

Hadron Physics with PANDA at FAIR

Ulrich Wiedner
Bochum University

Freiburg, March 21, 2007

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

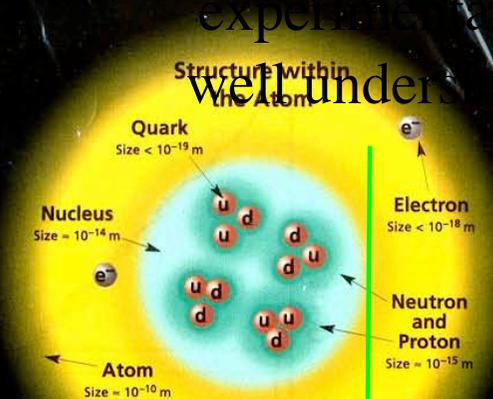
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it 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/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.0018	0
τ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
s strange	0.1	-1/3
c charm	1.3	2/3
b bottom	4.3	-1/3



BOSONS

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

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^\pm	80.4	± 1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

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 .

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV s} = 1.05 \times 10^{-34} \text{ J s}$.

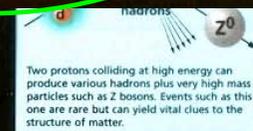
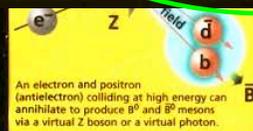
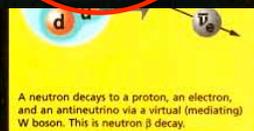
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
				Fundamental	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^{-41}	0.8	1	25	Not applicable to quarks
for two protons in nucleus	10^{-41}	10^{-4}	1	60	20
	10^{-36}	10^{-7}	1	Not applicable to hadrons	

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.

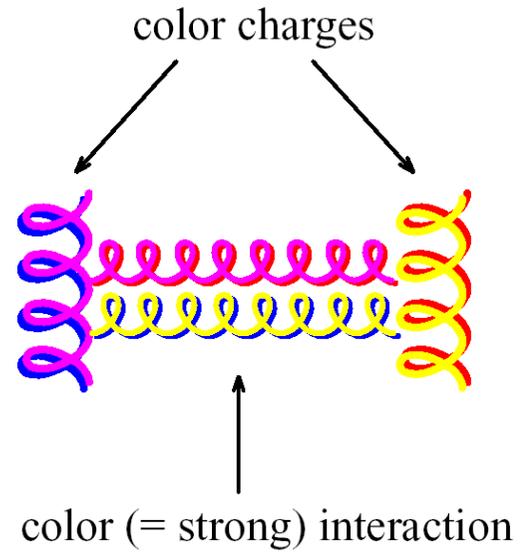
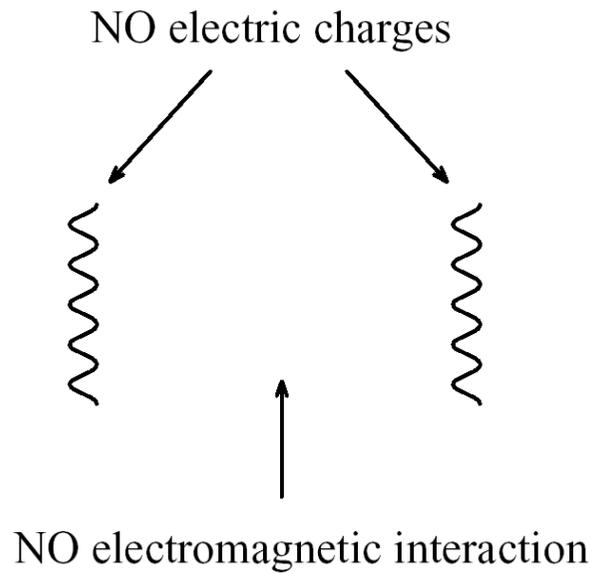


Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

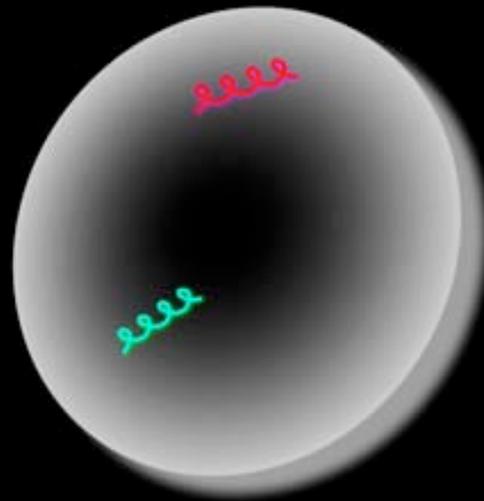
©2000 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and students. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

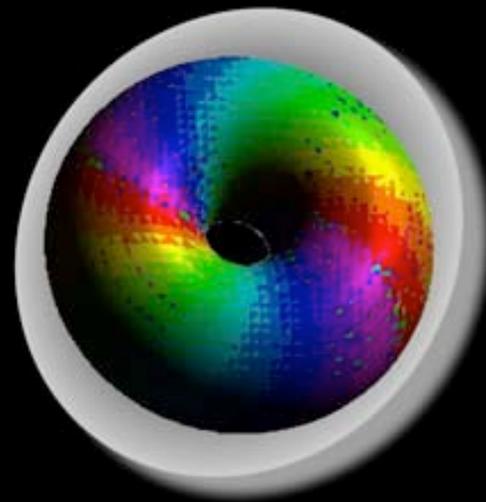
<http://CPEPweb.org>

Self Interaction of Color Fields



Glueballs





Glueballs, closed fluxtubes and $\eta(1440)$
Ludvig Faddeev, Antti Niemi and Ulrich Wiedner
Phys.Rev.D70:114033, 2004

Creation of Mass

A few % of the proton mass is generated due to the **Higgs mechanism**.

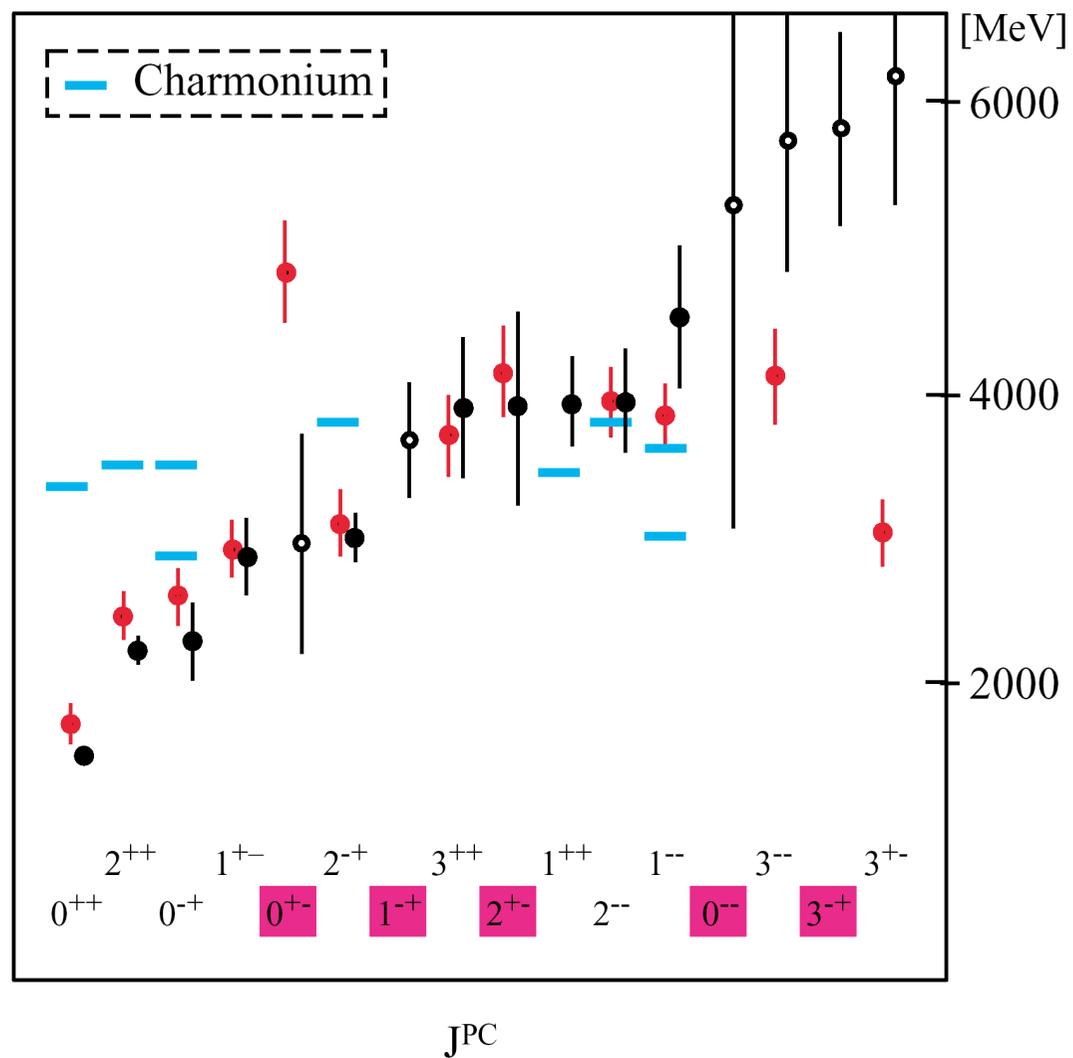
Most of the proton mass is created by the **strong interaction**.

HOW ??????

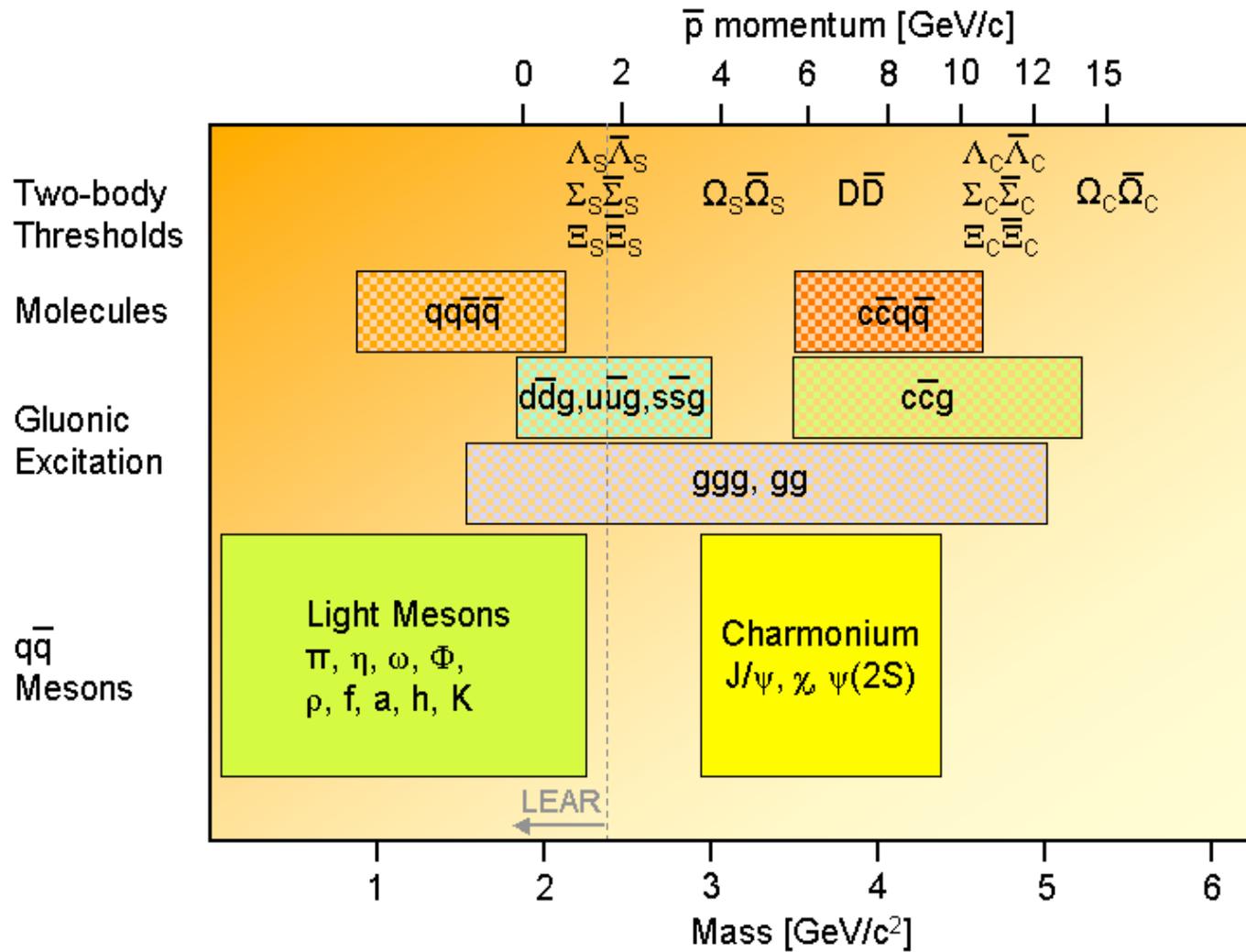
We do not understand most of the baryonic mass of the Universe.

Glueballs gain their mass solely by the strong interaction and are therefore an unique approach to the mass creation by the strong interaction.

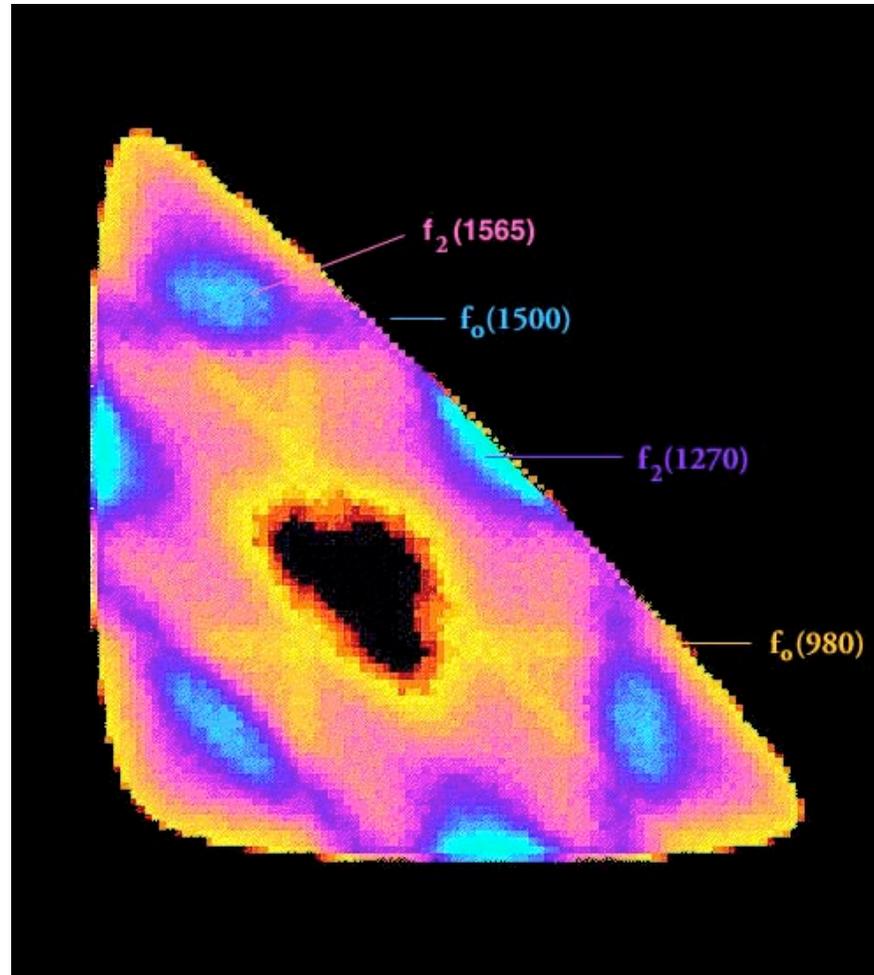
The glueball spectrum



QCD systems

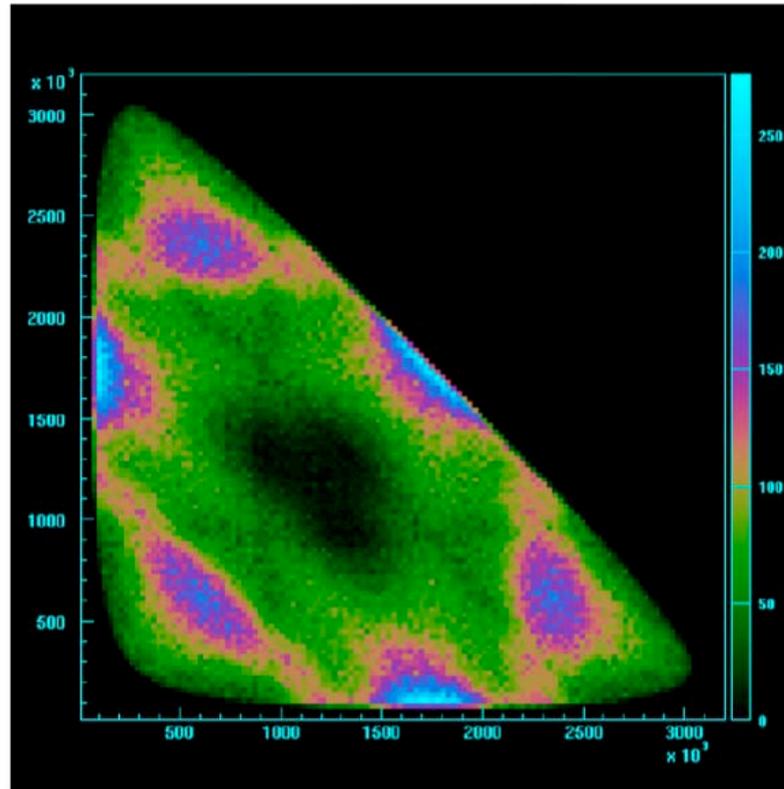


$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ Dalitz plot

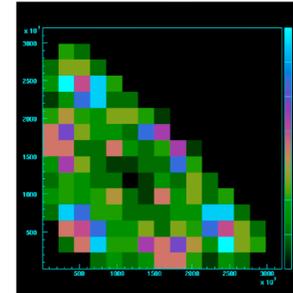


700000 events = 6×700000 entries

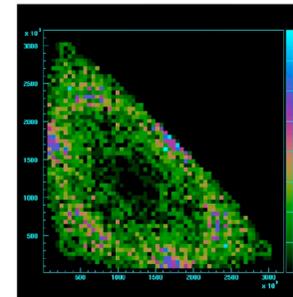
100,000 events



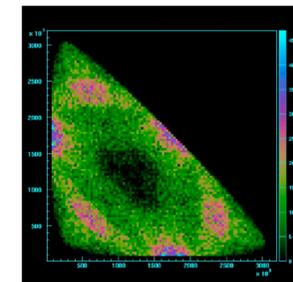
100 events

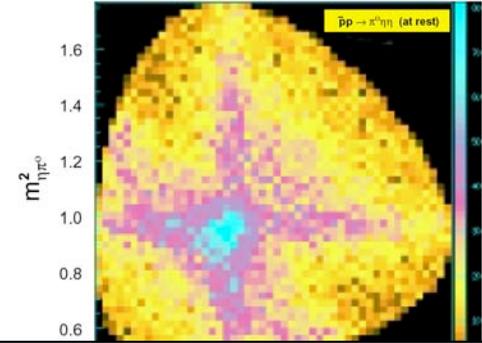
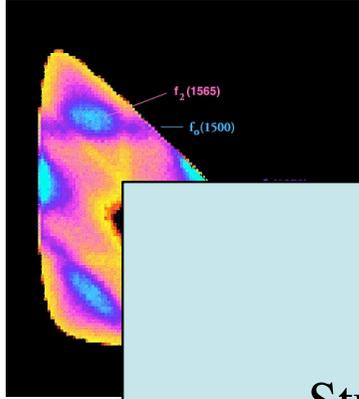


1000 events

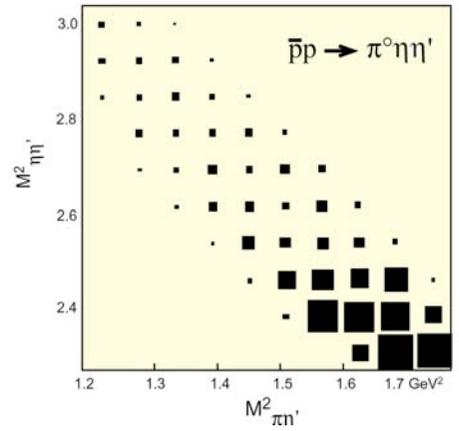
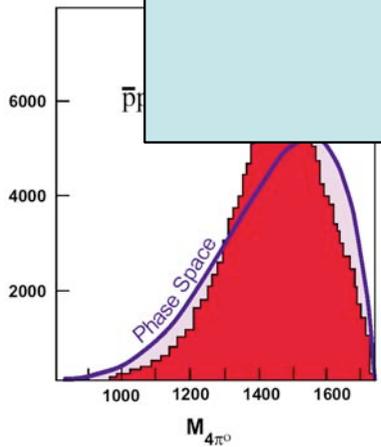
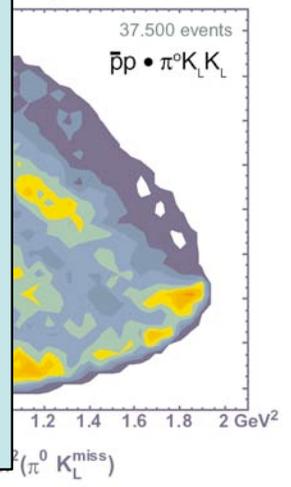


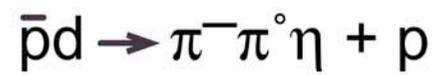
10,000 events





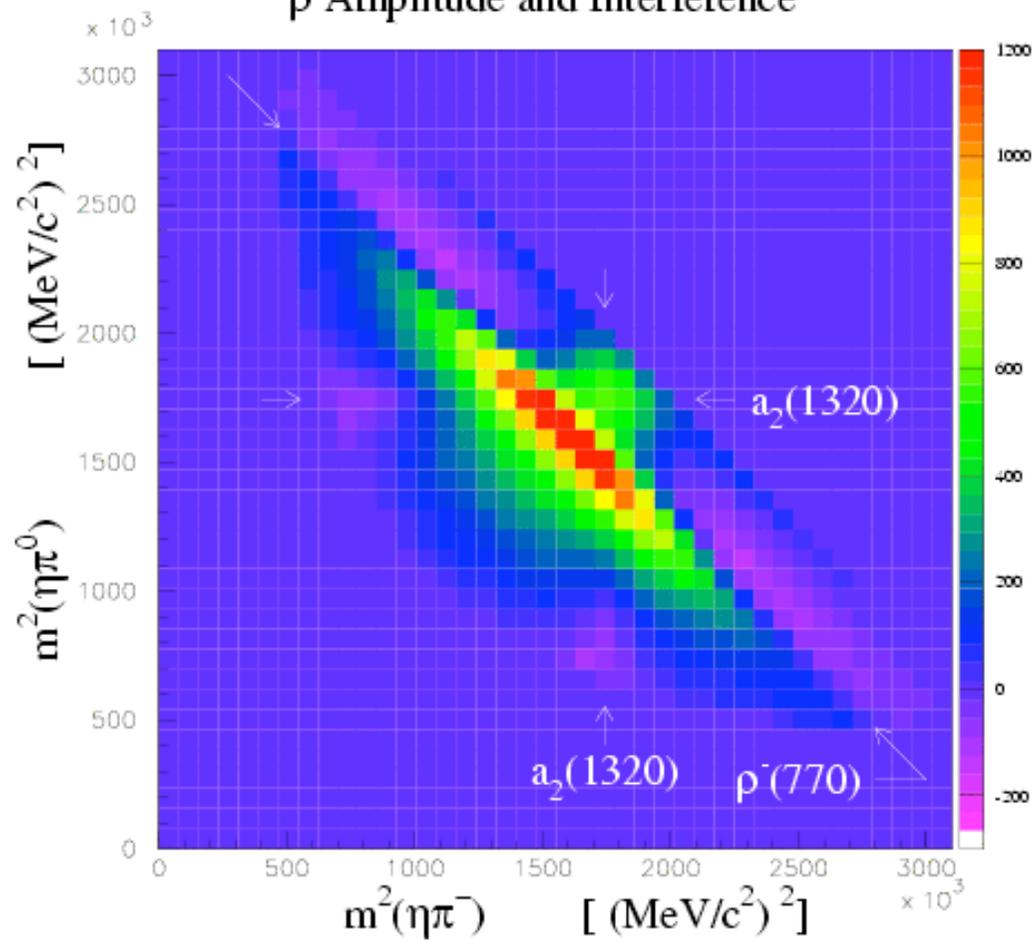
Study particles in a high-statistics, high-resolution 4π experiment in as many final states as possible.



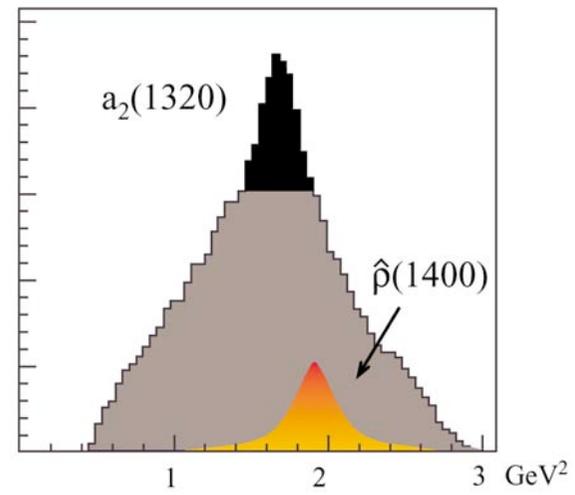


└── spectator
(<100 MeV/c)

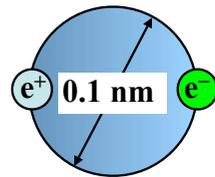
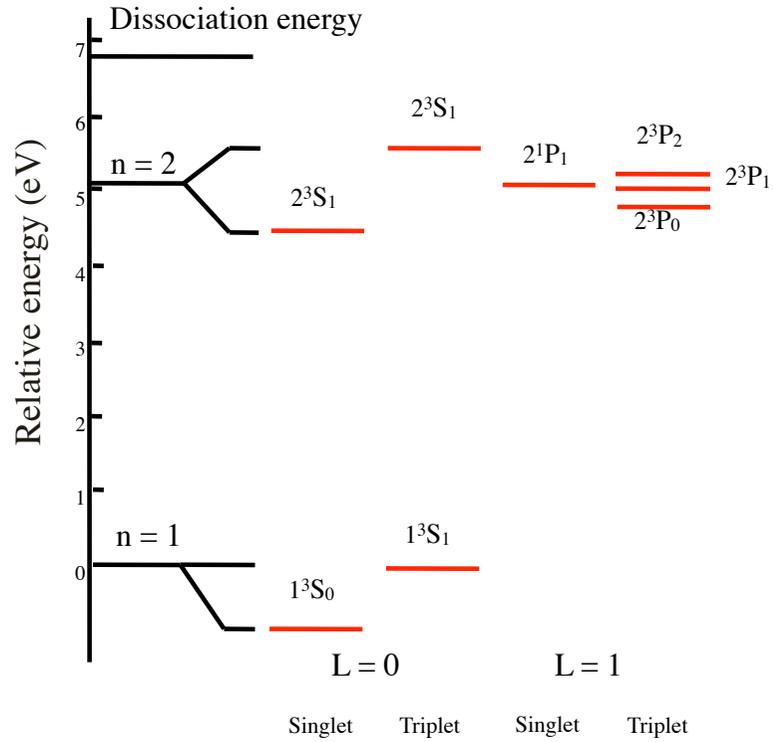
$\hat{\rho}$ Amplitude and Interference



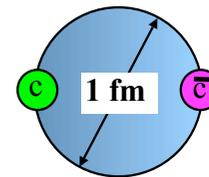
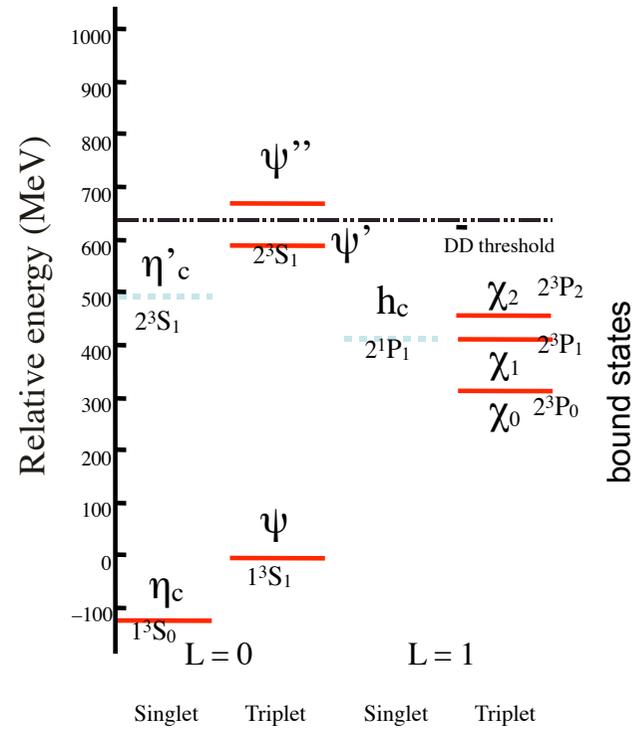
Exotic production in $\bar{p}p$:



Positronium



Charmonium

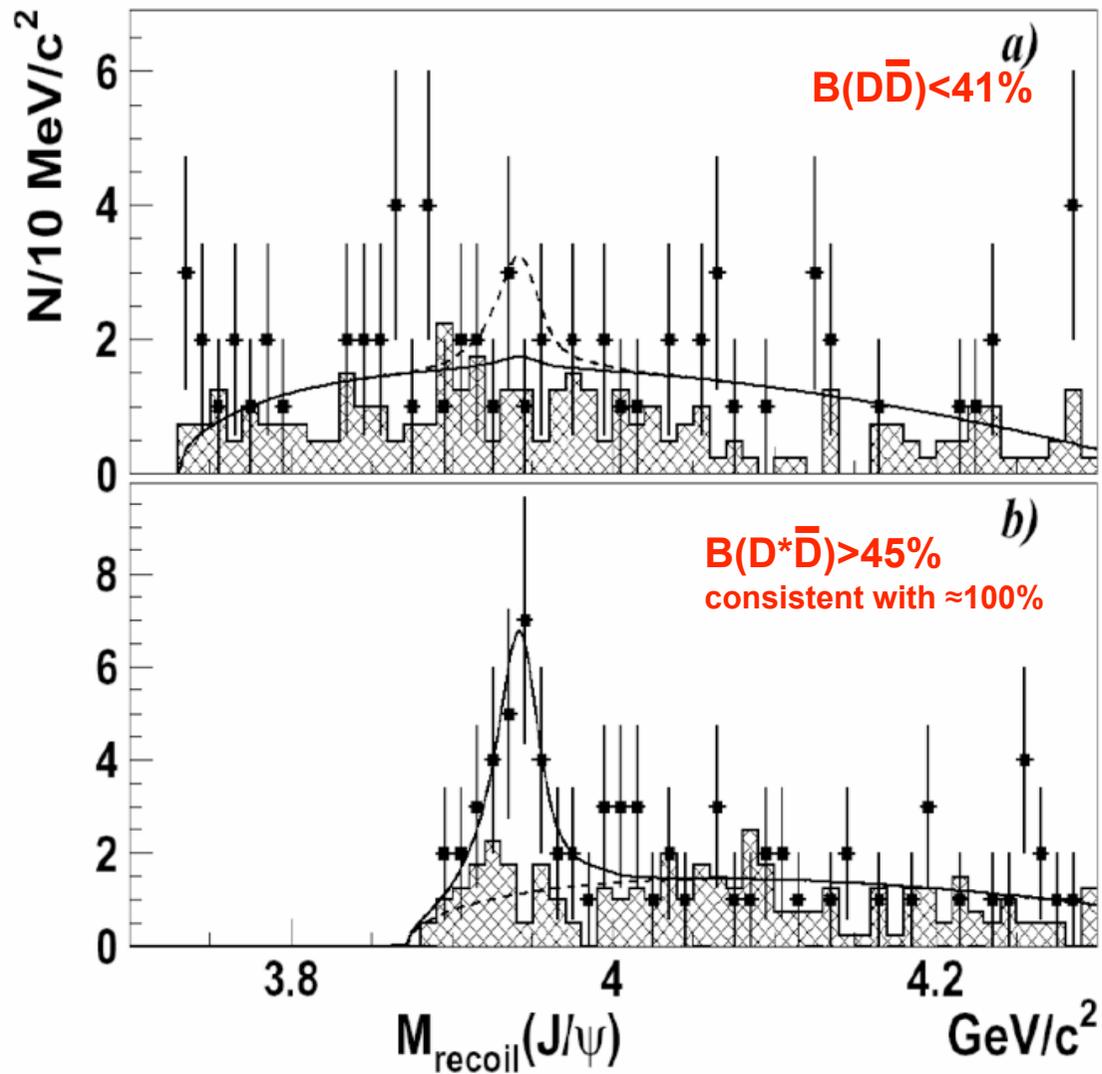


The X Y Z particles

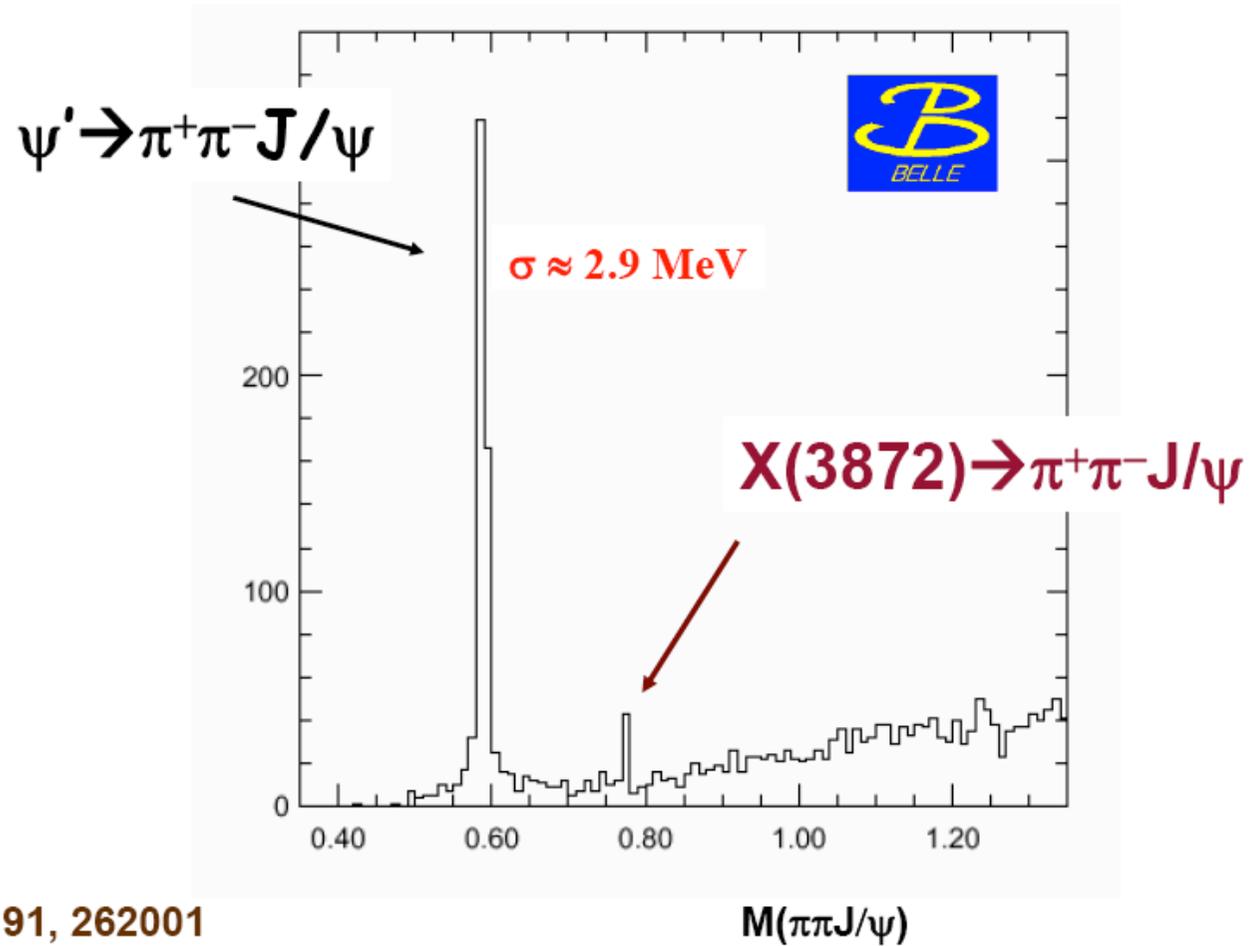
- X(3872) – B → K $\pi^+\pi^-J/\psi$
- Z(3930) – $\gamma\gamma$ → DD
- Y(3940) – B → K $\omega J/\psi$
- X(3940) – e^+e^- → J/ψ X & e^+e^- → J/ψ DD*
- Y(4260) – e^+e^- → γ $\pi^+\pi^-J/\psi$
- Y(4320) – e^+e^- → γ $\pi^+\pi^-\psi'$

Charmonium states?

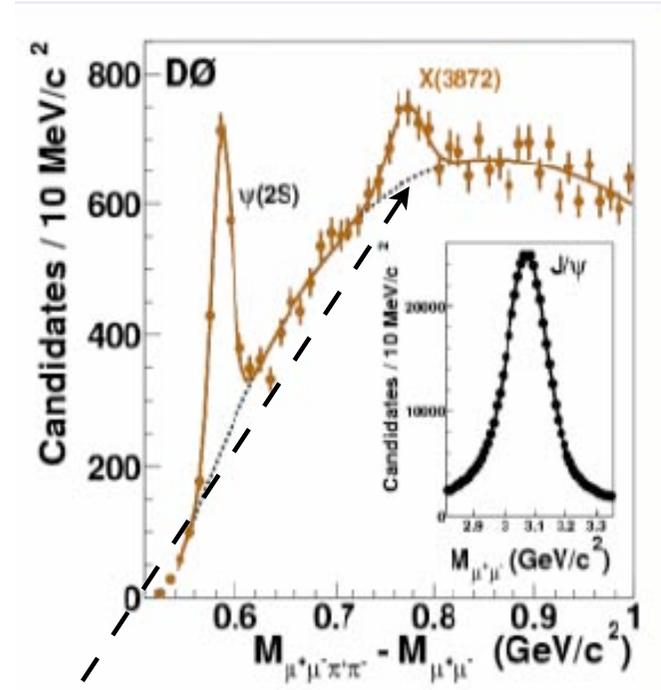
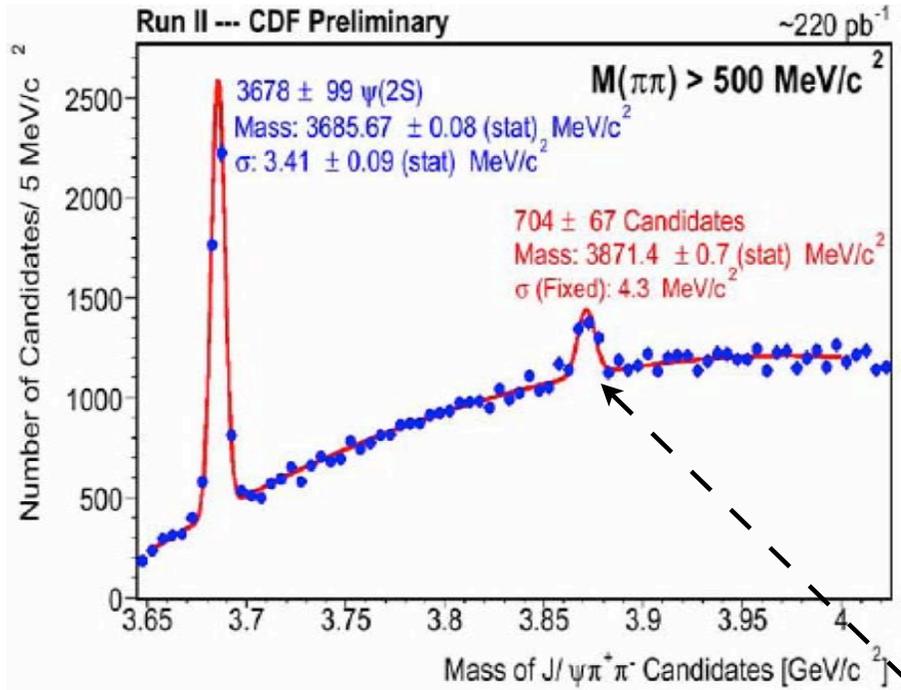
From $X(3940) \rightarrow D^*D$:
 $M = (3943 \pm 6 \pm 6) \text{ MeV}$
 $\Gamma = (15.4 \pm 10.1) \text{ MeV}$
 $\Gamma < 52 \text{ MeV}$ at 90%CL



The X(3872) at BELLE



The X(3872) seen at the TEVATRON in $\bar{p}p$

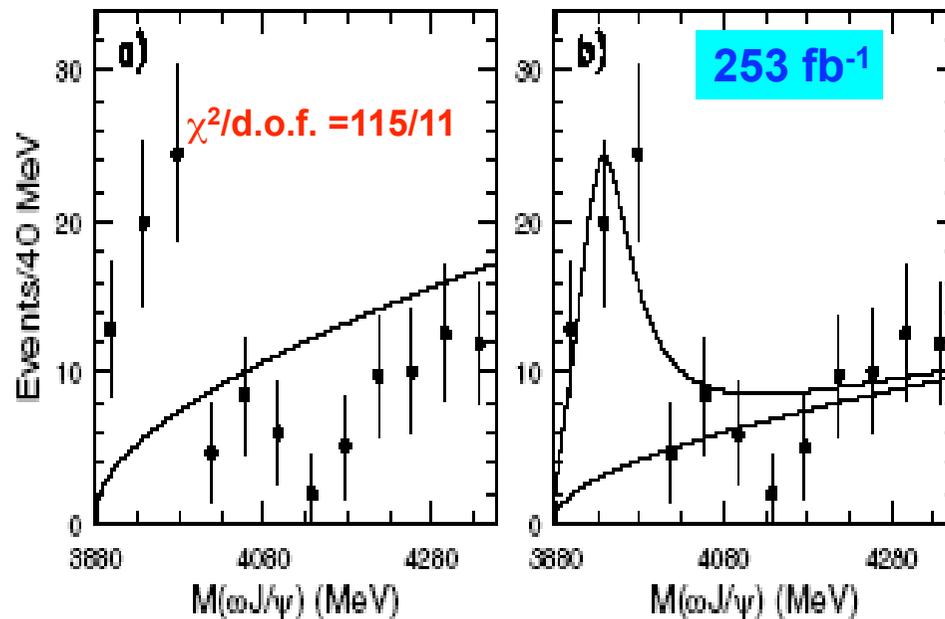


X(3872)

The Y(3940)



PRL 94 (2005) 182002



If it is treated as a S-wave BW:

$$M = 3943 \pm 11 \pm 13 \text{ MeV}/c^2$$

$$\Gamma = 87 \pm 22 \pm 26 \text{ MeV}/c^2$$

$$\chi^2/\text{d.o.f.} = 15.6/8$$

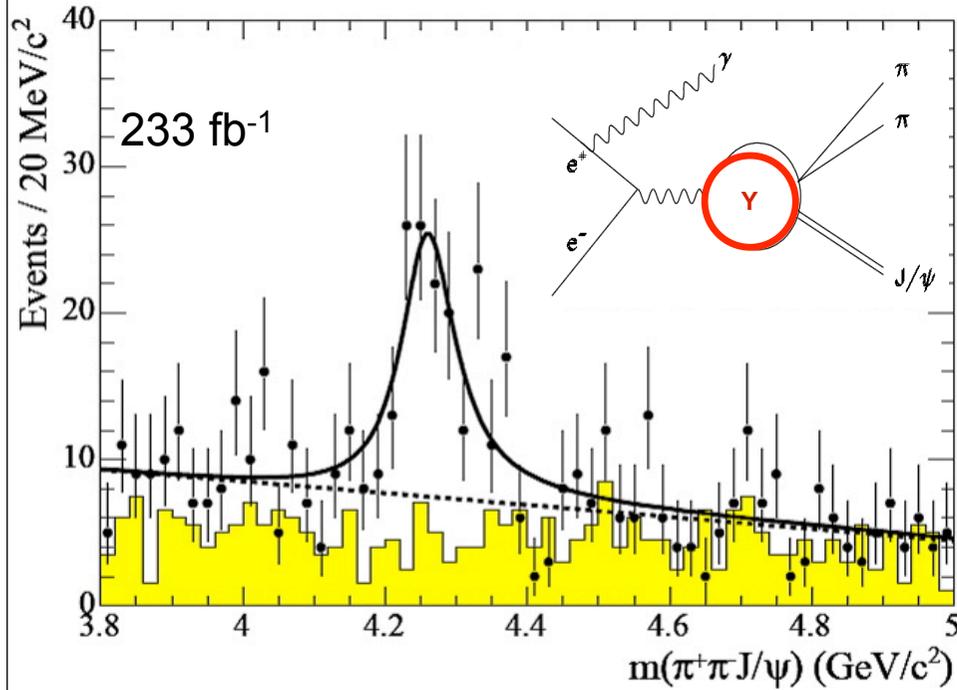
$$\text{stat. sig.} = 8.1\sigma$$

Above D^*D threshold but no decays into $D\bar{D}$ or $D^*\bar{D}$ final states seen !

Observed decay mode: $J/\psi + \omega$ is huge ($> 7 \text{ MeV}$)

$e^+e^- \rightarrow \gamma_{\text{ISR}} Y(4260)$ at BaBar

BaBar PRL95, 142001 (2005)



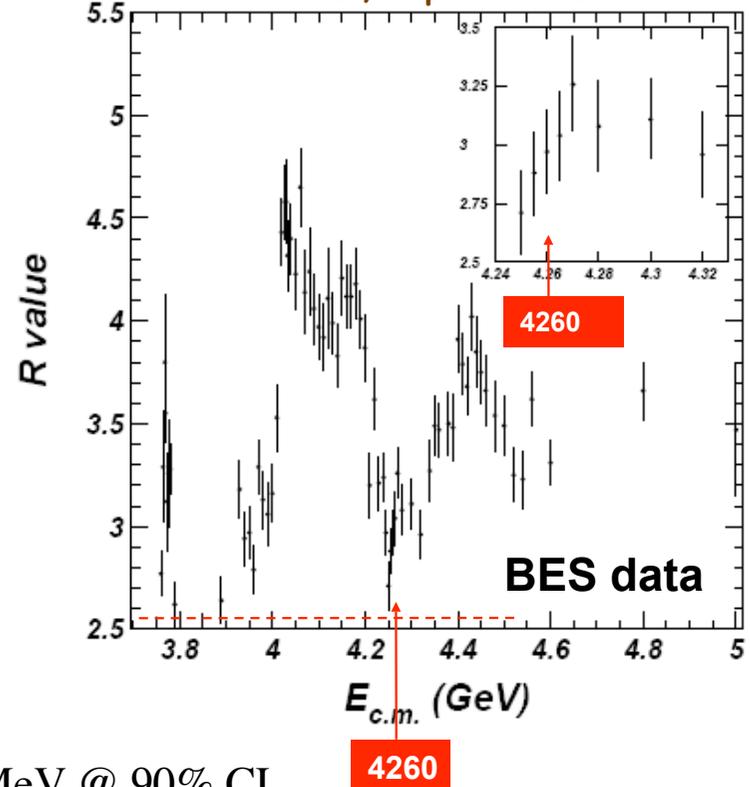
233 fb⁻¹

$$\sigma(e^+e^- \rightarrow \pi^+\pi^-J/\psi) \sim 50 \text{ pb}$$

$$\Gamma(Y4260) \rightarrow \pi^+\pi^-J/\psi > 1.6 \text{ MeV @ 90\% CL}$$

Not seen in $e^+e^- \rightarrow$ hadrons

X.H. Mo et al, hep-ex/0603024



BES data

Charmonium Production in $\bar{p}p$

$c\bar{c}$	J^{PC}	M [MeV]	Γ_{tot} [MeV]	Decay mode	$\sigma(M)^*$ [pb]	Events/day**
η_c	0^{-+}	2980	13.2	$\gamma\gamma$	550	4400
η_c	0^{-+}	2980	13.2	$\phi\phi$	3100	24800
$\eta_c' ???$	0^{-+}	3594		$\gamma\gamma$	120	960
J/ψ	1^{-}	3097	0.087	$e^+e^-/\mu^+\mu^-$	630000	5040000
ψ'	1^{-}	3686	0.277	$e^+e^-/\mu^+\mu^-$	4480	35840
ψ'	1^{-}	3686	0.277	$J/\psi X$	17600	140800
χ_{c0}	0^{++}	3415	14	$\gamma\gamma$	30	240
χ_{c0}	0^{++}	3415	14	$\gamma J/\psi$	52	416
χ_{c1}	1^{++}	3511	0.88	$\gamma J/\psi$	3600	28800
χ_{c2}	2^{++}	3556	2.0	$\gamma J/\psi$	3700	29600
χ_{c2}	2^{++}	3556	2.0	$\gamma\gamma$	220	1760
$c\bar{c}g$	1^{-}	(4100)	(0.2)	($J/\psi\eta$ ***)	(120)	(960)
$c\bar{c}g$	1^{-+}	(4000)	???	($J/\psi \omega, \phi, \gamma$)	(9)	(75)

* for selected decay mode

** $L = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, 50% accelerator and detector efficiency, integrated luminosity = $8 \text{ pb}^{-1}/\text{day}$

*** 1% B.R. for this decay mode

Prediction of Charmonium Production rates

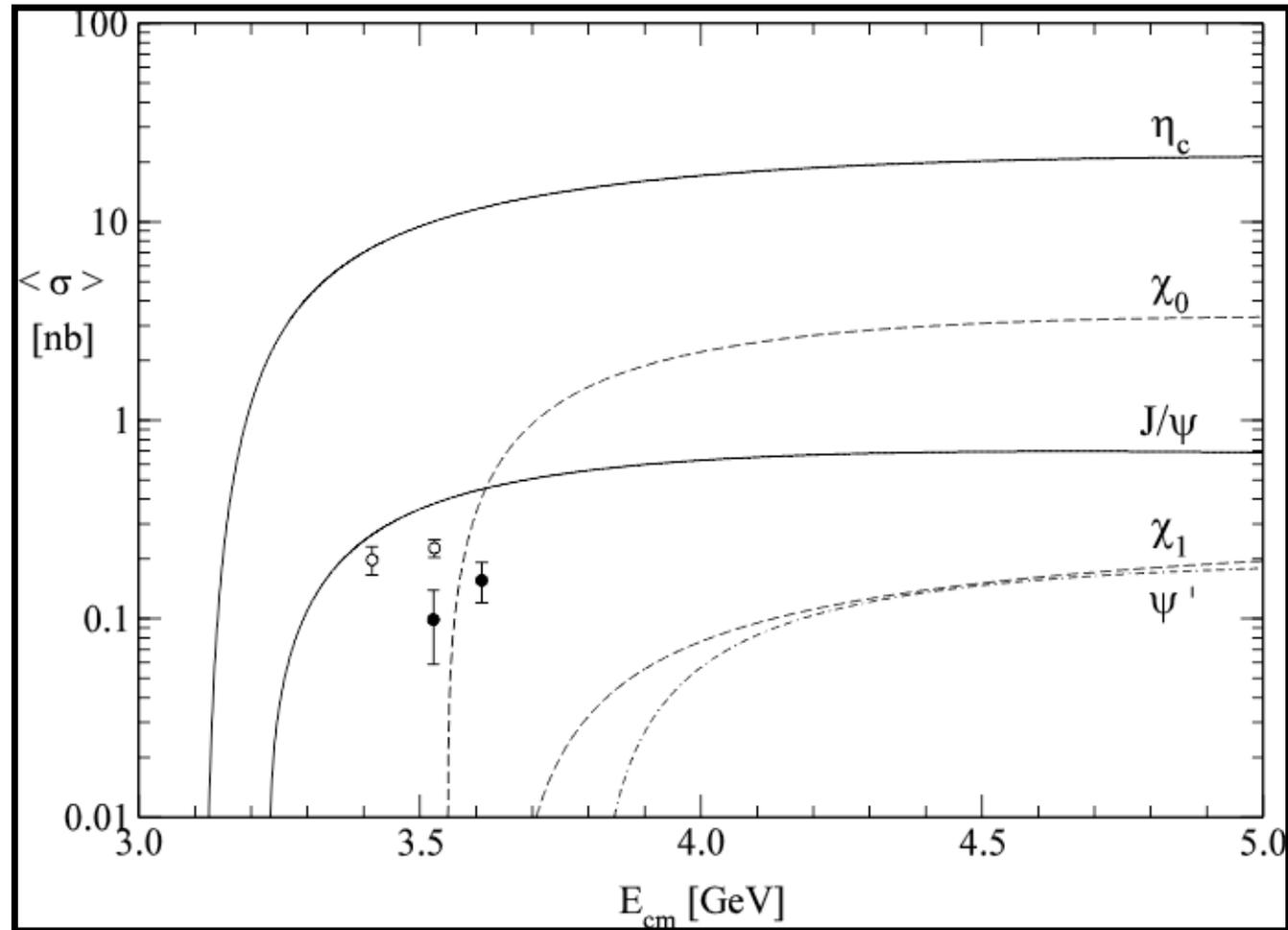


Reaction	$\sigma_{p\bar{p} \rightarrow m\Psi}^{max} [pb]$	$E_{cm}^{max} [GeV]$	$A_D [GeV^4]$
$p\bar{p} \rightarrow \pi^0 J/\psi$	420 ± 40	4.28	9.265
$p\bar{p} \rightarrow \eta J/\psi$	1520 ± 140	4.57	4.520
$p\bar{p} \rightarrow \rho^0 J/\psi$	< 450	4.80	2.114
$p\bar{p} \rightarrow \omega J/\psi$	1900 ± 400	4.80	2.053
$p\bar{p} \rightarrow \eta' J/\psi$	3300 ± 1500	4.99	0.765
$p\bar{p} \rightarrow \phi J/\psi$	280 ± 90	5.06	0.452
$p\bar{p} \rightarrow \pi^0 \psi'$	55 ± 8	5.14	30.50
$p\bar{p} \rightarrow \eta \psi'$	33 ± 8	5.38	20.98
$p\bar{p} \rightarrow \rho^0 \psi'$	38 ± 17	5.59	14.95
$p\bar{p} \rightarrow \omega \psi'$	46 ± 22	5.60	14.77
$p\bar{p} \rightarrow \phi \psi'$	< 28	5.84	9.12

A. Lundborg, T. Barnes, U. Wiedner: Phys. Rev. D73, 096003 (2006)

Results of a PCAC model of $\bar{p}p \rightarrow \Psi + \pi^0$

(T.Barnes and X.Li, hep-ph/0611340)



What is the nature of these states?

Quarkonia? Molecules? Hybrids?

Flatté form

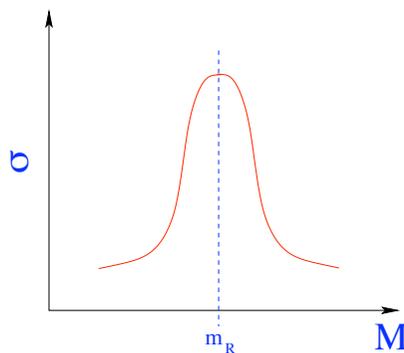
Introducing **inelasticity** (note $M = 2m + k^2/m$)

$$F \propto \frac{1}{M - m_R + i(g_M/2)\sqrt{m(M - 2m)} + i\Gamma_l/2}$$

→ for **quark states** gives

$$F \simeq \frac{1}{M - m_R + i\Gamma_l/2}$$

Denominator
analytic in M
(Breit–Wigner)



V. Baru, J. Haidenbauer, C. Hanhart,
A. Kudryavtsev and U. G. Meissner
Eur. Phys. J. A 23, 523 (2005).

Flatté form

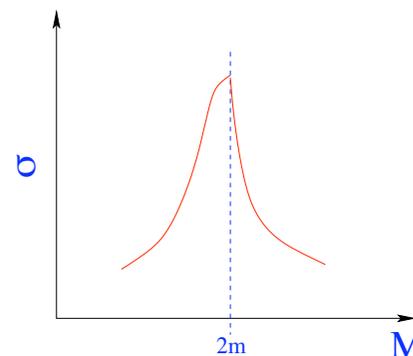
Introducing **inelasticity** (note $M = 2m + k^2/m$)

$$F \propto \frac{1}{M - m_R + i(g_M/2)\sqrt{m(M - 2m)} + i\Gamma_l/2}$$

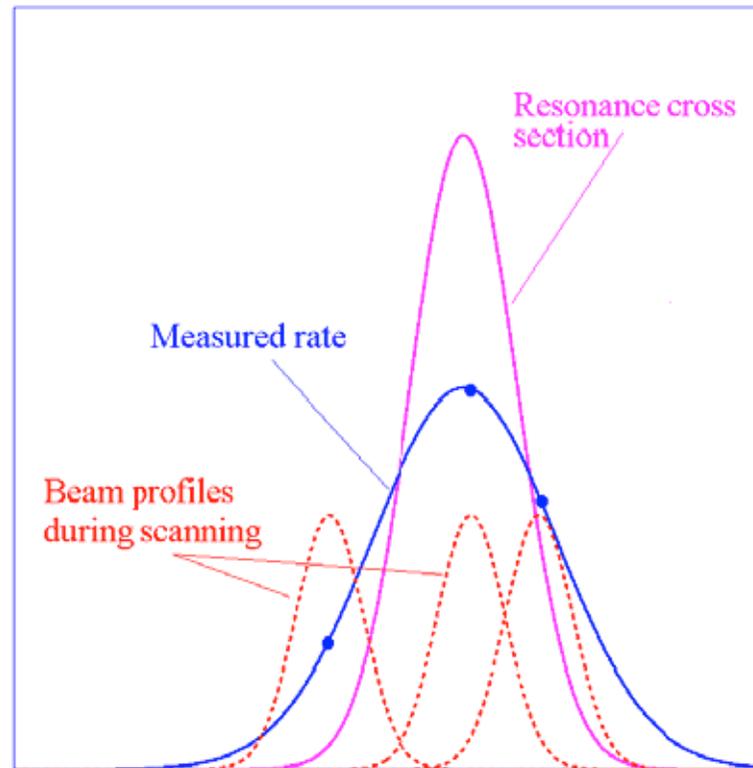
→ for **molecules** gives

$$F \propto \frac{1}{2m - m_R + i\frac{g_M}{2}k + i\frac{\Gamma_l}{2}}$$

Denominator
non-analytic in M



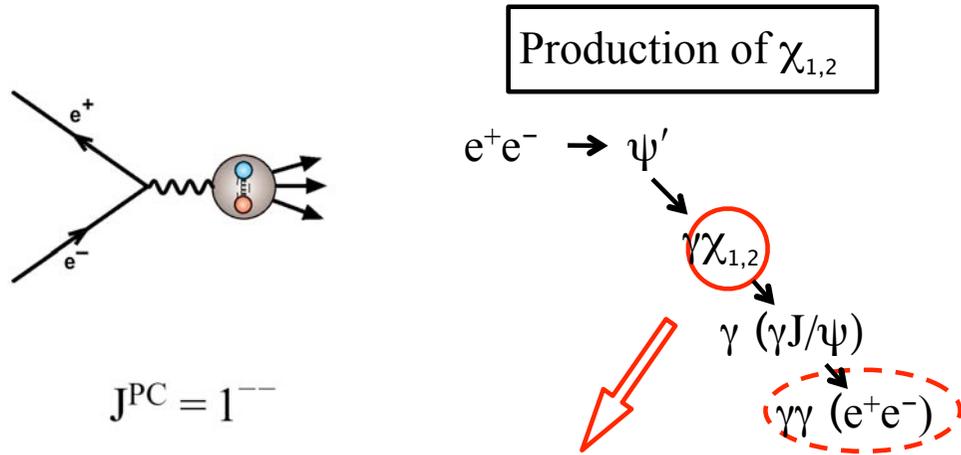
Resonance scan



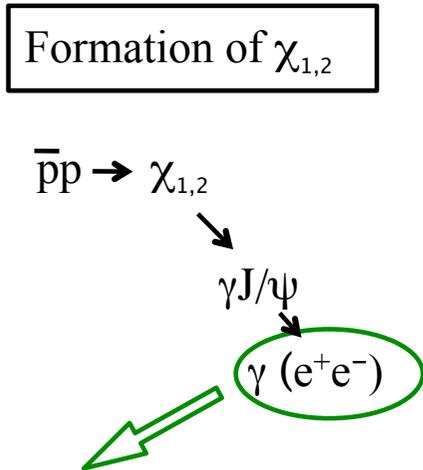
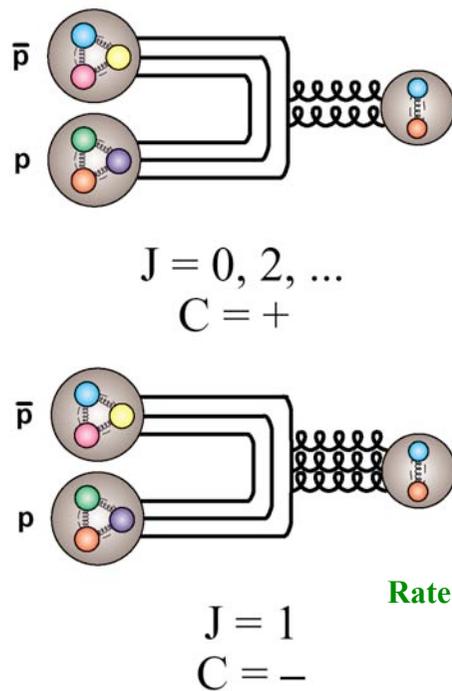
Measure rate of final state under study:

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

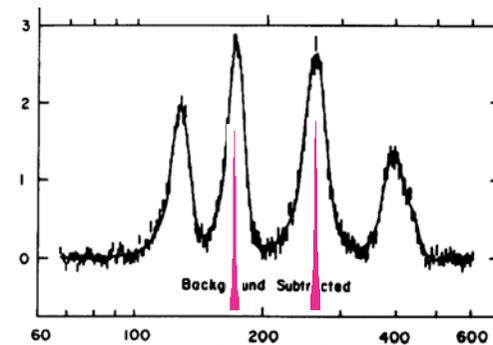
(K takes overlap between beam and resonance into account)



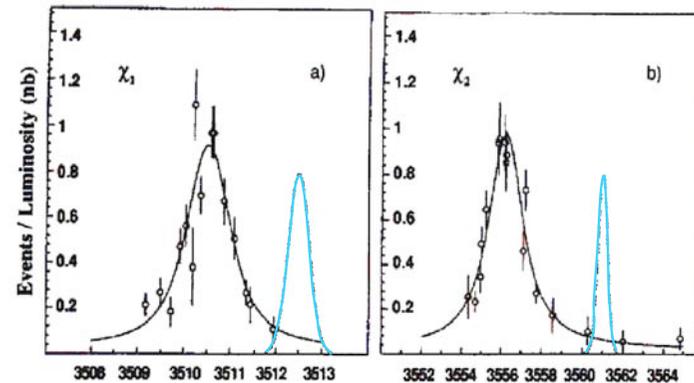
Reconstruction of invariant mass:
detector resolution dependent



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



E 760 (Fermilab)



σ_m (beam) = 0.5
MeV

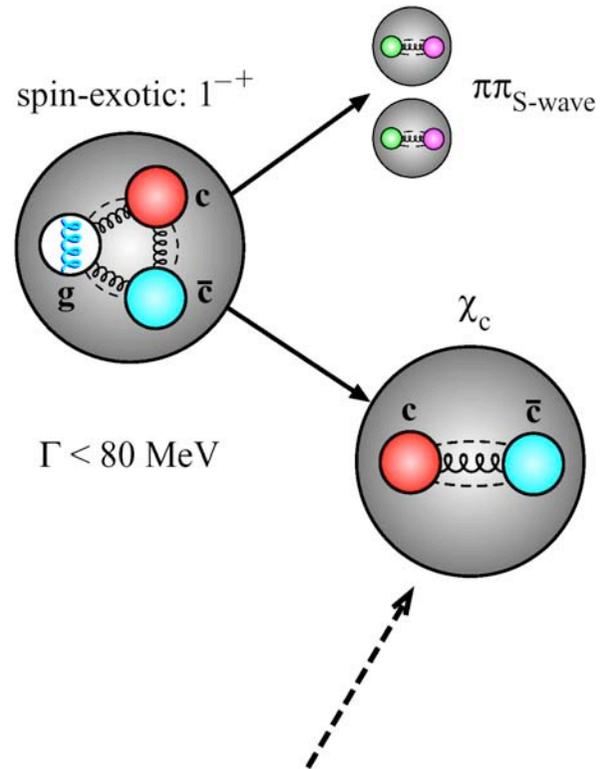
The X Y Z particles

- X(3872) – B → K $\pi^+\pi^-J/\psi$
- Z(3930) – $\gamma\gamma \rightarrow DD$
- Y(3940) – B → K $\omega J/\psi$
- X(3940) – $e^+e^- \rightarrow J/\psi X$ & $e^+e^- \rightarrow J/\psi DD^*$
- Y(4260) – $e^+e^- \rightarrow \gamma \pi^+\pi^-J/\psi$
- Y(4320) – $e^+e^- \rightarrow \gamma \pi^+\pi^-\psi'$

Unusual strong decay into hidden charm.

Decay of charmonium hybrids

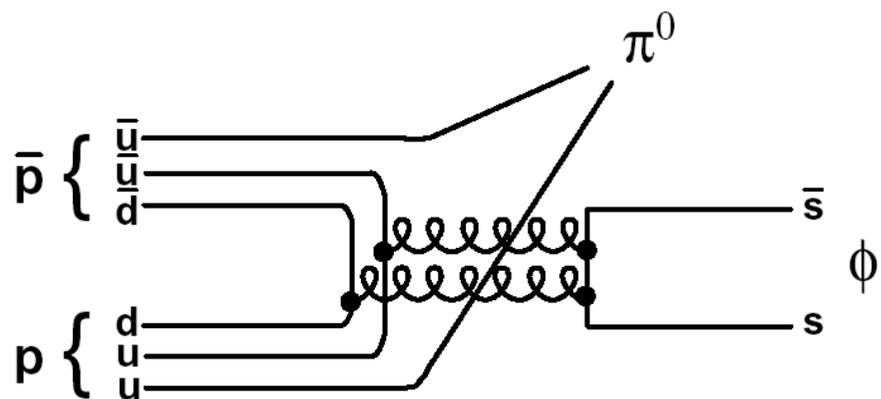
Lattice results*



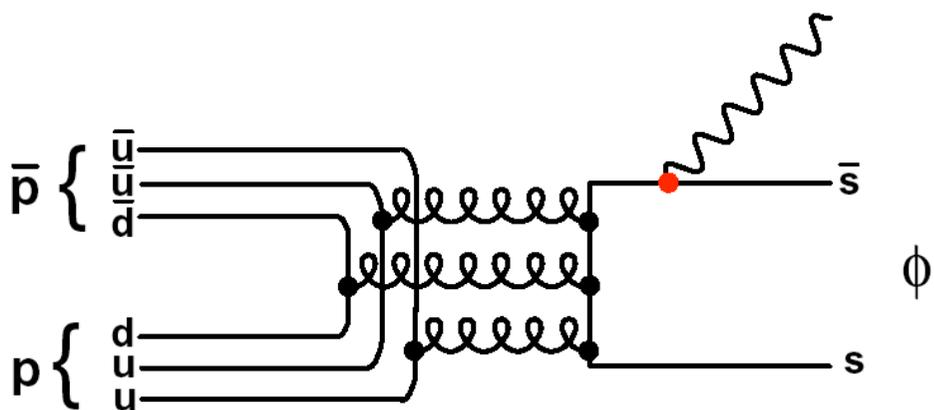
Decay of charmonium provides a clean "tag".

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

Learning about QCD processes

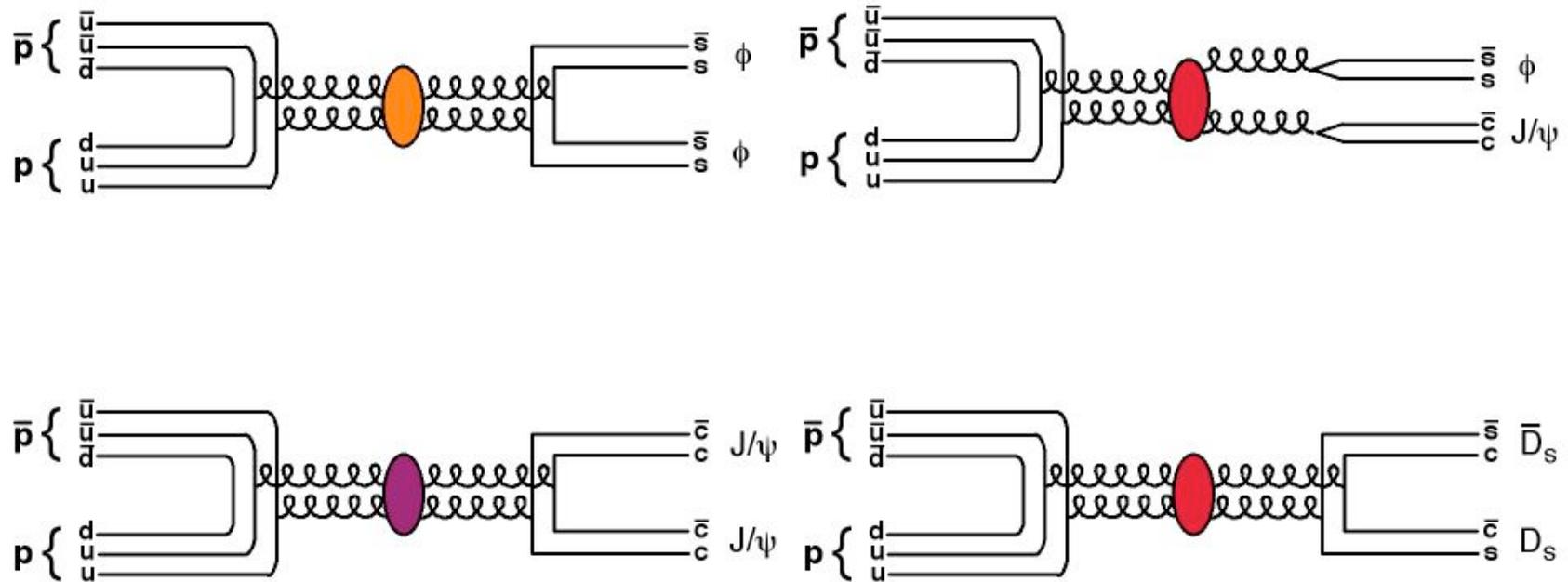


$$O(\alpha_s^4)$$

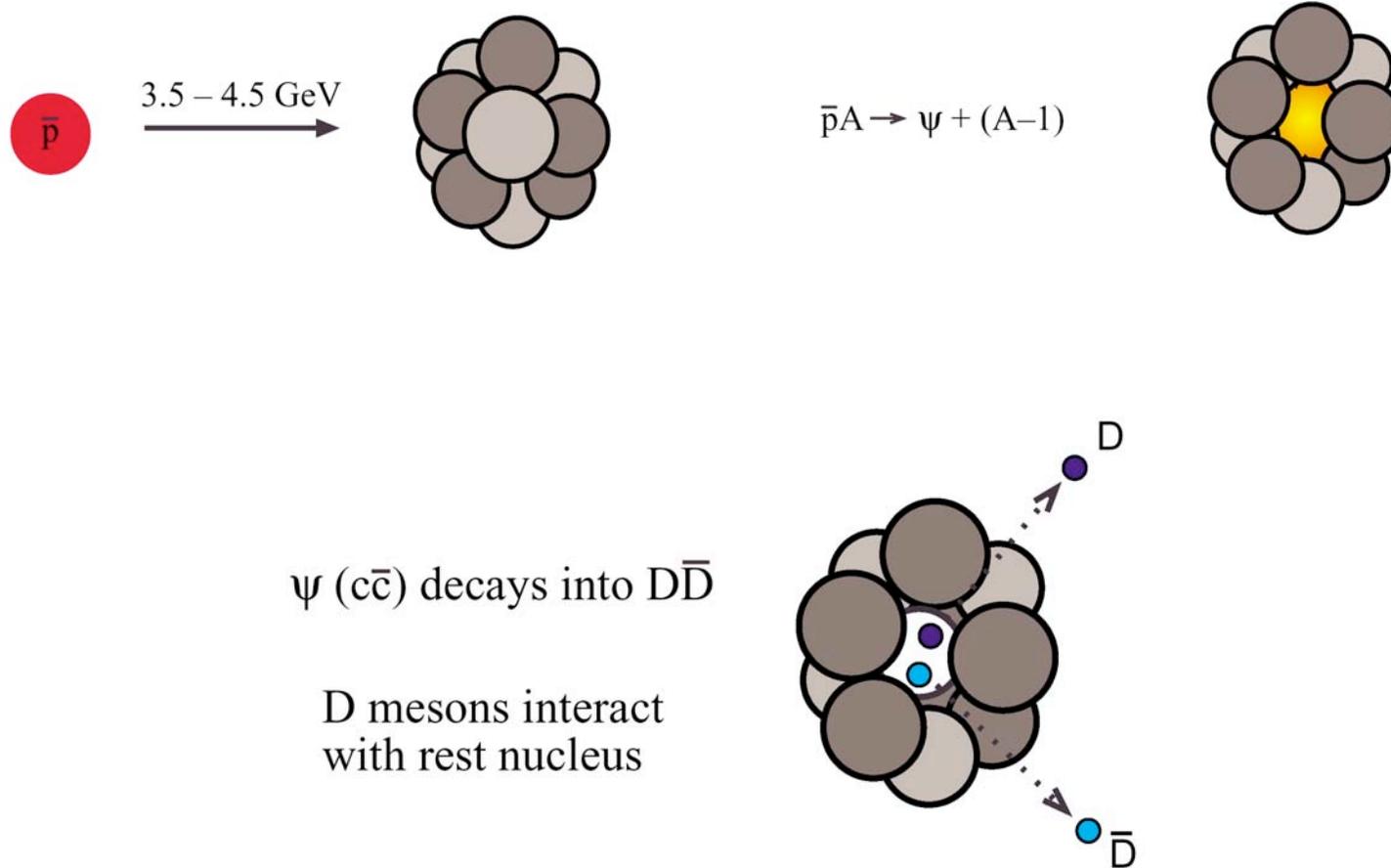


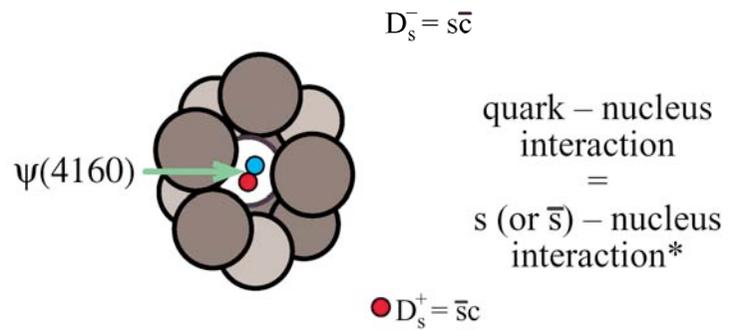
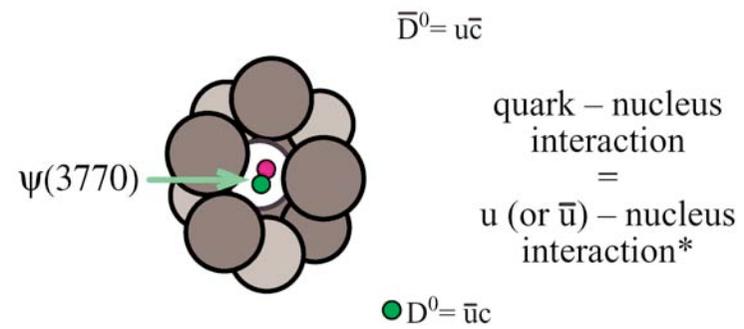
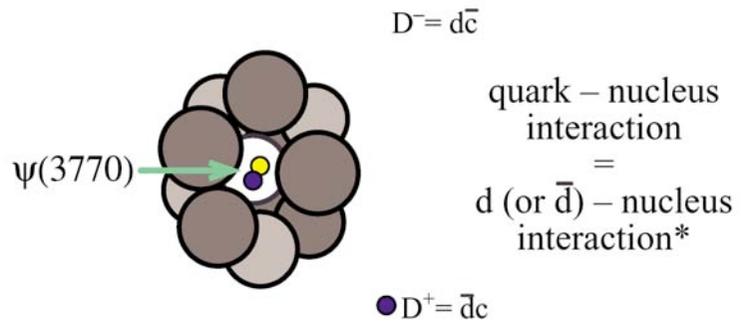
$$O(\alpha_s^6) O(\alpha)$$

OZI-violating processes



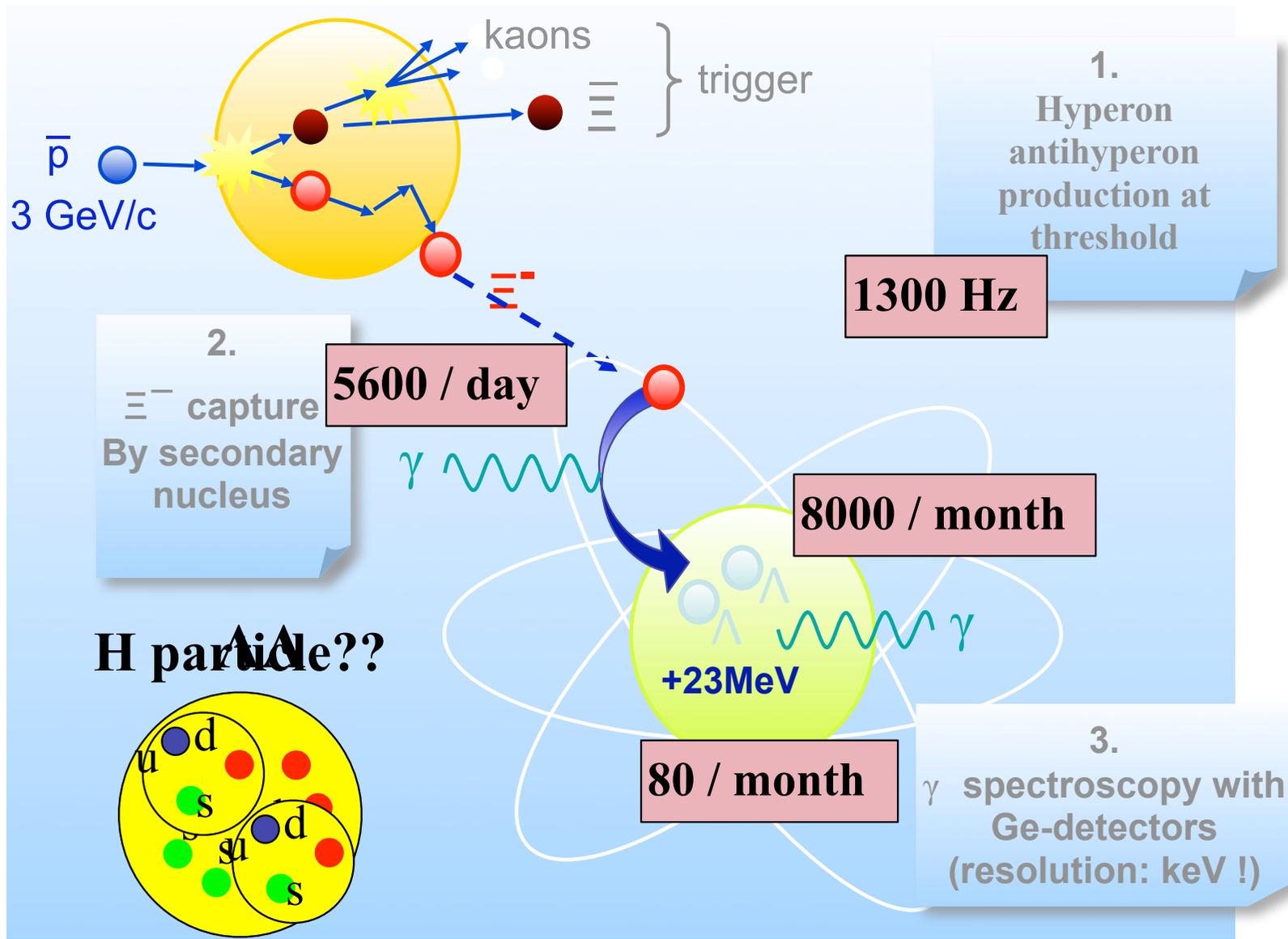
Antiproton-Nucleus Interaction



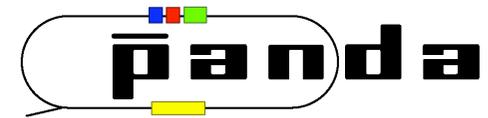


* ignoring c (or \bar{c}) – nucleus interaction

Production of double hypernuclei



PANDA Collaboration



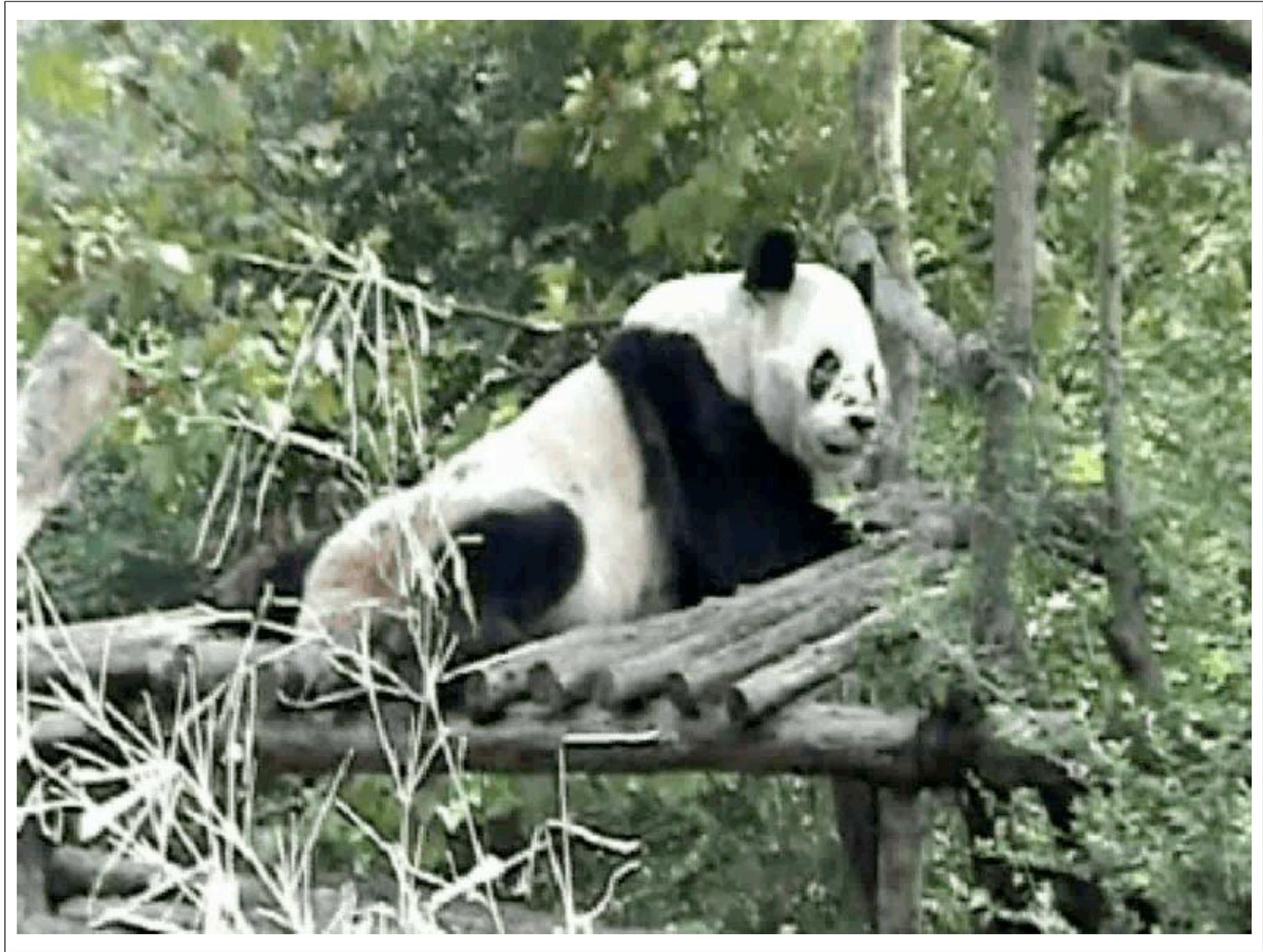
- At present a group of **400 physicists** from **50 institutions** from **16 countries**

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

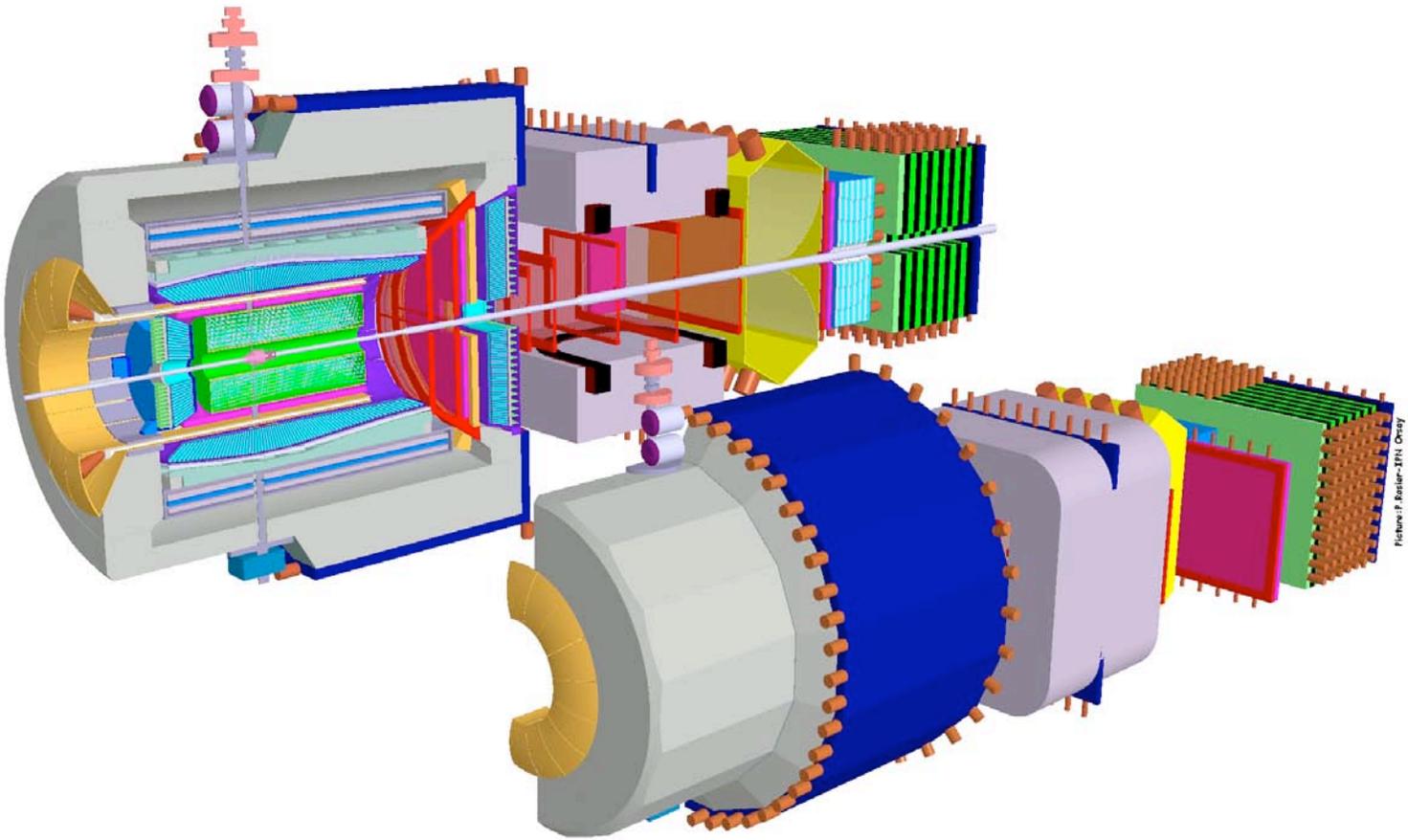
Basel, Beijing, Bochum, Bonn, Brescia, IFIN Bucharest, Catania, Cracow, Dresden, Edinburgh, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, LNF, Lund, Mainz, Minsk, TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, Piemonte Orientale, 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

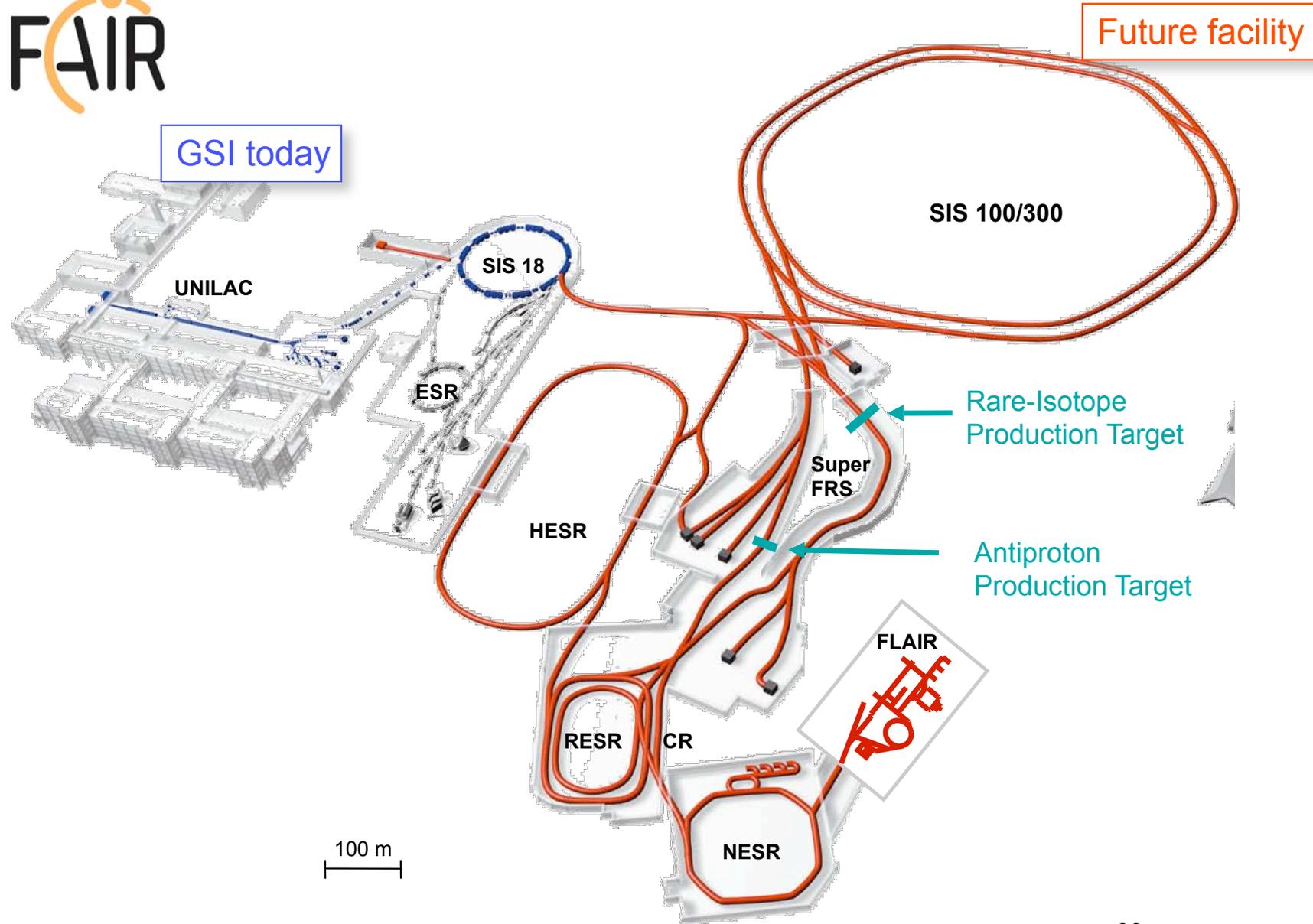
<http://www.gsi.de/panda>



The PANDA Detector



Picture: J. Reiser-TIN, Ony



Future facility

GSI today

SIS 100/300

SIS 18

UNILAC

ESR

Rare-Isotope
Production Target

Super
FRS

HESR

Antiproton
Production Target

FLAIR

RESR

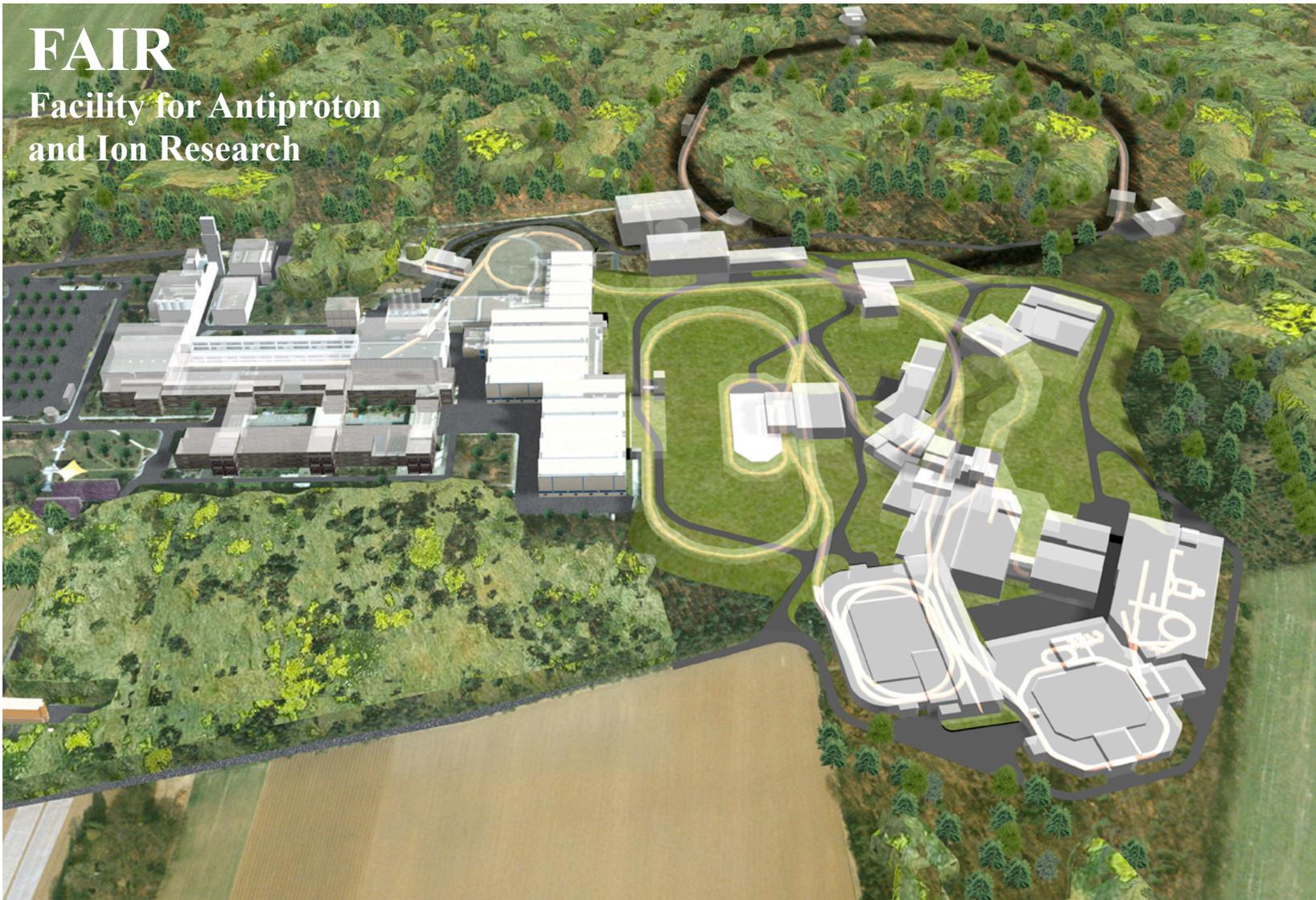
CR

NESR

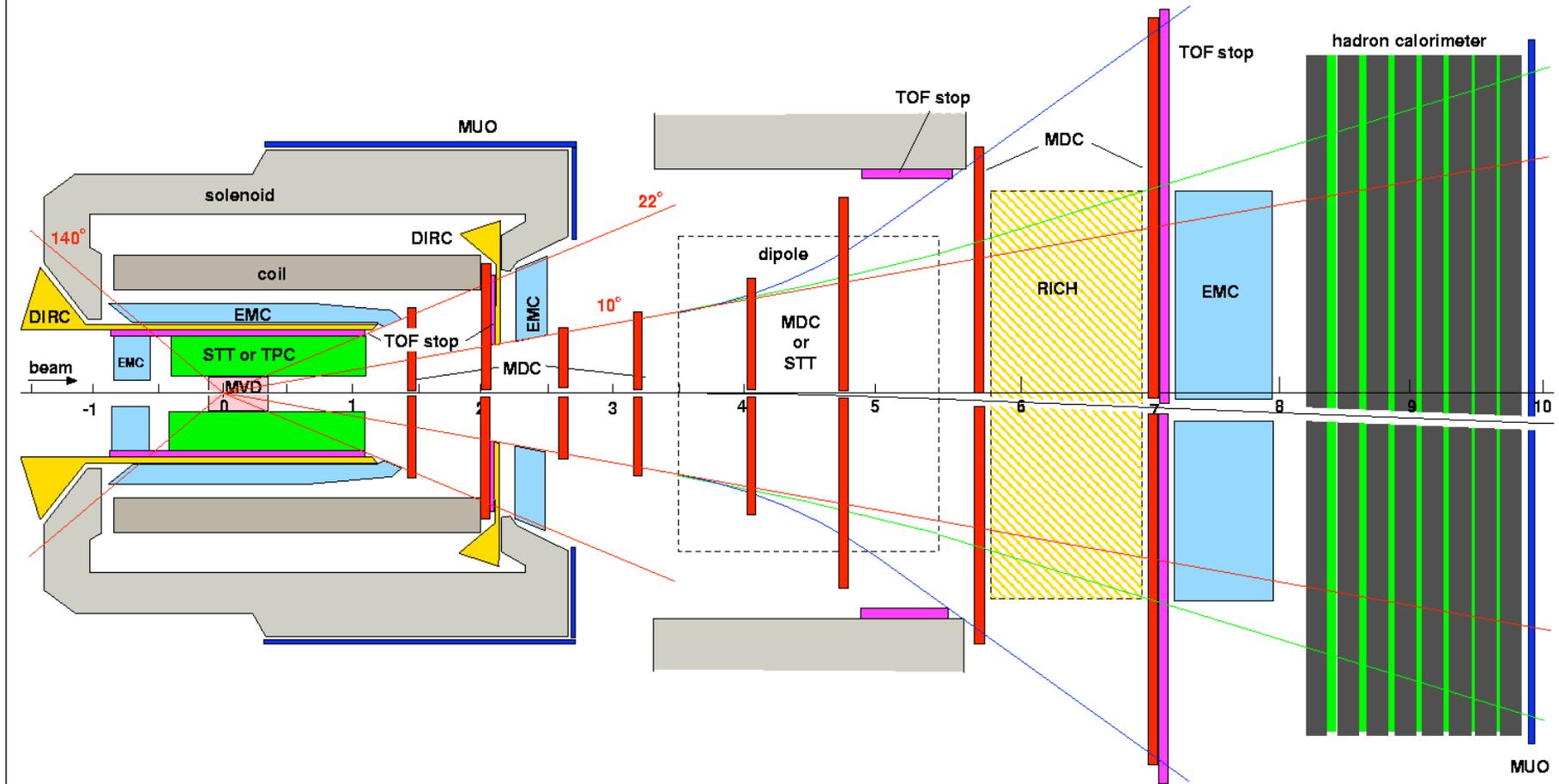
100 m

FAIR

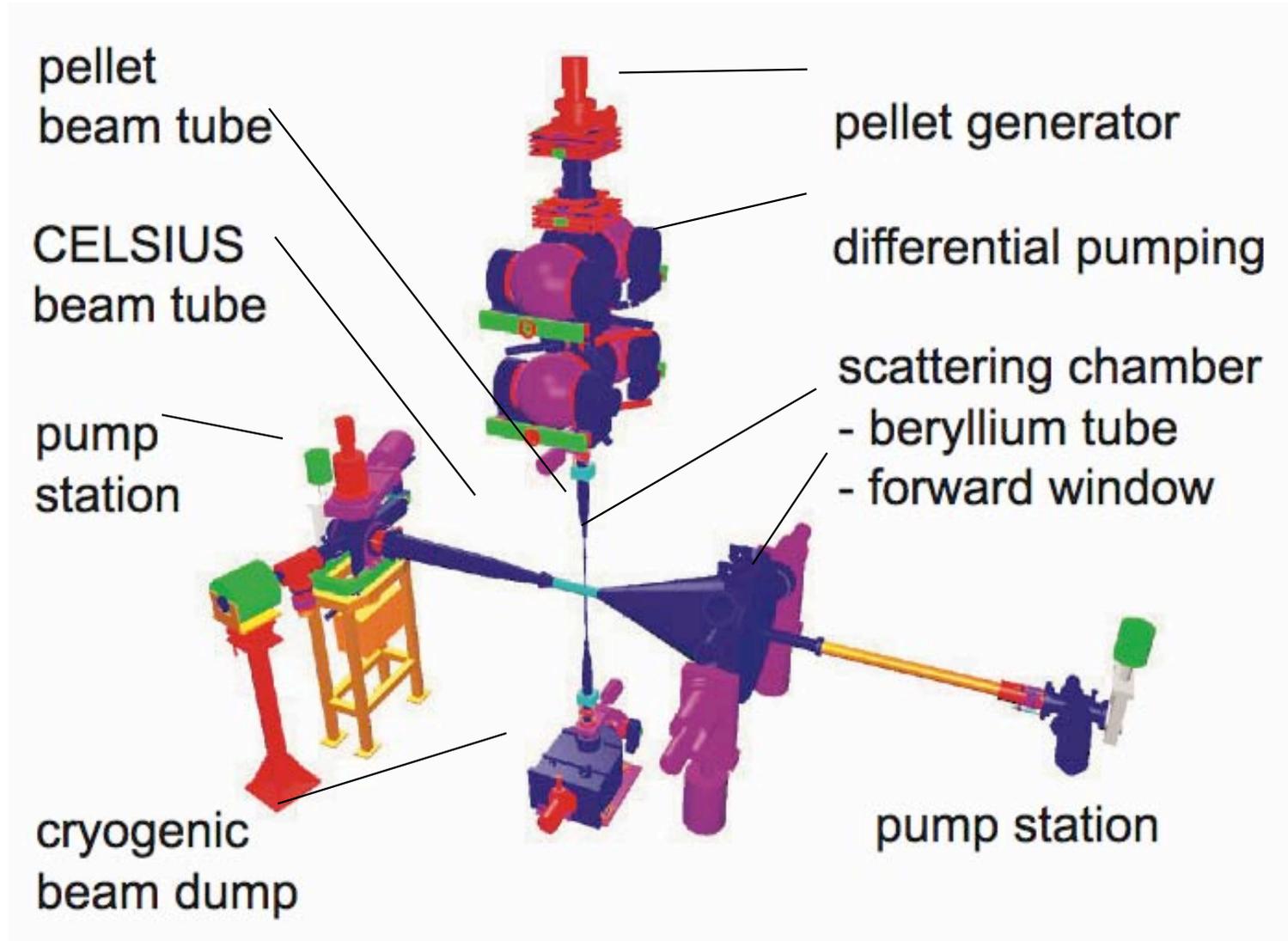
Facility for Antiproton
and Ion Research

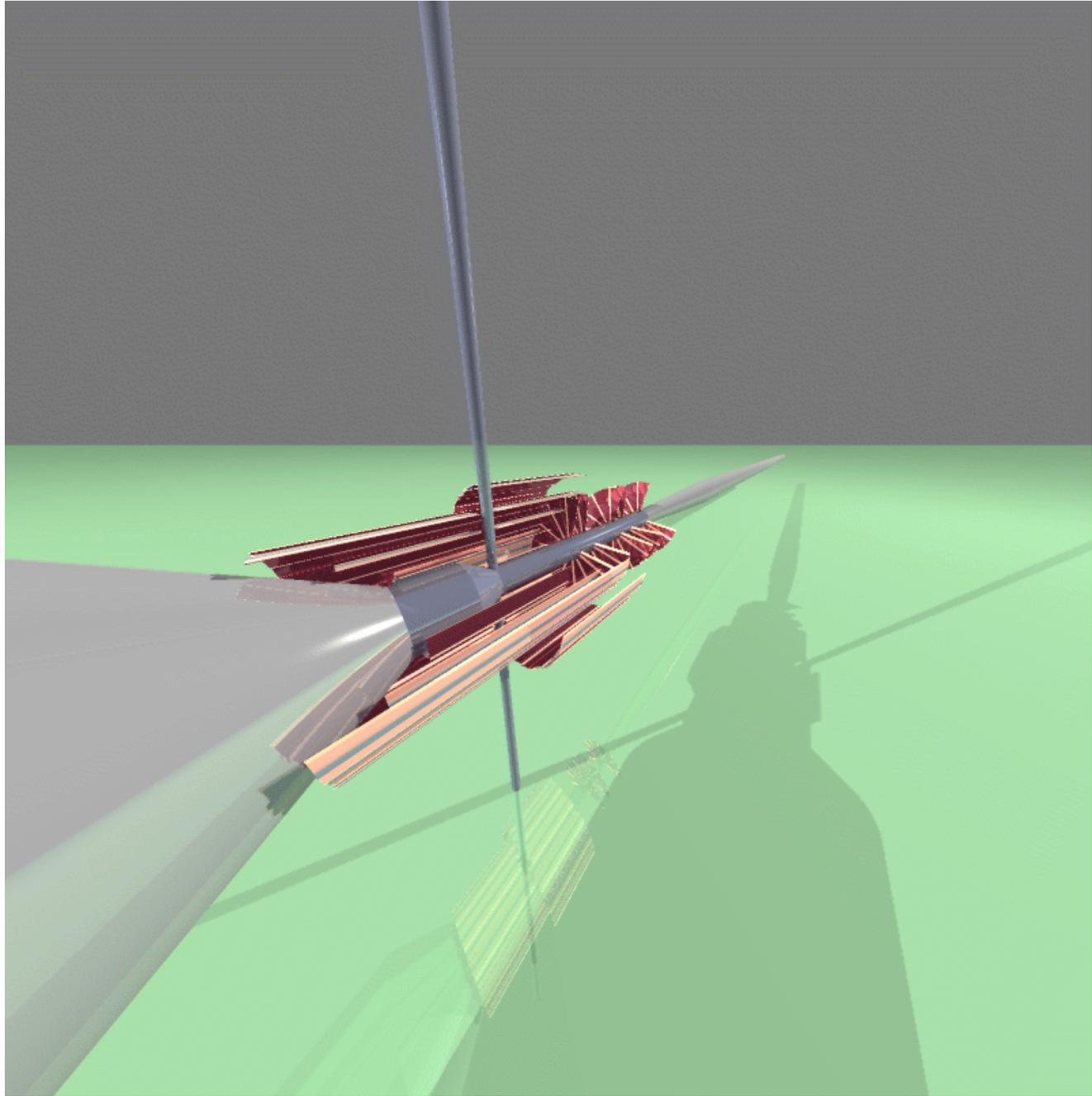


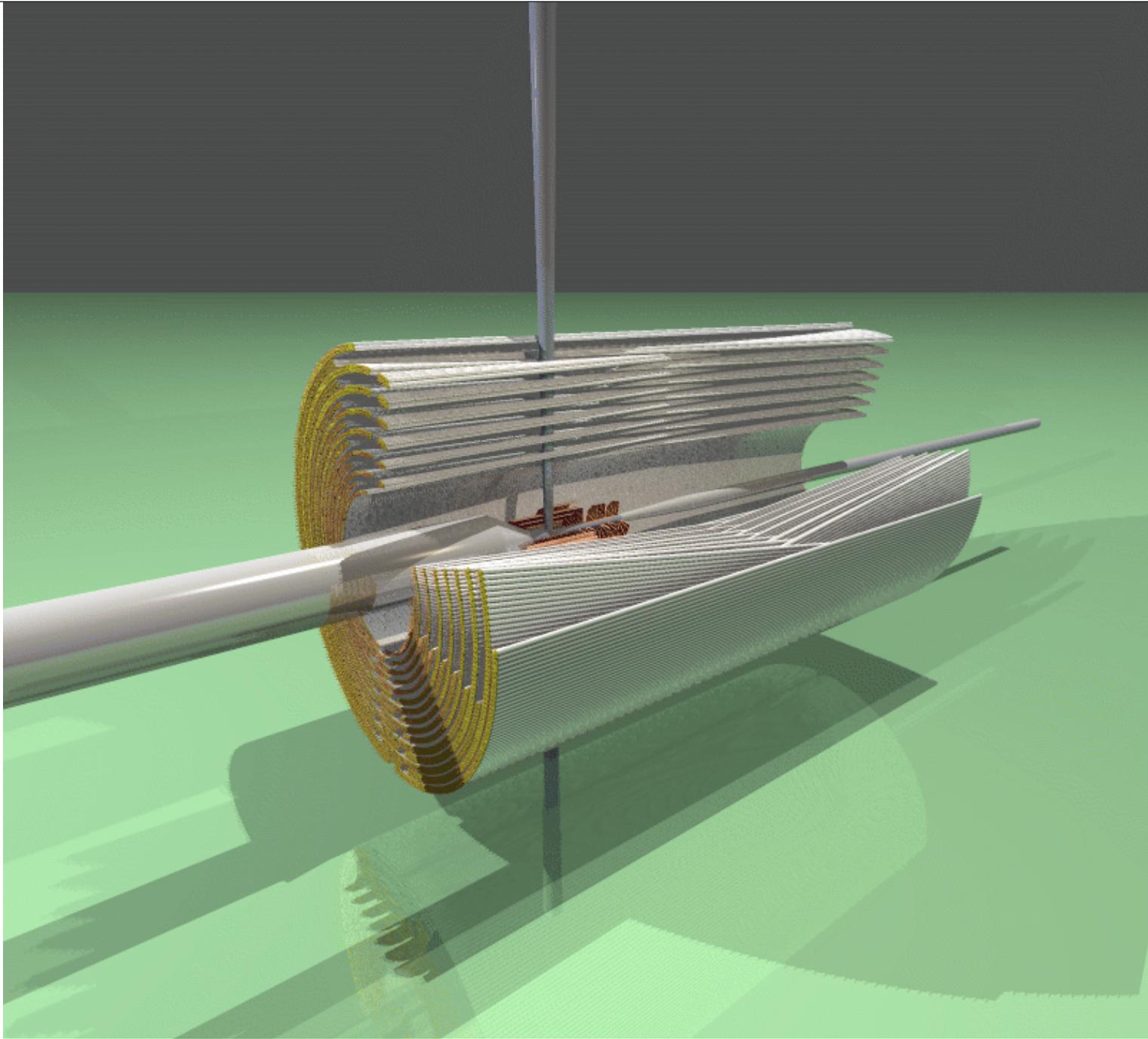
Layout of the detector (top view)



Pellet Target

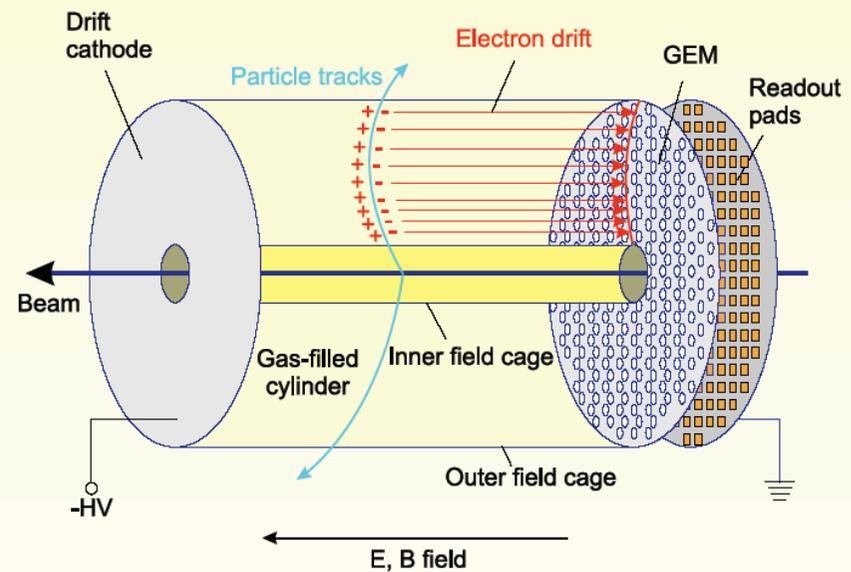






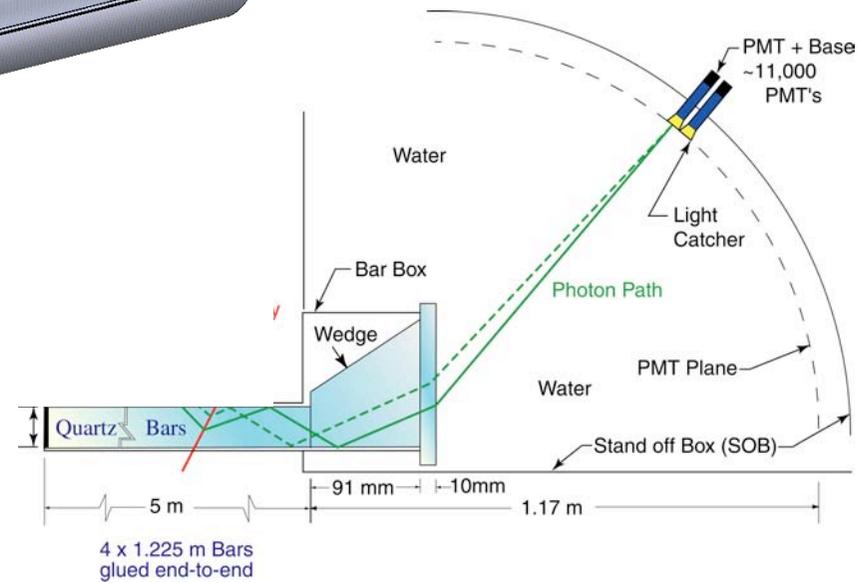
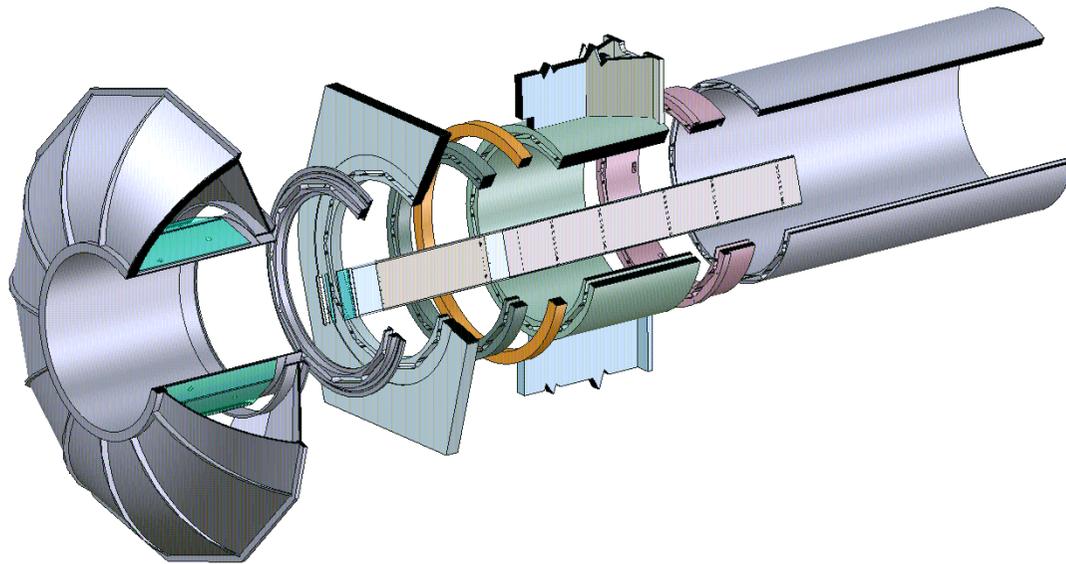
High-rate TPC with GEM readout

- **MPGD:** GEM, MicroMegas, ...
 - High granularity
 - Multi-track resolution $10\times$ better
 - Reduced $E \times B$ effect
 - Fast electron signal
 - Intrinsic ion feedback suppression
- TDR solution for **TESLA:**
 - No gating between bunches: $\Delta t = 337 \text{ ns}$
 - ~ 150 bunch crossings/readout cycle
 - $R = 1.7 \text{ m}$, $L = 2 \times 2.5 \text{ m}$
 - Ar-CO₂-CH₄ (93-2-5)
 - Barrel $3\% X_0$
 - $B = 4 \text{ T}$, $E = 230 \text{ V/cm}$
 - $\sigma_r < 100 \mu\text{m}$, $\sigma_{dE/dx} = 5\%$



Der BaBar DIRC (SLAC)

10000 PMTs !



The Electromagnetic Calorimeter

Required:

Fast, high resolution scintillator for γ between 10 MeV - 10 GeV

Counting rates 10^7 annihilations / s

Two possible solutions:

PbWO₄ (PWO) crystals

BGO crystals

lower light yield

slower and more expensive

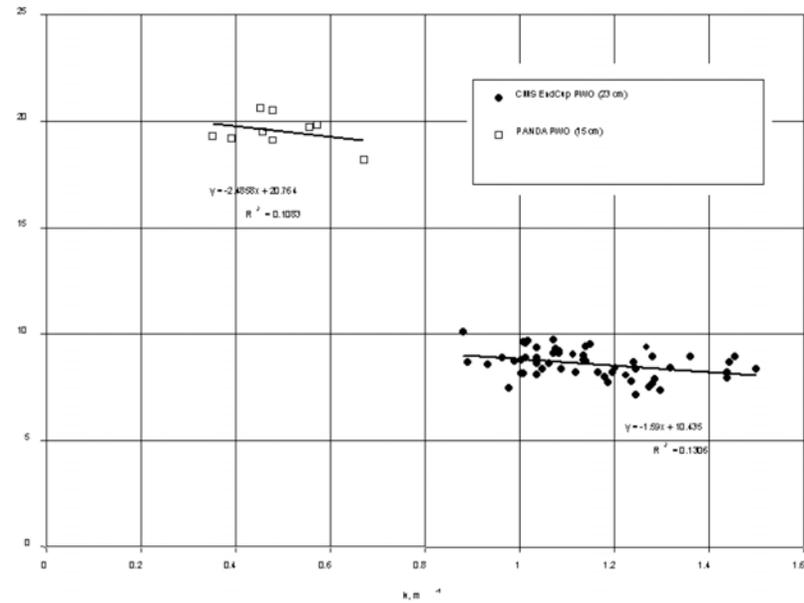
Crystal size: $2 \times 2 \text{ cm}^2 \times 22 X_0$

PWO crystals

(Bochum, Frankfurt, Giessen, GSI, KVI, Lund, Orsay, Protvino, Stockholm, Uppsala)



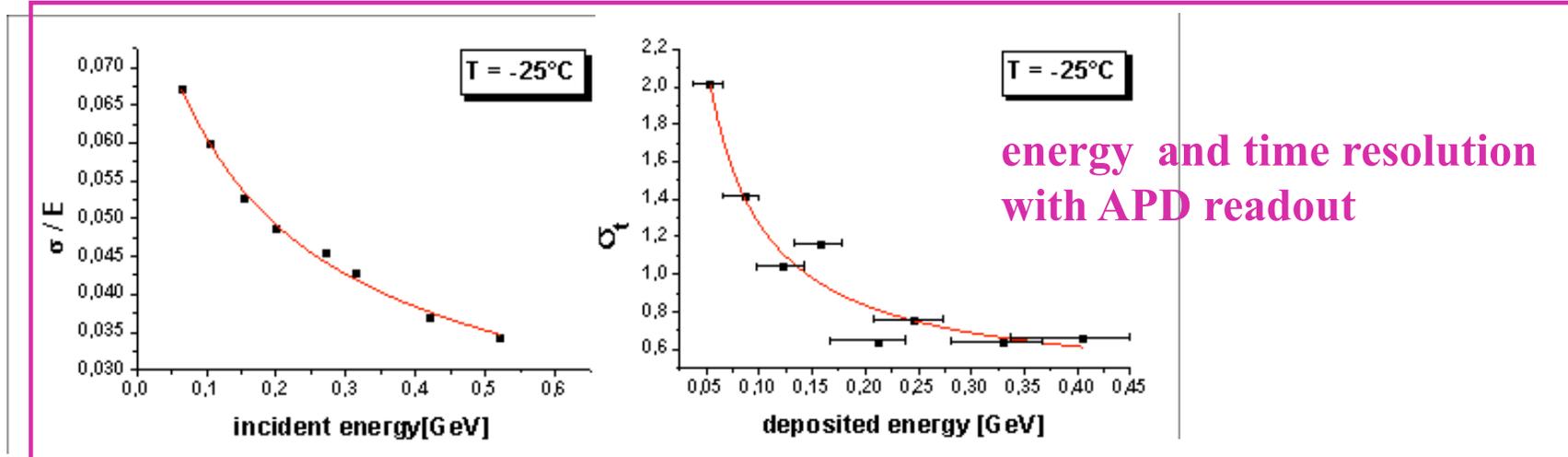
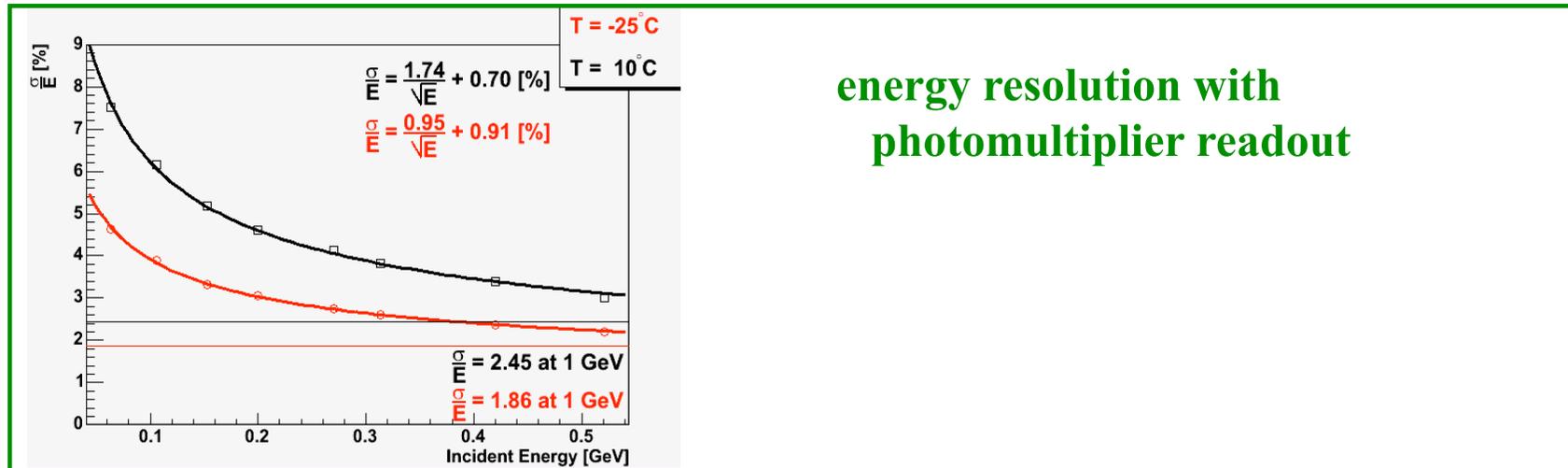
light yield of PANDA crystals
better than as CMS crystals



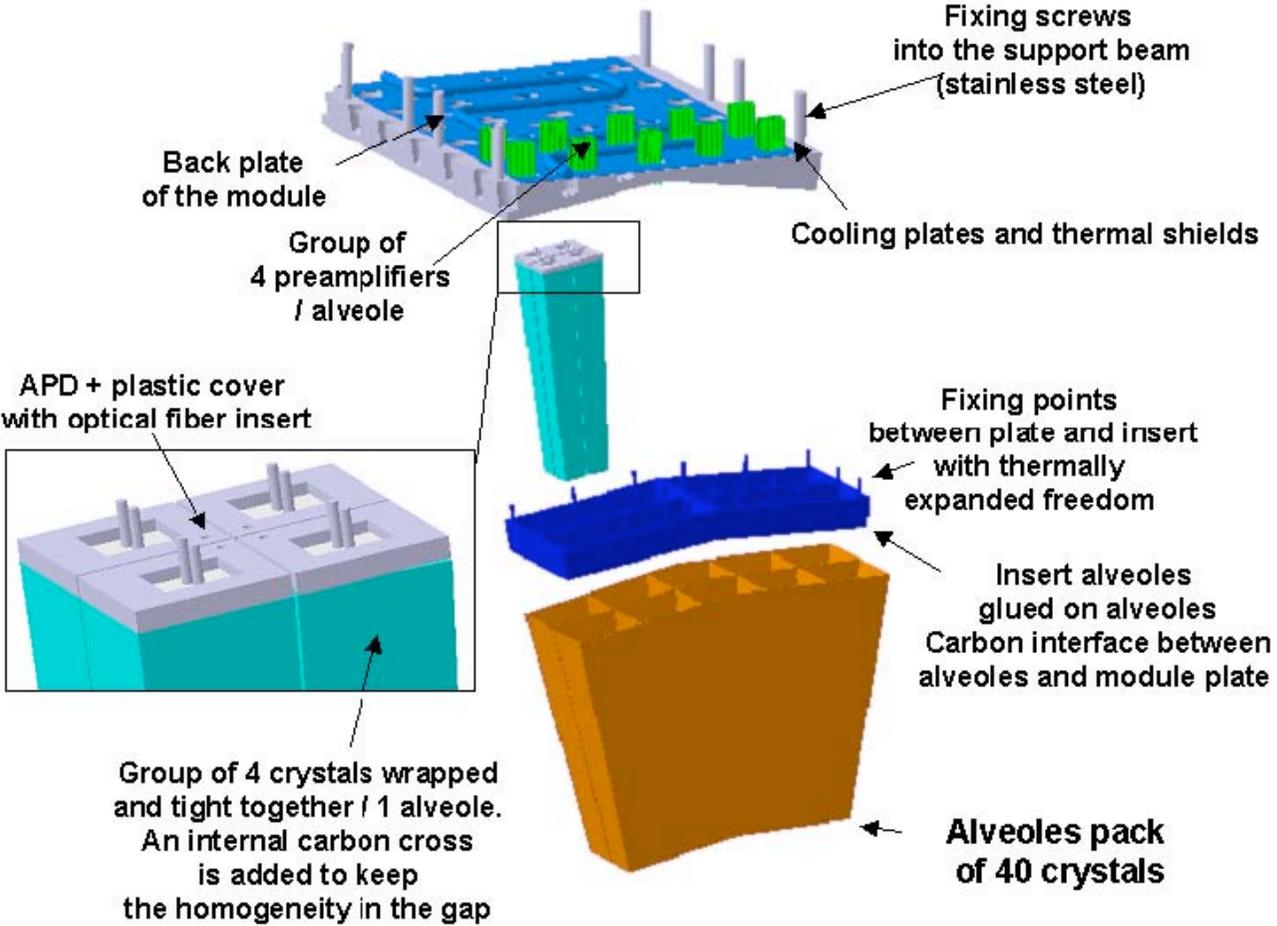
Scintillator Crystals

Target Electromagnetic Calorimeter

expected performance of PWO-II at cooled operation: 3 x 3 matrix

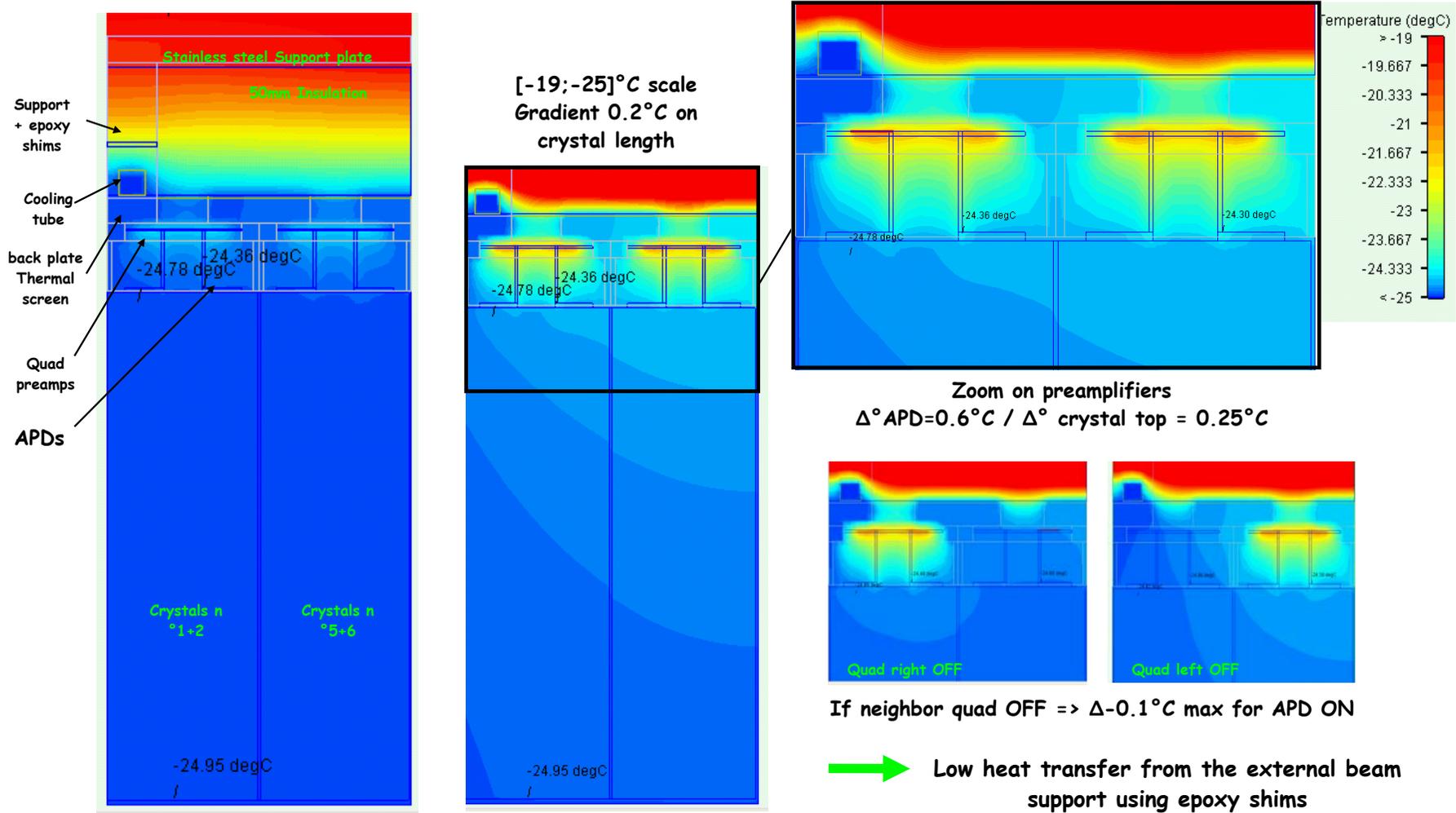


Single alveoli pack



Temperatur distribution with APDs

Half module: Simulation with two quads (50mW-4°C), 8 crystals and wire basal 23mm



[+20;-25°] scale
Complete map of temperature
Low external influence

➡ Preamplifiers to APD/crystals - conductivity by wires
Few convection and no gravity influence in the barrel (<0.1°)

➡ Possible variation in time (>0.1°) = only Δ° preamp power

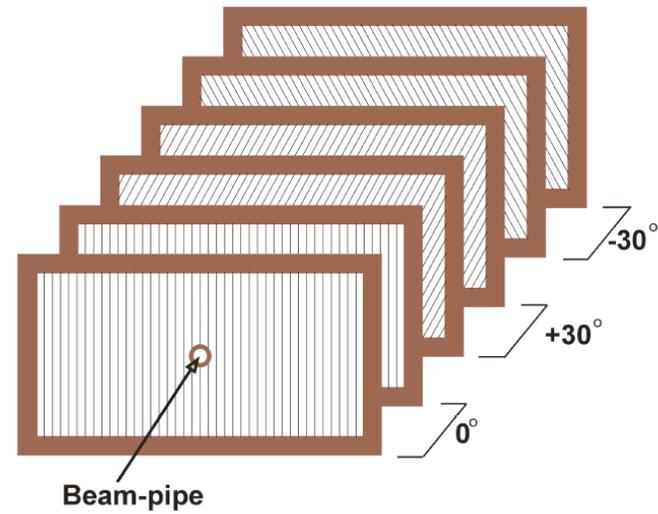
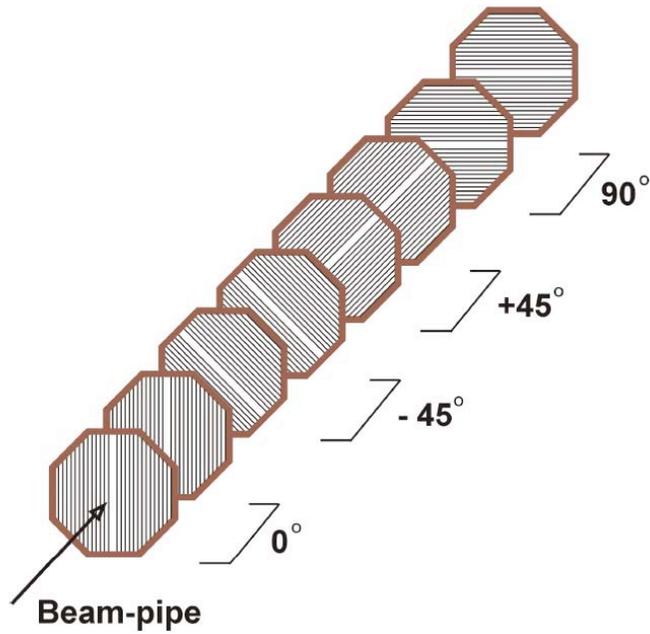


The Forward Spectrometer

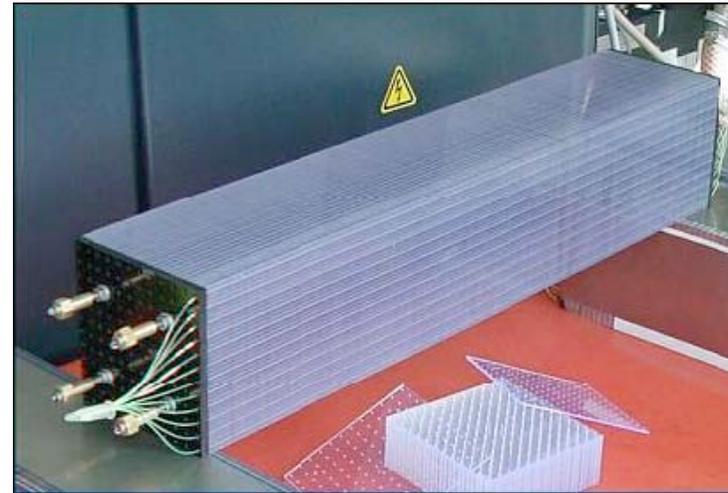
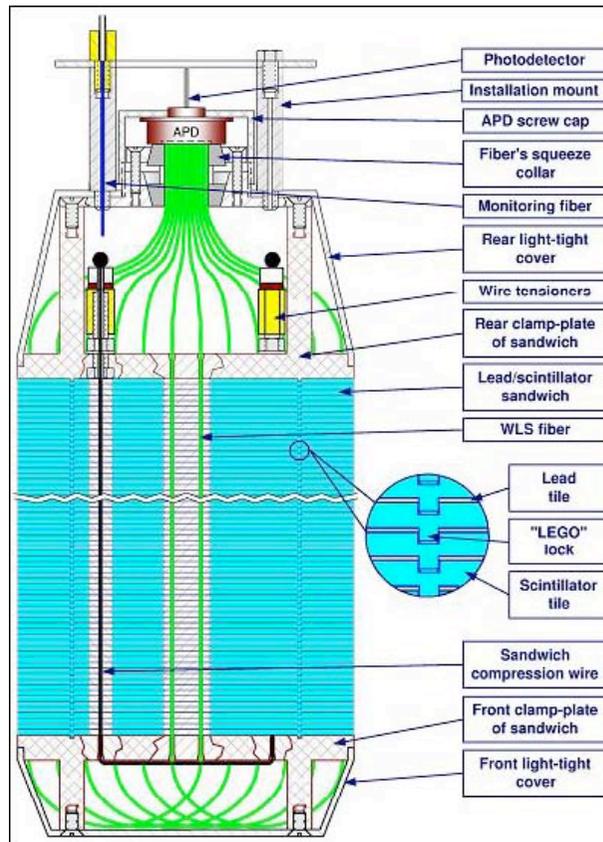
Tracking detectors:

MDC

DC



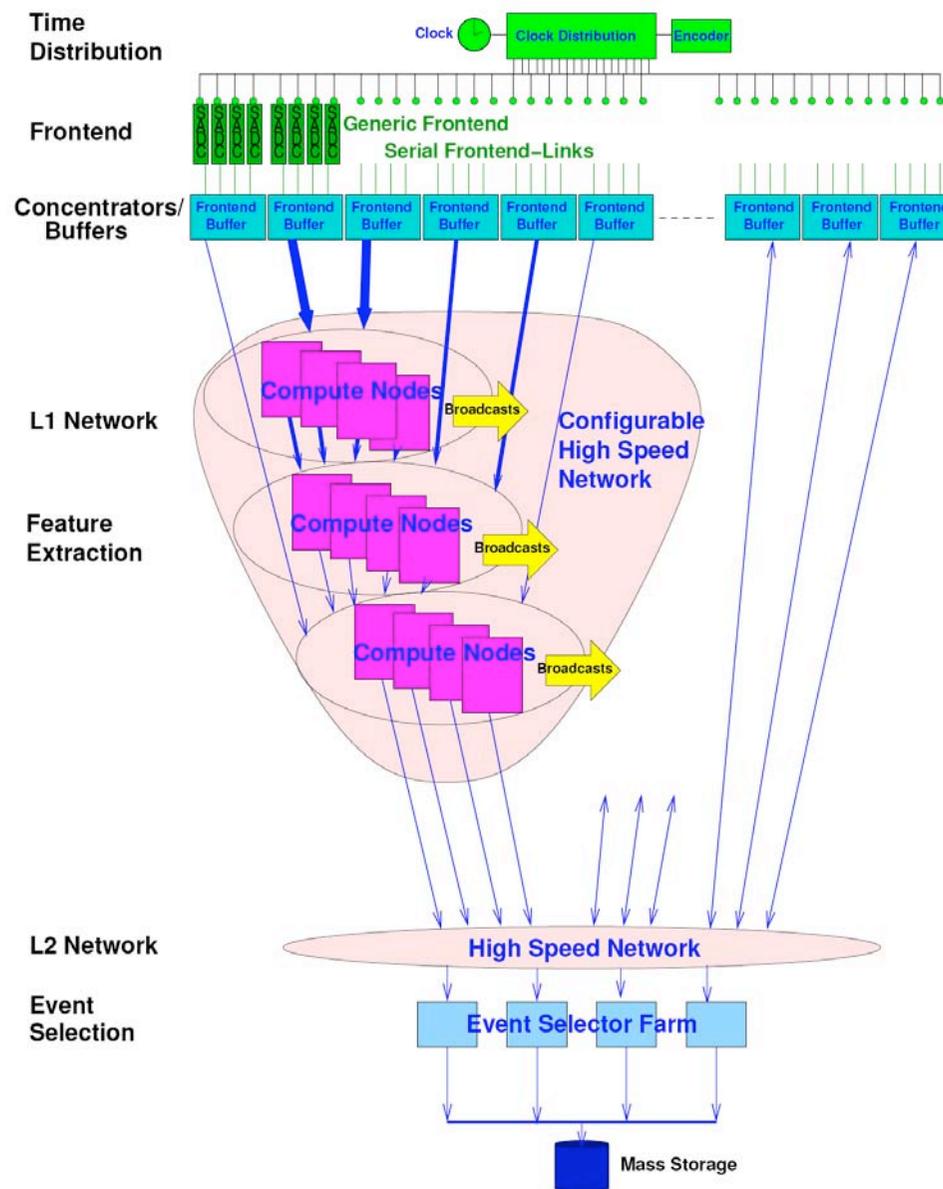
The Forward EMC



Shashlyk modules composed of lead absorbers and scintillators

$$\frac{\sigma(E)}{E} = (1.96 \pm 0.1)\% + \frac{(2.74 \pm 0.05)\%}{\sqrt{E[GeV]}}$$

DAQ and Trigger



Topics not mentioned

- baryon-antibaryon pair production
- CP violation in the charm sector
- J/ψ nucleon scattering
- inverted wide-angle Compton scattering
- form factor measurements
- open charm physics
- anti-deuteron production
- ...

Summary

Spectroscopy experiments are the basis of the quark model.

- The first glueballs and exotics have been found with antiprotons.
- $\bar{p}p$ provides the most precise charmonium data.
- Many other physics perspectives.

Antiprotons provide a versatile tool for QCD studies.

Hadron physics in Europe has a brilliant future with the FAIR facility and PANDA coming up.