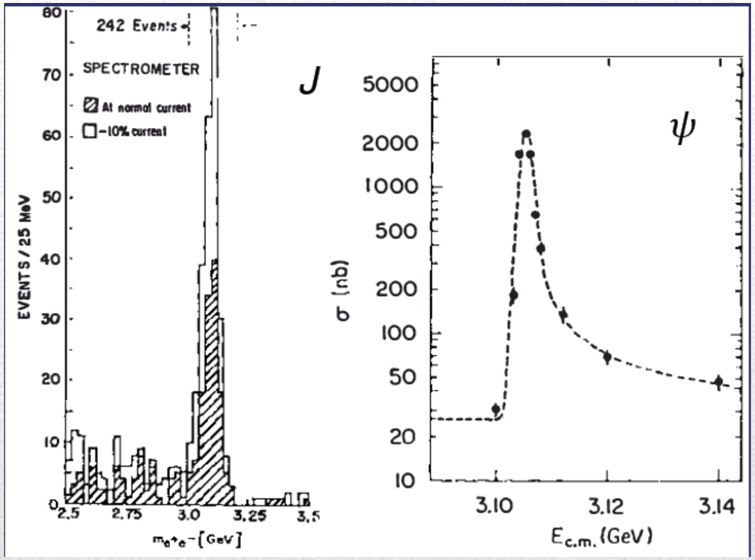
XYZ spectroscopy in photoproduction at future facilities

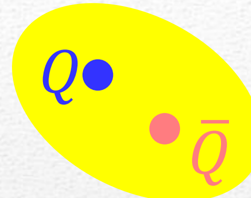
Alessandro Pilloni

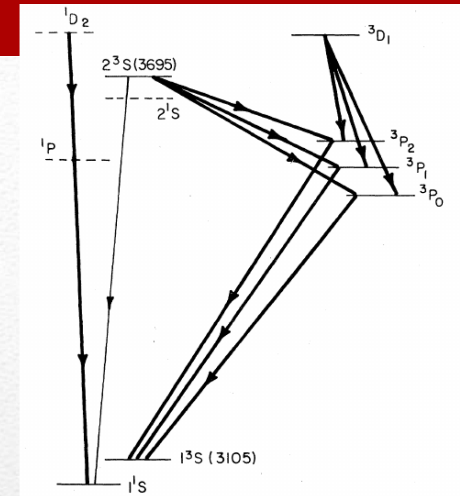
Physics opportunities with proton beams at SIS100
Wuppertal, February 7th, 2024

Università degli Studi di Messina
EXOHAD Exotic Hadrons Topical Collaboration
INFN Istituto Nazionale di Fisica Nucleare

Quarkonium orthodoxy







$$\alpha_s(M_Q) \sim 0.3$$

(perturbative regime)

OZI-rule, QCD multipole

Heavy quark spin flip suppressed by quark mass, approximate heavy quark spin symmetry (HQSS)

Potential models

(meaningful when $M_Q \to \infty$)

$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$

(Cornell potential)

Solve NR Schrödinger eq. → spectrum

Effective theories

(HQET, NRQCD, pNRQCD...)

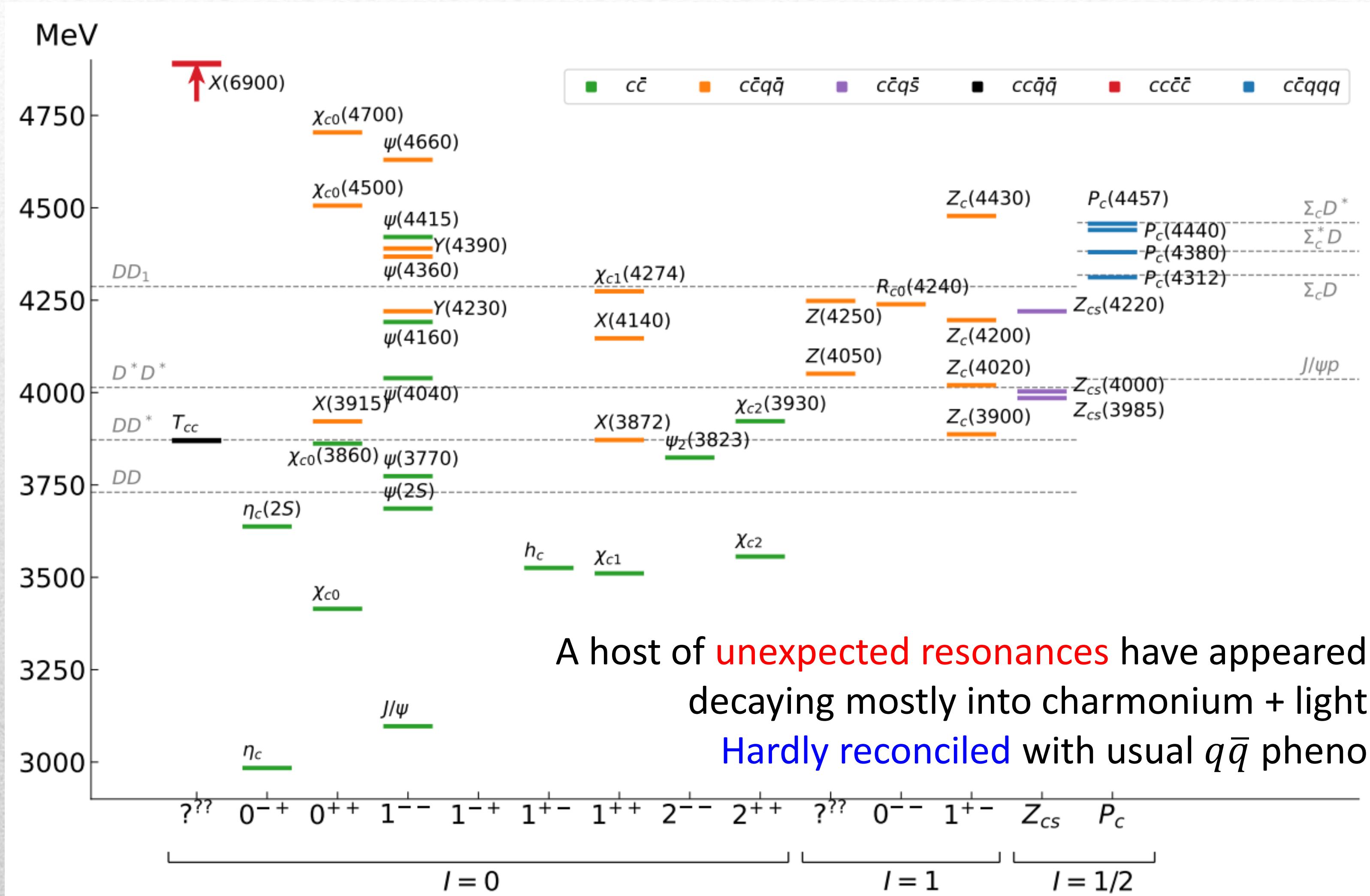
Integrate out heavy DOF

↓

(spectrum), decay & production rates

Exotic landscape in $c\bar{c}$

JPAC, PPNP



A host of unexpected resonances have appeared
decaying mostly into charmonium + light
Hardly reconciled with usual $q\bar{q}$ pheno

Exotic landscape

Broad mesons seen in b decay:
$X(4140)$, Z(4430), $Z_{cs}(4000)$...

Scarce consistency between various production mechanisms

Narrow structures seen in b decay:
$X(3872), P_c, (P_{cs})$

Narrow structures seen in e^+e^-:
$X(3872), Y(4260), Z_{c,b}^{(\prime)}$

Why photoproduction?

- It's new: no XYZ state has been uncontroversially seen so far
- Rescattering mechanisms that could mimic resonances in multibody decays can be controlled better (one can change the energy beam but not the B mass…)
- The framework is (relatively) clean from a theory point of view
- Radiative decays offer another way of discerning the nature of the states

Equivalent Photon Approximation

- The electromagnetic interaction of fast charged particles with nuclei can be reduced to the effective interaction of equivalent flux of photons distributed with some density n(ω) on a frequency (energy) spectrum.*
- The EPA (Weizsäcker-Williams' method) was derived in details by V.M. Budnev et al.** in the form applicable for the MC applications to simulate electronuclear processes.

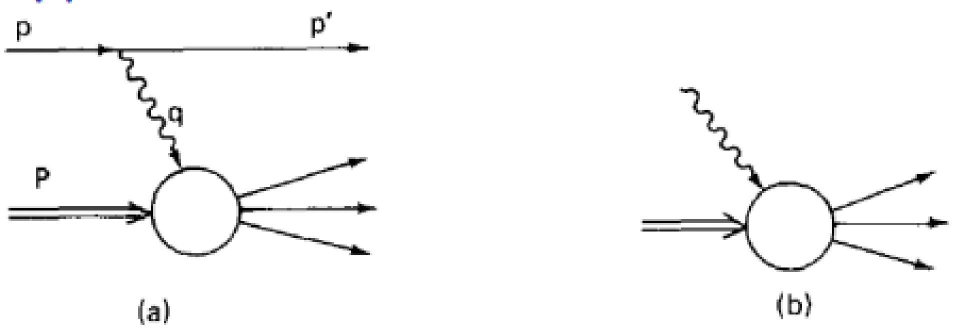


Fig. 35. Electroproduction and photo-absorption.

$$d\sigma_{ep} = \sigma_\gamma(\omega)\,dn$$

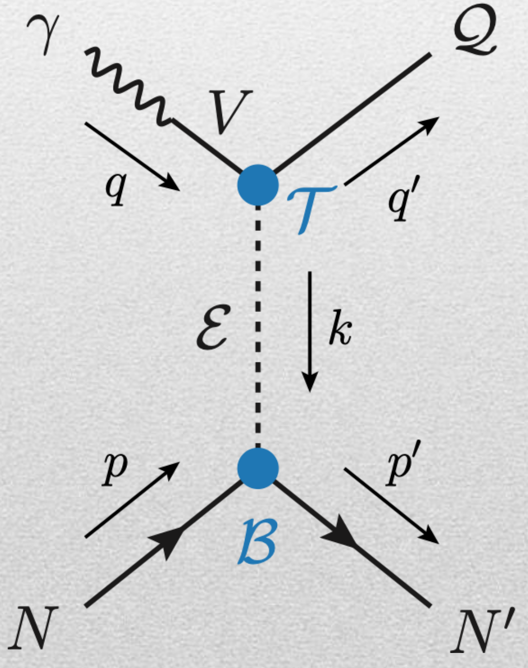
$$(E - \omega \gg m_e)$$

ω/E may be not small(!)

P. Degtiarenko

Exclusive (quasi-real) photoproduction

- XYZ have so far not been seen in photoproduction: independent confirmation
- Not affected by 3-body dynamics: determination of resonant nature
- Experiments with high luminosity in the appropriate energy range are promising
- We study near-threshold (LE) and high energies (HE)
- Couplings extracted from data as much as possible, not relying on the nature of XYZ



M. Albaladejo et al. [JPAC], PRD

$$< \lambda_Q \lambda'_N | T | \lambda_\gamma \lambda_N >= \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \mathcal{T}^{\alpha_1 \cdots \alpha_j}_{\lambda_V = \lambda_\gamma, \lambda_Q} \mathcal{P}_{\alpha_1 \cdots \alpha_j ; \beta_1 \cdots \beta_j} \mathcal{B}^{\beta_1 \cdots \beta_j}_{\lambda_N \lambda'_N}$$

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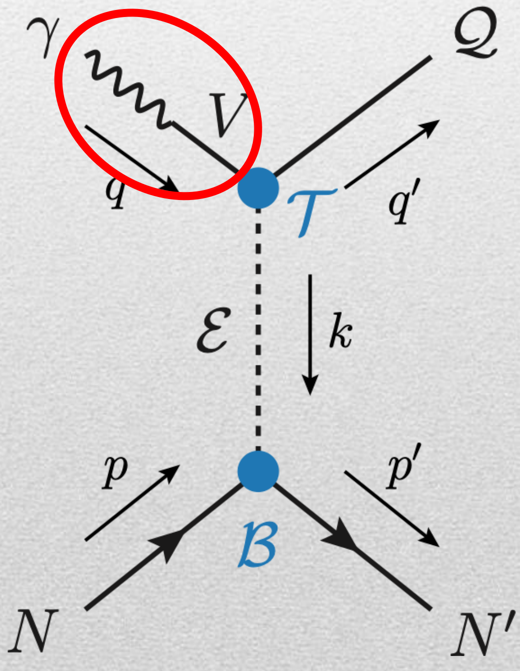

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VMD is used to couple the incoming photon to a vector quarkonium V

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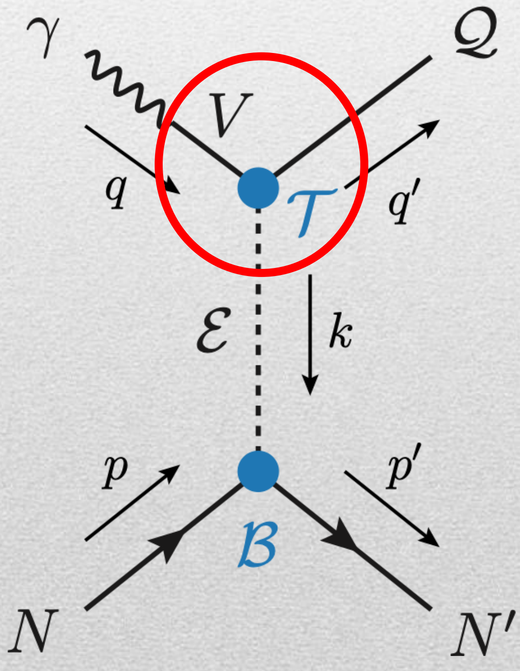

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Top vertex from measured $\mathcal{Q} \to V\mathcal{E}$ decay width

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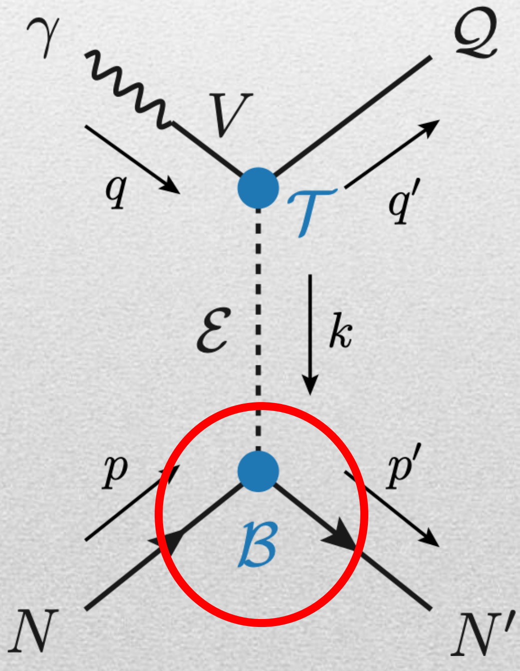

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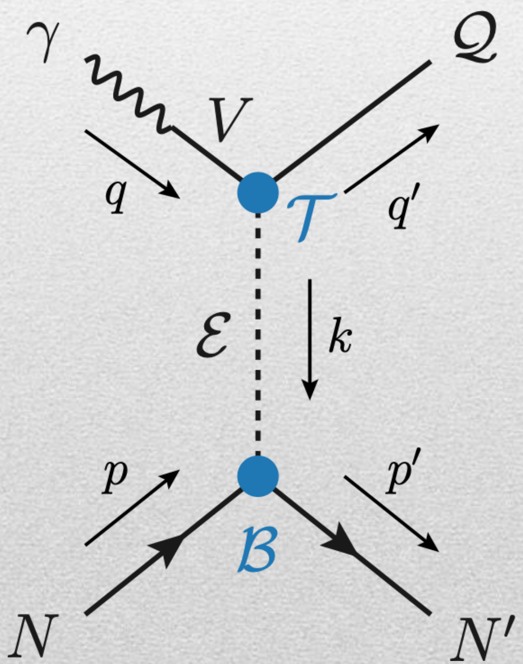
Bottom vertex from standard photoproduction pheno, exponential form factors to further suppress large t

Threshold vs. high energy

- Fixed-spin exchanges expected to hold in the low energy region
- t channel grows as s^j, exceeding unitarity bound, Regge physics kicks in: Reggeized tower of particles with arbitrary spin at HE



$$s^j \longrightarrow s^{\alpha_0+\alpha' t}$$

Holds at low energy, fixed spin

Holds at high energy, resummation of leading s power

- If $\varepsilon \neq \mathbb{P}$, $\alpha_0 < 1$, $d\sigma/dt$ decreases with energy
- Exchange of heavy particles further suppressed

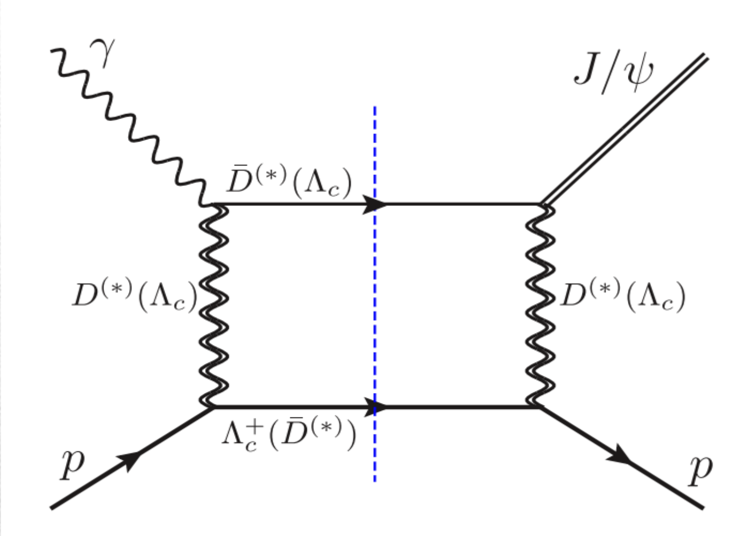
Exchanges vs. rescattering

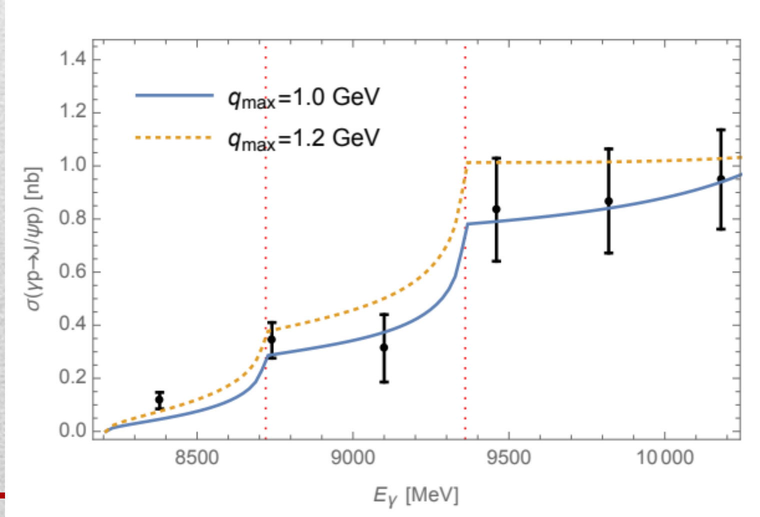
At threshold an alternative production mechanism can be given by open charm rescattering

The box mechanism, together with known couplings and form factors, saturate the J/ψ photoproduction cross section

M. Du et al., EPJC

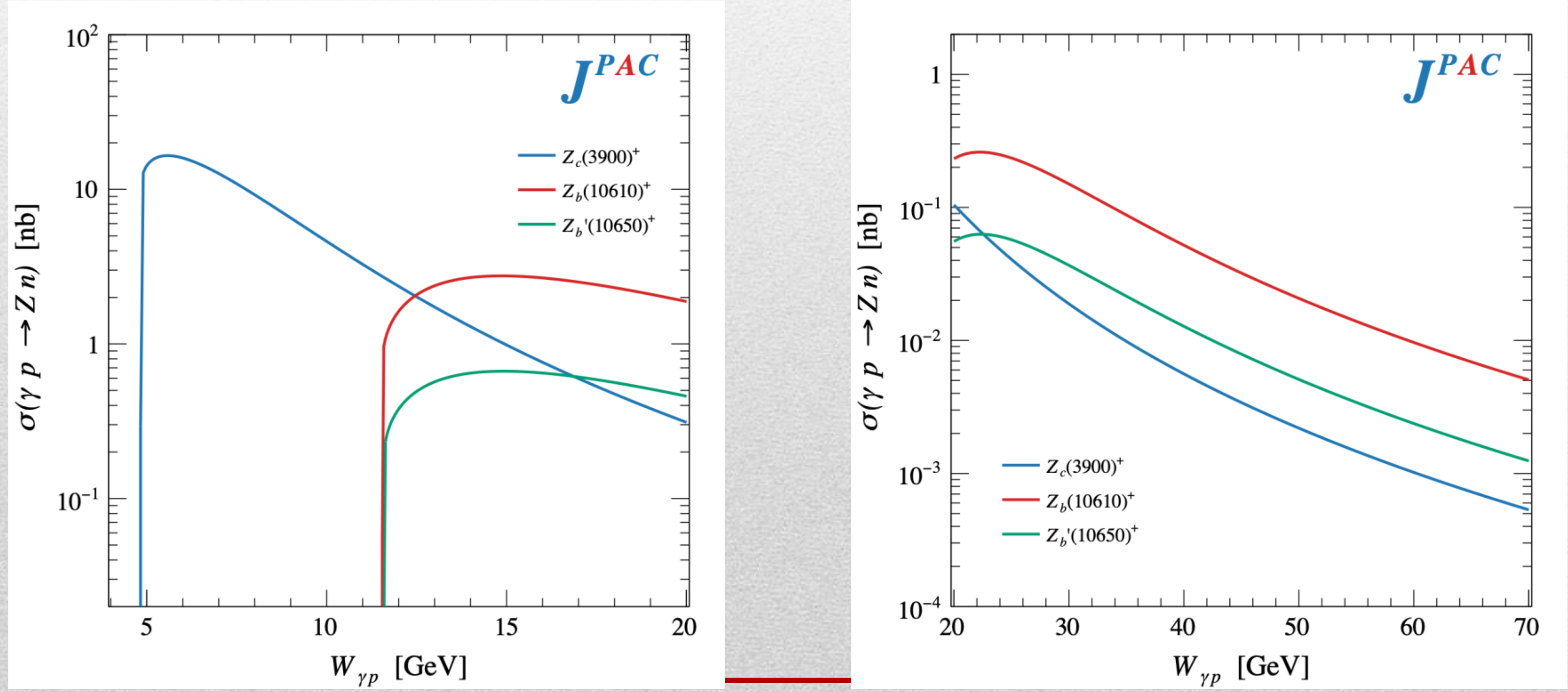
Duality arguments might suggest the two pictures are not alternative,
hopefully yielding to similar predictions





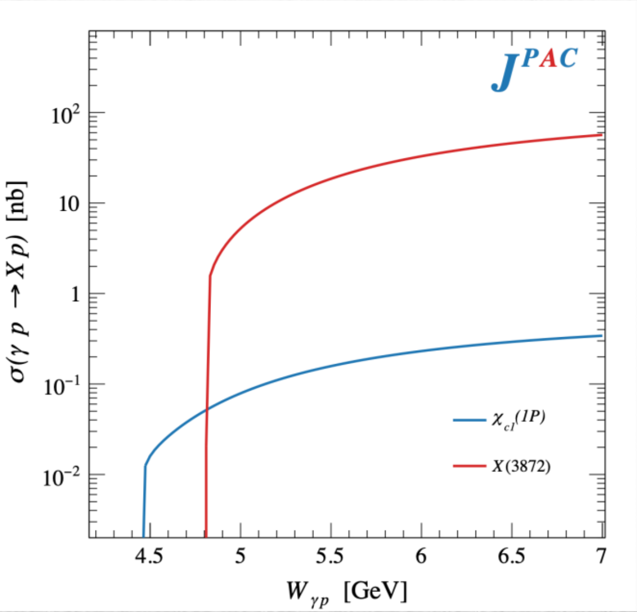
Z photoproduction

- The Zs are charged charmoniumlike 1^{+-} states close to open flavor thresholds
- Focus on $Z_c(3900)^+ \to J/\psi\, \pi^+, Z_b(10610)^+, Z_b'(10650)^+ \to \Upsilon(nS)\, \pi^+$
- The pion is exchanged in the t-channel

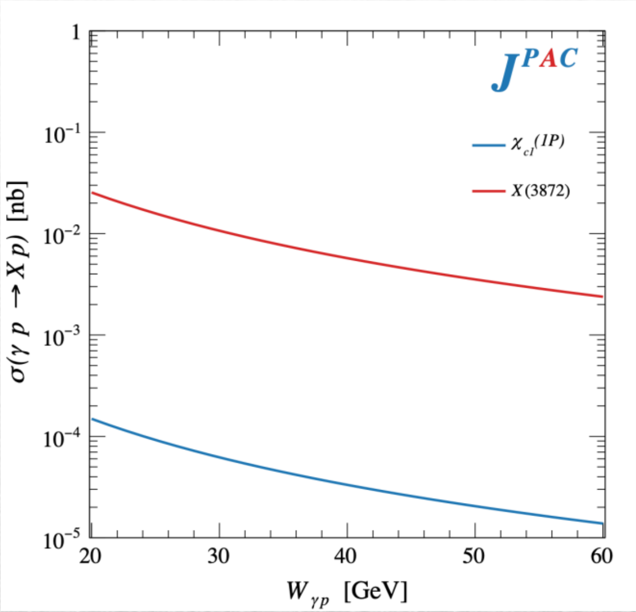


X photoproduction

- Focus on the famous 1^{++} $X(3872) \to J/\psi\, \rho, \omega$
- **ω** and **ρ** exchanges give main contributions:



Large theory uncertainty in the intermediate region



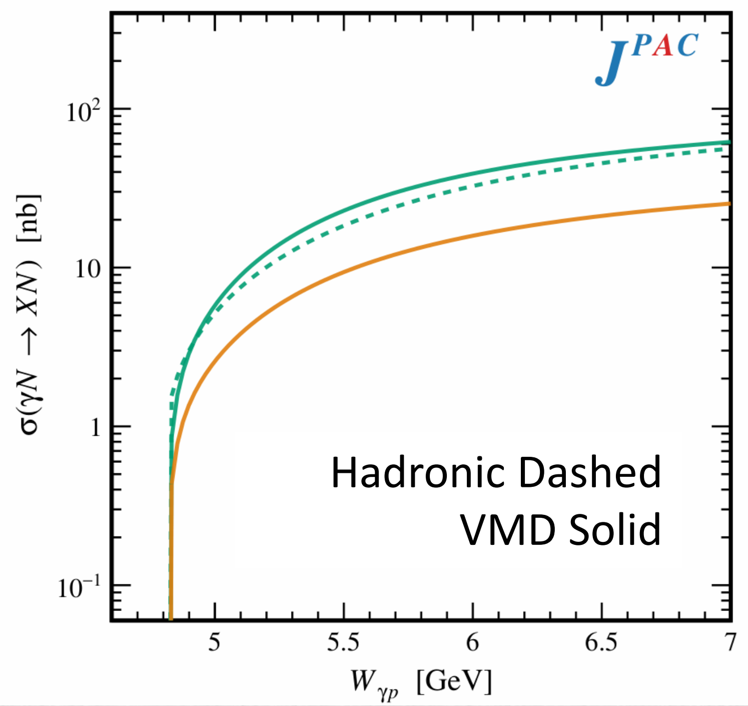
In defense of VMD

The weak point of the whole approach is the use of VMD
While in the light sector it works reasonably, for heavy states is not justified
There are hints that it fails badly for J/ψ photoproduction (see D. Winney's talk)

The X(3872) observed in purely hadronic and photonic modes gives us unique clue to efficacy of VMD

Belle extracted the coupling $X(3872) \to \gamma\gamma^*$, that can be compared with the VMD predictions from $X(3872) \to J/\psi\ \rho, \omega$

$\mathcal{Q}$	V	$\mathcal{E}$	$g_{\mathcal{Q}\gamma\gamma^*} \times 10^3$
$X(3872)$	γ	γ^*	3.2
	J/ψ	ρ	5.38
		ω	3.54



Y (vector) photoproduction

Diffractive production, dominated by Pomeron (2-gluon) exchange

$$R_Y = \frac{e f_\psi}{m_\psi} \sqrt{\frac{g^2(Y \to \psi\pi\pi)}{g^2(\psi \to \gamma g g)} \frac{g^2(\psi' \to \psi g g)}{g^2(\psi' \to \psi\pi\pi)}}$$

Existing data allow to put a 95% upper limit on the ratio of $\psi'/Y(4260)$ yields

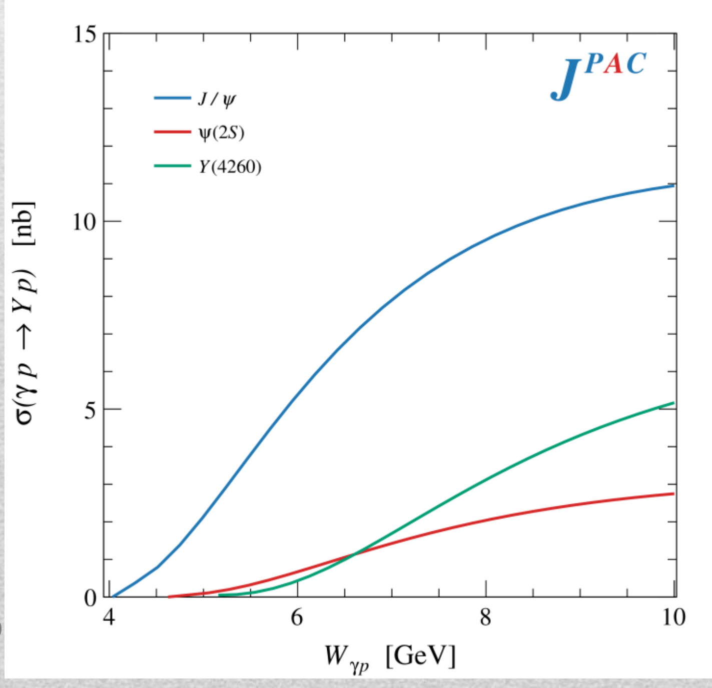
Assuming previous formula, one gets:

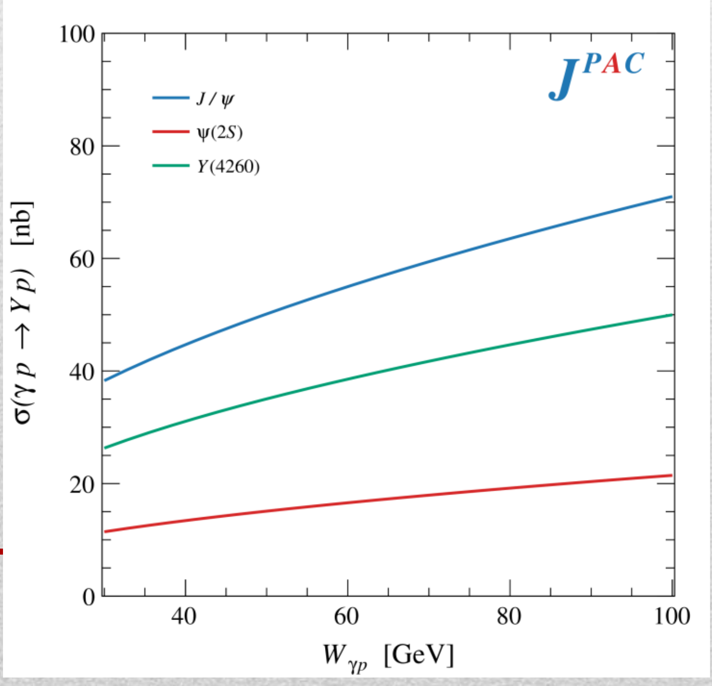
$\Gamma_{ee}^{Y} = 930\ eV$

(cfr. hep-ex/0603024, 2002.05641)

$BR(Y \to J/\psi\pi\pi) = 0.96\%$

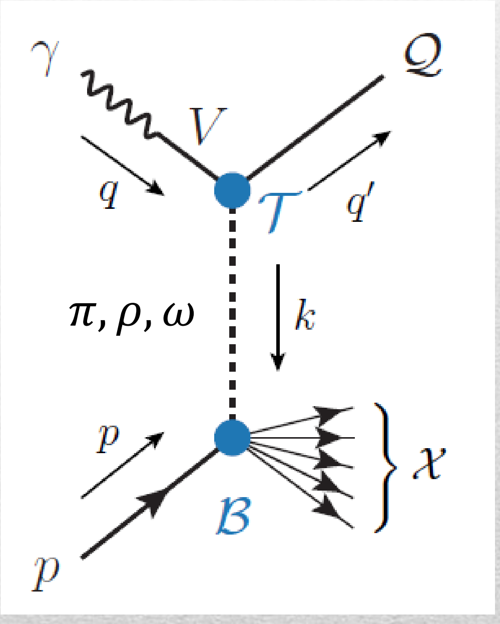
$R_Y = 0.84$

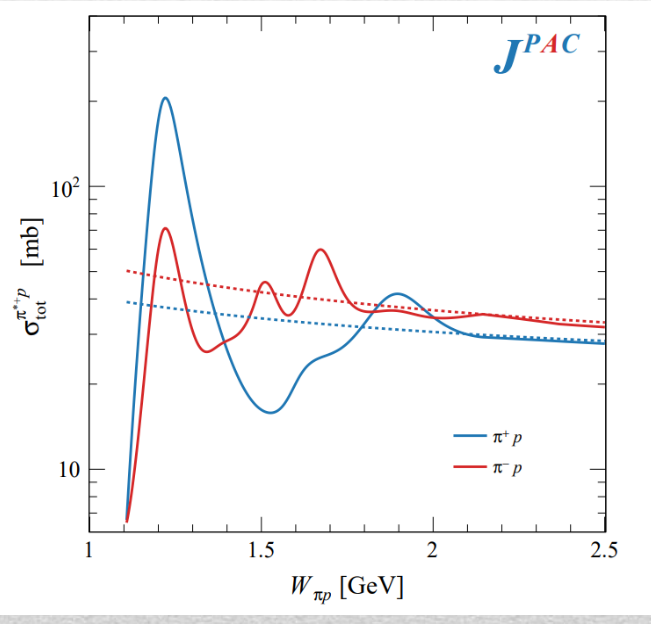


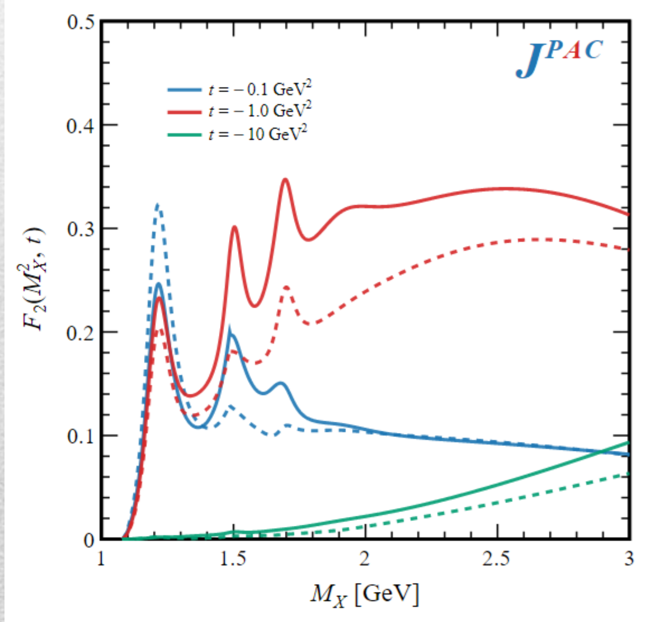


Semi-inclusive photoproduction

- Semi-inclusive cross sections are typically larger
- For small t and large x, one can assume the process to be dominated by pion/vector exchange
- The bottom vertex depends on the (known) total pion-nucleon cross section, or encoded in the PDFs at large x

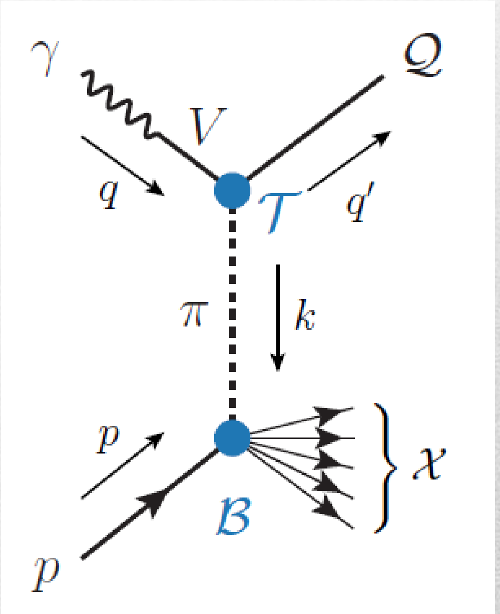


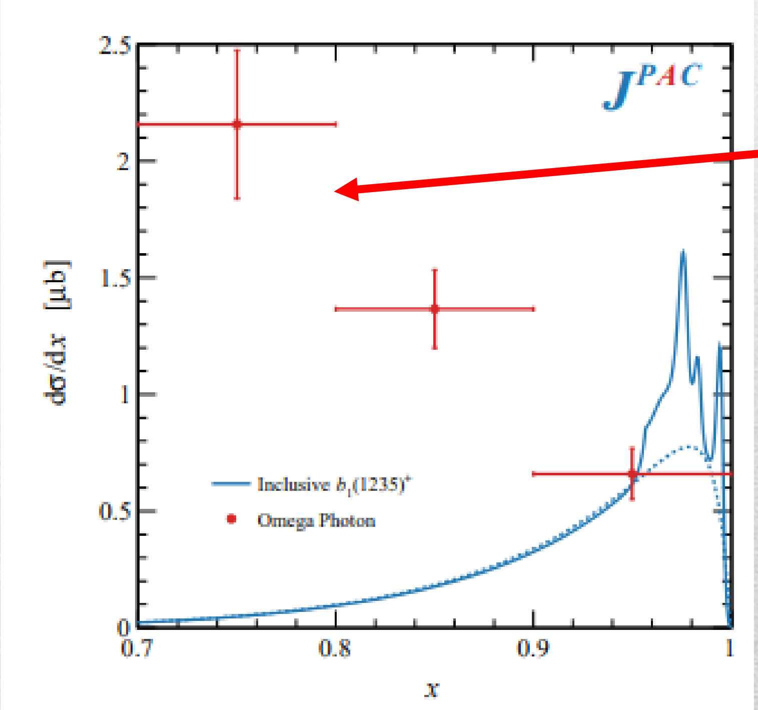




Semi-inclusive photoproduction (pion ex)

- The bottom vertex depends on the (known) pion-proton total cross section
- The pion is exchanged in the t-channel
- Model benchmarked on b_1 production



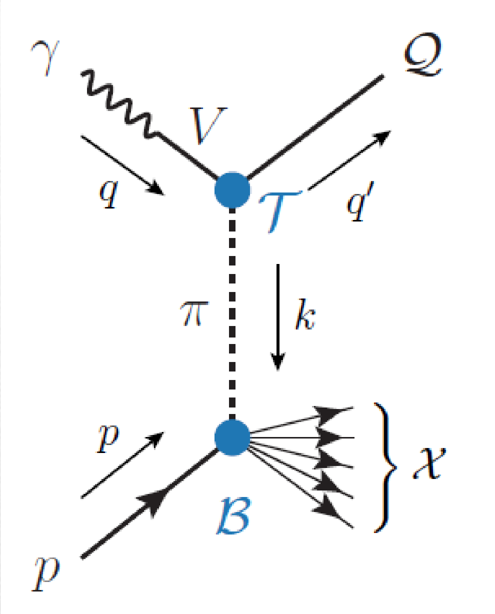


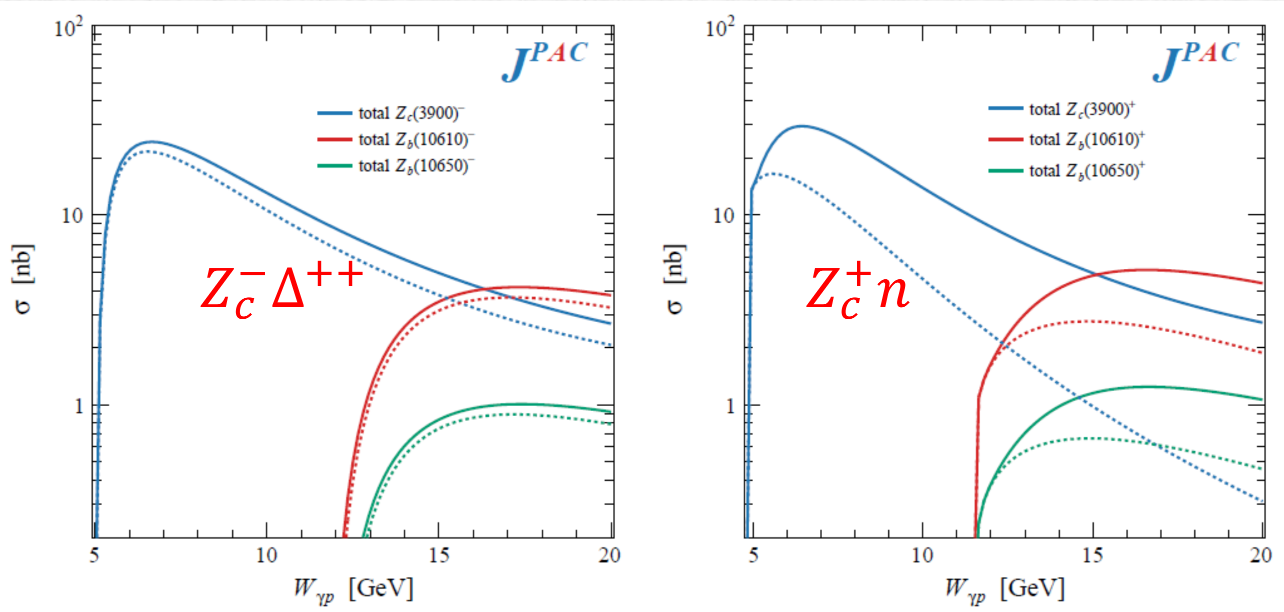
Model underestimates lower bins, conservative estimates

The model is expected to hold in the highest bin

Semi-inclusive photoproduction (pion ex)

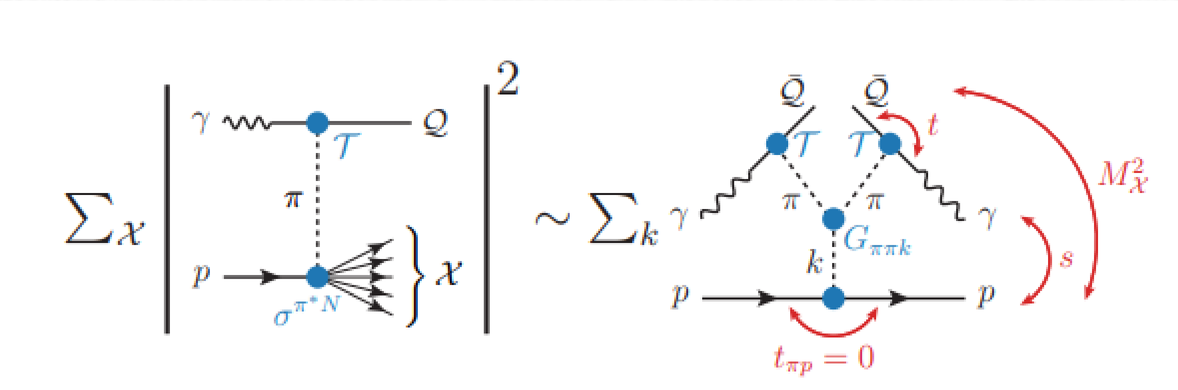
- For the Z_c^+, the inclusive cross section is sizably larger than the exclusive process





Semi-inclusive photoproduction (pion ex)

- At higher energies the triple Regge regime is reached, cross sections saturate

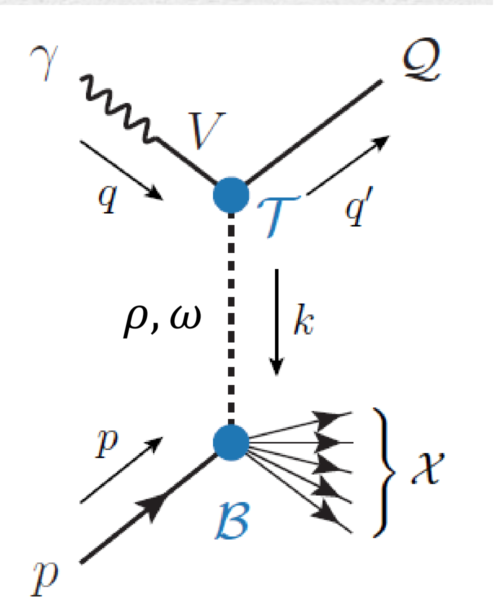


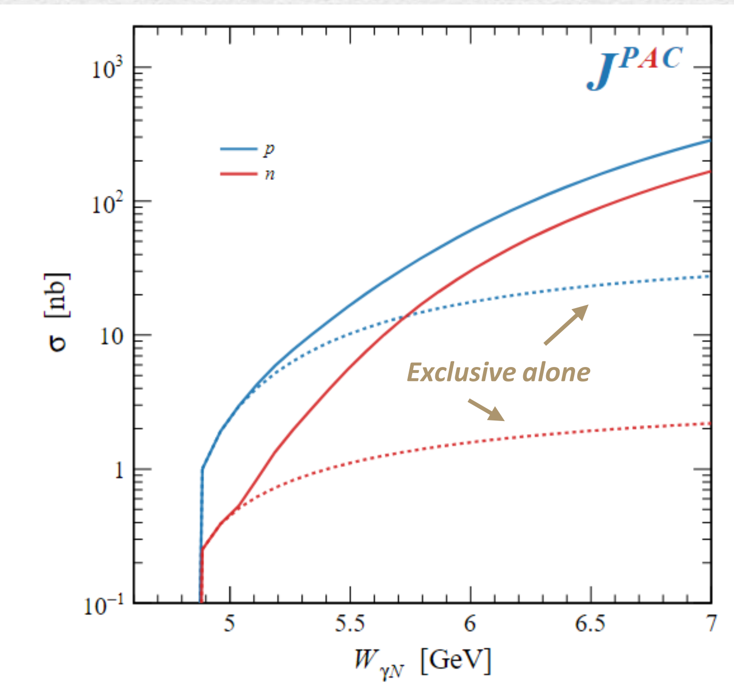
	$\sigma(\gamma p \to \mathcal{Q}^{\pm}\,\mathcal{X})$ [pb]			$\sigma(\gamma p \to \mathcal{Q}^{+} n)$ [pb]		
$\mathcal{Q}$	30 GeV	60 GeV	90 GeV	30 GeV	60 GeV	90 GeV
$b_1(1235)$	$60 \cdot 10^3$	$60 \cdot 10^3$	$61 \cdot 10^3$	43	2.3	$< 10^{-8}$
$Z_c(3900)$	187	146	140	19	1.0	$< 10^{-8}$
$Z_b(10610)$	163	15	5	150	10	$< 10^{-8}$
$Z_b(10650)$	40	4	1	37	2.4	$< 10^{-8}$

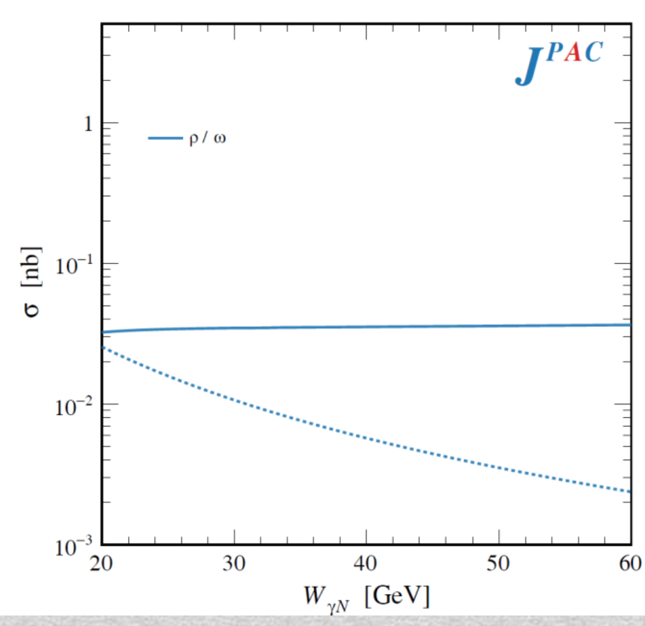
Semi-inclusive photoproduction (vector ex)

- PDFs encode the information about $\gamma\, p$ inclusive scattering for different photon polarizations
- Using VMD, one can infer the $\rho\, p$ and $\omega\, p$ inclusive cross sections
- We use the phenomenological parametrization in the resonance region

Christy and Bosted, PRC





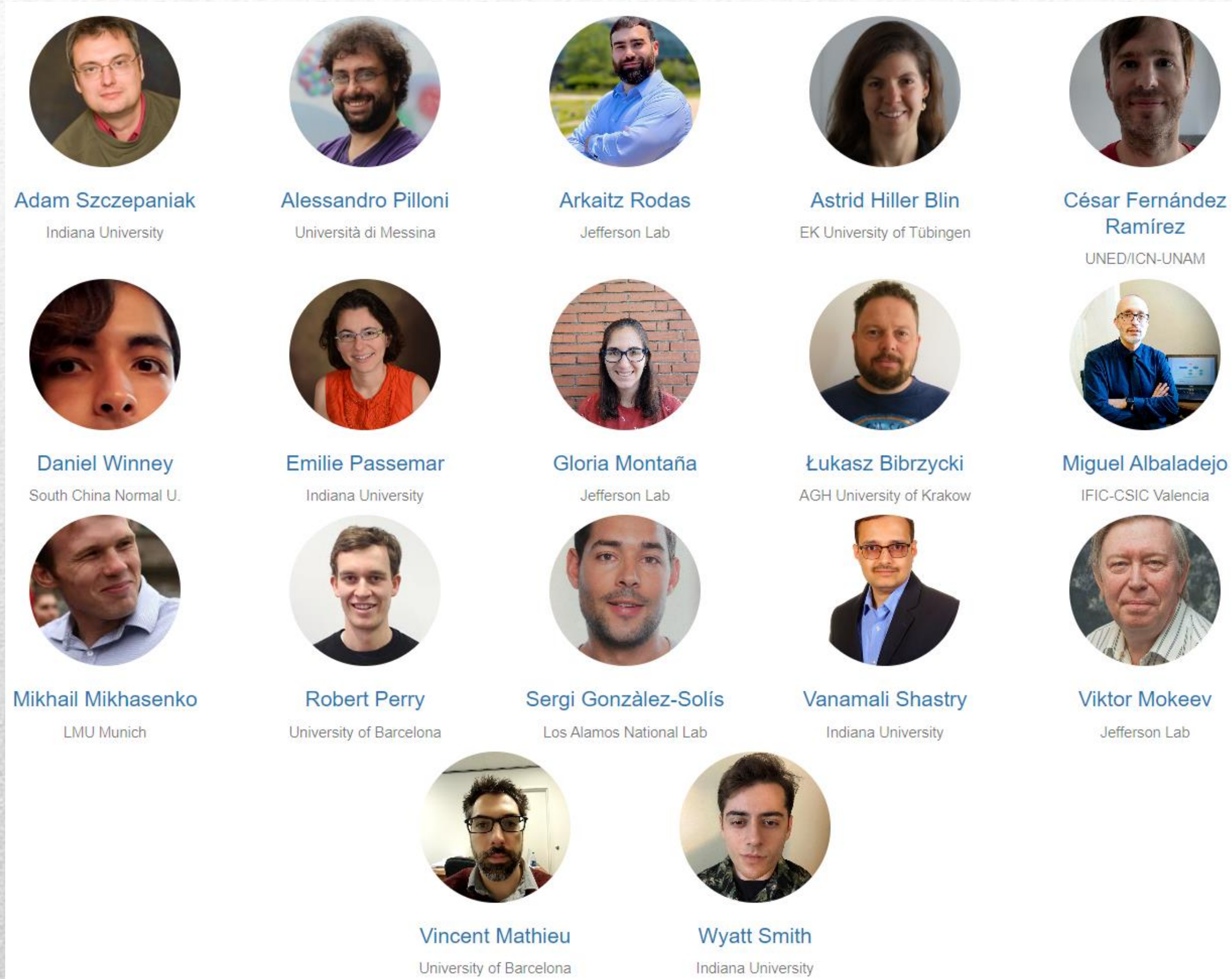


Conclusions

- Predictions for XYZ at new colliders are on the way
- New facilities that can measure XYZ with unexplored production mechanisms are extremely valuable
- It is important to estimate open charm cross section in oder to assess the validity of VMD, as well of factorization

Thank you!

Joint Physics Analysis Center



JPAC

Exclusive reactions: 2008.01001

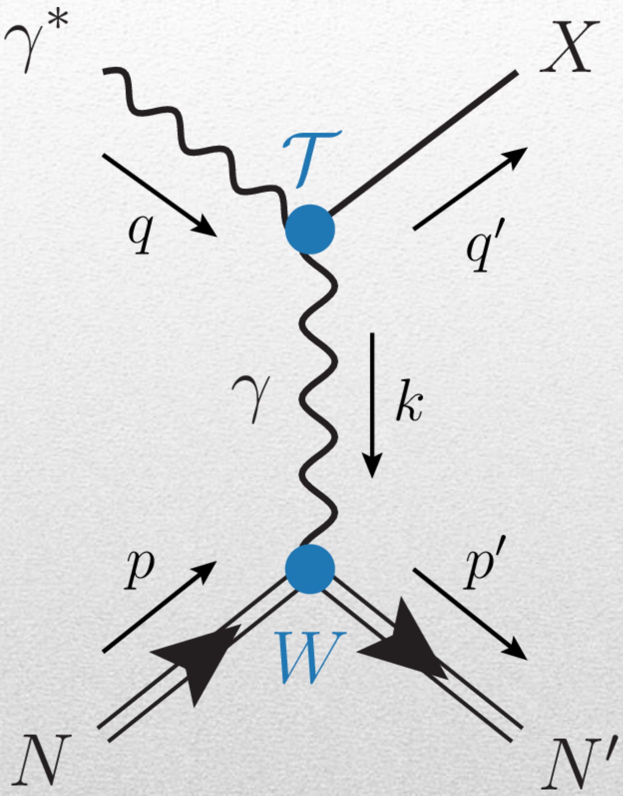
Inclusive reactions: 2209.05882

Code available on https://github.com/dwinney/jpacPhoto

https://jpac-physics.org

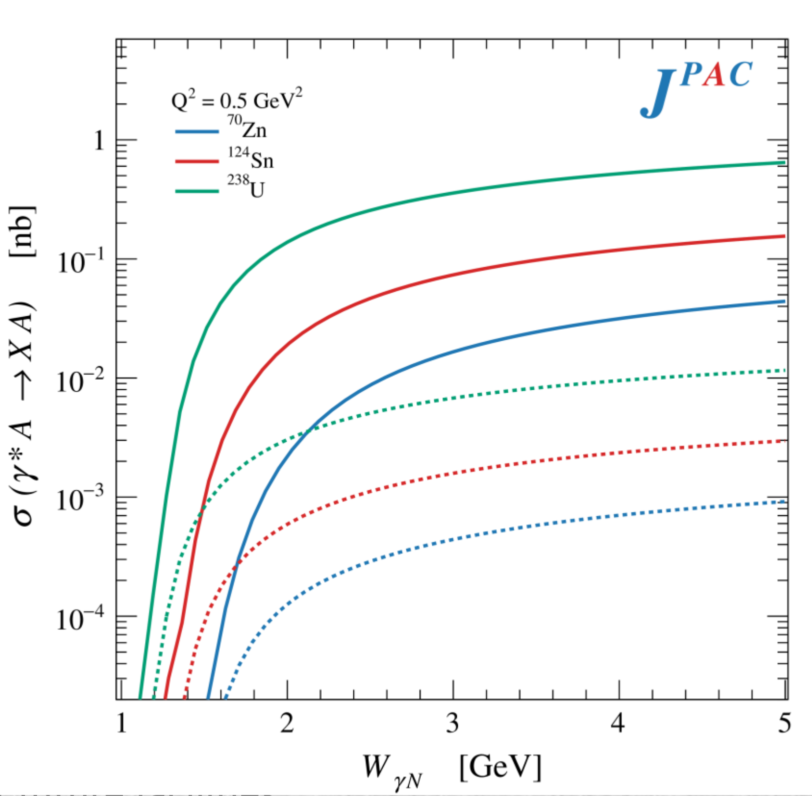
BACKUP

Primakoff X photoproduction



Using measurement of $\Gamma(X \to \gamma\gamma^*)$ from Belle, one can get predictions for Primakoff

Makes use of ion targets, enhancement of cross sections as Z^2



Y (vector) photoproduction

- Focus on the 1^{--} $Y(4260) \to J/\psi\, \pi^+\pi^-$, check with $\psi' \to J/\psi\, \pi^+\pi^-$
- Diffractive production, dominated by Pomeron (2-gluon) exchange
- Good candidates for EIC: diffractive production increases with energy!
- We have $\gamma\psi$-pomeron coupling from our analyses 1606.08912, 1907.09393

How to rescale from J/ψ to ψ' ?

$$R_{\psi'} = \sqrt{\frac{g^2(\psi' \to \gamma g g)}{g^2(\psi \to \gamma g g)}} \sim 0.55 \qquad g^2(\psi \to \gamma g g) = \frac{6 m_\psi \mathcal{B}(\psi \to \gamma g g)\Gamma_\psi}{\mathrm{PS}(\psi \to \gamma g g)}$$

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How to rescale from J/ψ to $Y(4260)$?

We assume VMD and $g^2(Y \to \psi\pi\pi) = g^2(Y \to \psi g g) \times g^2(gg \to \pi\pi)$ (Novikov & Shifman)

$$R_Y = \frac{e f_\psi}{m_\psi} \sqrt{\frac{g^2(Y \to \psi\pi\pi)}{g^2(\psi \to \gamma g g)} \frac{g^2(\psi' \to \psi g g)}{g^2(\psi' \to \psi\pi\pi)}}$$

Caveat : $BR(Y \to \psi\pi\pi)$ only known times the leptonic width Γ_{ee}^Y

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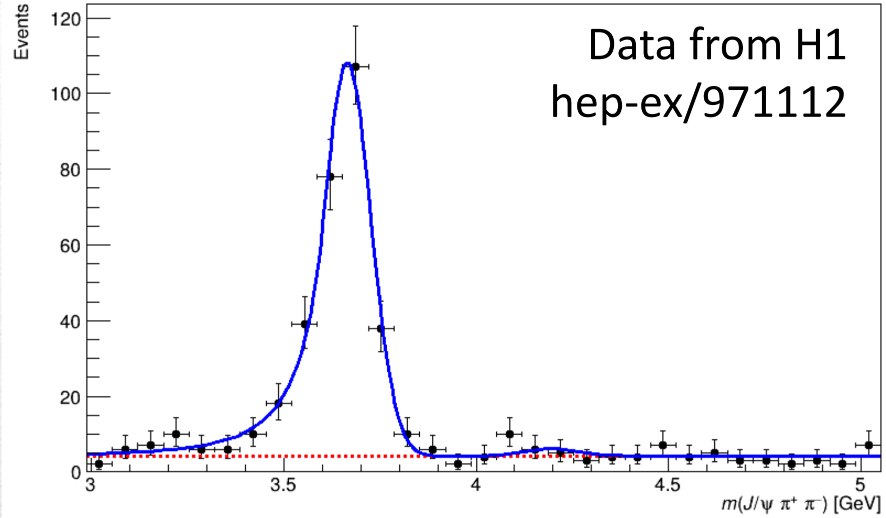

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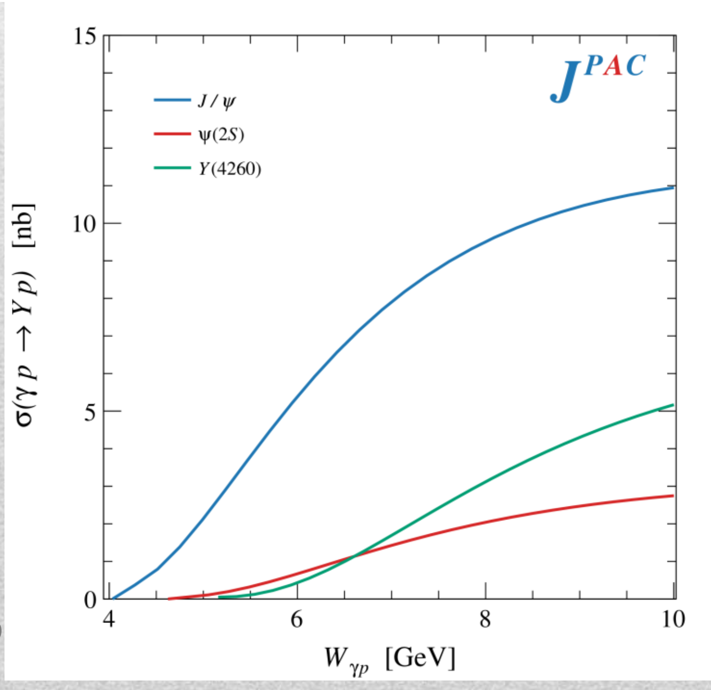
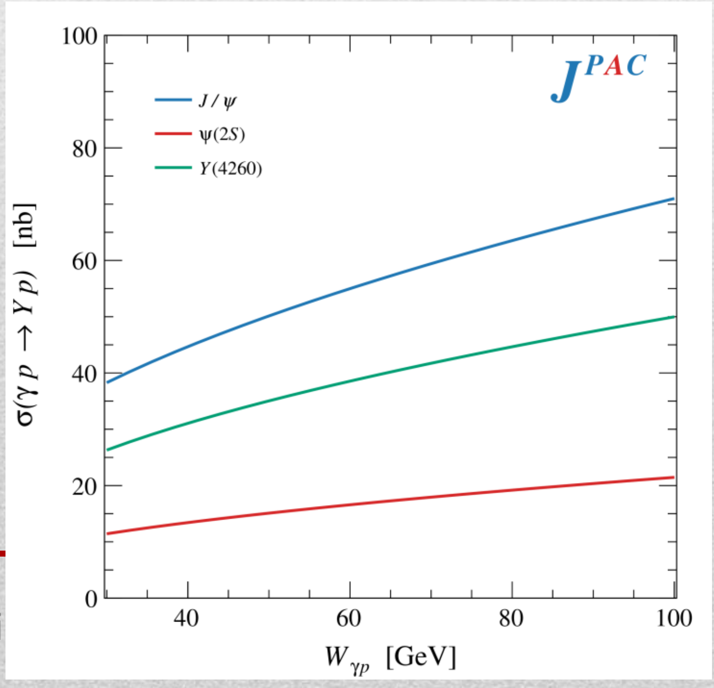


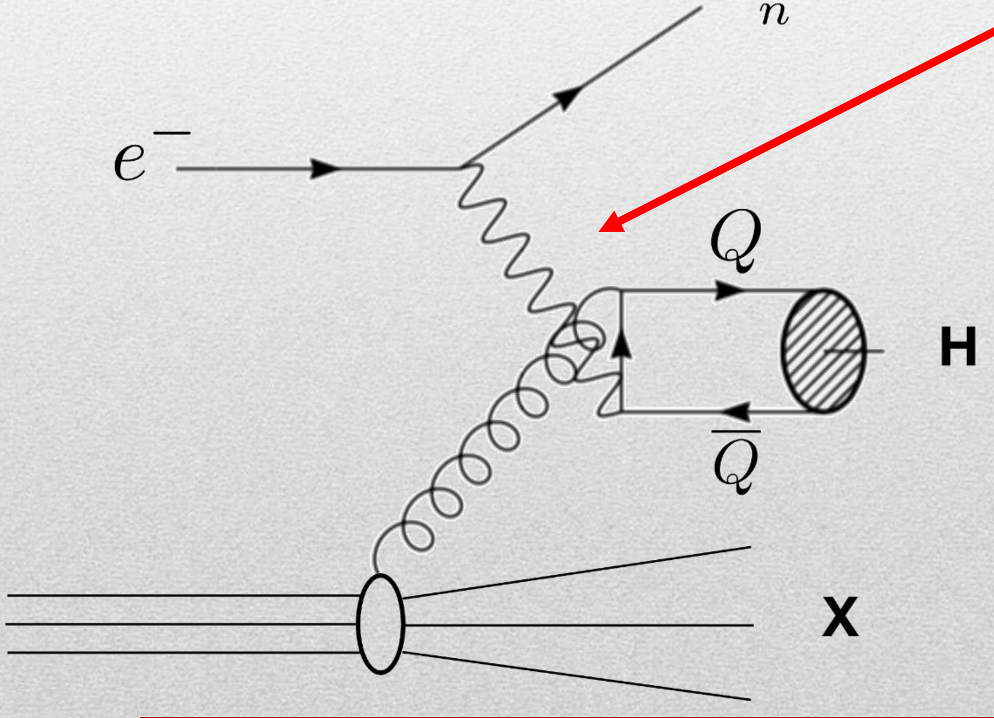


Semi-inclusive X production

X. Yao

For large Q^2 one can invoke NRQCD factorization to describe quarkonium(-like) production

$$d\sigma(e^- + p \to H + X) = \sum_n d\sigma(e^- + p \to Q\overline{Q}(n) + X)\langle\mathcal{O}^H(n)\rangle$$



Perturbative partonic matrix element, calculable

Nonperturbative transition matrix element $Q\bar{Q} \to H$ fitted from data

Semi-inclusive X production

One can assume the same NRQCD factorization for exotics, independent of their internal structure

$$\sigma[X(3872)] = \sum_n \hat{\sigma}[c\bar{c}_n] \, \langle \mathcal{O}_n^X \rangle$$

$$\mathrm{Br}[X \to J/\psi \pi^+ \pi^-] \left(\langle \mathcal{O}_8^X(^3S_1) \rangle + 0.159 \, \langle \mathcal{O}_8^X(^1S_0) \rangle + 0.085 \, \langle \mathcal{O}_1^X(^1S_0) \rangle + 0.00024 \, \langle \mathcal{O}_1^X(^3S_1) \rangle \right) = (2.7 \pm 0.6) \times 10^{-4} \text{ GeV}^3$$

Artoisenet and Braaten, PRD81, 114018 from Tevatron data

If one consider the first term only, it leads to

$$\mathrm{Br}[X \to J/\psi \pi^+ \pi^-] \sigma(X(3872), Q^2 > 1 \text{ GeV}) \approx 2.6 \text{ pb} \qquad \sqrt{s} = 100 \text{ GeV}$$

X. Yao