Search for exotics at $\bar{\text{P}}$ANDA

- Study of QCD bound states;
- Different theoretical/experimental approaches;
- The PANDA experimental program.

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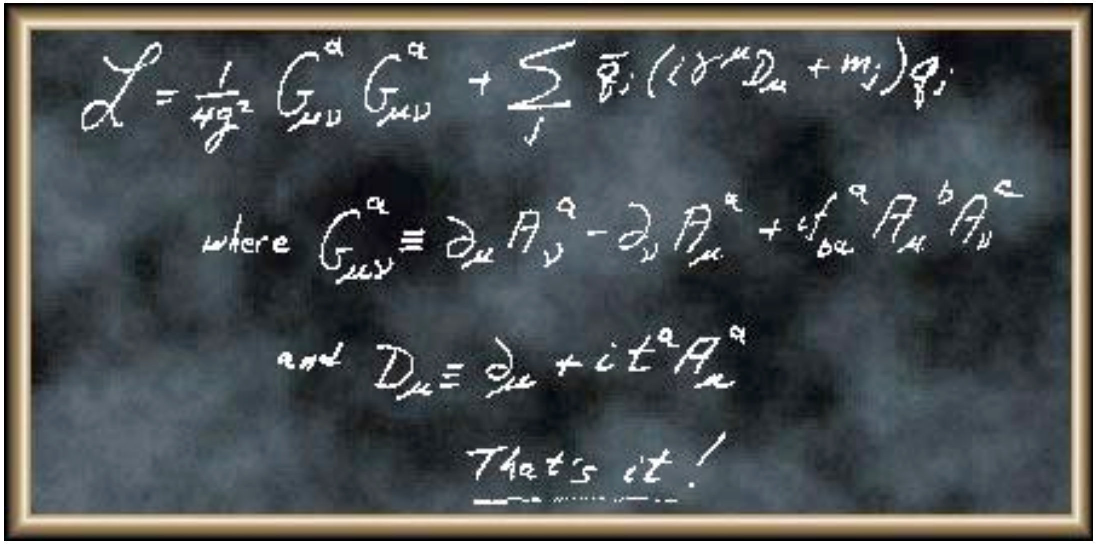
Quantum Chromodynamics



The QCD Lagrangian is, in principle, a simple and complete description of the strong interaction:

- there is just one overall coupling constant g

and

- six quark-mass parameters m_j for the six quark flavors

But,
it leads to equations that are hard to solve

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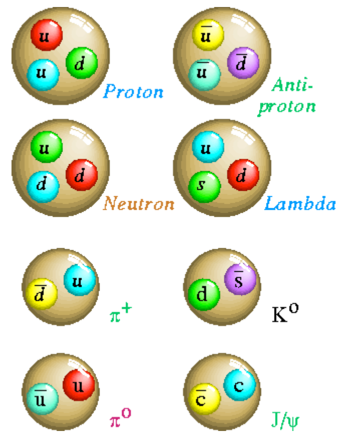
The Confinement

None of the particles that we've actually seen appear in the formula and none of the particles that appear in the formula has ever been observed.



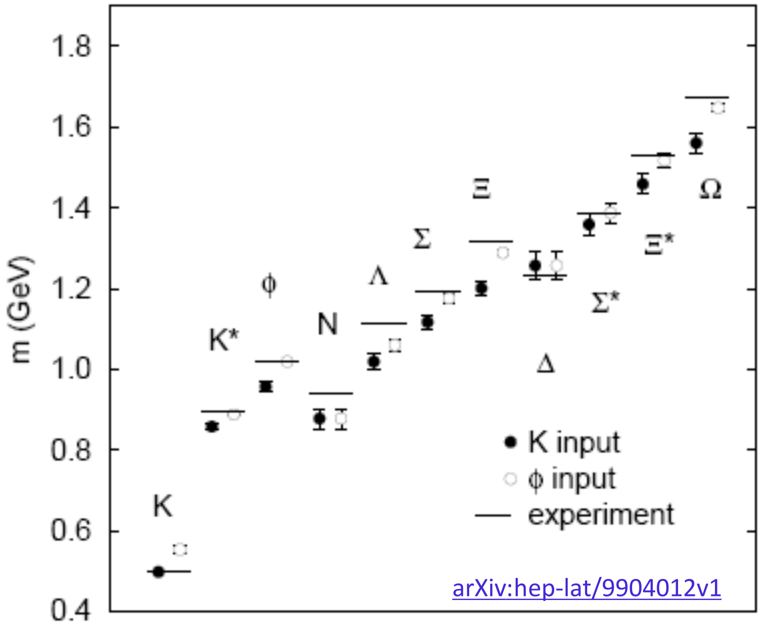
Furthermore, we've never seen particles carrying fractional electric charge, which we nonetheless ascribe to the quarks.

And certainly we haven't seen anything like gluons--massless particles mediating long-range strong forces.

So if QCD is to describe the world, it must explain why quarks and gluons cannot exist as isolated particles. That is the so-called confinement problem.

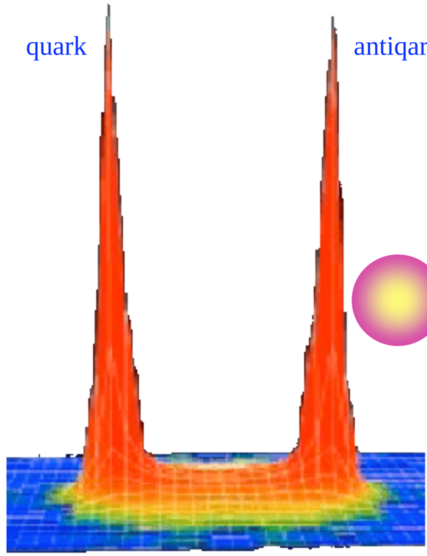
How do we solve the QCD problems?

The first approach is to try to solve the equations.
That's not easy.
Fortunately, powerful modern computers have made it possible to calculate a few of the key predictions of QCD directly.



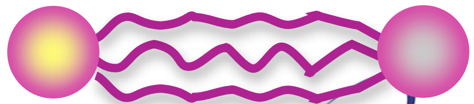
The agreement with the measured masses is at the 10% level.

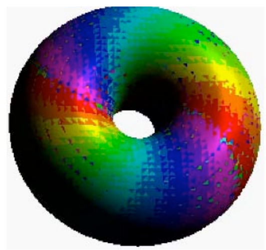
The second approach is that of creating phenomenological models that are simpler to deal with, but still bear some significant resemblance to the real thing.



Meson

Hybrid





Glueball

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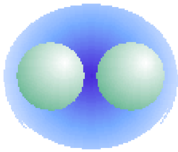
Exotic hadrons

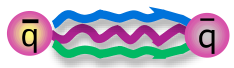
Regardless from the approach, the QCD spectrum is more rich than what is predicted by the naive quark model. Gluons carry color charge, therefore they can be explicit hadron components



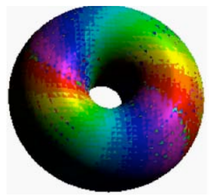
$$= \sum_i (q\bar{q})_i \sum_j g_j$$

The "exotic hadrons" fall in 3 general categories:

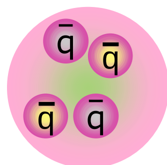
Hybrids $(q\bar{q})\,g$



Glueballs gg



Multi-quarks $(q\bar{q})(q\bar{q})$



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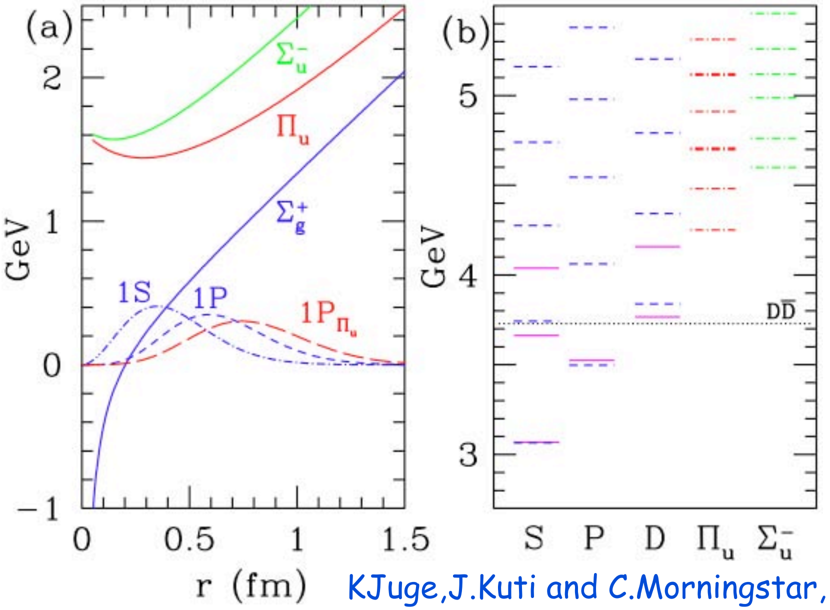
Hybrids

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

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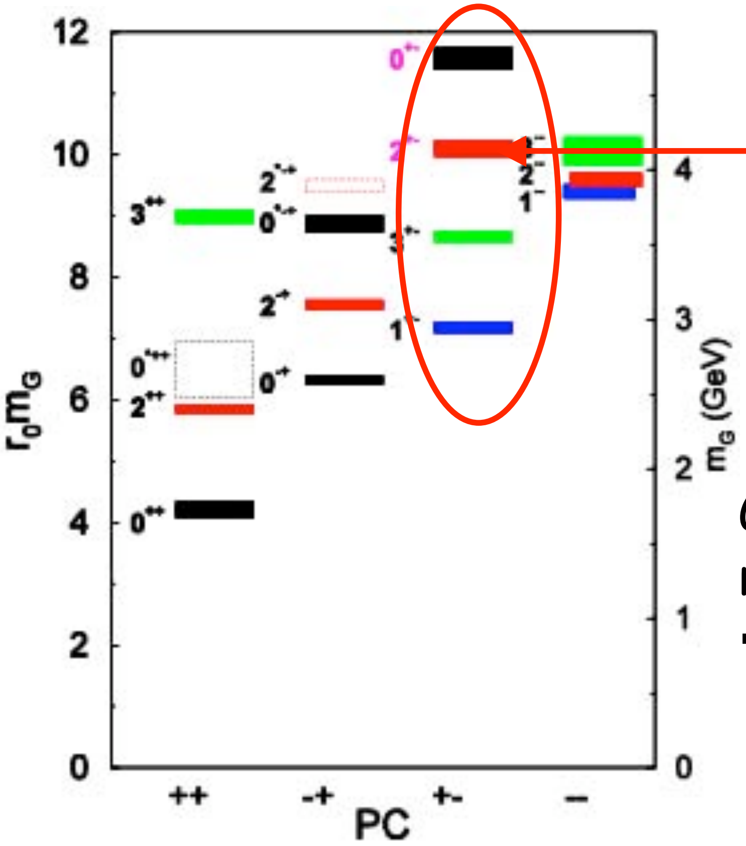
Glueballs

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))

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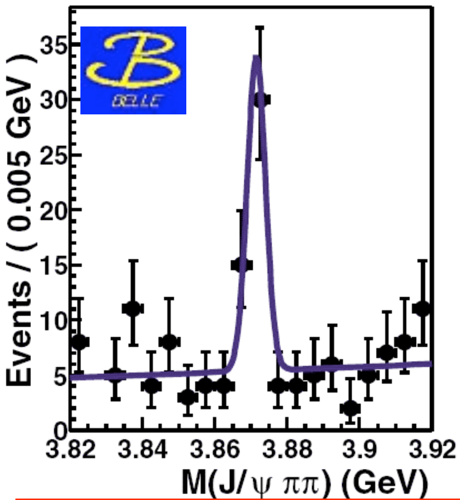
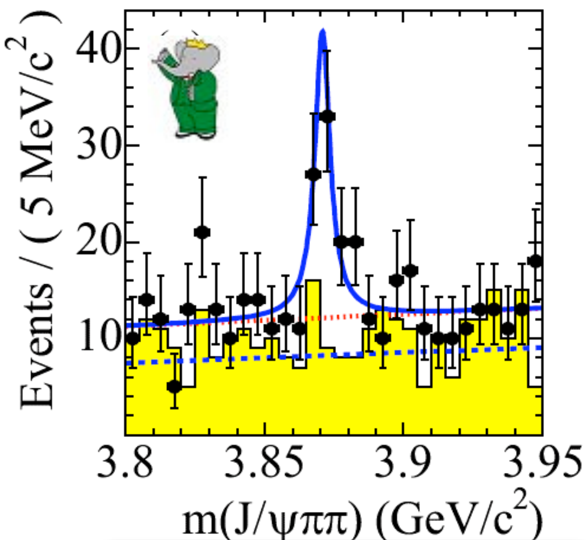
Multi-quarks

These states are expected to be loosely bound ➔ large widths. Nevertheless, the vicinity of a strong threshold can reduce the widths. This is the case of $a_0(980)$ and $f_0(975)$ that are close to the $K\bar{K}$ threshold, and can be an explanation for X(3872).



Phys.Rev. Lett.91,262001 (2003)



Phys.Rev. D71,071103 (2005)
Phys.Rev. D73,011101 (2006)

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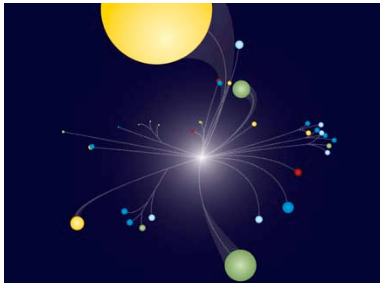
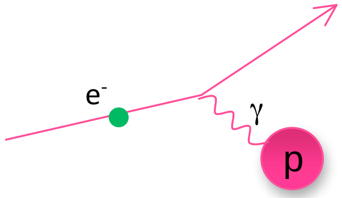
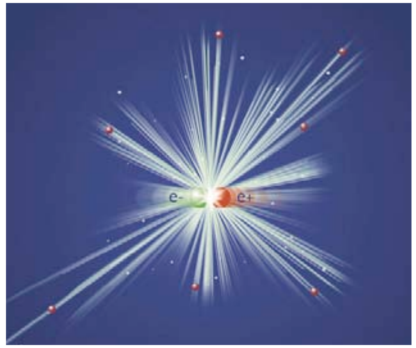
Experimental approach

High statistics and high quality data are necessary to help constraining the theory.



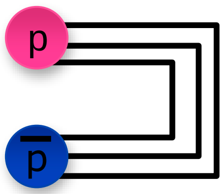




Different experimental techniques can be used to focus on different aspects:

The selection of special working conditions or of final states helps filtering initial/final state quantum numbers

- In proton-antiproton annihilations complex objects collide
- The interaction occurs between two beams of (anti)quarks and gluons



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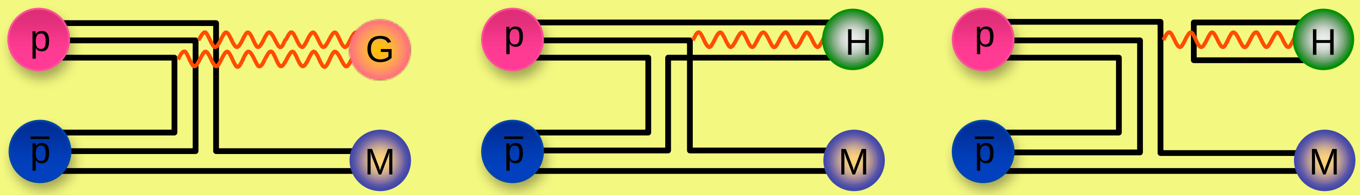
Spectroscopy with antiprotons

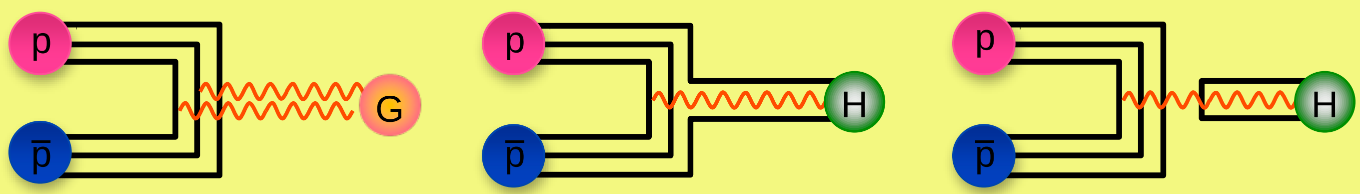
Two are the mechanisms to access particular final states:



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



Exotic hadrons

In the light meson region, more than 10 states have been classified as possible "Exotics". Almost all of them have been seen in $p\bar{p}$...

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^{++}

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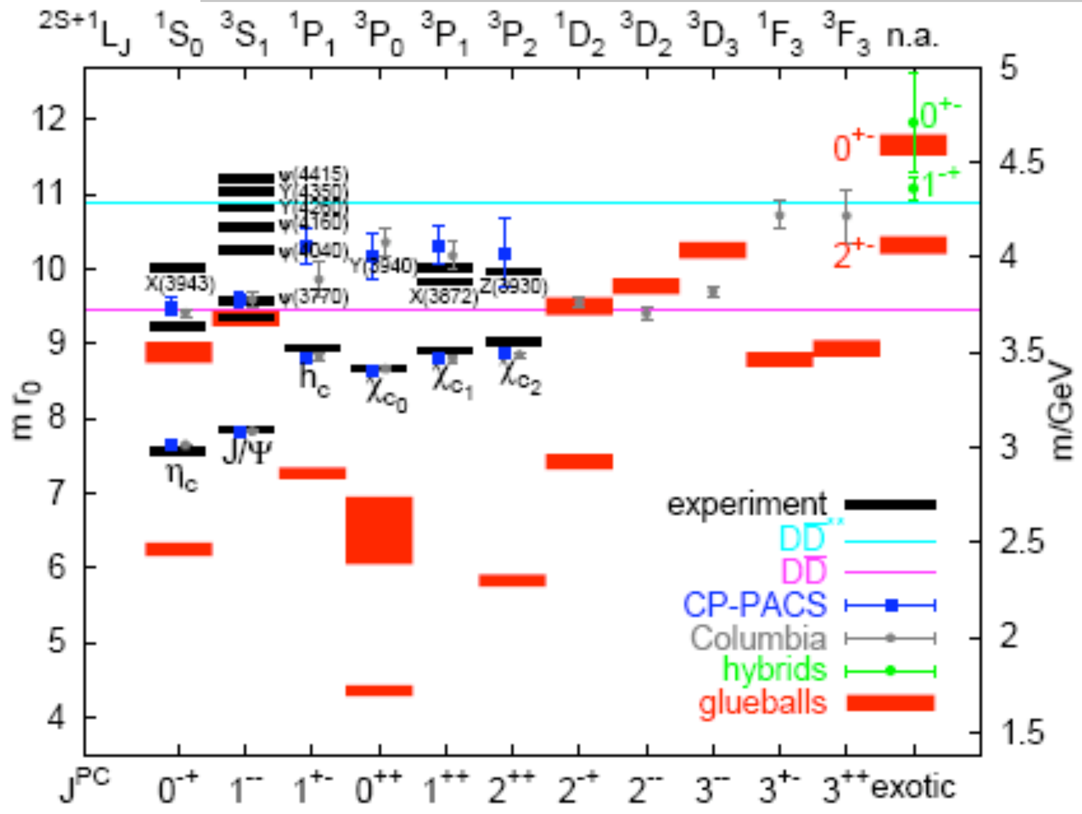
Charmonium region

Charmonium spectrum, glueballs, spin-exotics $c\bar{c}$-glue hybrids with experimental results



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

arXiv:hep-lat/0608004

Quantum numbers assignment become clear only with high statistics and different final states

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Antiproton's power

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

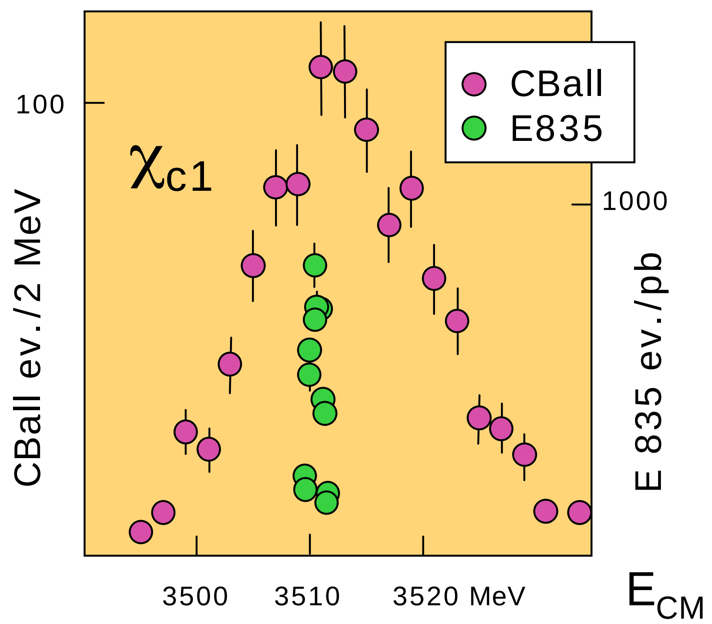
$\bar{p}\,p \to \chi_{1,2} \to \gamma J/\psi \to \gamma e^+e^-$

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (moderate mass resolution)

- $p\bar{p}$ reactions:

  - All states directly formed (very good mass resolution)



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

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

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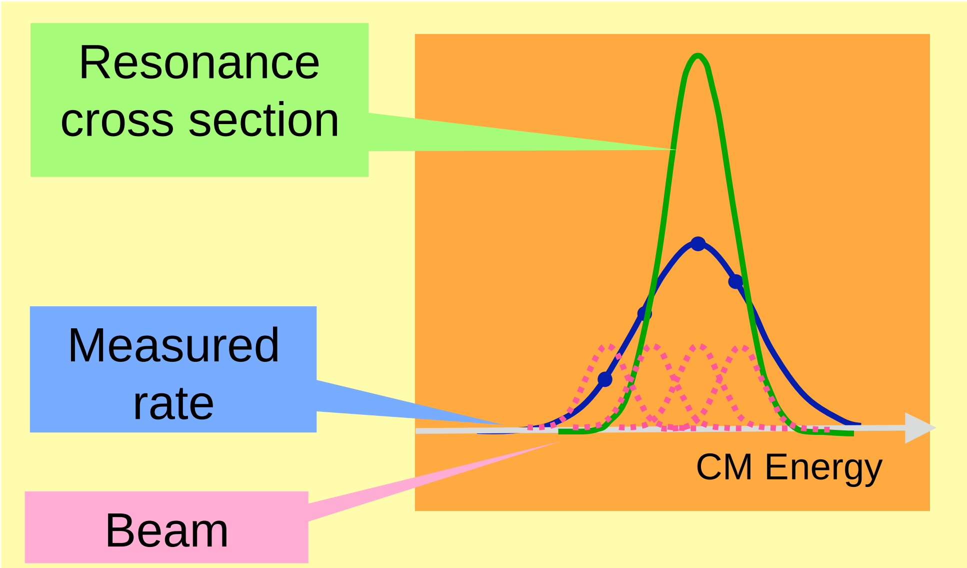
Antiproton's power

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



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

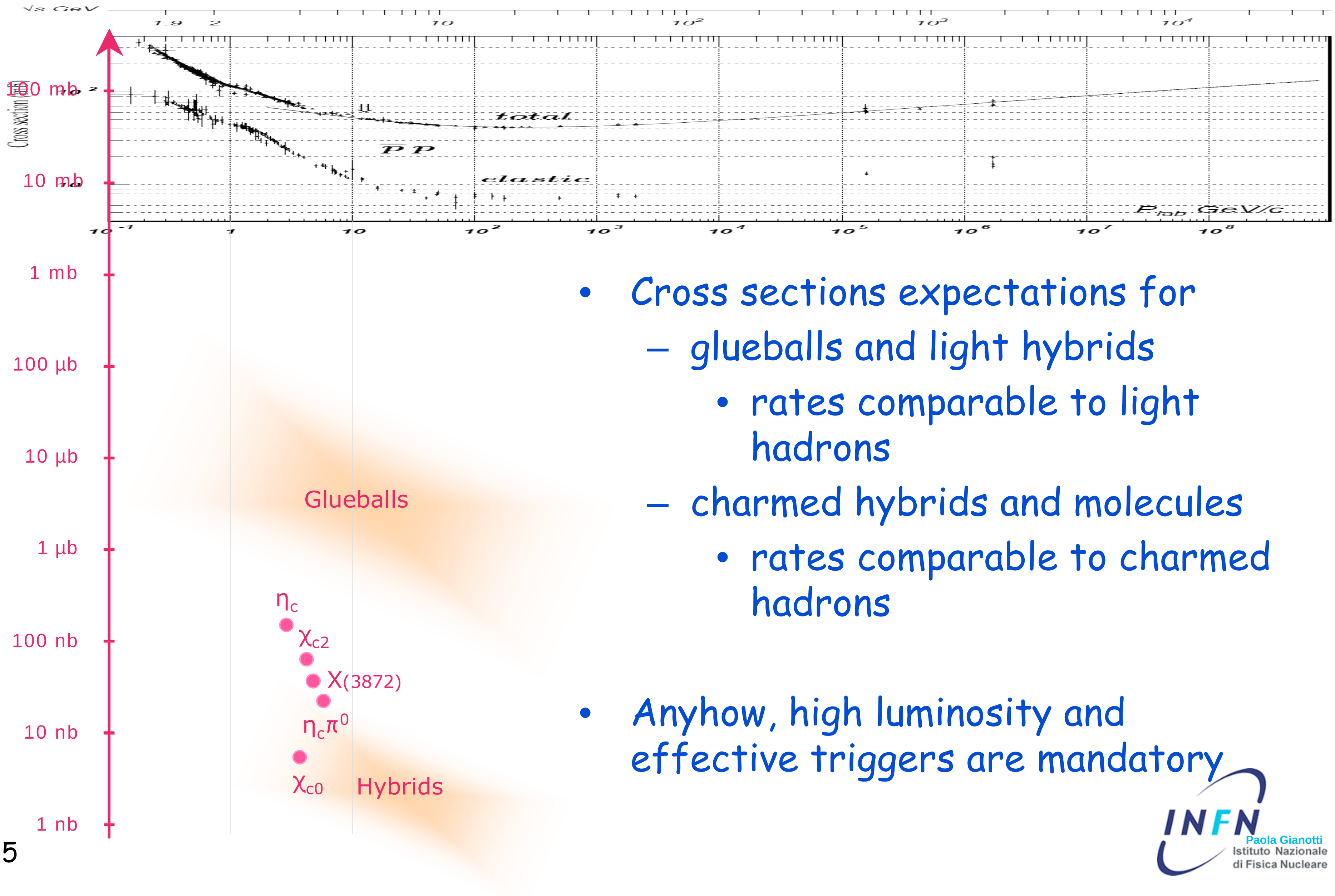
The production rate of a certain final state ν is a convolution of the BW cross section

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 Γ_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.

$\bar{p}p$ cross section-exclusive final states



- Cross sections expectations for
  - glueballs and light hybrids
    - rates comparable to light hadrons
  - charmed hybrids and molecules
    - rates comparable to charmed hadrons

- Anyhow, high luminosity and effective triggers are mandatory

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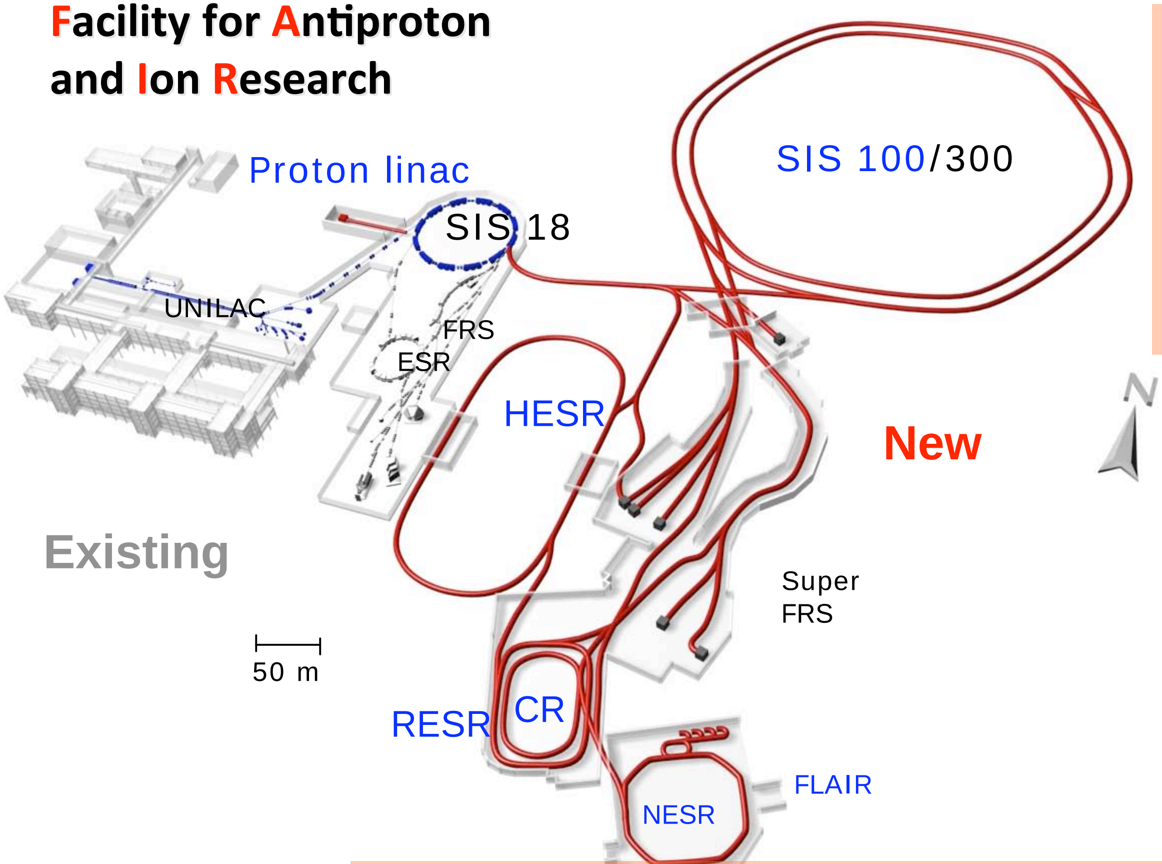
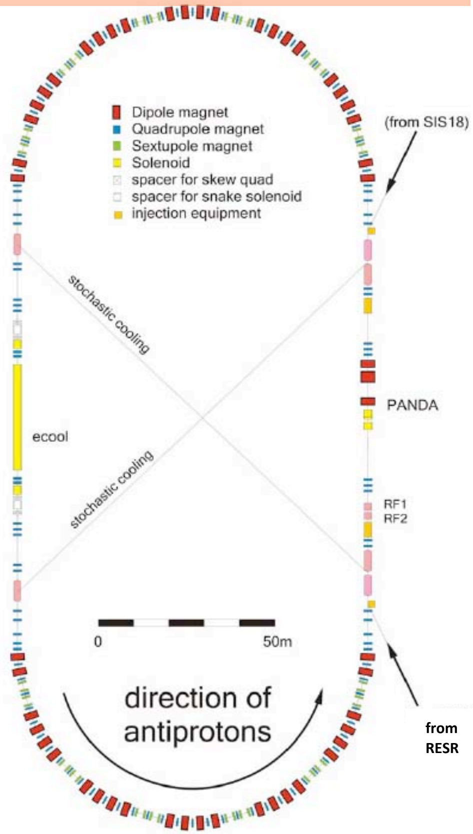
FAIR: *the new antiproton facility*

Facility for Antiproton and Ion Research



Antiproton production

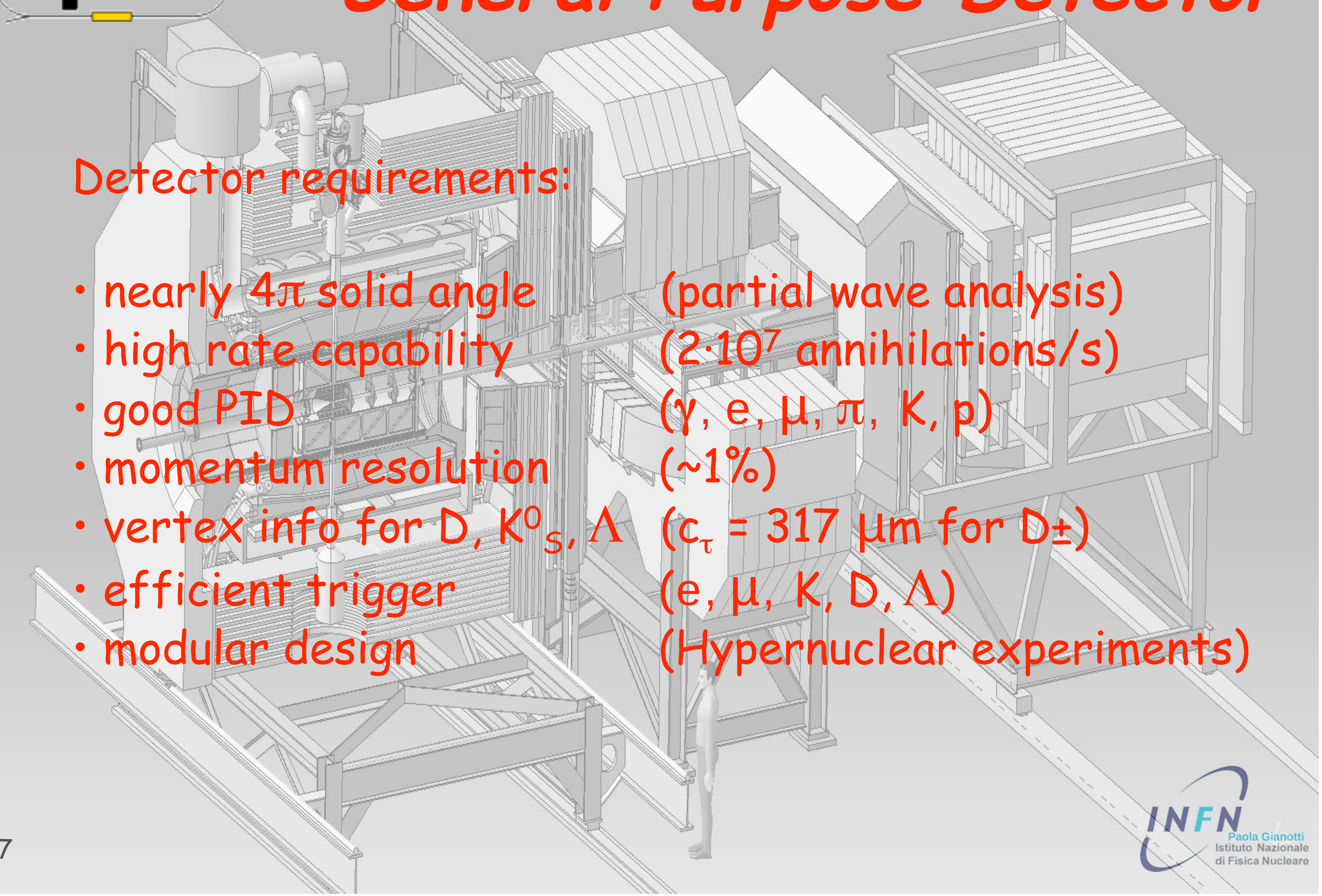
- Proton Linac 50 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on target
- Collect in CR, cool in RESR



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

- Injection of $\bar{p}$ at 3.7 GeV
- Slow synchrotron (1.5-15 GeV)
- Luminosity up to L~ 2×10^{32} $cm^{-2}s^{-1}$
- Beam cooling (stochastic & electron)

General Purpose Detector



Detector requirements:

- nearly 4π solid angle (partial wave analysis)
- high rate capability ($2 \cdot 10^7$ annihilations/s)
- good PID (γ, e, μ, π, K, p)
- momentum resolution (~1%)
- vertex info for D, $K^0{}_S$, Λ (c_τ = 317 μm for D±)
- efficient trigger (e, μ, K, D, Λ)
- modular design (Hypernuclear experiments)

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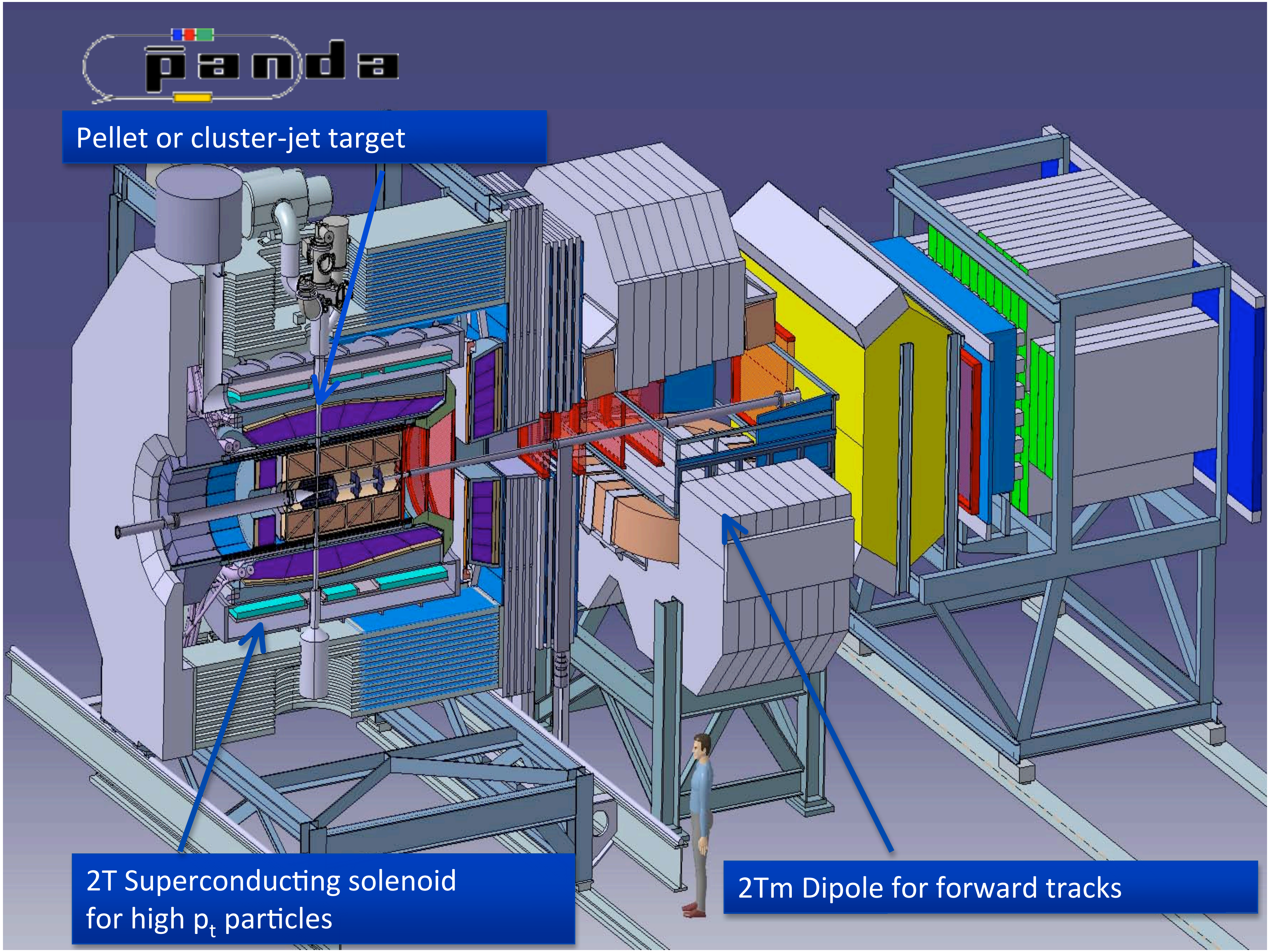
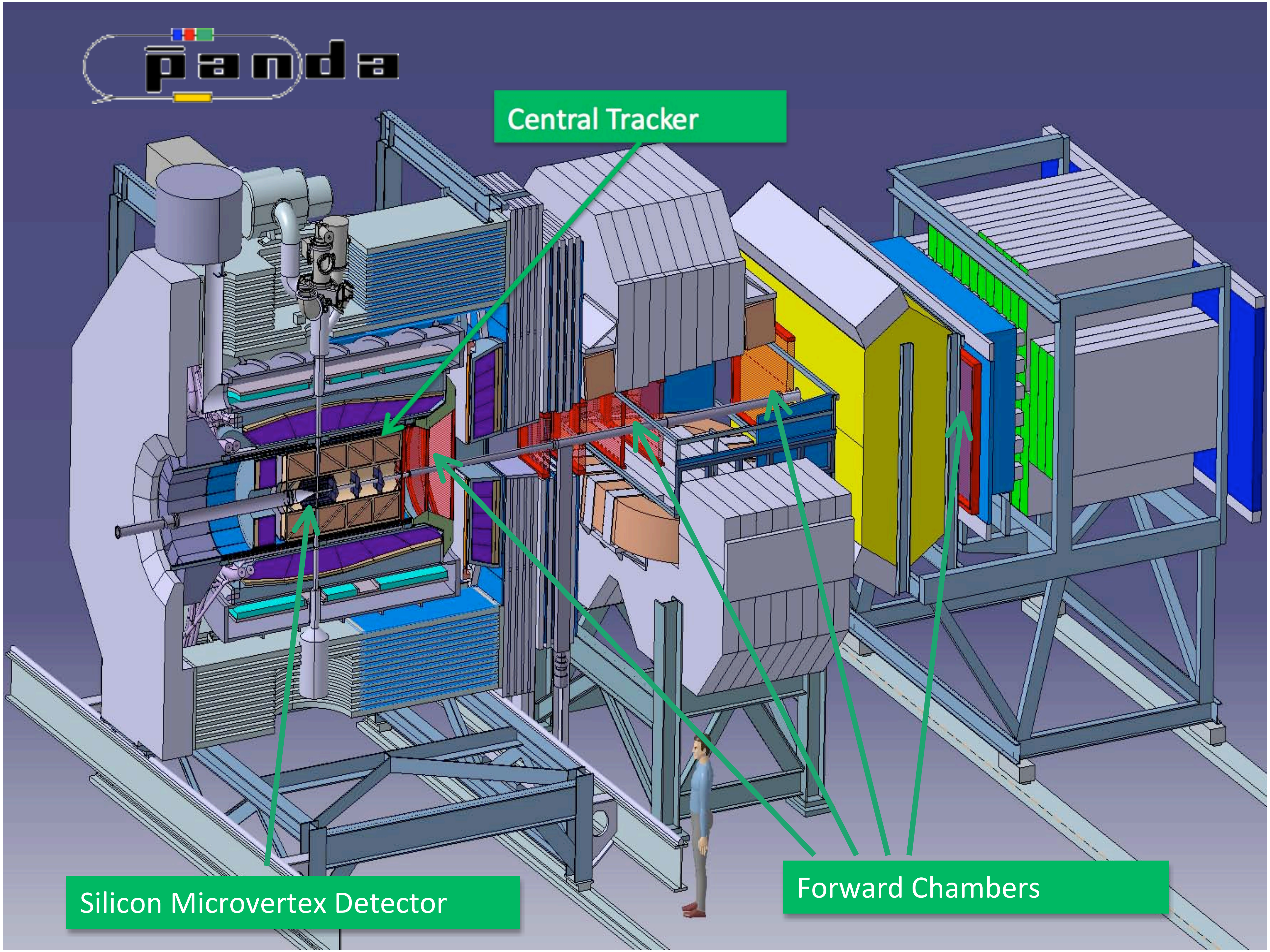
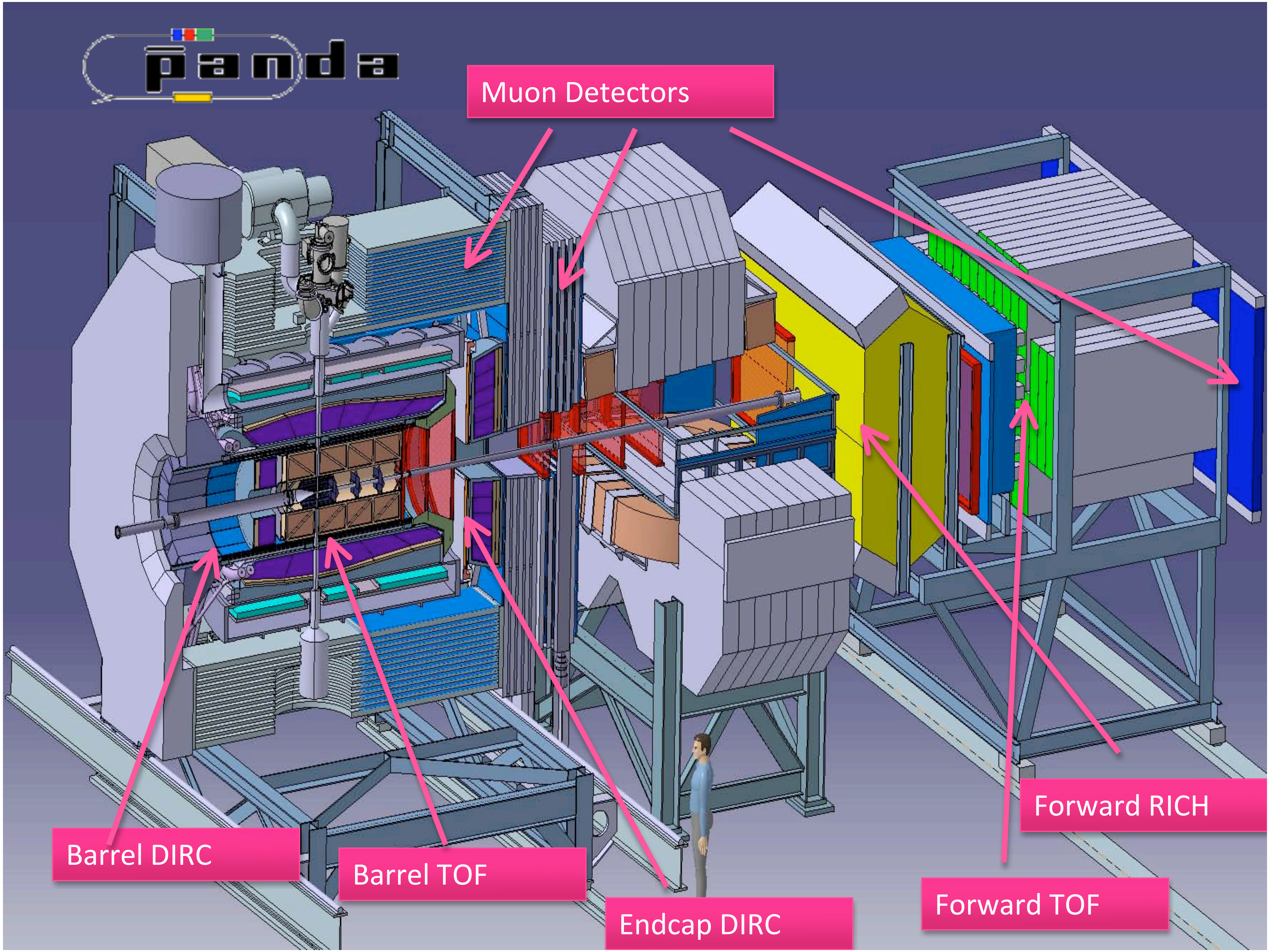
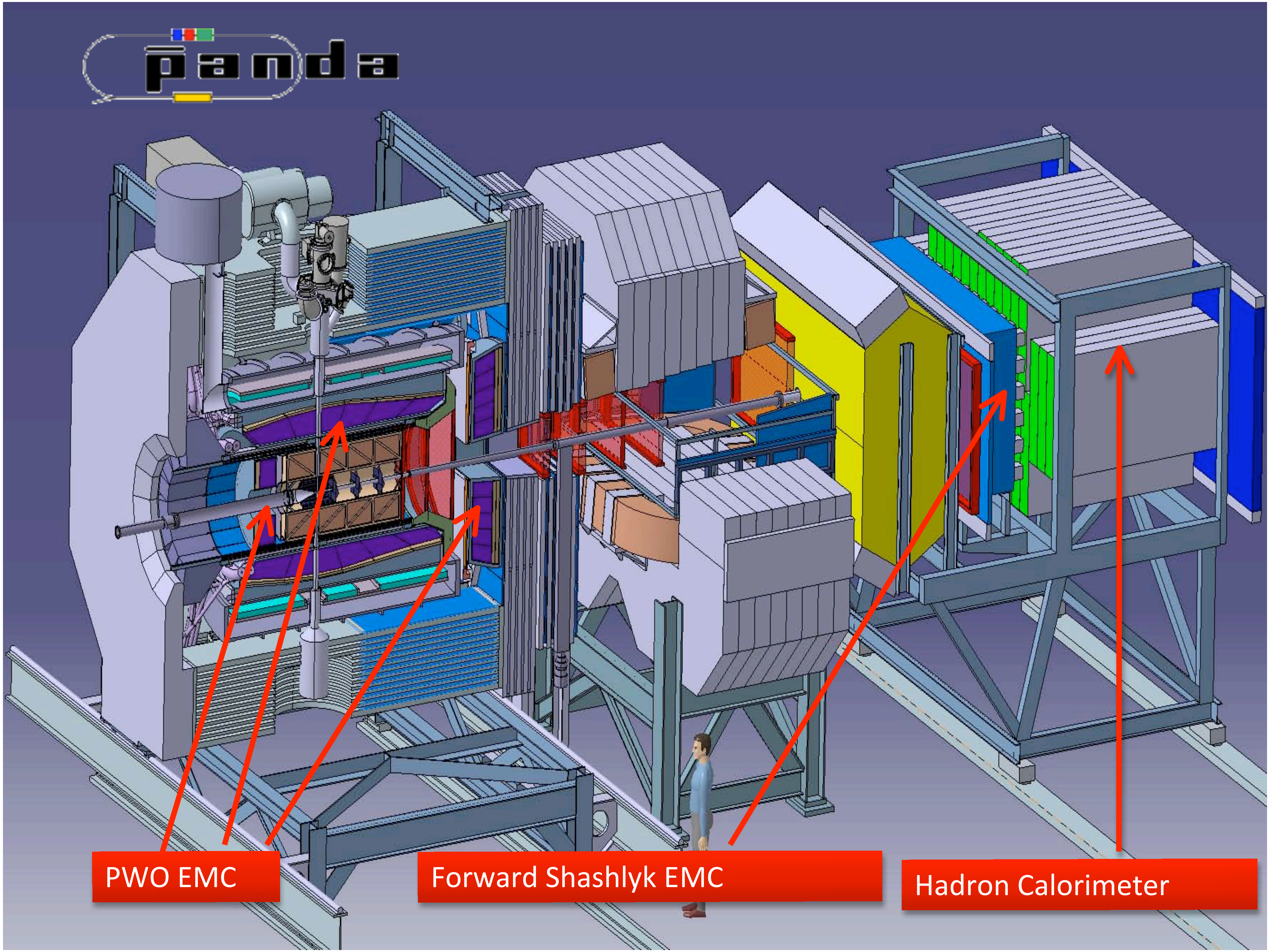

Pellet or cluster-jet target
2T Superconducting solenoid
for high p_t particles
2Tm Dipole for forward tracks


panda
Central Tracker
Silicon Microvertex Detector
Forward Chambers

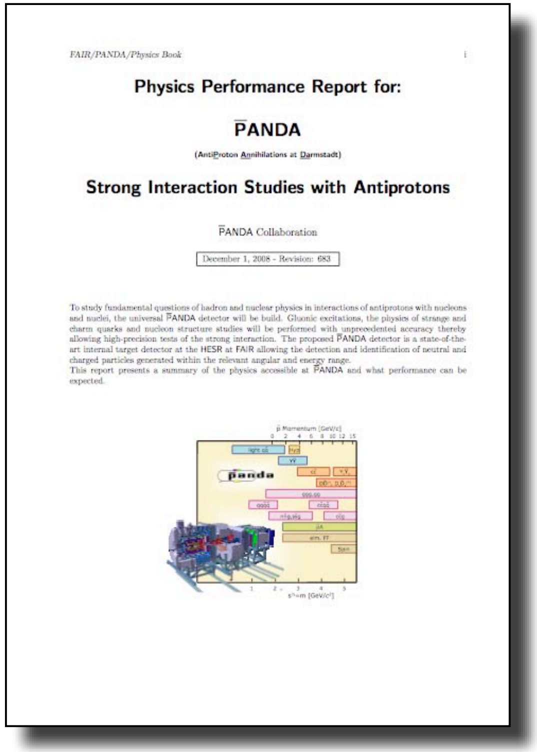

panda
Muon Detectors
Barrel DIRC
Barrel TOF
Endcap DIRC
Forward TOF
Forward RICH


panda
PWO EMC
Forward Shashlyk EMC
Hadron Calorimeter

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

2008 has seen a big effort of the Collaboration preparing the PANDA 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.

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Benchmark Channels

PANDA 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:

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

$\chi_{c1}\pi^0\pi^0$ ← → $D^0\overline{D}^{0*}$

Signal & Background reactions

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

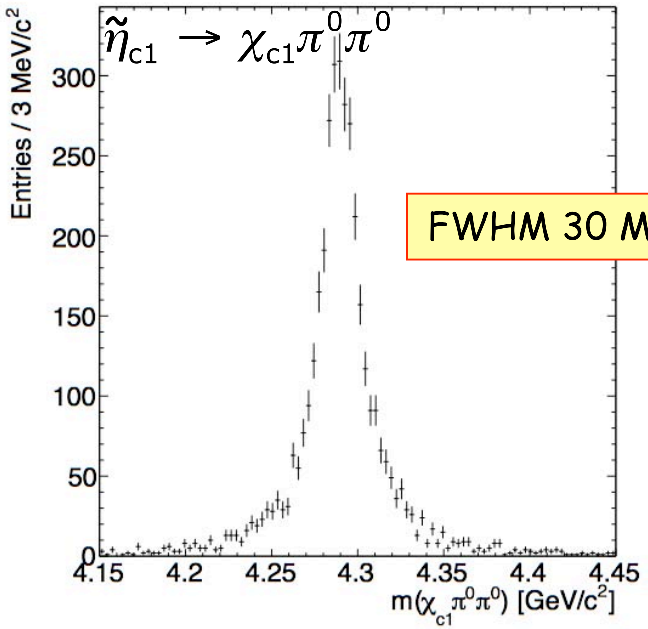
Signal & Background reactions

$\bar{p}p \rightarrow$	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%

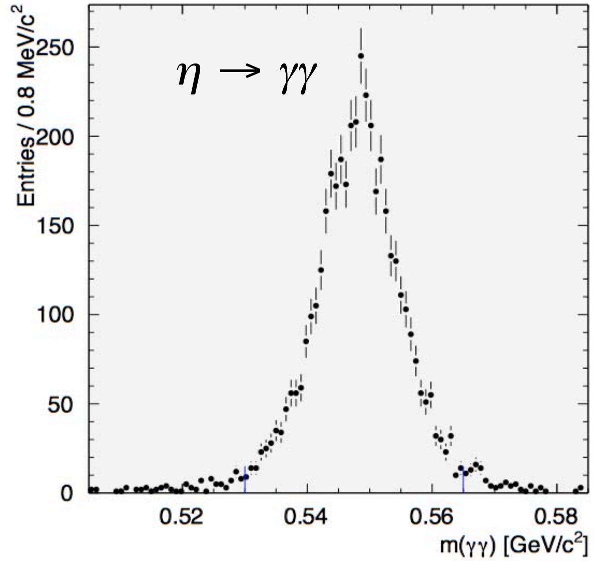
Charmonium hybrid

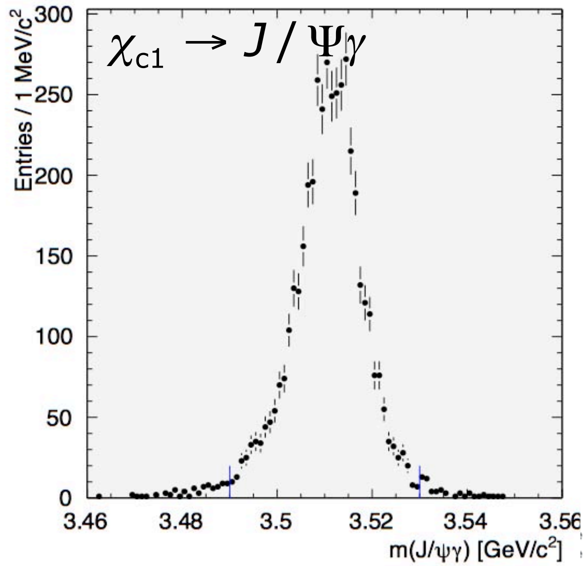
$\bar{p}p \rightarrow \tilde{\eta}_{c1}\,\eta$

$\tilde{\eta}_{c1} \rightarrow \chi_{c1}\pi^0\pi^0$



FWHM 30 MeV/c^2





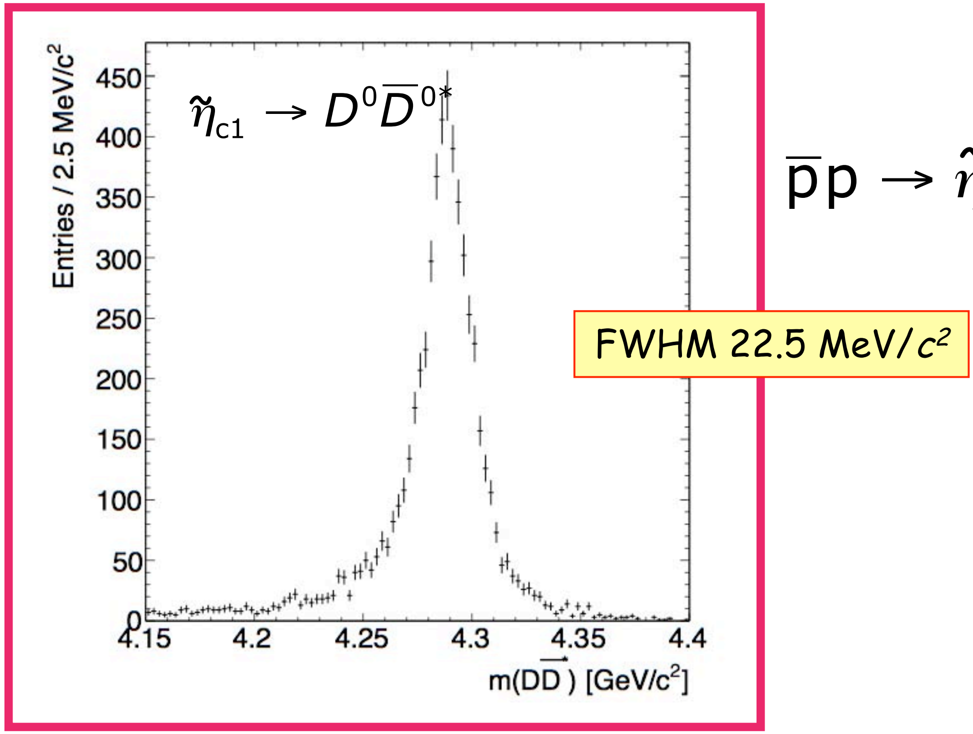
We generated $2\cdot10^5$ events at 15 GeV/c with:

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

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

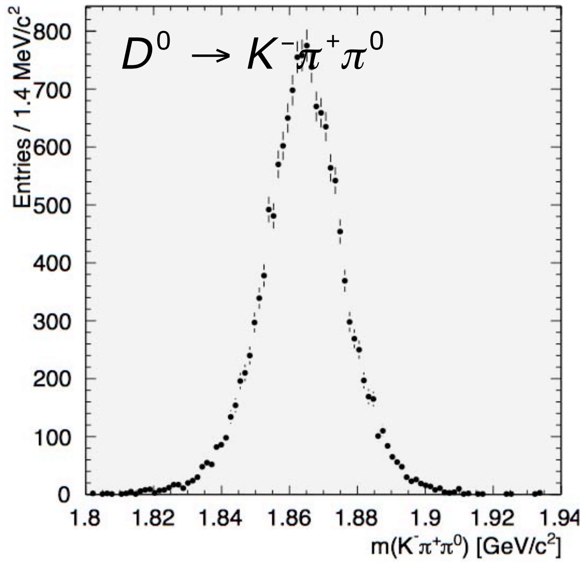
9C fit: beam, η, χ_{c1}, J/Ψ and π^0 mass constraints. Final reconstruction efficiency 6,83%, background suppression 10^3

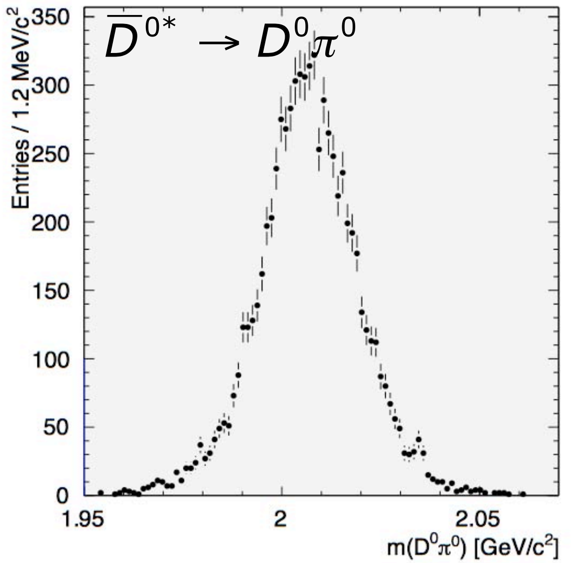
Charmonium hybrid



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

$\to D^0\overline{D}^{0*}$





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

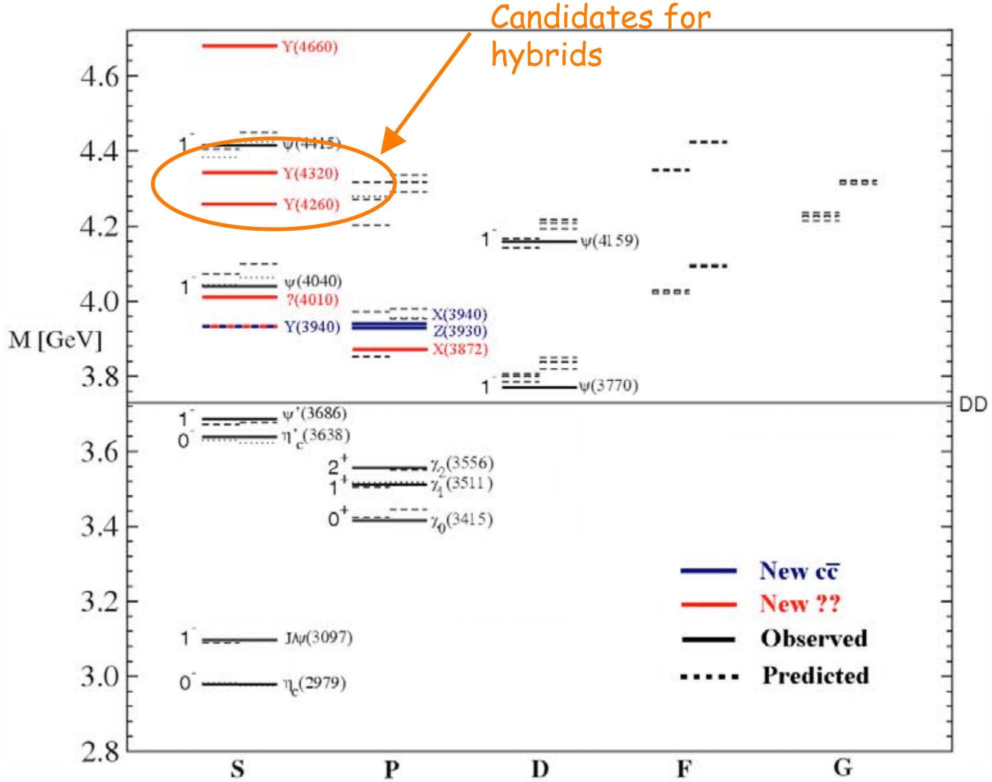
$$\overline{D}^{0*} \to D^0\pi^0 \quad D^0 \to K^-\pi^+\pi^0 \quad \eta \to \gamma\gamma$$

11C fit: beam, D^0, $\overline{D}^{0*}$, η and π^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 PANDA spectrometer with sufficient event rates and background suppression.



We concentrated on the formation reactions:

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

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

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Y(3940)

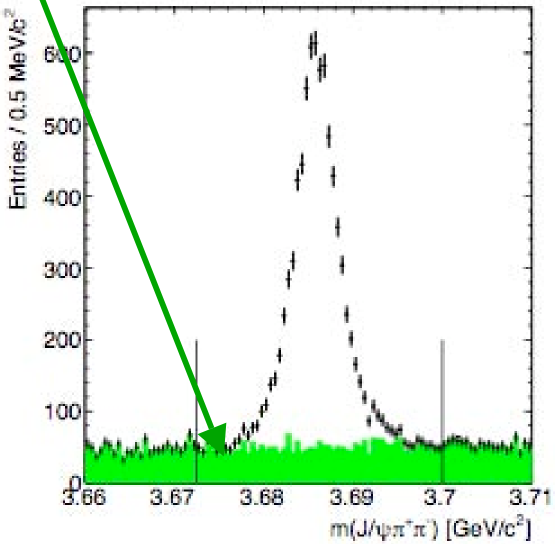
$\bar{p}p \to Y(3940) \to J/\Psi\omega$ 10^4 signal events have been generated, ~10^6 for each background reaction

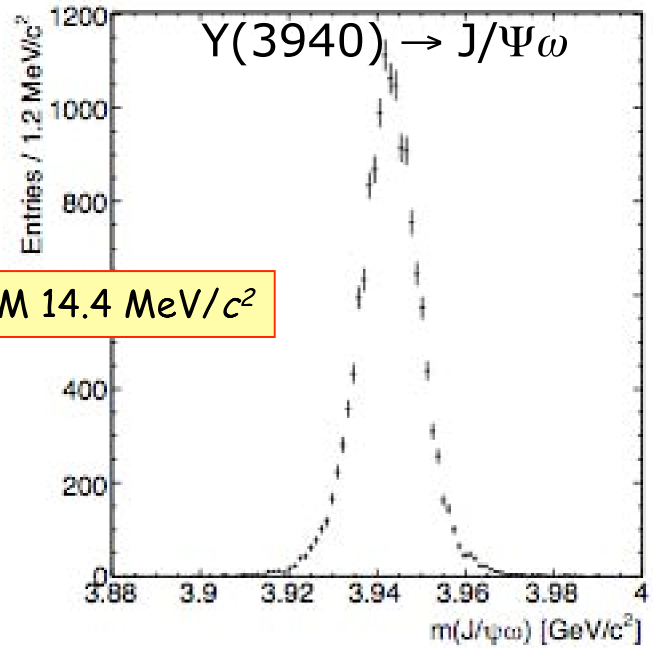
$J/\Psi \to e^+e^-$, $\omega \to \pi^+\pi^-\pi^0$

Background reactions

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

Reaction $\bar{p}p \to$	σ	$\mathcal{B}$
$Y \to J/\psi\omega$	σ_S	$5.2\,\% \times \mathcal{B}(Y \to J/\psi\omega)$
$\pi^+\pi^-\pi^0\rho^0$	149 μb*	100 %
$\pi^+\pi^-\pi^-\rho^+$	198 μb*	100 %
$\pi^+\pi^-\omega$	23.9 μb*	100 %
$\psi(2S)\pi^0$	55 pb	3.73 %
$Y \to J/\psi\rho\pi$	σ	$5.9\,\% \times \mathcal{B}(Y \to J/\psi\rho\pi)$





FWHM 14.4 MeV/c^2

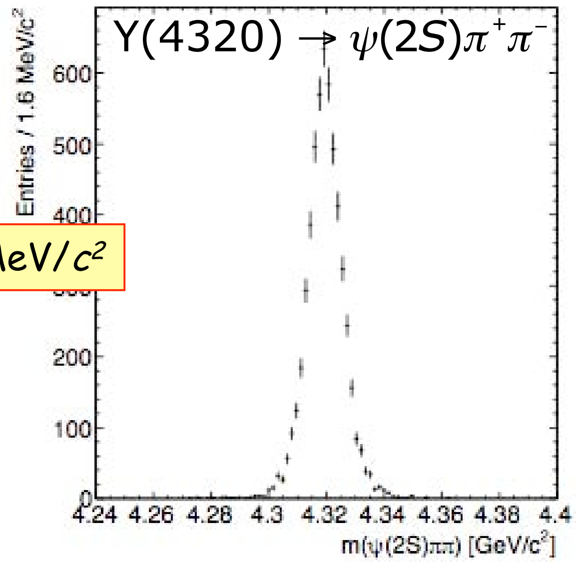
Reaction	η
$\pi^+\pi^-\pi^0\rho^0$	$> 1.1 \cdot 10^9$
$\pi^+\pi^-\pi^-\rho^+$	$> 1.05 \cdot 10^9$
$\pi^+\pi^-\omega$	$> 1.08 \cdot 10^8$
$\psi(2S)\pi^0$	$3.33 \cdot 10^3$
$J/\psi\pi^-\rho^+$	25
$J/\psi\pi^0\rho^0$	22.1

6C fit: beam, J/Ψ, π^0 mass constraints. Reconstruction eff. 14,7%, background suppression for different reactions

Y(4320)

$\bar{p}p \rightarrow Y(4320) \rightarrow \psi(2S)\pi^+\pi^-$
$\quad\quad \hookrightarrow J/\Psi\pi^+\pi^-$
$\quad\quad\quad \hookrightarrow e^+e^-$

$2 \cdot 10^4$ 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

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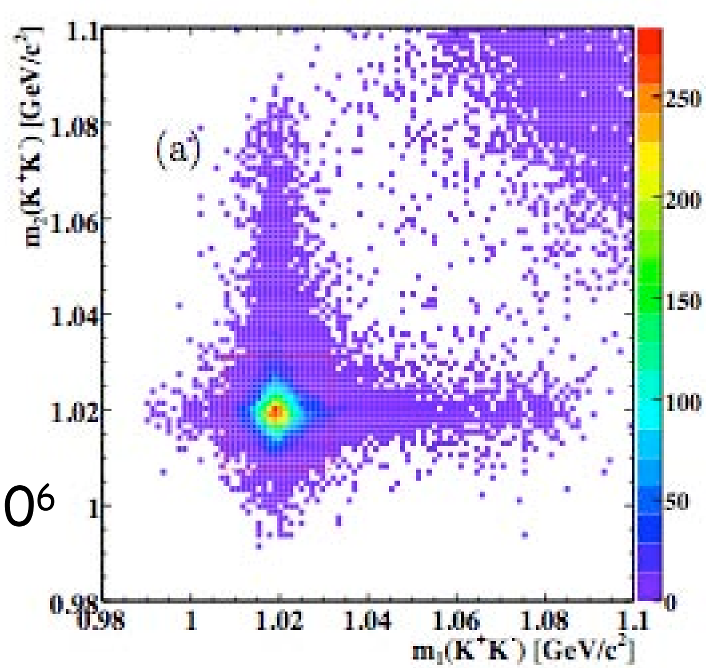
$\bar{p}p \rightarrow f_2(2000\text{-}2500) \rightarrow \phi\phi$

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:

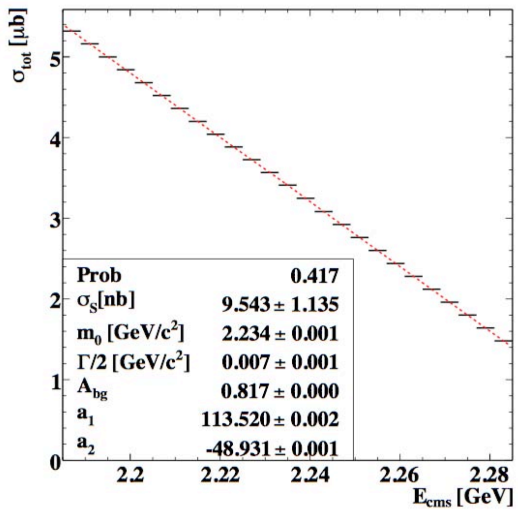
- reconstruction of the signal;
- evaluation of the background level;
- simulation of the energy scan.

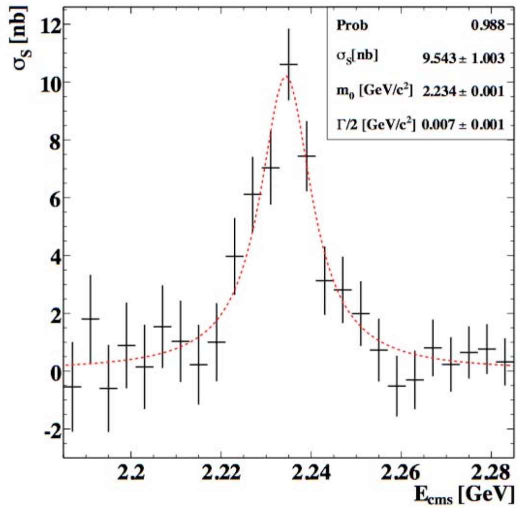
We generated $50 \cdot 10^3$ signal events and 10^6 bck events.

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

σ_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

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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
$\bar{p}p \to (D^0 D^{0*})\eta$:	BR($\Psi \to D^0 D^{0*}$)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 ?)

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