Puzzle for the Vector Meson Threshold Photoproduction

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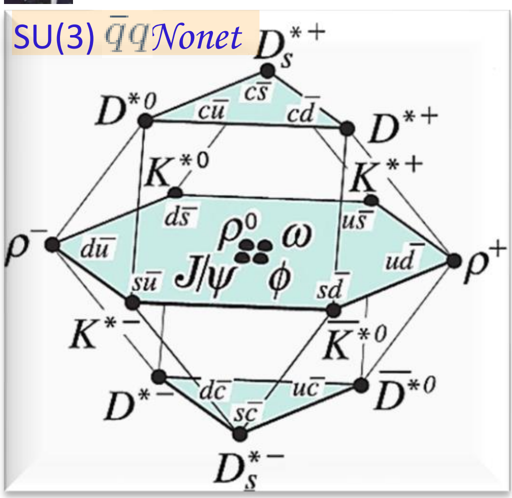
Outline

- *Vector Meson Zoo.*
- *Vector Meson Nucleon Scattering Length.*
  - *MAMI & ELPH for Omega.*
  - *JLab for Phi & J/Psi.*
    - *JLab for Phi.*
    - *JLab for J/Psi.*
  - *From CNF to EIC for Upsilon.*
- *How Unique LHCb Pc Evidence.*
- *Introduction to Interference.*
  - *Alternative Solution for GlueX J/Psi data.*
  - *Cusp effects.*
- *Summary.*

Vector Meson 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
$D^{*0}(2007)$	$c\bar{u}$	< 2.1
$J/\psi(1S)(3097)$	$c\bar{c}$	0.093
$\psi'(2S)(3686)$	$c\bar{c}$	0.284
$\Upsilon(1S)(9460)$	$b\bar{b}$	0.052

SLAC

SLAC

Open Charm

Charmonium

Quarkonium

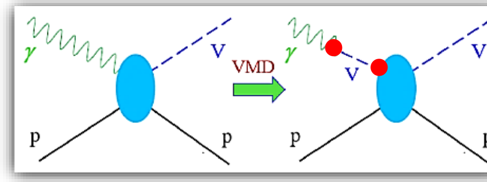
To avoid broad ***width*** problem @ threshold, we are not considering this case to determine **VN SL**.

There is difference between 1S & 2S states due to `*zero*' in radial **WF**s.

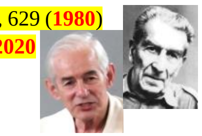
- Let me focus on **4** ***vector mesons*** from q̄q *Nonet* which widths are **narrow** enough to study *meson photoproduction* @ threshold & where data or quasidata are available.

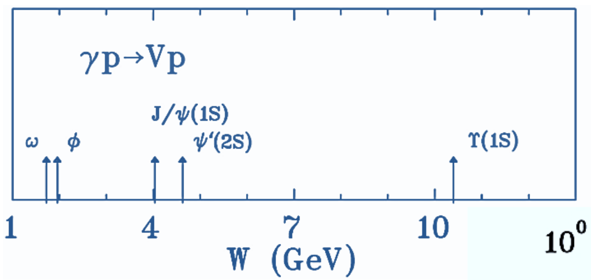
Vector Meson – Nucleon SL

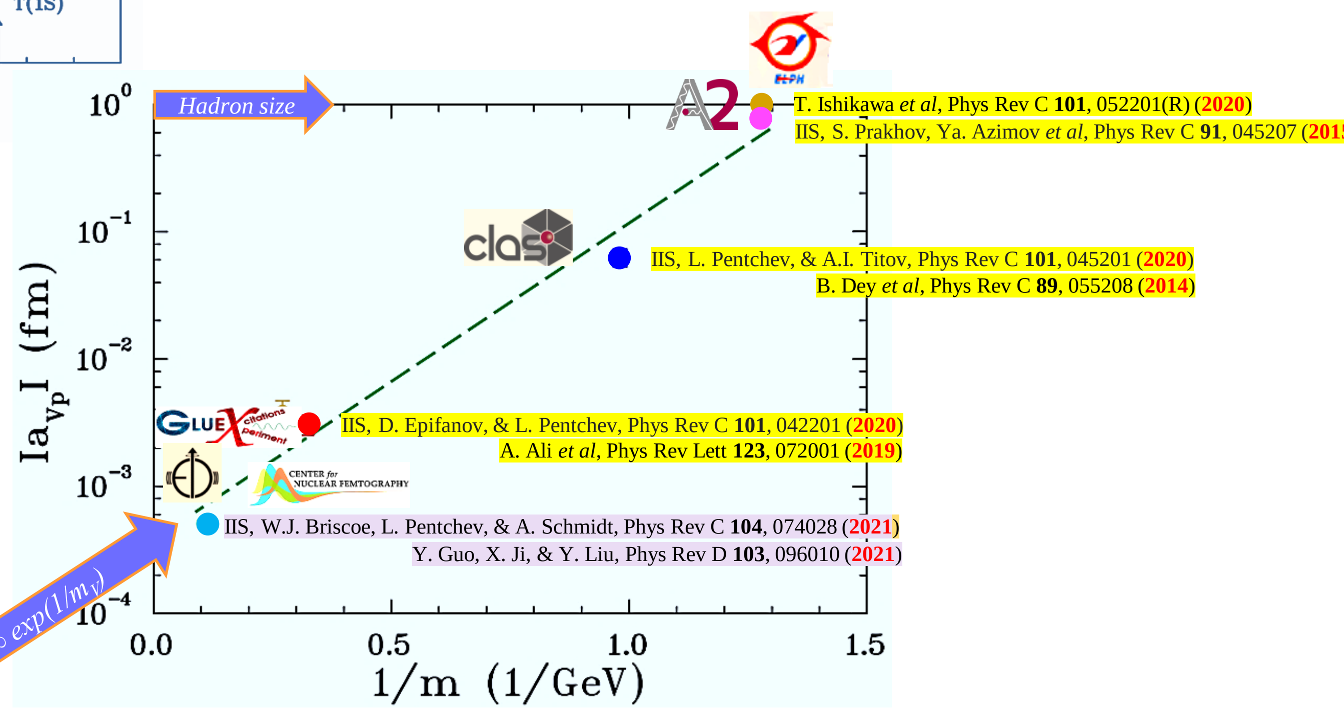
- Due to ***small size*** of *"young"* ***V*** vs *"old"* ***V***, measured & predicted ***SL*** is very small.
- ***V*** created by photon @ threshold then most probably ***V*** is not *formed completely*, & its radius is smaller than that for normal (*"old"*) ***V***.
- Therefore, one observes stronger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



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







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

Vector Meson – Nucleon Scattering Length Determination

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

$q \to 0$

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

VM CM momentum

photon CM momentum

$k = (s - M^2) / 2\, s^{1/2}$

Invariant amplitude of *VM* photoproduction

Fine-structure constant

VMD coupling constant, related to *VM* ***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* $h_{Vp} = \sqrt{b_1}$ where b_1 came from ***best fit***

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

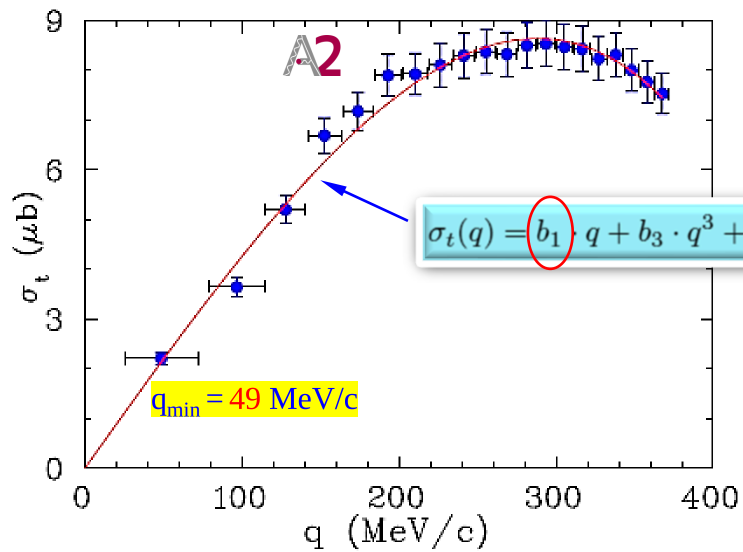
that is determined by interplay of strong (*hadronic*) & ***EM*** dynamics as

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

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

$\gamma p \to \omega p \to \pi^0 \gamma p \to 3\gamma p$ Measurements from A2 & ELPH

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



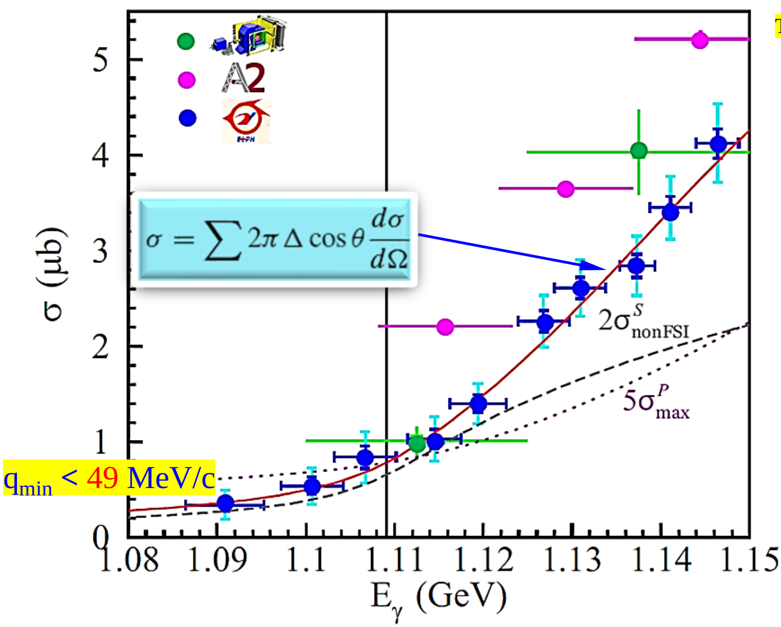
IIS, S. Prakhov, Ya. Azimov *et al*, Phys Rev C **91**, 045207 (2015)

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

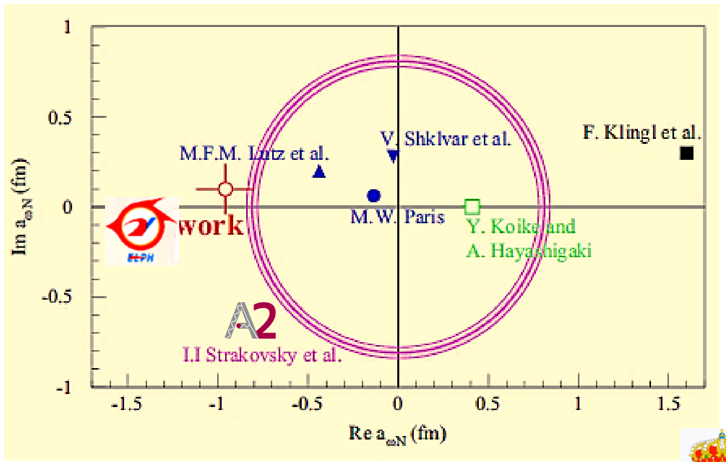
$$d\sigma/d\Omega(E_\gamma, \cos\theta) = \sum_{j=0} A_j(E_\gamma)P_j(\cos\theta)$$

confirms σ_t determination

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



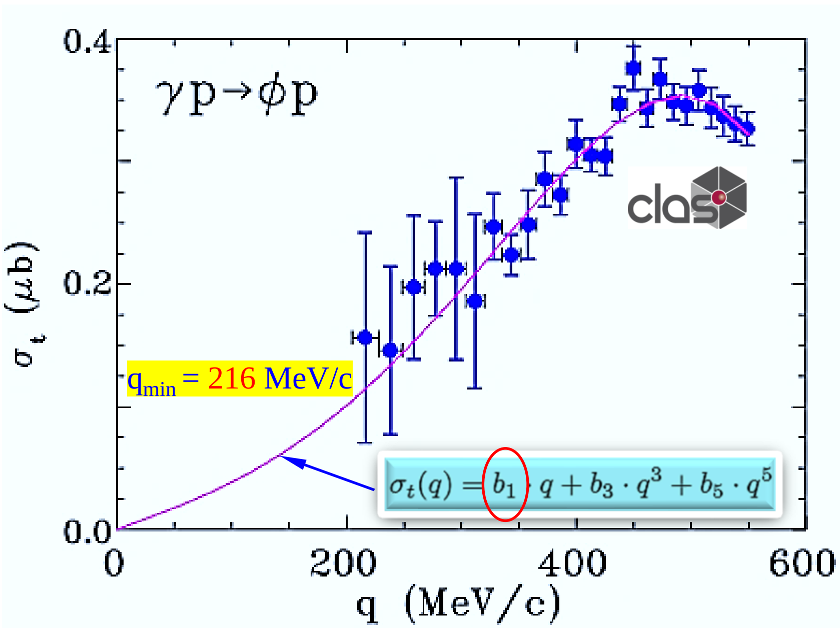
T. Ishikawa *et al*, Phys Rev C **101**, 052201(R) (2020)



$\gamma p \to \phi p \to K^+K^- p$ *Measurements* *from* clas

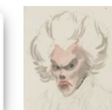
PDG BR($\phi \to K^+K^-$) = 49.2%

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



- $\cos\theta$ 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 σ_t

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

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

Experimental Evidence for Attractive $p\phi$ Interaction from

S. Acharya *et al*. Phys Rev Lett **127**, 172301 (**2021**)

- Recently, Collaboration has deduced spin averaged $p\phi$ **SL**

$$a_{\phi N} = -(0.85 \pm 0.34 \pm 0.14) + i(0.16 \pm 0.10 \pm 0.09)\ \text{fm}$$

from *two-particle momentum correlation function* using *Lednicky-Lyuboshits* approach

R. Lednicky & V.L. Lyuboshits, Sov J Nucl Phys **35**, 770 (**1982**)

- Actually, is doing *two-particle correlations* of combined $p\phi$ & $\bar{p}\phi$ pairs measured in *high-multiplicity* in ***pp*** collisions @ W = **13** TeV.
- Besides, FSI correlation **C**(**k**) depends on production mechanism.
- Then, assumes that *proton* & ϕ are produced *independently* @ ~**1** fm distance.
- Another problem is that it is practically impossible to observe $p\phi$ (or any *vector meson*) correlation (@ very small $p\phi$ energy, *i.e.*, *near threshold*) @ CERN (with or another detector).

Attractive $\mathcal{N}\phi$ *Interaction from*

- Using (2 + 1)-flavor lattice QCD simulations with nearly physical quark masses, HAL has simulated ϕN scattering process for spin **3/2** channel

$$a_{\phi N}^{(3/2)} = -1.43 \pm 0.23^{+0.36}_{-0.06} \text{ fm}$$

Y. Lyu *et al* Phys Rev D **106**, 074507 (2022)

- Instead of ϕ photoprod process, they simulated ϕN elastic scattering reaction.

Note, however, that in case of photoproduction, we deal not with completely formatted ϕ meson but with $s\bar{s}$ pair which only @ end will form ϕ meson.
Amplitude of this pair interaction with nucleon may be not exactly equal to that for ϕN amplitude.
Long ago this was called "***young***" effect.

- ϕN system is assumed as "*on lattice*" & this result is but "*numerical experiment*."

- Using lattice calculations for spin **3/2** ϕN interaction by HAL are used to constrain spin **1/2** counterpart from fit of experimental ϕp correlation function measured by ALICE.

S. Acharya *et al*. Phys Rev Lett **127**, 172301 (2021)

- Corresponding **SL** is

$$a_{\phi N}^{(1/2)} = -\left(1.54^{+0.53}_{-0.53}(stat)^{+0.16}_{-0.09}(syst)\right) + i\left(0.00^{+0.35}_{-0.00}(stat)^{+0.16}_{-0.00}(syst)\right) \text{ fm}$$

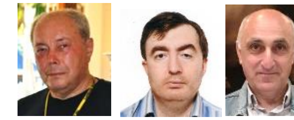
E. Chizzali *et al* Phys Lett B **848**,138358 (2024)

- See comments above.

- Combination of Lattice spin **3/2** & **1/2** gives huge **SL**.

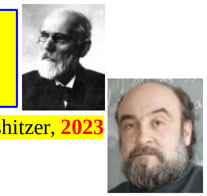
$J/\psi p$ Scattering Length from GlueX

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

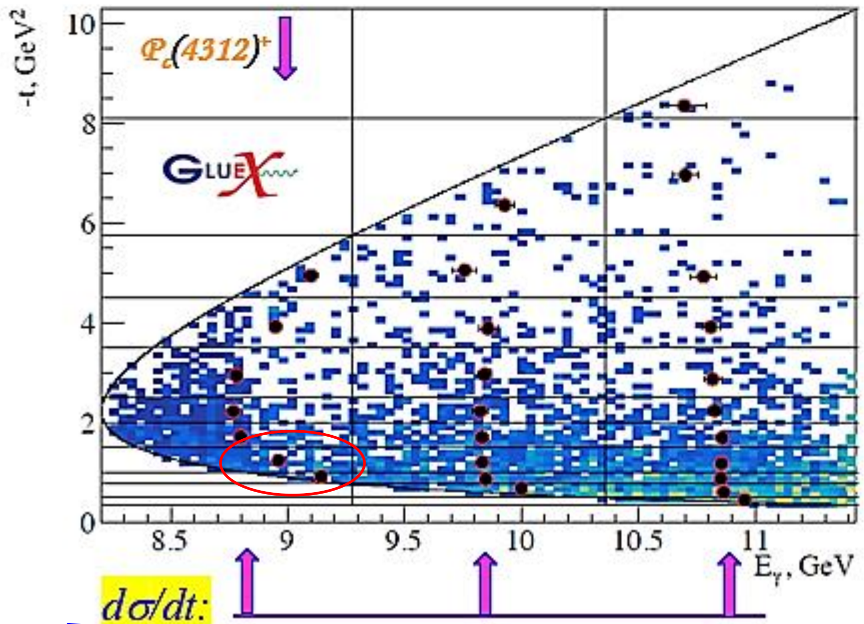


- All previous *theoretical* results (including *potential* approaches & *LQCD* calculations) gave much-much larger ***SL***.

- Most probably so large SL results from *large distances tail* of *van der Waals potential* which in QCD should be killed by *confinement*.



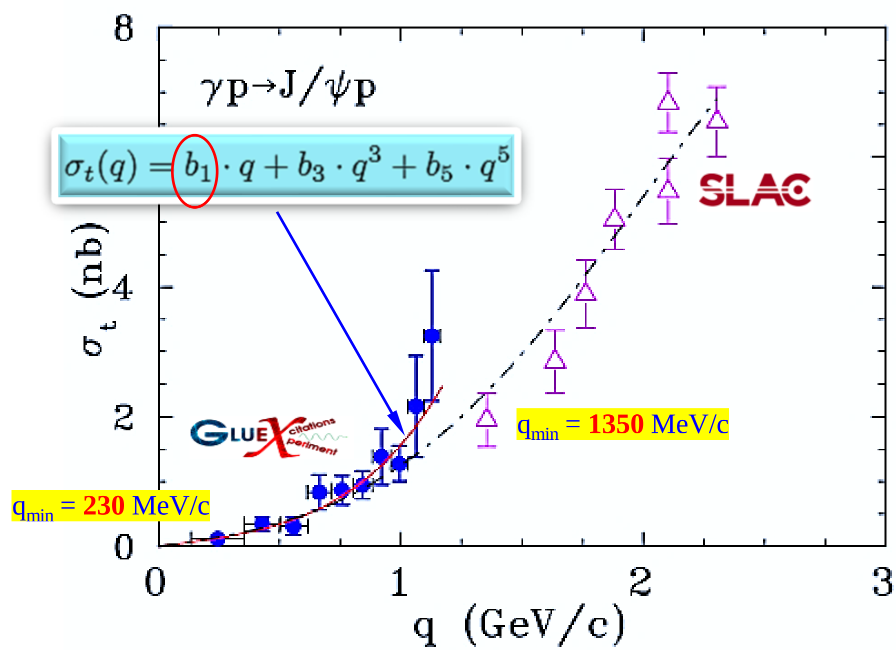
Courtesy of Yuri Dokshitzer, **2023**



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

BR($J/\psi \to \mu^+\mu^-$) = (**5.961**±0.033)%

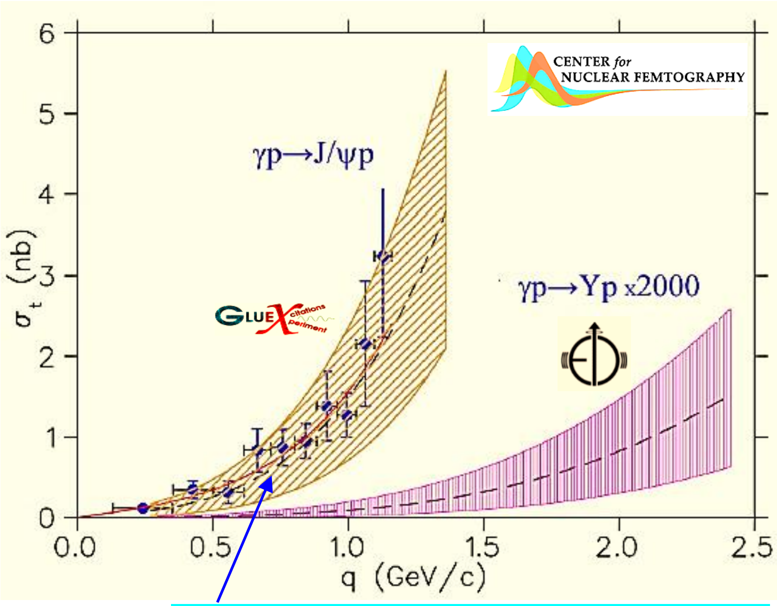
In progress



- Near threshold, ***S***-wave dominates & Xsec does not depend on **SL**, (*i.e.*, does not depend on ***t***); Xsec depends on ***s***, so that extrapolation in ***s*** seems justified.
- Extrapolation to ***t* = 0** covers too large an interval (**δt** = **2.23** GeV²), so that we can not guarantee that *slope* will remain constant @ **b** = **1.67** GeV⁻² over this large interval.

Expectation from via CENTER *for* NUCLEAR FEMTOGRAPHY

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



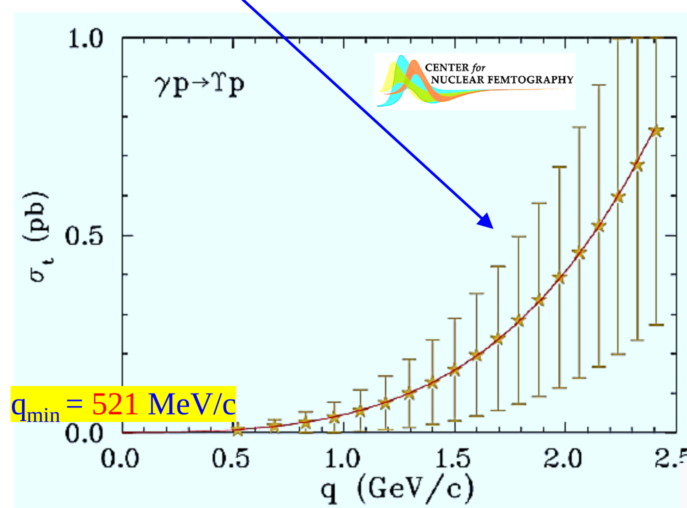
- Theoretical fit of GlueX data @ 95% C.L.

- *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 ***Y*** 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.



q_{min} = 521 MeV/c

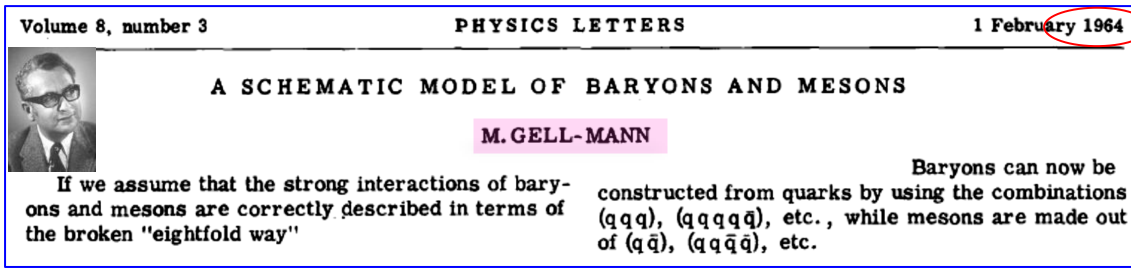
- It was assumed total integrated luminosity of 100 fb^{-1} for photoproduction @ , which corresponds to 116 days of beam with 10^{34} cm^{-2} s^{-1}, for MC calculations.

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

Bump Hunting

Narrow Pentaquarks from $\Lambda_b \to J/\psi p K^-$

- QCD gives rise to *hadron spectrum*.


Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

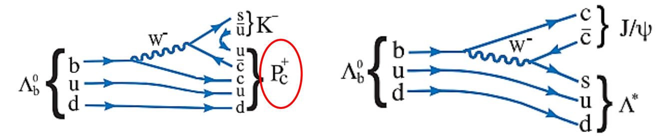
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" ... Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc.

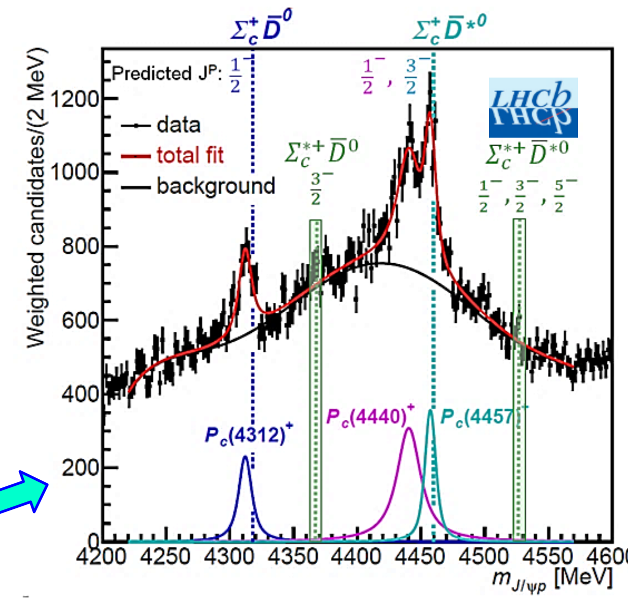
- Many $\bar{q}q$ & qqq states have been *observed*.


PDG 220 & 100.

- $\bar{q}q\bar{q}q$, $qqq\bar{q}q$ … *are not forbidden* or we *do not know* it yet.

- LHCb claims *evidence* for ***four*** *hidden-charm* qqq $c\bar{c}$ *states* near *open-charm* decay thresholds for $\Sigma_c^+ \bar{D}^0$ & $\Sigma_c^+ \bar{D}^{*0}$ in $\Lambda_b \to J/\psi\, p\, K^-$ decays.





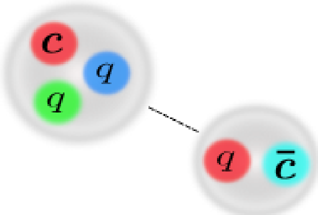
R. Aaij *et al*, Phys Rev Lett **122**, 222001 (**2019**)

State	M (MeV)	$\Gamma[Pc \to J/\psi + p]$ (MeV)	Significance
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	7.3 σ
$P_c(4337)^+$	4337^{+7+2}_{-4-2}	29^{+26+13}_{-12-14}	3.1 − 3.7 σ
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	5.4
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	5.4

- Bump *hunting*:
  - no *quantum numbers*
  - no *pole positions*

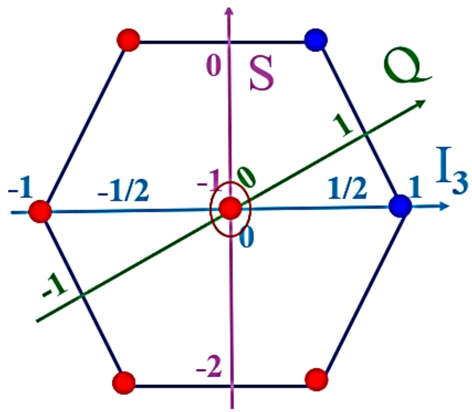
$SU(3)$ *Multiplets*

Assumed to be Meson-Baryon Molecules



1 — $P^{0}_{cs}(4337)$ — $\bar{D}^{(*)}\Sigma_c^{(*)}$, $\bar{D}_s^{(*)}\Lambda_c$

8



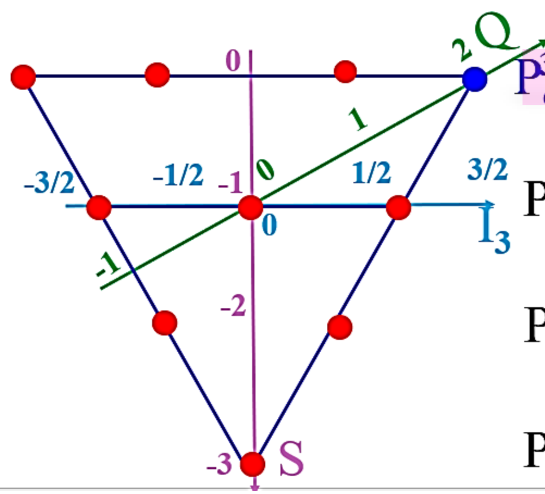
$P^{1/2}_{c}(4440)$ — $\bar{D}^{(*)}\Lambda$, $\bar{D}^{(*)}\Sigma_c^{(*)}$

$P^{0}_{cs}(4457)$ — $\bar{D}^{(*)}\Sigma_c^{(*)}$, $\bar{D}^{(*)}\Sigma'_c$, $\bar{D}_s^{(*)}\Sigma_c^{(*)}$

P^{1}_{cs}

$P^{1/2}_{css}$ — $\bar{D}_s^{(*)}\Sigma_c^{(*)}$, $\bar{D}_s^{(*)}\Sigma'_c$

10



$P^{3/2}_{c}(4312)$ — $\bar{D}^{(*)}\Sigma_c^{(*)}$

P^{1}_{cs}

$P^{1/2}_{css}$

P^{0}_{csss}

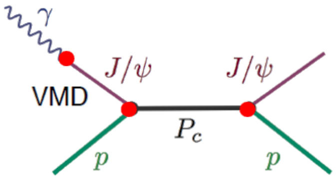
LHCb	M (MeV)	$\Gamma[Pc \to J/\psi + p]$ (MeV)	Significance
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$7.3\ \sigma$
$P_c(4337)^+$	4337^{+7+2}_{-4-2}	29^{+26+13}_{-12-14}	$3.1 - 3.7\ \sigma$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$5.4\ \sigma$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$5.4\ \sigma$

R. Aaij *et al*, Phys Rev Lett **122**, 222001 (**2019**)

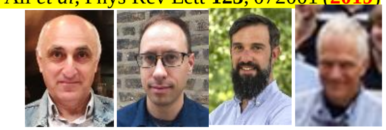
In **$D^{(*)}$**, parentheses mean that there are ***two*** spin states **D** & **D***

Courtesy of Atsushi Hosaka, **2024**

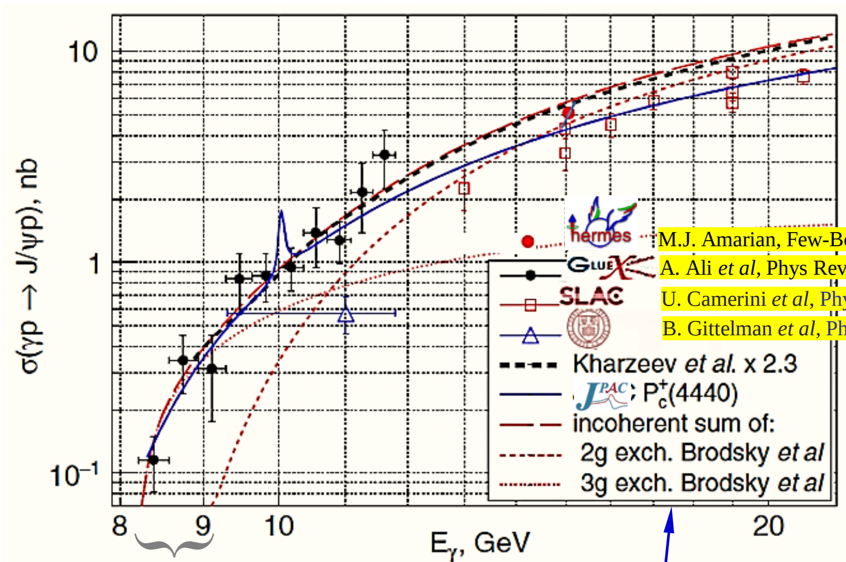
How Bump Hunting works in 2019 GlueX *data ?*



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



2016–2017 data: **469**±22 $\gamma p \to J/\psi p \to e^+e^- p$ & **68** pb^{-1}



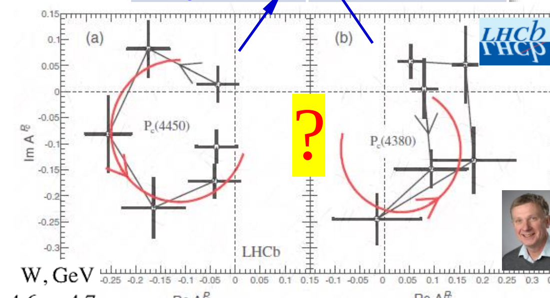
M.J. Amarian, Few-Body Syst Suppl. **11**, 359 (**1999**)
A. Ali *et al*, Phys Rev Lett **123**, 072001 (**2019**)
U. Camerini *et al*, Phys Rev Lett **35**, 483 (**1975**)
B. Gittelman *et al*, Phys Rev Lett **35**, 1616 (**1975**)

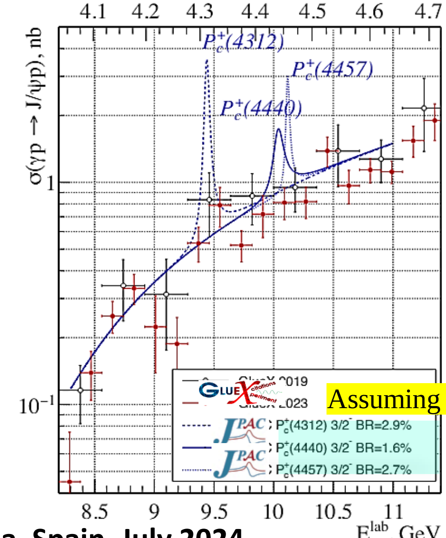
D. Kharzeev, H. Satz, A. Syamtomov, & G. Zinovjev, Nucl Phys A **661**, 568 (**1999**)
JPAC A.N. Hiller Blin *et al*, Phys Rev D **94**, 034002 (**2016**)
S. Brodsky, E. Chudakov, P. Hoyer, & J.M. Laget, Phys Lett B **498**, 23 (**2001**)

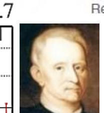
- Near *threshold*, ***3g*** works better than ***2g***

- GlueX sees *no evidence* for LHCb P_cs
  Upper limits @ 90% CL

State	Upper Limit
$P_c(4312)$	**4.6** %
$P_c(4440)$	**2.3** %
$P_c(4457)$	**3.8** %







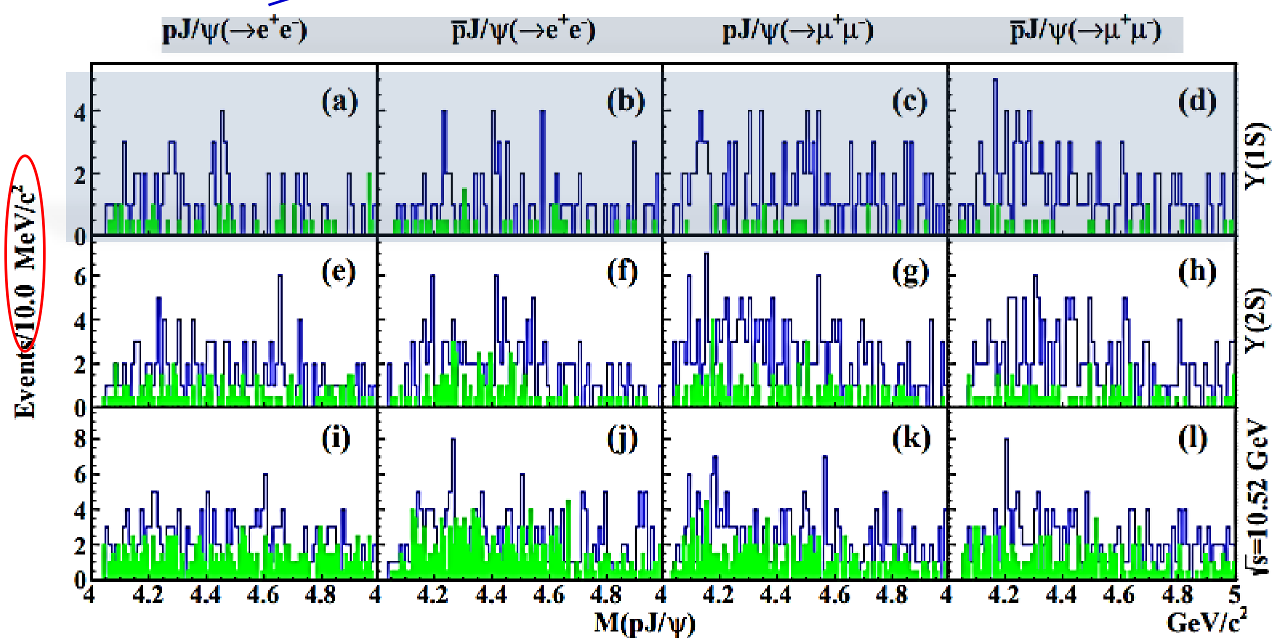
Assuming $J^P = 3/2^-$

Search for Pentaquark State Decaying into pJ/ψ in $\Upsilon(1S)$ Inclusive Decays @ BELLE

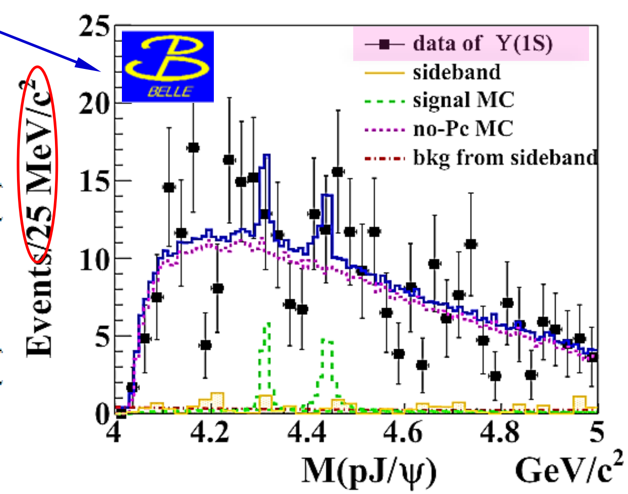
Bump Hunting

X. Dong *et al* arXiv:2403.04340 [hep-ex]

- Using the data samples of 102 million $\Upsilon(1S)$ and 158 million $\Upsilon(2S)$ events collected by the Belle detector, we search for a pentaquark state in the pJ/ψ final state from $\Upsilon(1,2S)$ inclusive decays. Here, the charge-conjugate $\bar{p}J/\psi$ is included. We observe clear pJ/ψ production in $\Upsilon(1,2S)$ decays and measure the branching fractions to be $\mathcal{B}[\Upsilon(1S) \to pJ/\psi + anything] = [4.27 \pm 0.16(stat.) \pm 0.20(syst.)] \times 10^{-5}$ and $\mathcal{B}[\Upsilon(2S) \to pJ/\psi + anything] = [3.59 \pm 0.14(stat.) \pm 0.16(syst.)] \times 10^{-5}$. We also measure the cross section of inclusive pJ/ψ production in e^+e^- annihilation to be $\sigma(e^+e^- \to pJ/\psi + anything) = [57.5 \pm 2.1(stat.) \pm 2.5(syst.)]$ fb at $\sqrt{s} = 10.52$ GeV using an 89.5 fb^{-1} continuum data sample. There is no significant $P_c(4312)^+$, $P_c(4440)^+$ or $P_c(4457)^+$ signal found in the pJ/ψ final states in $\Upsilon(1,2S)$ inclusive decays. We determine the upper limits of $\mathcal{B}[\Upsilon(1,2S) \to P_c^+ + anything] \cdot \mathcal{B}(P_c^+ \to pJ/\psi)$ to be at the 10^{-6} level.



Best case



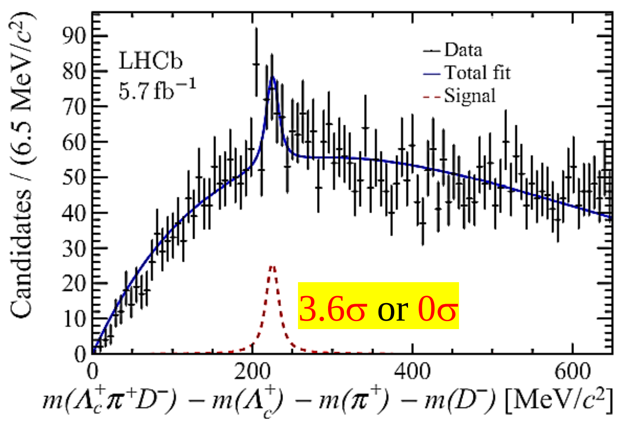
- No evidence for Pc(4312), Pc(4440), Pc(4457) in Y(1S) decay

Bump Hunting

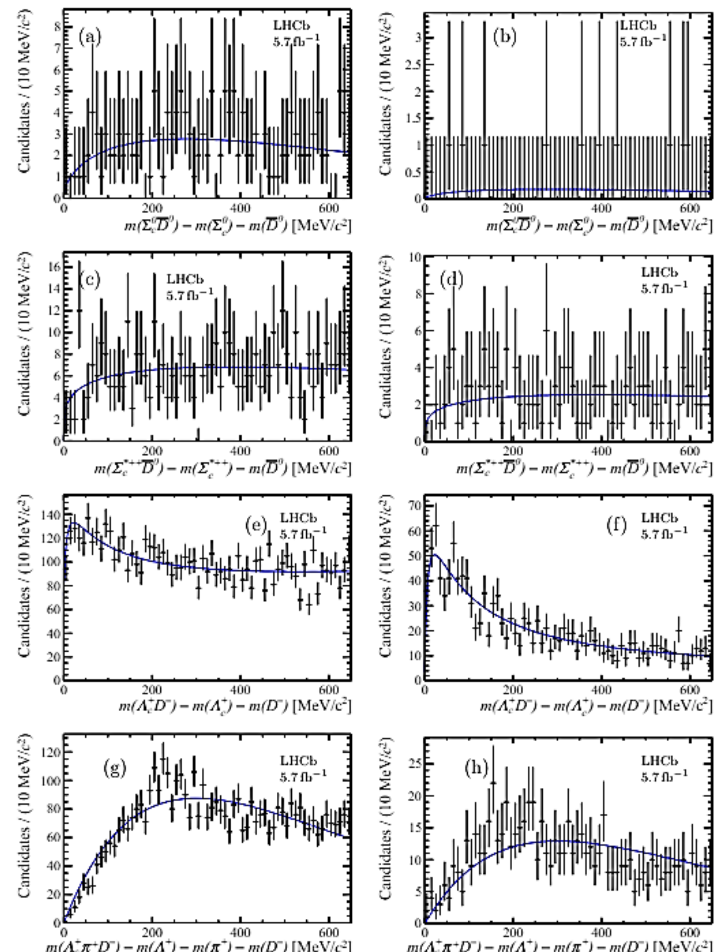
Search for Pentaquark State in Charm Hadron Final State @ LHCb

R. Arij *et al* arXiv:2404.07131 [hep-ex]

- A search for hidden-charm pentaquark states decaying to a range of $\Sigma_c\overline{D}$ and $\Lambda_c^+\overline{D}$ final states, as well as doubly-charmed pentaquark states to $\Sigma_c D$ and $\Lambda_c^+ D$, is made using samples of proton-proton collision data corresponding to an integrated luminosity of $5.7\,\mathrm{fb}^{-1}$ recorded by the LHCb detector at $\sqrt{s} = 13\,\mathrm{TeV}$. Since no significant signals are found, upper limits are set on the pentaquark yields relative to that of the Λ_c^+ baryon in the $\Lambda_c^+ \to pK^-\pi^+$ decay mode. The known pentaquark states are also investigated, and their signal yields are found to be consistent with zero in all cases.



Best case



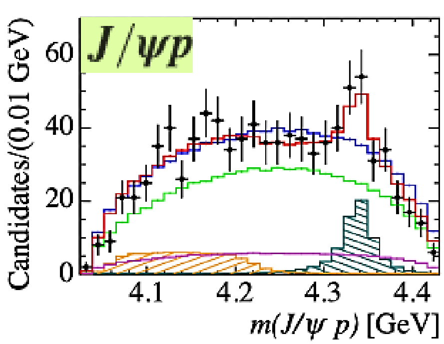
- I do not think these new results *may ``kill'' hidden charm states*.
- Point is that we do not know theoretically expected Xsec & BR.
- Now, these results are just some additional constraints on pentaquark model.

Search for Pentaquark State in $J/\psi p$ & $J/\psi\bar{p}$ in $B_s^0 \to J/\psi p\bar{p}$ Decays
Observation of $J/\psi\Lambda$ Res Consistent with Strange 5q Candidate in $B^- \to J/\psi\Lambda\bar{p}$ Decay

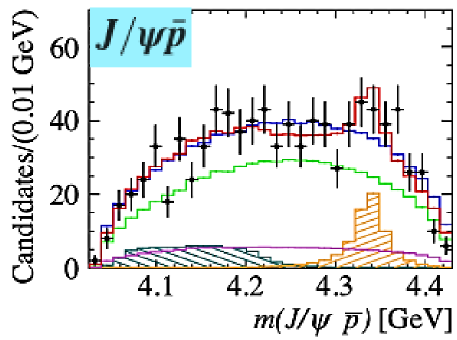
Bump Hunting

- An amplitude analysis of flavor-untagged $B_s^0 \to J/\psi p\bar{p}$ decays is performed using a sample of 797 ± 31 decays reconstructed with the LHCb detector. The data, collected in proton-proton collisions between 2011 and 2018, correspond to an integrated luminosity of 9 fb^{-1}. Evidence for a new structure in the $J/\psi p$ and $J/\psi\bar{p}$ systems with a mass of $4337^{+7}_{-4}\,^{+2}_{-2}$ MeV and a width of $29^{+26}_{-12}\,^{+14}_{-14}$ MeV is found, where the first uncertainty is statistical and the second systematic, with a significance in the range of 3.1 to 3.7σ, depending on the assigned J^P hypothesis.

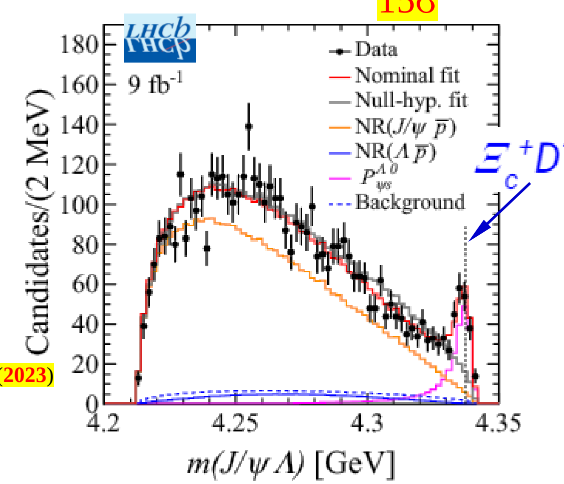
R. Arij *et al* Phys Rev Lett **128**, 062001 (2022)



3.1σ to 3.7σ



15σ

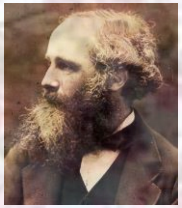


- An amplitude analysis of $B^- \to J/\psi\Lambda\bar{p}$ decays is performed using 4400 signal candidates selected on a data sample of pp collisions recorded at center-of-mass energies of 7, 8, and 13 TeV with the LHCb detector, corresponding to an integrated luminosity of 9 fb^{-1}. A narrow resonance in the $J/\psi\Lambda$ system, consistent with a pentaquark candidate with strangeness, is observed with high significance. The mass and the width of this new state are measured to be $4338.2 \pm 0.7 \pm 0.4$ MeV and $7.0 \pm 1.2 \pm 1.3$ MeV, where the first uncertainty is statistical and the second systematic. The spin is determined to be 1/2 and negative parity is preferred. Because of the small Q-value of the reaction, the most precise single measurement of the B^- mass to date, $5279.44 \pm 0.05 \pm 0.07$ MeV, is obtained.

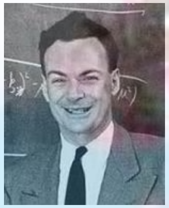
R. Arij *et al* Phys Rev Lett **131**, 031901 (2023)

- They claim that mass resolution is much better than 10 MeV (4337-4312 = 25 MeV).
- However, one can *exclude* that P(4337) is the same as P(4312).

Introduction to Interference



When looking at Maxwell equations,
it is hard to imagine how beautiful the rainbow is.
Richard Feynman

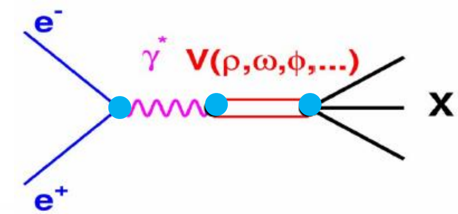


Similar may be said about *Quantum Interference*.

Everybody knows that the interference does exist.
But it is not always easy to imagine
how it will work in a particular case.
Yakov Azimov

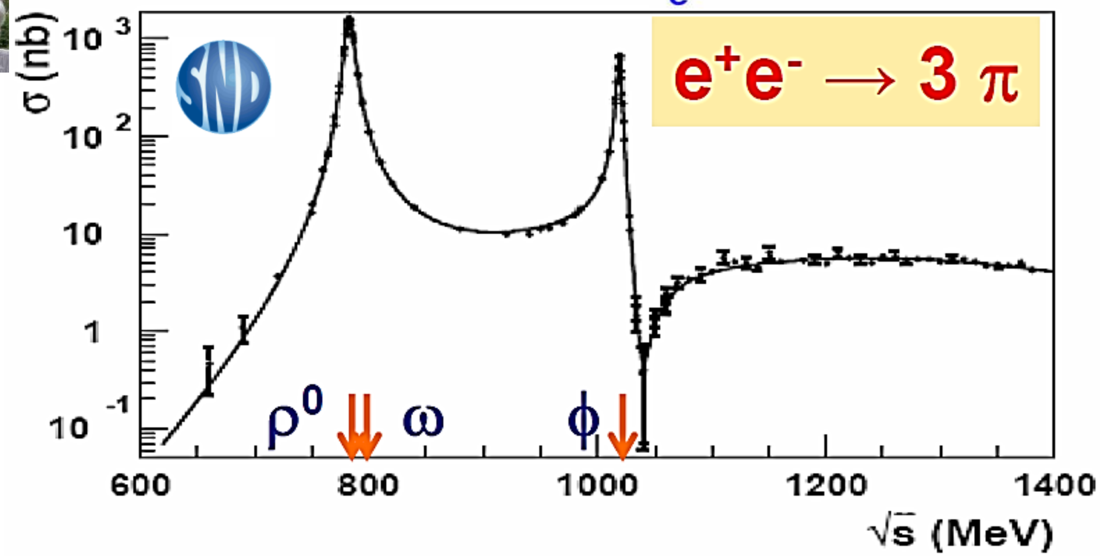
Ya. Azimov, J Phys G **37**, 023001 (**2010**)

- *Quantum Interference* may be *seen* in complementary variable – energy (mass in rest frame):
- It is seen here as *deformation* of **BW** peaks.



PDG $\Gamma(\rho^0)$ = 149.4 MeV; $\Gamma(\omega)$ = 8.5 MeV; $\Gamma(\phi)$ = 4.3 MeV

$\Gamma(\rho^0\to3\pi)$ = 0.015 MeV Isospin violated
$\Gamma(\omega\to3\pi)$ = 7.58 MeV
$\Gamma(\phi\to3\pi)$ = 0.65 MeV Zweig rule violated



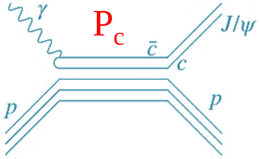
- Bkg near ϕ changes slowly

  ⇓

  nearly standard interference curve, instead of ϕ–peak: both bump & dip, each has form different from **BW** max/min different from ϕ-*mass* ρ.

- ρ-contribution here deforms ω-*tails*.
- Curve is fit with ω, ϕ, ρ, ω', & ω''.

M. Achasov, Nucl Phys B Proc Suppl **162**, 114 (**2006**)



Recipe for Possible Interpretation of GlueX *Dip*

IIS, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, & R.L. Workman, Phys Rev C **108**, 015202 (**2023**)



- Experimental total Xsec of inelastic binary reaction: $\sigma_t = \int_0^{2\pi}\int_0^{\pi} \frac{d\sigma}{d\Omega}\,\sin\theta\, d\theta\, d\phi$

J/ψ polar production *angle*

J/ψ azimuthal production *angle*

Photon CM *momentum*

- Phenomenological total Xsec: $\sigma_t = \frac{\pi}{4k^2}\sum_{J=0}^{\infty}(2J+1)\,|f|^2$

  Using *Landau-Livshitz* normalization

Total angular momentum
(2J+1) = 1 for ***S***-wave
= 3 for ***P***-wave

- Partial Amplitude: $f = b + R\cdot\exp(2i\alpha)$

  There is 1 free parameter for *interference* ***α***

Relative *phase shift*

It comes from **fit** of total Xsec

IIS, A.V. Kravtsov, & M.G. Ryskin, Sov J Nucl Phys **40**. 274 (**1984**)

- Non-Res: $b = \sqrt{A\,q\ +\ B\,q^3}$

  There are 2 free parameters for *background* ***A*** & ***B***

VM CM *momentum*

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

Energy ***independent width*** (***P_c*** is too ***narrow***)

Mass

- Relativistic BW: $R = \frac{2\Gamma M}{[(M)^2 - s] - i\Gamma M}\,X$

- Partial Width: $X = \frac{\sqrt{\Gamma(\gamma+p)\;\Gamma(J/\psi+p)}}{\Gamma} = \sqrt{X(\gamma+p)\;X(J/\psi+p)}$

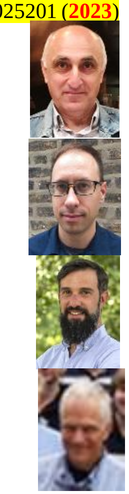
  There are 3 free parameters for *resonance* ***M***, ***Γ***, & ***X***

Partial decay widths of
P_c→J/ψ p &
P_c→γ p.

Alternative Solution for GlueX Data

IIS, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, & R.L. Workman, Phys Rev C **108**, 015202 (**2023**)

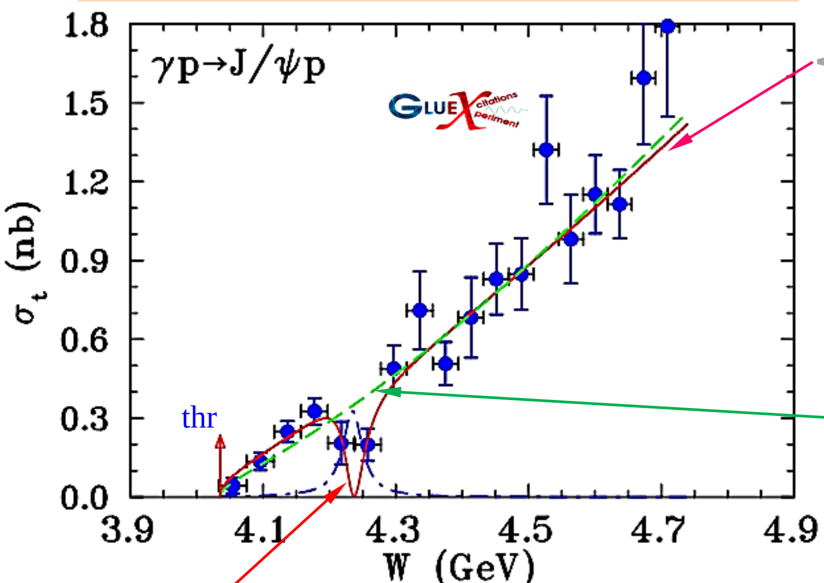
S. Adhikari *et al*, Phys Rev C **108**, 025201 (**2023**)



- We suggested to apply *rearrangement interference* for revealing *faint* resonance signals (***amplification*** by *interference* with *strong* background signal).
- Relative *phase* α leads to *constructive* (***bump***) or *destructive* (***dip***) *interference* for particular **PW**.

$$f = b + R \cdot \exp(2i\alpha)$$

2016–2018 data: **2270**±58 $\gamma p \to J/\psi p \to e^+e^- p$ & **320** pb^{-1}



Resonance: χ^2/ndf=11.99/12=**1.00**

M= 4235 ±8 MeV
Γ= 35.4±8.2 MeV
X= 0.023±0.005
α= 40.8±5.7 deg

Resolution ~6 MeV

Background:
A= 0.00251±0.00046 nb GeV/c
B= 0.00688±0.00083 nb/GeV/c

No Resonance: χ^2/ndf=19.74/16=**1.23**
A= 0.00183±0.00040 nb GeV/c
B= 0.00766±0.00077 nb/GeV/c

- If "*bump*" is imposed on GlueX data "*by hand*" (consider 7th - 9th energy values up from threshold), qualitative description of data up to **W** = **4.35** GeV is possible, but with higher χ^2, if our fit form is used.

- *Dip position* does not correspond to *real mass* of **P_c(4312)$^+$**.
- It may depend on reaction *mechanism* [including *cusps* (*open charm*)] & background choices.

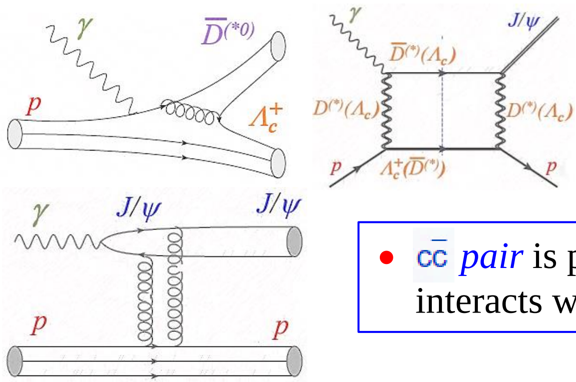
- Obtained mass in our analysis is almost **77** MeV below LHCb determination but it cannot exclude that this is $P_c(4312)^+$.

Deciphering Mechanism of Near-Threshold J/ψ Photoproduction

Meng-Lin Du, V. Baru, Feng-Kun Guo, Ch. Hanhart, U.-G. Meissner, A. Nefediev, & IIS, Eur Phys J C **80**, 1053 (**2020**)

- It was shown that *fluctuation* of *photon* into *open charm* $\gamma p \to \Lambda_c \bar{D}$. is preferable than into *Charmonium J/ψ*.

K. Boreskov, A. Capella, A. Kaidalov, & J. Tran Than Van, Phys Rev D **47**, 919 (**1993**)

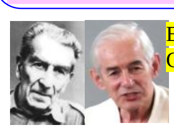


- $c\bar{c}$ *pair* is produced by *1g* & interacts with *proton*.

- $c\bar{c}$ *pair* is produced by *photon* via *VMD* & interacts with *proton* through *2g* exchange.

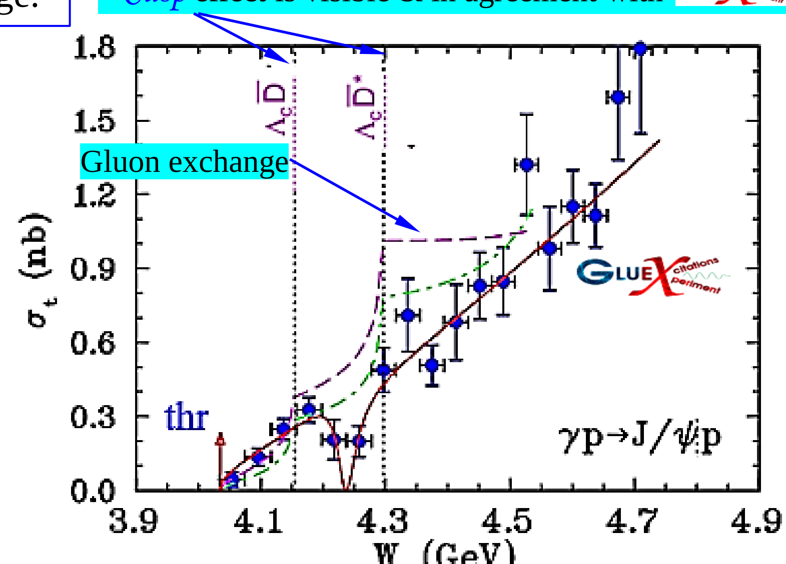
- These ***two** mechanisms* act simultaneously. Assuming there is only ***first*** one, then key consequence: *threshold cusps* **!**
- There is no fit to GlueX data.

- One should study *two-component* problem accounting for *interference* between these *two components*.
- Effect of *charm* exchange is smaller than *gluon* exchange.
- *Gluon* contribution can be strongly *suppressed* due to "*young*" effect.



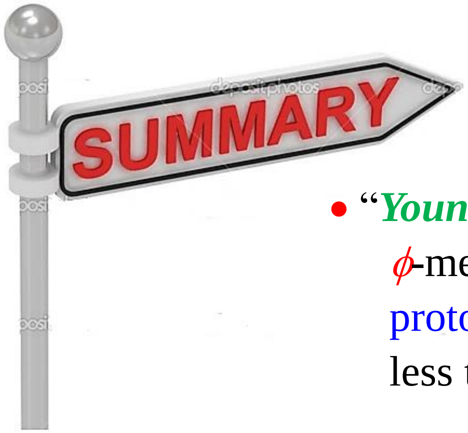
E.L. Feinberg, Sov Phys Usp, **23**, 629 (**1980**)
Courtesy of Misha Ryskin, July **2020**

- *Cusp* effect is visible & in agreement with GlueX.

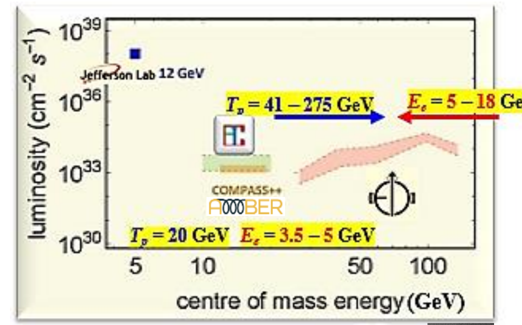


- Interference between *open charm* & *gluon exchange* may produce *dip*, but there is room for *resonance*.

IIS, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, R.L. Workman, Phys Rev C **108**, 015202 (**2023**)



- “***Young***” VM hypothesis may explain fact that obtained **SL** value for ϕ-meson nucleon 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 that J/ψ-meson.



- Future & high-quality experiments will have chance to evaluate physics for J/ψ- & Y-mesons.

- It allows us to understand dynamics of $c\bar{c}$ & $b\bar{b}$ production @ threshold & to look for effect of LHCb $P_c(4312)$.

- J-PARC ability to measure $\pi^- p \to \phi n$ & $\pi^- p \to J/\psi\, n$ @ thresholds, which are free from **VMD**, is important input to phenomenology (PWA).

- ***Polarized measurements*** are important contribution for model independent PWA.

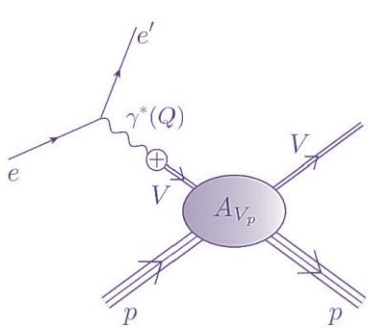
Tens Tens preguntes al parlant?

igor@gwu.edu
Igor Strakovsky

La Sargada

Exclusive ϕ *Electroproduction from* CLAS

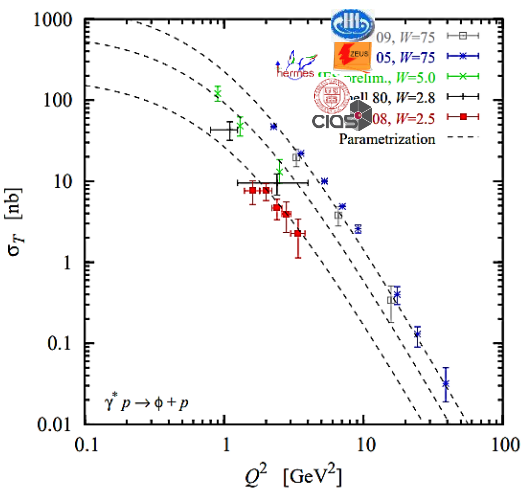
F.-X. Girod, M. Guidal, A. Kubarovsky, V. Kubarovsky, P. Stoler, C. Weiss *et al*, PR12–12–007 (**2012**)

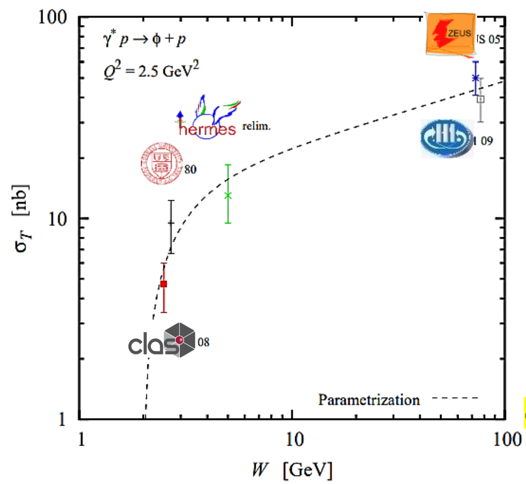


- Don't have *vector meson* beams, so experiments @ modern ***EM***-accelerators attempt to access such interactions via ***EM*** production reactions ***ep → e'Vp***.

- ϕ-meson electroproduction DB is limited & there are no thr measurements which are suitable to evaluate ϕ*N* **SL**.

- Simple empirical parametrization for Xsec was constructed.

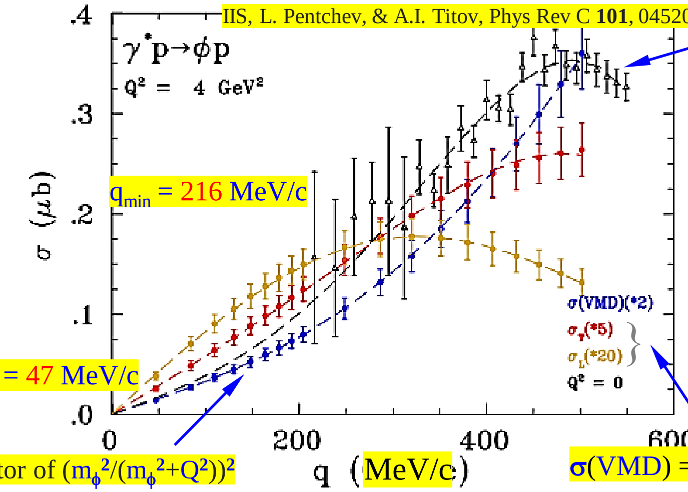




Courtesy of Christian Weiss, **2012**

- Diff Xsec dσ/dt is sensitive probe of strangeness D-term of proton. No fit to high energy data.

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



Scaled by factor of $(m_\phi^2/(m_\phi^2+Q^2))^2$

σ(VMD) = $\sigma_T + \sigma_L$

$\sigma_T > \sigma_L$

Quasi-data from Y. Hatta & M. Strikman, Phys Lett B **817**, 136295 (**2021**)

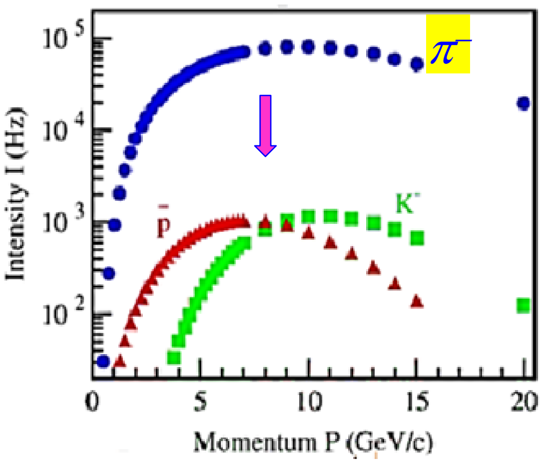
New CLAS12 data for ϕ ElectroProd on proton, ep → e' ϕ p,
@ **11** GeV beam energy with CLAS spectrometer *will come soon*.
Kinematic range extends in W from ϕ-meson thr **1.96** GeV to **5** GeV,
Q^2 from **1** to **12** GeV^2, & $|t\text{-}t_{min}|$ from near zero to **4** GeV^2.

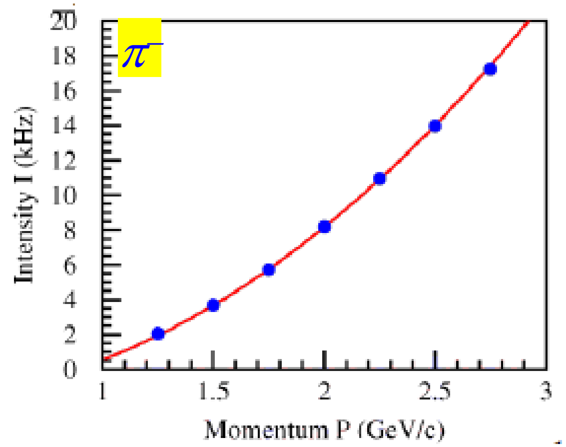
Bump Hunting

J-PARC for $\pi^- p \to \phi\, p$ & $\pi^- p \to J/\psi\, p$

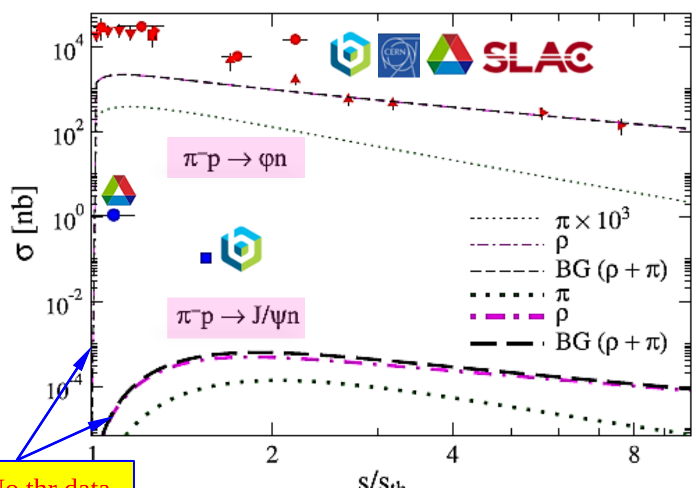
P95 Proposal, J-PARC, **2024**
High-p, **2024**

Hidden Charm Production





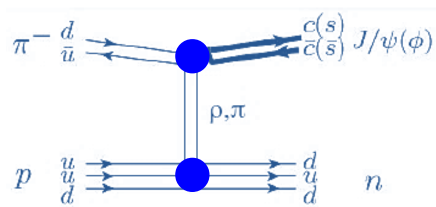
- ***High-p*** can detect J/ψ to e^+e^- & $\mu^+\mu^-$ pairs.
- ***High-p*** can use incident beam **P** = **2** – **20** GeV/c from **π20** beamline.
- One can measure J/ψ production @ **P** = **8** – **10** GeV/c.
- $\mathbf{W}_{thr}$ = **4** GeV ($\mathbf{P}_{thr}$ = **8.06** GeV/c).
- Momentum bite is expected to be ±**3**%.



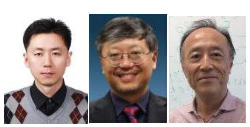
No thr data

10^6

$g_{\phi\rho\pi} > g_{J/\psi\rho\pi}$



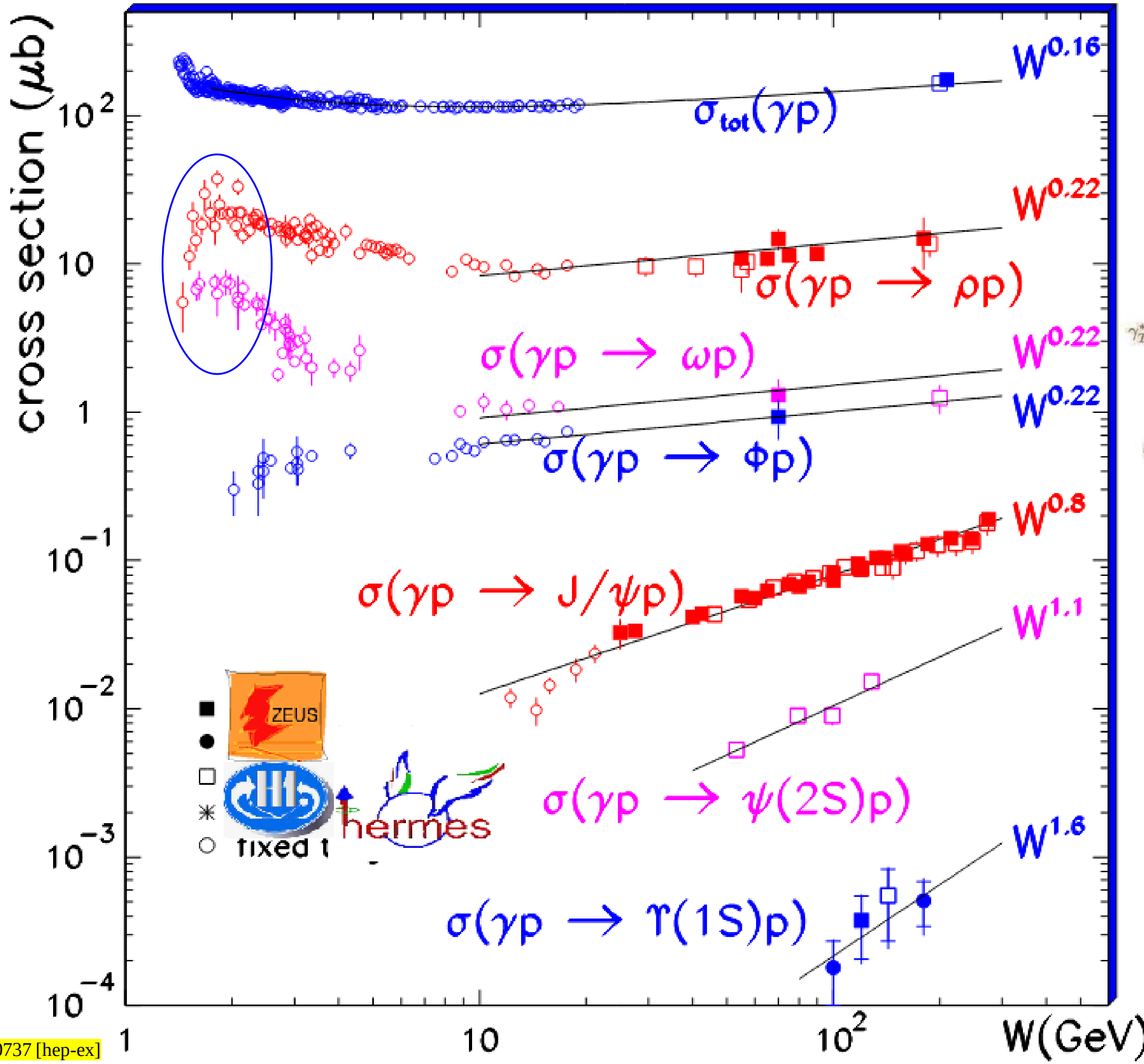
S.H. Kim, H.C. Kim, & A. Hosaka, Phys Lett B **763**, 358 (**2016**)

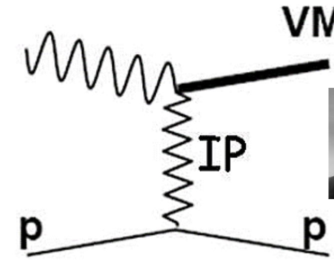


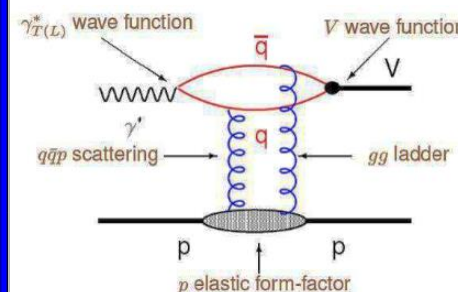
- New ***High-p*** measurement allows to understand dynamics of $c\bar{c}$ production @ threshold.
- It is free from VMD & allows to determine J/ψ p SL independently on GlueX
- It allows to look for effect of LHCb P_c

STAY TUNED

Studying Transition from Soft to Hard Regime of Strong Interactions in $\gamma p \to Vp$



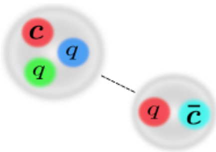




A. Levy, arXiv:0711.0737 [hep-ex]

Interpretation of $\mathcal{P}_c(4312)^+$

- Interpretation of $P_c(4312)^+$ is consistent with



- *Molecules* $\bar{D}^{(*)}\Lambda_c$ & $\bar{D}^{(*)}\Sigma_c^{(*)}$ coupled to *hidden charm* 5q.

Y. Yamaguchi, A. Hosaka, S. Takeuchi, & M. Takizawa, J Phys G **47**, 053001 (**2020**)

M.I. Eides & V.Yu. Petrov, Phys Rev D **98**, 114037 (**2018**)

Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, & M. Takizawa, Phys Rev D **96**, 114031 (**2017**)

- Possibility of *compact bound state*.

IIS, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, & R.L. Workman, Phys Rev C **108**, 015202 (**2023**)

Z. Zhang, J. Liu, J. Hu, Q. Wang, & U.-G. Meißner, Science Bulletin **68**, 981 (**2023**)

X.-W. Wang, Z.-G. Wang, G.-L. Yu, & Q. Xin, Sci. China Phys Mech Astron **65**, 291011 (**2022**)

M.I. Eides, V.Y. Petrov, & M.V. Polyakov, Mod Phys Lett A **35**, 2050151 (**2020**)

- *Pole structure* of $P_c(4312)^+$ & uniformized *S-matrix*.

L.M. Santos, V.A.A. Chavez, & D.L. Sombillo, arXiv:**2405**.11906 [hep-ph]

D. Winney *et al*, Phys Rev D **108**, 5 (**2023**)

Interference

Ya. Azimov, J Phys G **37**, 023001 (**2010**)

- Same phenomenon may be *seen* in complementary variable – energy (mass in rest frame)**:**
- It is seen here as *deformation* of **BW** peaks.

- Pure **BW** term: $|a\,(E - E_0 + i\,\Gamma/2)^{-1}|^2 = |a|^2\,[(E - E_0)^2 + \Gamma^2/4]^{-1}$

- **BW** with background: $|B + a\,(E - E_0 + i\,\Gamma/2)^{-1}|^2$

$$= |B|^2$$ may depend on *E*

$$+ |a|^2\,[(E - E_0)^2 + \Gamma^2/4]^{-1}$$

$$+ [2\,|B\,a|\cos\phi\,(E - E_0) + |B\,a|\sin\phi\,\Gamma] \times [(E - E_0)^2 + \Gamma^2/4]^{-1}$$ interference term

Role of interference depends on relative value & on relative phase ϕ of ***B*** & ***a***;
it is ***linear*** in ***a***, may change sign & be either **positive** or **negative.**

- @ small value of |***a***/***B***| interference term may be more essential than **proper BW** contribution.
- Due to additional *E*-dependence, interference *may change **sign***, provide either bump, or **dip**, or **both**.
- **Bump** &/or **dip positions** are, in general, **shifted** from *true position* of resonance.
- Same resonance may interfere differently in different decay modes.