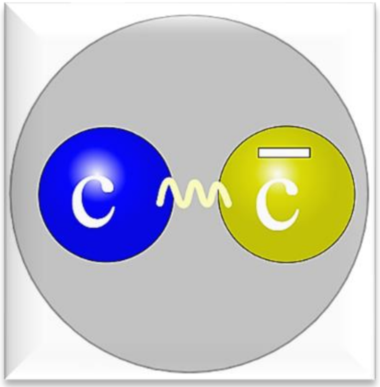
Extrapolation goes down from **100 GeV** using *2g* exchange

IS, W.J. Briscoe, L. Pentchev, & A. Schmidt, Phys Rev C **104**, 074028 (2021

~~Theory~~
~~LQCD~~
~~PWA~~
Phenomenology

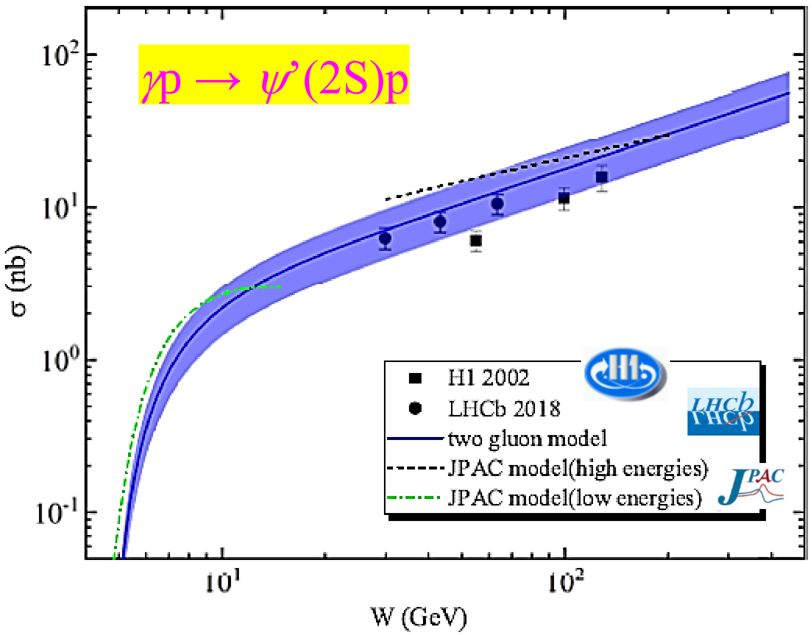
- Not so much known about *Y*p *SL*.

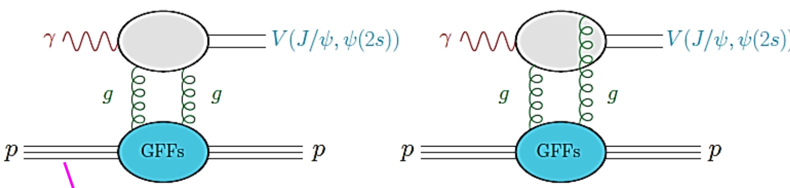
EIC for Psi’

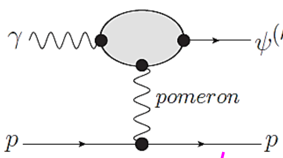


Expectation from

Xiao-Yun Wang, Fancong Zeng, & Quanjin Wang, Phys Rev D **105**, 096033 (2022)





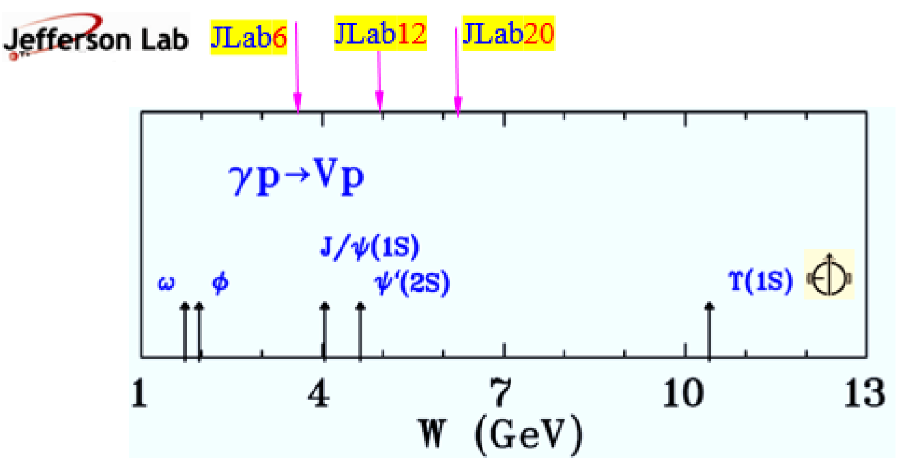


Method	$\lvert\alpha_{\psi'(2S)p}\rvert$
2g exchange model	1.31 ± 0.92
Effective Pomeron Model	3.24 ±0.63

Xiao-Yun Wang, Fancong Zeng, & IS , Phys Rev C **106**, 015202 (2022)

- Masses of $\psi'(2S)$ & $J/\psi(1S)$ are close to each other but due to another ***radial wave function***, *SL*s will be different.
- Phenomenological $J/\psi(1S)$ *SL* agrees with theoretical $\psi'(2S)$ *SL*.

Vector Meson – Nucleon SL



Total Cross Sections for Vector Meson Photoproduction off Proton

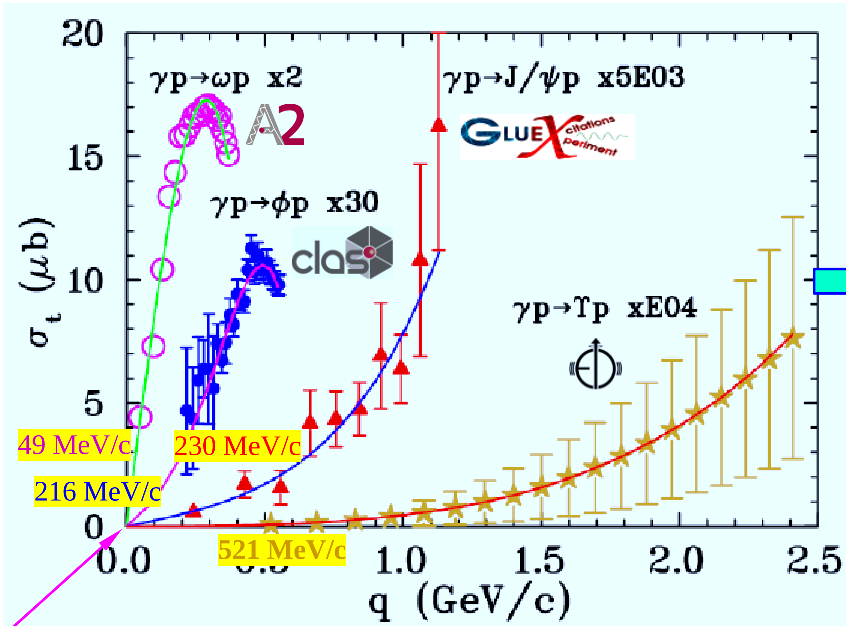
- Traditionally, σ_t behavior of near-threshold binary *inelastic* reaction

$$m_a + M_b < m_c + M_d$$

is described as series of ***odd*** powers in q (*even* powers in case of *elastic*).

$$\sigma_t(q) = b_1 \cdot q + b_3 \cdot q^3 + b_5 \cdot q^5$$

- ***Linear*** term is determined by two independent ***S***-waves only with total spin ***1***/***2*** &/or ***3***/***2***.
- Contributions to ***cubic*** term come from both ***P***-wave amplitudes & ***W*** dependence of ***S***-wave amplitudes,
- ***Fifth***-order term arises from ***D***-waves & ***W*** dependencies of ***S***- & ***P***-waves.



- Our *assumption* is that there is no *VN* ***bound state*** below experimental q_{min}.

A2: b_1 = (**4.42**±0.14) x 10^{-2} μb/(MeV/c)
IS, S. Prakhov, Ya. Azimov *et al*, Phys Rev C **91**, 045207 (2015)

CLAS: b_1 = (**3.40**±1.15) x 10^{-4} μb/(MeV/c)
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101**, 045201 (2020)

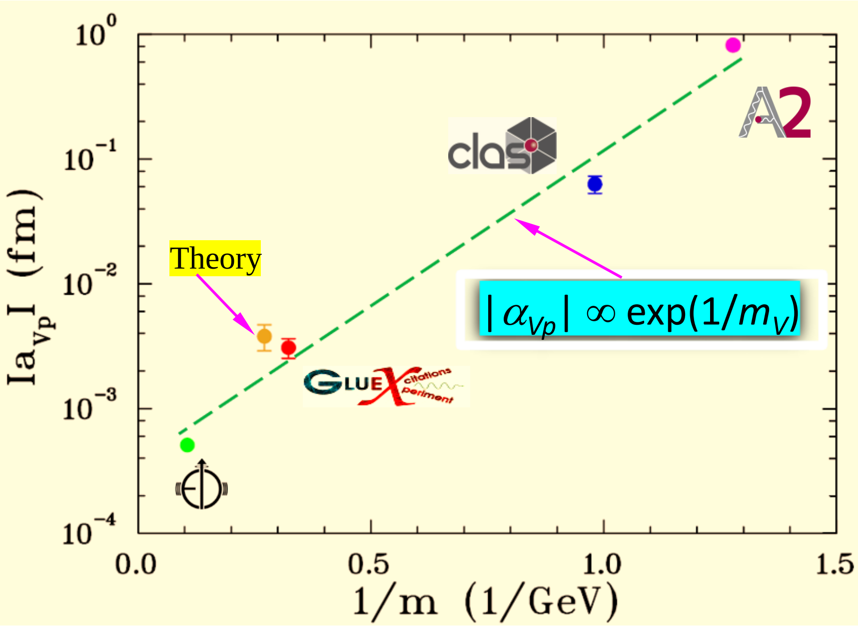
GlueX: b_1 = (**0.46**±0.16) x 10^{-6} μb/(MeV/c)
IS, D. Epifanov, & L. Pentchev, Phys Rev C **101**, 042201 (2020)

b_1 = (**0.37**±0.04) x 10^{-9} μb/(MeV/c)
IS, W.J. Briscoe, L. Pentchev, & A. Schmidt, Phys Rev C **104**, 074028 (2021)

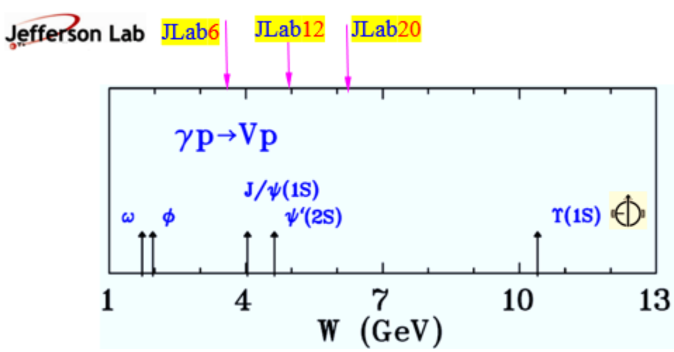
- Dramatic differences in hadronic factors $h_{Vp} = \sqrt{b_1}$, as slopes (b_1) of σ_t @ threshold as function of q varies significantly from ω to ϕ to J/ψ.

- Therefore, such big difference in *SL* is determined mainly by *hadronic* factor h_{Vp}.

Vector Meson – Nucleon SL

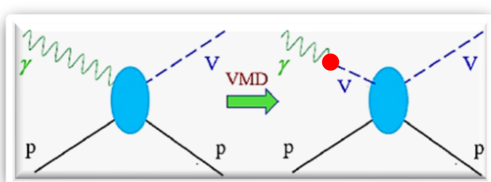


- Such big difference in *SL*s of ***Vp*** systems is determined mainly by hadronic factor h_{Vp}, & reflects strong weakening of interaction in $\bar{b}b-p$ & $\bar{c}c-p$ systems compared to that of *light* $\bar{q}q$-*p* (*q* = *u*, *d*) configurations.
- Interaction in $\bar{s}s-p$ has intermediate strength that is manifested in intermediate value of *ϕp SL*.



- Such small value of *ϕp SL* compared to typical ***hadron*** size of **1 fm**, indicates that proton is more transparent for *ϕ*-meson compared to *ω*-meson, & is much less transparent than for *J/ψ* -meson.

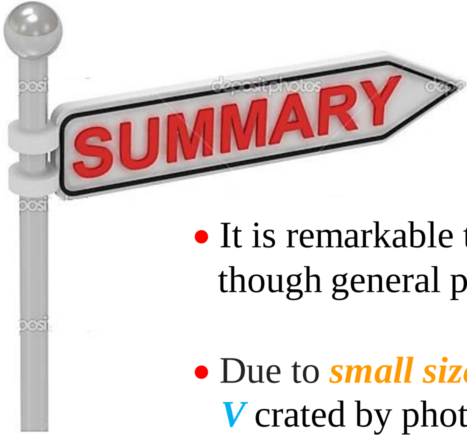
$$|\alpha_{\Upsilon p}| << |\alpha_{\psi' p}| \leq |\alpha_{J/\psi p}| << |\alpha_{\phi p}| << |\alpha_{\omega p}|$$



- *p→V* coupling $\bar{q}q$ is proportional to α_s & *separation* of corresponding quarks.
- This *separation* (in *zero approximation*) is proportional to $1/m_V$.

Courtesy of Misha Ryskin, July 2020

Outlook: A View of Future



- It is remarkable that proton is quite so *transparent* to ***J/ψ***, $|\alpha_{\Upsilon p}| << |\alpha_{\psi' p}| \le |\alpha_{J/\psi p}| << |\alpha_{\phi p}| << |\alpha_{\omega p}|$
  though general progression from ***ω*** to ***ϕ*** to ***J/ψ*** to probably **Υ** & ***ψ'***

- Due to ***small size*** of "*young*" ***V*** vs "*old*" ***V***, measured & predicted *SL* is very small.
  V crated by photon @ threshold then most probably ***V*** is not formed completely &
  its radius is smaller than that for normal ("*old*") ***V***.
  Therefore, one observe stronger suppression for ***Vp*** interaction.

- ***Light*** *V*s can be "*young*" as well. This depends on kinematics.
  Another point is that for slow ***heavy*** quark, one need more time to reach *equilibrium*,
  i.e., to form final (long-living/static) ***V***.

- Our phenomenology determined *q-bar-q* – ***p SL*** which is smaller than ***V-p SL***
  Quantitatively, there will be some difference between ***V-p SL*** & that for *q-bar-q* pair & ***p***.
  Or our results are low level of ***V-p SL*** determination.

- Most *theoretical* calculations using gluonic *van der Waals* interaction disagree with
  our *phenomenological* results. Specifically, they do not consider ***V*** *young* effect.

- This should be calculated within some *model*.
  In general, result depends on *energy*, *quark mass*, & *overlap integral* between *q-bar-q* pair WF & *V* WF
  (this put some constrain on size of ***q-bar-q*** pair).

- We found strong exponential increase of ***V-p*** *SL* with inverse mass of *V*s. $|\alpha_{Vp}| \propto \exp(1/m_V)$

- Obviously, & facilities will open new *window* in solving the ***VN SL*** puzzle.
  It will allow to make deal with "*young*" Υ-meson as well.

- Jefferson Lab *upgrade* will help to solve *puzzle* as well.

- It was observed that J/ψ-N cross section measured via J/ψ re-scattering/absorption inside nucleus is anomaly small in case of low energy photoproduction.
  This can be explained by fact that we dealt with "*young*" J/ψ of too small radius.
  Υ-photoproduction on both proton & ***nucleus*** will extend our J/ψ study.

- In case of J/ψ (even Υ) ***electroproduction***, we deal with the "*young*" J/ψ (Υ) for larger Q^2 & we will have smaller formation time & correspondingly smaller radius of heavy *Charmonium* & *Quarkonium*.

Gracias por la invitación y su atención.

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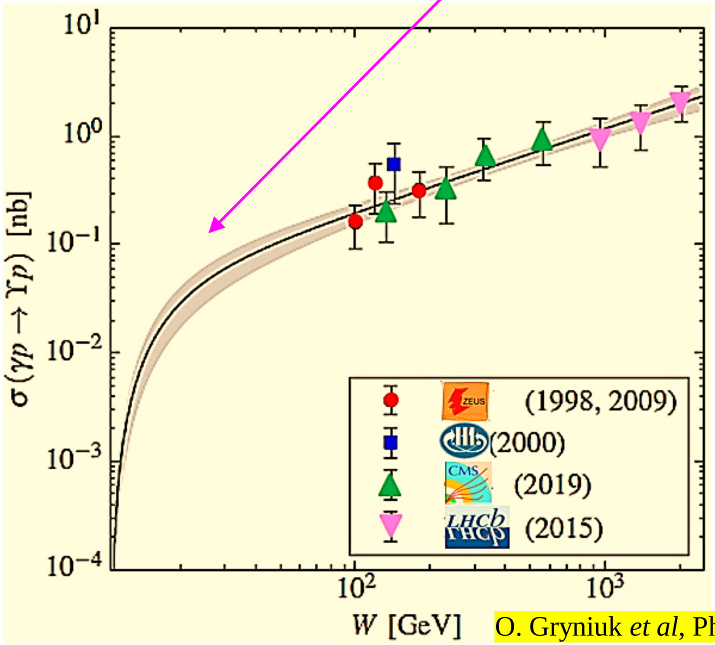
BACKUP

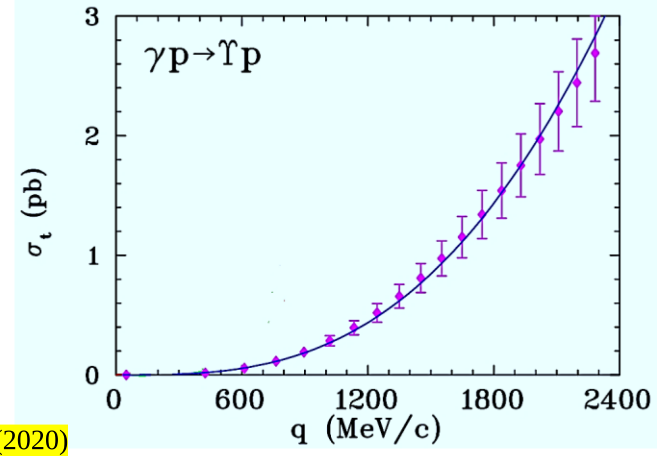
Alternative Expectation from

- Extrapolation goes down from **100 GeV** using *2g* exchange which disagreed with GlueX J/ψ threshold data.



O. Gryniuk *et al*, Phys Rev D **102**, 014016 (2020)

- One cannot use it because b_1 has unphysical meaning.



$|\alpha_{\Upsilon p}|$ = **0.066**$\pm$0.001 fm

or

$|\alpha_{\Upsilon p}|$ = **0.016**$\pm$0.001 fm

Factor of difference with our phenomenology is 600 or 150