# Hadron Spectroscopy

## And the $\bar{P}$ANDA experiment

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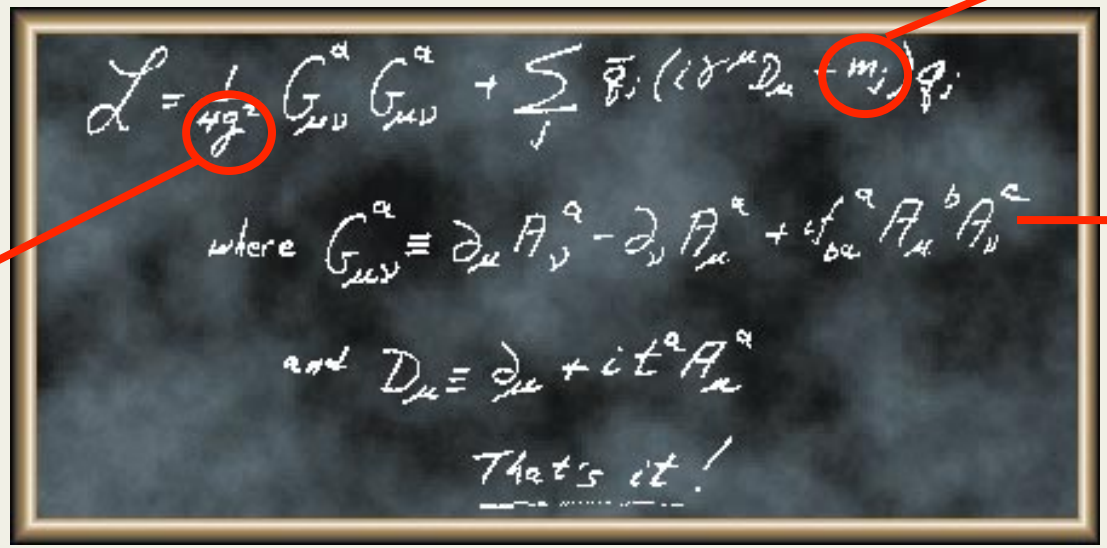
# Outline

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

# 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.

# Quantum Chromodynamics

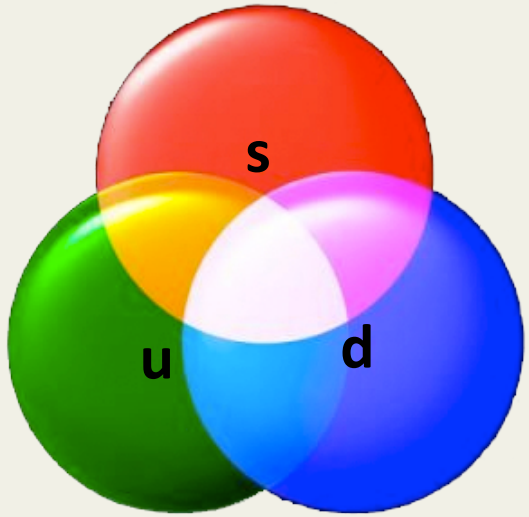
QCD is a Gauge invariant Quantum Field Theory based on a local SU(3) symmetry group:

- **matter**: quarks are the fundamental building blocks;

$q_i^f$ { i = red, green, blue; f = u, d, s, c, b, t }

spin = 1/2

charge 2/3; -1/3



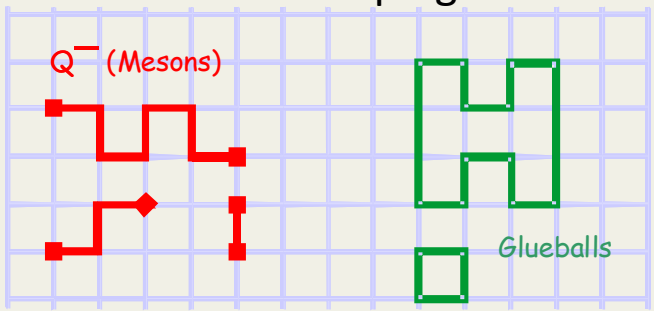

- **interaction carriers**: 8 massless spin-1 gluons in the 8-dim representation of SU(3). They carry color determining the non-analyticity of the theory;

- **coupling constant**: it appears to increase with distance → perturbative calculations are possible only at short distances (large energies).

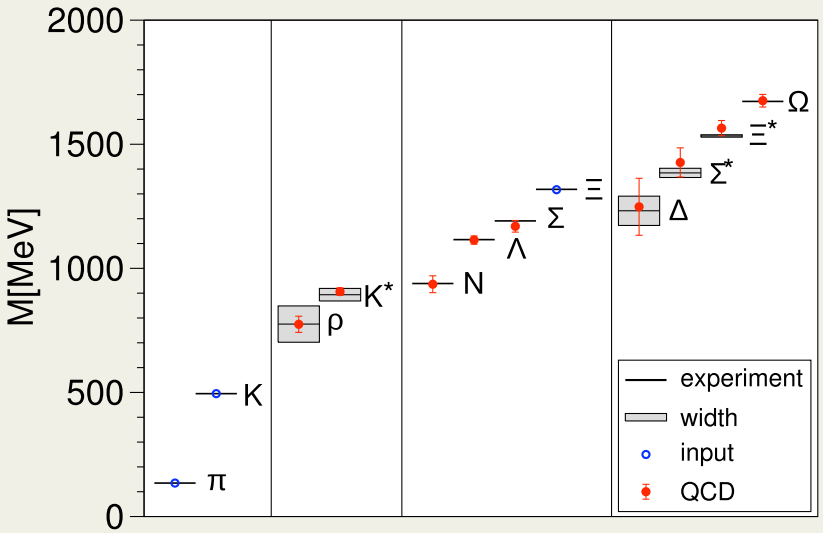
Hadrons are color-singlet (*i.e. not* colored) combinations of quarks, anti-quarks, and gluons.

# 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.

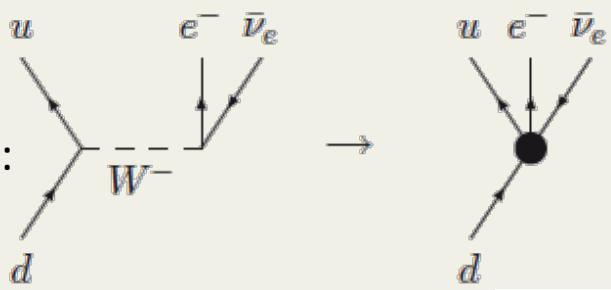
# Effective Field Theories

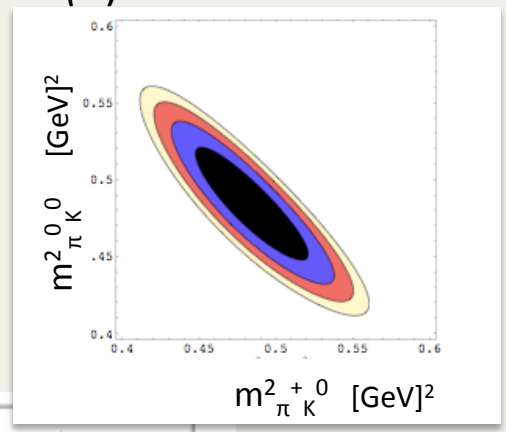
Effective Field Theories (EFT) are based on the assumption that scales much smaller/bigger than those under study shouldn't matter.

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

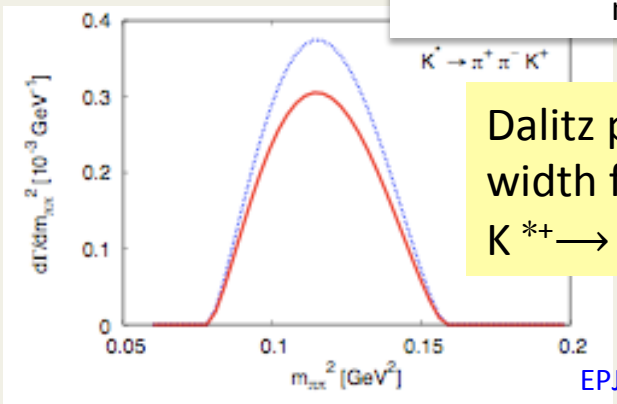
Classical dynamics(mechanics) *v << c(Ext>>ħ)* can be seen as an EFT because it does not consider the contribution of the terms that are related with *c(ħ)*.

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.

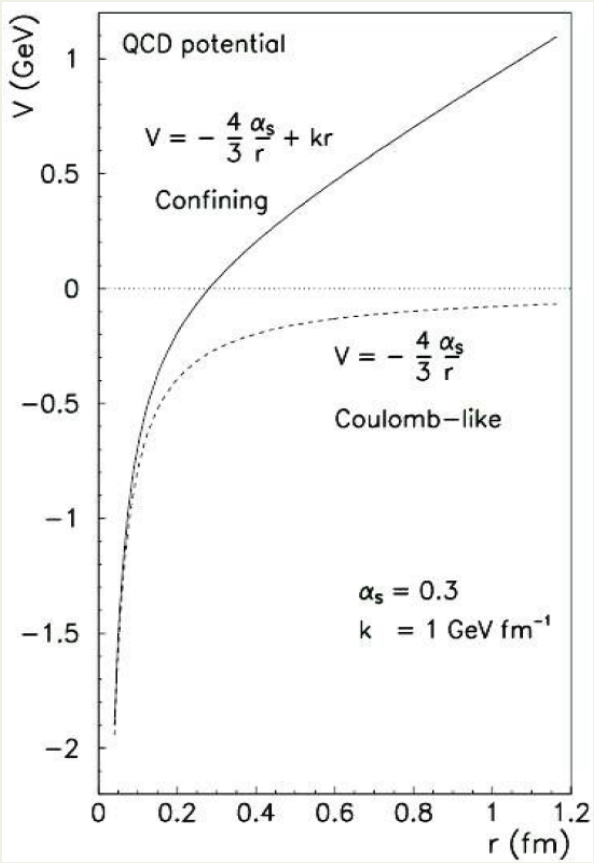



Dalitz plot and decay width for the channel $K^{*+} \longrightarrow \pi^+ K^0 \pi^0$

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

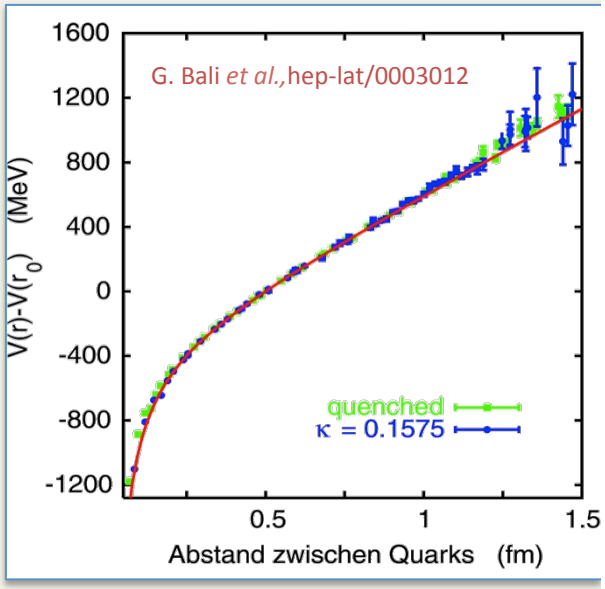
# Phenomenological quark-potential models

Quarkomium states may be described by potential models. Many specific quark models exist, but most contain a similar basic set of dynamical ingredients.




$$V(r) = \underbrace{\overbrace{\frac{4}{3}\frac{\alpha_S}{r}}^{V_v}}_{\text{Vector part}} + \underbrace{\overbrace{kr}^{V_s}}_{\text{Scalar part}} + \underbrace{V_{LS}}_{\text{Spin-Orbit}} + \underbrace{V_{SS}}_{\text{Spin-Spin}} + \underbrace{V_T}_{\text{Tensor Term}}$$

Potential of non-relativistic quarks has been recently obtained by lattice QCD giving more strength to the phenomenological models.



# The hadron 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.

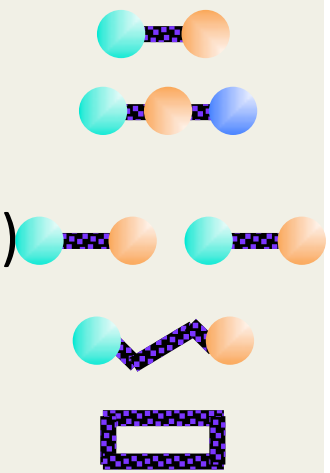
Mesons $q\bar{q}$

Baryons $qqq$

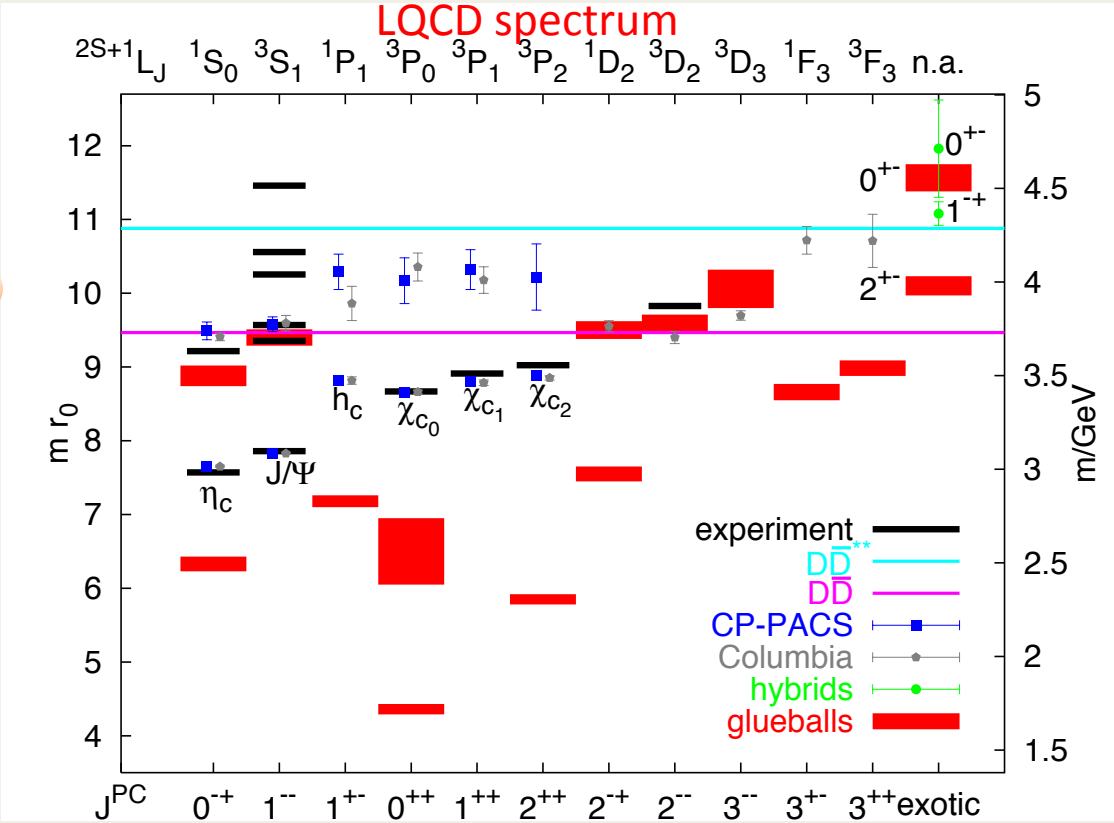
Multiquarks $(q\bar{q})(q\bar{q})$

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

Glueballs $gg$



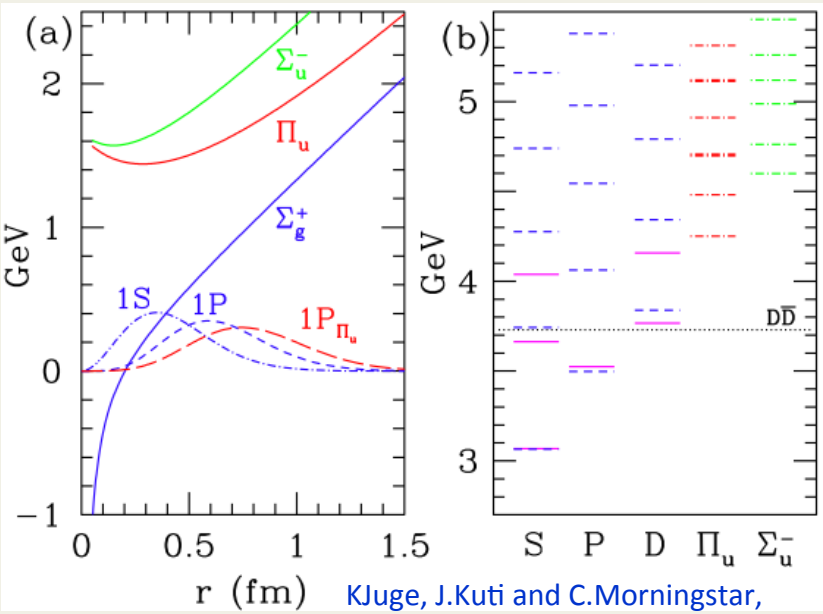
By the way experimentally $\frac{\sigma_{\pi p}}{\sigma_{pp}} \approx \frac{2}{3}$




*G. S. Bali, Int.J.Mod.Phys. A21 (2006) 5610-5617*

# 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.



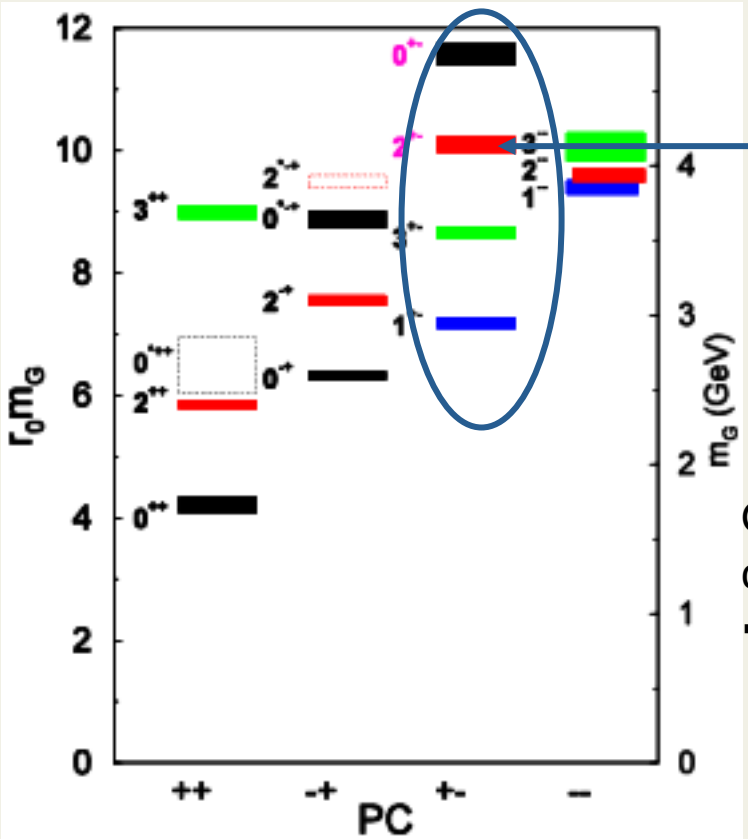

KJuge, J.Kuti and C.Morningstar, PRL 90, 161601 (2003)

| $q\bar{q}$ | 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

# Glueballs

LQCD makes rather accurate predictions for glueballs.
As for hybrids they can have exotic quantum numbers ➔oddballs




The lightest oddball, with $J^{PC}=2^{+-}$, is expected with a mass of 4.3 GeV/$c^2$.

Glueballs don't have to obey to the OZI rule➔they can decay in any channel.
➔ their width is completely unknown

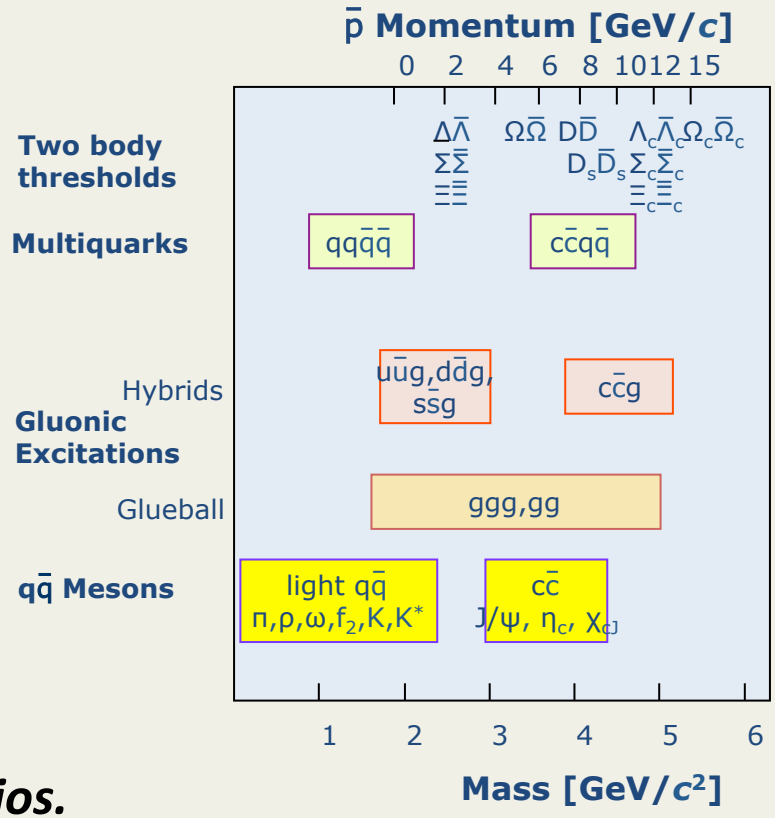
LQCD glueball spectrum
C.J.Monningstar and M.Peardon, Phys. Rev. D60, 034509 (1999))

# 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

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

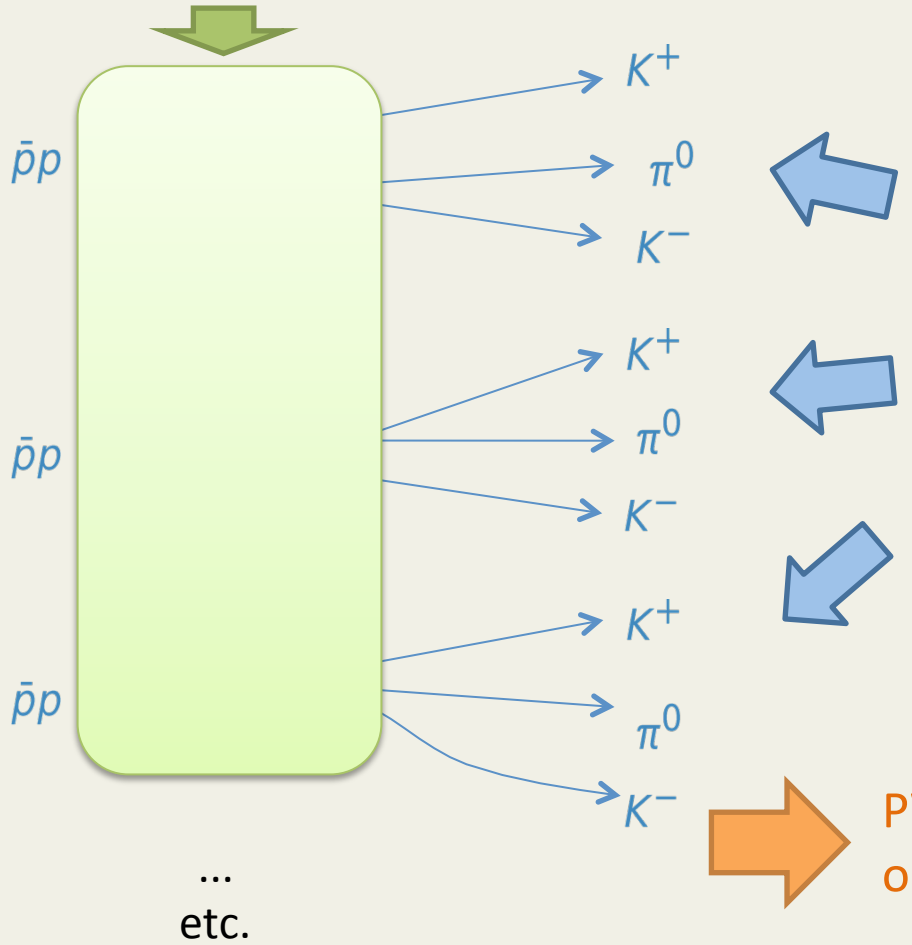
is an example of a Partial Wave Analysis.

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

# An example

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

What *really* happened...

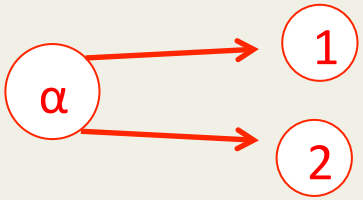



What you see is always the same ...

PWA = technique helps to find out what happens in between

# 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 $\lambda_2$ $\quad h \equiv \vec{S} \cdot \vec{p}/|\vec{p}|$

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

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 $e^+ e^-$ collider

# $\pi_1(1400)$ hybrid

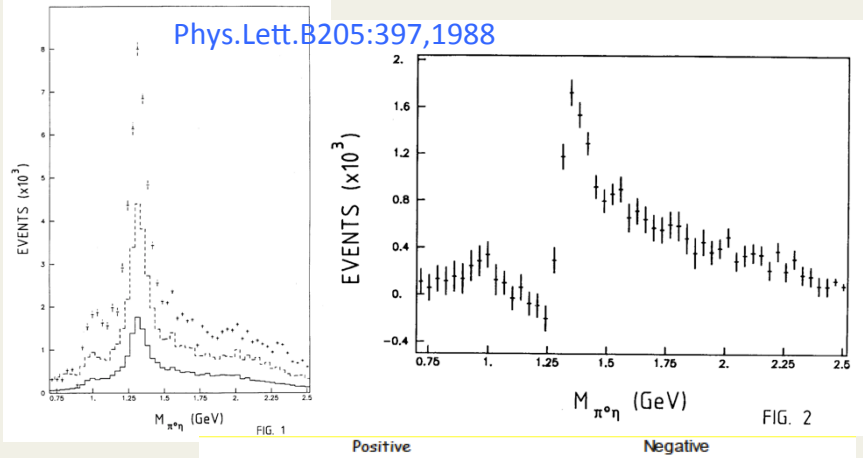
In 1988 GAMS saw a strong B/F asymmetry for the η produced in the reaction $\pi^- p \to \pi^0 \eta n$
In the mass region 1400 MeV/$c^2$ . This can only be determined by an odd wave with q.n. $1^{-+}$.

In 1991 a new more sophisticated PWA analysis gave ambiguous results.

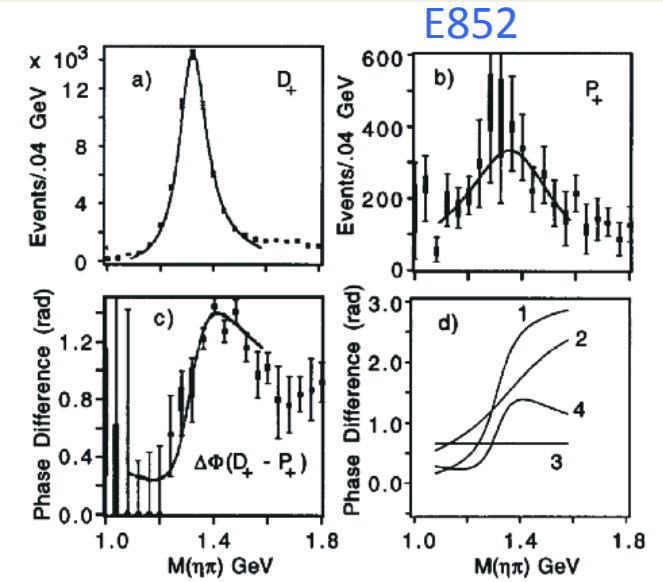
BNL E852 and Cristal Barrel @CERN experiments collected new data in different environments

$$\pi^- p \to \pi^0 \eta n ; \pi^- \eta p$$

Phys.Lett.B205:397,1988

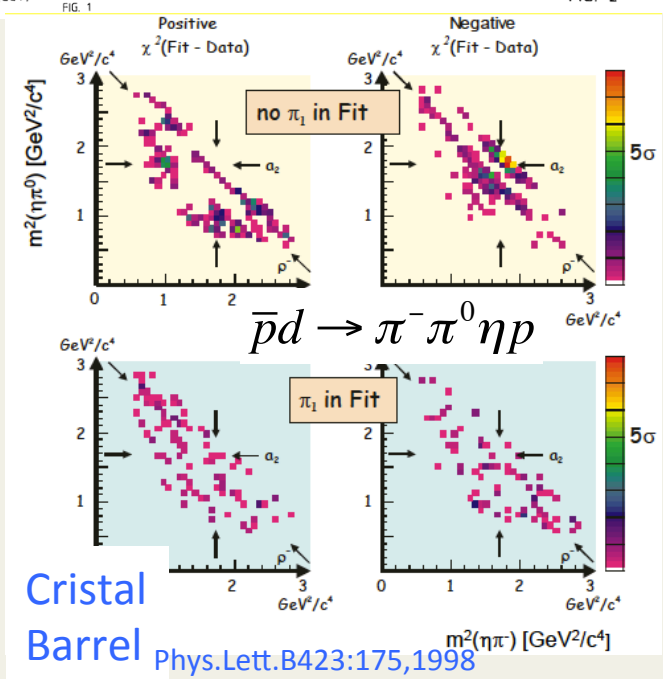



E852




phasemotion at $a_2$ tail visible

Phys.Lett.B657:27,2007




$$\bar{p}d \to \pi^- \pi^0 \eta p$$

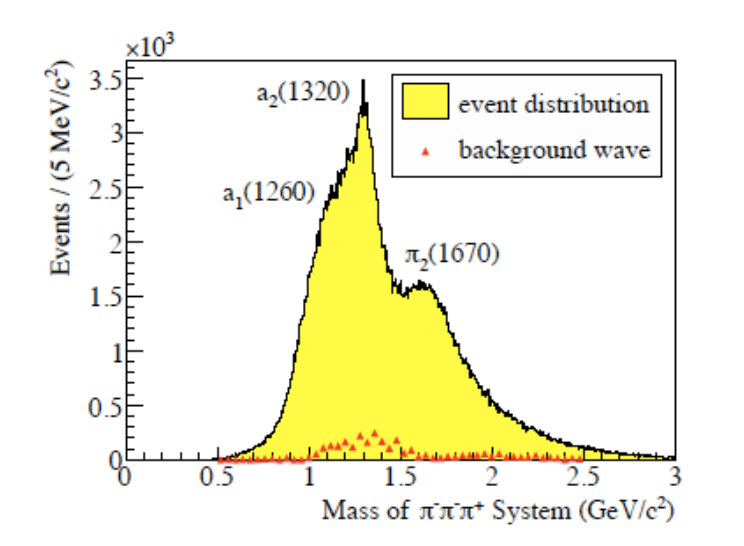
Cristal Barrel

Phys.Lett.B423:175,1998

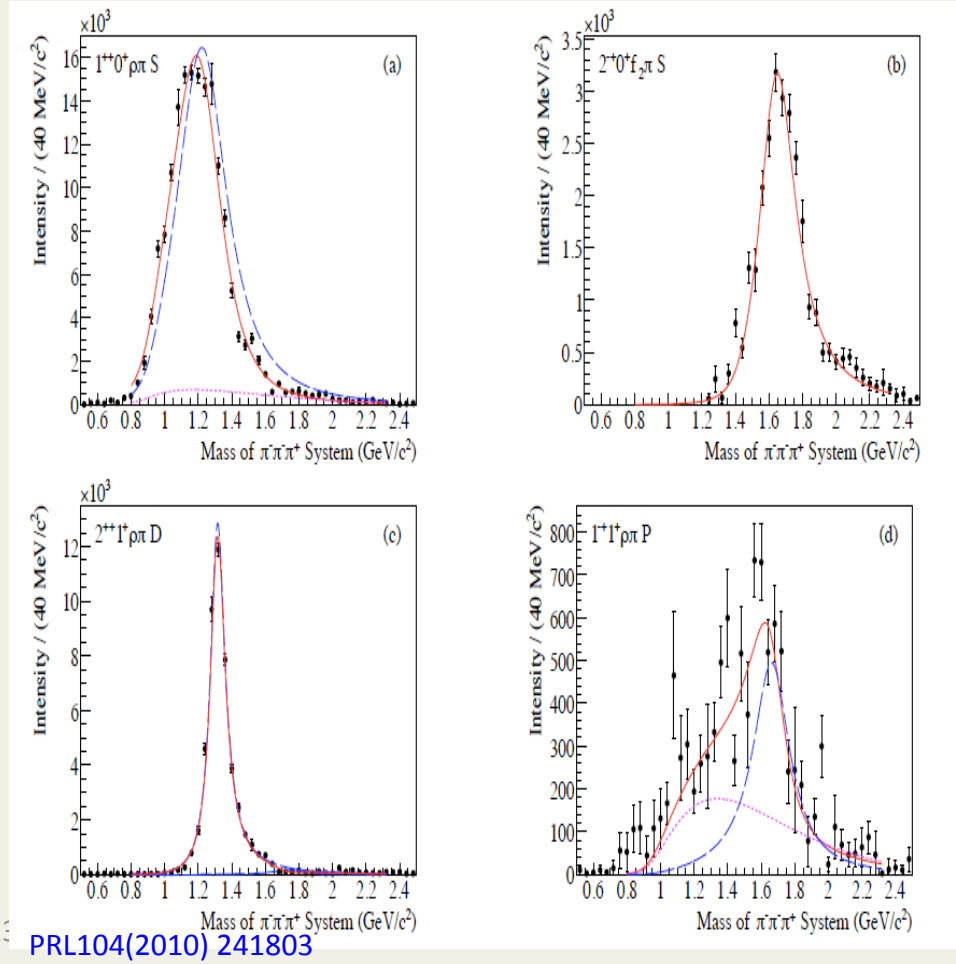
# $\pi_1(1600)$

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

↳ $\pi^-\pi^-\pi^+$




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




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

PRL104(2010) 241803

# $\pi_1(1600)$

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

# Exotic hadrons

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

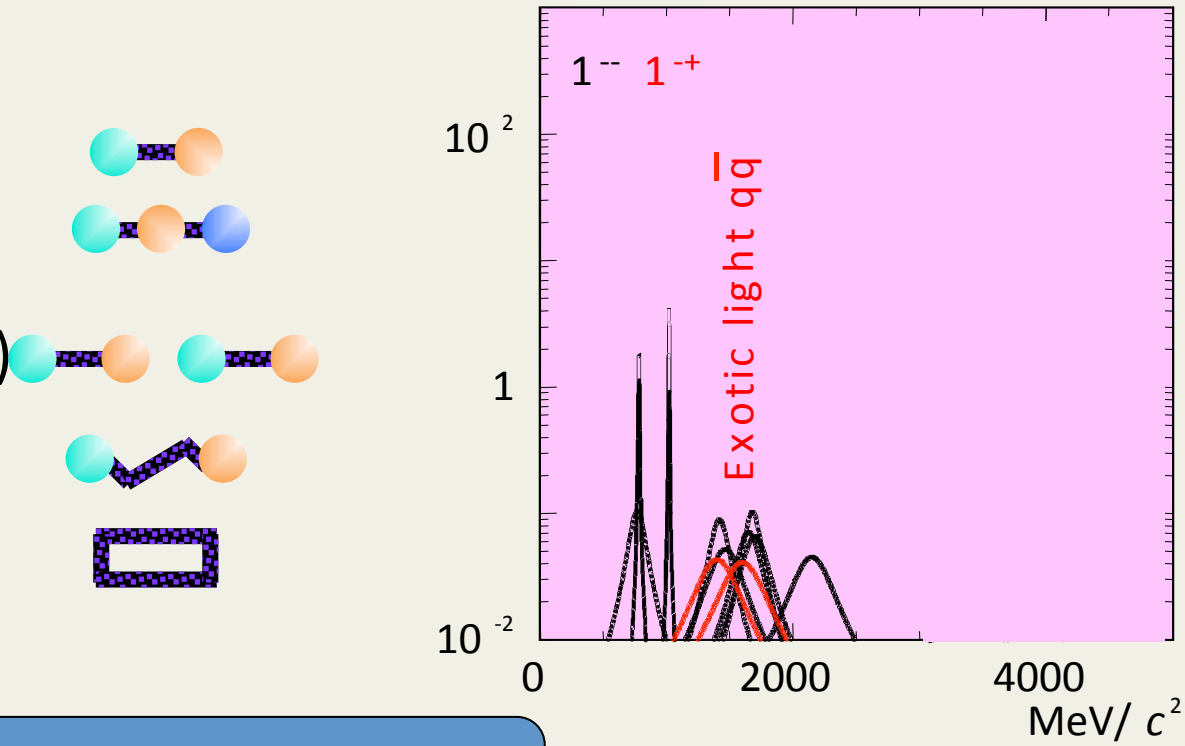
Mesons $q\bar{q}$

Baryons $qqq$

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

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

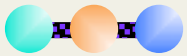
Glueballs $gg$

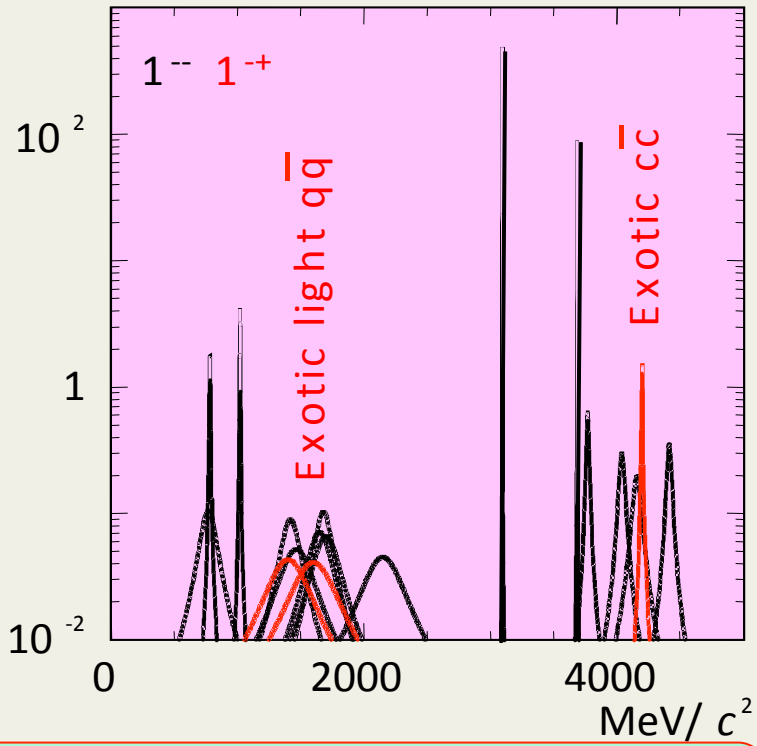



In the light meson energy range exotic states overlap with conventional states

# 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:

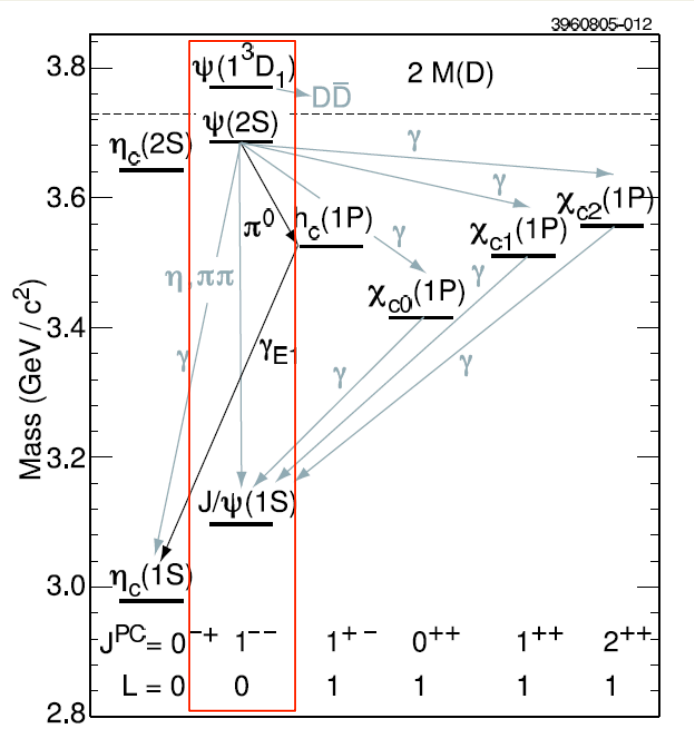
- $e^+e^-$ interactions at the Y(4S) energy:
  BaBar, BELLE, CLEO 2

- $e^+e^- \rightarrow$ charmonium energy:
  CLEO-c, BES-II, BES-III

- $\bar{p}p$ Tevatron collider:
  CDF, D0

# Charmonium states

Charmonium states are under study since many years since this is the energy range where potential models are tuned.
Data come mainly from $e^+e^-$ machines where $1^{--}$ states can be directly formed.




Hyperfine splitting of charmonium states give access to $V_{SS}$ component of quark potential model

The only measured hyperfine splitting was

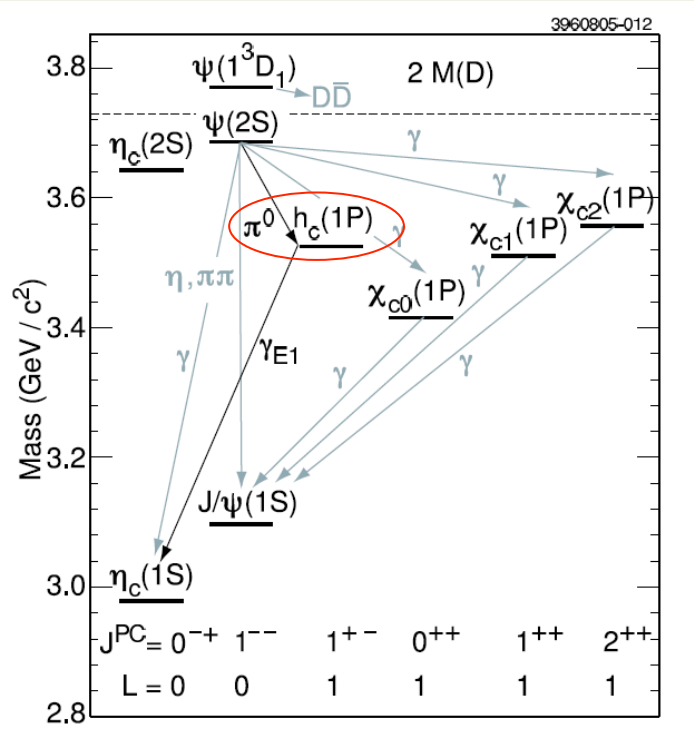
$$\Delta M_{hf}(1S)_{c\bar{c}} \equiv M(J/\psi) - M(\eta_c) = 116.6 \pm 1.0 \text{ MeV}$$

Recently $\eta'_c(2^1S_0)$ has been identified by Belle [PRL89 (2002)102001] and the mass measured also by CLEO and BaBar in two photon fusion.

$$\Delta M_{hf}(2S)_{c\bar{c}} \equiv M(\psi'(2^3S_1)) - M(\eta'_c(2^1S_0)) = 49 \pm 4 \text{ MeV}$$

# $h_c(^1P_1)$ charmonium state

The process $\psi' \to \pi^0 h_c$ is the only way to produce $h_c$ from $\psi'$ decay ➔ Limited phase space




From the assumption of a small $V_{SS}$ interaction it was expected

$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = 0$$

**Theoretical predictions of branching ratios:**

$B(\psi(2S) \to \pi^0 h_c) = (0.4\text{-}1.3) \times 10^{-3}$

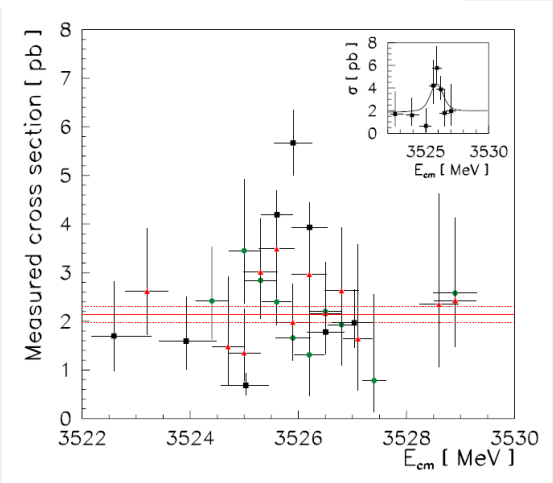
$B(h_c \to \gamma\eta_c) = 41\%$ (NRQCD)

$B(h_c \to \gamma\eta_c) = 88\%$ (PQCD)

(Y.P.Kuang, PRD65,094024 (2002))

$B(h_c \to \gamma\eta_c) = 38\%$

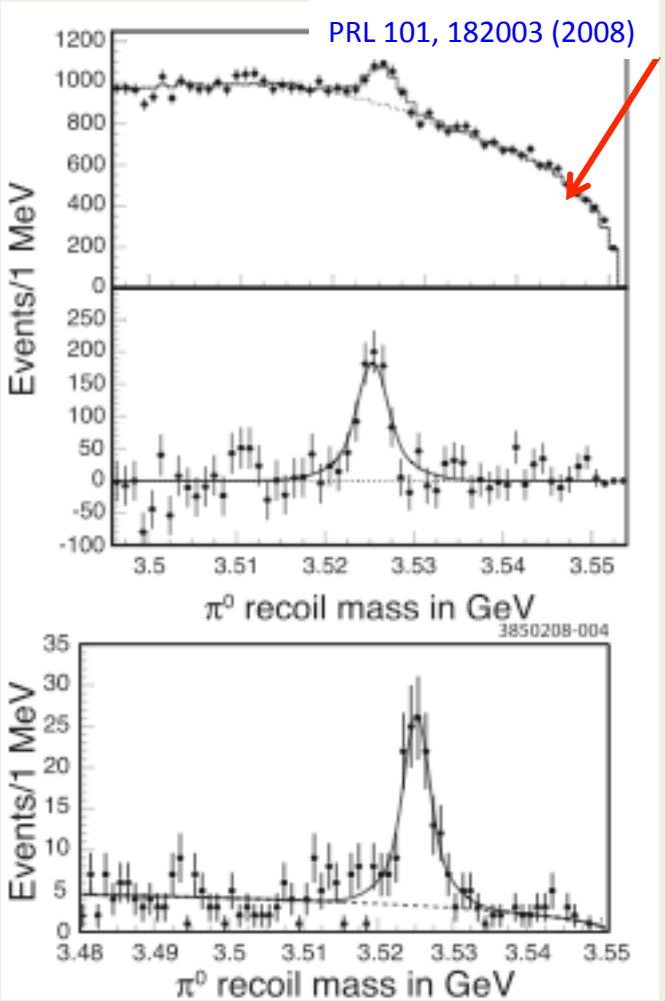
(S. Godfrey and J.Rosner,PRD66,014012(2002))




There were attempt to produce $h_c$ in $p\bar{p}$ annhilitation at Fermilab (E760,E835) but the statistic was very poor.

# $h_c(^1P_1)$ charmonium state

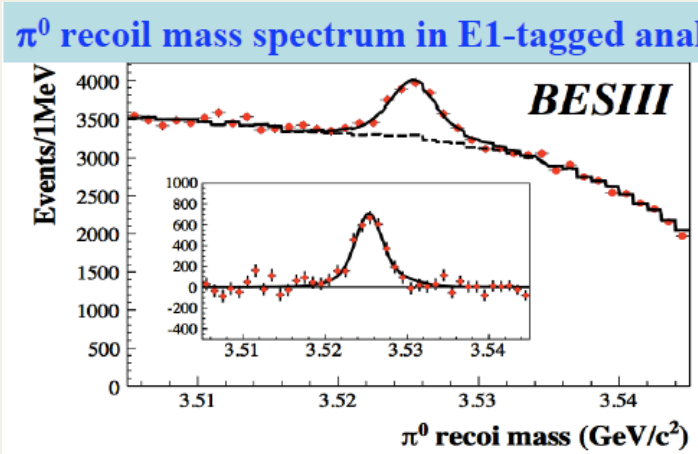
$$e^+e^- \to \psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$$ The ψ' decay mode is isospin violating




The CLEO experiment was able to find it with a significance of 13 σ in $\psi'$ decay by means of an exclusive analysis.

The width and the BF $\psi' \to \pi^0 h_c$ were not measured.

A similar analysis, with higher statistic, was also done by BES




$M(h_c) = 3525.40 \pm 0.13$ MeV/$c^2$
$\Gamma(h_c) = 0.73 \pm 0.45$ MeV/$c^2$

| | |
|---|---|
| $Br(\psi' \to \pi^0 h_c)$ | $(8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$ |
| $Br(h_c \to \gamma\eta_c)$ | $(54.3 \pm 6.7 \pm 5.2)\%$ |

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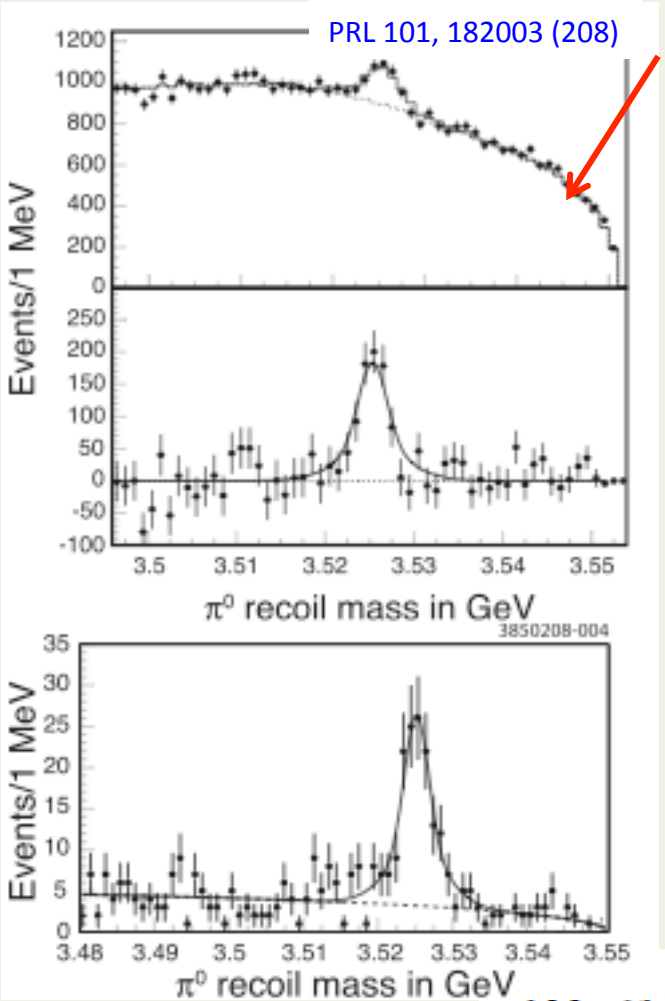


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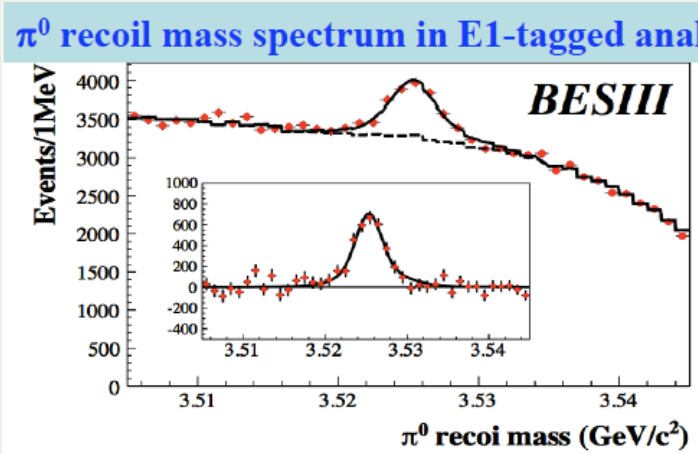


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|---|---|
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| [illegible] | [illegible]2)% |

$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = -0.10 \pm 0.13 \pm 0.18 \text{MeV}/c^2$$

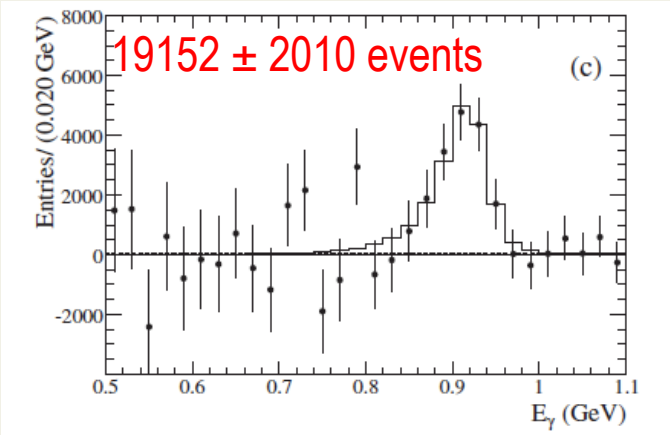
Center of gravity of P-states

# Bottomonium

The $\Upsilon(1^3S_1)$ state of bottomonium was discovered in 1977.
The ground state spin-singlet partner, $\eta_b(1^1S_0)$, has been found only recently by the BaBar Collaboration by studing $\Upsilon(3S) \to \gamma\, \eta_b(1S)$ [PRL101,071801,2008]
Then confirmed in $\Upsilon(2S) \to \gamma\, \eta_b(1S)$ [PRL103, 161801,2009]

The observation of the $\eta_b$ is an important validation of Lattice QCD predictions

➔ BF $(\Upsilon(3S) \to \gamma\, \eta_b) = (4.5 \pm 0.5\,[\text{stat.}] \pm 1.2\,[\text{syst.}]) \times 10^{-4}$



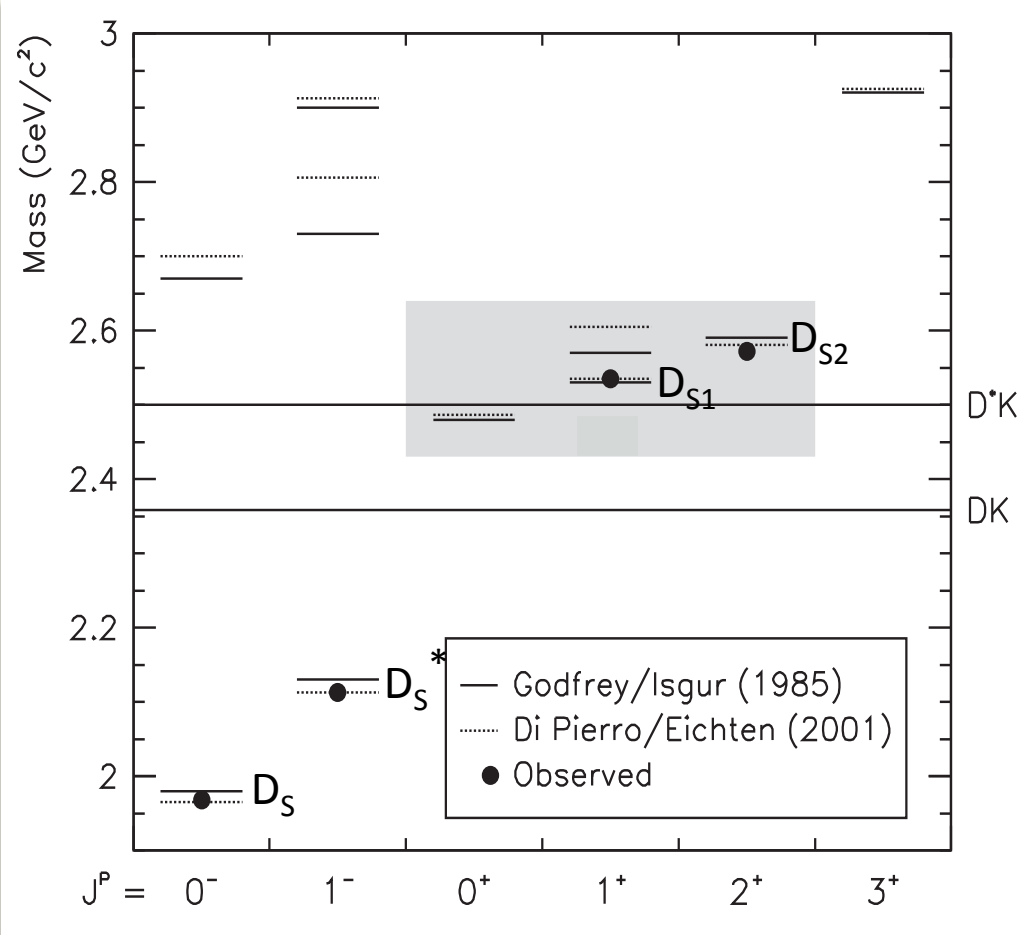

Mass of the $\eta_b(1S)$:

- Peak in $\gamma$ energy spectrum at $E_\gamma = 921.2^{+2.1}_{-2.8}(\text{stat})\,\text{MeV}$
- Corresponds to $\eta_b$ mass 9391.1±3.1 MeV/$c^2$
- The hyperfine $(\Upsilon(1S)\text{-}\eta_b(1S))$ mass splitting is 69.9 ± 3.1 MeV/$C^2$

# OpenCharm states

For the states $c(\bar{u}/\bar{d})$ theory and experiment were in agreement.

The quark model describes the spectrum of heavy-light systems and it was expected to be able to predict unobserved excited $D_s(c\bar{s})$ mesons with good accuracy

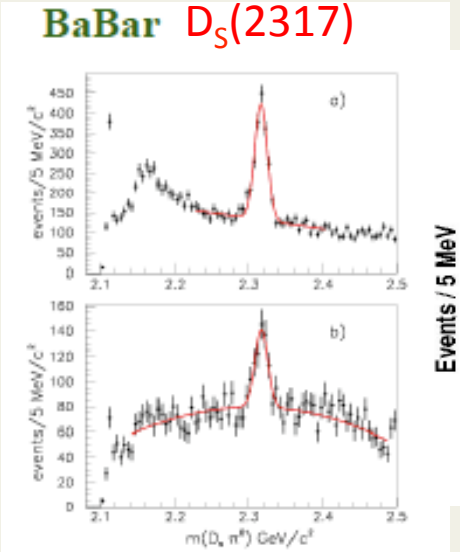



B. Aubert et al., PRD74, 032007 (2006).

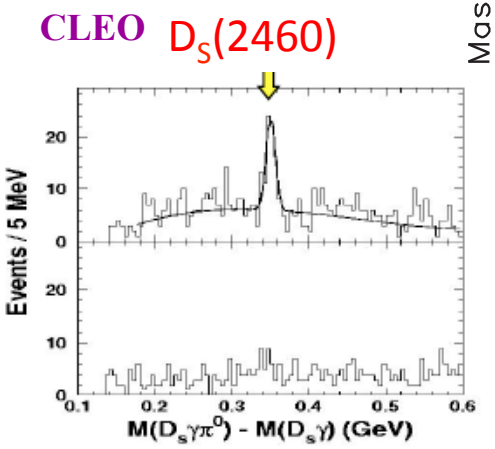
# OpenCharm states

The discovery of the new $D_{SJ}$ states has brought into question potential models

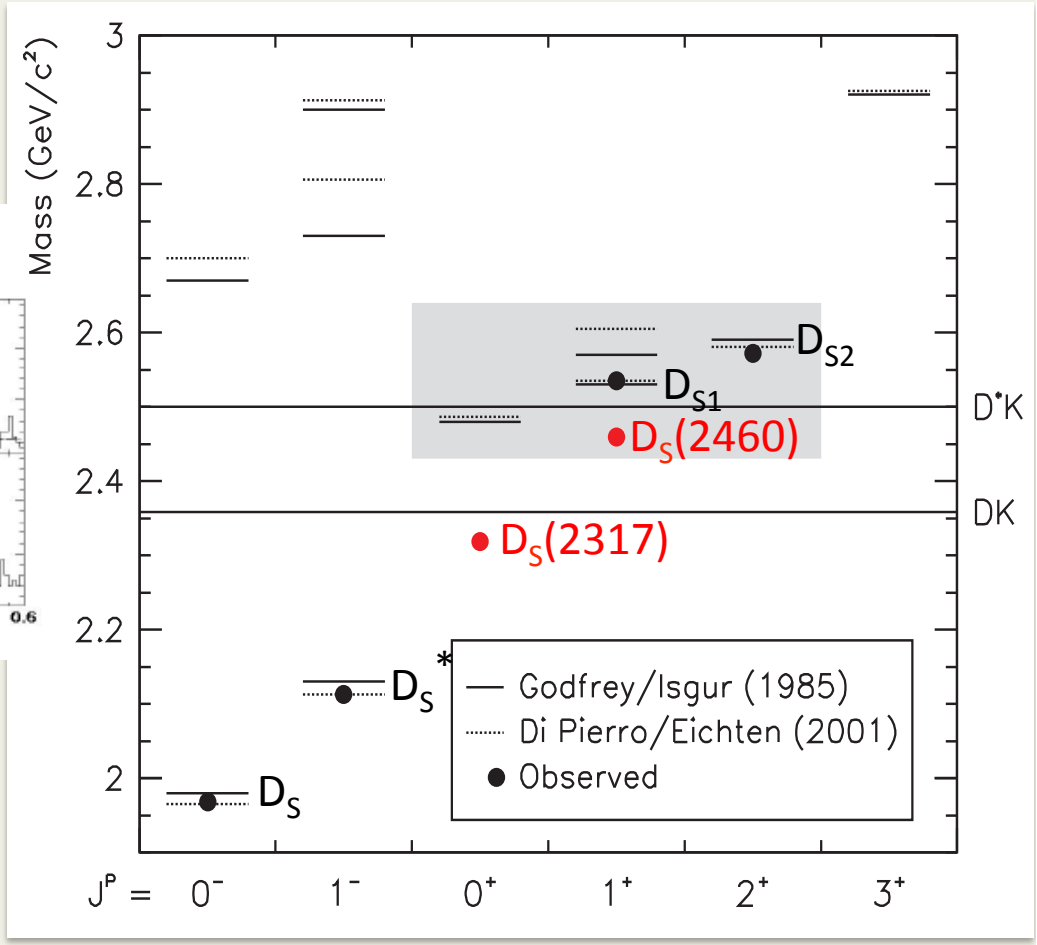
Two new states $D_S(2317)$ and $D_S(2460)$ were discovered in $e^+e^- \to \bar{c}c$ events, then observed in B decays by Babar, Belle and CLEO




PR D74 032007



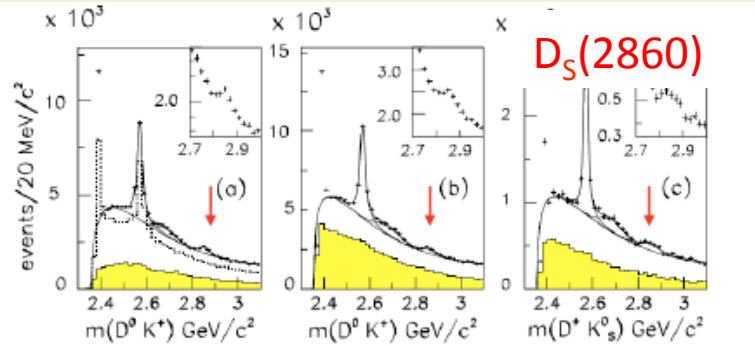

PR D68 03200



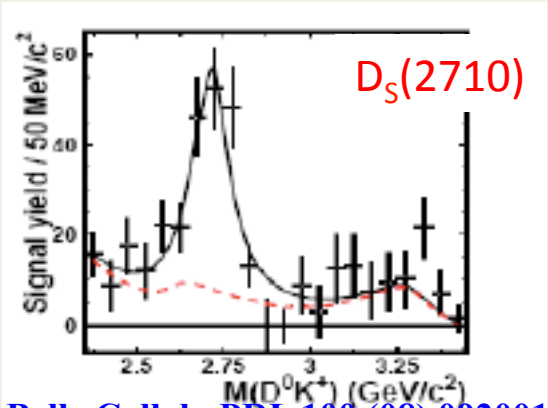

The identification of these states as the $0^+$ and $1^+$ $\bar{c}s$ states is difficult within the potential model

# OpenCharm states

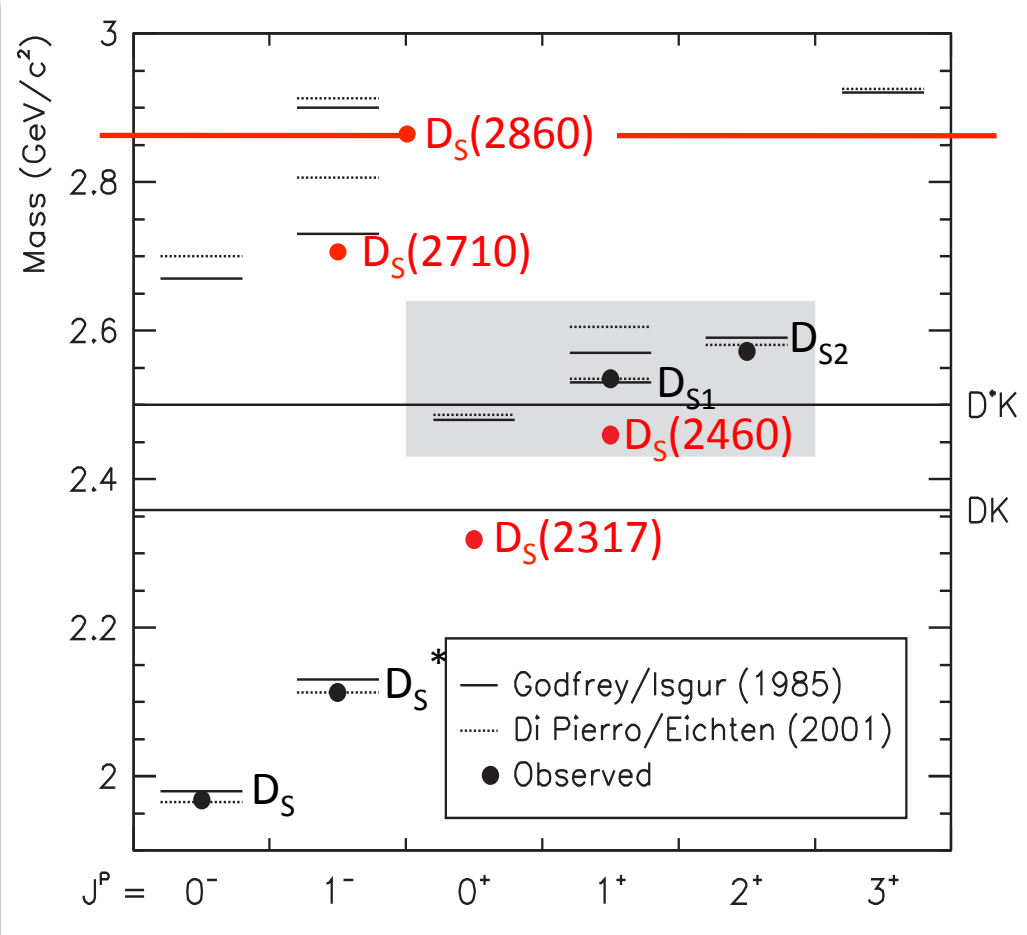
The discovery of the new $D_{SJ}$ states continued …




BaBar Collab., PRL 97 (06) 222001




Belle Collab, PRL 100 (08) 092001



# OpenCharm states

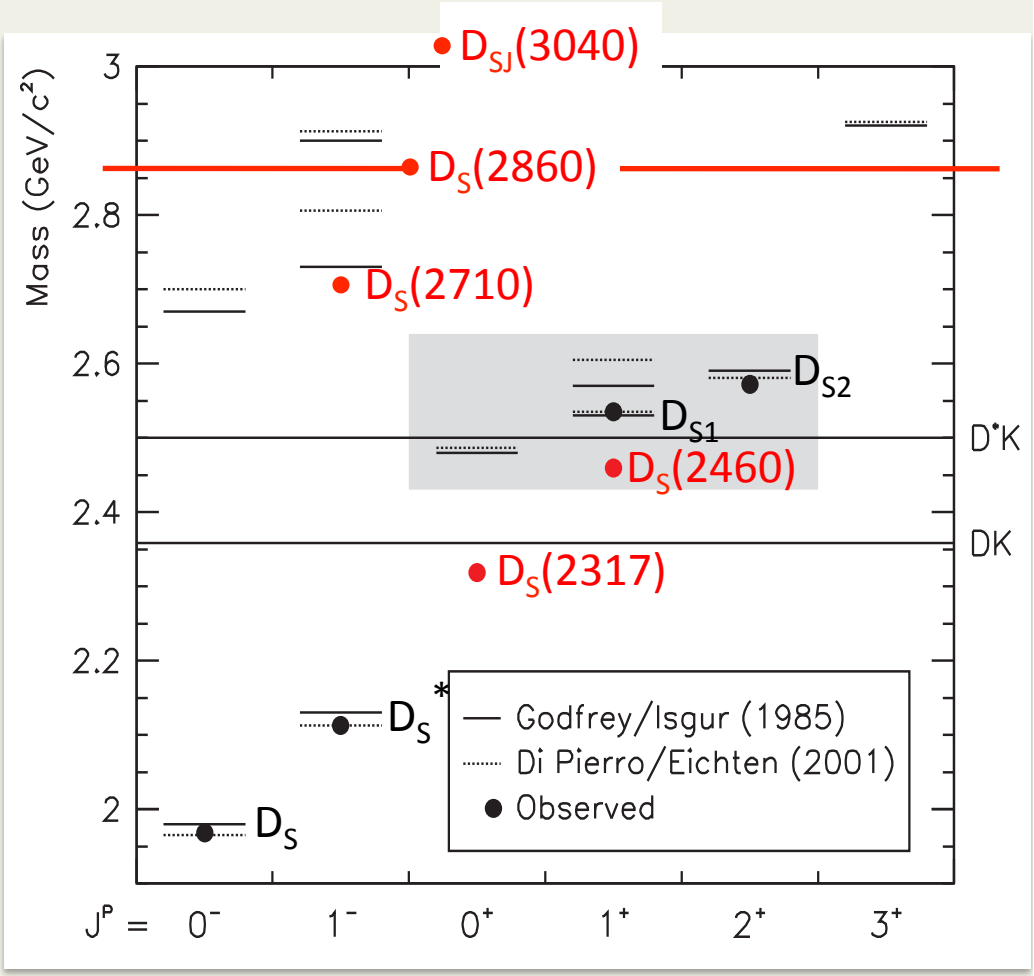
The assignment of the q.n. to the $D_S(2710)$ was possible thanks to an analysis performed by BaBar studing *DK*, *D*K* final states.

In the same analysis an other broad structure in the *D*K* distribution $D_{SJ}(3040)$

$$m(D_{s1}^*(2710)^+) = 2710 \pm 2_{\text{stat}}(^{+12}_{-7})_{\text{syst}}\ \text{MeV}/c^2,$$
$$\Gamma = 149 \pm 7_{\text{stat}}(^{+39}_{-52})_{\text{syst}}\ \text{MeV},$$

$$m(D_{sJ}^*(2860)^+) = 2862 \pm 2_{\text{stat}}(^{+5}_{-2})_{\text{syst}}\ \text{MeV}/c^2,$$
$$\Gamma = 48 \pm 3_{\text{stat}} \pm 6_{\text{syst}}\ \text{MeV},$$

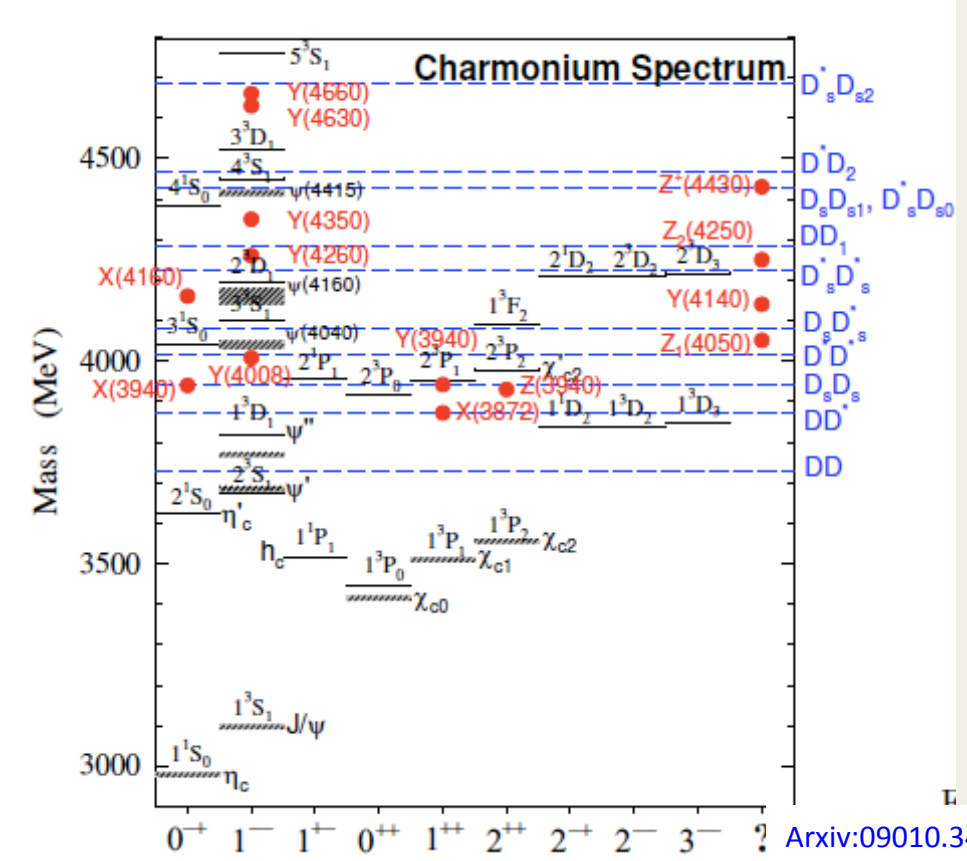
$$m(D_{sJ}(3040)) = 3044 \pm 8_{\text{stat}}(^{+30}_{-5})_{\text{syst}}\ \text{MeV}/c^2,$$
$$\Gamma = 239 \pm 35_{\text{stat}}(^{+46}_{-42})_{\text{syst}}\ \text{MeV}.$$




There is a problem for the potential models in describing excited states

# Mesons

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



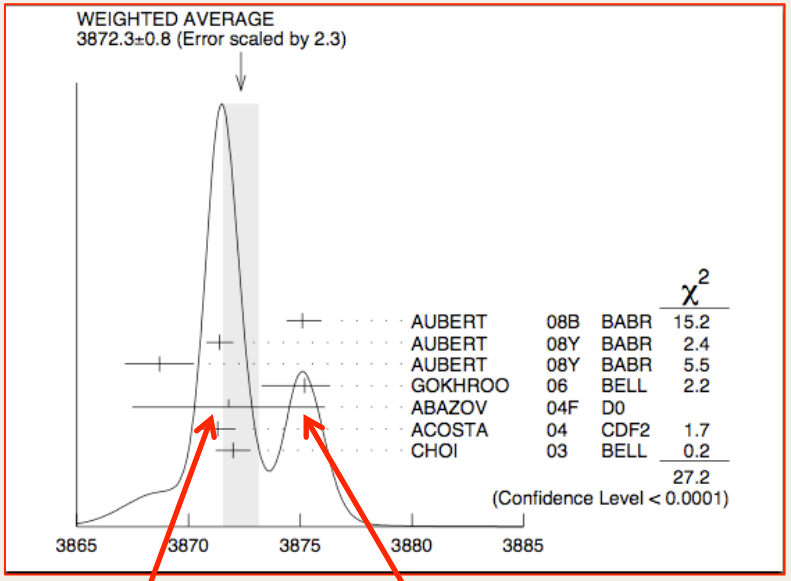

- masses are barely known;
- often widths are just upper limits;
- few final states have been studied;
- statistics are poor;
- quantum number assignment is possible for few states;
- some resonances need confirmation…

There are problems of compatibility Theory - Experiment

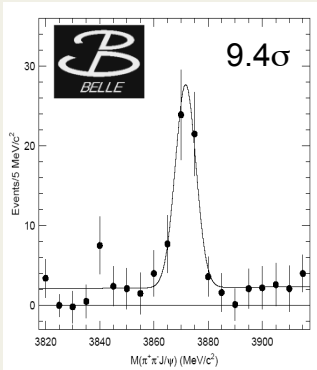
Arxiv:09010.3409v2 [hep-th]

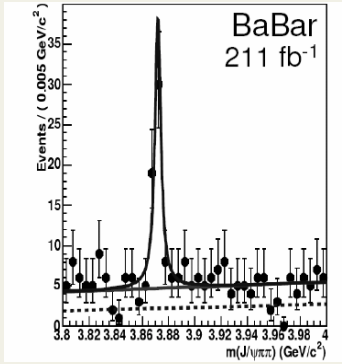
# X(3872)

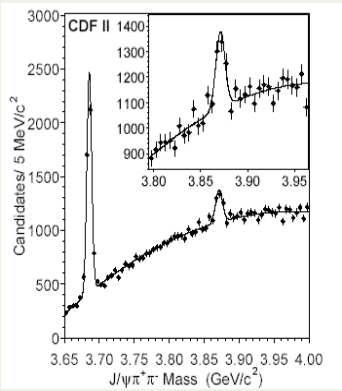
Discovered at Belle (+ CDF, D0, BaBar, …) in $B^+ \to X K^+$
$X \to J/\psi \pi^+\pi^-$ is the best known but the more obscure.

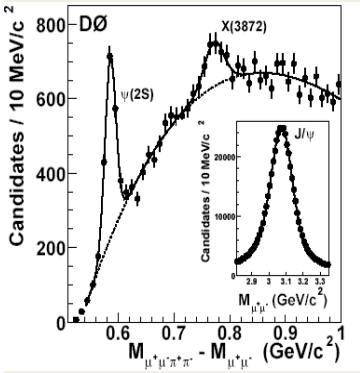



$X \to J/\psi \pi^+\pi^-$ $\quad$ $X \to D^0\bar{D}^0,\ D^0\bar{D}^0\pi^0$




Mass measurements, in different final states, seam different. X(3872) lays 0.42 MeV below $D^{*0}\bar{D}^0$ . Width is narrow < 2.3 MeV/$c^2$ @ 90% C.L.. C parity +

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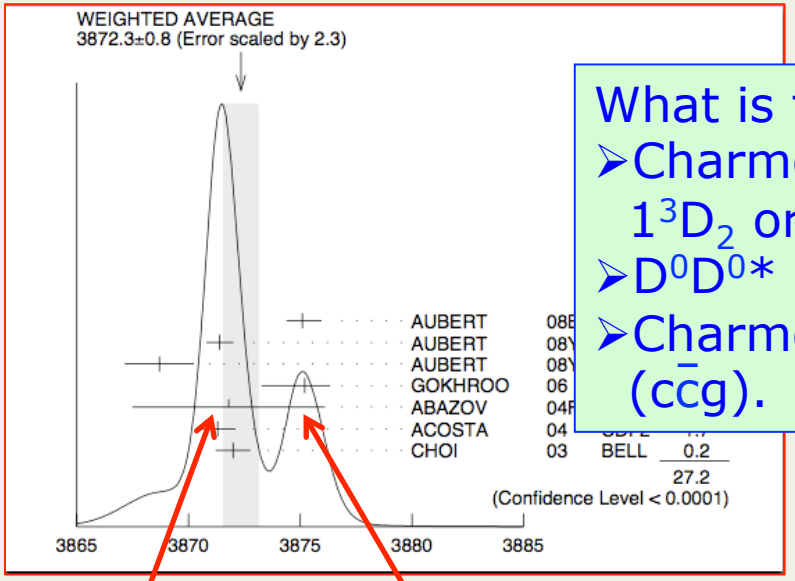
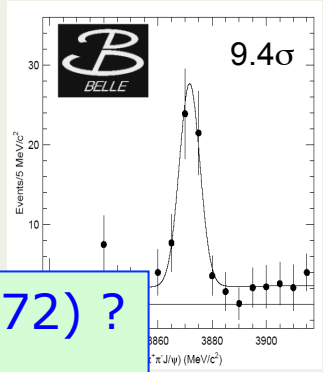
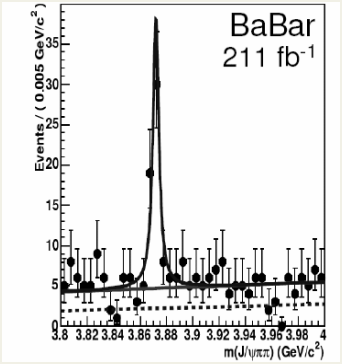
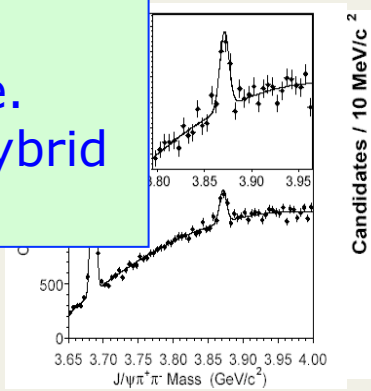
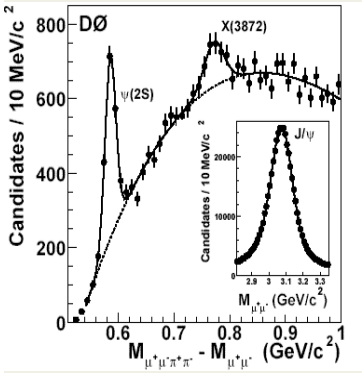



What is the X(3872) ?
- Charmonium $1^3D_2$ or $1^3D_3$.
- $D^0D^{0*}$ molecule.
- Charmonium hybrid ($c\bar{c}g$).



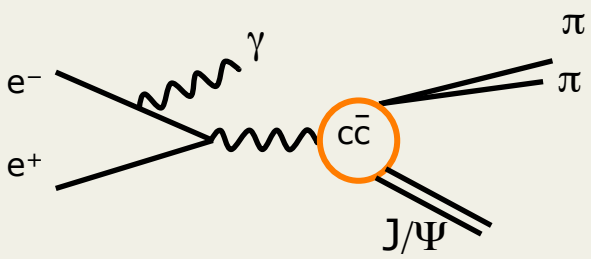

$X \to J/\psi \pi^+\pi^-$ $\quad$ $X \to D^0\bar{D}^0$, $D^0\bar{D}^0\pi^0$

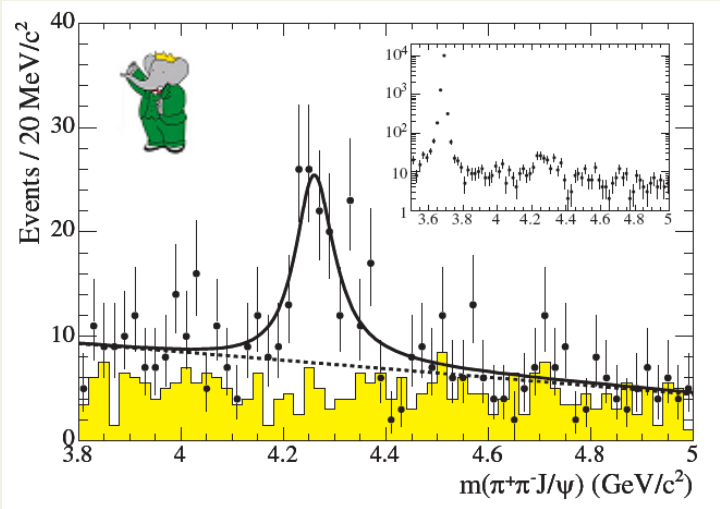
Mass measurements, in different final states, seam different. X(3872) lays 0.42 MeV below $D^{*0}\bar{D}^0$ . Width is narrow < 2.3 MeV/$c^2$ @ 90% C.L.. C parity +

# Y(4260)

It is the first of the "Y" states. It has been discovered by BaBar with the technique of initial state radiation in one year of data taking.

PRL95, 142001 (2005)



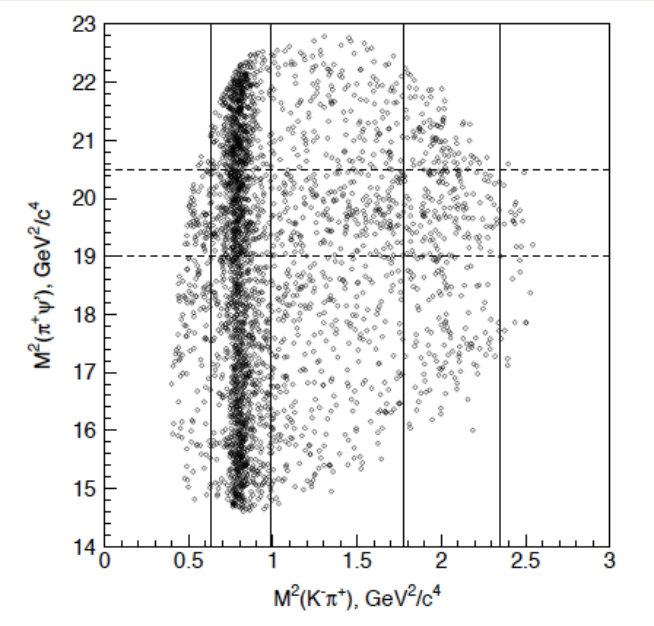

Today there are six Y states. Q.N. are $1^{--}$

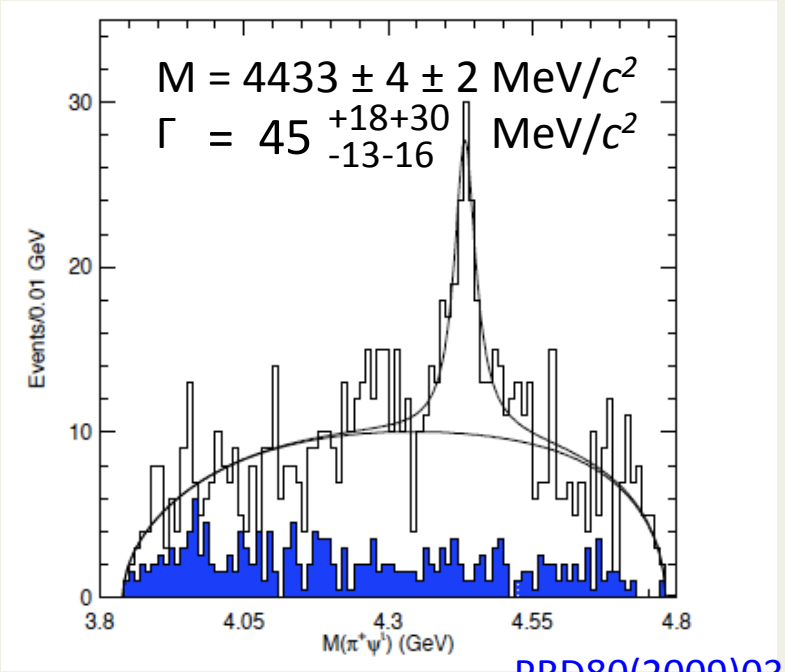
The Y(4260) appears to represent an overpopulation of the expected $1^{--}$ states. The absence of open charm production speaks against it being a conventional $c\bar{c}$ state

The flux tube model and LQCD predict the lowest $c\bar{c}g$ hybrid at ~ 4200 MeV/$c^2$.

# Z(4430)

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



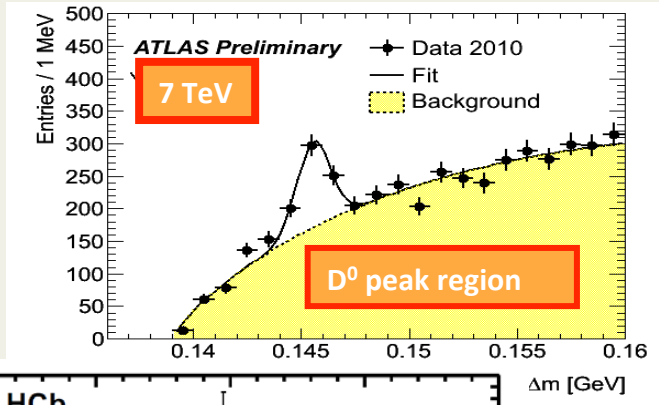

PRD80(2009)031104

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

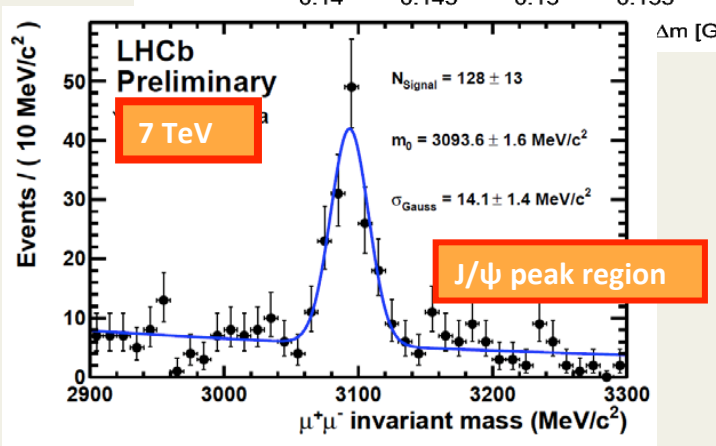
If this peak has to be interpreted as a meson state, it must have an exotic structure: its minimal quark content should be $|c\bar{c}u\bar{d}\rangle$.

# The future

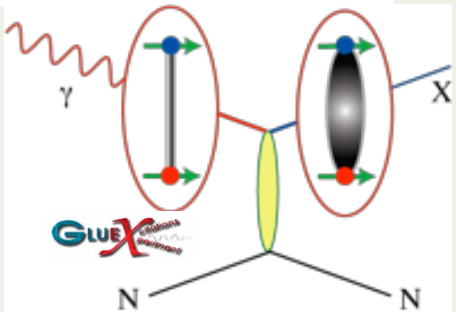
We can expect in the future further results from $e^+e^-$ machines Belle, SuperBelle, BES…
but without big surprises




LHC experiments (mainly LHCb) will provide some results….
but they are not tailored for this physics



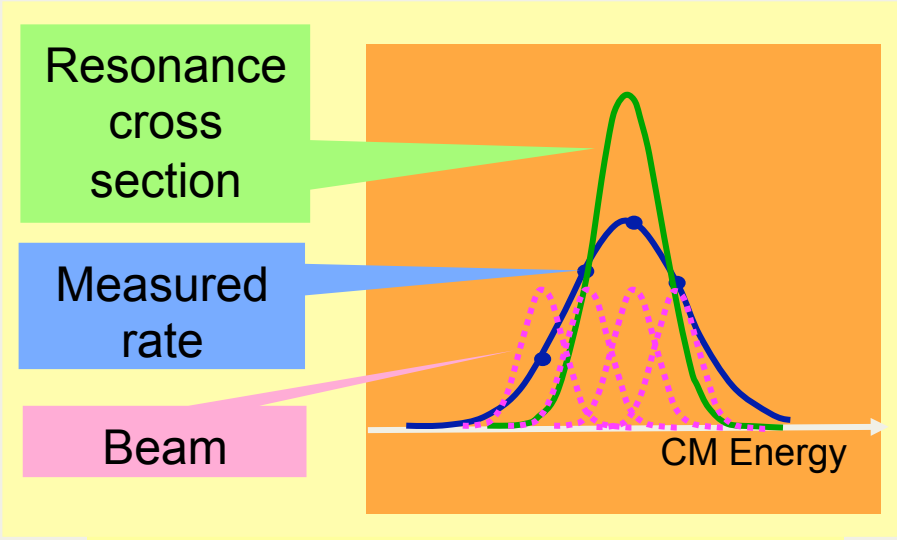

The Jlab 12 GeV upgrade foresees a program of spectroscopy …
in the energy range were broad overlapping states lay




We have the renascence of antiproton facility with FAIR at Darmstadt…
here the antiproton storage ring has been designed primarily for hadron spectroscopy

# Antiproton power

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




- $e^+e^-$: typical mass res. ~ 10 MeV
- Fermilab: 240 keV
- HESR: ~30 keV

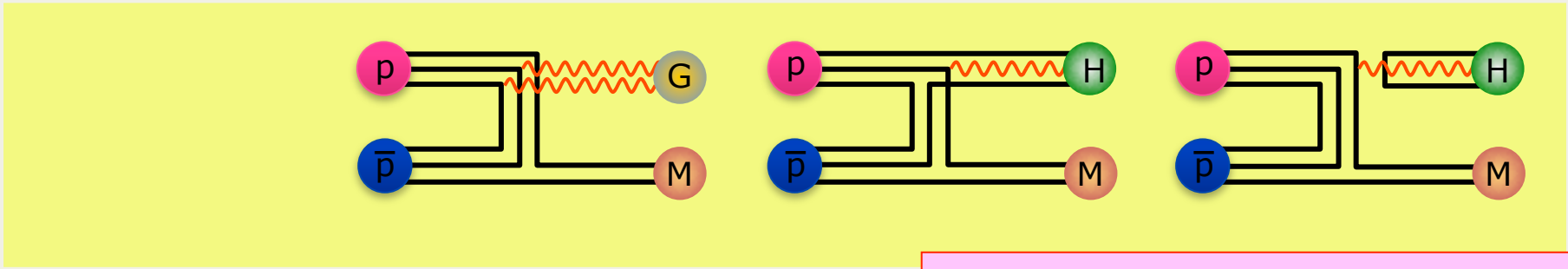
The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

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

The resonance mass $M_R$, total width $\Gamma_R$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy $E$ using a maximum likelihood fit.

# Spectroscopy with antiprotons

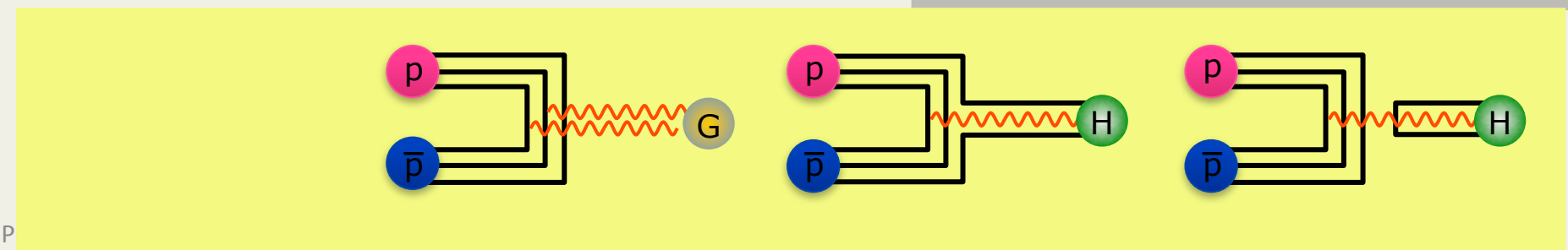
Two are the mechanisms to access particular final states:




Even exotic quantum numbers can be reached σ ~100 pb

Exotic states are produced with rates similar to $q\bar{q}$ conventional systems

All ordinary quantum numbers can be reached σ ~1 μb



# Antiproton power

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

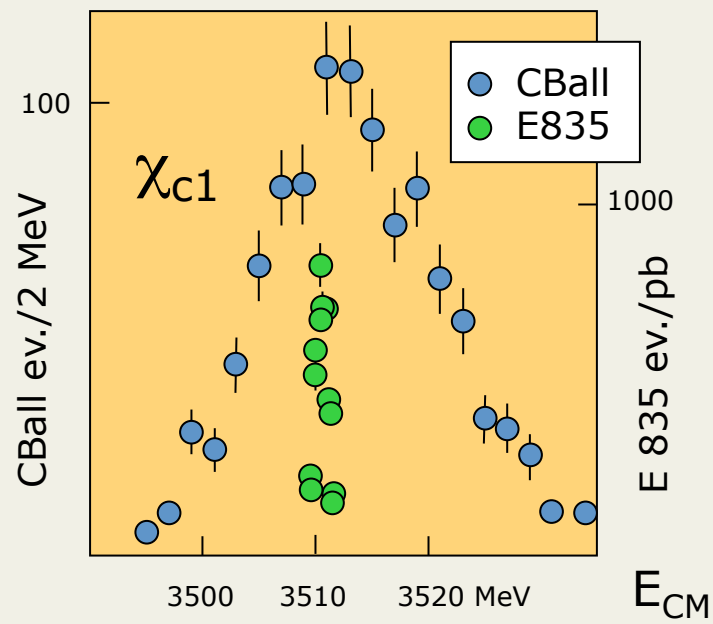
$\bar{p}\, p \to \chi_{1,2} \to \gamma J/\psi \to \gamma e^+e^-$

- $e^+e^-$ interactions:

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

- $p\bar{p}$ reactions:

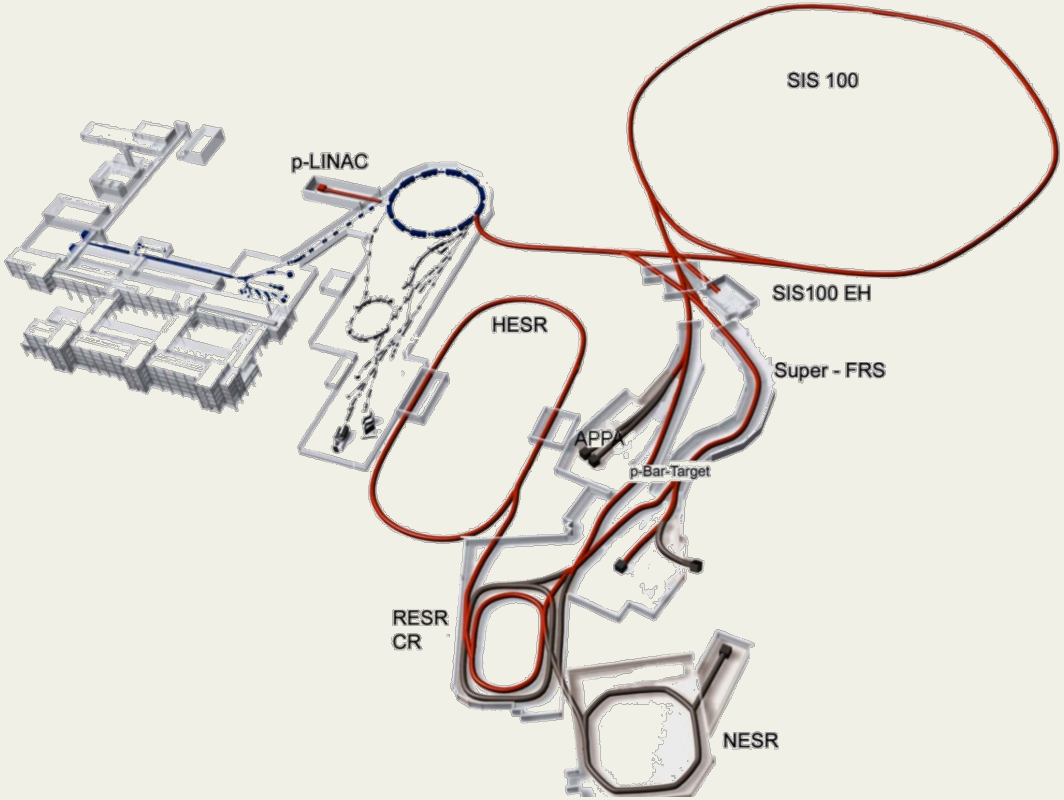
  - Most states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled $\Delta p/p \sim 10^{-4}$)




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

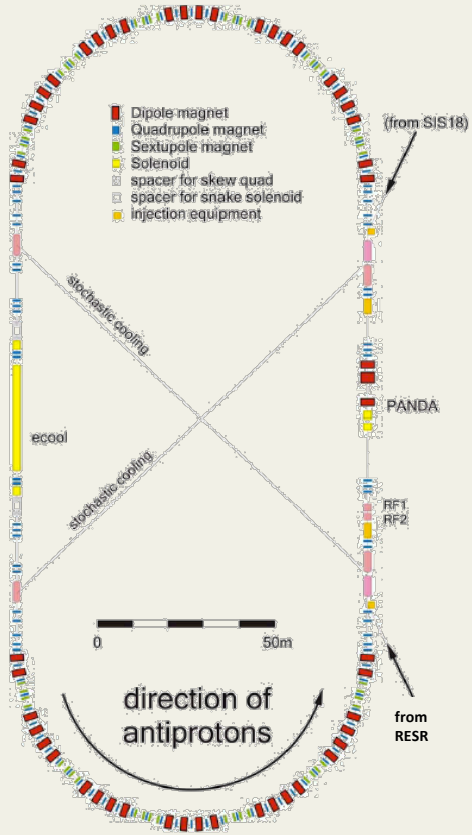
$Br(e^+e^- \to \psi') \cdot Br(\psi' \to \gamma\eta_c) = 2.5\ 10^{-5}$

# Facility for Antiproton and Ion Research




**Antiproton production**

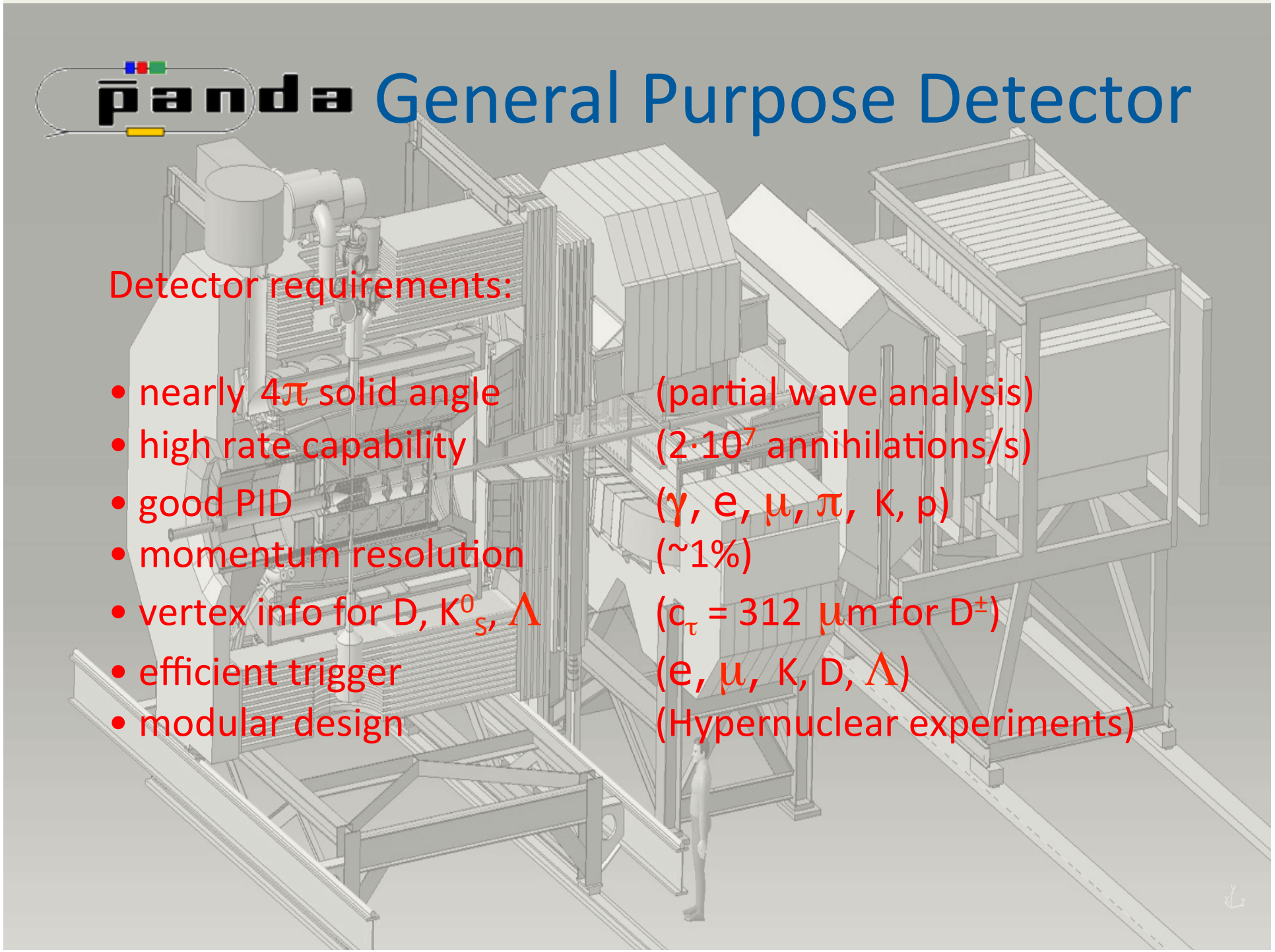
- Proton Linac 50 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on target
- Collect in CR, cool in RESR




**HESR:** Storage ring for $\bar{p}$

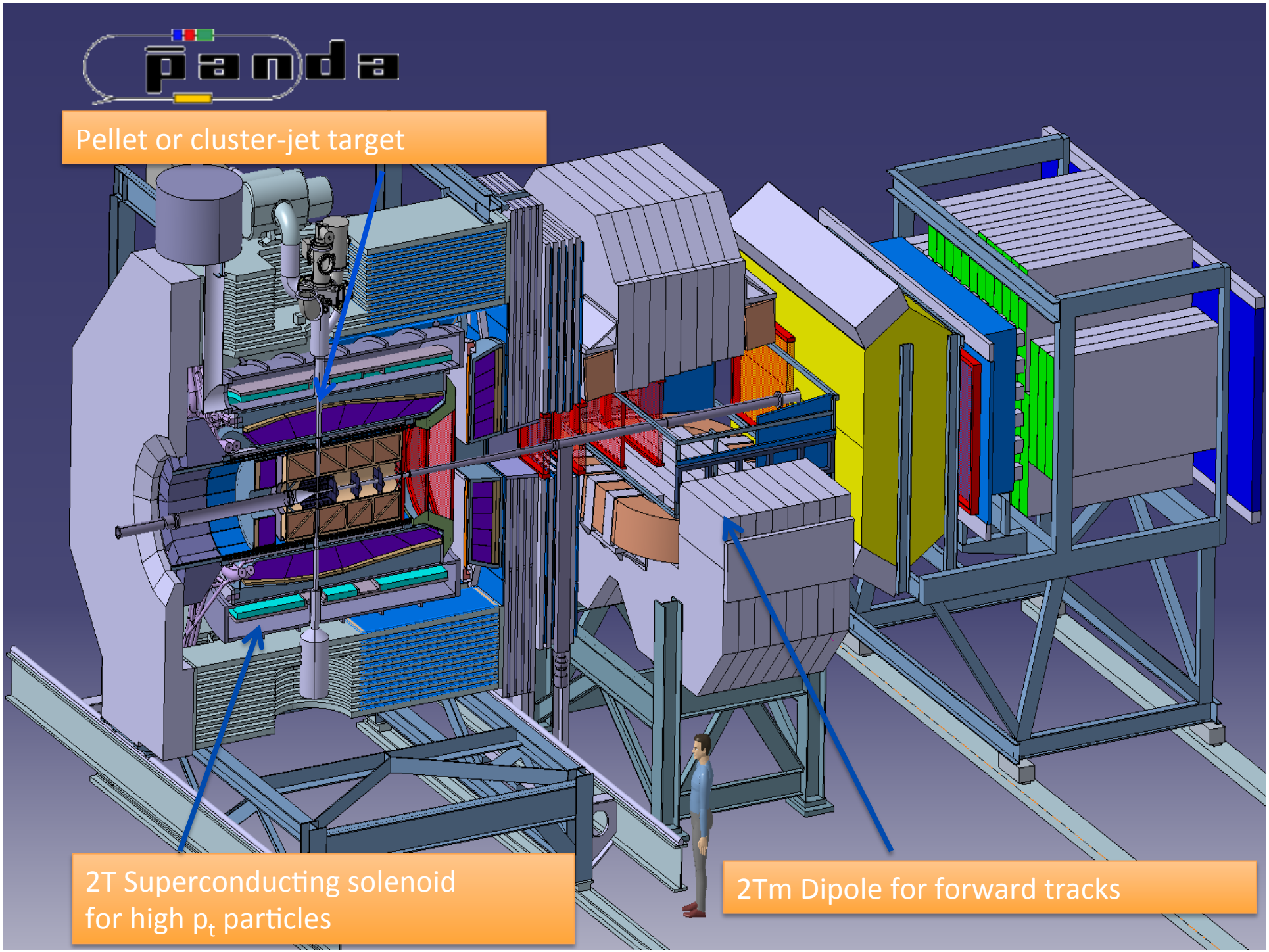
- Injection of $\bar{p}$ at 3.7 GeV/*c*
- Slow synchrotron (1.5-15 GeV/*c*)
- Luminosity up to L~ $2\times10^{32}$ $cm^{-2}s^{-1}$
- Beam cooling (stochastic & electron)

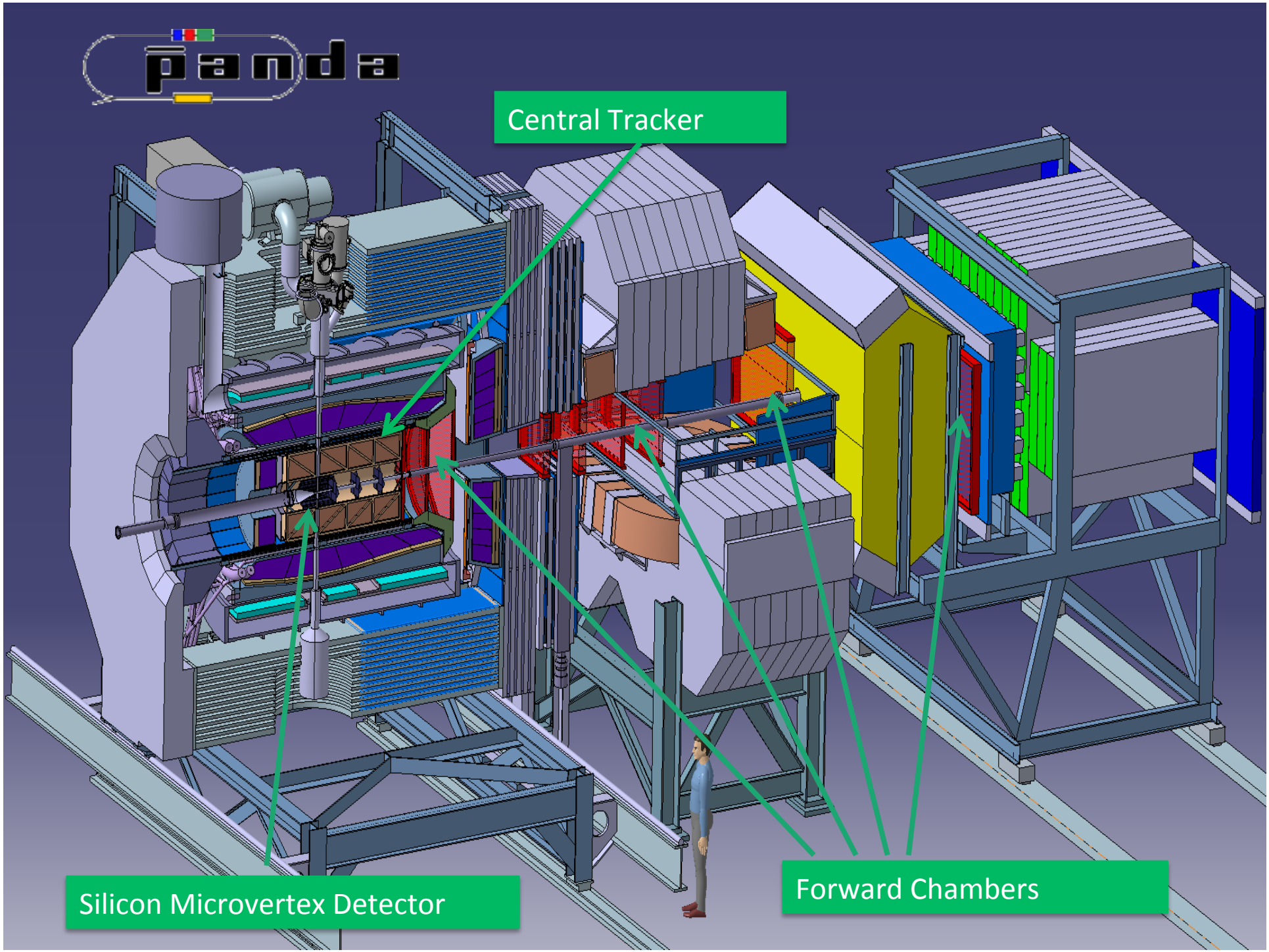
# General Purpose Detector

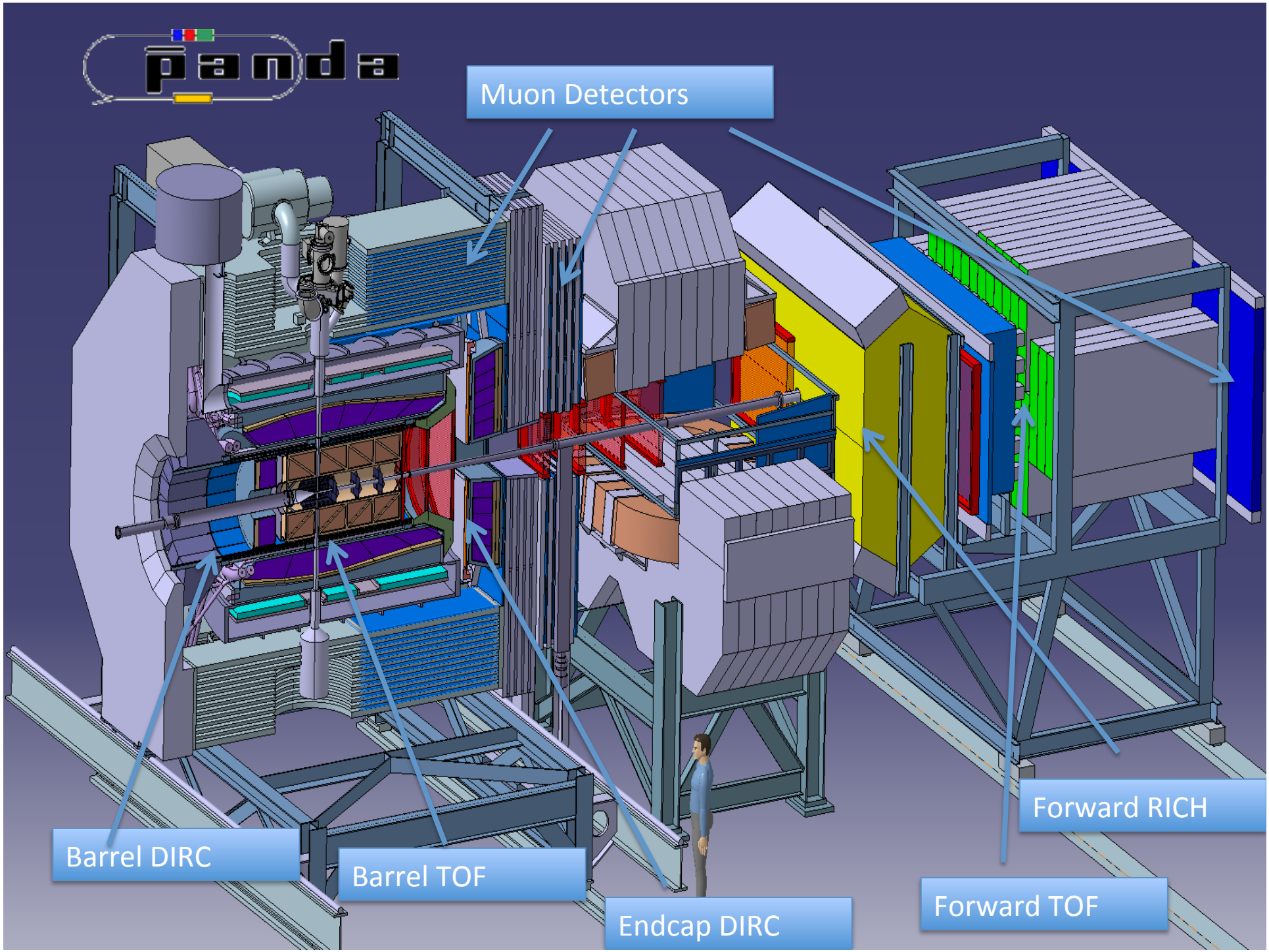


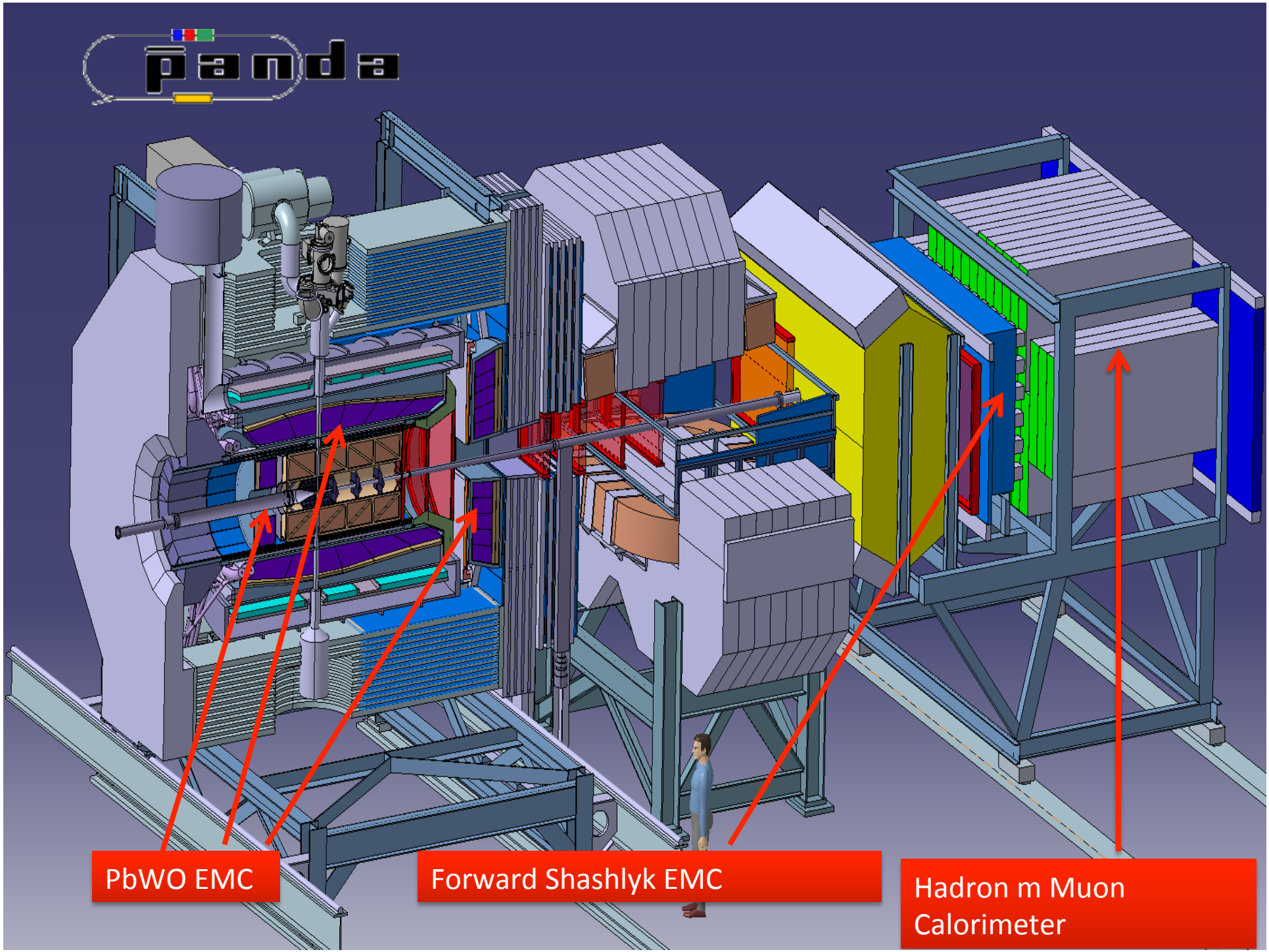
Detector requirements:

- nearly $4\pi$ solid angle (partial wave analysis)
- high rate capability ($2 \cdot 10^7$ annihilations/s)
- good PID ($\gamma$, e, $\mu$, $\pi$, K, p)
- momentum resolution (~1%)
- vertex info for D, $K^0_S$, $\Lambda$ ($c_\tau$ = 312 $\mu$m for $D^\pm$)
- efficient trigger (e, $\mu$, K, D, $\Lambda$)
- modular design (Hypernuclear experiments)


p̄anda
Pellet or cluster-jet target
2T Superconducting solenoid
for high $p_t$ particles
2Tm Dipole for forward tracks


p̄anda
Central Tracker
Silicon Microvertex Detector
Forward Chambers

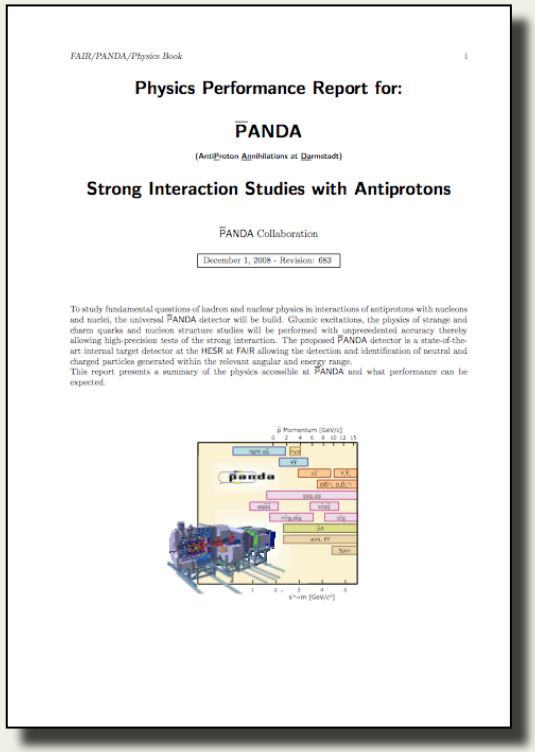

p̄anda
Muon Detectors
Barrel DIRC
Barrel TOF
Endcap DIRC
Forward TOF
Forward RICH


PbWO EMC
Forward Shashlyk EMC
Hadron m Muon Calorimeter

# The $\overline{\text{P}}$ANDA Physics Book

2008 has seen a big effort of the Collaboration preparing the $\overline{\text{P}}$ANDA Physics Book.

More than 200 pages have been produced to describe all the aspects of the scientific program.
Detailed simulations have been performed to evaluate detector performance on many benchmark channels.



*FAIR/PANDA/Physics Book* i

**Physics Performance Report for:**

**$\overline{\text{P}}$ANDA**

(AntiProton Annihilations at Darmstadt)

**Strong Interaction Studies with Antiprotons**

$\overline{\text{P}}$ANDA Collaboration

December 1, 2008 - Revision: 683

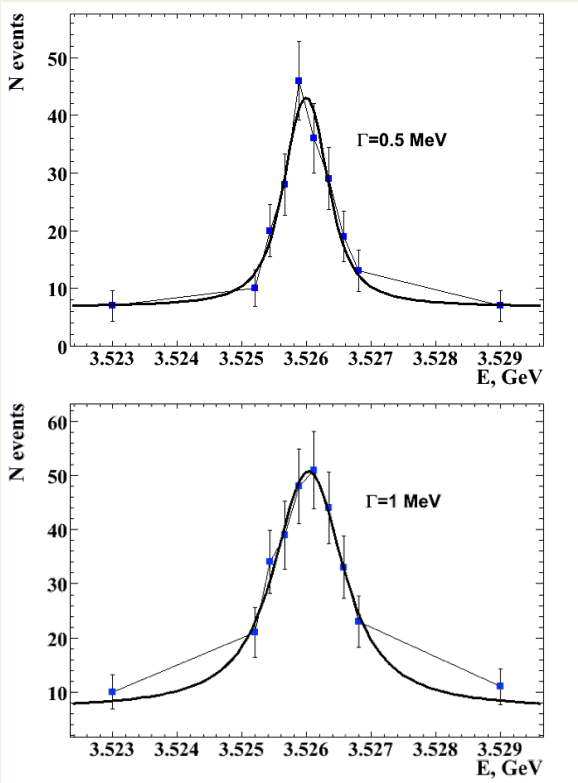
To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.

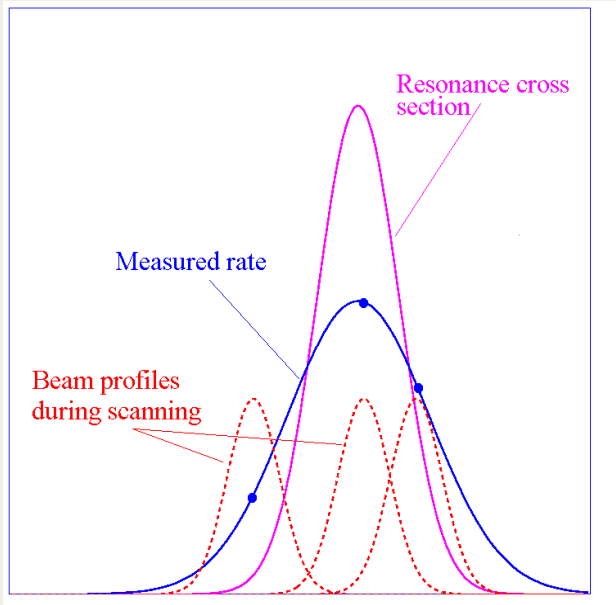
[arXiv:0903.3905v1](arXiv:0903.3905v1)

# Charmonium states width

Thanks to the precise HESR momentum definition, widths of known states can be precisely measured with an energy scan.

Energy scan of 10 values around the $h_c$ mass, width upper limit is 1MeV; each point represents a 5 day data taking in high luminosity mode, for the channel: $h_c \rightarrow \eta_c \gamma \rightarrow \phi\phi\gamma \rightarrow 4K\gamma$ with a S/B 8:1




Sensitivity

| $\Gamma_{R,MC}$[MeV] | $\Gamma_{R,reco}$[MeV] | $\Delta\Gamma_R$[MeV] |
|---|---|---|
| 1 | 0.92 | 0.24 |
| 0.75 | 0.72 | 0.18 |
| 0.5 | 0.52 | 0.14 |

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Thanks to the precise HESR momentum definition, widths of known states can be precisely measured with an energy scan.

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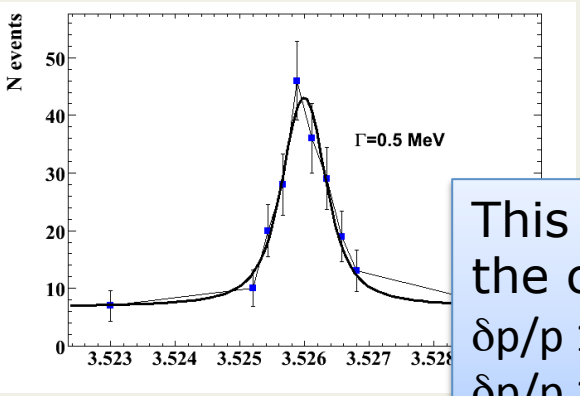
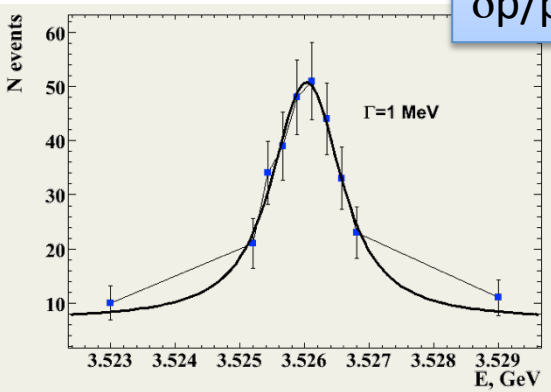
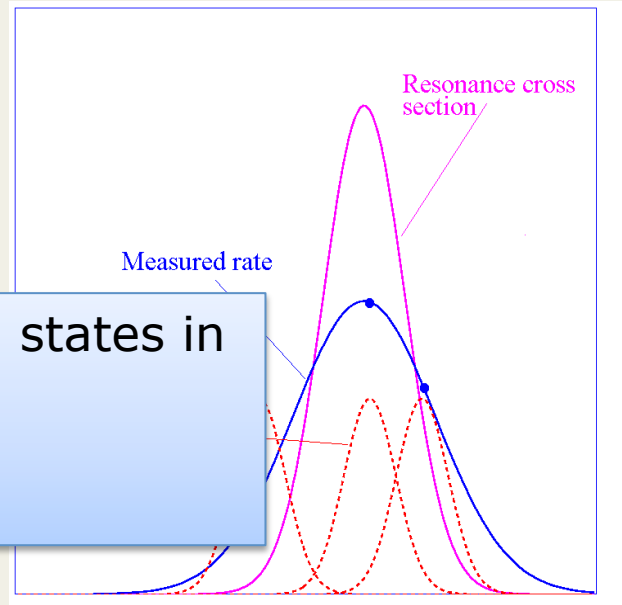



This holds for all known states in the charmonium region

$\delta p/p\ 10^{-4} \longrightarrow \Gamma$ 100 KeV

$\delta p/p\ 10^{-5} \longrightarrow \Gamma$ 10 KeV




Sensitivity

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|---|---|---|
| 1 | 0.92 | 0.24 |
| 0.75 | 0.72 | 0.18 |
| 0.5 | 0.52 | 0.14 |

# Charmonium hybrid

P̄ANDA strategy to look for an hypothetical hybrid $\tilde{\eta}$ ($J^{PC}=1^{-+}$, mass ≈ 4.3 GeV/$c^2$, width 20 MeV) is that of searching it in the channels:

$$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta$$

$$\chi_{c1}\pi^0\pi^0 \longleftrightarrow D^0\bar{D}^{0*}$$

Signal & Background reactions

| $\bar{p}p \rightarrow$ | | B |
|---|---|---|
| $\tilde{\eta}_{c1}\eta$ | 33 pb | $0.82\,\% \times \mathcal{B}(\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0)$ |
| $\chi_{c0}\pi^0\pi^0\eta$ | | 0.03 % |
| $\chi_{c1}\pi^0\eta\eta$ | | 0.32 % |
| $\chi_{c1}\pi^0\pi^0\pi^0\eta$ | | 0.81 % |
| $J/\psi\pi^0\pi^0\pi^0\eta$ | | 2.26 % |

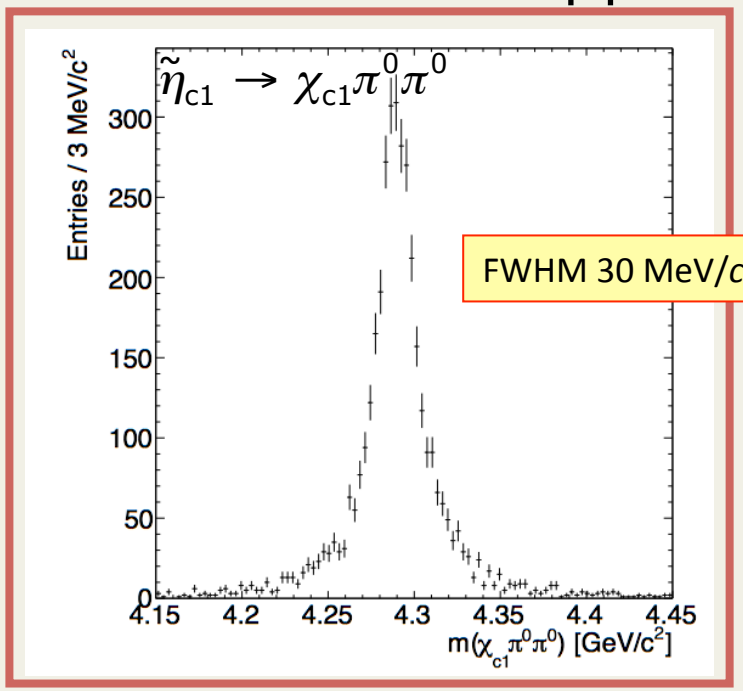
Signal & Background reactions

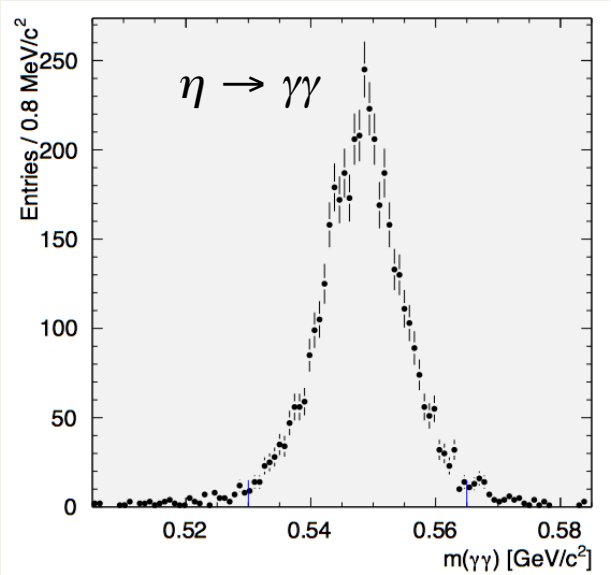
| $\bar{p}p \rightarrow$ | $\mathcal{B}$ |
|---|---|
| $\tilde{\eta}_{c1}\eta$ | $0.47\% \times \mathcal{B}(\tilde{\eta}_{c1} \rightarrow D^0\overline{D}^{*0})$ |
| $D^0\overline{D}^{*0}\eta$ | $3.2\% \times \mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^0\pi^0) = 0.16\%^*$ |
| $D^0\overline{D}^{*0}\pi^0$ | 1.17% |

# Charmonium hybrid

$$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta$$

$$\hookrightarrow \chi_{c1}\pi^0\pi^0$$

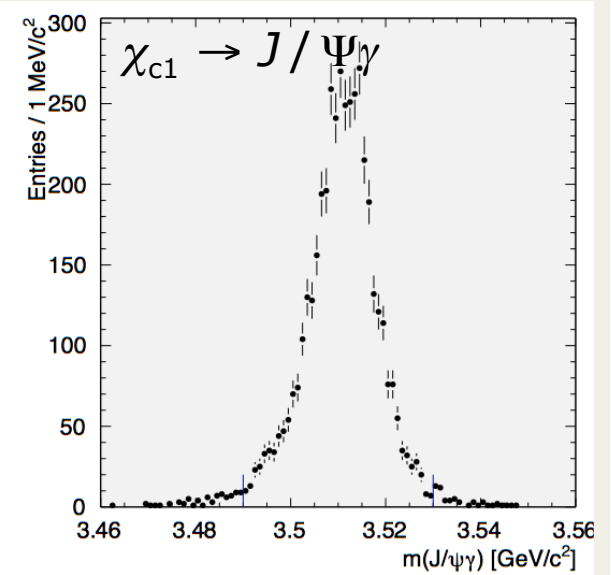



We generated $2 \bullet 10^5$ events at 15 GeV/$c$ with:

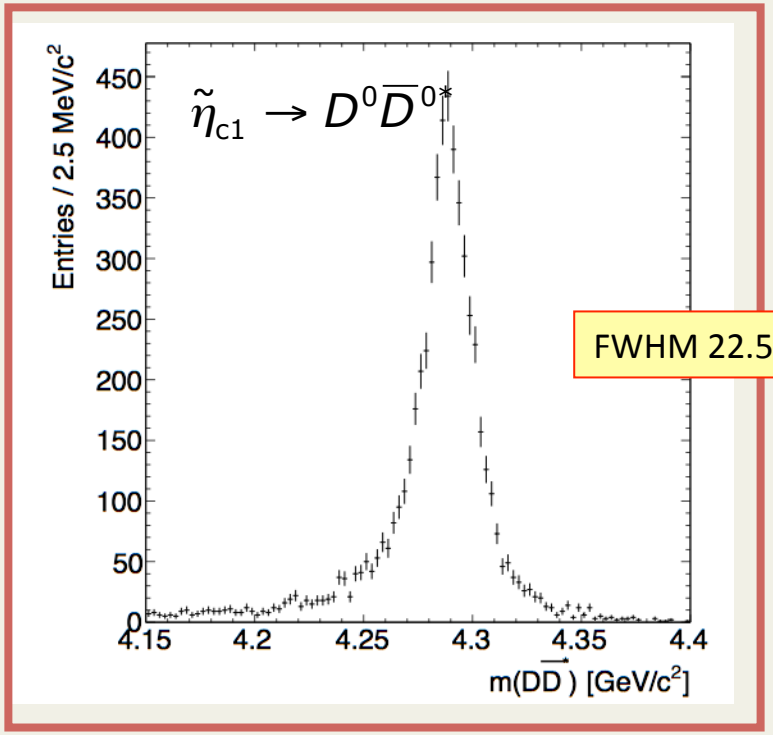
$$\chi_{c1} \rightarrow J/\Psi\gamma$$

$$\hookrightarrow e^+e^-$$



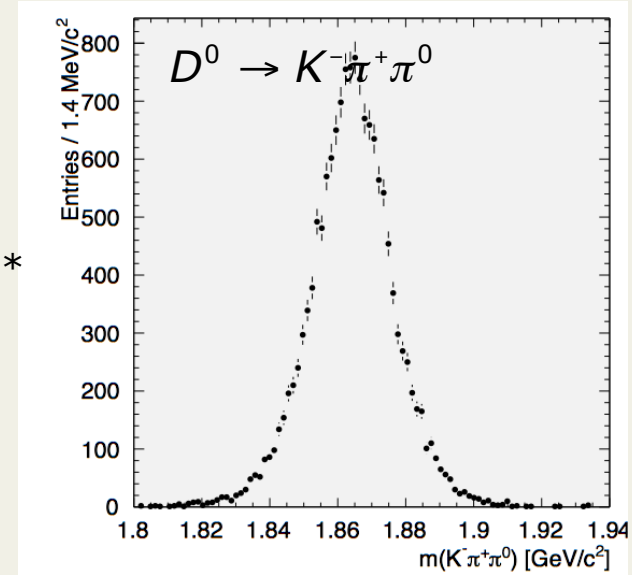

9C fit: beam, $\eta$, $\chi_{c1}$, J/$\Psi$ and $\pi^0$ mass constraints.
Final reconstruction efficiency 6,83%, background suppression $10^3$

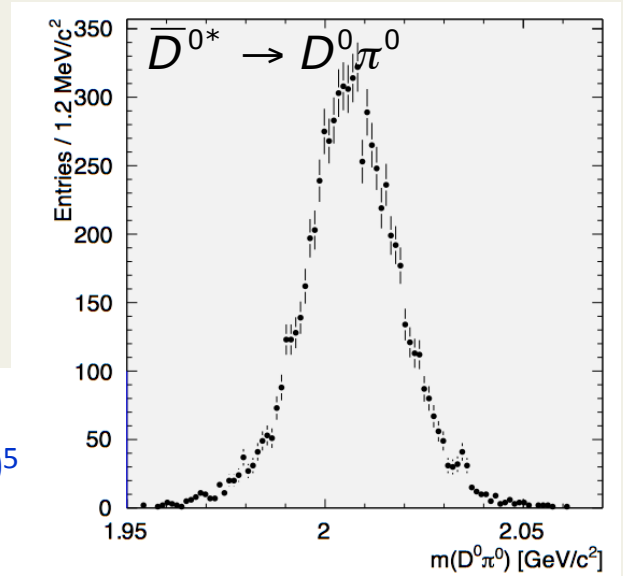
# Charmonium hybrid




$\bar{p}p \to \tilde{\eta}_{c1}\,\eta$

$\tilde{\eta}_{c1} \to D^0\overline{D}^{0*}$




We generated $1 \bullet 10^6$ events at 15 GeV/$c$ with:

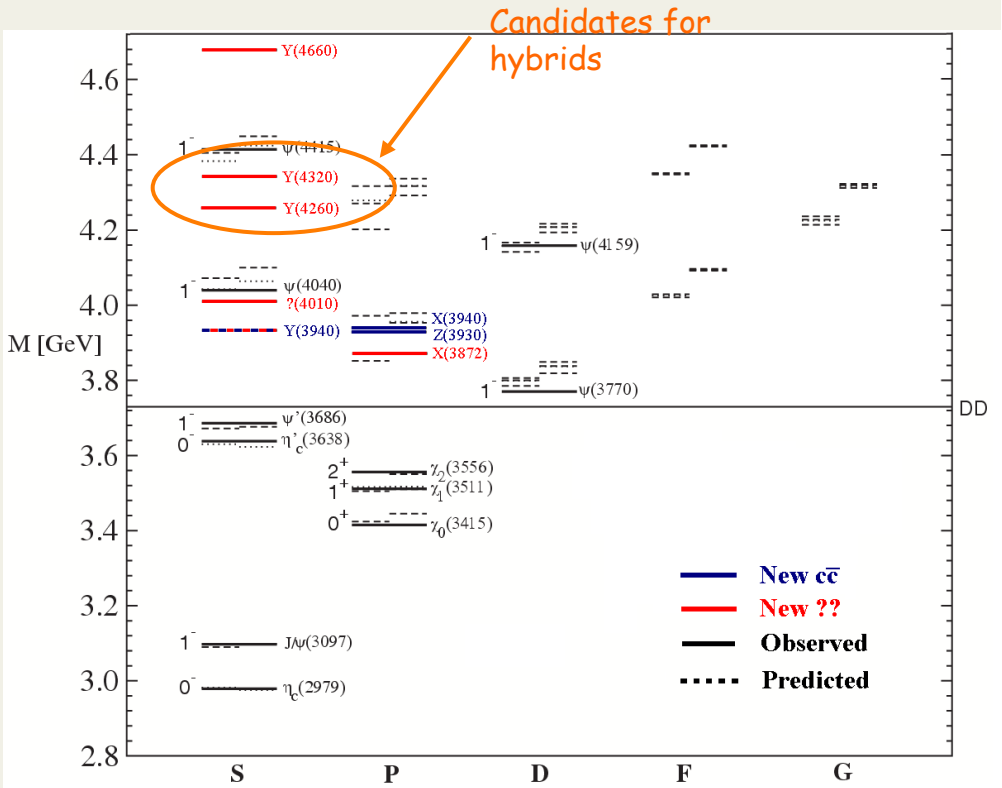
$$\overline{D}^{0*} \to D^0\pi^0 \quad D^0 \to K^-\pi^+\pi^0 \quad \eta \to \gamma\gamma$$

11C fit: beam, $D^0$, $D^{0*}$, $\eta$ and $\pi^0$ mass constraints.
Final reconstruction efficiency 5,17%, background suppression $10^5$

# Other states

Several states denoted as X , Y and Z have been recently detected, whose nature is controversially debated and which are possibly not conventional charmonium states.

These states can be detected with the $\bar{P}$ANDA spectrometer with sufficient event rates and background suppression.




We concentrated on the formation reactions:

$\bar{p}p \rightarrow Y(3940) \rightarrow J/\Psi\omega$

$\bar{p}p \rightarrow Y(4320) \rightarrow \psi(2S)\pi^+\pi^-$

# Y(3940)

$\bar{p}p \rightarrow Y(3940) \rightarrow J/\Psi\omega$ $10^4$ signal events have been generated, ~$10^6$ for each background reaction

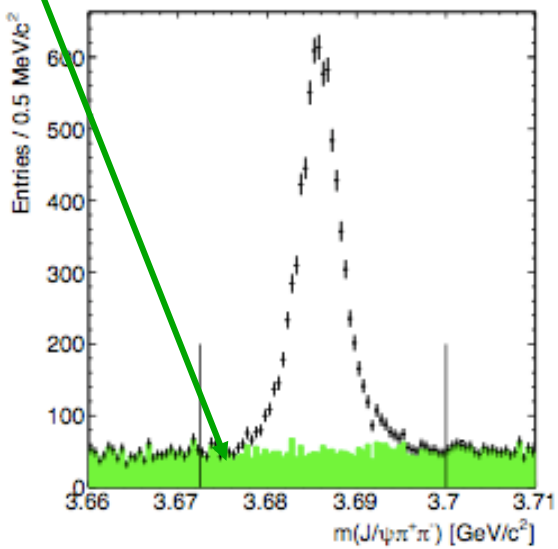
$\omega \rightarrow \pi^+\pi^-\pi^0$

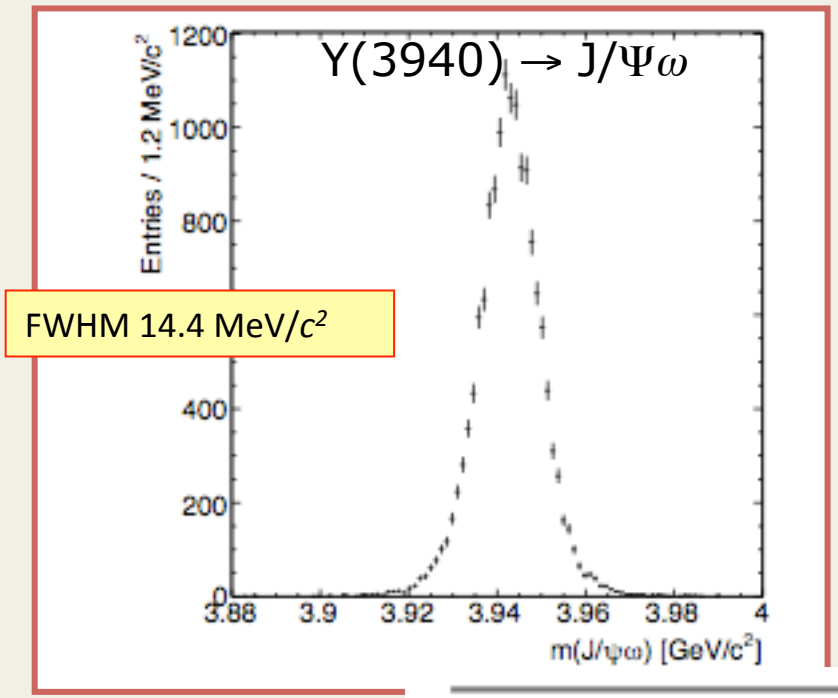
$J/\Psi \rightarrow e^+e^-$

Background reactions

| Reaction $\bar{p}p \rightarrow$ | $\sigma$ | $\mathcal{B}$ |
|---|---|---|
| $Y \rightarrow J/\psi\omega$ | $\sigma_S$ | $5.2\,\% \times \mathcal{B}(Y \rightarrow J/\psi\omega)$ |
| $\pi^+\pi^-\pi^0\rho^0$ | $149\,\mu b^*$ | $100\,\%$ |
| $\pi^+\pi^-\pi^-\rho^+$ | $198\,\mu b^*$ | $100\,\%$ |
| $\pi^+\pi^-\omega$ | $23.9\,\mu b^*$ | $100\,\%$ |
| $\psi(2S)\pi^0$ | $55$ pb | $3.73\,\%$ |
| $Y \rightarrow J/\psi\rho\pi$ | $\sigma$ | $5.9\,\% \times \mathcal{B}(Y \rightarrow J/\psi\rho\pi)$ |

None of these cross-sections has been measured in this energy range




FWHM 14.4 MeV/$c^2$

| Reaction | $\eta$ |
|---|---|
| $\pi^+\pi^-\pi^0\rho^0$ | $> 1.1 \cdot 10^9$ |
| $\pi^+\pi^-\pi^-\rho^+$ | $> 1.05 \cdot 10^9$ |
| $\pi^+\pi^-\omega$ | $> 1.08 \cdot 10^8$ |
| $\psi(2S)\pi^0$ | $3.33 \cdot 10^3$ |
| $J/\psi\pi^-\rho^+$ | $25$ |
| $J/\psi\pi^0\rho^0$ | $22.1$ |

6C fit: beam, $J/\Psi$, $\pi^0$ mass constraints. Reconstruction eff. 14,7%, background suppression for different reactions

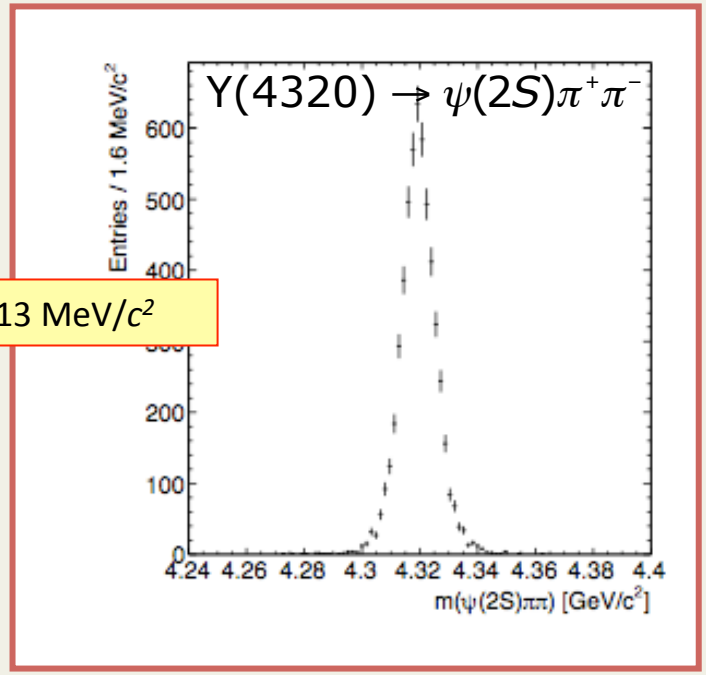
# Y(4320)

$\bar{p}p \rightarrow Y(4320) \rightarrow \psi(2S)\pi^+\pi^-$

$\hookrightarrow J/\Psi\pi^+\pi^-$

$\hookrightarrow e^+e^-$

$2 \bullet 10^4$ signal events have been generated at $\bar{p}$ momentum 8,9578 GeV/$c$ and $10^6$ $3\pi^+3\pi^-$ background events




FWHM 13 MeV/$c^2$

6C fit: beam, J/Ψ, ψ(2S) mass constraints. Reconstruction efficiency 14,9%, background suppression $10^6$

# $p\bar{p} \rightarrow f_2(2000\text{-}2500) \rightarrow \phi\phi$

The primary goal of this study is to test our capability of reconstructing $\phi\phi$ final states which are expected to be good for exotics (glueball) searching.

This is the region where the BES experiment found an evidence for a tensor ($J^{PC} = 2^{++}$) glueball candidate $\xi(2230)$.

The detection of a possible resonant signal require an energy scan around the central energy value in order to measure the dynamic behavior of the cross-section.

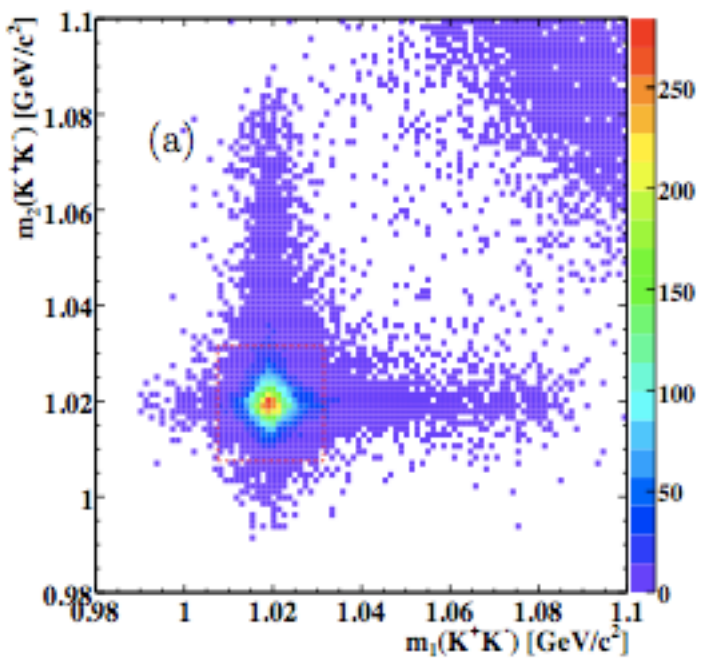
$$\bar{p}p \rightarrow f_2 \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$$

The analysis consists in 3 steps:

- reconstruction of the signal;
- evaluation of the background level;
- simulation of the energy scan.

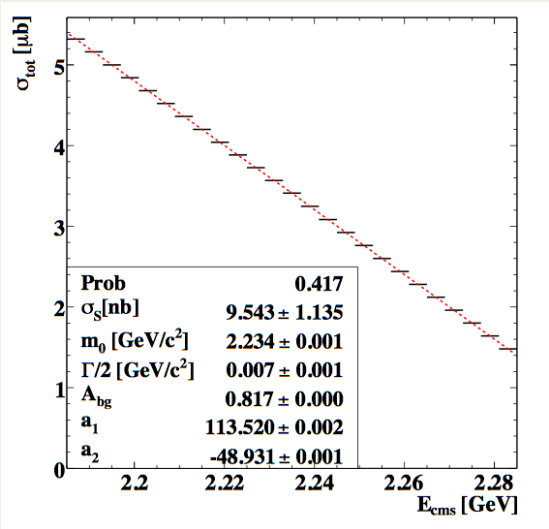
We generated 50 $\bullet 10^3$ signal events and $10^6$ bck events.

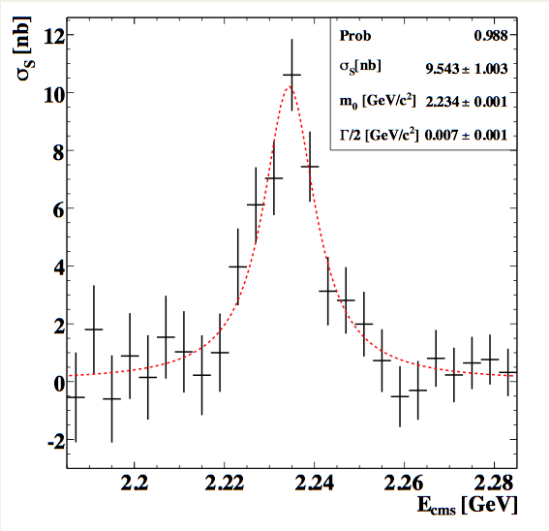
4C fit: efficiency 25%



# $f_2(2235)$ energy scan

We made the assumption of a mass value of 2235 MeV/$c^2$ and a widths of 15 MeV/$c^2$




Fit of the total cross section and the derived signal cross-section
For a scan width of 10 nb

Needed beam time to achieve a 10σ significance

| $\sigma_S$ [nb] | Beam time $T_b$ (≈) |
|---|---|
| 1 | 13.7 y |
| 5 | 200 d |
| 10 | 50 d |
| 100 | 12 h |
| 500 | 0.5 h |
| 1000 | 7.2 min |

# Expected event rates

reconstructed signal events/day

assume: int. luminosity of $8pb^{-1}$/ day and cross section of 1nb

| | |
|---|---|
| $Y(4260)\to J/\Psi\eta$, $J/\Psi\to e^+e^-$: | $BR(Y(4260)\to J/\Psi\eta)$x 169 events/day |
| $J/\Psi\to\mu^+\mu^-$: | $BR(Y(4260)\to J/\Psi\eta)$x 144 events/day |
| $Y(3940)\to J/\Psi\omega$, $J/\Psi\to e^+e^-$: | $BR(Y(3940)\to J/\Psi\omega)$x 91 events/day |
| $J/\Psi\to\mu^+\mu^-$: | $BR(Y(3940)\to J/\Psi\omega)$x 70 events/day |
| $Y(4320)\to\Psi(2S)\pi^+\pi^-$, $J/\Psi\to e^+e^-$: | $BR(Y(4320)\to\Psi(2S)\pi^+\pi^-)$x 34 events/day |
| $\bar{p}p\to(\chi_{c1}\pi^0\pi^0)\eta$, $J/\Psi\to e^+e^-$: | $BR(\Psi\to\chi_{c1}\pi^0\pi^0)$x 3.1 events/day |
| $J/\Psi\to\mu^+\mu^-$: | $BR(\Psi\to\chi_{c1}\pi^0\pi^0)$x 3.6 events/day |
| $\bar{p}p\to(D^0\bar{D}^{0*})\eta$: | $BR(\Psi\to D^0D^{0*})$x 1.9 events/day |

1 $\bar{p}$-year running (~200 d) at $p_{\bar{p}}$=15 GeV/*c* for a survey additional running at optimized momentum (tuned on finding) to improve PWA sensitivity (final goal: total ~600 d, ~3 p-year ?)

# 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. At least 3 states: X(3872), Y(4260), Z(4430) are strong candidates for being **exotics.**

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

7. New, high quality data will certainly come form the $\bar{P}$ANDA experiment @ FAIR.

# Exercise 1

At PANDA we want to study an hypotetical glueball H of mass ~4250 MeV/$c^2$ with the reaction $\bar{p}p \rightarrow K^+K^-$ H

Which is the minimum $\bar{p}$ momentum required?

Once you measured the mass, how can you determine precisely the width?

# Exercise 2

Cherenkov radiation is emitted by a high-energy charged particle which moves through a medium with a velocity greater than the velocity of light propagation in the medium.

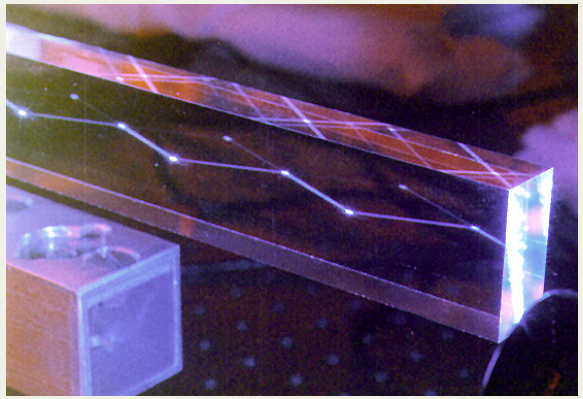
Derive the relationship among the particle velocity $v = \beta c$, the index of refraction n of the medium, and the angle $\theta$ at which the Cherenkov radiation is emitted relative to the line of flight of the particle.

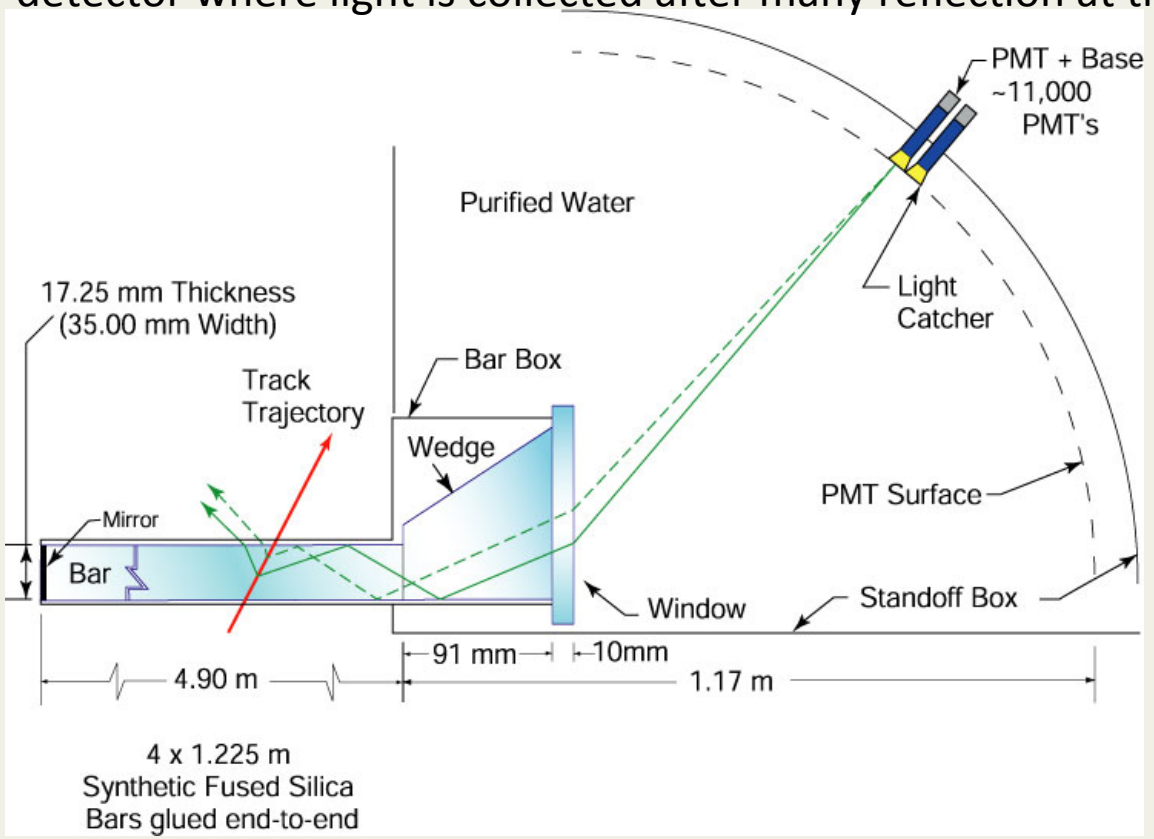
If the quartz bars of the PANDA DIRC detector have a refraction index $n = 1.4585$, evaluate the Cherenkov threshold for pions, kaons and electrons.

# Exercice 3

At PANDA Particle Identification (PID) is a crucial task.
List all the detectors and the experimental technique you know to perform PID in different energy ranges.

A DIRC is a special Cherenkov detector where light is collected after many reflection at the end of the radiator slabs.






Why the slabs polishing is so crucial?

# Exercise 4

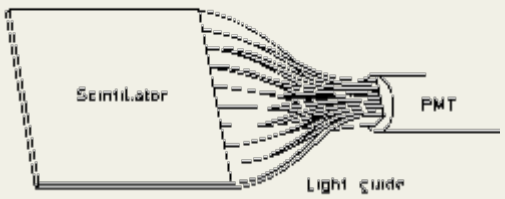
According to the quark model verify the following statements:

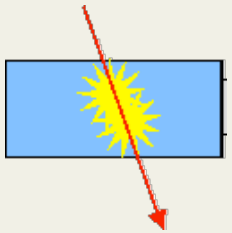
- Baryons won't have spin 1;
- Which can be the quark composition of an antibaryon of electric charge +2;
- Why mesons with charge +1 and strangeness −1 are not possible?

| Symbol | Quark | Charge |
|---|---|---|
| u | *up* | 2/3 |
| d | *down* | -1/3 |
| c | *charm* | 2/3 |
| s | *strange* | -1/3 |
| t | *top* | 2/3 |
| b | *bottom* | -1/3 |

# Exercise 5

Plastic scintillators are detectors producing light when crossed by charged particles. The produced light is proportional to the energy released by the particle.



Some typical parameters of scintillator detectors are:

| | |
|---|---|
| • MIP energy loss | 2MeV/cm |
| • scintillation efficiency | 1 photon/100 eV |
| • collection efficiency (# photons reaching PMT) | 0.1 |
| • quantum efficiency of PMT | 0.25 |
| • PMT gain | $10^6$ |
| • PMT collection time | 50 ns |

What size has an electrical signal we get from a plastic scintillator 1 cm thick?