Update on VM Photoproduction @ Threshold

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- Proposed experiments with EIC that are aimed to measure *Charmonium* & *Quarkonium* in Photo- & ElectroProduction off proton & nuclei @ threshold.
- They will allow further studies of J/ψ–N and Υ–N interactions & will also give access to variety of other interesting physics aspects that are present in near-threshold region.
- There is special interest to study J/ψ–N & Υ-N interaction because of ***small size*** of *Charmonium* & *Quarkonium* that can be used to probe internal structure of nucleon.
- This is *Hard Process* (with scale defined by charm quark mass) with some similarity to DIS, however, J/ψ–N & Υ–N are not sensitive to *EM* but *Gluonic* distribution.
- Experimentally, *Charmonium*–N & *Quarkonium*–N interaction can be investigated using J/ψ & Υ PhotoProduction within *VMD* model.
- Moreover, ***VM***s can, compared to other mesons, be measured to very high precision. This stems from fact that ***VM***s have same quantum numbers as ***Photon*** $I^G(J^{PC}) = 0^-(1^{--})$.

* Supported by DE-SC0016583

VM–Nucleon SL Determination

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

- For evaluation of *absolute* value of *VM–N SL*,
  we apply *VMD* approach that
  links near-threshold photoproduction *Xsections* of *γp→VMp* & elastic *VMp→VMp*

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

k is **photon** CM momentum $k = (s - M^2) / 2 s^{1/2}$
q is *VM* CM momentum
$\mathbf{T^{\gamma p\to Vp}}$ is the invariant amplitude of *VM* PhotoProduction
α is fine-structure constant
$\mathbf{g_V}$ is VMD coupling constant, related to *VM* **EM** decay width $\Gamma_{V\to e+e-}$

$$g_V = \sqrt{\frac{\pi\alpha^2 m_V}{3\Gamma_{V\to e^+e^-}}}$$

- Finally, one can express *absolute* value of *SL* as product of
  pure *EM VMD*-motivated kinematic factor
  $R_V^2 = \alpha m_V k/12\pi\Gamma_{V\to e^+e^-}$ & $h_{Vp} = \sqrt{b_1}$,
  where b_1 came from best-fit $\sigma_t(q) = b_1 q + b_3 q^3 + b_5 q^5$,
  that is determined by interplay of strong (hadronic) & *EM* dynamics as

$$|\alpha_{Vp}| = R_V h_{Vp}$$

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

VMD Approach: EM Factor

VMD coupling constant $g_V = \sqrt{\frac{\pi \alpha^2 m_V}{3\Gamma_{V\to e^+e^-}}}$

EM factor $R_V^2 = \alpha m_V k / 12\pi\Gamma_{V\to e^+e^-}$

PDG	V	m_V	$\Gamma_{V\to e+e-}$	g_V	R_V
		(MeV)	(keV)		($MeV^{1/2}$)
	ω	782.65	0.60±0.02	8.53±0.14	390.5±6.4
	ϕ	1019.461	1.27±0.04	6.69±0.10	342.5±5.3
	J/ψ	3096.916	5.55±0.11	5.58±0.07	454.9±4.1
	Y	9460.30	1.340±0.018	19.84±0.14	2655.0±162.2

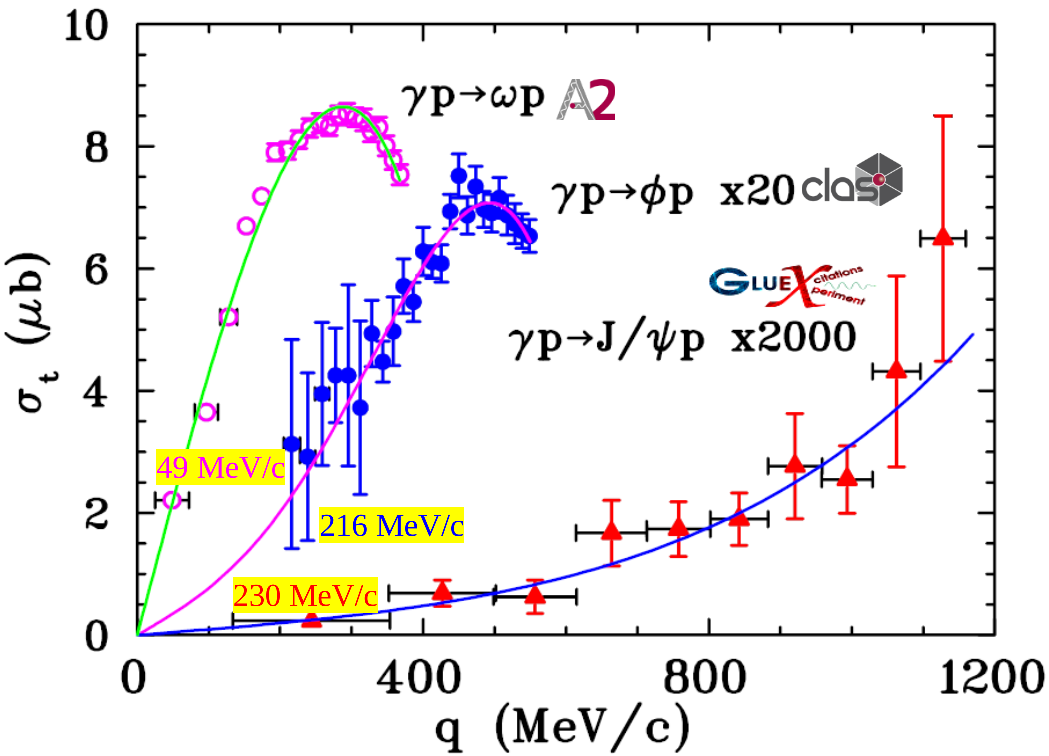
- EM factor R_V for each VM are close to each other, except Y.

Total Cross Sections for VM 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).

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

- *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**±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)

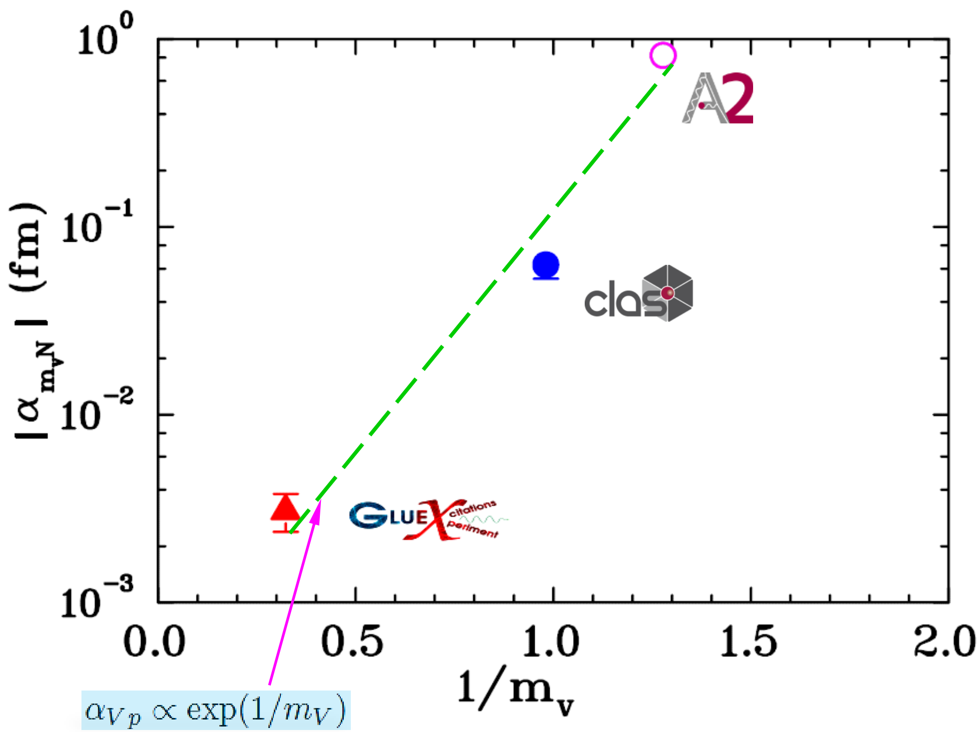
GlueX: b_1 = (**0.46**±0.16) x 10^{-6} μb/(MeV/c)
IS, D. Epifanov, & L. Pentchev, Phys Rev C **101**, 042201 (2020)

- Dramatic differences in hadronic factors $h_{Vp} = (b_1)^{1/2}$, 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* of *VM*s is determined mainly by hadronic factor h_{Vp}.

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

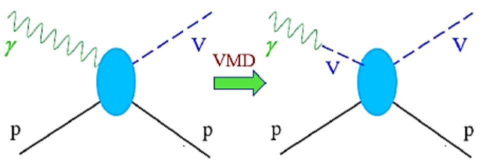
$$|\alpha_{Vp}| = R_V h_{Vp}$$



$$\alpha_{Vp} \propto \exp(1/m_V)$$

- 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.

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

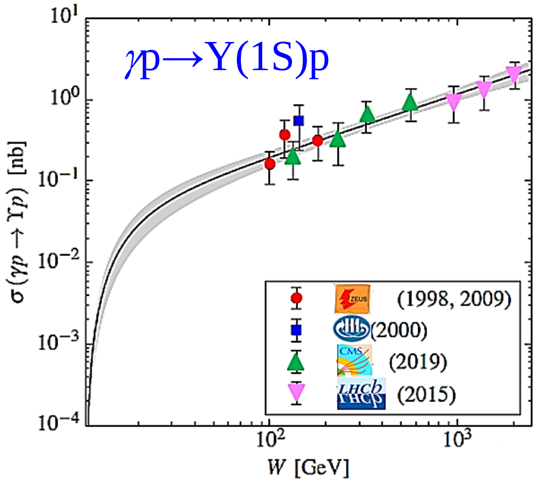


- *p→V* coupling is proportional to α_s & *separation* of corresponding quarks. This *separation* (in zero approximation) is proportional to $1/m_V$.

Courtesy of Michael Ryskin, July 2020

Expectation from

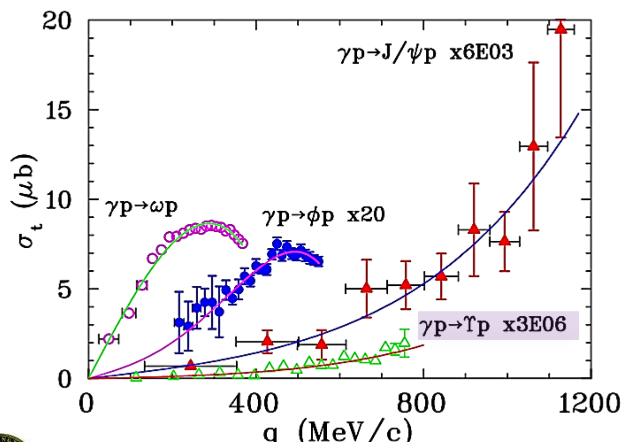
- Such small value of ***ϕp*** *SL* compared to typical hadron size of **1 fm**, indicates that proton is more transparent for ***ϕ***-meson compared to ***ω***-meson, & is much less transparent than for ***J/ψ***-meson.



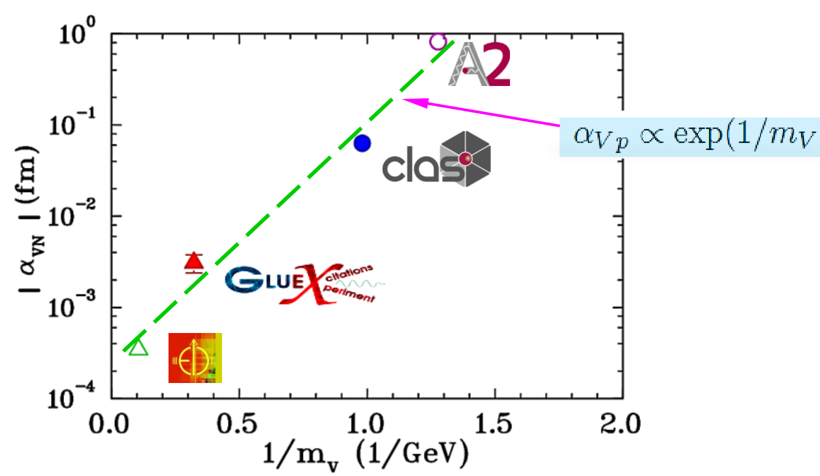
$\sigma_t(\gamma p\to Y(1S)p) \sim 0.01 \times \sigma_t(\gamma p\to J/\psi p)$

O. Gryniuk *et al*, arXiv:2005.09293 [hep-ph]

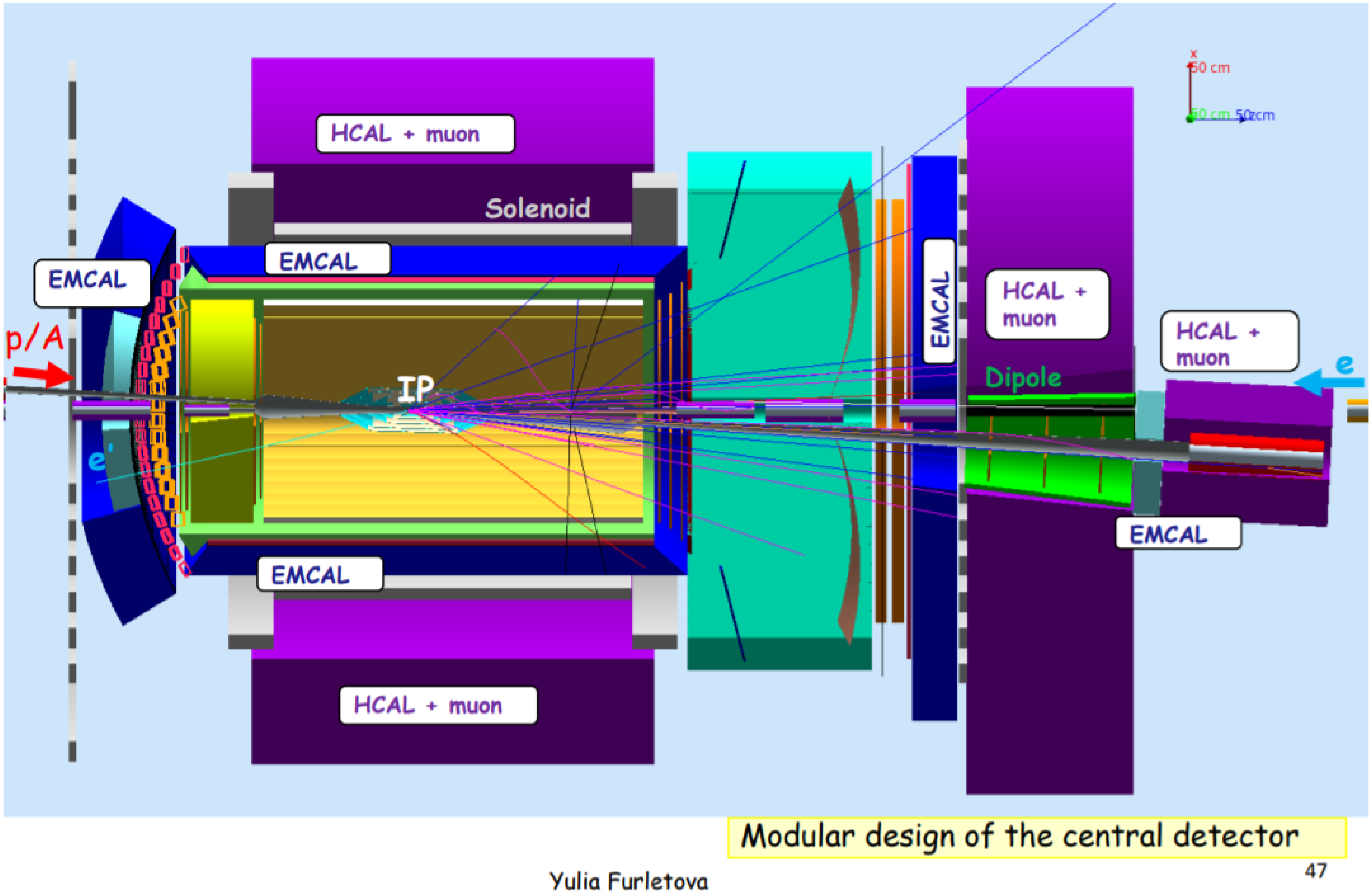
- GlueX threshold experiment projects on EIC measurements for ***Y(1S)p***.



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



EIC Central detector overview



Courtesy of Yulia Furletova, June 2020

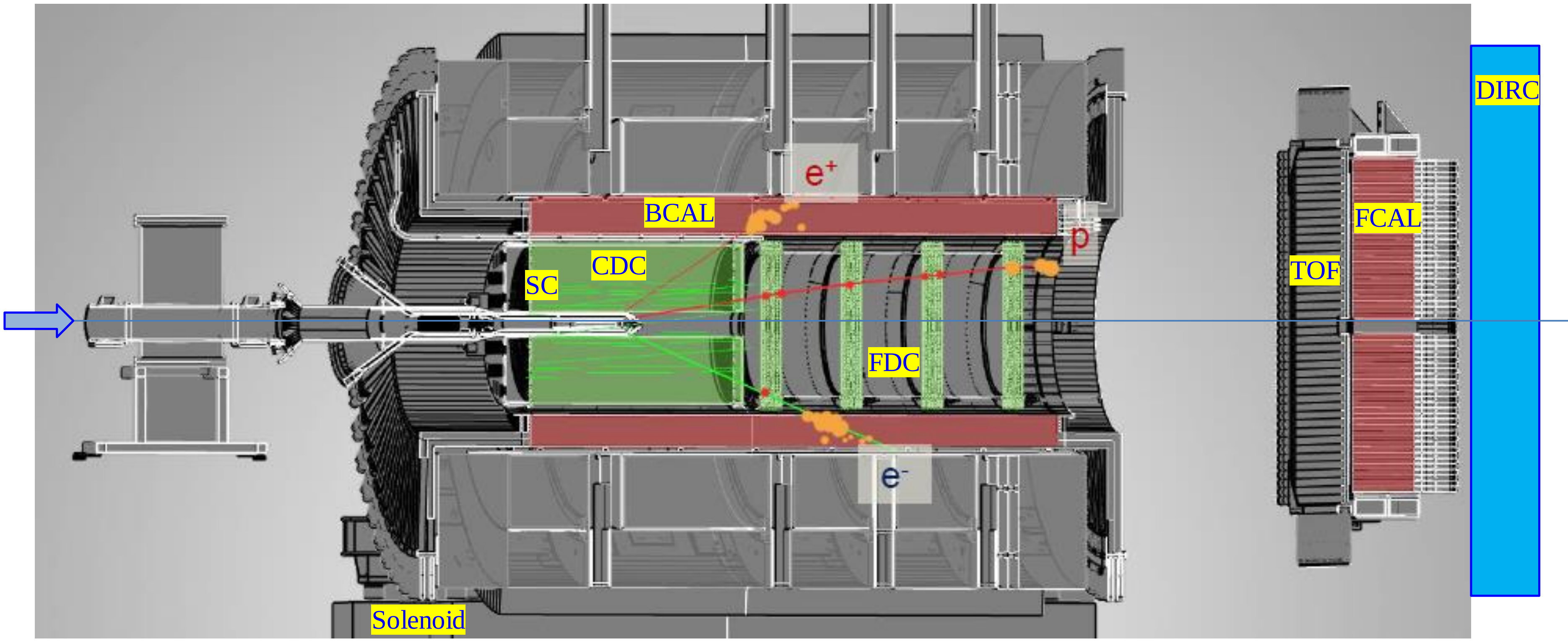
Exclusive Reaction $\gamma p \longrightarrow J/\psi p \longrightarrow e^+e^- p$ @ J/ψ *Threshold*

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

PDG particle data group

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

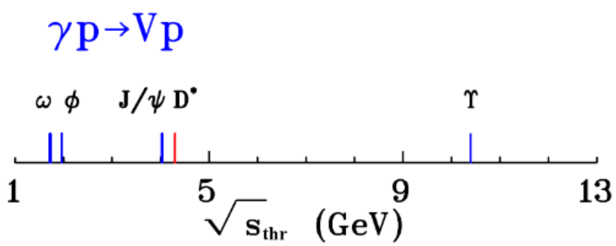
BR($J/\psi \rightarrow \mu^+\mu^-$) = (5.961±0.033)% BR($\Upsilon \rightarrow \mu^+\mu^-$) = (2.48±0.05)%



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

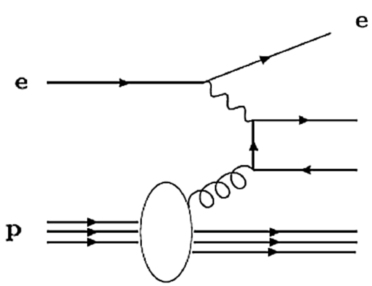
Charm Photo- & Electroproduction

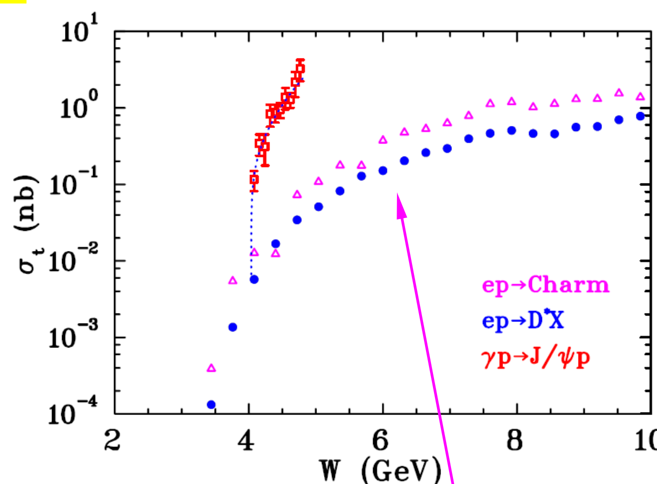
- It was shown that fluctuation of **photon** into *Open Charm* $\gamma p \to \bar{D}^0 \Lambda_c^+$ is preferable than into *Charmonium* J/ψ. Suppression is just available phase space: W_{thr}(*Open Charm*) = **4.30** GeV while W_{thr}(*Charmonium*) = **4.03** GeV). K. Boreskov *et al*, Phys Rev D **47**, 919 (1993)



- There are no σ_t for *Open Charm* @ threshold.

Boson Gluon Fusion (BGF) LO & NLO



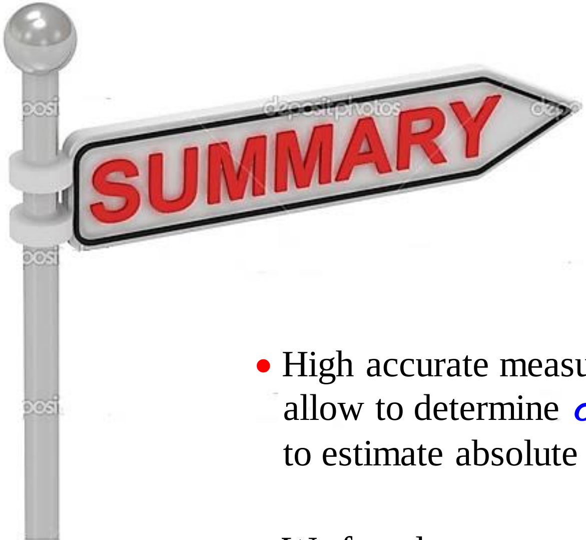


e^- x **p**: **10** x **100** GeV
$Q^2 < 1$ GeV^2

Courtesy of Sergey Furletov, July 2020

For Electroproduction - HVQDIS: B.W. Harris & J. Smith, Phys Rev D **57**, 2806 (1998)

For Photoproduction - FMNR: S. Frixione P. Nason, & G. Ridolfi, Nucl Phys B **454**, 3 (1995)



- High accurate measurements near-threshold by A2, clas, & GlueX allow to determine σ_t of reactions $\gamma p \to VMp$ & to estimate absolute value of *VM*-*p* *SL*s 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 *VM*-*p* *SL* with inverse mass of *VM*s $\alpha_{Vp} \propto \exp(1/m_V)$

- It is remarkable that proton is quite so *transparent* to J/ψ, though general progression from ω to ϕ to J/ψ is perhaps qualitatively reasonable on account of *OZI* rule $|\alpha_{J/\psi p}| \ll |\alpha_{\phi p}| \ll |\alpha_{\omega p}|$

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

  E.L. Feinberg, Sov Phys Usp, **23**, 629 (1980)

  Courtesy of Michael Ryskin, July 2020

- **Light** *VM*s can be '***young***' as well

  This depends on particular kinema $|\alpha_{J/\psi p}| \ll |\alpha_{\phi p}| \ll |\alpha_{\omega p}|$

  Another point is that for slow ***heavy*** quark, one need more time to reach *equilibrium*, i.e., to form final (long-living/static) *VM*.

- Obviously, facility will open new window in solving the ***VM-N SL*** puzzle.
  It will allow to make deal with `***young***' ***Υ***-meson as well.

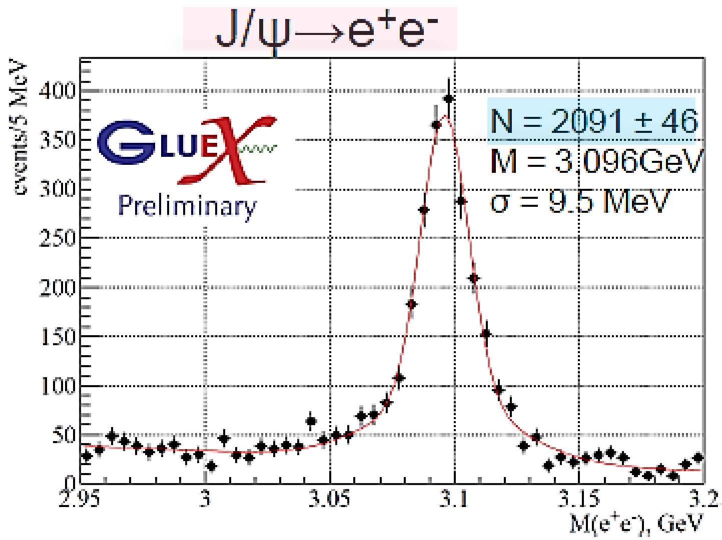
- It was observed that ***J/ψ-N*** cross section measured via ***J/ψ*** re-scattering/absorption inside nucleus is anomaly small in case of low energy photoproduction.
  This can be explained by fact that we dealt with `***young***' ***J/ψ*** of too small radius.
  Υ-photoproduction on both proton &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

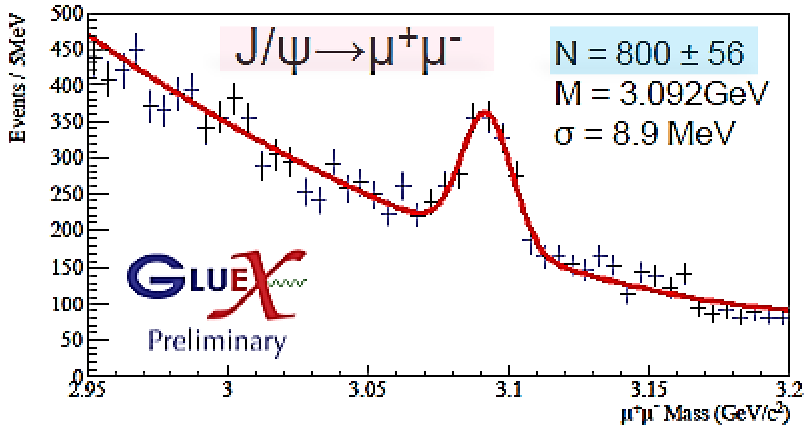
- In case of ***J/ψ*** (even ***Υ***) electroproduction, we deal with the `***young***' ***J/ψ*** (**Υ**) for larger ***Q^2***
  & we will have smaller formation time & correspondingly smaller radius of heavy
  Charmonium & *Quarkonium*.

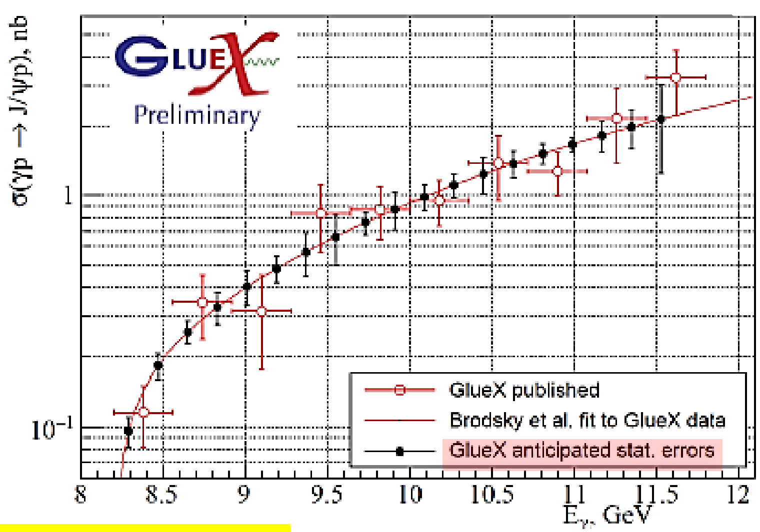
Backup

Expectation from Jefferson Lab

• Total GlueX statistics for 2016–2018







Courtesy of Alex Austeregesilo, JLUO, June 2020

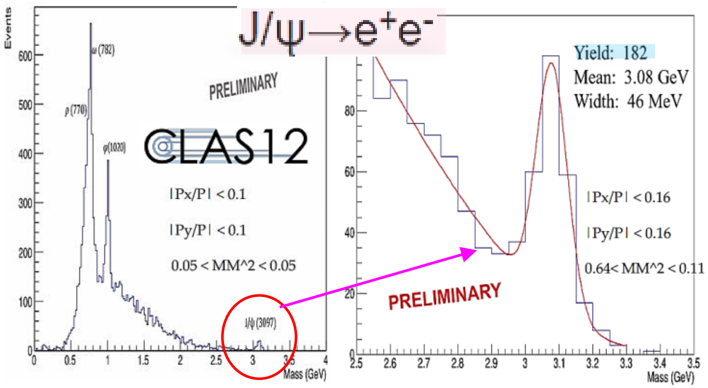
Expectation from Jefferson Lab

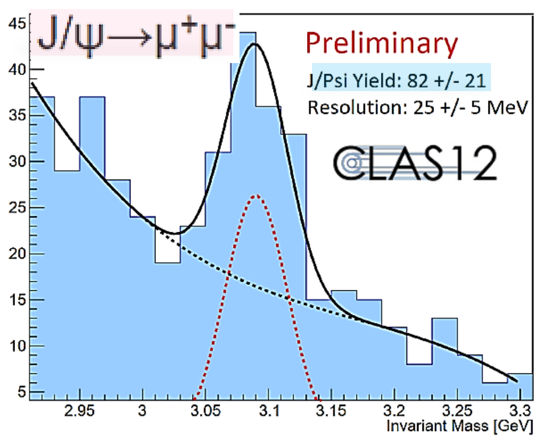
- Present & future experiments @ CLAS12 & $007^{J/\psi}$ that are aimed to measure charmonium production on proton & nuclei will allow further studies of $J/\psi N$ interaction & will give also access to variety of other ***interesting*** physics aspects that are present in near-threshold region.

Fall 2018 dataset

Time-like Compton Scattering & J/ψ Photoproduction (E12-12-001A)

J/ψ→e⁺e⁻

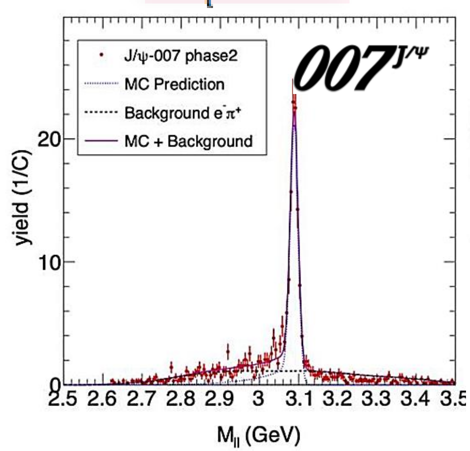


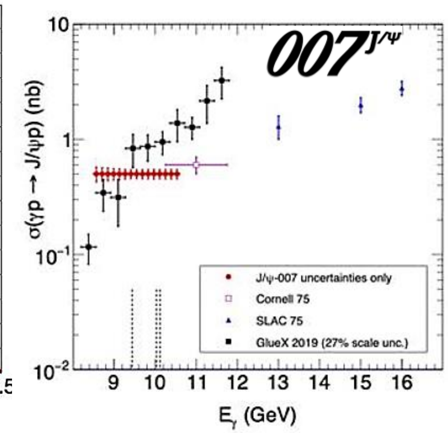


- σ_t is unmeasurable in both cases & requires extraction from $d\sigma/dt$.
- Critical factor is how close to *threshold* both experiments will go .

Search for LHCb Charmed "Pentaquark" using Photoproduction of J/ψ @ Threshold in Hall C @ Jefferson Lab (E12-16-007)

J/ψ→e⁺e⁻





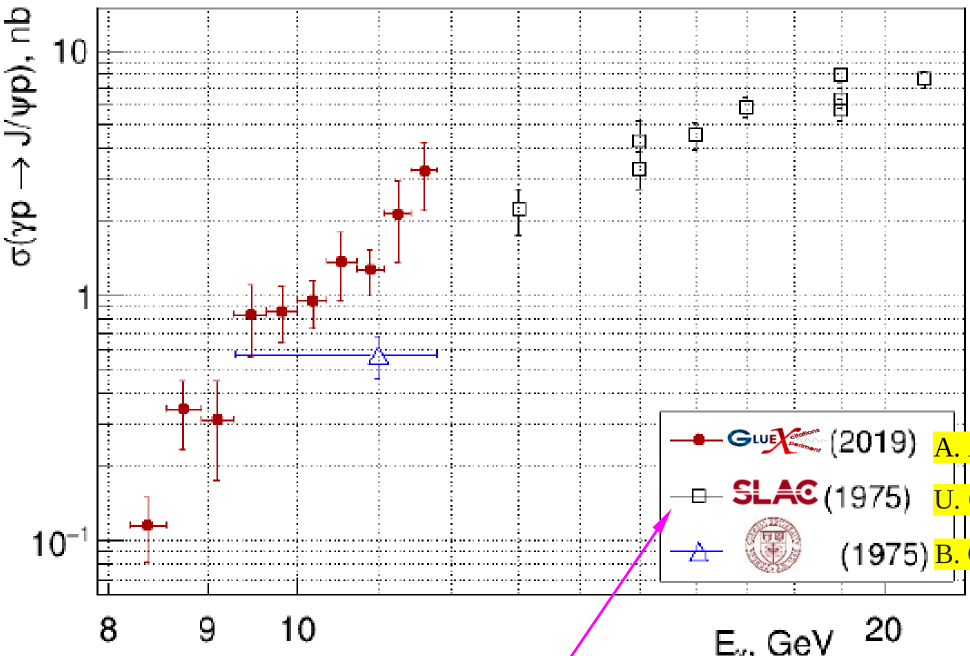
Courtesy of Joseph Newton & Richard Tyson, CLAS Collab meeting, July 2020

Courtesy of Burcu Duran & Sylvester Joosten, APS April 2020

Total Xsection for $\gamma p \to J/\psi p \to e^+e^- p$ @ J/ψ Threshold

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

$$\sigma_{J/\psi}(E_\gamma) = \frac{N_{J/\psi}(E_\gamma)}{N_{BH}(E_\gamma)} \frac{\sigma_{BH}(E_\gamma)}{\mathcal{B}_{J/\psi}} \frac{\varepsilon_{BH}(E_\gamma)}{\varepsilon_{J/\psi}(E_\gamma)}$$



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

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

B. Gittelman *et al*, Phys Rev Lett **35**, 1616 (1975)

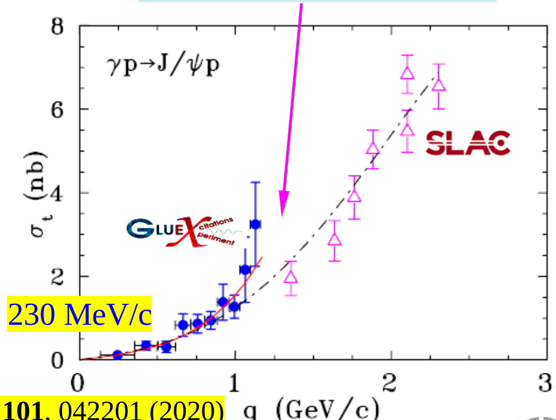
- Yields [**N**(J/ψ) & **N**(BH)] extracted from fits of **M**(e^+e^-) & **E**/**p** in bins of energy.
- **σ**(BH) calculated using analytical & numerical results of *EM* tree level diagrams.
- Syst errors of individual data points assigned to max deviation when varying fitting methods.
- Errors dominated by statistics.

- SLAC experiment measured $d\sigma/dt$ at $t = t_{min}$ as function of E_γ.
- To determine σ_t from SLAC data, GlueX used *dipole* t-dependence.

- There is no discrepancy between GlueX & SLAC data.

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

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



230 MeV/c

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