Search for Glueballs and Hybrids in Antiproton-Proton Annihilations

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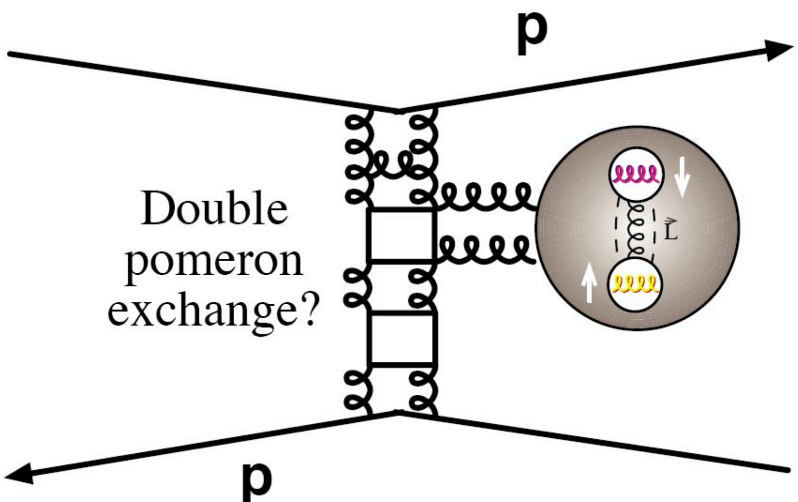
Ruhr-Universität Bochum

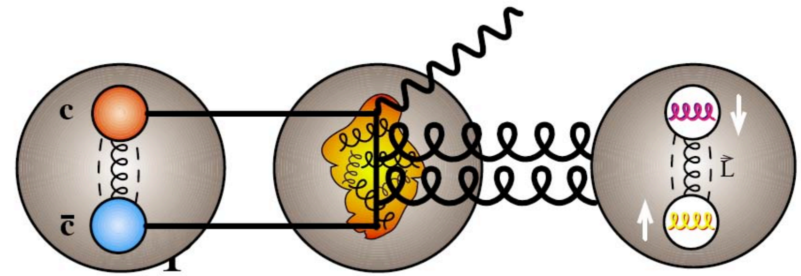
INT-JLAB Workshop on Hadron Spectroscopy, November 9, 2009

Experiment: look for

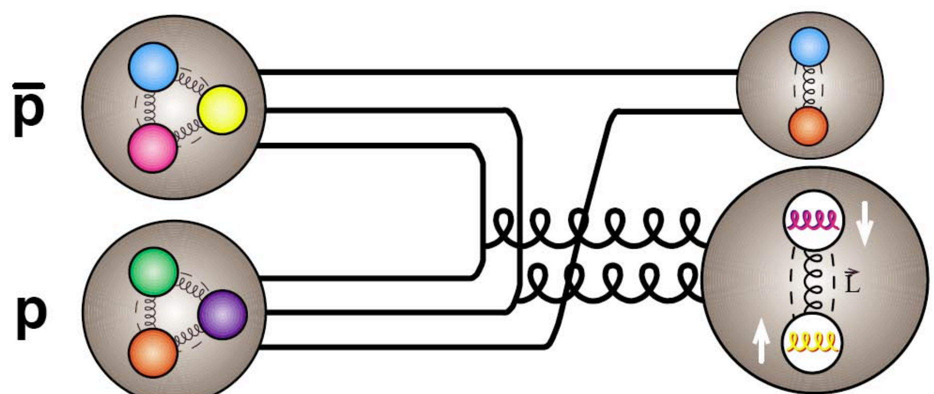
Gluon-rich Processes



WA 79, WA 102

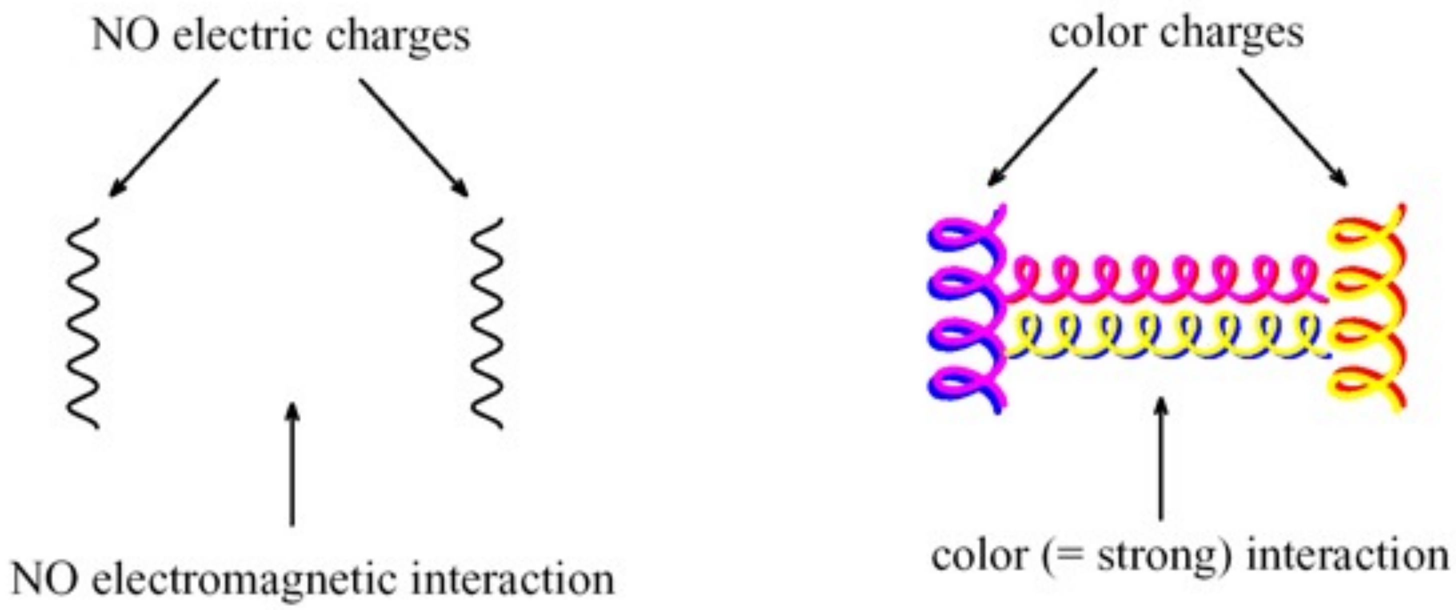


MARK III, DM2, BES



ASTERIX, Crystal Barrel, OBELIX, E835

Self Interaction of Color Fields



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

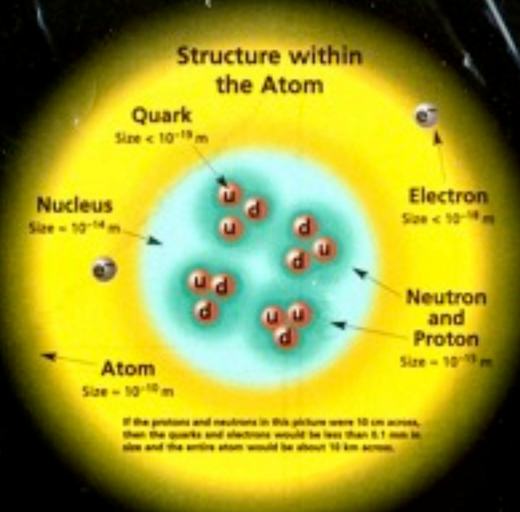
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and *W* and *Z* bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

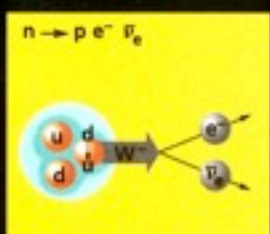
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

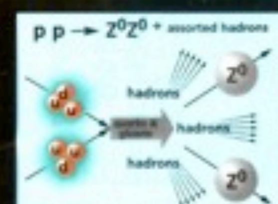
Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:
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American Physical Society, Division of Particles and Fields
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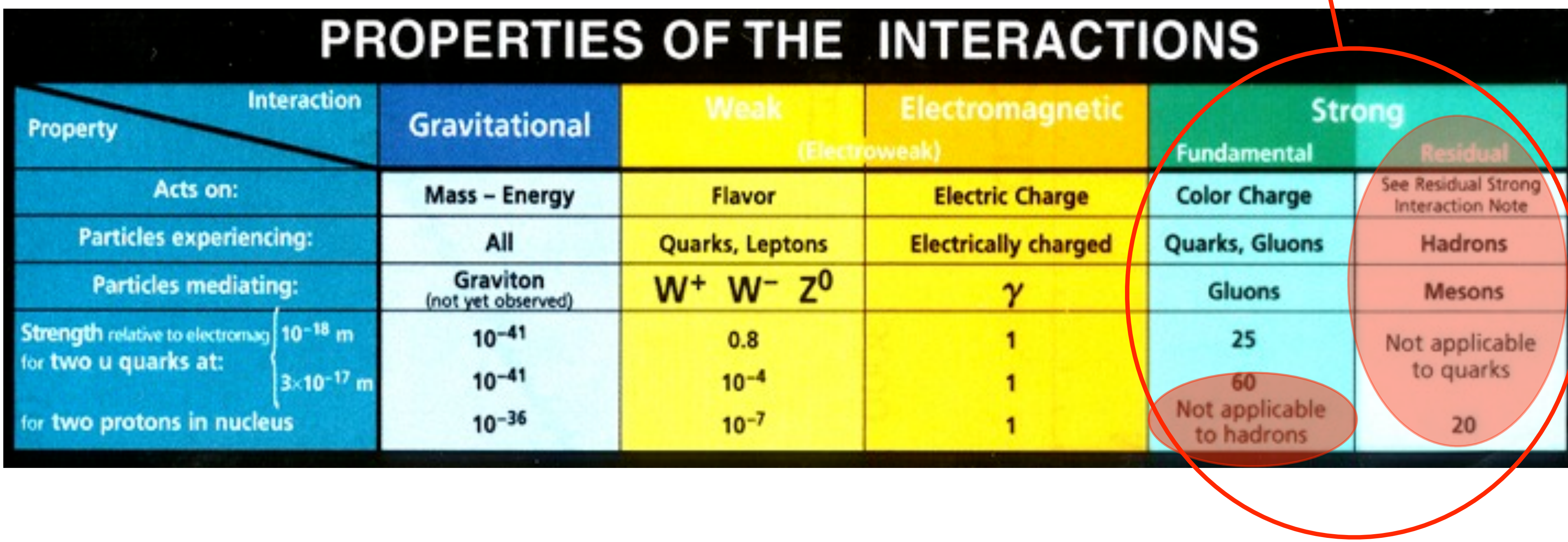

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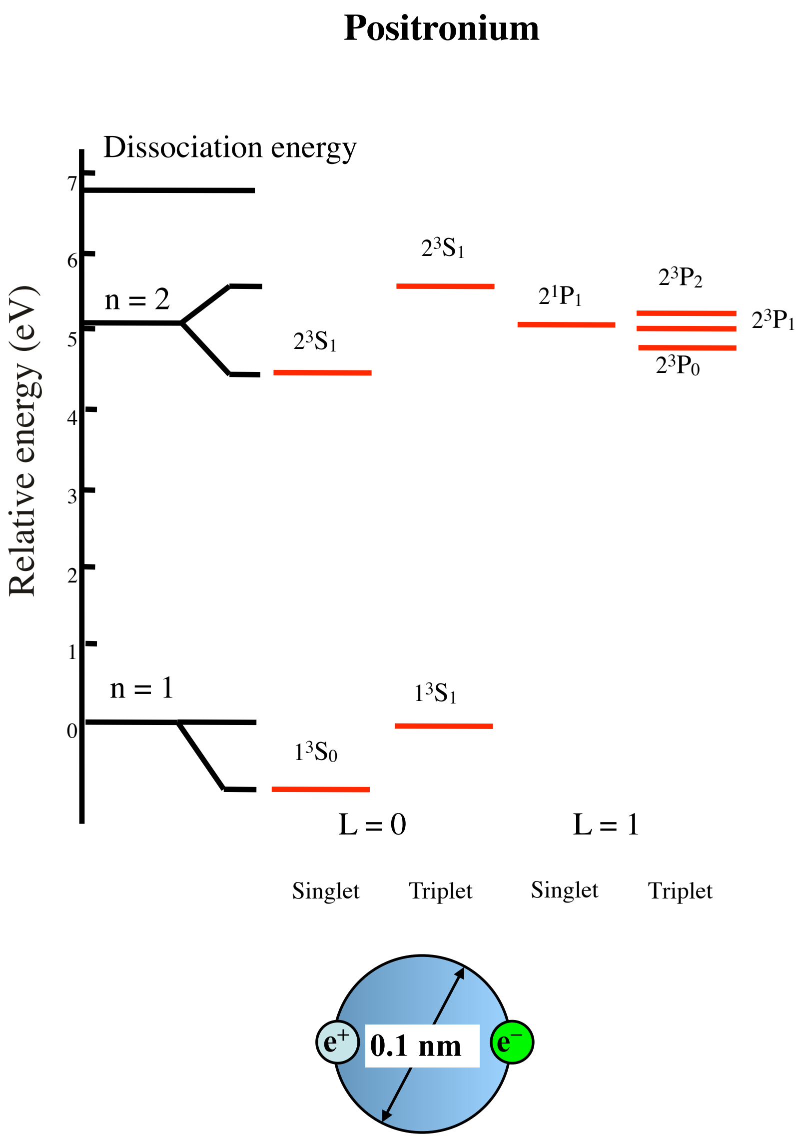
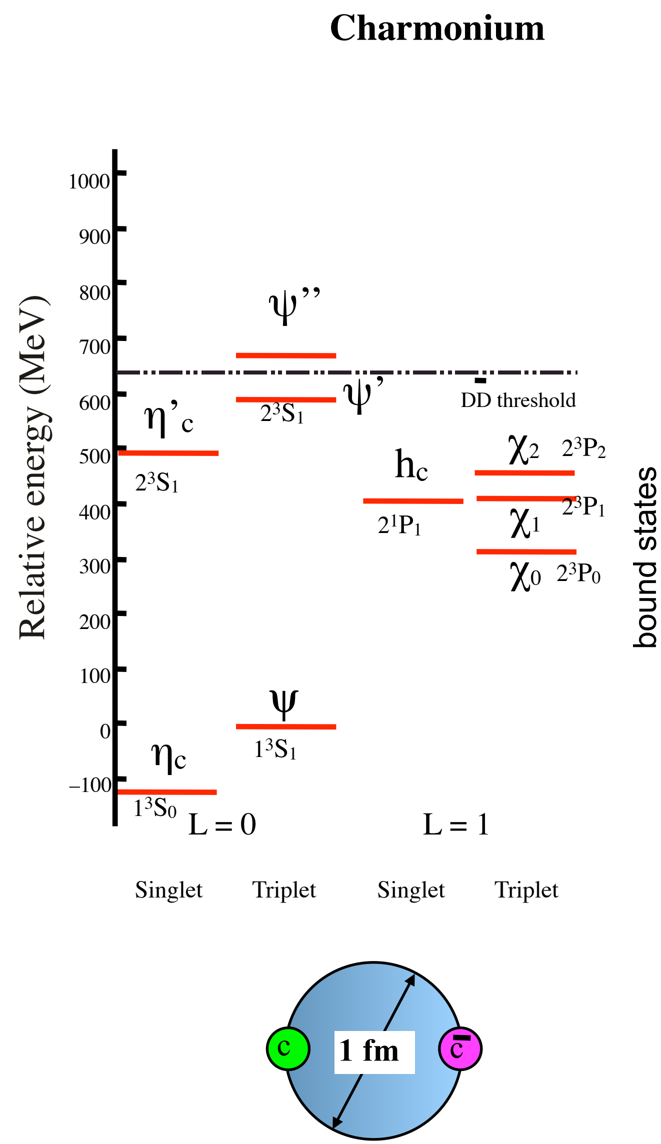
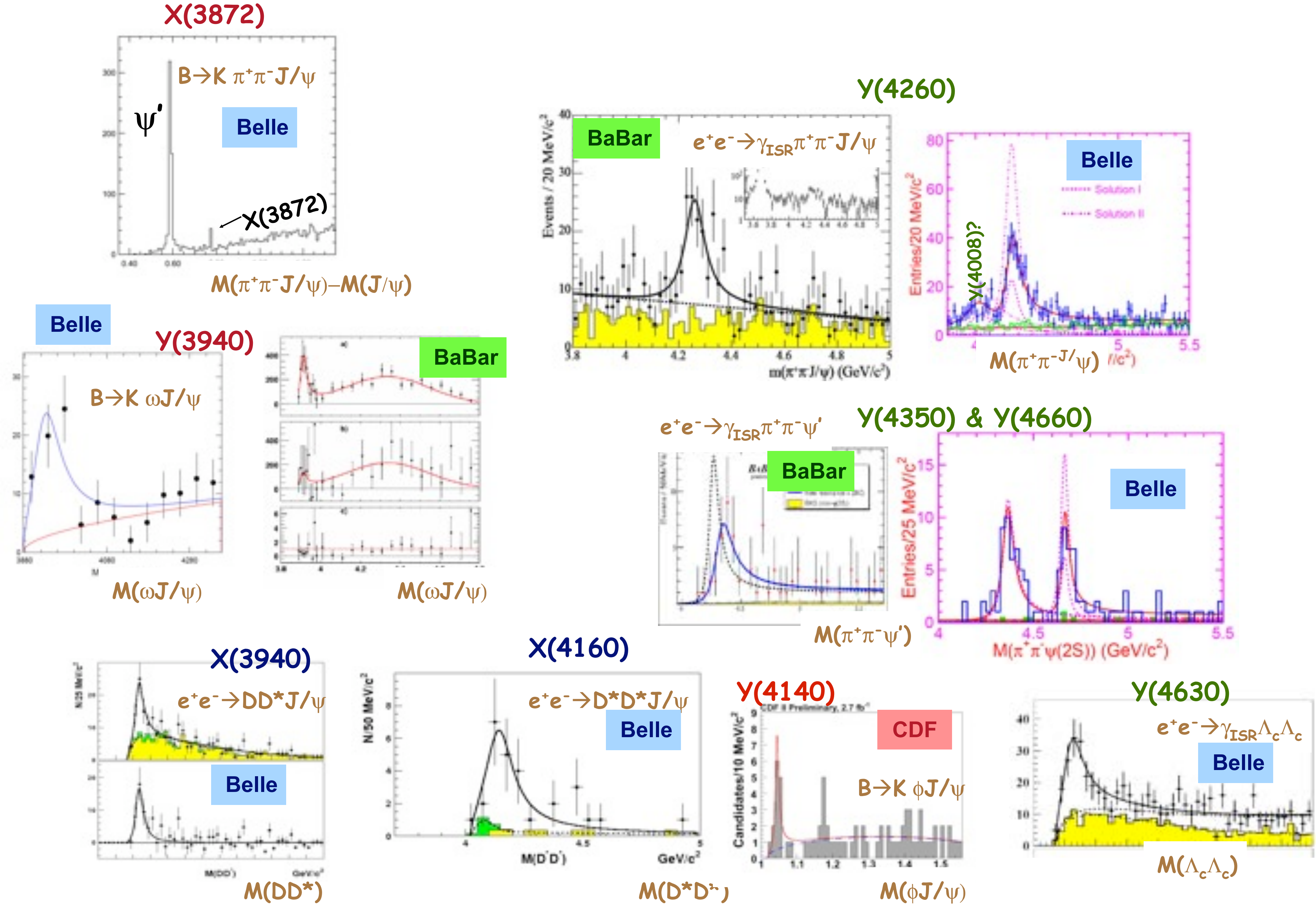


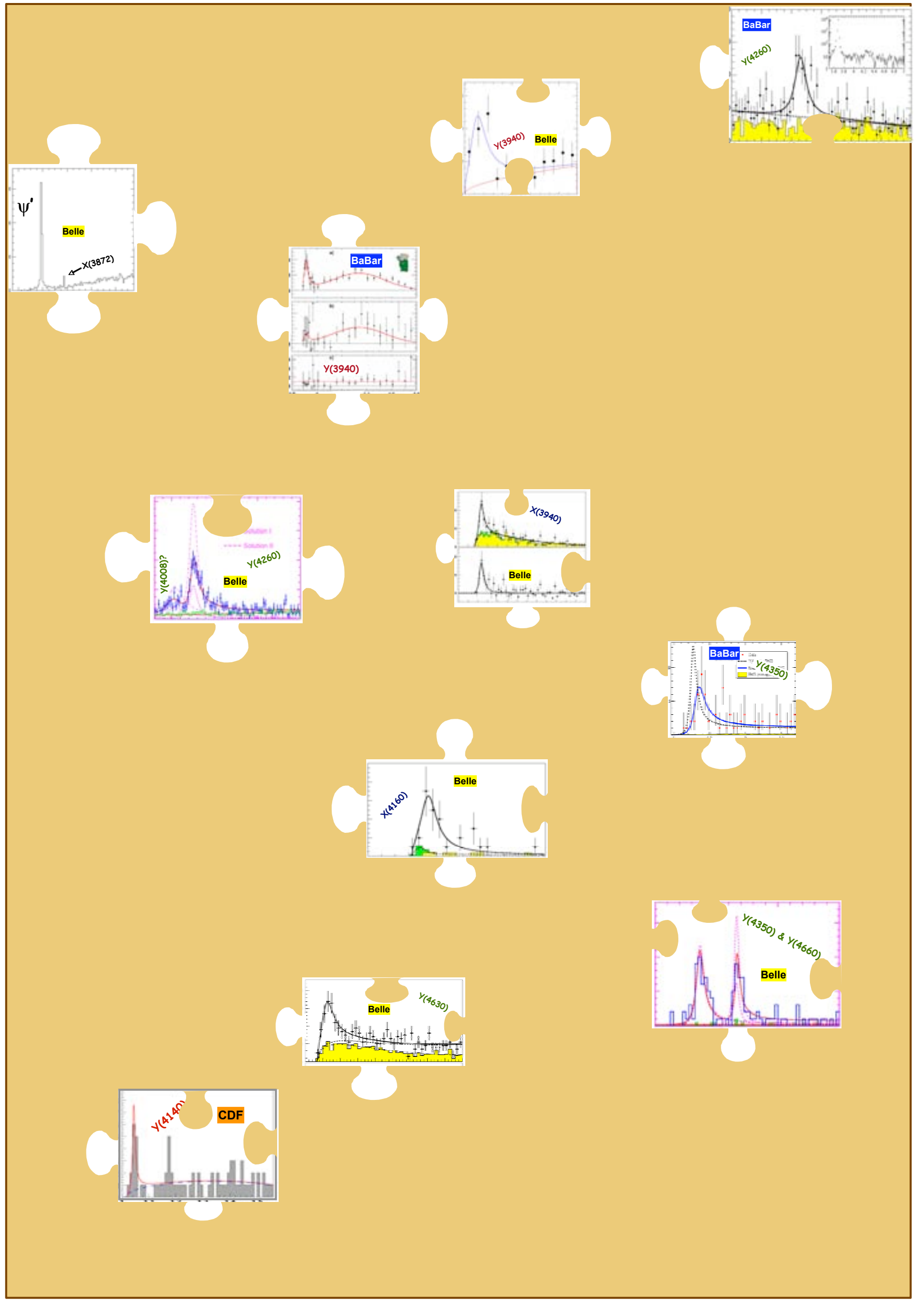
Positronium
Dissociation energy
Relative energy (eV)
n = 2
n = 1
2^3S_1
2^1P_1
2^3P_2
2^3P_1
2^3P_0
1^3S_1
1^3S_0
L = 0
L = 1
Singlet
Triplet
Singlet
Triplet
e^+
0.1 nm
e^-



Charmonium
Relative energy (MeV)
ψ''
ψ'
DD threshold
η'c
2^3S_1
h_c
2^1P_1
χ_2 2^3P_2
χ_1 2^3P_1
χ_0 2^3P_0
ψ
1^3S_1
η_c
1^3S_0
bound states
L = 0
L = 1
Singlet
Triplet
Singlet
Triplet
c
1 fm
c̄

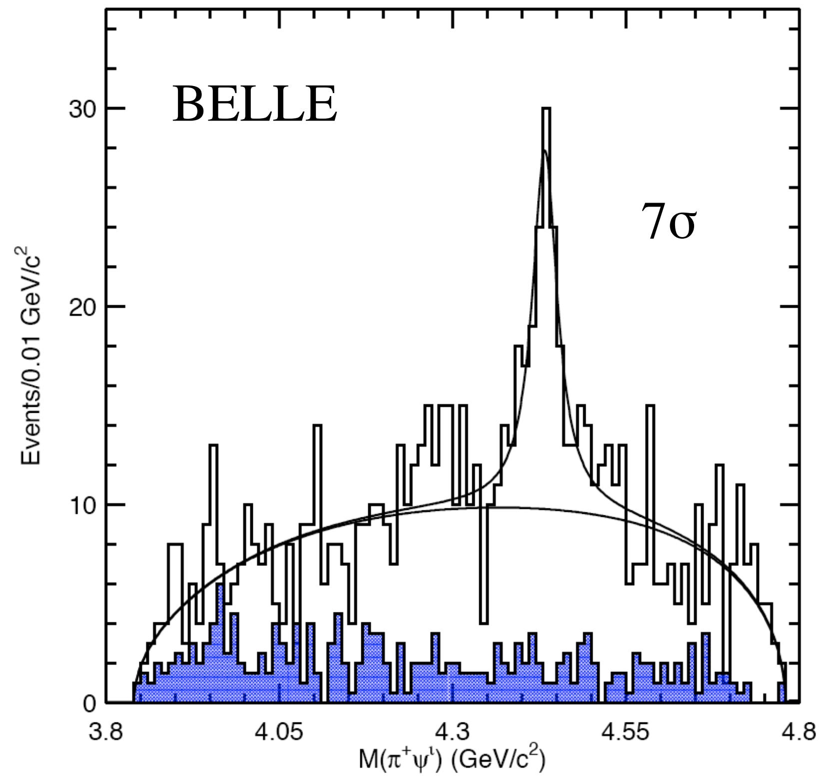
X and Y mesons





BaBar
Y(4260)
Y(3940)
Belle
ψ'
Belle
X(3872)
BaBar
Y(3940)
Y(4008)?
Y(4260)
Belle
X(3940)
Belle
BaBar
Y(4350)
Belle
X(4160)
Y(4350) & Y(4660)
Belle
Belle
Y(4630)
CDF

Z^+ (4430) - a new state of matter (tetraquark?) decaying into $\pi^+\psi'$



$$M = (4.433 \pm 0.004\ (\text{stat}) \pm 0.001\ (\text{syst}))\ \text{GeV}$$

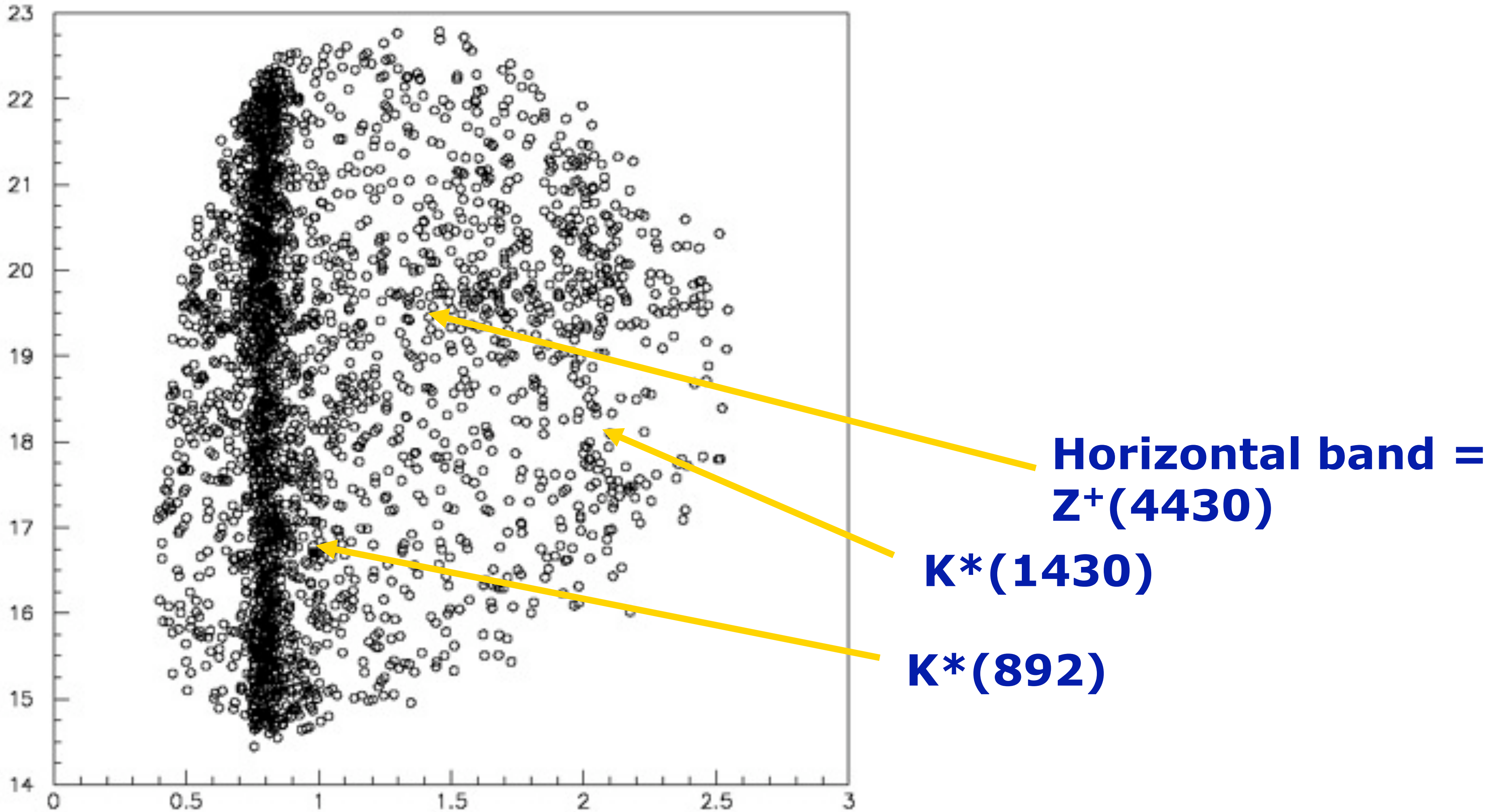
$$\Gamma = (0.044^{+0.017}_{-0.011}\ (\text{stat})^{+0.030}_{-0.011}\ (\text{syst}))\ \text{GeV}$$

$$\mathcal{B}(B \therefore KZ(4430) \times \mathcal{B}(Z \therefore \pi^+\psi') = (4.1 \pm 1.0\ (stat) \pm 1.3\ (syst)) \times 10^{-5}$$

PRL 100, 142001 (2008)
arXiv:0708.1790 [hep-ex]

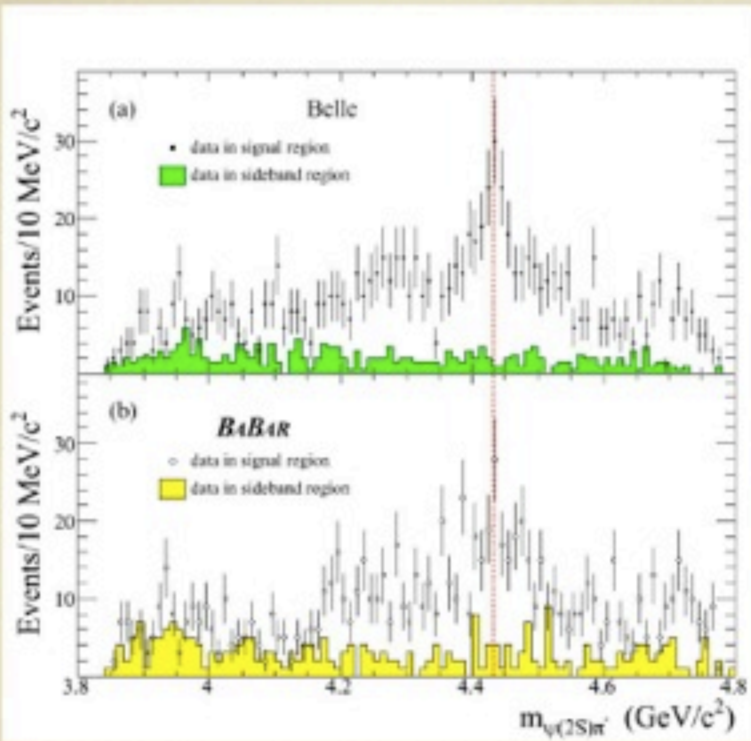
$Z^+(4430)$

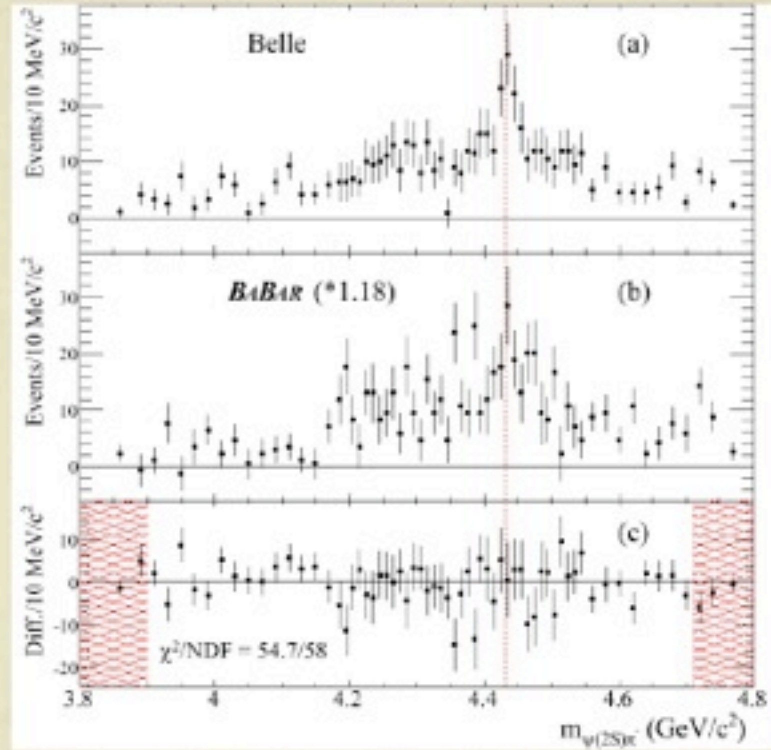
PRL 100, 142001 (2008)



Belle-BaBar comparison

Not applied efficiency correction to the data and applying the K* veto



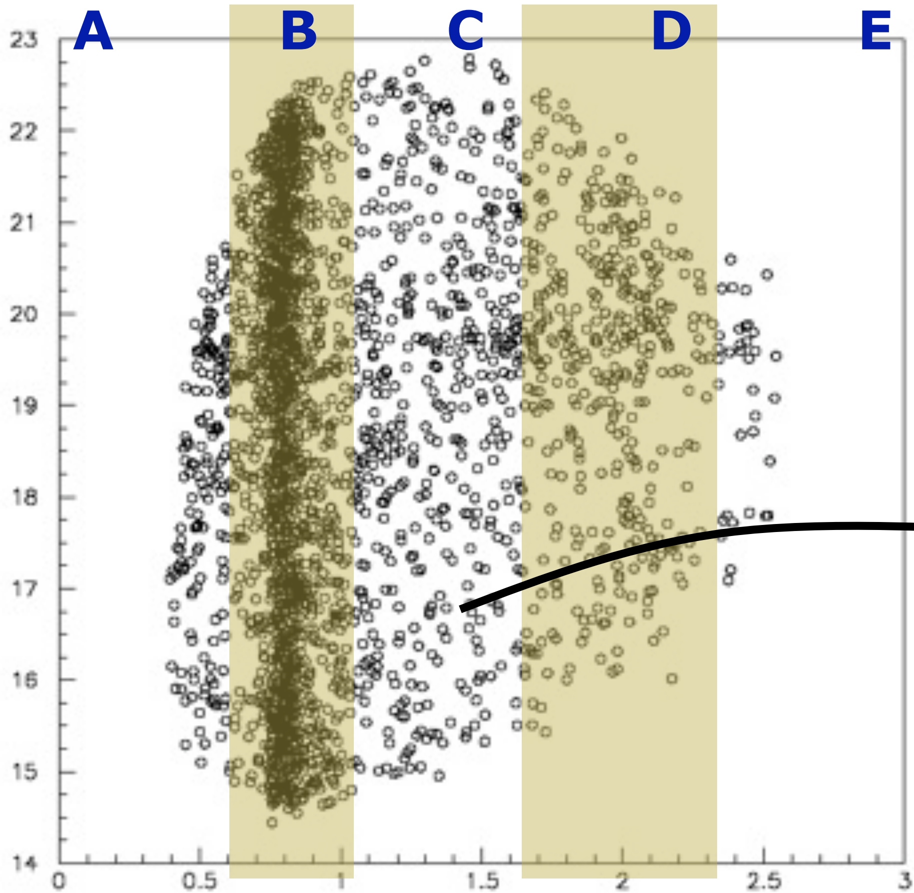


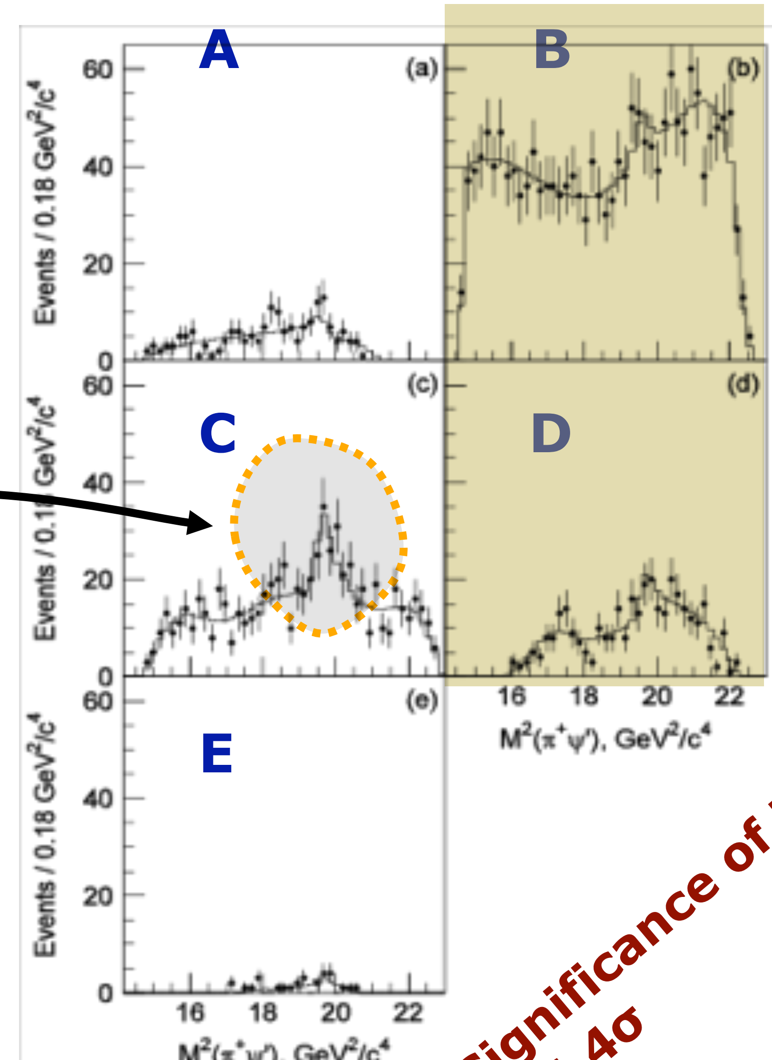
Both Belle and *BABAR* data are re-binned (to calculate χ^2) and side-band subtracted

The *BABAR* data are normalized to the Belle sample.

The data distributions are statistically consistent (χ^2=54.7/58)

NEW results on Z(4430)$^+$ from Dalitz plot fit



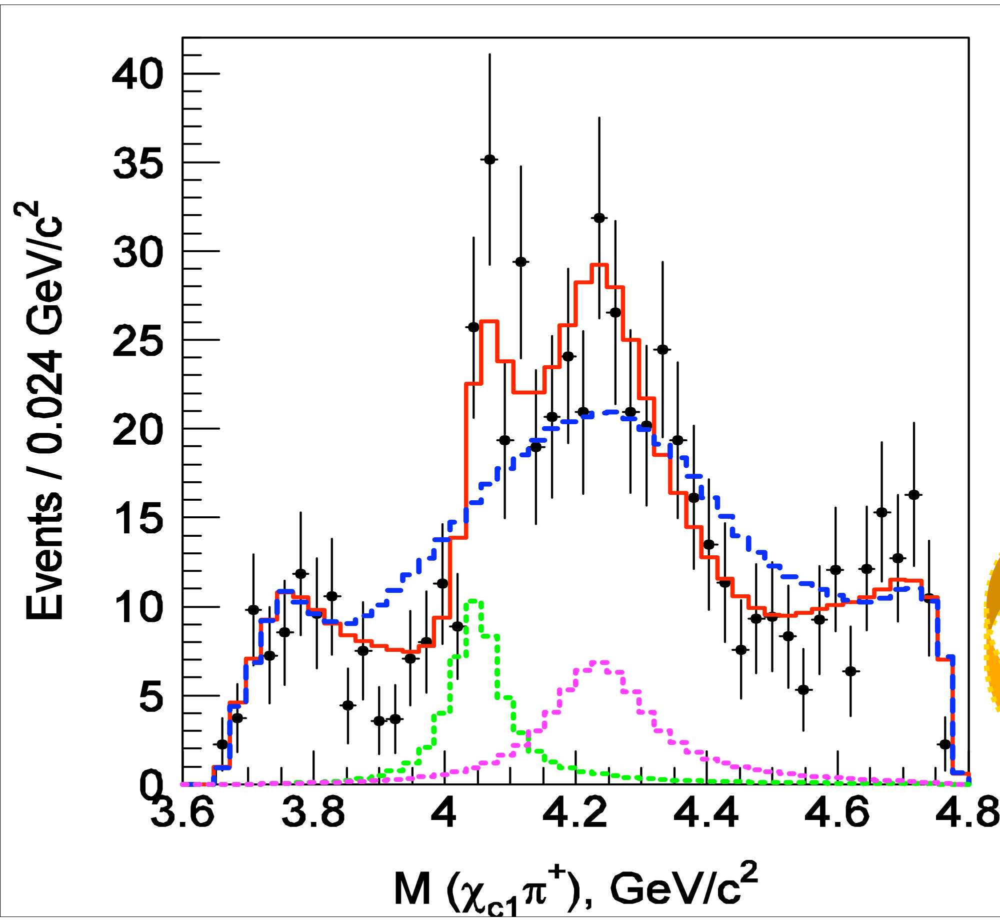


The results of the DP fit in its slices with Z:

Confidence Level of the fit WITH Z(4430)$^+$ is 36%

Significance of Z is 6.4σ

Parameters of the new EXOTIC $Z^+_{1,2} \to \pi^+\chi_{c1}$ states and Mass($\pi^+\chi_{c1}$) distribution



No discrimination between J=0 or 1

$$M_1 = (4051 \pm 14^{+20}_{-41})\ \mathrm{MeV}/c^2,$$
$$\Gamma_1 = (82^{+21+47}_{-17-22})\ \mathrm{MeV},$$
$$M_2 = (4248^{+44+180}_{-29-35})\ \mathrm{MeV}/c^2,$$
$$\Gamma_2 = (177^{+54+316}_{-39-61})\ \mathrm{MeV},$$

with the product branching fractions of

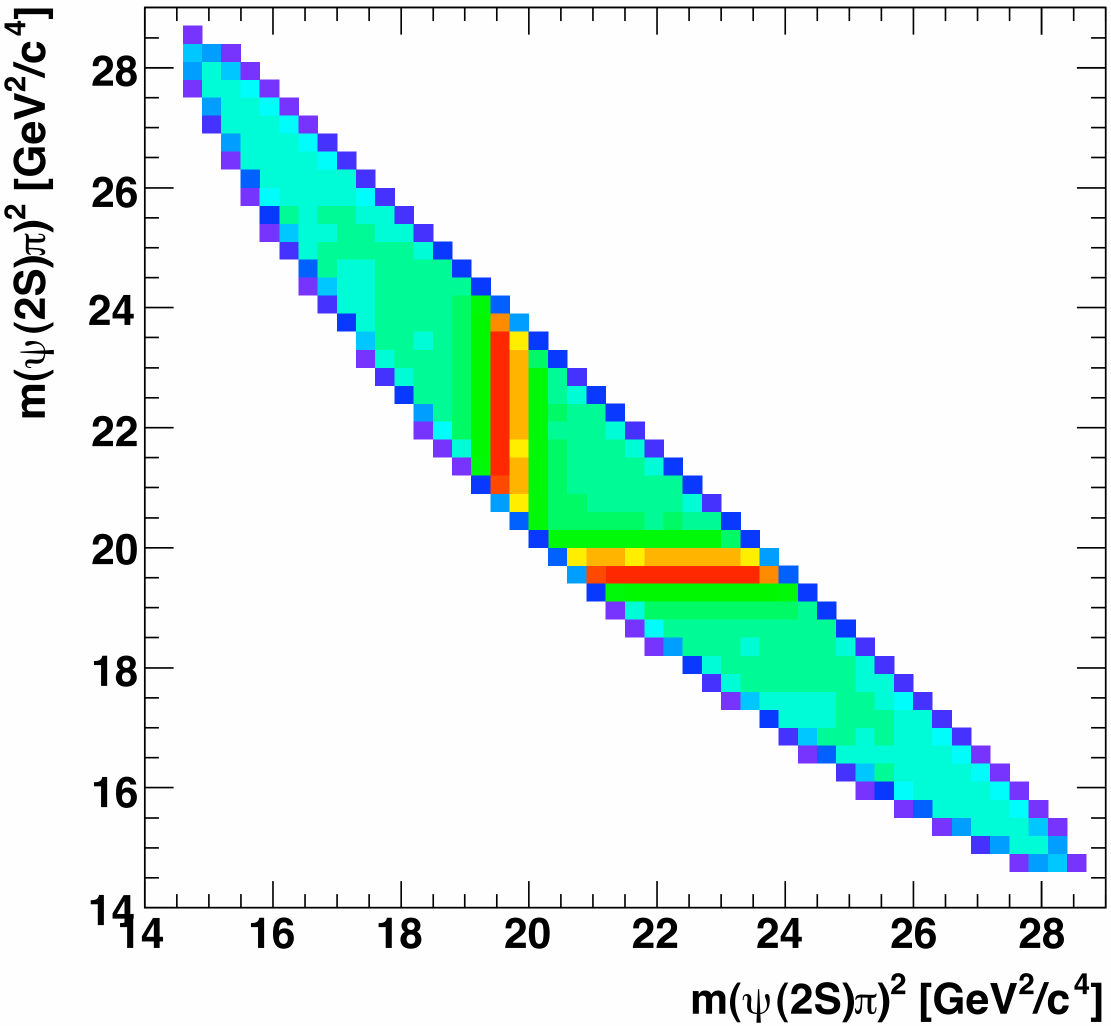
$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+ \chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$
$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-0.5}) \times 10^{-5},$$

are the same order as obtained for other, possibly exotic X,Y,Z states.

S. Olsen's conclusion at the Charmed Exotic Workshop (2009):

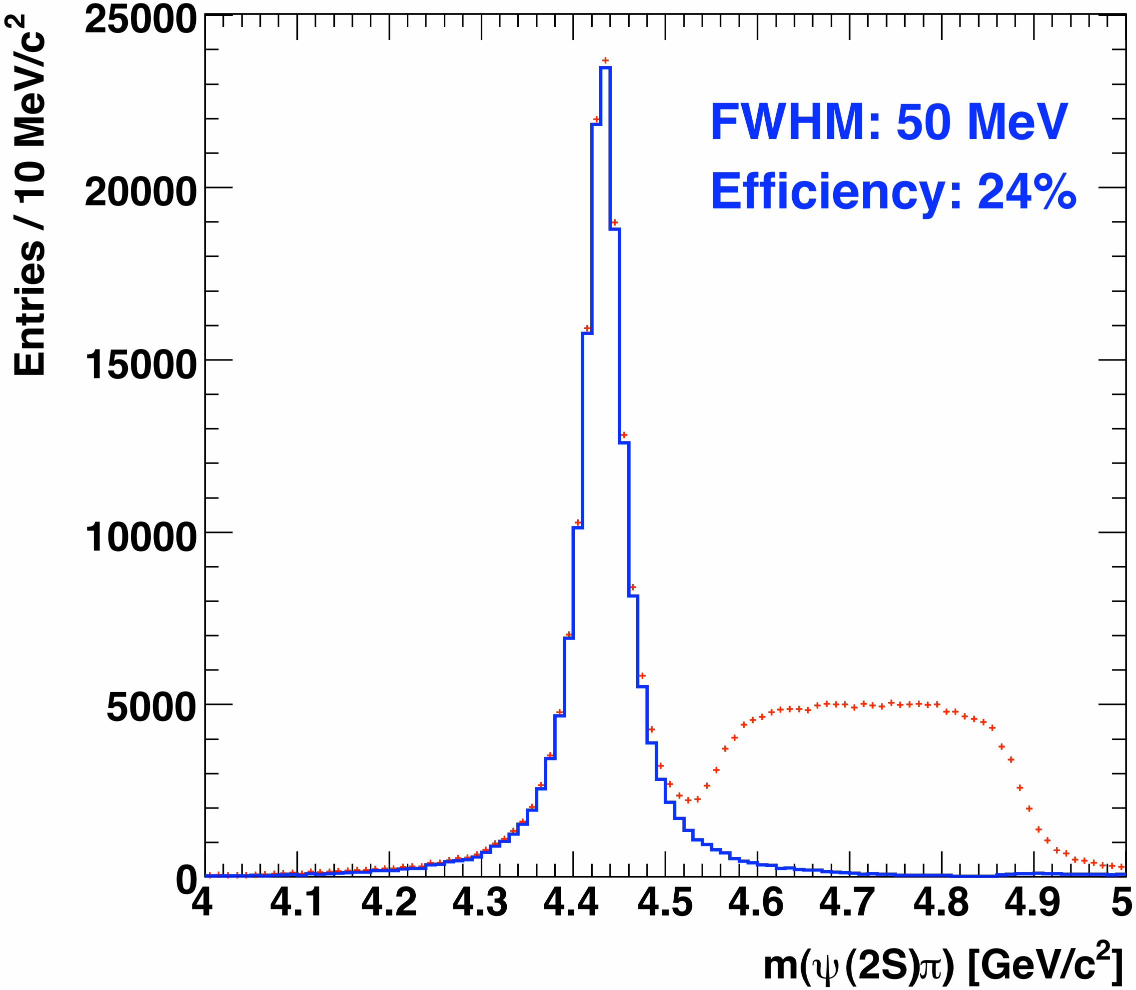
- $Z(4430)^+$ signal in $B \rightarrow K\pi\psi'$ persists with a more complete amplitude analysis.
  - signif. ~6σ, product Bf ~3×10^{-5} (with large errors)
- No significant contradiction with the BaBar results
  - signif. = 2~3σ, Product Bf<3×10^{-5}
- $Z_1(4050)$ & $Z_2(4250)$, seen in $B \rightarrow K\pi\chi_{c1}$, have similar properties (*i.e.* M & Γ) & product Bf's
  - signif. (at least one Z^+)>10σ; (two Z^+ states)>5σ

PANDA: $\bar{p}p \rightarrow Z^+(4430) + \pi^-$



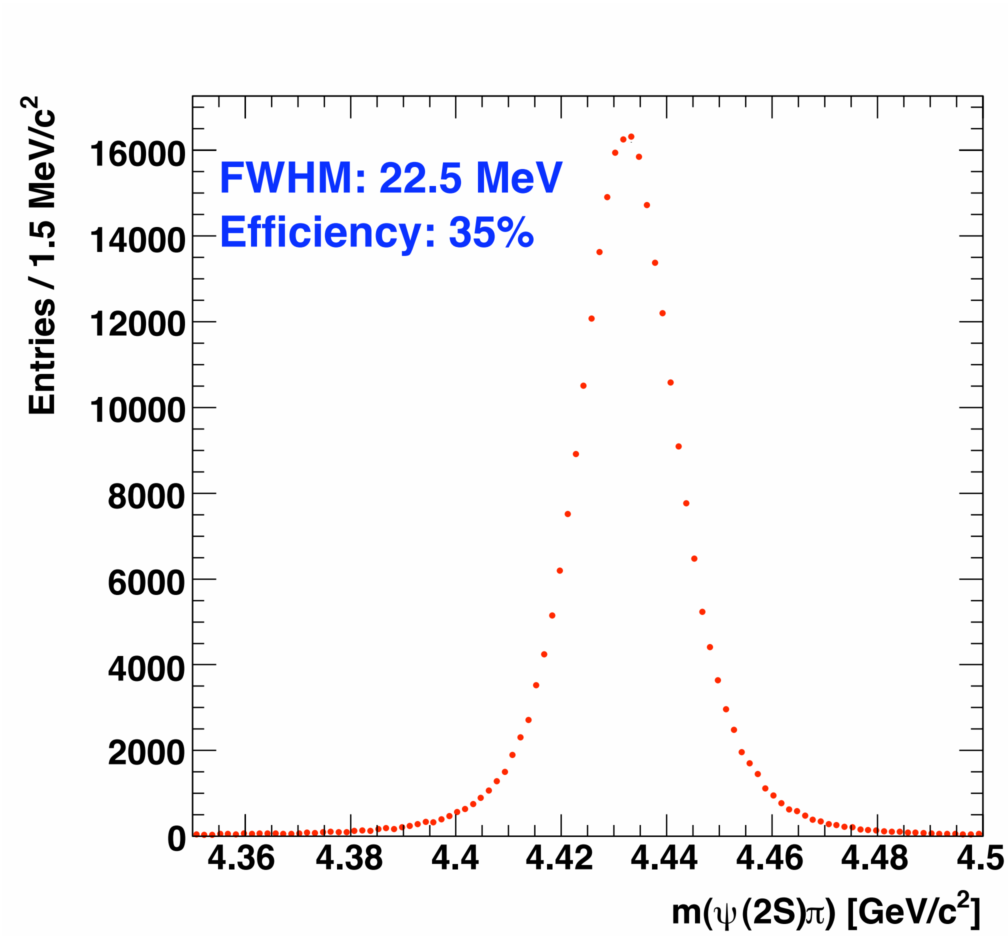
PANDA: $\bar{p}p \rightarrow Z^+(4430) + \pi^-$

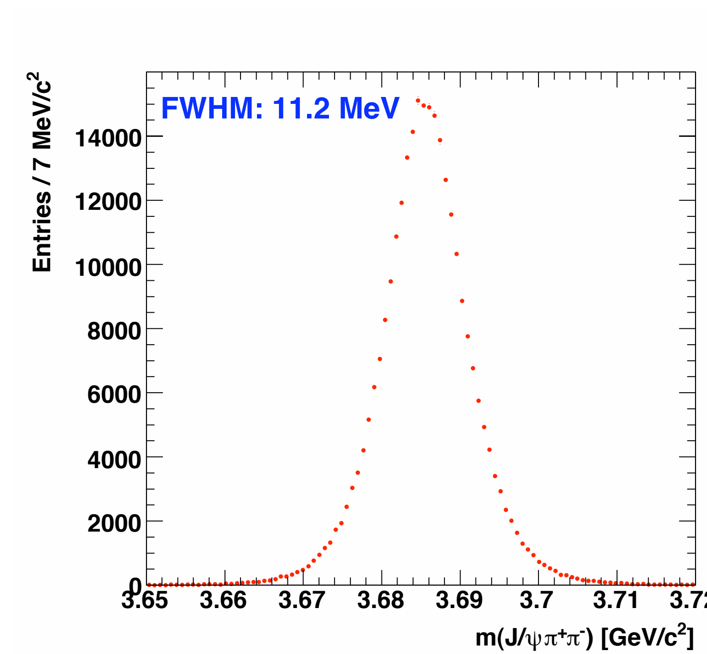
$\hookrightarrow \psi(2S)\pi^+ \rightarrow J/\psi\ \pi^+\pi^-$



PANDA: $\bar{p}d \rightarrow Z^{-}(4430) + p$

$\hookrightarrow \psi(2S)\pi^{-} \rightarrow J/\psi\, \pi^{+}\pi^{-}$

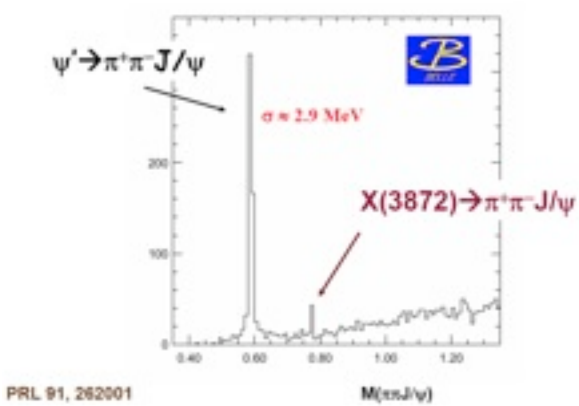


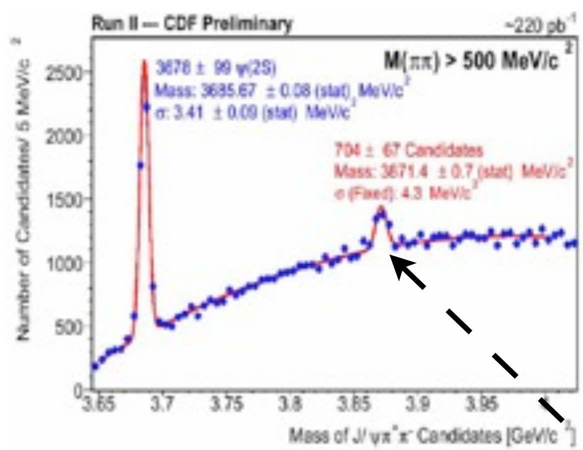


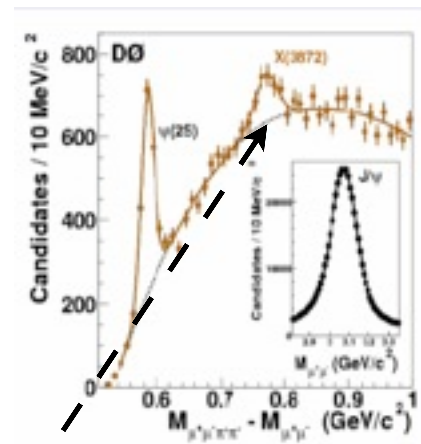
X(3872)

$\mathrm{B} \to KX;\ p\bar{p}$
$\mathrm{X} \to \pi^+\pi^- J/\psi$
$\mathrm{X} \to \pi^+\pi^-\pi^0 J/\psi$
$\mathrm{X} \to \gamma J/\psi;\ X \to \gamma\psi(2S)$
$\mathrm{X(3875)} \to D^0 \bar{D}^0 \pi^0$

$\mathrm{J^{PC}} = 1^{++}$
$\mathrm{M} = 3871.4 \pm 0.6$
$\Gamma < 2.3$
$> 10\,\sigma$







X(3872)

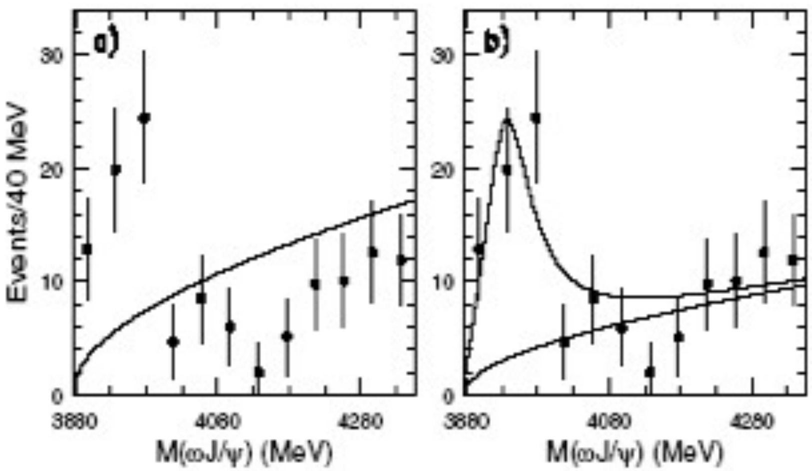
?

DD* molecule
threshold effect
<u>tetraquark</u>

Y(3940)

$B \to KY$
$Y \to \omega J/\psi$

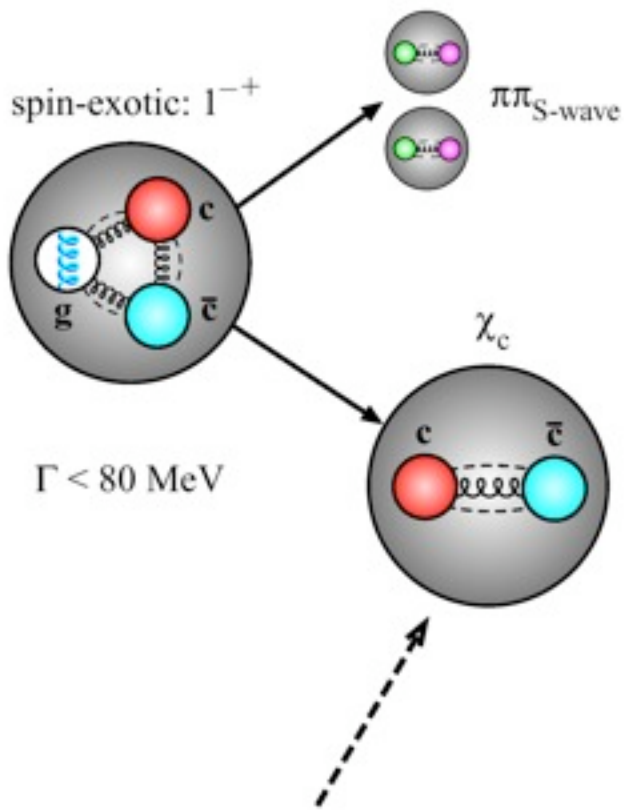
$\mathrm{J}^{\mathrm{PC}} = \mathrm{J}^{P+}$
$\mathrm{M} = 3943 \pm 17$
$\Gamma = 87 \pm 34$
$8\,\sigma$



Observed decay mode: J/ψ + ω is huge (> 7 MeV)

Decay of charmonium hybrids

Lattice results*



Decay of charmonium provides a clean "tag".

*UKQCD, C. McNeile et al.; Phys.Rev.D 65:094505, 2002; C. Michael, hep-lat/0207017.

What is the nature of these states?

Quarkonia? Molecules? Hybrids?

PANDA antiproton physics has advantages:

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Production vs. Formation

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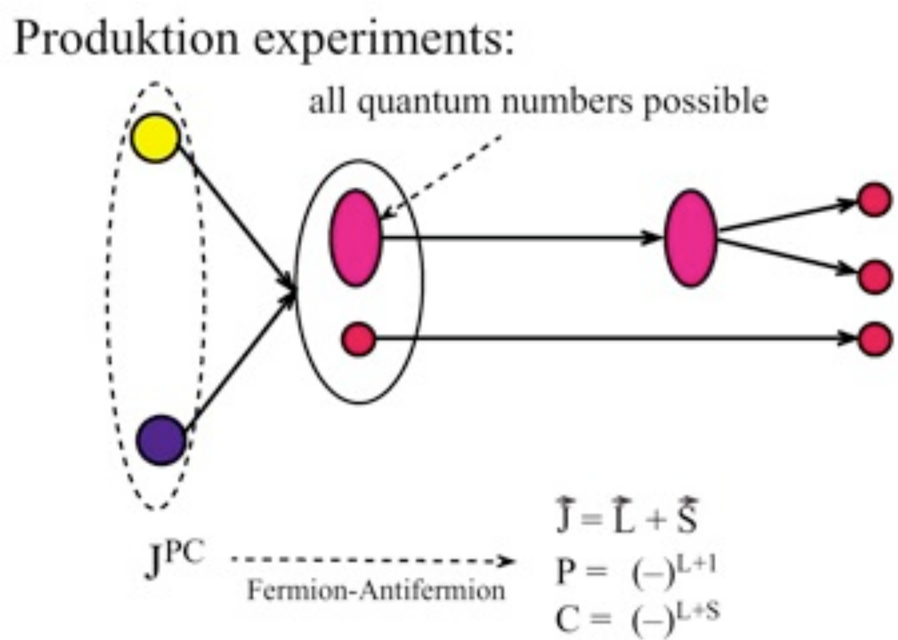
Production vs. Formation



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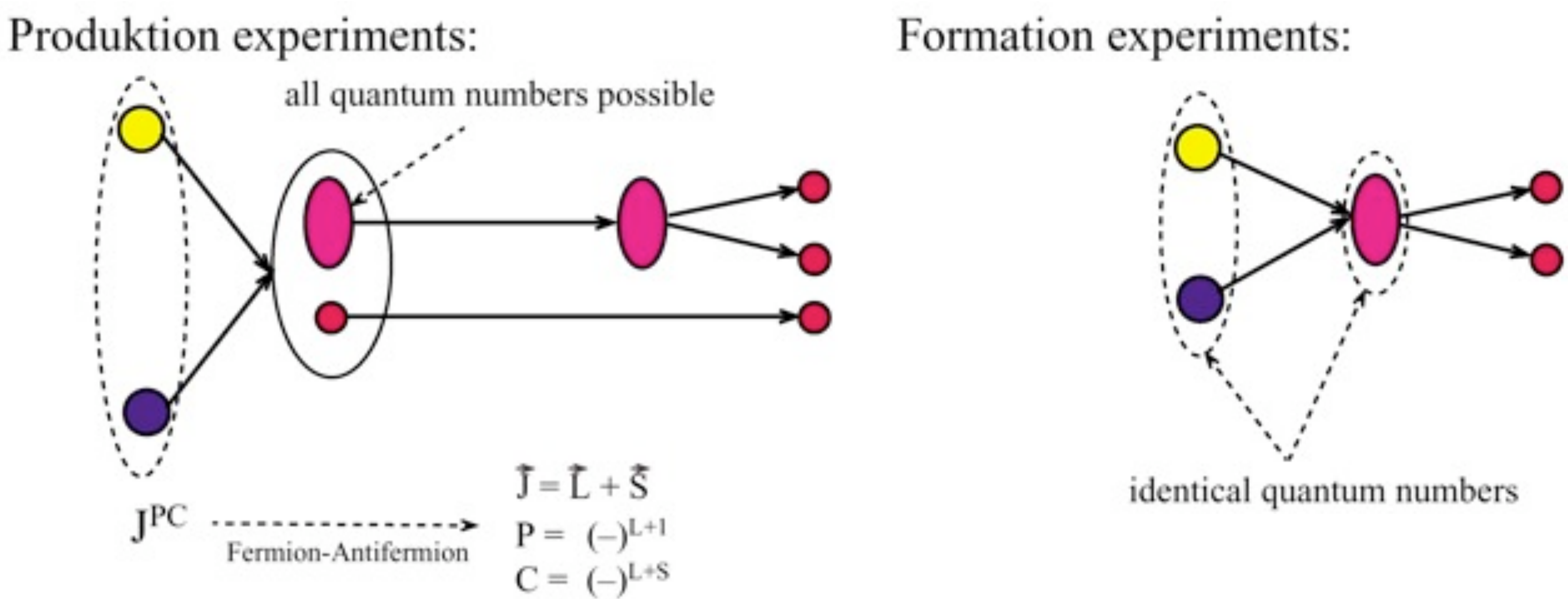
Production vs. Formation



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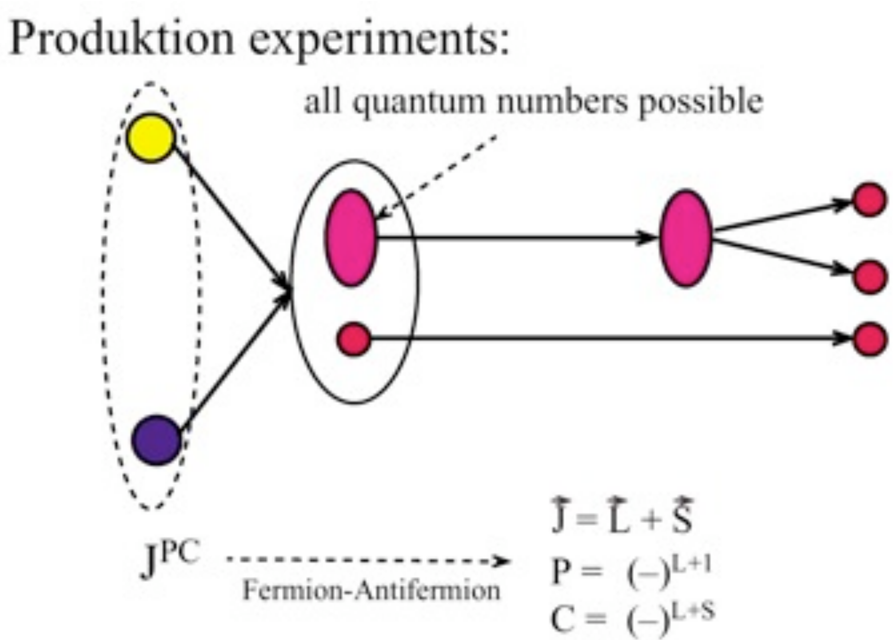
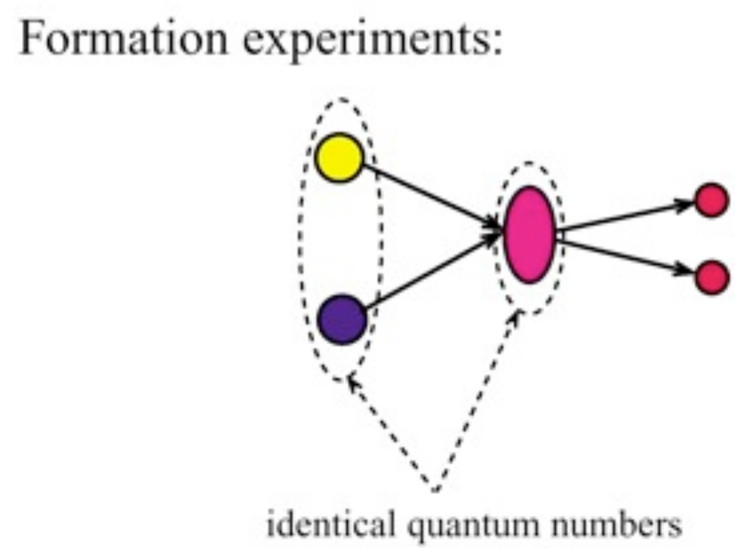
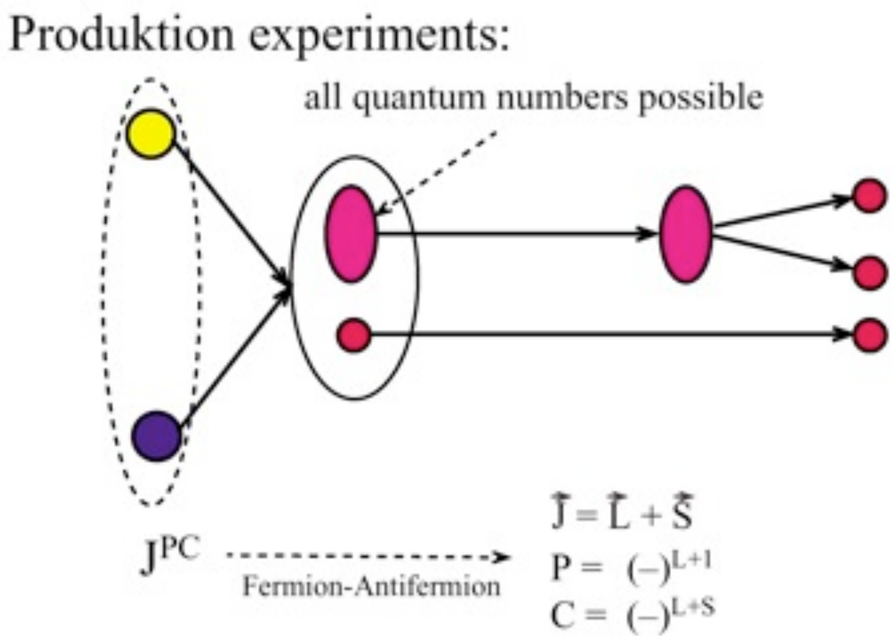


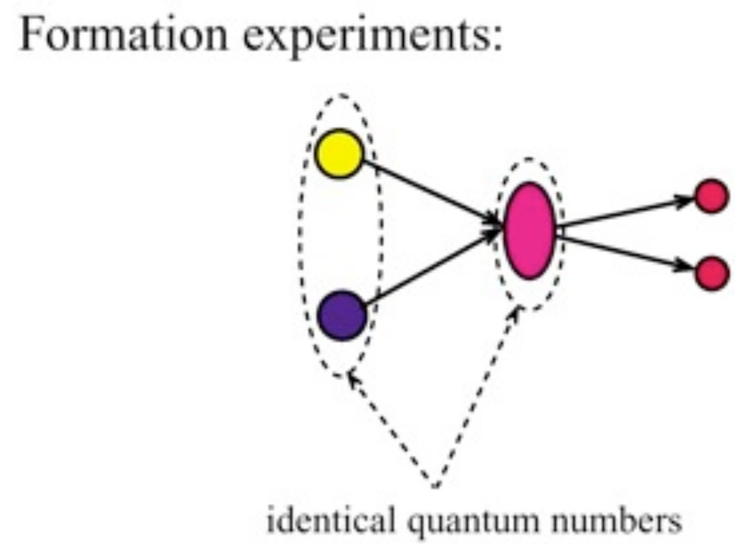


Discovery potential

PANDA antiproton physics has advantages:

Production vs. Formation





Discovery potential

Precision physics

Formation experiments cannot produce exotic J^{PC}.

Formation experiments <u>cannot</u> produce exotic J^{PC}.

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Signal in production but no signal in formation

Formation experiments cannot produce exotic J^{PC}.

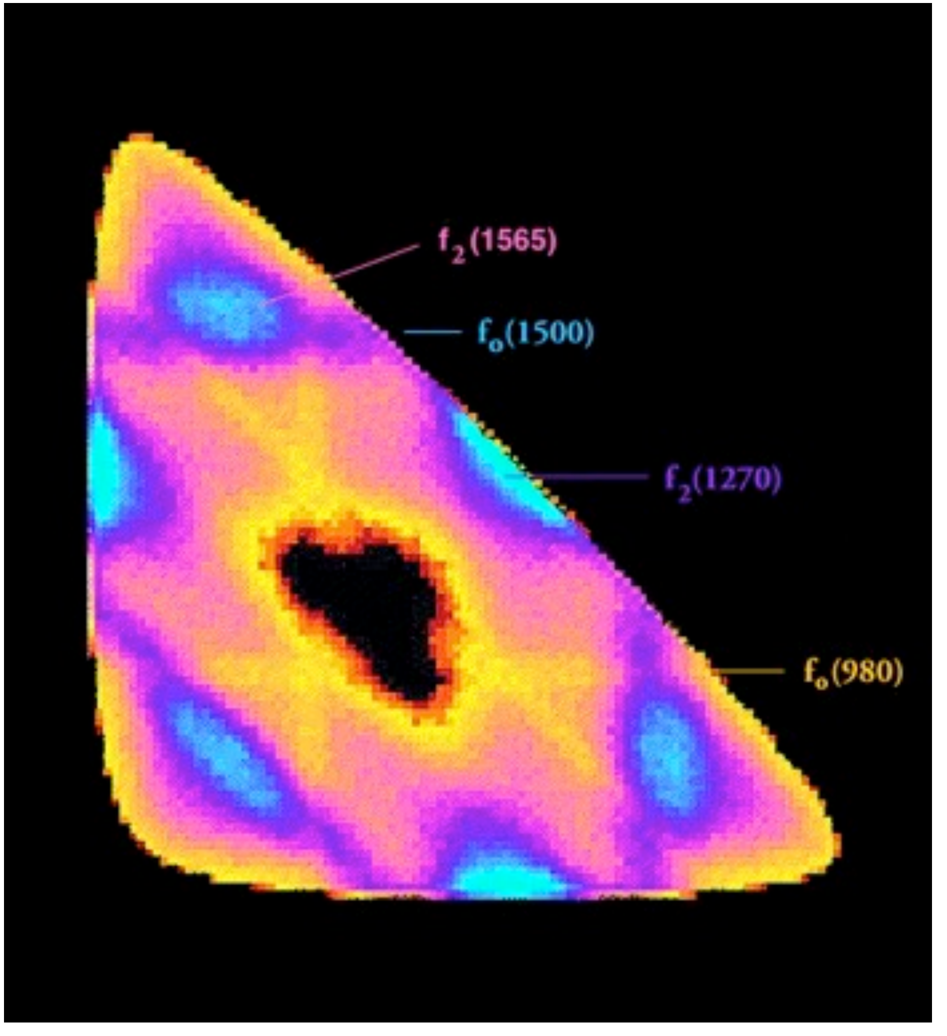
Production experiments can produce exotic J^{PC}.

Signal in production but no signal in formation

→ very interesting ←

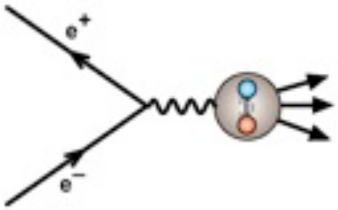
Crystal Barrel

$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ Dalitz plot



700000 events = 6×700000 entries

Production of $\chi_{1,2}$



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

$e^+e^- \rightarrow \psi'$

$\rightarrow \gamma\chi_{1,2}$

$\rightarrow \gamma\ (\gamma J/\psi)$

$\rightarrow \gamma\gamma\ (e^+e^-)$

Reconstruction of invariant mass:
detector resolution dependent

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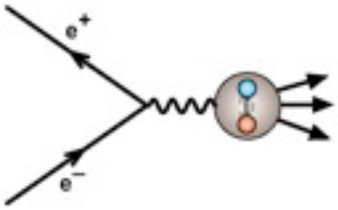

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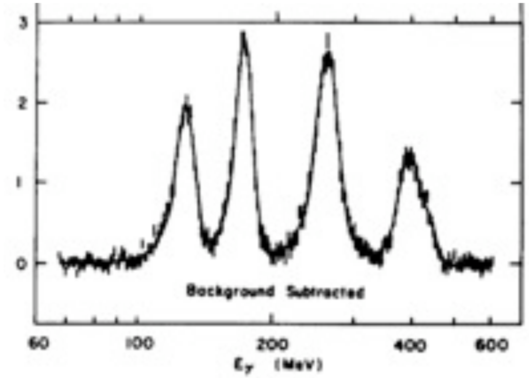

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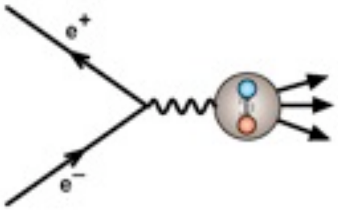

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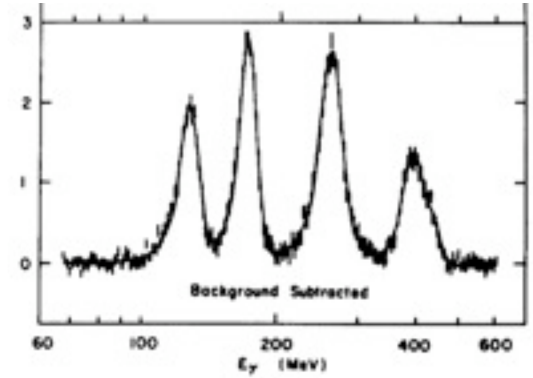
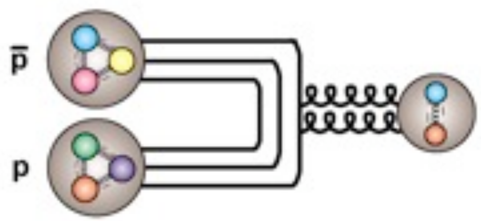
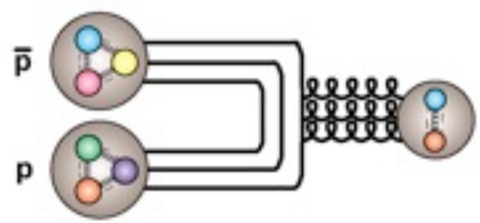




$J = 0, 2, \ldots$
$C = +$



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$C = -$

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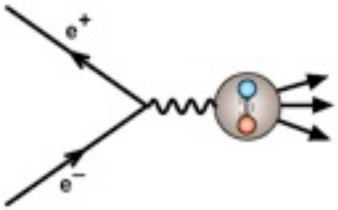
$\searrow \gamma(e^+e^-)$

Rate measurement (beam energy dependent):
detector resolution "independent"



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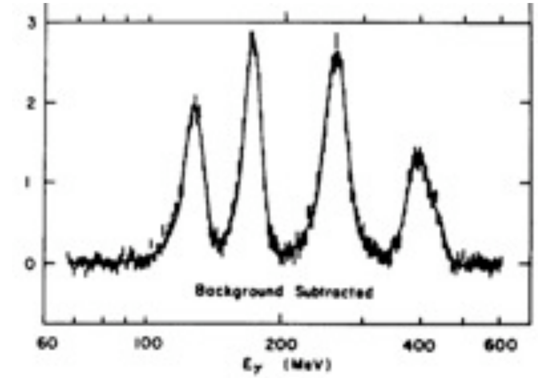

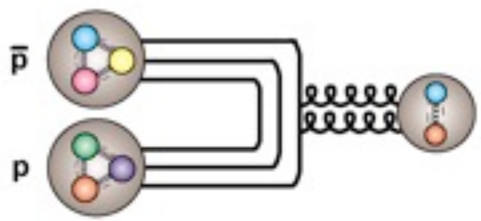

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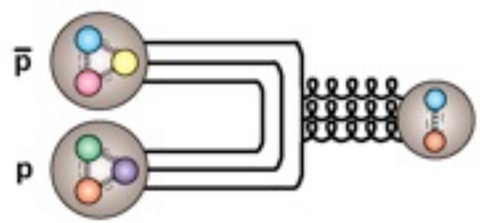

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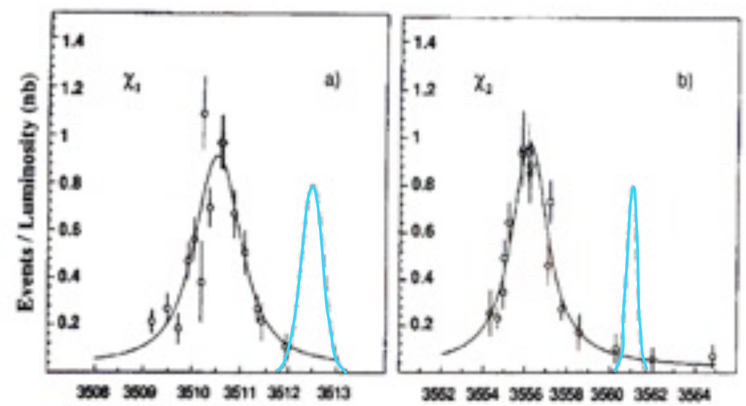
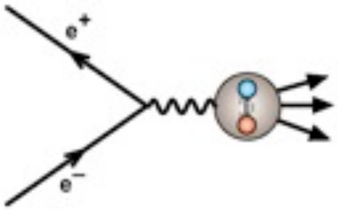
E 760 (Fermilab)



σ_m (beam) = 0.5 MeV



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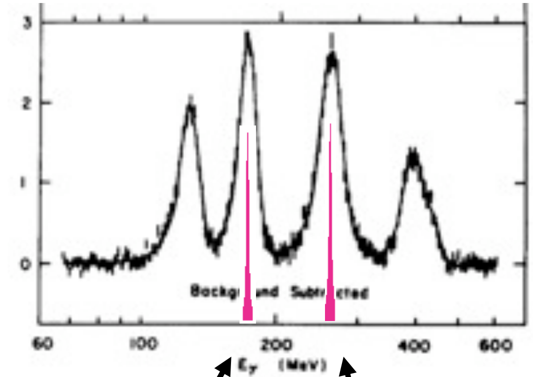

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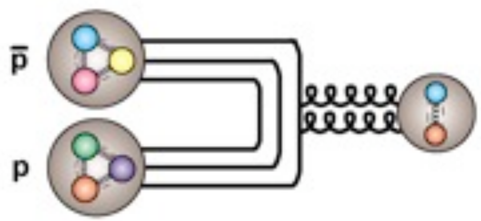

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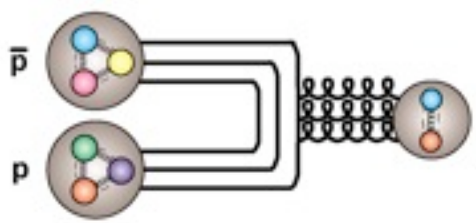

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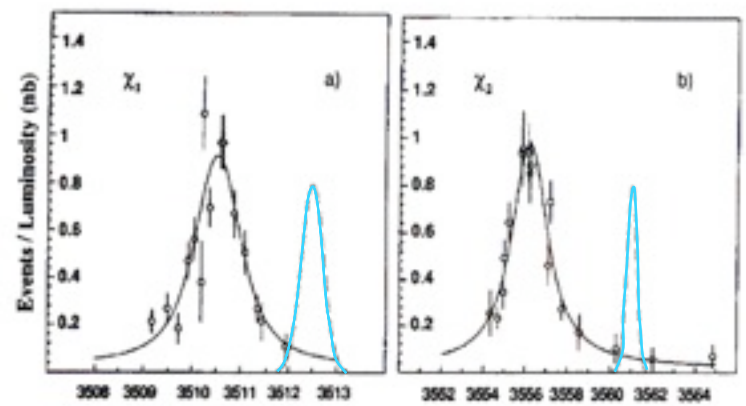

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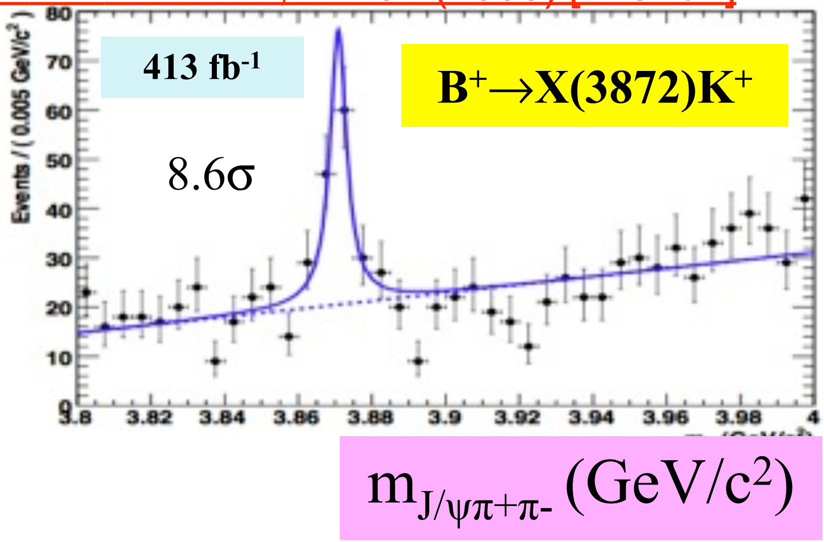
The width of the XYZ states cannot be determined in decays (limited detector resolution) but in scanning experiments with antiprotons.

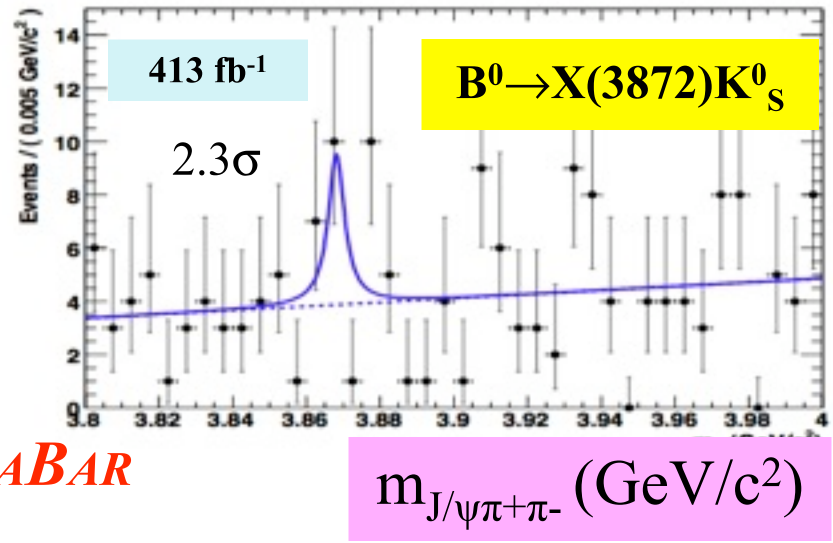
$X(3872) \rightarrow \pi^+\pi^- J/\psi$ in BaBar

recent results

BABAR: PRD 77,111101 (2008) [413 fb^{-1}]



BABAR

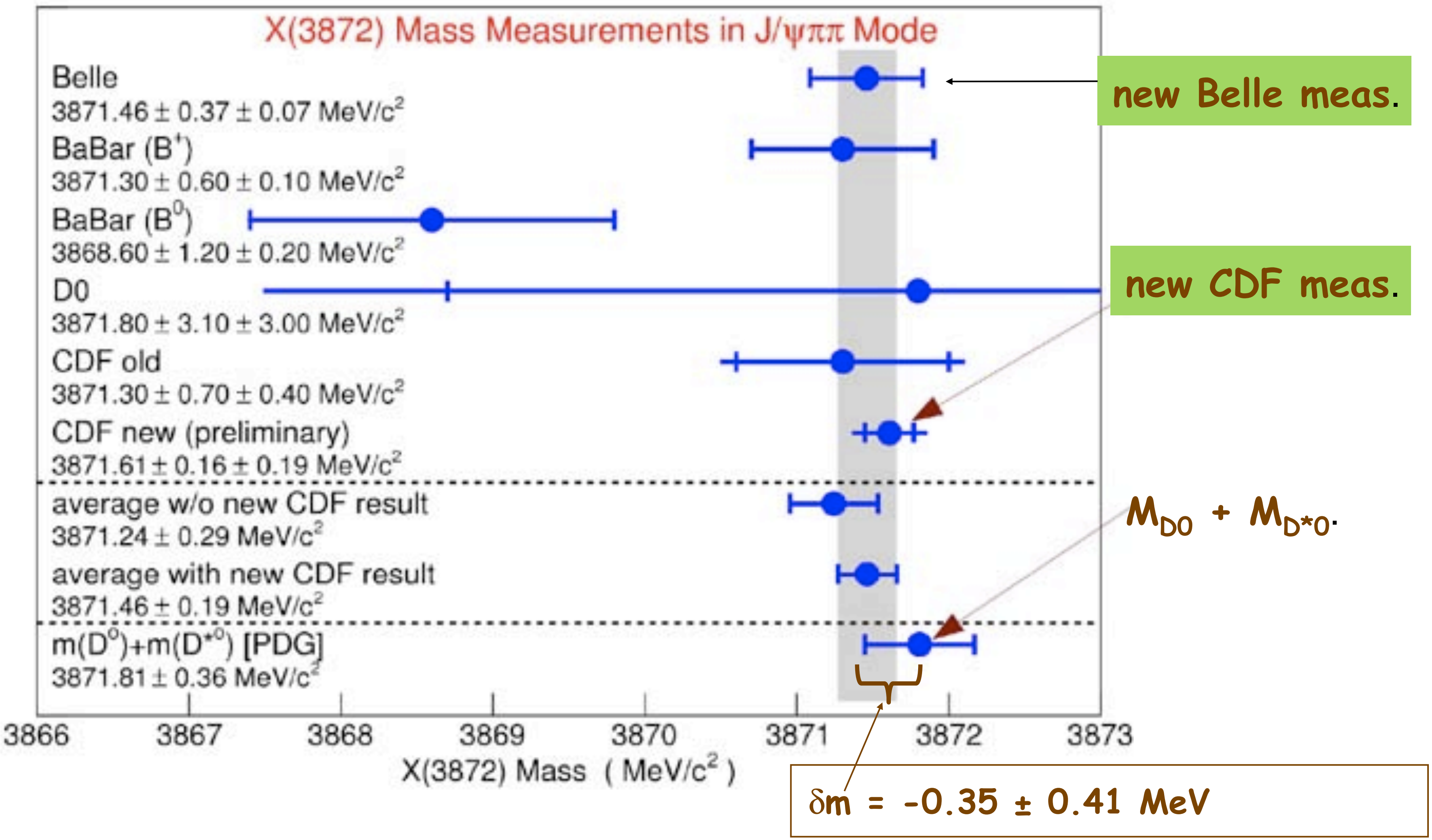


$$\delta M_X = M(X \text{ from } B^\pm) - M(X \text{ from } B^0)$$
$$= (2.7 \pm 1.6 \pm 0.4) \text{ MeV}$$

$$R = \frac{BR(B^0 \rightarrow X(3872)K^0)}{BR(B^\pm \rightarrow X(3872)K^\pm)} = 0.41 \pm 0.24 \pm 0.05$$

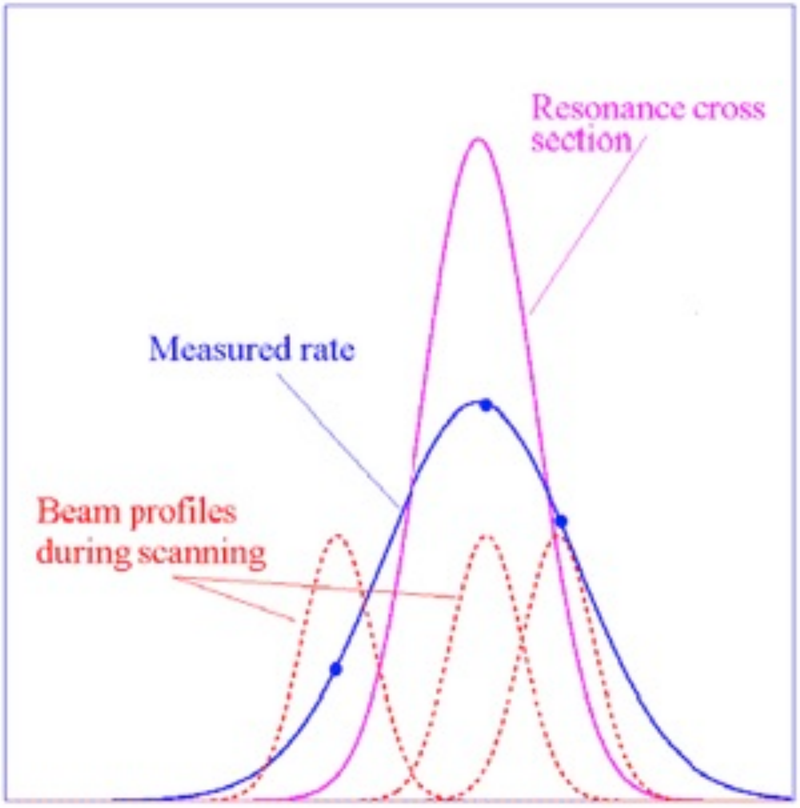
M(X(3872)) $\pi^+\pi^- J/\psi$ mode only

$\langle M_X \rangle = 3871.46 \pm 0.19$ MeV



S. Olsen @ charmed exotics workshop 2009

Resonance scan



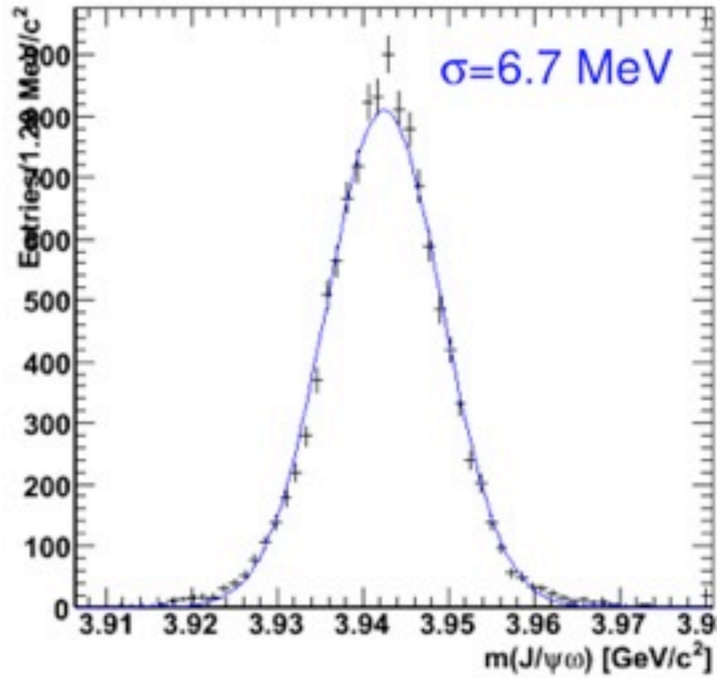
Measure rate of final state under study:

$$R_i = L_0 \bullet \sigma(p_i) \bullet K\ (\Delta p/p,\ |p_i - p_R|)$$

(K takes overlap between beam and resonance into account)

J/Ψω selection

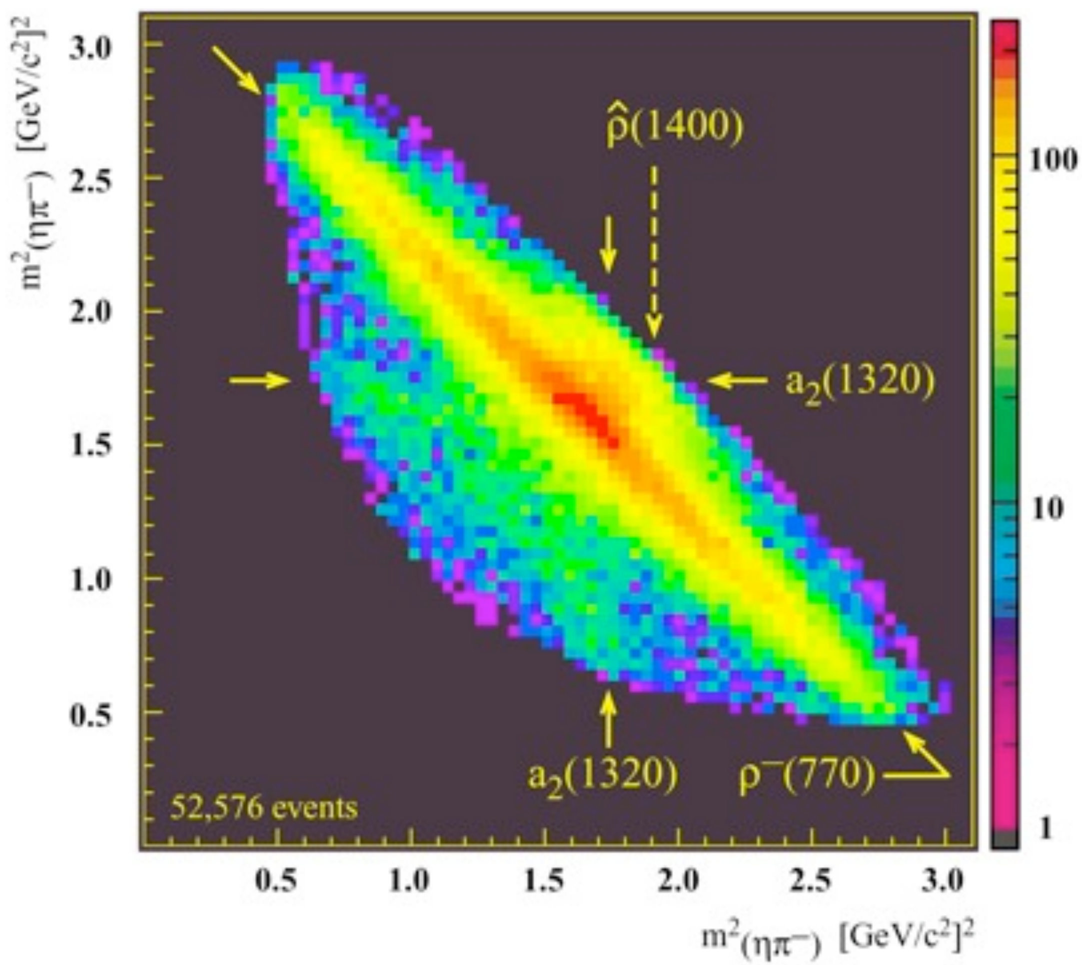
- 40k J/Ψω events at Y(3940)
  - $J/\Psi \to l^+l^-$, $\omega \to \pi^+\pi^-\pi^0$
- selection
  - PID: $p(l^+)>0.2$, $p(l^-)>0.85$
  - PID: $p(\pi^+)>0.2$, $m(\gamma\gamma) \in [115;150]$ MeV
  - 6C fit: beam, J/Ψ and π^0 mass constraint
  - mass windows
    - $m(e^+e^-) \in [3.07;3.12]$ GeV
    - $m(\pi^+\pi^-\pi^0) \in [750;810]$ MeV
  - J/Ψω cand. w/ biggest CL>0.1%
  - veto on $\Psi(2S) \to J/\Psi\pi^+\pi^-$
    - $m(J/\Psi\pi^+\pi^-) \in [3.6725;3.7]$GeV



Reconstruction efficiency: 16.5%
Product of branching ratios:
BR(Y(3940)→J/Ψω)x10.7%
Assume: int. lum. 8pb-1/day
cross sec. of 1nb
Expect BR(Y(3940)→J/Ψω)x140 evts/day

$\bar{p}d \rightarrow \pi^-\pi^\circ\eta + p$

spectator (<100 MeV/c)



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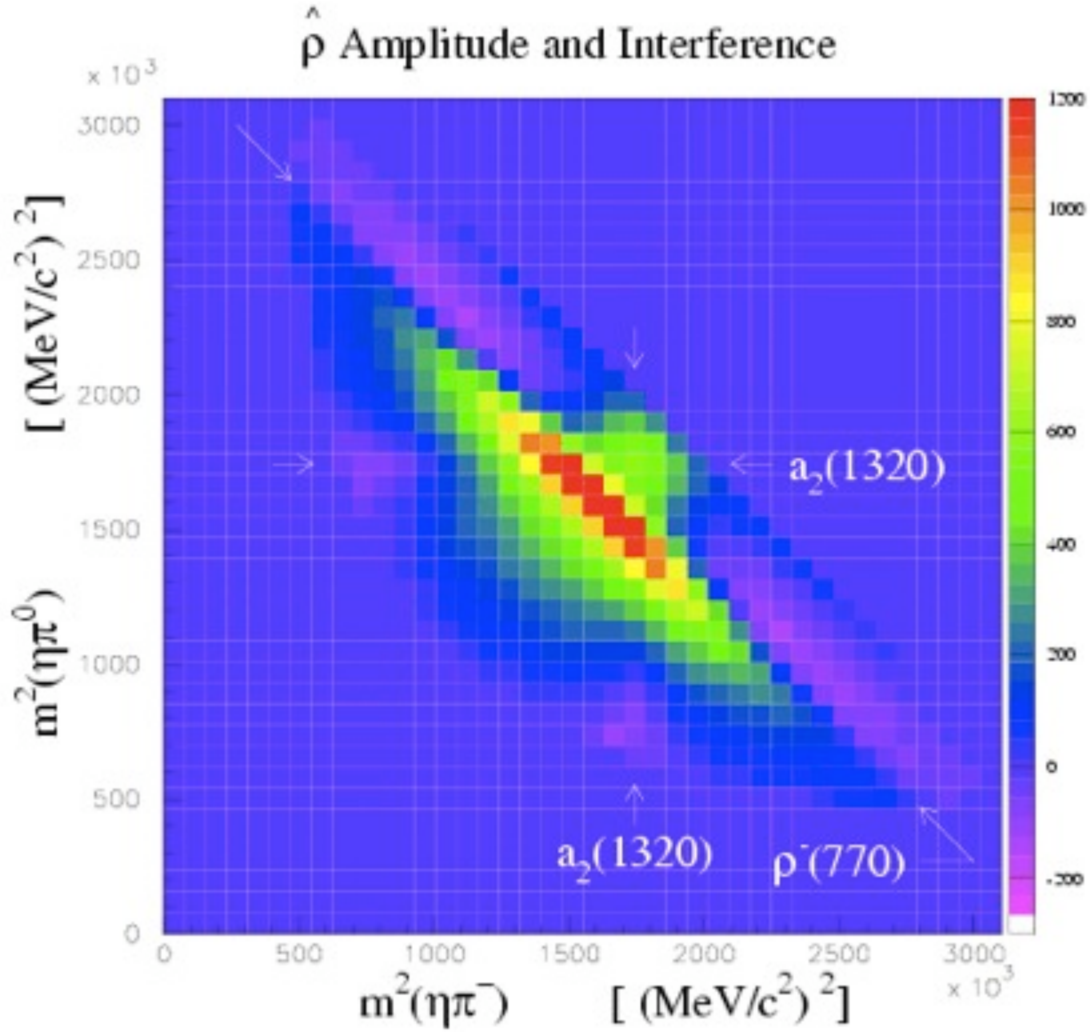

Properties of the $\pi_1(1400)$

Decay: $(\eta\pi)_{L=1}$

Mass: 1400 ± 30 MeV

Width: 310 ± 70 MeV

Quantum numbers: $J^{PC} = 1^{-+}$

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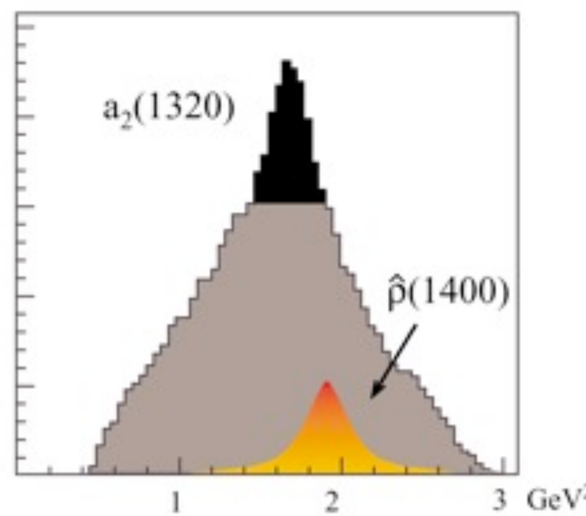
Previous indications of this resonance:

$\pi^- p \rightarrow (\pi^0\eta)n$ (GAMS/CERN, 100 GeV/c, 1988)
$\pi^- p \rightarrow (\pi^0\eta)n$ (VES/Serpukhov, 100 GeV/c, 1993)
$\pi^- p \rightarrow (\pi^0\eta)n$ (E852/Brookhaven, 18 GeV/c, 1997))

M: 1300 - 1400 MeV/c^2, Γ: 150 - 400 MeV

Exotic production in $p\bar{p}$:



What is the nature of these states?

Quarkonia? Molecules? Hybrids?

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➥ Wait for PANDA

Glueballs

Glueballs $\rightarrow$ Creation of Mass

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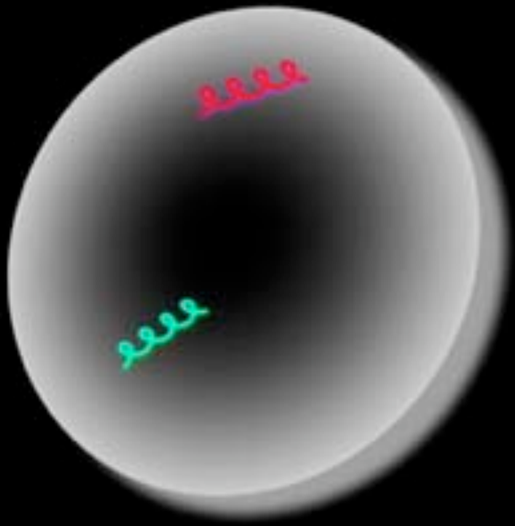
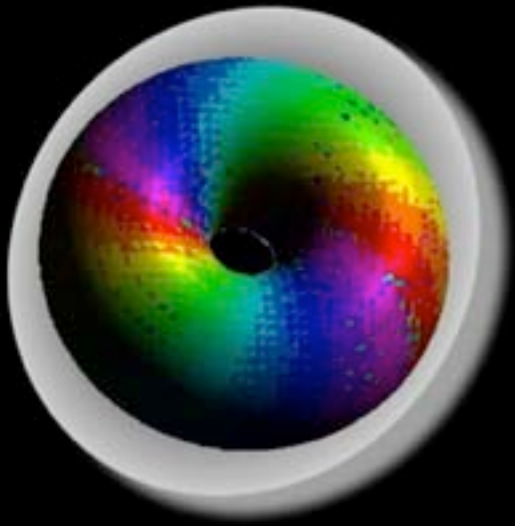
Glueballs



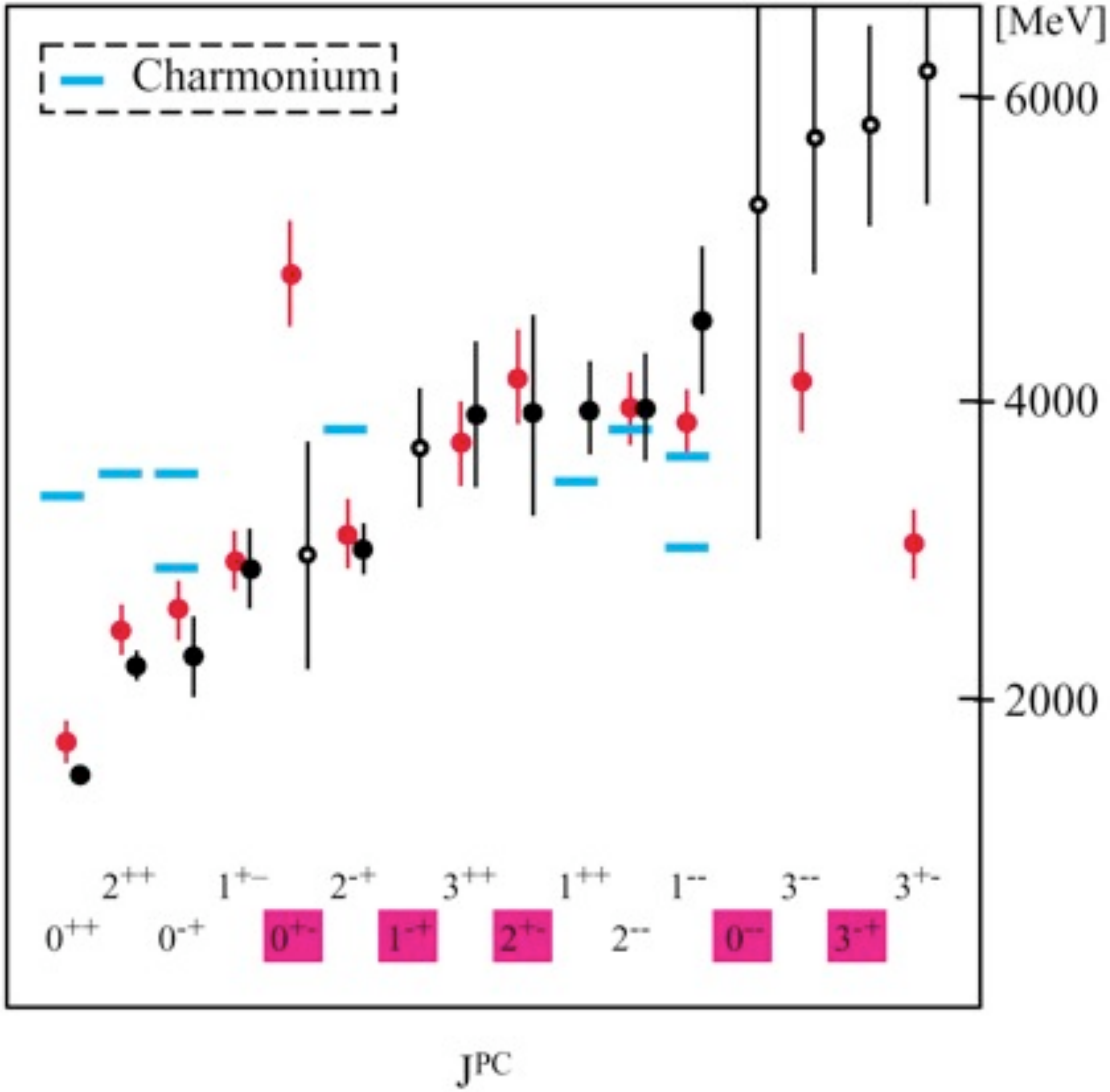


Glueballs, closed fluxtubes and η(1440)

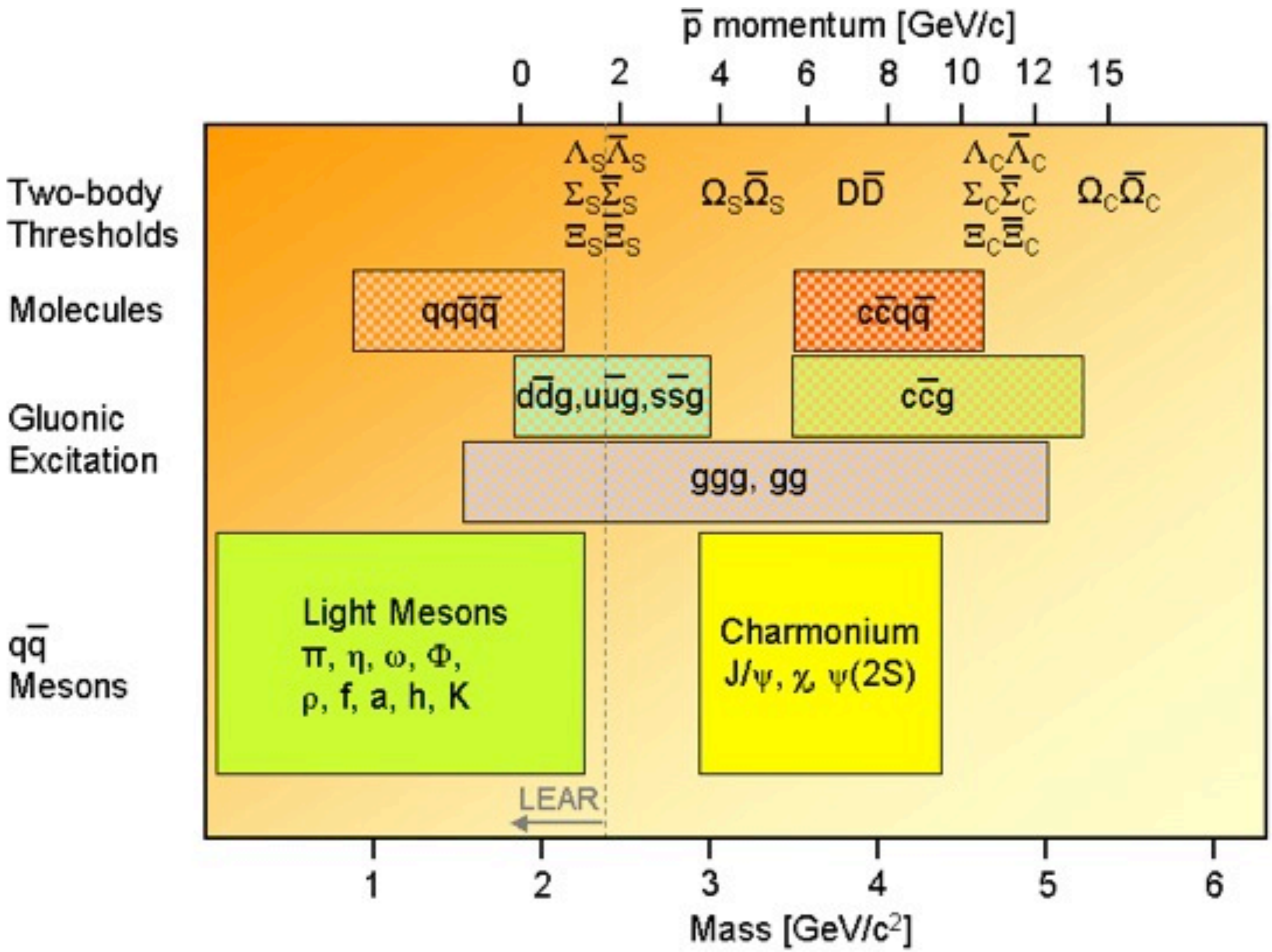
Ludvig Faddeev, Antti Niemi and Ulrich Wiedner

Phys.Rev.D70:114033, 2004

The glueball spectrum

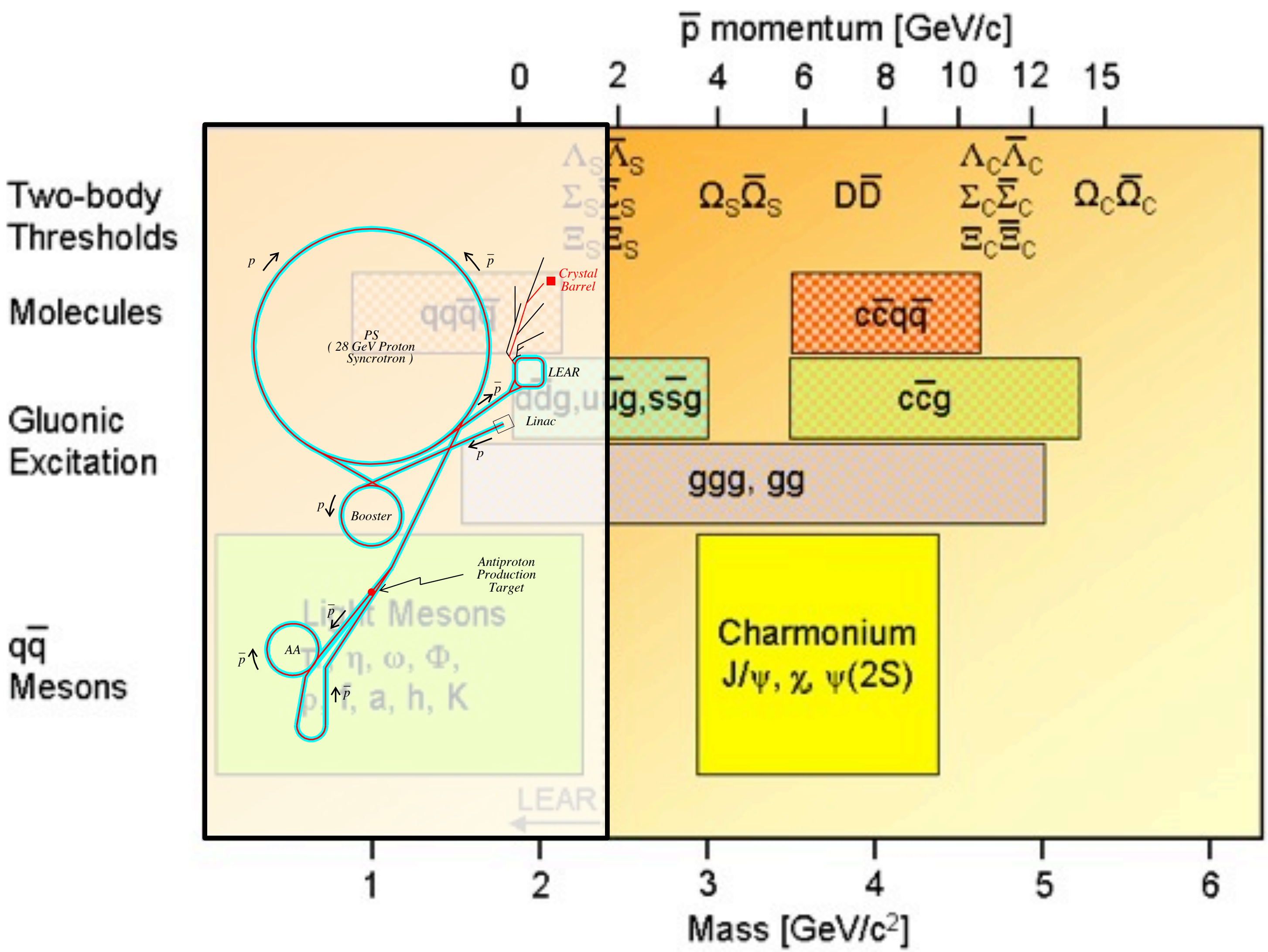


QCD systems



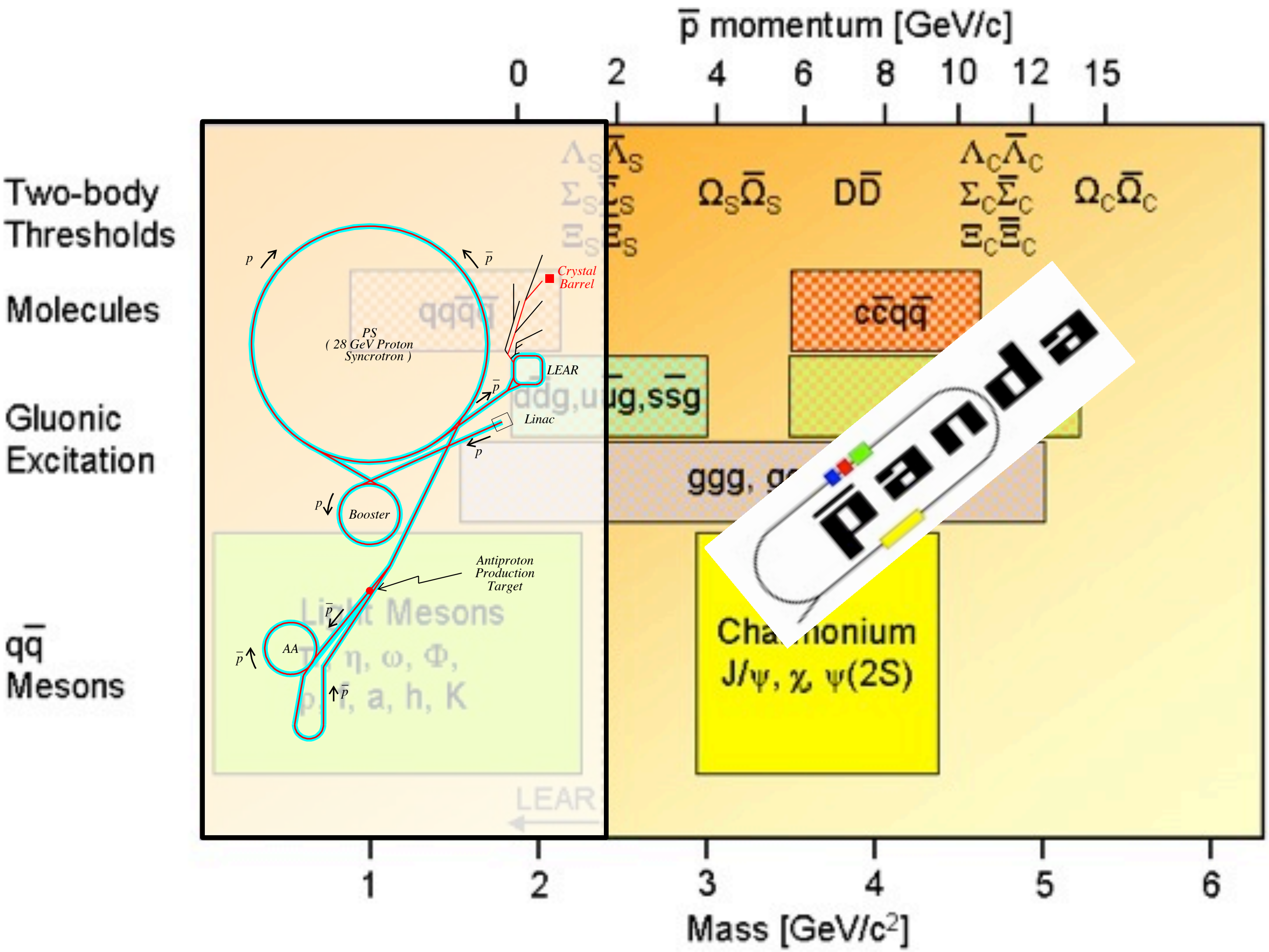
p̄ momentum [GeV/c]
0
2
4
6
8
10
12
15
Two-body Thresholds
Molecules
Gluonic Excitation
qq̄ Mesons
$\Lambda_S\bar{\Lambda}_S$
$\Sigma_S\bar{\Sigma}_S$
$\Xi_S\bar{\Xi}_S$
$\Omega_S\bar{\Omega}_S$
$D\bar{D}$
$\Lambda_C\bar{\Lambda}_C$
$\Sigma_C\bar{\Sigma}_C$
$\Xi_C\bar{\Xi}_C$
$\Omega_C\bar{\Omega}_C$
$qq\bar{q}\bar{q}$
$c\bar{c}q\bar{q}$
$d\bar{d}g, u\bar{u}g, s\bar{s}g$
$c\bar{c}g$
ggg, gg
Light Mesons
π, η, ω, Φ,
ρ, f, a, h, K
Charmonium
J/ψ, χ, ψ(2S)
LEAR
1
2
3
4
5
6
Mass [GeV/c²]

QCD systems



p̄ momentum [GeV/c]
0
2
4
6
8
10
12
15
Two-body Thresholds
Molecules
Gluonic Excitation
qq̄ Mesons
Λ_S Λ̄_S
Σ_S Σ̄_S
Ξ_S Ξ̄_S
Ω_S Ω̄_S
DD̄
Λ_C Λ̄_C
Σ_C Σ̄_C
Ξ_C Ξ̄_C
Ω_C Ω̄_C
qqq̄q̄
cc̄qq̄
ddg,uūg,ss̄g
cc̄g
ggg, gg
Light Mesons
Charmonium
J/ψ, χ, ψ(2S)
LEAR
PS
(28 GeV Proton Syncrotron)
Crystal Barrel
LEAR
Linac
Booster
Antiproton Production Target
AA
1
2
3
4
5
6
Mass [GeV/c²]

QCD systems



p̄ momentum [GeV/c]
0 2 4 6 8 10 12 15
Two-body Thresholds
Molecules
Gluonic Excitation
qq̄ Mesons
ΩsΩ̄s
DD̄
ΛcΛ̄c
ΣcΣ̄c
ΞcΞ̄c
ΩcΩ̄c
cc̄qq̄
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LEAR
Linac
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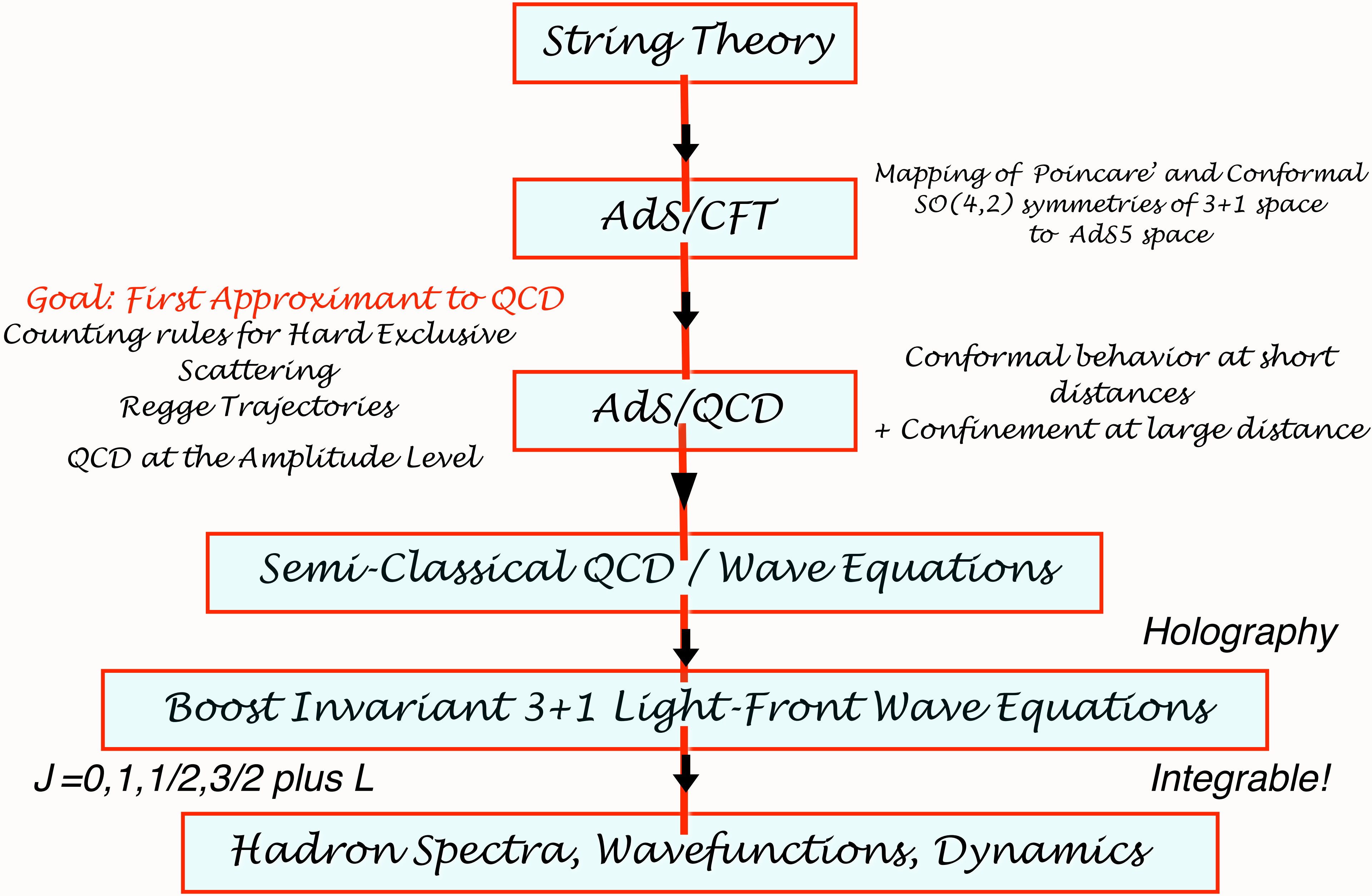
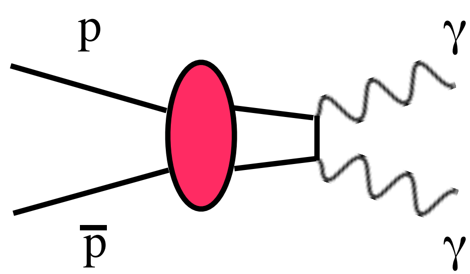
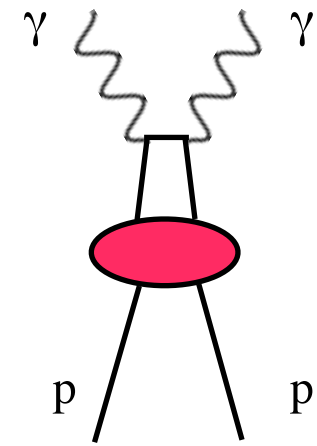
Antiproton Production Target
AA
LEAR
1 2 3 4 5 6
Mass [GeV/c2]

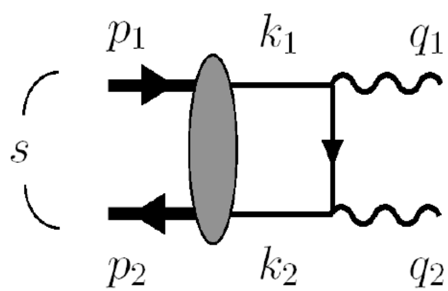

String Theory
AdS/CFT
Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space to AdS5 space
Goal: First Approximant to QCD
Counting rules for Hard Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level
AdS/QCD
Conformal behavior at short distances
+ Confinement at large distance
Semi-Classical QCD / Wave Equations
Holography
Boost Invariant 3+1 Light-Front Wave Equations
J =0,1,1/2,3/2 plus L
Integrable!
Hadron Spectra, Wavefunctions, Dynamics

Electromagnetic Processes: $\bar{p}p \rightarrow \gamma\gamma$



crossed-channel
Compton scattering





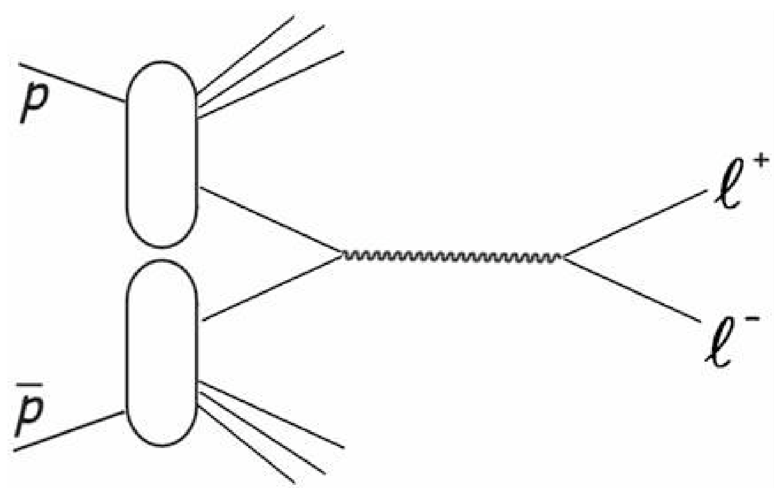
Handbag diagram separates a soft part described by GPDs from a hard $q\bar{q}$ annihilation process

Predicted rates*: several thousand / month or above

Exp. problem: Background channels like $\pi^0\gamma$ or $\pi^0\pi^0$ 5× - 100× stronger.

*A. Freund, A. Radyushkin, A. Schäfer, and C. Weiss, Phys. Rev. Lett. 90, 092001 (2003).

Study of Drell-Yan processes might contribute to the knowledge of parton distribution functions (polarized nuclear targets?).



How to Calculate Meson Spectra from String Theory

Johanna Erdmenger

Max-Planck-Institut für Physik, München

work in collaboration with J. Babington, Z. Guralnik, I. Kirsch (HU Berlin),
R. Apreda, J. Große (HU Berlin/MPI München), N. Evans (Southampton)

For a review see: Eur.Phys.J.A35:81-133,2008

AdS/CFT Correspondence

(Maldacena 1997, AdS: Anti de Sitter space, CFT: conformal field theory)

- Duality Quantum Field Theory ⇔ Gravity Theory
- Arises from String Theory in a particular low-energy limit
- Duality: Quantum field theory at strong coupling

  ⇔ Gravity theory at weak coupling
- Works for large N gauge theories at large 't Hooft coupling λ

Conformal field theory in four dimensions

⇔ Supergravity Theory on $AdS_5 \times S^5$

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Comparison with experimental results

$\mathrm{D4/D8/\bar{D}8}$ brane model – spontaneous breaking of $SU(N_f) \times SU(N_f)$

Sakai+Sugimoto 12/2004

vector and axial vector mesons

(obtained from gauge field fluctuations as described by the DBI action)

meson mass ratio:

Experiment:

$$\frac{m_{a_1}^2}{m_\rho^2} = \frac{(1230\mathrm{MeV})^2}{(776\mathrm{MeV})^2} = 2.51$$

Stringy model:

$$\frac{m_{a_1}^2}{m_\rho^2} = 2.4$$

($\rho : C = -1, a_1 : C = +1$)

In the model of Sakai+Sugimoto, it is also possible to have $N_f > 1$.

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LBNL-42987
UCB-PTH-99/08
hep-th/9903142

Glueball Mass Spectrum from Supergravity*

see also: JHEP 9901:017,1999

Csaba Csáki† and John Terning
Theoretical Physics Group
Ernest Orlando Lawrence Berkeley National Laboratory
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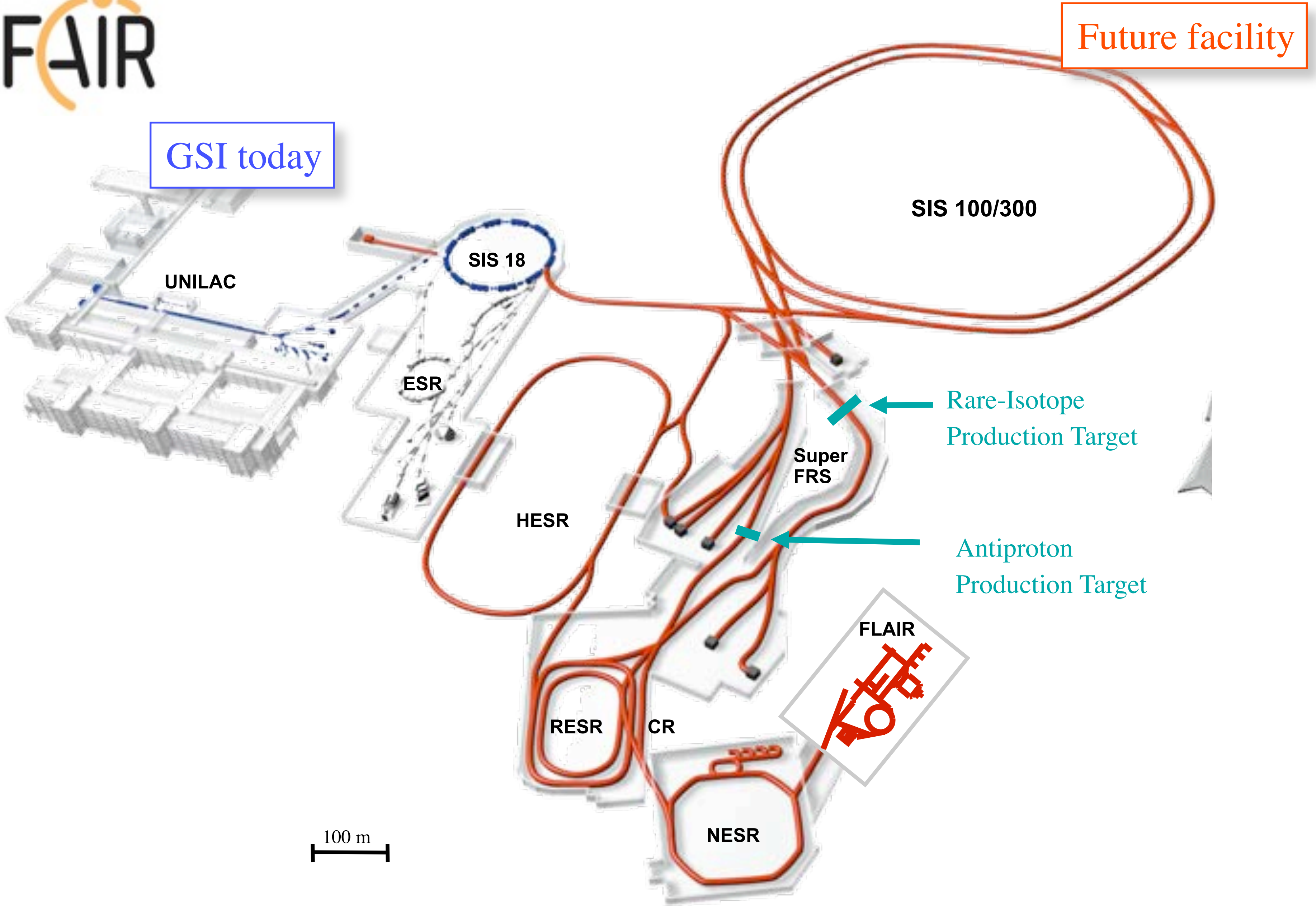
…

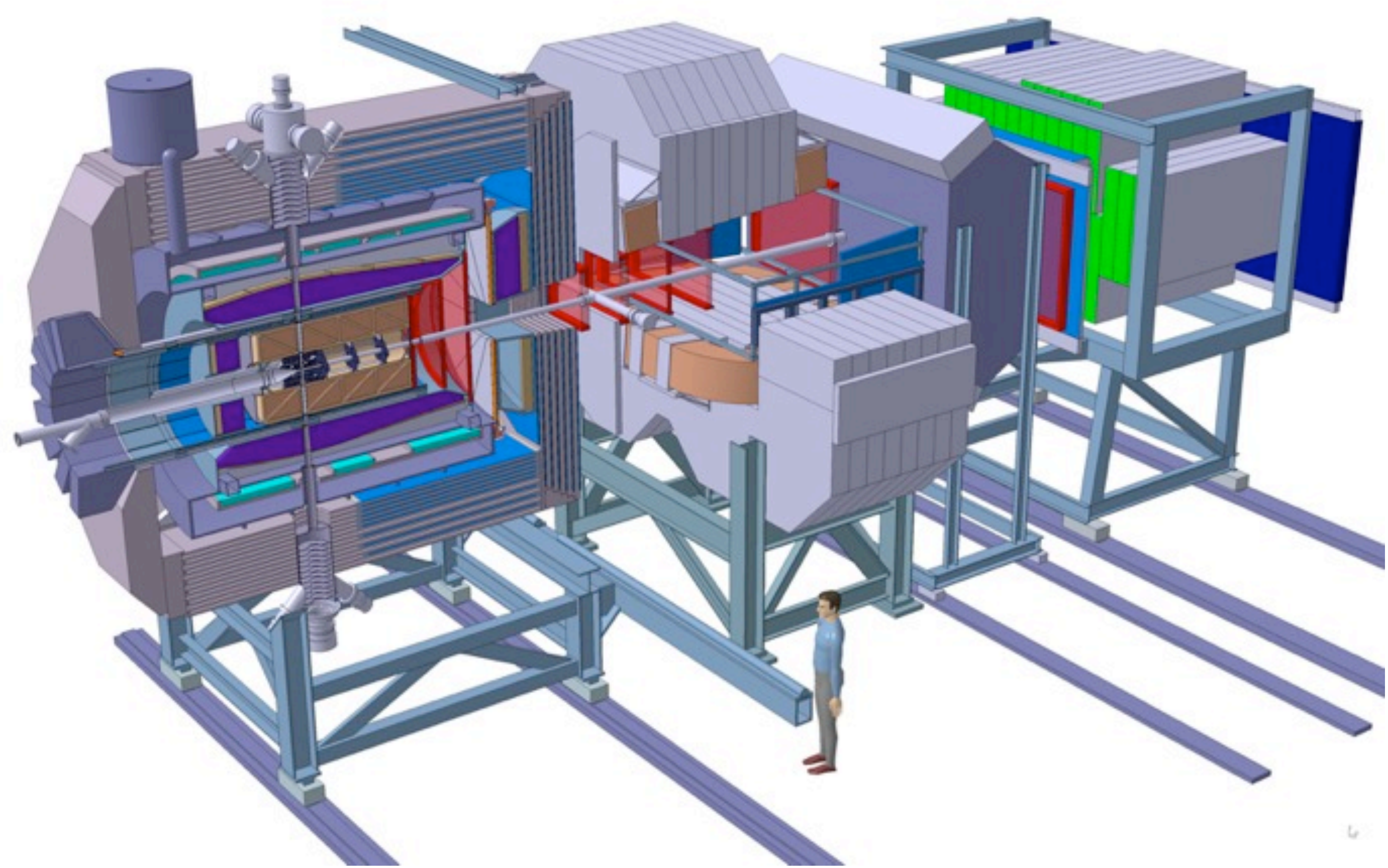
TABLE III. Masses of the first few 0^{++} glueballs in QCD_4, in GeV, from supergravity compared to the available lattice results. The first column gives the lattice result [7,16,17], the second the supergravity result for $a = 0$ while the third the supergravity result in the $a \to \infty$ limit. The change from $a = 0$ to $a = \infty$ in the supergravity predictions is tiny. Note, that for the excited state the supergravity calculation came before the lattice results.

state	lattice, $N = 3$	supergravity $a = 0$	supergravity $a \to \infty$
0^{++}	1.61 ± 0.15	1.61 (input)	1.61 (input)
0^{++*}	2.48 ± 0.18	2.55	2.56
0^{++**}	-	3.46	3.48
0^{++***}	-	4.36	4.40

…


Future facility
GSI today
SIS 100/300
SIS 18
UNILAC
ESR
HESR
Super
FRS
Rare-Isotope
Production Target
Antiproton
Production Target
FLAIR
RESR
CR
NESR
100 m

The PANDA Detector



PANDA Collaboration

- At present a group of **420 physicists** from 54 institutions and 16 countries

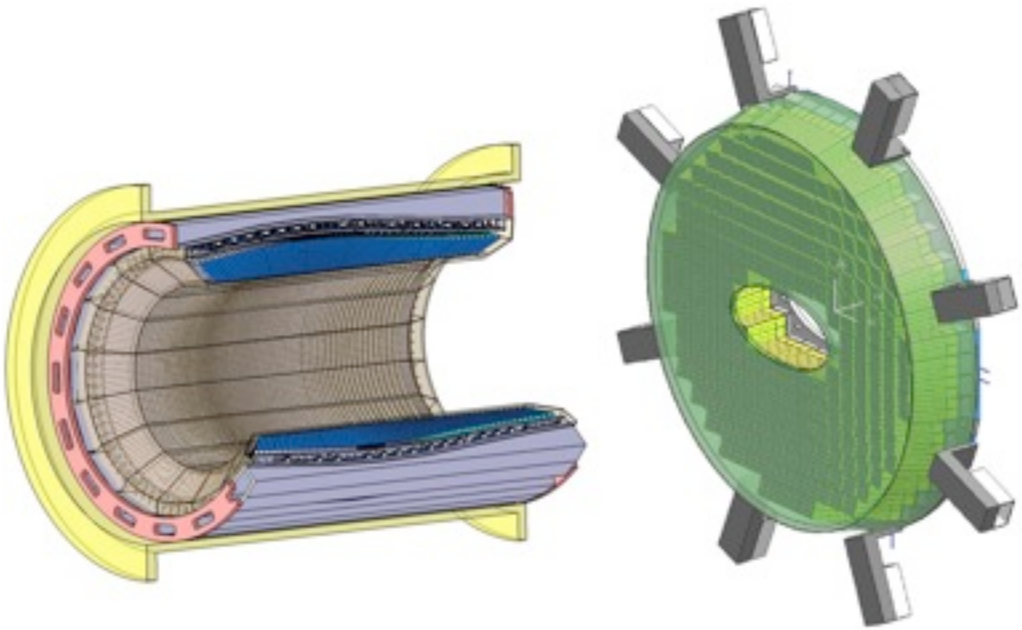
Austria – Belaruz – China – France – Germany – India – Italy – The Netherlands – Poland – Romania – Russia – Spain – Sweden – Switzerland – U.K. – U.S.A.

Basel, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, Catania, IIT Chicago, AGH-UST Cracow, JGU 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

Spokesperson: Ulrich Wiedner (Bochum)

http://www.gsi.de/panda

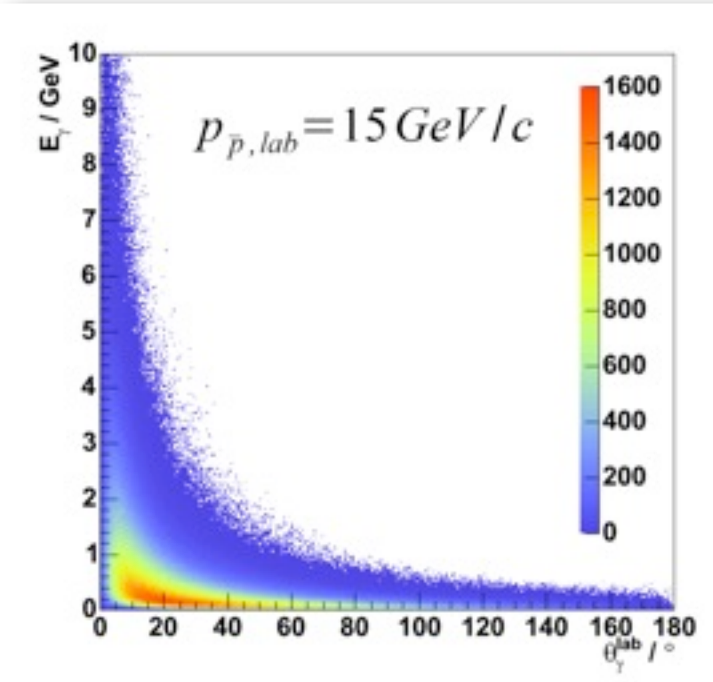
The PANDA EMC



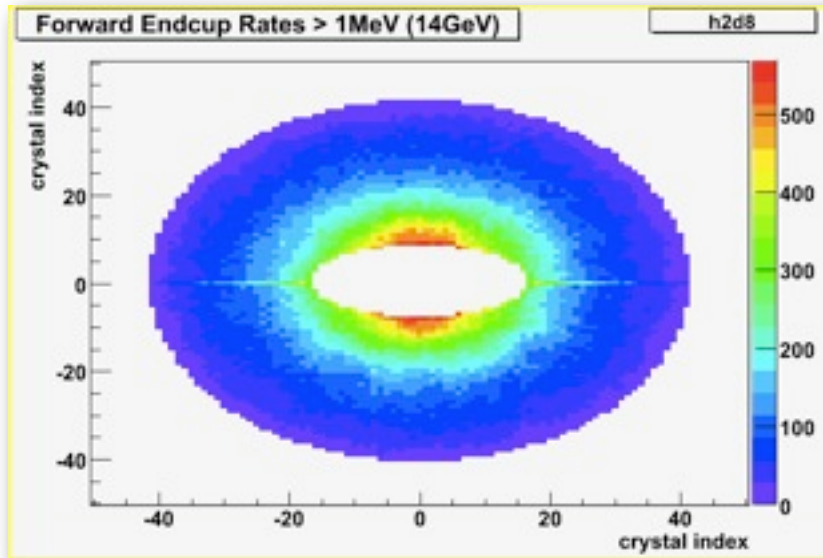
Partners:
Sweden (Uppsala, Lund, KTH Stockholm, Stockholm), KVI, Basel, Germany (Bochum, Giessen, GSI)

The Forward EMC is more challenging than the CMS-EMC:

- γ energies between 0.01 - 15 GeV
- very high count rates (up to 500 kHz)



J. Zhong, Bochum



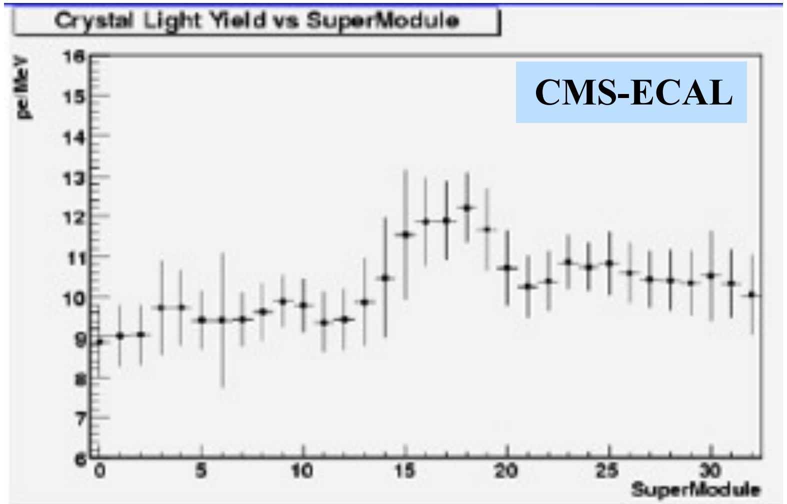
absorbed energy dose:

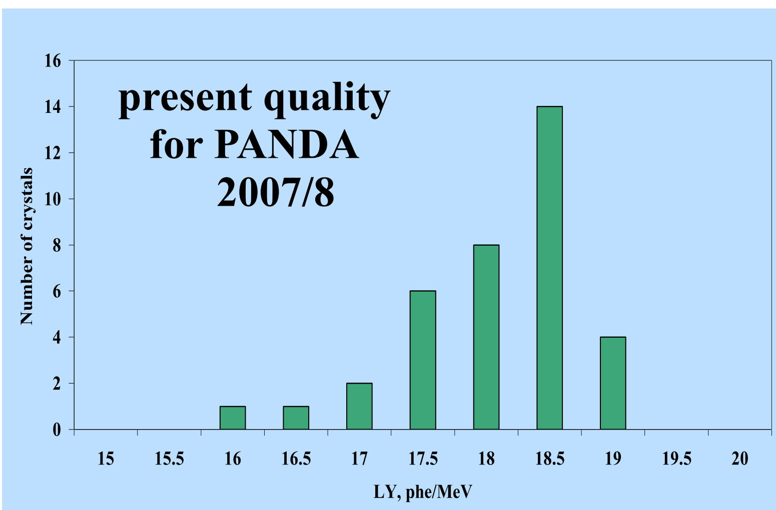
- @14GeV (innermost) 11.9 mJ/h
- @6GeV (innermost) 5.7 mJ/h

M. Kotulla, Giessen

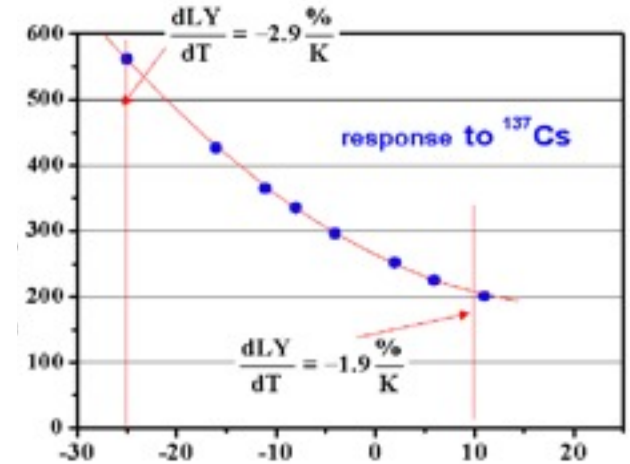
The PANDA-EMC will be better:

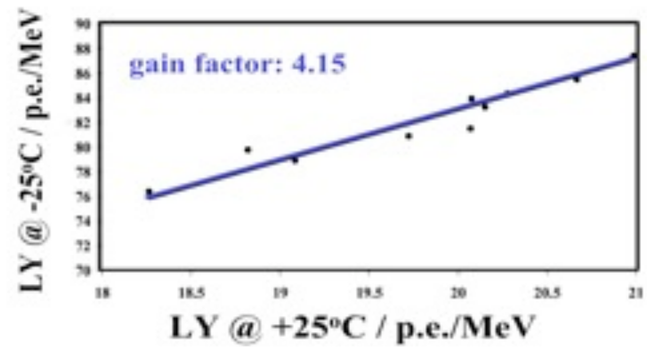
light yield





cooling





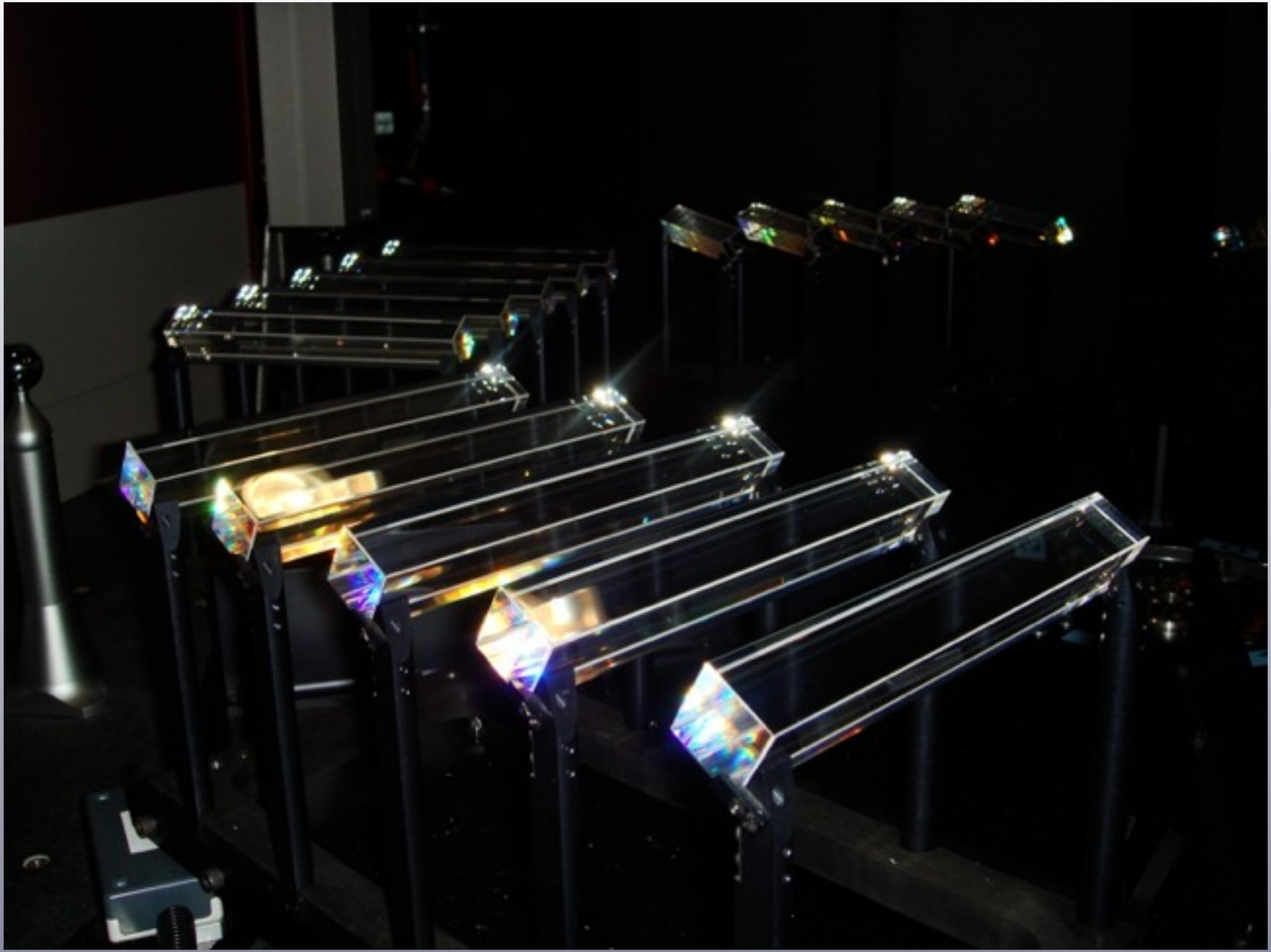
@-25°C: 90p.e./MeV, 18%QE

for APD-readout: A = 2cm², 70%QE **150p.e./MeV**

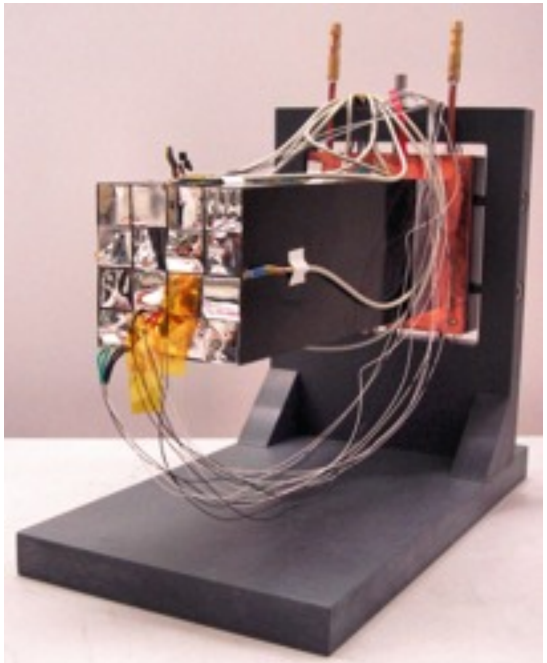
to be considered: light collection in tapered crystals
radiation damage
uniformity due to surface treatment

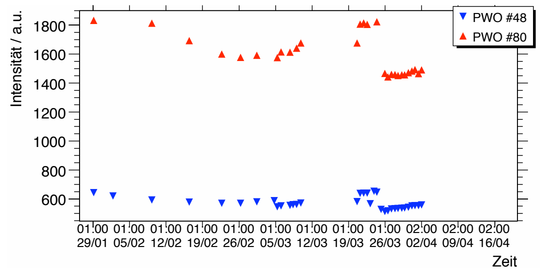
R. Novotny, Giessen

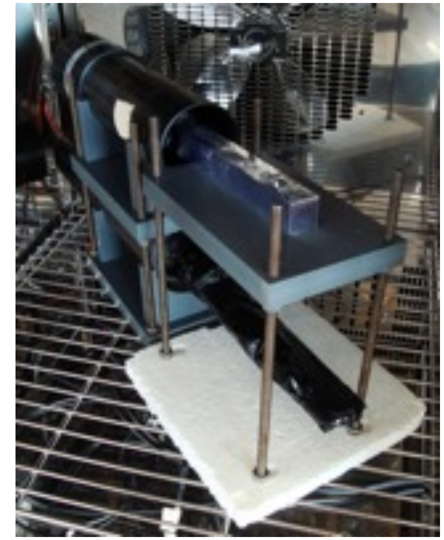

JOHANSSON
RADIATION
LIMIT

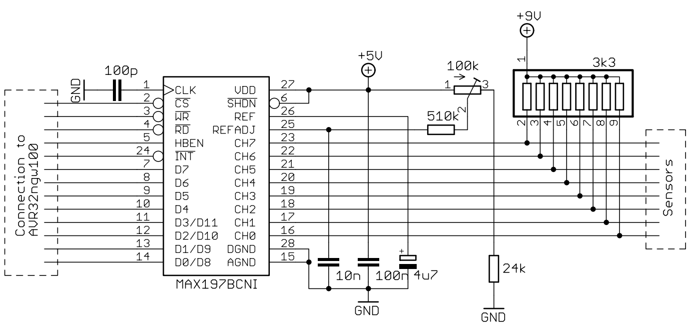


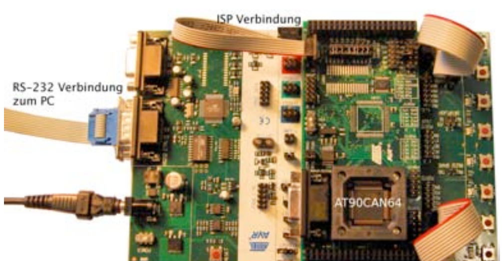
Hardware activities

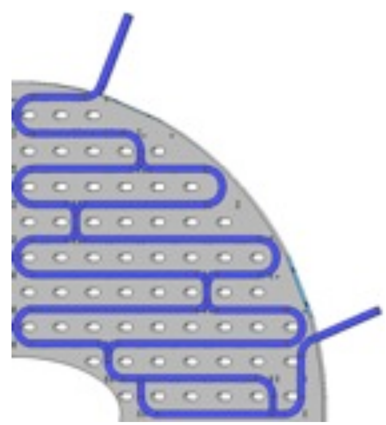


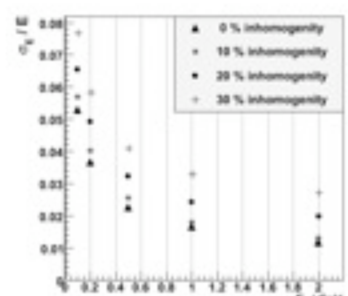


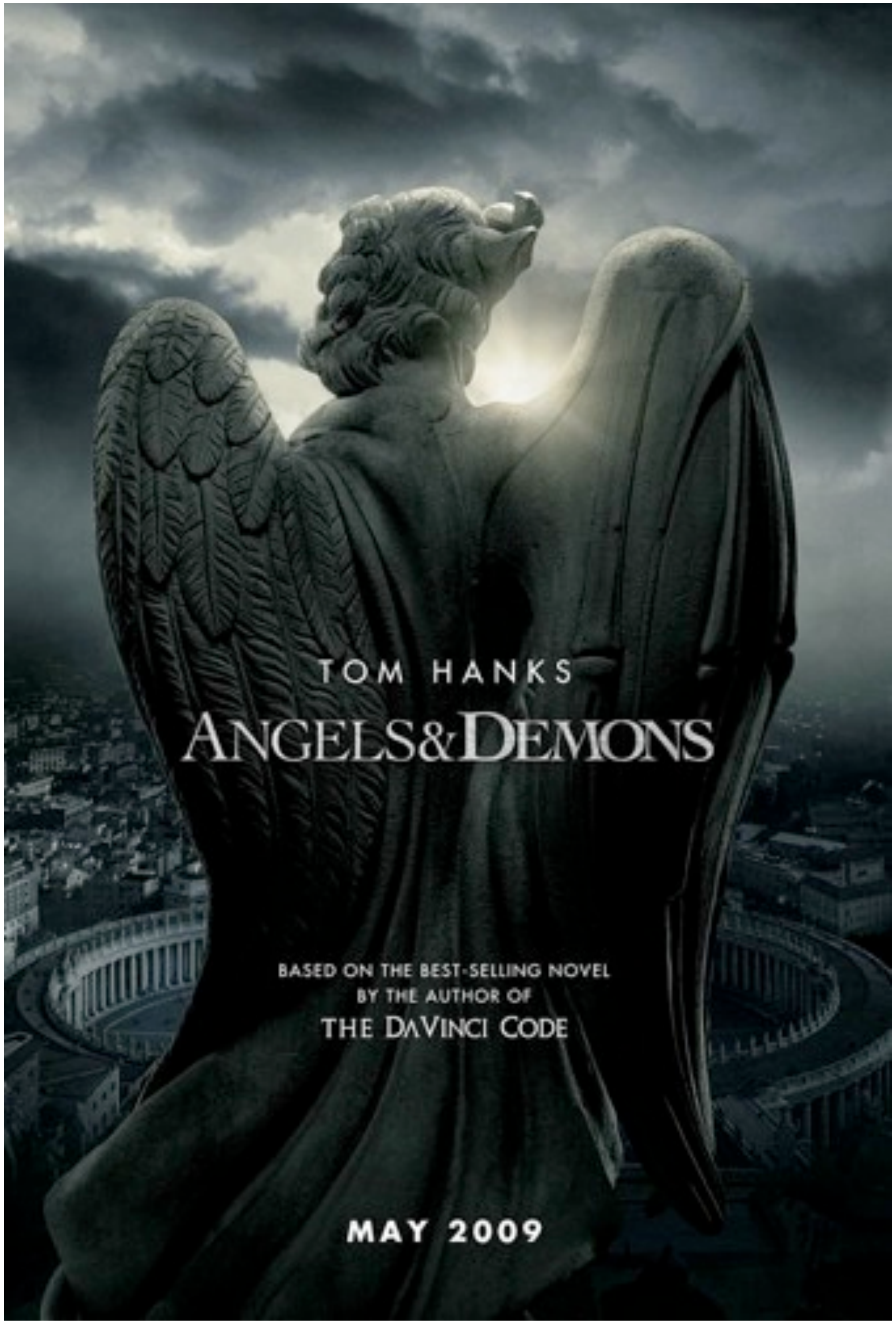












Cost: 1 g antimatter:

1 P€ (10^{15} €)

Cost: FAIR:

1 B€ (10^{9} €)

Thank you for your attention!