Vector Meson-Nucleon Scattering Lengths from Omega to Upsilon

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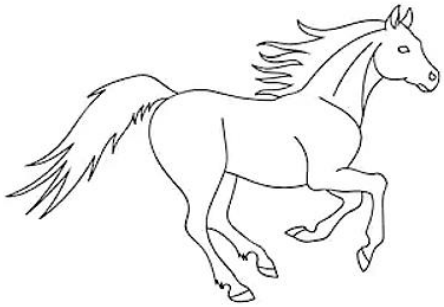
Heavy vector meson photoproduction is sample of hard processes corresponding to relatively large scale $\mu_c \sim (0.5 - 1)M_V$

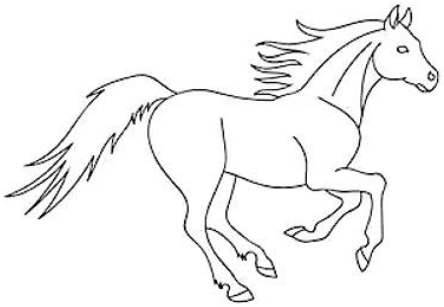
2108.02871 [hep-ph]

Supported by DE-SC0016583

Outline



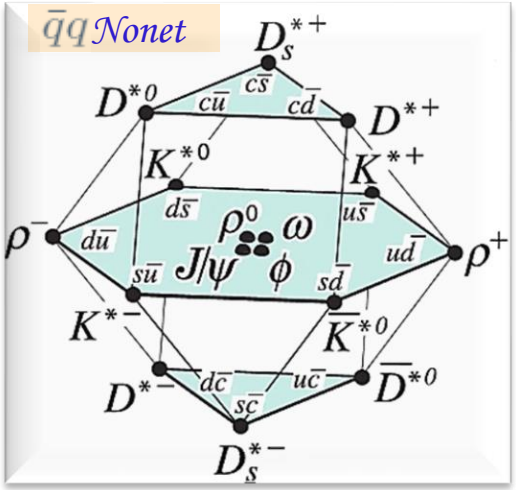
- Vector meson domestic *Zoo*.
- Vector meson – nucleon *SL* determination.
- Threshold kinematics.
- *VMD* approach.
- *EM* properties of vector mesons.
- *Fit* threshold total cross sections.
- Vector meson – nucleon *SL*.
- Expectation from *EIC*.
- Summary.



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***.

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

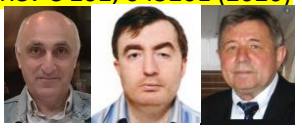


Name	Quark Content	Γ (MeV)	
$\rho^+(770)$	$u\bar{d}$	148	
$\rho^0(770)$	$\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d})$	149	
$\omega(782)$	$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$	8.5	
$K^{*+}(892)$	$u\bar{s}$	51	
$K^{*0}(892)$	$d\bar{s}$	47	
$\phi(1020)$	$s\bar{s}$	4.3	
$D^{*+}(2010)$	$c\bar{d}$	0.083	*Open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

- We will focus on **4** vector mesons from $\bar{q}q$ ***Nonet*** which widths are **narrow** enough to study meson photoproduction @ threshold & where data are available.

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*

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

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

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

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

where b_1 came from best fit $\sigma_t = b_1 q + b_3 q^3 + b_5 q^5$

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

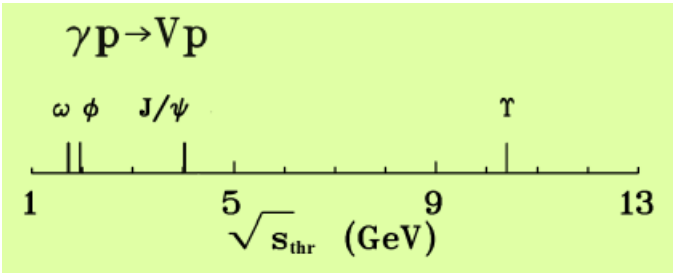
$$|\alpha_{Vp}| = B_V\cdot h_{Vp}$$

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

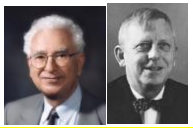
Kinematical Parameters for Vector Meson Photoproduction off Proton @ Thresholds

Vector-Meson	m_V (MeV)	$\sqrt{s_{thr}}$ (MeV)	E_{thr} (MeV)	k_{thr} (MeV/c)
$\omega(782)$	782.65	1720.9	1109.1	604.7
$\phi(1020)$	1019.461	1957.7	1573.3	754.0
$J/\psi(1S)$	3096.900	4035.2	8207.8	1908.5
$\Upsilon(1S)$	9460.30	10398.6	57152.9	5156.9

for *EIC*



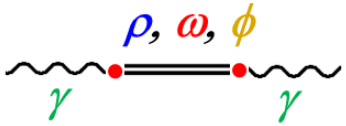
VMD Approach

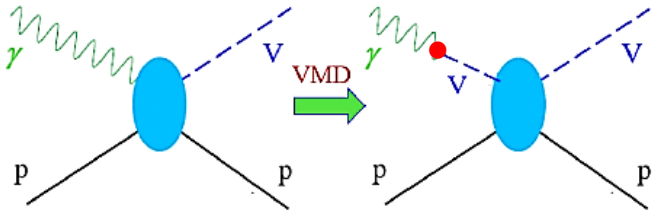



- Vector Meson Dominance model relying on transparent current-field identities

M. Gell-Mann & F. Zachariasen, Phys Rev **124**, 953 (1961)
J.J. Sakurai, *Currents and Mesons* (The University of Chicago Press, Chicago, 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 $J/\psi p$ *SL* from meson photoproduction.

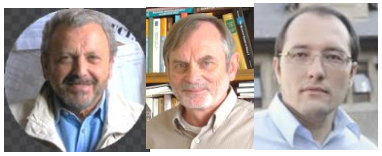
Courtesy of Arkady Vainshtein & Misha Ryskin, July 2020

- To estimate theoretical uncertainty related to *VMD* model, one refer to estimation of cross section of J/ψ photoproduction in *multiperipheral model* & found strong energy dependence close to threshold because non-diagonal $\gamma p \to Vp$ & elastic $Vp \to Vp$ 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)

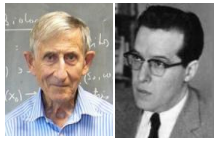
- Color factor for *charmonium* is **1**/**9** while for *open charm* is **8**/**9**.

B.Z. Kopeliovich, I. Schmidt, & M. Siddikov, Phys Rev C **95**, 065203 (2017)



- 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 $Vp \to Vp$ 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, arXiv:2107.03488 [hep-ph]

Vector Meson 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

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

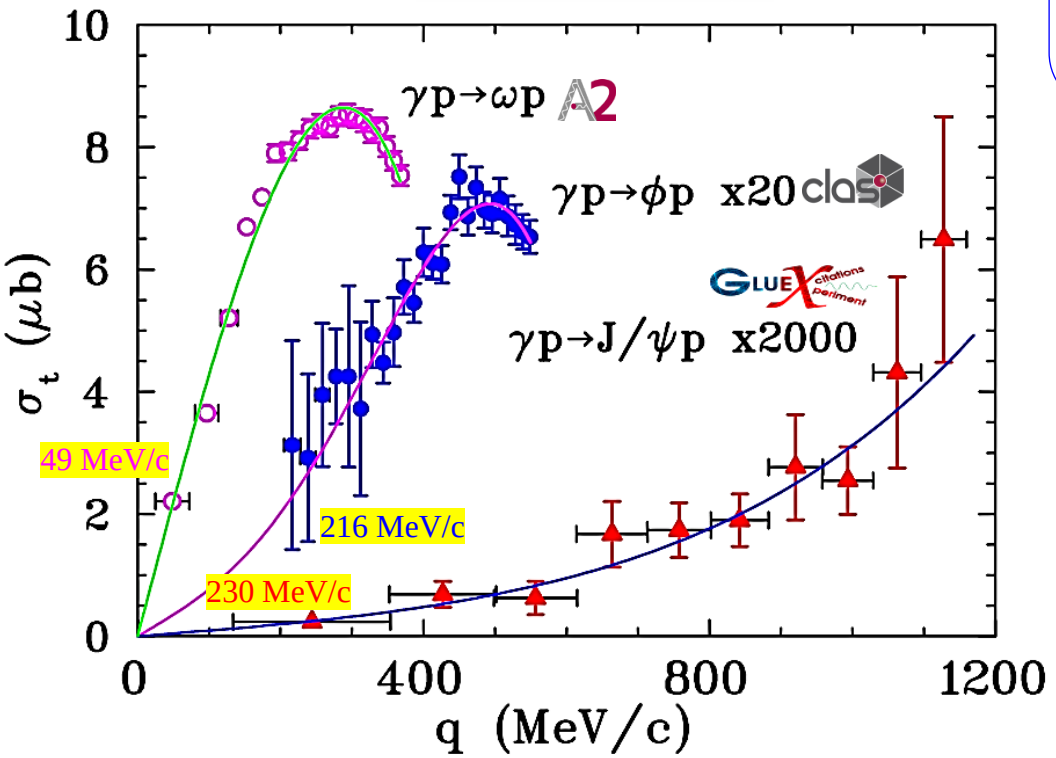
Vector-Meson	$\Gamma(V \to e^+e^-)$ (keV)	g_V	B_V (MeV$^{1/2}$)
$\omega(782)$	0.60±0.02	8.53±0.14	390.49±6.35
$\phi(1020)$	1.27±0.04	6.69±0.10	342.50±5.27
$J/\psi(1S)$	5.53±0.10	5.59±0.05	454.92±4.06
$\Upsilon(1S)$	1.340±0.018	19.85±1.21	2654.96±162.15

- *EM* factor B_V for each *vector meson* are close to each other.

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*).

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



- ***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.

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

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

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

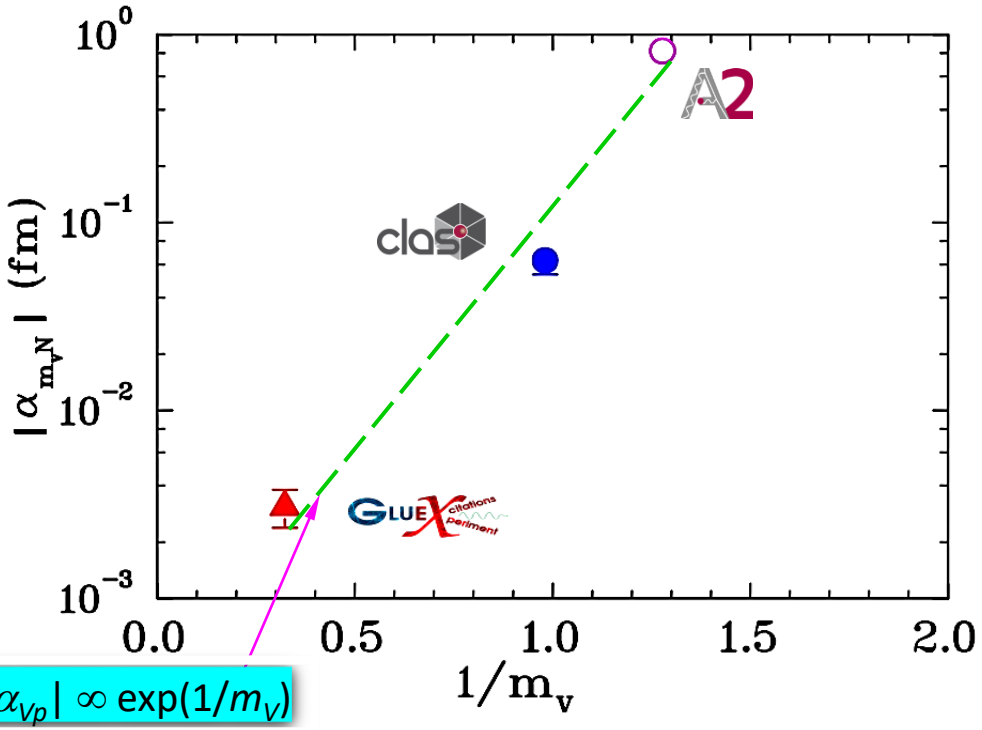
- Dramatic differences in hadronic factors $h_{Vp} = \sqrt{b_1}$, as slopes (b_1) of σ_t @ threshold as function of ***q*** varies significantly from ω to ϕ to J/ψ.

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

Vector Meson – Nucleon SL

- ***EM*** factor B_V for each vector meson are close to each other.
- Therefore, such big difference in *SL* is determined mainly by **hadronic** factor h_{Vp}.

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



- 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.

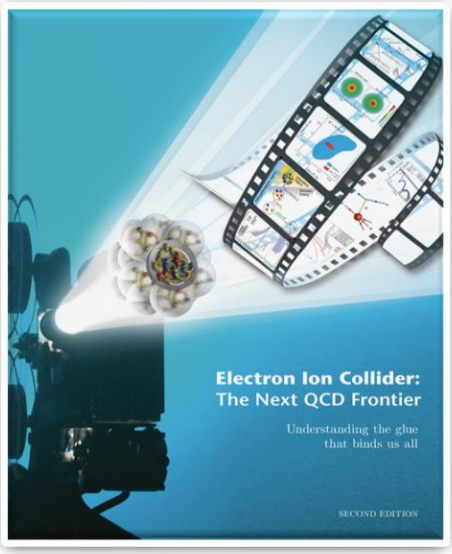
$$|\alpha_{J/\psi p}| << |\alpha_{\phi p}| << |\alpha_{\omega p}|$$

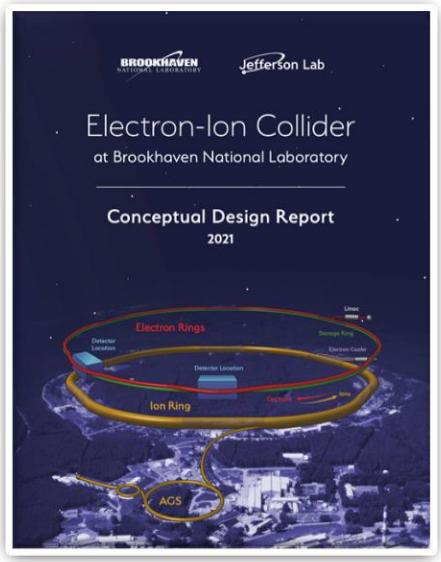
- $p \rightarrow V$ coupling is proportional to α_s & *separation* of corresponding quarks. This *separation* (in zero approximation) is proportional to $1/m_V$.

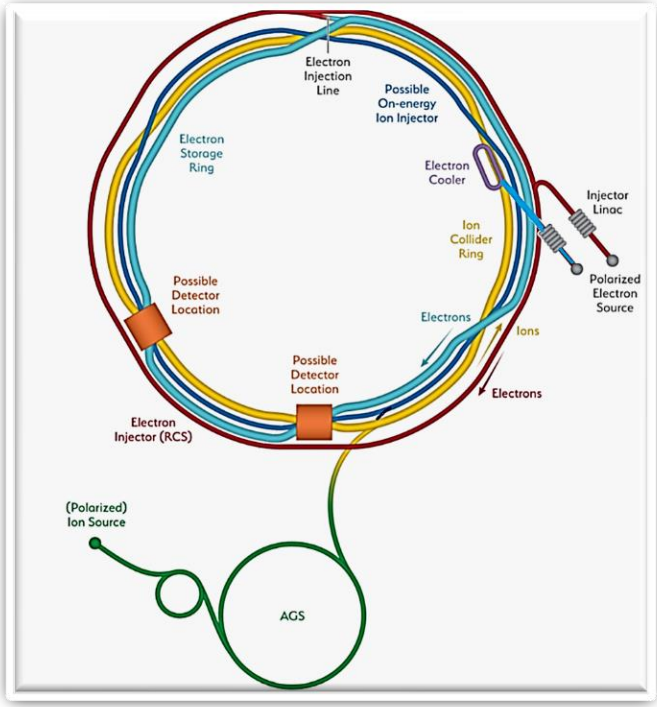
Courtesy of Misha Ryskin, July 2020

The US Electron Ion Collider

- New tool for precision QCD in 2030's







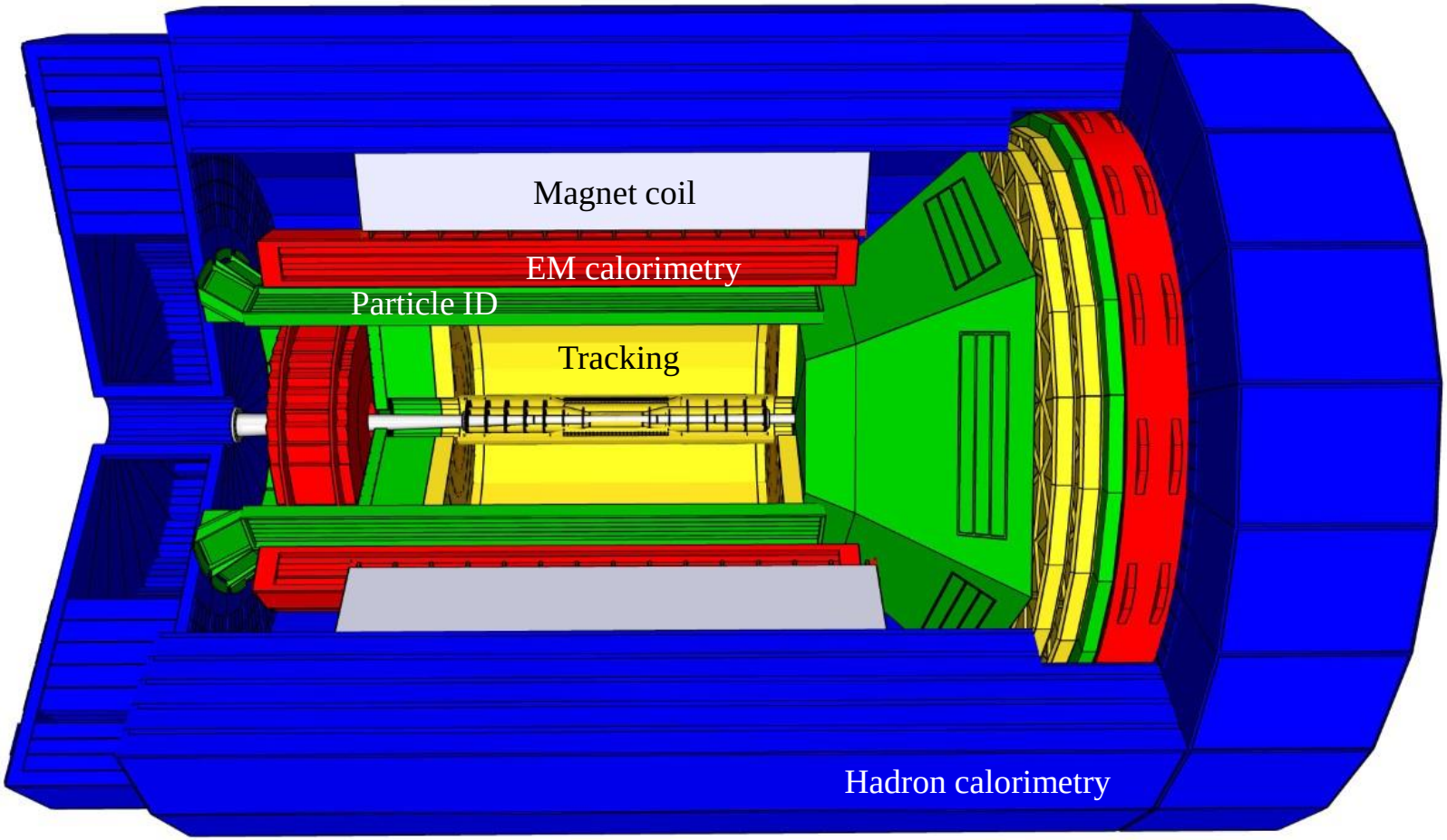
T_p = 41 – 275 GeV

E_e = 5 – 18 GeV

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

Overview of example EIC Central Detector

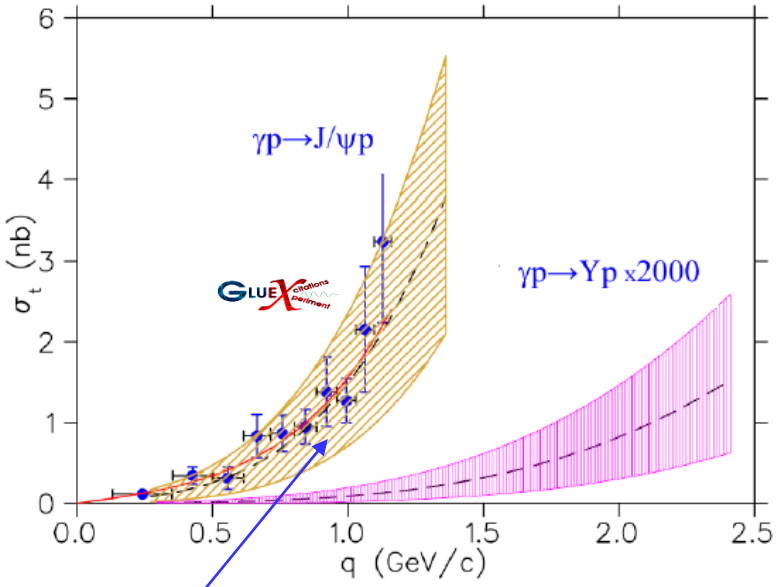
- Based on new 3T Magnet (as assumed by ATHENA)



PDG BR($J/\psi \to e^+e^-$) = (5.971±0.032)% BR($\Upsilon \to e^+e^-$) = (2.38±0.11)%

Courtesy of Rolf Ent, July 2021

Expectation from



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

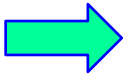
- ***QCD*** production amplitude can be factorized in terms of *gluonic generalized parton distributions* (*GPD*) & ***quarkonium*** distribution amplitude on one side & hard *quark-gluon* interaction on other side.

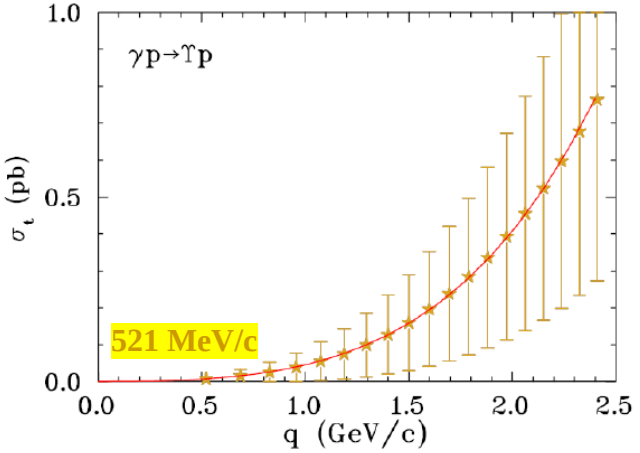
Y. Guo, X. Ji, & Y. Liu, Phys Rev D **103**, 096010 (2021)

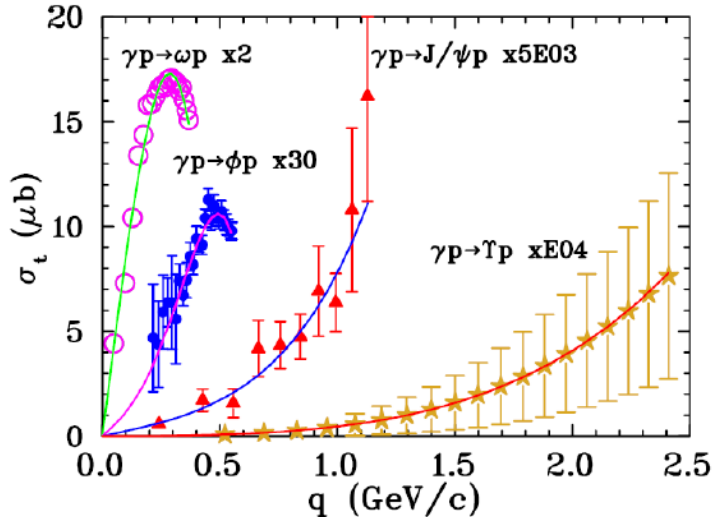
- *Quasi-data* were generated using ***QCD*** approach using ***EIC*** detector properties.
- Further optimization of the low-Q^2 taggers may allow even smaller q_{min} to be achieved.

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

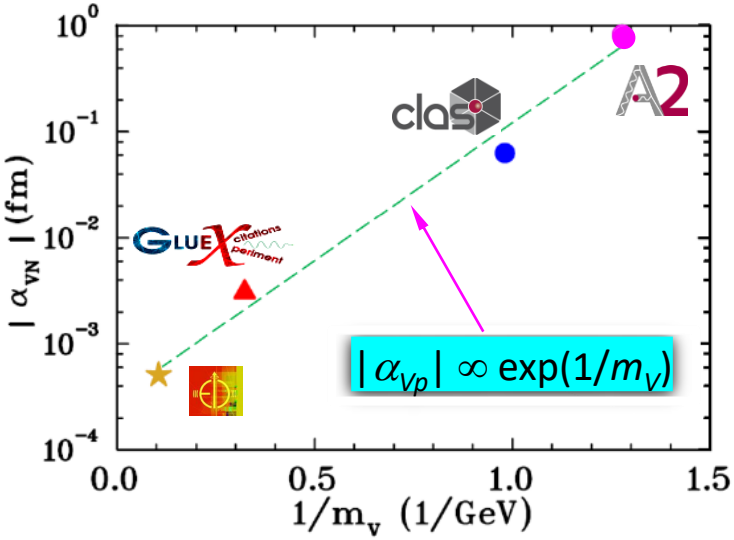
O. Gryniuk *et al*, Phys Rev D **102**, 014016 (2020)





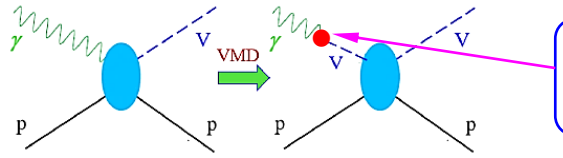


- Such big difference in *SL*s of ***Vp*** systems is determined mainly by hadronic factor h_{Vp}, & reflects strong weakening of interaction in $\bar{b}b$–*p* & $\bar{c}c$–*p* systems compared to that of light $\bar{q}q$–*p* ($q = u,d$) configurations.
- Interaction in $\bar{s}s$–*p* has intermediate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



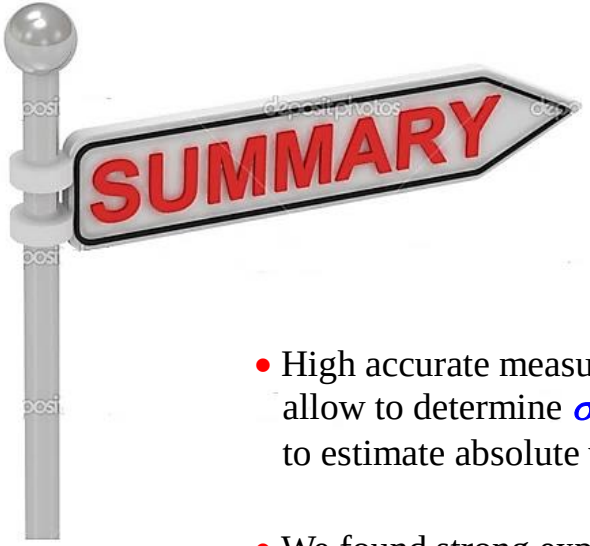
- Such small value of ϕp *SL* compared to typical ***hadron*** size of **1 fm**, indicates that proton is more transparent for ϕ-meson compared to ω-meson, & is much less transparent than for J/ψ-meson.

$$|\alpha_{\gamma p}| << |\alpha_{J/\psi p}| << |\alpha_{\phi p}| << |\alpha_{\omega p}|$$



- $p \to V$ 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



- High accurate measurements near-threshold by A2, CLAS, & GlueX allow to determine σ_t of reactions $\gamma p \to Vp$ & to estimate absolute value of Vp SLs within VMD model.

IS, S. Prakhov, Ya. Azimov *et al*, Phys Rev C **91**, 045207 (2015)
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101**, 045201 (2020)
IS, D. Epifanov, & L. Pentchev, Phys Rev C **101**, 042201 (2020)

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

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

- Due to ***small size*** of '*young*' V vs '*old*' V, measured 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*** Vs can be '*young*' as well. This depends on particular 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.

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

THANKS

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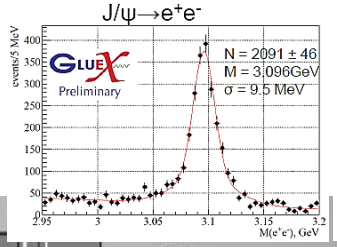
Backup

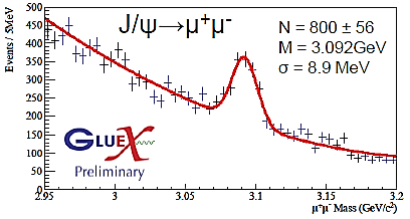
Exclusive Reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^- p$ @ J/ψ Threshold

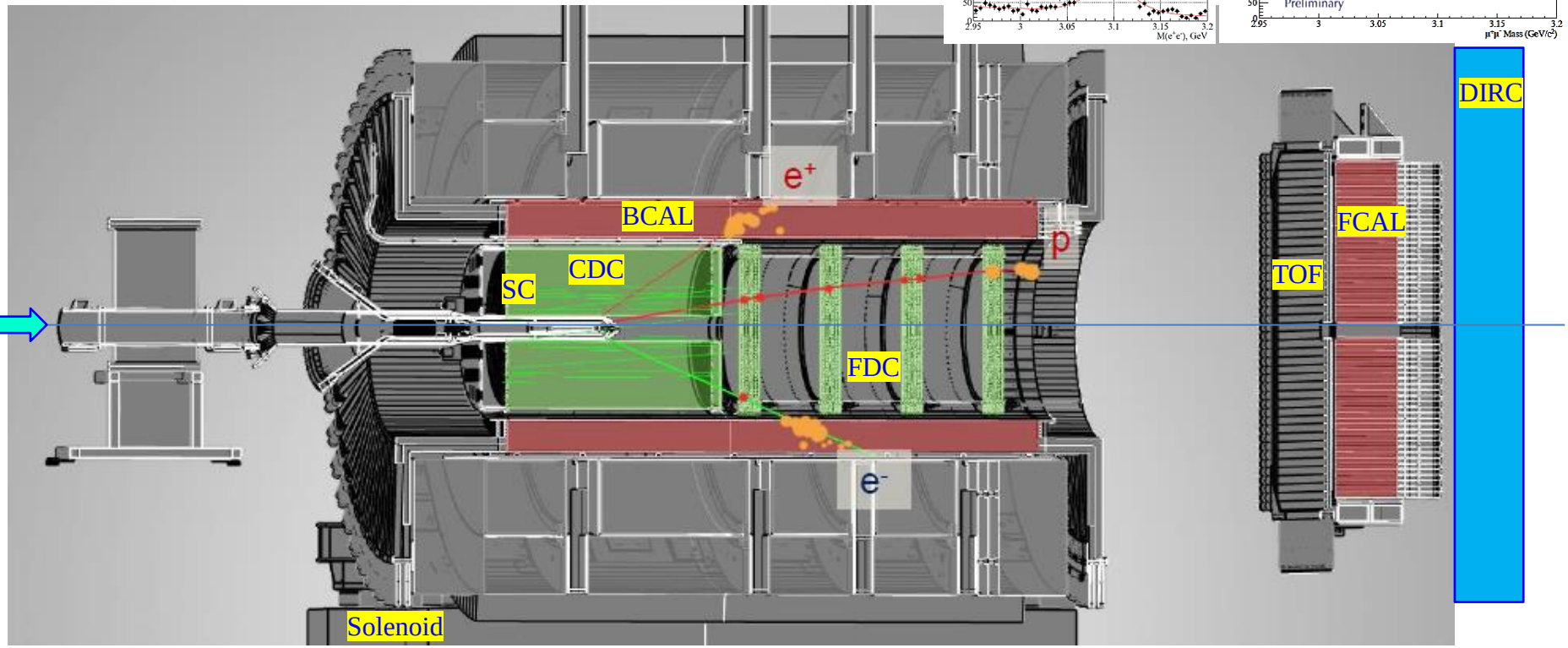
A. Ali *et al*, Phys Rev Lett **123**, 072001 (2019)

PDG BR($J/\psi \rightarrow e^+e^-$) = (5.971±0.032)% BR($Y \rightarrow e^+e^-$) = (2.38±0.11)%

BR($J/\psi \rightarrow e^+e^-$) = (5.961±0.033)% BR($Y \rightarrow \mu^+\mu^-$) = (2.48±0.05)%



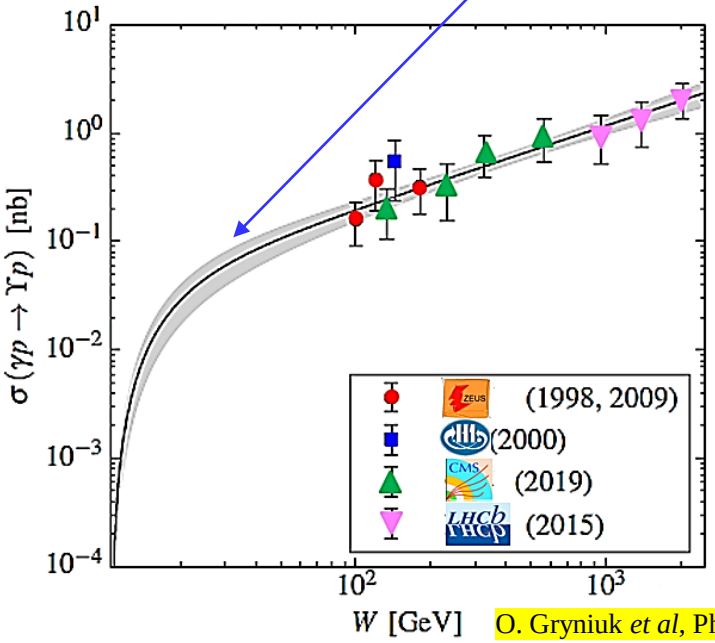




- *Electrons* separated from *pions* by **E/p** – energy deposition in calorimeters over measured momentum (*pions* >10^3 times more than *electrons*) .

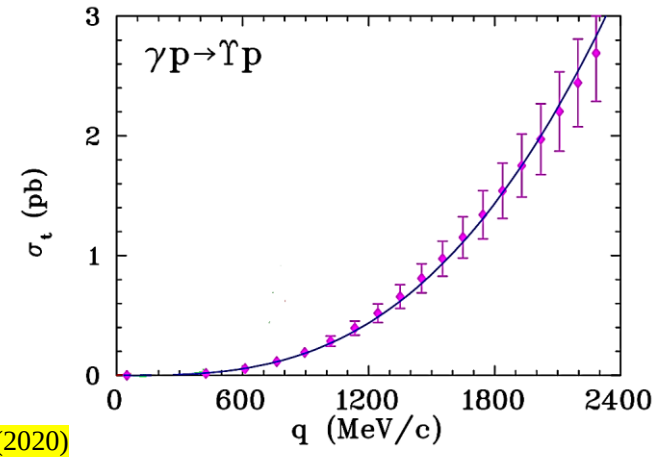
Alternative Expectation from

- 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.



$|\alpha_{\gamma p}|$ = **0.066**±0.001 fm
or
$|\alpha_{\gamma p}|$ = **0.016**±0.001 fm

Factor of difference with our phenomenology is 600 or 150

- Obviously, facility will open new window in solving the ***VN SL*** puzzle.
  It will allow to make deal with `*young*' ***Y***-meson 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.
  Y-photoproduction on both proton & ***nucleus*** will extend our ***J/ψ*** study.

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