Photoproduction of ordinary and exotic charmonia

Alessandro Pilloni

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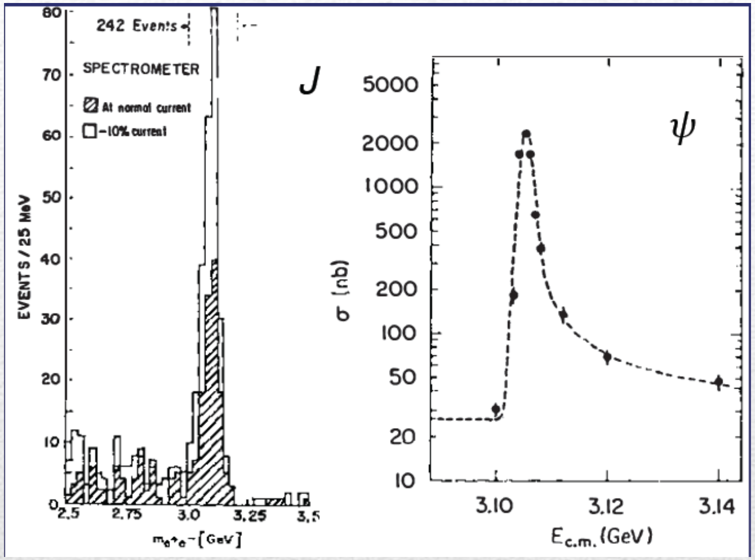
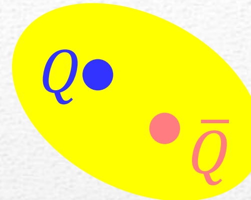
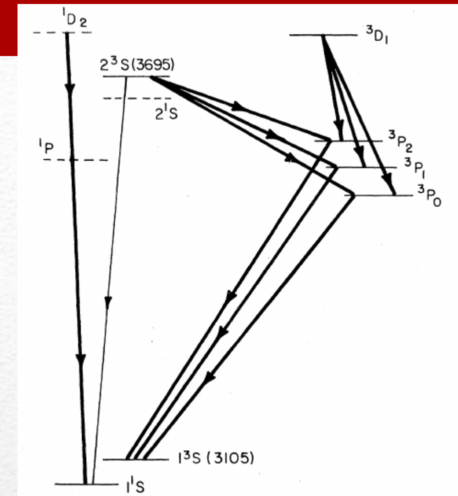
Università degli Studi di Messina
ExoHad Exotic Hadrons Topical Collaboration
INFN Istituto Nazionale di Fisica Nucleare

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...)

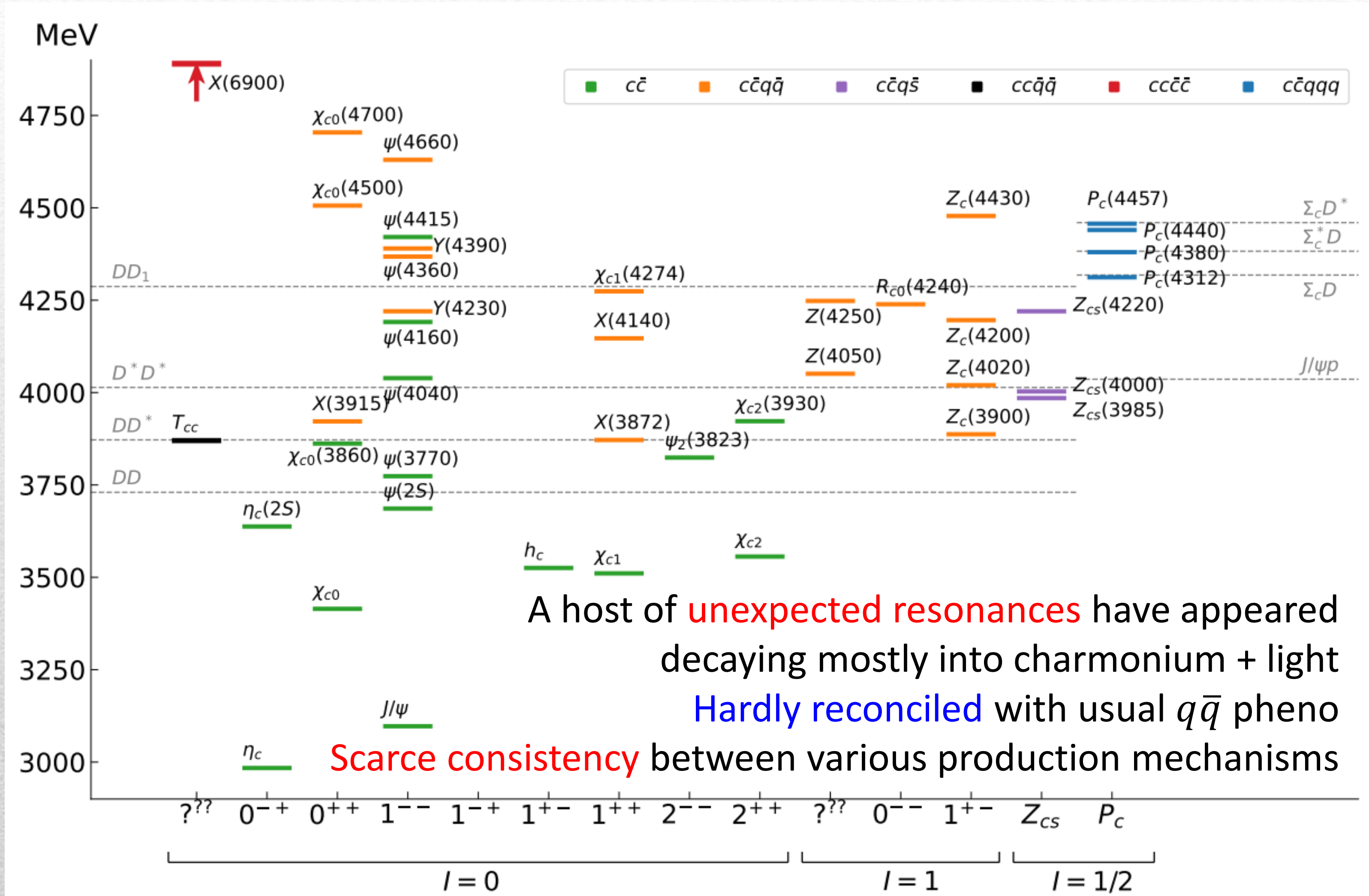
Integrate out heavy DOF

↓

(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

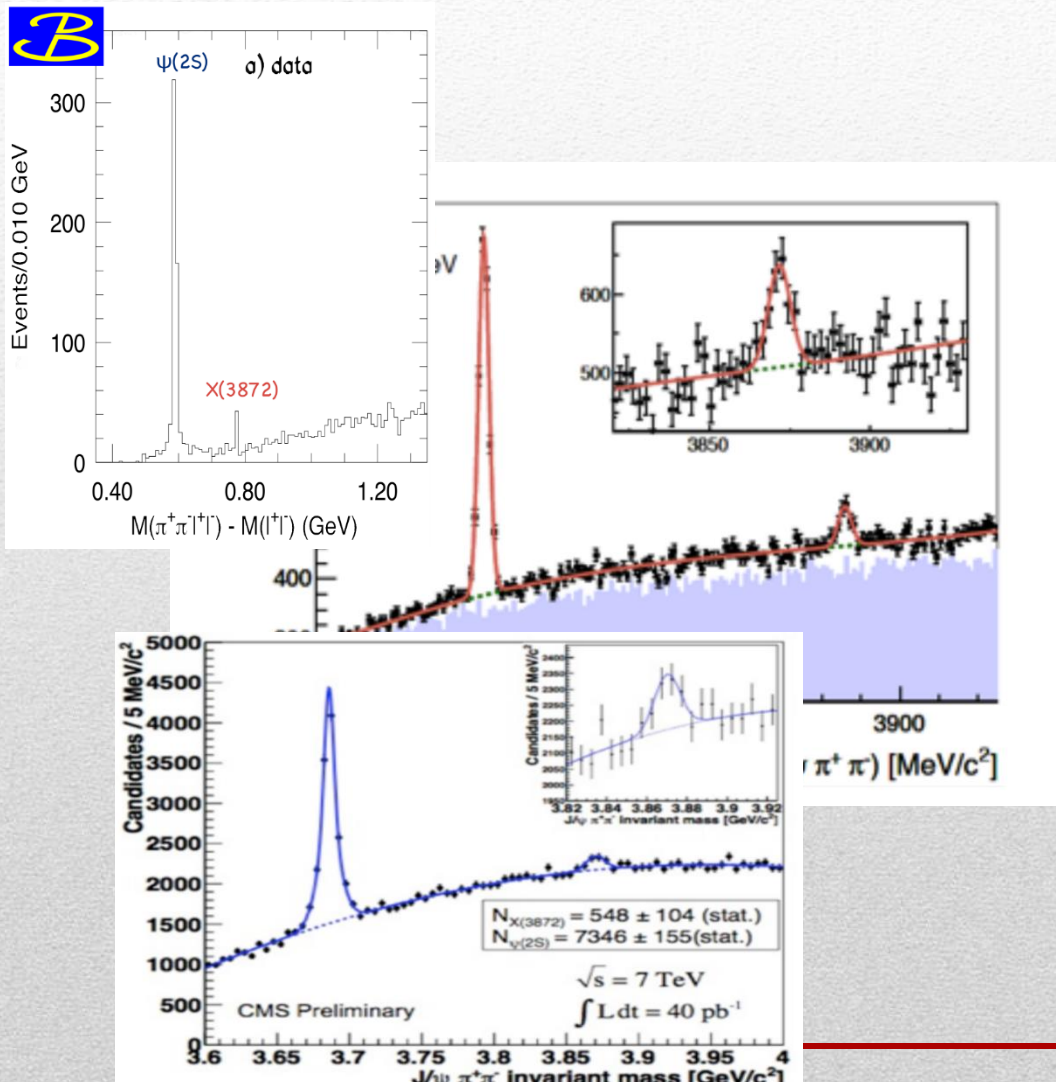
Scarce consistency between various production mechanisms

Definition of exotics

Despite it's wrong, the vaste majority of hadrons obeys QM
Whatever is beyond $q\bar{q}$ for mesons and qqq for baryons is exotic

- Flavor exotics: e.g. doubly charged meson, baryon with positive strangeness
  Ex.: T_{cc}^{+} with $cc\bar{u}\bar{d}$; if OZI rule enforced, $Z_{c,b}$ with $c\bar{c}u\bar{d}$, P_c…
- Spin exotics: J^{PC} not allowed in QM
  Ex.: $\pi_1(1600)$ has $J^{PC} = 1^{-+}$
- Criptoexotics: J^{PC} allowed, but properties not compatible with QM expectations
  Ex.: $Y(4260)$, $\Lambda(1405)$, hybrid baryons, $X(3872)$

$X(3872)$

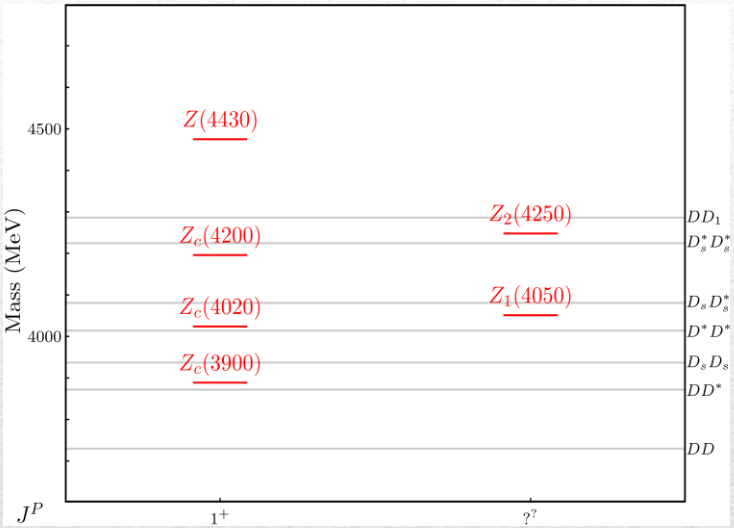


- Discovered in
  $B \to K\, X \to K\, J/\psi\, \pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \ \omega)}{\Gamma(X\to J/\psi\ \ \rho)} \sim 1.1 \pm 0.4$
- Mass prediction not compatible with $\chi_{c1}(2P)$

$M = 3871.65 \pm 0.06\ \text{MeV}$
$M_X - M_{DD^*} = -3 \pm 192\ \text{keV}$
$\Gamma = 1.19 \pm 0.21\ \text{MeV}$

Charged Z states: $Z_c(3900), Z_c'(4020)$

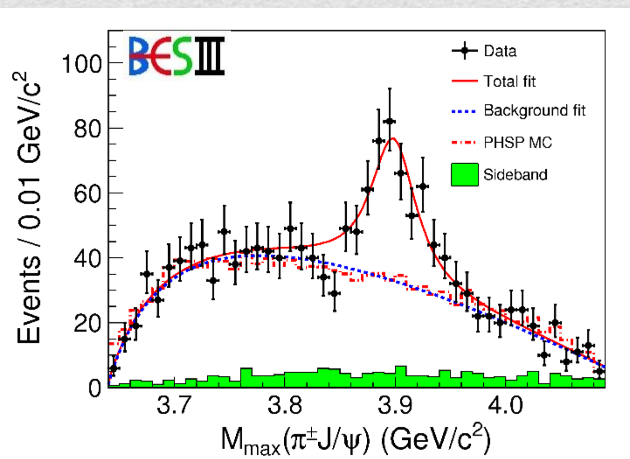
Charged quarkonium-like resonances have been found, **4q needed**

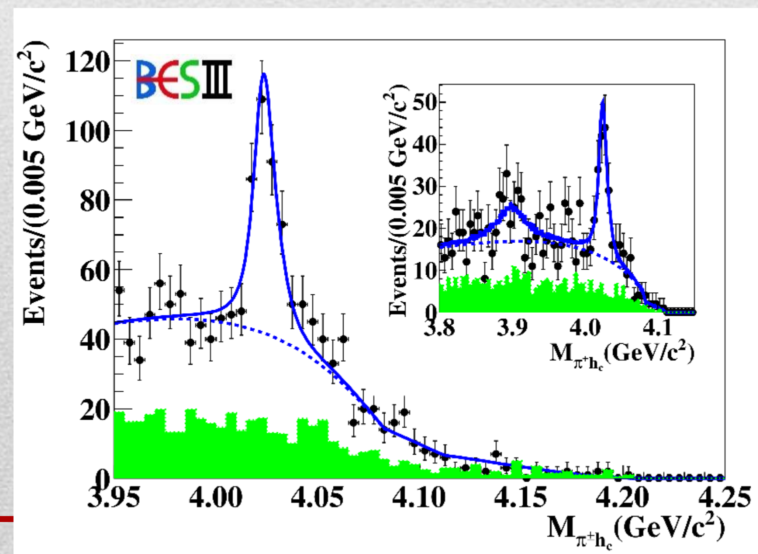


Two states $J^{PC} = 1^{+-}$ appear slightly above $D^{(*)}D^*$ thresholds

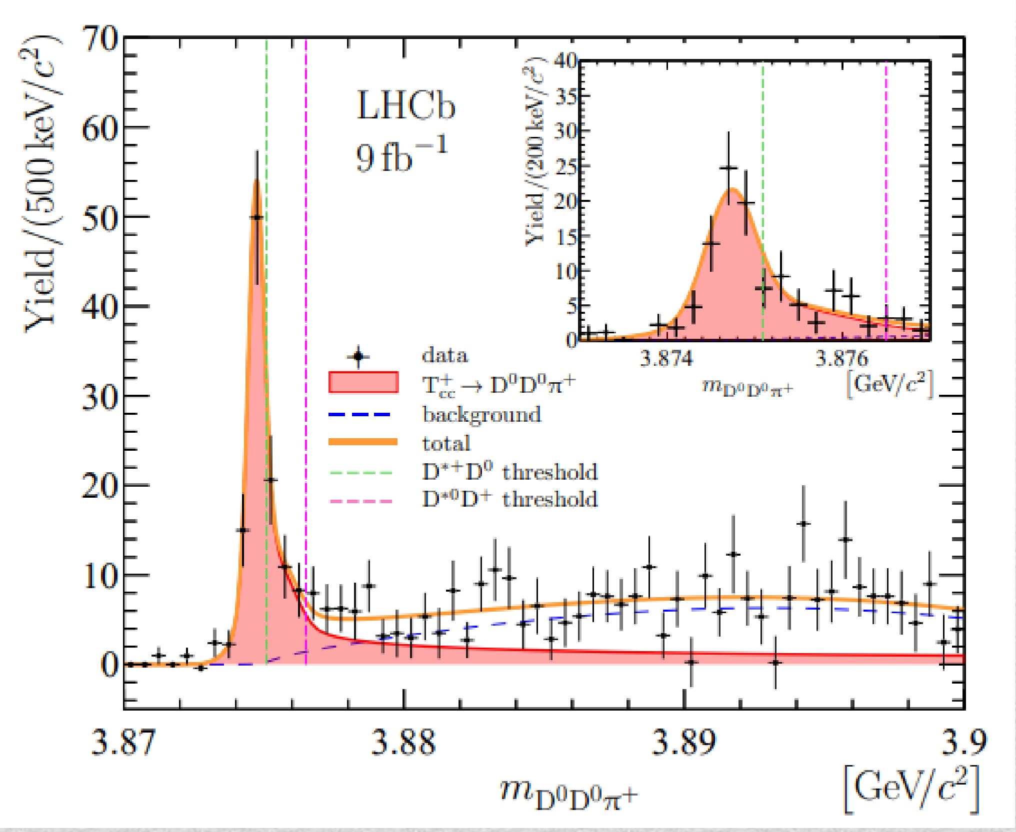
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





Very open charm: the T_{cc}^+



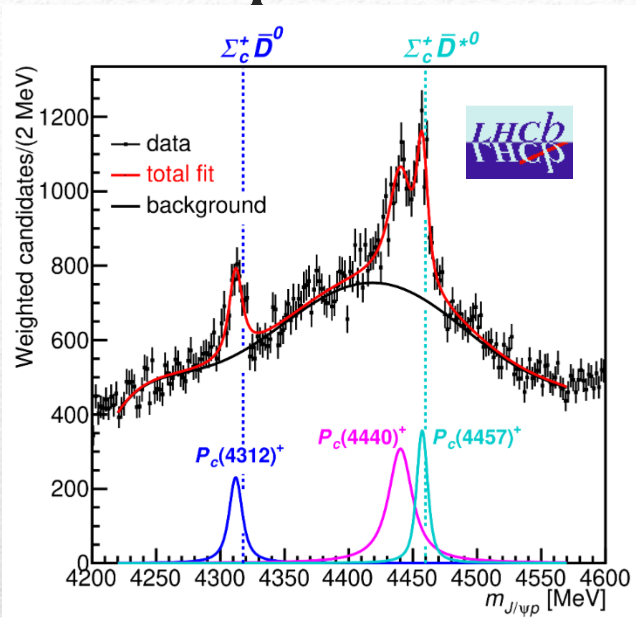
A supernarrow state is seen at the $D^{*+}D^0$ threshold

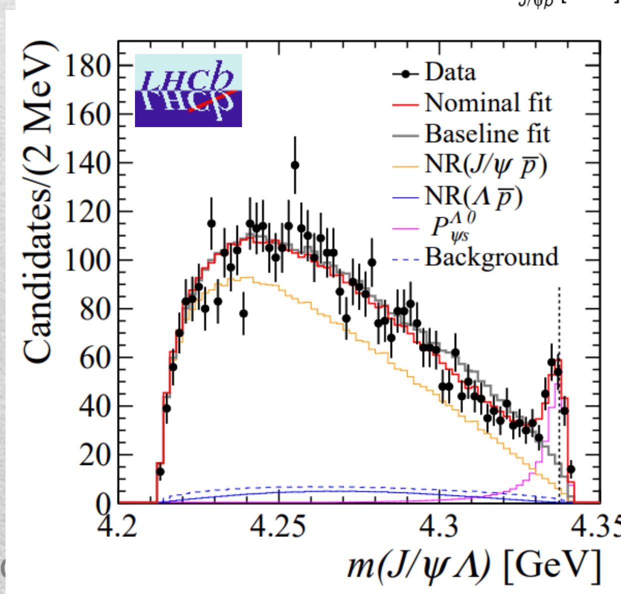
BW parameters give

$\delta m_{BW} = -273 \pm 61 \text{ keV}$
$\Gamma_{BW} = 410 \pm 65 \text{ keV}$

It cannot mix with ordinary charmonia
It does not have lighter open channels

Pentaquarks





LHCb, PRL 115, 072001
LHCb, PRL 117, 082003
LHCb, PRL 122, 222001
LHCb, PRL131, 031901

Initially a broad and a narrow state with opposite parities seen in $\Lambda_b \to J/\psi\ p\ K^-$ decay

A higher statistics 1D analysis is able to resolve the fine structure of the $P_c(4450)$ peak.

Moreover, a new isolated $P_c(4312)$ at the $\Sigma_c^+ \overline{D}^0$ threshold appears

Evidence for strange partners as well

Options on the market

Quark-level calculations:

- Quark models, pNRQCD, Hybrids, ...
- Spectrum generally calculated as bound states of some potential
- Decay rates as «overlap integrals» between two static configurations

Comprehensive picture ✓ Little scattering dynamics ✘

Hadron level calculations:

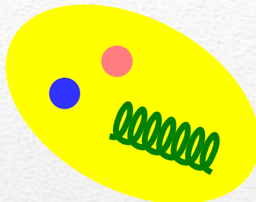
- Compact states vs. molecules, triangles...
- States as poles of scattering amplitudes
- Couplings as residues at the poles

Scattering dynamics ✓ More case-by-case ✓✘

Models for every taste

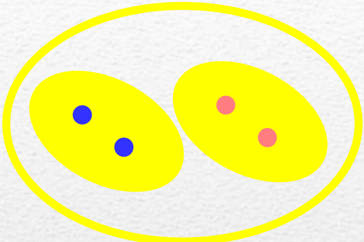
Compact

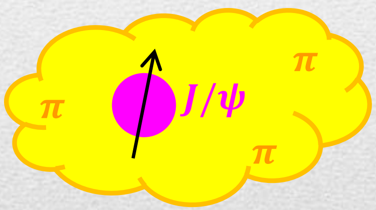
Extended



Hybrids
Containing gluonic degrees of freedom

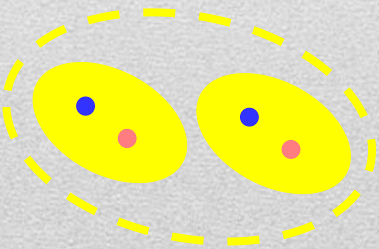
Multiquark
Several (cluster) of valence quarks





Hadroquarkonium
Heavy core interacting with a light cloud via Van der Waals forces

Rescattering effects
Structures generated by cross-channel rescattering, very process-dependent



Molecule
Bound or virtual state generated by long-range exchange forces

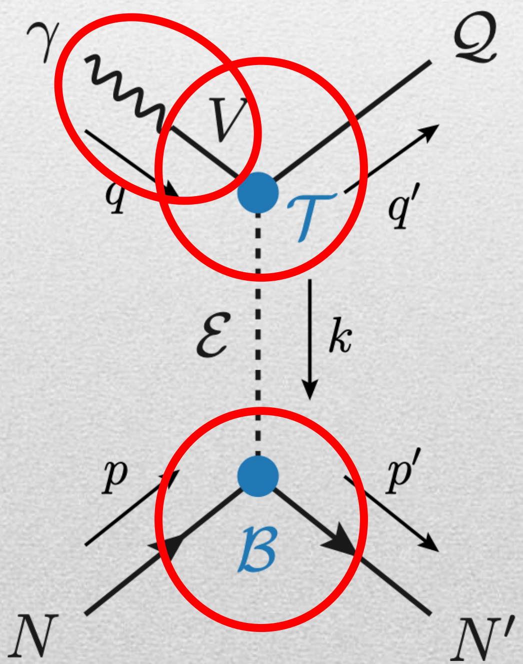
Why photoproduction?

- 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: probing the short-range properties of the wave function and compare with model predictions
- Once seen, Q^2 of transition form factors will give new observables crucial to assess the nature of these exotics

Exclusive (quasi-real) photoproduction

- We study near-threshold (LE) and high energies (HE) regimes with different formalisms
- In lack of strong s-channel footprints (resonances, thresholds), production can be described by dual t-channel exchanges
- Couplings extracted from data as much as possible, not relying on the nature of XYZ

Albaladejo et al., PRD 102, 114010
Winney et al., PRD 106, 094009
Winney et al., PRD 109, 114035



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

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

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

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

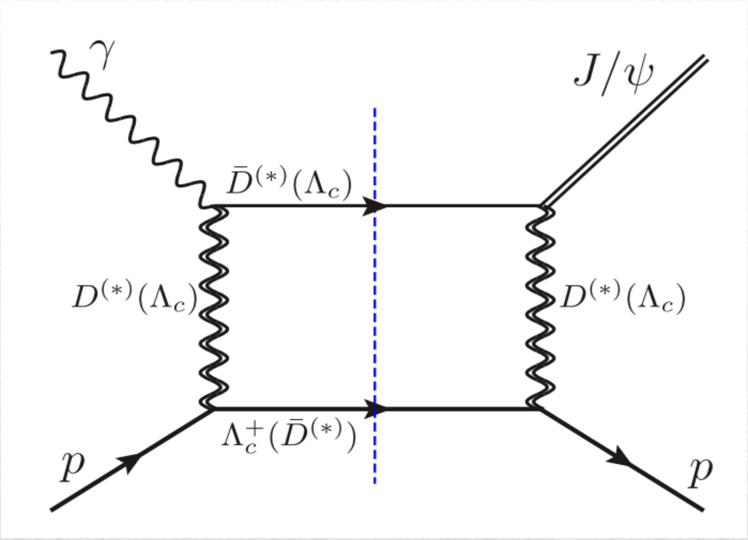
Exchanges vs. rescattering

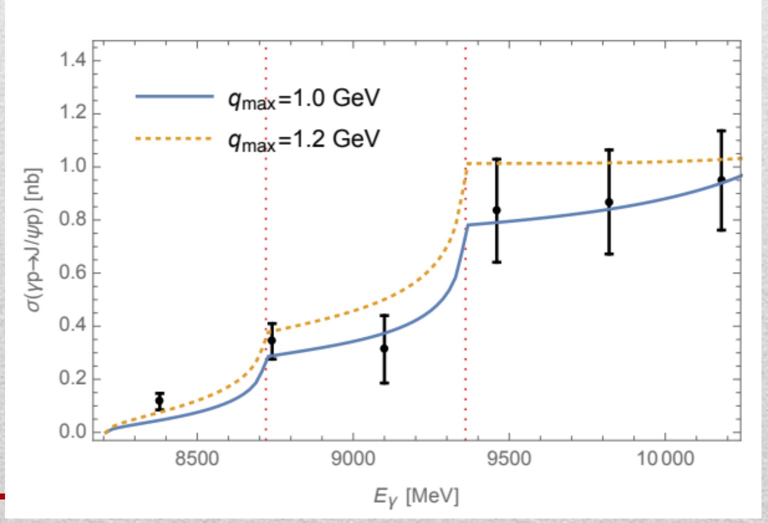
At threshold an alternative production mechanism can be given by open charm rescattering

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





In defense of VMD

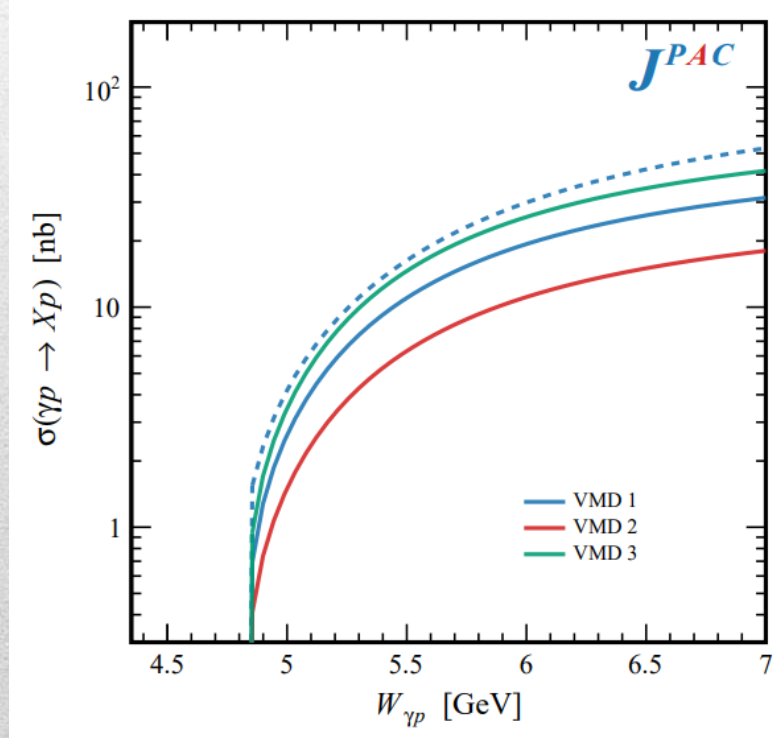
The weak point of the whole approach is the use of VMD
While in the light sector it works reasonably, for heavy states is not justified
There are hints that it fails badly for J/ψ photoproduction

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 $X(3872) \to J/\psi\,\gamma$

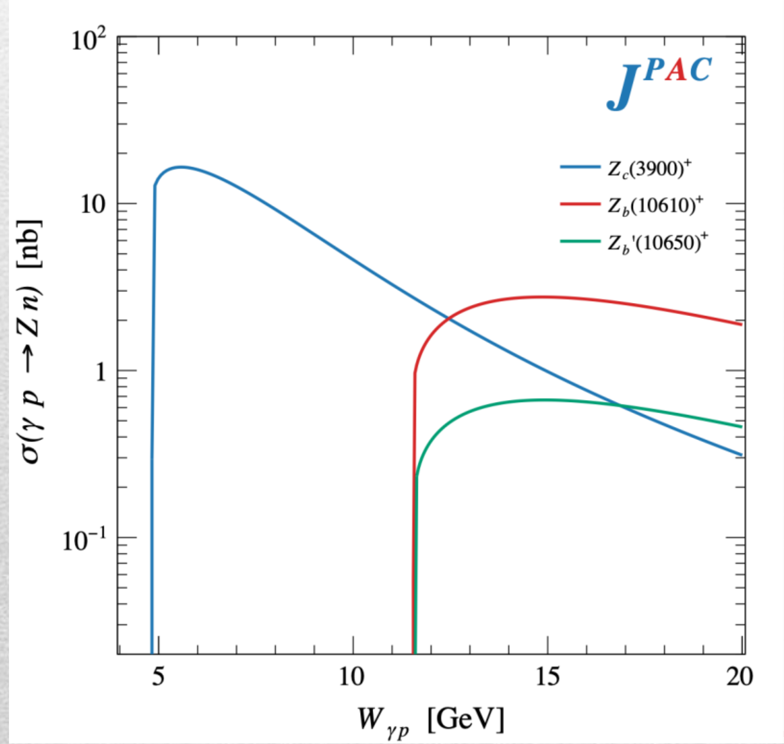
Other estimates give results within a factor of 3

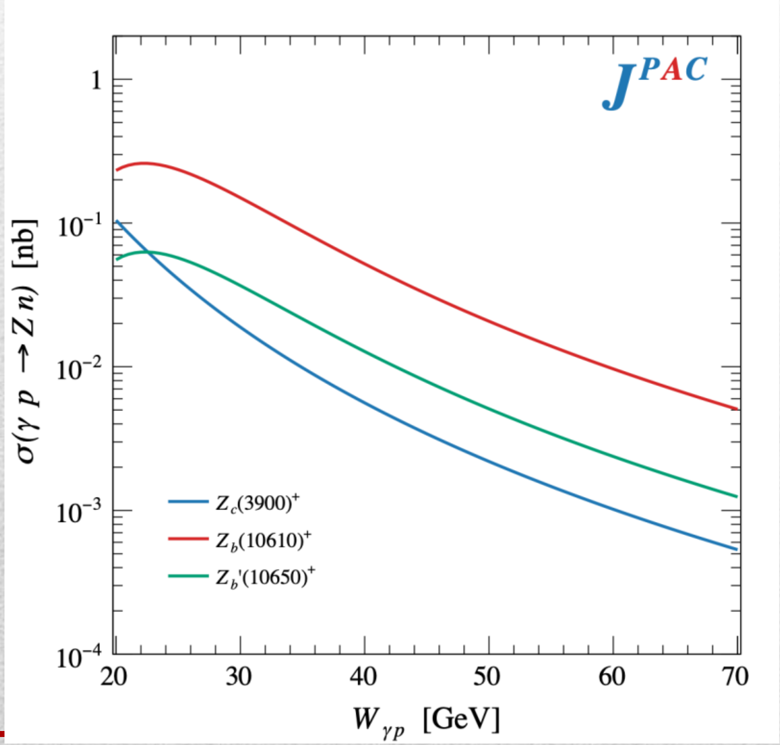
$$g_{X\gamma\gamma} = \frac{g^{(\text{meas.})}_{X\psi\gamma}}{\gamma_\psi} = 3.2 \times 10^{-3}$$



Z photoproduction

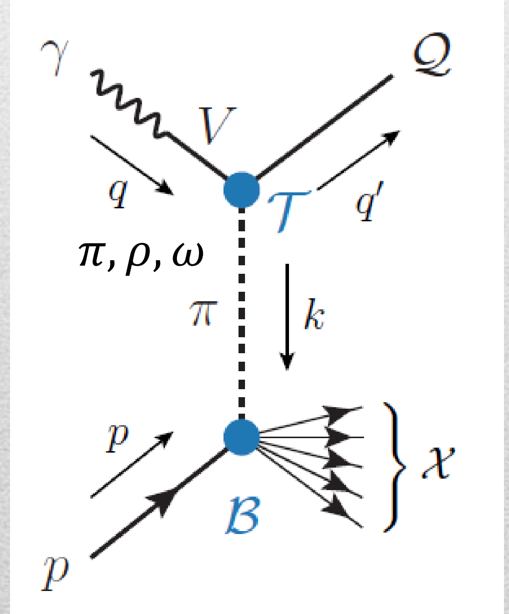
- The Zs are charged charmoniumlike 1^{+-} states close to open flavor thresholds
- Focus on $Z_c(3900)^+ \to J/\psi\,\pi^+, Z_b(10610)^+, Z_b'(10650)^+ \to \Upsilon(nS)\,\pi^+$
- The pion is exchanged in the t-channel

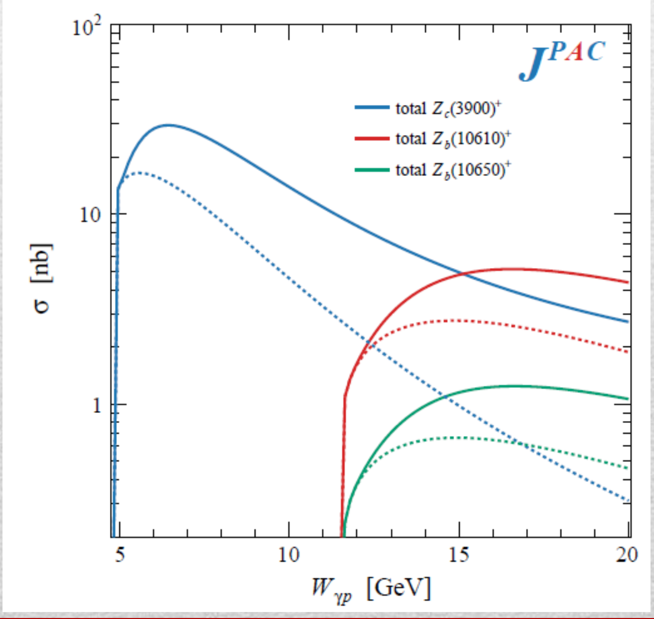


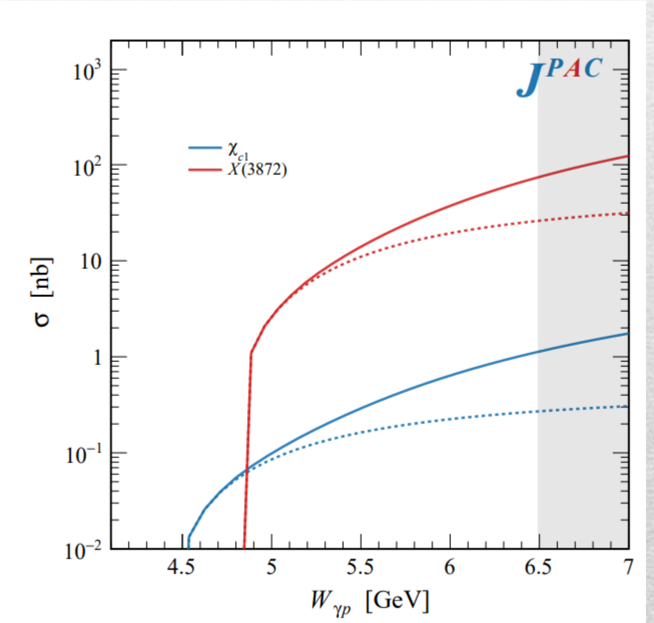


Semi-inclusive photoproduction

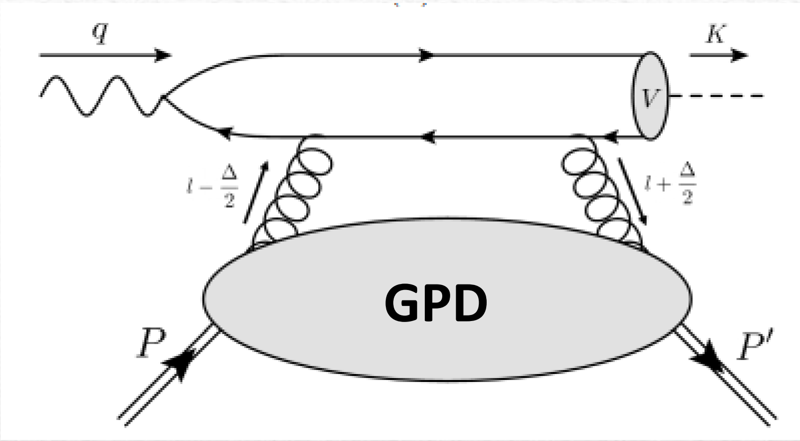
- Semi-inclusive cross sections are typically larger
- For small t and large x, one can assume the process to be dominated by pion/vector exchange
- The bottom vertex depends on the (known) total pion-nucleon cross section, or encoded in the PDFs at large x







J/ψ photoproduction at threshold



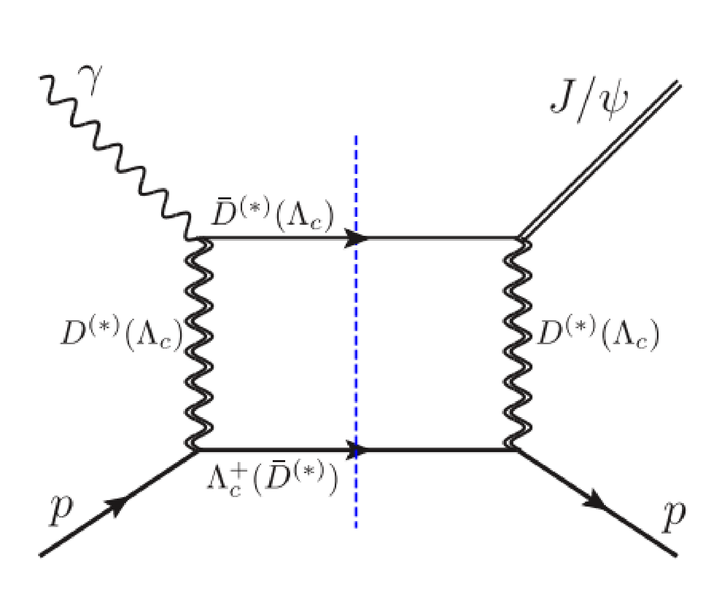
The common lore is that the study of vector quarkonium photoproduction at threshold is directly related to nucleon matrix elements

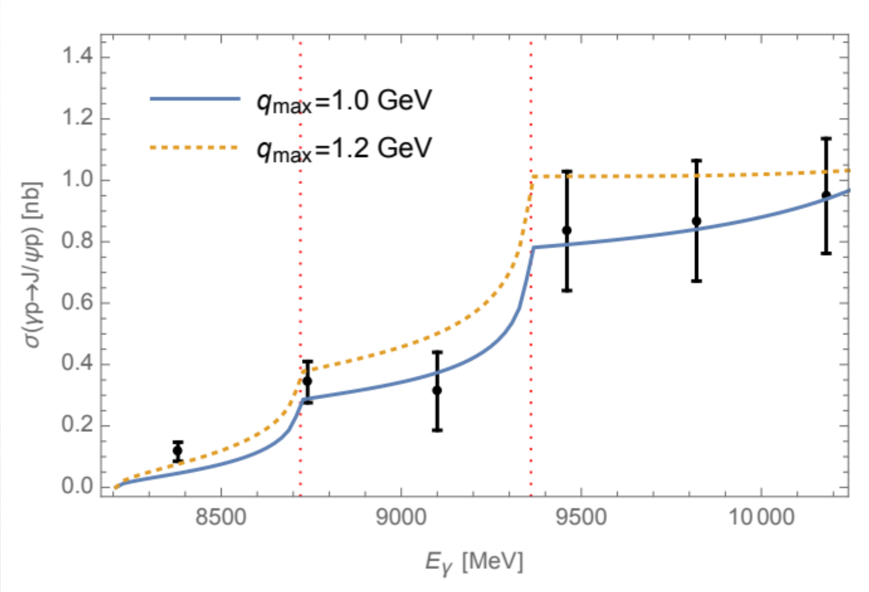
Assumptions:

1. Factorization proof for timelike DVCS can be extended at threshold as the heavy quark mass plays the role of a hard scale
2. The top vertex contains the trivial γ-ψ coupling $|\psi(0)|^2$
3. The exchange of anything but gluons is (OZI-, mass-) suppressed
4. The exchange is dynamically dominated by gluons carrying $J = 2$

Then one extracts matrix element of the energy momentum tensor $\langle p'|T_{\mu\nu}(0)|p\rangle$

Role of open charm



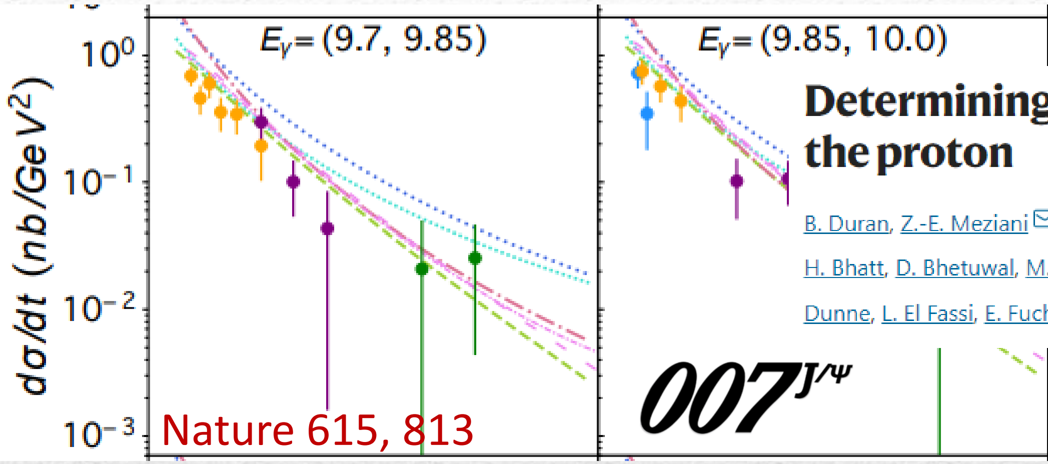


Du et al. Eur.Phys.J.C 80, 11, 1053

The role of intermediate open charm thresholds has been pointed out,
Maybe «all that glitters is not glue» ….

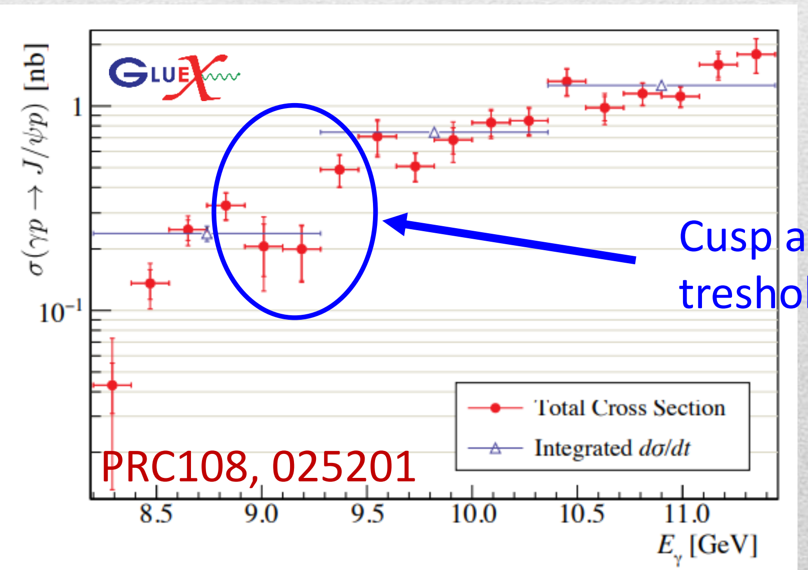
Calculation based on EFT and known couplings, S-wave saturates the cross section

J/ψ photoproduction at threshold

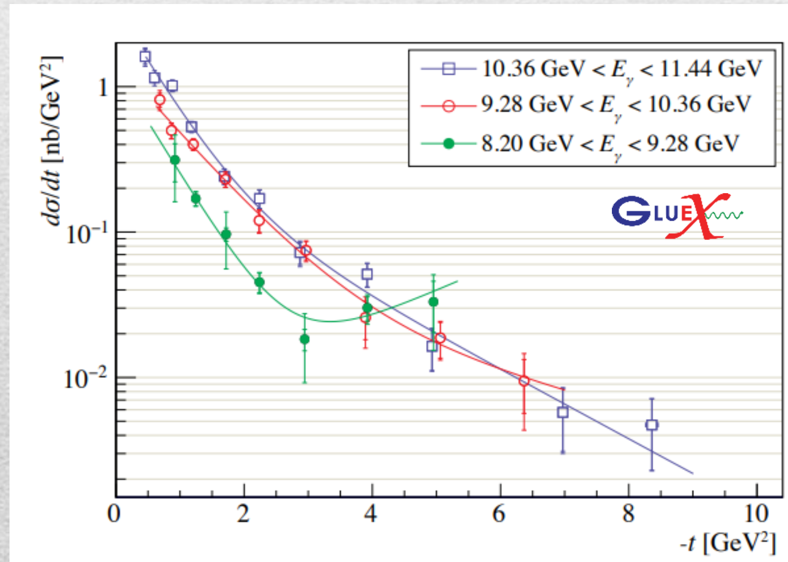


Determining the gluonic gravitational form factors of the proton

B. Duran, Z.-E. Meziani, S. Joosten, M. K. Jones, S. Prasad, C. Peng, W. Armstrong, H. Atac, E. Chudakov, H. Bhatt, D. Bhetuwal, M. Boer, A. Camsonne, J.-P. Chen, M. M. Dalton, N. Deokar, M. Diefenthaler, J. Dunne, L. El Fassi, E. Fuchey, H. Gao, D. Gaskell, O. Hansen, F. Hauenstein, ... Z. Zhao + Show authors



Cusp at the $\Lambda_c \overline{D}^*$ treshold



Unitary reanalysis

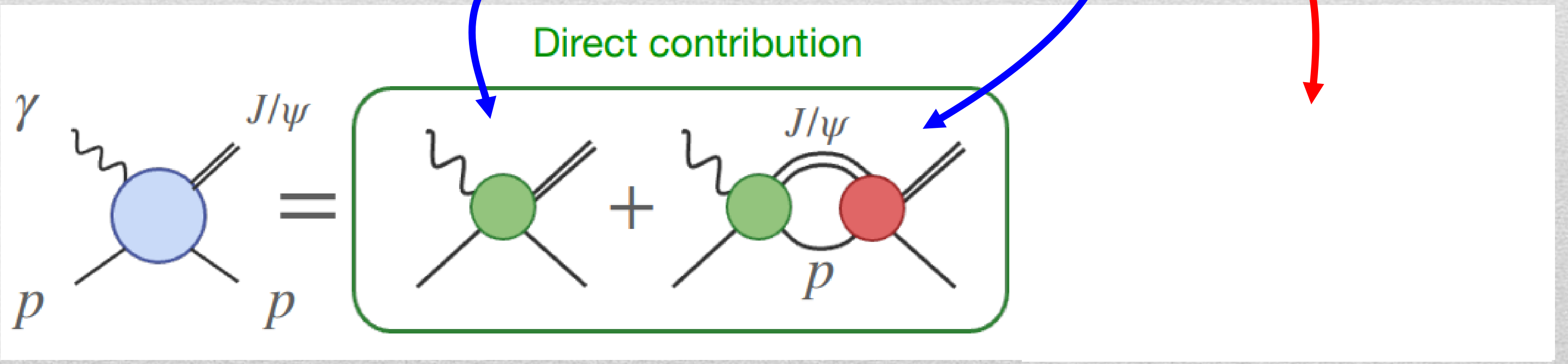
Winney *et al.* PRD 108, 054018

- Differential and total cross sections are fitted with a unitary model
- In lack of polarization observables and SDME,
  only orbital angular momentum is considered (spinless approx.)
- Truncated sum of PWs, $\ell \leq 3$

$$F(s,t) = \sum_{\ell} (2\ell+1)\, P_\ell(\cos\theta)\; F_\ell(s)$$

$$F_\ell(s) = f_\ell\,(1 + G\,T_\ell) = f_\ell\,(1 - G\,K_\ell)^{-1}$$
$$T_\ell(s) = K_\ell\,(1 - G\,K_\ell)^{-1}\,,$$

The dominant S-wave can include coupled channels,
for higher waves cusps are suppressed and there is no point



Contribution of open charm

$$\zeta_{\text{th}} = \frac{\left|F^{\psi p}_{\text{direct}}(s_{\text{th}})\right|}{\left|F^{\psi p}_{\text{direct}}(s_{\text{th}})\right| + \left|F^{\psi p}_{\text{indirect}}(s_{\text{th}})\right|} .$$

Naively Wilk's theorem says
the single channel is unfavored at 3.7σ
(no look elsewhere etc.),
indication but not the end of the story

Contribution of open charm $> 25\%$ at 90% CL

	1C	**2C**	**3C-NR**	**3C-R**
Parameters	9	13	15	15
χ^2	166	144	141	143
χ^2/dof	1.25	1.12	1.11	1.13
ζ_{th}	1	[0.56, 0.74]	[0.36, 0.63]	[0.03, 0.62]

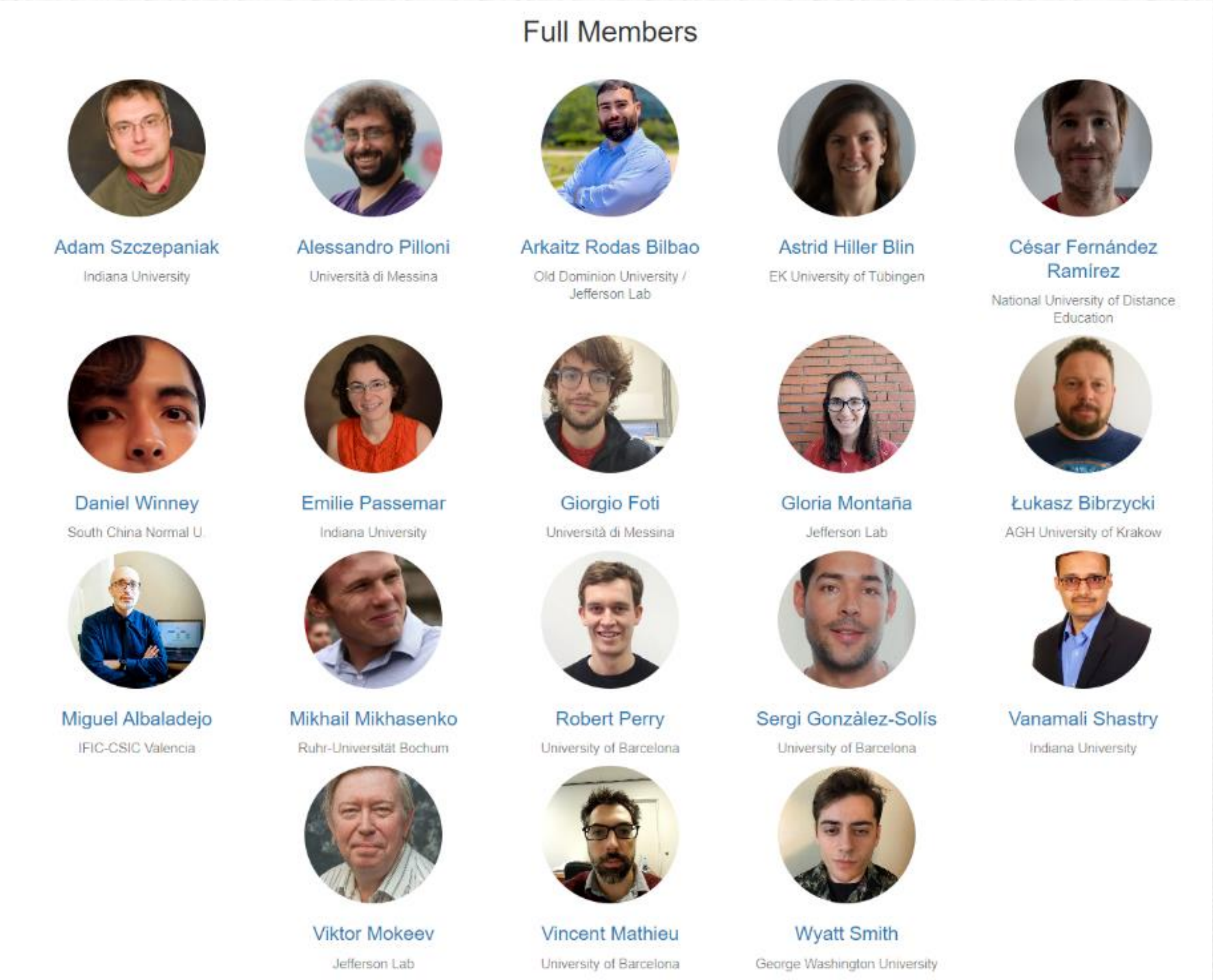
Conclusions & prospects

The study of heavy-heavy quark sector is a challenging task
Experiments are very prolific! Constant feedback on predictions

- Study of spectra and decay patterns will improve our understanding of the dynamics of QCD building blocks
- Complementary models are useful to describe the XYZ sector
- New facilities that can measure XYZ with unexplored production mechanisms are extremely valuable

Thank you

Joint Physics Analysis Center

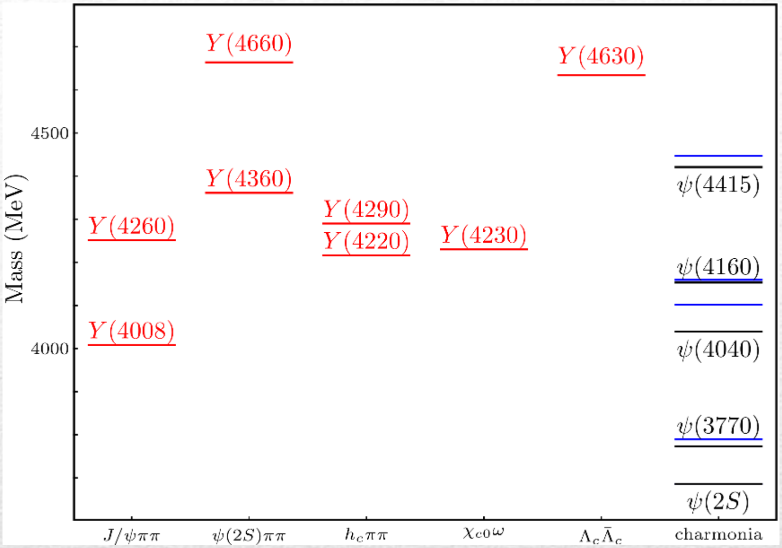


Code available on https://github.com/dwinney/jpacPhoto

https://jpac-physics.org

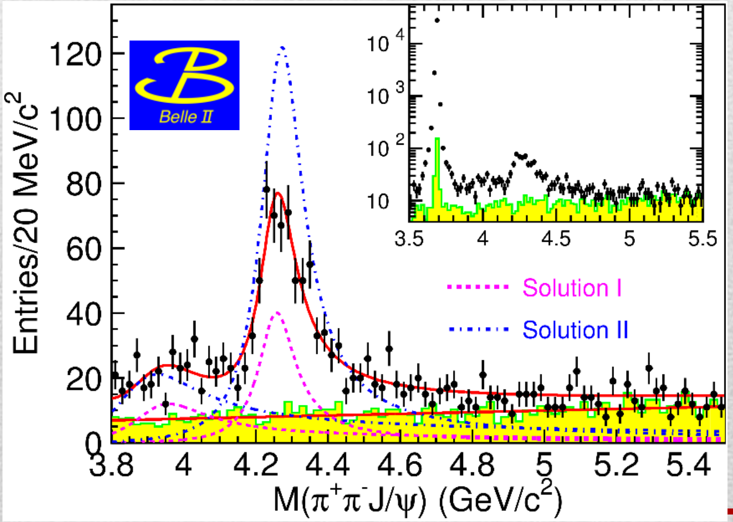
BACKUP

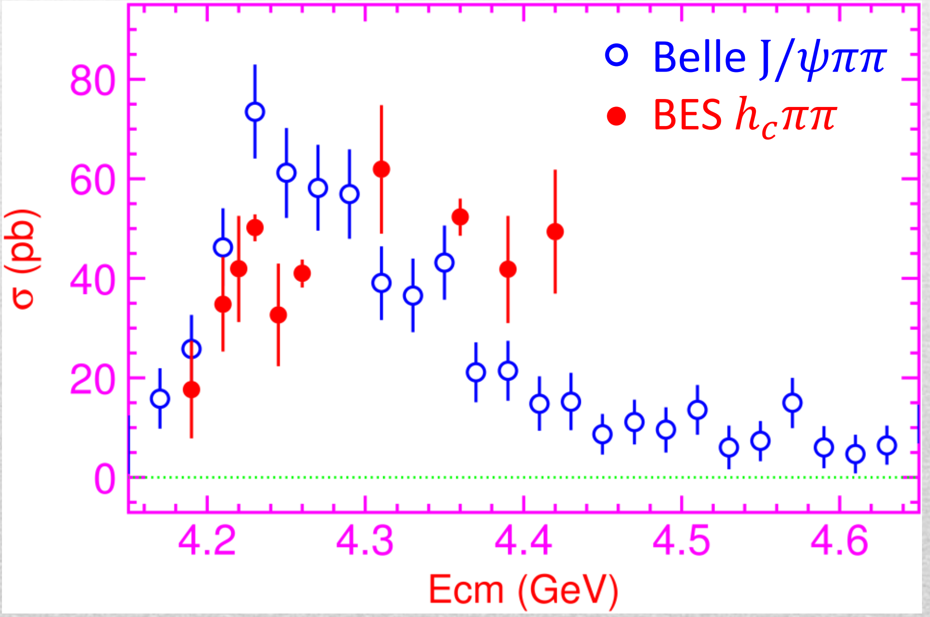
Vector Y states



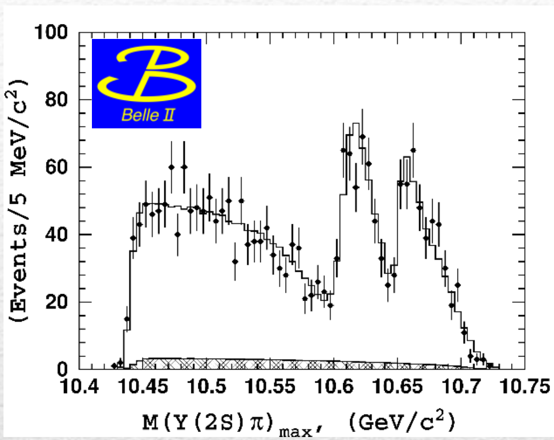
Lots of unexpected $J^{PC} = 1^{--}$ states
found in ISR/direct production (and nowhere else!)
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

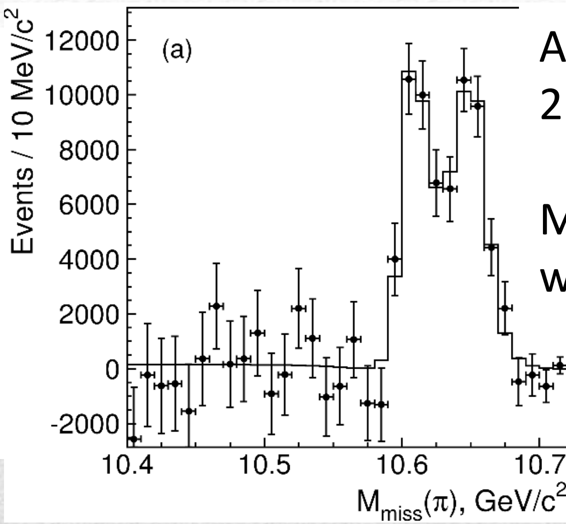
Not seen decaying into open charm pairs
Large HQSS violation





Charged Z states: $Z_b(10610), Z_b'(10650)$





Anomalous dipion width in $\Upsilon(5S)$,
2 orders of magnitude larger than $\Upsilon(nS)$

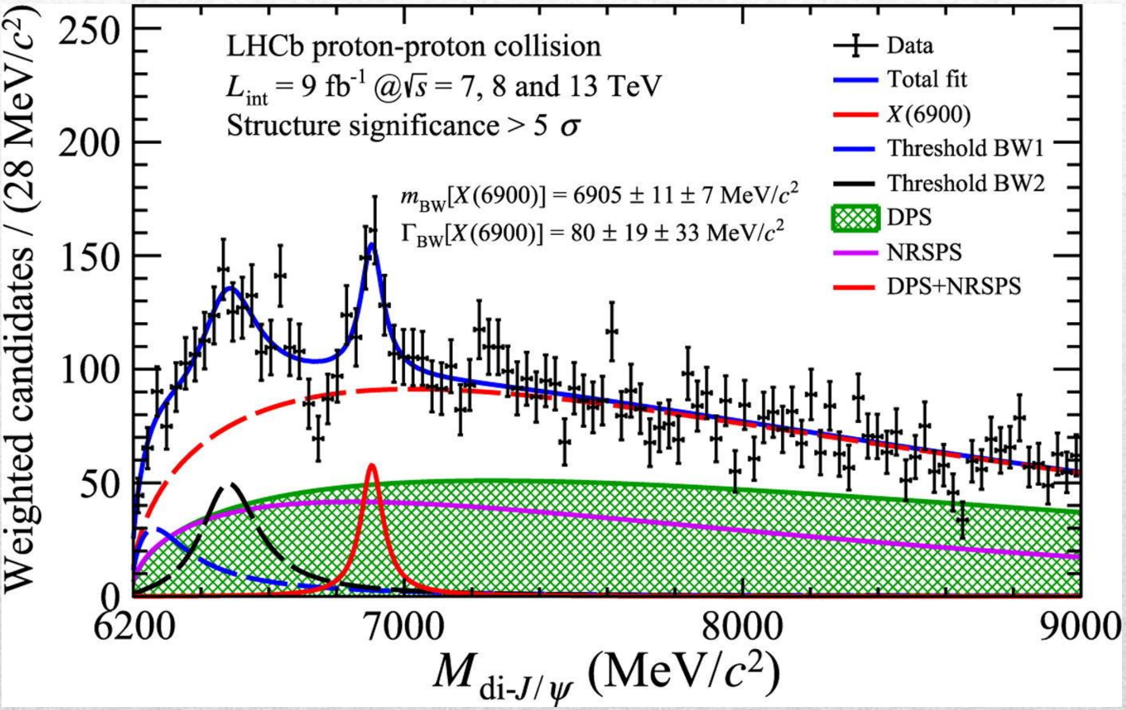
Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$ which violates HQSS

2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

$\Upsilon(5S) \to Z_b'(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to \bar{B}^{*0}B^{*+}\pi^-$
$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV

Fully charm: the $X(6900)$



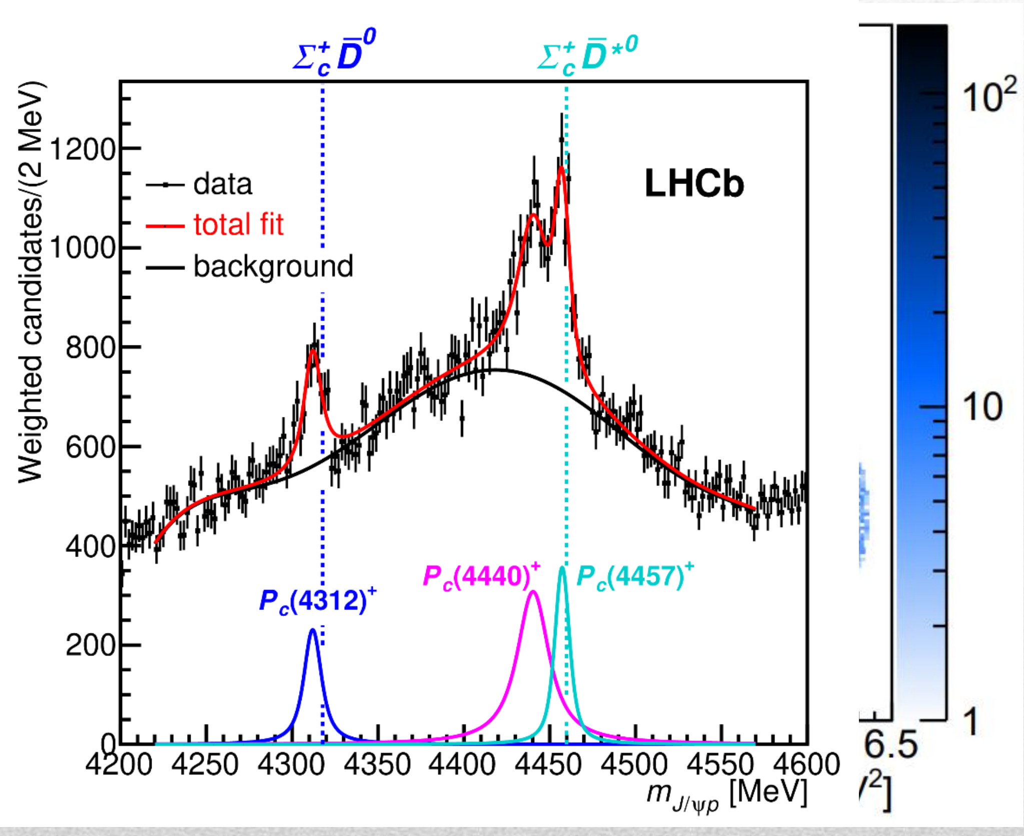
Two structures are seen in the $J/\psi\, J/\psi$ spectrum

The heavier one is narrower and well assessed

The nature of the lighter one is unclear

Pentaquarks

LHCb, PRL 115, 072001
LHCb, PRL 117, 082003



States seen in $\Lambda_b \to (J/\psi\, p)\, K^-$,

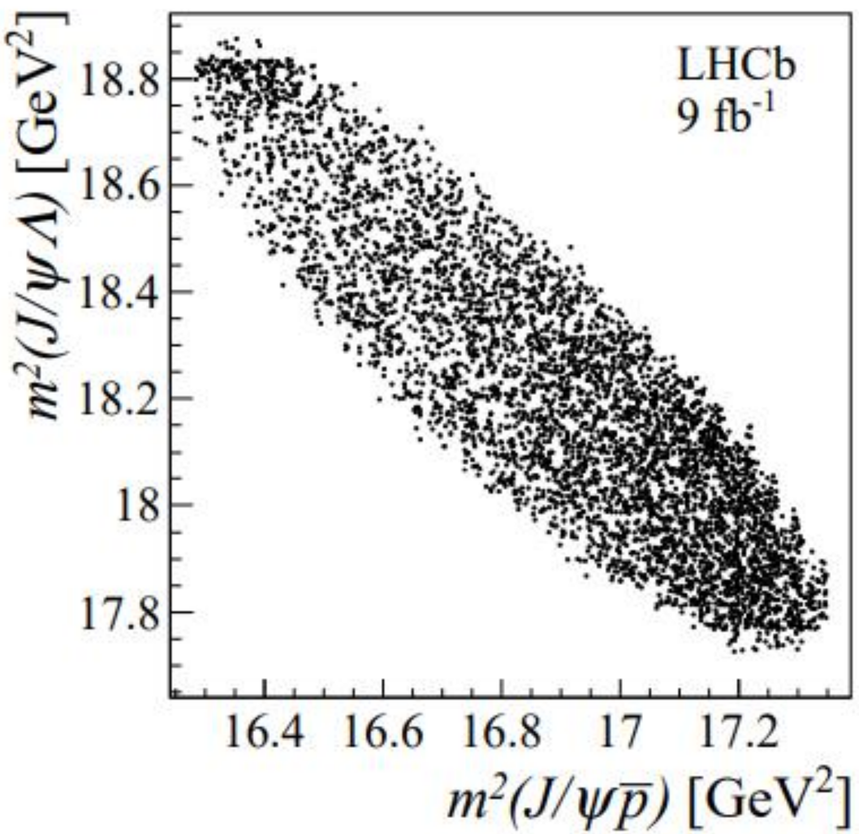
Original analysis found a narrow and a broad states

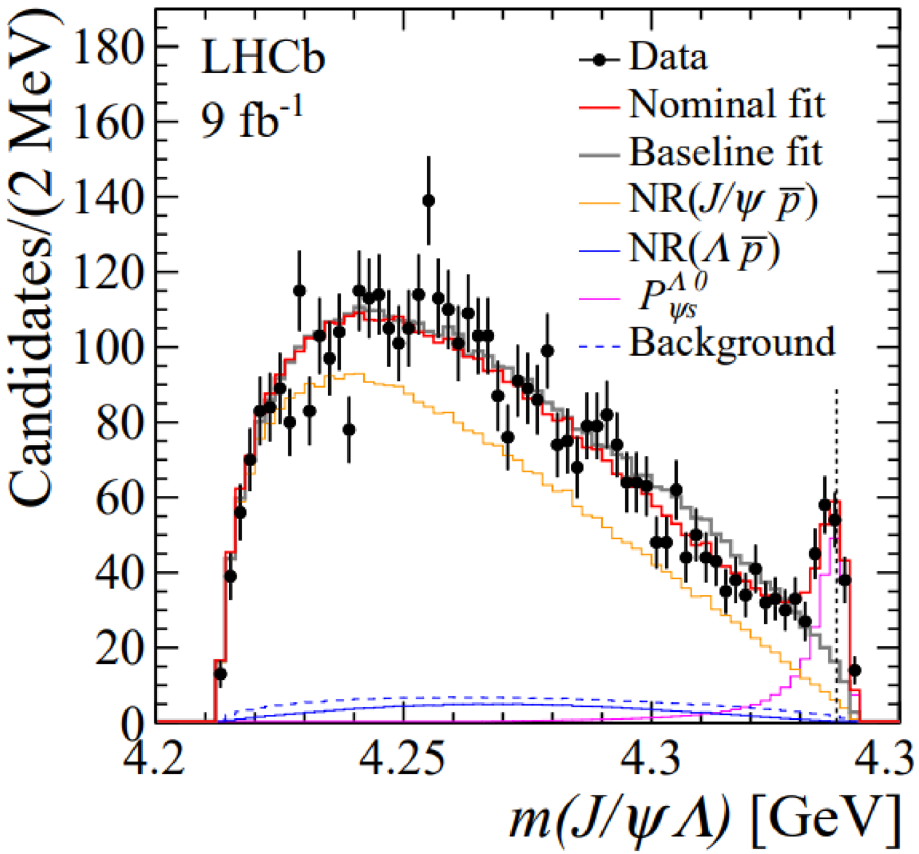
The subsequent 1D update find 3 narrow ones

The lightest $P_c(4312)$ appears as an isolated peak at the $\Sigma_c^+ \bar{D}^0$ threshold

Strange pentaquarks

Can you search pentaquarks in meson decays? $B^- \to J/\psi\, \Lambda^0\ \bar{p}$



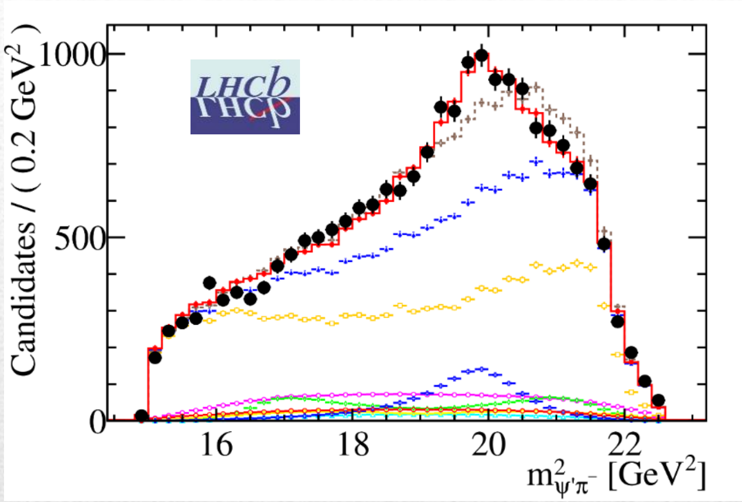


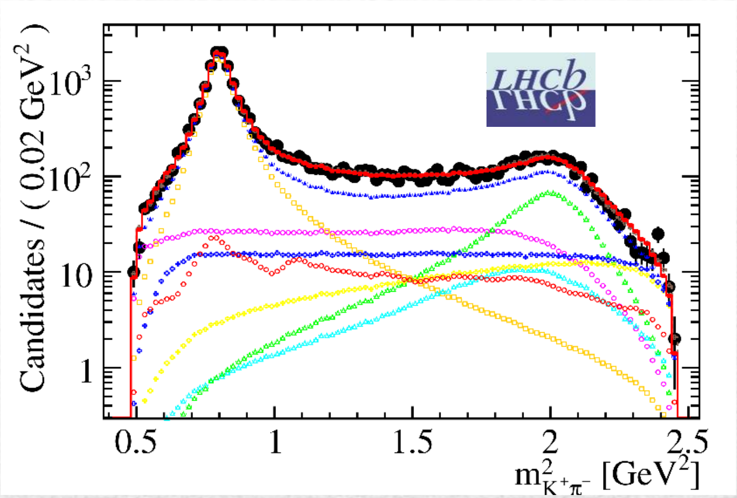
Broad exotics in B decays

Lots of new exotics have been seen by LHCb with multidimensional amplitude analyses of $B \to$ 3+ body

Most of these are broad, and the precise determination can crucially depend on the amplitude model, so that the resonant nature cannot be assessed with the same strong statements as for the narrow guys

Charged Z states: $Z(4430)$

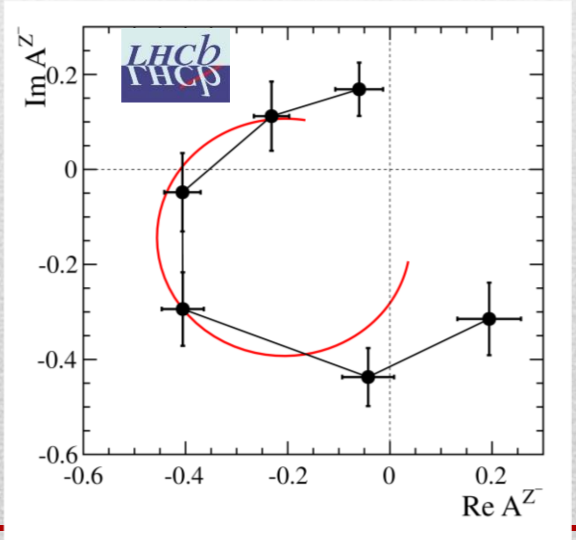




$$Z(4430)^+ \to \psi(2S)\,\pi^+$$
$$I^G J^{PC} = 1^+ 1^{+-}$$

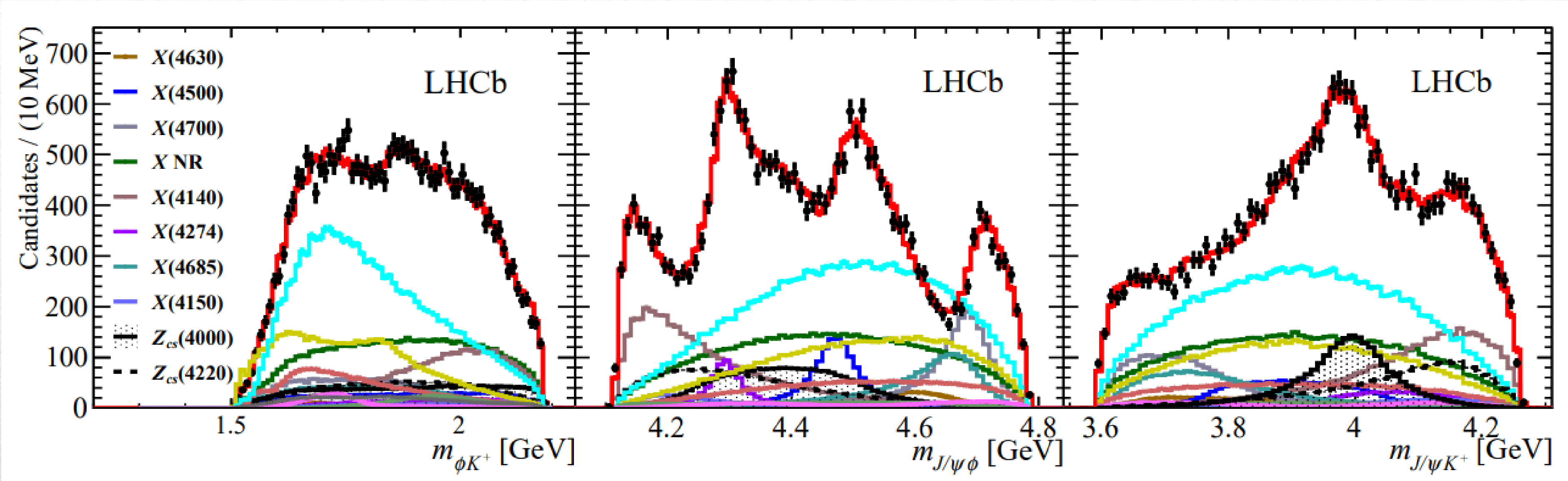
$$M = 4475 \pm 7^{+15}_{-25}\text{ MeV}$$
$$\Gamma = 172 \pm 13^{+37}_{-34}\text{MeV}$$

Far from open charm thresholds



If the amplitude is a free complex number, in each bin of $m^2_{\psi'\pi^-}$, the resonant behaviour appears as well

Tetraquarks: the $B^+ \to J/\psi\, \phi\, K^+$ decay

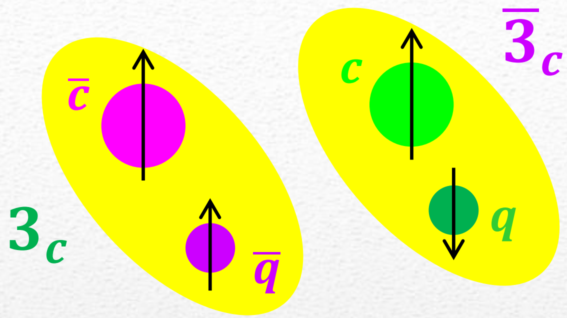


In $J/\psi\,\phi$: $\begin{cases} 1 \times\ 1^{-+} \\ 2 \times\ \ 0^{++} \\ 3 \times\ 1^{++} \end{cases}$

In $J/\psi\, K^+$: $2 \times 1^+$

Widths from 50 to 230 MeV

Tetraquarks

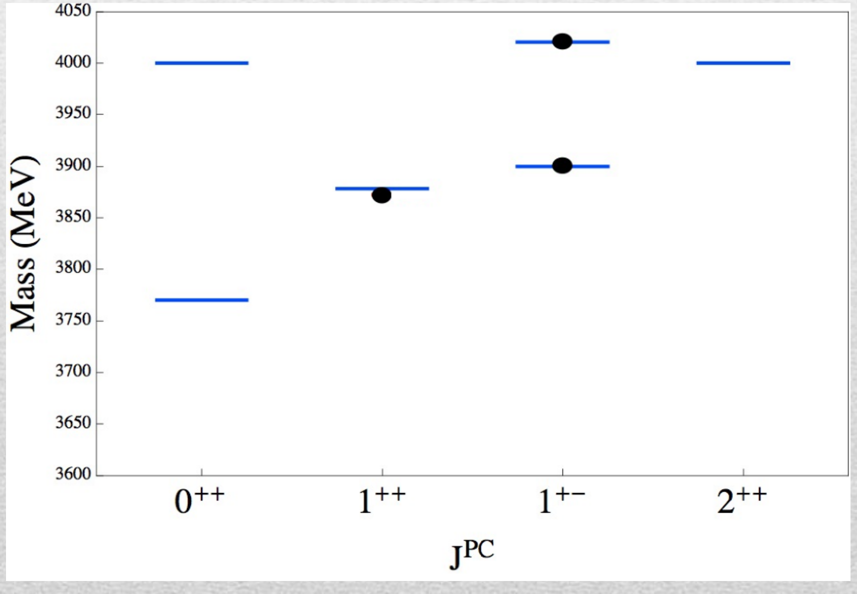


In a constituent quark model, we can think of a **diquark-antidiquark compact state**

$$[cq]_{S=0,1}[\bar{c}\bar{q}']_{S=0,1}$$

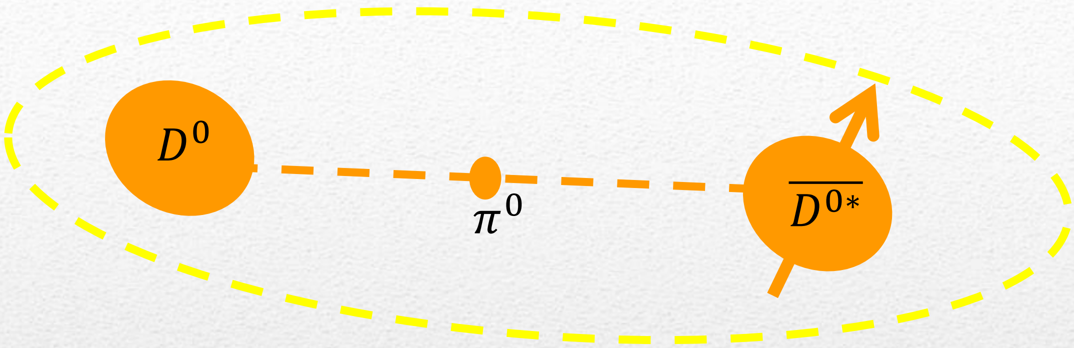
Maiani, Piccinini, Polosa, Riquer PRD71 014028
same + Faccini, AP, PRD87 111102
Maiani, Piccinini, Polosa, Riquer PRD71 014028

Calculations in the Born-Oppenheimer approximation for open flavor,
Maiani, AP, Polosa, Riquer PLB836 137624



Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

Molecules



Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305

$X(3872) \sim \bar{D}^0 D^{*0}$
$Z_c(3900) \sim \bar{D}^0 D^{*+}$
$Z_c'(4020) \sim \bar{D}^{*0} D^{*+}$
$Y(4260) \sim \bar{D} D_1$

A deuteron-like meson pair, the interaction is mediated by the exchange of light mesons

- Good description of decay patterns (mostly to constituents) and $X(3872)$ isospin violation ✓
- States appear close to thresholds ✓ Binding energy varies from -70 to -0.1 MeV ✗
- Unclear spectrum (a state for each threshold?) – depends on potential models ✗
- Some non-predictive model-independent relations (Weinberg's theorem) ✓

$$V_\pi(r) = \frac{g_{\pi N}^2}{3}(\vec{\tau_1}\cdot\vec{\tau_2})\left\{[3(\vec{\sigma_1}\cdot\hat{r})(\vec{\sigma_2}\cdot\hat{r}) - (\vec{\sigma_1}\cdot\vec{\sigma_2})]\left(1+\frac{3}{(m_\pi r)^2}+\frac{3}{m_\pi r}\right)+(\vec{\sigma_1}\cdot\vec{\sigma_2})\right\}\frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

Constituent quark model

Godfrey and Isgur, PRD 32, 189
Capstick and Isgur, PRD 33, 2809

- Relativized QM Hamiltonian

$$H = \sum_i \sqrt{p_i^2 + m_i^2} + \sum_{i<j} V_{\mathrm{conf}}(r_{ij}) + V_{\mathrm{hyp}}(r_{ij}) + V_{\mathrm{so}}(r_{ij})$$

- Confining potential

$$V_{\mathrm{conf}}(r_{ij}) = -\left(\frac{3}{4}c + \frac{3}{4}\beta r_{ij} - \frac{\alpha_{\mathrm{s}}(r_{ij})}{r_{ij}}\right) \mathbf{F}_i \cdot \mathbf{F}_j$$

- Hyperfine interaction

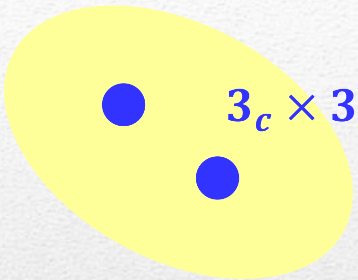
$$V_{\mathrm{hyp}}(r_{ij}) = -\frac{\alpha_{\mathrm{s}}(r_{ij})}{m_i m_j}\left[\frac{8\pi}{3}\mathbf{S}_i \cdot \mathbf{S}_j\, \delta^3(\mathbf{r}_{ij}) + \frac{1}{r_{ij}^3}\left(\frac{3\ \mathbf{S}_i\cdot\mathbf{r}_{ij}\ \mathbf{S}_j\cdot\mathbf{r}_{ij}}{r^2} - \mathbf{S}_i \cdot \mathbf{S}_j\right)\right] \mathbf{F}_i \cdot \mathbf{F}_j$$

- Spin-orbit interaction

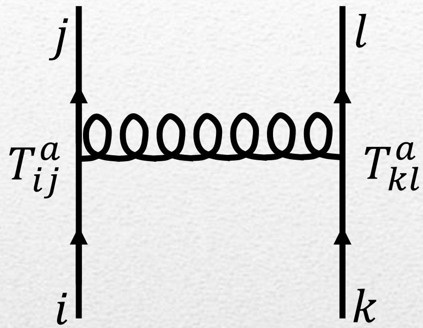
$$V_{\mathrm{so}}(r_{ij}) = -\frac{\alpha_{\mathrm{s}}(r_{ij})}{r_{ij}^3}\left(\frac{1}{m_i} + \frac{1}{m_j}\right)\left(\frac{\mathbf{S}_i}{m_i} + \frac{\mathbf{S}_j}{m_j}\right) \cdot \mathbf{L}\, \mathbf{F}_i \cdot \mathbf{F}_j$$

Diquarks

Attraction and repulsion in 1-gluon exchange approximation is given by



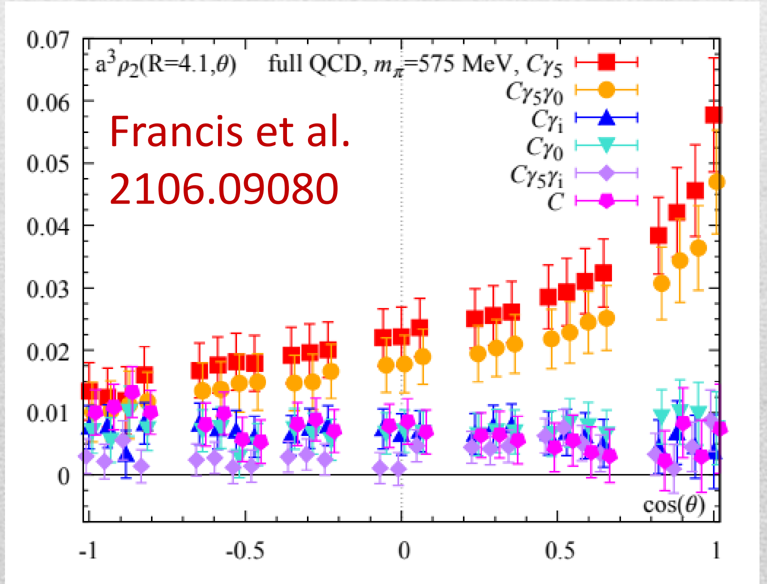
$\mathbf{3}_c \times \mathbf{3}_c \in \bar{\mathbf{3}}_c$

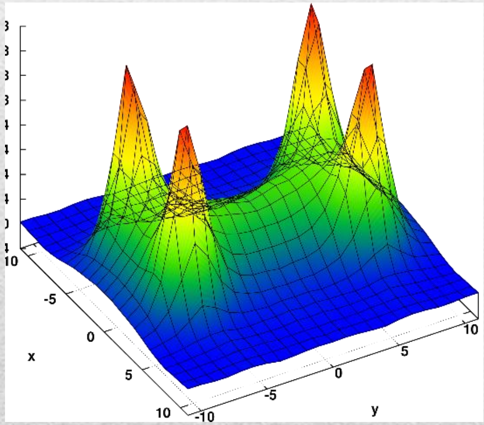


$$R = \frac{1}{2}\left(C_2(R_{12}) - C_2(R_1) - C_2(R_2)\right)$$

$$R_1 = -\frac{4}{3}, R_8 = +\frac{1}{6}$$

$$R_3 = -\frac{2}{3}, R_6 = +\frac{1}{3}$$



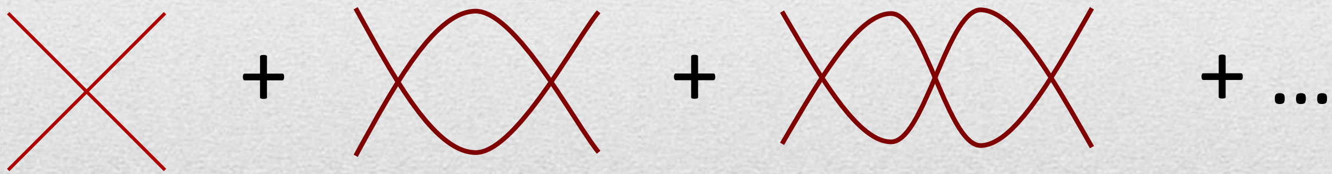


H-shape with a 4 quark system
Cardoso, Cardoso, Bicudo, PRD84, 054508

Weinberg's criterion and lineshapes

Let us imagine to have a theory with a bound state with a binding momentum much smaller than the inverse of the range of the potential

The potential is just a delta function,
we calculate the $2 \to 2$ scattering amplitude



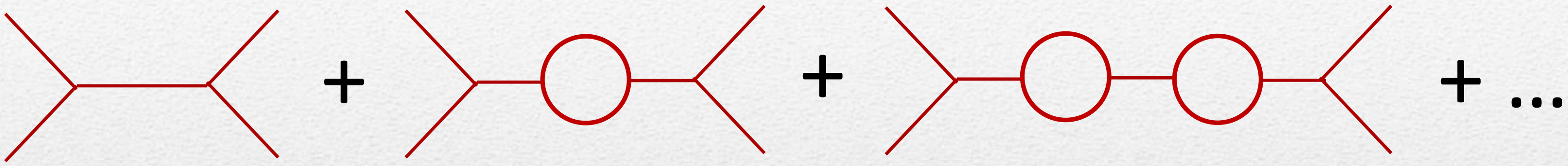
$$A(E) = \frac{1}{1/a - i\sqrt{2\mu E}}$$

This has a pole at $E = -E_B = -\frac{1}{2\mu a^2}$

and residue $g^2 = \sqrt{\frac{2E_B}{\mu}}$

Weinberg's criterion and lineshapes

Now let us consider the propagation of a bare intermediate state



$$A(E) = \frac{g_0^2}{E_0 - E - i g_0^2 \sqrt{2\mu E}} = \frac{g_0^2}{-E_B - E - i g_0^2 \sqrt{2\mu E} - g_0^2 \sqrt{2\mu E_B}}$$

This has a pole at E_B and residue $g^2 = \sqrt{\frac{2E_B}{\mu}}(1-Z)$ where Z is the w.f. renormalization,

$Z = \left(1 + g_0^2 \sqrt{\frac{\mu}{2E_B}}\right)^{-1}$ = overlap between the bare state and the continuum

Weinberg's criterion and lineshapes

The amplitude can be rewritten as

$$A(E) = \frac{1}{\frac{1}{a} + \frac{1}{2} r_0 k^2 - ik}$$

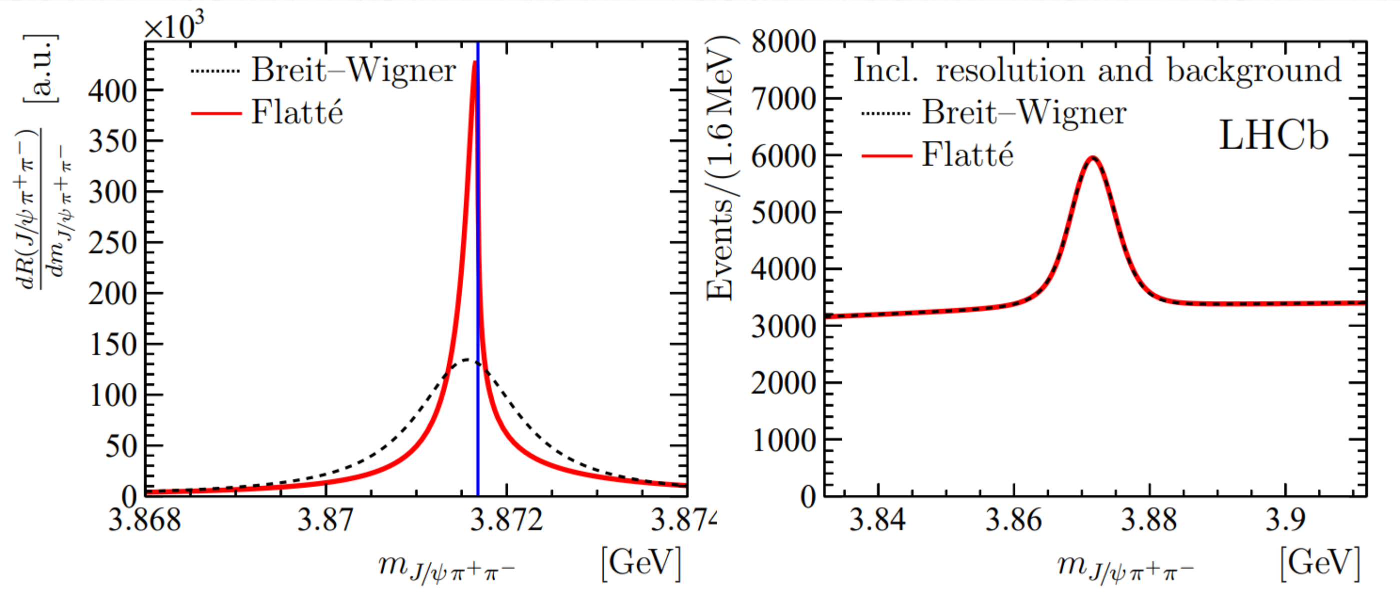
Thus identifying $a = -2\,\frac{1-Z}{2-Z}\frac{1}{\sqrt{2\mu E_B}}, r_0 = -\frac{Z}{1-Z}\frac{1}{\sqrt{2\mu E_B}}$

So a negative r_0 points to a short range component in the wave function

This is true up to corrections of the order of the range of the potential, which btw are positive under general assumptions

Esposito, Maiani, Pilloni, Polosa, Riquer, 105 (2022) 3, L031503

The lineshape of the $X(3872)$



Blue line is $D^0\overline{D^{*0}}$, D^+D^{*-} is $\delta = 8.2$ MeV heavier

Because of experimental resolution, different lineshapes are indistinguishable

Unitary parametrizations tend to be narrower,
$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10$ MeV, $\Gamma_{fl} = 0.22^{+0.07+0.11}_{-0.06-0.13}$ MeV

The lineshape of the $X(3872)$

Esposito, Maiani, AP, Polosa, Riquer, PRD 105 (2022) 3, L031503

LHCb data is fitted with the Flatte' parametrization

Two options: a) set $\delta = 0$ b) I expand at threshold

The $D^0 \overline{D}^{*0}$ threshold

The $D^+ D^{*-}$ threshold

$$t^{-1}(E) \propto E - m_X^0 + \frac{i}{2} g_{\text{LHCb}} \left(\sqrt{2\mu E} + \sqrt{2\mu_+ (E - \delta)} \right) + \frac{i}{2} \left(\Gamma_\rho^0(E) + \Gamma_\omega^0(E) + \Gamma_0^0 \right)$$

The $J/\psi\ \rho, \omega$, and other unknown channels

This considers coupled channel, but Weinberg's criterion applies to single channel bound states only

The lineshape of the $X(3872)$

Esposito, Maiani, AP, Polosa, Riquer, PRD 105 (2022) 3, L031503

Option b) $-5.34\ \text{fm} \lesssim r_0 \lesssim -1.56\ \text{fm}$

Option a) $-3.78\ \text{fm} \lesssim (r_0)_{\delta\to 0} \lesssim 0\ \text{fm}$

According to Weinberg's, the first result points to a sizeable short-range structure of the X(3872)

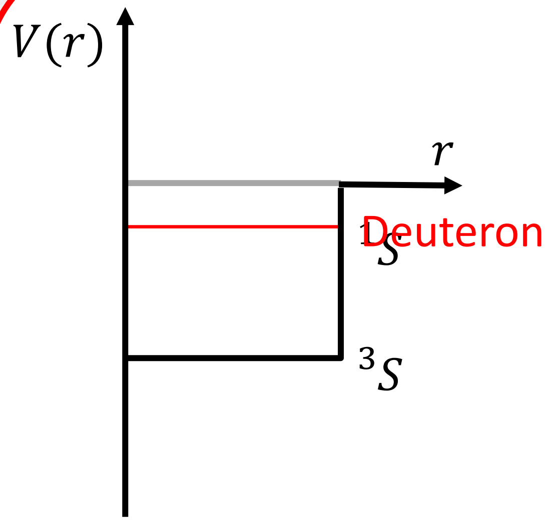
Still disagreement on how to perform the extraction though

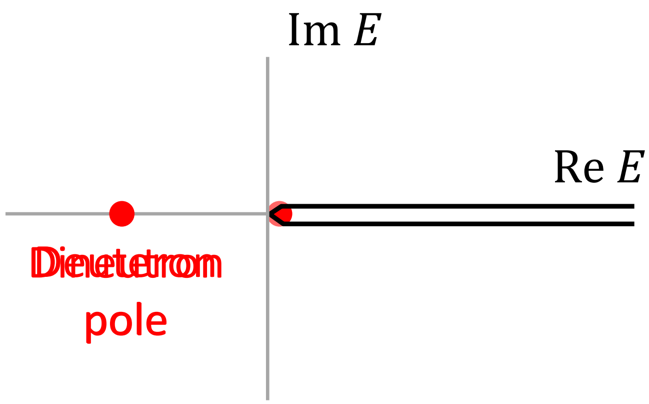
Bound and virtual states

Example from np scattering

Decreasing the potential strength, the pole reaches the threshold

The pole jumps on the 2nd sheet (dineutron), bound state on the real axis 1st sheet (deuteron)





Minimal(istic) model for $P_c(4312)$

(LHCb data)

Fernandez-Ramirez, AP *et al.* (JPAC), PRL 123, 092001

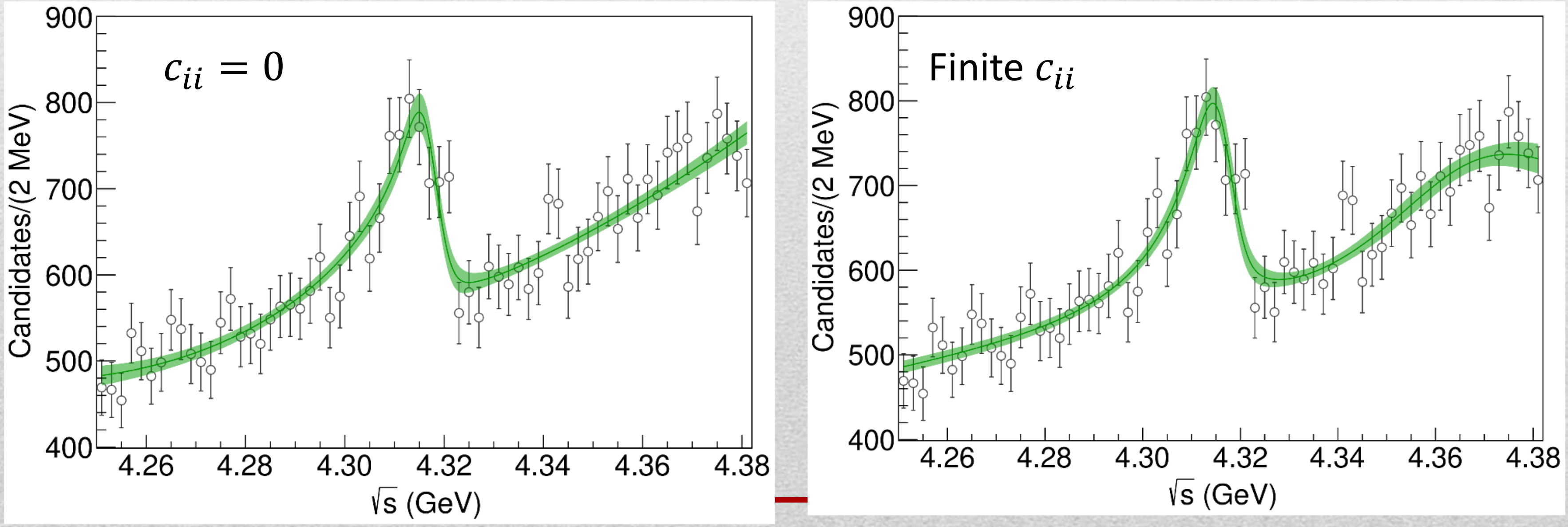
$$\frac{dN}{d\sqrt{s}} = \rho(s)\left[|F(s)|^2 + b_0 + b_1 s\right]$$

Effective range expansion

$$F(s) = (N_1 + N_2 s)\, T_{11}(s)$$

$$T(s) = \begin{pmatrix} m_{11} - c_{11}s - i\rho_1(s) & m_{12} \\ m_{12} & m_{22} - c_{22}s - i\rho_2(s) \end{pmatrix}^{-1}$$

We can set $c_{ii} = 0$ to reduce to the scattering length approximation



Minimal(istic) model for $P_c(4312)$

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Effective range expansion

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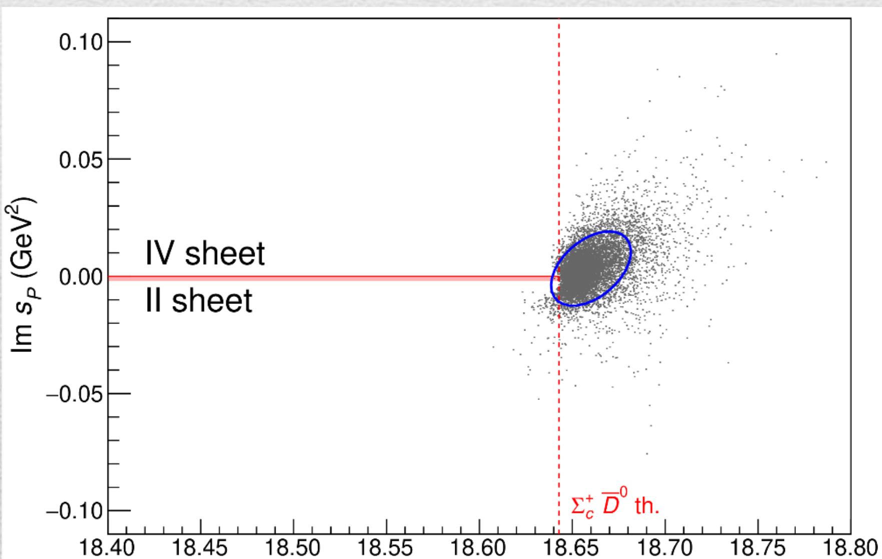
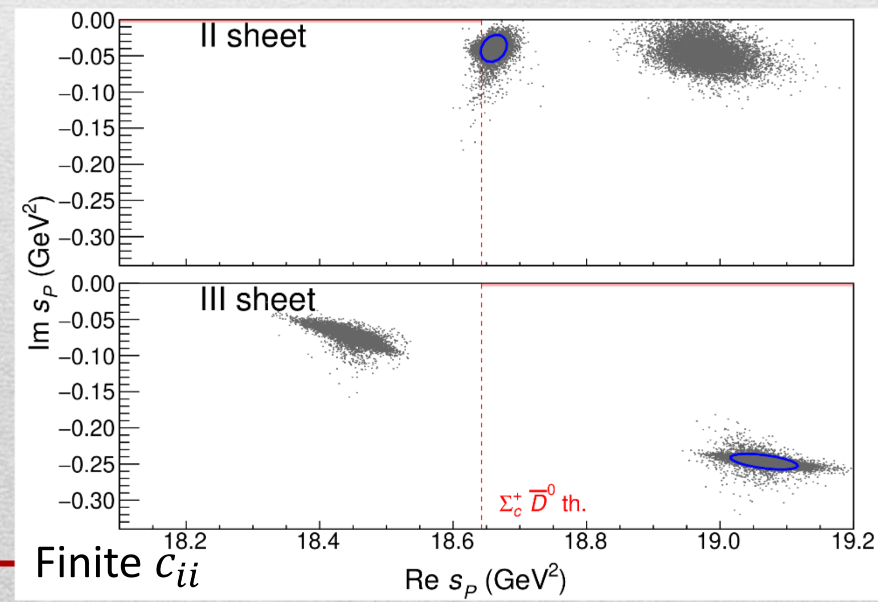


$c_{ii} = 0$



Finite c_{ii}

Minimal(istic) model for $P_c(4312)$

$$\frac{dN}{d\sqrt{s}} = \rho(s)\left[|F(s)|^2 + b_0 + b_1 s\right]$$

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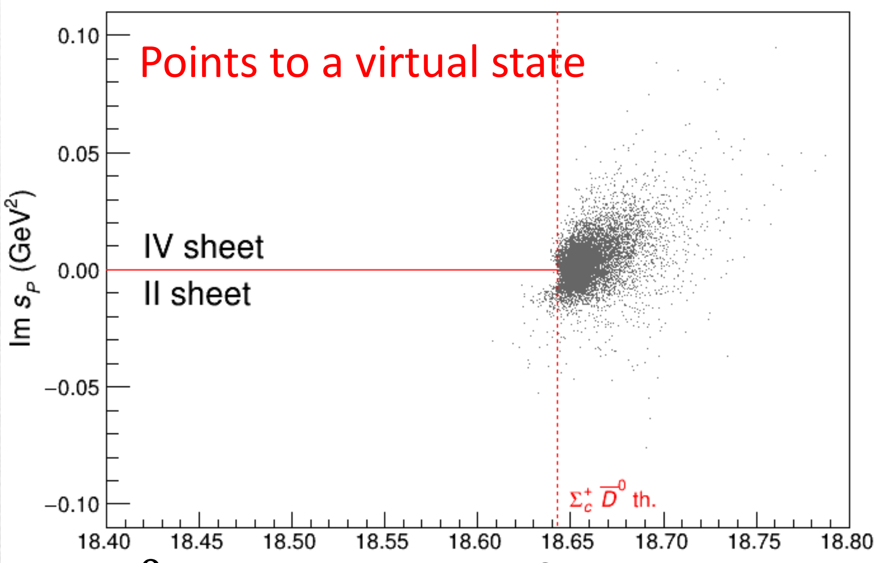
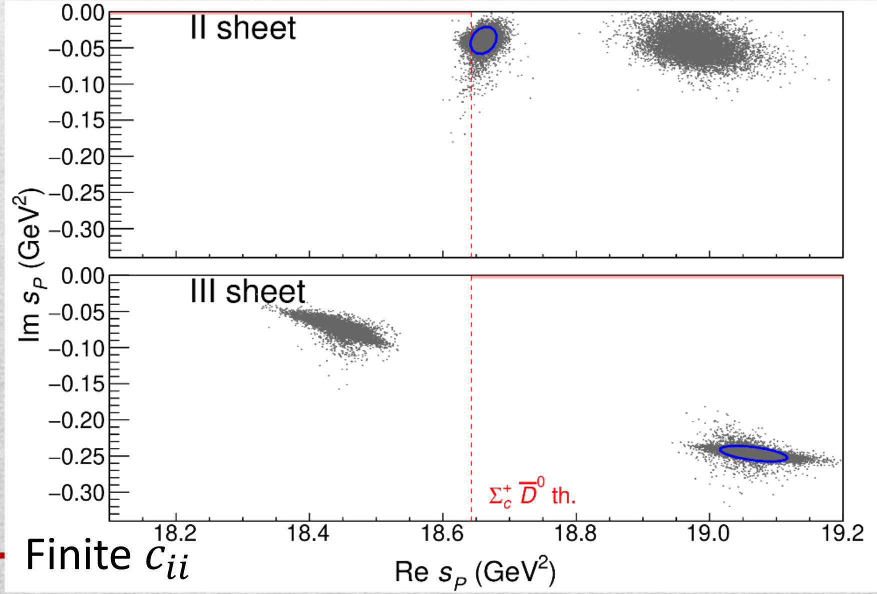


$c_{ii} = 0$

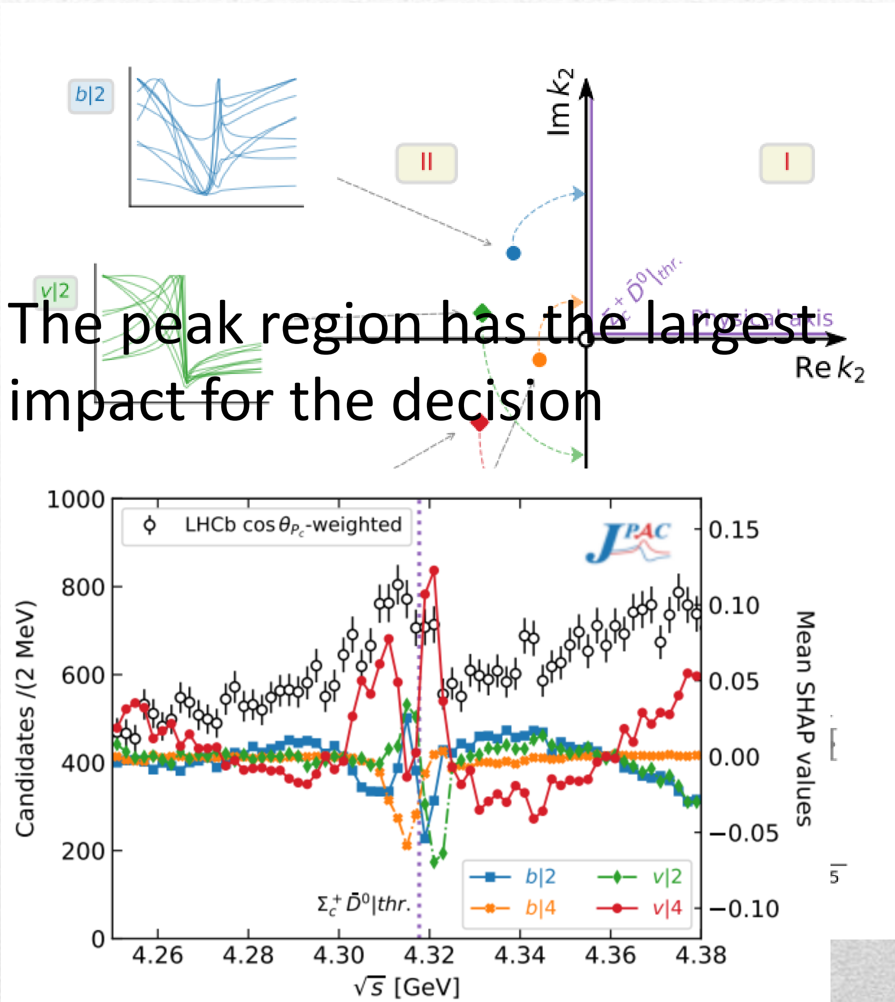


Finite c_{ii}

Minimal(istic) model with ANN

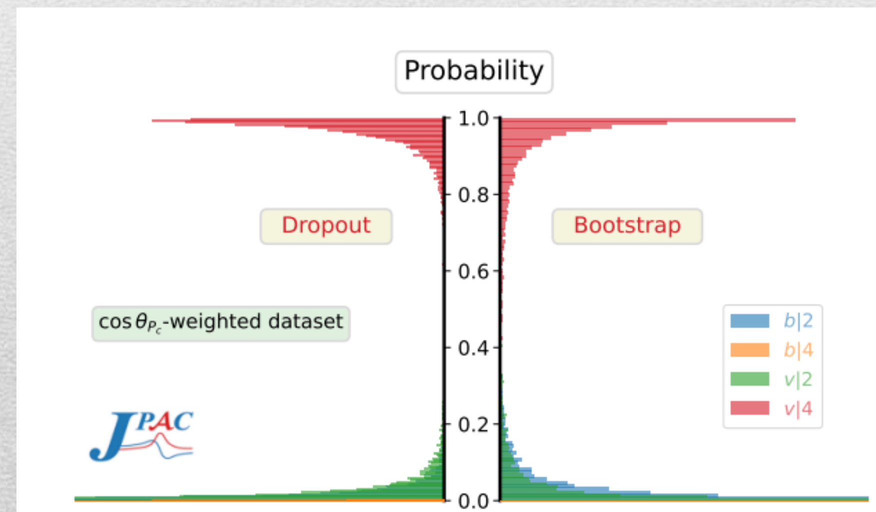
Ng, *et al.* (JPAC), PRD 105, L091501

The peak region has the largest impact for the decision

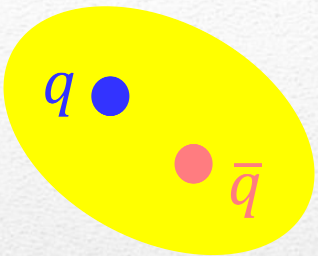


	$b\|2$	$b\|4$	$v\|2$	$v\|4$
$\cos\theta_{P_c}$-weighted	0.6%	$< 0.01\%$	1.1%	98.3%
$m_{Kp} > 1.9\,\text{GeV}$	1.4%	$< 0.1\%$	1.6%	97.0%
m_{Kp} all	5.4%	$< 0.1\%$	21.0%	73.6%

Highest probability for a virtual state in the IV sheet



Dictionary – Quark model



L = orbital angular momentum
S = spin $q + \bar{q}$

J = total angular momentum
= exp. measured spin

I = isospin = 0 for quarkonia

$$L - S \leq J \leq L + S$$
$$P = (-1)^{L+1}, C = (-1)^{L+S}$$
$$G = (-1)^{L+S+I}$$

J^{PC}	L	S	Charmonium $(c\bar{c})$	Bottomonium $(b\bar{b})$
0^{-+}	0 (S-wave)	0	$\eta_c(nS)$	$\eta_b(nS)$
1^{--}		1	$\psi(nS)$	$\Upsilon(nS)$
1^{+-}	1 (P-wave)	0	$h_c(nP)$	$h_b(nP)$
0^{++}		1	$\chi_{c0}(nP)$	$\chi_{b0}(nP)$
1^{++}		1	$\chi_{c1}(nP)$	$\chi_{b1}(nP)$
2^{++}		1	$\chi_{c2}(nP)$	$\chi_{b2}(nP)$

But $J/\psi = \psi(1S)$, $\psi' = \psi(2S)$

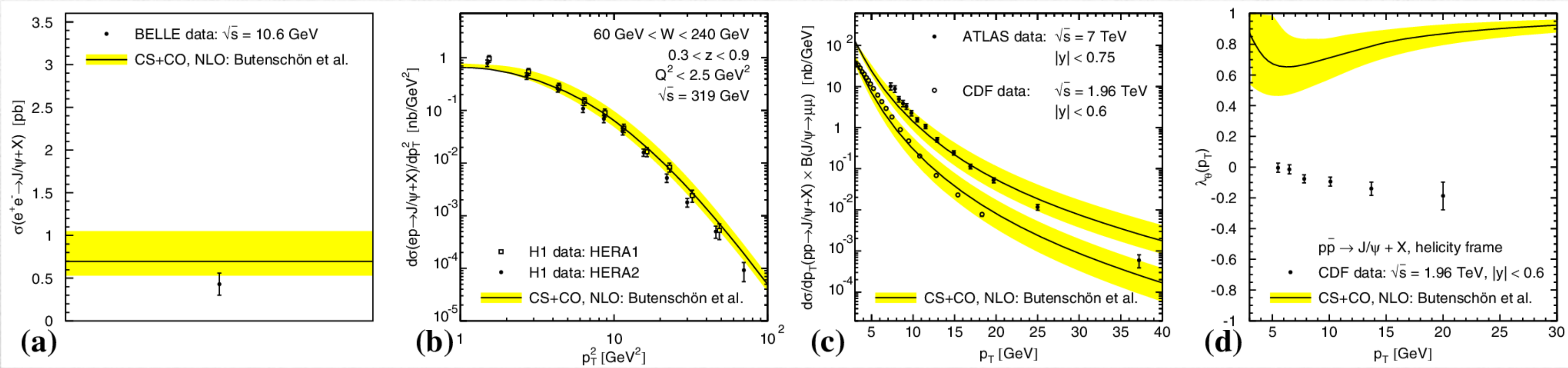
Multiscale system

Systematically integrate out the heavy scale,
$m_Q \gg \Lambda_{QCD}$

$$m_Q \gg m_Q v \gg m_Q v^2$$

Full QCD → NRQCD → pNRQCD

$m_b \sim 5 \text{ GeV}, m_c \sim 1.5 \text{ GeV}$
$v_b^2 \sim 0.1, v_c^2 \sim 0.3$



Factorization (to be proved) of universal LDMEs

Good description of many production channels, some known puzzles (polarizations)

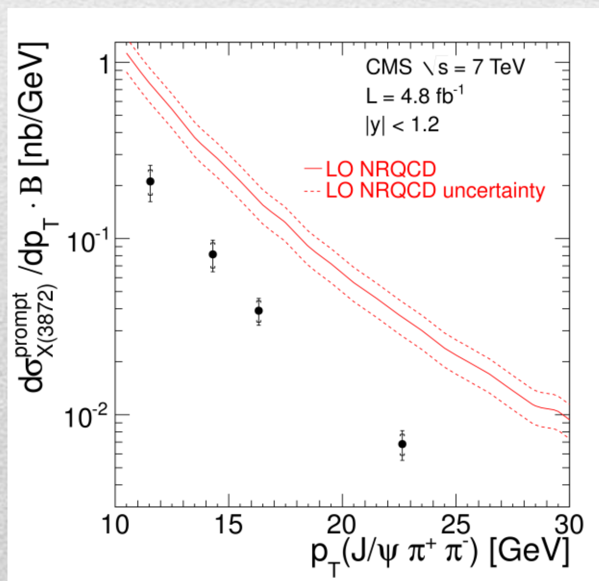
$X(3872)$

Large prompt production
at hadron colliders

$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$

$\sigma_{PR} \times B(X \to J/\psi\pi\pi)$
$= (1.06 \pm 0.11 \pm 0.15)$ nb

CMS, JHEP 1304, 154

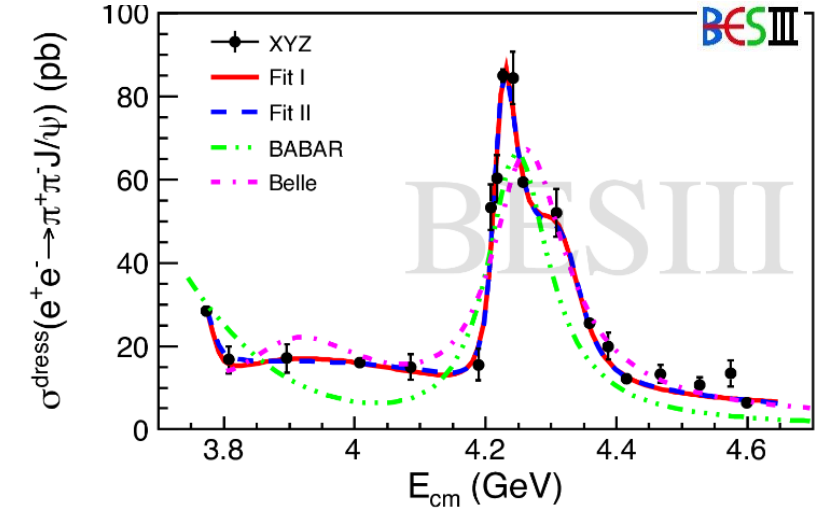


B decay mode	X decay mode	product br[illegible]ing fraction ($\times 10^5$)		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	(*BABAR*,[26] Belle[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	*BABAR*[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle[25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	(*BABAR*,[26] Belle[25])		
		$0.35 \pm 0.19 \pm 0.04$	*BABAR*[26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle[25]		
$(K^+\pi^-)_{NR}X$	$X \to \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle[106]		
$K^{*0}X$	$X \to \pi\pi J/\psi$	< 0.34, 90% C.L.	Belle[106]		
KX	$X \to \omega J/\psi$	$R = 0.8 \pm 0.3$	*BABAR*[33]	$0.061^{+0.024}_{-0.036}$	$0.77^{+0.28}_{-0.32}$
K^+X		$0.6 \pm 0.2 \pm 0.1$	*BABAR*[33]		
K^0X		$0.6 \pm 0.3 \pm 0.1$	*BABAR*[33]		
KX	$X \to \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4$ [illegible]	Belle[32]		
K^+X	$X \to D^{*0}\bar{D}^0$	$\mathbf{8.5 \pm 2.6}$	(*BABAR*,[38] Belle[37])	$0.614^{+0.166}_{-0.074}$	$8.2^{+2.3}_{-2.8}$
		$16.7 \pm 3.6 \pm 4.7$	*BABAR*[38]		
		$7.7 \pm 1.6 \pm 1.0$	Belle[37]		
K^0X	$X \to D^{*0}\bar{D}^0$	$\mathbf{12 \pm 4}$	(*BABAR*,[38] Belle[37])		
		$22 \pm 10 \pm 4$	*BABAR*[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle[37]		
K^+X	$X \to \gamma J/\psi$	$\mathbf{0.202 \pm 0.038}$	(*BABAR*,[35] Belle[34])	$0.019^{+0.005}_{-0.009}$	$0.24^{+0.05}_{-0.06}$
K^+X		$0.28 \pm 0.08 \pm 0.01$	*BABAR*[35]		
		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle[34]		
K^0X		$0.26 \pm 0.18 \pm 0.02$	*BABAR*[35]		
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle[34]		
K^+X	$X \to \gamma\psi(2S)$	$\mathbf{0.44 \pm 0.12}$	*BABAR*[35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
K^+X		$0.95 \pm 0.27 \pm 0.06$	*BABAR*[35]		
		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle[34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb[36]		
K^0X		$1.14 \pm 0.55 \pm 0.10$	*BABAR*[35]		
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle[34]		
K^+X	$X \to \gamma\chi_{c1}$	$< 9.6 \times 10^{-3}$	Belle[23]	$< 1.0 \times 10^{-3}$	< 0.014
K^+X	$X \to \gamma\chi_{c2}$	< 0.016	Belle[23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \to \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle[111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \to \eta J/\psi$	< 1.05	*BABAR*[112]	< 0.11	< 1.55
K^+X	$X \to p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb[110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Vector Y states in BESIII

BESIII, PRL118, 092002 (2017)

BESIII, PRL118, 092001 (2017) $e^+e^- \to J/\psi\,\pi\pi$

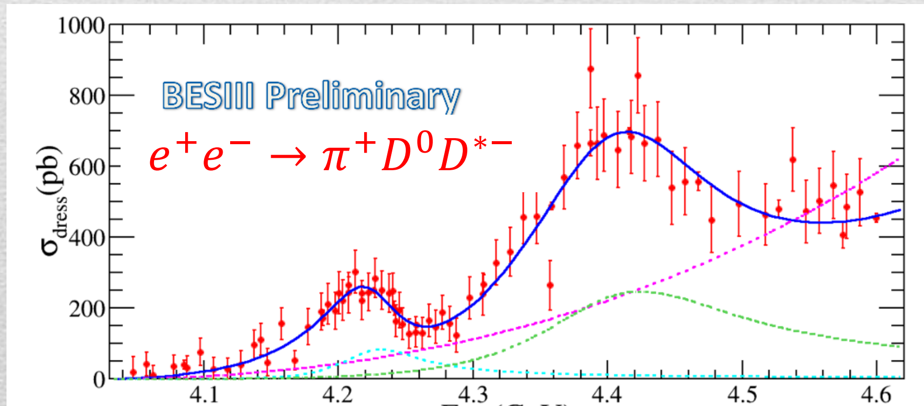


Parameters	Solution I	Solution II
$\Gamma_{e^+e^-}\mathcal{B}[\psi(3770)\to\pi^+\pi^-J/\psi]$		0.5 ± 0.1 (0
$\Gamma_{e^+e^-}\mathcal{B}(R_1\to\pi^+\pi^-J/\psi)$	$8.8^{+1.5}_{-2.2}\,(\cdots)$	$6.8^{+1.1}_{-1.5}\,(\cdots)$
$\Gamma_{e^+e^-}\mathcal{B}(R_2\to\pi^+\pi^-J/\psi)$	$13.3\pm1.4\,(12.0\pm1.0)$	$9.2\pm0.7\,(8.9\pm0.6)$
$\Gamma_{e^+e^-}\mathcal{B}(R_3\to\pi^+\pi^-J/\psi)$	$21.1\pm3.9\,(17.9\pm3.3)$	$1.7^{+0.8}_{-0.6}\,(1.1^{+0.5}_{-0.4})$
ϕ_1	$-58\pm11\,(-33\pm8)$	$-116^{+9}_{-10}\,(-81^{+7}_{-8})$
ϕ_2	$-156\pm5\,(-132\pm3)$	$68\pm24\,(107\pm20)$

New BESIII data show a peculiar lineshape for the $Y(4260)$

The state appear lighter and narrower, compatible with the ones in $h_c\pi\pi$ and $\chi_{c0}\omega$

A broader old-fashioned $Y(4260)$ is appearing in $\bar{D}D^*\pi$, maybe indicating a $\bar{D}D_1$ dominance

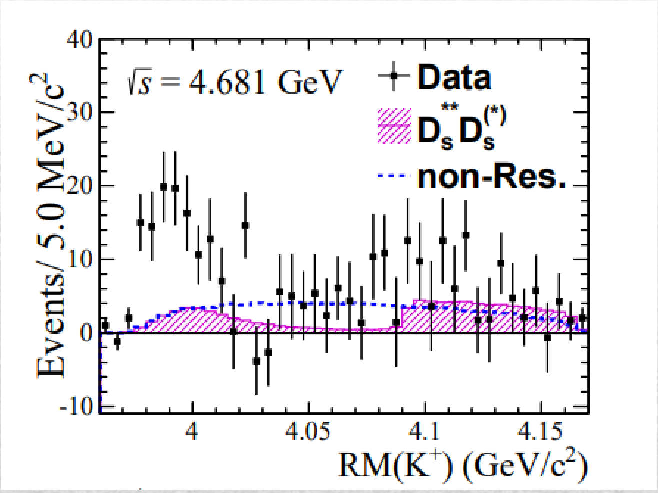


Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$M(Y(4220)) = (4224.8\pm5.6\pm4.0)$ MeV/c², $\Gamma(Y(4220)) = (72.3\pm9.1\pm0.9)$ MeV.
$M(Y(4390)) = (4400.1\pm9.3\pm2.1)$ MeV/c², $\Gamma(Y(4220)) = (181.7\pm16.9\pm7.4)$ MeV.

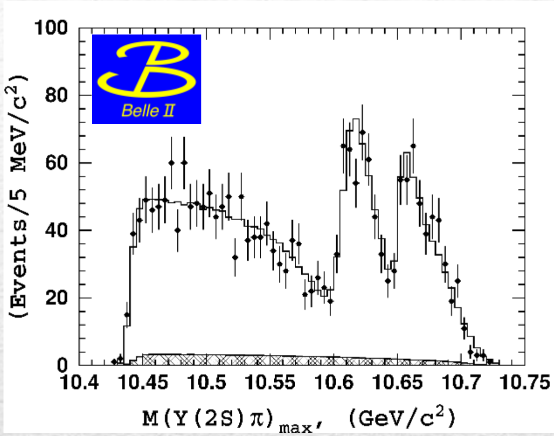
A Strange partner : $Z_{cs}(3985)$

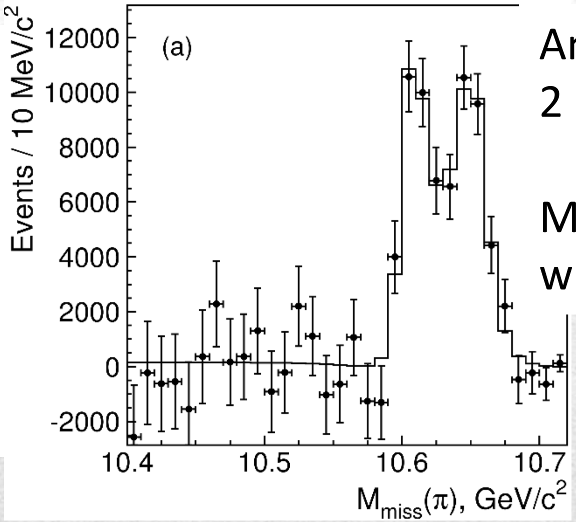
A strange partner of the $Z_c(3900)$seems to appear in open charm decays



$$e^+e^- \to Z_{cs}(3985)^+K^- \to D_s^+\overline{D^{*0}}\,K^-$$
$$M = 3982.5^{+1.8}_{-2.6} \pm 2.1\text{ MeV}, \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0\text{ MeV}$$

Charged Z states: $Z_b(10610), Z_b'(10650)$





Anomalous dipion width in $\Upsilon(5S)$, 2 orders of magnitude larger than $\Upsilon(nS)$

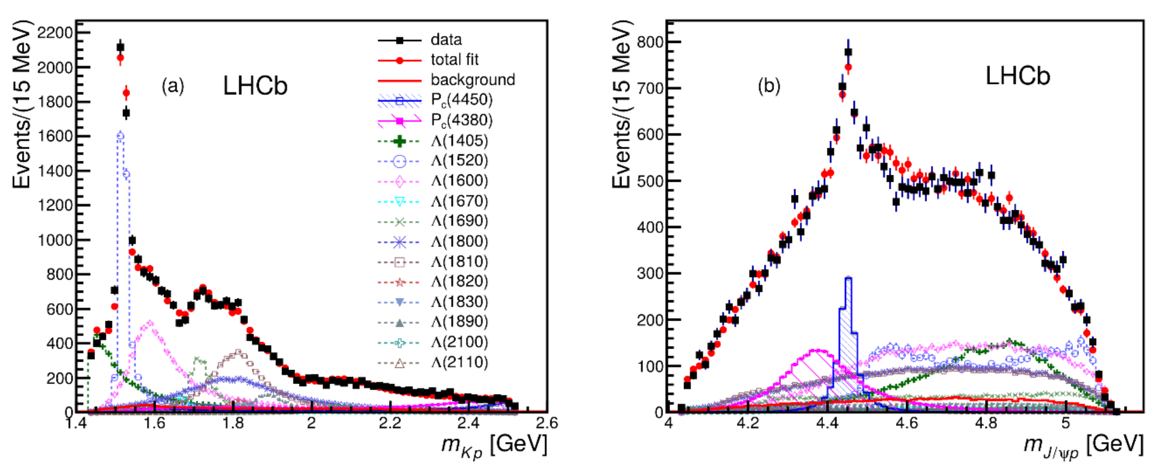
Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$ which violates HQSS

2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

$\Upsilon(5S) \to Z_b'(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to \bar{B}^{*0}B^{*+}\pi^-$
$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV

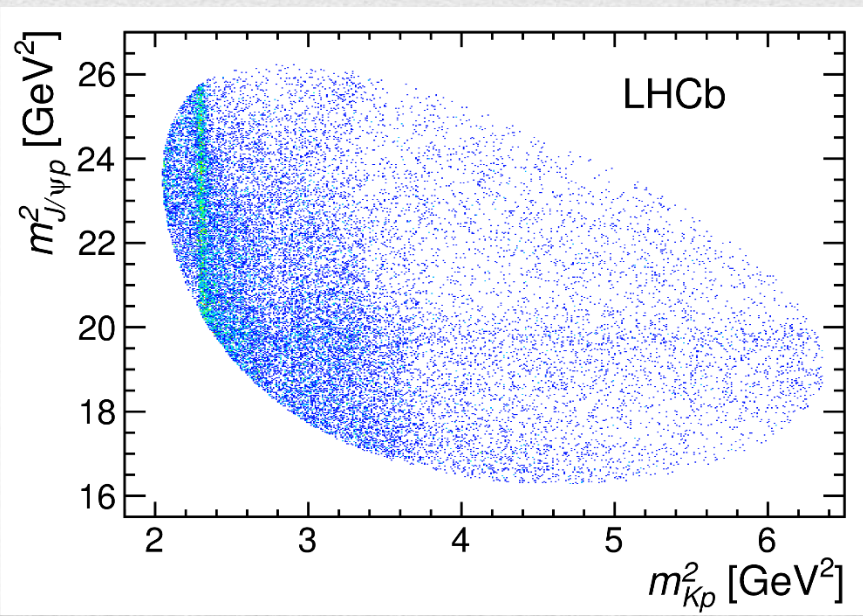
Pentaquarks!



LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$, evidence in $\Lambda_b \to (J/\psi\, p)\, \pi^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$



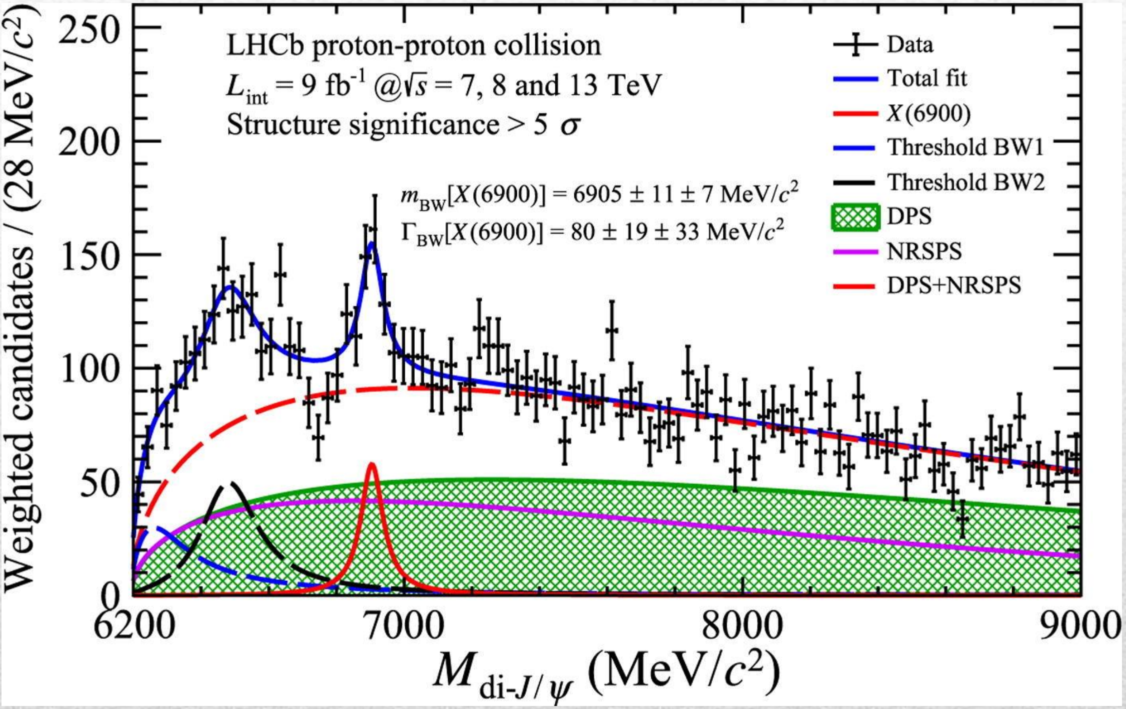
Quantum numbers

$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by Λ^* (model dependence?)

No obvious threshold nearby

Fully charm: the $X(6900)$



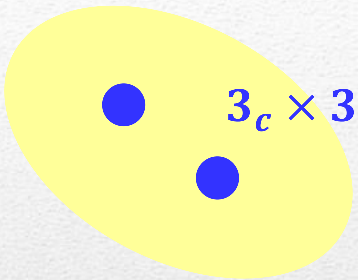
Two structures are seen in the $J/\psi\ J/\psi$ spectrum

The heavier one is narrower and well assessed

The nature of the lighter one is unclear

Diquarks

Attraction and repulsion in 1-gluon exchange approximation is given by

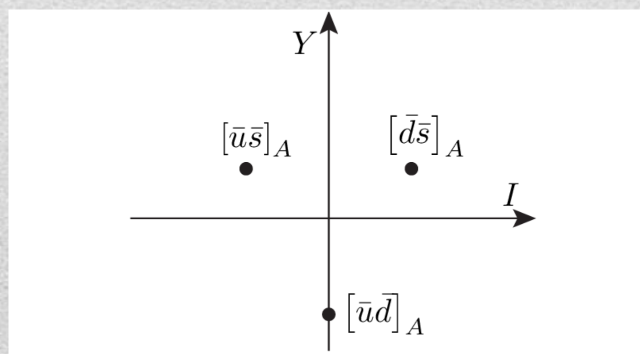


$\mathbf{3}_c \times \mathbf{3}_c \in \bar{\mathbf{3}}_c$

Now the two quarks are identical particles, they obey Fermi statistics
If we restrict to the ground state in S-wave, we have two options

$\bar{\mathbf{3}}_{color}(A) \times \bar{\mathbf{3}}_{flavor}(A) \times \mathbf{1}_{spin}(A)$ «Good» diquark

$\bar{\mathbf{3}}_{color}(A) \times \mathbf{6}_{flavor}(S) \times \mathbf{3}_{spin}(S)$ «Bad» diquark



Because of spin-spin interaction,
good diquark are lighter, and easier to produce

From the flavor point of view, it behaves like an antiquark

A little theorem (Landau-Smorodinski)

- Consider the Schroedinger's equation for the radial wave function of the molecular constituents

$$u_k''(r) + \left[k^2 - U(r)\right] u_k(r) = 0$$

with $U(r) = 2\mu V(r)$, $V(r) < 0$ is the potential, assumed to be attractive everywhere.

- We consider the wave function for two values of the momentum: $u_{k_{1,2}} \equiv u_{1,2}$

With simple manipulations we find the identity

$$u_2 u_1' - u_2' u_1 \Big|_0^R = (k_2^2 - k_1^2) \int_0^R dr\, u_2 u_1 \quad \text{(A)}$$

R >> a_0, the range of the potential ($\simeq 1/m_\pi$).

- Consider now the free equation, $\psi_k''(r) + k^2 \psi_k(r) = 0$, from which we also obtain

$$\psi_2 \psi_1' - \psi_2' \psi_1 \Big|_0^R = (k_2^2 - k_1^2) \int_0^R dr\, \psi_2 \psi_1 \quad \text{(B)}$$

- Normalizing to unity at r=0, the general expression for ψ_k is

$$\psi_k(r) = \frac{\sin(kr + \delta(k))}{\sin \delta(k)}, \quad \text{and:} \quad \psi_k'(0) = k \cot \delta(k).$$

- The radial wave function u_k vanishes at r=0, and we normalize so that it tends exactly to the corresponding ψ_k for large enough radii.
- Now, subtract (A) from (B) and let $R \to \infty$ (the integral now is convergent) to find

$$k_2 \cot \delta(k_2) - k_1 \cot \delta(k_1) = (k_2^2 - k_1^2) \int_0^\infty dr\, (\psi_2 \psi_1 - u_2 u_1)$$

L. Maiani

$$k_2 \cot\delta(k_2) - k_1 \cot\delta(k_1) = (k_2^2 - k_1^2)\int_0^\infty dr\,(\psi_2\psi_1 - u_2 u_1) \quad \text{(C)}$$

We compare (C) with the parameters of the scattering amplitude.

First we set $k_1 = 0$. Since $\lim_{k_1 \to 0} k_1 \cot\delta(k_1) = -\kappa_0$

$$k_2 \cot\delta(k_2) = -\kappa_0 + k_2^2 \int_0^\infty dr\,\left(\psi_2\psi_0 - u_2 u_0\right)$$

For small momenta: $k_2 \cot\delta(k_2) = -\kappa_0 + \frac{1}{2} r_0 k_2^2 + \ldots$ so that

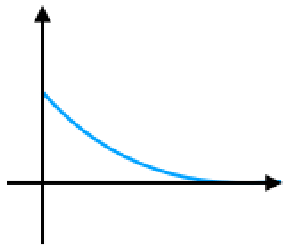
$$\boxed{r_0 = 2\int_0^\infty dr\,(\psi_0^2 - u_0^2)}$$

We know that $u_0(0) = 0$, $\psi_0(0) = 1$. Defining $\Delta(r) = \psi_0(r) - u_0(r)$ we have

$$\Delta(0) = +1,\ \Delta(\infty) = 0$$

The equations of motion imply $\Delta''(r) = -U(r)u_0(r)$. In presence of a single bound state, where u(r) has no nodes, we get

$$\Delta''(r) > 0 \rightarrow \psi_0(r) > u_0(r) \qquad \text{that is}$$

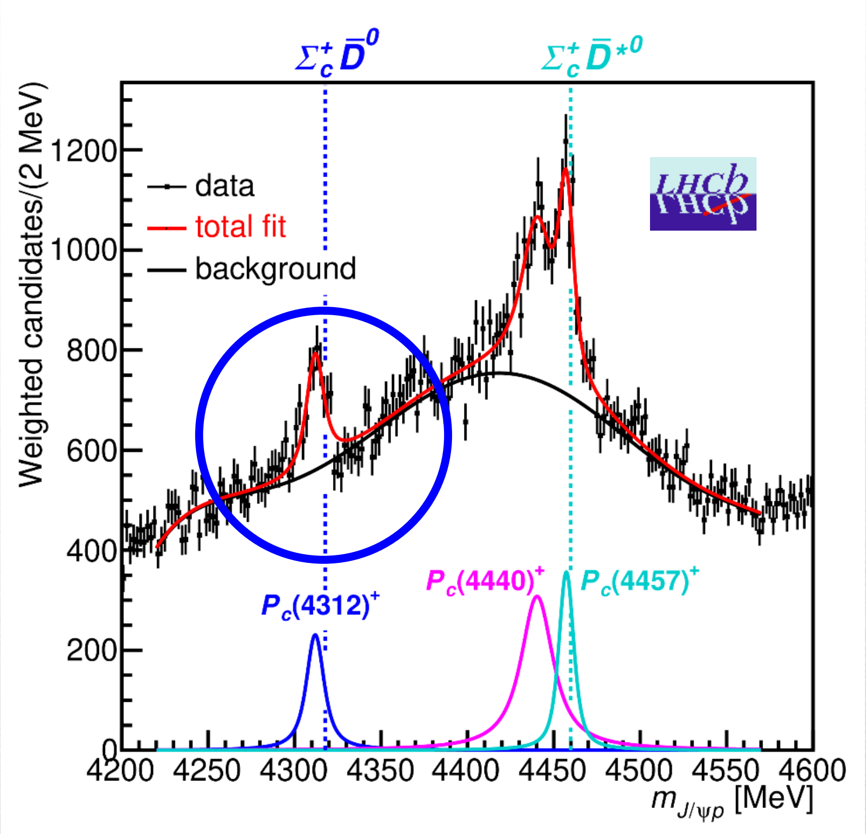


$$\boxed{r_0 > 0}$$

- reassuringly: $r_0(\text{deuteron}) = +1.75$ fm,
- conversely a negative value of $r_0 > 0$ implies $Z > 0$

L. Maiani

New pentaquarks discovered



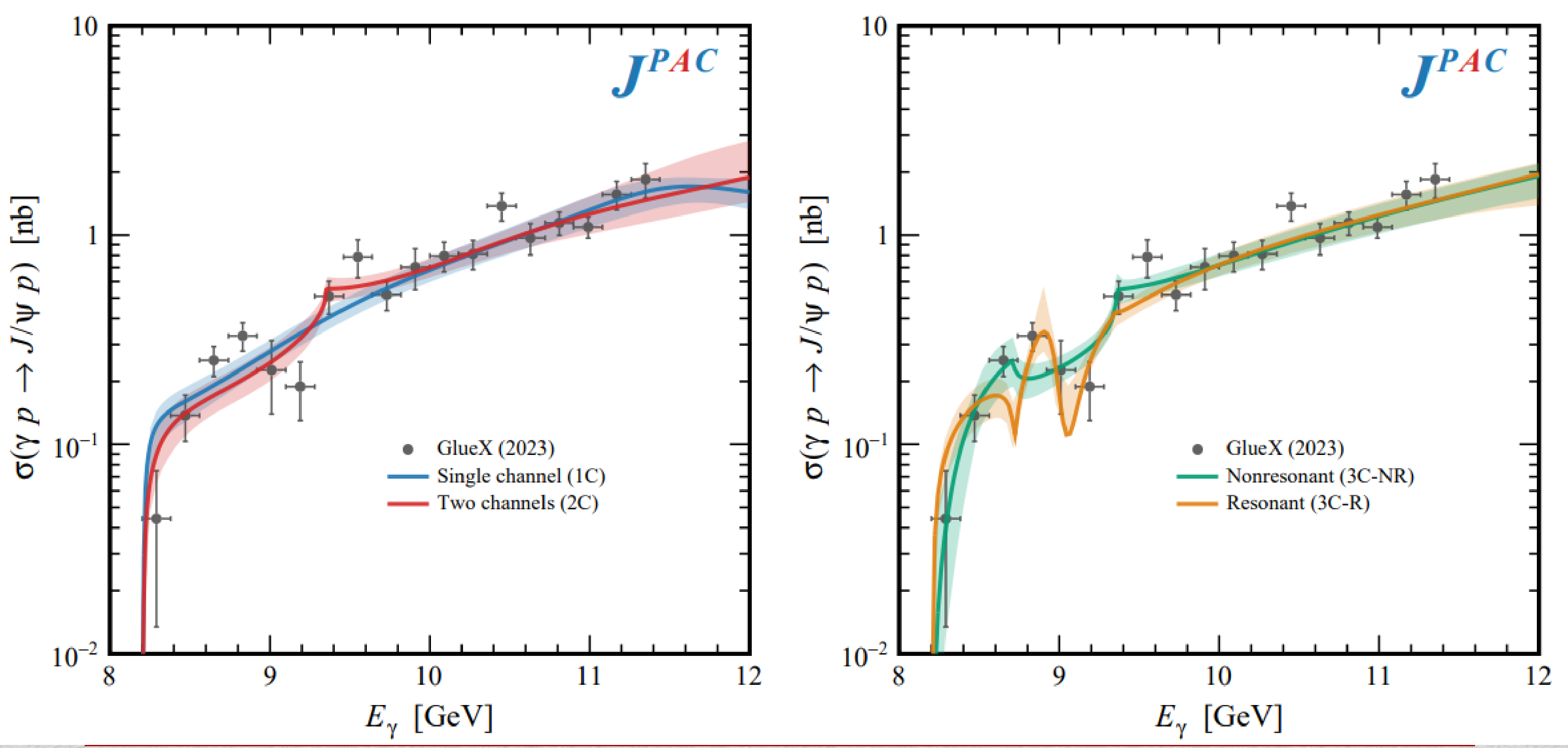
The lowest $P_c(4312)$ appears as an isolated peak at the $\Sigma_c^+ \bar{D}^0$ threshold

A detailed study of the lineshape provides insight on its nature

Bottom-up:
DON'T YOU DARE describing everything!!!
Focus on the peak region

Total cross section

1. **Single channel (1C):** Only interactions involving the $J/\psi\, p$ are included;
2. **Two channels (2C):** We include contributions from an intermediate $\bar{D}^{*}\Lambda_c$ channel;[2]
3. **Three channels (3C):** We include both $\bar{D}^{(*)}\Lambda_c$ channels. In this case we find two classes of solutions which we discuss separately below.



Minimal(istic) model for $P_c(4312)$

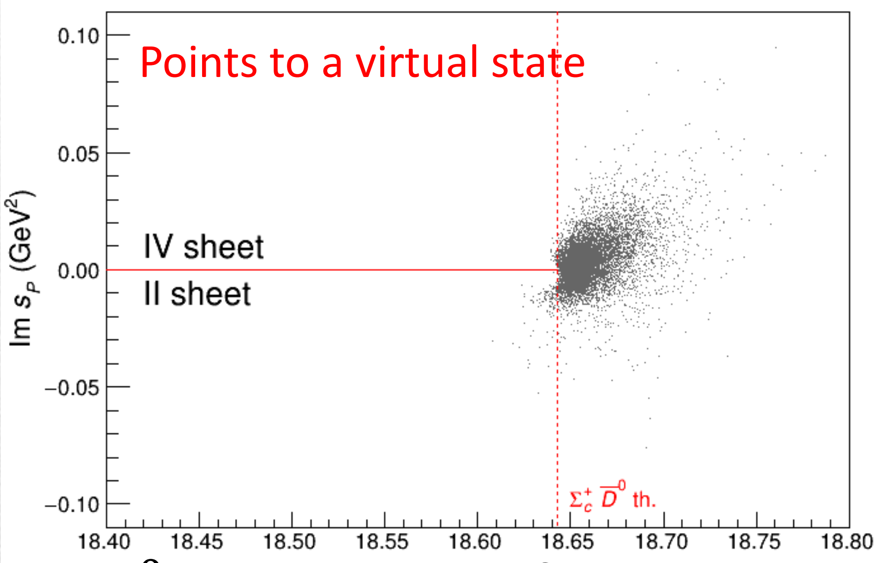
$$\frac{dN}{d\sqrt{s}} = \rho(s)\left[|F(s)|^2 + b_0 + b_1 s\right]$$

Effective range expansion

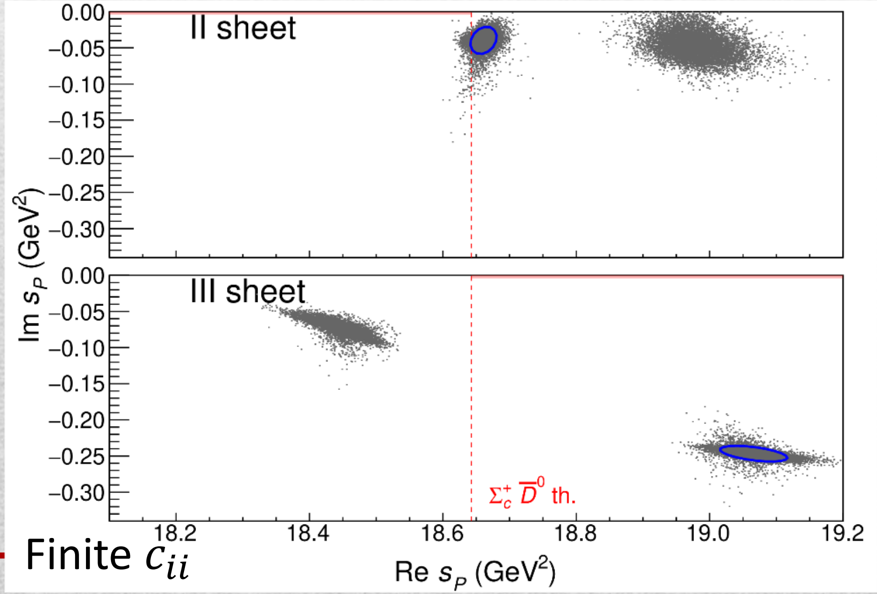
$$F(s) = (N_1 + N_2 s)\, T_{11}(s)$$

We can set $c_{ii} = 0$ to reduce to the scattering length approximation

$$T(s) = \begin{pmatrix} m_{11} - c_{11}s - i\rho_1(s) & m_{12} \\ m_{12} & m_{22} - c_{22}s - i\rho_2(s) \end{pmatrix}^{-1}$$



$c_{ii} = 0$



Finite c_{ii}

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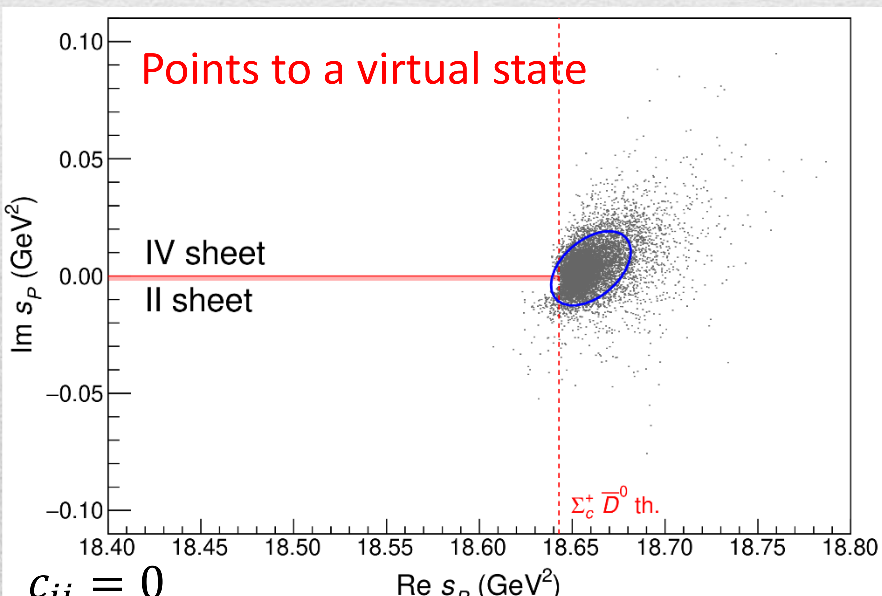

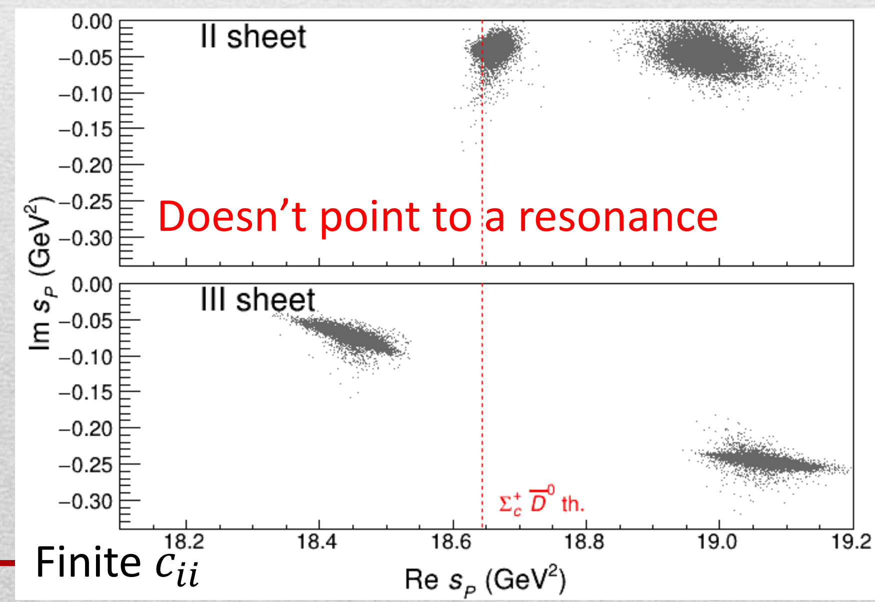

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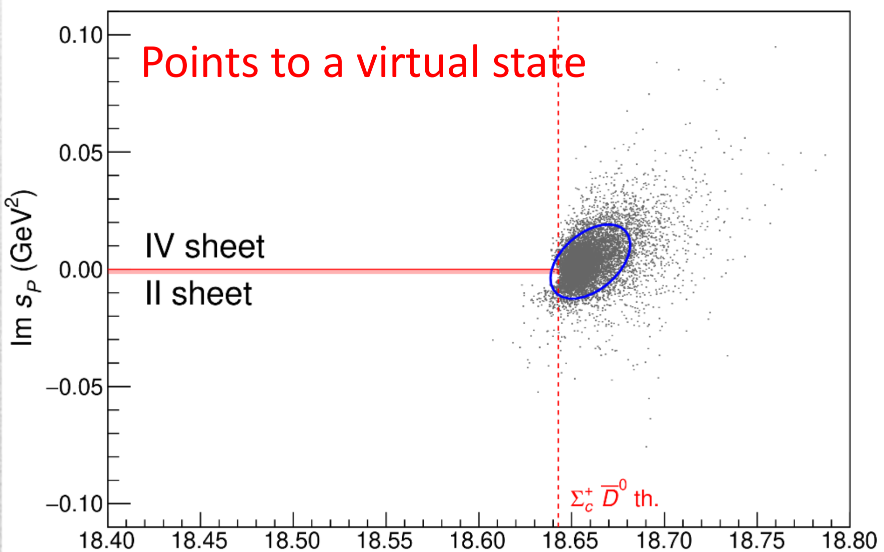
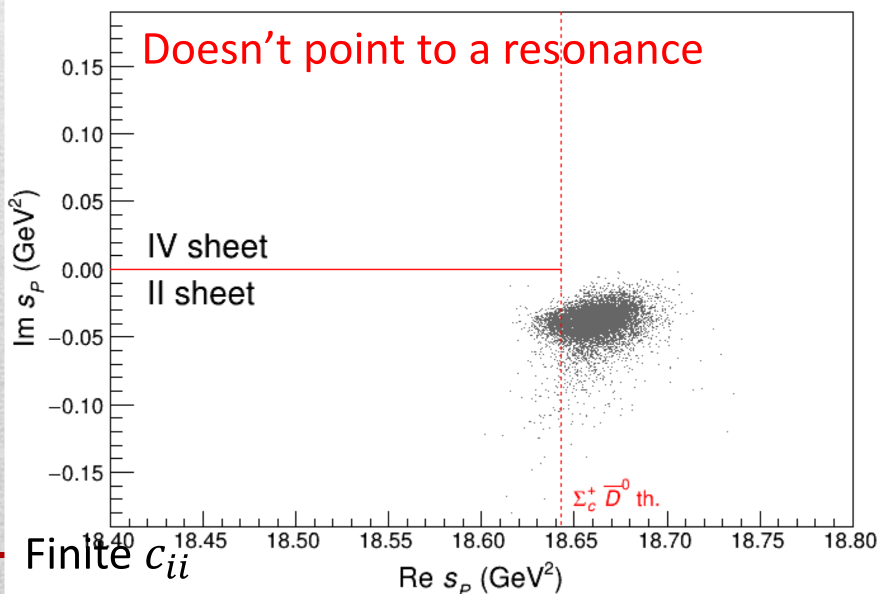


$c_{ii} = 0$

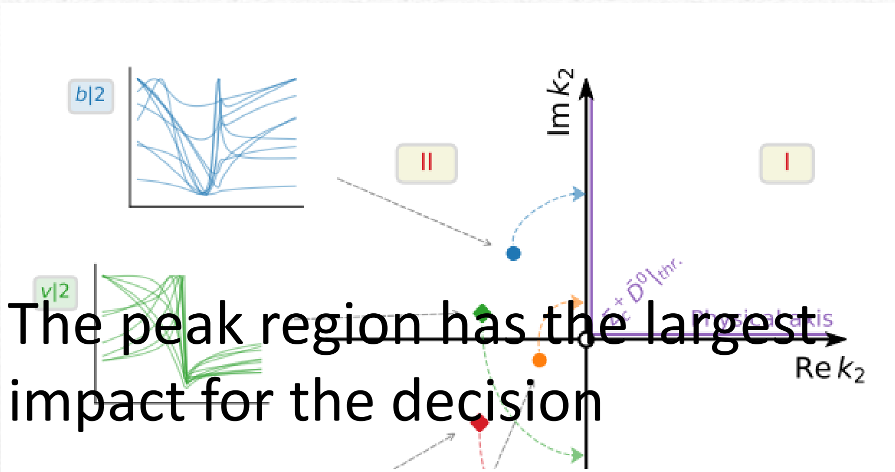


Finite c_{ii}

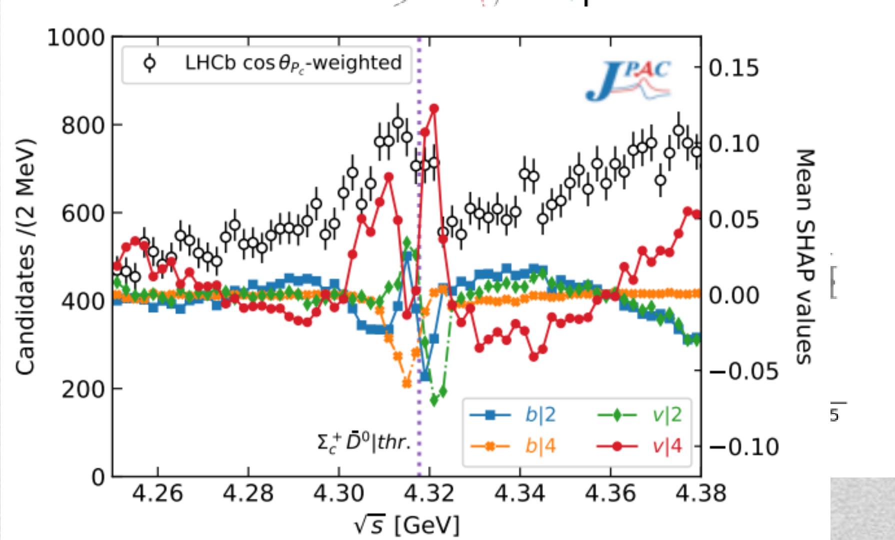
Minimal(istic) model with ANN

Ng, *et al.* (JPAC), PRD 105, L091501

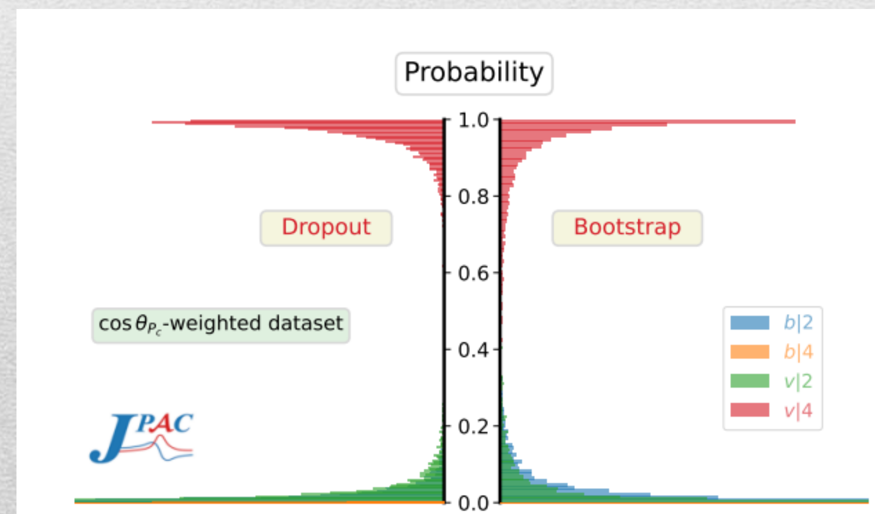
	$b\|2$	$b\|4$	$v\|2$	$v\|4$
$\cos\theta_{P_c}$-weighted	0.6%	$< 0.01\%$	1.1%	98.3%
$m_{Kp} > 1.9\,\text{GeV}$	1.4%	$< 0.1\%$	1.6%	97.0%
m_{Kp} all	5.4%	$< 0.1\%$	21.0%	73.6%



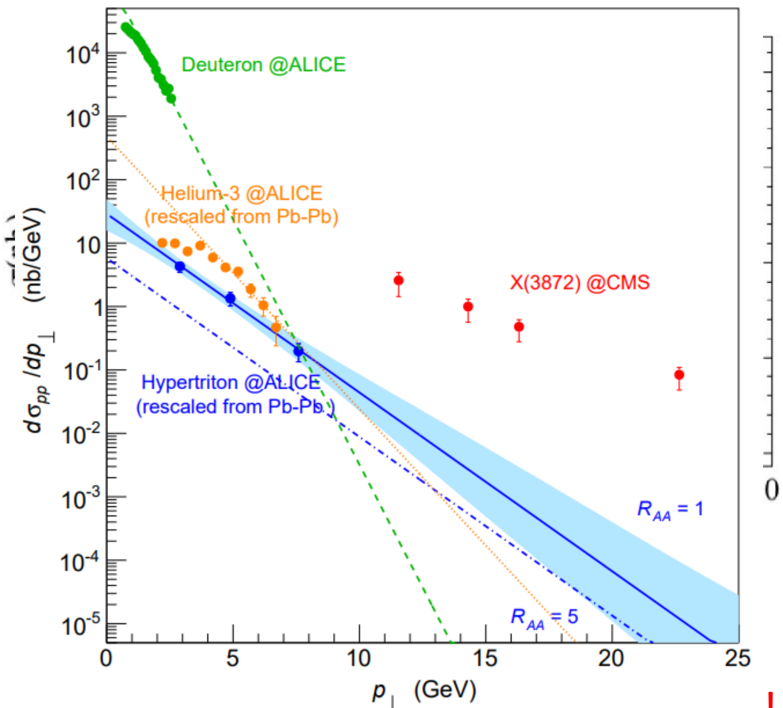
The peak region has the largest impact for the decision



Highest probability for a virtual state in the IV sheet



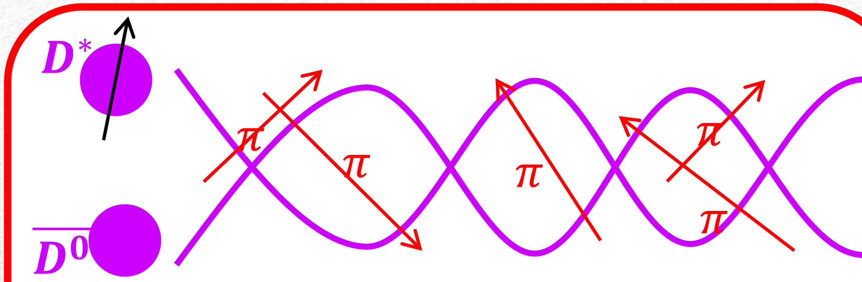
Prompt production of $X(3872)$



The comparison of production of other light nuclei suggests a different behavior

Bignamini *et al.* PRL103 (2009) 162001

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92 (2015) 3, 034028



A solution can be FSI (rescattering of DD^*), which allow k_{max} to be as large as $5m_\pi$, $\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

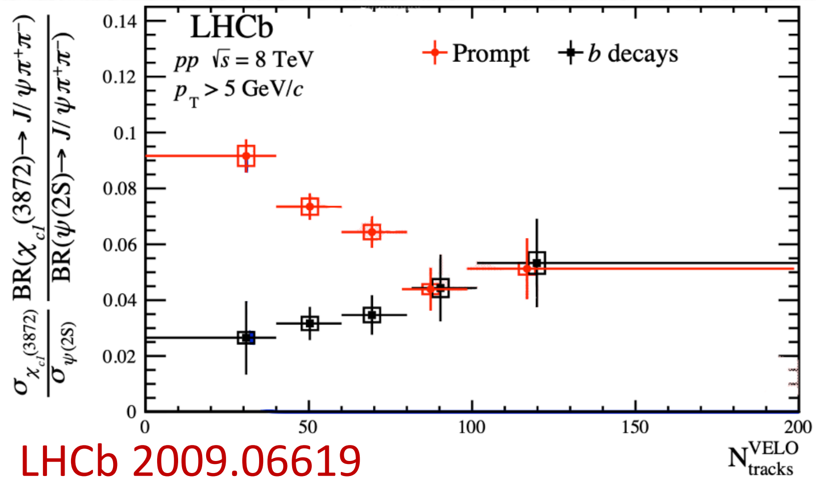
However, this is controversial because of the presence of comover that interfere with DD^* propagation

Bignamini *et al.* PLB684, 228-230

Esposito, Piccinini, AP, Polosa, JMP 4, 1569

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

Multiplicity dependence



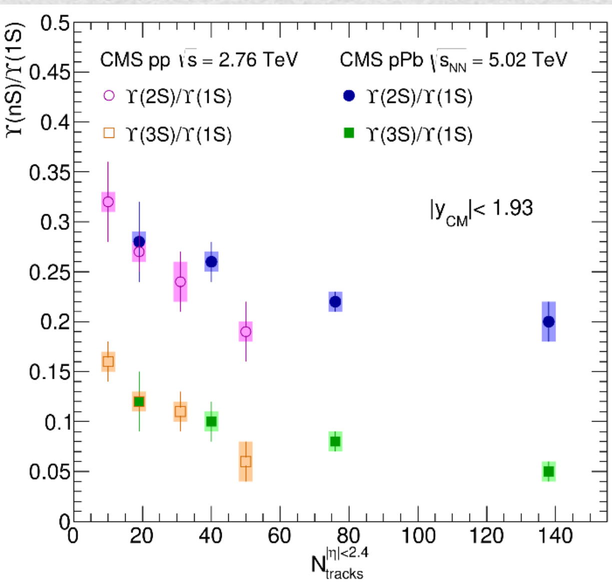
LHCb 2009.06619

The $X(3872)$ is more and more suppressed wrt $\psi(2S)$ when more comovers are present

Does it make the $X(3872)$ a fragile molecule?

No.

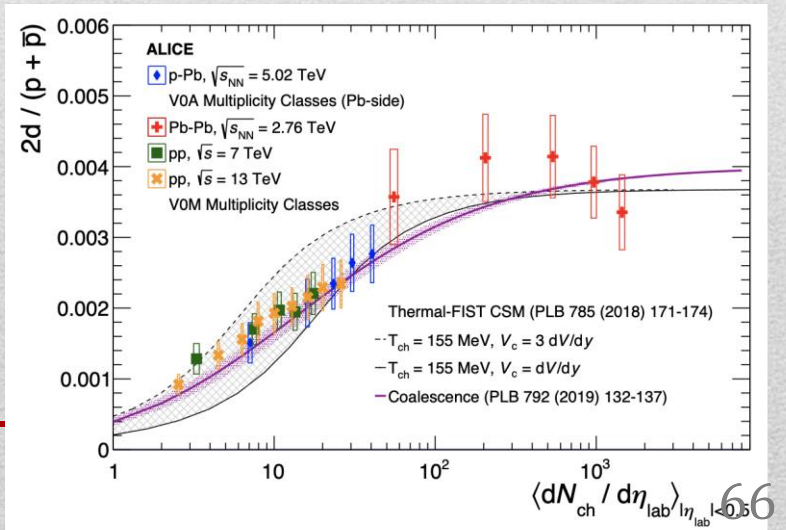
CMS JHEP04(2014), 103



$\Upsilon(2S)$ and $\Upsilon(3S)$ are not molecules, but they decrease

Deuteron is a molecule, but it increases

ALICE EPJC80, 9, 889



The comover model

The interaction with final state comoving particles can help create/destroy a hadron

Baym PLB138, 18

For a compact state in pp collisions the number evolves following

hadron yield

destruction cross section

$$\tau \frac{dN_\mathcal{Q}}{d\tau} = -\langle v\sigma \rangle_\mathcal{Q} \rho_c N_\mathcal{Q}$$

comover density at initial time (Glauber model) $\propto N_{ch}$

In the Comover Interaction Model one takes $\langle v\sigma \rangle_\mathcal{Q} \sim \pi r_\mathcal{Q}^2$

This has proved to be successful at describing pPb and PbPb data

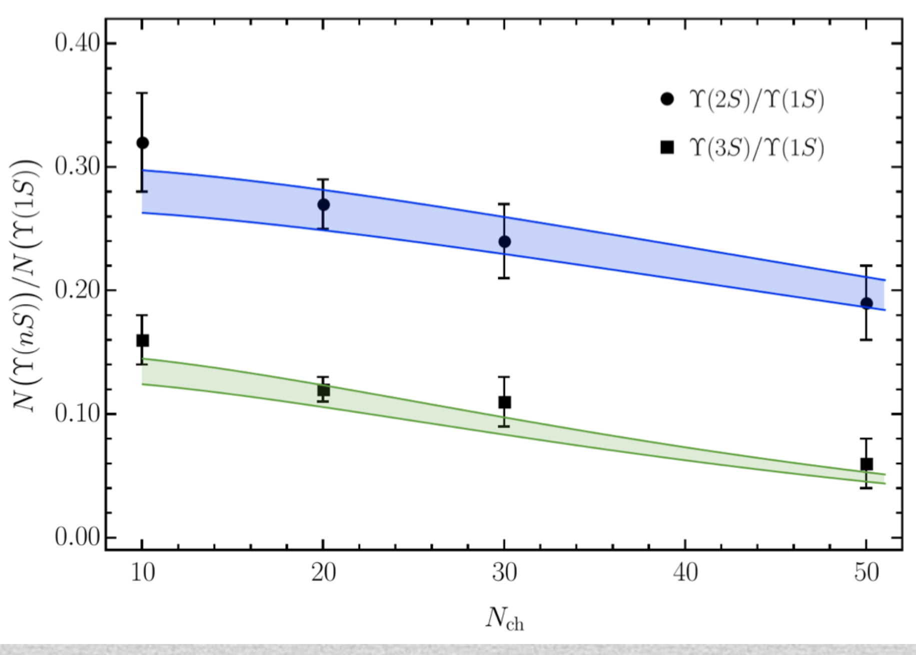
Ferreiro PLB749, 98

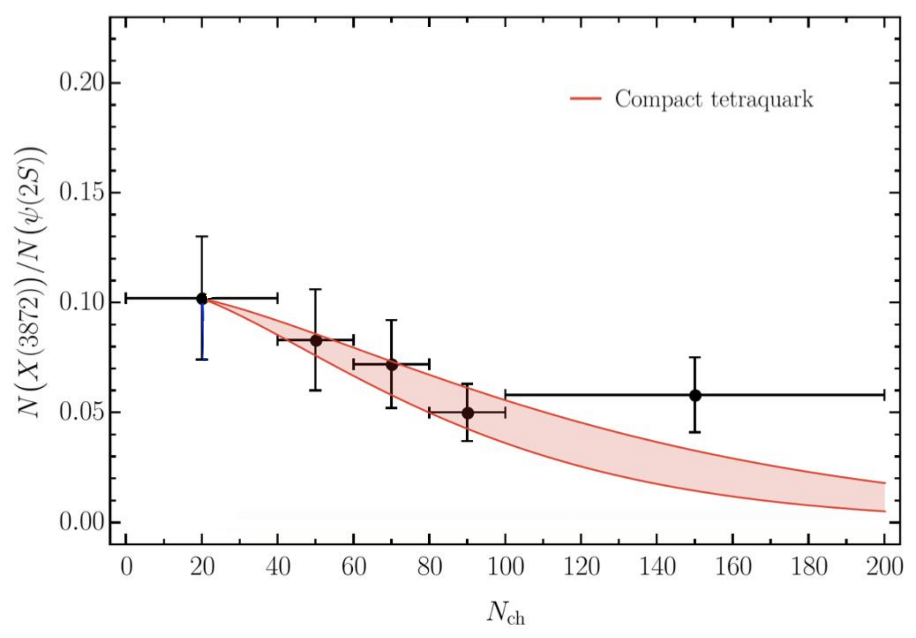
Ferreiro, Lansberg JHEP10(2018), 94

Bottomonia & $X(3872)$

Further validate the model using CMS pp data
Using same cross sections as in pPb and PbPb

Same model for a compact $X(3872)$





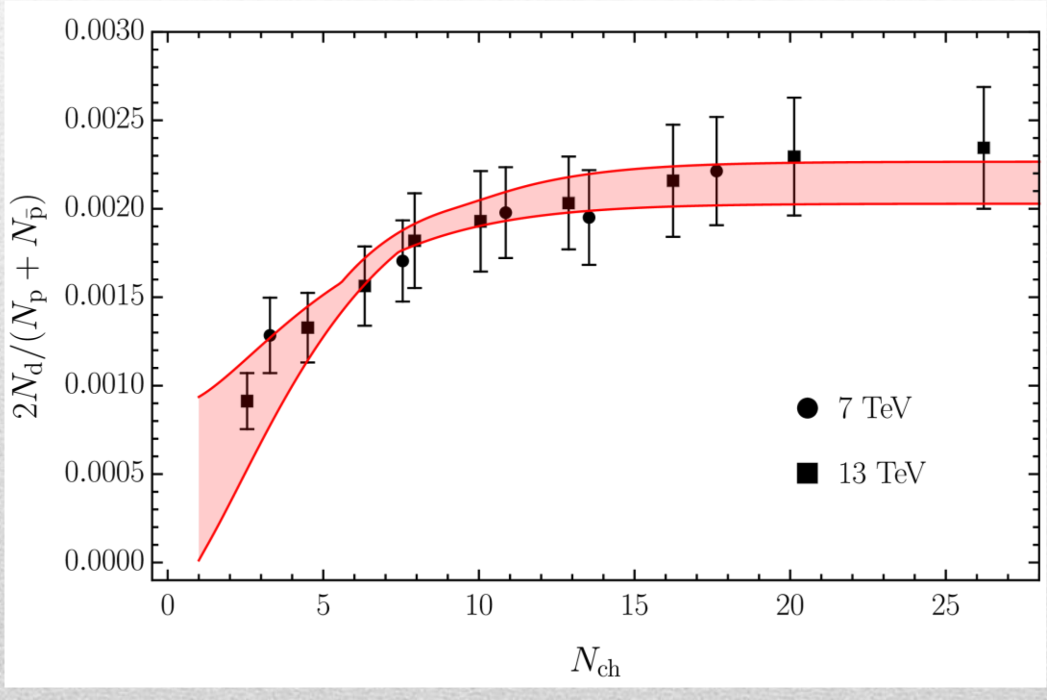
Esposito, Ferreiro, AP, Polosa, Salgado EPJC 81 (2021) 7, 669

Deuteron in coalescence model

Solution of the evolution equation with recombination

$$\frac{N_m}{N_h} = \frac{\langle v\sigma\rangle_m}{\langle v\sigma\rangle_m + \langle v\sigma\rangle_{hh}} + \left(\frac{N_m^0}{N_h^0} - \frac{\langle v\sigma\rangle_m}{\langle v\sigma\rangle_m + \langle v\sigma\rangle_{hh}}\right) e^{-(\langle v\sigma\rangle_m + \langle v\sigma\rangle_{hh})\rho_c \ln(\rho_c/\rho_c^{pp})}$$

Numbers of molecule at $t = 0$,
≈ 0 in Pythia



The coalescence momentum for deuteron is known to be $\Lambda = 50 \div 200$ MeV

Cross sections calculated from scattering of constituents

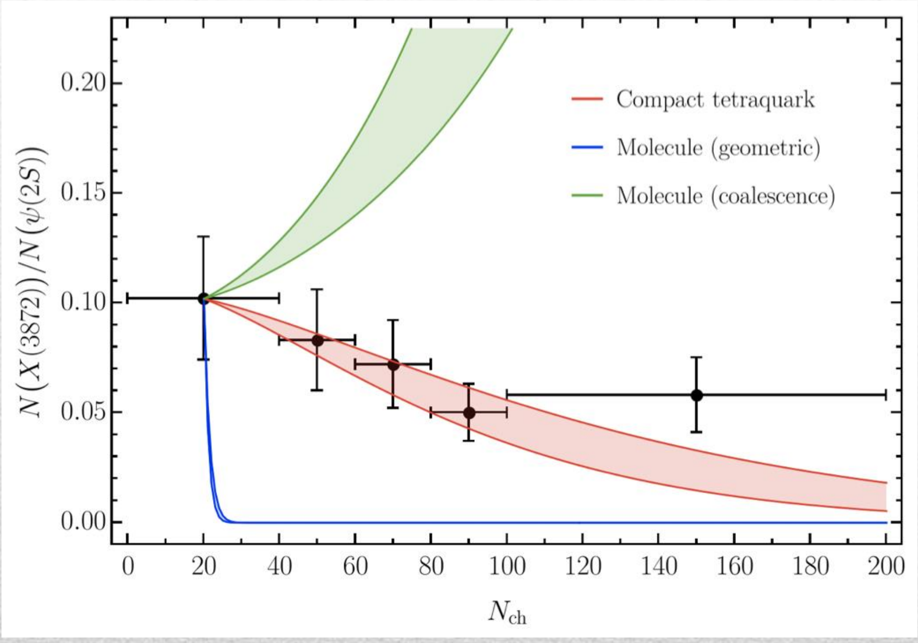
$X(3872)$ again

The coalescence momentum
for the $X(3872)$ is $\Lambda = 30 \div 300$ MeV

Controversies for N_m/N_h:
How is the X produced?

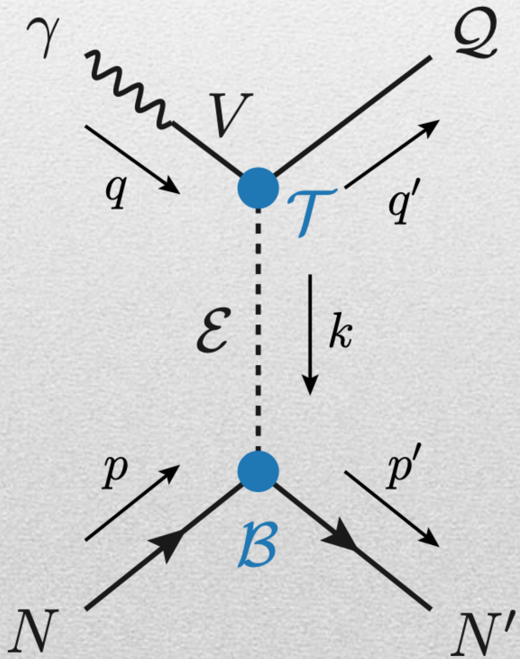
- Through $\bar{D}^0 D^{*0}$: $N_m/N_h \approx 0$
- Through $\chi_{c1}(2P)$: $N_m/N_h \approx 1$

The difference shown with a green band



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



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

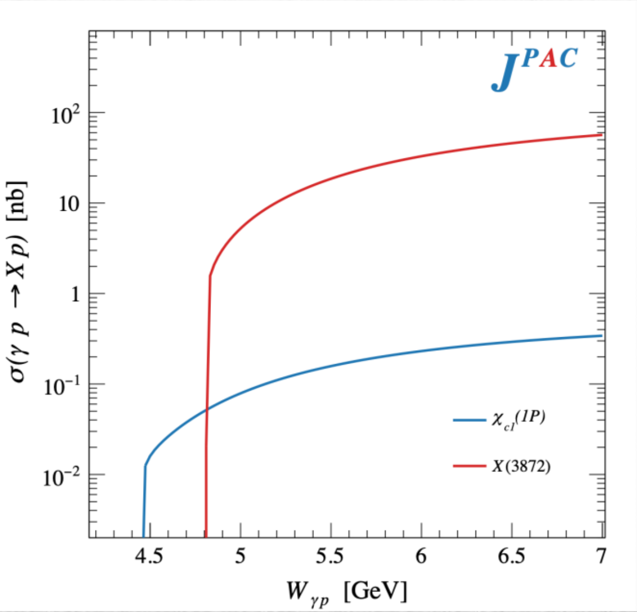
Holds at low energy, fixed spin

Holds at high energy, resummation of leading s power

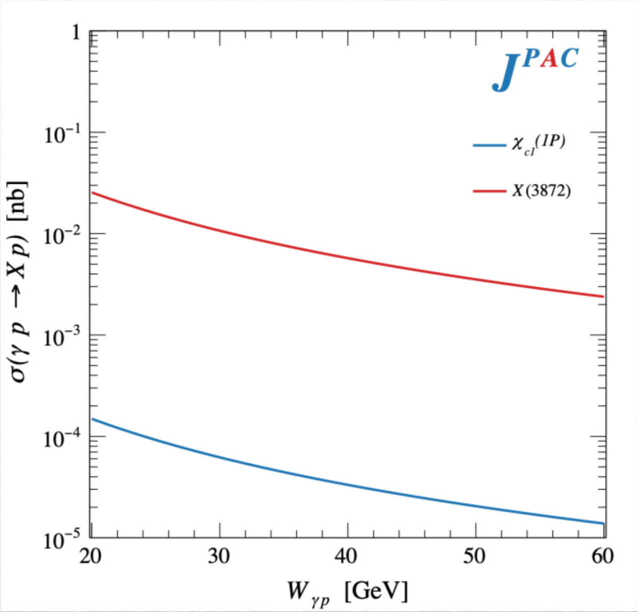
- If $\varepsilon \neq \mathbb{P}$, $\alpha_0 < 1$, $d\sigma/dt$ decreases with energy
- Exchange of heavy particles further suppressed

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



Y (vector) photoproduction

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

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

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

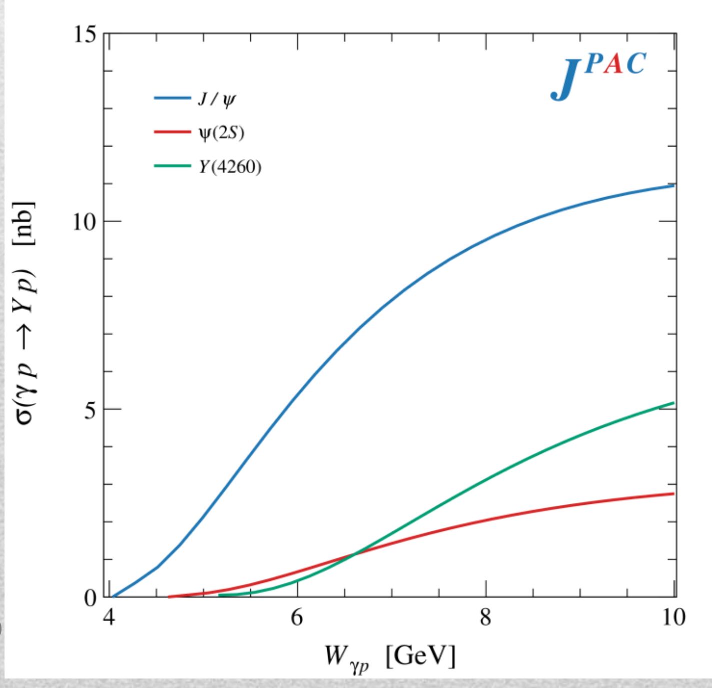
Assuming previous formula, one gets:

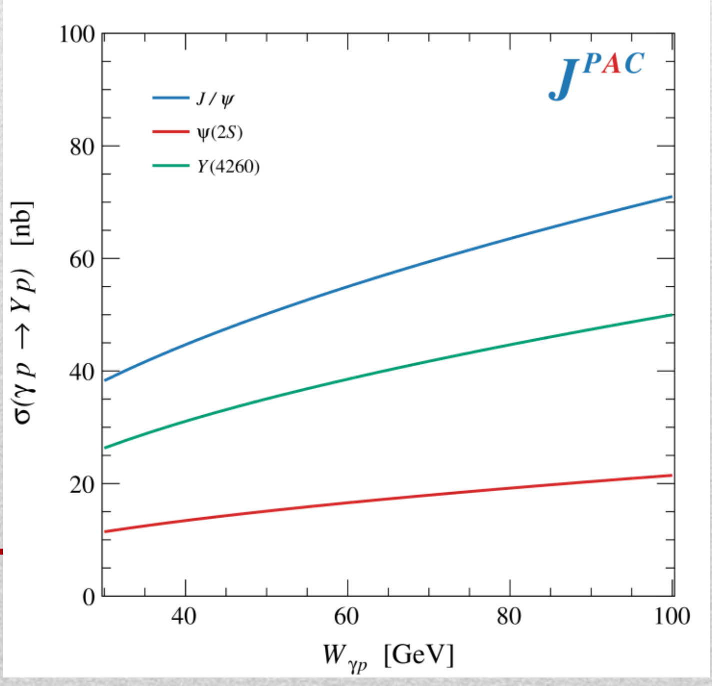
$\Gamma_{ee}^{Y} = 930\ eV$

(cfr. hep-ex/0603024, 2002.05641)

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

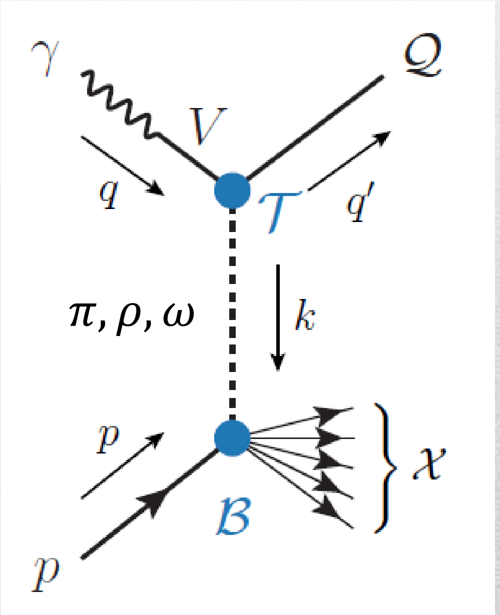
$R_Y = 0.84$

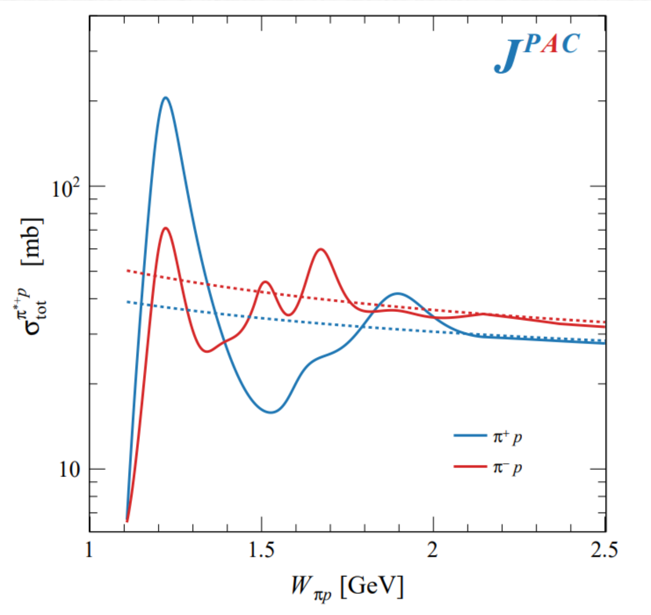


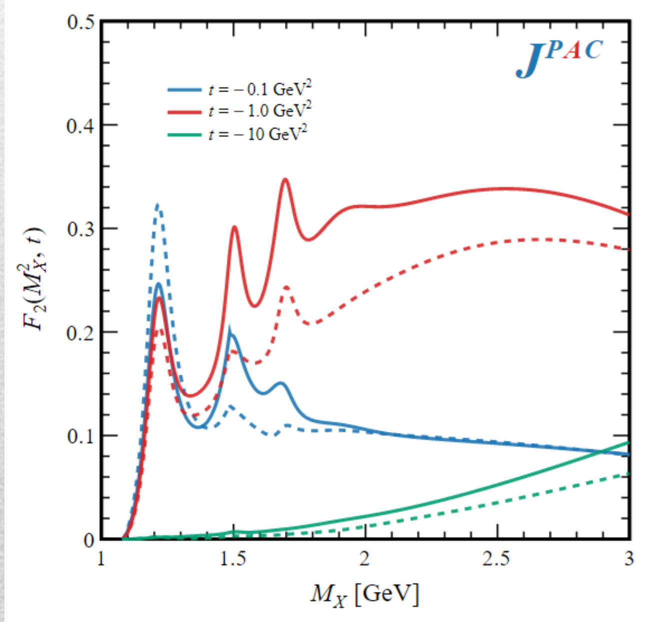


Semi-inclusive photoproduction

- 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

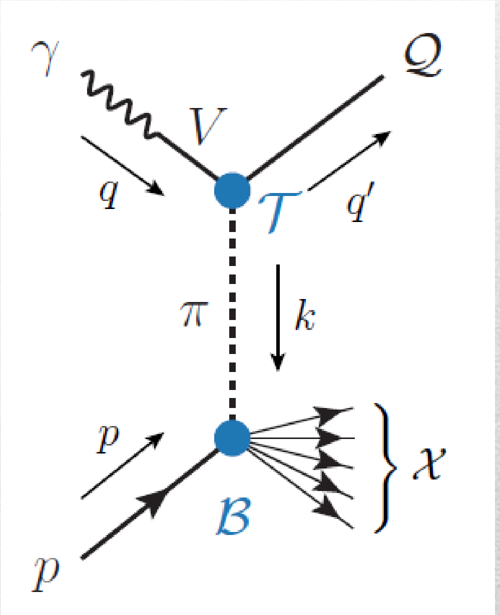


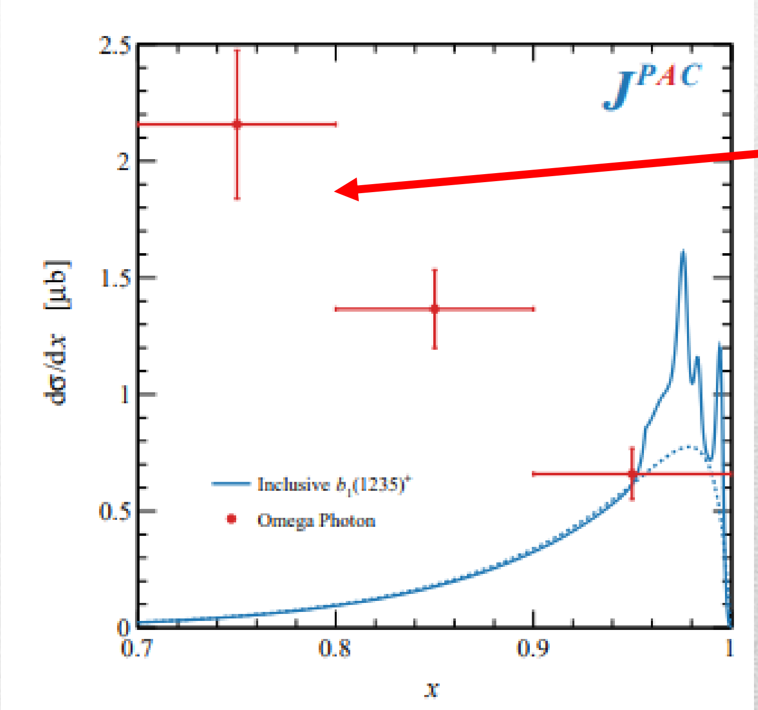




Semi-inclusive photoproduction (pion ex)

- 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



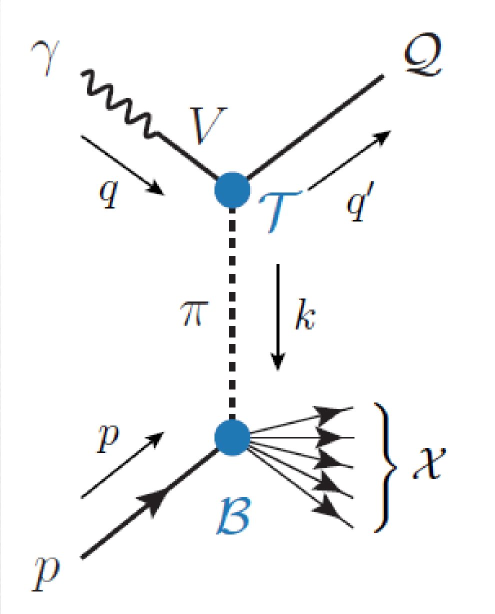


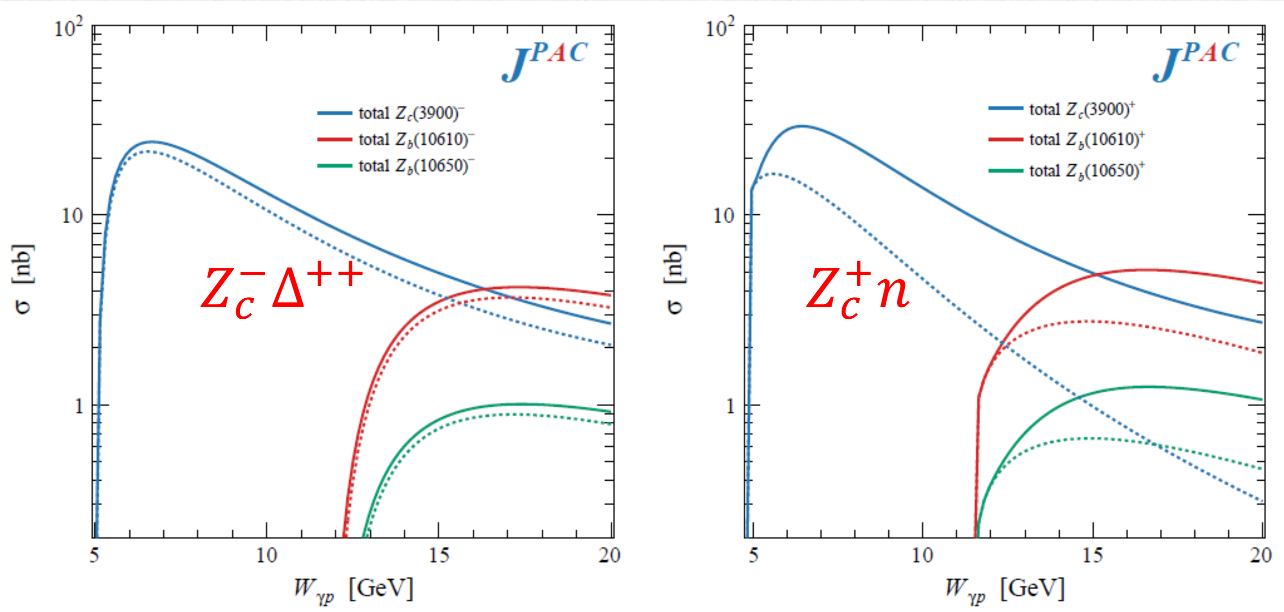
Model underestimates lower bins, conservative estimates

The model is expected to hold in the highest bin

Semi-inclusive photoproduction (pion ex)

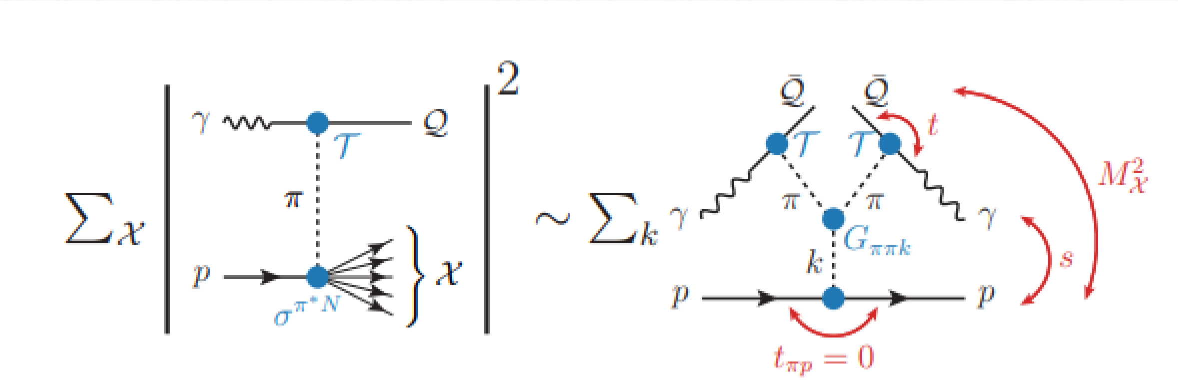
- For the Z_c^+, the inclusive cross section is sizably larger than the exclusive process





Semi-inclusive photoproduction (pion ex)

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

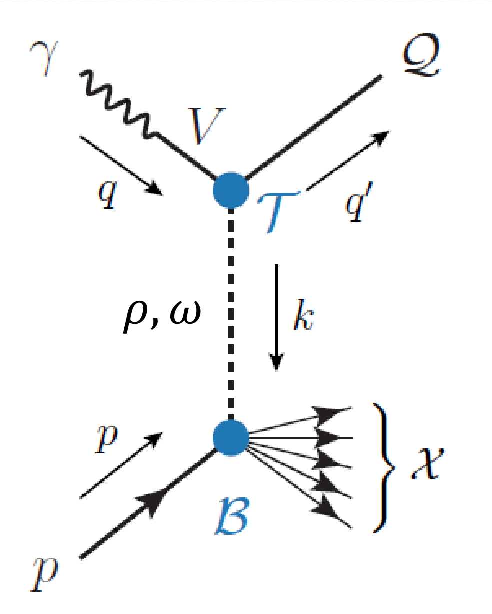


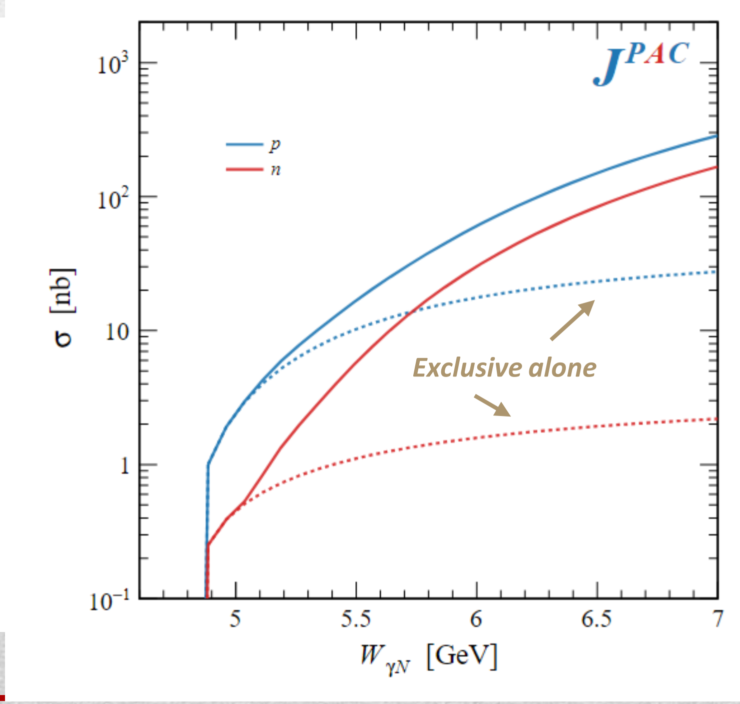
	$\sigma(\gamma p \to \mathcal{Q}^\pm \mathcal{X})$ [pb]			$\sigma(\gamma p \to \mathcal{Q}^+ n)$ [pb]		
$\mathcal{Q}$	30 GeV	60 GeV	90 GeV	30 GeV	60 GeV	90 GeV
$b_1(1235)$	$60 \cdot 10^3$	$60 \cdot 10^3$	$61 \cdot 10^3$	43	2.3	$< 10^{-8}$
$Z_c(3900)$	187	146	140	19	1.0	$< 10^{-8}$
$Z_b(10610)$	163	15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

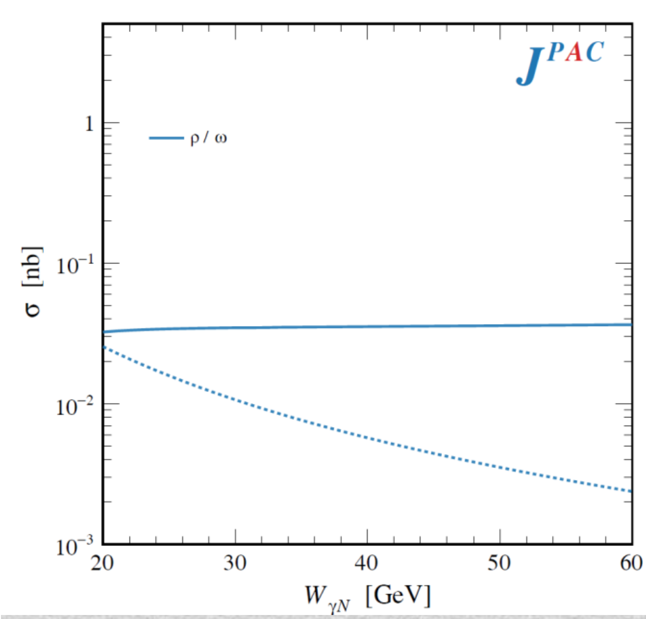
Semi-inclusive photoproduction (vector ex)

- 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

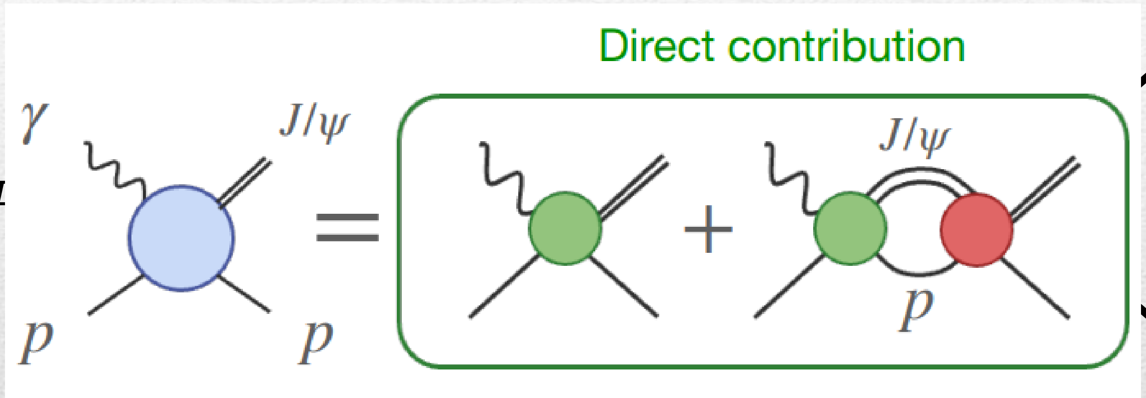






Vector Meson Dominance

Since unitary model parametrize separately the production and scattering amplitude, one can compare with the predictions of VMD



ψ

p

$$F_\ell(s) = f_\ell\,(1 + G\,T_\ell)$$

But $G(s_{\text{th}}) = 0$

The value of the scattering amplitude at threshold is called scattering length
According to VMD, a small photoproduction cross sections implies a small scattering length O(1am)

With the unitary model, the value of the amplitude at threshold is an unrelated parameter, the scattering length enters with the energy dependence

$$\text{VMD: } F^{\psi p}(s_{\text{th}}, x) = -8\pi\sqrt{s_{\text{th}}}\, g_{\gamma\psi}\, a_{\psi p}$$

$$\text{1C: } F^{\psi p}(s \to s_{\text{th}}, \theta) = n_S^{\psi p}\,(1 - i\,q\,a_{\psi p})$$

Vector Meson Dominance

$$R_{\text{VMD}}(x) = \left| \frac{F^{\psi p}(s_{\text{th}}, x)/g_{\gamma\psi}}{T^{\psi p, \psi p}(s_{\text{th}}, x)} \right|$$

VMD badly excluded, except for the poorly constrained 3C-R model

Scattering lengths generally of O(1fm), but smaller ones are not excluded

Crucial to constrain better these fits by measuring open charm final states

	1C	**2C**	**3C-NR**	**3C-R**
Parameters	9	13	15	15
χ^2	166	144	141	143
χ^2/dof	1.25	1.12	1.11	1.13
ζ_{th}	1	$[0.56,\ 0.74]$	$[0.36,\ 0.63]$	$[0.03,\ 0.62]$
$R_{\text{VMD}}(\theta=0)$	$[0.45,\ 0.73] \times 10^{-2}$	$[0.39,\ 1.62] \times 10^{-2}$	$[0.03,\ 1.74] \times 10^{-2}$	$[1.4 \times 10^{-2},\ 0.58]$
$R_{\text{VMD}}(t=0)$	$[1.3,\ 2.0] \times 10^{-2}$	$[1.3,\ 5.1] \times 10^{-2}$	$[0.08,\ 8.9] \times 10^{-2}$	$[5.4 \times 10^{-2}, 1.8]$
$a_{\psi p}$ [fm]	$[0.56,\ 1.00]$	$[0.11,\ 0.79]$	$[-2.77,\ 0.35]$	$[-0.04,\ 0.19]$