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# Experimental techniques in hadron spectroscopy

**3rd International Conference on New Frontiers in Physics**

**FAIR Workshop**

# Outline

- Theoretical motivations;
- Experimental introduction;
- Low energy sector;
- Open-Charm and Charmonium spectroscopy;
- Exotic states;
- Baryonic states.

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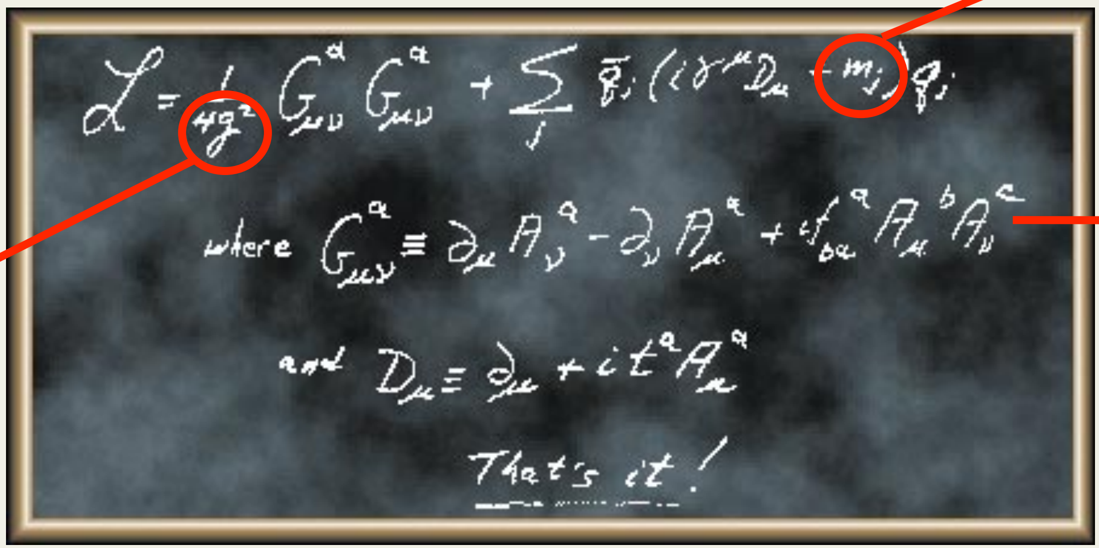
- Theoretical motivations;
- Experimental introduction;
- Low energy sector;
- Open-Charm and Charmonium spectroscopy;
- Exotic states;
- ~~Baryonic states.~~

# Quantum Chromodynamics

Quantum ChromoDynamics (QCD) is the theory of strong interactions that bind quarks and gluons together to form hadrons.

QCD is a nonlinear theory that is not analytically solvable.

masses of the 6 quark flavours




gluon field

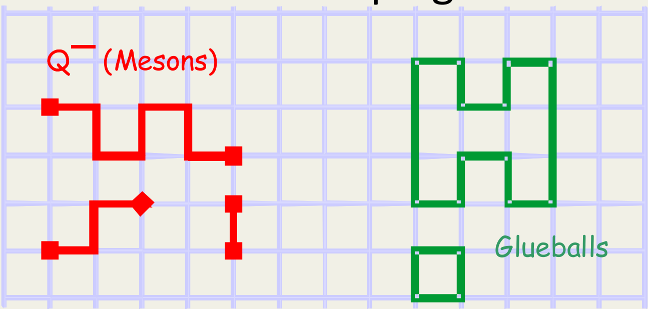
*g*
coupling constant

*From F.A. Wilczek QCD Lecture*

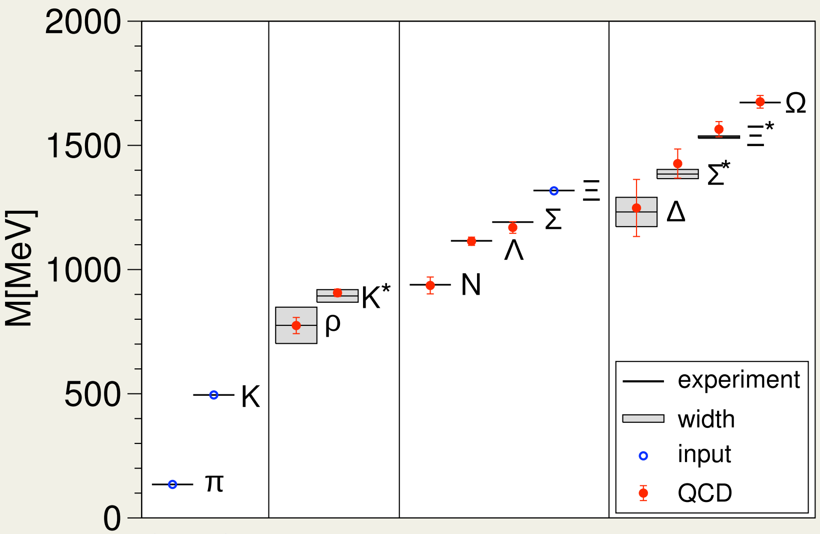
For the equivalent quantum field theory of weak force and electromagnetism, approximations using perturbation expansions in the interaction strength give very accurate results. However, since the QCD interaction is "so strong", perturbative approximations often fail.

# Lattice QCD

In order to solve QCD at long distances, Wilson [*PRD* 10:2445-2459, 1974] introduced lattice gauge theory, in which the space-time continuum is discretized on a lattice keeping the gauge symmetry intact.




This discretization allows a non-perturbative approximation to the theory that is successively improvable by increasing the lattice size and decreasing the lattice spacing.
It also makes the gauge theory amenable to numerical simulation by computer.




Science **322** (2008) 1224 [arXiv:0906.3599 [hep-lat]].

The simulation of the quark interactions requires the computation of a large, highly non-local matrix determinant, which is extremely time consuming. This determinant arises from the dynamics of the quarks. The simplest way to proceed is thus to ignore the quark dynamics and work in the so-called quenched approximation, with only gluonic degrees of freedom.

Nowadays the agreement with the measured masses is at the few% level.

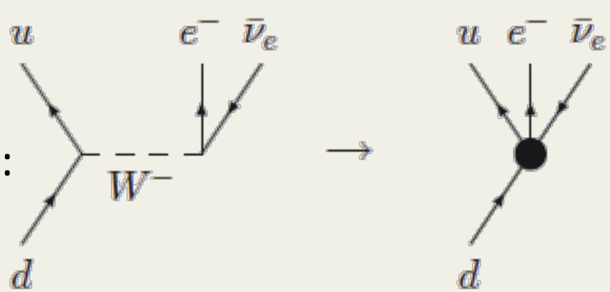
# Effective Field Theories

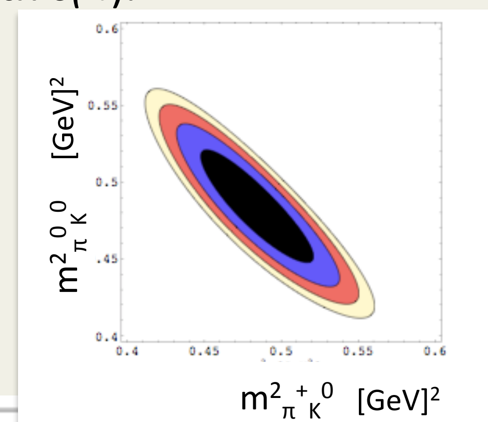
Effective Field Theories (EFT) are based on the assumption that scales much smaller/bigger than those under study shouldn't matter.

i.e. One can calculate the hydrogen atom spectrum very precisely without knowing top quark mass!

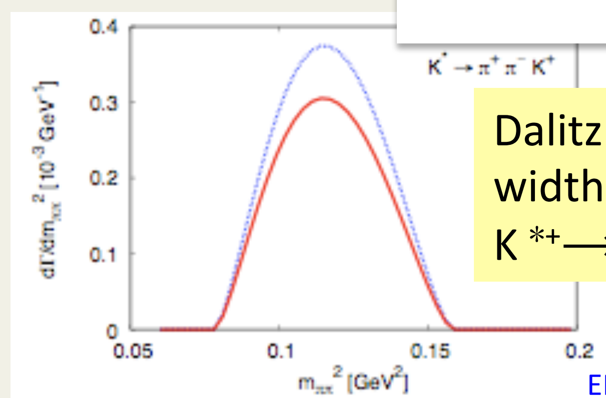
Classical dynamics (mechanics) $v << c(E\cdot t>>\hbar)$ can be seen as an EFT because it does not consider the contribution of the terms that are related with $c(\hbar)$.

Weak interaction:




Within this framework ChPT is the EFT of QCD in the light quark sector and it has significantly contributed to our understanding of strong interaction at hadron scale.

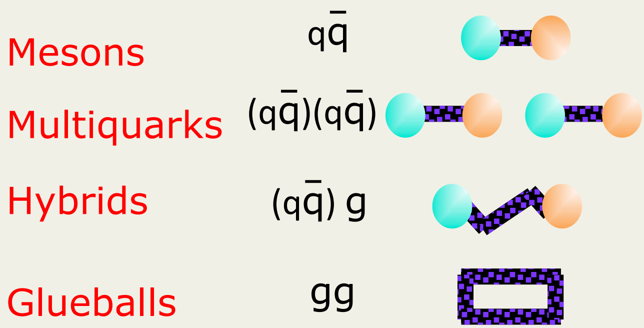



Dalitz plot and decay width for the channel $K^{*+} \longrightarrow \pi^+ K^0 \pi^0$

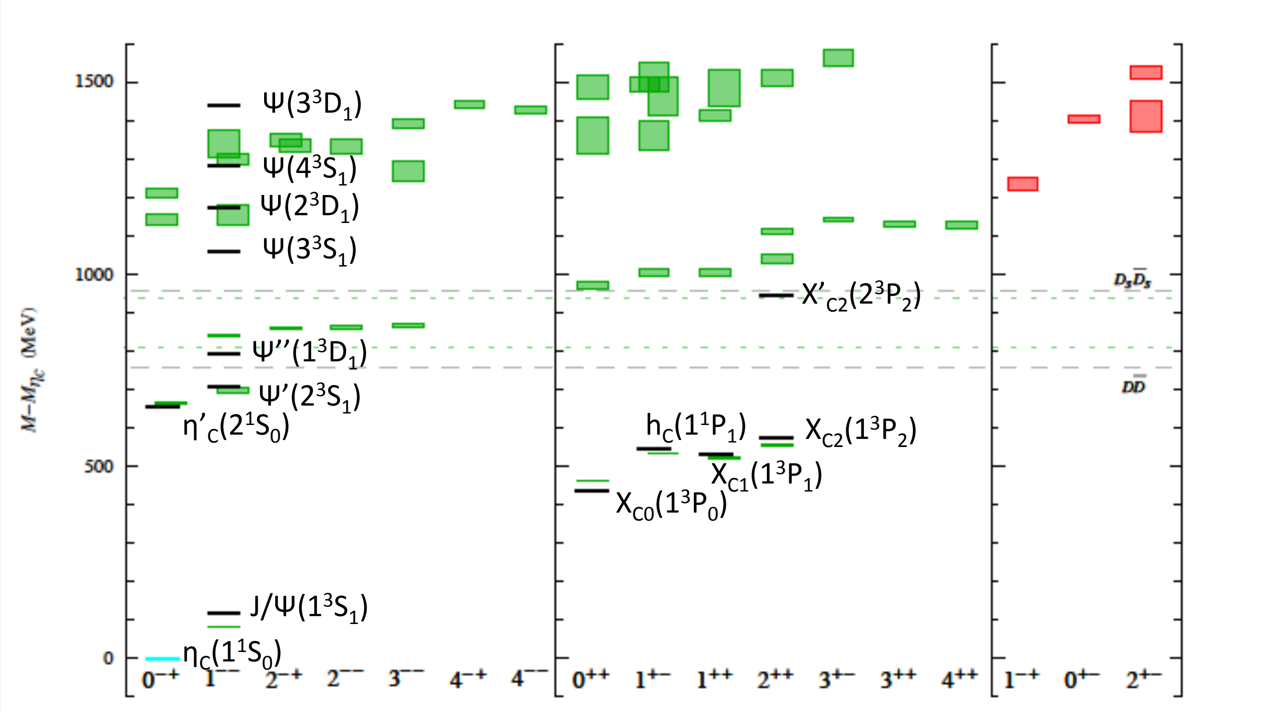
EPJA39:205,2009
arXiv:0807.4686 [hep-ph]

# Charmonium spectrum

The whole set of theoretical approaches rely on approximations and/or free parameters that must be constrained. Furthermore, They all predict states with explicit gluon content.




LQCD spectrum




Charmonium spectrum from **JHEP 1207 (2012) 126**
Black lines are experimental values, the red and green boxes are the calculates states.

# The experimental point of view

- Can we observe experimentally gluonic degrees of freedom?

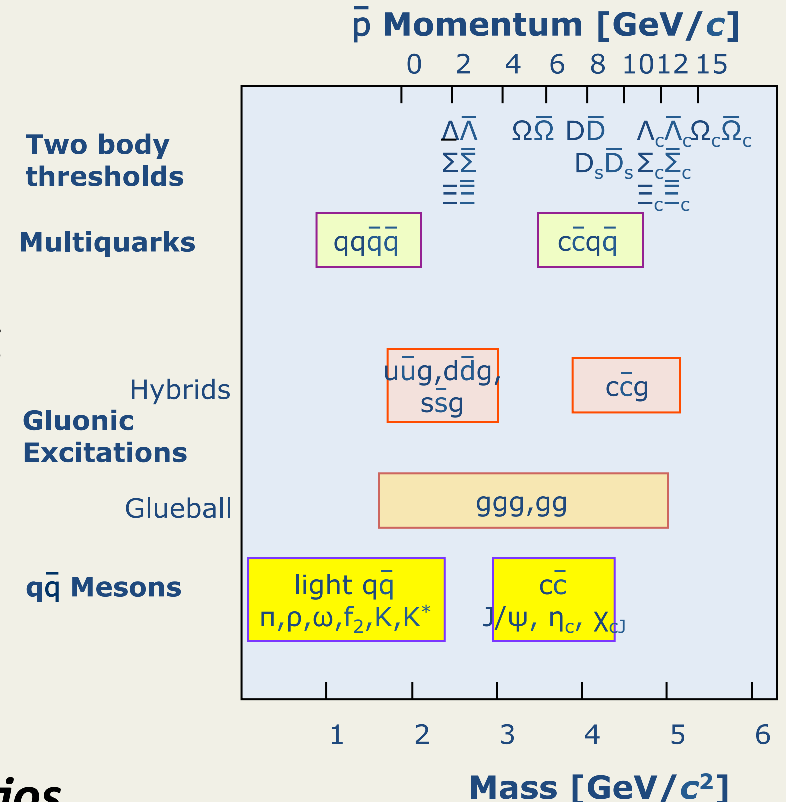
- How would these manifest themselves in terms of the excitation spectrum and also in the strong decays of hadrons?

Three are the main goals of hadron spectroscopy:

- *Identify the physical states and their quantum numbers, and measure their **masses and widths.***

- *Determine their **decay modes and branching ratios.***

- *Study the underlying **dynamics of production and decay.***



# Partial Wave Analysis I

Partial Wave Analysis (PWA) techniques are used to describe complex, overlapping, interfering states.

A multiparticle phase space is expanded into a (truncated) series of angular momentum functions which describe the reaction matrix element.

$$|\alpha\rangle = \sum_{\ell} c_\ell |\ell\rangle$$

The matrix element *M* of some "decay operator" *U* is written as

$$\mathcal{M} = \langle f|U|i\rangle = \langle f|U_A U_B \cdots |i\rangle$$

The goal is to learn something about *U* parameterizing *M*, and determining the fitting parameters from the data. These parameters are the coefficients of "partial waves".

The elastic scattering of a non relativistic spinless particle from a static central potential

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2 \quad \text{where } f(\theta) = \frac{1}{k}\sum_{\ell=0}^{\infty}(2\ell+1)P_\ell(\cos\theta)e^{i\delta_\ell}\sin\delta_\ell$$

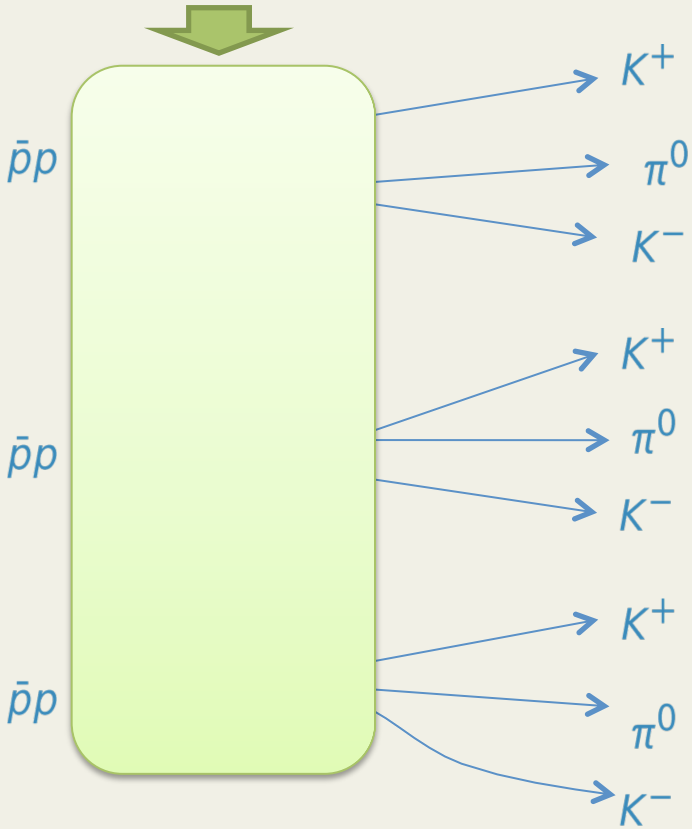
is an example of a Partial Wave Analysis.

[B. S. Zou and D. V. Bugg, EPJA 16, 537 (2003)]

# A practical example

- Consider reaction $\bar{p}p \rightarrow K^+K^-\pi^0$

What *really* happened...




...
etc.

# A practical example

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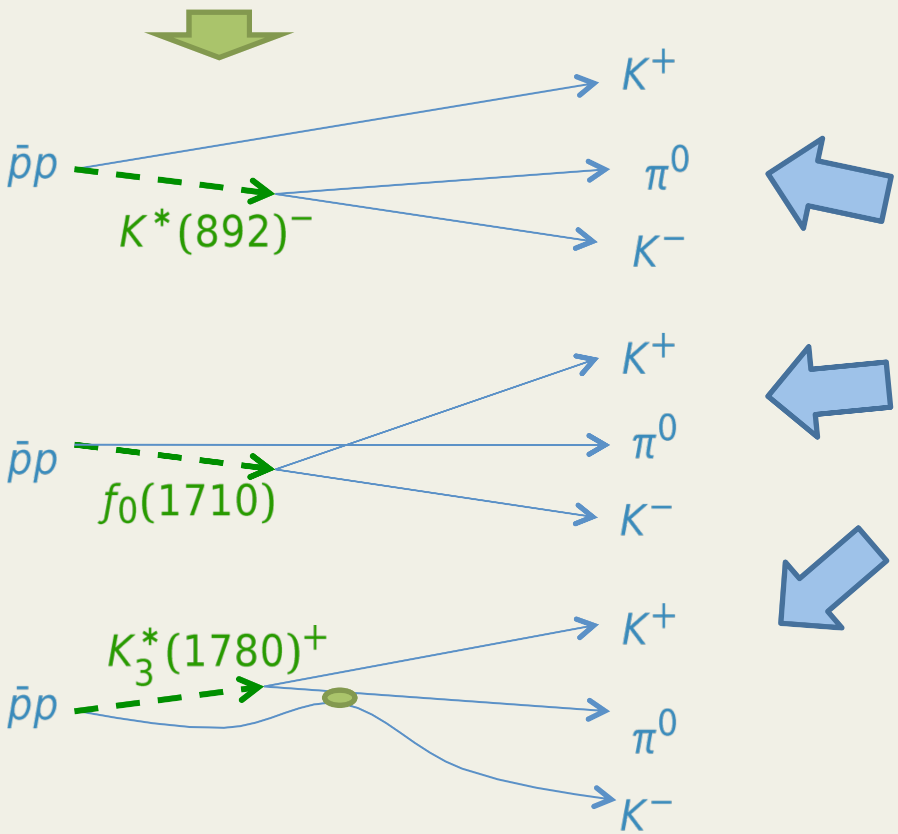


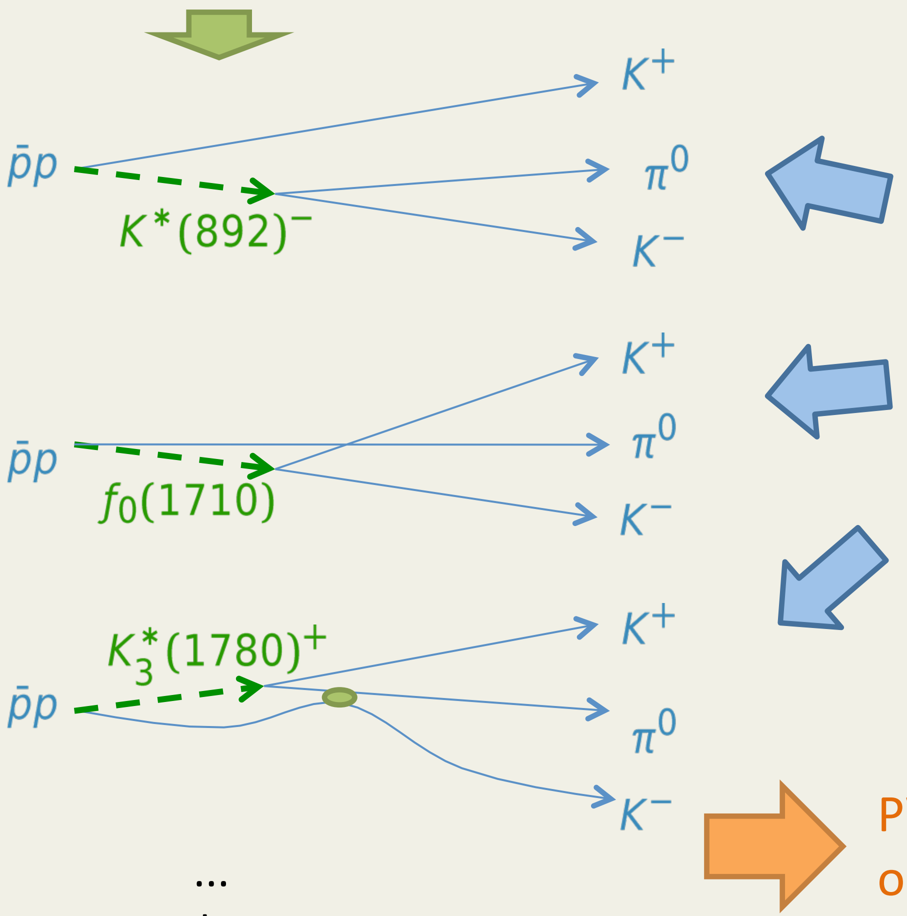

What we see is always the same final state ...

...
etc.

# A practical example

- Consider reaction $\bar{p}p \rightarrow K^+K^-\pi^0$

What *really* happened...



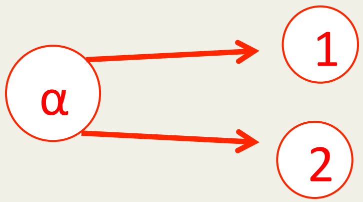

What we see is always the same final state ...

PWA = technique helps to find out what happens in between

...
etc.

# Partial Wave Analysis II

Usually, multiparticle final states are described in the so called “isobar model" in which all decays are considered as two body chains.




particle α has angular momentum quantum numbers J and M, particles 1 and 2 have helicities $\lambda_1$ and $\lambda_2$ $h \equiv \vec{S} \cdot \vec{p}/|\vec{p}|$

$$\mathcal{M} = \langle f|U|i\rangle = \langle 1+2|U|\alpha\rangle = \langle \theta, \phi, \lambda_1, \lambda_2|U|JM\rangle$$

The best fit values of the free parameters are determined using an extended maximum likelihood technique or minimizing $\chi^2$ of a set of histograms

# The low energy (< 2GeV) range

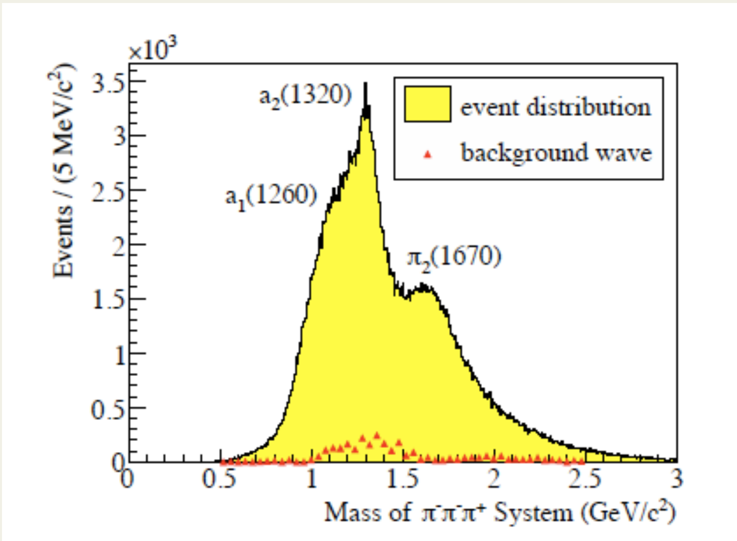
In the last 20 years many steps forward in the field were possible thanks to the variety of facilities available all over the world.

| Main non-$q\bar{q}$ candidates | |
|---|---|
| $f_0(980)$ | 4q state - molecule |
| $f_0(1500)$ | $0^{++}$ glueball candidate |
| $f_0(1370)$ | $0^{++}$ glueball candidate |
| $f_0(1710)$ | $0^{++}$ glueball candidate |
| $\eta(1410)$; $\eta(1460)$ | $0^{-+}$ glueball candidate |
| $f_1(1420)$ | hybrid, 4q state |
| $\pi_1(1400)$ | hybrid candidate $1^{-+}$ |
| $\pi_1(1600)$ | hybrid candidate $1^{-+}$ |
| $\pi$ (1800) | hybrid candidate $0^{-+}$ |
| $\pi_2(1900)$ | hybrid candidate $2^{-+}$ |
| $\pi_1(2000)$ | hybrid candidate $1^{-+}$ |
| $a_2'(2100)$ | hybrid candidate $1^{++}$ |

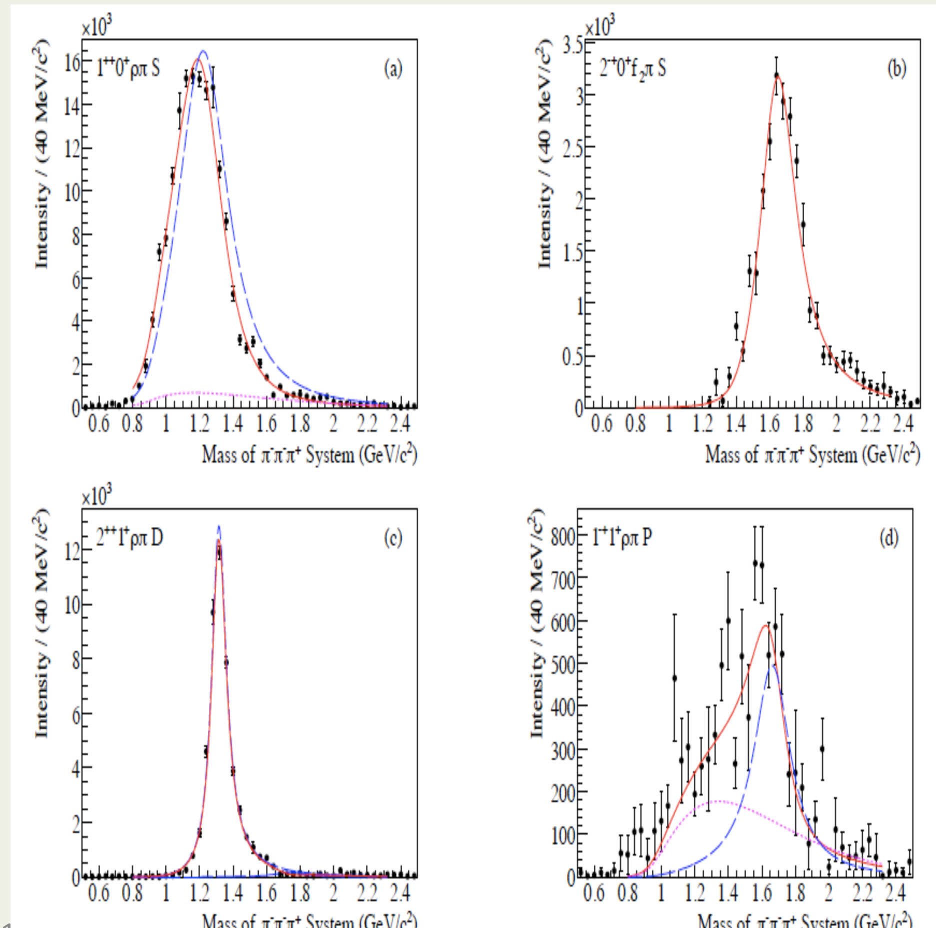
Nowadays confirmation of predictions, together with unexpected results, are still coming out mainly from $e^+ e^-$ colliders

# $\pi_1(1600)$

420.000 diffractive events $\pi^-$+Pb→X + $(Pb)_{reco}$ collected by COMPASS exp. @190 GeV/c
↳ $\pi^-\pi^-\pi^+$




acceptance-corrected intensities of the three most prominent waves and of the exotic one




PRL104(2010) 241803

A Partial Wave Analysis (PWA) of this data set was performed by using the isobar model in which a multi-particle final state is described by a sequence of two-body decays

# $\pi_1(1600)$

All known isovector and isoscalar ππ resonances have been included: σ(600) and $f_0(1370)$, ρ(770), $f_0(980)$, $f_2(1270)$, and $\rho_3(1690)$
$\sigma(600)\pi^-$ with L = 0 and $J^P = 0^-$ is used to consider direct 3-body decay into $\pi^-\pi^-\pi^+$
background wave = uniform 3-body phase space added incoherently

| Resonance | Mass (MeV/$c^2$) | Width (MeV/$c^2$) | Intensity (%) | Channel $J^{PC}M^{\epsilon}$[isobar]$L$ | Mass [26] (MeV/$c^2$) | Width [26] (MeV/$c^2$) |
|---|---|---|---|---|---|---|
| $a_1(1260)$ | $1255 \pm 6^{+7}_{-17}$ | $367 \pm 9^{+28}_{-25}$ | $67 \pm 3^{+4}_{-20}$ | $1^{++}0^{+}\ \rho\pi\ S$ | $1230 \pm 40$ | $250 - 600$ |
| $a_2(1320)$ | $1321 \pm 1^{+0}_{-7}$ | $110 \pm 2^{+2}_{-15}$ | $19.2 \pm 0.6^{+0.3}_{-2.2}$ | $2^{++}1^{+}\ \rho\pi\ D$ | $1318.3 \pm 0.6$ | $107 \pm 5$ |
| $\pi_1(1600)$ | $1660 \pm 10^{+0}_{-64}$ | $269 \pm 21^{+42}_{-64}$ | $1.7 \pm 0.2^{+0.9}_{-0.1}$ | $1^{-+}1^{+}\ \rho\pi\ P$ | $1662^{+15}_{-11}$ | $234 \pm 50$ |
| $\pi_2(1670)$ | $1658 \pm 3^{+24}_{-8}$ | $271 \pm 9^{+22}_{-24}$ | $10.0 \pm 0.4^{+0.7}_{-0.7}$ | $2^{-+}0^{+}\ f_2\pi\ S$ | $1672.4 \pm 3.2$ | $259 \pm 9$ |
| $\pi(1800)$ | $1785 \pm 9^{+12}_{-6}$ | $208 \pm 22^{+21}_{-37}$ | $0.8 \pm 0.1^{+0.3}_{-0.1}$ | $0^{-+}0^{+}\ f_0\pi\ S$ | $1816 \pm 14$ | $208 \pm 12$ |
| $a_4(2040)$ | $1885 \pm 13^{+50}_{-2}$ | $294 \pm 25^{+46}_{-19}$ | $1.0 \pm 0.3^{+0.1}_{-0.1}$ | $4^{++}1^{+}\ \rho\pi\ G$ | $2001 \pm 10$ | $313 \pm 31$ |

A total of 42 partial waves are included in the first step of the fit. The $\chi^2$ fit of the spin-density matrix elements obtained for each mass bin is performed in the mass range from 0.8 to 2.32 GeV/$c^2$

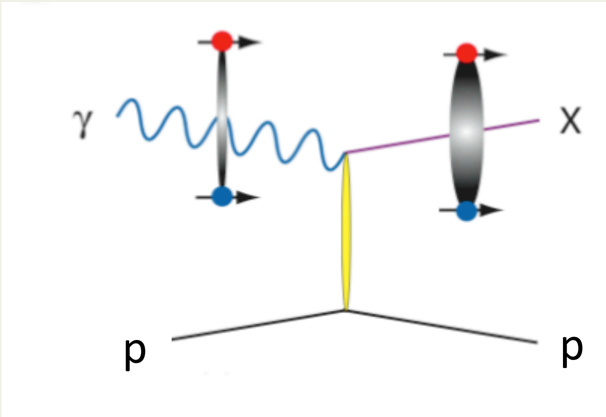
comparison with BNL E852 results for
$\pi^- p \rightarrow \pi^+\pi^\pm\pi^-\pi^0\pi^0(p/n)$ @ 18 GeV/c

| resonance | decay | mass(MeV/$c^2$) | width(MeV/$c^2$) |
|---|---|---|---|
| $a_4(2040)$ | $(\omega\rho)^D_2$ | $1985 \pm 10 \pm 13$ | $231 \pm 30 \pm 46$ |
| $a_2(1700)$ | $(\omega\rho)^S_2$ | $1721 \pm 13 \pm 44$ | $279 \pm 49 \pm 66$ |
| $a_2(2000)$ | $(\omega\rho)^S_2$ | $2003 \pm 10 \pm 19$ | $249 \pm 23 \pm 32$ |
| $\pi_1(1600)$ | $(b_1\pi)^S_1$ | $1664 \pm 8 \pm 10$ | $185 \pm 25 \pm 28$ |
| $\pi_1(2000)$ | $(b_1\pi)^S_1$ | $2014 \pm 20 \pm 16$ | $230 \pm 32 \pm 73$ |

# GlueX experiment

**Goal**: map the spectrum of exotic hybrid mesons

**Method**: Photo-produce hybrids off proton target and detect daughter particles from exotic hybrid meson decay




*detectable final state*

$$\vec{\gamma} + p \rightarrow p + X$$
$\hookrightarrow b_1\pi$
$\hookrightarrow \omega\pi$
$\hookrightarrow \pi\pi\pi$

$5\pi + 1p$

*9GeV linearly polarized*

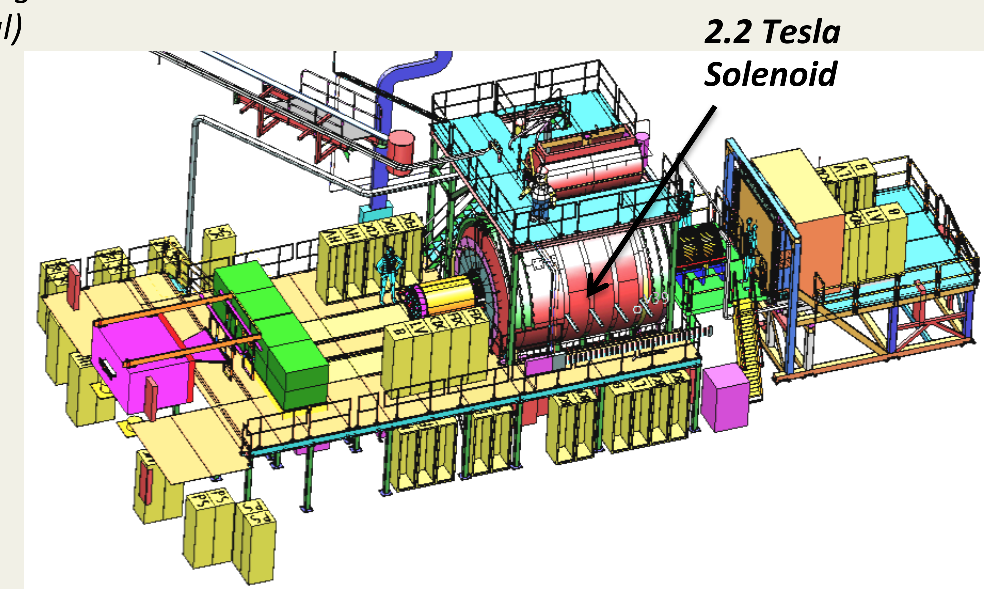
*hybrid meson*

*(mixed charged and neutral)*

$$\vec{\gamma} + p \rightarrow p + X$$
$\hookrightarrow f_1\pi$
$\hookrightarrow \eta\pi$
$\hookrightarrow \pi\pi\pi$

$5\pi + 1p$

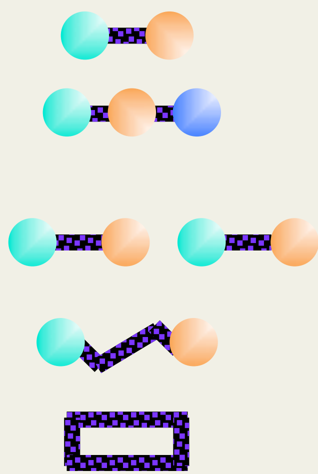
- 2.2T superconducting solenoidal magnet
- Fixed target ($LH_2$)
- $10^8$ tagged γ/s (8.4-9.0GeV)
- hermetic
- exploiting polarization

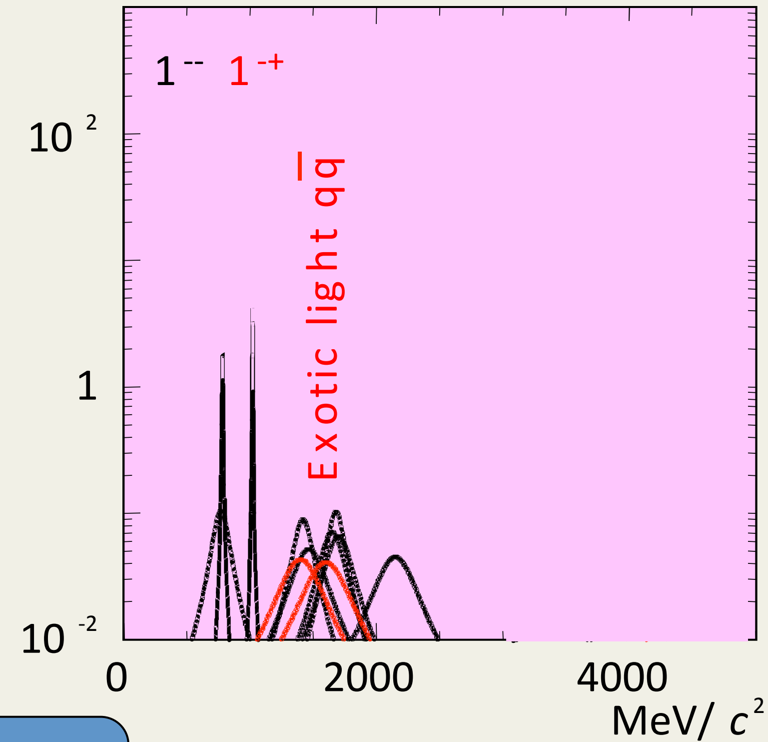


# Exotic hadrons

The identification of exotic states is an important key to understand hadron spectrum and the process of mass generation.

| | | |
|---|---|---|
| Mesons | $q\bar{q}$ | |
| Baryons | qqq | |
| Multiquarks | $(q\bar{q})(q\bar{q})$ | |
| Hybrids | $(q\bar{q})$ g | |
| Glueballs | gg | |






In the light meson energy range exotic states overlap with conventional states

# Exotic hadrons

The identification of exotic states is an important key to understand hadron spectrum and the process of mass generation.

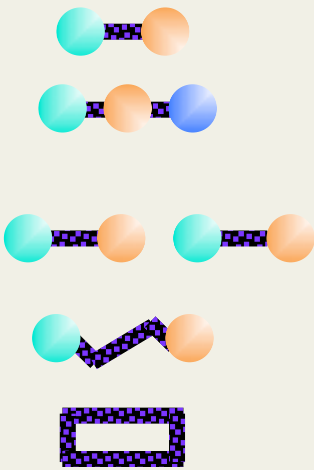
Mesons $q\bar{q}$

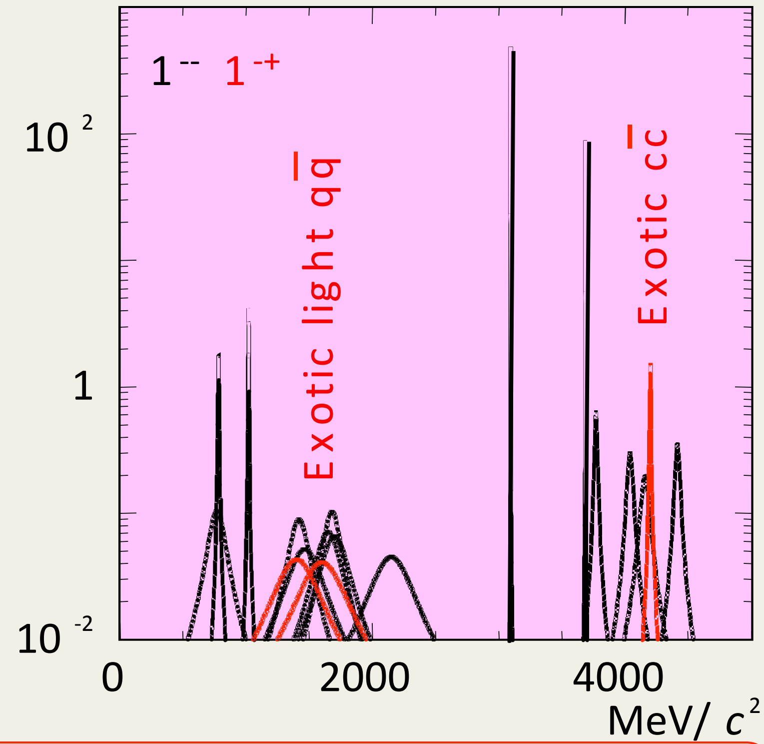
Baryons $qqq$

Multiquarks $(q\bar{q})(q\bar{q})$

Hybrids $(q\bar{q})\,g$

Glueballs $gg$





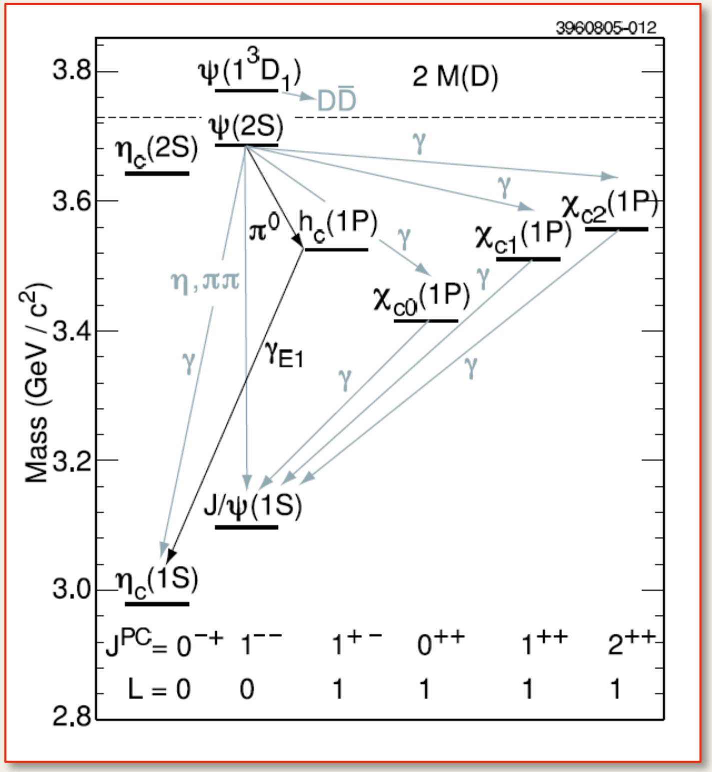

In the charmonium energy region the density of states is lower and also the overlap

# New Data

Hadron spectroscopy has made considerable progresses in the last years by moving to higher energy regions.

Large data sets have been collected by several experiments:

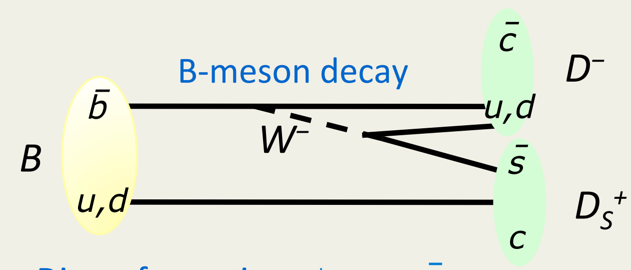
- $e^+e^-$ interactions at the Y(4S) energy:
  BaBar, BELLE, CLEO 2
- $e^+e^- \to$ charmonium energy:
  CLEO-c, BES-II, BES-III
- $\bar{p}p$ Tevatron collider:
  CDF, D0
- pp LHC collider:
  LHCb, ...



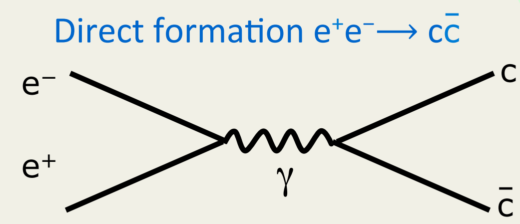
# OpenCharm and Charmonium spectroscopy

New charm spectroscopy data came from:

- B decays (lower spin favored)

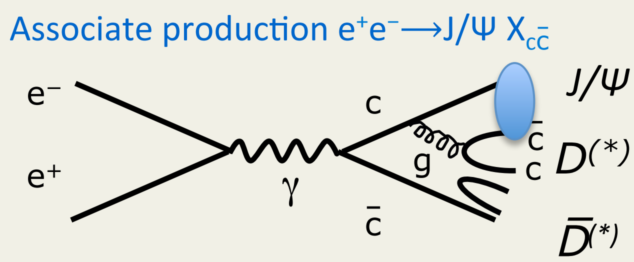



- inclusive $e^+e^- \to \bar{c}c$ (all spins allowed)

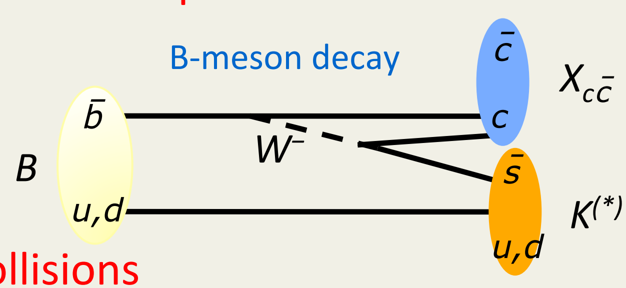



New charmonium spectroscopy data came from:

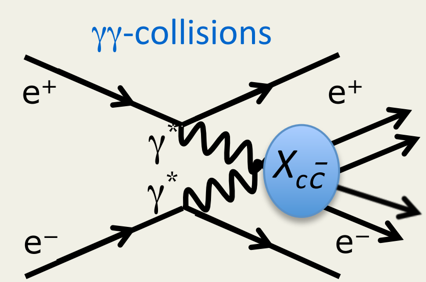
- Direct formation
- Associate chramonium production
  C = +



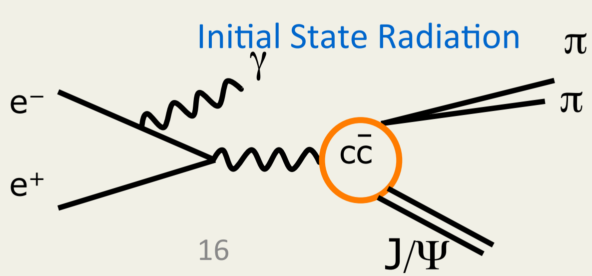

- B decays

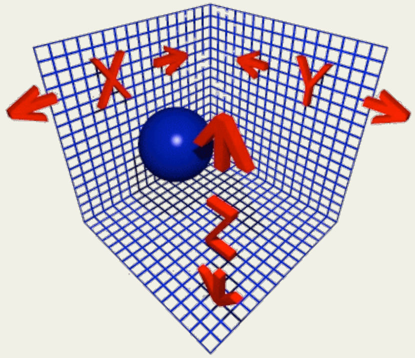



- two photon collisions
  $J \neq 1$



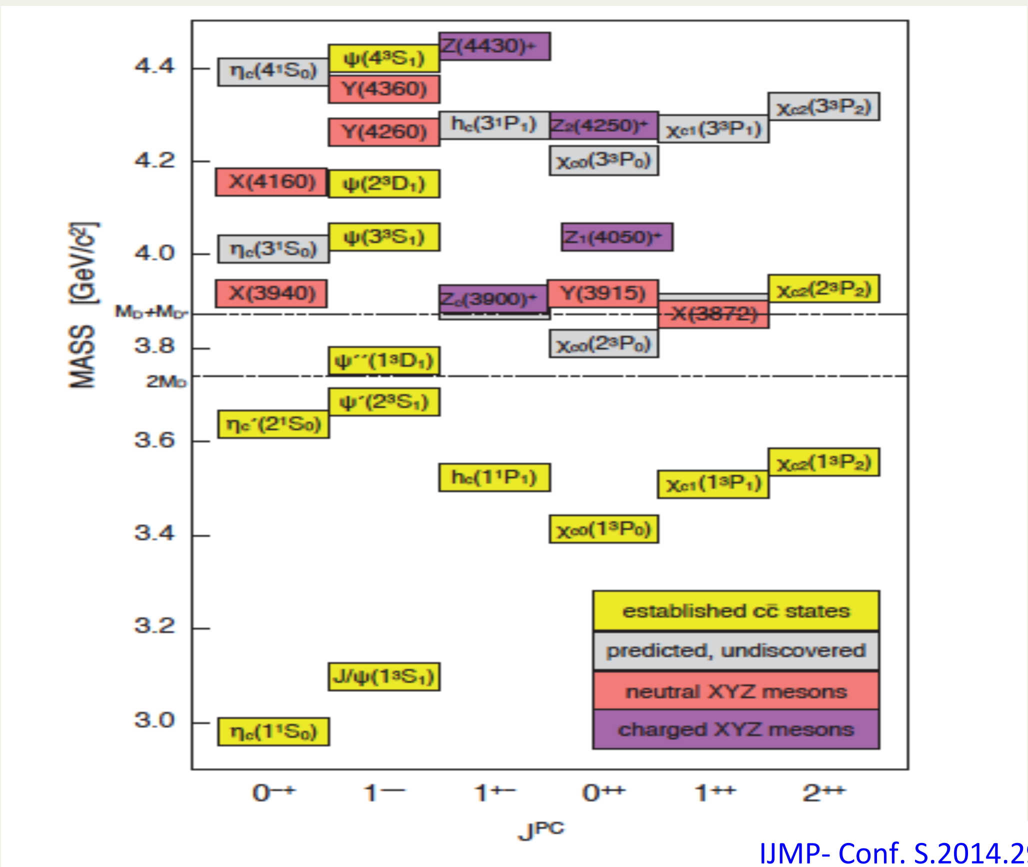

- initial state radiation






# Mesons

Without entering into the details of each state some general consideration can be drawn.




IJMP- Conf. S.2014.29

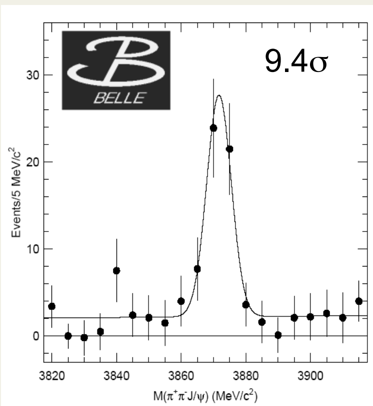
- masses are barely known;
- often widths are just upper limits;
- few final states have been studied;
- statistics are poor;
- quantum number assignment is possible for few states;
- some resonances need confirmation…

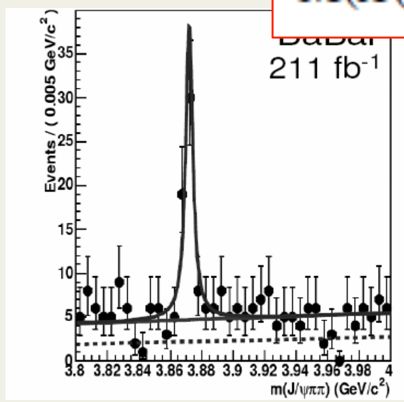
There are problems of compatibility Theory - Experiment

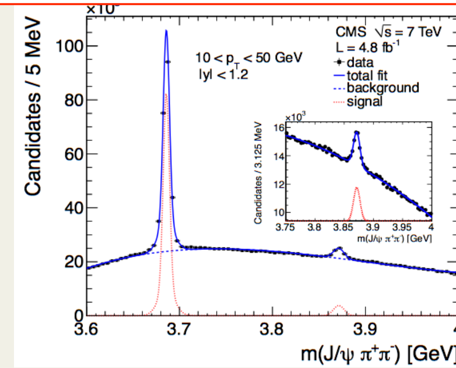
# X(3872)

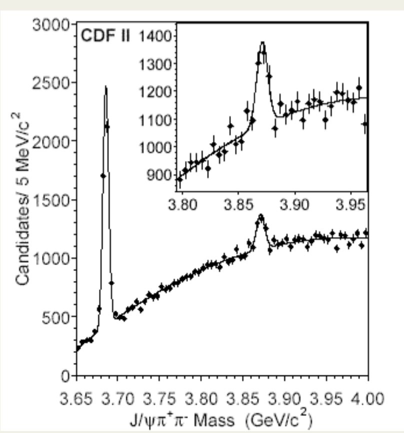
Discovered in 2003 by Belle (+ CDF, D0, BaBar, LHCb …) in $B^+ \to X K^+$ $X \to J/\psi\pi^+\pi^-$ is the big brother of the new "charmonium like" states. The mass is currently known with < 1.0 MeV/$c^2$ precision. For the width we have only an upper limit.

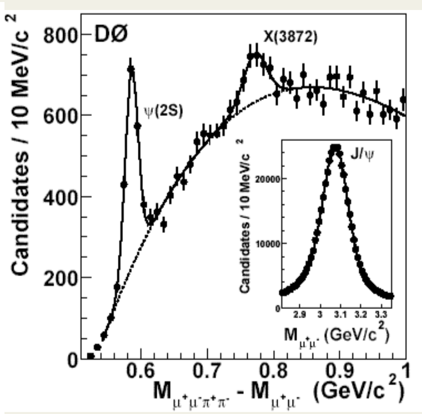
$$M(X(3872)) = 3871.95 \pm 0.48(\text{stat}) \pm 0.12(\text{syst})\ \text{MeV}/c^2$$

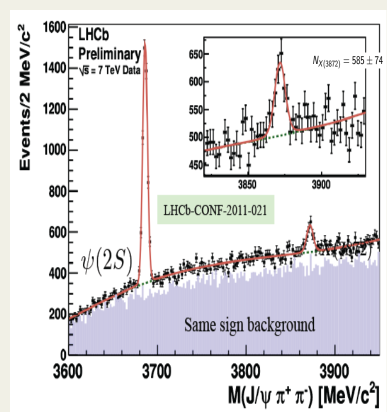



X(3872) has been observed in several decay channels

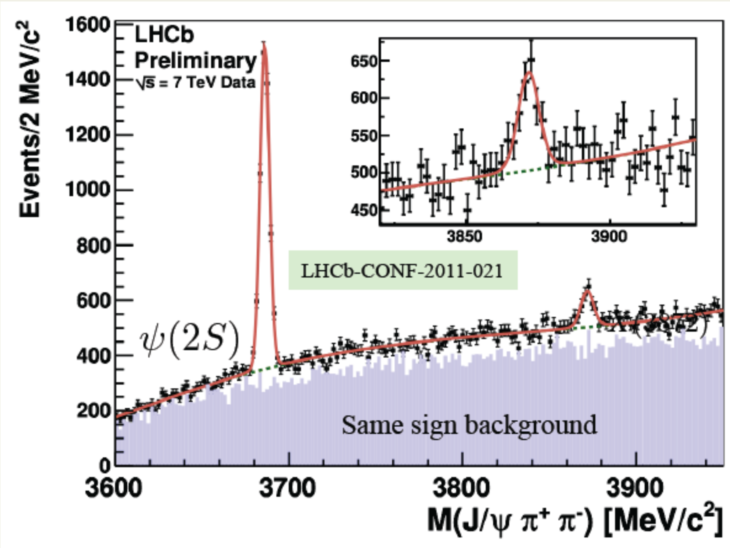
$J/\psi\pi^+\pi^-$, $D^*\bar{D}^0$, $J/\psi\gamma$, $J/\psi\omega$

Interpretations oscillate:

- charmonium state;
- $D^*\bar{D}^0$ molecule;
- tetra-quark state.

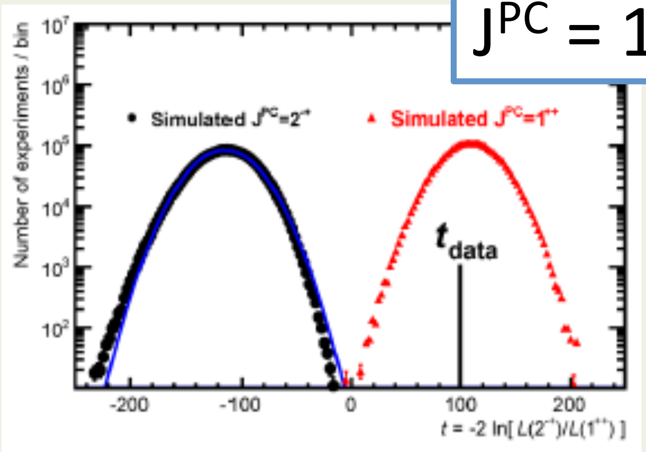
X(3872) lays 0.42 MeV below $D^{*0}\bar{D}^0$ . Width is narrow < 1.2 MeV/$c^2$ @ 90% C.L.

# The X(3872) at LHCb




LHCb using a sample of 313 ± 26 candidates performed a full five-dimensional amplitude analysis of the angular correlations between the decay products: $B^+ \to K^+X(3872)$; $X(3872) \to J/\Psi\ \pi^+\pi^-$, $J/\Psi \to \mu^+\mu^-$.

The result of the multidimensional likelihood-ratio test favors $J^{PC} = 1^{++}$ with more than 8σ significance.

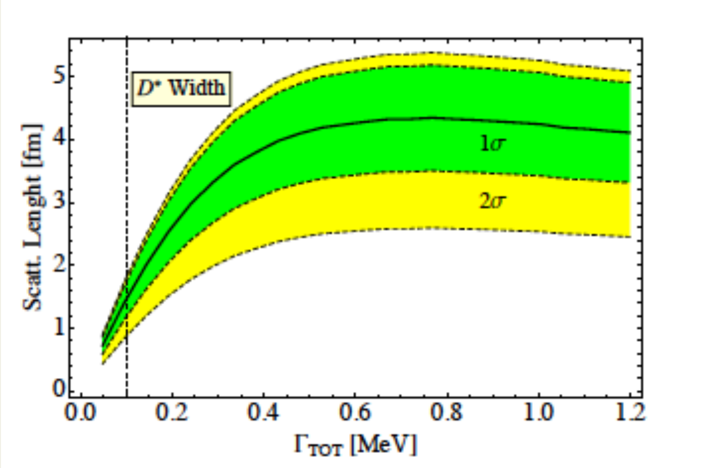



$J^{PC} = 1^{++}$

This ruled out some interpretations. Nowadays, the most accredited ascriptions are a four-quark state ($c\bar{c}q\bar{q}$) or a $D^0\bar{D}^{0*}$ molecule.

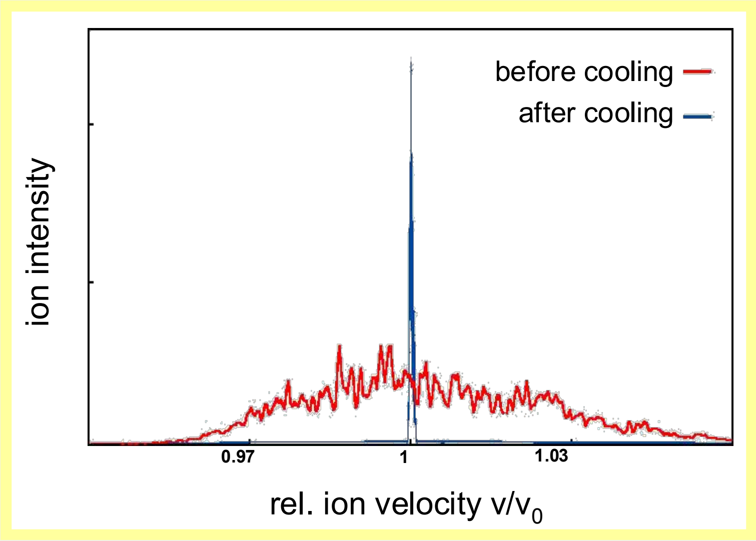
Scattering length for the $D^0\bar{D}^{0*} \to X \to D^0\bar{D}^{0*}$ process as a function of the X total width.

**[JMP 4 (2013) 1569]**



# Antiproton power

$\bar{p}$-beams can be cooled → Excellent resonance resolution



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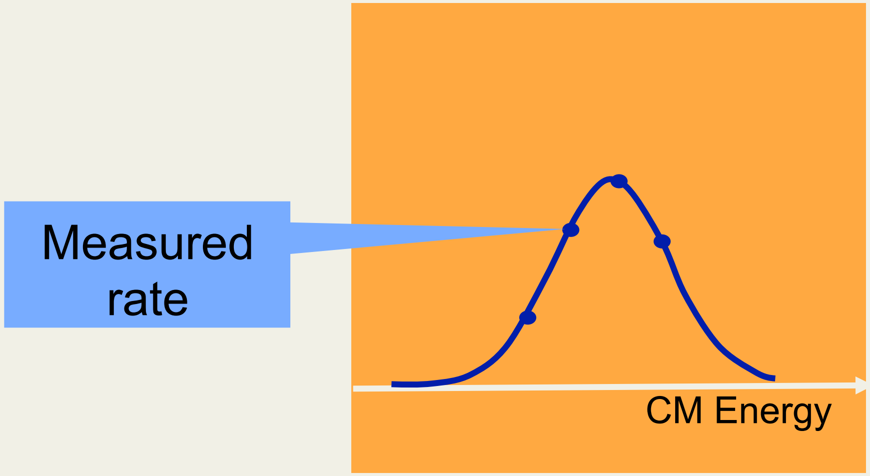


The production rate of a certain final state ν

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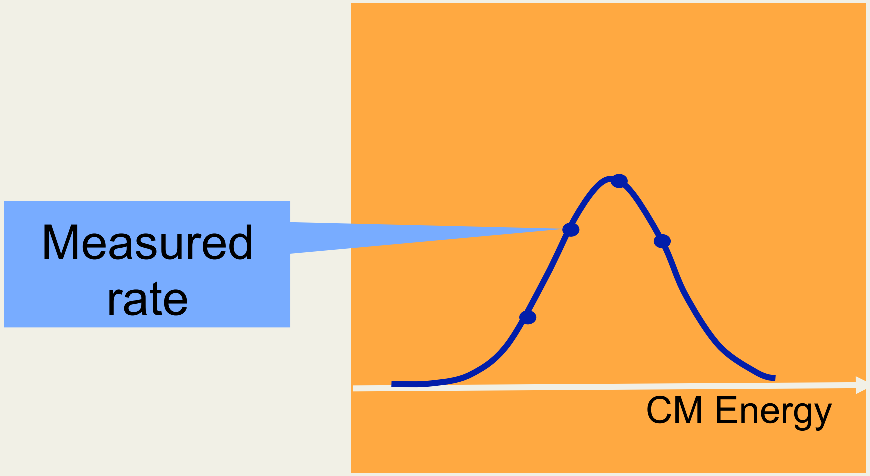


The production rate of a certain final state $\nu$ is a convolution of the

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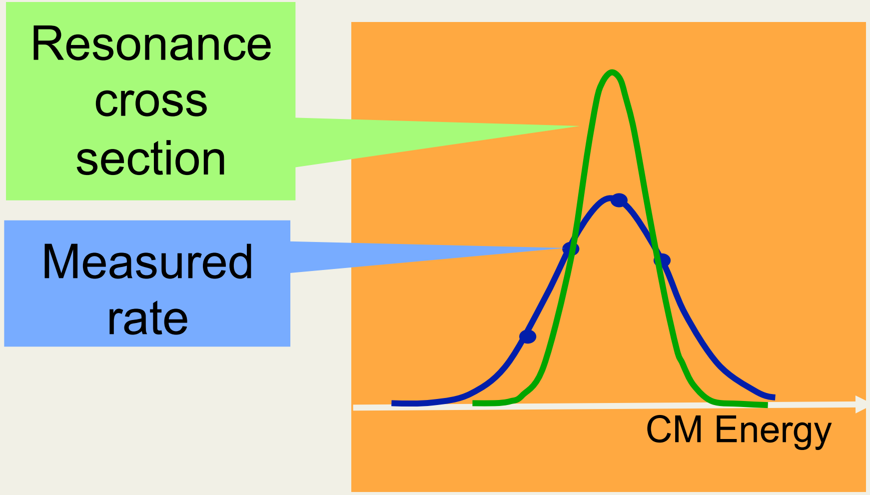
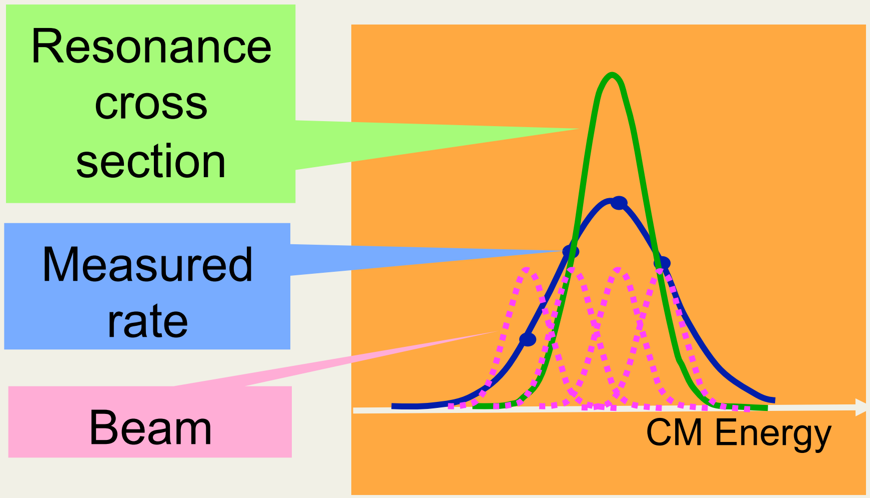



The production rate of a certain final state ν is a convolution of the BW cross section

# Antiproton power

$\bar{p}$-beams can be cooled → Excellent resonance resolution




The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

# Antiproton power

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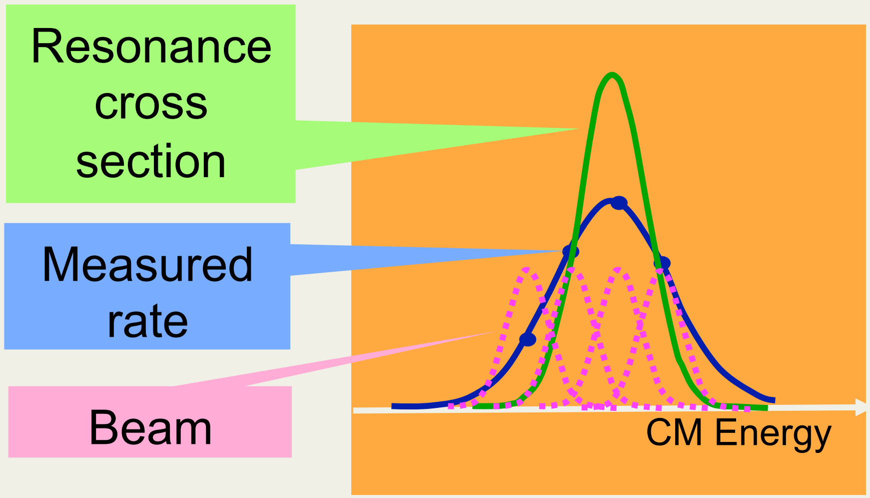
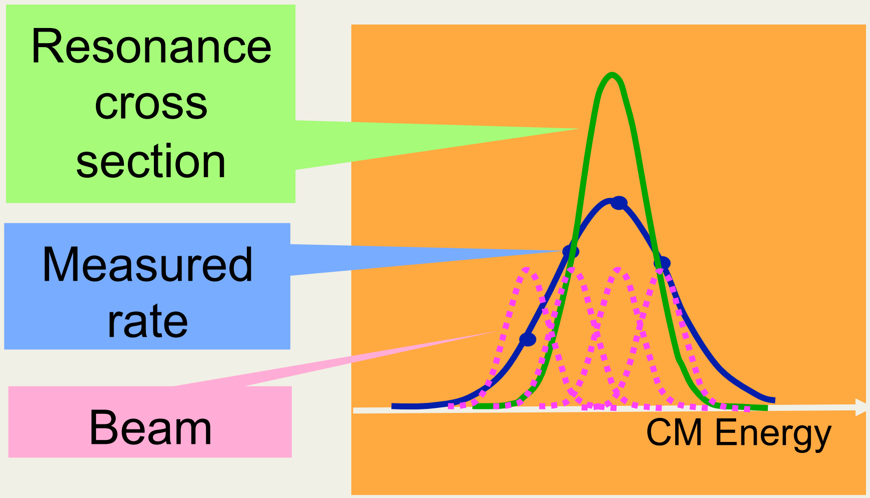



The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0 \left\{ \varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E) + \sigma_b \right\}$$

# Antiproton power

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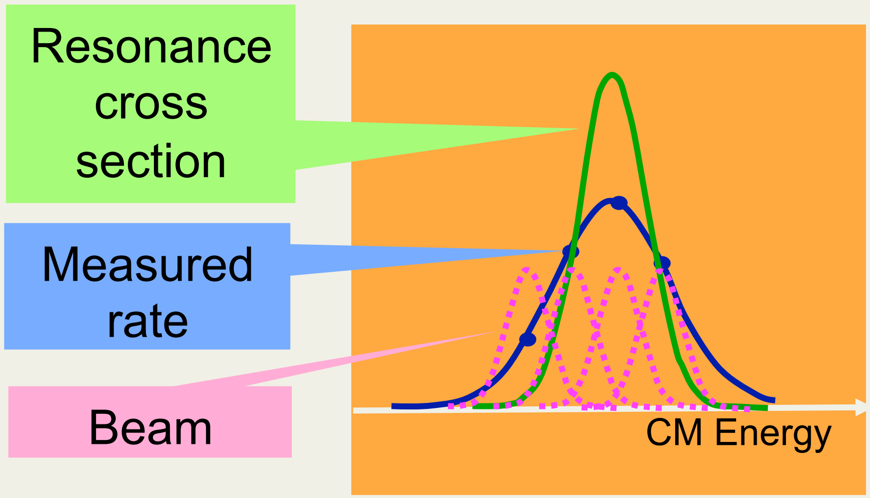
The resonance mass $M_R$, total width $\Gamma_R$ and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy $E$.

# Antiproton power




- $e^+e^-$: typical mass res. ~ 10 MeV
- Fermilab: 240 keV
- HESR: ~60 keV

The production rate of a certain final state $\nu$ is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0\{\varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E) + \sigma_b\}$$

The resonance mass $M_R$, total width $\Gamma_R$ and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy $E$.

# X(3872) @ PANDA

The narrow width of X(3872) can be precisely determined with an energy scan

Input parameters:

m = 3.872 GeV/$c^2$

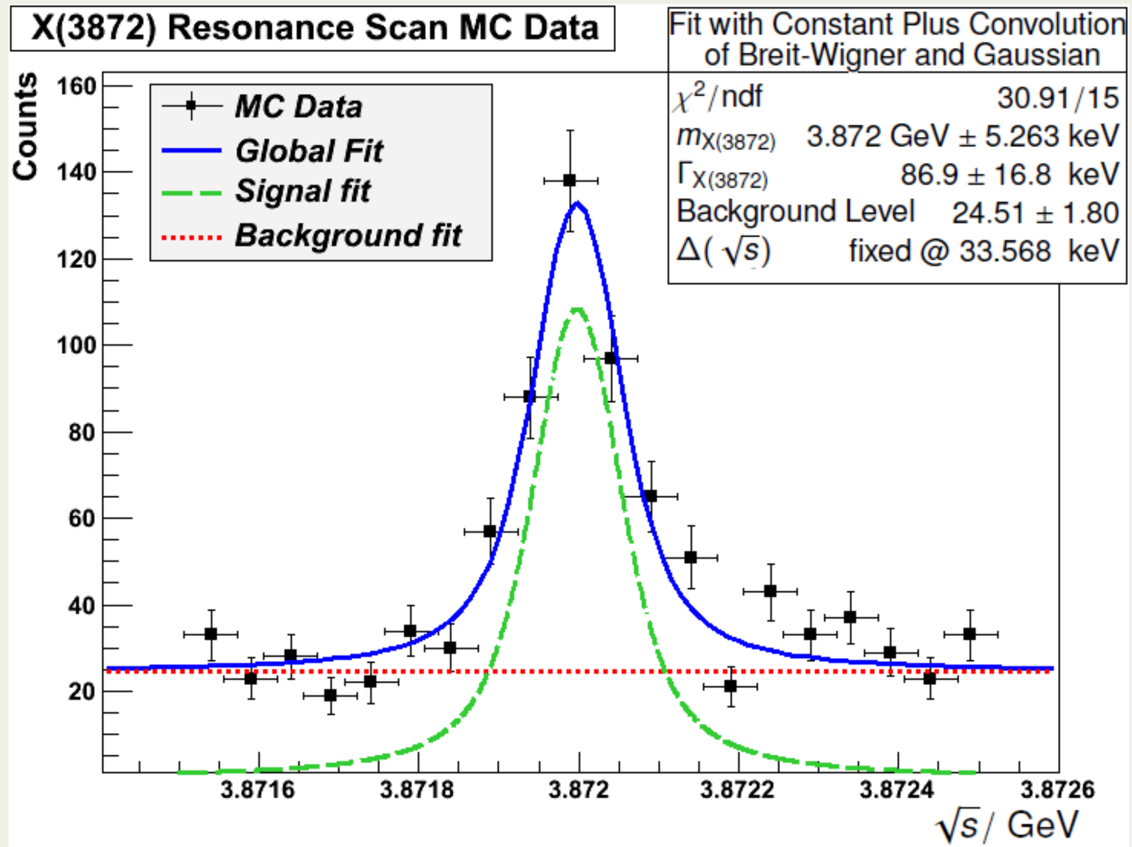
Γ = 1 MeV/$c^2$

→ Unfolding beam profile

($\Delta p/p = 3 \cdot 10^{-5}$)

Mass resolution~ 5 keV/$c^2$

Width precision~ 10-20%




for each data point only statistical errors are included

Many decay channels will be studied at the same time

# Antiproton power

- $e^+e^-$ interactions:

- $p\bar{p}$ reactions:

# Antiproton power

- $e^+e^-$ interactions:

  - Only $1^{--}$ states are formed
  - Other states only by secondary decays (moderate mass resolution related to the detector 5÷10 MeV)

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# Antiproton power

$e^+e^- \rightarrow \psi(2S)$
$\rightarrow \gamma\chi_{1,2}$
$\rightarrow \gamma\gamma J/\psi$
$\rightarrow \gamma\gamma e^+e^-$

$\bar{p}\, p \rightarrow \chi_{1,2}$
$\rightarrow \gamma J/\psi$
$\rightarrow \gamma e^+e^-$

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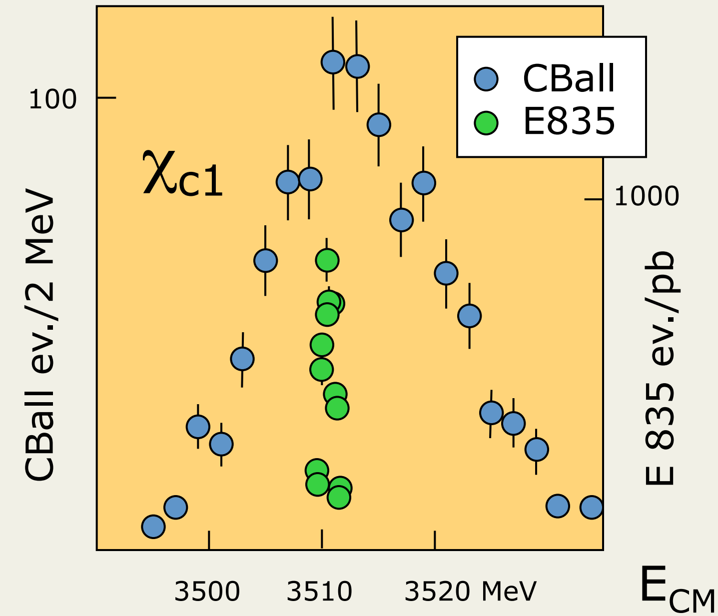

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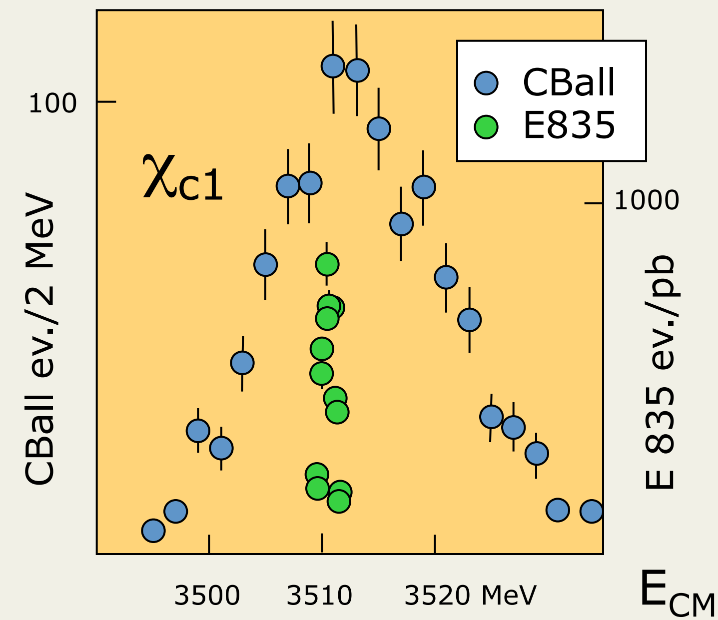
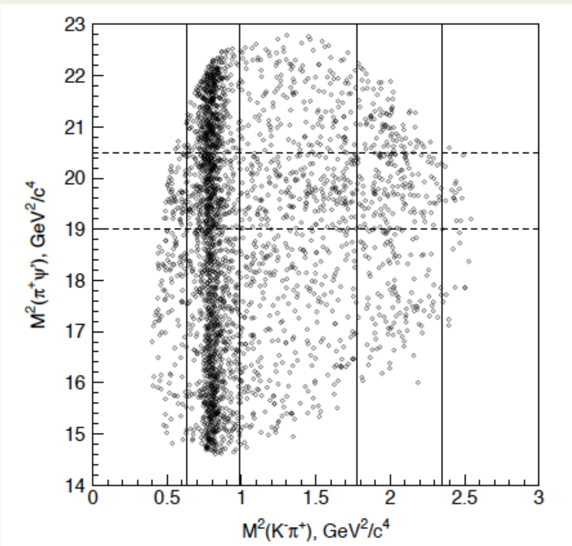


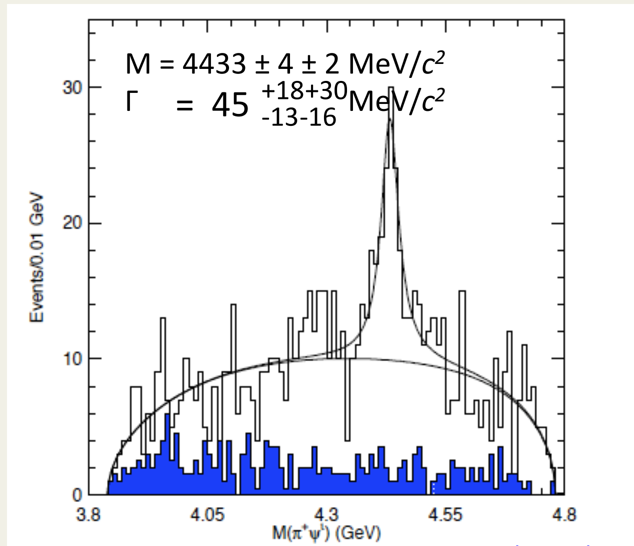

$Br(\bar{p}p \rightarrow \eta_c) = 1.2\ 10^{-3}$

$Br(e^+e^- \rightarrow \psi') \cdot Br(\psi' \rightarrow \gamma\eta_c) = 2.5\ 10^{-5}$

# Z(4430)

In 2008, Belle studying B → $K\pi^{\pm}\psi'$ observed in the $\pi^{\pm}\psi'$ invariant mass distribution a structure near 4.43 GeV



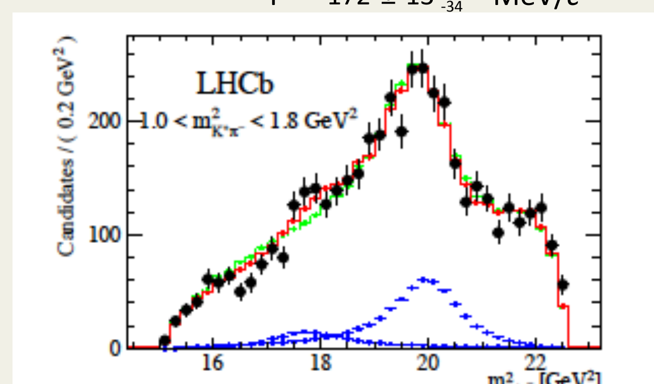




PRD80(2009)031104

A re-analysis cutting K* region confirmed the evidence, but with different mass (4443) and larger width (~110).

These findings have been recently confirmed by LHCb

M = 4475 ± 7 $^{+15}_{-25}$ MeV/$c^2$
Γ = 172 ± 13 $^{+37}_{-34}$ MeV/$c^2$



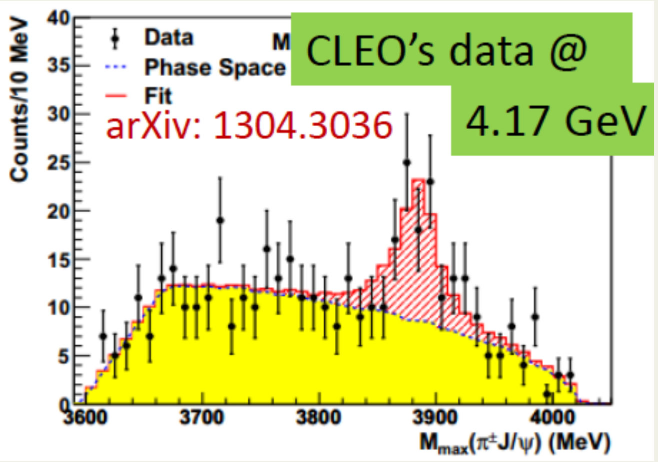

arXiv:1404.1903 [hep-ex].

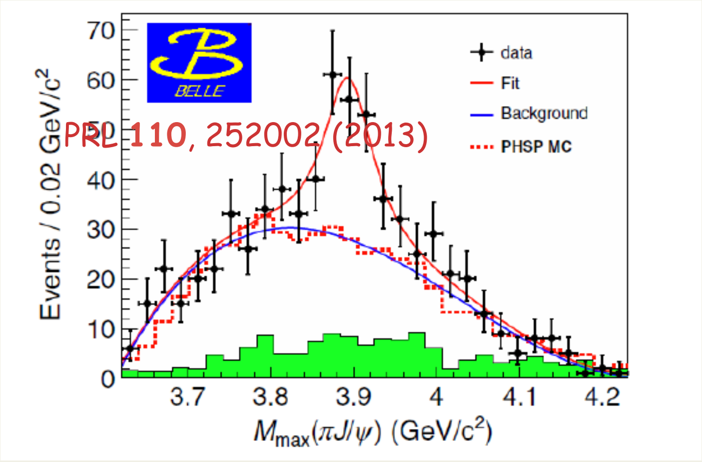
If this peak has to be interpreted as a meson state, it must have an exotic structure: its minimal quark content should be $|c\bar{c}u\bar{d}>$.

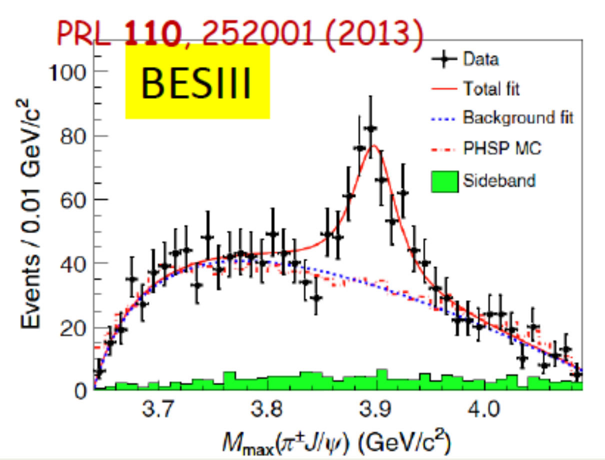
There are also hints of an other state at mass ~4240 MeV/$c^2$
Red histogram: fit with $0^-$ and $1^+$ states
Green histogram: fit with only $1^+$ state
In blue $0^-$ and $1^+$ contribution

# Charged multi-quark states

The first has been the Z(4430) observed in the invariant mass $\Psi'\pi^{\pm}$ by Belle, followed by other states in the bottomomium energy range.
BESIII collaboration discovered a charged charmonium-like axial meson $Z^{+}_{c} \rightarrow J/\Psi\pi^{\pm}$ (M= 3899±6 MeV, Γ = 46±22 MeV), confirmed by Belle and CLEO. The simplest quantum numbers assignment is $J^{PG} = 1^{++}$, G being the G-parity.



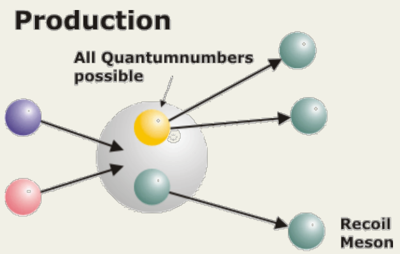



# Spectroscopy with antiprotons

Two are the mechanisms to access particular final states:

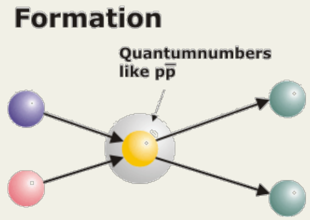
**Production**

all $J^{PC}$ available




**Formation**

only selected $J^{PC}$



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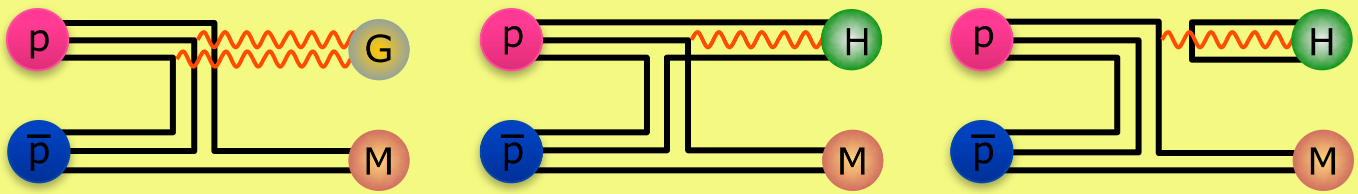
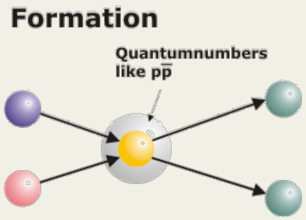



Even exotic quantum numbers can be reached σ ~100 pb

**Formation**

only selected $J^{PC}$



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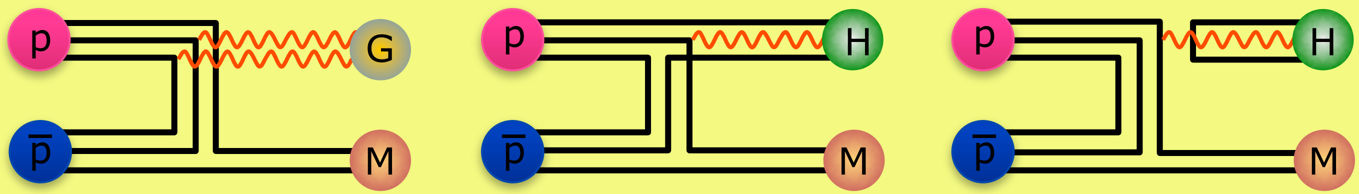
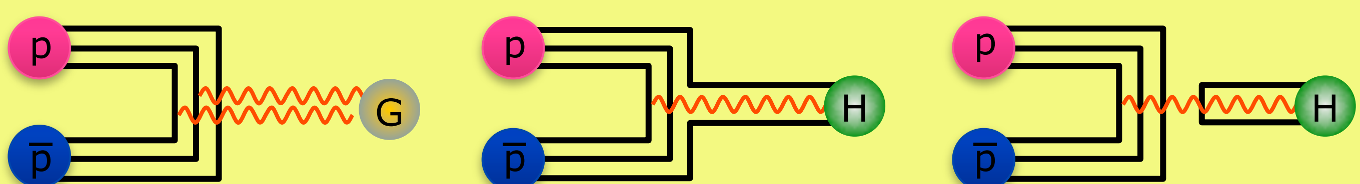


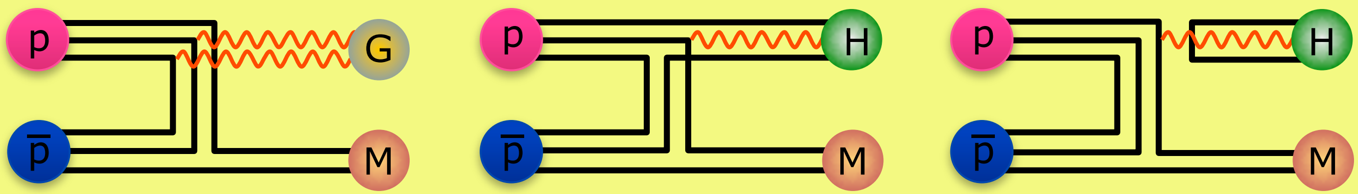

Even exotic quantum numbers can be reached σ ~100 pb

All ordinary quantum numbers can be reached σ ~1 μb



# Spectroscopy with antiprotons

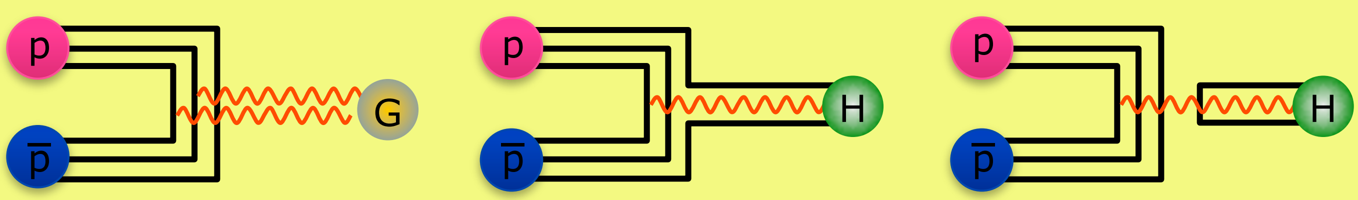
Two are the mechanisms to access particular final states:




Even exotic quantum numbers can be reached σ ~100 pb

**Exotic states can be studied exploiting the two complementary production mechanisms**

All ordinary quantum numbers can be reached σ ~1 μb



# Z$^{\pm}$ states @ $\bar{\text{p}}$anda

$\bar{\text{P}}$ANDA can study the Z$^{\pm}$ states in both production and formation experiments.

In the production experiment, the Z$^{\pm}$ would be produced, e.g., in the reaction

$$\bar{p}p \rightarrow Z^{\pm}\pi^{\mp}$$

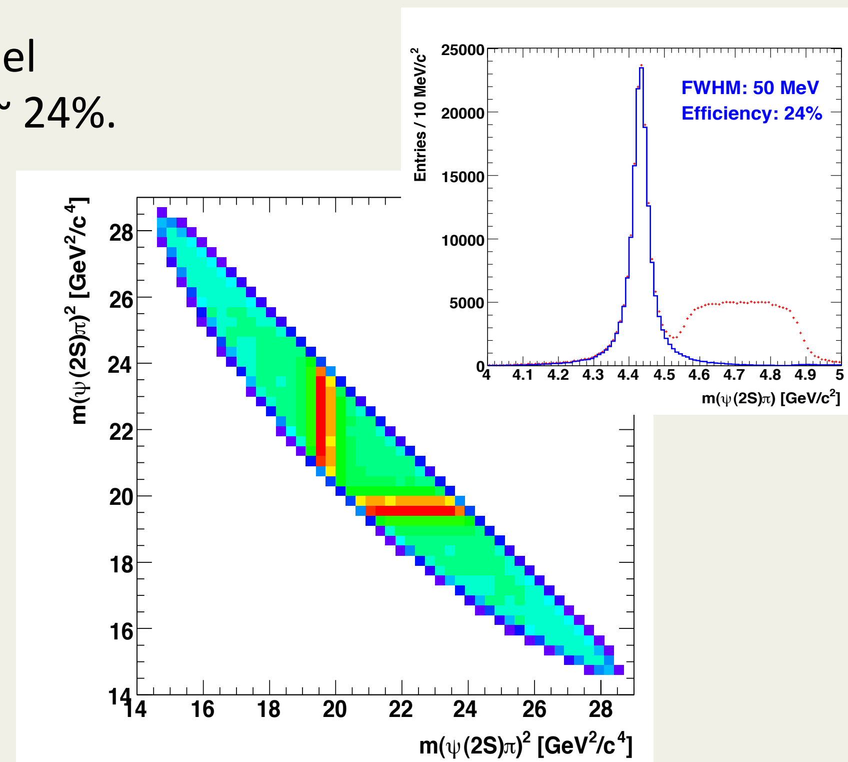
The subsequent decay chain could then be: Z$^{+}$(4430) → ψ(2S)π$^{+}$ → J/ψπ$^{+}$ π$^{-}$ π$^{+}$ → e$^{+}$e$^{-}$ π$^{+}$ π$^{-}$ π$^{+}$

The reconstruction efficiency for the Z$^{+}$(4430) channel has been studied in Monte Carlo calculations and is ~ 24%.

In formation mode Z$^{\pm}$ states can be produced by using a deuterium target:

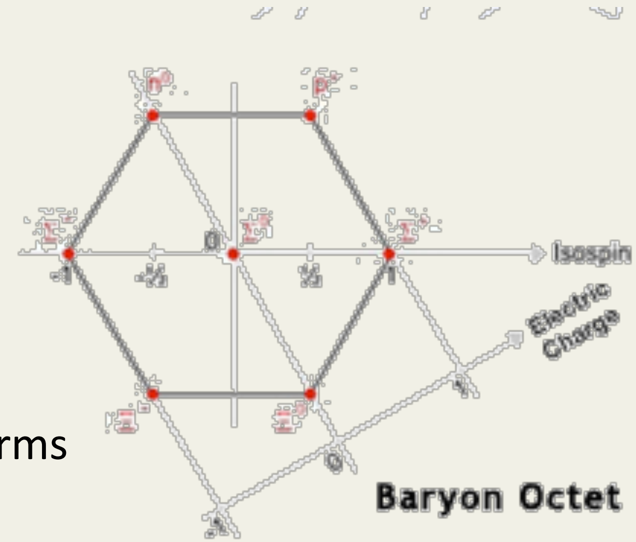
$$\bar{p}d \rightarrow Z^{-}p_{spectator}$$

The reconstruction efficiency for this channel studied in Monte Carlo reactions is ~ 35%.

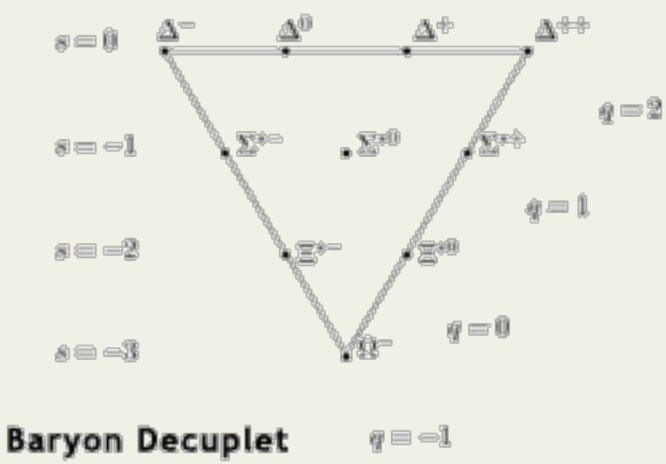


# Baryon sector

The investigation of the baryon-baryon interactions is crucial for a deeper understanding of nuclei, structure of neutron matter and astrophysics aspects, etc...




Chiral effective field theories have tried since long time to describe baryon-baryon interaction and recently also lattice QCD calculations allowed to approach nuclear physics in terms of fundamental theory of the strong interaction.



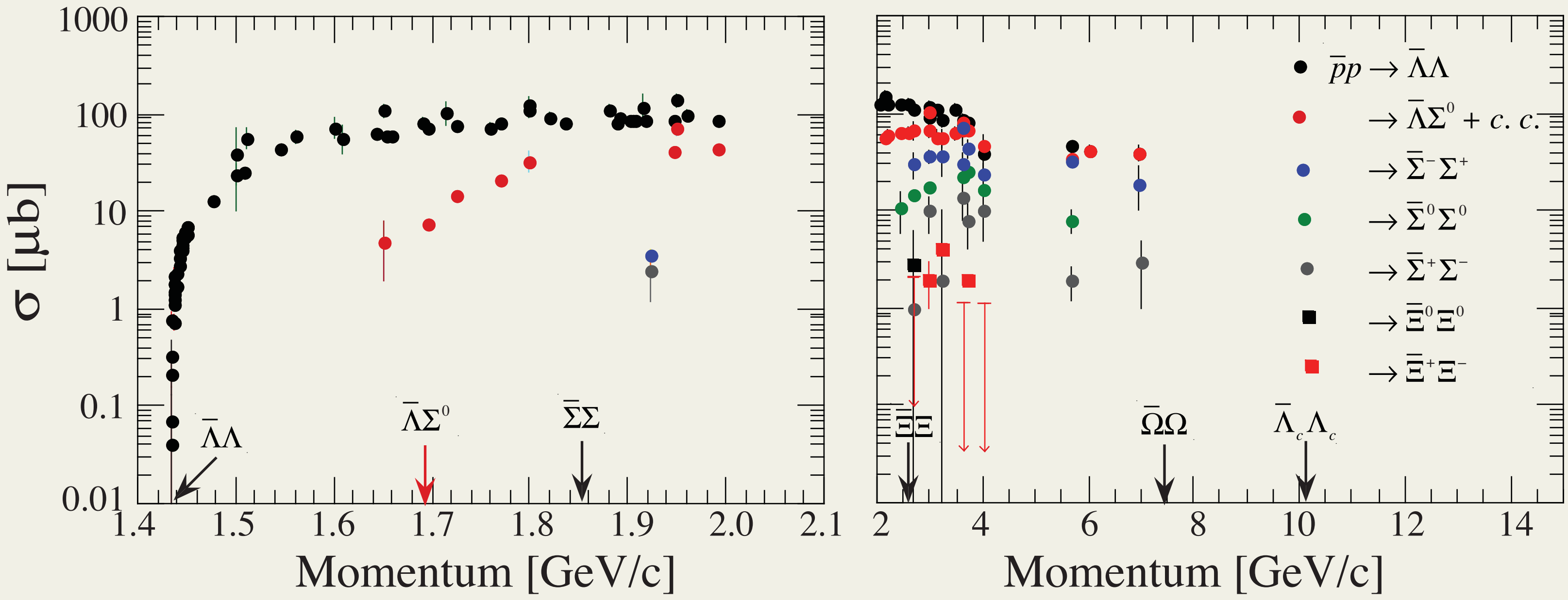

The experimental investigation of the nature of baryon bound states has gone in parallel with meson spectroscopy, nevertheless there are still many open problems and there is lack of high quality data.

# Strange Baryon Spectroscopy

In the quark picture hyperon pair production either involves the creation of a quark-antiquark pair or the knock out of such pairs out of the nucleon sea.

Hence, the importance of quark degrees of freedom with respect to the hadronic ones can be studied by measuring the reactions of the type

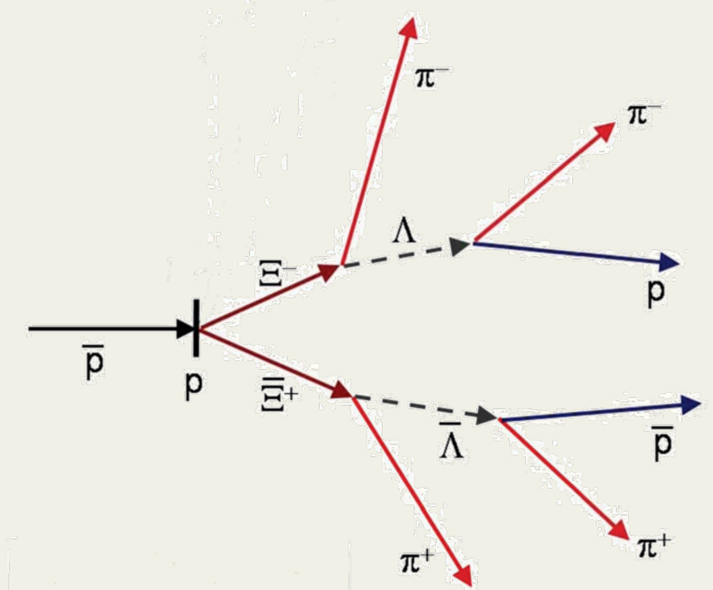
$\bar{p}p \rightarrow \bar{Y}Y$



# QCD Dynamics

The experimental data set available is far from being complete. All strange hyperons and single charmed hyperons are energetically accessible in $\bar{p}p$ collisions at $\bar{P}$ANDA.

In $\bar{P}$ANDA $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$, $\bar{\Lambda}\Xi$, $\Lambda\bar{\Xi}$, $\Xi\bar{\Xi}$ , $\Sigma\bar{\Sigma}$, $\Omega\bar{\Omega}$, $\Lambda_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Sigma}_c$, $\Omega_c\bar{\Omega}_c$
can be produced allowing the study of the dependences on spin observables.




| Channel 1.64 GeV/$c$ | Rec. eff. | $\sigma$ [$\mu$b] | Signal |
|---|---|---|---|
| $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ | 0.11 | 64 | 1 |
| $\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$ | $1.2 \cdot 10^{-5}$ | $\sim 10$ | $4.2 \cdot 10^{-5}$ |
| Channel 4 GeV/$c$ | | | |
| $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ | 0.23 | $\sim 50$ | 1 |
| $\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$ | $< 3 \cdot 10^{-6}$ | $3.5 \cdot 10^3$ | $< 2.2 \cdot 10^{-3}$ |
| $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$ | $5.1 \cdot 10^{-4}$ | $\sim 50$ | $2.2 \cdot 10^{-3}$ |
| $\bar{p}p \rightarrow \bar{\Lambda}\Sigma(1385)$ | $< 3 \cdot 10^{-6}$ | $\sim 50$ | $< 1.3 \cdot 10^{-5}$ |
| $\bar{p}p \rightarrow \bar{\Sigma}^0\Sigma^0$ | $< 3 \cdot 10^{-6}$ | $\sim 50$ | $< 1.3 \cdot 10^{-5}$ |
| Channel 15 GeV/$c$ | | | |
| $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$ | 0.14 | $\sim 10$ | 1 |
| $\bar{p}p \rightarrow \bar{p}p\pi^+\pi^-$ | $< 1 \cdot 10^{-6}$ | $1 \cdot 10^3$ | $< 2 \cdot 10^{-3}$ |
| $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$ | $2.3 \cdot 10^{-3}$ | $\sim 10$ | $1.6 \cdot 10^{-2}$ |
| $\bar{p}p \rightarrow \bar{\Lambda}\Sigma(1385)$ | $3.3 \cdot 10^{-5}$ | 60 | $1.4 \cdot 10^{-3}$ |
| $\bar{p}p \rightarrow \bar{\Sigma}^0\Sigma^0$ | $3.0 \cdot 10^{-4}$ | $\sim 10$ | $2.1 \cdot 10^{-3}$ |
| DPM | $< 1 \cdot 10^{-6}$ | $5 \cdot 10^4$ | $< .09$ |
| Channel 4 GeV/$c$ | Rec. eff. | $\sigma$ ($\mu$b) | Signal |
| $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$ | 0.19 | $\sim 2$ | 1 |
| $\bar{p}p \rightarrow \bar{\Sigma}^+(1385)\Sigma^-(1385)$ | $< 1 \cdot 10^{-6}$ | $\sim 60$ | $< 2 \cdot 10^{-4}$ |

By comparing several reactions involving different quark flavors the OZI rule and its possible violation, can be tested.

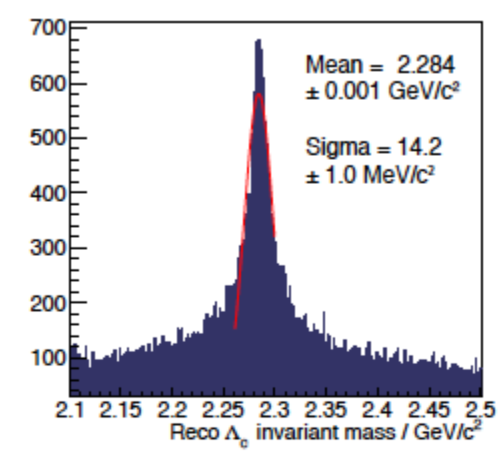
# $\bar{p}p \to \Lambda_c \bar{\Lambda}_c$ @ P̄ANDA

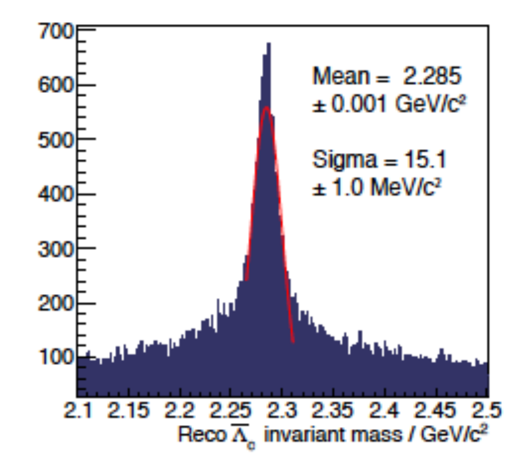
Different theoretical predictions estimated the $p\bar{p} \to \Lambda_c + \bar{\Lambda}_c$ cross section at the P̄ANDA energies: the value ranges between some tens of nb to 200 nb.

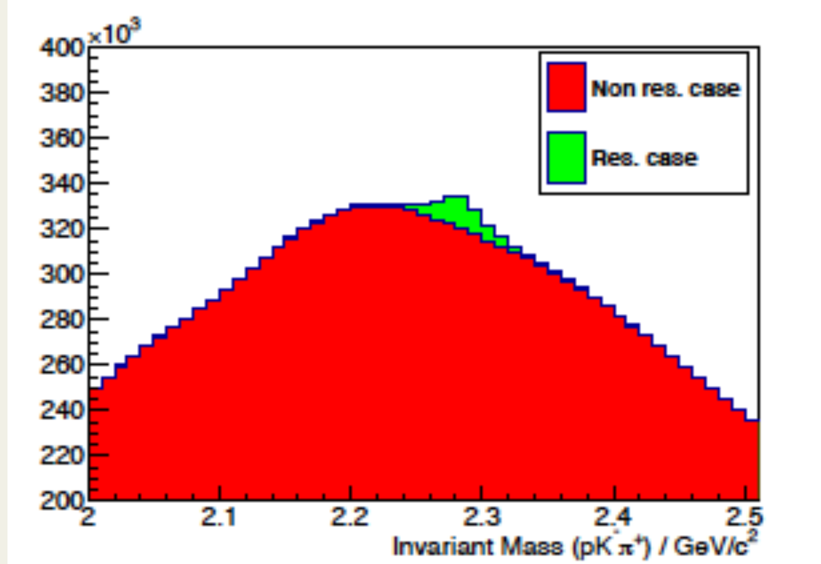
We considered the following decay chain: $\bar{p}p \to \Lambda_c^+(2286)\bar{\Lambda}_c^-(2286)$, with $\Lambda_c^+ \to pK^-\pi^+$ and $\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-$

at the maximum beam momentum (15 GeV/*c*; √s = 5.474 GeV )

For the background we assumed $\sigma(\sqrt{s} = 5.474\ \mathrm{GeV})_{\bar{p}p \to pK^-\pi^+\bar{p}K^+\pi^-} = 0.020\ \mathrm{mb}$
extrapolating from measurements at √s = 7.862 GeV



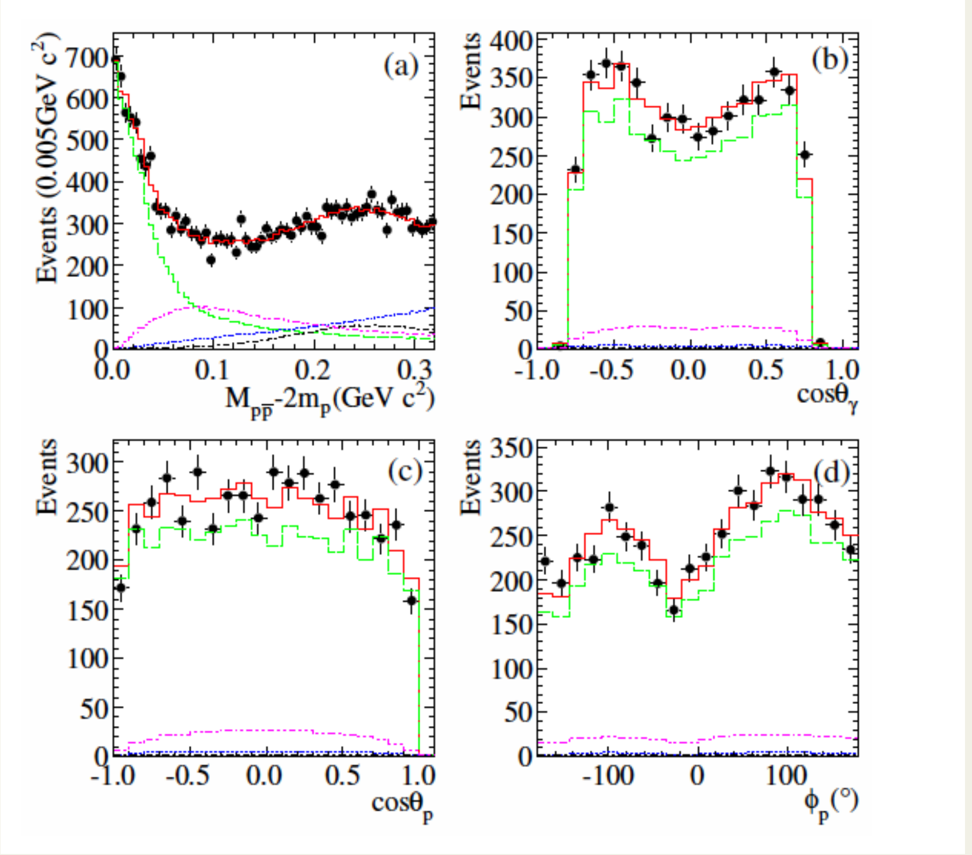



# Di-Baryons

In 2003, the BESII experiment reported the observation of a near-threshold enhancement in the p$\bar{p}$ invariant mass spectrum in the radiative $J/\psi \to \gamma p\bar{p}$ decay. BESIII with a high statistics sample performed a full PWA.

The final result is a spin parity assignment $0^{-+}$ for the X(p$\bar{p}$) state with mass $1832^{+19}_{-5}(stat.)^{+18}_{-17}(syst.)Mev/c^2$ and $\Gamma < 76MeV/c^2$




There is no experimental evidence in $J/\psi \to \pi^0 p\bar{p}$ ;$\Upsilon(2S) \to \gamma p\bar{p}$

$J/\psi \to \omega p\bar{p}$

while for $\psi(2S) \to \gamma p\bar{p}$ the production rate R respect to the J/psi is ~ 5%.

It was proposed to associate this state with a broad (190 MeV) enhancement observed in B meson decay or to X(1835) seen in $J/\psi \to \gamma\pi^+\pi^-\eta'$

# ΛΛ Hypernuclei

## Status of the art:

| Nucleus | $B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{A}Z)$ [MeV] | $\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{A}Z)$ [MeV] | Reference | Reaction |
|---|---|---|---|---|
| ${}_{\Lambda\Lambda}{}^{10}Be$ | 17.7± 0.4 | 4.3±0.4 | M.Danysz et al., PRL.11(1963) 29 | $K^- + A \rightarrow K^+ + \Xi^-$ |
| ${}_{\Lambda\Lambda}{}^{6}He$ | 10.9±0.5 | 4.6±0.5 | D.J.Prowse, PRL.17(1966) 782 | $K^- + A \rightarrow K^+ + \Xi^-$ |
| ${}_{\Lambda\Lambda}{}^{10}Be$ | 8.5±0.7 | -4.9±0.7 | KEK-E176 | $K^- + p \rightarrow K^+ + \Xi^-$ (q.f) |
| ${}_{\Lambda\Lambda}{}^{13}B$ | $27.6 \pm 0.7^{+0.18}_{-0.11}$ | $4.9 \pm 0.7^{+0.18}_{-0.11}$ | S.Aoki et al., PTP.85(1991) 1287 | $K^- + p \rightarrow K^+ + \Xi^-$ (q.f) |
| ${}_{\Lambda\Lambda}{}^{12}B$ | | 4.5±0.5 | P.Khaustov et al., PRC.61(2000)027601 | $({}^{12}C)_{atom}\Xi^- \rightarrow {}^{12}B_{\Lambda\Lambda} + n$ |
| ${}_{\Lambda\Lambda}{}^{6}He$ | 6.91±0.16 | 0.67±0.17 | KEK-E373,NAGARA J.H. Ahn et al., PRC.88(2013) 014003 | $K^- + p \rightarrow K^+ + \Xi^-$ (q.f) |
| ${}_{\Lambda\Lambda}{}^{12}B$ | | $\sigma\ (\theta<8^0) \approx$ 6-10nb | K.Yamamoto et al., PLB.478(2000) 401 | $K^- + {}^{12}C \rightarrow K^+ + {}^{12}B_{\Lambda\Lambda}$ |

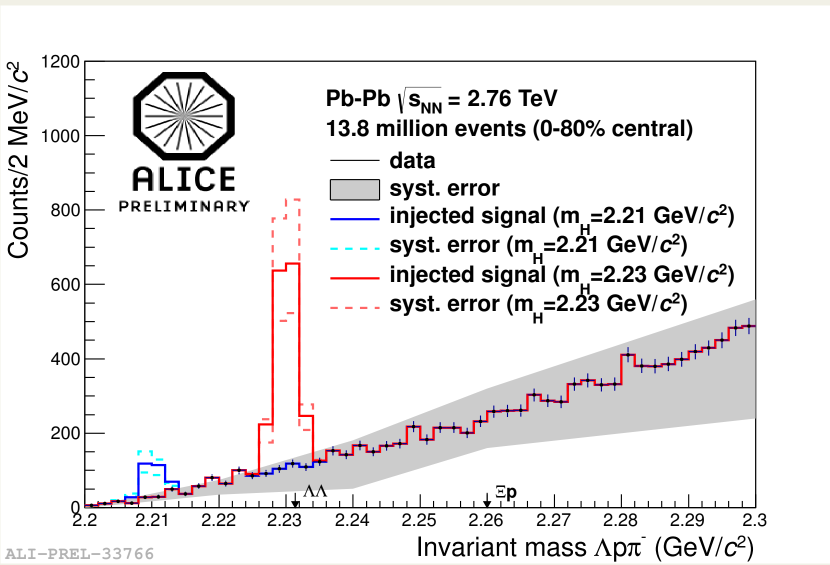
## Features:

$$-V_{\Lambda\Lambda} = \Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{\ A}Z) \equiv B_{\Lambda\Lambda}({}_{\Lambda\Lambda}^{\ A}Z) - 2B_{\Lambda}({}_{\Lambda}^{A-1}Z)$$

- **Binding energy →** parameters in potential models
- **Core of the ΛΛ interaction ($V_{\Lambda\Lambda}$)** : needs of several A-hypernuclei
- ΛΛ interaction: only I=0 ***non****-strange mesons* contributes (only ω,η)
- **Weak Decay presents some peculiarities**

# H-Dibarion

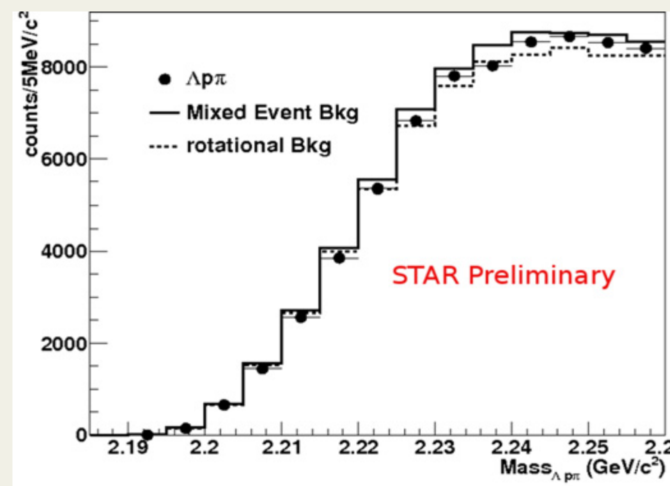
The measurement of the $_{\Lambda\Lambda}{}^{6}He$ binding energy has triggered new speculations on the H-dibarion existence [PRL106 (2011)162001]. The original prediction of a 6-quark state with a binding ≃ 81 MeV has been ruled out.




Nowadays, the only possibility is for a baryon-baryon molecule with $M_H \approx 2m_\Lambda - 7$ MeV

HI collision experiments searched in the $\Lambda$p invariant mass system for a possible signal.

A deeper knowledge of S=−2 sector would help to extend models that have been successful in describing the S=0 and −1 sectors to account for SU(3) symmetry.

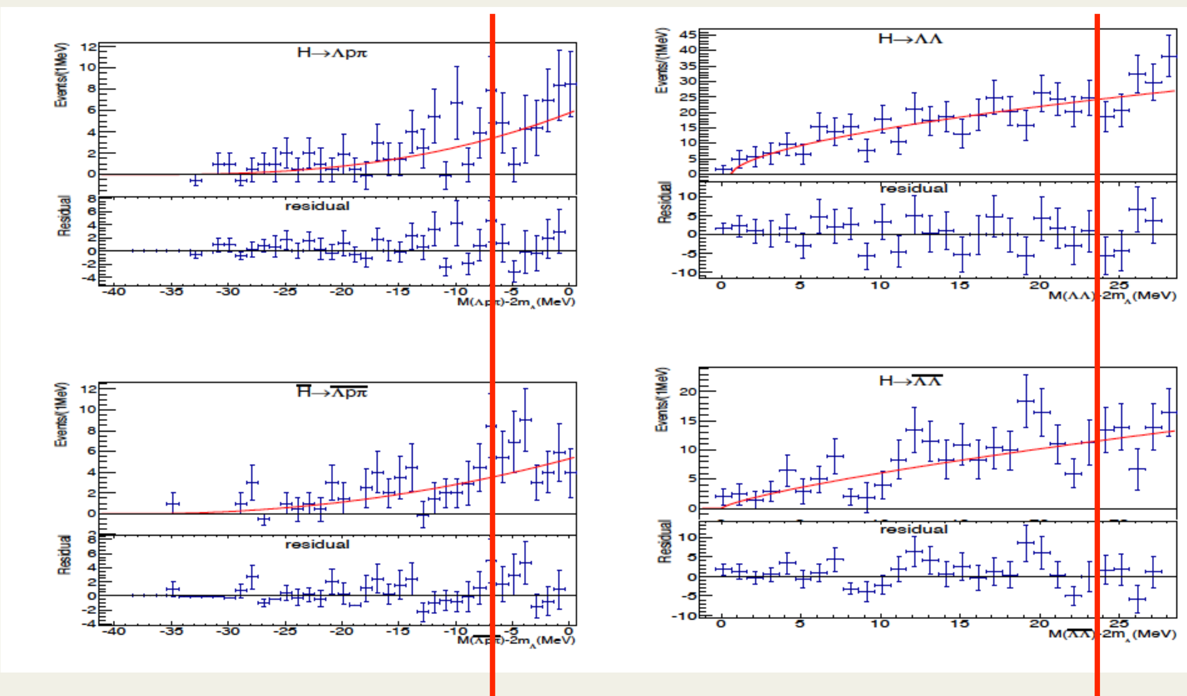


# H-Dibarion

Decays of narrow Y(nS)(n =1, 2, 3) resonances seems well suited for strange multiquark search. The Y(nS) states are flavor-SU(3) singlets that primarily decay via annihilation into three gluons. The gluons materialize into $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ pairs creating final states with a high density of quarks and antiquarks in a limited volume.

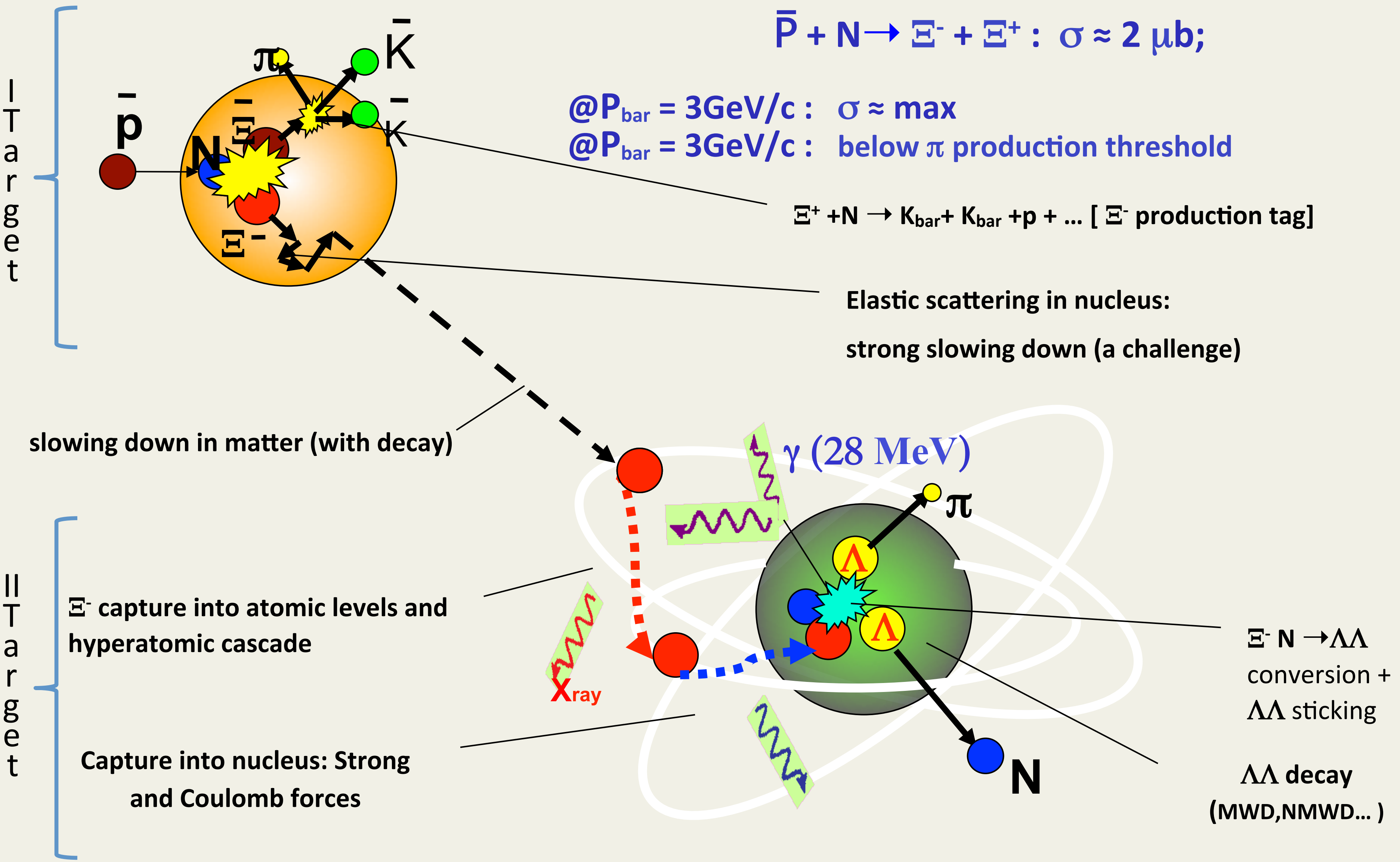
For masses below threshold, the H would decay via $\Delta S = +1$ weak transitions to $\Lambda n$, $\Sigma^- p$, $\Sigma^0 n$ or $\Lambda p \pi^-$. For masses above $2m_\Lambda$, but below $m_{\Xi^0} + m_n$ ($= 2m_\Lambda + 23.1$ MeV), the H would decay via strong interactions to $\Lambda\Lambda$.

PRL 110, 222002 (2013)




A search has then been made by Belle in the $\Lambda p \pi^-$, $\Lambda\Lambda$ and invariant mass distributions.

# Doubly strange systems @ $\bar{p}$anda

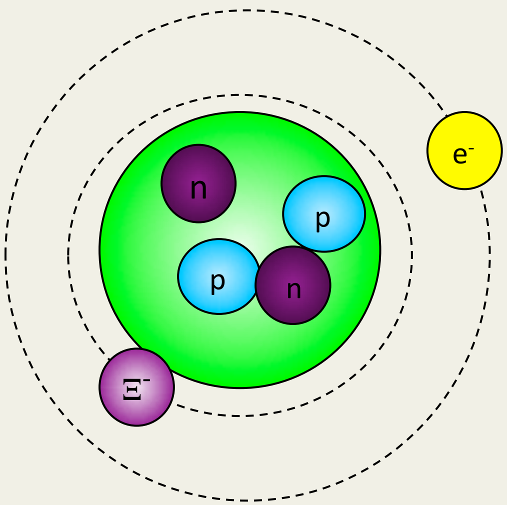


# Doubly strange systems

(S=±2) hyperon –antihyperon systems are fully accessible at P̄ANDA

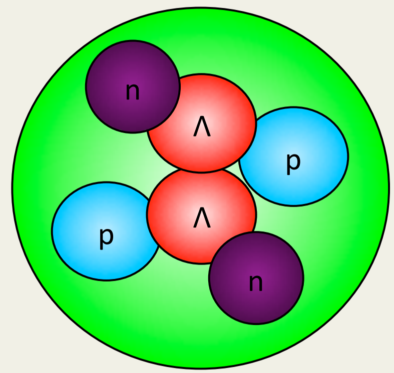
**Exotic hyperatom:**

**$\Xi^-$ occupies an atomic level**




**Double Λ Hypernucleus:**

**2 Λ 's replace 2 nucleons in a nucle**




***ΛΛ strong interaction***

- only possible in double hypernuclei
- YY potential: attractive/repulsive?
- hyperfragments probability dependence on YY potential

*One Boson Exchange features*

ΛΛ → ΛΛ: only *non strange, I =0 meson* exchange (ω,η...)

ΛΛ weak interaction: hyperon induced decay:

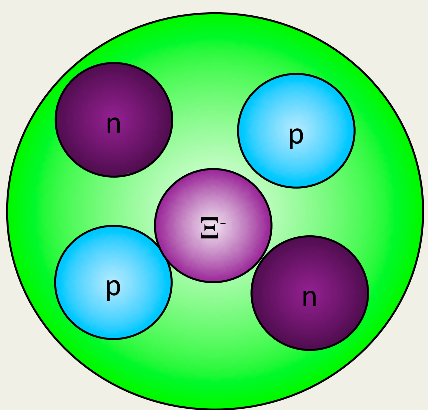
- ΛΛ → Λ n: $\Gamma_{\Lambda n} << \Gamma_{free}$ (expected)
- ΛΛ → $\Sigma^-$p: $\Gamma_{\Sigma p} << \Gamma_{free}$ (expected)

***$\Xi^-$ -nucleus interaction***

- Atomic orbits overlap nucleus
- Strong interaction and Coulomb force interplay
- Lowest atomic levels are shifted and broadened
- Potential: Coulomb + optical

**Doubly Strange Hypernucleus:**

**$\Xi^-$ occupies a nuclear level**




***Ξ -N interaction:***

- short range interaction
- long range interaction
- .....

# Afterword

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The Phaistos Disc is a disk of fired clay from the Minoan palace of Phaistos of Crete (2 millenium B.C.).
It is covered on both sides with a spiral of stamped symbols. Its purpose and meaning, and even its original geographical place of manufacture, remain disputed, making it one of the most famous mysteries of archaeology.

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# Summary

1. LQCD, EFT and QCD-motivated quark potential models describe the properties of the hadron spectrum quite well for the ground states.

2. In the last few years many expected states have been found and their measured properties are in good agreement with the model's predictions.

3. There is an accumulation of mesons with mass in the region between 3800 MeV/$c^2$ and 4700 MeV/$c^2$ that are not easily explained.

4. These states are relatively narrow although many of them are well above open-charm thresholds. Many of them have partial widths for decays to charmonium + light hadrons that are at the ~MeV scale, which is much larger than typical $c\bar{c}$ charmonium meson states.

5. There are  strong **exotic** candidates: X(3872), Y(4260), $Z^{\pm}$.

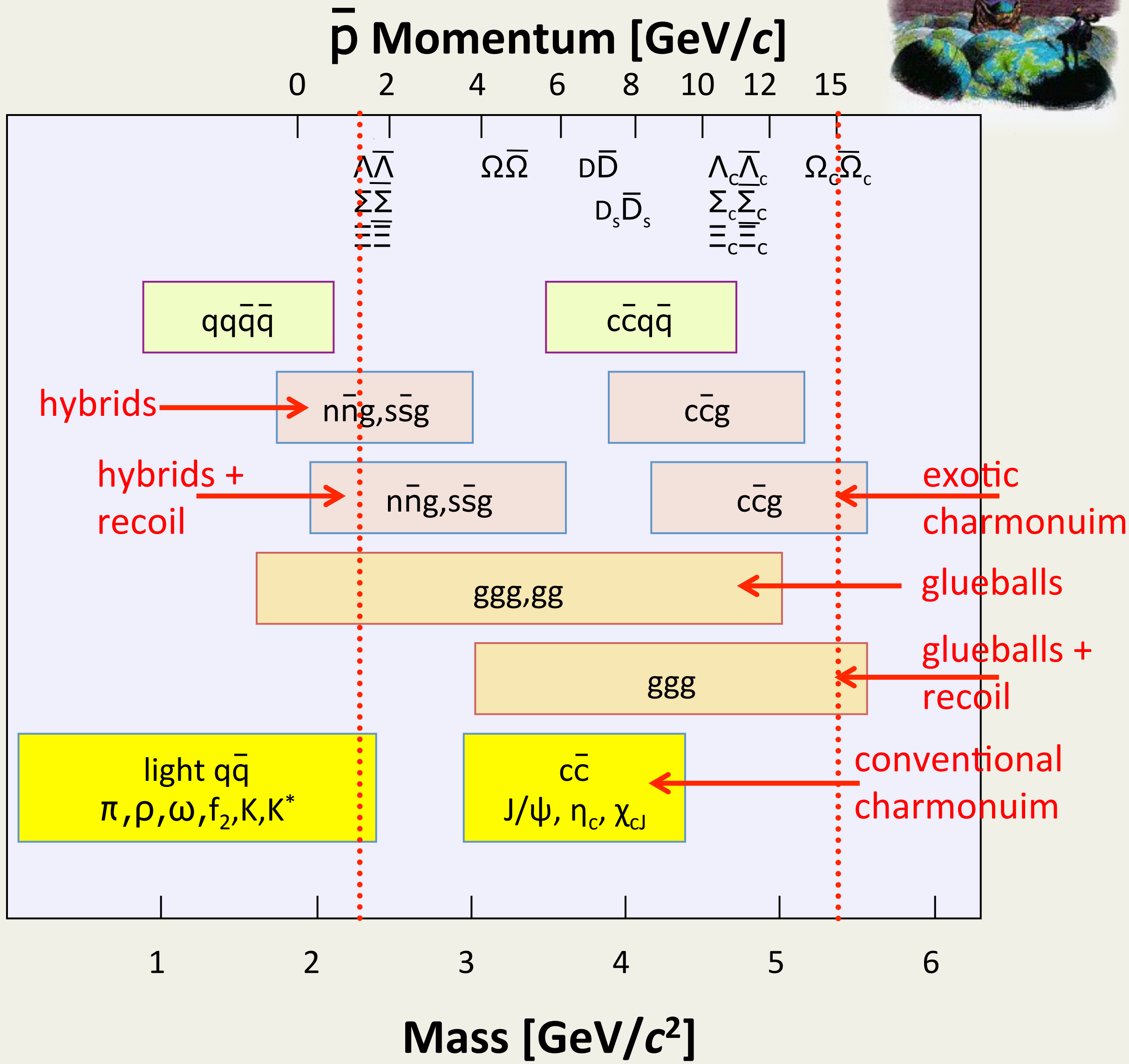
6. There are some problems with the theory when dealing with highly excited states.

7. New, high quality data will certainly come form the new experiment like GlueX and $\bar{\text{P}}$ANDA.

# Backup

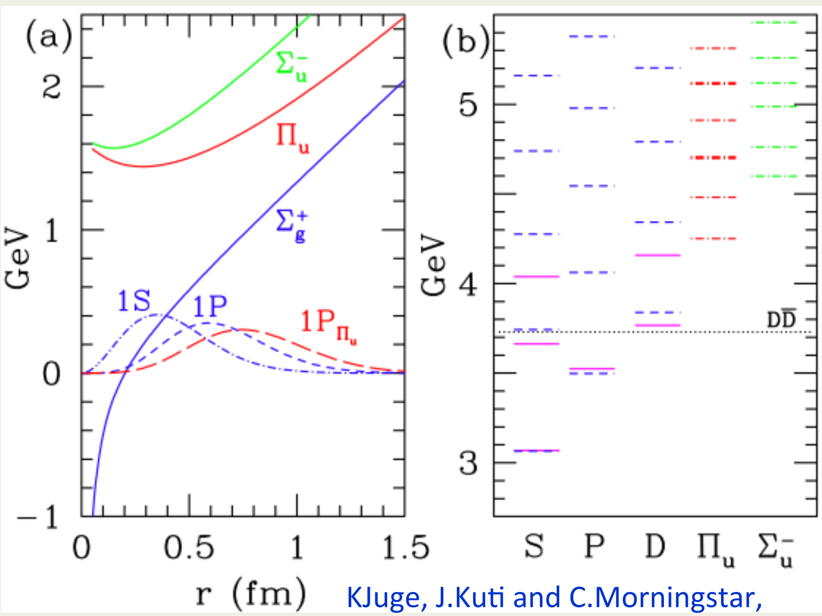
# panda Scientific program

- Meson spectroscopy
  - light mesons
  - charmonium
  - exotic states
    - ✓glueballs
    - ✓ hybrids
    - ✓molecules/multiquarks
  - open charm
- Baryon/antibaryon production
- Charm in nuclei
- Hypernuclei
- Em. form factors of the proton
- Generalized Parton Distributions



# Hybrids

In the simplest scenario, an hybrid is a meson with an explicit glue content. Adding a gluon ($J^P=1^+;1^-$) to a $q\bar{q}$ pair corresponds to create two possible hybrid states. Some of these combinations can even have exotic quantum numbers.




KJuge, J.Kuti and C.Morningstar, PRL 90, 161601 (2003)

| $q\bar{q}$ | Gluon $1^-$ (TM) | Gluon $1^+$(TE) |
|---|---|---|
| $^1S_0$, $0^{-+}$ | $1^{++}$ $\tilde{\chi}_{c1}$ | $1^{--}$ $\tilde{\psi}$ |
| $^3S_1$, $1^{--}$ | $0^{+-}$ $\tilde{h}_{c0}$ | $0^{-+}$ $\tilde{\eta}_{c0}$ |
| | $1^{+-}$ $\tilde{h}_{c1}$ | $1^{-+}$ $\tilde{\eta}_{c1}$ |
| | $2^{+-}$ $\tilde{h}_{c2}$ | $2^{-+}$ $\tilde{\eta}_{c2}$ |

Theoretical models agree to expect 8 exotic charmonia in the 3-5 GeV/$c^2$ mass region. The lighter should be a $1^{-+}$ state with a mass of about 4.3 GeV/$c^2$. Quantum numbers and mass splitting are also predicted ➔ the observation of the whole pattern would be an unambiguous signature

# Estimation of cross-sections

Unknown cross section for charmonium production in $p\bar{p}$ can be evaluated from the corresponding measured Branching Ratios (taking $s = M_X^2$):

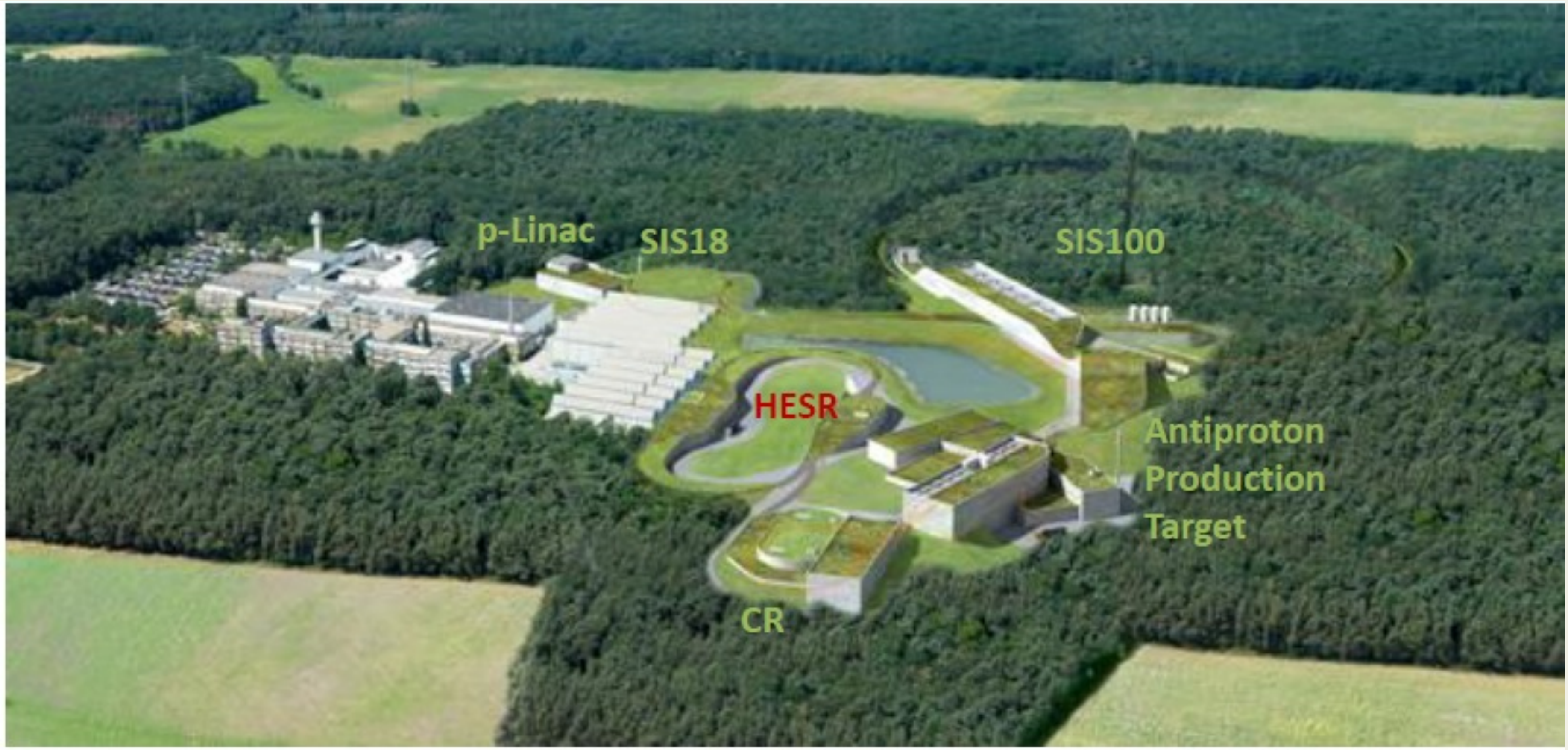
$$\sigma(\bar{p}p) \to X = \frac{4\pi(2J+1)}{M_X^2 - 4m_p^2} Br(X \to \bar{p}p)$$

| State X | $J^{PC}$ | $\sqrt{s}$ GeV | $Br(X\to p\bar{p})$ [$10^{-4}$] | $\sigma\to p\bar{p}$ [nb] |
|---|---|---|---|---|
| $\psi'$ | $1^{--}$ | 3.686 | 2.75 ± 0.12 | 402 ± 18 |
| $\eta'_c$ | $0^{-+}$ | 3.639 | 1.85 ± 1.26 | 93 ± 63 |
| $h_c$ | $1^{+-}$ | 3.525 | 8.95 ± 5.21 | 1470 ± 860 |

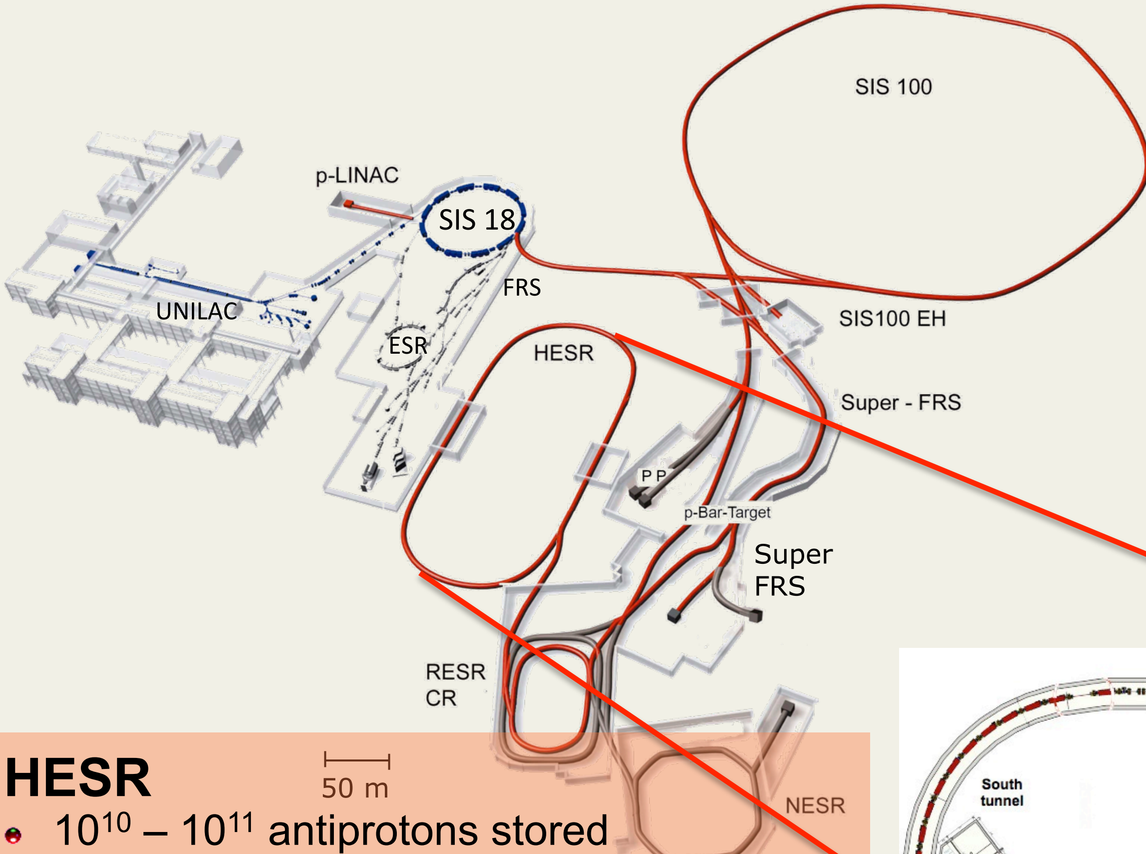
$$\int L dt = 8 pb^{-1}/day$$

we can expect between 100 and several thousand charmonia per day in production. The formation cross section is then usually 2-3 orders of magnitude bigger for narrow states.

# FAIR artistic view



# Facility for Antiproton and Ion Research

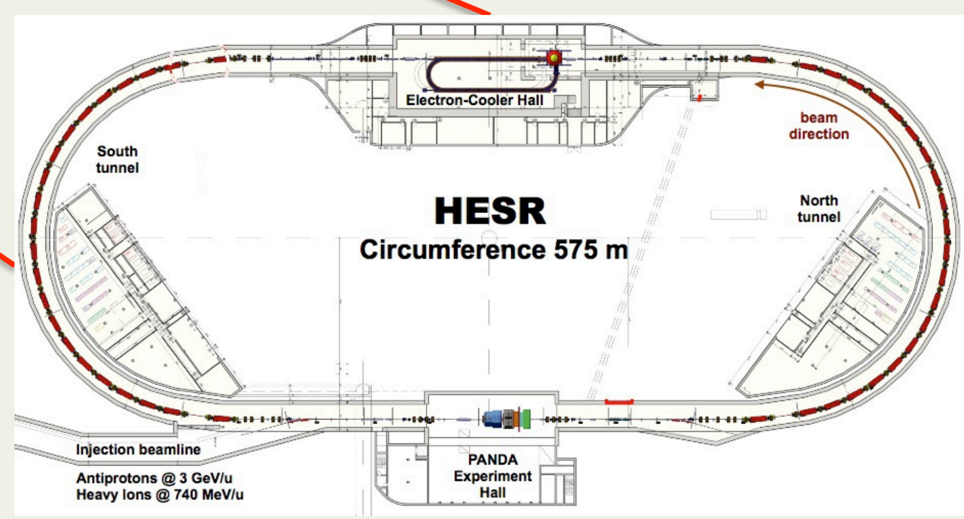



## Antiproton production

- Proton Linac 70 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on Cu target
- Collection in CR, fast cooling
- Accumulation in RESR
- Storage and usage in HESR

## HESR

- $10^{10}$ – $10^{11}$ antiprotons stored
- Slow synchrotron (1.5 – 15 GeV/*c*)
- Tick Internal target $4 \cdot 10^{15}$ cm$^{-2}$
- $\Delta p/p \leq 4 \cdot 10^{-5}$
- Luminosity up to $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
- Beam cooling (stochastic & electron)
- Beam life time > 30 min



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