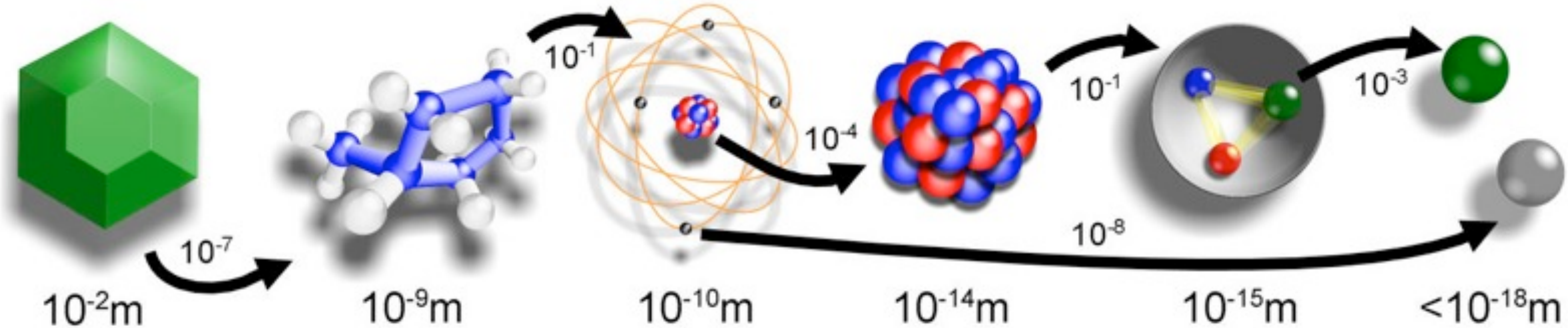
Hadron Physics - Achievements and future goals

Ulrich Wiedner
(Ruhr-University Bochum)

DPG spring meeting, Dresden, 7.3.2013



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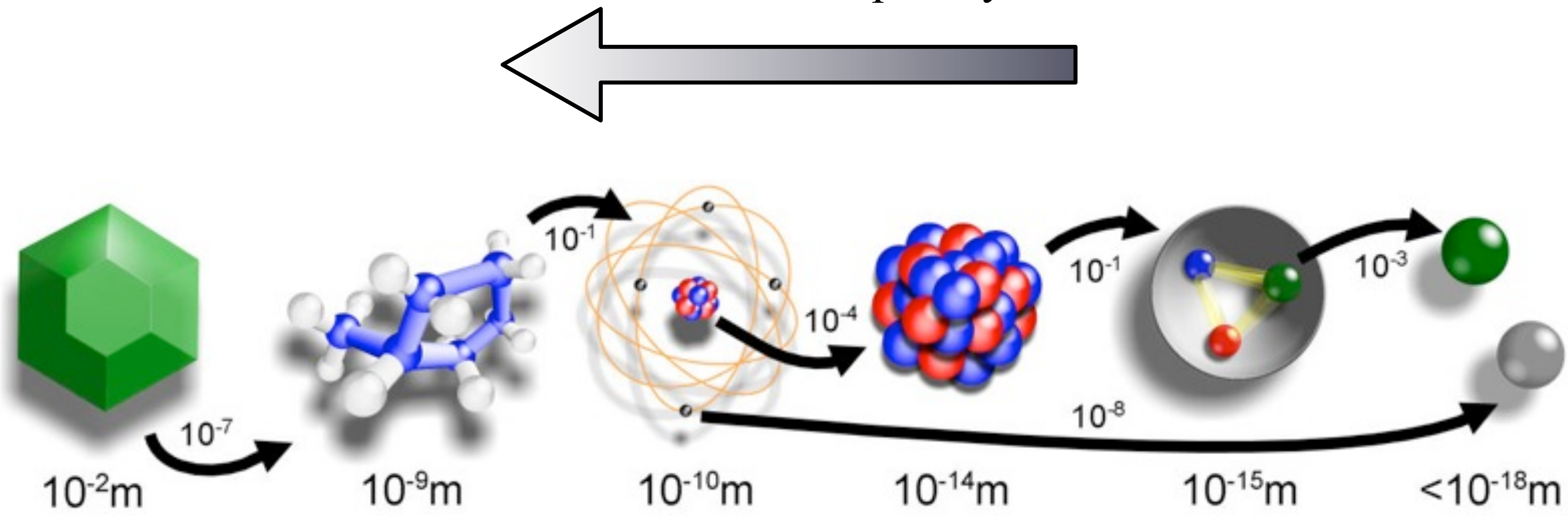
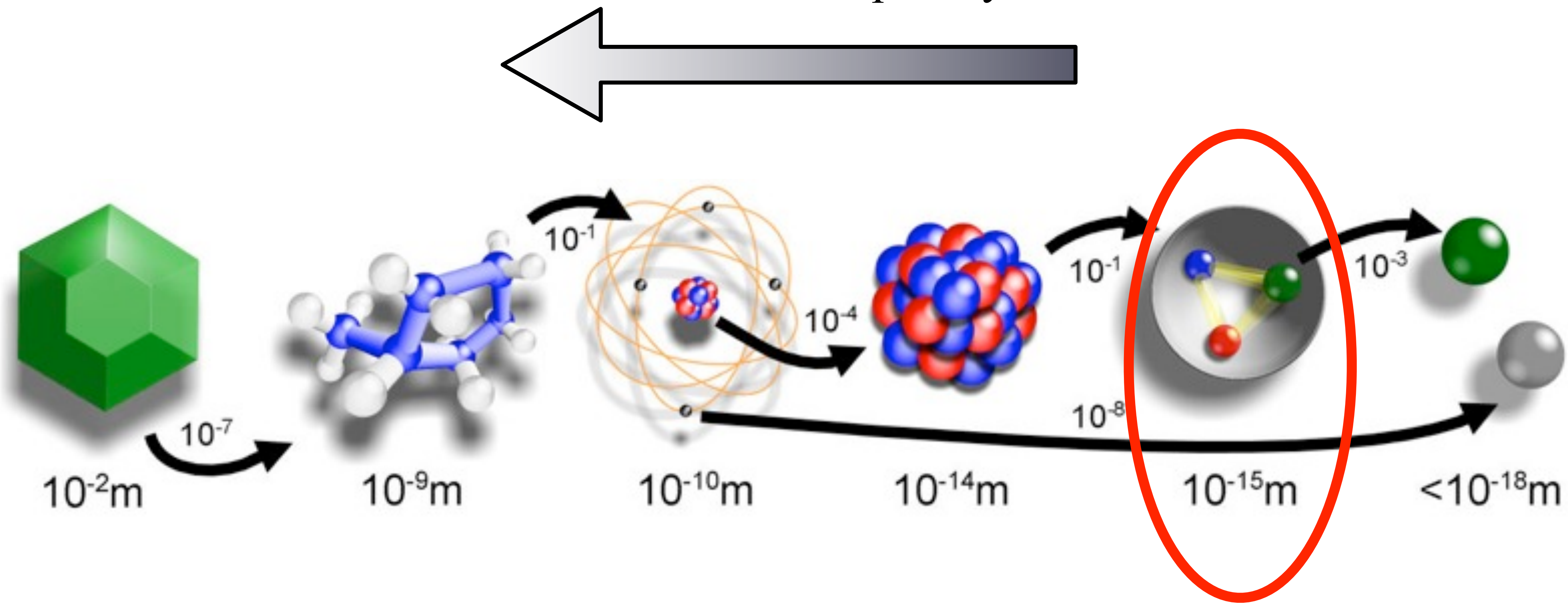
Level of complexity



Level of complexity



Hadron Physics

How to study hadrons?

- *Observe them as existing particles*

  γ / lepton beams are excellent probes (mostly of the nucleon)

- *Build them together in a controlled manner*

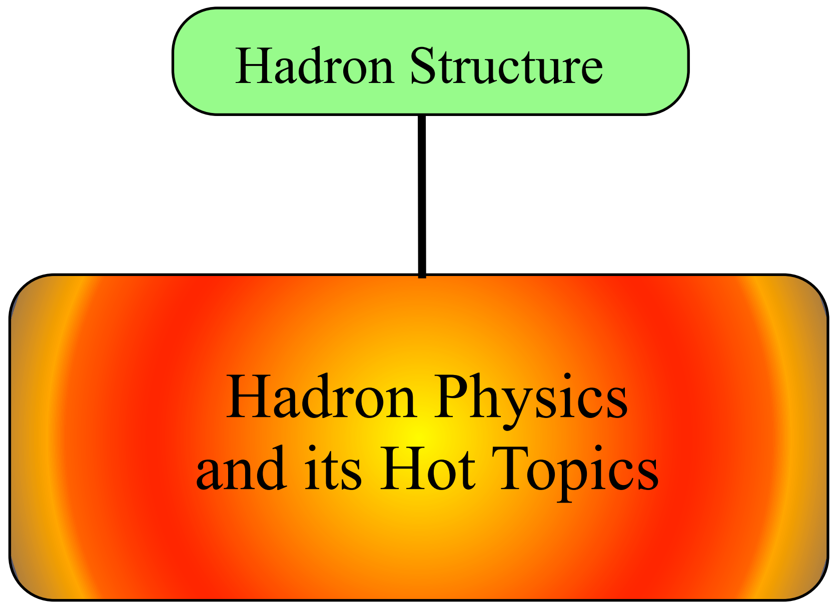
  - e^+e^- collider can produce vector mesons (other particles in decays)
  - hadron beams have high production cross sections but little control (except for antiprotons)

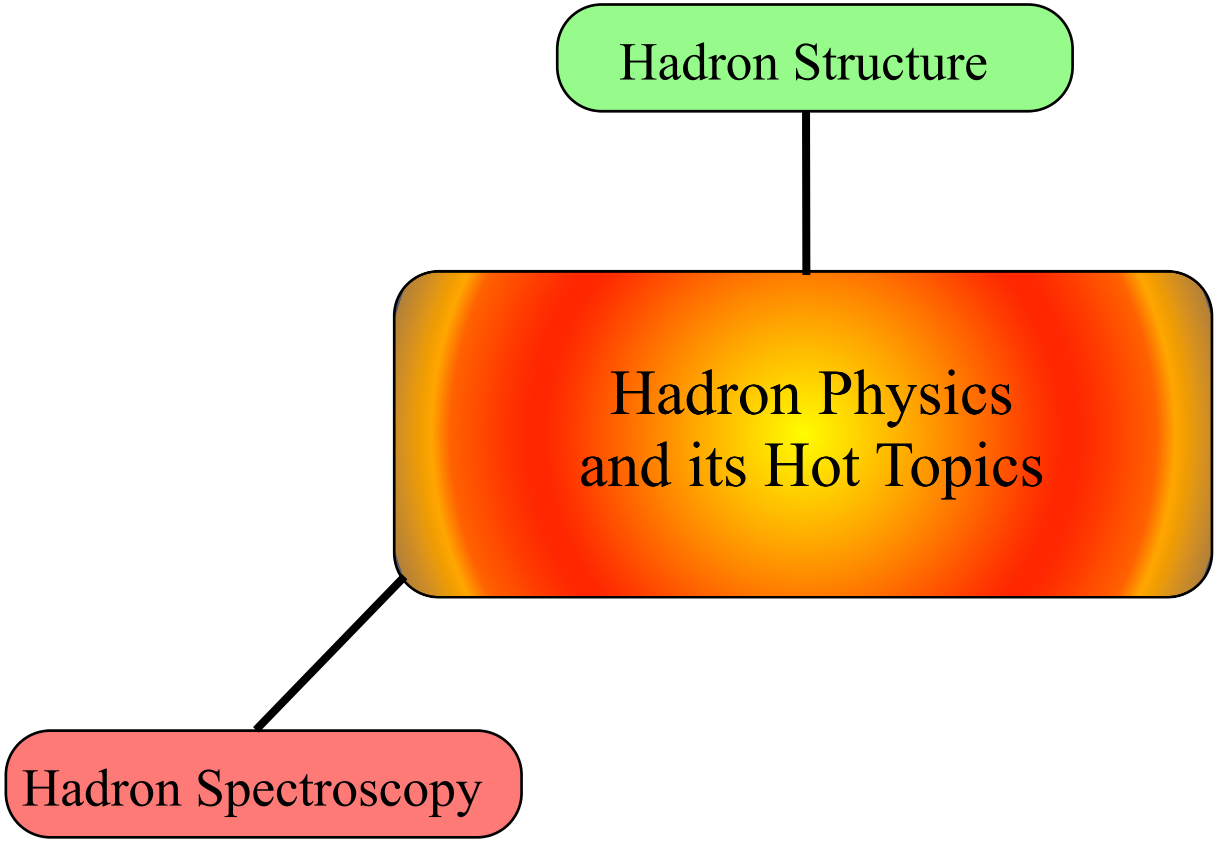
- *Study their interaction among each others*

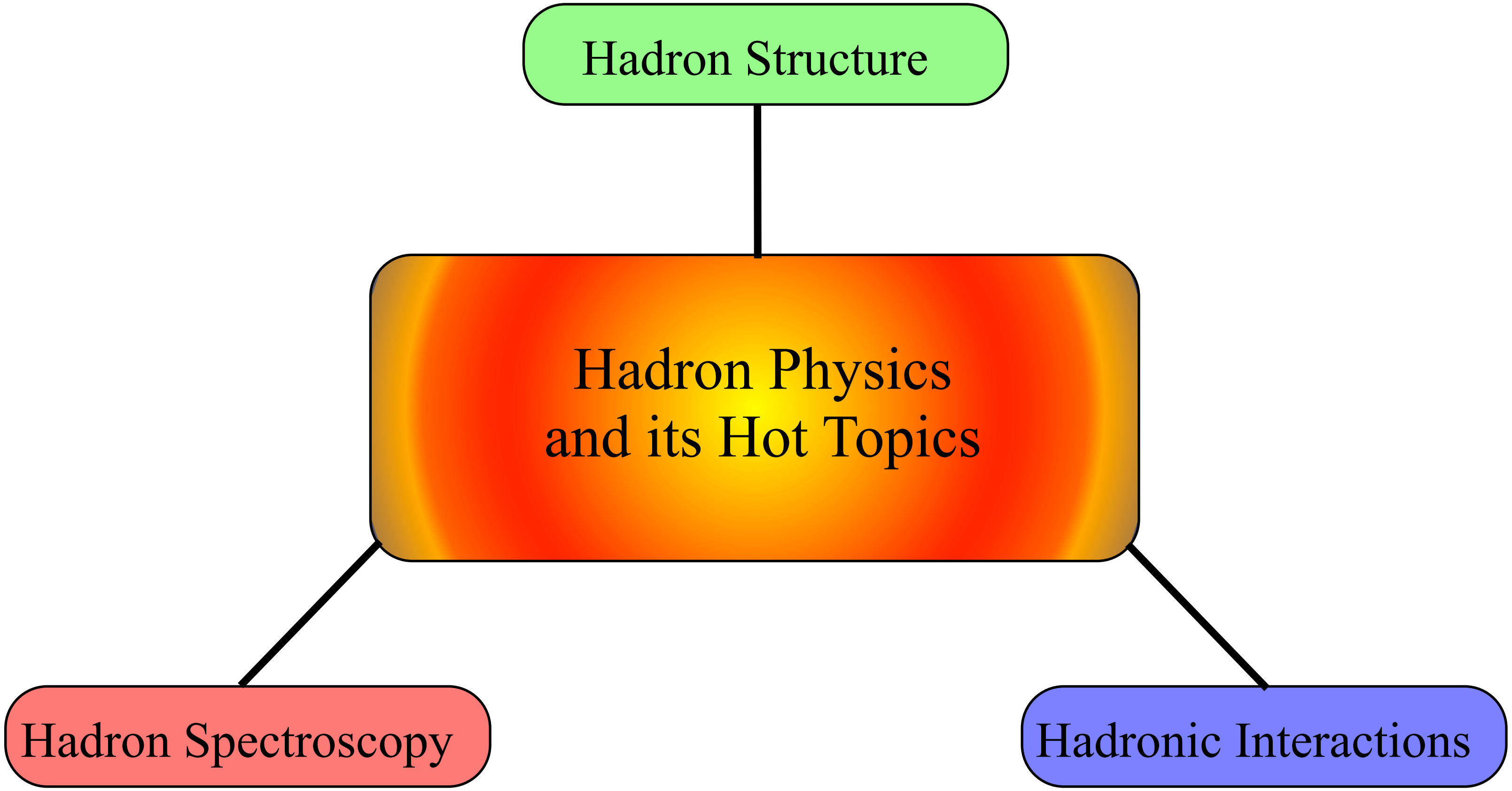
The results from hadron physics will leads to an understanding of a (non-perturbative) interaction among the fundamental quarks.

Ulrich Wiedner

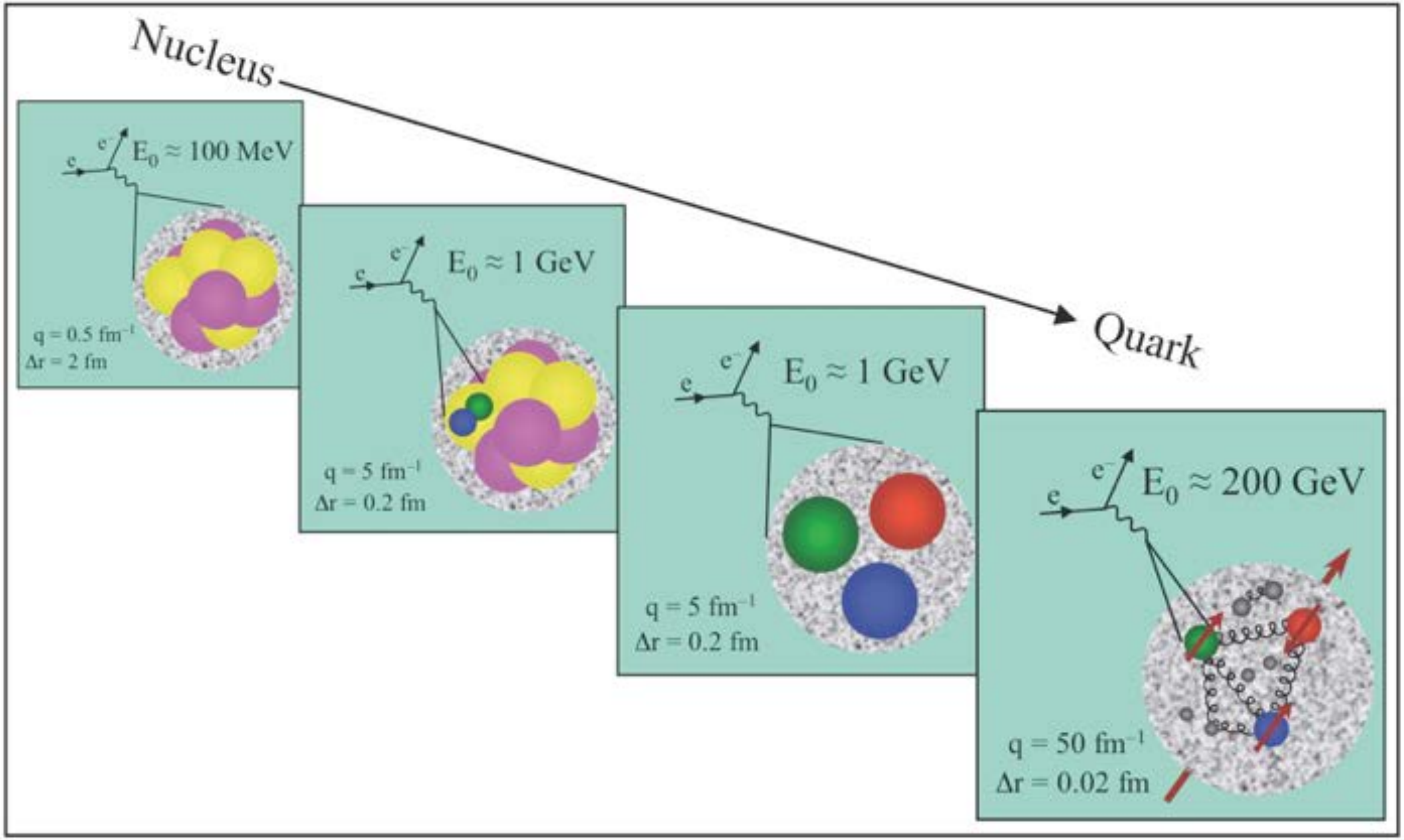
Hadron Physics and its Hot Topics


Hadron Structure
Hadron Physics
and its Hot Topics


Hadron Structure
Hadron Physics
and its Hot Topics
Hadron Spectroscopy

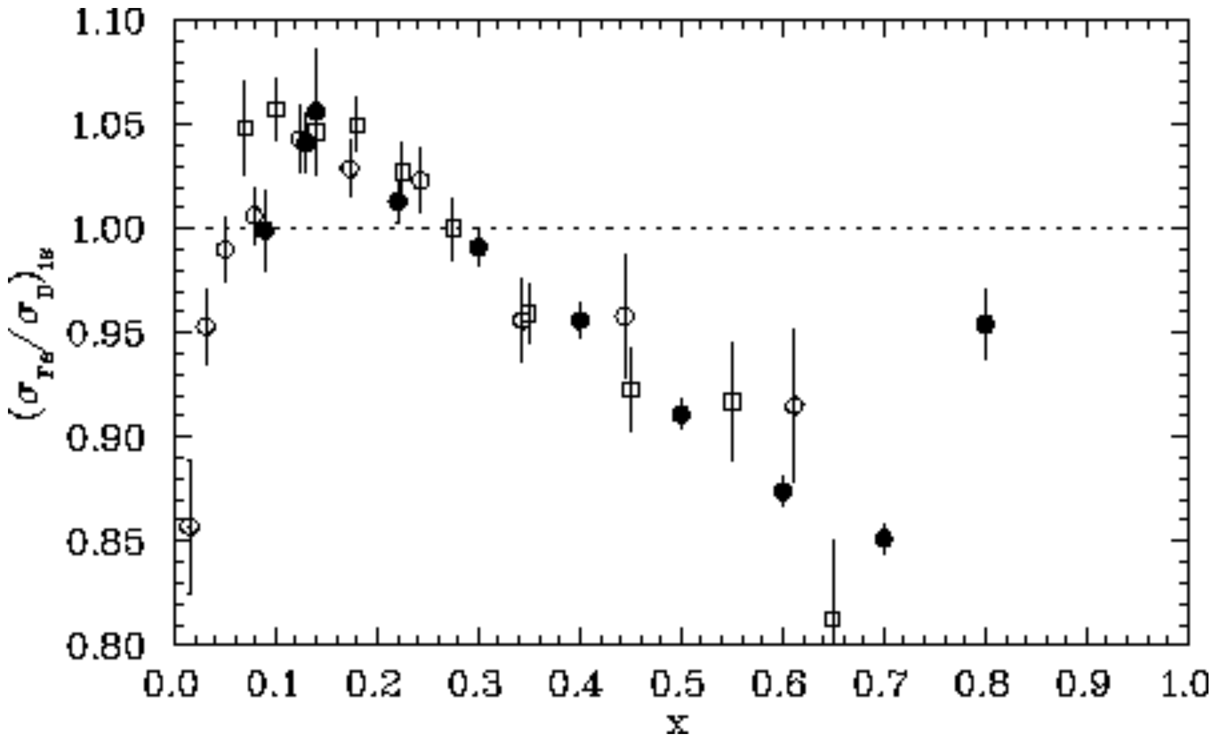

Hadron Structure
Hadron Physics
and its Hot Topics
Hadron Spectroscopy
Hadronic Interactions

Hadronic Structure



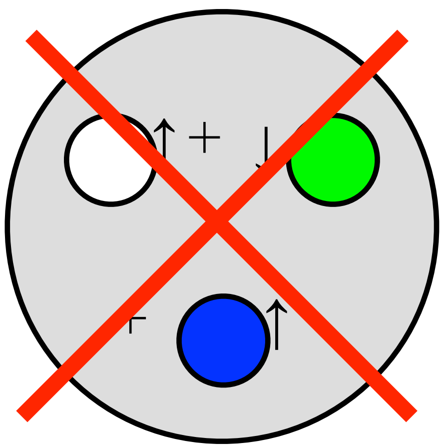
The EMC effect

Muons on nuclear targets to measure nuclear structure functions.

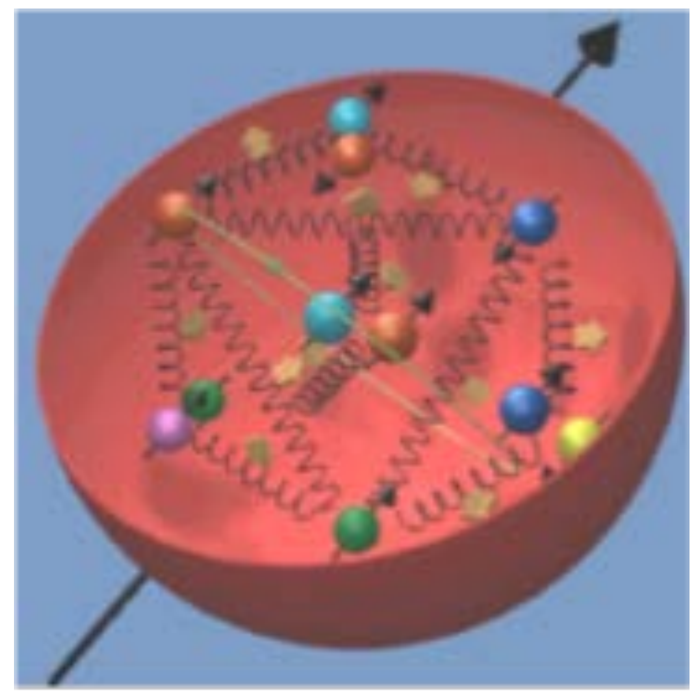


σ_{Fe}/σ_D ratios as a function of *x* from EMC (hollow circles), SLAC (solid circles), and BCDMS (squares). The data have been averaged over Q^2 and corrected for neutron excess (*i.e.* for isoscaler nuclei)

$\Uparrow \; = $

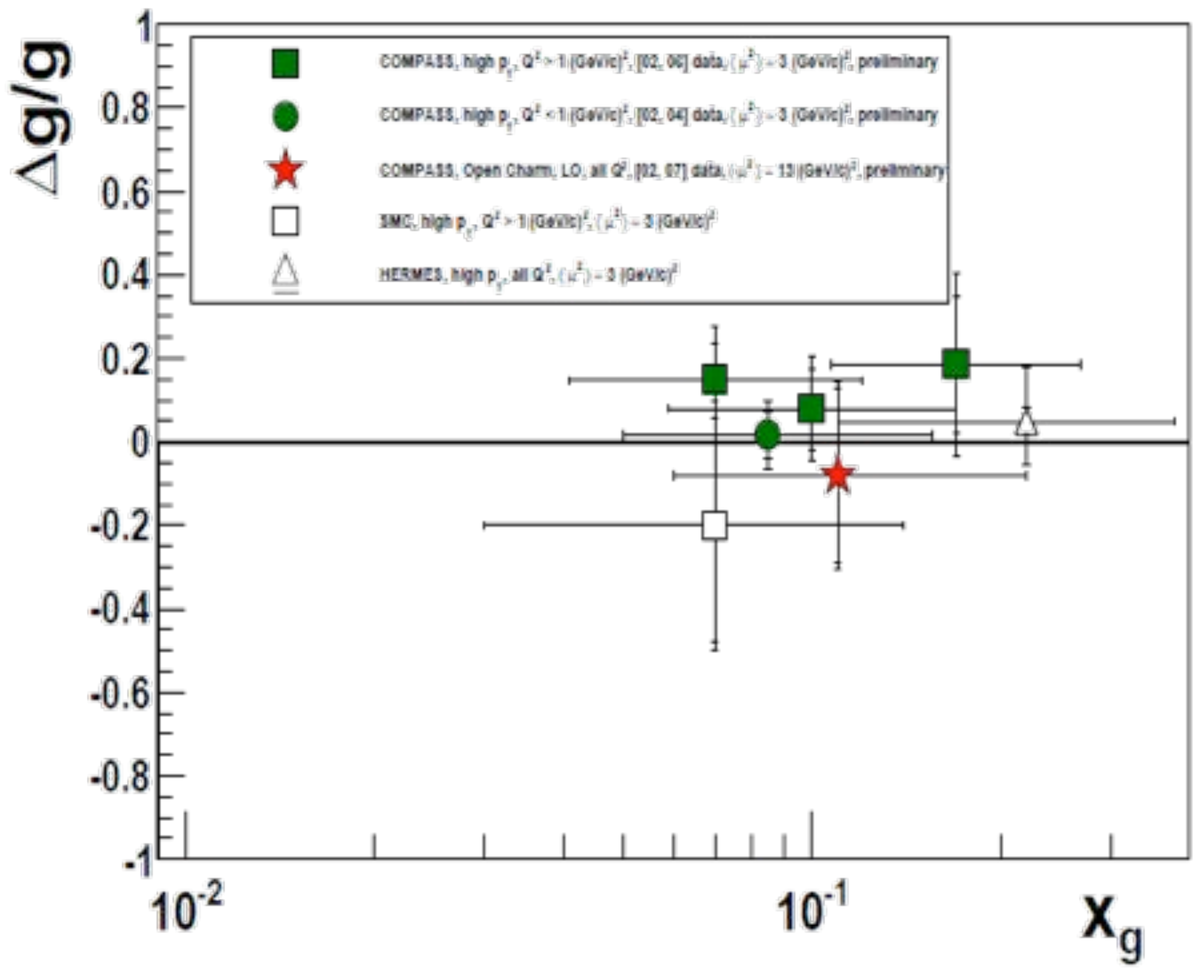


$=$



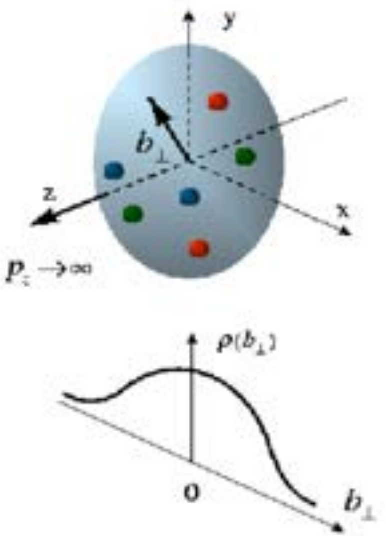
Proton

Gluon polarization results from SMC, HERMES, and COMPASS

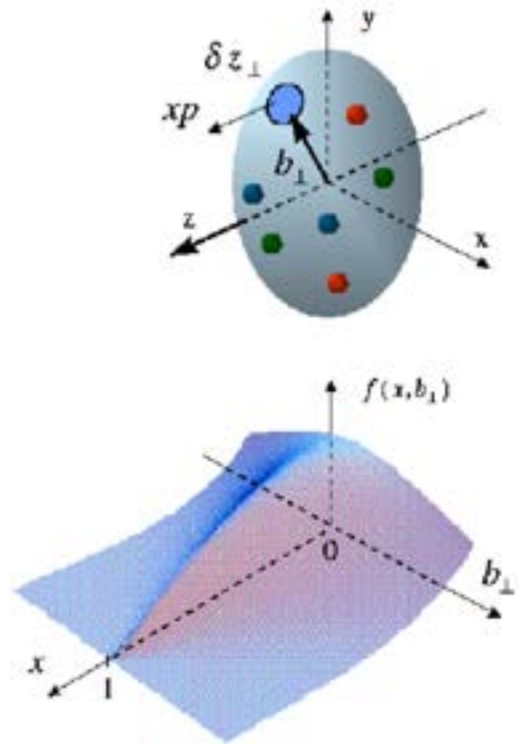


- The gluon polarisation is rather small
- confirmed by polarised *pp* at RHIC

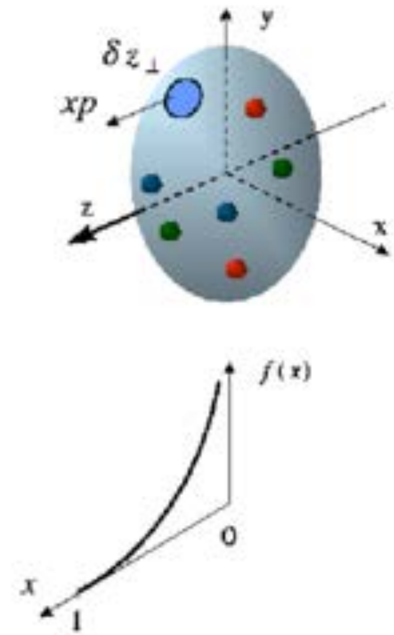
More than form factors and quark distributions ⇒ Generalized Parton Distributions (GPDs)



Elastic scattering reveals
form factors:
transverse charge and
current densities



Common description:
GPDs are *correlated* quark momentum
and helicity distributions in
transverse space (tomography)

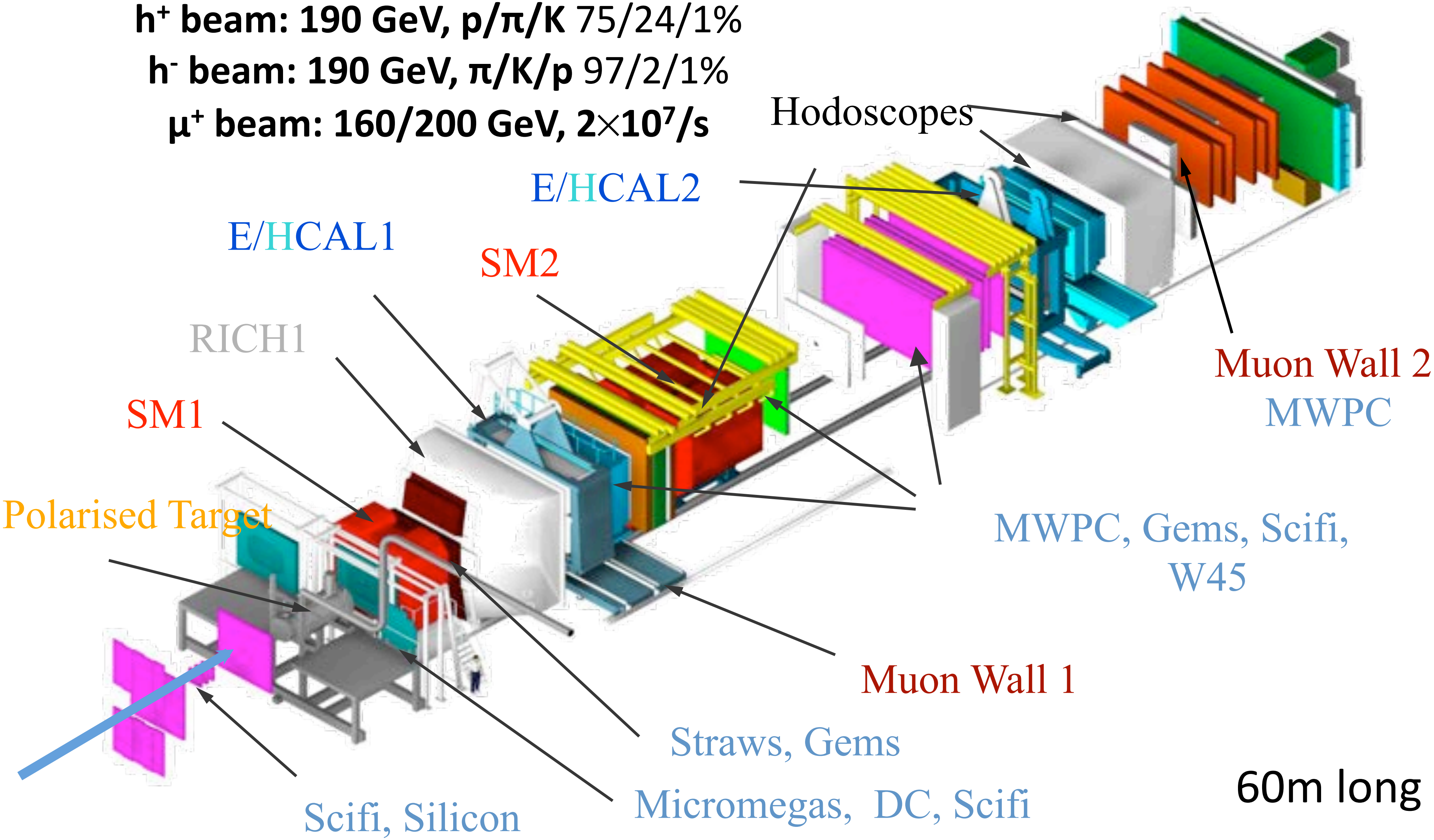


Deep inelastic scattering:
Structure functions:
quark *longitudinal*
momentum & helicity
distributions

Extending longitudinal quark momentum & helicity distributions
⇒ transverse momentum distributions (TMDs).

COMPASS spectrometer

h⁺ beam: 190 GeV, p/π/K 75/24/1%
h⁻ beam: 190 GeV, π/K/p 97/2/1%
μ⁺ beam: 160/200 GeV, 2×10⁷/s



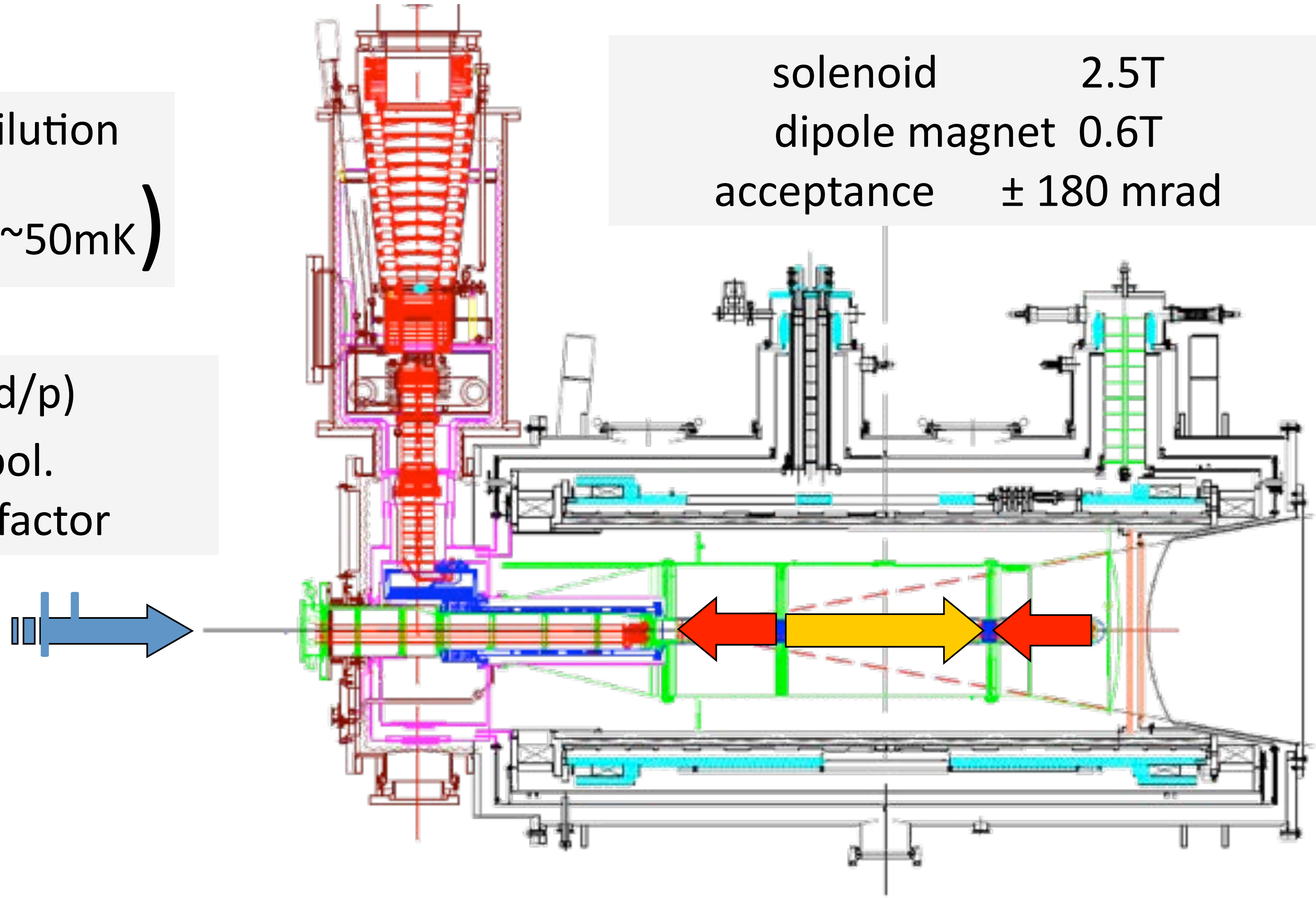
60m long

Polarized target system

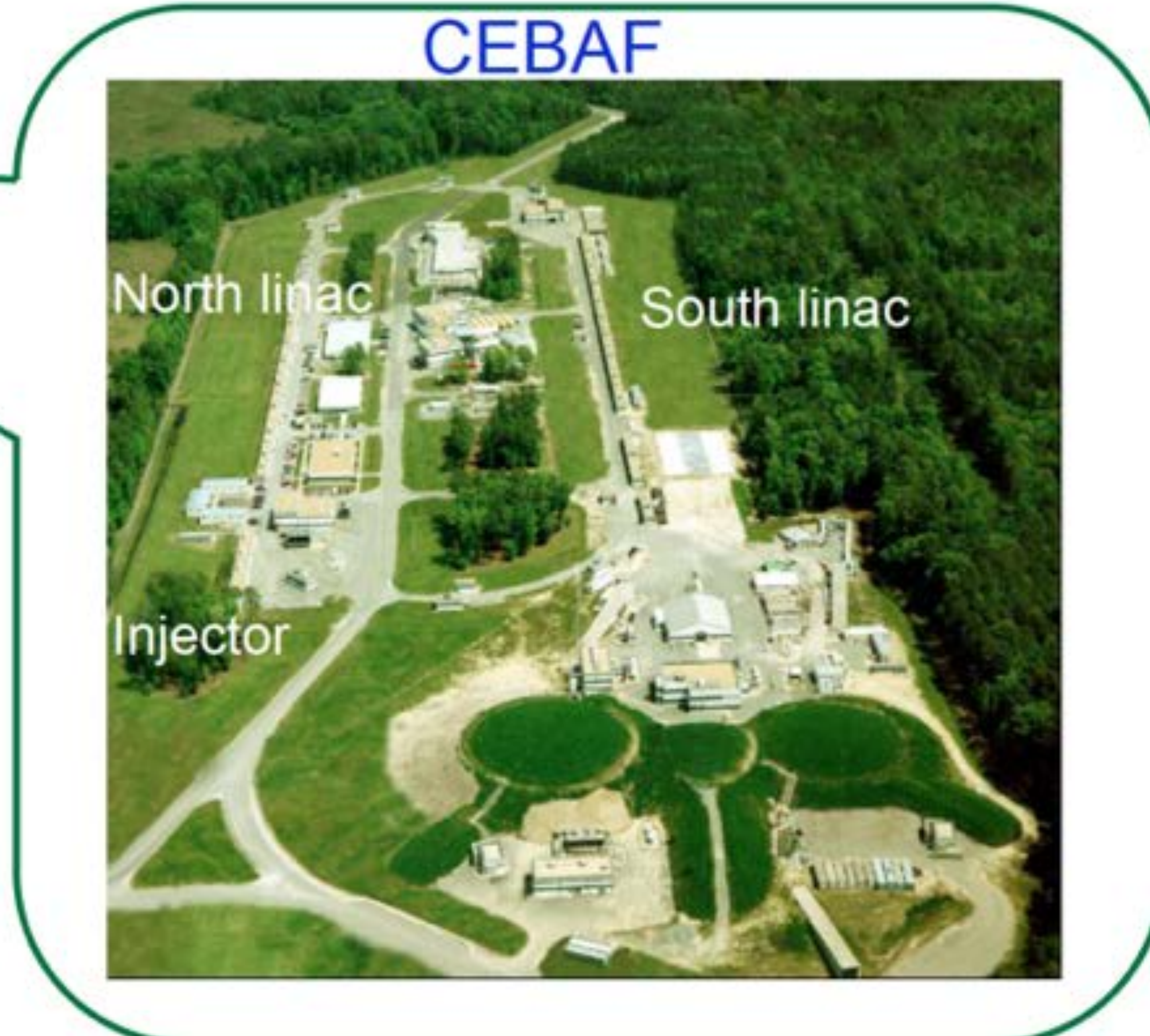
$^3He - ^4He$ dilution refrigerator (T~50mK)

$^6LiD/NH_3$ (d/p)
50/90% pol.
40/16% dil. factor

solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad



Jefferson Lab



E_{max} = 6 GeV → 12 GeV

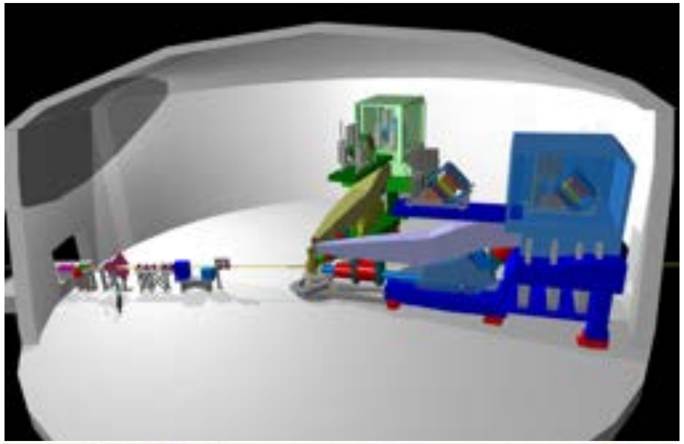
I_{max} = 200 μA

P = 85%

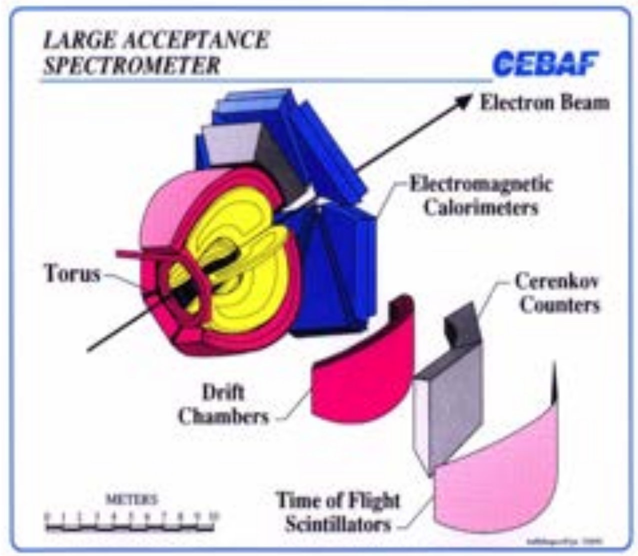
CW – 1497 MHz bunch structure (499 MHz/Hall)

Simultaneous delivery of different energy/intensity CW beam to 3 Halls

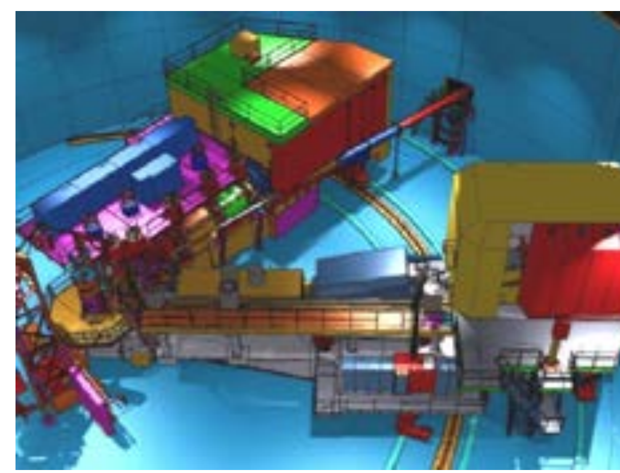
Hall A:
Nucleon form factors



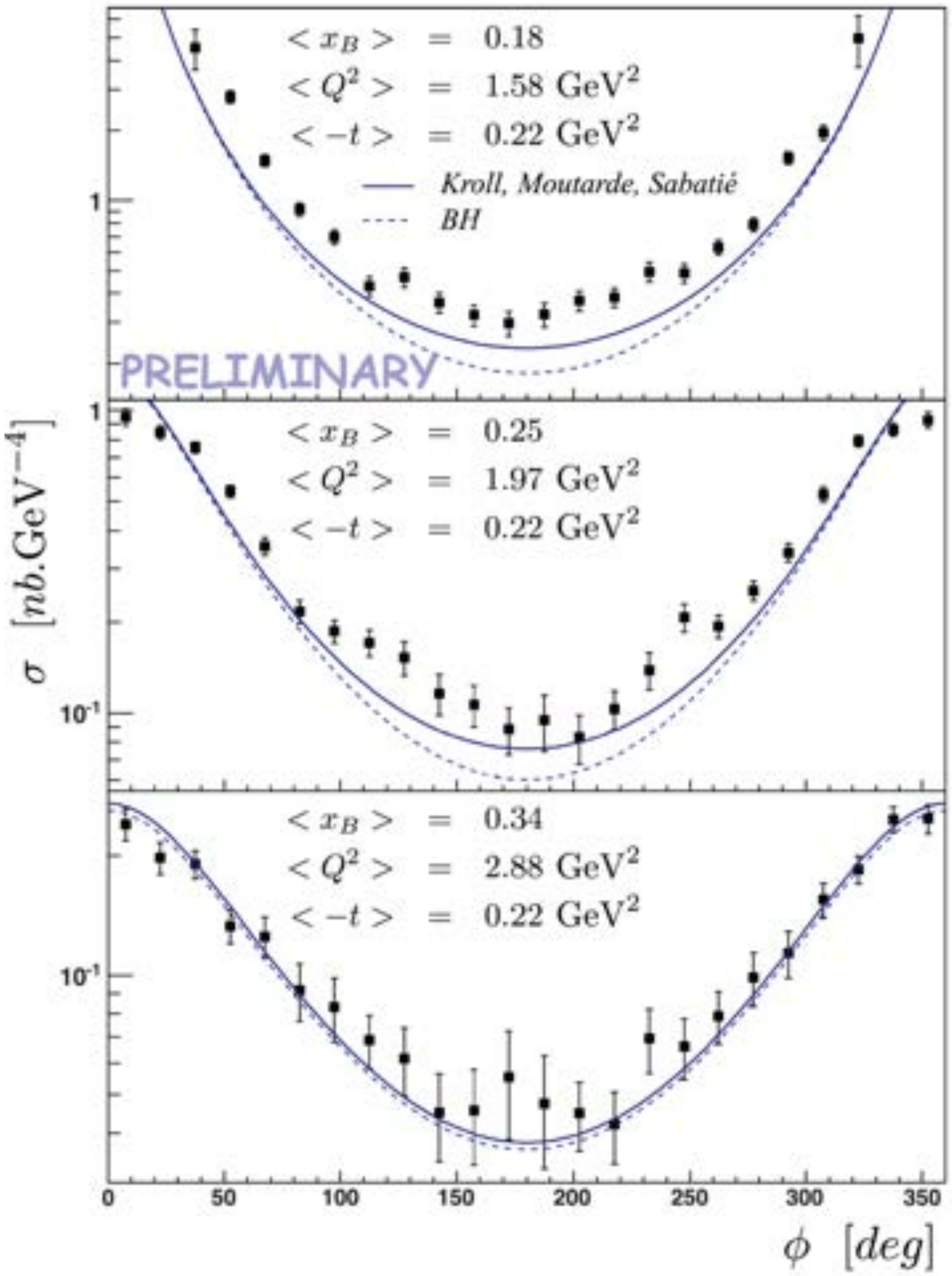
Hall B:
Nucleon structure (GPDs)



Hall C:
Quark properties in nucleons and nuclei

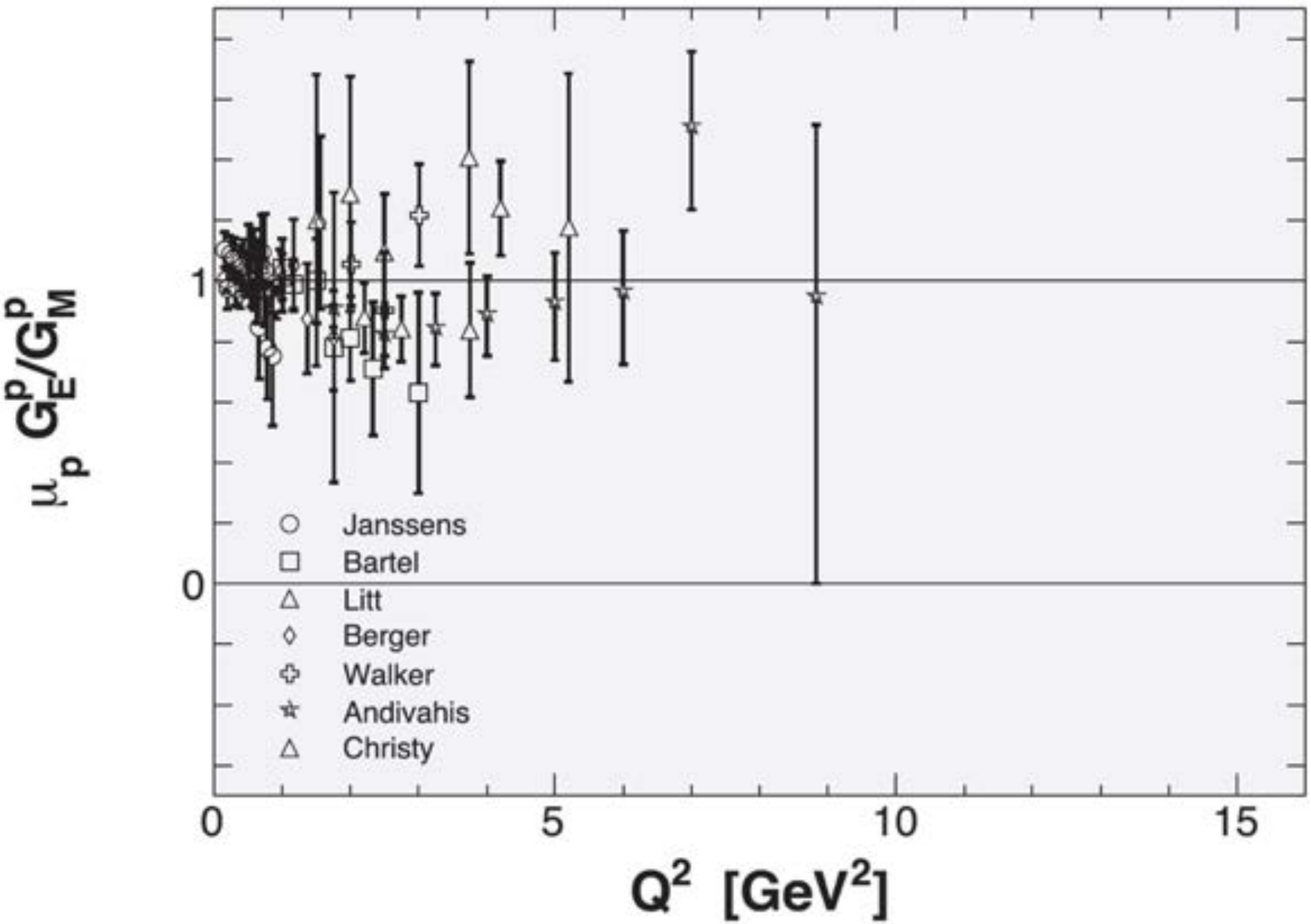


GPDs



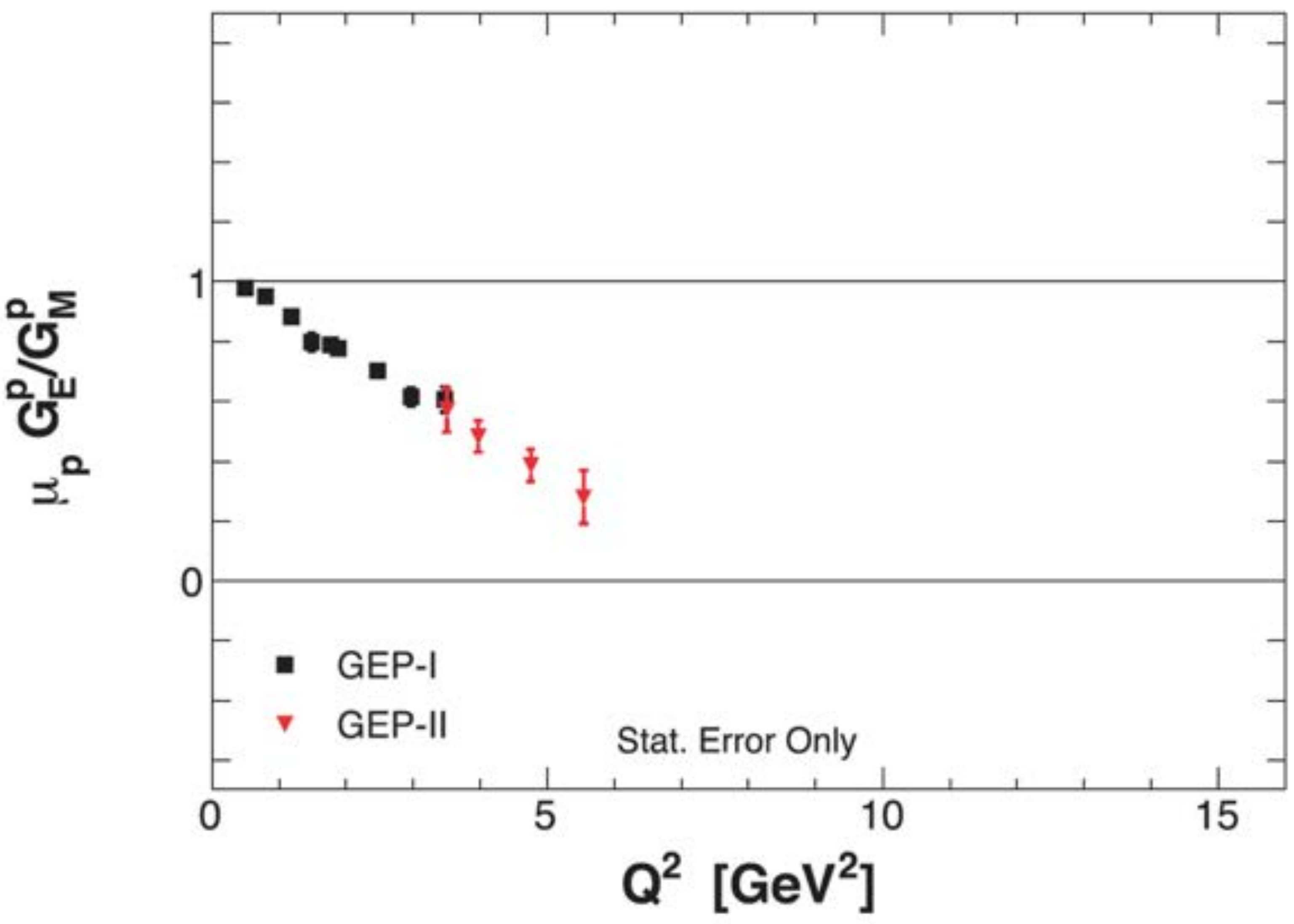
E1-DVCS experiment (2005)
Beam : 5.766 GeV, ~80% polarized
Luminosity : 33.3 fb^{-1}
Target : LH2
Mostly sensitive to GPD H
More data to come from 2009 run

Data on G_E^p/G_M^p prior to JLab



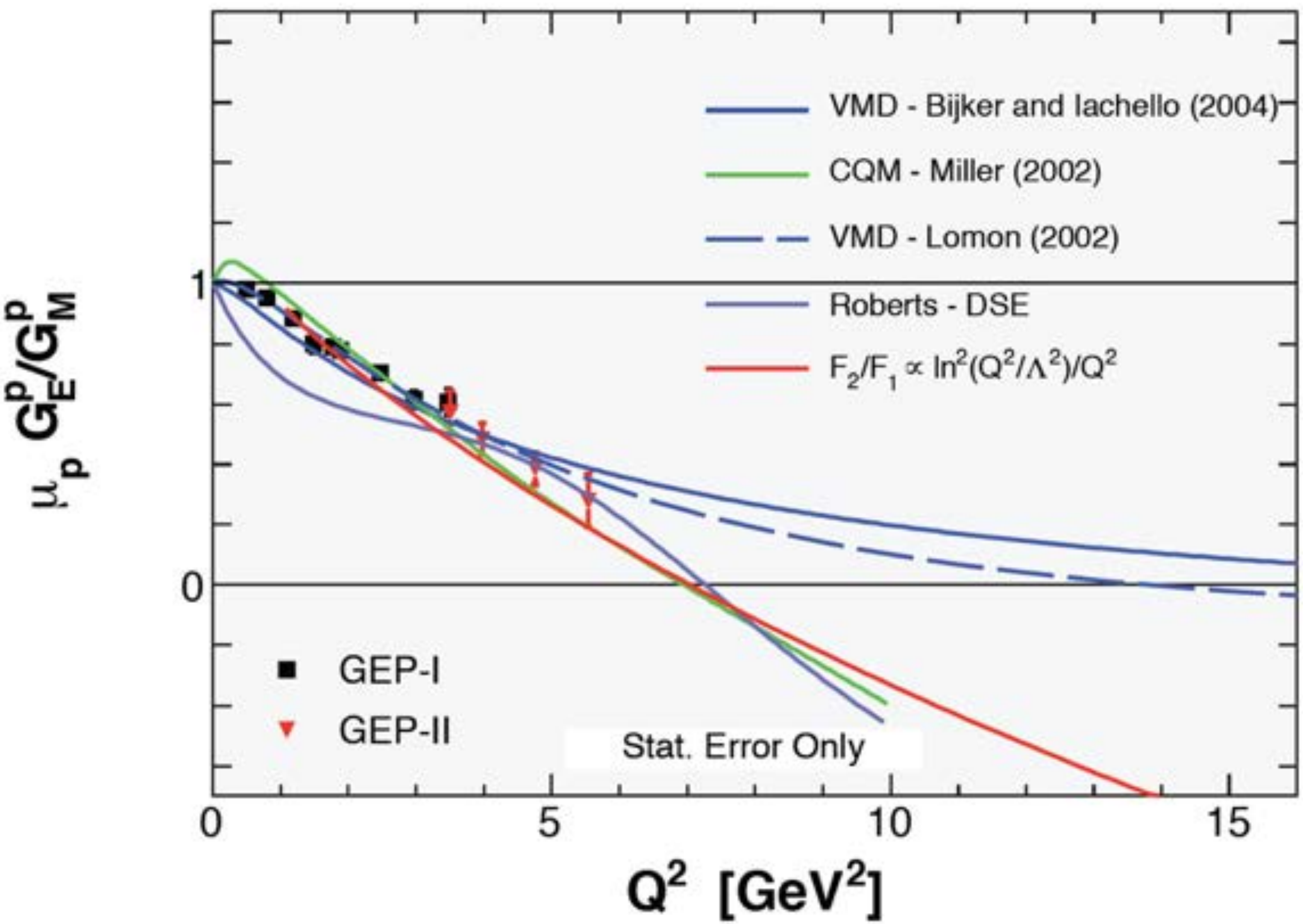
Expectation: G_E^p/G_M^p remains constant

Precision data on G_E^p/G_M^p at high Q^2 from JLab



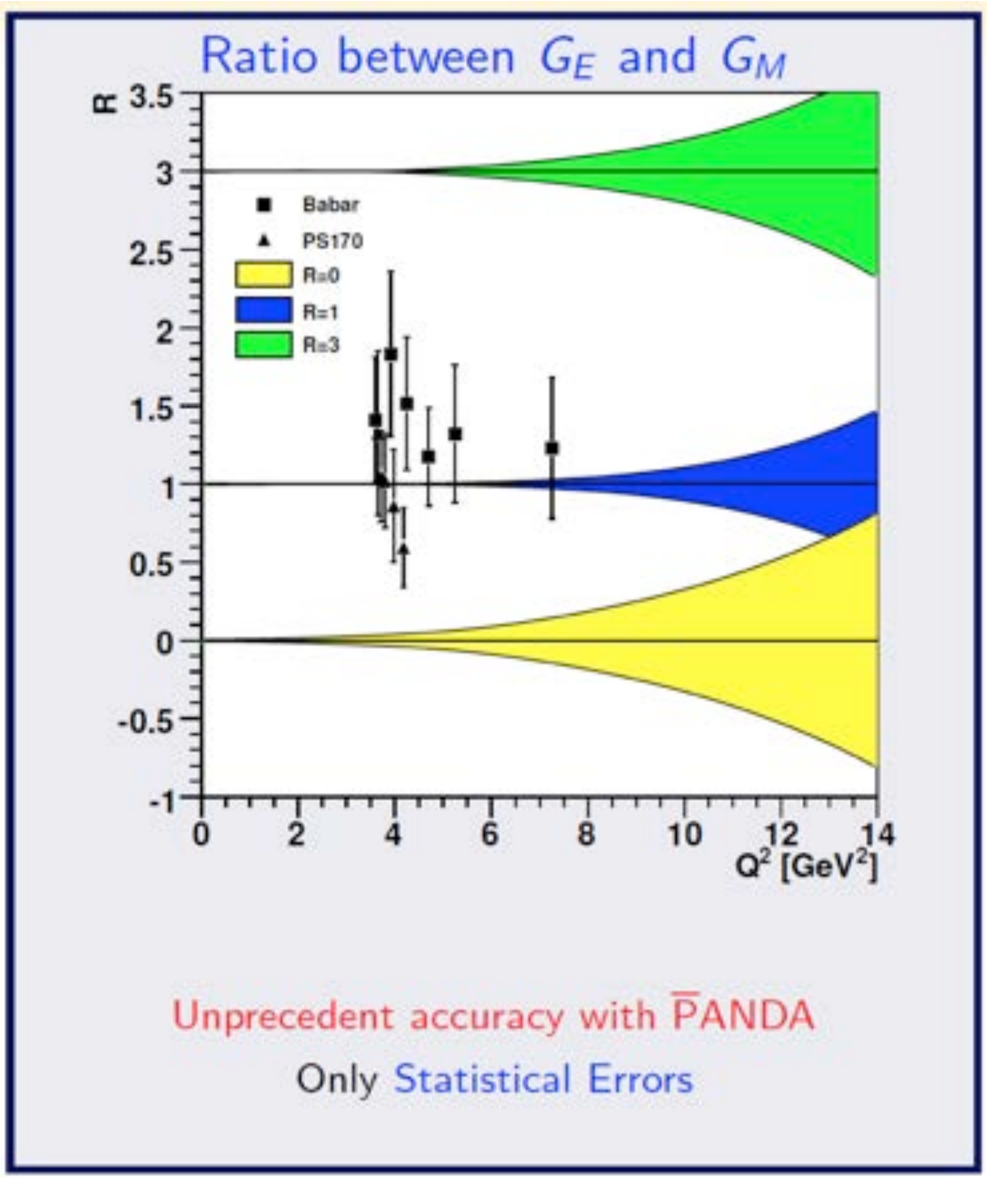
⇒ New theoretical effort to understand the nucleon in terms of QCD degrees of freedom.

Precision data on G_E^p/G_M^p at high Q^2 from JLab



Often interpretations invoked the importance of quark orbital angular momentum (quark OAM)

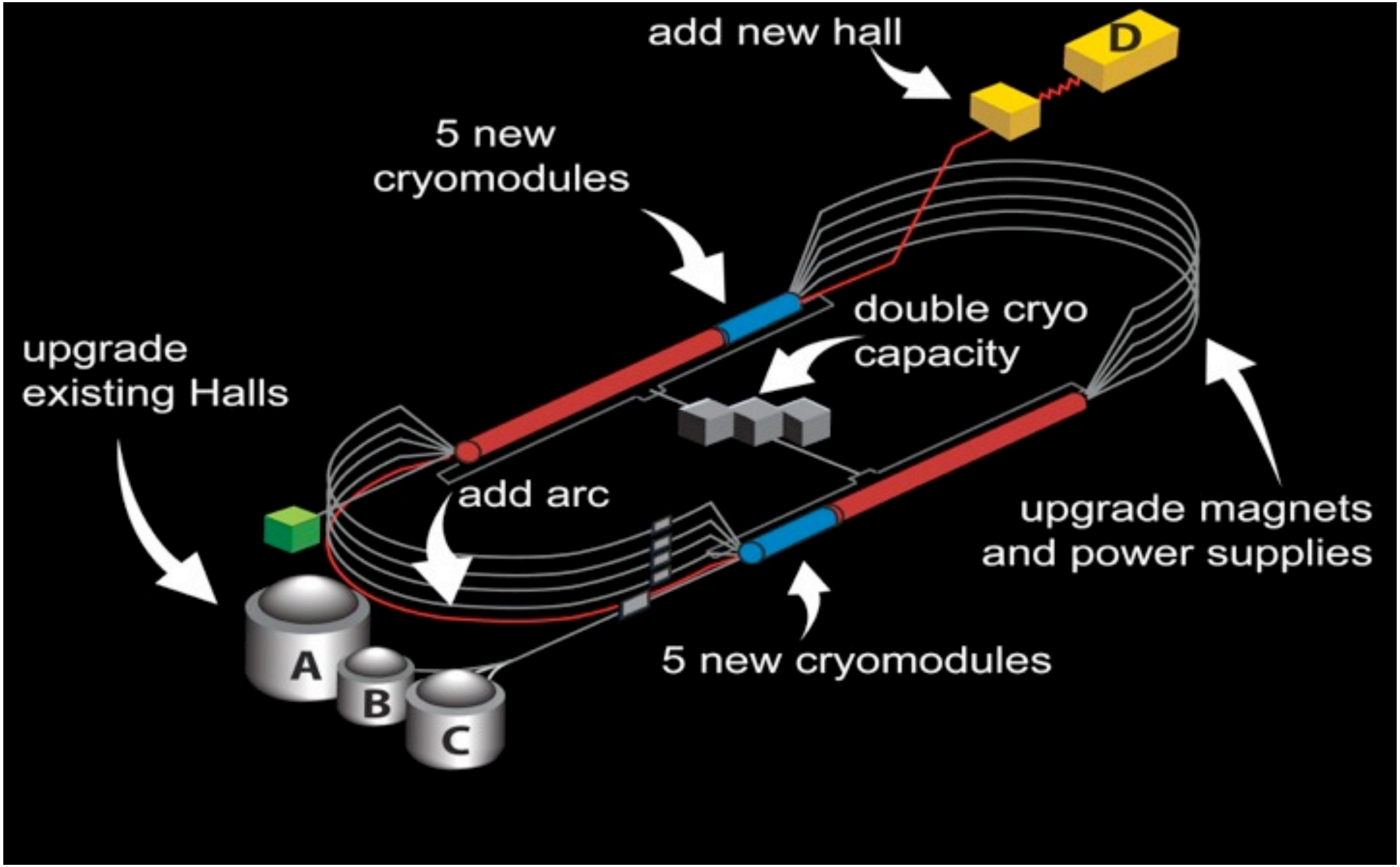
More high Q^2 data needed!



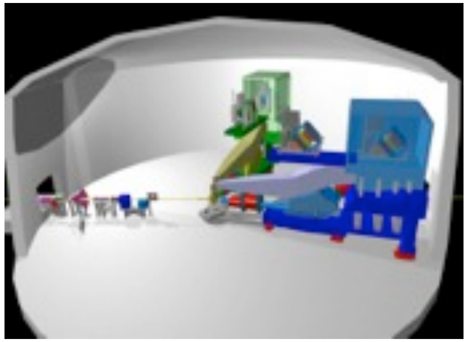
$$R = \frac{G_E}{G_M}$$

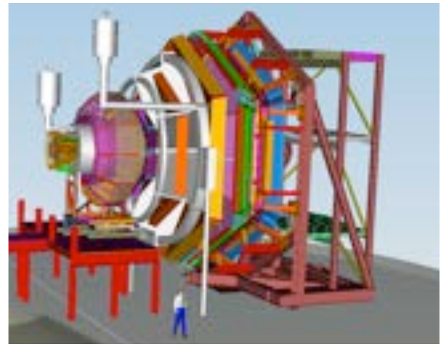
PANDA will measure the form factors in the biggest q^2 range for a single experiment up to values of ~14 GeV^2/c^4 (beam time dependent).

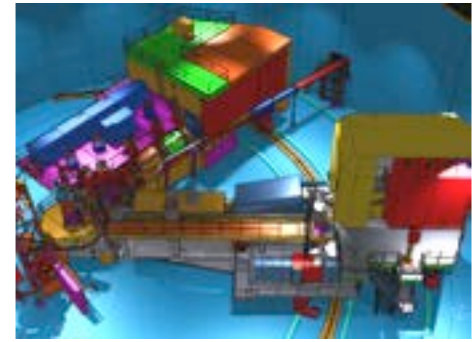
JLAB - 12 GeV


add new hall
D
5 new
cryomodules
double cryo
capacity
upgrade
existing Halls
add arc
upgrade magnets
and power supplies
A
B
C
5 new cryomodules

The planned Jefferson Laboratory Experiments







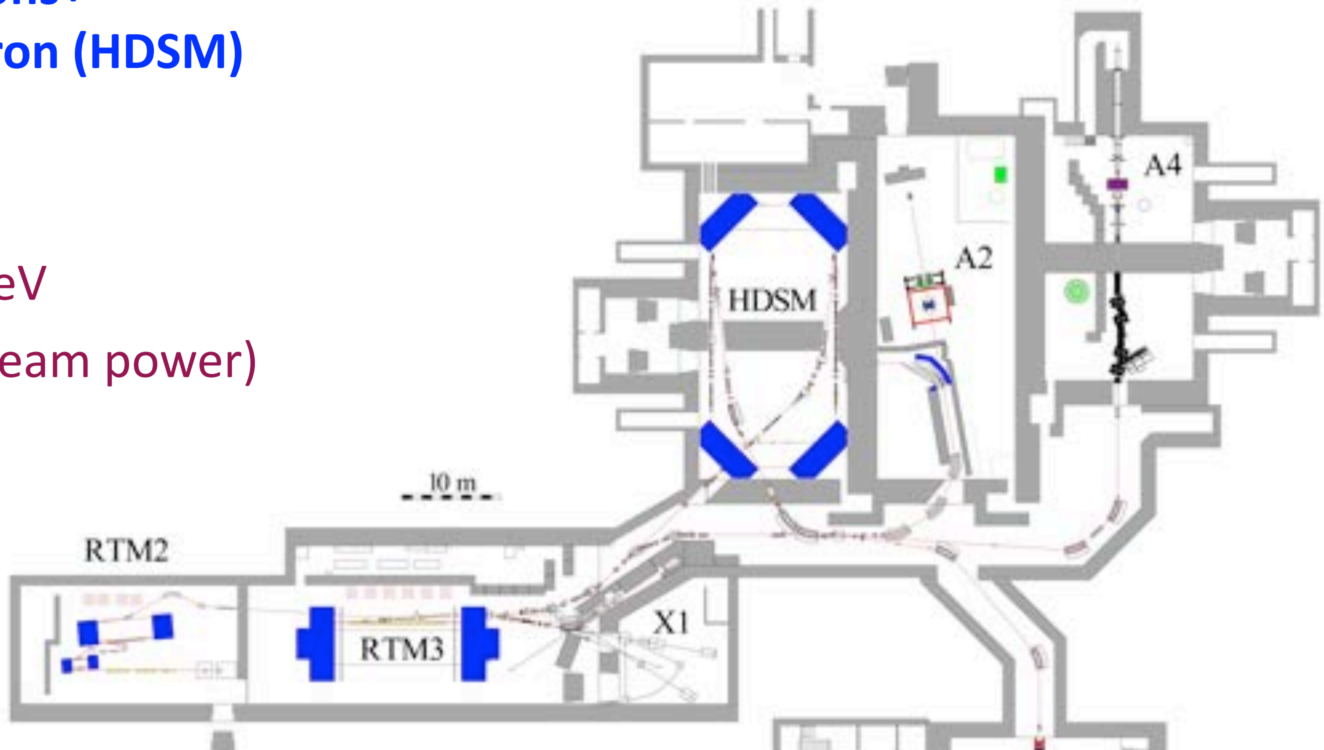
Hall A	Hall B	Hall C
installation space	luminosity 10^{35}	energy reach
	hermeticity	precision
11 GeV beamline		
target flexibility		
excellent momentum resolution	good momentum/angle resolution	excellent momentum resolution
luminosity up to 10^{38} - 10^{39}	high multiplicity reconstruction	luminosity up to 10^{38} - 10^{39}
particle ID		

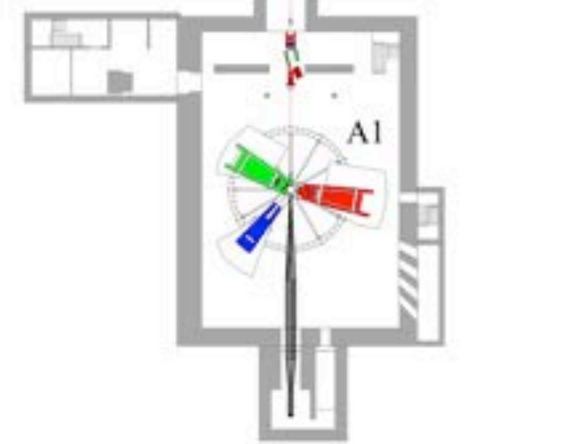
The Mainz Microtron MAMI

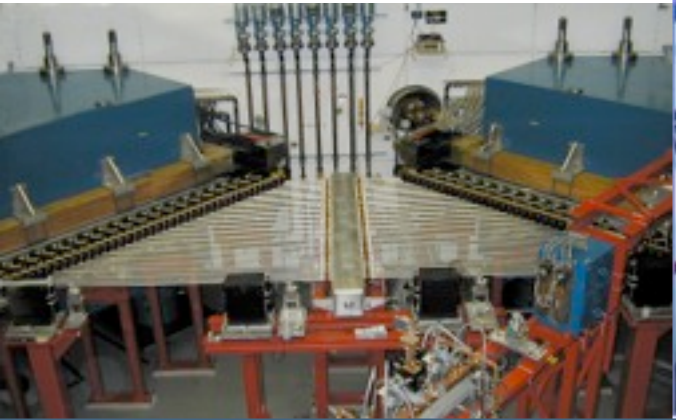
Cascade of 3 Racetrack Microtrons+
Harmonic Double-Sided Microtron (HDSM)

MAMI C Beam Parameter:

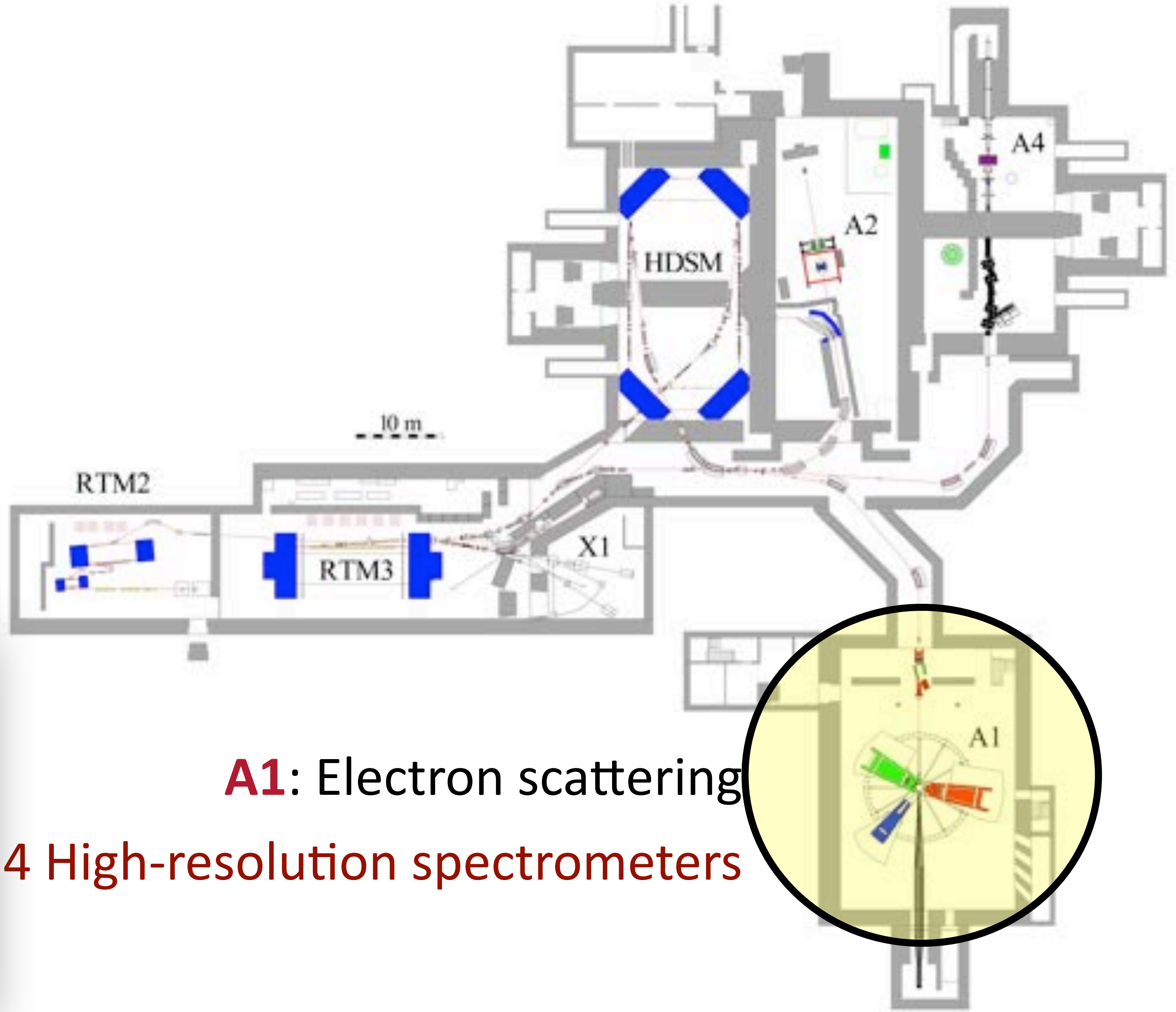
- **max. Energy 1.6 GeV**
- Energy Resolution σ_E<0.100MeV
- max. 100µA current (150kW beam power)
- ca. 80% Beam Polarisation







Experiments at MAMI



A1: Electron scattering

4 High-resolution spectrometers

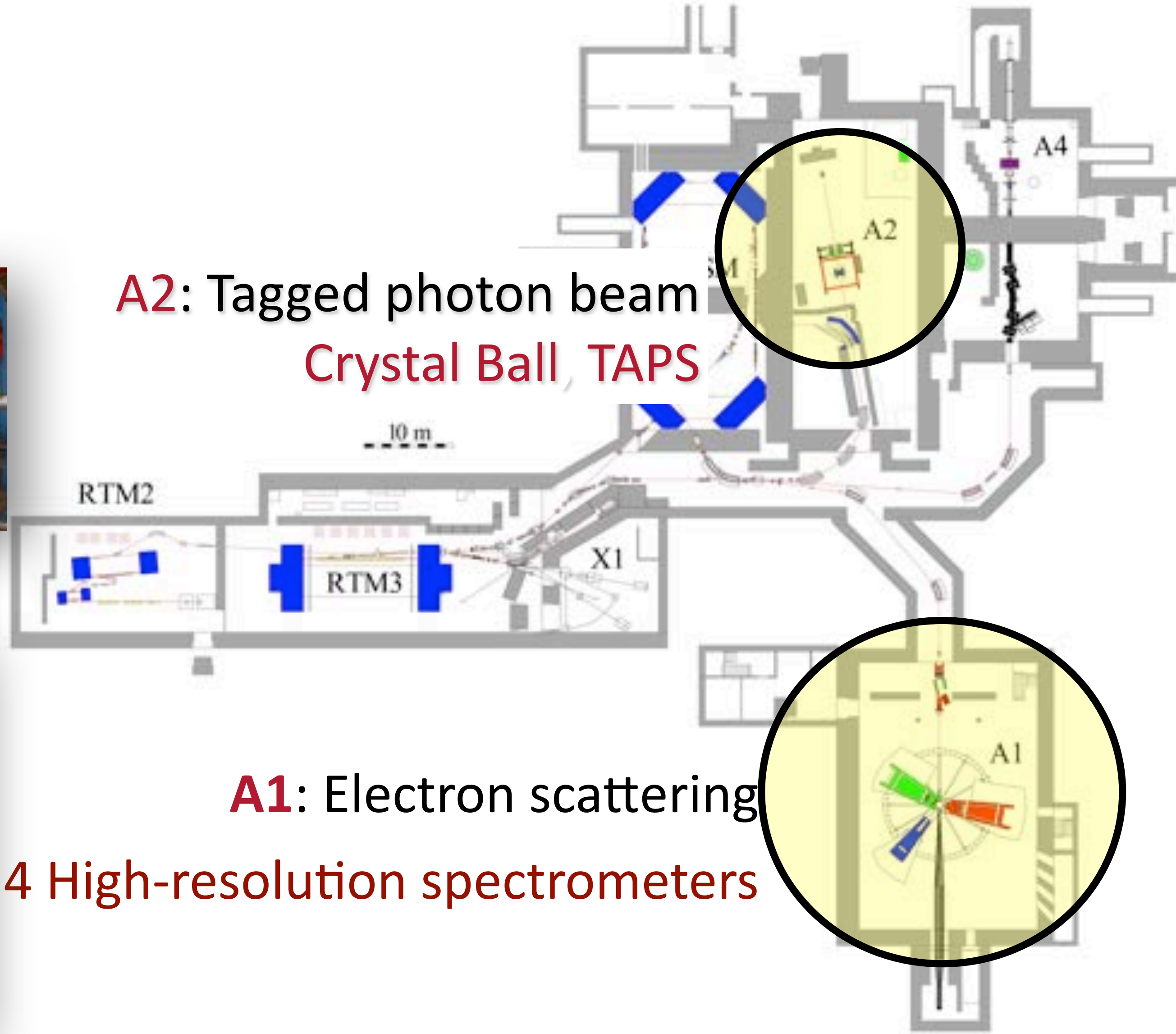
Experiments at MAMI

A2: Tagged photon beam

Crystal Ball, TAPS

A1: Electron scattering

4 High-resolution spectrometers



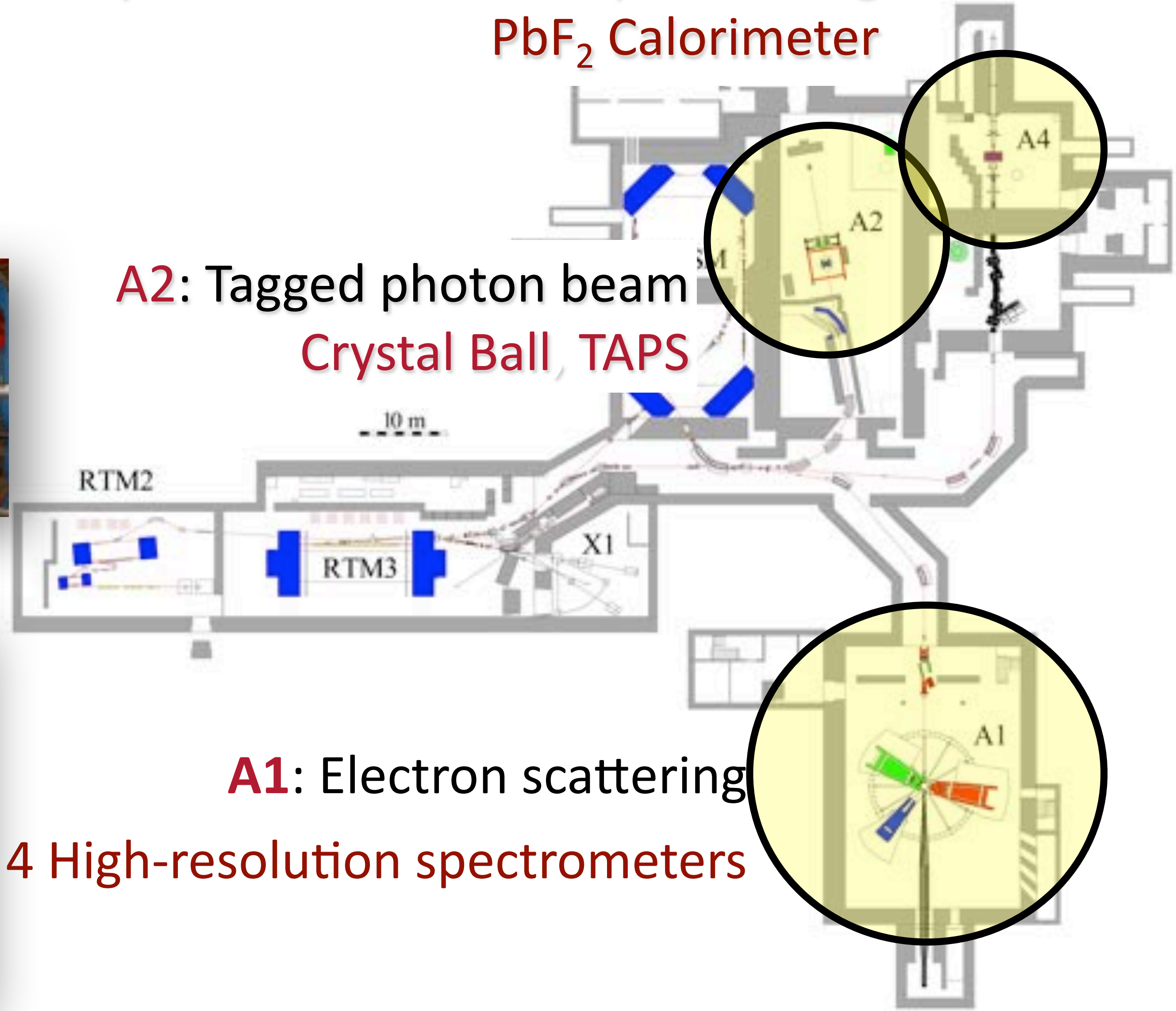
Experiments at MAMI

A4: Parity-violation in elastic ep scattering

PbF_2 Calorimeter

A2: Tagged photon beam

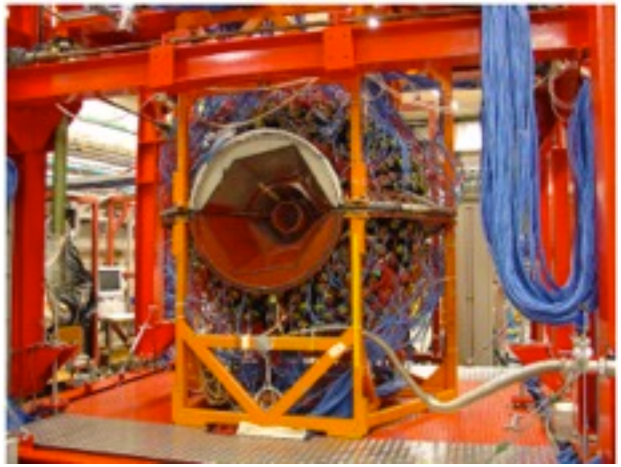
Crystal Ball, TAPS



A1: Electron scattering

4 High-resolution spectrometers

Highlights A2: Crystal Ball at MAMI



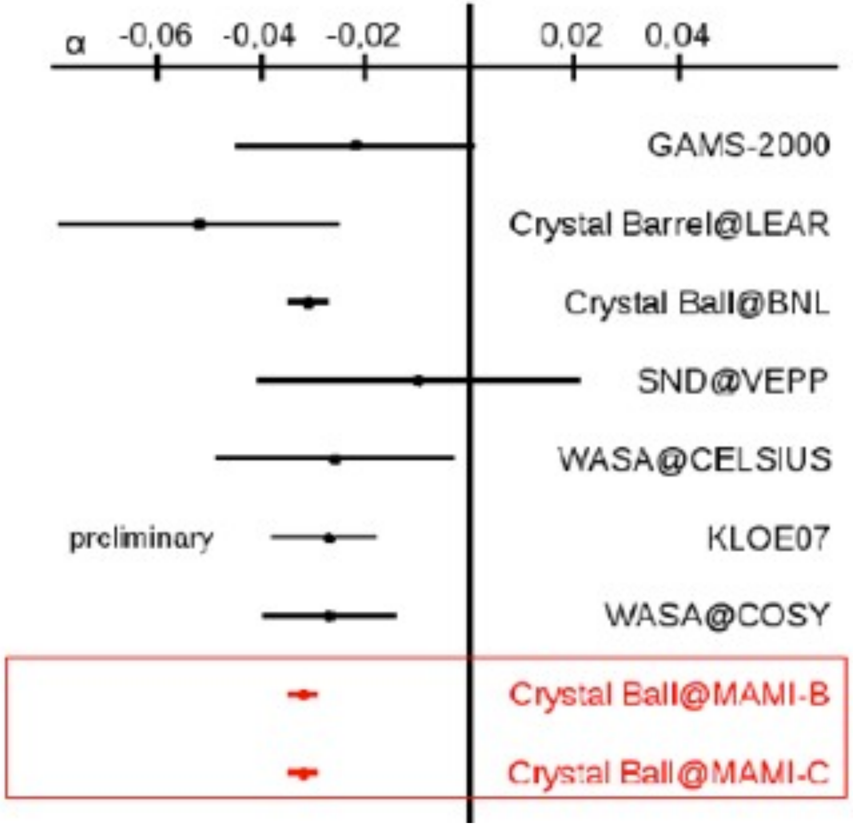
Crystal Ball Detector:

SLAC → DESY → BNL → Mainz

Hermetic self-triggering spectrometer

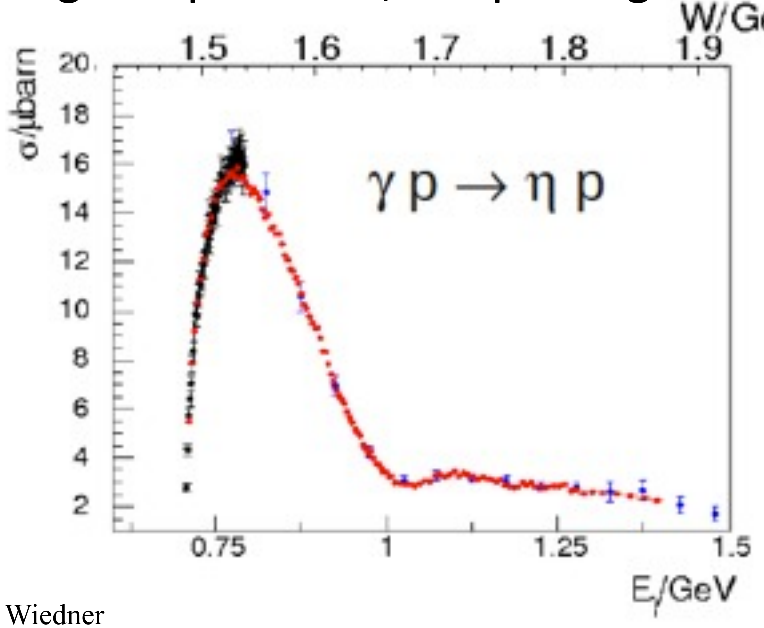
Meson decays:

e.g. slope parameter α in $\eta \rightarrow 3\pi^0$



Meson photo production:

Highest precision, all spin degrees of freedom



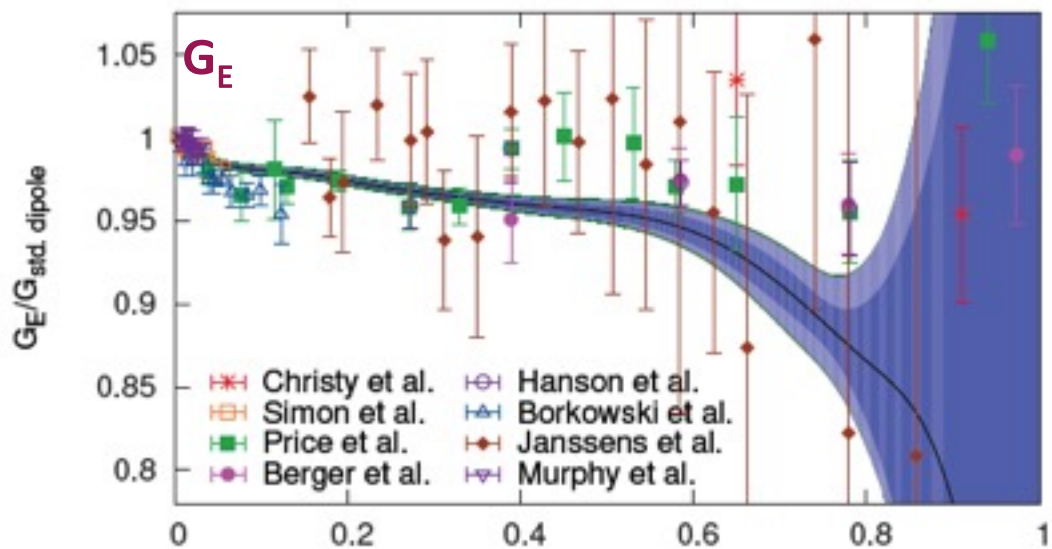
Highlight A1: Proton Radius Puzzle

Form Factor for elastic ep scattering:

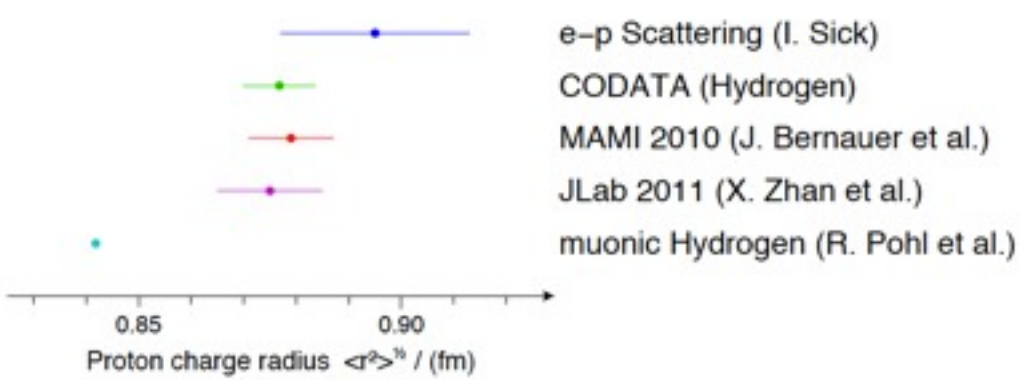
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{\varepsilon(1+\tau)} \left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]$$

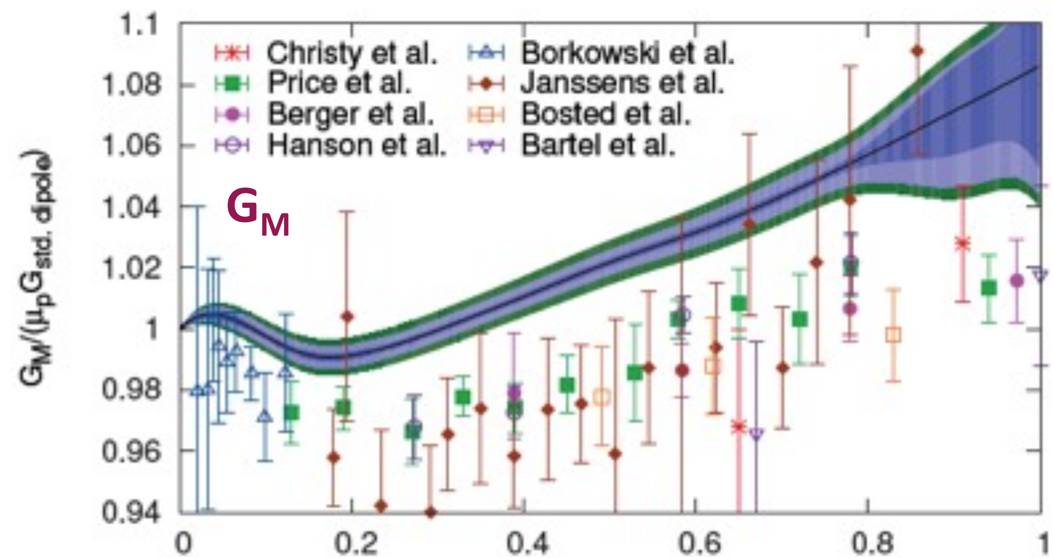
$$\left\langle r^2_{E/M} \right\rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \frac{\mathrm{d}G_{E/M}(Q^2)}{\mathrm{d}Q^2}\bigg|_{Q^2=0}$$

MAMI: $\langle r_E \rangle = 0{,}879(8)$ fm



Proton radius puzzle:
Recent PSI measurement of muonic hydrogen in conflict with ep scattering results :





ANDREW PICKERING

Constructing QUARKS

A Sociological History of Particle Physics

45 Two further developments connected with the CERN antiproton project can be noted here. These concern alternative uses of the cooled antiproton beam. Although the beam was designed to feed the SPS, it could be and was used to fill the ISR. The beam was ready before modifications to the SPS were complete, and the first CERN $p\bar{p}$ observations were made at the ISR (see Schopper 1981b, 14, and note 12 above). Also, the advent of a cooled antiproton beam revived interest in low-energy antiproton physics at CERN. From 1977 onwards plans were laid for the construction of LEAR (the Low-Energy Antiproton Ring). LEAR was intended to take cooled antiprotons and make them available as beams for fixed-target experiments at energies between 0.1 and 2 GeV. In general, LEAR experiments promised to increase the quality of data on low-energy antiproton interactions enormously: its beams would be at least a thousand times more intense than conventional antiproton beams and of extremely well defined momentum, making possible extremely accurate measurements. Possible uses for LEAR included topics in nuclear and atomic physics. The principal HEP interest in LEAR centred upon baryonium searches and precision measurements on charmonium states. More conventional attributes of $p\bar{p}$ interactions could also be studied.

LEAR was intended to enter operation in 1983; for its history, details of its construction and the experimental programme envisaged, see Gastaldi and Klapisch (1981) and Jacob (1980).

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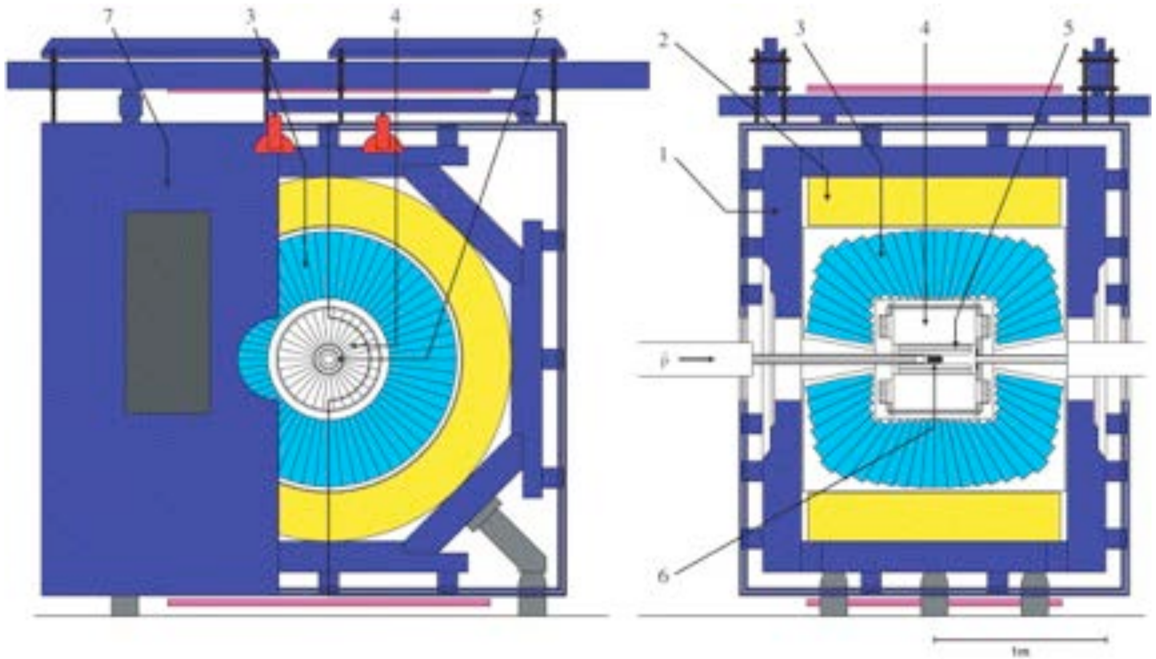
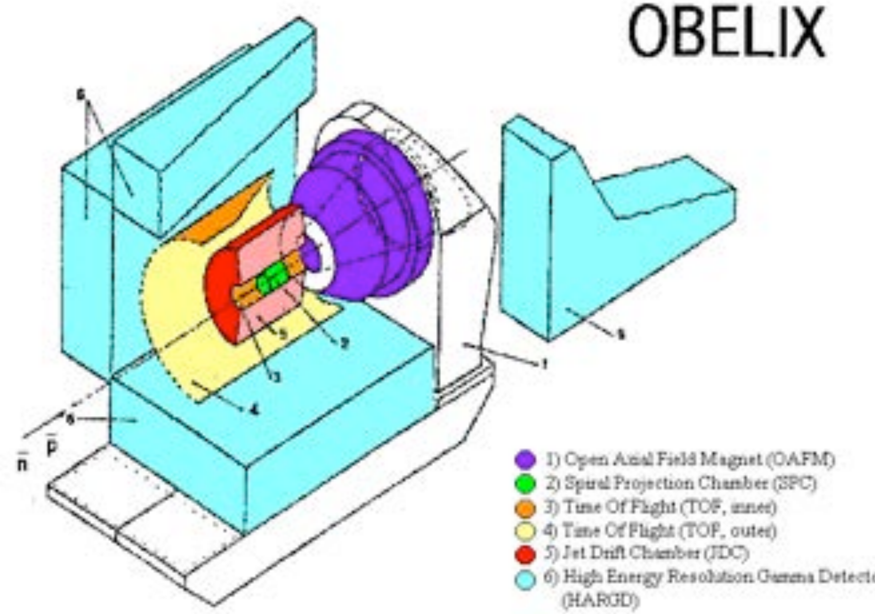
New, high resolution 4π detectors

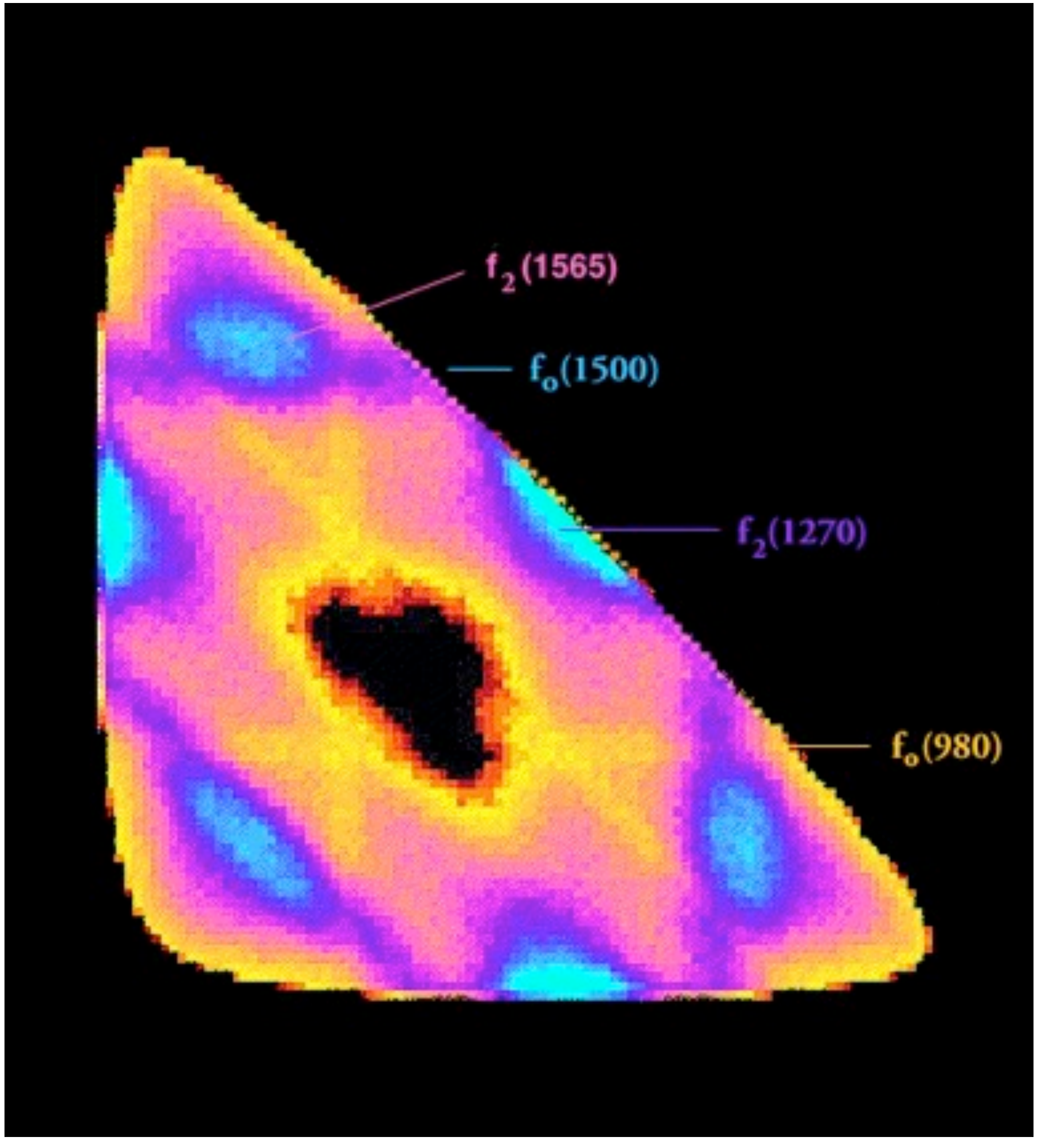


Crystal Barrel

OBELIX

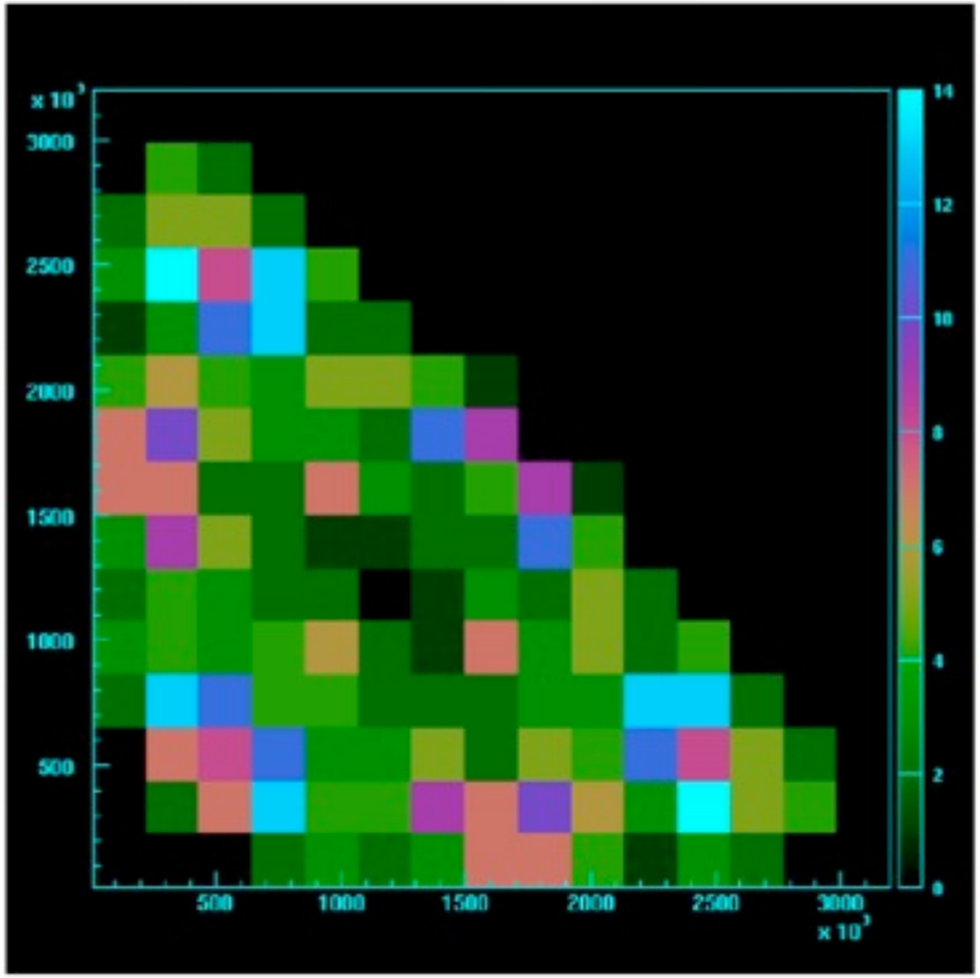


$p\bar{p} \rightarrow \pi^0\pi^0\pi^0$ Dalitz plot



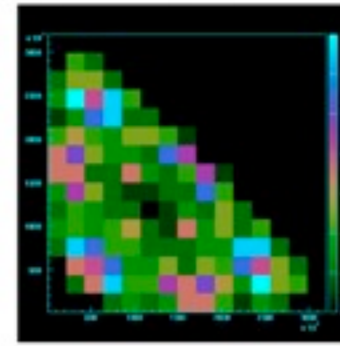
700000 events = 6×700000 entries

100 events

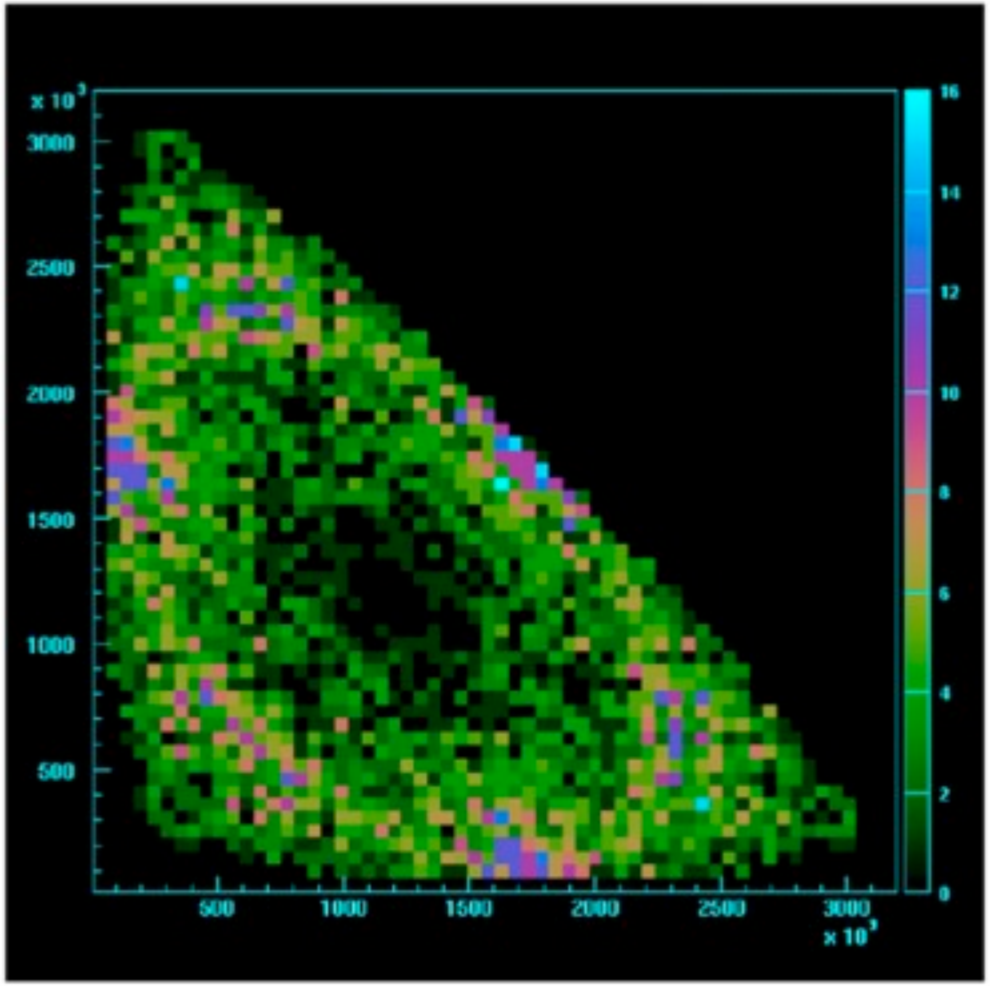


x 10³
3000
2500
2000
1500
1000
500
500
1000
1500
2000
2500
3000
x 10³
14
12
10
8
6
4
2
0

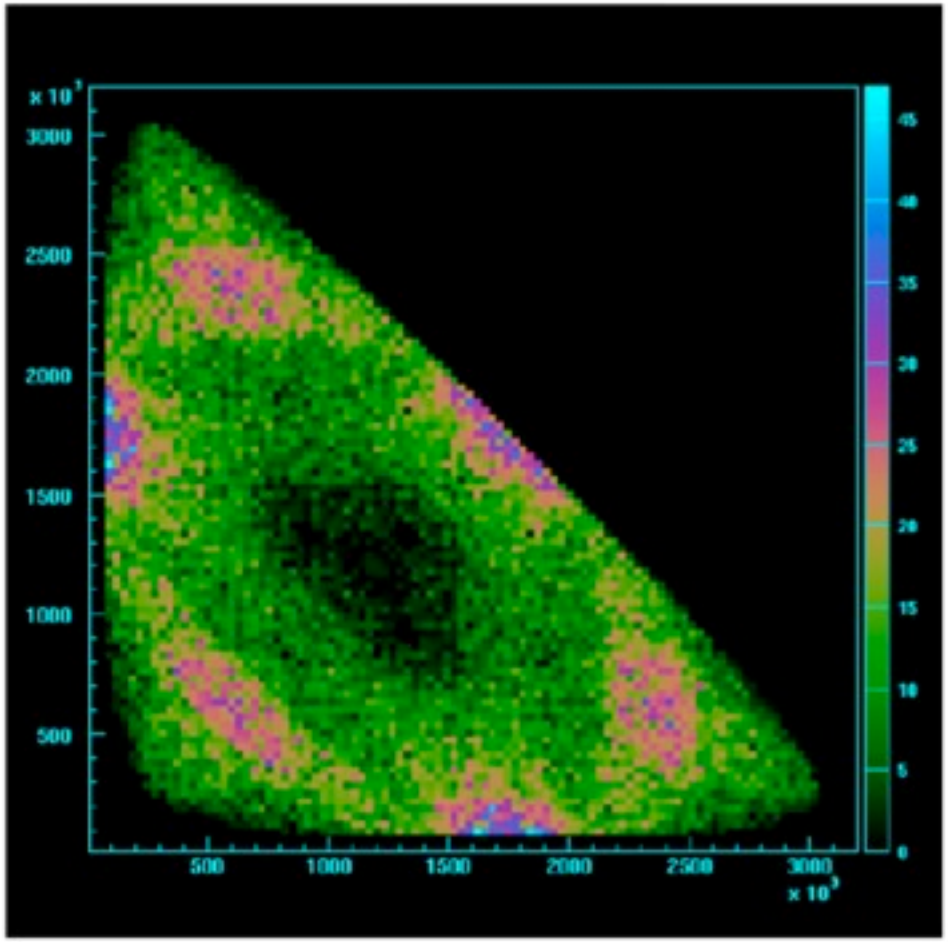
100 events



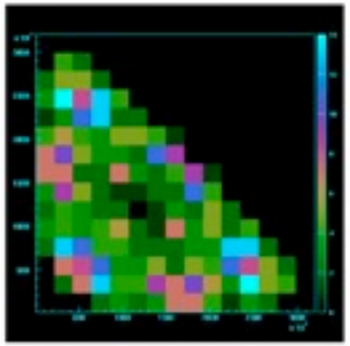
1000 events



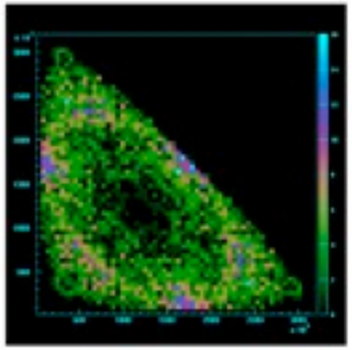
10,000 events



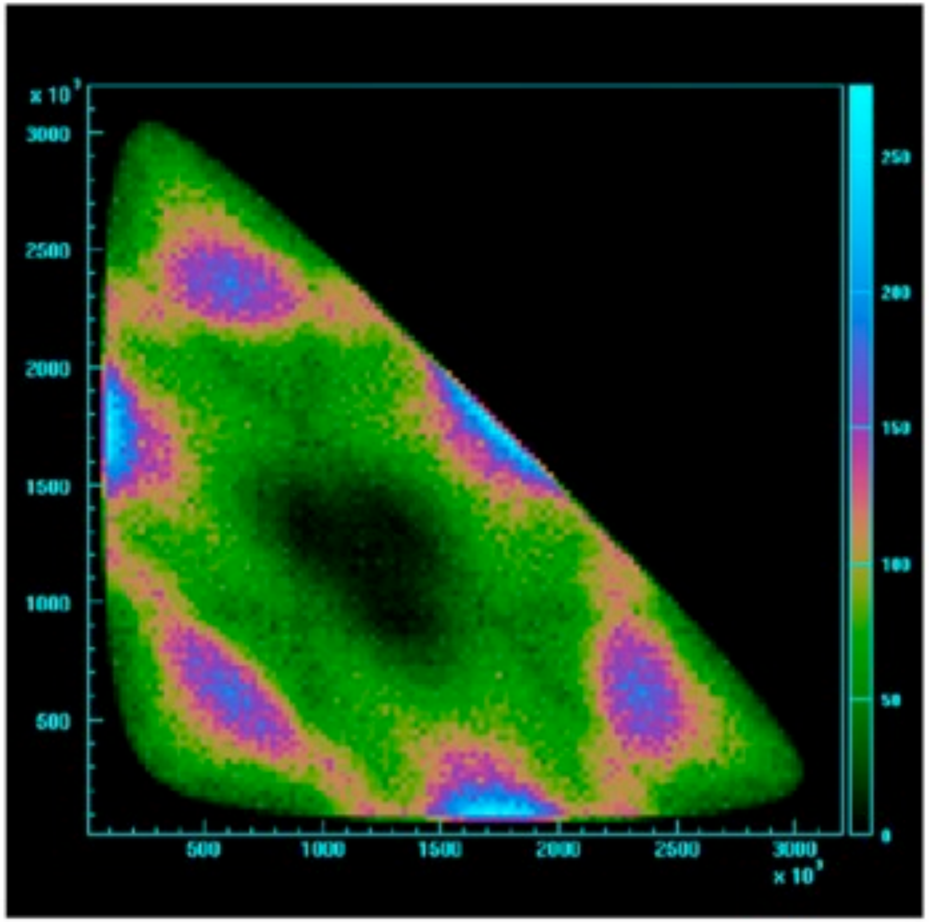
100 events



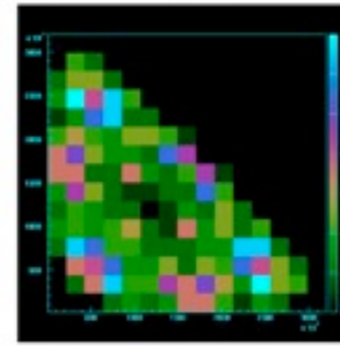
1000 events



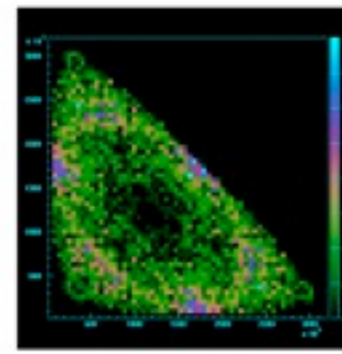
100,000 events



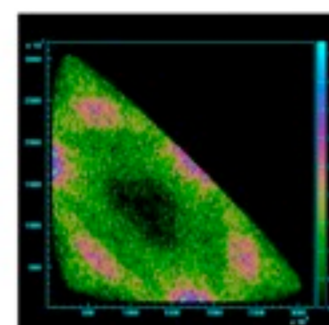
100 events



1000 events

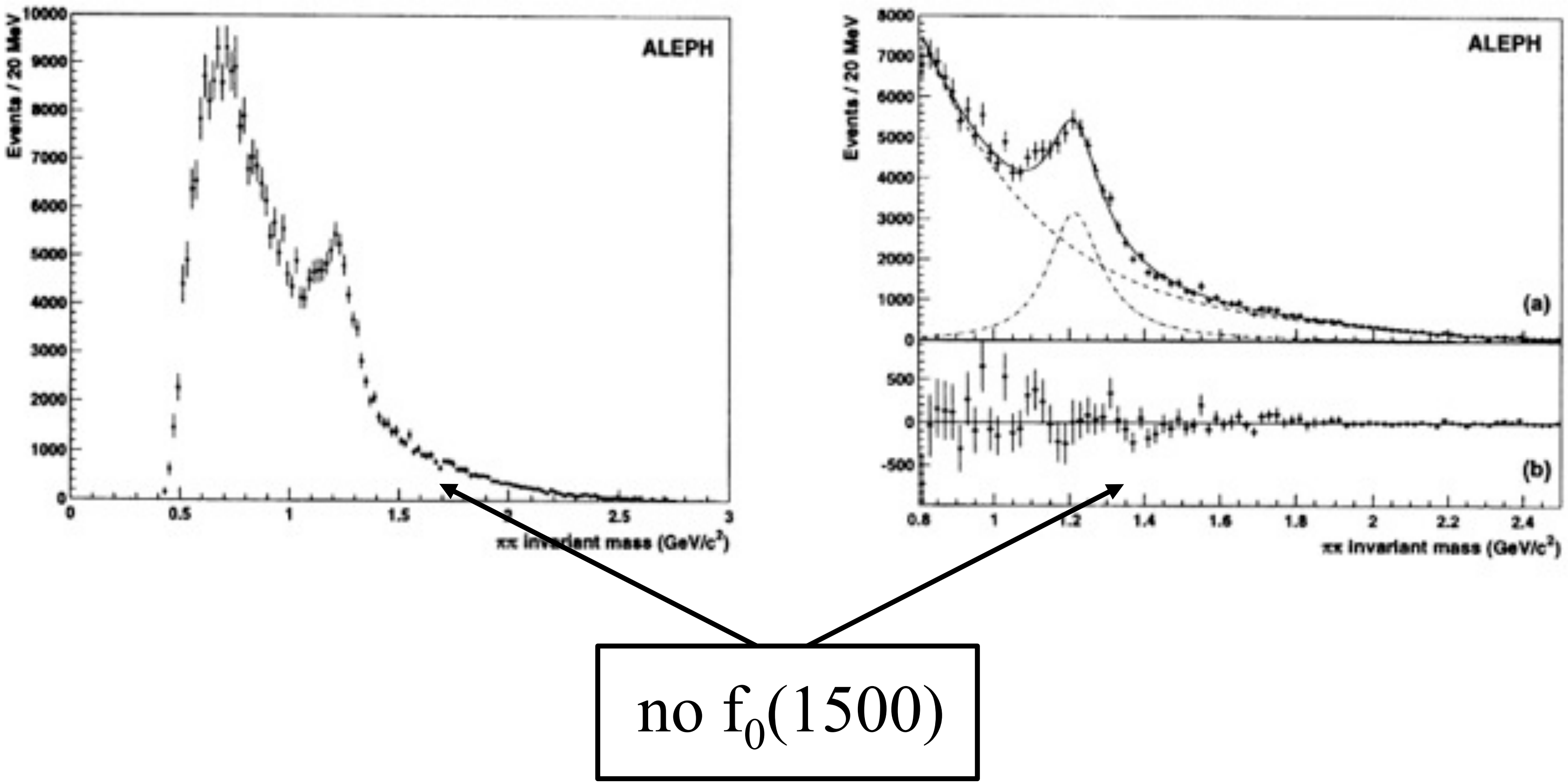


10,000 events



γγ collisions from ALEPH

(anti-glueball filter)

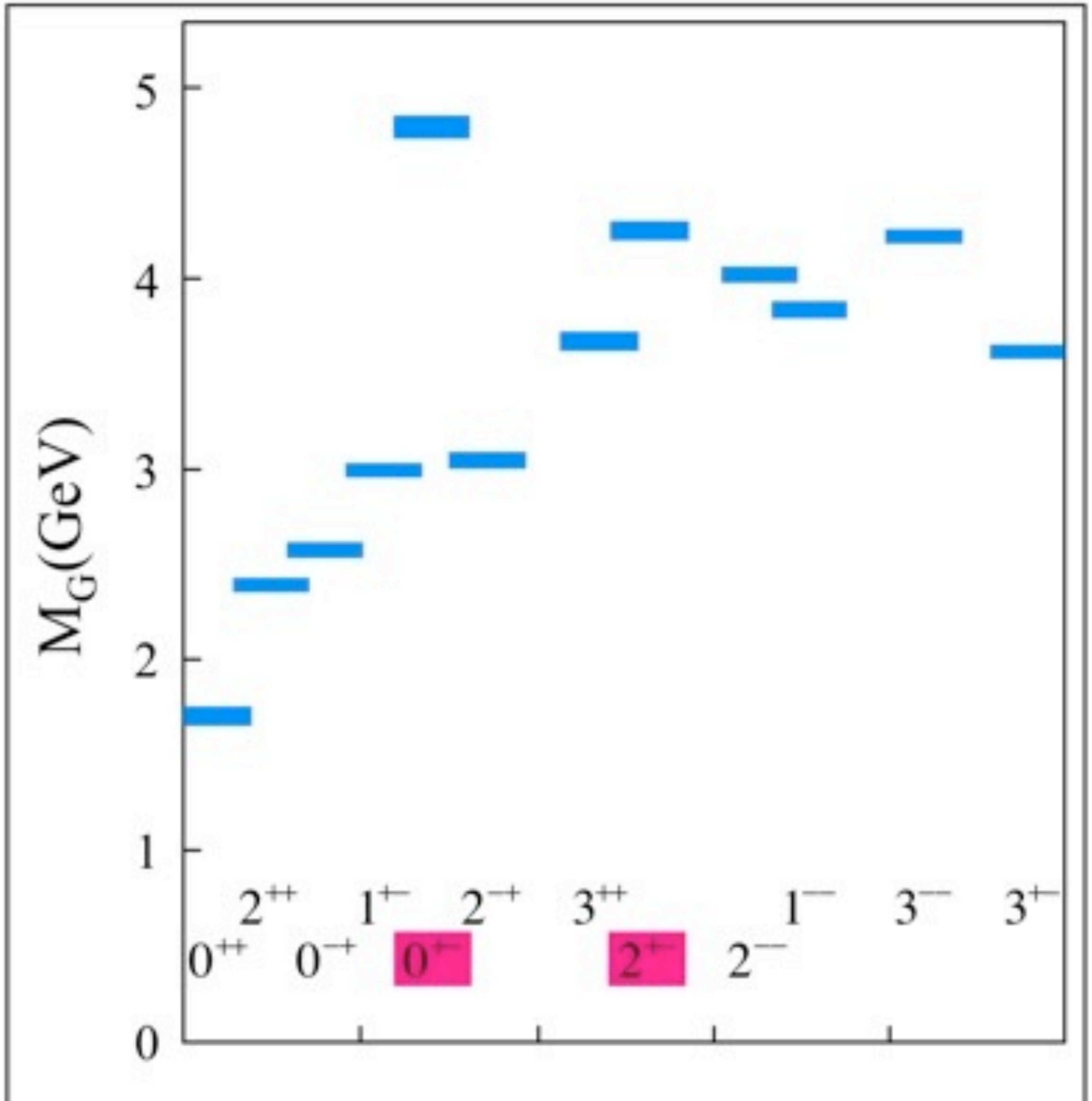


upper limit:

$$\Gamma(\gamma\gamma \to f_0(1500) \bullet BR(f_0(1500) \to \pi^+\pi^-) < 0.31 \text{ keV}$$

Phys. Lett. B472 (2000) 189.

The glueball spectrum



Glueballs → Creation of Mass

A few % of a hadron (proton) mass is generated due to the **Higgs mechanism**.

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

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

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 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 $AdS_5 \times S^5$

taken from Johanna Erdmenger (MPI Physik München)

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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
University of California, Berkeley, CA 94720
and
Department of Physics
University of California, Berkeley, CA 94720

…

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

…

Hadron physics is the place on earth to study non-Abelian massless gauge boson - gauge boson interaction in a controlled manner.

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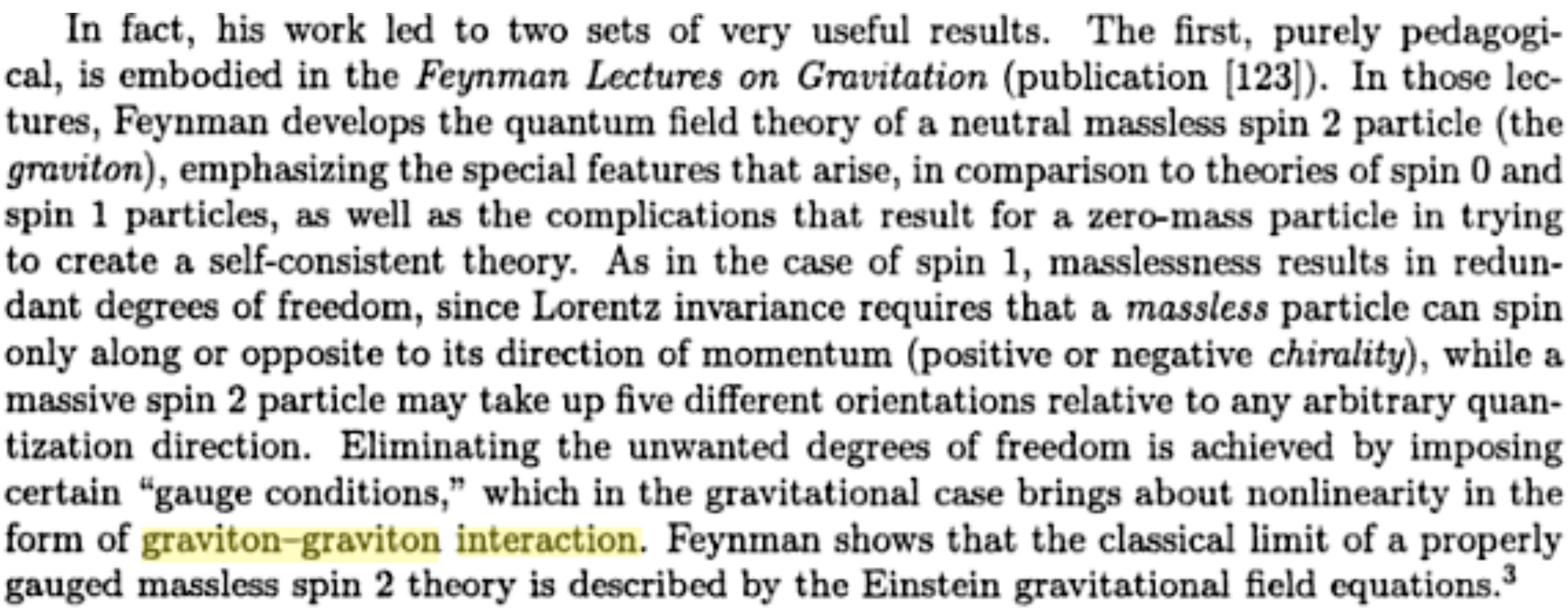
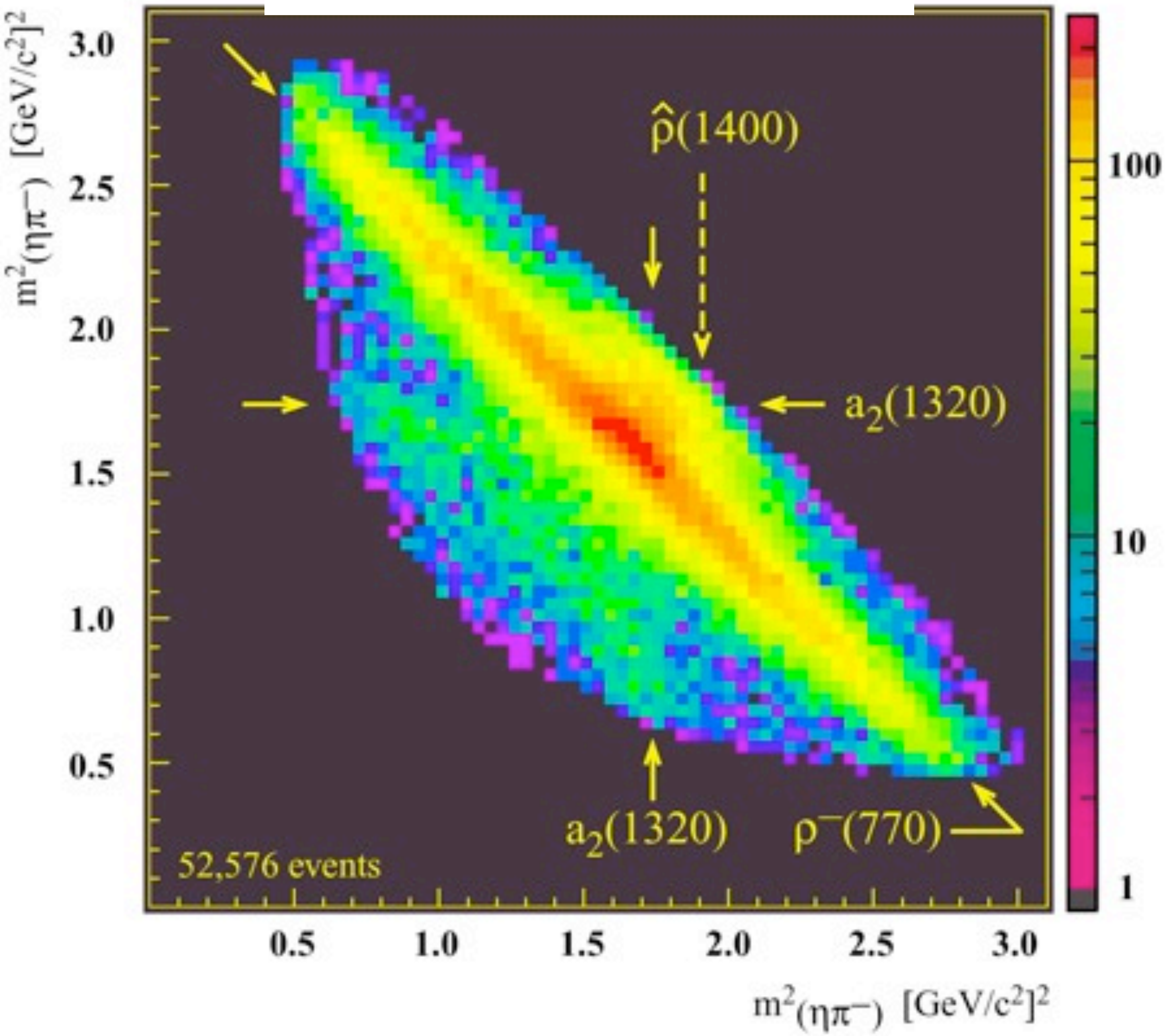
Feynman lectures on gravitation:


In fact, his work led to two sets of very useful results. The first, purely pedagogical, is embodied in the *Feynman Lectures on Gravitation* (publication [123]). In those lectures, Feynman develops the quantum field theory of a neutral massless spin 2 particle (the *graviton*), emphasizing the special features that arise, in comparison to theories of spin 0 and spin 1 particles, as well as the complications that result for a zero-mass particle in trying to create a self-consistent theory. As in the case of spin 1, masslessness results in redundant degrees of freedom, since Lorentz invariance requires that a *massless* particle can spin only along or opposite to its direction of momentum (positive or negative *chirality*), while a massive spin 2 particle may take up five different orientations relative to any arbitrary quantization direction. Eliminating the unwanted degrees of freedom is achieved by imposing certain "gauge conditions," which in the gravitational case brings about nonlinearity in the form of graviton–graviton interaction. Feynman shows that the classical limit of a properly gauged massless spin 2 theory is described by the Einstein gravitational field equations.[3]

Crystal Barrel

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

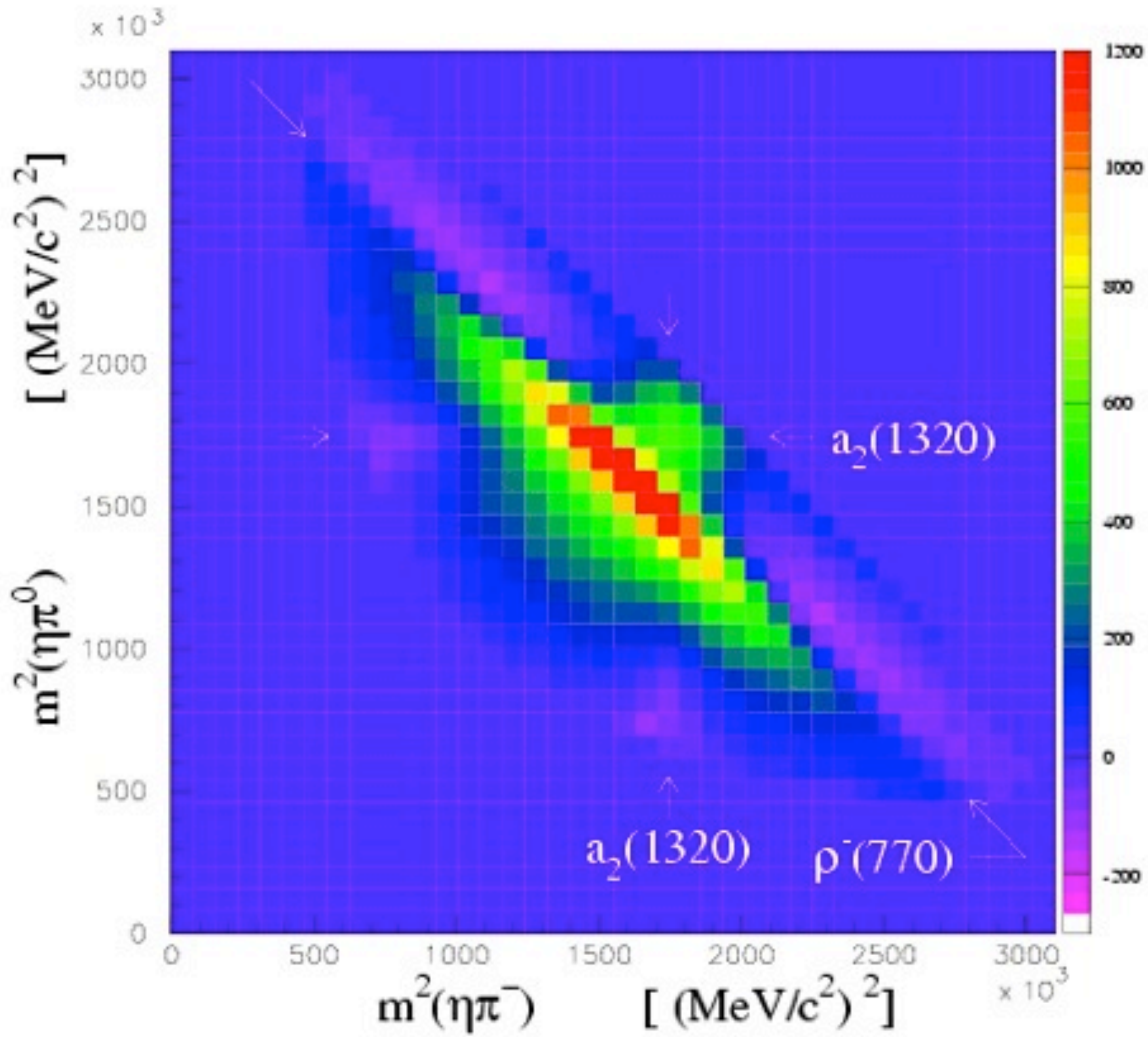
spectator (<100 MeV/c)



Crystal Barrel

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

spectator
(<100 MeV/c)



Properties of the $\pi_1(1400)$

Decay: $(\eta\pi)_{L=1}$
Mass: 1400 ± 30 MeV
Width: 310 ± 70 MeV
Quantum numbers: $J^{PC} = 1^{-+}$ → not possible from $q\bar{q}$

$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

Previous indications of this resonance:

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

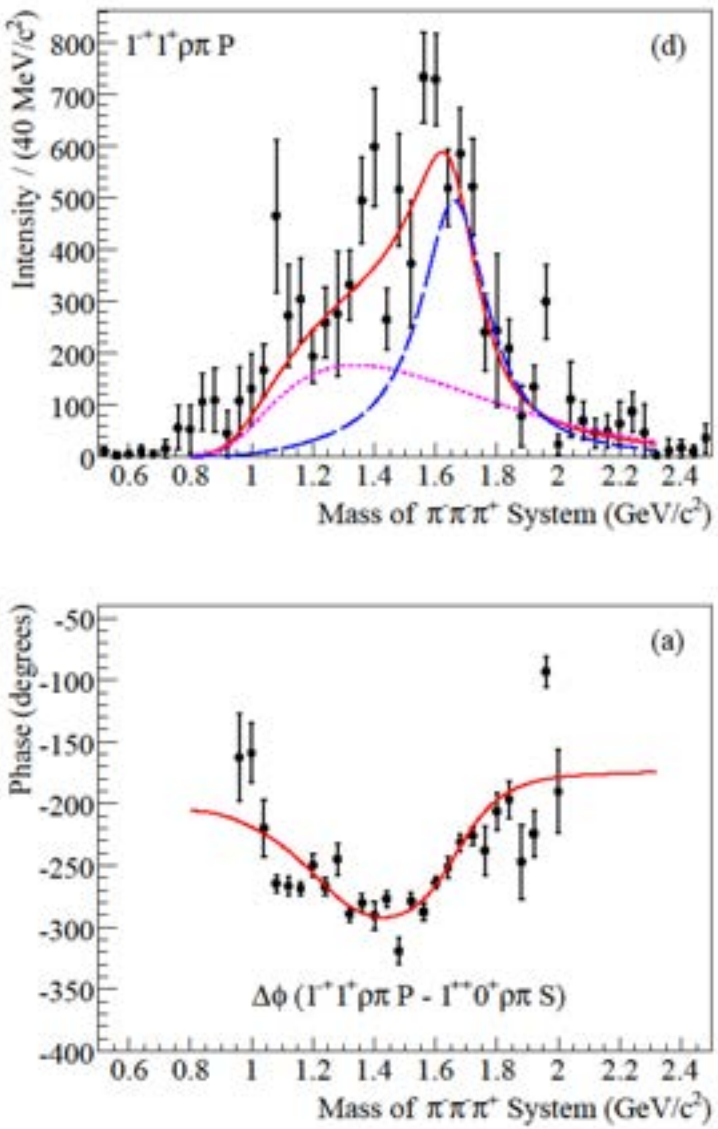
M: 1300 - 1400 MeV/c², Γ: 150 - 400 MeV

$J^{PC}=1^{-+}$ – Pb vs H Target

$\pi^- \text{Pb} \rightarrow \pi^- \pi^- \pi^+ \text{Pb}$

$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$

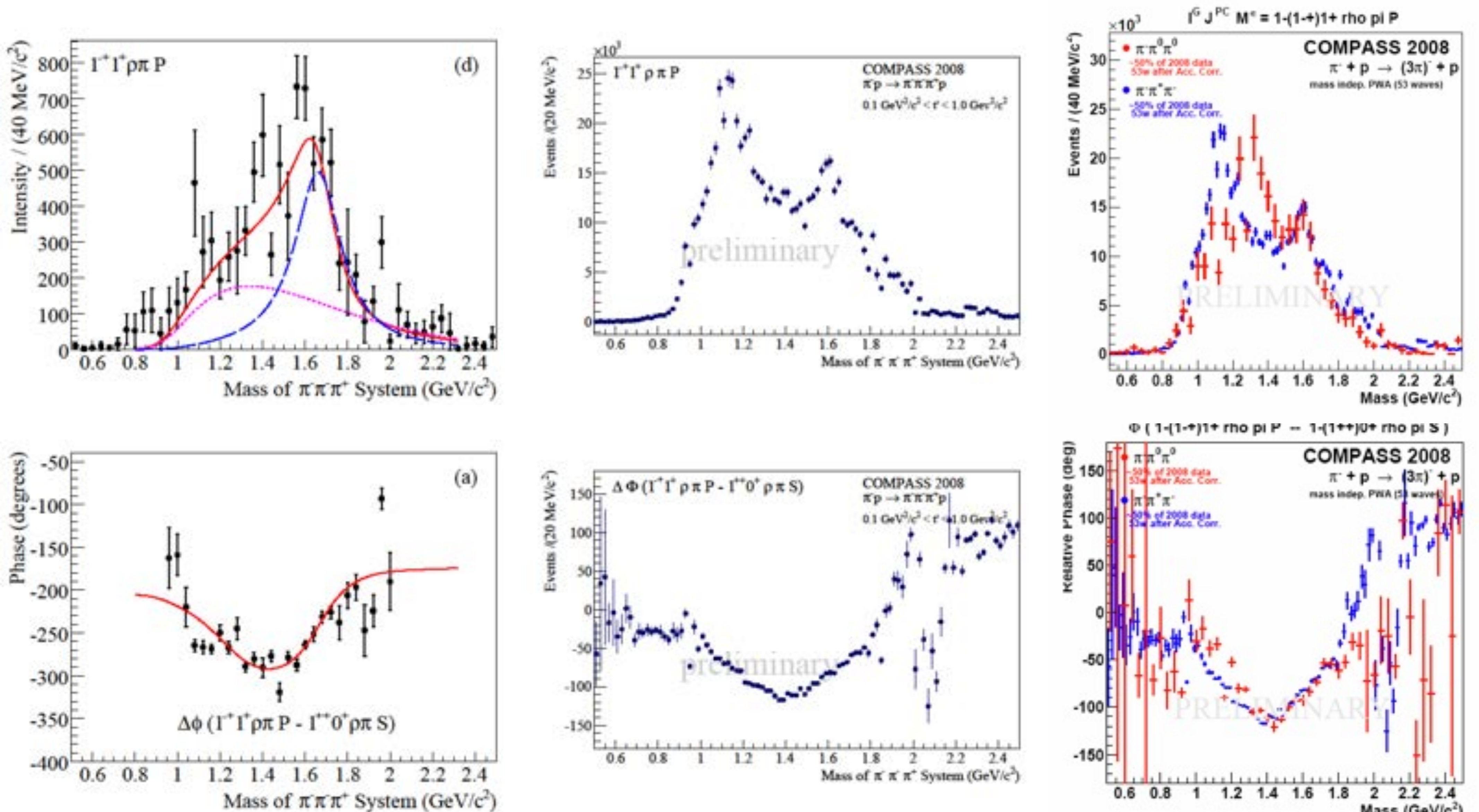
$\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$



[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]

J^{PC}=1^{-+} – Pb vs H Target

$\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$ | $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ | $\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$

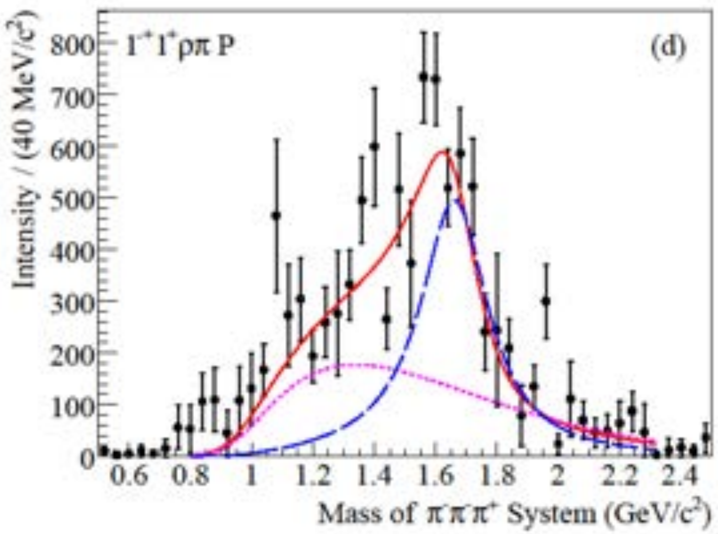


[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]

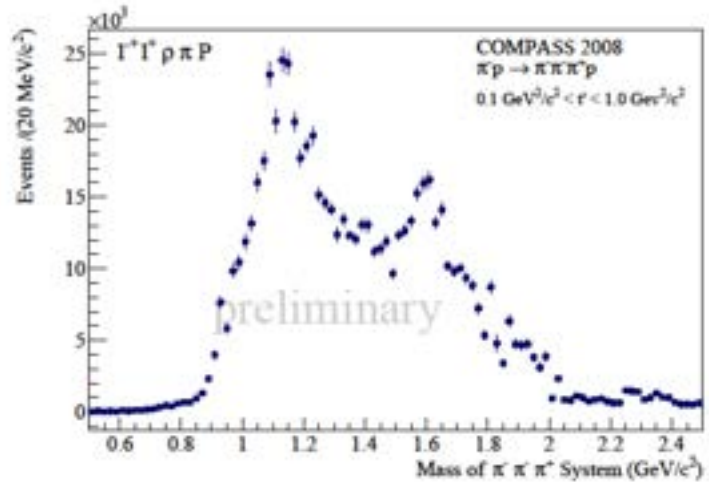
[F. Haas, arXiv:1109.1789 (2011)]

$J^{PC}=1^{-+}$ – Pb vs H Target

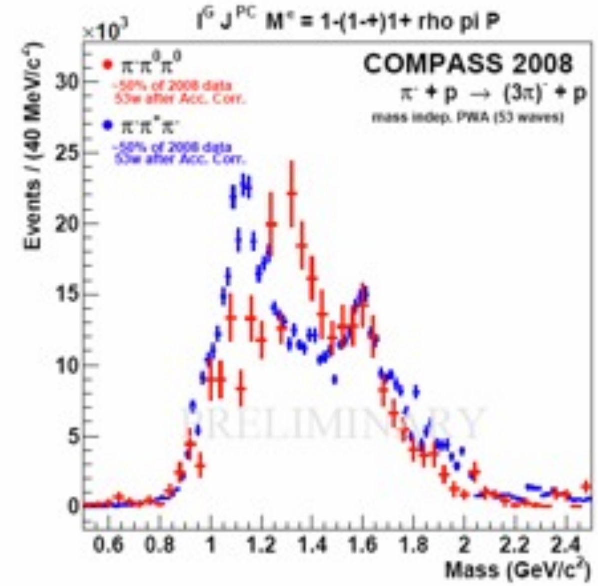
$\pi^- \mathrm{Pb} \rightarrow \pi^- \pi^- \pi^+ \mathrm{Pb}$

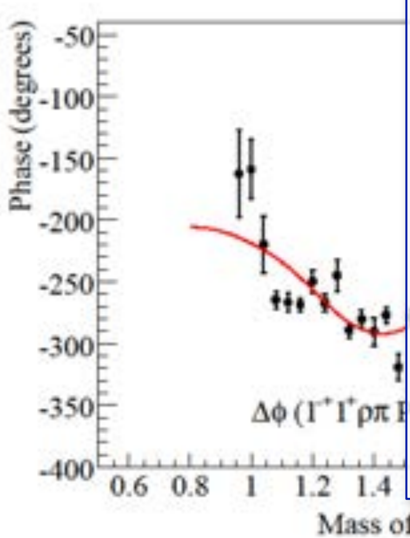


$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$

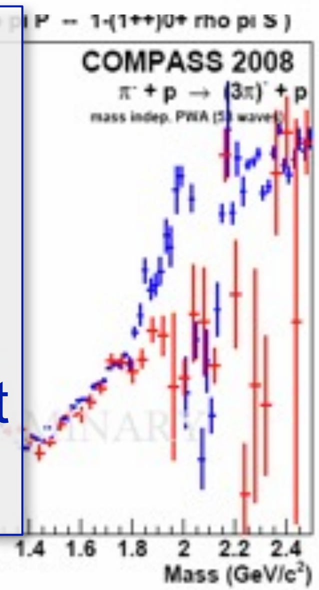


$\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$





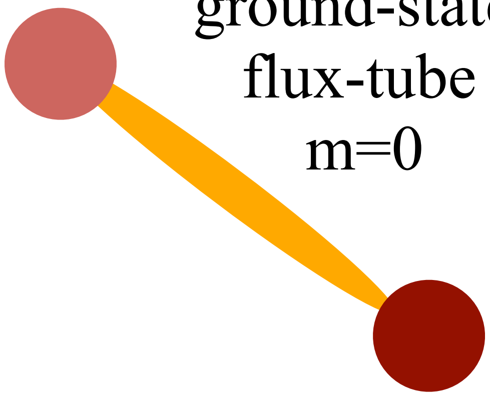
- Peak at 1.67 GeV/c² for both targets
- Phase motion indicates resonant behavior
- Structure at 1.2 GeV/c² unstable w.r.t. fit model
- No fit to spin-density matrix yet for H target
- Production of M=1 states enhanced for heavy target
- Non-resonant background to be understood



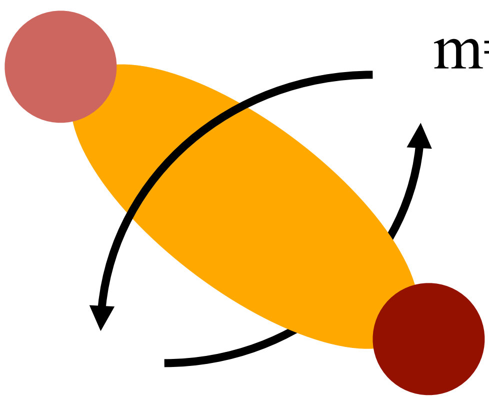
[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]

[F. Haas, arXiv:1109.1789 (2011)]

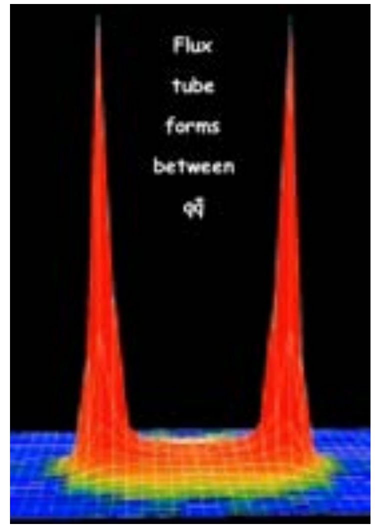
Gluonic Excitations – Hybrids at JLAB 12 GeV

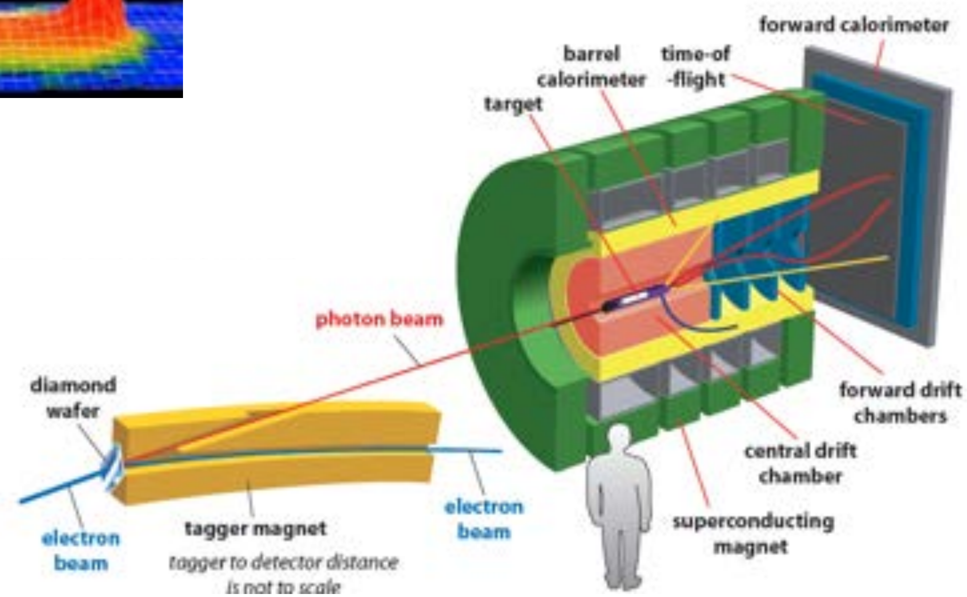


ground-state
flux-tube
m=0



excited flux-tube
m=1

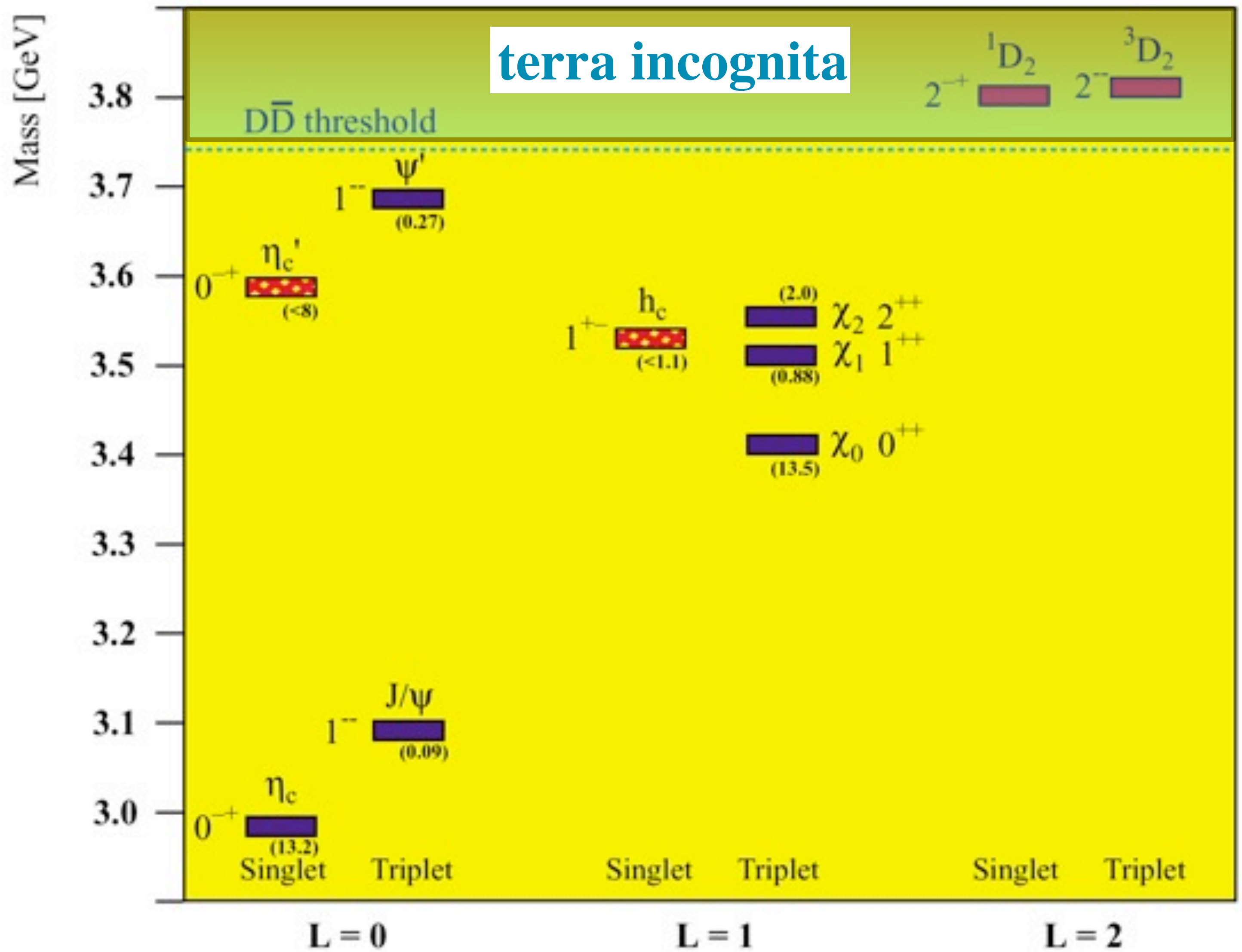




Gluonic Excitations provide an experimental measurement of the excited QCD potential.

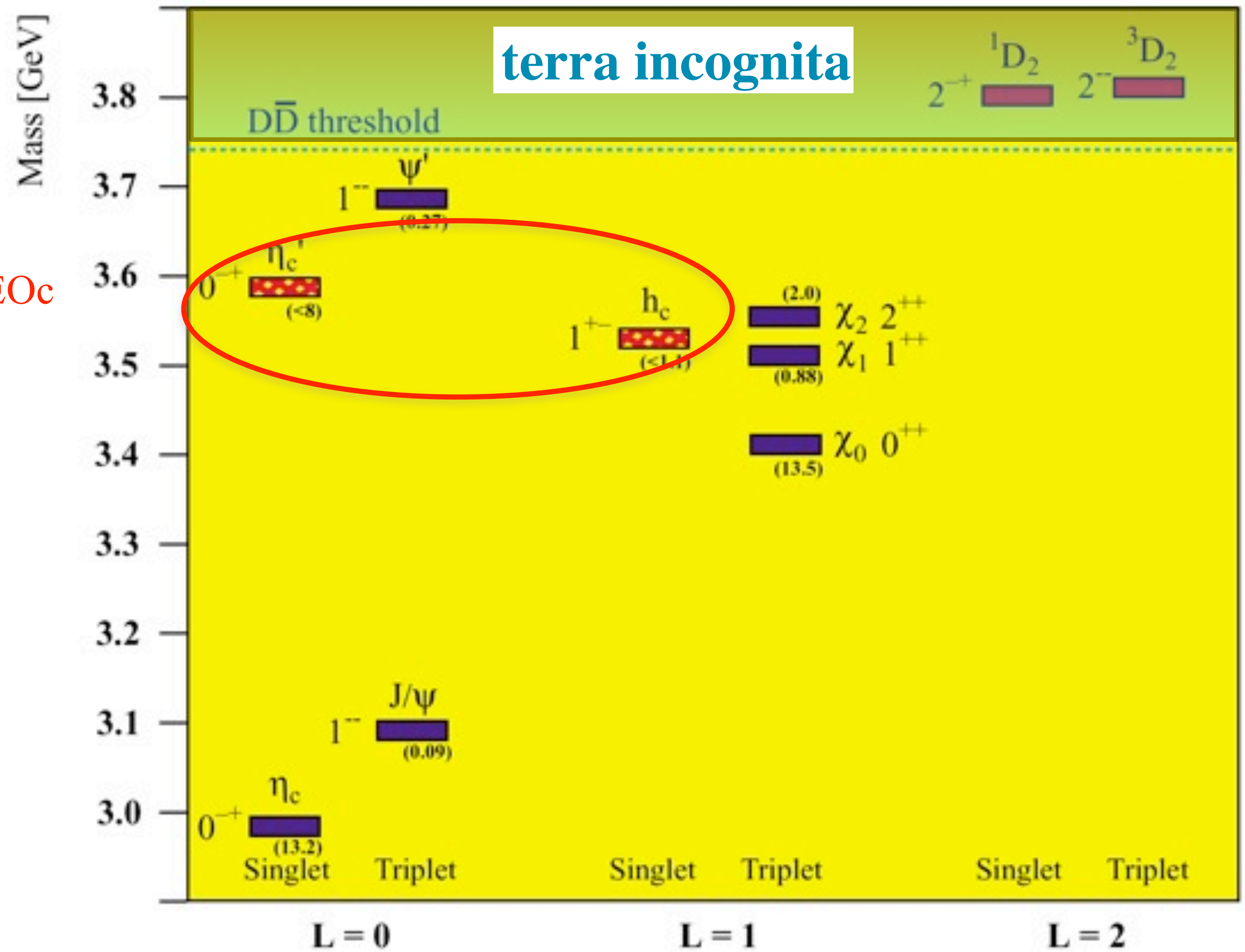
... at Hall D

The charmonium spectrum

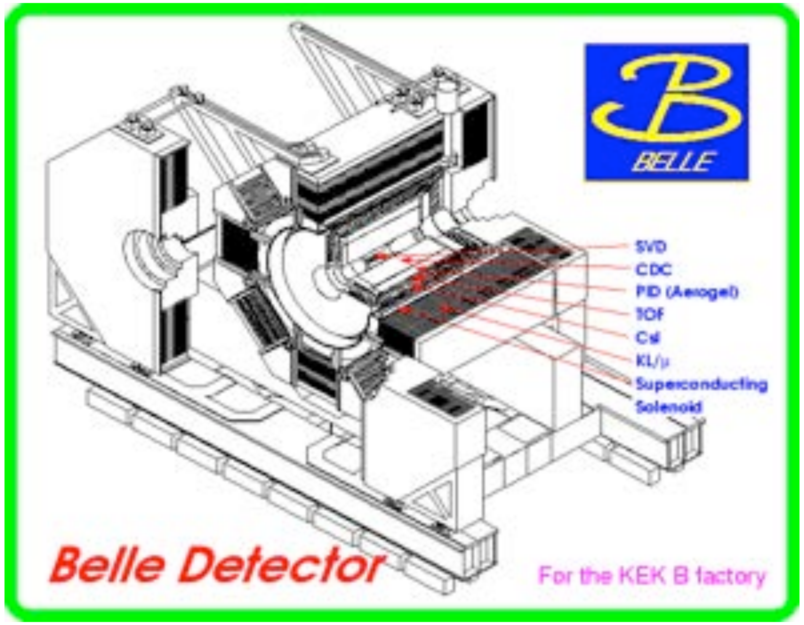


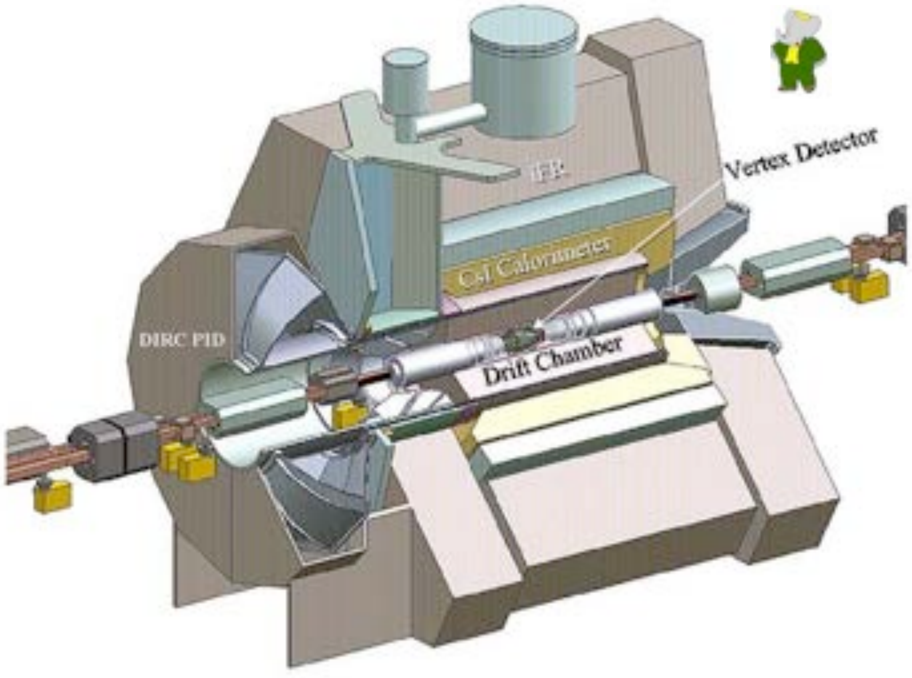
The charmonium spectrum

E835/CLEOc



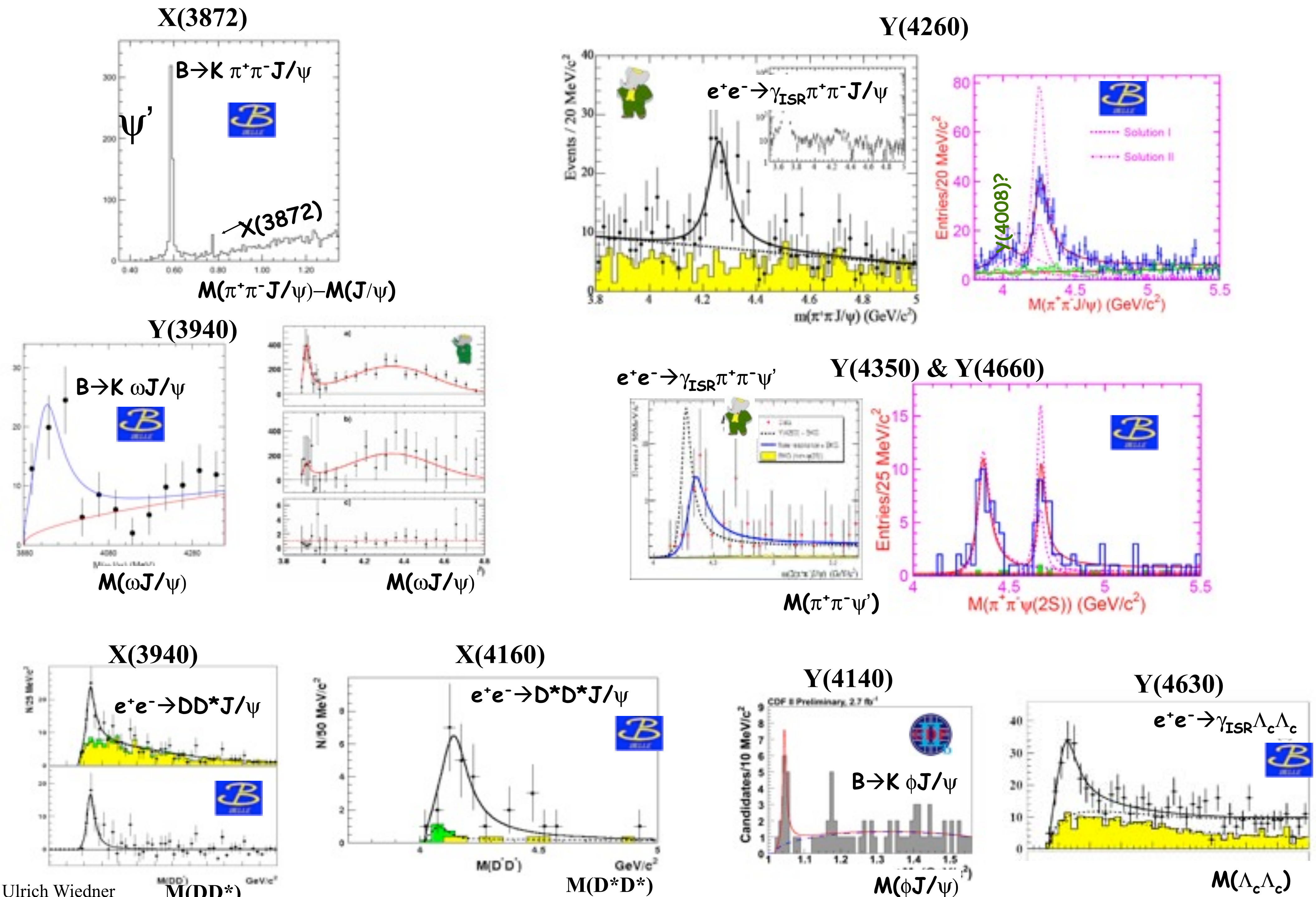
Detectors at B-factories





BaBar detector

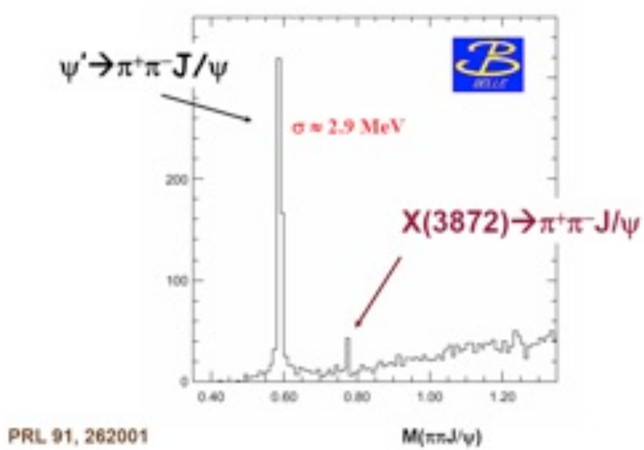
X and Y mesons

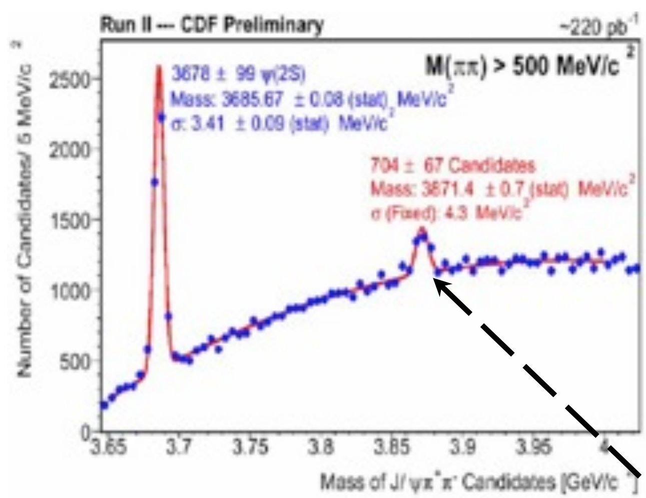


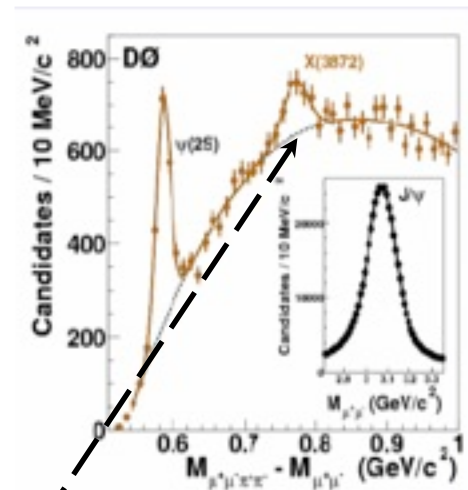
X(3872)

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

$J^{PC} = 1^{++}$ (or 2^{-+})
M = 3871.68 ± 0.17 MeV
Γ < 1.2 MeV
> 10 σ





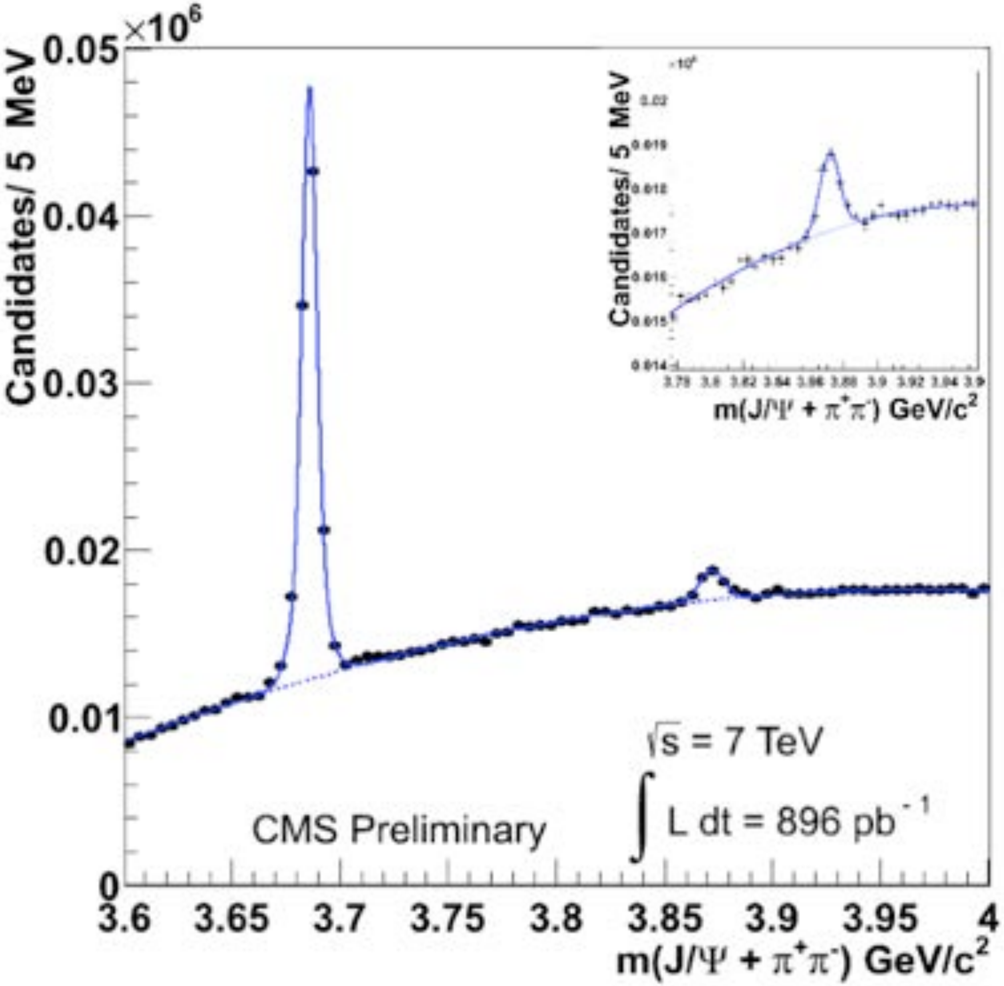


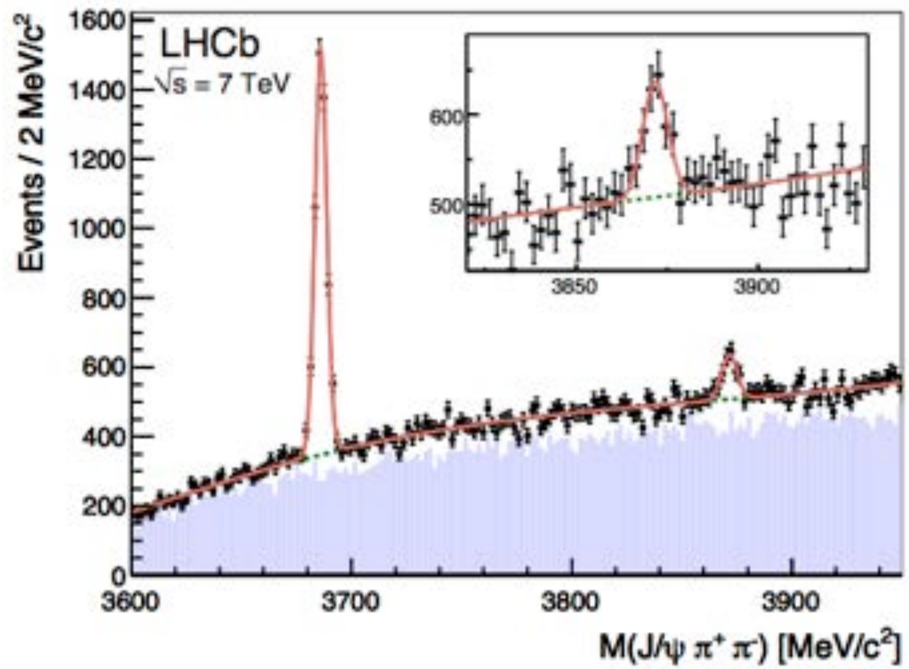
X(3872)

?

DD* molecule
threshold effect
tetraquark

CMS: PoS EPS-HEP2011 (2011) 177

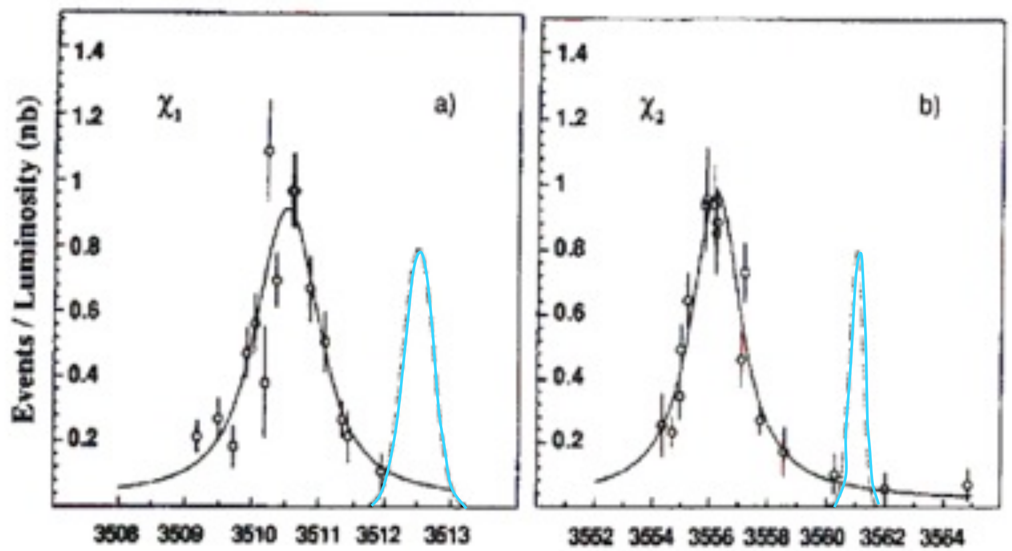




EPJC 72, 1972 (2012)

The formation of resonances (ALL non-exotic q.n.) in antiproton annihilations allows precision studies

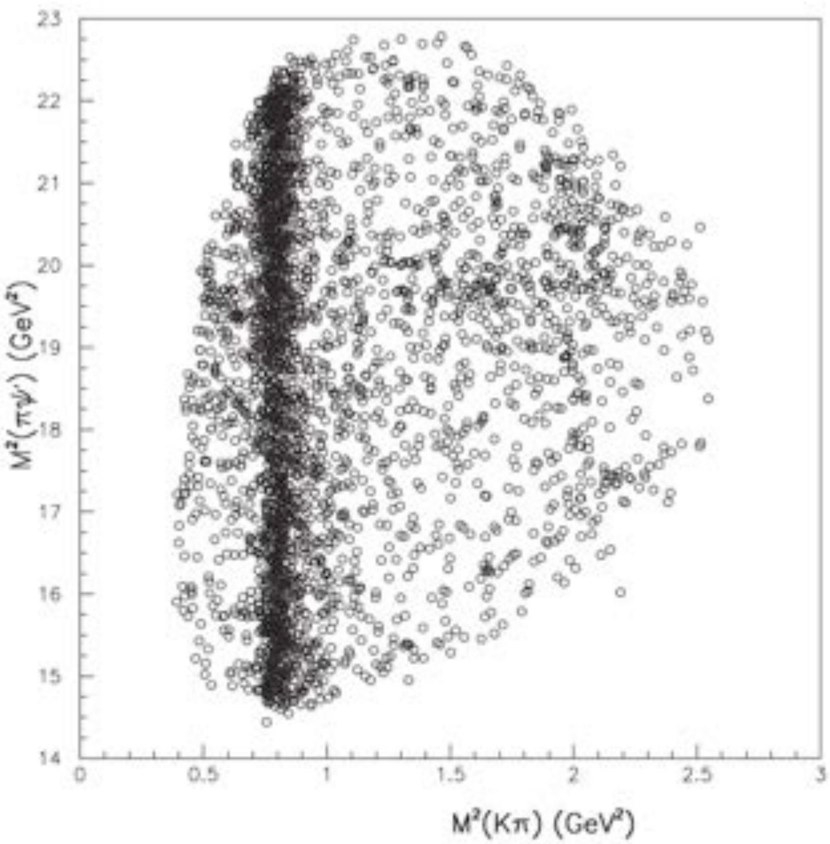
E 760 (Fermilab)

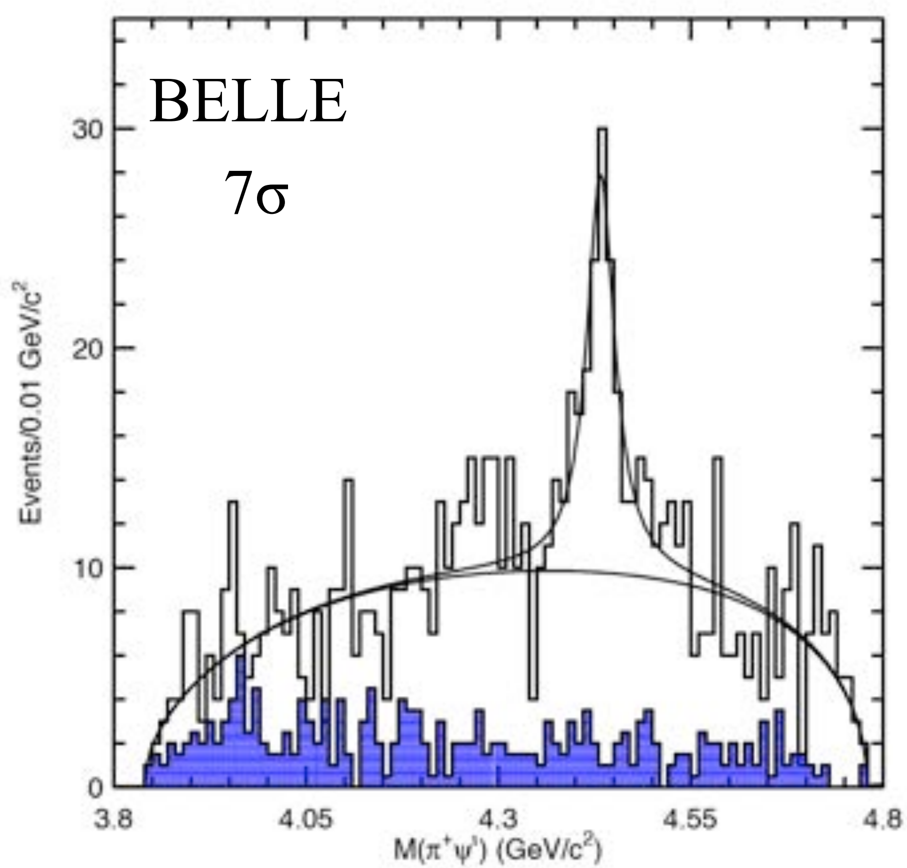


σ_m (beam) = 0.5 MeV

→ Future antiproton beams with HESR @ FAIR + PANDA

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





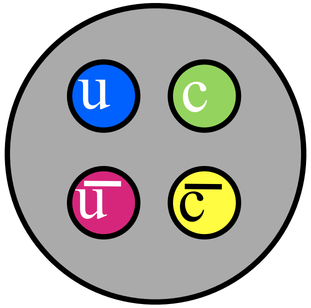
$$M = (4.433 \pm 0.004\ (\text{stat}) \pm 0.001\ (\text{syst}))\ \text{GeV}$$

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

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

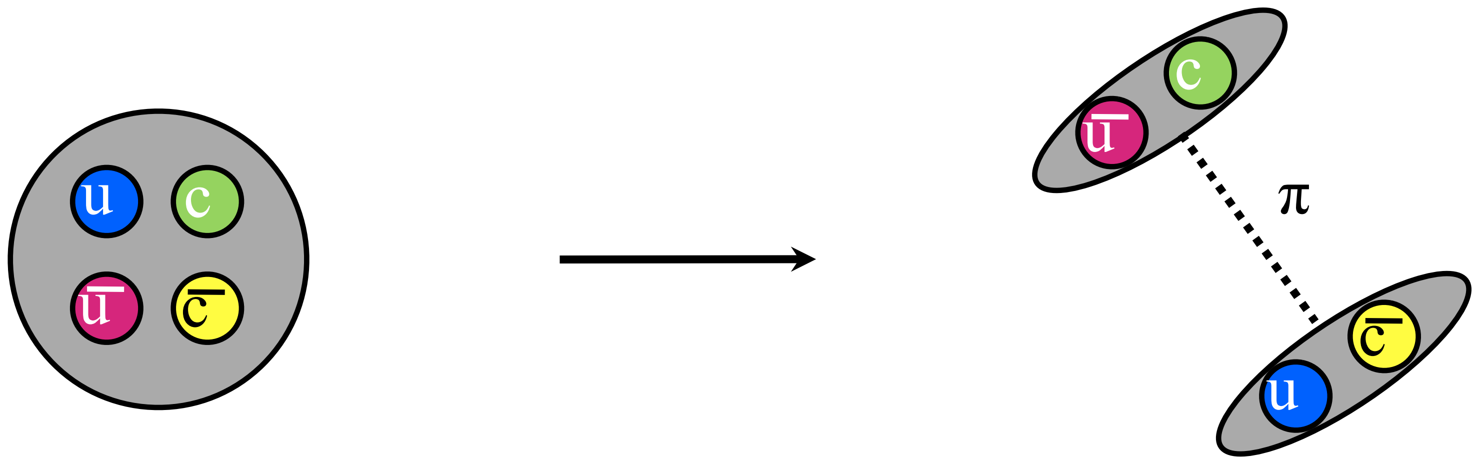
PRL 100, 142001 (2008)
arXiv:0708.1790 [hep-ex]

4-quark state



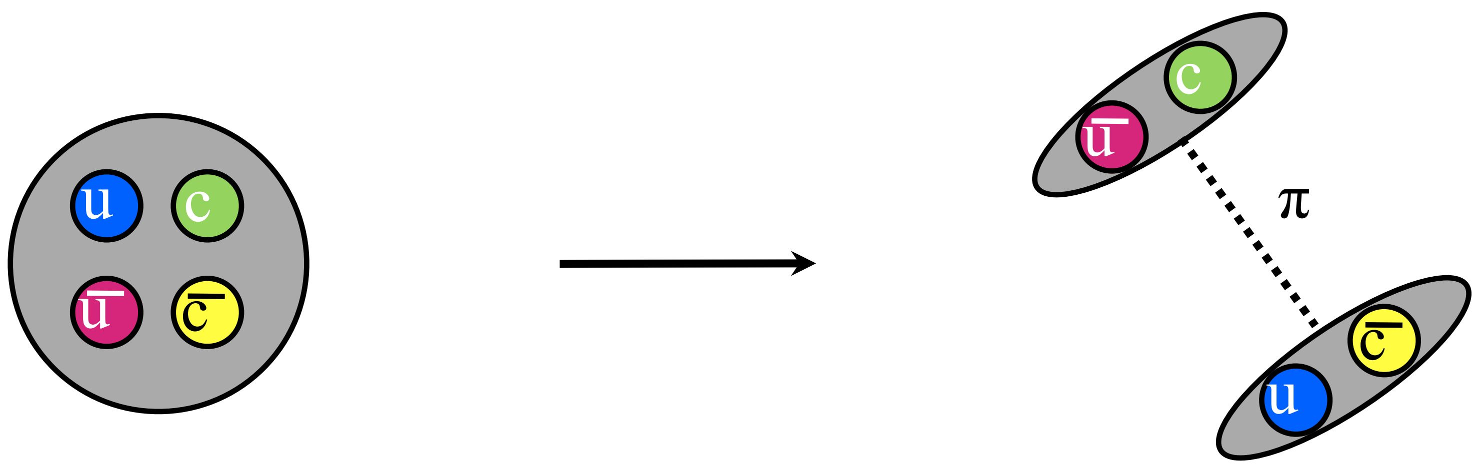
4-quark state

D-$\bar{\text{D}}$-“molecule”



4-quark state

D-$\bar{D}$-“molecule”



Transition from color forces to colourless nuclear forces ?

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

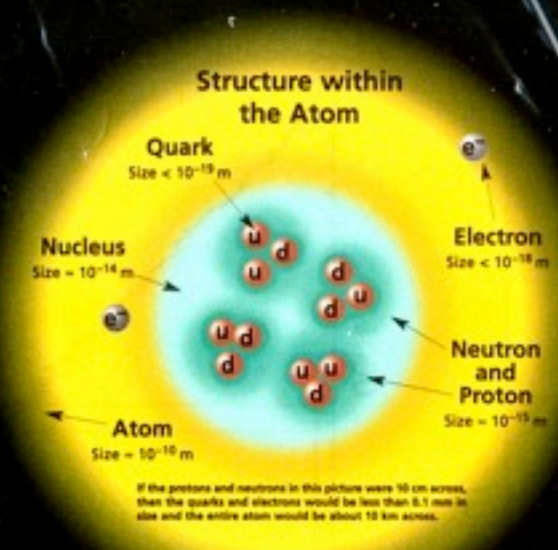
Quarks spin = 1/2

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.



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.

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

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	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

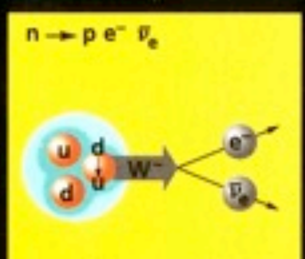
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter

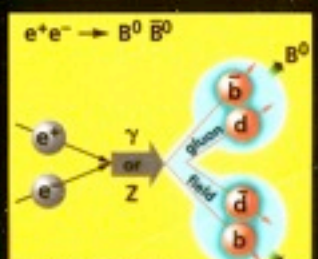
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not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

Figures

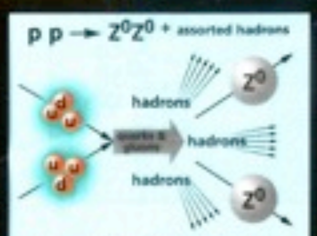
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



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:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

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	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

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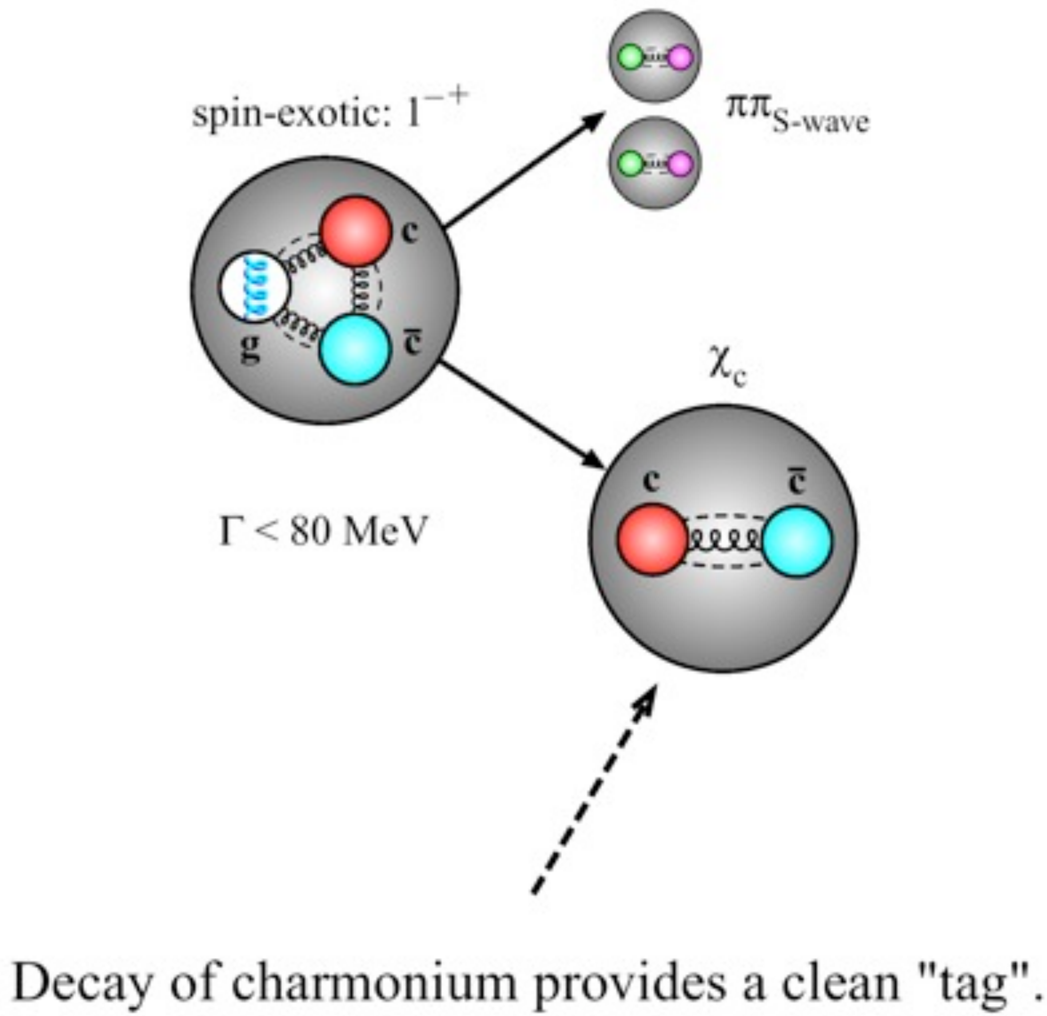
Decay of charmonium hybrids

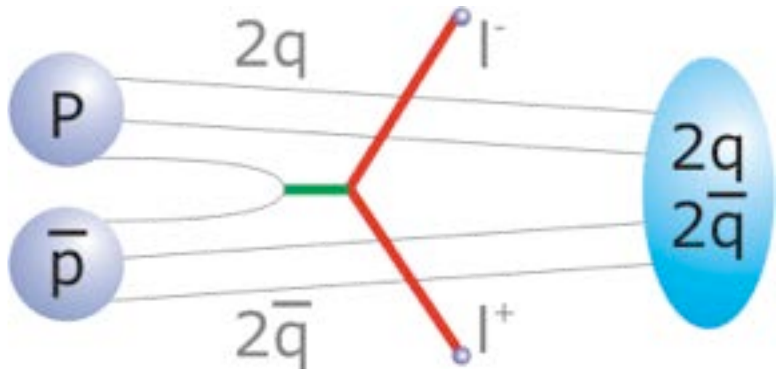
Lattice results*



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

Proton-Antiproton contains already a 4-Quark-System

Idea: Dilepton-Tag from Drell-Yan-Production



Bannikov, Gornuschkin, Kopeliovich, Krumshtein and Sapozhnikov, JINR E1-92-344 (1992)

Advantages

- Trigger
- less J^{PC}-Ambiguities
- 1200 E./day @ 12 GeV
- 300 E./day @ 5-8 GeV
  antiproton-Beam
  (for $L=10^{32}cm^{-2}s^{-1}$)

Exotics

Exotics

What we know:

Exotics

What we know:

$\pi_1(1400)$

Mass: 1400 ± 30 MeV
Width: 310 ± 70 MeV
Decay: $(\eta\pi)_{L=1}$
$J^{PC} = 1^{-+}$

A. Abele et al.,
Phys. Lett. B 423 (1998) 175.

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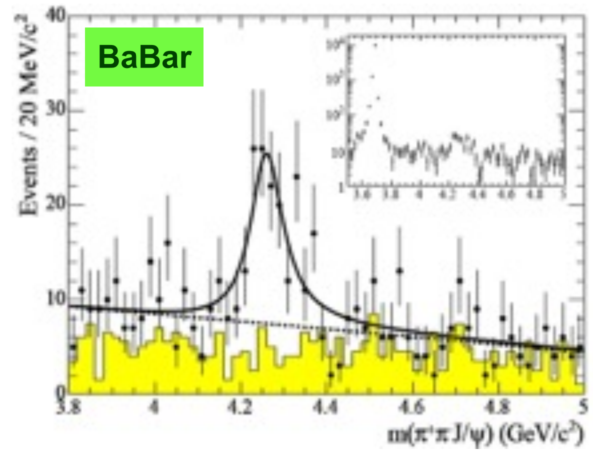

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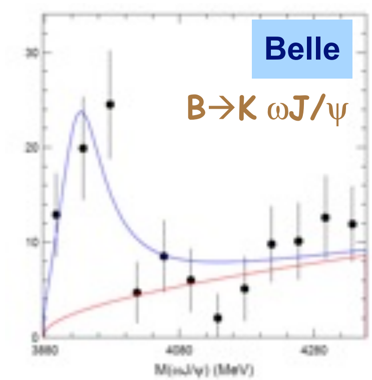

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BROAD (~300 MeV)
(likely unmixed)

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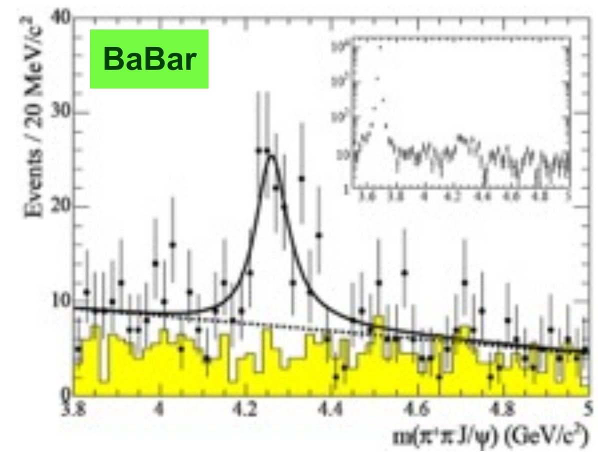

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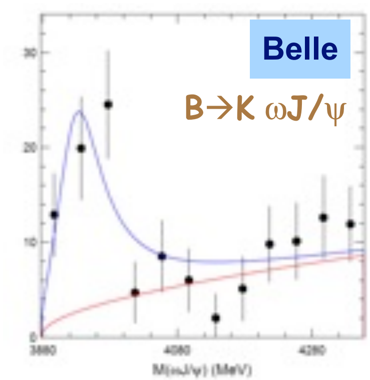

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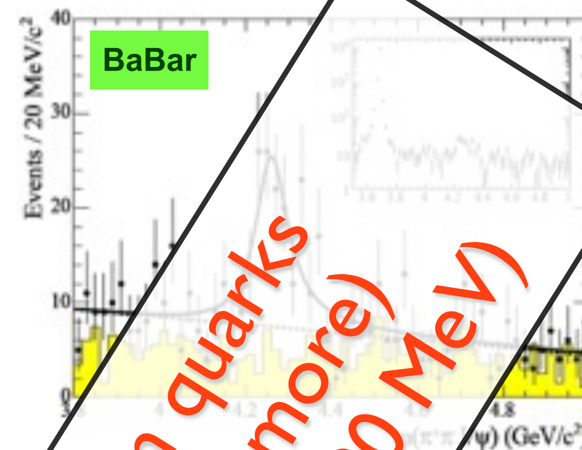

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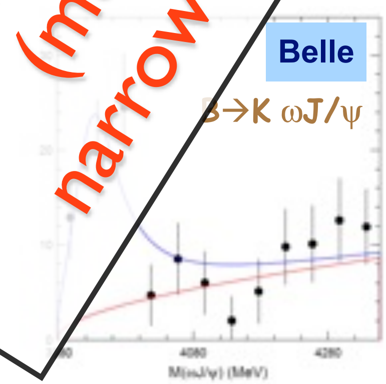

charm quarks (much more) narrow (~80 MeV)

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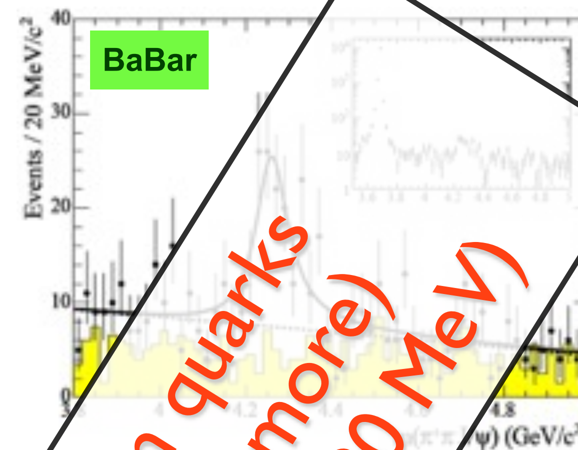

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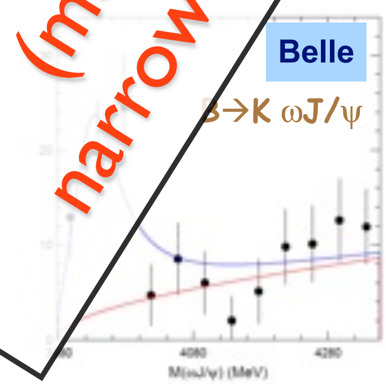

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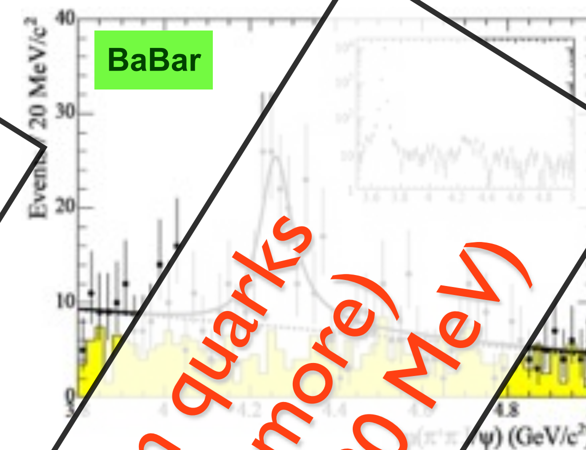

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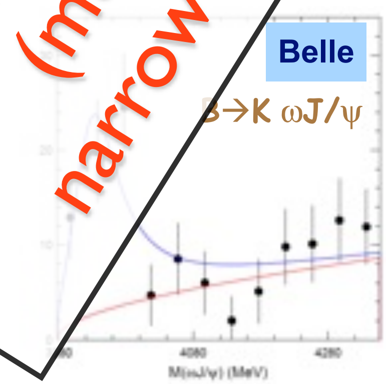

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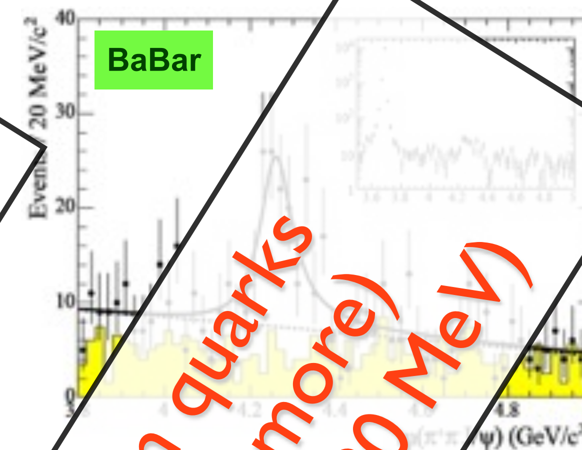

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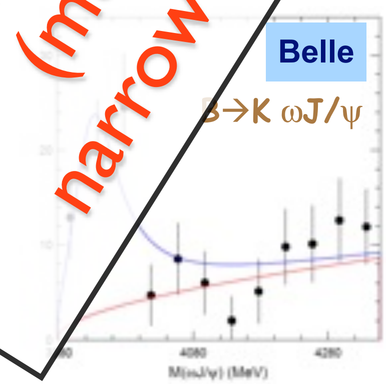

PANDA

Exotics

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M.G. Alekseev et al., PRL 104 (2010) 241803

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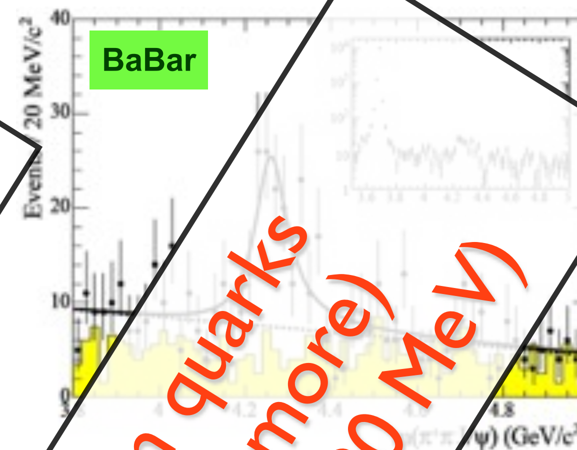

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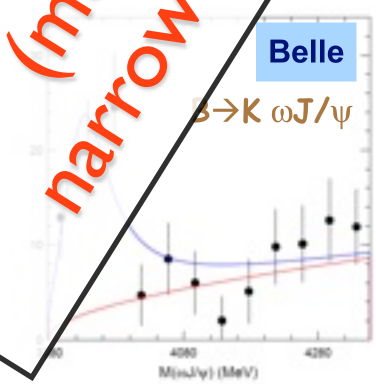


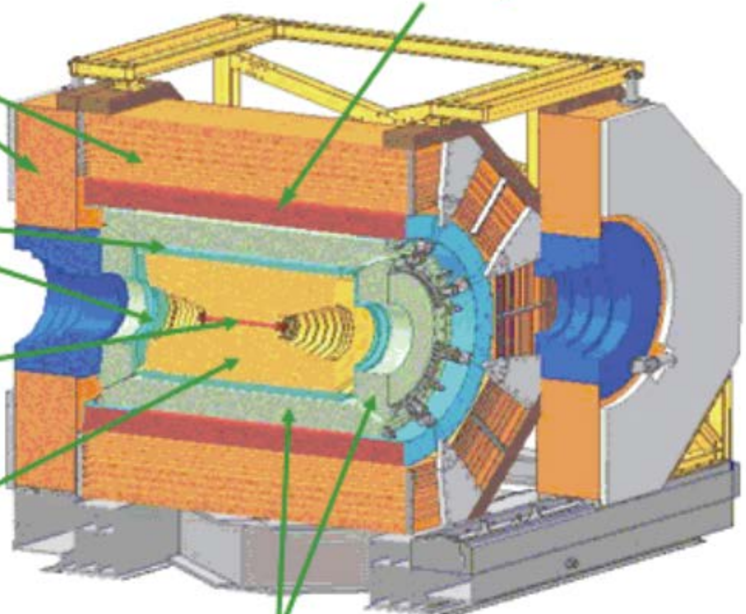
charm quarks (much more) narrow (~80 MeV)

JLAB@12 GeV

PANDA

BES in Beijing

The BESIII Detector



$\sigma_{TOF} \approx 80\,ps$

$$\frac{\Delta p_t}{p_t} = 0.5\% \;\; @ \;\; 1GeV$$

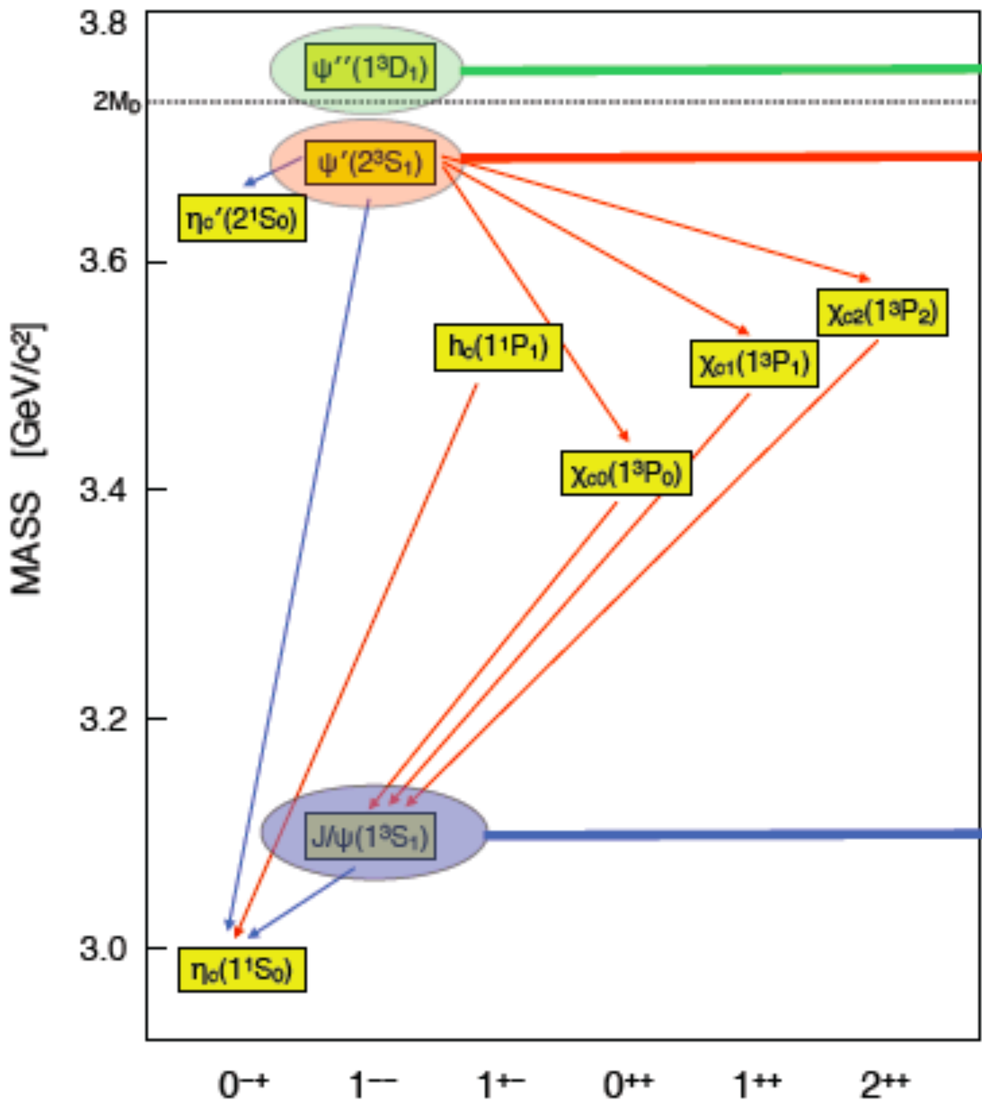
$$\sigma(dE/dx) = 6\%$$

$$\frac{\Delta E_\gamma}{E_\gamma} = 2.5\% \;\; @ \;\; 1GeV$$

To Tiananmen Square (~10 km)

BESIII data samples

(+data taken at 3.65 GeV and resonance scans)



~2.9 fb^{-1}

~106 million (+more)

NEW

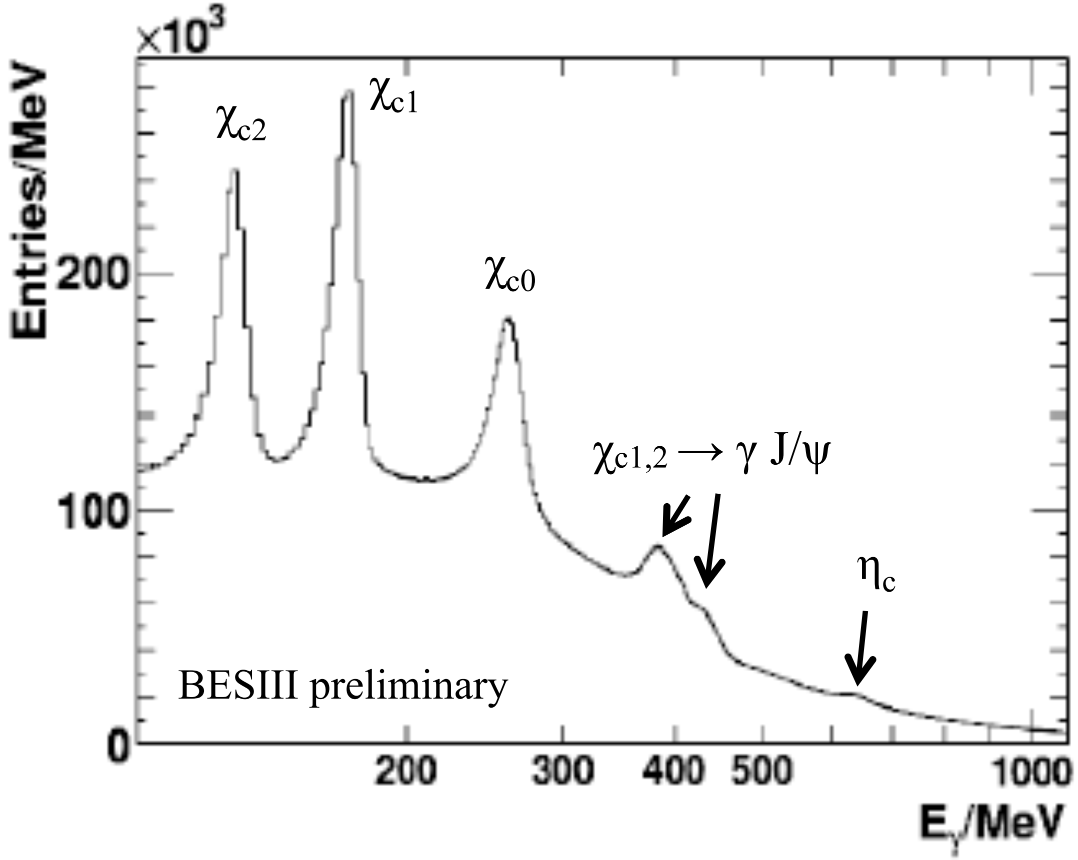
0.5 fb^{-1} @4010 MeV
0.5 fb^{-1} @4260 MeV
0.5 fb^{-1} @4360 MeV (ongoing!)

≈1.2 billion (225M analyzed)

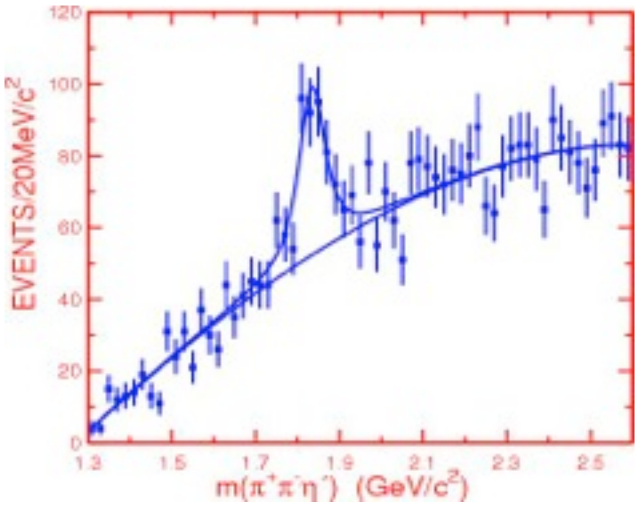
~10-20x previous generation charmonium factories

BESIII data quality

$\psi' \rightarrow \gamma X$

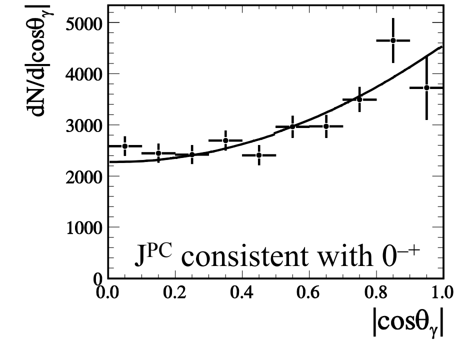


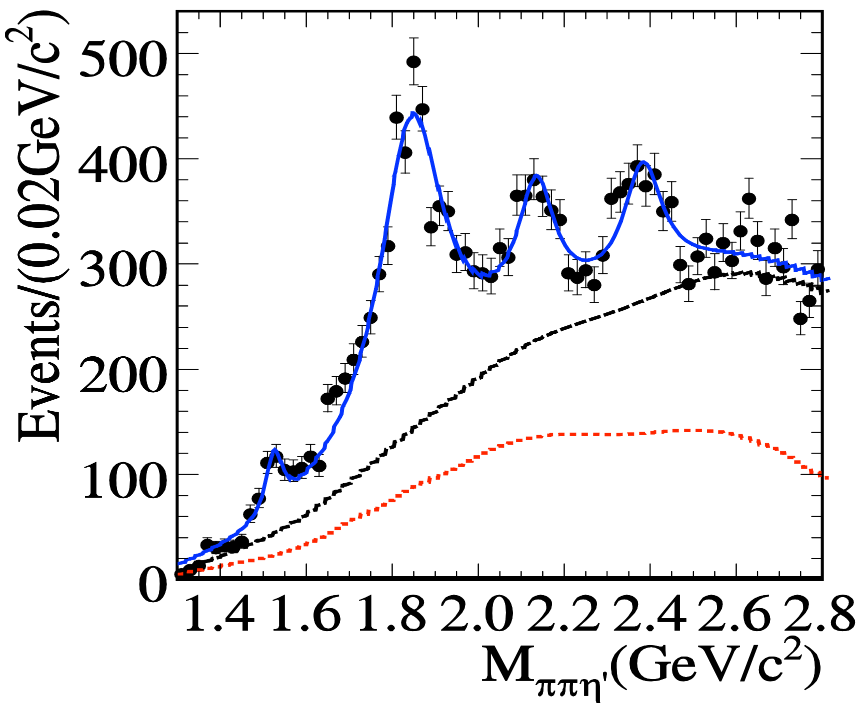
The X(1835) at BES



BESII PRL 95, 262001 (2005)

$$J/\psi \to \gamma\eta'\pi^+\pi^-$$





BESIII PRL 106, 072002 (2011)

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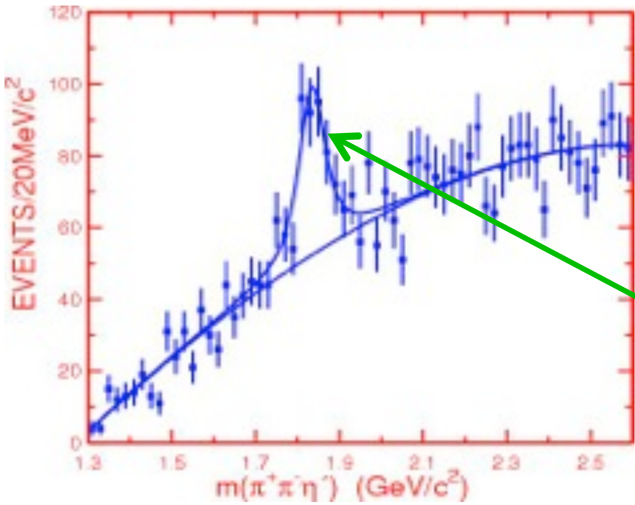

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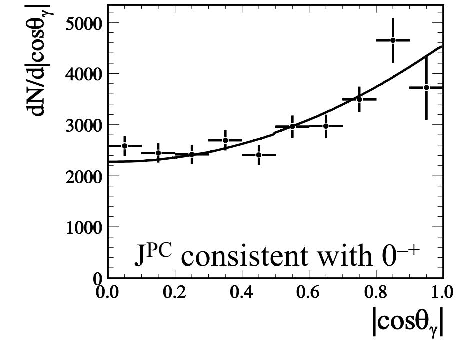
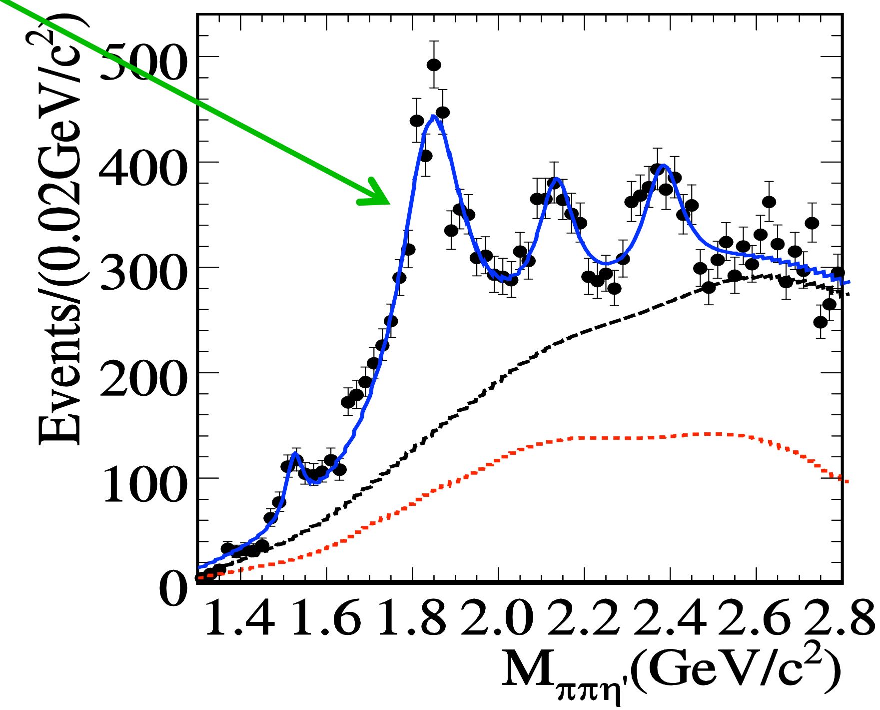


Confirmation of X(1835)



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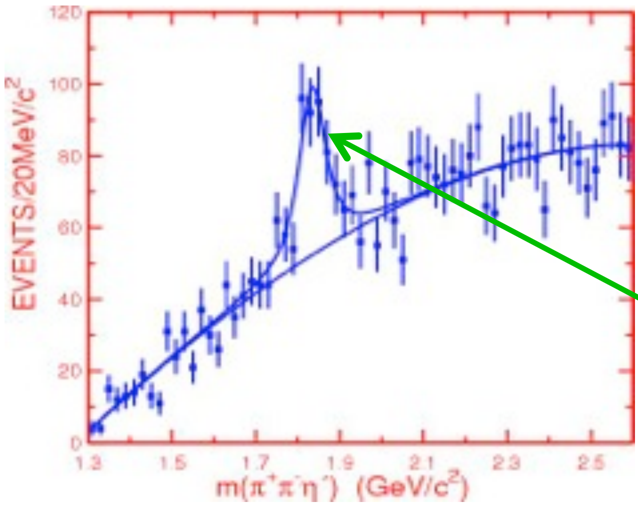

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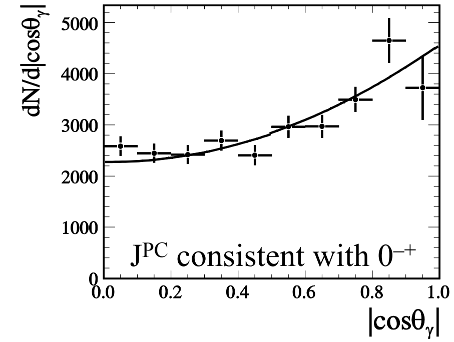

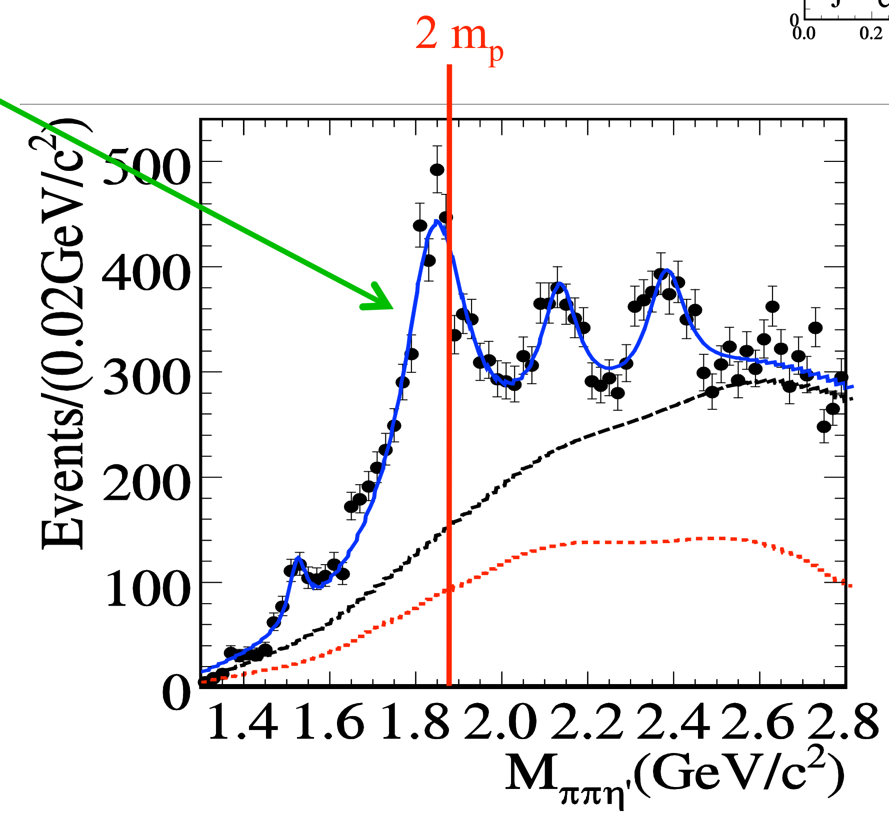

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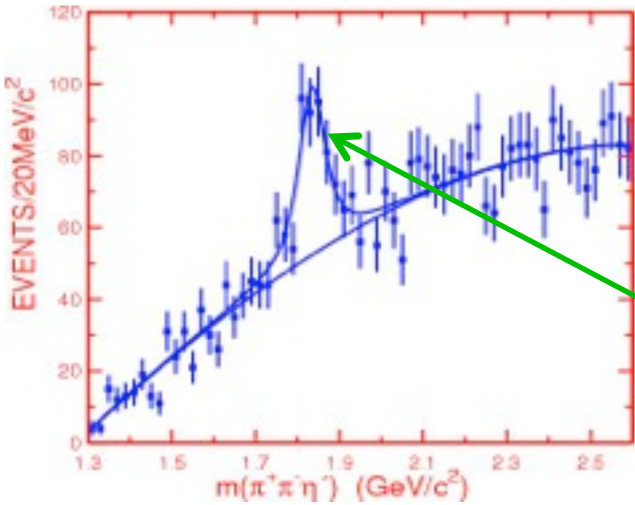

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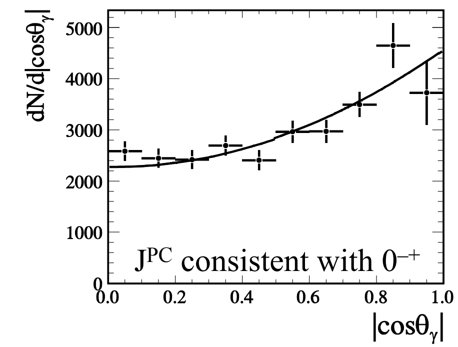
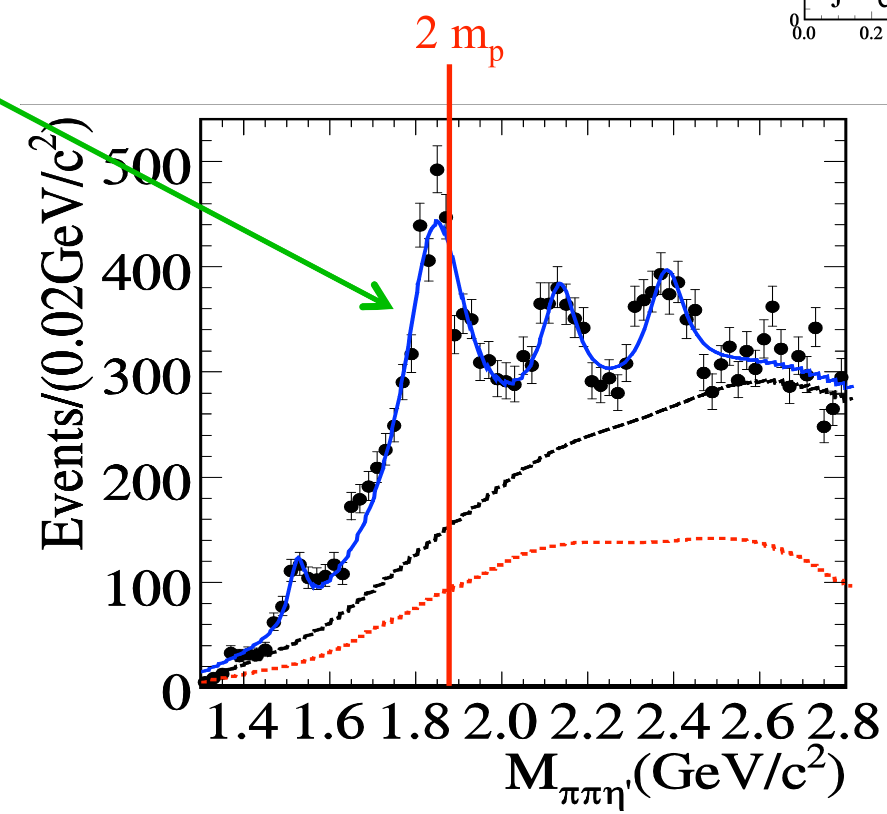


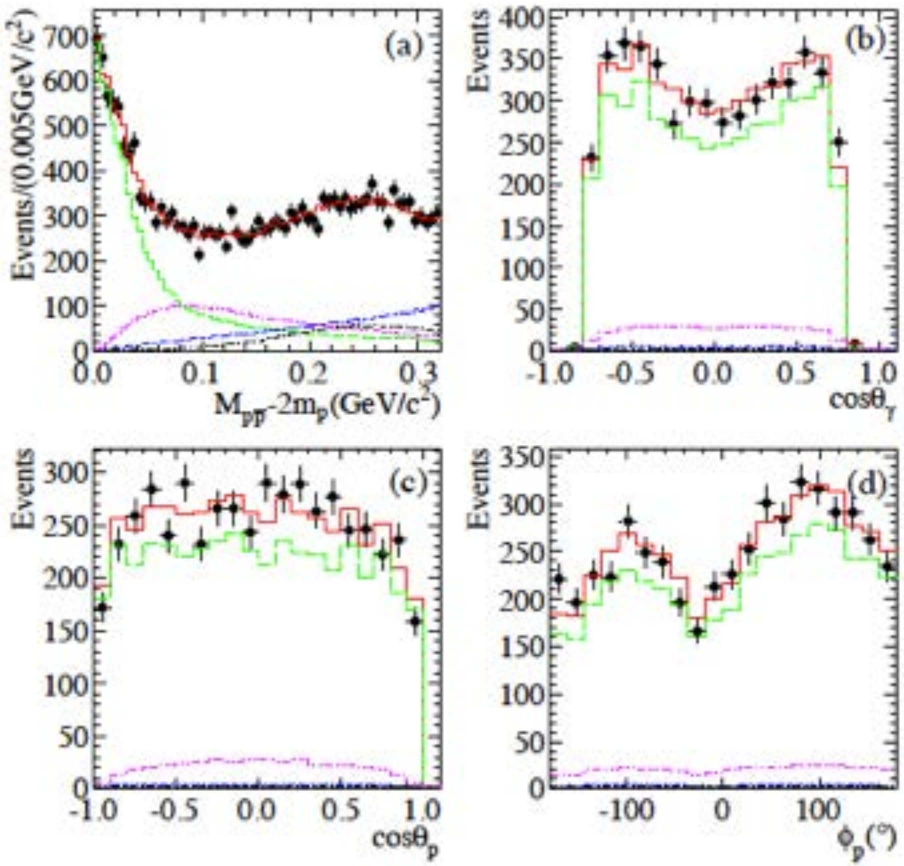


Confirmation of X(1835)

BESIII PRL 106, 072002 (2011)

X(1835) M=$1836.5\pm3.0^{+5.6}_{-2.}$ Γ=$190.1\pm9.0^{+38}_{-36}$ >20σ

$J/\psi \to \gamma p\bar{p}$



BESIII PRL 108, 112003 (2012)

Partial wave analysis:

- $J^{PC} = 0^{-+} > 6.8\sigma$ better than other assignments

Fermi & Yang in 1949
(7 years before $\overline{\mathrm{p}}$ discovery):

If $N\overline{N}$ potential is attractive, they could bind to form π-like states.

THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

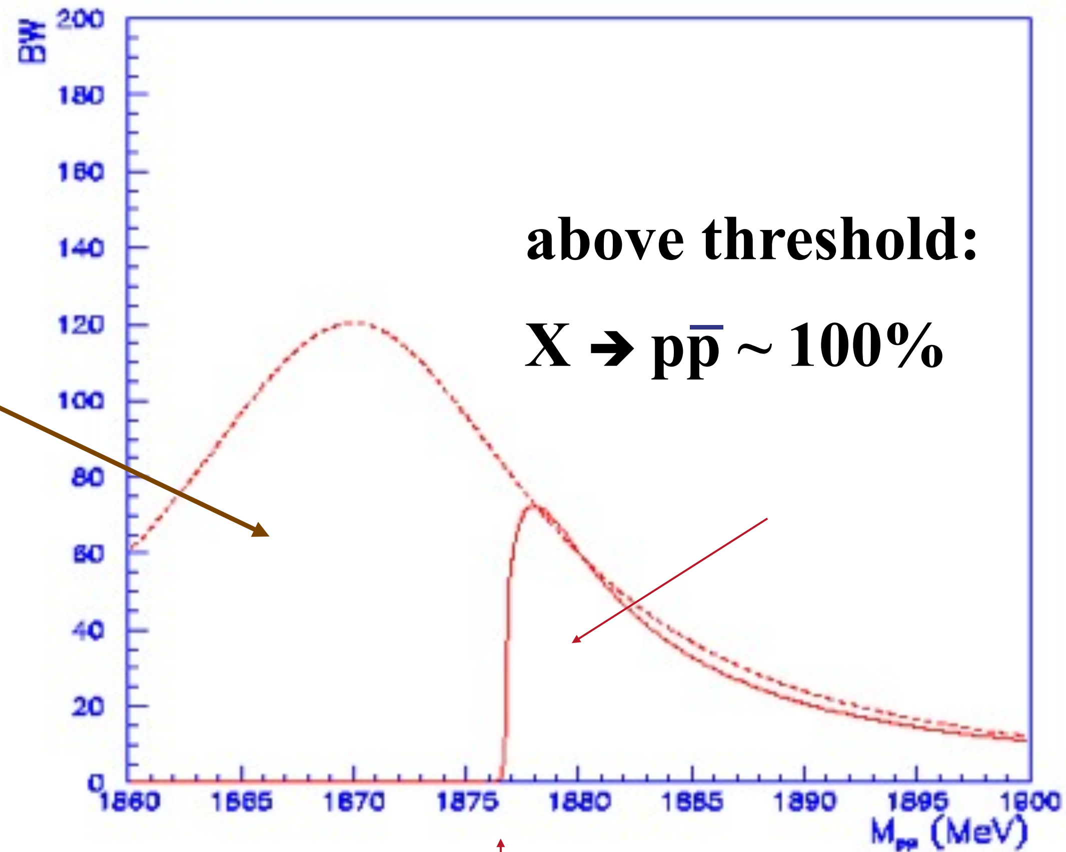
The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

Expectation for $p\bar{p}$ bound-state meson

below-threshold: p and $\bar{p}$ annihilate to mesons

above threshold:

$X \rightarrow p\bar{p} \sim 100\%$

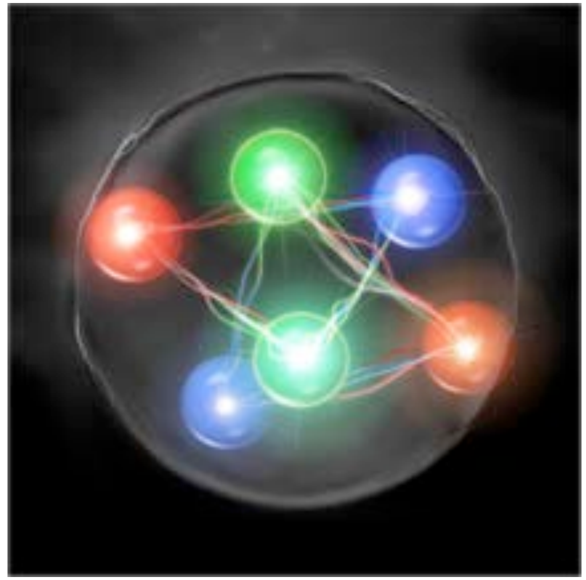


$m_p + m_p$

I=0, $J^{PC} = 0^{-+}$ init. state:
$p\bar{p} \rightarrow \pi^+\pi^-\eta'$ is common

Phys. Rev. C **72**, 015208 (2005) G.J. Ding and M.L.Yan
Comm. Theor. Phys. 42, 844 (2004) C.S. Gao and S.L. Zhu

Baryonium: the H-particle



Picture: Wikipedia

Perhaps a Stable Dihyperon*

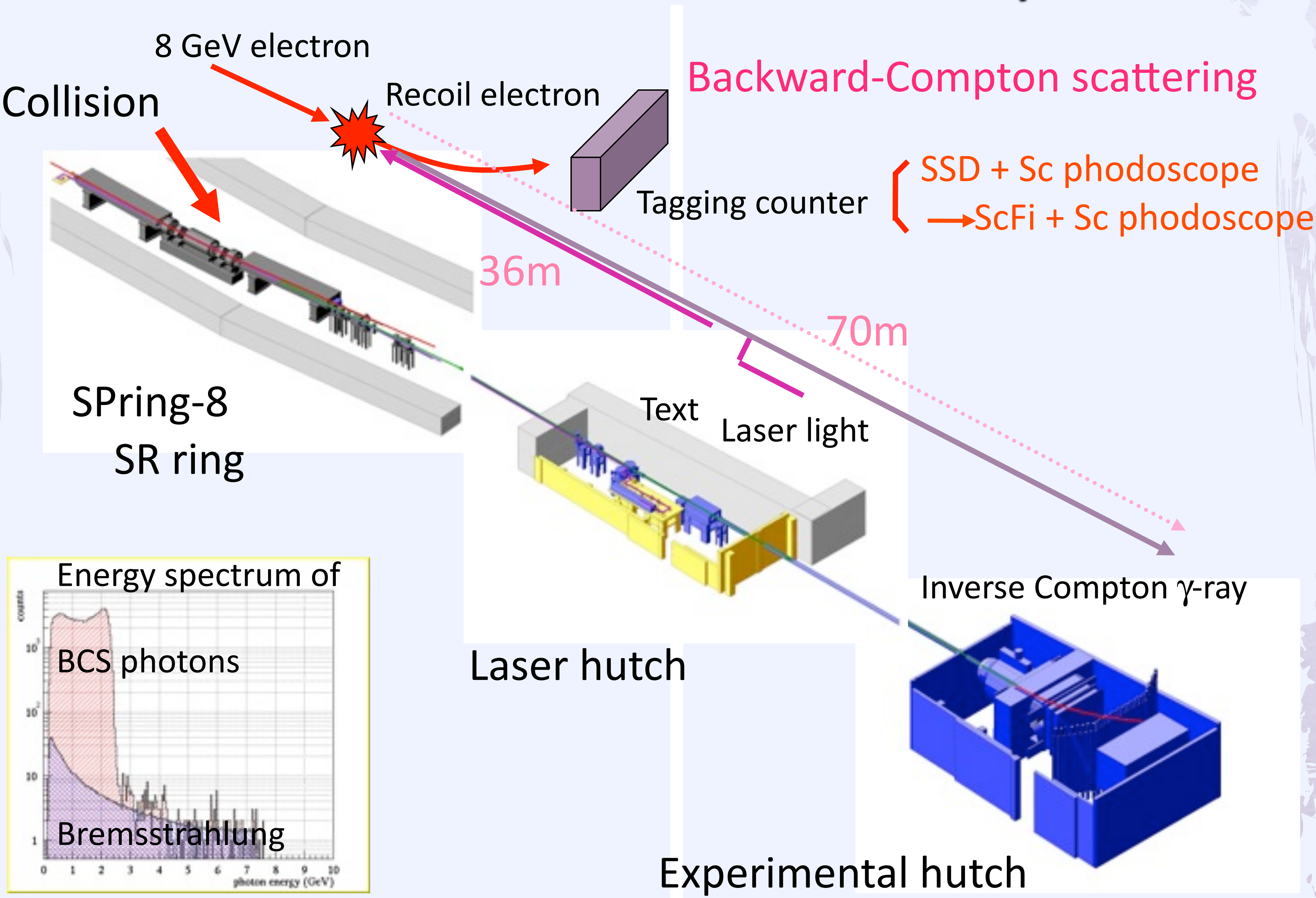
R. L. Jaffe†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Department of Physics and Laboratory of Nuclear Science,‡ Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

R.L. Jaffe; *Phys. Rev. Lett. 38: 195 (1977)*

LEPS @ SPring-8

Schematic view of the LEPS facility



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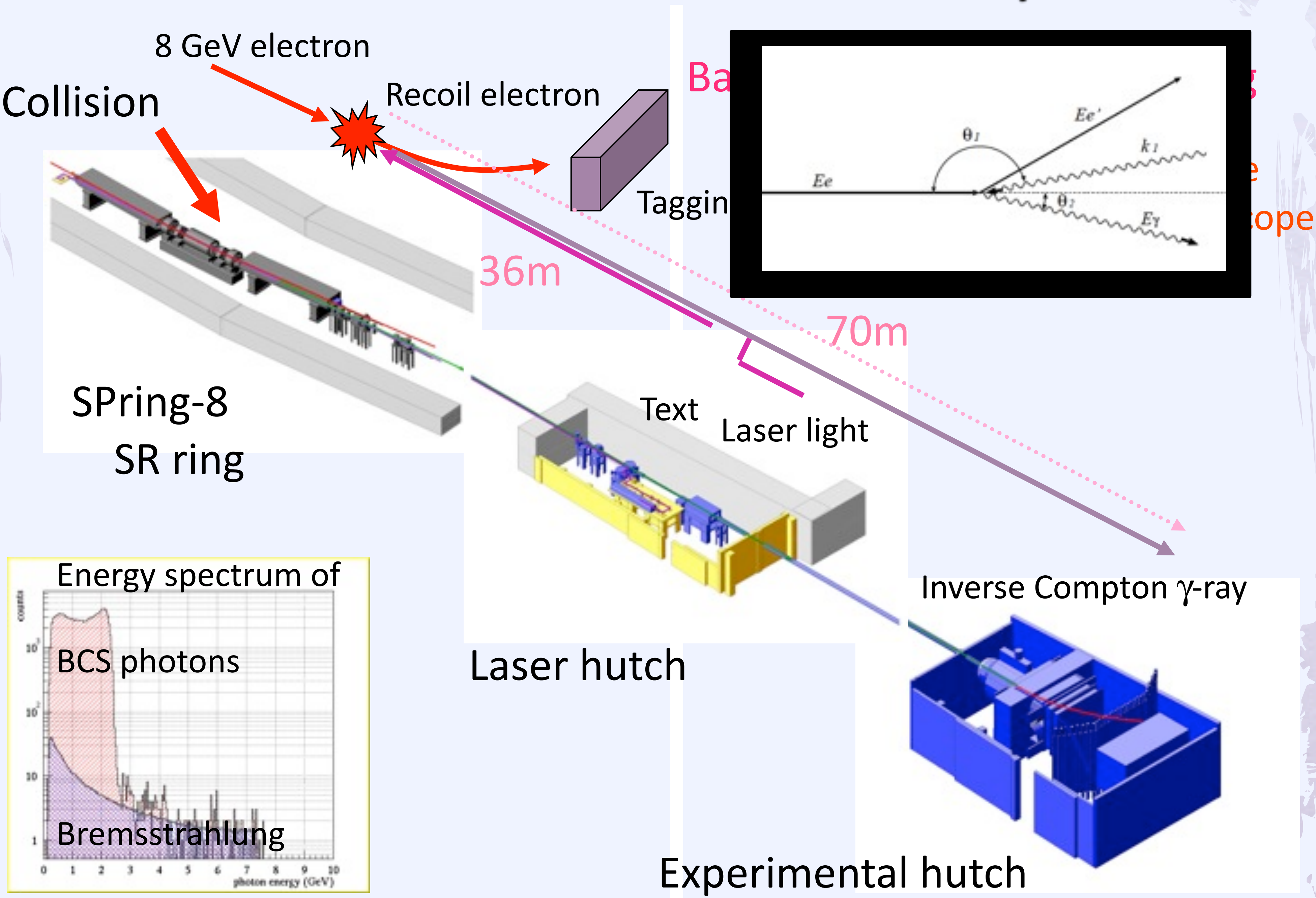
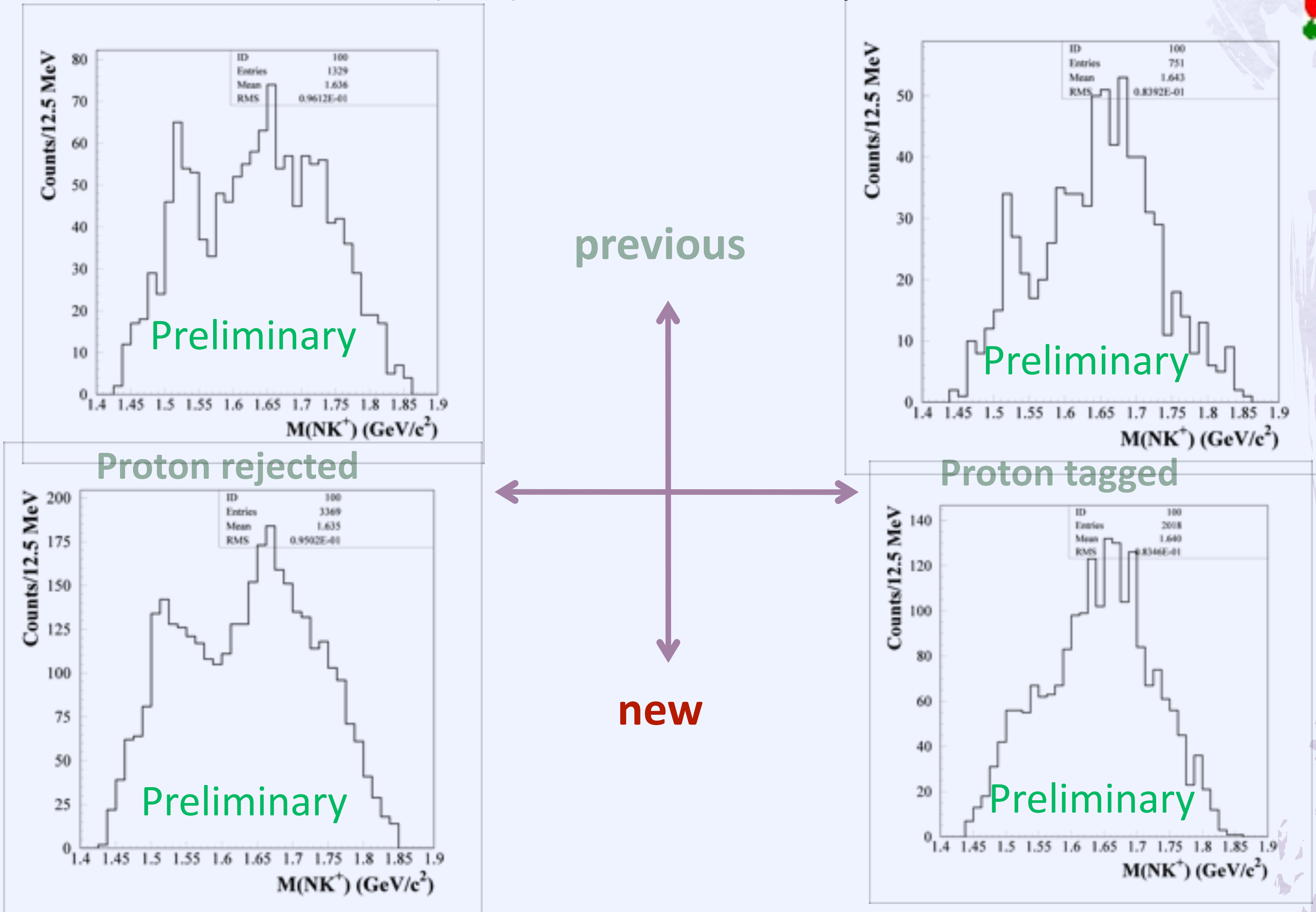


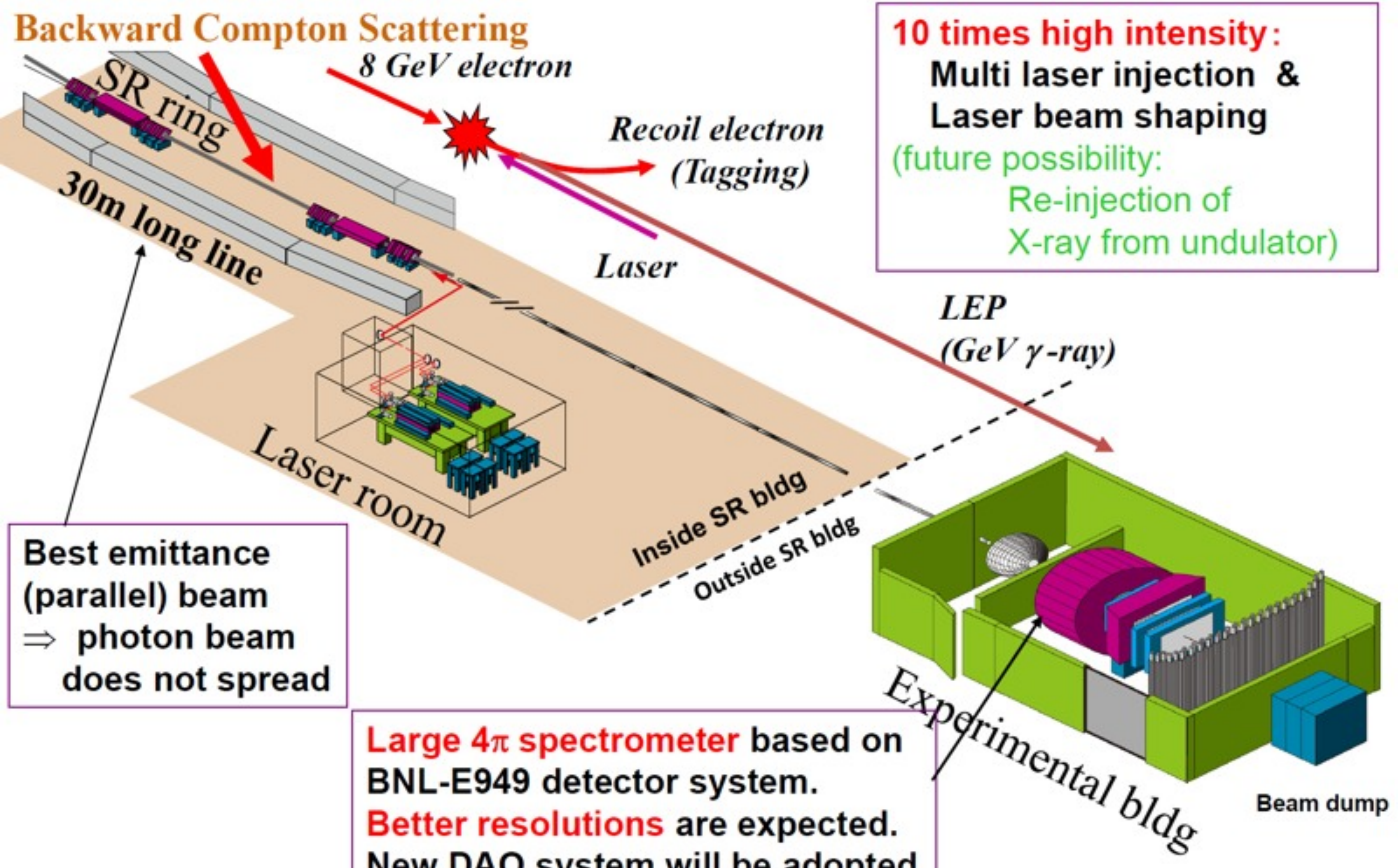
Ulrich Wiedner

M(NK⁺) for exclusive samples



- Peak is seen in tagged events for the previous data while not seen in the new data.
- An enhancement is seen in proton rejected events in the both data.

Schematic view of the LEPS2 facility

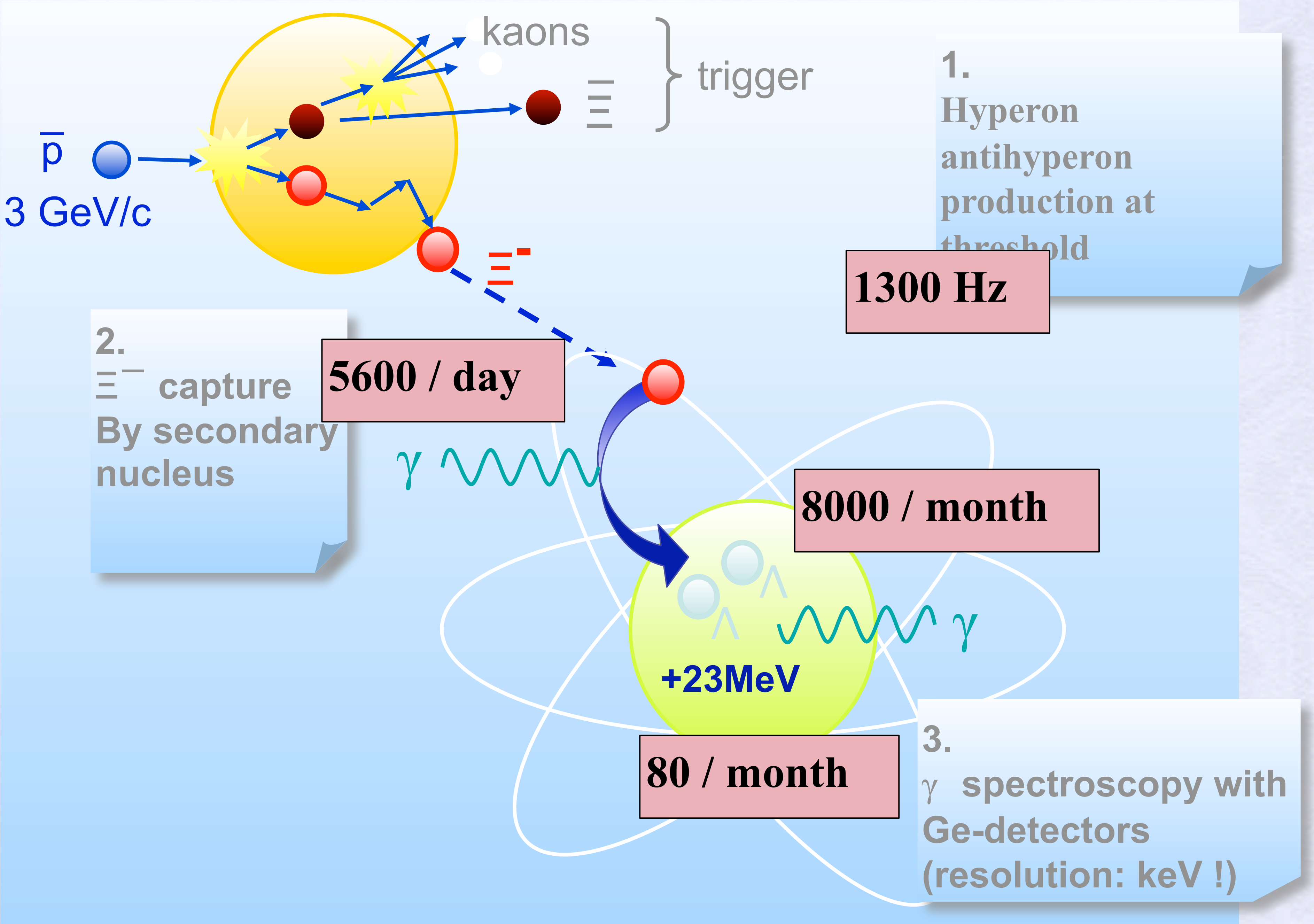


10 times high intensity:
Multi laser injection & Laser beam shaping
(future possibility: Re-injection of X-ray from undulator)

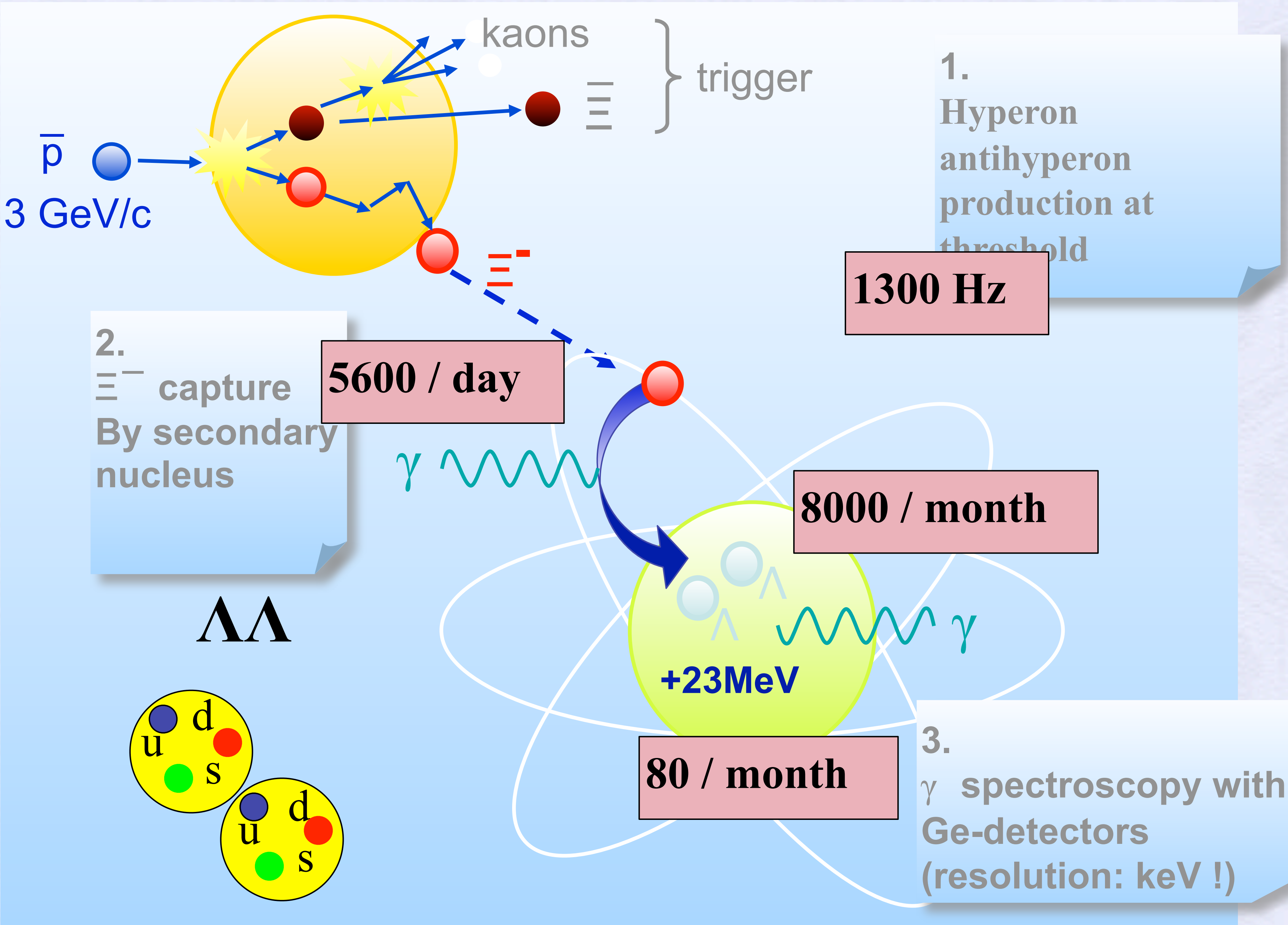
Best emittance (parallel) beam
⇒ photon beam does not spread

Large 4π spectrometer based on BNL-E949 detector system.
Better resolutions are expected.
New DAQ system will be adopted

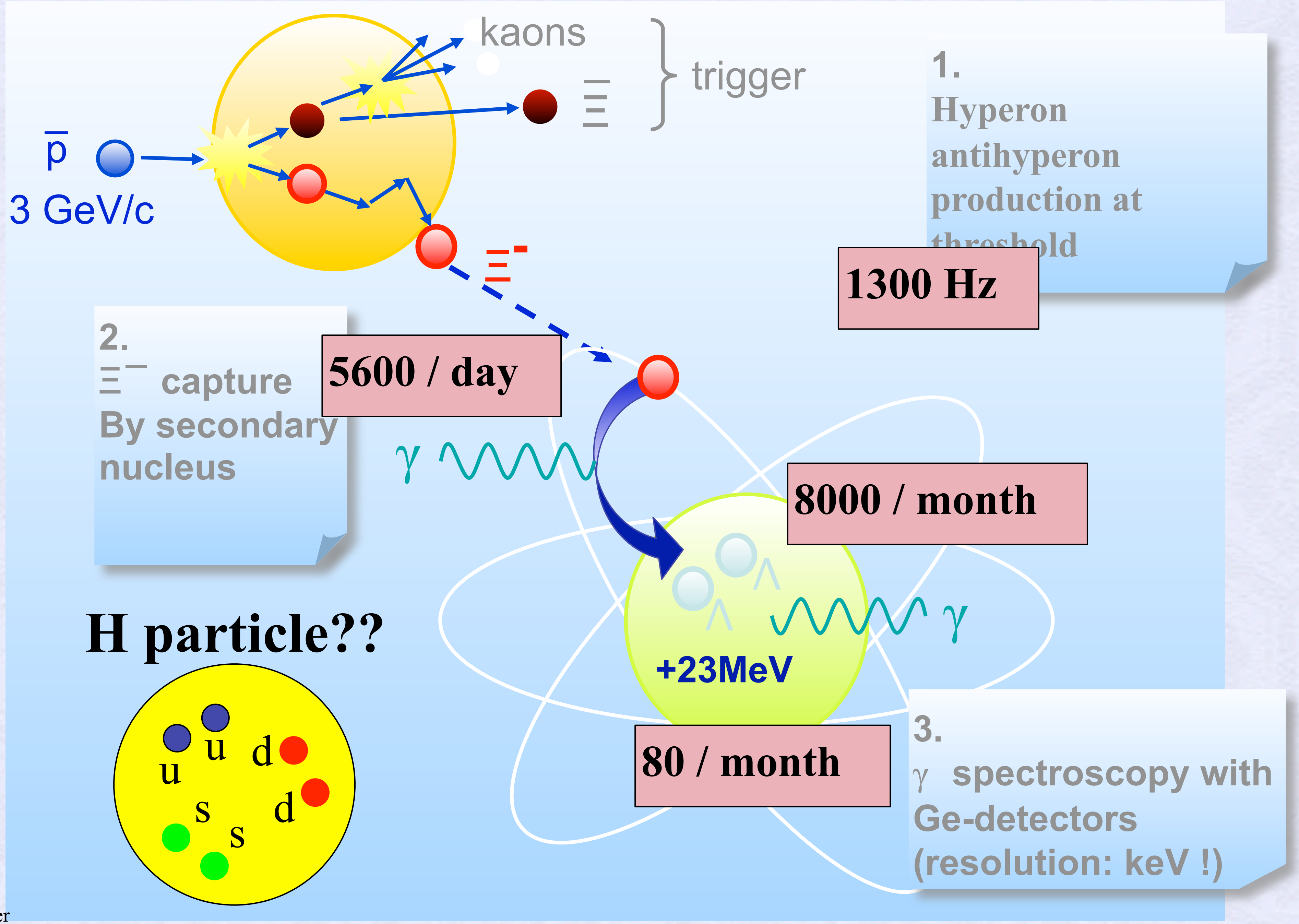
Production of double hypernuclei



Production of double hypernuclei

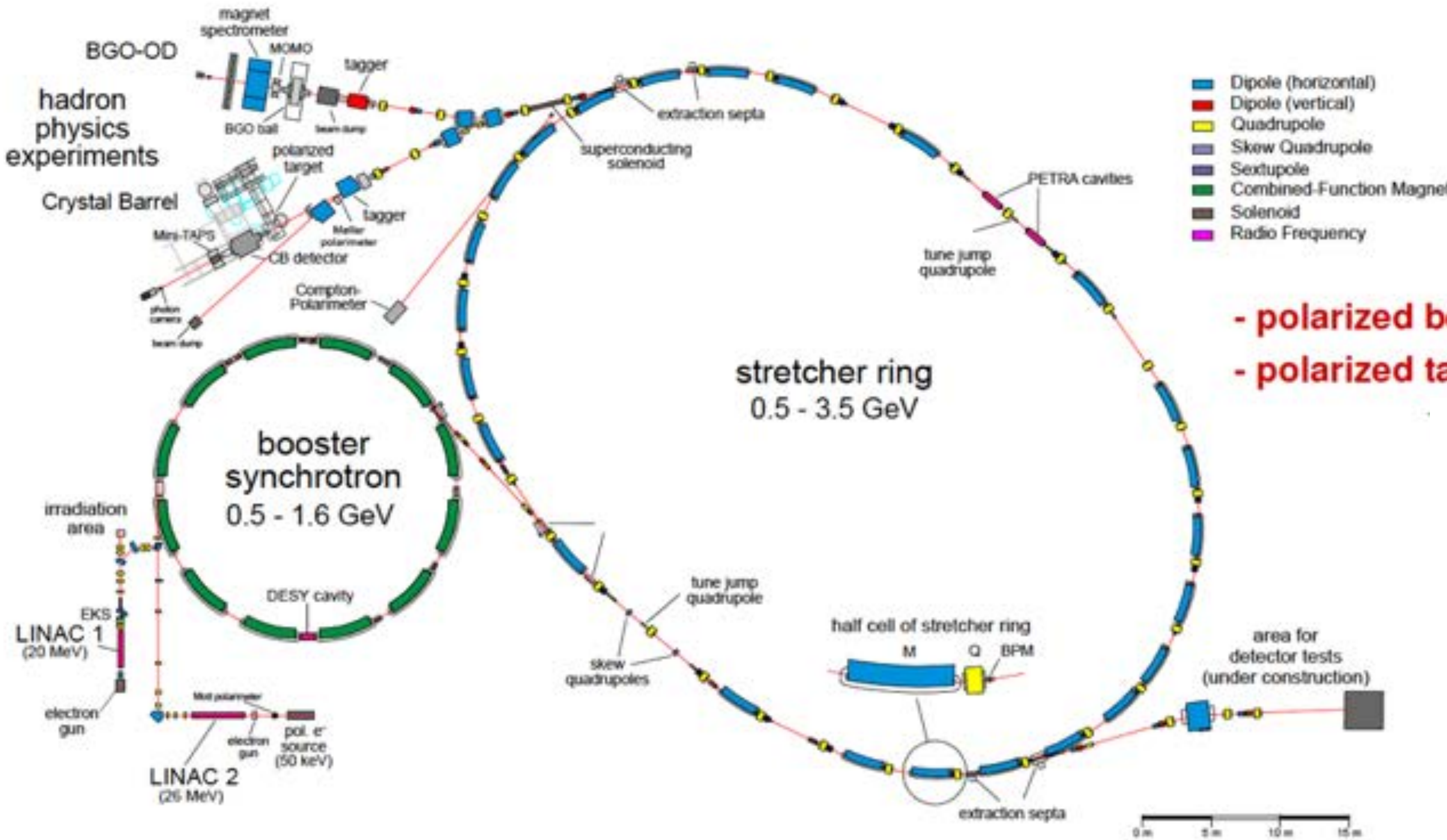


Production of double hypernuclei



Ulrich Wiedner

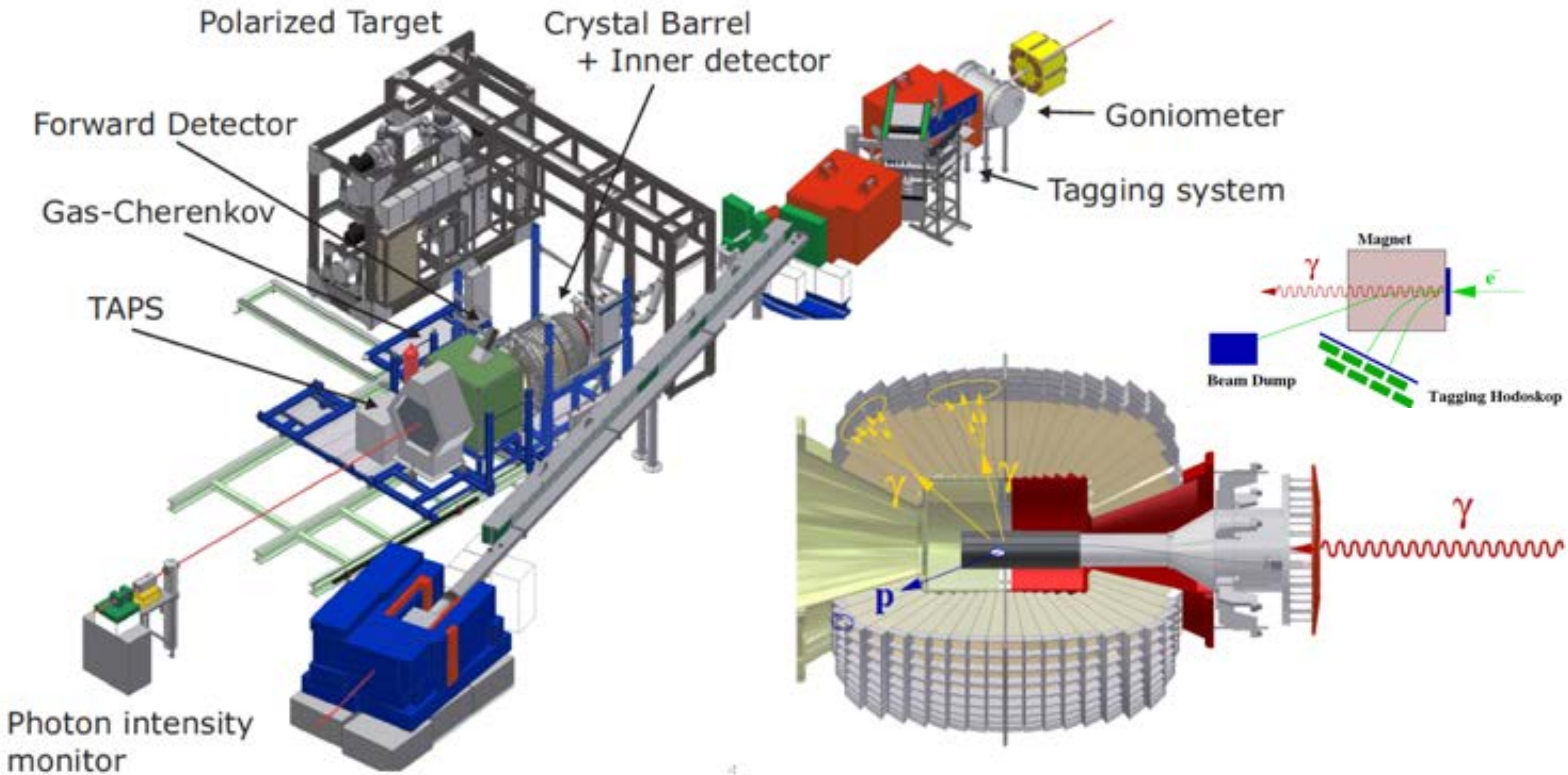
Bonn: the ELSA accelerator



- polarized beam
- polarized target

⇒ Polarized and unpolarized e^--beam ⇒ photoproduction experiments

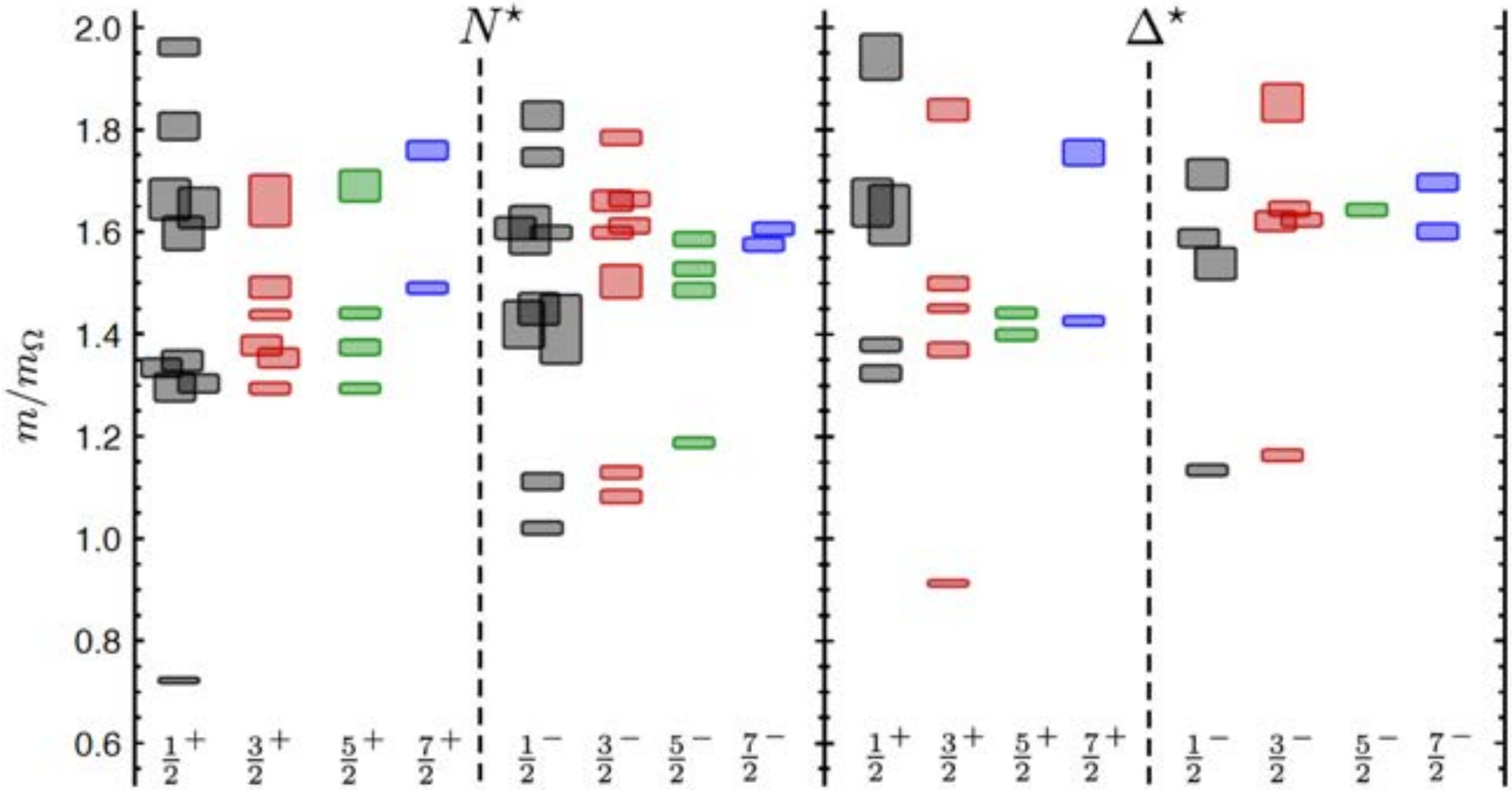
The CBELSA experiment in Bonn



⇒ Experiments with polarized beams and polarized targets

Single and multi-meson photoproduction, proton and neutron targets

↔ **Double polarization program**



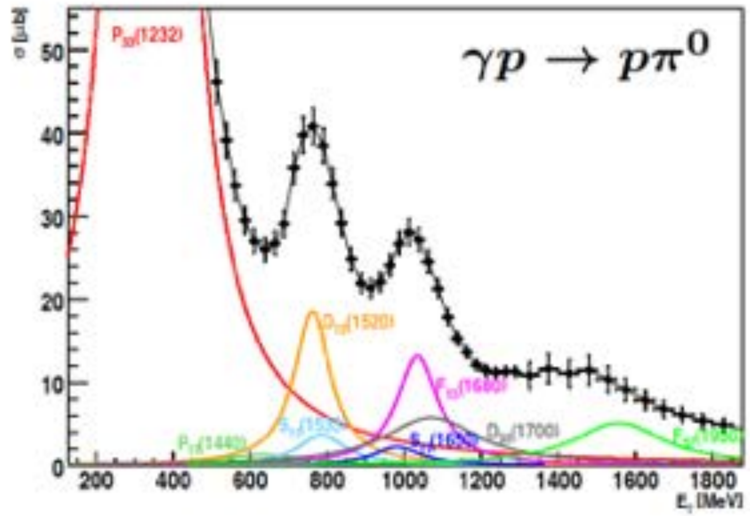
Lattice spectrum of nucleons and deltas at m_π=396 MeV

Phys. Rev. D.84.074508 (2011)

Baryon spectroscopy

⇒ **Good understanding of the spectrum and the properties (e.g. decays) of the resonances needed !**

Experimentally:
Broad and strongly overlapping resonances



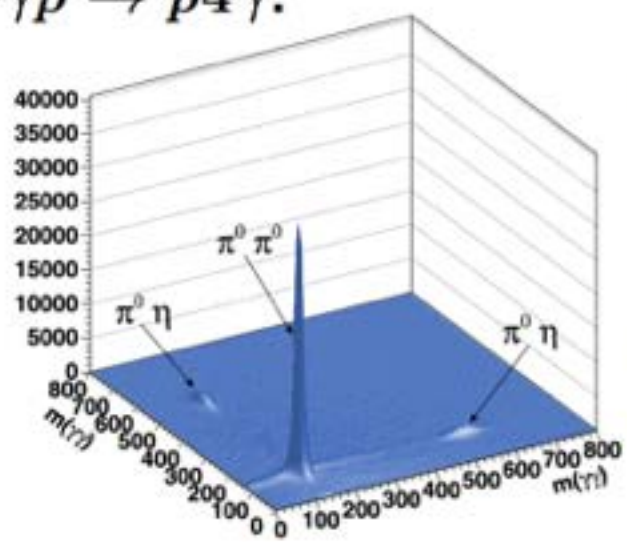
Important:
→ **Investigation of different final states**
→ **Measurement of polarization observables (unambiguous PWA)**

⇓

Single and double meson photoproduction with the CBELSA/TAPS experiment

- polarized beam
- polarized target

$\gamma p \rightarrow p4\gamma$:



Data quality:

→ **low background good resolution**

clear observation of $\gamma p \rightarrow p2\pi^0$, $\gamma p \rightarrow p\pi^0\eta$

CBELSA in Bonn: baryon spectroscopy with polarized beam and target

High quality double polarization data taken with polarized beam and polarized target, selected example:

$\gamma p \rightarrow p\pi^0$:

PWAs:

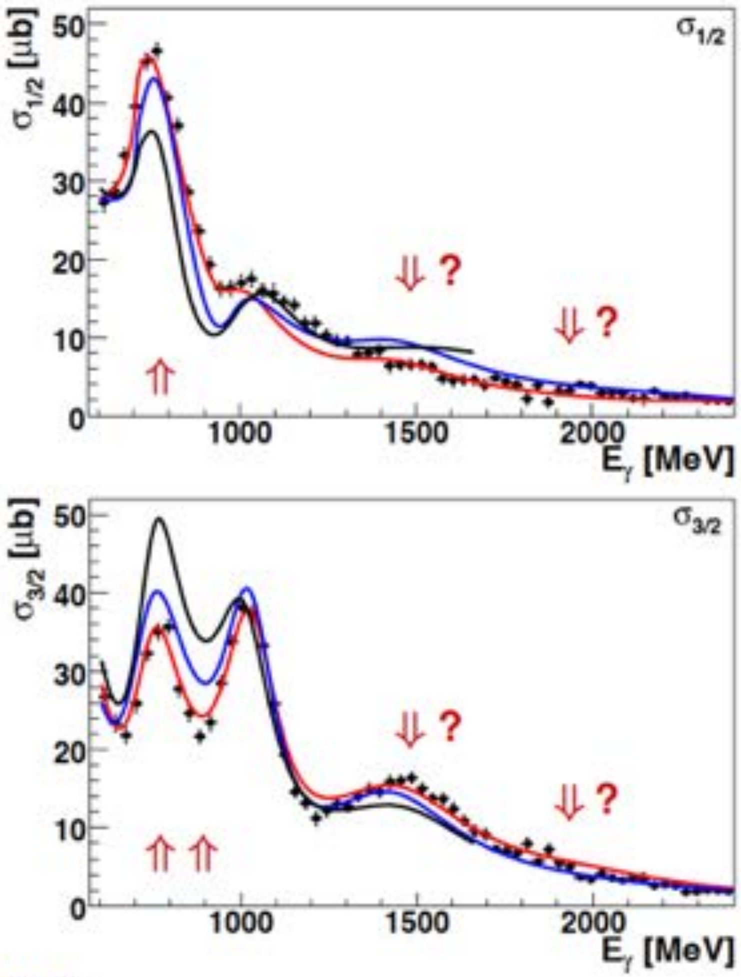
SAID, MAID

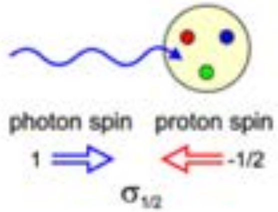
BnGa (↔A.2)

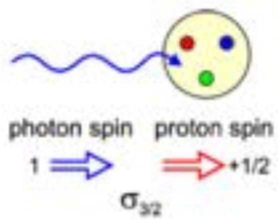
↔ describe the so far existing photoproduction data, but ...

large deviations observed →

Differences even at low energies where everything was thought to be well understood ... →







⇒ **Sensitivity on high mass resonances !**

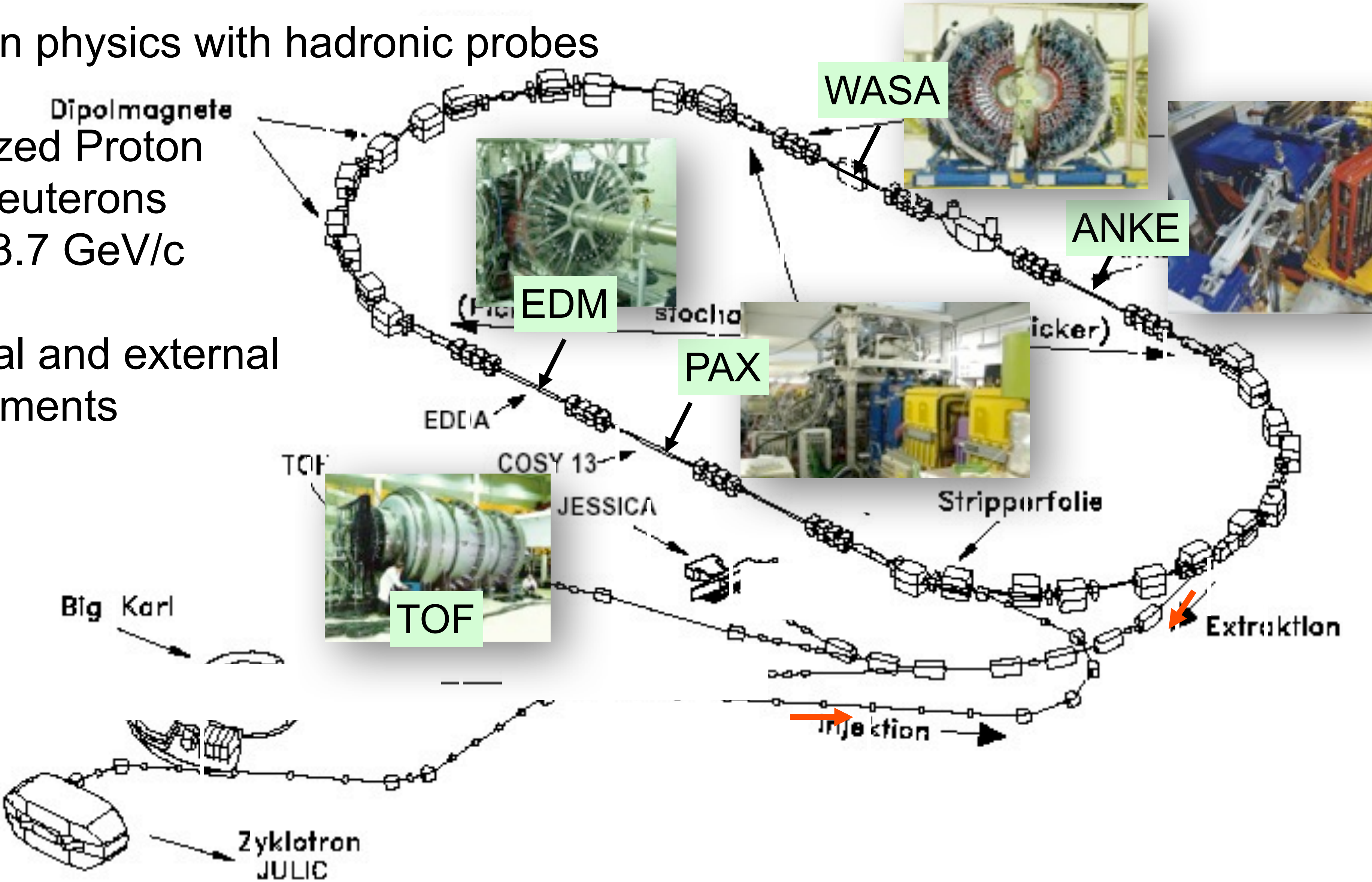
Double polarization measurements:
First paper (G) published (PRL 109), further data ready for publication

COSY – Experimental Facilities

Hadron physics with hadronic probes

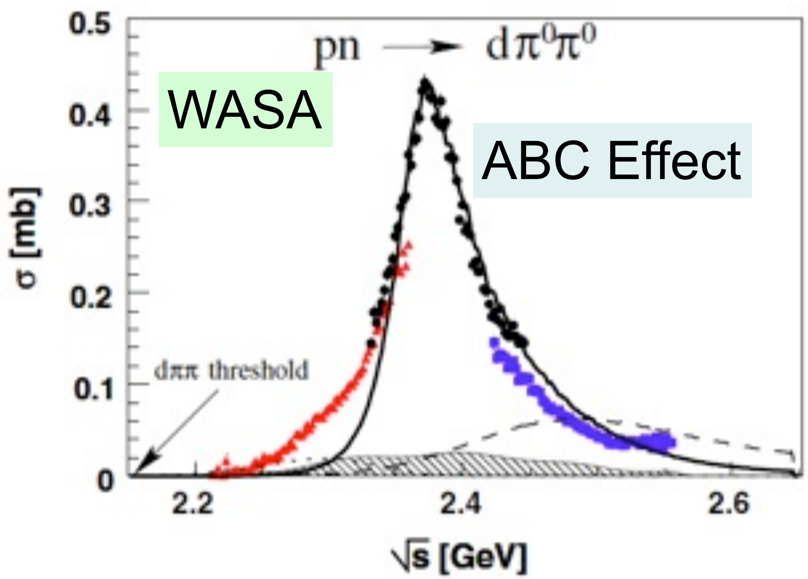
Polarized Proton and Deuterons up to 3.7 GeV/c

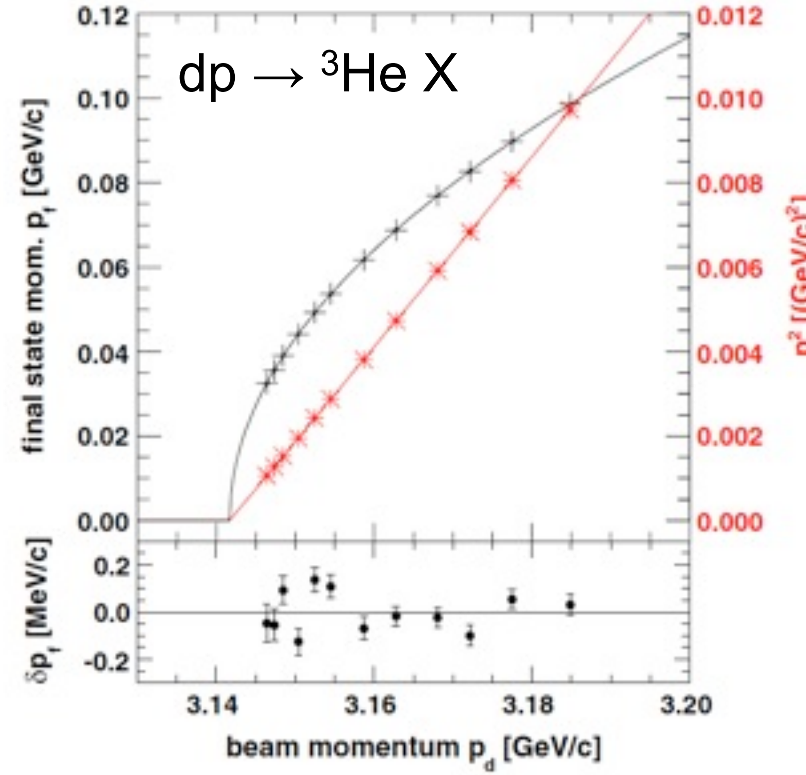
Internal and external experiments

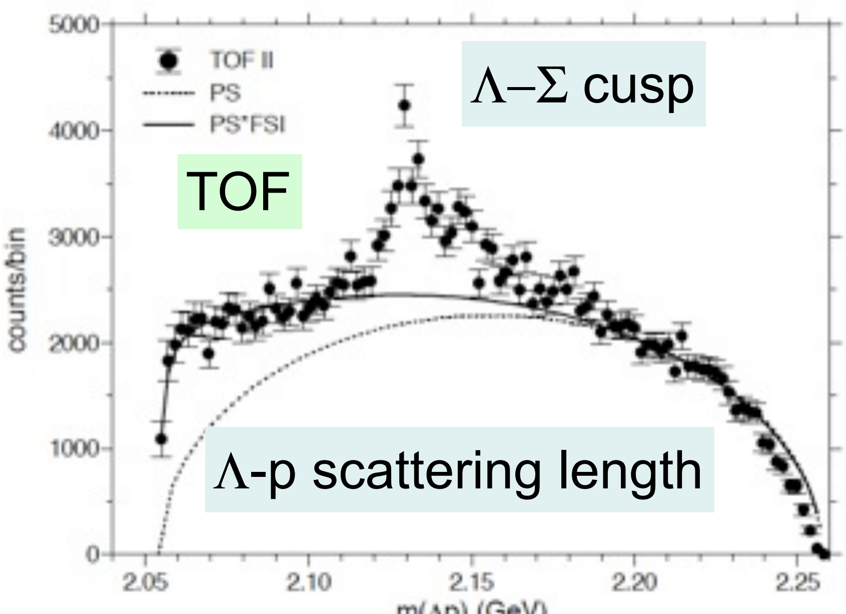


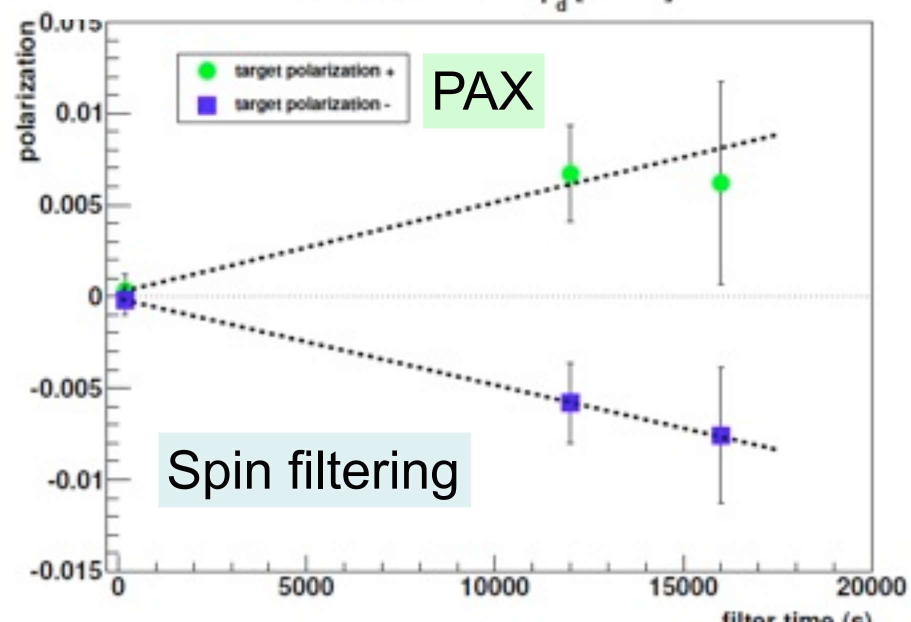
COSY – Experimental Facilities

Selected Recent Physics Results





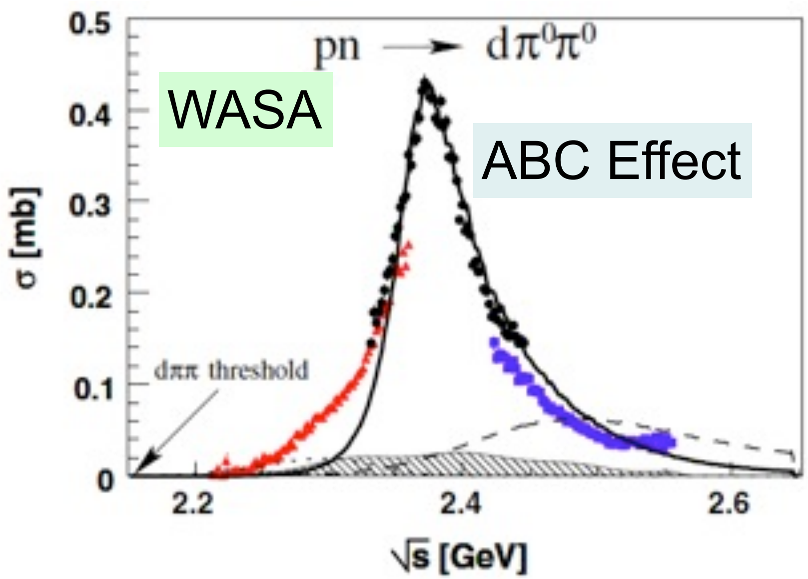


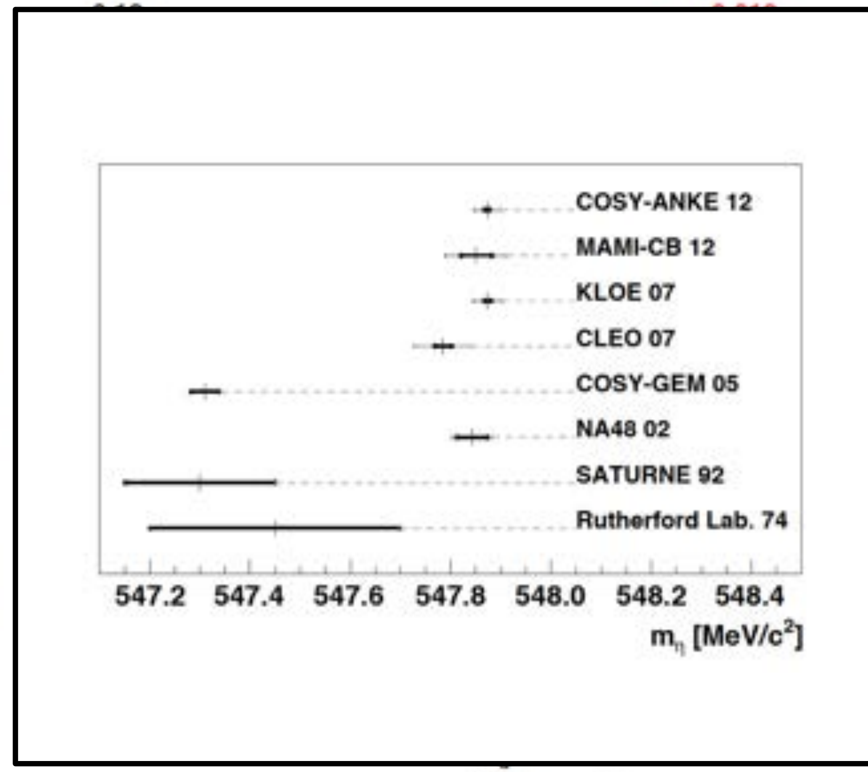


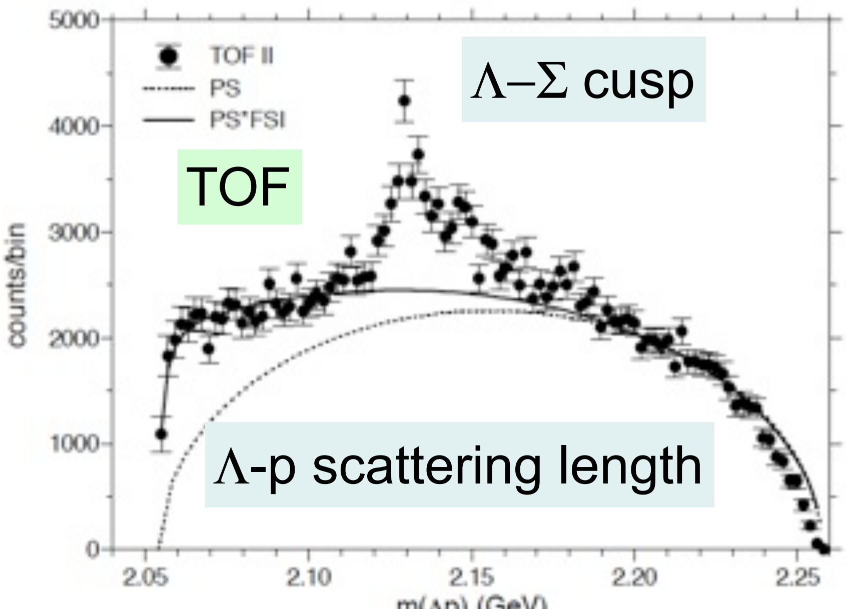
Ulrich Wiedner

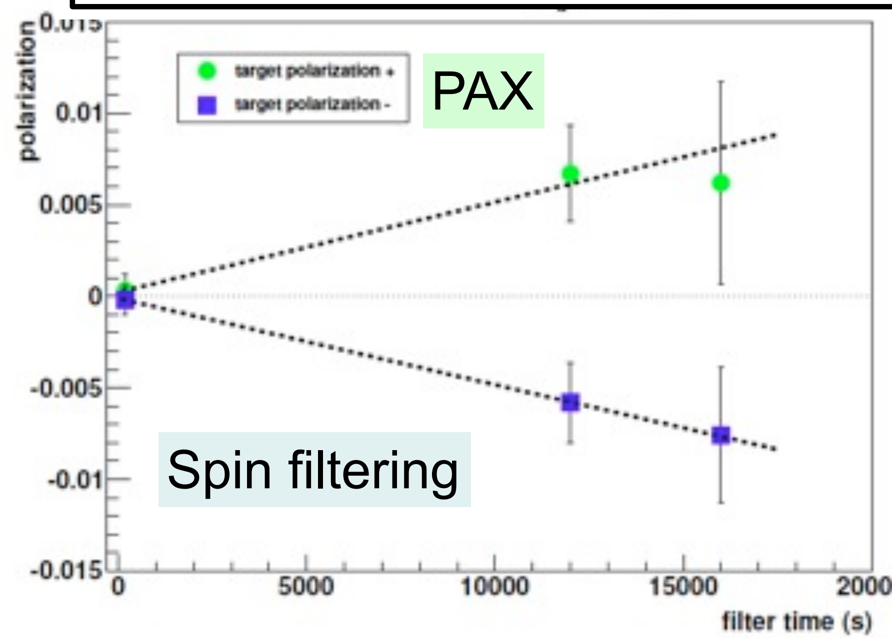
COSY – Experimental Facilities

Selected Recent Physics Results

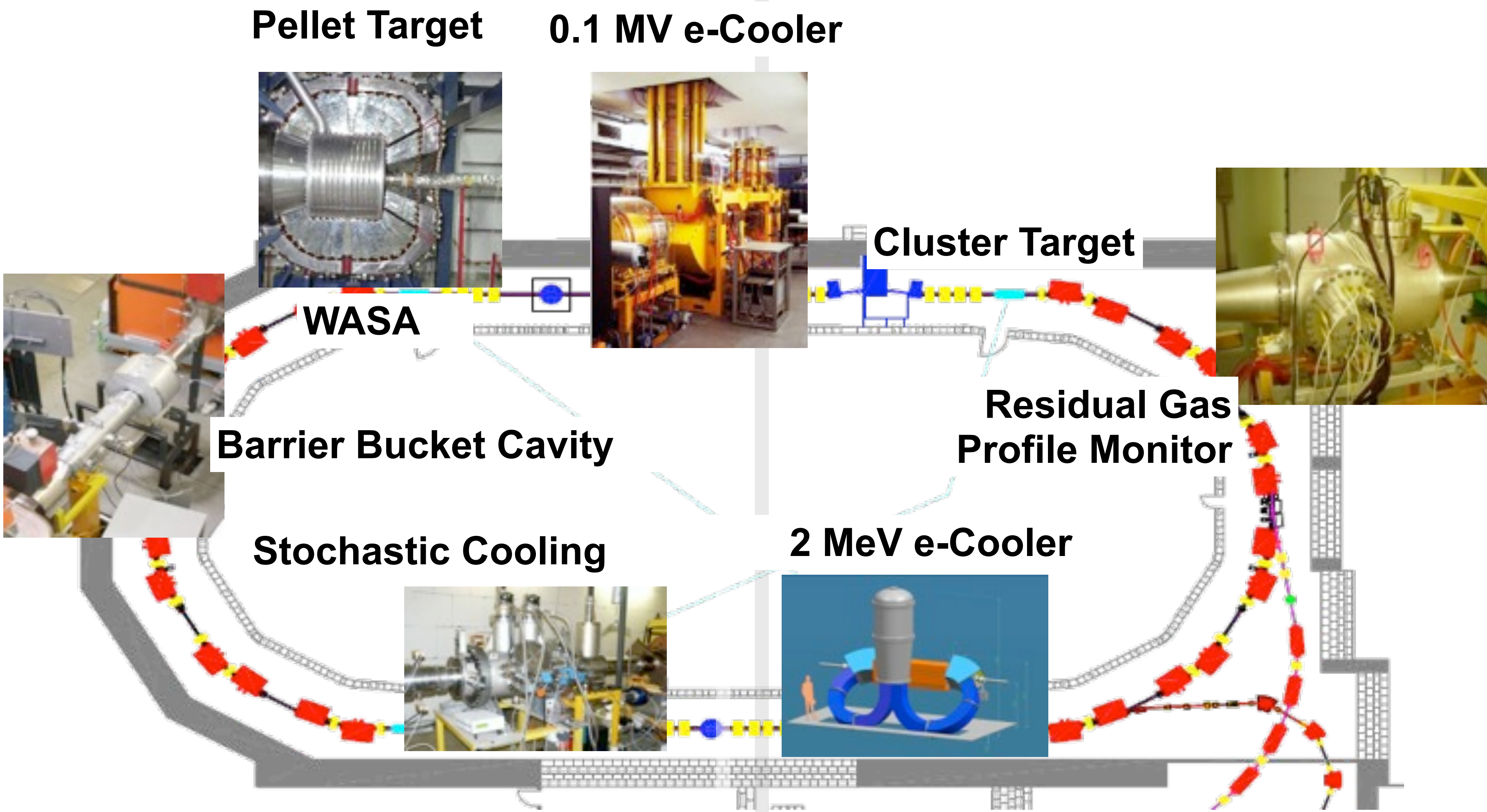








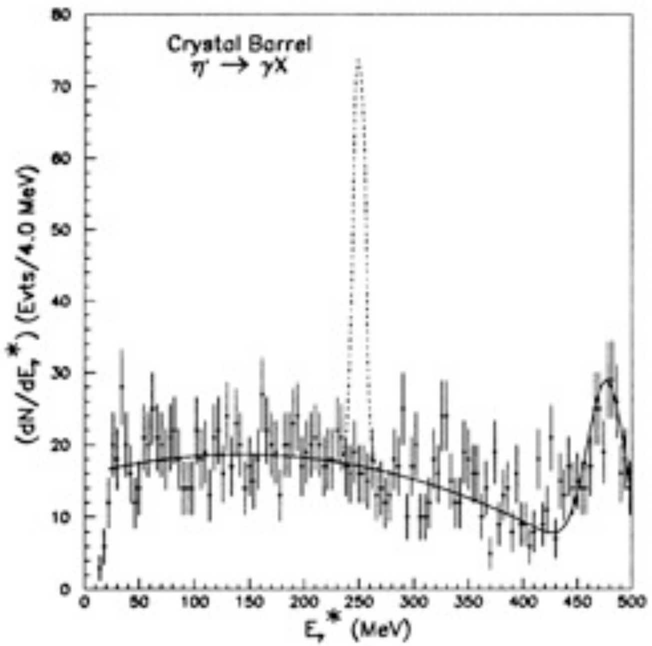
Accelerator Development for COSY and HESR

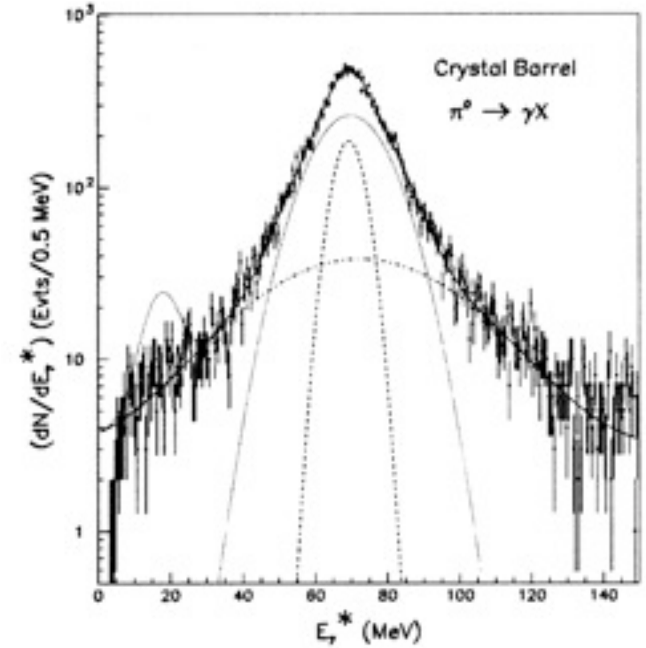


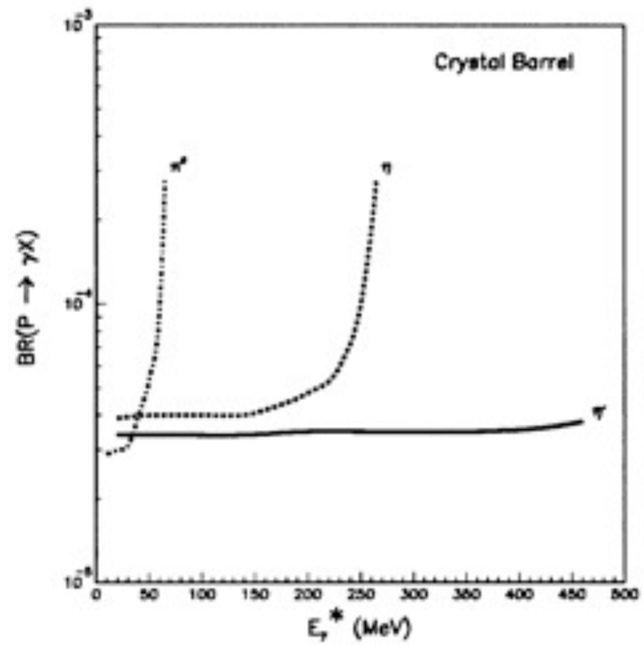
+ Detector tests for various FAIR experiments
+ Functional Preassembly of PANDA

Physics beyond the Standard Model

Crystal Barrel@LEAR: Search for unknown bosons in particle decays







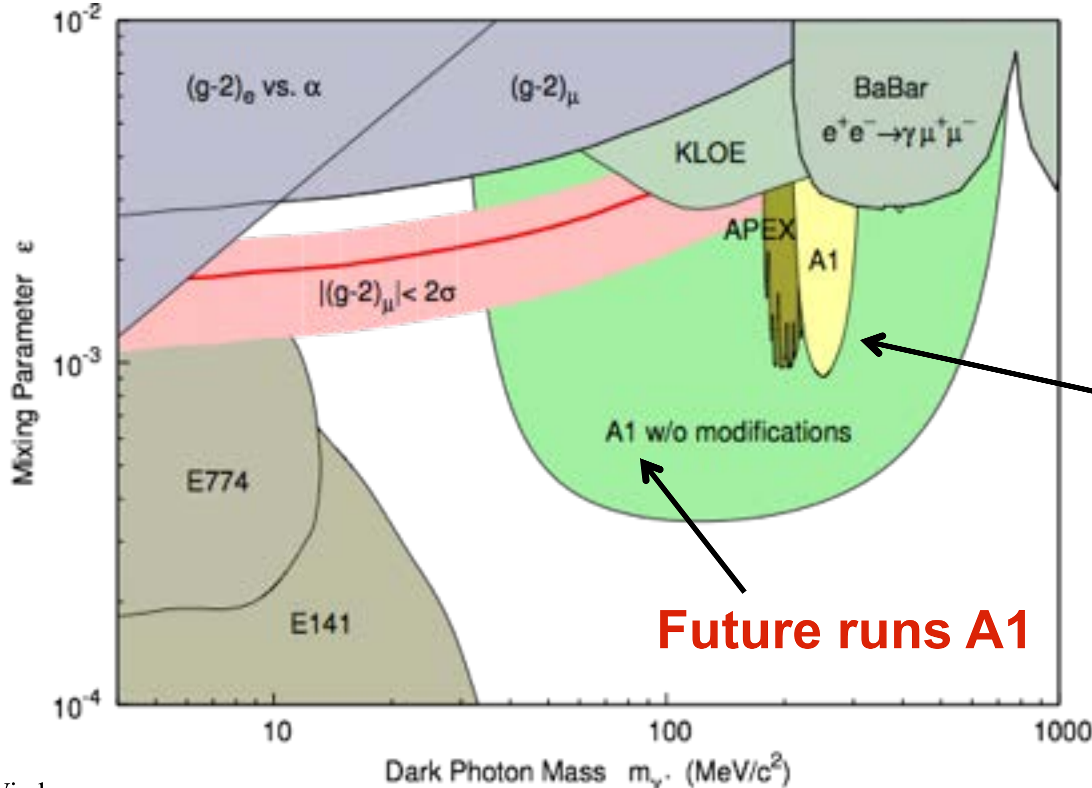
Ulrich Wiedner

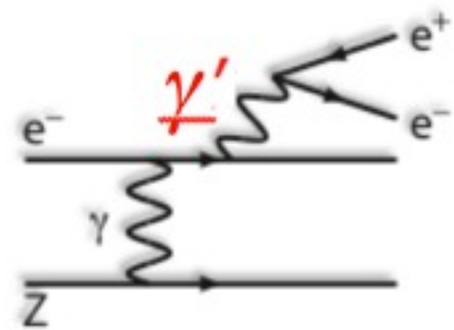
Highlight A1: Dark Photon Search

New massive force carrier of extra U(1) gauge group; predicted e.g. in string theory

Search for the O(GeV/c^2) mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies**
- Could explain presently seen **deviation of 3.6σ** between SM and $(g-2)_\mu$ measurement

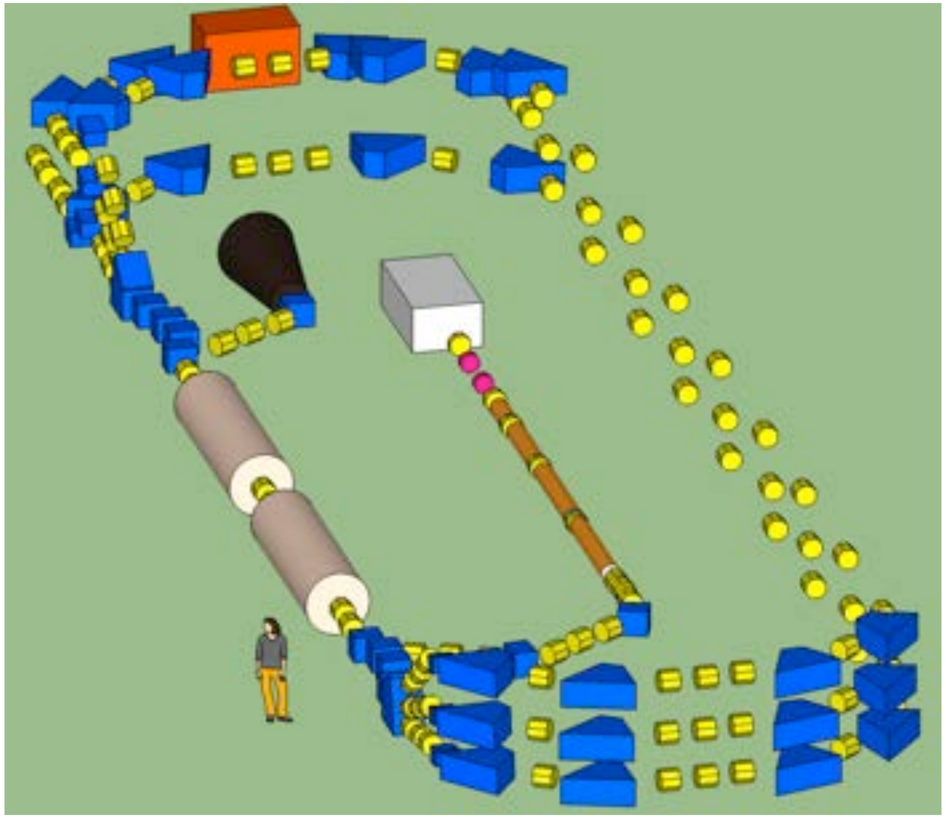




Exclusion range from **MAMI / A1 spectrometers** during **4 days test run**

A1/MAMI
Phys. Rev. Lett. 2011

Outlook: MESA Acclerator



Mainz Energy Recovering Superconducting Accelerator

- **Challenging accelerator project**
- High-gradient superconducting
- Extracted beam mode or ERL mode

Energy: <155 MeV

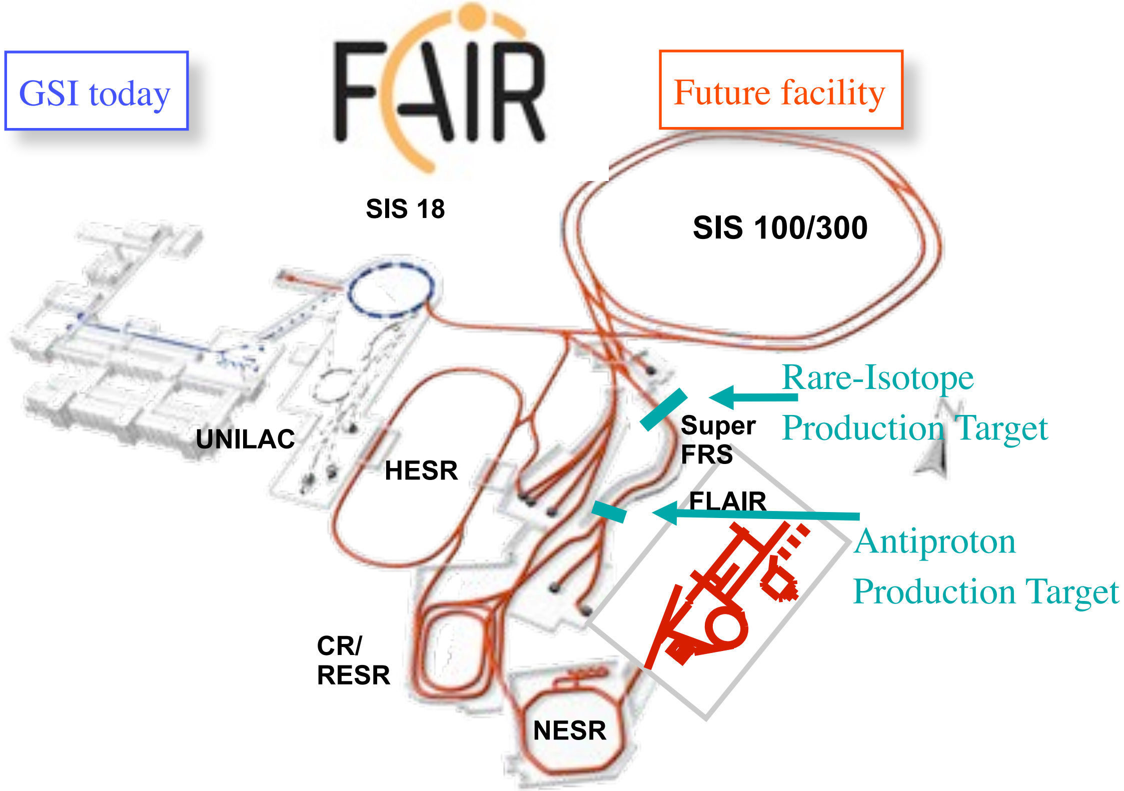
Extracted beam: LH_2 target → 10^{39} cm

ERL mode: Internal gas target

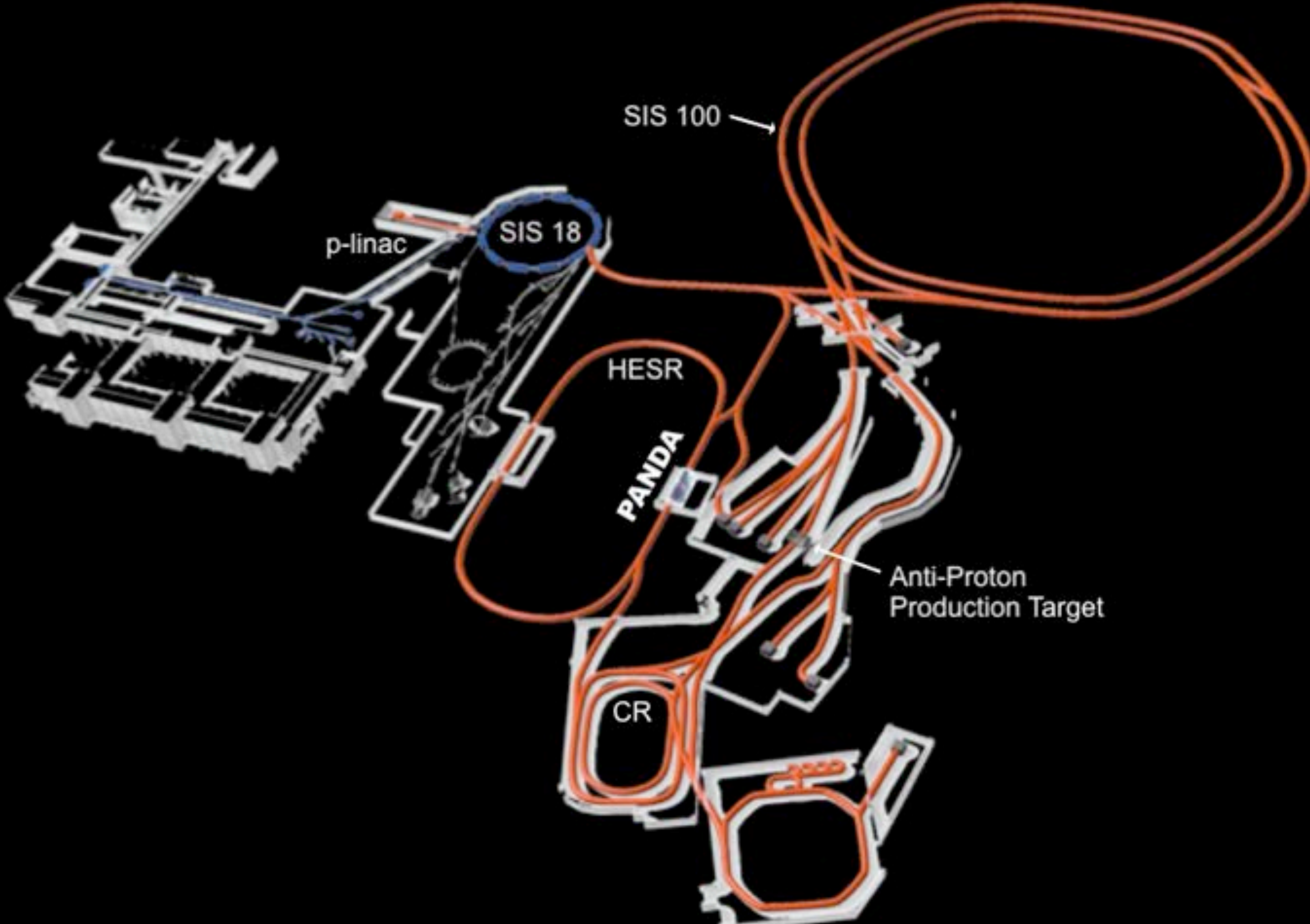
- **Flagship experiments in low-energy particle, hadron and nuclear physics**
- Precision measurement of weak mixing angle $\sin^2\theta_W$ at low Q^2

  → unique precision test of the Standard Model
- Search for the Dark Photon at low masses

Occupancy of Hall D in January 2012 and of the tagger hall in February 2012.


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

August 2012


SIS 100
p-linac
SIS 18
HESR
PANDA
Anti-Proton
Production Target
CR

Thanks to:

Andrea Bressan,
Volker Burkert,
Achim Denig,
Bernhard Ketzer
Curtis Meyer,
Norihito Muramatsu
Takashi Nakano,
Jim Ritman,
Stepan Stepanyan,
Ulrike Thoma
Masaru Yosoi
Patrizia Rossi
Stephen Olsen

Looking forward to a bright and interesting future of hadron physics.