# *Testing the predicted dynamically generated hidden charm $X$ scalar state through the $D\bar{D}$ invariant mass spectrum and the radiative decay of the $\psi(3770)$.*

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in collaboration with

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# Talk

- Introduction
- Model for dynamically generating resonances
- Dynamically generated states
- $D\bar{D}$ invariant mass spectrum
- Radiative decay
- Overview

# Introduction

- New experimental developments have resulted in the discovery of many new and unexpected (unpredicted) states above charm threshold. Ex. $D^*_{s0}(2317)$, $D_{s1}(2460)$, $X(3872)$, ...
- Still in the last couple of years many more new hidden charm states have been claimed by experiments. Ex. $X(3940)$, $Y(4260)$, ...
- All these discoveries have sparked the interest of many research groups and many theoretical models have been proposed in order to accommodate such states. In particular the use of chiral Lagrangians with unitarization techniques, which already described many states as dynamically generated ones has also been successfully in describing some of the charmed and hidden charm newly found states.
- Apart from describing known states the theory also predicts new ones. Ex: Scalar X(3.7GeV)
- What kind of experiments can help us to find this new states?

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# Model

- The model consists in extending the lowest order chiral Lagrangian from $SU(3)$ to $SU(4)$ and then explicitly break $SU(4)$ symmetry to $SU(3)$.
- First a field is constructed:

$$\Phi = \sum_{i=1}^{15} \frac{\varphi_i}{\sqrt{2}} \lambda_i$$

$$J_\mu = \partial_\mu \Phi \Phi - \Phi \partial_\mu \Phi$$

- A $SU(4)$ singlet may be added to $\Phi$ in order to write it in the physical basis:

$$\Phi = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & \pi^+ & K^+ & \overline{D^0} \\ \pi^- & \frac{\eta}{\sqrt{3}} - \frac{\pi^0}{\sqrt{2}} + \frac{\eta'}{\sqrt{6}} & K^0 & D^- \\ K^- & \overline{K^0} & \sqrt{\frac{2}{3}}\eta' - \frac{\eta}{\sqrt{3}} & {D_s}^- \\ D^0 & D^+ & {D_s}^+ & \eta_c \end{pmatrix}$$

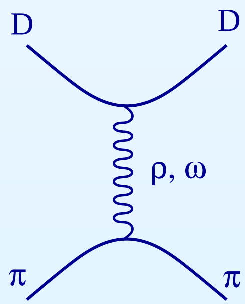
# Model

- The Lagrangian is built by coupling this current to itself plus a mass term:

$$\mathcal{L} = \frac{1}{12f^2} Tr(J_\mu J^\mu + \Phi^4 M)$$

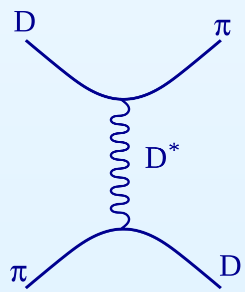
- The mass term is diagonal: $M = diagonal(m_\pi^2, m_\pi^2, 2m_K^2 - m_\pi^2, 2m_D^2 - m_\pi^2)$
- The $SU(4)$ symmetry is implicitly broken by the different masses of the particles and explicitly broken in two ways:
  - The parameter $f$: $f = f_\pi = 93$ MeV for light mesons, and $f = f_D = 165$ MeV for heavy ones.
  - Suppressing heavy meson exchanges in the underlying dynamics.

$\underline{J_{\bar{3}3\mu} J^\mu_{88}}$




$\sim \frac{1}{m_L^2}$

$\underline{J_{\bar{3}8\mu} J^\mu_{83}}$




$\sim \frac{1}{m_H^2}$

Suppression factor:

$$\gamma = \frac{m_L^2}{m_H^2}$$

# Model

- From the Lagrangian we get the tree level amplitudes, project them into s-wave and construct the potential.
  $\mathcal{L} \rightarrow \mathcal{M} \rightarrow V$
- The potential is plugged in the scattering equation.
  $T = V + VGT$
- In an on-shell formalism this is an algebraic equation which can be inverted.
  $T = (\hat{1} - VG)^{-1}V$
- $G$ contains the two meson propagator for each channel, it has a loop, must be regularized so we get a free parameter: $\alpha$.
- We can calculate the T-matrix in the complex energy plane and identify poles in the second Riemann sheet. $\rightarrow$ RESONANCES!
- For each pole we can calculate its residues in each channel, which gives us information on the coupling of the resonance to the channel.
  Close to the pole position: $T_{ij} \sim \frac{g_i g_j}{s - s_{pole}}$
- Also the scattering of pseudo scalars with vector mesons can be studied following similar steps.

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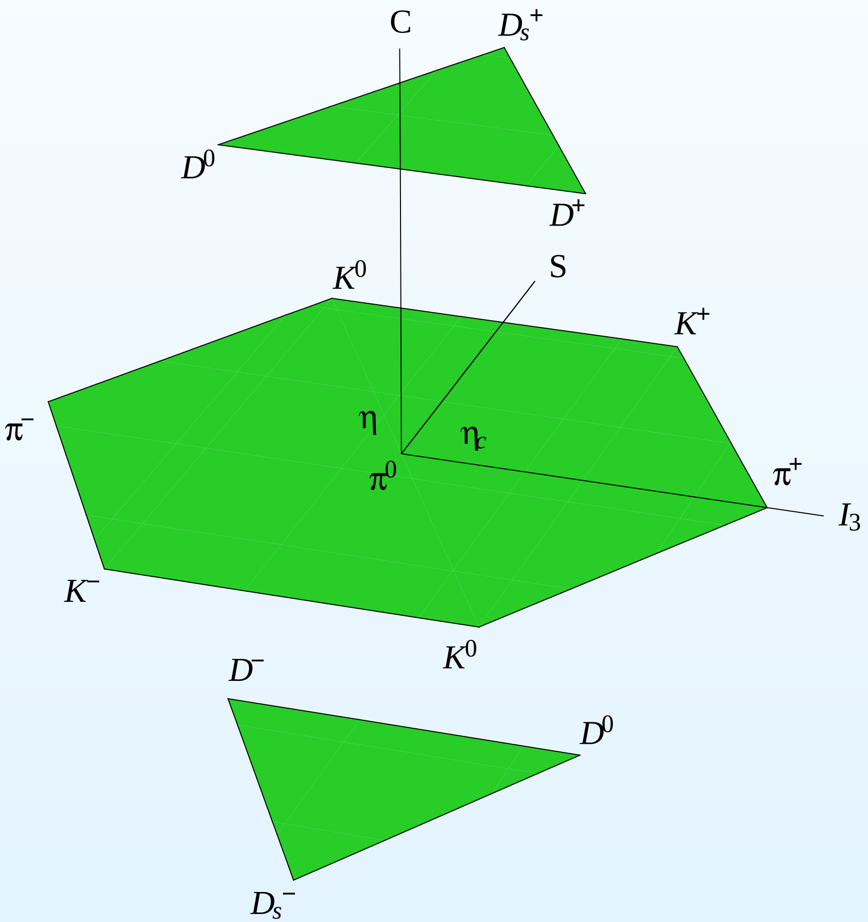
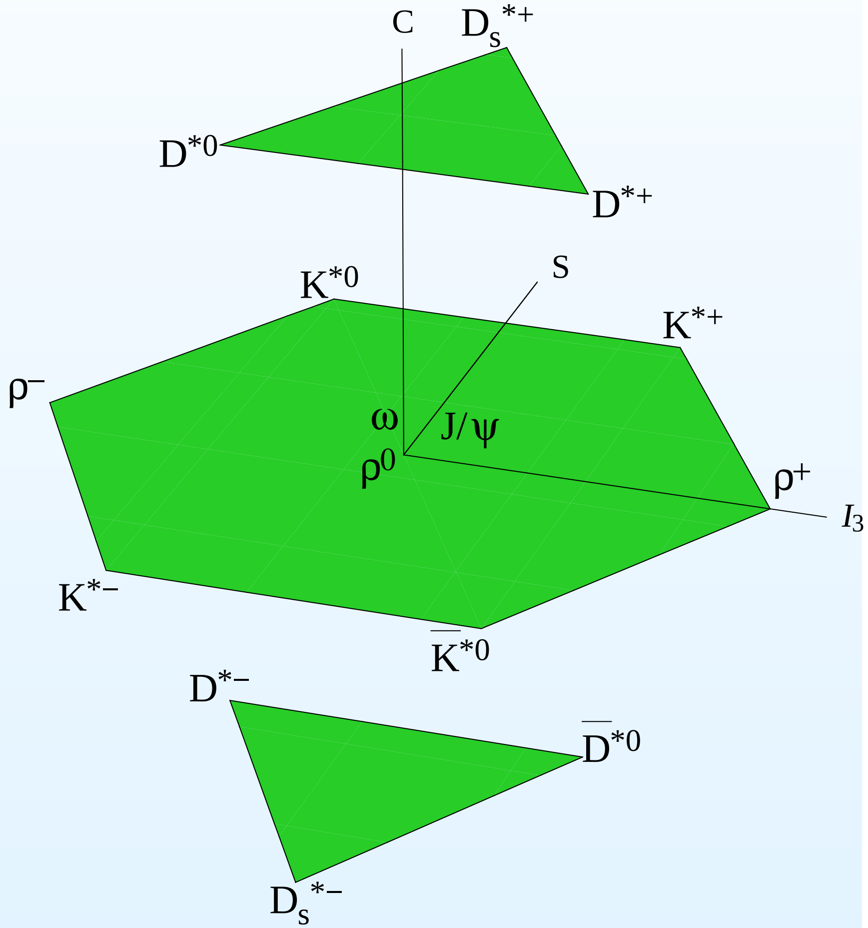
# Dynamically Generated States

## 15-plet of pseudoscalar mesons:




## 15-plet of vector mesons:



# Dynamically Generated States

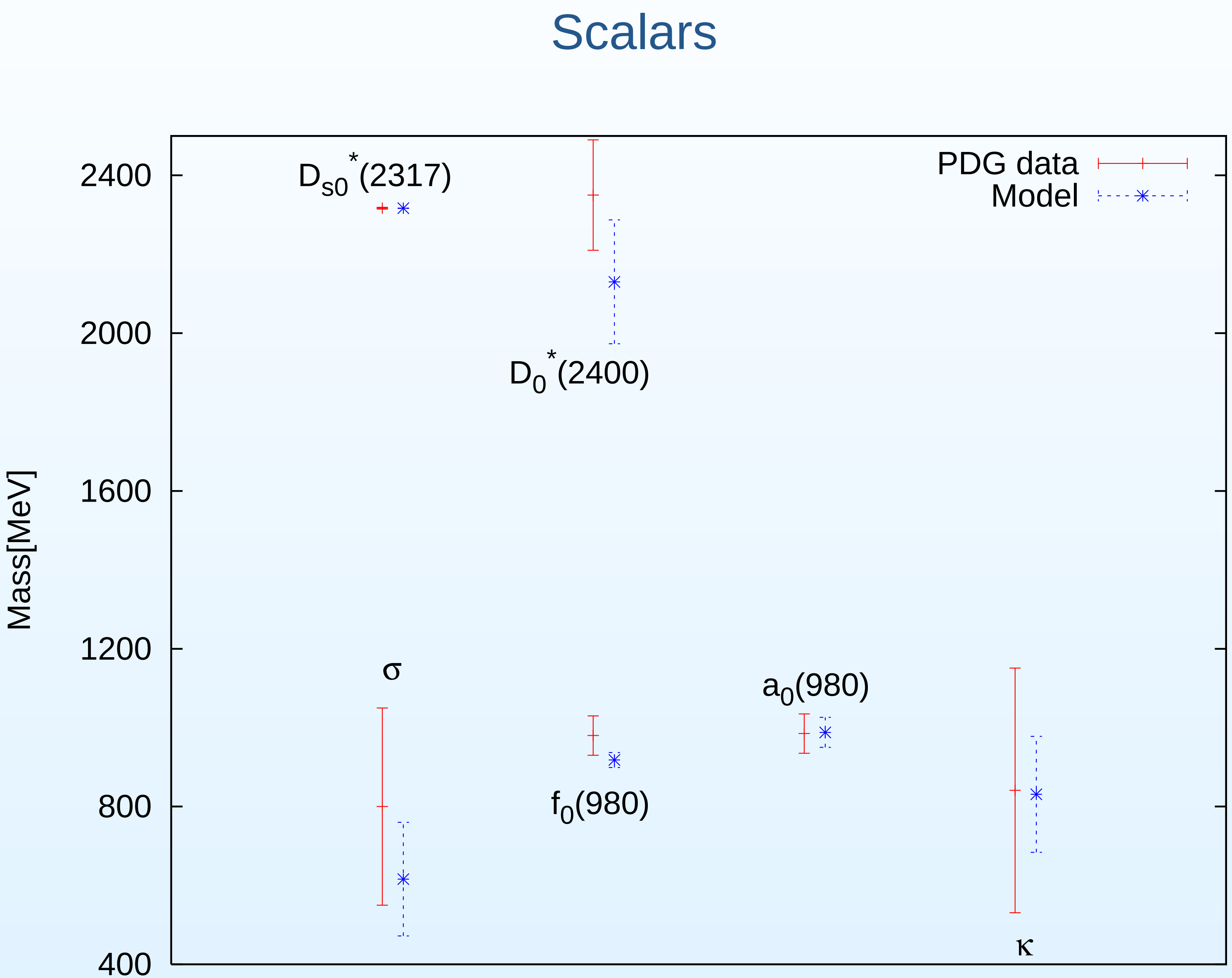
| C | Interacting multiplets |
|---|---|
| 2 | $\bar{3}\otimes\bar{3}\longrightarrow 3\oplus\bar{6}$ |
| 1 | $\bar{3}\otimes 8\longrightarrow 1\bar{5}\oplus\bar{3}\oplus 6$ |
| | $\bar{3}\otimes 1\longrightarrow\bar{3}$ |
| 0 | $\bar{3}\otimes 3\longrightarrow 8\oplus 1$ |
| | $1\otimes 1\longrightarrow 1$ |
| | $8\otimes 1\longrightarrow 8$ |
| | $8\otimes 8\longrightarrow 1\oplus 8_s\oplus 8_a$ |
| | $\oplus 10\oplus 1\bar{0}\oplus 27$ |

Scalars

| C | Interacting multiplets |
|---|---|
| 2 | $\bar{3}\otimes\bar{3}^*\longrightarrow 3\oplus\bar{6}$ |
| 1 | $\bar{3}\otimes 8^*\longrightarrow 1\bar{5}\oplus\bar{3}\oplus 6$ |
| | $8\otimes\bar{3}^*\longrightarrow 1\bar{5}\oplus\bar{3}\oplus 6$ |
| | $\bar{3}\otimes 1^*\longrightarrow\bar{3}$ |
| | $1\otimes\bar{3}^*\longrightarrow\bar{3}$ |
| 0 | $\bar{3}\otimes 3^*\longrightarrow 8\oplus 1$ |
| | $3\otimes\bar{3}^*\longrightarrow 8\oplus 1$ |
| | $1\otimes 1^*\longrightarrow 1$ |
| | $8\otimes 1^*\longrightarrow 8$ |
| | $1\otimes 8^*\longrightarrow 8$ |
| | $8\otimes 8^*\longrightarrow 1\oplus 8_s\oplus 8_a\oplus 10\oplus 1\bar{0}\oplus 27$ |

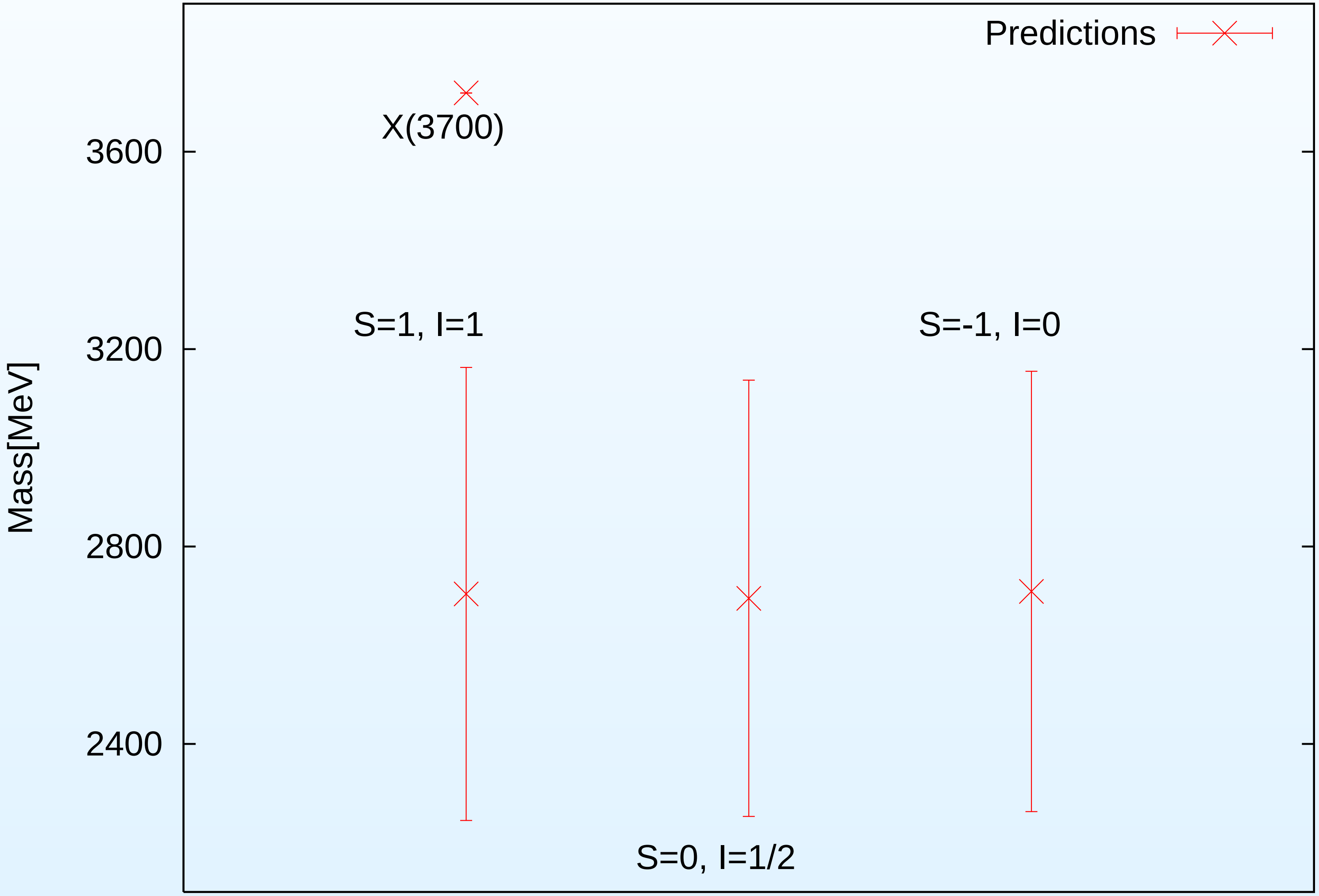
Axials

# Dynamically Generated States - Spectrum



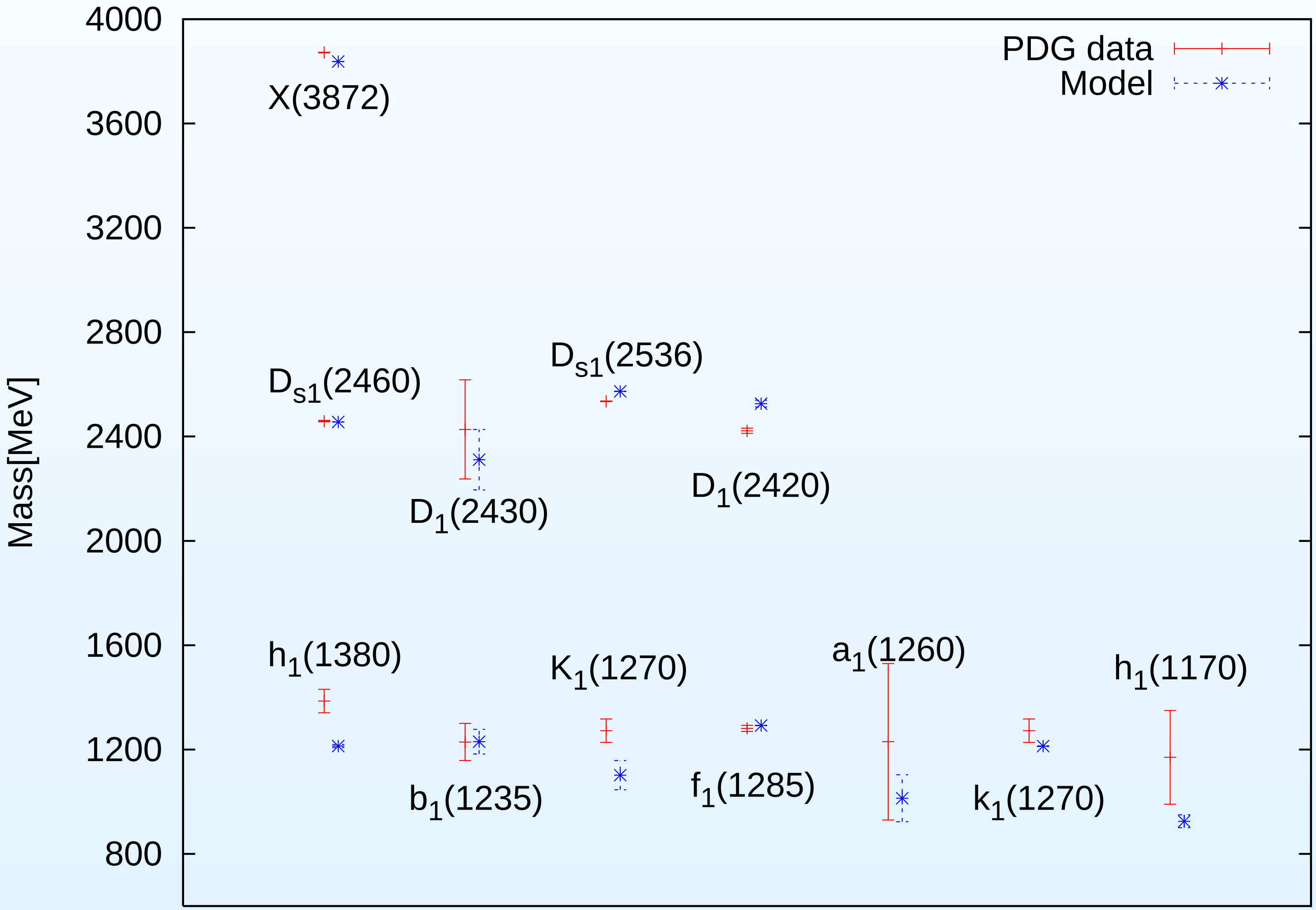
# Dynamically Generated States - Spectrum

## Scalars - Predictions



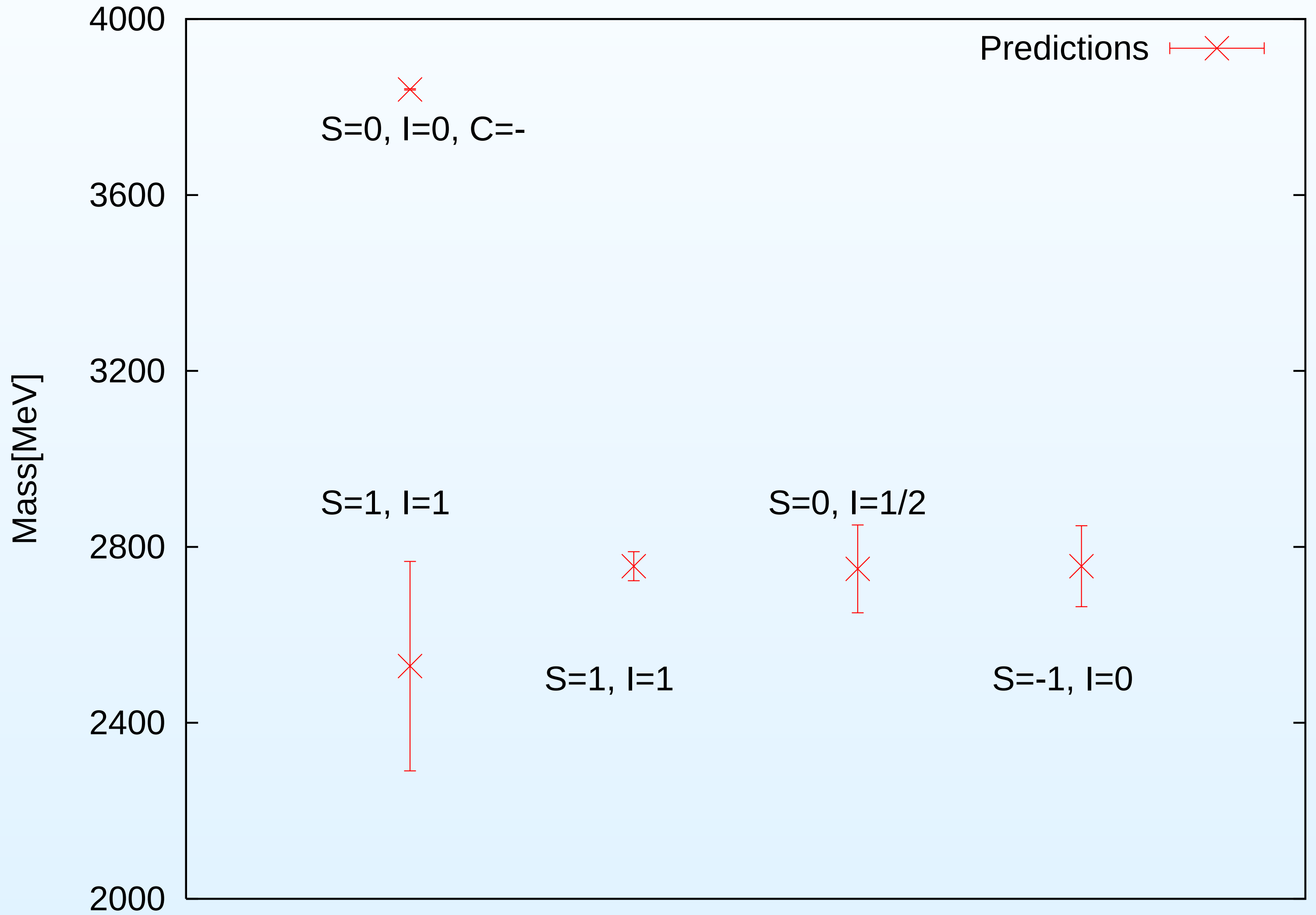
# Dynamically Generated States - Spectrum

## Axials



# Dynamically Generated States - Spectrum

## Axials - Predictions

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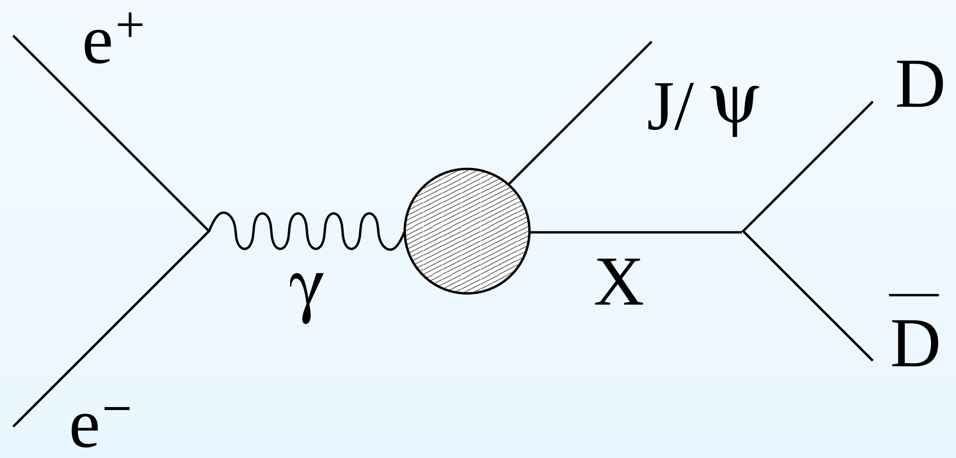
# $D\bar{D}$ Invariant mass spectrum

- Belle has measured the reactions $e^+e^- \longrightarrow J/\psi D\bar{D}$, $J/\psi D\bar{D}^*$, $J/\psi D^*\bar{D}^*$ which present a strong threshold enhancement leading to the claim of new resonances [Belle Collaboration PRL100,202001].
- Belle‘s reaction can be microscopically interpreted from the diagram:

$i\mathcal{T} =$




- $D\bar{D}$ pair close to threshold $\longrightarrow$ only the $X$ propagator is strongly energy dependent.
- if $X$ has Breit-Wigner form:

$$\mathcal{T} \quad \sim \quad \frac{1}{M^2_{inv}(D\bar{D}) - M^2_X + i\Gamma_X M_X}$$

# $D\bar{D}$ Invariant mass spectrum

- One can integrate the amplitude over the phase-space to get the cross section:

$$\sigma = \frac{1}{V_{rel}(e^+e^-)} \frac{m_{e^-}}{E_{e^-}} \frac{m_{e^+}}{E_{e^+}} \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E_{J/\psi}(p)} \int \frac{d^3k}{(2\pi)^3} \frac{1}{2E_D(k)}$$
$$\times \int \frac{d^3k'}{(2\pi)^3} \frac{1}{2E_{\bar{D}}(k')} (2\pi)^4 \delta(p_{e^+} + p_{e^-} - p - k - k')|\mathcal{T}|^2$$

- Assuming that $\mathcal{T}$ depends only on the $D\bar{D}$ invariant mass, one can calculate the differential cross section:

$$\frac{d\sigma}{dM_{inv}(D\bar{D})} = \frac{1}{(2\pi)^3} \frac{m_e^2}{s\sqrt{s}} |\vec{k}||\vec{p}||\mathcal{T}|^2$$

# $D\bar{D}$ Invariant mass spectrum

How to apply the model to describe Belle's reaction?

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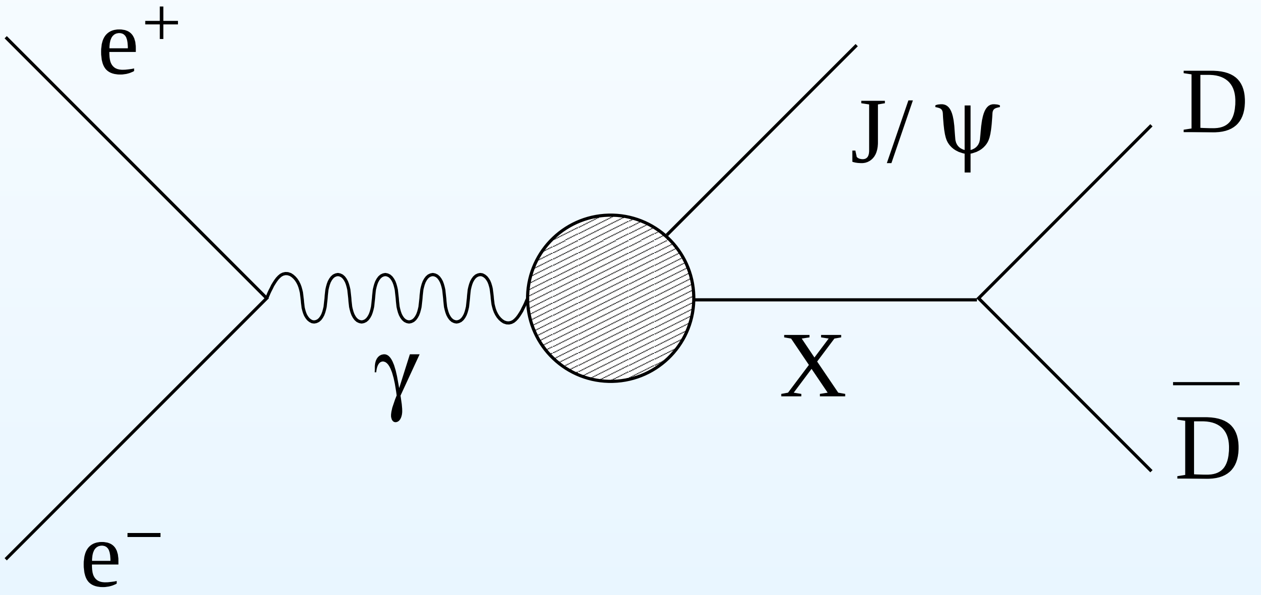
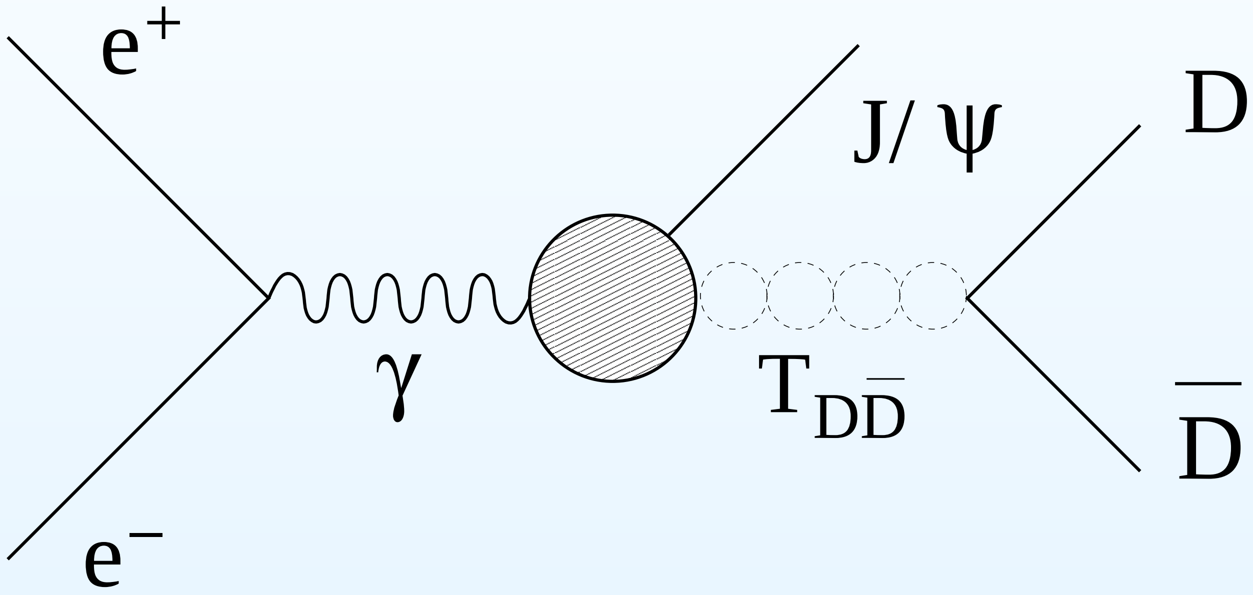



If $X$ has Breit-Wigner form:

$$\mathcal{T} \quad \sim \quad \frac{1}{M_{inv}^2(D\bar{D}) - M_X^2 + i\Gamma_X M_X}$$

# $D\bar{D}$ Invariant mass spectrum

How to apply the model to describe Belle's reaction?

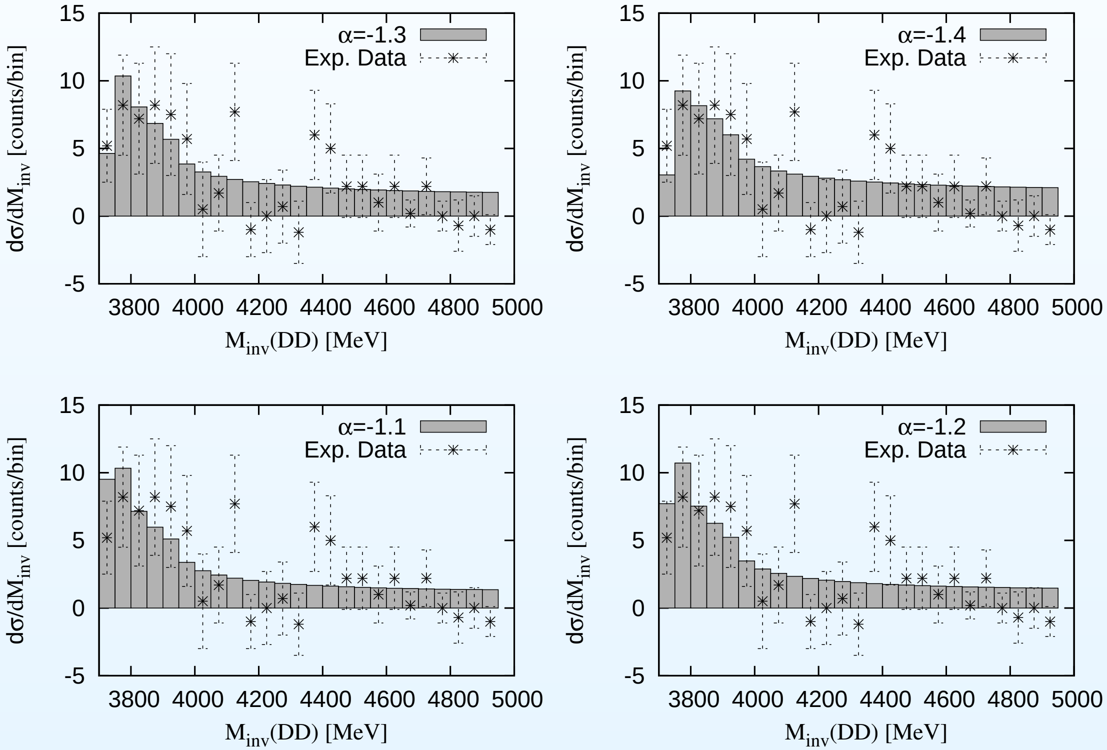



If $X$ is dynamically generated:

$$\mathcal{T} \quad \sim \quad (\hat{1} - VG)^{-1} V$$

# $D\bar{D}$ Invariant mass spectrum

## Our results:




$\frac{\chi^2}{d.o.f} \sim 1$ in all plots

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# Radiative Decay

- We want now to study the following reaction:

$$\psi(P, \epsilon_\psi) \to X(Q) + \gamma(K, \epsilon_\gamma)$$

- The vector particles fulfill Lorentz condition:

$$\begin{aligned} P_\mu \epsilon^\mu_\psi &= 0 \\ K_\mu \epsilon^\mu_\gamma &= 0 \end{aligned}$$

- The amplitude for this process should have the form:

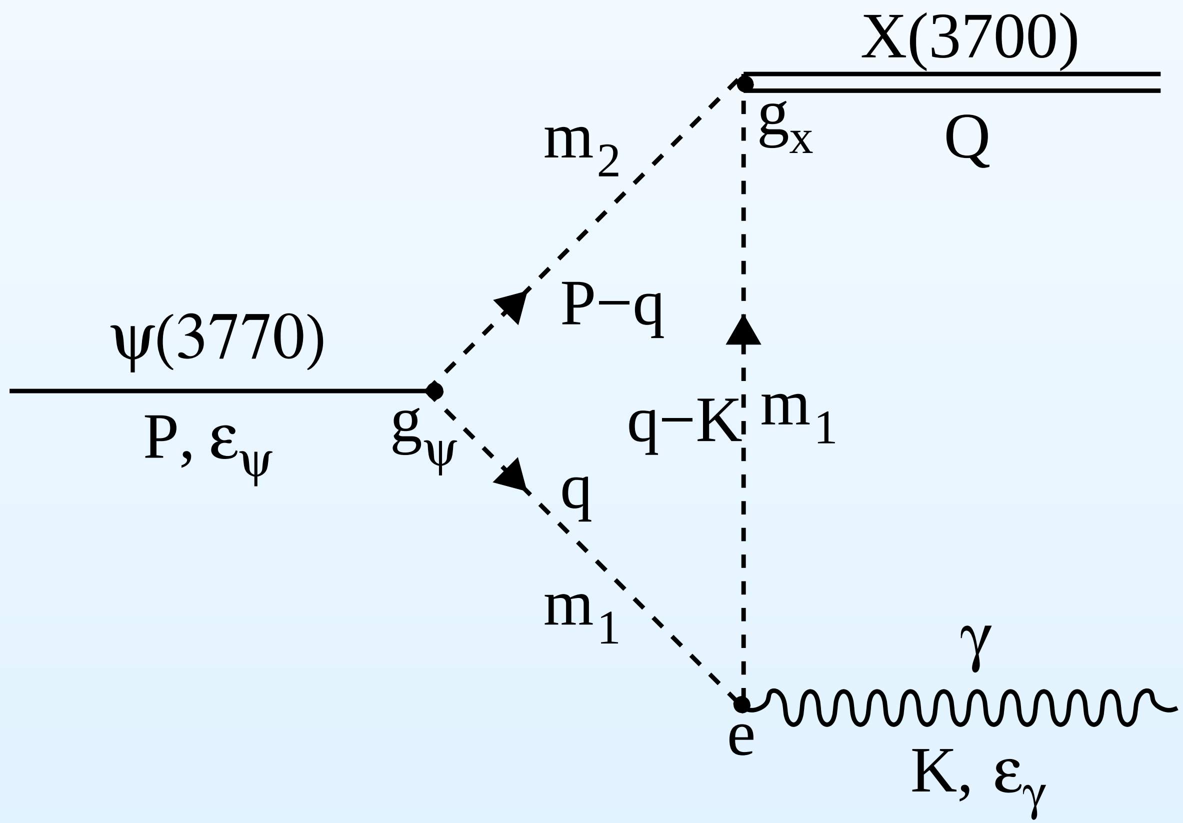
$$-i\mathcal{M} = \epsilon^\mu_\psi \epsilon^\nu_\gamma \mathcal{T}_{\mu\nu}$$

- By Lorentz invariance we can write:

$$\mathcal{T}_{\mu\nu} = a g_{\mu\nu} + b P_\mu P_\nu + c P_\mu K_\nu + d P_\nu K_\mu + e K_\mu K_\nu .$$

# Radiative Decay

- Because of the Lorentz condition over the vector particles the terms $b$, $c$ and $e$ will not contribute to the amplitude.
- By gauge invariance ($K^\nu \mathcal{T}_{\mu\nu} = 0$) the terms $a$ and $d$ are related: $a = -dK.P$.
- Considering only pseudoscalars in the loop, there is only one one-loop diagram contributing to the $d$ term:



# Radiative Decay

- Evaluation of the $d$-term is straightforward (and convergent):

$$d = i\frac{g_\psi g_X e}{2\pi^2}\int_0^1 dx \int_0^x dy\, \frac{y(1-x)}{s+i\epsilon}$$
$$s = (1-x)(xm_\psi^2 - m_2^2 - 2yP.K) - xm_1^2$$

- Summing over the photon polarization, averaging over the vector meson polarization and integrating over the phase-space, we get the radiative decay width:

$$\Gamma_{\psi\to X\gamma} = \frac{p}{12\pi m_\psi^2}(P.K)^2|d|^2,$$

# Radiative Decay

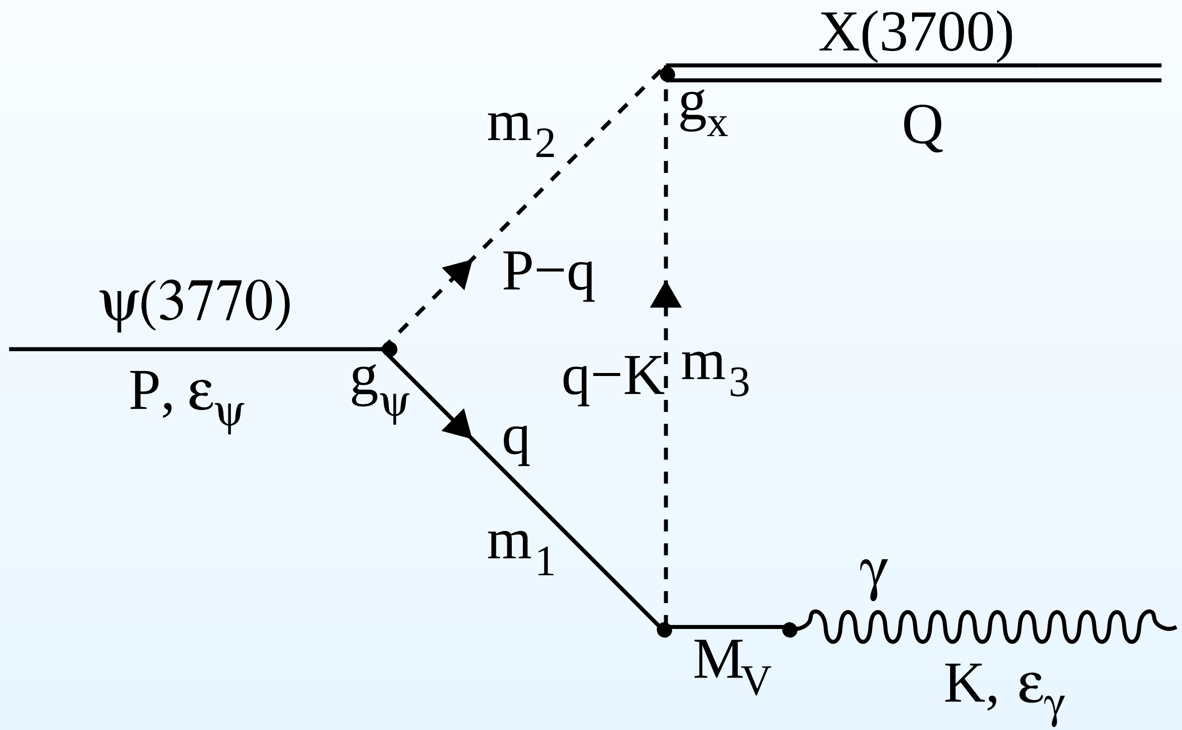
- We show results for different values of $\alpha_H$.

| $\alpha_H$ | $\sqrt{s}_{pole}$ [MeV] | $g_D$ [GeV] | $g_{D_s}$ [GeV] | $E_\gamma$ [MeV] | $\Gamma$ [KeV] | Br [$10^{-5}$] |
|---|---|---|---|---|---|---|
| -1.40 | 3702-i27 | 8.06+i1.29 | 7.83-i1.34 | 65.35 | 1.93 | 7.7 |
| -1.35 | 3713-i21 | 6.52+i1.54 | 6.39-i1.06 | 58.54 | 0.99 | 4.0 |
| -1.30 | 3722-i18 | 5.96+i1.69 | 5.90-i0.87 | 49.67 | 0.65 | 2.6 |
| -1.25 | 3730-i15 | 5.39+i1.91 | 5.42-i0.60 | 41.77 | 0.43 | 1.7 |

- These branching ratios are of the same order of magnitude of the $\phi \to a_0(980)\gamma$ decay, which goes through kaon loops.
- The feasibility of the experiment relies upon statistics. BEPC-II is expected to produce $\sim 3.5 \times 10^7$ $\psi(3770)$ events in one year of run, this would imply around 1000 decays into $X(3700)\gamma$ ($\alpha = -1.3$), which should be enough to produce a clear photon energy peak around 50 MeV.

# Radiative Decay

- we have also considered the contribution of diagrams with anomalous couplings:




- we also calculate theoretical uncertainties by considering the uncertainties in the parameters of the model.
- our final result is:

$$\Gamma_{\psi \to X\gamma} = (1.05 \pm 0.41) \text{ KeV}$$

# Overview

- We have calculated the radiative decay of $\psi(3770)$ into the dynamically generated $X(3700)$ state.
- The $X(3700)$ is a stable result (prediction) of a model that has successfully described lots of well known resonances and some of their properties.
- There is already some evidence for the existence of a scalar resonance in the Belle's measurement of the $D\bar{D}$ invariant mass spectrum in the reaction $e^+e^- \to J/\psi D\bar{D}$.
- The branching fractions obtained ($10^{-4}$-$10^{-5}$) are of the same order of magnitude as other already measured similar decays (ex. $\phi \to a_0(980)\gamma$).
- The upgraded BEPC-II facility should generate enough statistics in order to observe this decay.
- We hope to stimulate experimental efforts to confirm (or discard) the existence of the $X(3700)$.

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