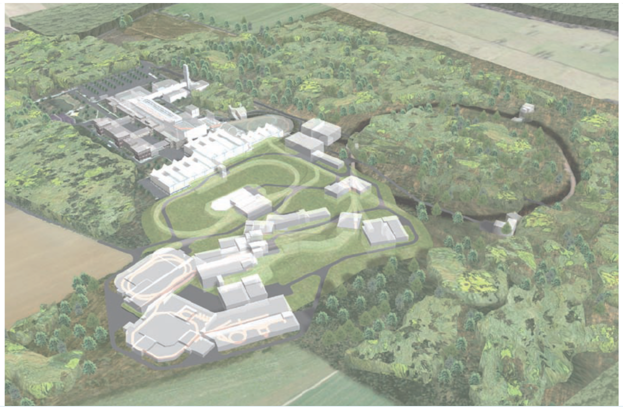
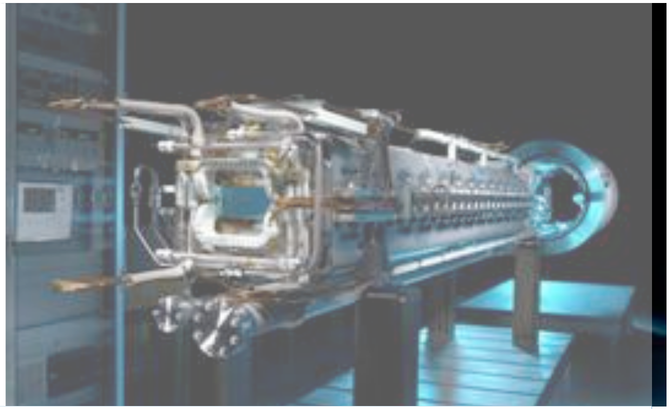


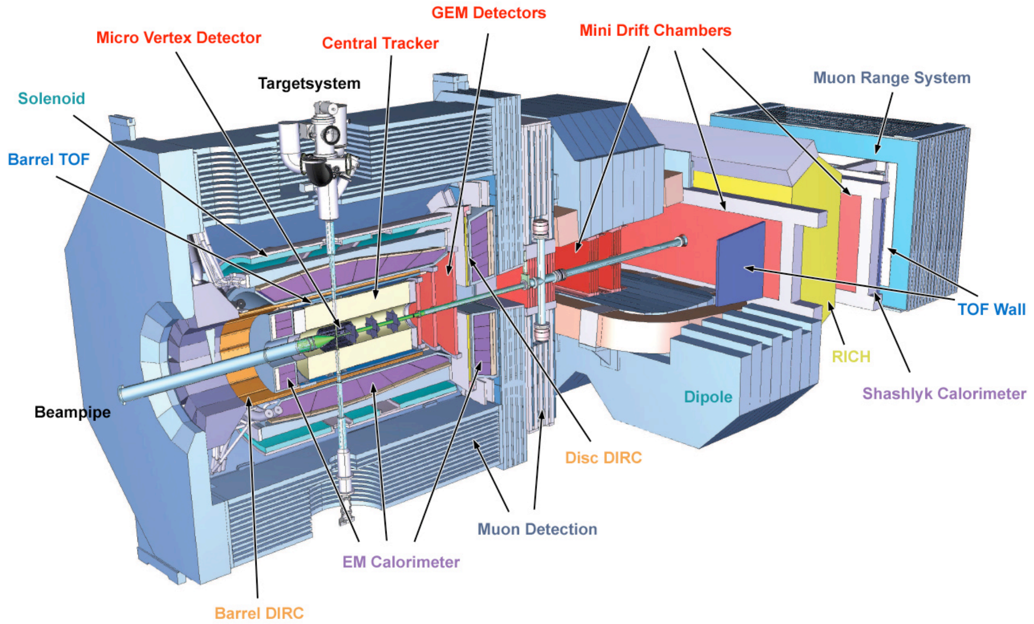


Antiproton Physics with $\bar{\text{P}}$ANDA at FAIR

Paola Gianotti
INFN Istituto Nazionale di Fisica Nucleare

PANDA Scientific Program

- Charmonium/open charm spectroscopy
- Exotic states
- Strange and charmed baryons
- Hadrons in the nuclear medium
- Hypernuclear physics
- Nucleon structure via e.m. processes



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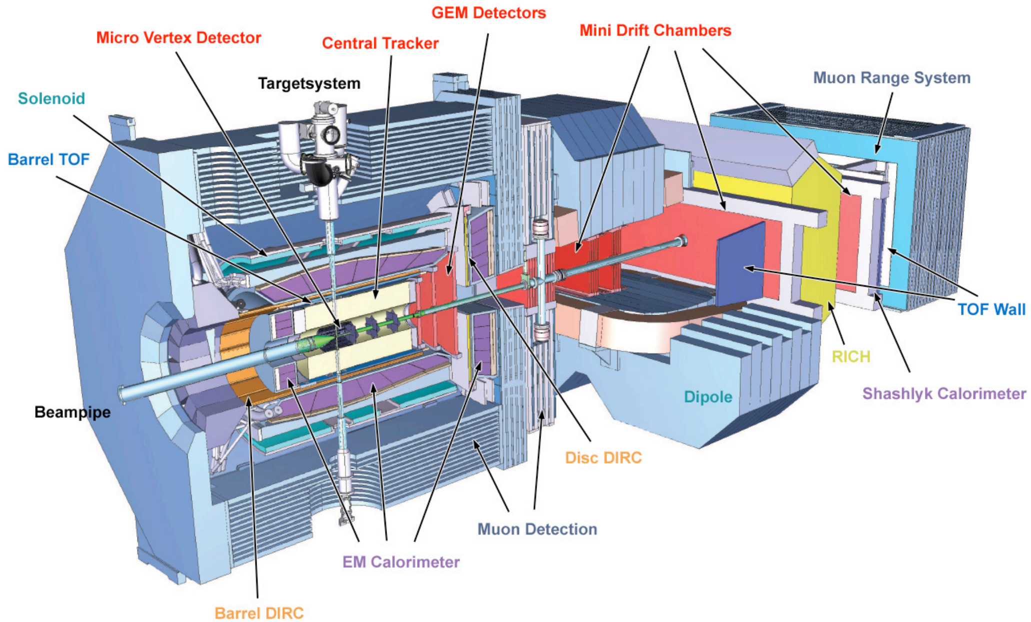
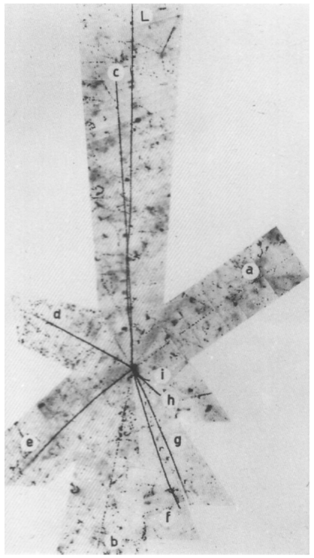


Antiproton physics has a great past

- $\bar{p}p$-Colliders (SPS CERN, Tevatron Fermilab)
- Conventional $\bar{p}$-beams (LBL, BNL, CERN, Fermilab, KEK, ...)
- $\bar{p}$-Storage Rings (LEAR, AD (CERN); Antiproton Accumulator (Fermilab))

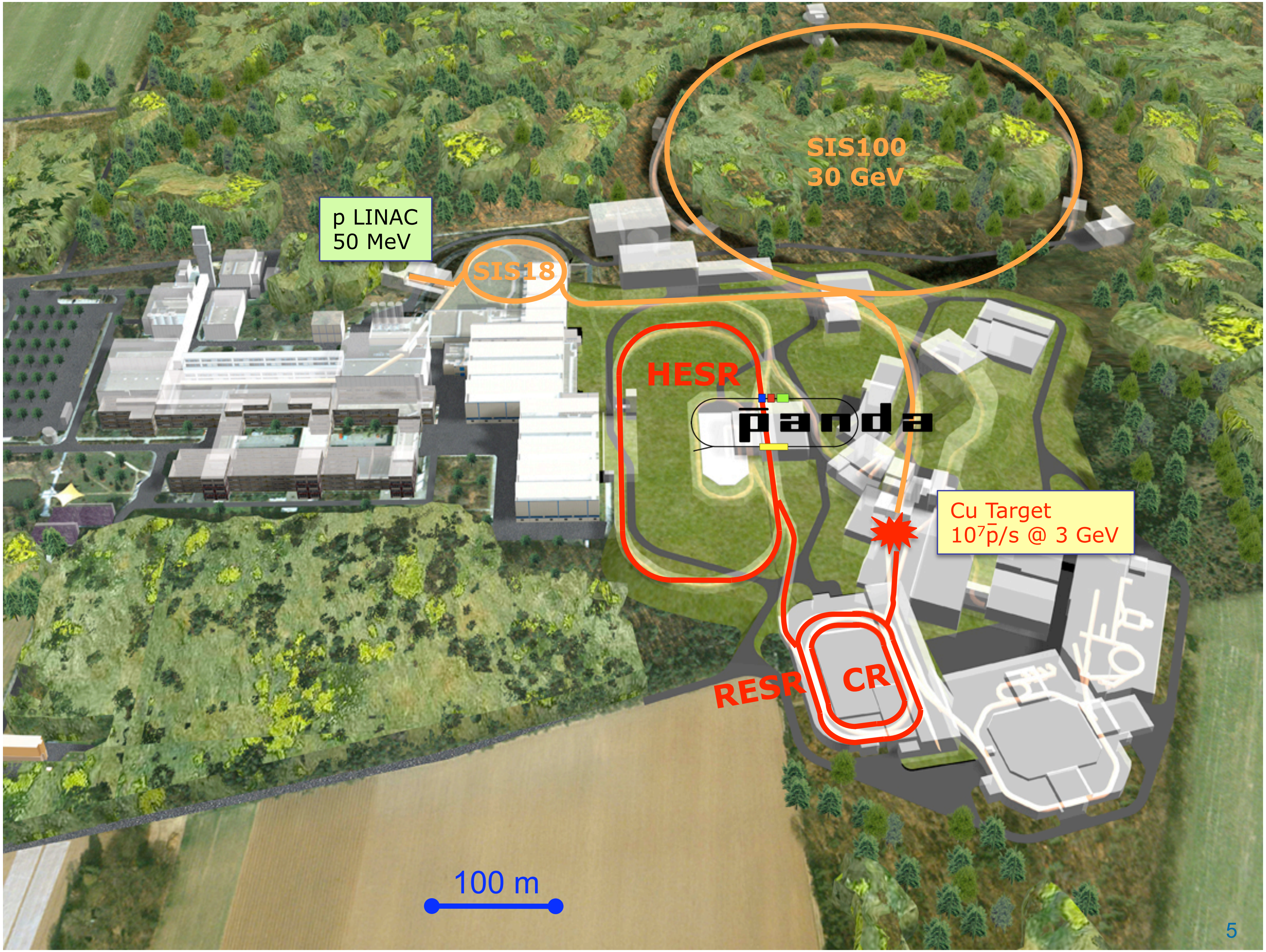
Big and fundamental discoveries and precision measurements where possible thanks to antiprotons:

- Z, $W^{\pm}$ bosons discovery;
- top quark discovery;
- B_s oscillation discovery
- anti-hydrogen production;
- Meson Spectroscopy (u, d, s, c);
- $\bar{p}$-nucleus interaction;
- $\bar{p}$-Atoms;
- $\bar{p}$/p-mass ratio;
- hadron therapy study.

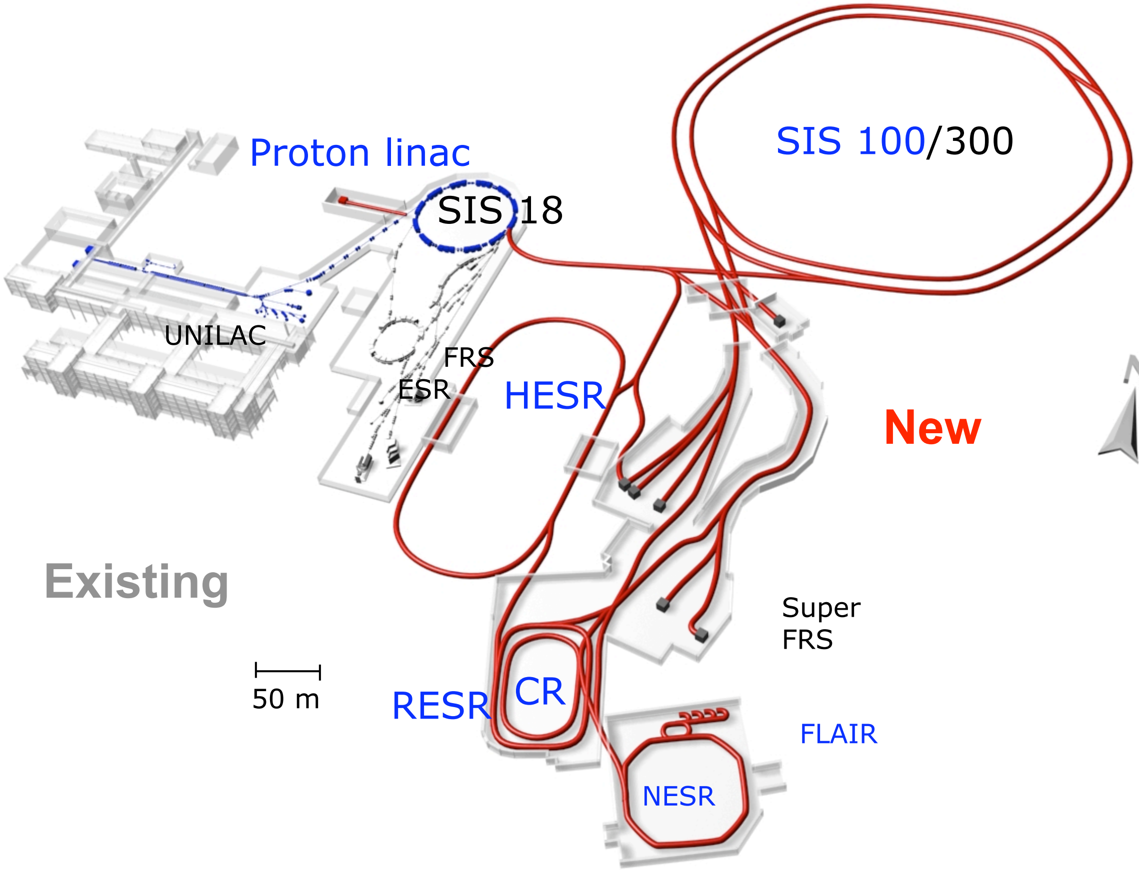


first $\bar{p}$ star obesrved at Berkley by E.Segrè and coll.

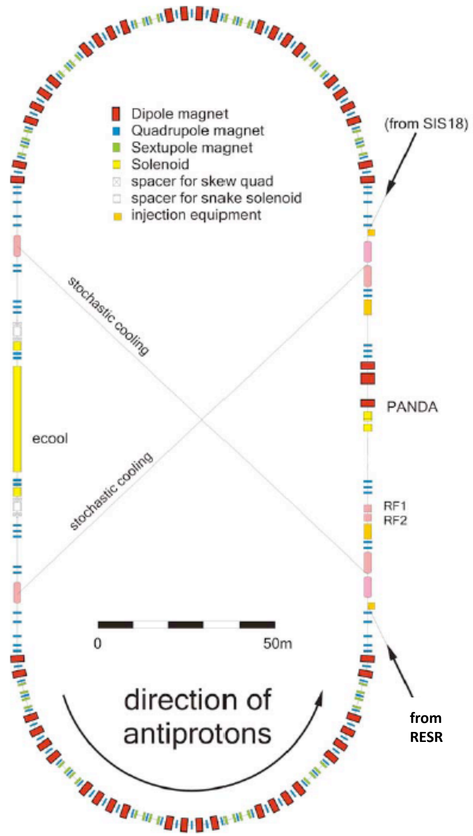
Which is the future of antiproton physics?


SIS100
30 GeV
p LINAC
50 MeV
SIS18
HESR
p̄anda
Cu Target
$10^7 \bar{p}$/s @ 3 GeV
RESR
CR
100 m

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



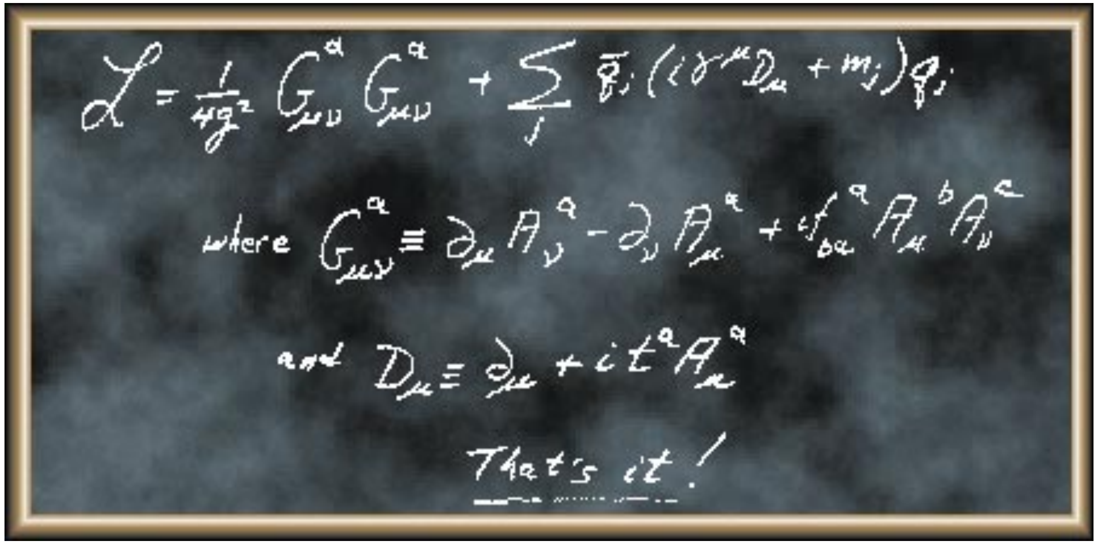
HESR: Storage ring for $\bar{p}$
- Injection of $\bar{p}$ at 3.7 GeV/c
- Slow synchrotron (1.5-15 GeV/c)
- Luminosity up to L~ $2x10^{32}$ $cm^{-2}s^{-1}$
- Beam cooling (stochastic & electron)

Development of Project Staging

2003	**Recommendation by WissenschaftsRat – FAIR Realisation in three stages**						
2005	**Entire Facility** **Baseline Technical Report**						
2007	**Phase A**						**Phase B** SIS300
2009	**Module 0** SIS100	**Module 1** expt areas CBM/HADES and APPA	**Module 2** Super-FRS fixed target area NuSTAR	**Module 3** pbar facility, incl. CR for PANDA, options for NuSTAR	**Module 4** LEB for NuSTAR, NESR for NuSTAR and APPA, FLAIR for APPA	**Module 5** RESR nominal intensity for PANDA & parallel operation with NuSTAR and APPA	**Module 6** SIS300

Modularized Start Version (Modules 0–3)

Quantum Chromodynamics



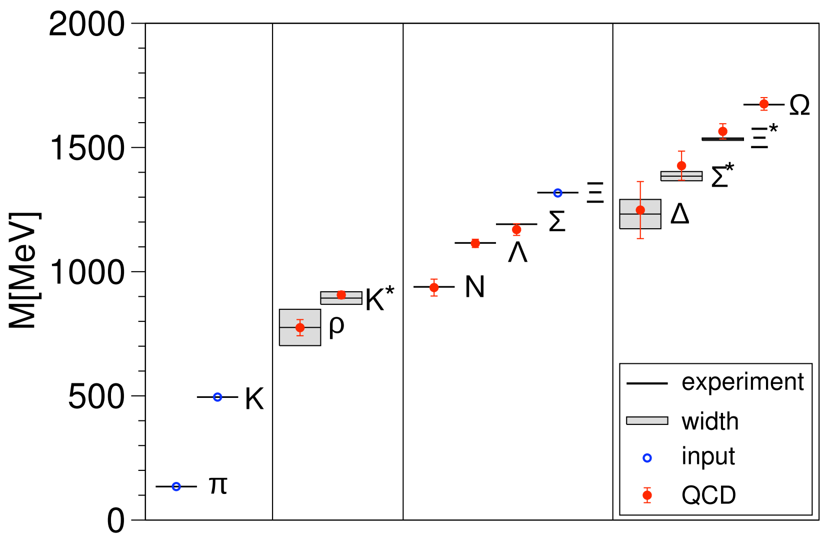
From A. Wilcecz QCD Lecture

The QCD Lagrangian is, in principle, a 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

Theoretical approaches

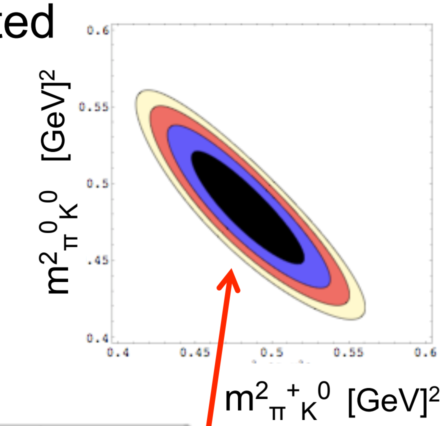
The first approach, Lattice QCD, solves the equations numerically.
That's not easy.
Fortunately, powerful modern computers have made it possible to calculate a few of the key predictions of QCD directly.

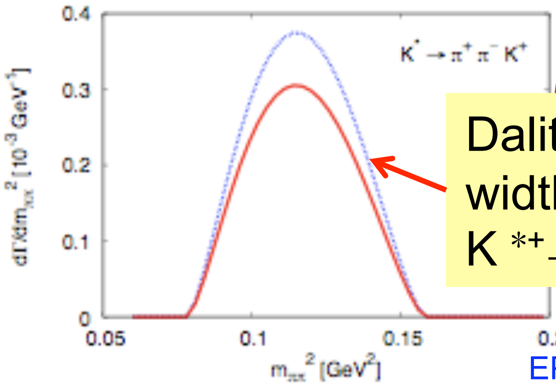


Science **322** (2008) 1224
[arXiv:0906.3599 [hep-lat]].

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

The second approach, Effective Field Theories, creates phenomenological models that are simpler to deal with, but keep resemblance to the real things.
Cross-sections and branching fractions can be predicted





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

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

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)

- $p\bar{p}$ reactions:

  - Most states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled)

Antiproton 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:

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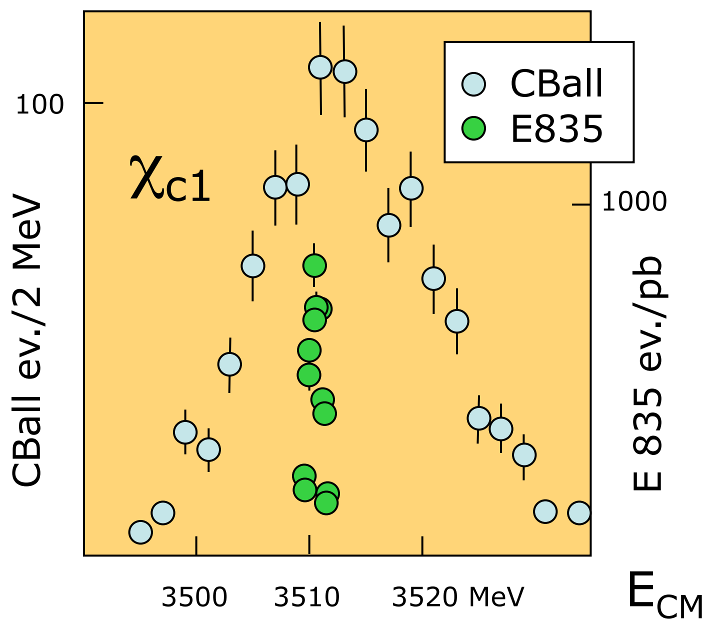

Antiproton power

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

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

- e^+e^- interactions:

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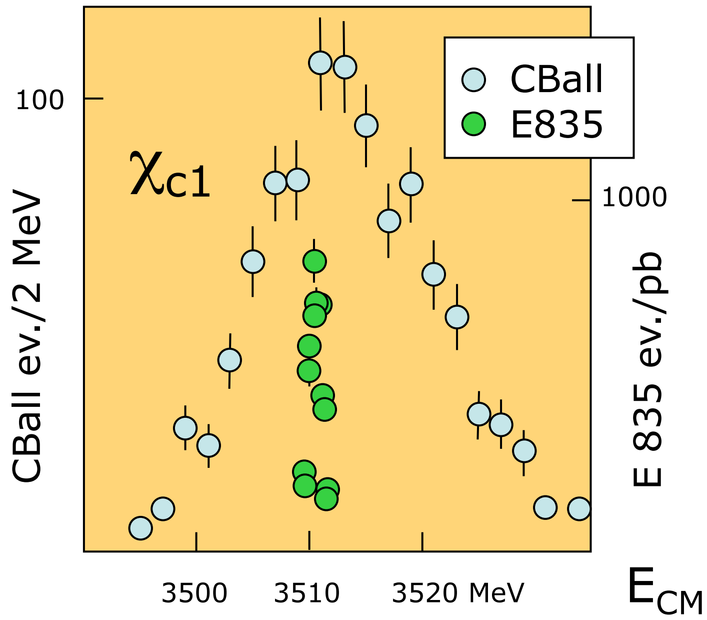


$Br(p\bar{p} \to \eta_c) = 1.2\ 10^{-3}$

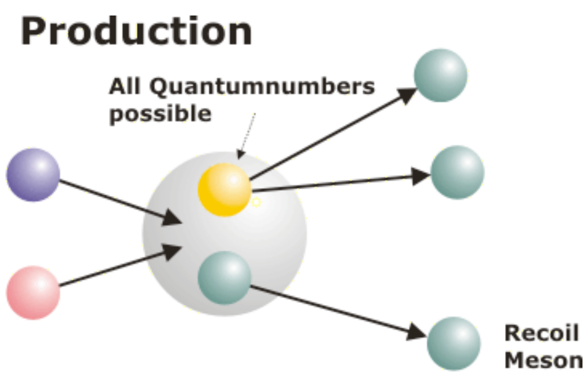
$Br(e^+e^- \to \psi) \cdot Br(\psi \to \gamma\eta_c) = 2.5\ 10^{-5}$

Spectroscopy with antiprotons

There are two mechanisms to access particular final states:

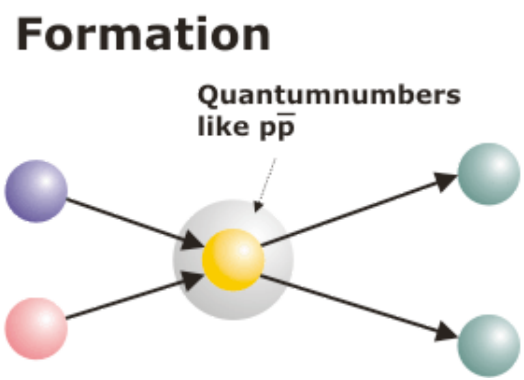
Production

all J^{PC} available



Formation

only selected J^{PC}



Spectroscopy with antiprotons

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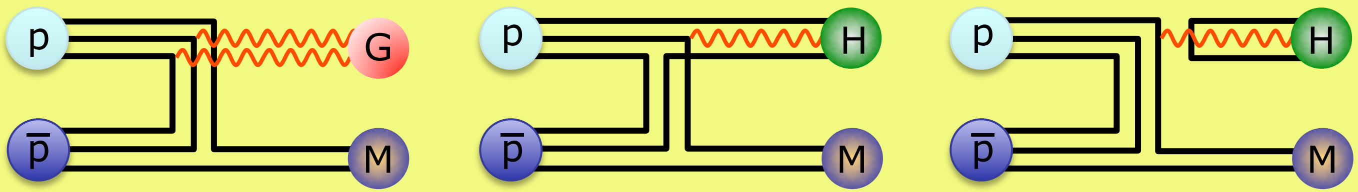
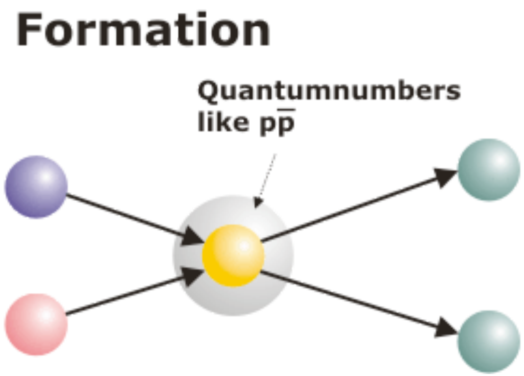


Even exotic quantum numbers can be reached σ ~100 pb

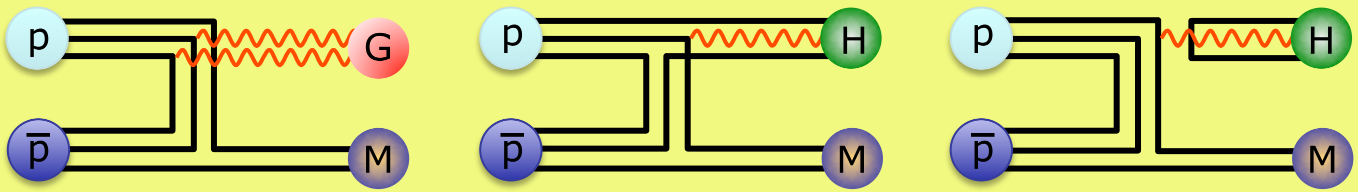
Formation

only selected J^{PC}



Spectroscopy with antiprotons

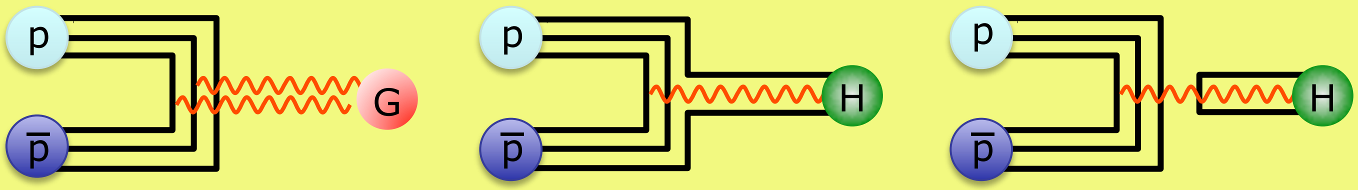
Production



Even exotic quantum numbers can be reached σ ~100 pb

All ordinary quantum numbers can be reached σ ~1 µb

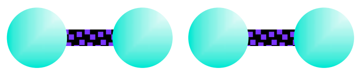
Formation



Exotic hadrons

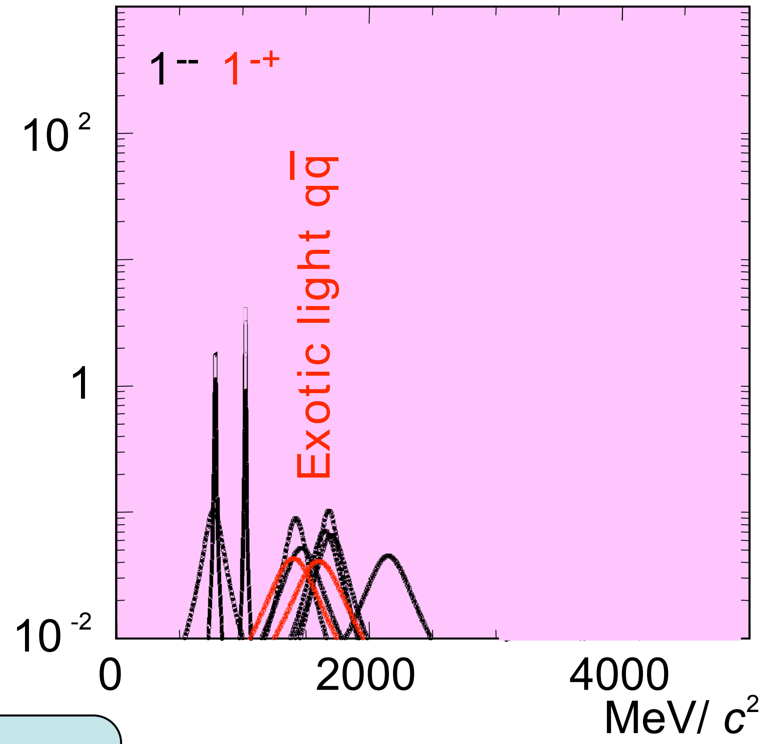
The QCD spectrum is much rich than that of the naive quark model
also the gluons can act as hadron components

The "exotic hadrons" fall in 3 general categories:

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

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

Glueballs gg 



In the light meson spectrum exotic states overlap with conventional states

Exotic hadrons

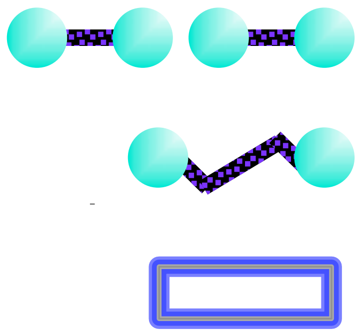
The QCD spectrum is much rich than that of the naive quark model also the gluons can act as hadron components

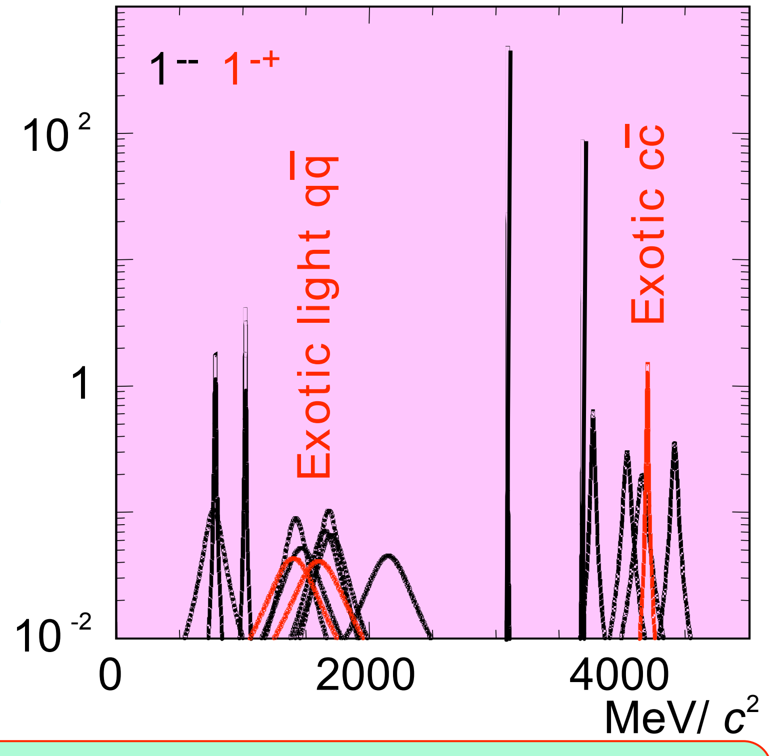
The "exotic hadrons" fall in 3 general categories:

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

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

Glueballs gg

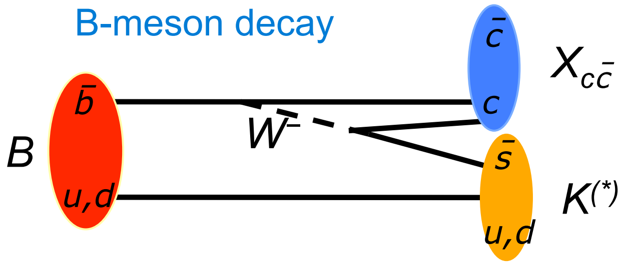




In the $c\bar{c}$ meson spectrum the density of states is lower and therefore the overlap

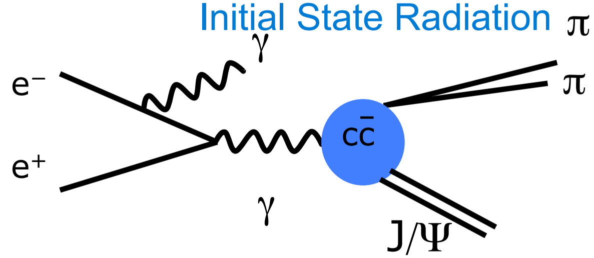
XYZ Mesons

B-meson decay



X(3872) Belle, Babar, Cleo, CDF, D0
Y(3940) Belle, Babar
Y(4140)? CDF
Z(4430)
Z_1(4050) } Belle
Z_2(4250)

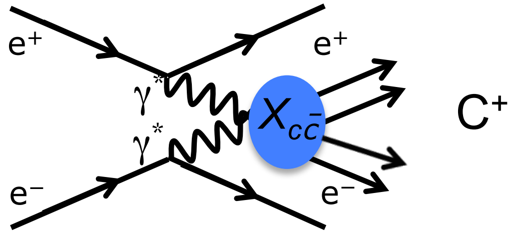
Initial State Radiation



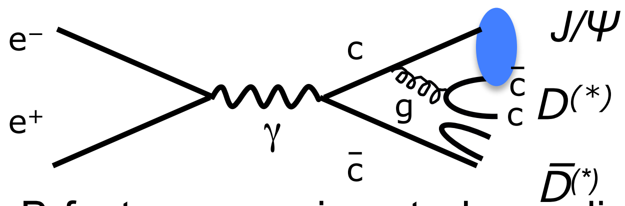
1^{--} states
X(4008)? Belle
Y(4260) BaBar, Belle,CLEO
Y(4350) BaBar, Belle
Y(4660) Belle

X(3915) Belle
Z(3930) Belle
Y(4350) Belle

γγ-collisions



Associate production
$e^+e^- \to J/\Psi\ X_{c\bar{c}}$



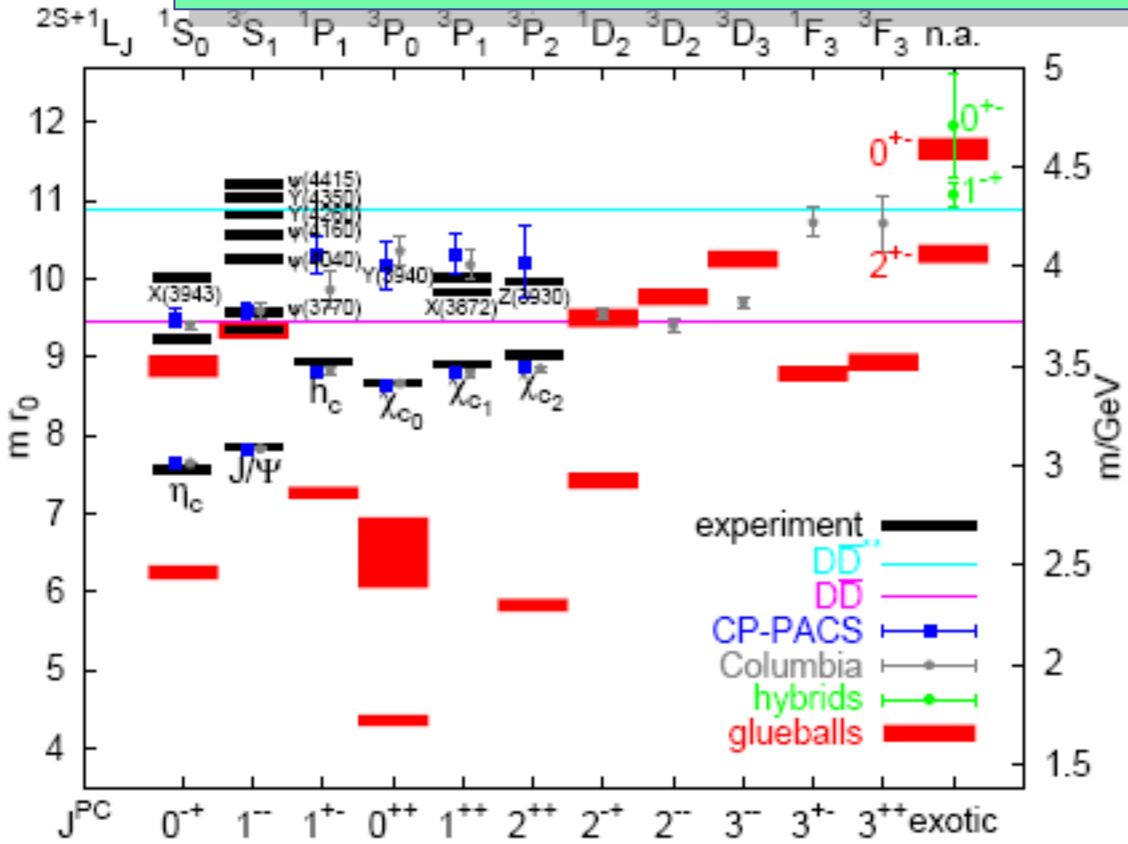
X(3940) Belle
X(4160) Belle

The B-factory experiments have discovered a large number of candidates for charmonium and charmonium-like meson states, many of which can not be easily accommodated by theory. State parameters are still largely unknown. Few events collected in 10 years of running

PANDA will detect 100 events per day

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

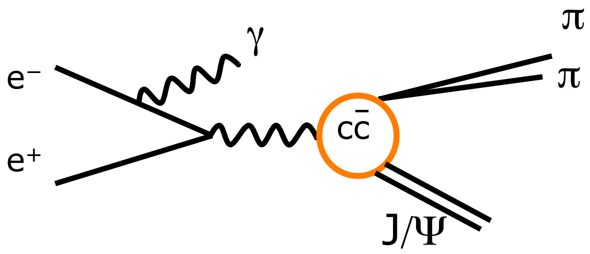
arXiv:hep-lat/0608004

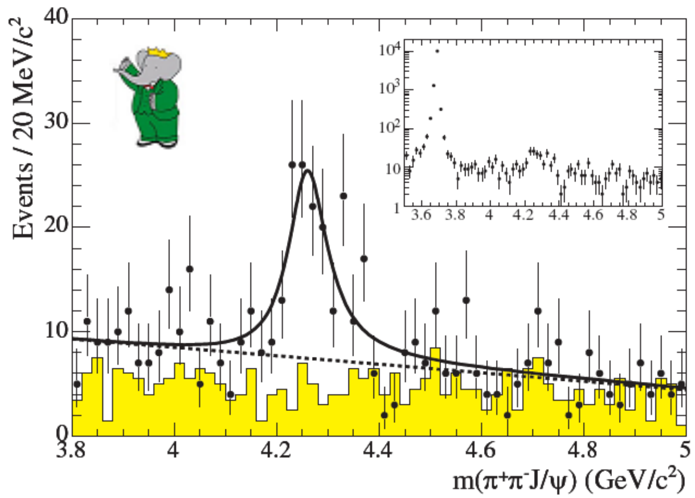
Quantum numbers assignment become clear only with high statistics and different final states

Y(4260)

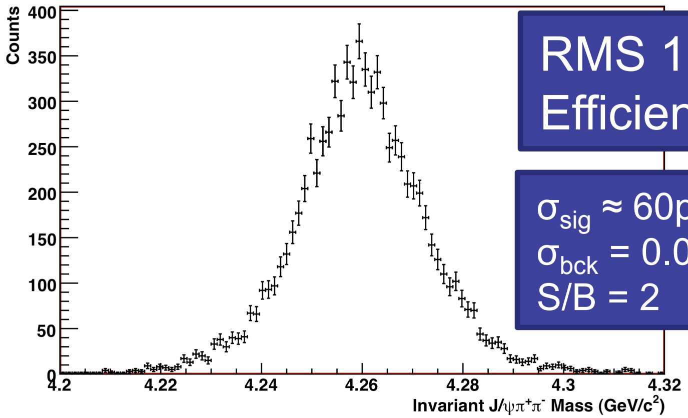
This state has been discovered by BaBar with the technique of initial state radiation in one year of data taking

PRL95, 142001 (2005)





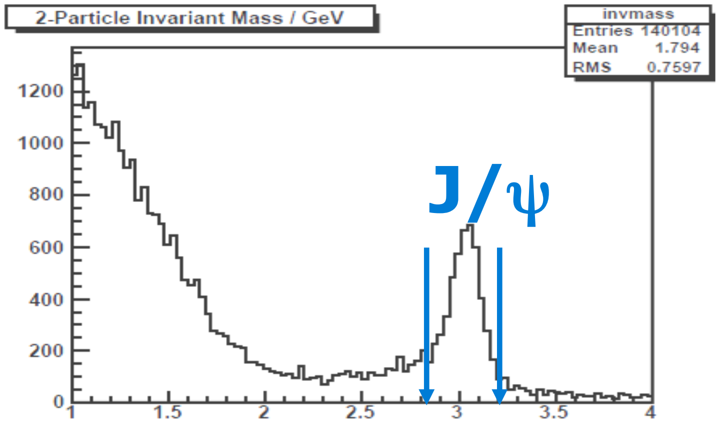
Panda can study $\bar{p}p \rightarrow Y(4260) \rightarrow J/\Psi\pi^+\pi^-$



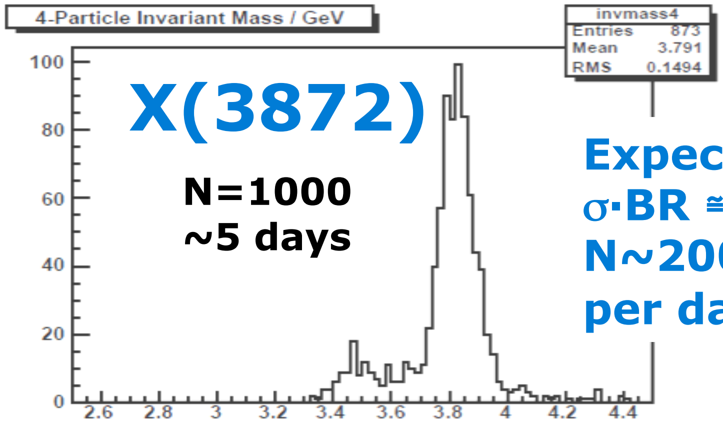
RMS 13.4 MeV
Efficiency 33%

$\sigma_{sig} \approx 60$pb
$\sigma_{bck} = 0.046$mb
S/B = 2

X(3872) at PANDA $\bar{p}p \to J/\Psi\pi^+\pi^-$

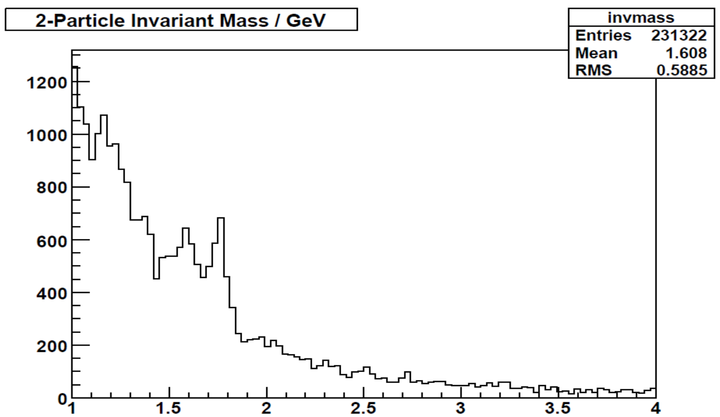


2-Particle Invariant Mass / GeV



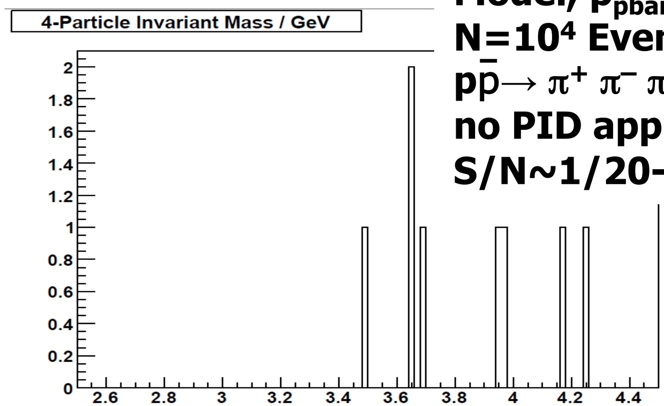
4-Particle Invariant Mass / GeV

Expected Yield:
$\sigma \cdot BR \cong 250$ pb
N~200 events per day



2-Particle Invariant Mass / GeV

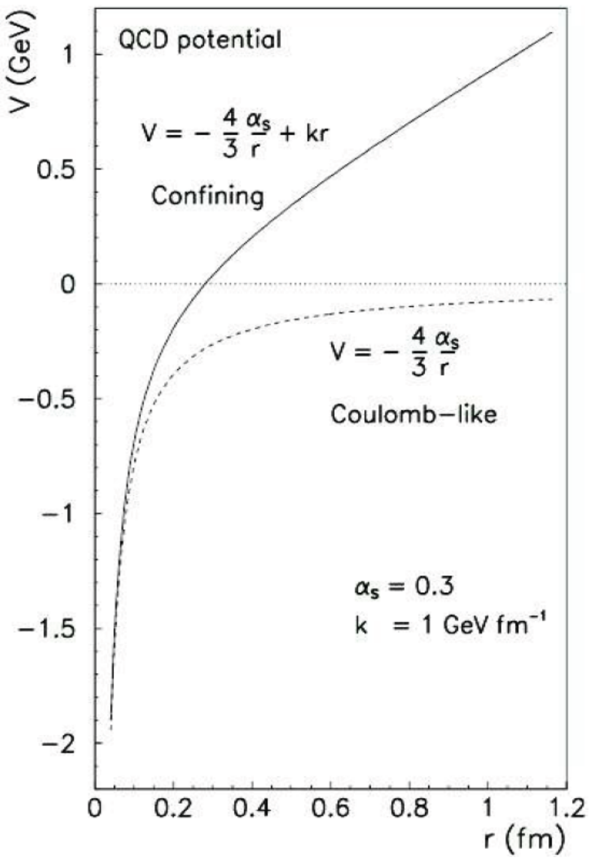
Background: Dual Parton Model, p_{pbar}=6.991 GeV/c, N=10^4 Events
$\bar{p}p \to \pi^+\pi^-\pi^+\pi^-$ σ~0.05 mb
no PID applied
S/N~1/20-1/30



4-Particle Invariant Mass / GeV

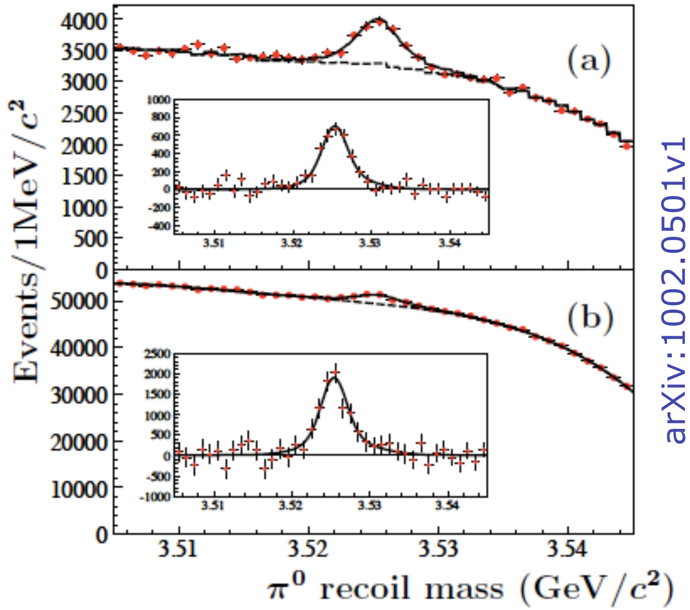
$h_c\ {}^1{}_1P$ state

A precise knowledge of h_c parameters will determine the spin component of $q\bar{q}$ potential.



$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr + V_{LS} + V_{SS} + V_T$$

Seen in $e^+e^- \to \Psi(2S) \to \pi^0 h_c \to \pi^0 \gamma \eta_c$



arXiv:1002.0501v1

h_c $^1{}_1P$ state

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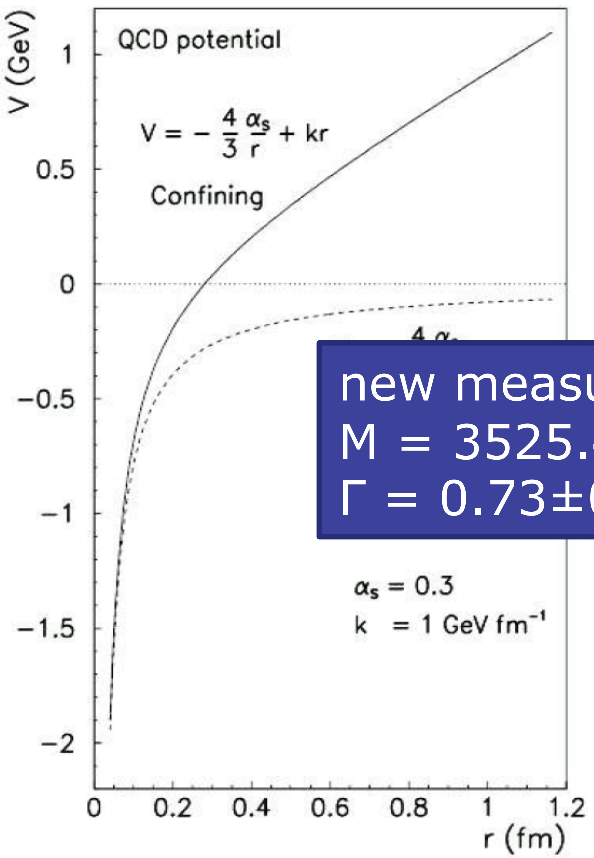

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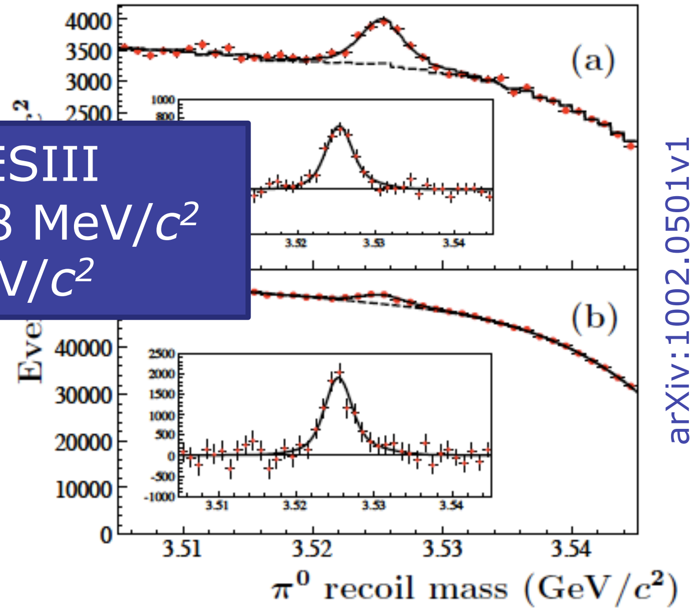


new measurement by BESIII
M = 3525.40±0.13±0.18 MeV/c^2
Γ = 0.73±0.45±0.28 MeV/c^2

arXiv:1002.0501v1

h_c $^1{}_1P$ state @ $\bar{P}ANDA$

$h_c \to \eta_c\gamma \to 3\gamma$

Good tag with E_γ=503MeV
signal eff. 8.2%

In high luminosity mode
we expect 20 signal events/day

Rejection of main sources of bck

Channel	S/B ratio
$\bar{p}p \to \pi^0\pi^0$	> 94
$\bar{p}p \to \pi^0\gamma$	> 164
$\bar{p}p \to \pi^0\eta$	> 88
$\bar{p}p \to \eta\eta$	> 87
$\bar{p}p \to \pi^0\eta'$	> 250

$h_c \to \eta_c\gamma \to \phi\phi\gamma \to 4K\gamma$

Good tag with E_γ=503MeV
signal eff. 25%

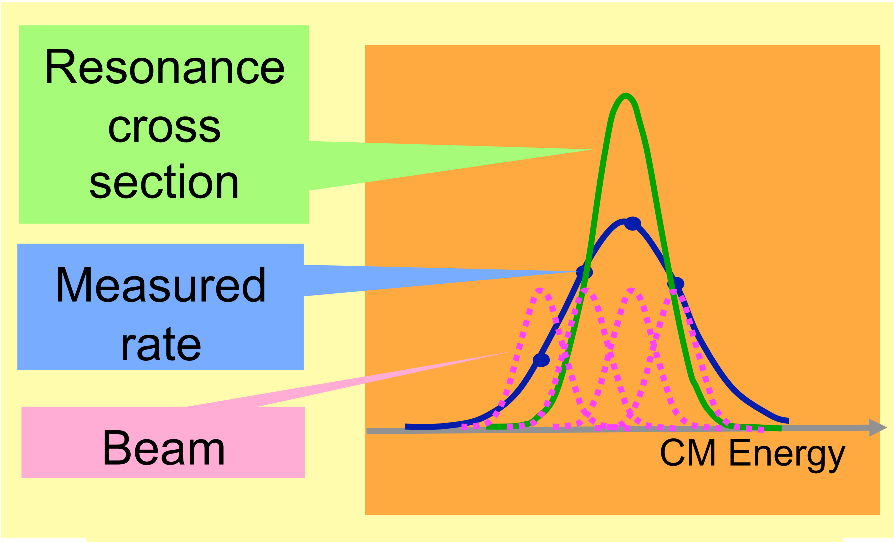
In high luminosity mode
we expect 92 signal
events/day

Rejection of main sources of bck

channel	Signal/Background
$\bar{p}p \to K^+K^-K^+K^-\pi^0$	8
$\bar{p}p \to \phi K^+K^-\pi^0$	8
$\bar{p}p \to \phi\phi\pi^0$	> 10
$\bar{p}p \to K^+K^-\pi^+\pi^-\pi^0$	> 12

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,ΔE)*:

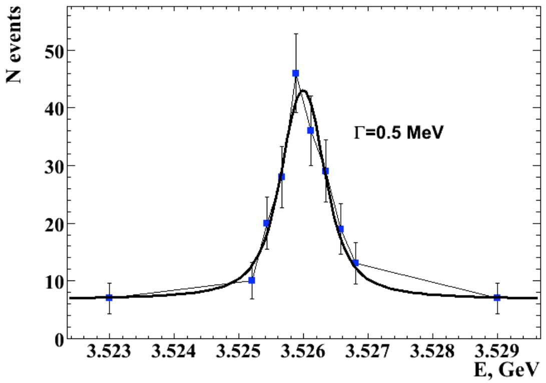
$$\nu = L_0 \{ \varepsilon \int dE f(E,\Delta E) \sigma_{BW}(E) + \sigma_b \}$$

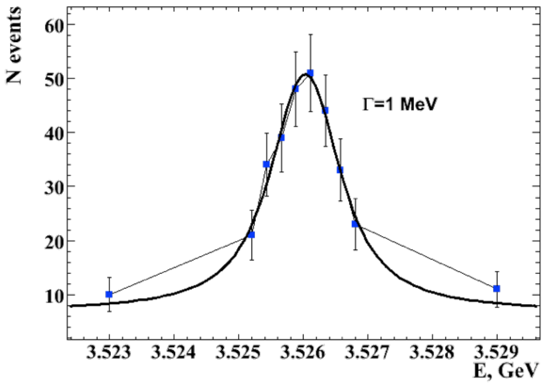
The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

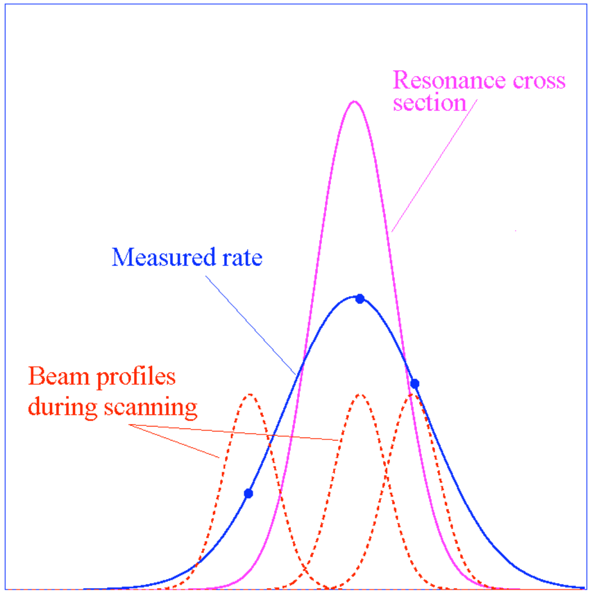
Charmonium states width

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, module 5 available, for the channel: $h_c \to \eta_c\gamma \to \phi\phi\gamma \to 4K\gamma$ with a S/B 8:1







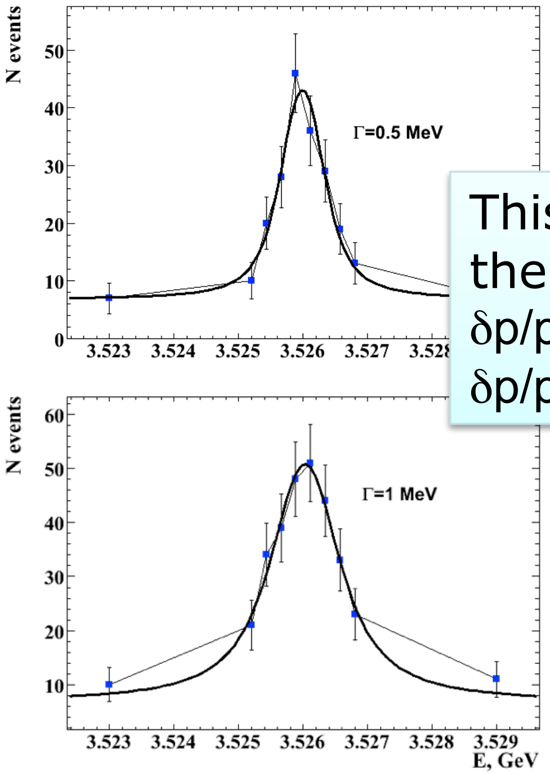
Sensitivity

$\Gamma_{R,MC}$[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

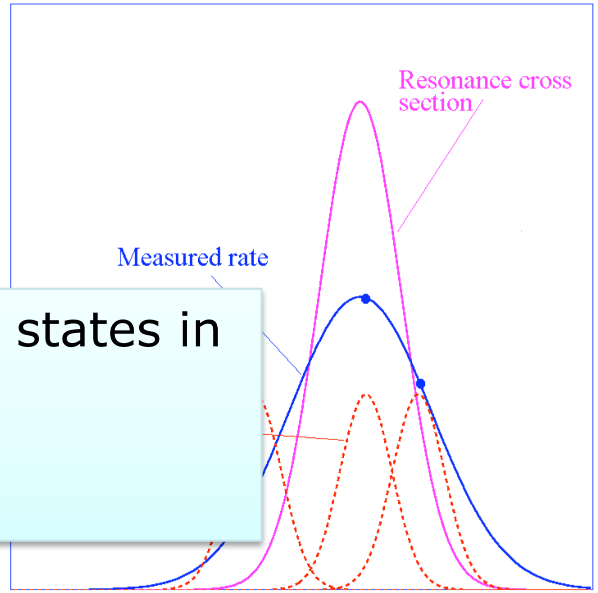
Charmonium states width

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, module 5 available, for the channel: $h_c \to \eta_c\gamma \to \phi\phi\gamma \to 4K\gamma$ with a S/B 8:1



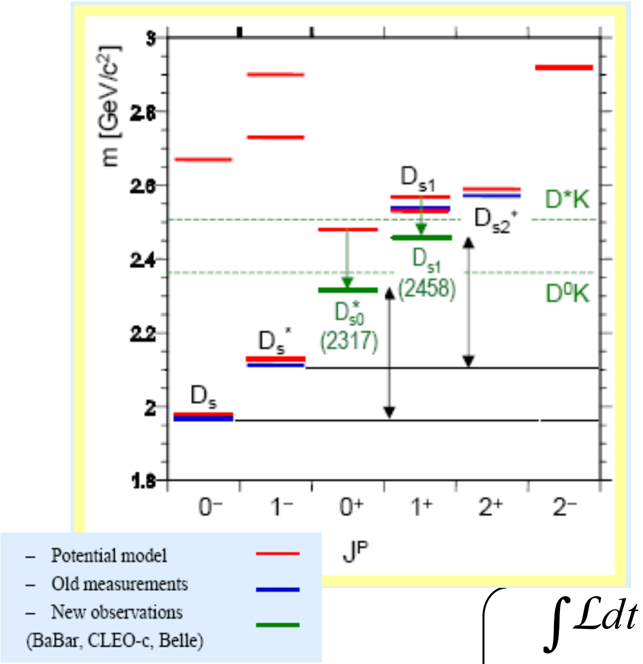
This holds for all known states in the charmonium region
$\delta p/p\ 10^{-4} \to \Gamma$ 100 KeV
$\delta p/p\ 10^{-5} \to \Gamma$ 10 KeV



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

Open Charm: $D_{S0}(2317)$



New mesons consisting of a heavy and a light constituent have been detected. These states are narrow, and due to detector resolution an upper limit for the Γ of few MeV has been defined.

With PANDA a different experimental approach can be tempted since the production cross section around threshold depends on the total width.

input

$$\int \mathcal{L}dt = 126\ pb^{-1} \text{(14 days)}$$

$$S/B = 1/3$$

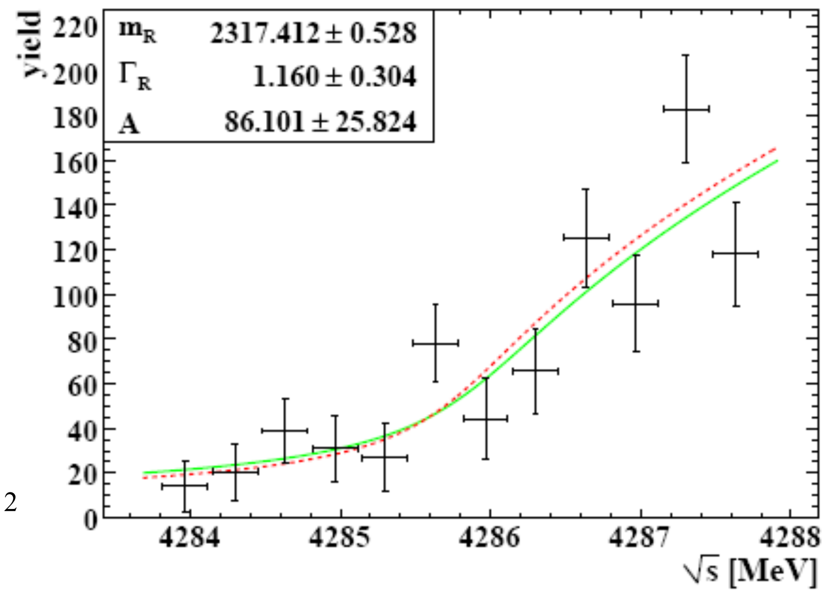
$$\Gamma = 1\ MeV$$

$$m = 2317.30\ MeV/c^2$$

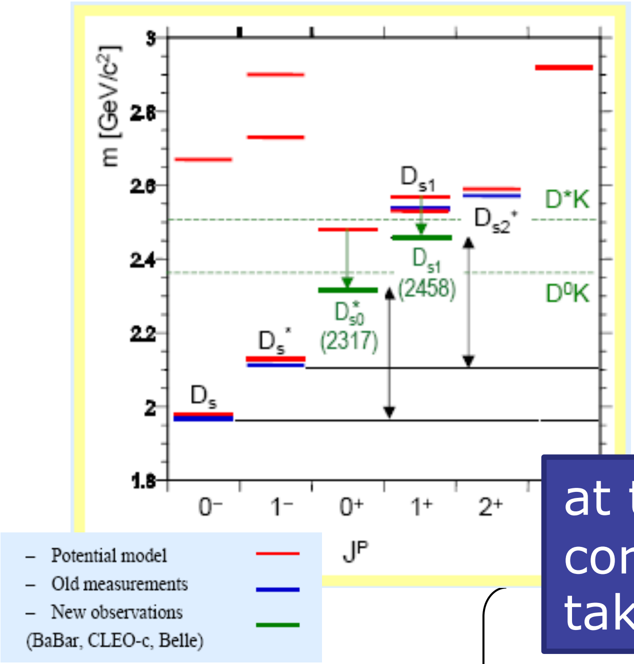
output

$$\Gamma = (1.16 \pm 0.30)\ MeV$$

$$m = (2317.41 \pm 0.53)\ MeV/c^2$$



Open Charm: $D_{S0}(2317)$



New mesons consisting of a heavy and a light constituent have been detected. These states are narrow, and due to detector resolution an upper limit for the Γ of few MeV has been defined.

With PANDA a different experimental approach can be tempted since the production cross section around threshold depends on the total width.

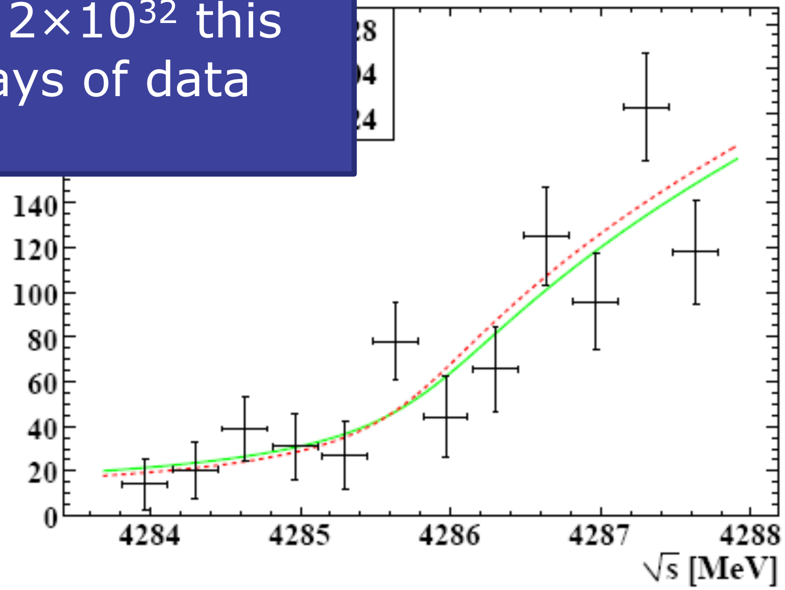
at the luminosity of 2×10^{32} this corresponds a 14 days of data taking

input

$$S/B = 1/3$$
$$\Gamma = 1\ MeV$$
$$m = 2317.30\ MeV/c^2$$

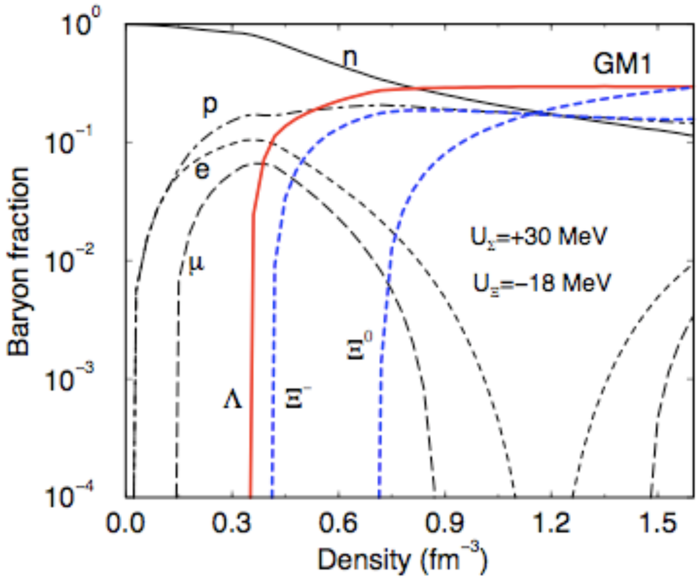
output

$$\Gamma = (1.16 \pm 0.30)\ MeV$$
$$m = (2317.41 \pm 0.53)\ MeV/c^2$$



Baryon-Baryon Interaction

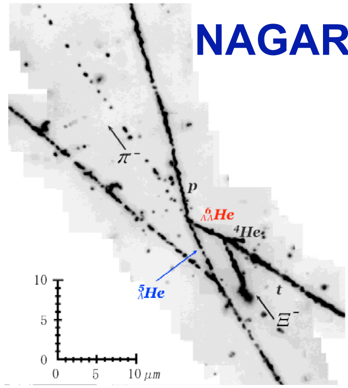
The knowledge of Baryon-Baryon potential is essential for the understanding of the composition of nuclear matter.



The fraction of baryons and leptons in neutron star matter arXiv:0801.3791v1

Nuclear *NN* forces are known, *YN* interaction, thanks to hypernuclear physics, is relatively known, but *YY* interaction is completely unknown, there are just a few double Λ hypernuclear events.

NAGARA



ΛΛ-hypernuclei, Ξ-atoms, Ω-atoms allow to have an insight to more complex nuclear systems containing strangeness (neutron stars, hyperon-stars, strange-quark stars, …)

A new way for double strange systems

- **Up to now double strange systems have been produced by K^- beams in the reaction:**

K^- (N, Ξ^-) K^+ (N- quasi free or bound in nucleus)

  - **S=-2 baryon can be produced via:**

$$\bar{p} + p \longrightarrow \Xi^- + \Xi^+$$
$$\bar{p} + n \longrightarrow \Xi^- + \overline{\Xi}^0$$

$\sigma_{reaction}$ = 2μb at 3GeV/c
700.000$\Xi^-\Xi$bar /h

Goal:

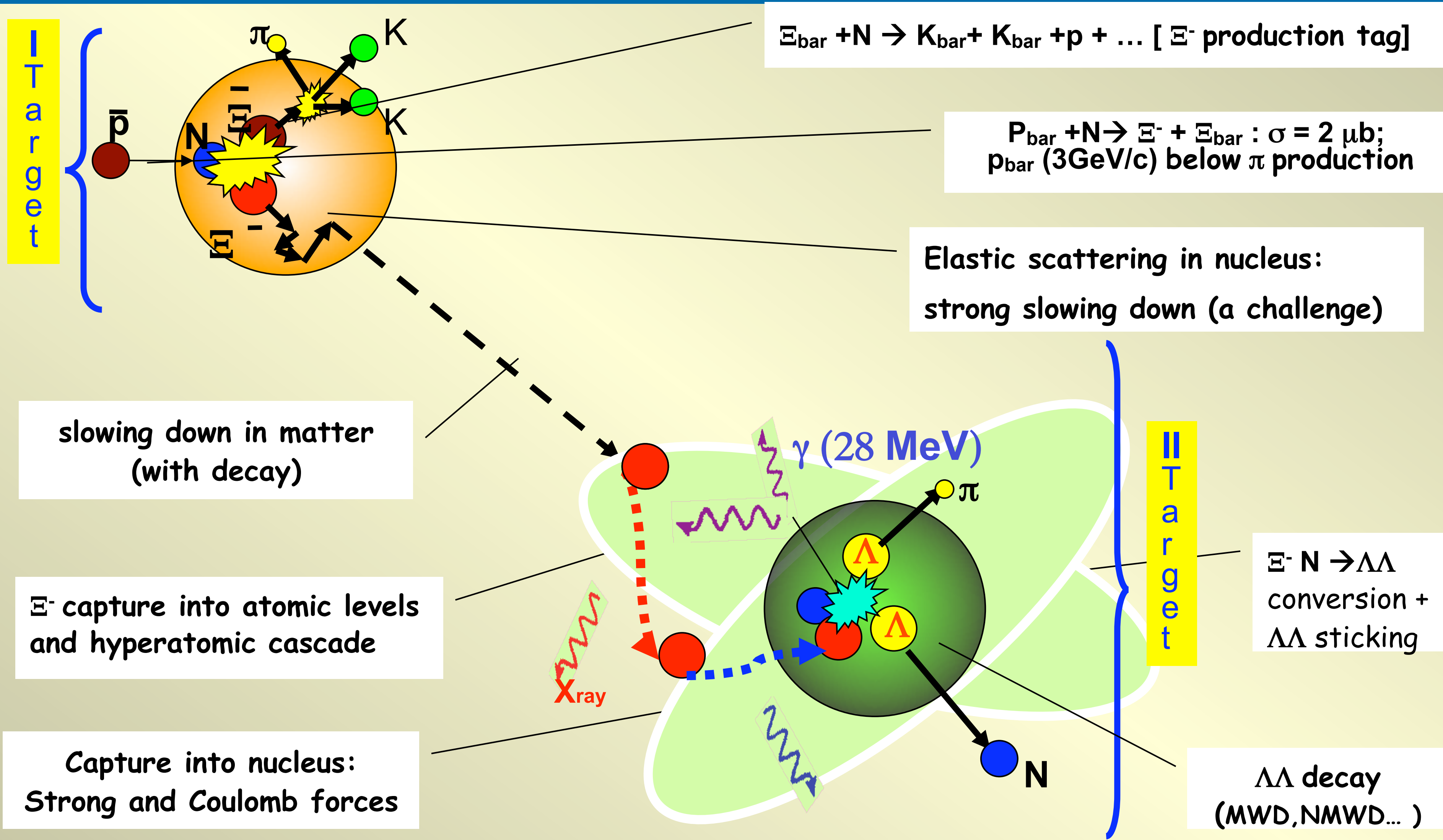
maximize the "stopped Ξ^-" with a suitable set-up

- **Choice of the target:**

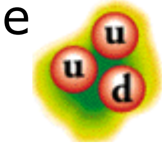
free protons (hydrogen target) **or** protons and neutrons in a **nucleus** (quasi-free reactions)

  - **Advantages of nuclear target** ☺ :
    a) higher cross section (scaling as ~$A^{2/3}$)
    b) Ξ^- slowing down in dense (nuclear) matter
  - **Disadvantages of nuclear target** ☹ :
    c) high background (annihilation)
    d) high beam consuming (beam losses)

70 Double Strange Systems/h are expected within P̄ANDA

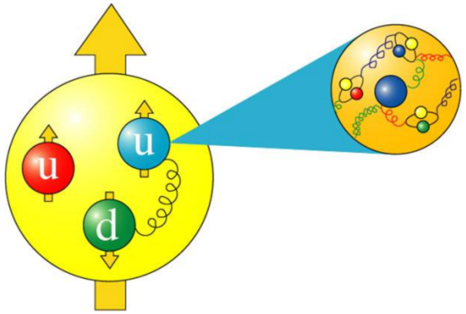


The Hadron's structure



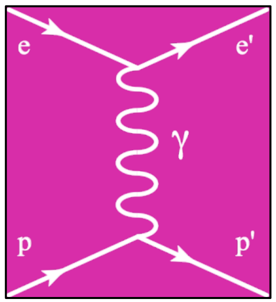
Properties of hadrons are only determined to a small degree by the constituent quarks.

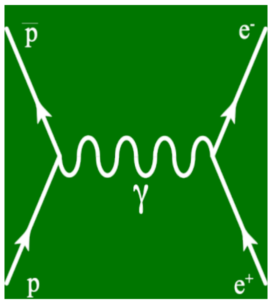
Quarks and gluons dynamics plays a fundamental role in the definitions of hadron's properties: mass, spin, etc…

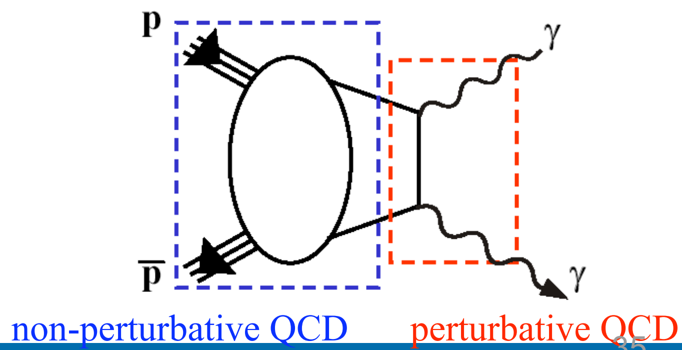


Generalized Parton Distributions (GPDs) contain both the usual form factors and structure functions, but in addition they include correlations between states of different longitudinal and transverse momenta. GPDs give a three-dimensional picture of the nucleon.

Nucleon Form Factors have been mainly studied using electromagnetic probes, but the physical diagrams can be inverted… and a complementary approach can be used



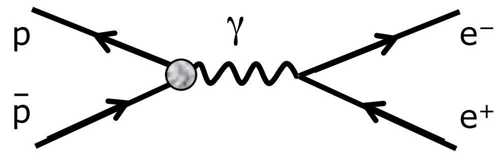




In a similar way Deeply Virtual Compton Scattering (DVCS) can be crossed-studied

Proton Form Factors in Time-Like region: G_E and G_M

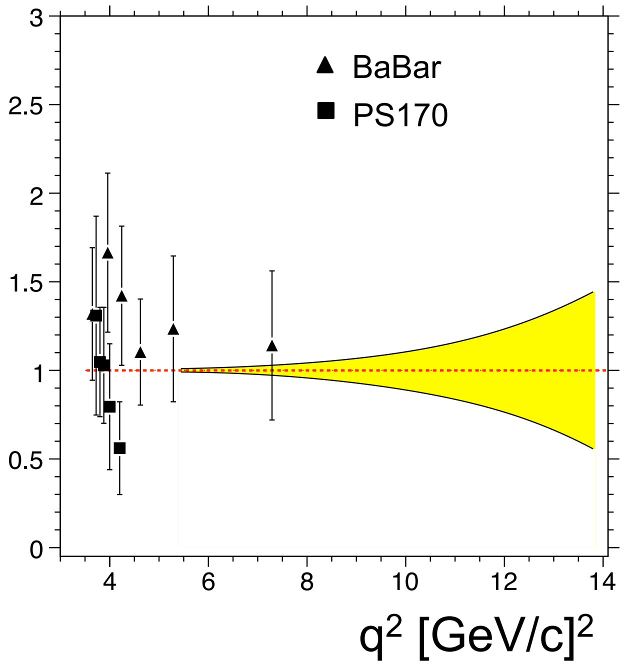
Form Factors in the Time Like region in a wide $q^2>0$ range



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2 (1+\cos^2\theta^*) + \frac{4m_N^2}{s} |G_E(s)|^2 \sin^2\theta^* \right]$$

$$\sigma = \frac{4\alpha^2 \pi \beta C}{3s}\left[|G_M(s)|^2 + \frac{2m_N^2}{s} |G_E(s)|^2 \right]$$

$R=|G_E|/|G_M|$



Born approx. $q^2=s$

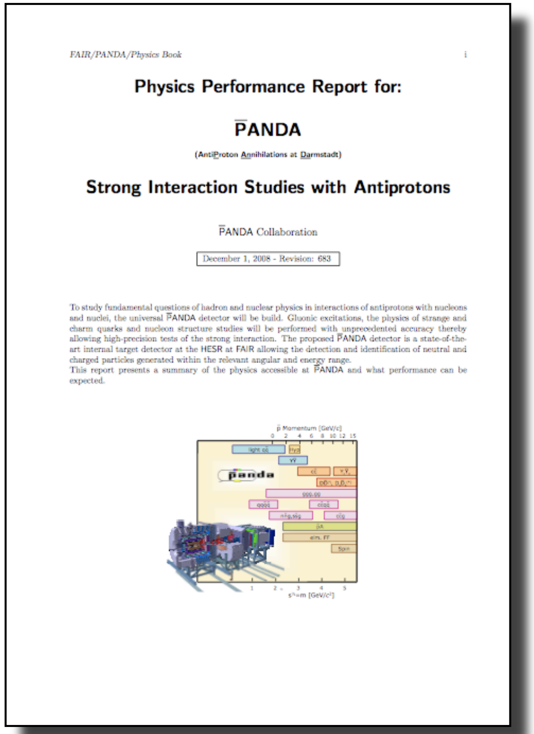
Expected errors on R as a function on q^2 for $G_E=G_M$.
BaBar and PS170 data are shown for comparison

π rejection @ $10^9 \div 10^{10}$

Physics Performance Report

2008 has seen the Collaboration preparing the first $\overline{\text{P}}$ANDA Physics Book.

Within this document, we produced a complete description of 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

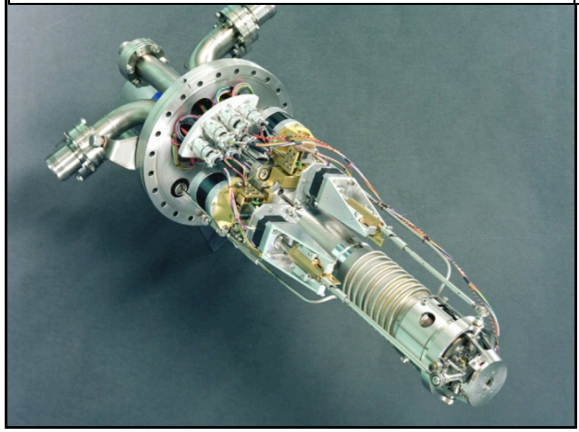
December 1, 2008 - Revision: 683

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.

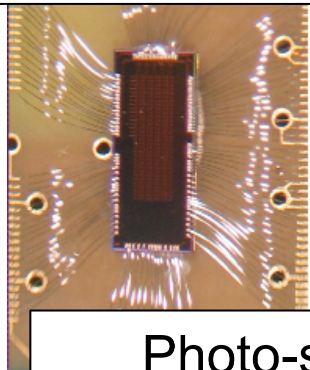
arXiv:0903.3905v1

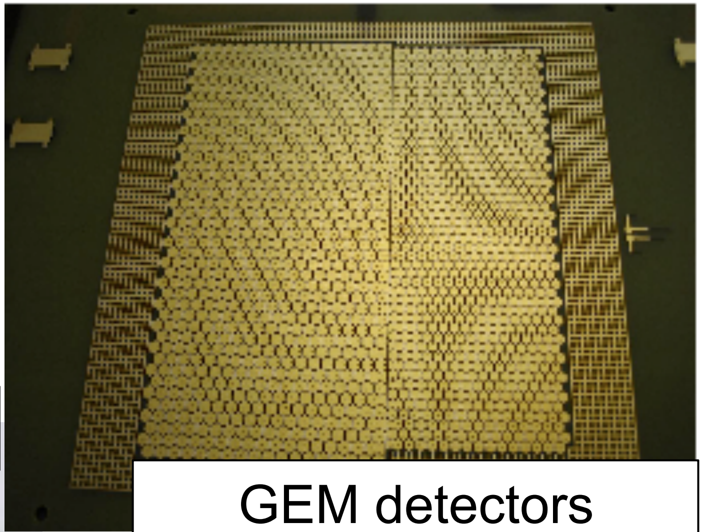
R&D activity within $\bar{\text{P}}$ANDA

Nozzle and cold head



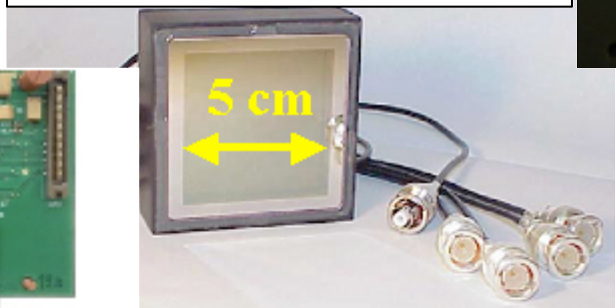
ASICS:CMOS 130 nm

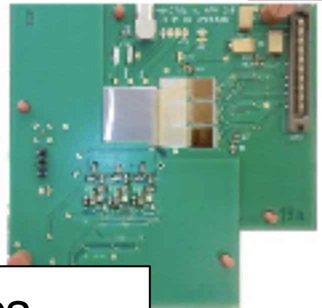




GEM detectors

Photo-sensors

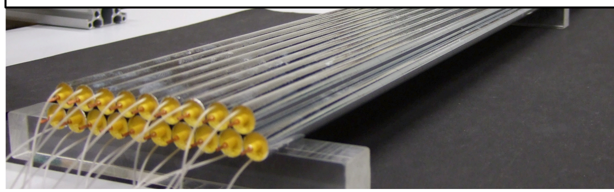




Electronics

Shashlyk

Straw Tubes detectors



EMC crystals

Summary

$\bar{p}$-induced reactions studied with $\bar{P}$ANDA@FAIR have an enormous impact in particle physics

- All $q\bar{q}$ states can be formed directly (not only 1^{--})
  ↳ Discovery potential
- $\bar{p}$ momentum can be tuned
  ↳ Precision studies can be performed
- High probability for production of exotic states
  ↳ 2 states 1^{-+} are predicted in the charmonium energy region
- Low final state multiplicities
  ↳ Allows complete PWA
- $\bar{p}$ are extremely versatile
  ↳ Nucleon structure can be studied, DDS, etc…
- High luminosity
  ↳ Maximizes the yield, and then rare phenomena can be studied

The Collaboration

At present 410 physicists from 53 institutions in 16 countries

Basel, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, Catania, IIT Chicago, Cracow, IFJ PAN Cracow, Cracow UT, Edinburgh, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow,TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, IHEP Protvino, PNPI St.Petersburg, KTH Stockholm, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien