# Hadron Physics - experimental approaches to remaining questions in the Standard Model

Ulrich Wiedner
(Ruhr-University Bochum)

Hirschegg, 17.01.2014

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 |
|---|---|---|
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | –1 |

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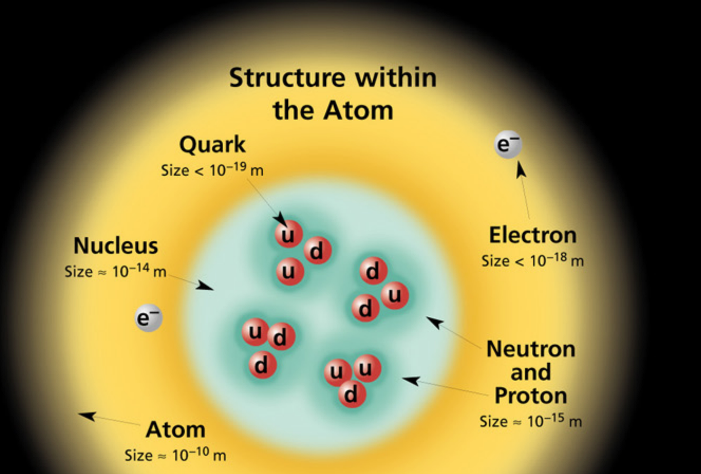
| d down | 0.006 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | –1/3 |

**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 $1.60\times10^{-19}$ coulombs.

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




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

## BOSONS

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

### Unified Electroweak spin = 1

| Name | Mass GeV/c² | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | –1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

### Strong (color) spin = 1

| Name | Mass GeV/c² | Electric charge |
|---|---|---|
| g gluon | 0 | 0 |

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

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

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

## PROPERTIES OF THE INTERACTIONS

| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | 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: $3\times10^{-17}$ 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 |

### 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 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | –1 | 1.672 | 3/2 |

### Mesons $q\bar{q}$

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There are about 140 types of mesons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
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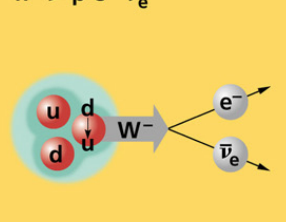
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | –1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2 .980 | 0 |

**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., $Z^0$, $\gamma$, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

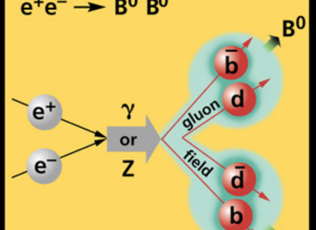
**Figures**
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



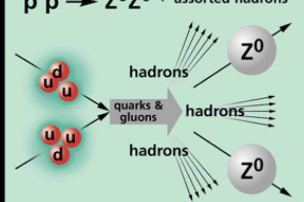

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$




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.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons




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**
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**This chart has been made possible by the generous support of:**
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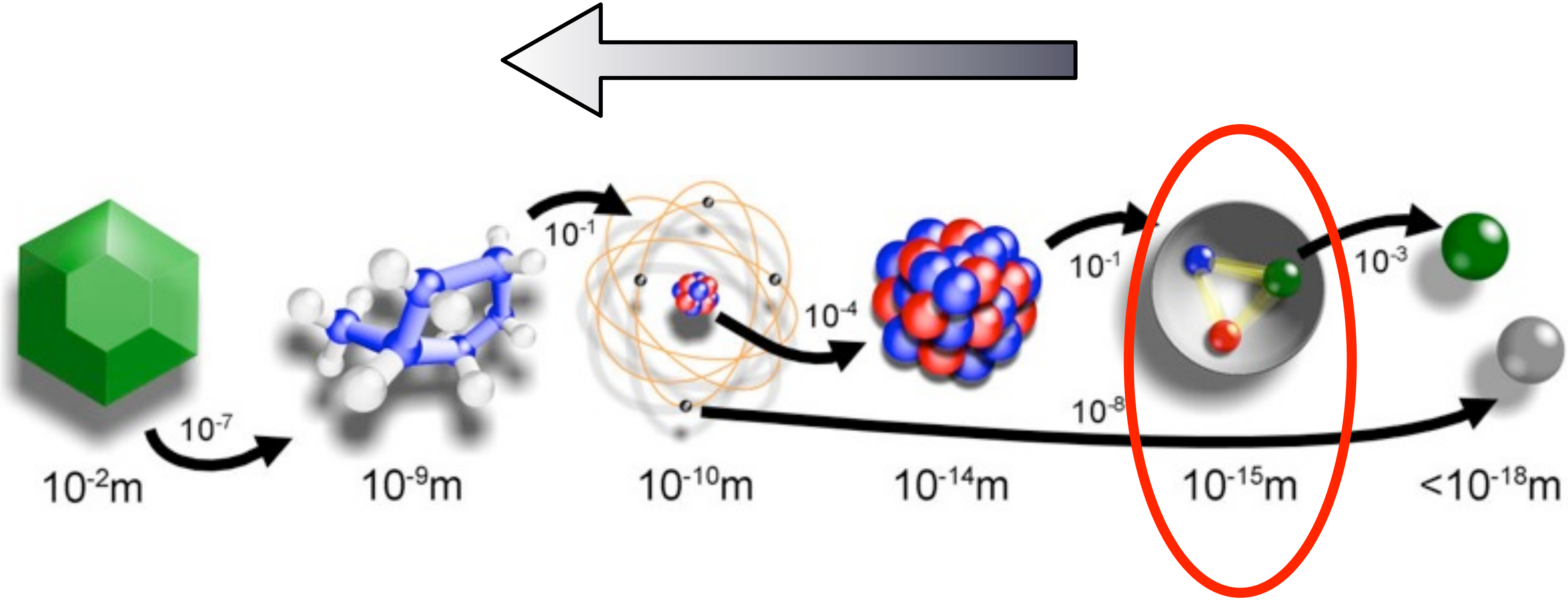
**http://CPEPweb.org**

Level of complexity




Hadron Physics

# *How to study hadrons?*

- *Observe them as existing particles*

  $\gamma$ / 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 lead to an understanding of a (non-perturbative) interaction among the fundamental quarks.

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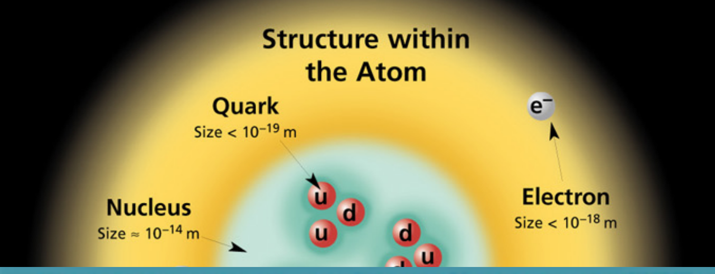


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| Property \ Interact… | | | | Strong …nental | Strong Residual |
|---|---|---|---|---|---|
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| Particles experiencing: | | | | …Gluons | Hadrons |
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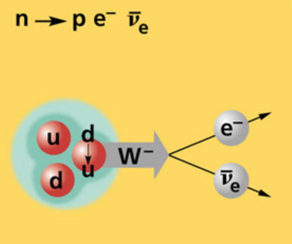


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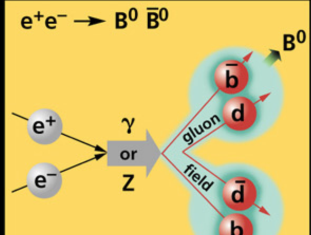


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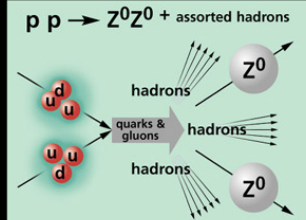


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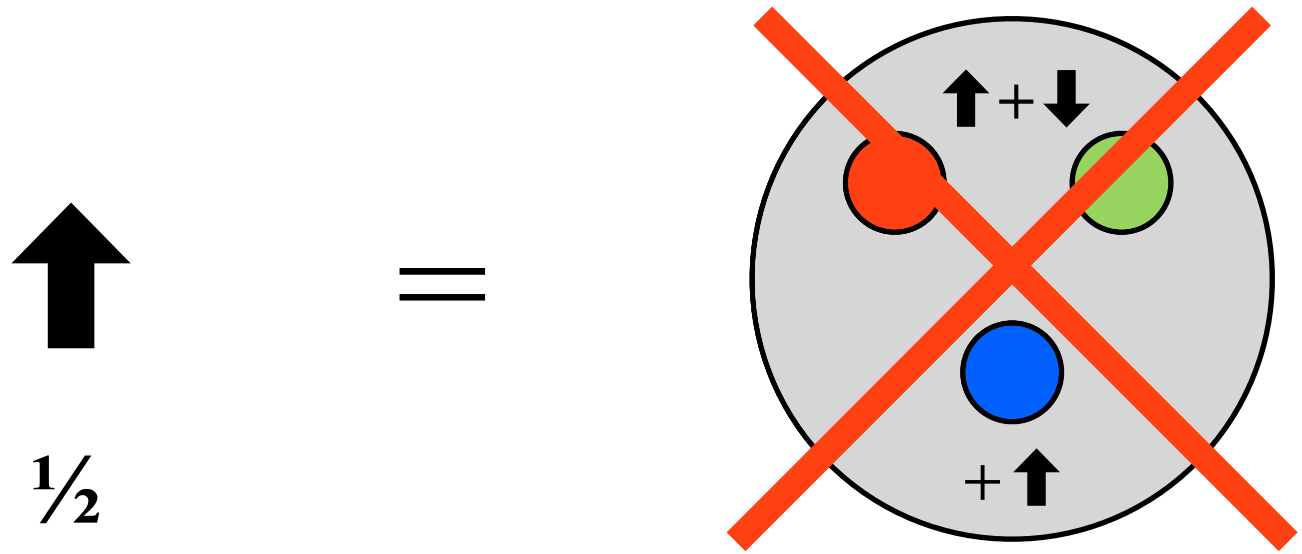
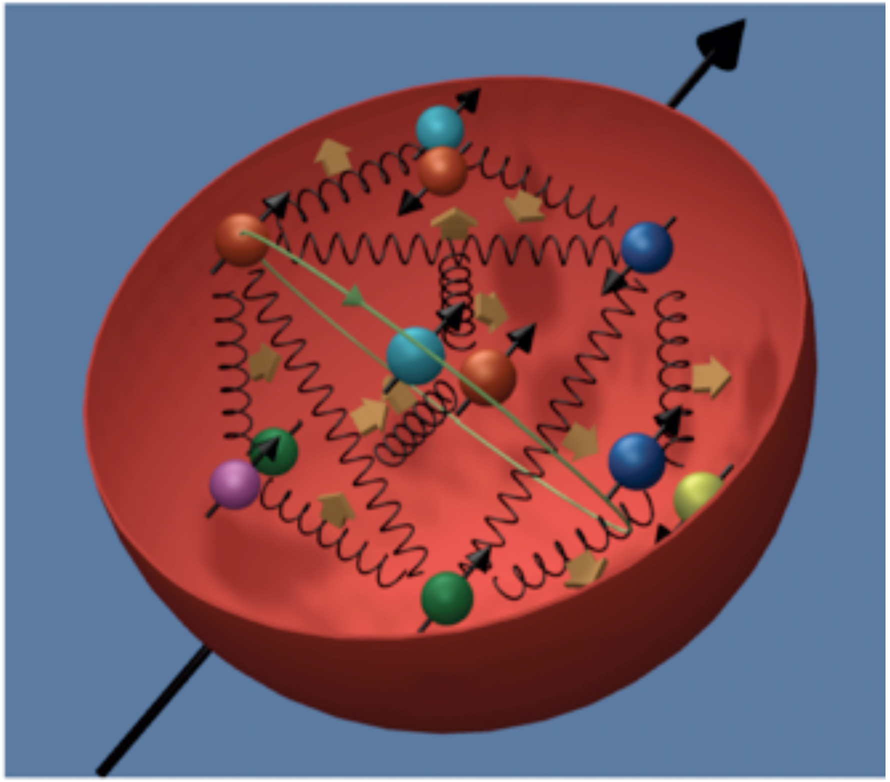
# Spin of the proton

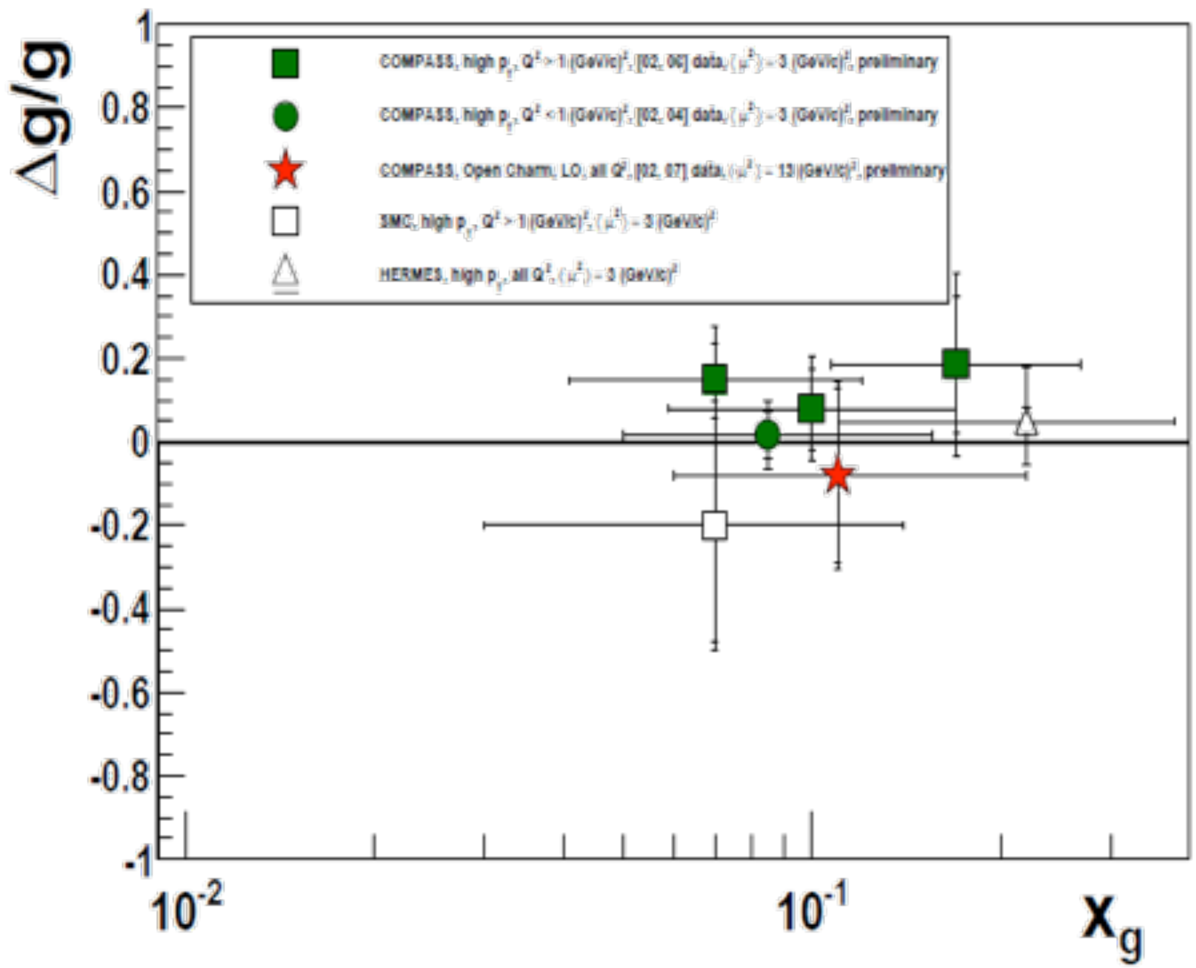



$$\frac{1}{2}\hbar == \sum_q \frac{1}{2} S_q^z + S_g^z + \sum_q L_q^z + L_g^z$$

# The Nucleon (as composed by fundamental particles)



# Gluon polarization results from SMC, HERMES, and COMPASS

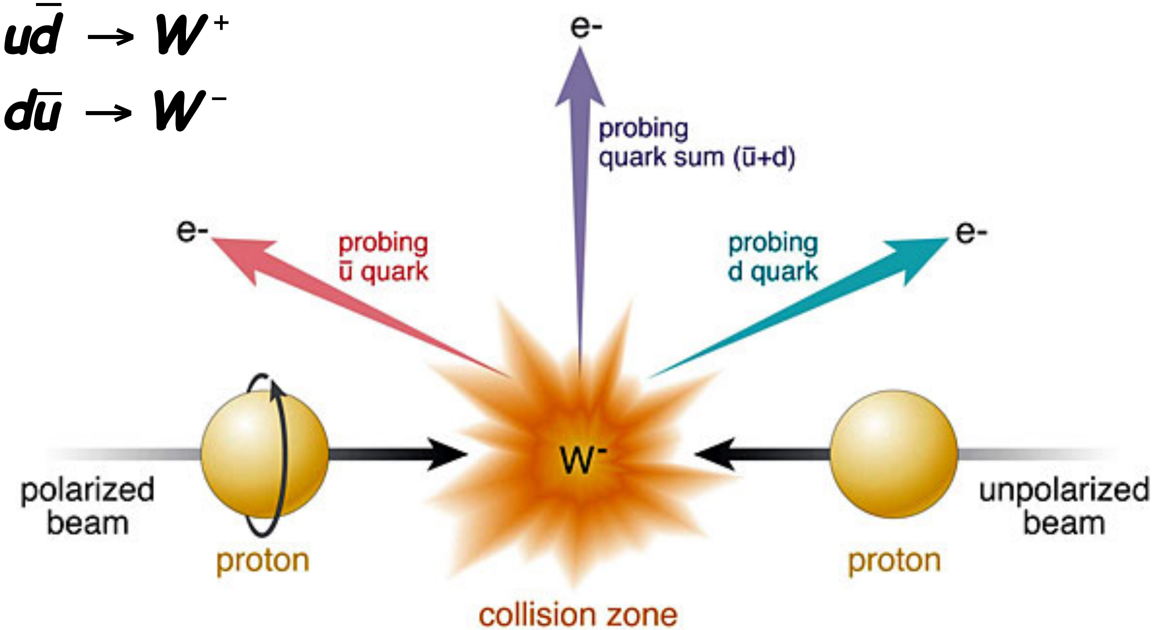



- The gluon polarisation is rather small
- Maybe some slightly higher values from polarised pp data at RHIC

# New investigations of the proton structure at RHIC

$u\bar{d} \rightarrow W^+$

$d\bar{u} \rightarrow W^-$

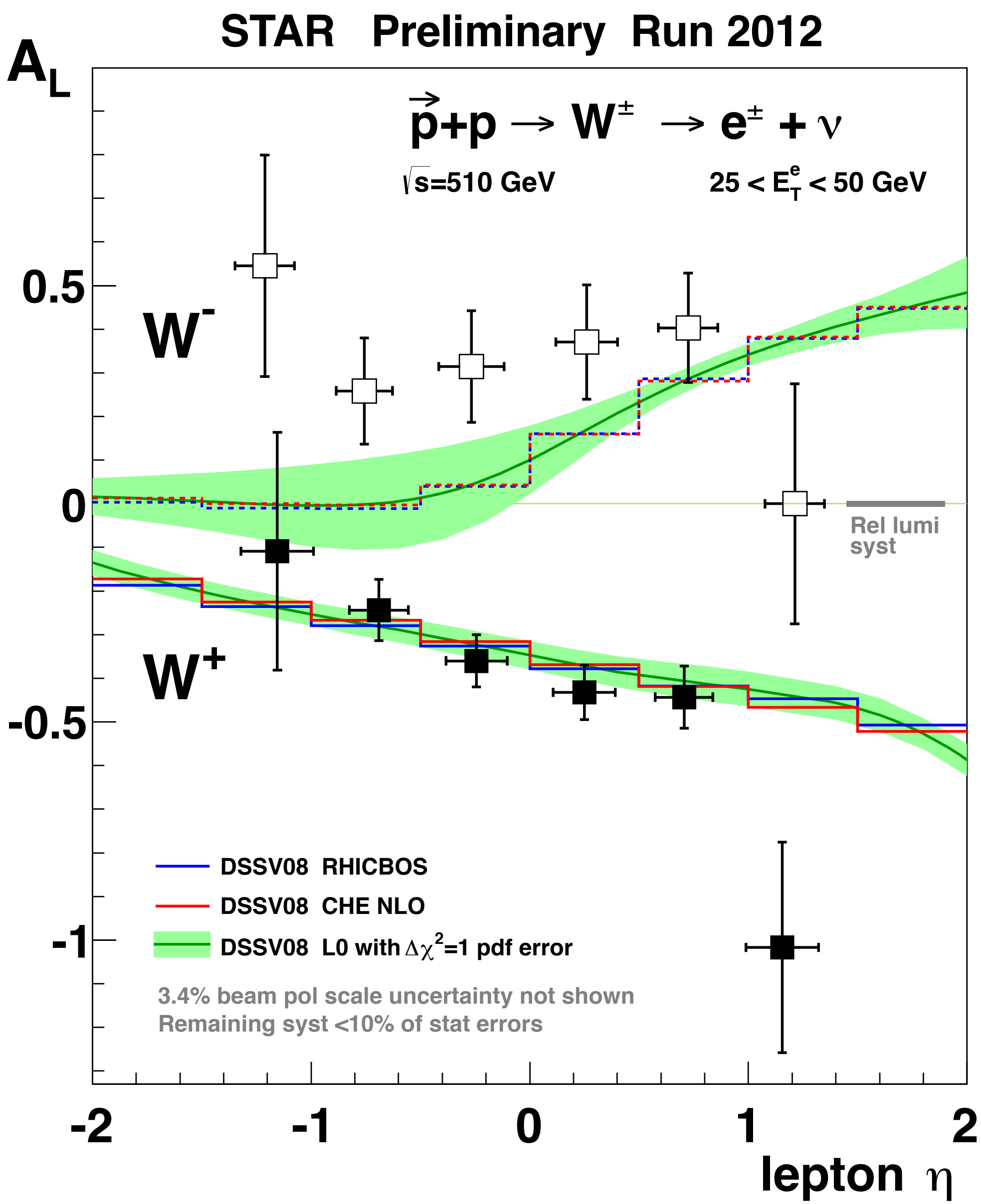



The W is maximally parity violating ⇒ W's couple only to one parton helicity and therefore large Δu and Δd result in large asymmetries.

$$A_L^{e^-} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

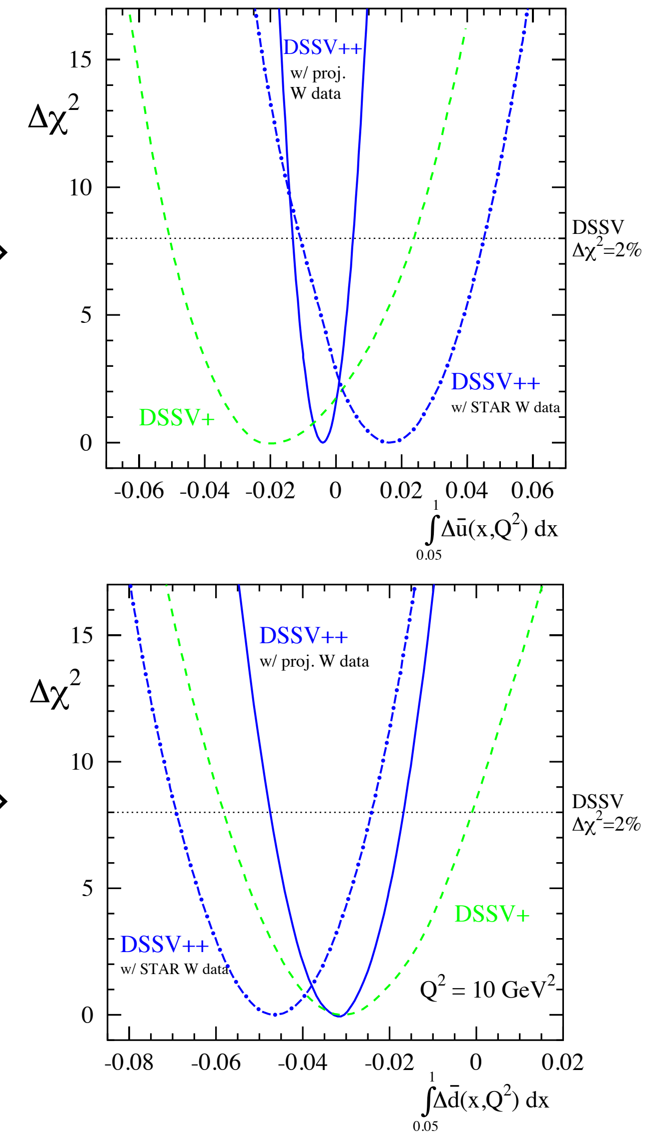
**very high Q2-scale**
**extremely clean theoretically**
**No Fragmentation function**

# Impact of the W-results




$\Delta\bar{u}$ $\Rightarrow$

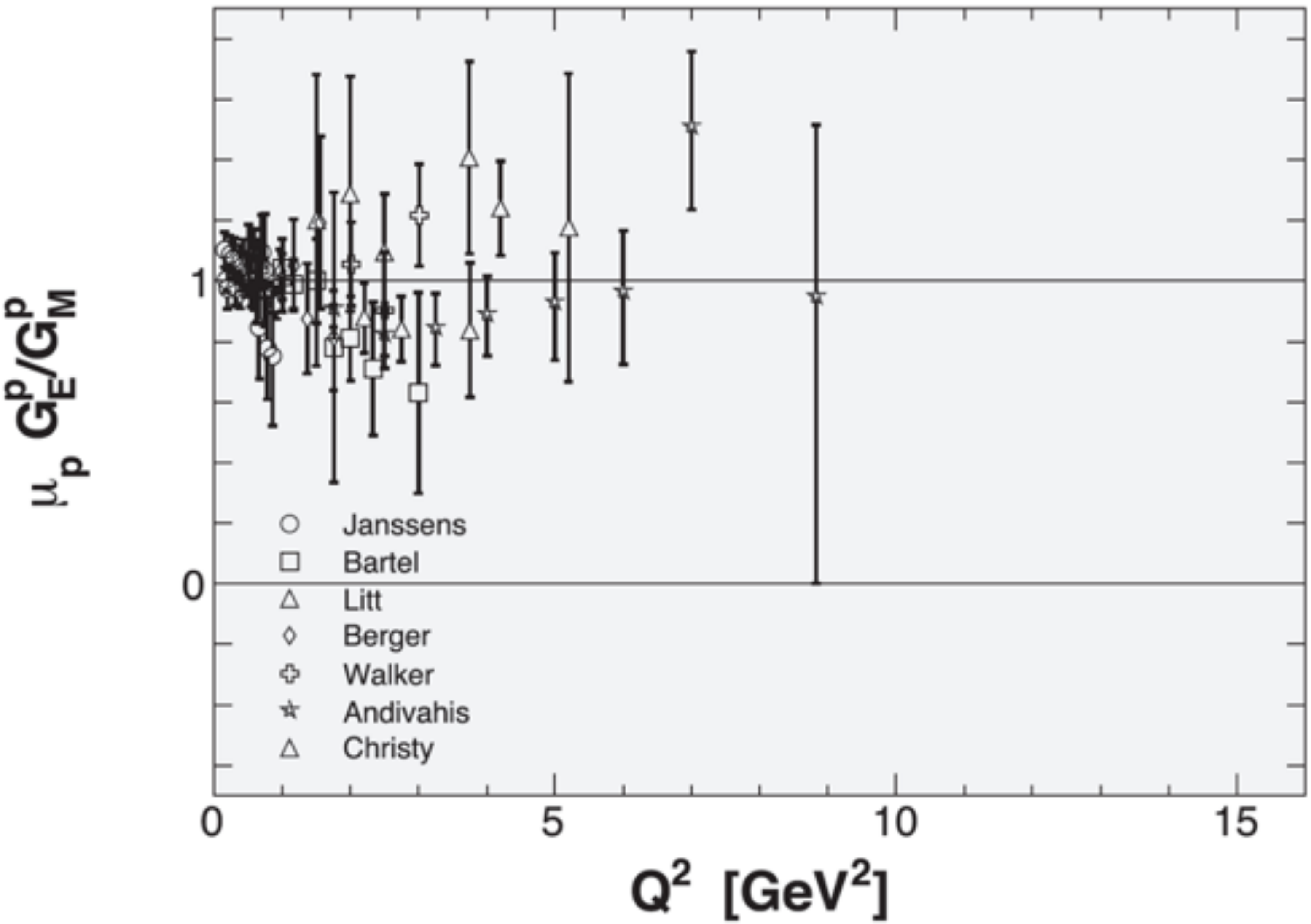
$\Delta\bar{d}$ $\Rightarrow$




Aschenauer et al.: arXiv:1304.0079

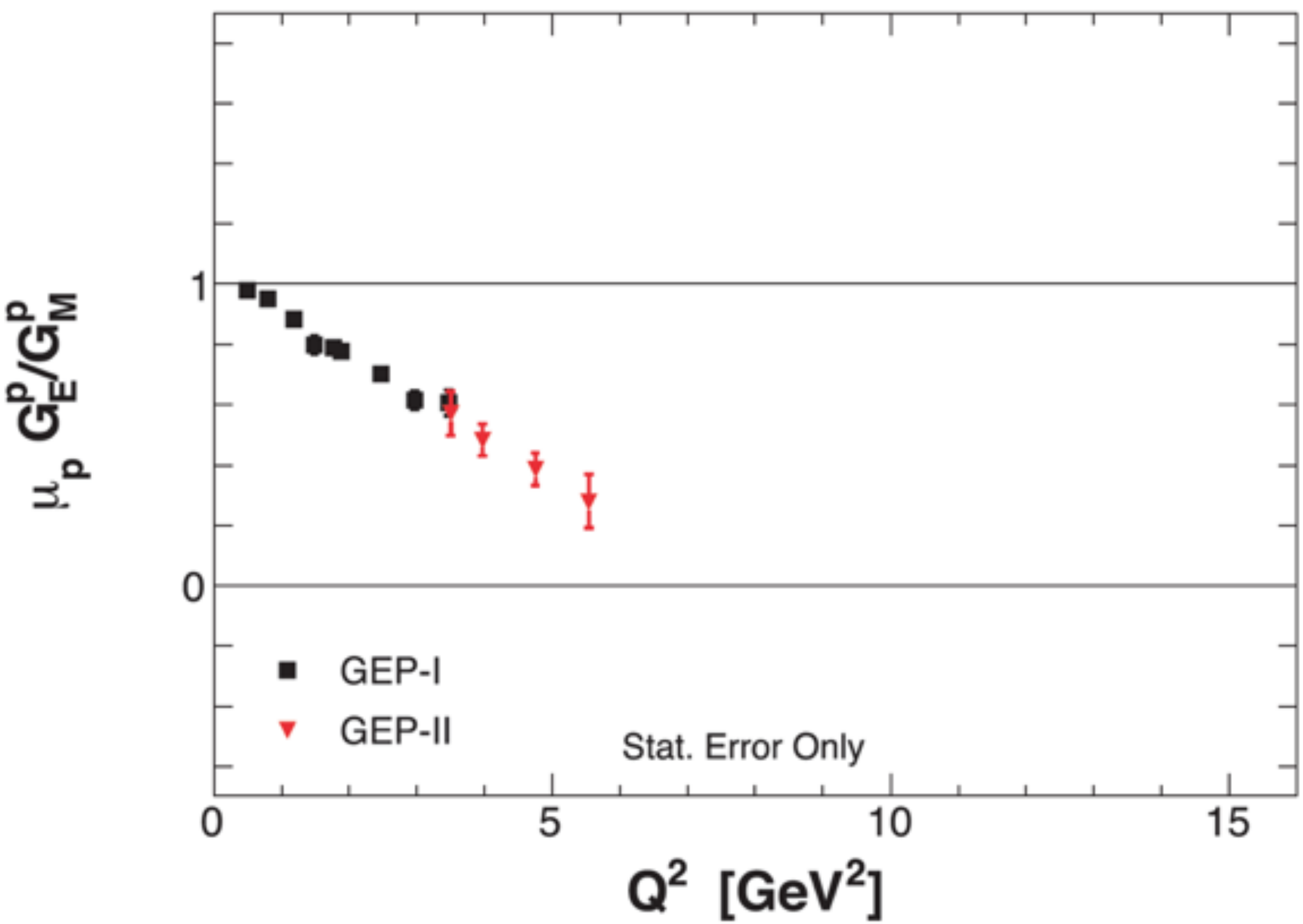
*Form factors*

## 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.

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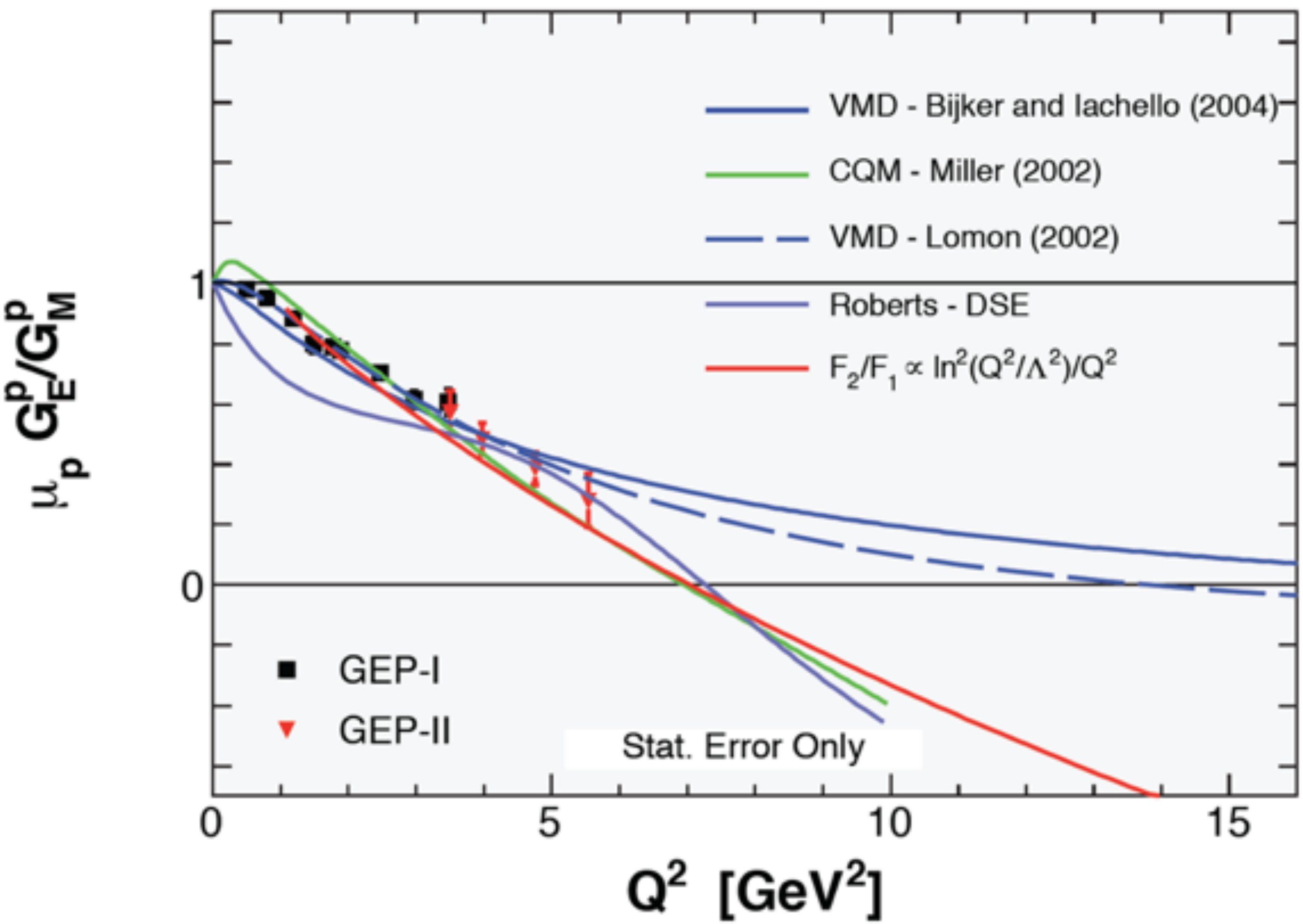
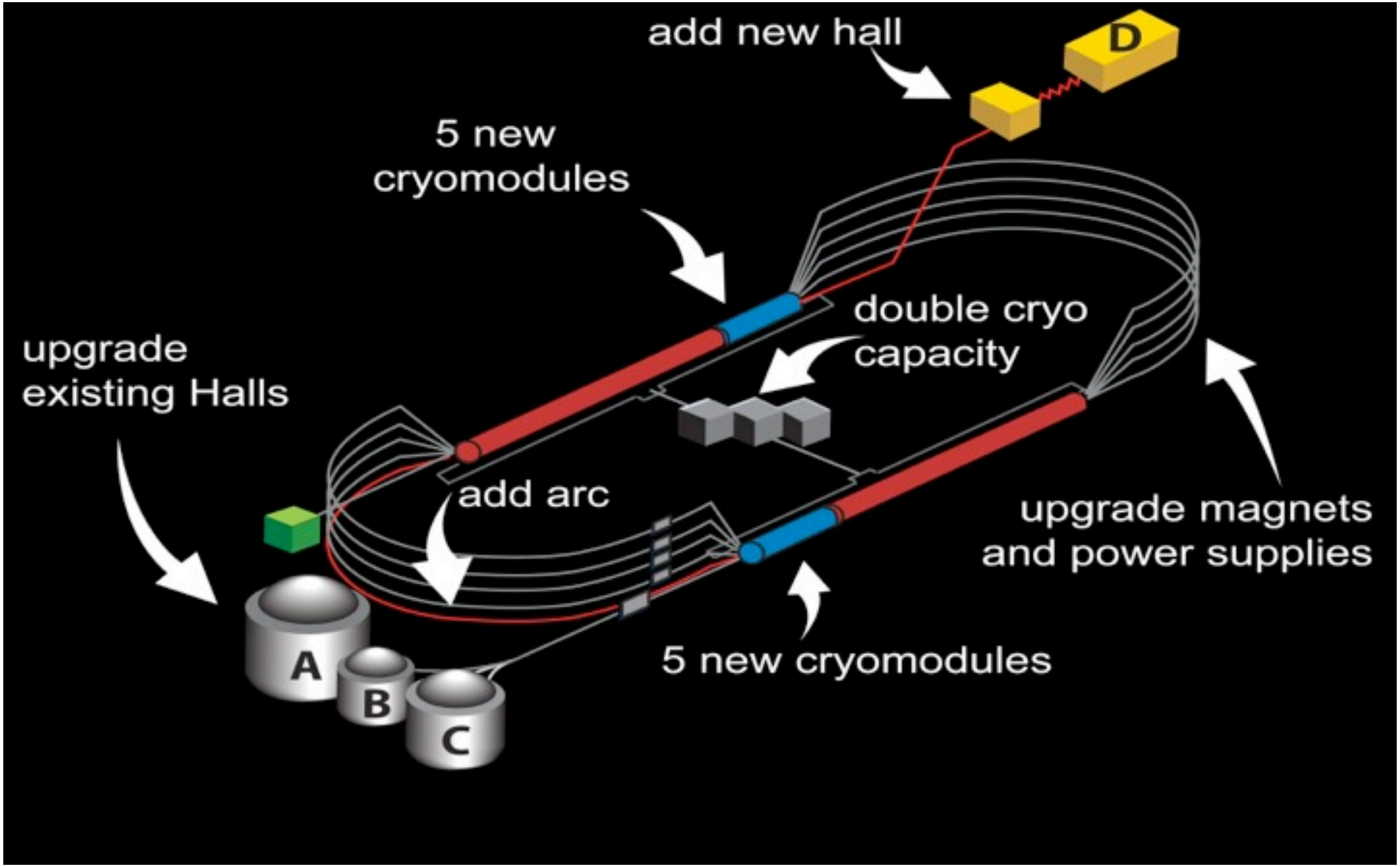


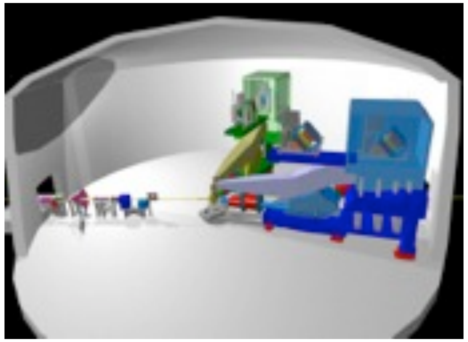

Often interpretations invoked the importance of quark orbital angular momentum (quark OAM)

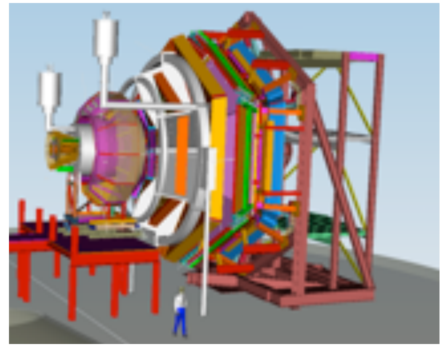
More high $Q^2$ data needed!

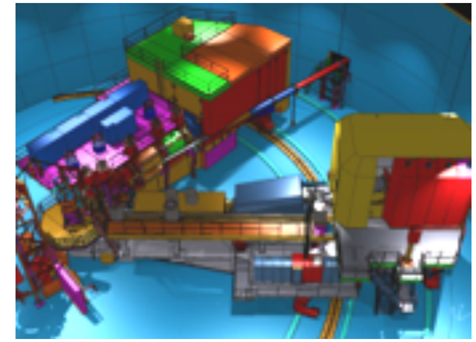
# JLAB - 12 GeV


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

# The planned Jefferson Laboratory Experiments

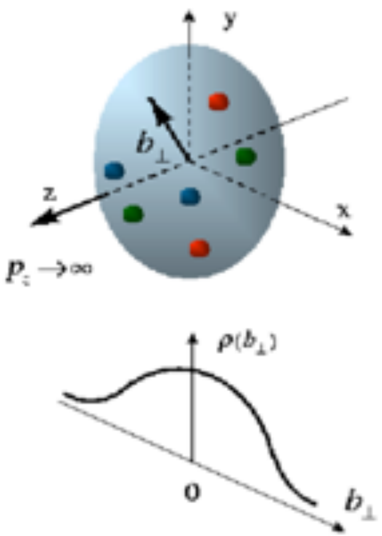




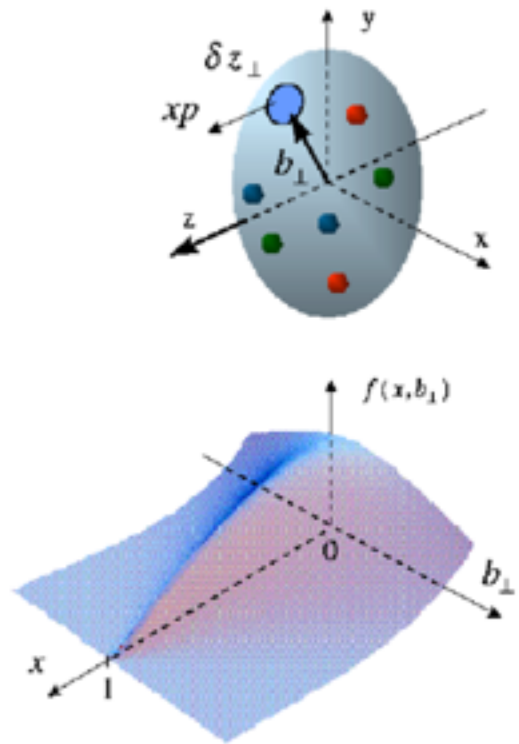


| Hall A | Hall B | Hall C |
|---|---|---|
| installation space | luminosity $10^{35}$ | energy reach |
| | hermeticity | precision |
| | 11 GeV beamline | |
| | target flexibility | |
| excellent momentum resolution | good momentum/angle resolution | excellent momentum resolution |
| luminosity up to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

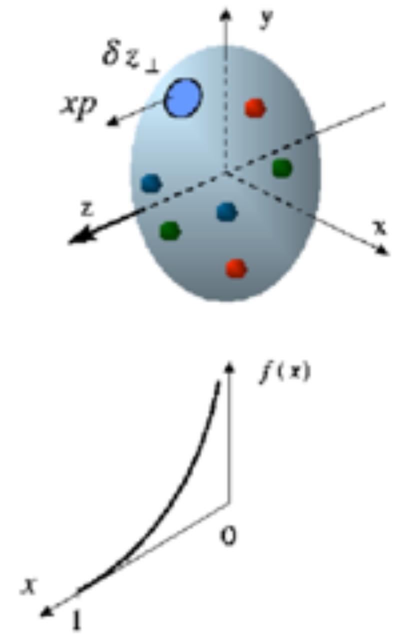
# More than form factors and quark distributions
# ⇒ Generalized Parton Distributions (GPDs)




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).

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 |
|---|---|---|
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | –1 |

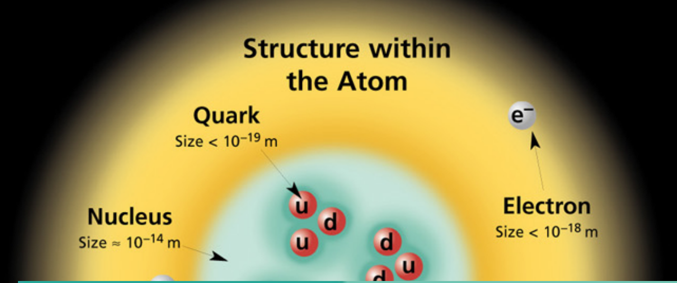
**Quarks** spin = 1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.003 | 2/3 |
| d down | 0.006 | –1/3 |
| 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 $1.60\times10^{-19}$ 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/$c^2$ (remember $E = mc^2$), where 1 GeV = $10^9$ eV = $1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/$c^2$ = $1.67\times10^{-27}$ kg.




## BOSONS

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

**Unified Electroweak** spin = 1

| Name | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | –1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

**Strong (color)** spin = 1

| Name | Mass GeV/$c^2$ | 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.

| Strong | |
|---|---|
| Fundamental | Residual |
| Color Charge | See Residual Strong Interaction Note |
| Quarks, Gluons | Hadrons |
| Gluons | Mesons |
| 25 | Not applicable to quarks |
| 60 Not applicable to hadrons | 20 |

PR... NS

| Property \ Interaction | | | | Strong Fundamental | Strong Residual |
|---|---|---|---|---|---|
| Acts on: | | | | ...or Charge | See Residual Strong Interaction Note |
| Particles experiencing: | | | | ...rks, Gluons | Hadrons |
| Particles mediating: | ...iton (not yet observed) | ...W⁺ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

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

| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | 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 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | –1 | 1.672 | 3/2 |

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

| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | –1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | 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., $Z^0$, $\gamma$, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

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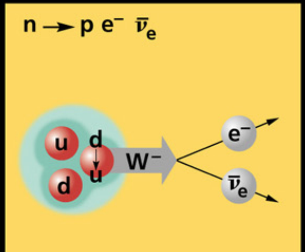
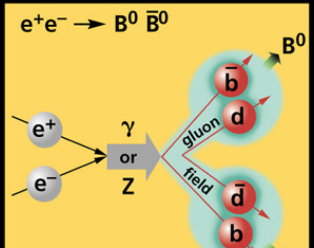
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.




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

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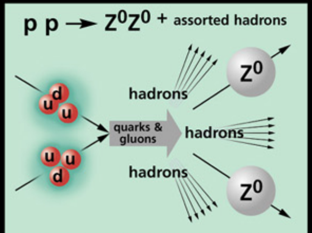


Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

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**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**

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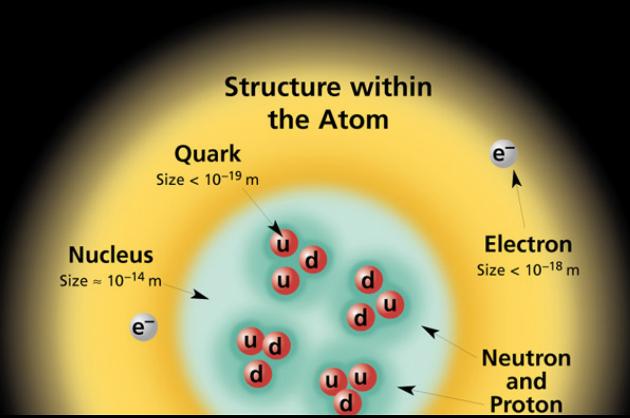


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| | | | | | |
|---|---|---|---|---|---|
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| n | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
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| | | | | | |
|---|---|---|---|---|---|
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| | | | | | |
|---|---|---|---|---|---|
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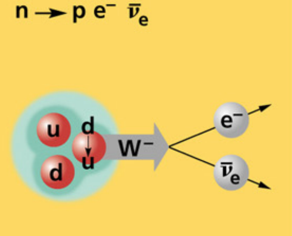
$n \rightarrow p\, e^- \,\bar{\nu}_e$

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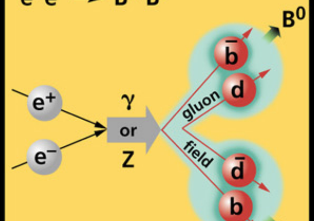
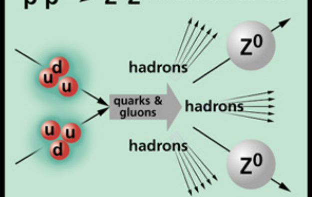



An electron and positron (antielectron) colliding at high energy can annihilate to produce $B^0$ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons

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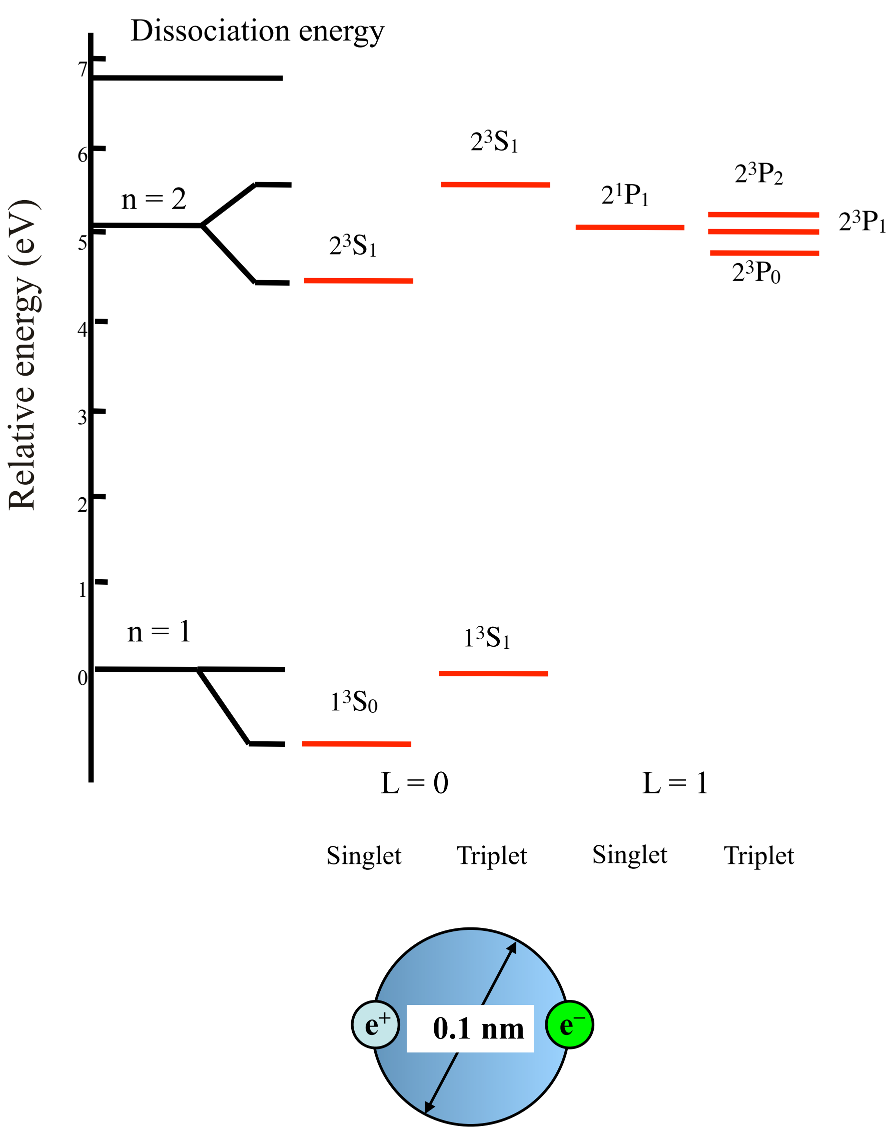
**BURLE** INDUSTRIES, INC.

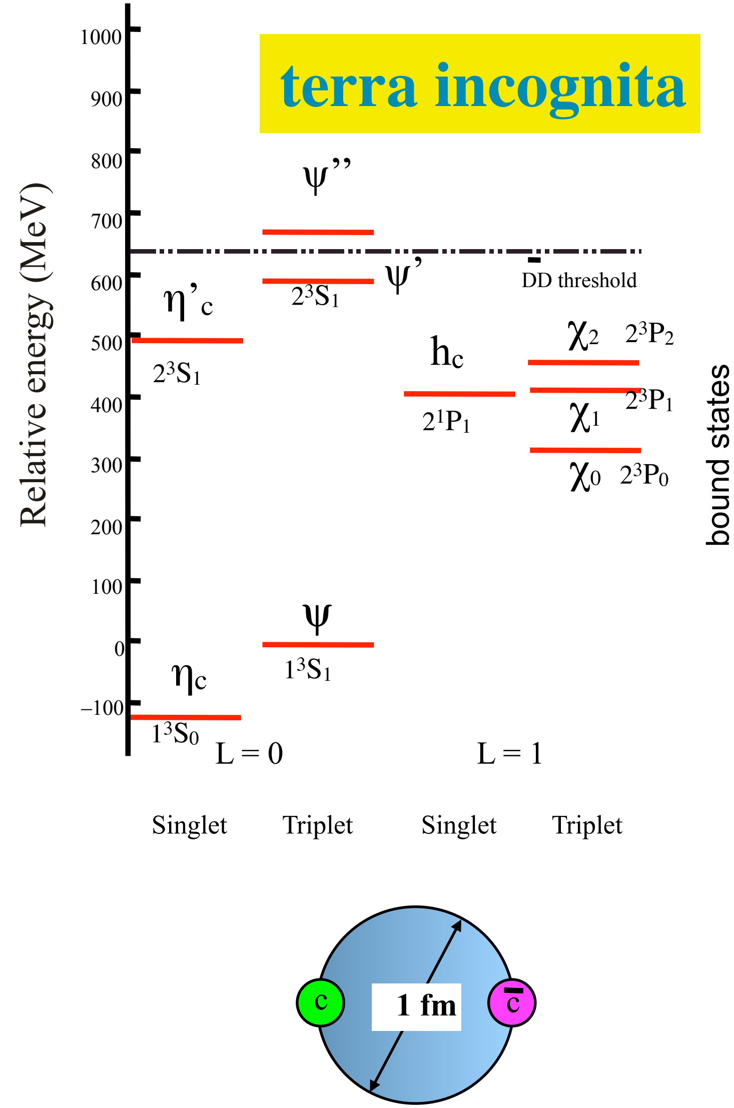



**http://CPEPweb.org**

# Positronium



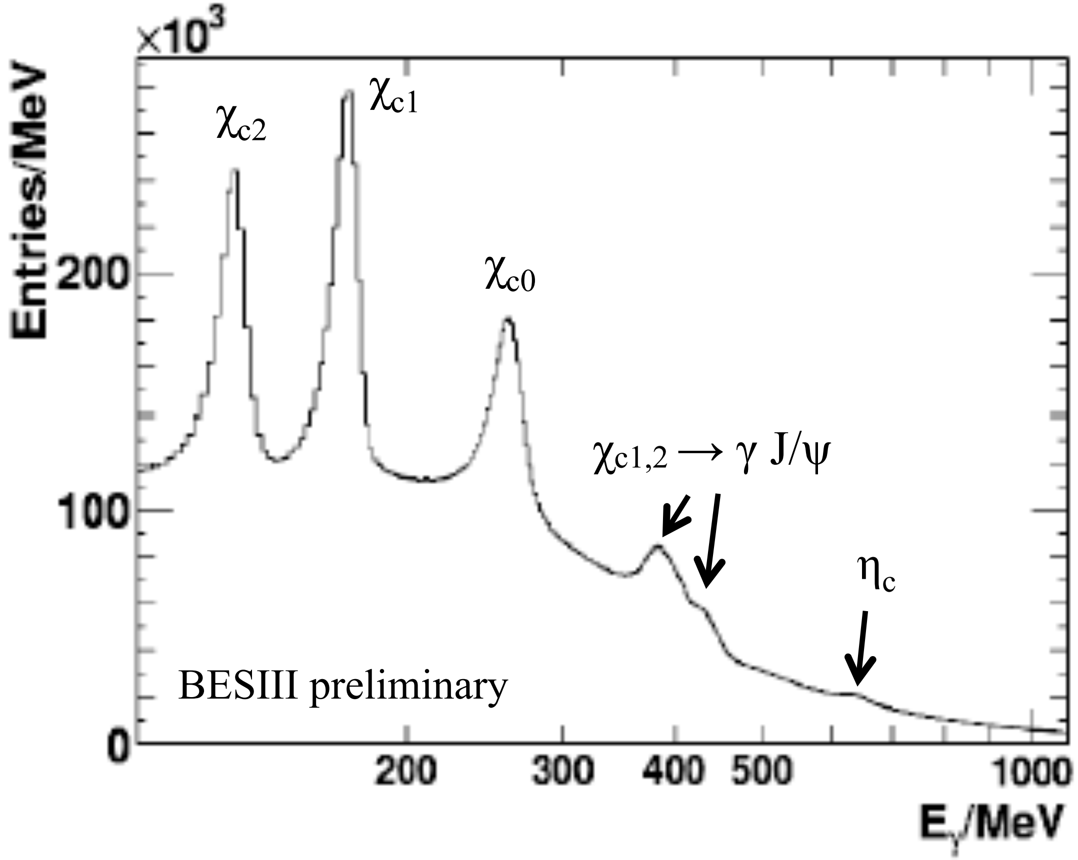

# Charmonium



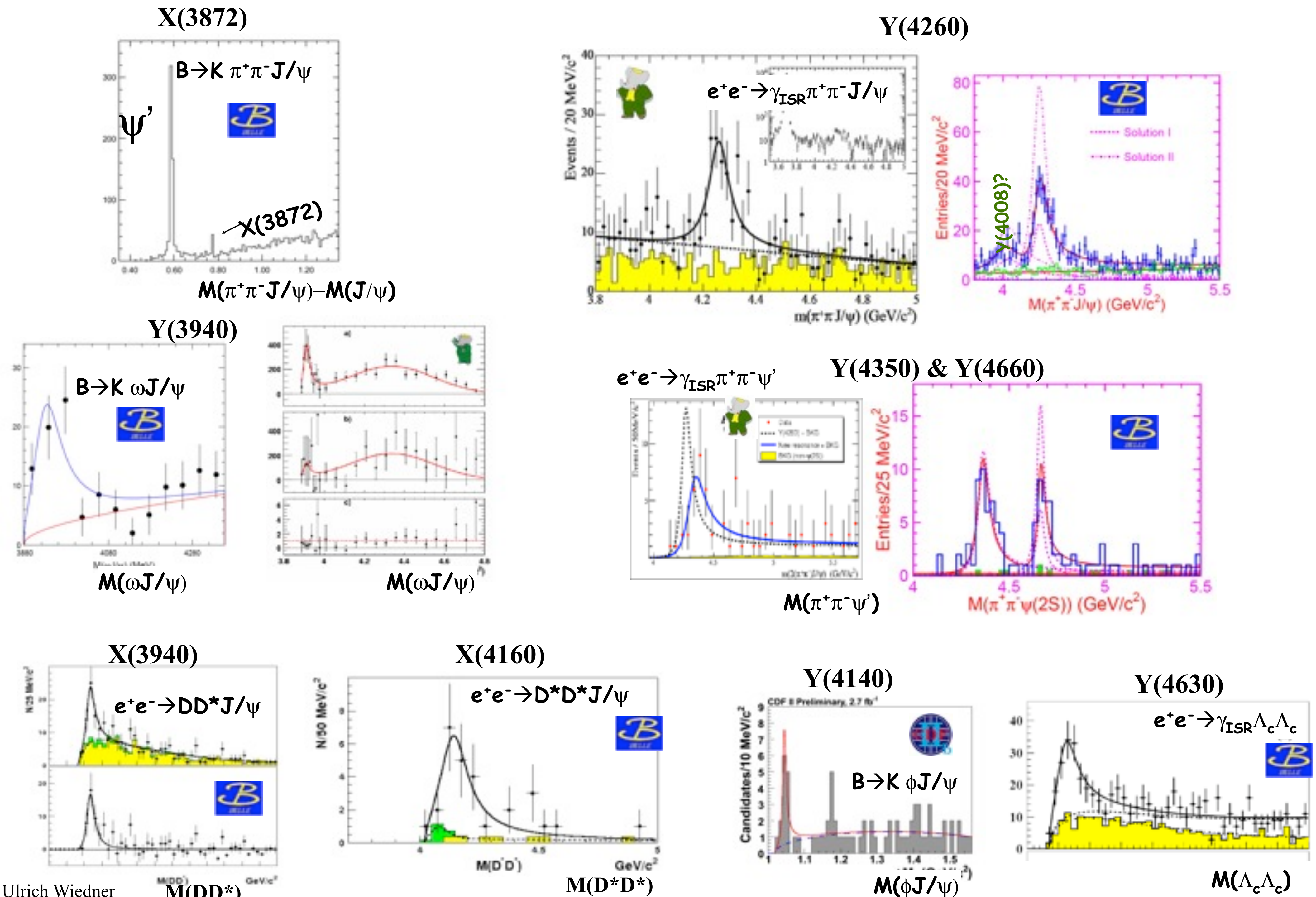

Ulrich Wiedner

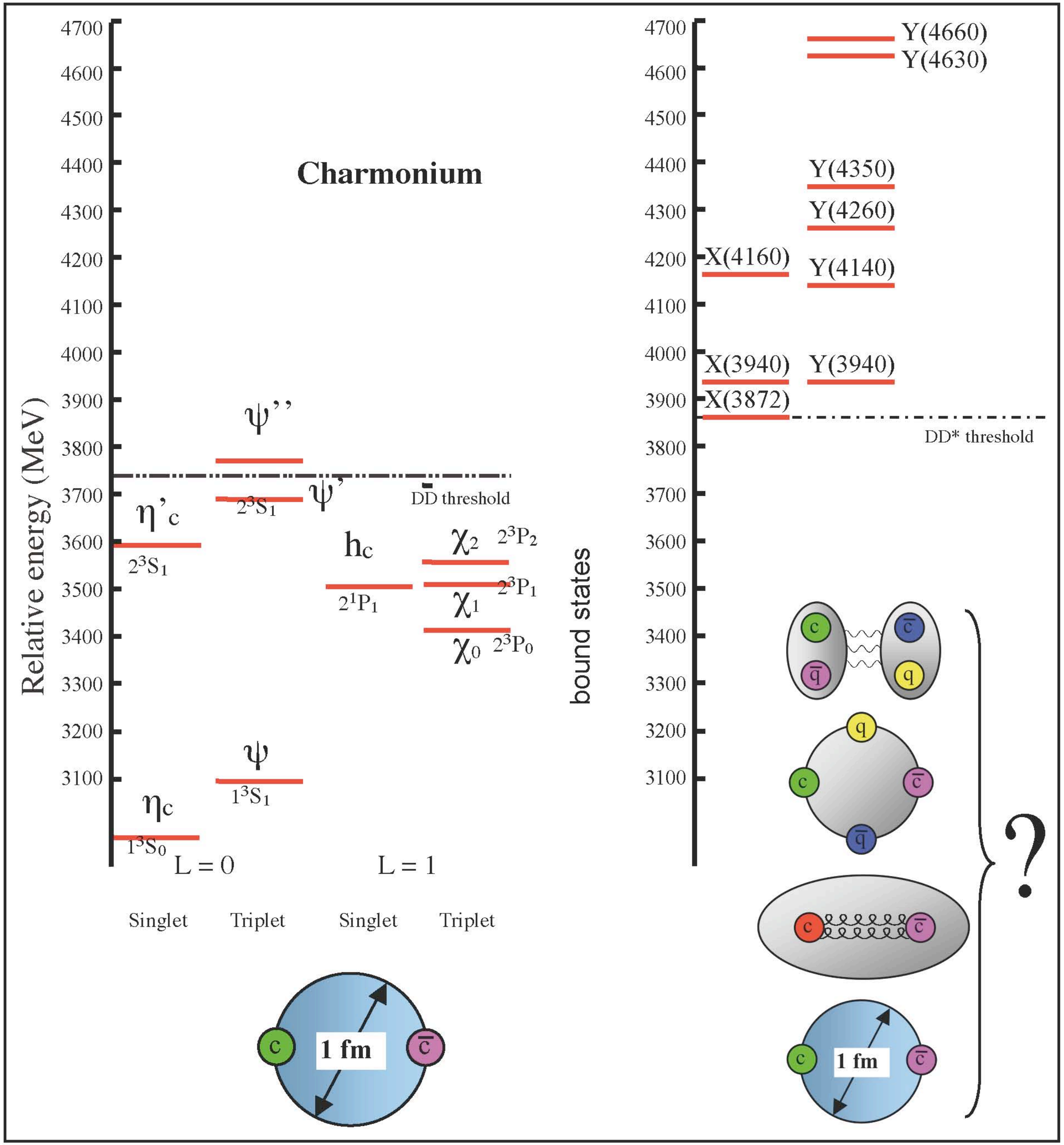
# BESIII data quality

$\psi' \to \gamma X$



# X and Y mesons



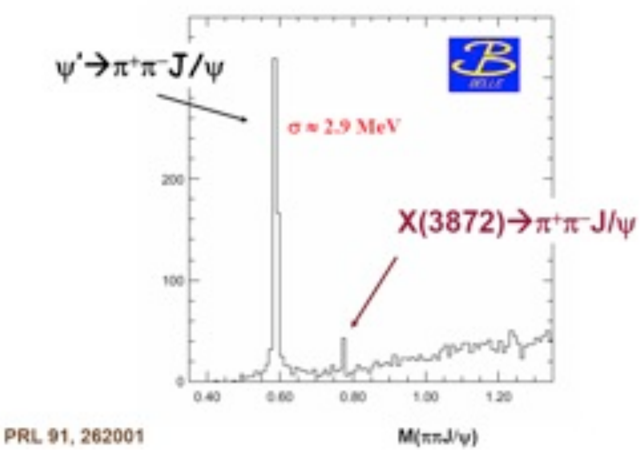


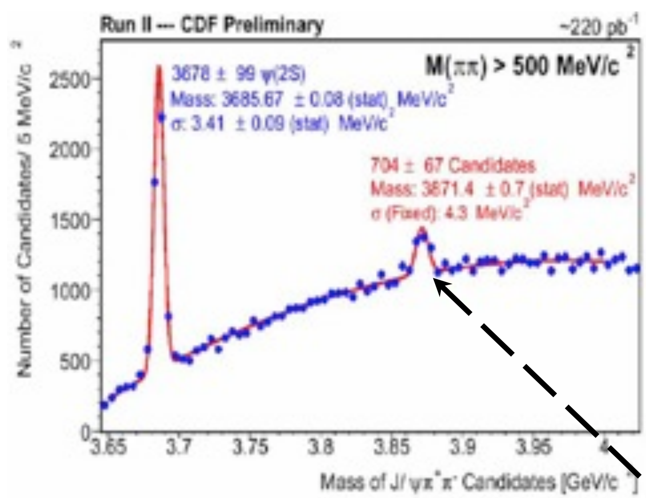

Ulrich Wiedner

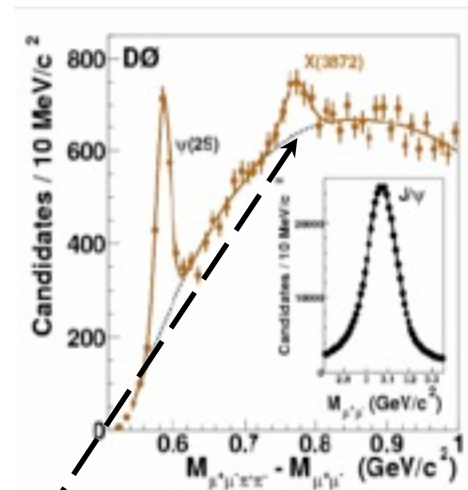
# X(3872)

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

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



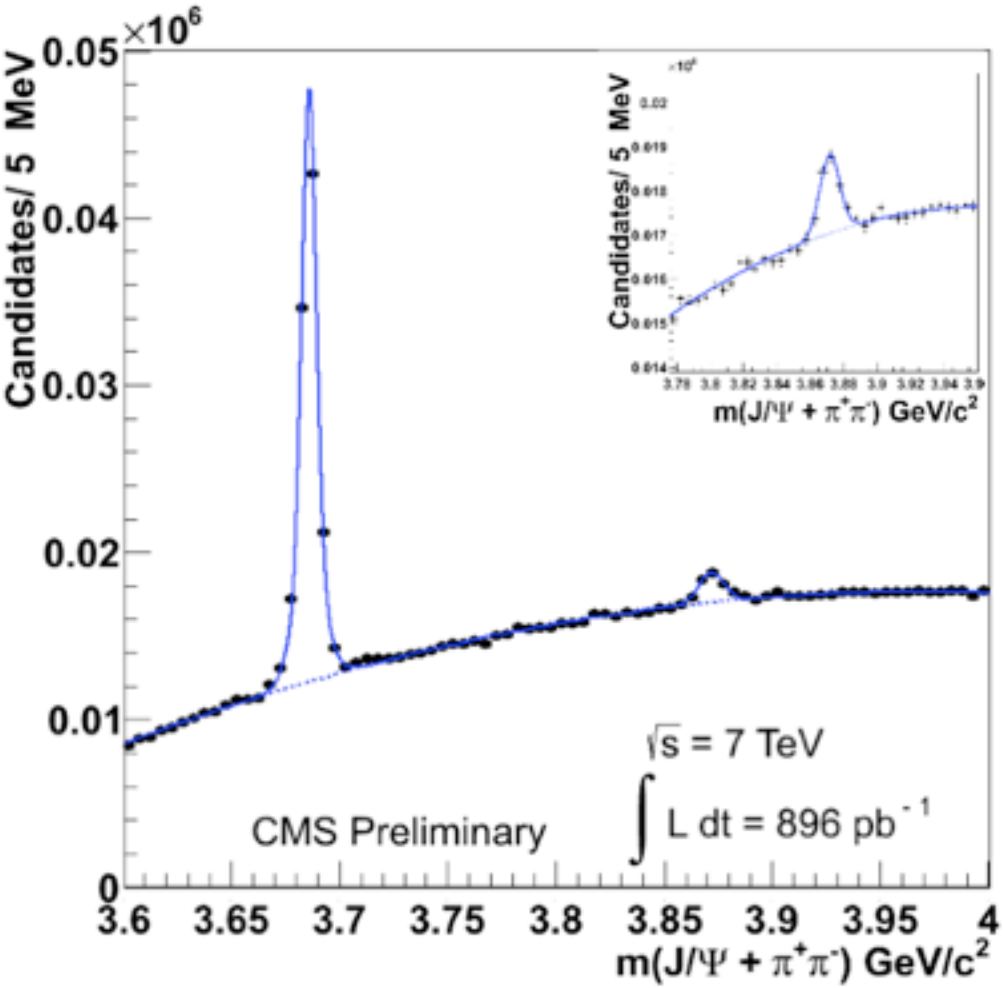



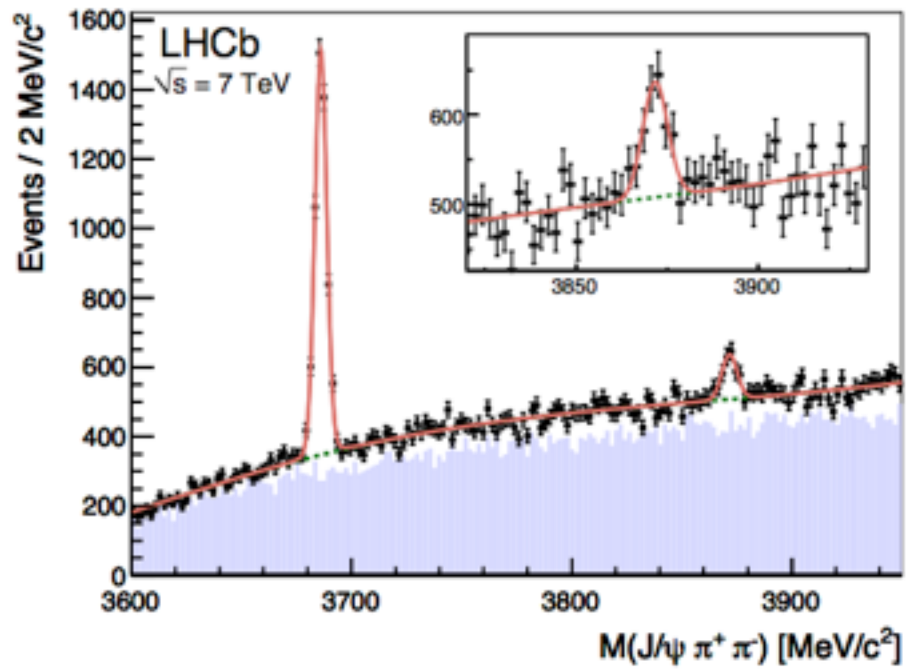

X(3872)

?

DD* molecule
threshold effect
tetraquark

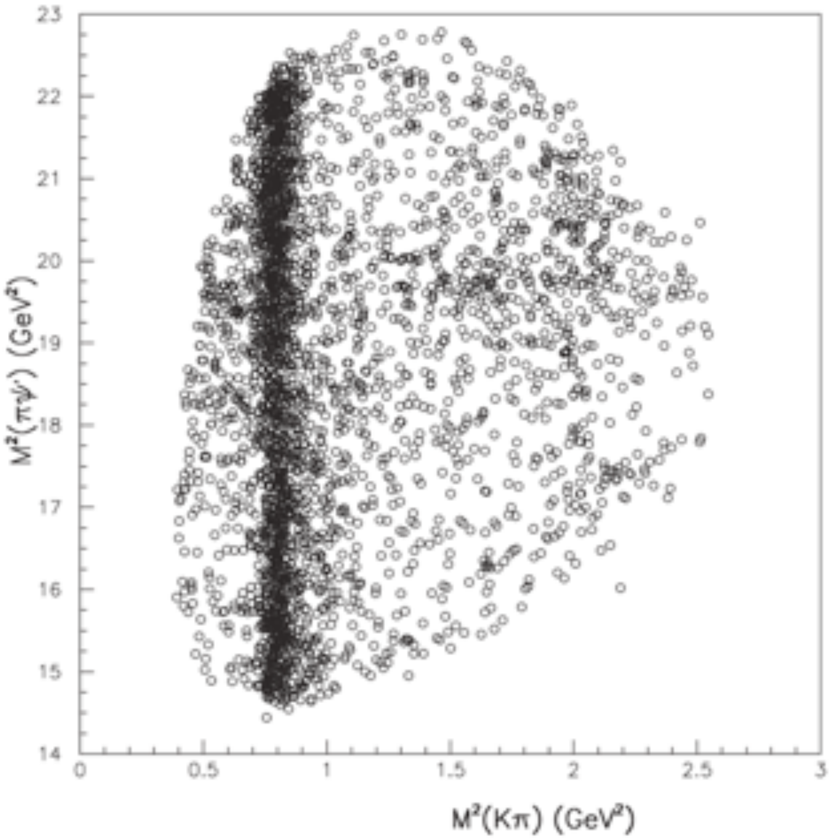
CMS: PoS EPS-HEP2011 (2011) 177

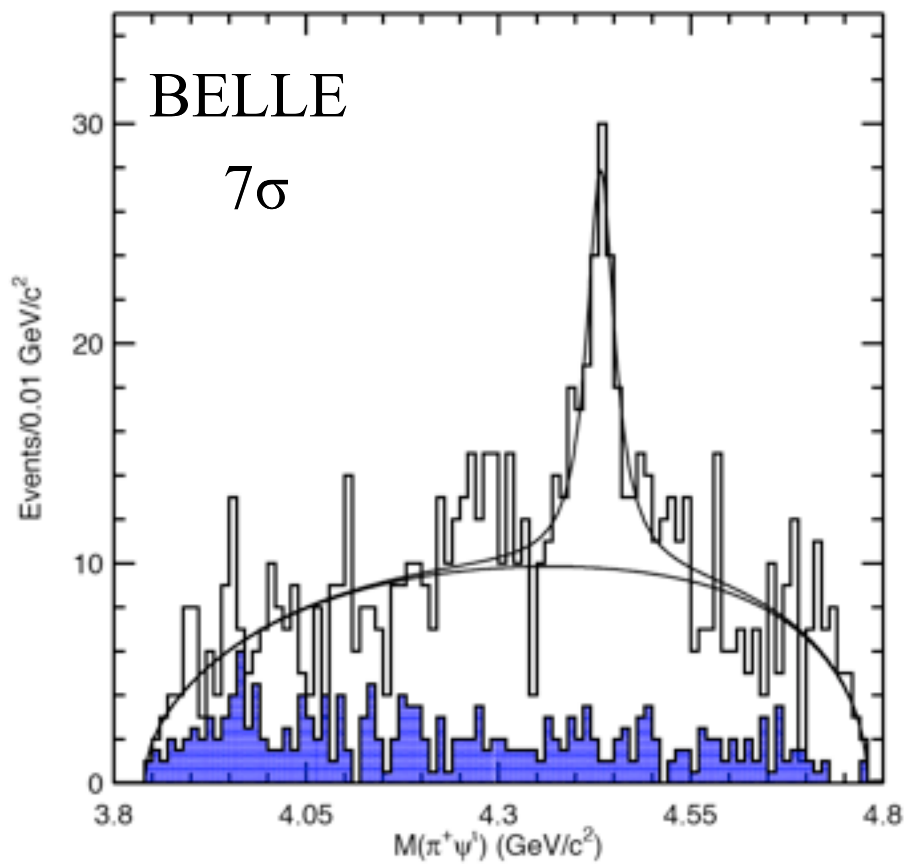



EPJC 72, 1972 (2012)

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




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

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

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


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

# BESIII data samples

2009 : 106 M $\psi(2S)$ events (×4 CLEOc)

225 M $J/\psi$ events (×4 BESII)

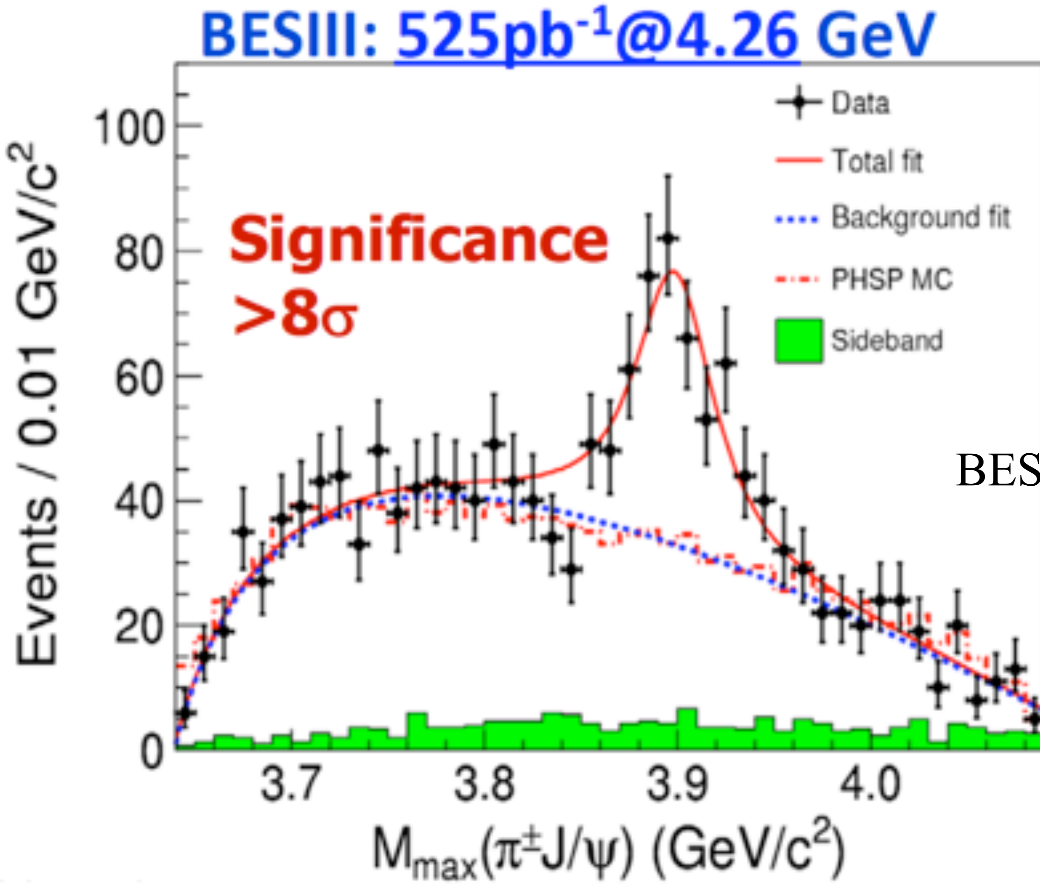
2010 - 2011 : 2.9 $fb^{-1}$ $\psi(3770)$

~ 30 $pb^{-1}$ $\tau$ mass scan

2012: ~ 0.4 billion $\psi(2S)$ events
~ 1 billion $J/\psi$ events
R scan [2.0, 3.65] GeV

2013: ~ 1.1, 0.8, 0.5 fb-1 @ 4.23, 4.26, 4.36 GeV
and scan in vicinity

# Observation of $Z_c(3900)$ at BESIII

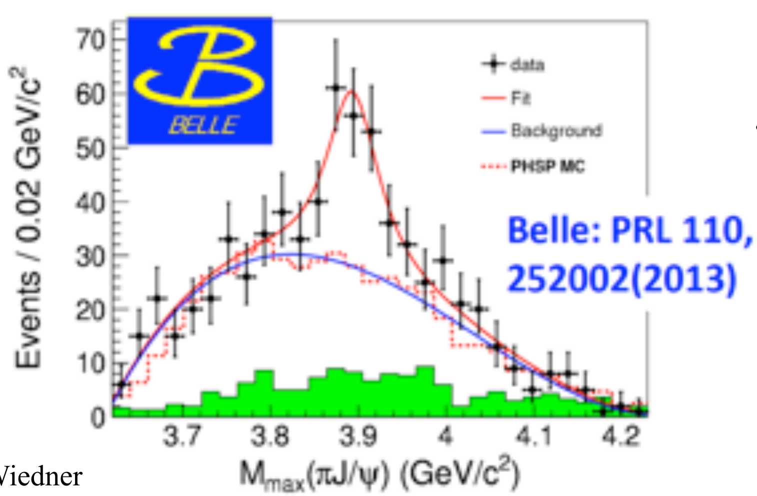



$M = 3899.0 \pm 3.6 \pm 4.9$ MeV

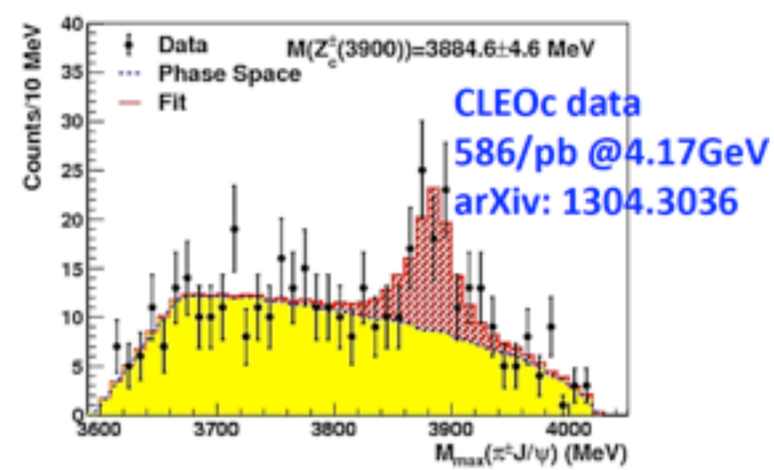
$\Gamma = 46 \pm 10 \pm 20$ MeV

$307 \pm 48$ events

BESIII: PRL110, 252001 (2013)



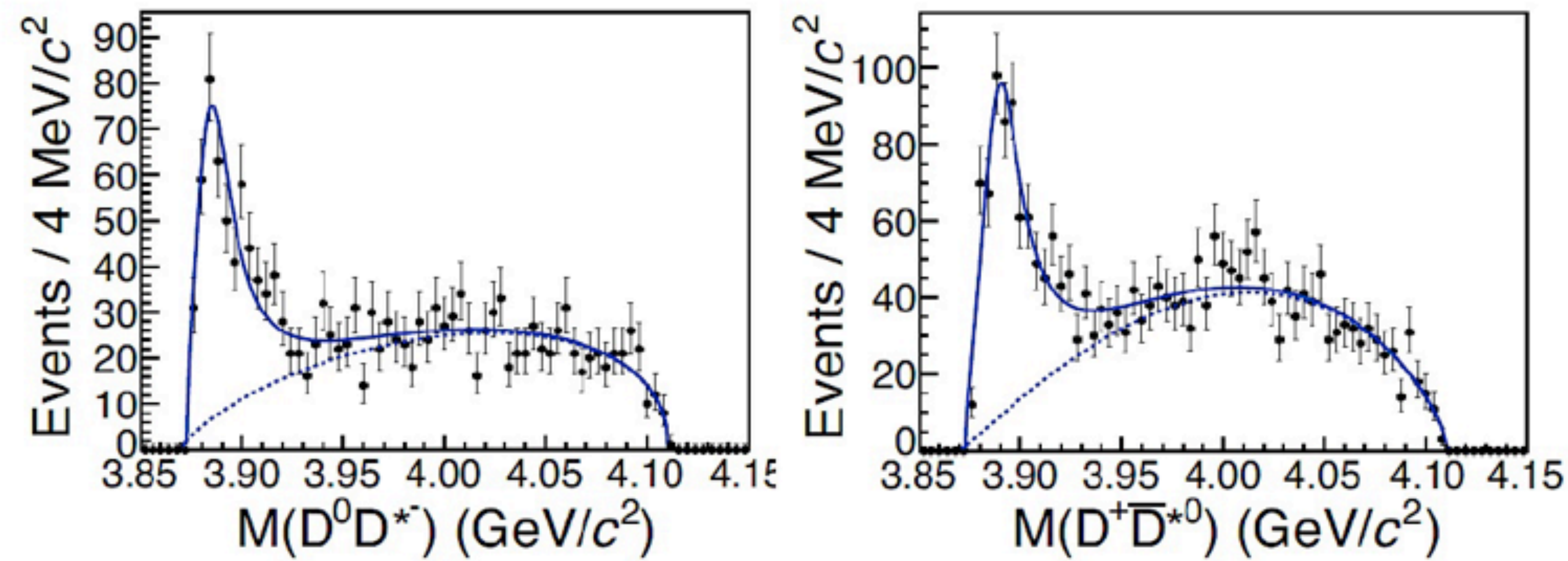

... quickly confirmed



# Observation of $Z_c(3885)$ in $e^+e^- \rightarrow \pi^- (D^*D)^+$

BESIII: 1310.1163

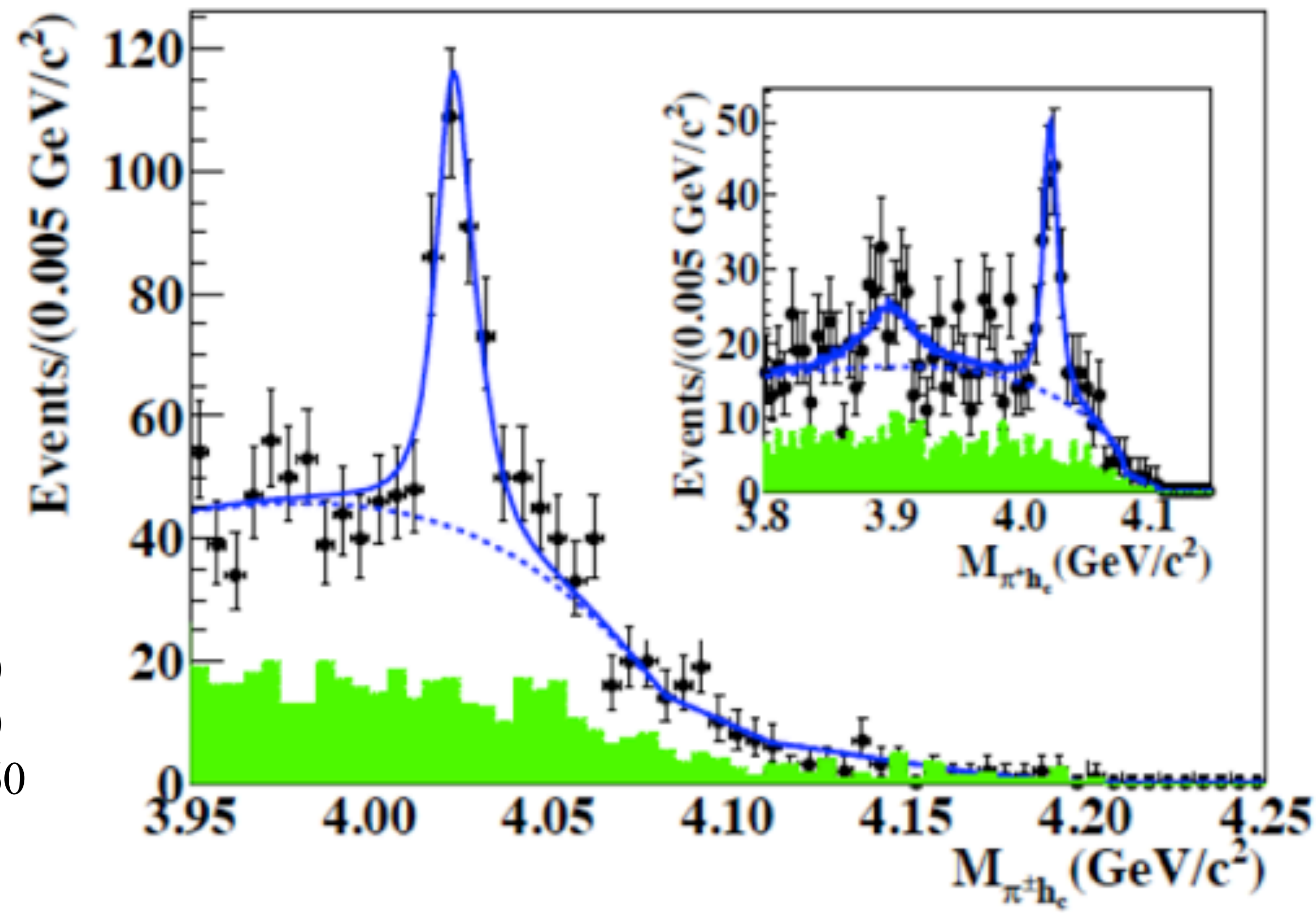
525 pb-1 @ 4.260 GeV




M = 3883.9±1.5±4.2 MeV; Γ = 24.8±3.3±11.0 MeV

# $e^+e^- \to \pi Z_c(4020) \to \pi^+\pi^- h_c$

BESIII: 1309.1896



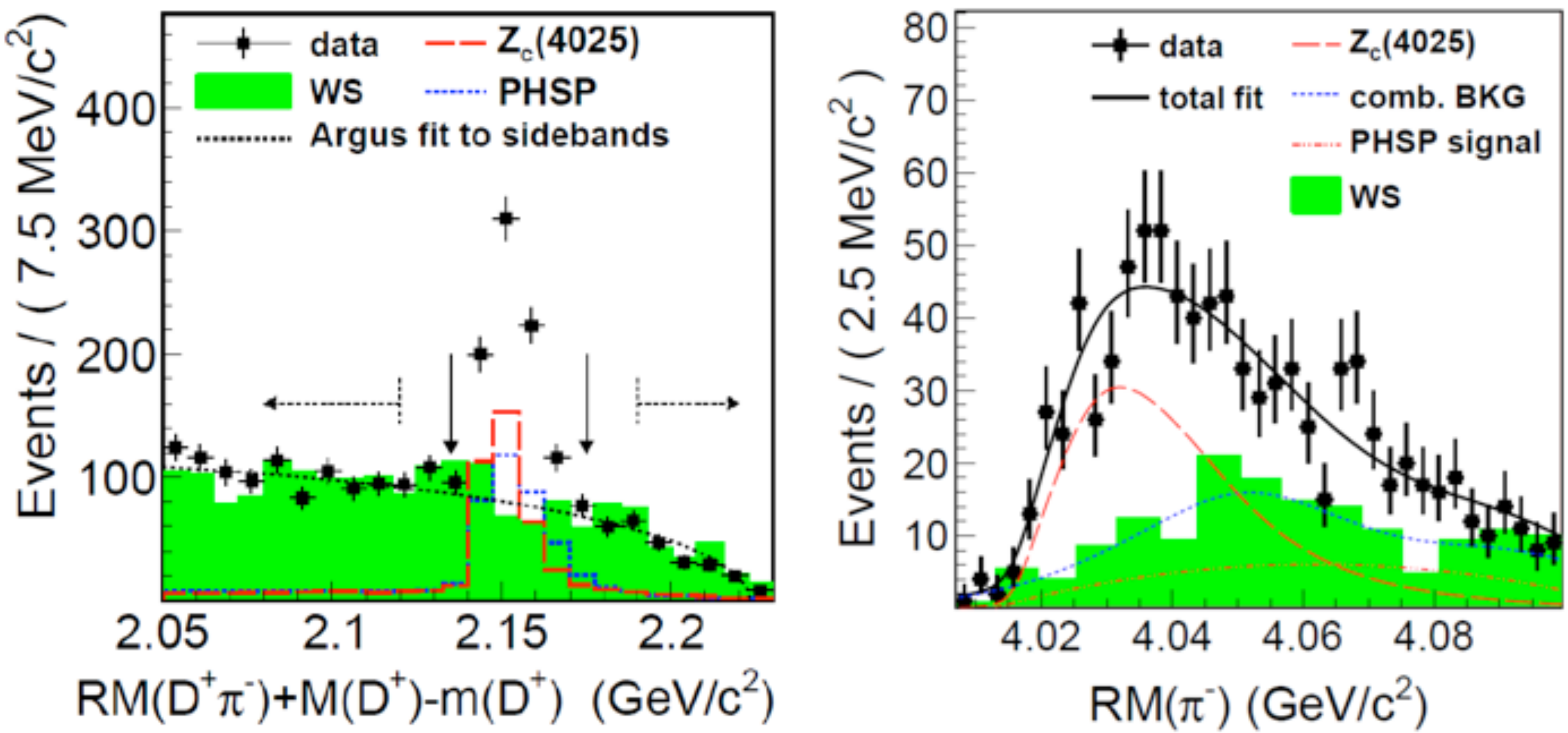

8.7±1.9±2.8±1.4 pb @ 4.230
7.4±1.7±2.1±1.2 pb @ 4.260
10.3±2.3±3.1±1.6 pb @ 4.360

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 $\eta_c$ decay modes:

$M = 4022.9\pm0.8\pm2.7$ MeV/$c^2$ $\Gamma = 7.9\pm2.7\pm2.6$ MeV

## $e^+e^- \to \pi Z_c(4025) \to \pi^- (D^*\bar{D}^*)^+$

BESIII: 1308.2760




Fit to $\pi^\pm$ recoil mass yields 401±47 Zc(4025) events $\Rightarrow$ >10σ

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV; $\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

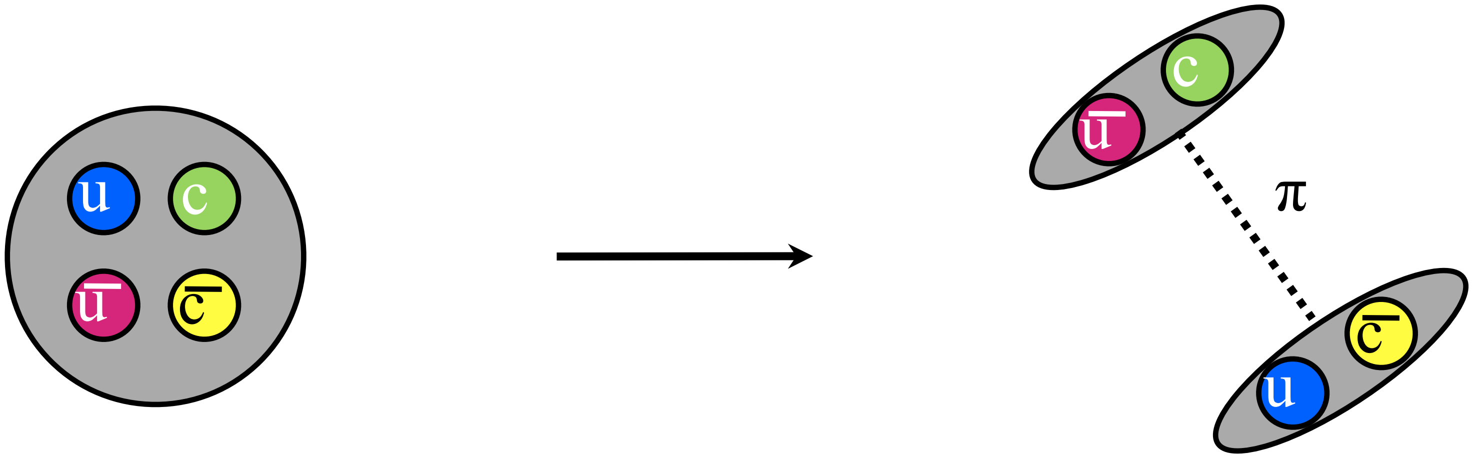
$$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp(4025) \to \pi^\pm (D^*\bar{D}^*)^\mp)}{e^+e^- \to \pi^\pm (D^*\bar{D}^*)^\mp} = (65 \pm 9 \pm 6)\%$$

A new class of particles have been observed:

- At least 4-quarks
- Charged
- Close to threshold DD thresholds
- They couple to DD final states larger than to charmonia

4-quark state

D-$\bar{D}$-“molecule”




Transition from color forces to colorless nuclear forces ?

Ulrich Wiedner

# The future: PANDA

Proton-Antiproton contains already a 4-Quark-System

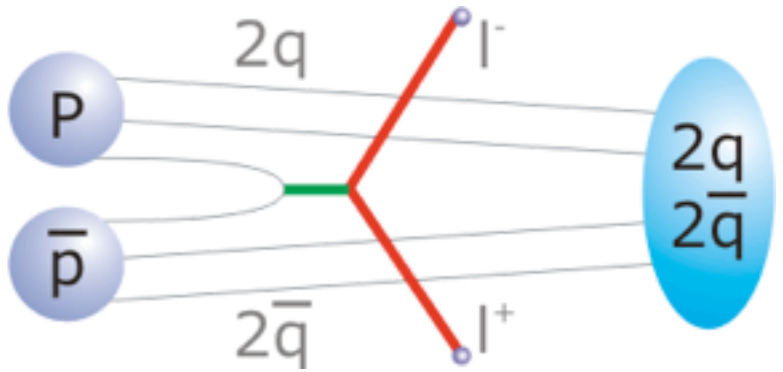
Idea: Dilepton-Tag from Drell-Yan-Production

Advantages

- Trigger
- less $J^{PC}$-Ambiguities
- 1200 E./day @ 12 GeV
- 300 E./day @ 5-8 GeV

  antiproton-Beam

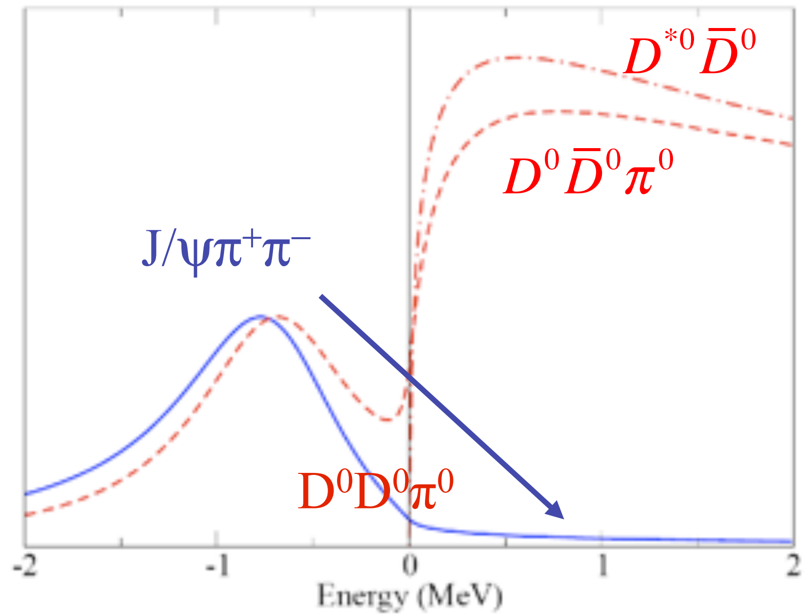
  (for $L=10^{32}cm^{-2}s^{-1}$)




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

# How to progress further in the understanding of the new states?

It is important to determine the resonance curve precisely ...




The line shapes for virtual state and bound state are the same *above* threshold but differ dramatically *below* threshold.

**Analysis of $J/\psi\,\pi^+\pi^-$ and $D^0\bar{D}^0\pi^0$ Decays of the $X(3872)$**


Eric Braaten and James Stapleton

*Physics Department, Ohio State University, Columbus, Ohio 43210, USA*

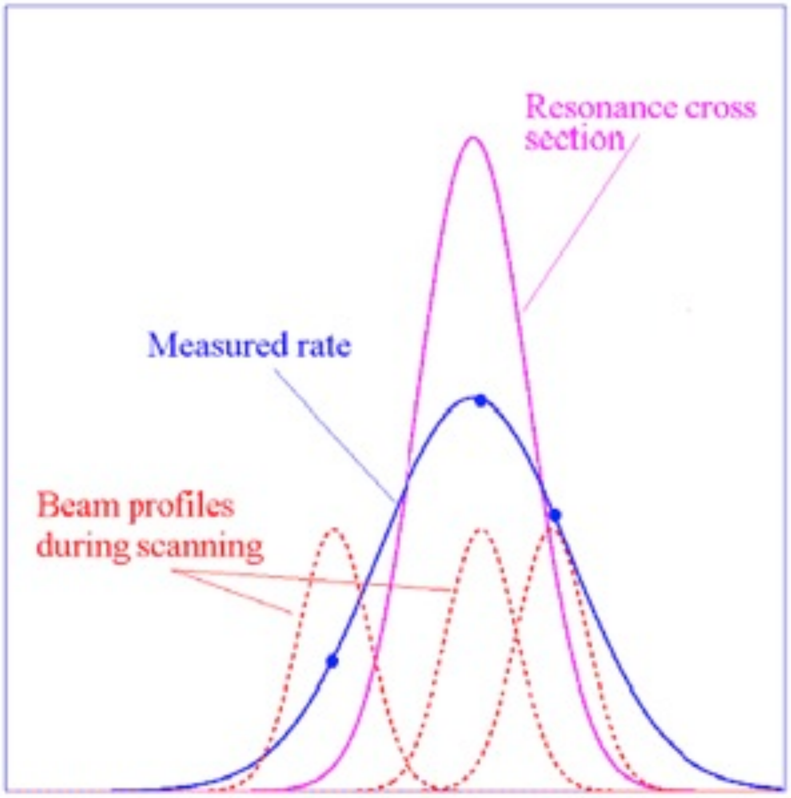


(Dated: July 17, 2009)

Phys.Rev. D81 (2010) 014019

# Resonance scan with varying $\bar{p}$ momentum at PANDA

(possible for states with all quantum numbers)



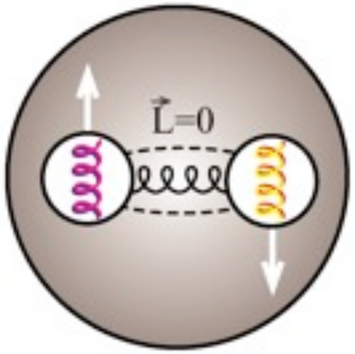

Measure rate of final state under study:

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

(K takes overlap between beam and resonance into account)

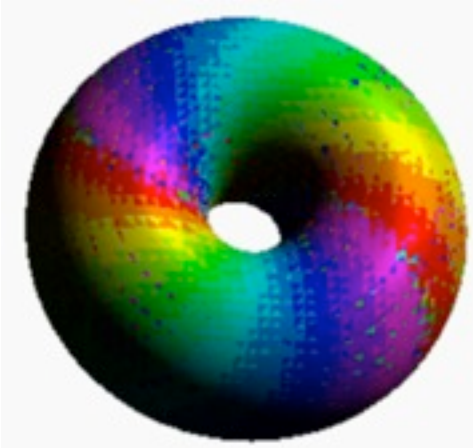
# Other QCD states: Glueballs

The structure of glueballs



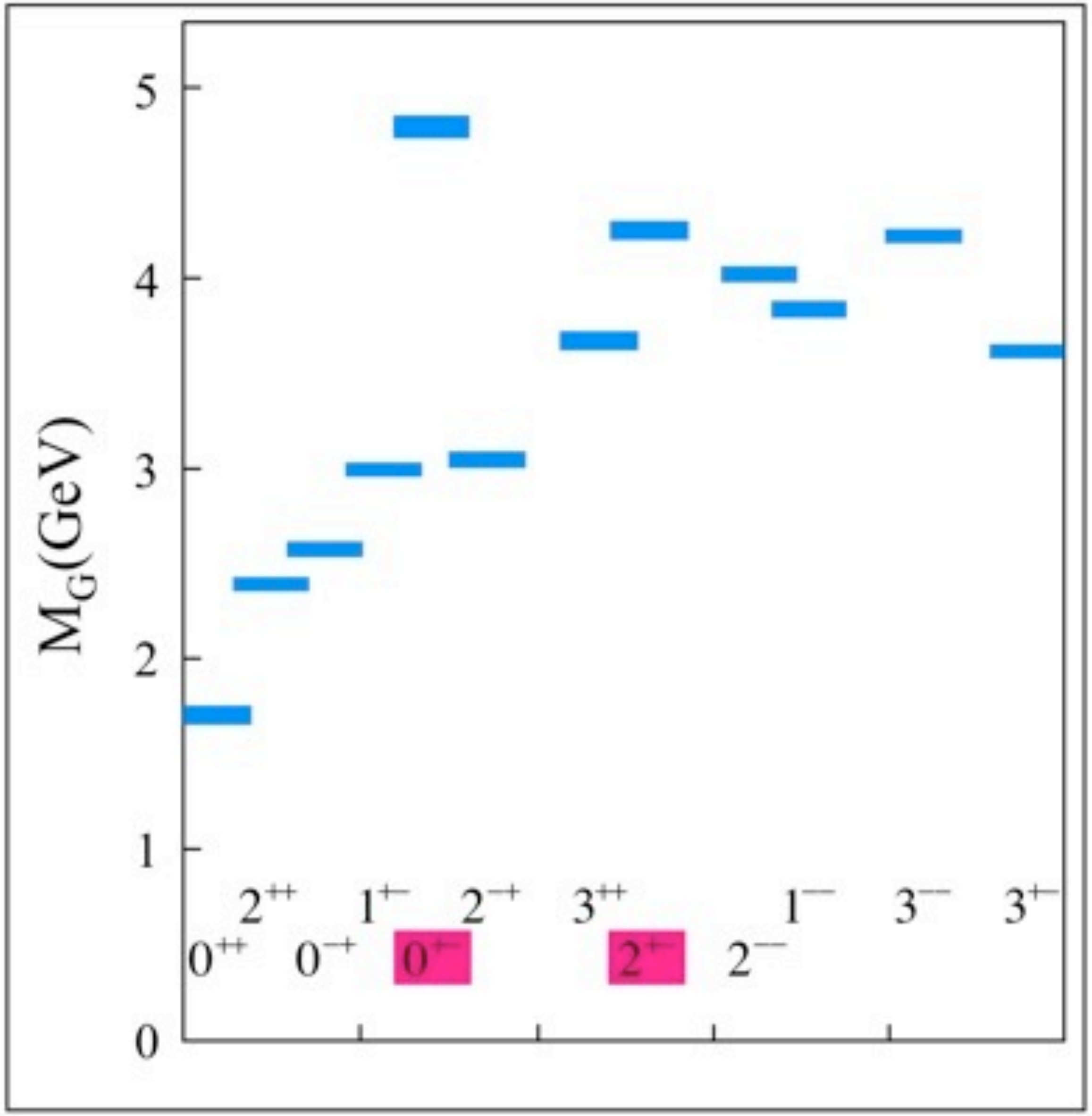

Glueball (gg)

Are glueballs configurations of twisted or knotted colored flux?



GLUEBALLS, FLUXTUBES AND η(1440).
L. Fadeev, A. Niemi and U. Wiedner
Phys.Rev.D70:114033, 2004

# A possible glueball spectrum



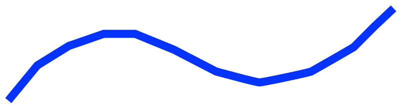
# Glueballs → Creation of Mass

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

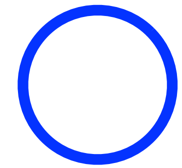
**Most** of the proton mass is created by the **strong interaction**.

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

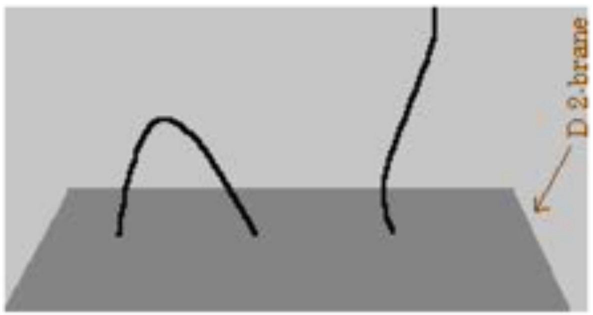
## Open Strings



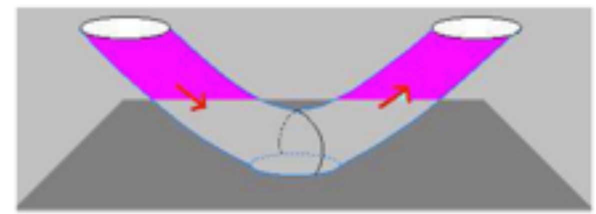
## Closed Strings



## String World

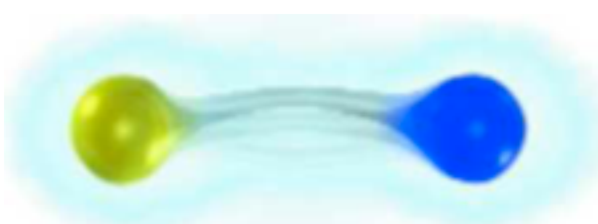



representing gauge theories

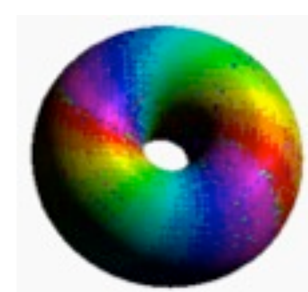


representing gravitation

## Hadron World



meson



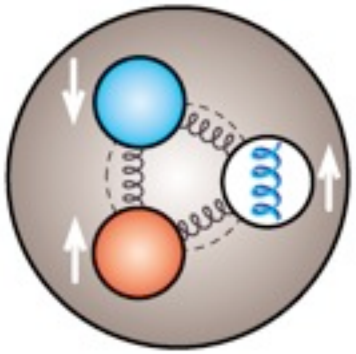
glueball

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

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]

# Hybrids



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

Gluons contribute to the quantum numbers of the particle.

Mesons are fermion-antifermion systems, which follow rules:

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

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

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

possible from $q\bar{q}$

$$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$$

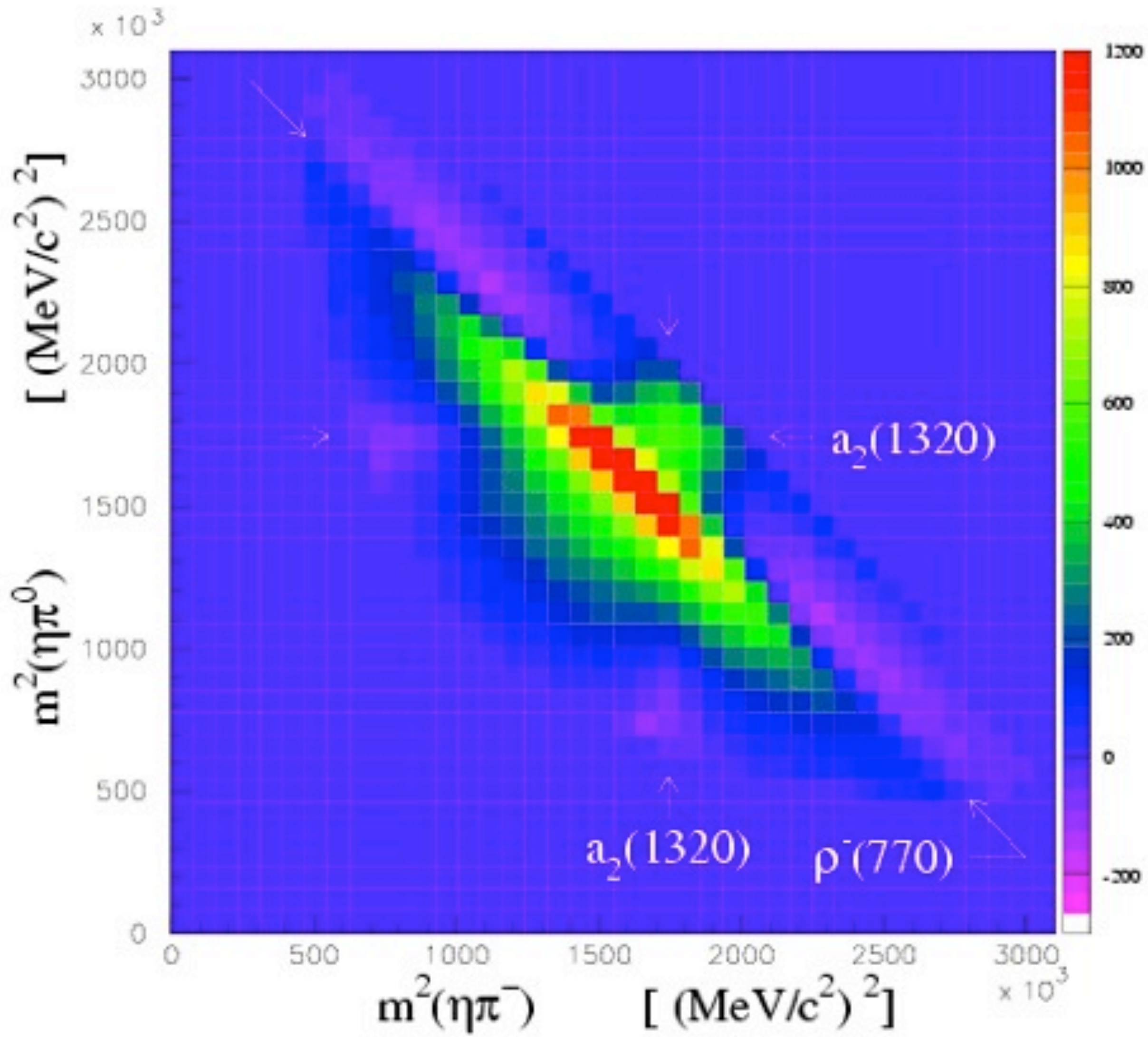
not possible from $q\bar{q}$

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$$

# Crystal Barrel

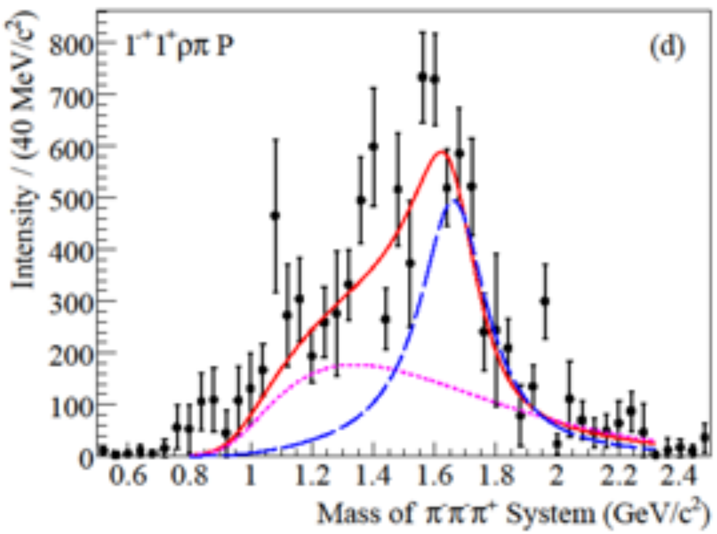
$$\bar{p}d \rightarrow \pi^- \pi^\circ \eta + p$$

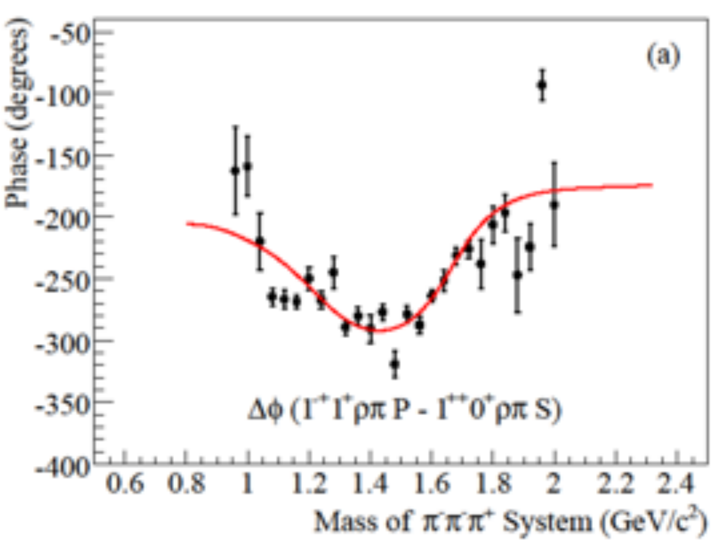
spectator
(<100 MeV/c)



# $J^{PC}=1^{-+}$ – Pb vs H Target

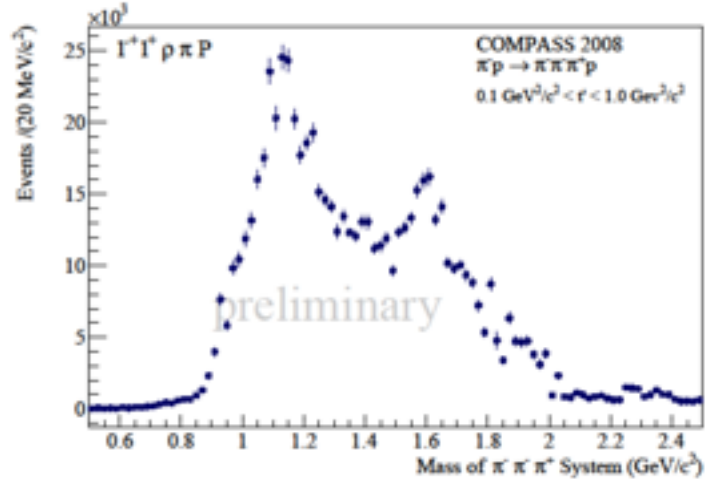
$\pi^- Pb \rightarrow \pi^- \pi^- \pi^+ Pb$

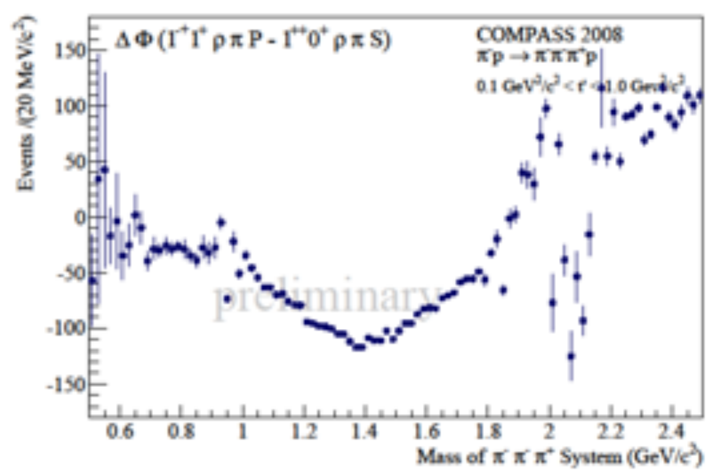



[Alekseev et al., Phys. Rev. Lett. 104, 241803 (2010)]

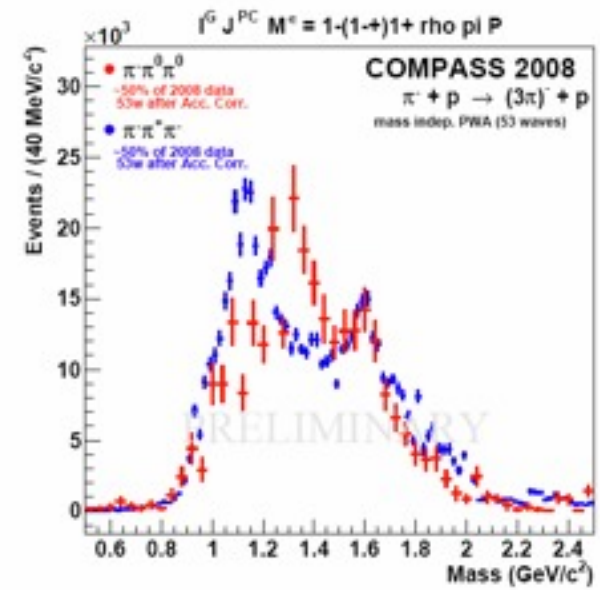
$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$

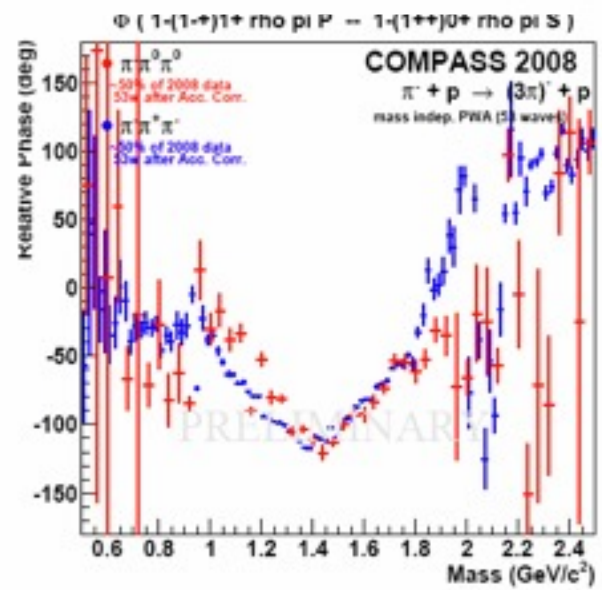



[F. Haas, arXiv:1109.1789 (2011)]

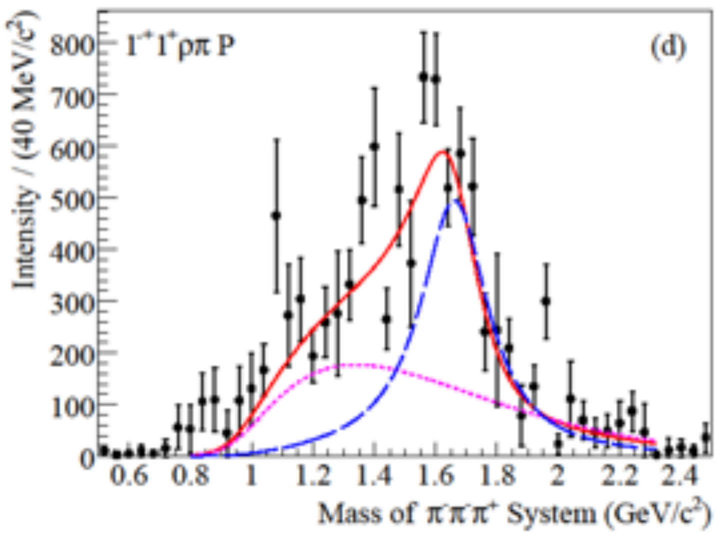
$\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$

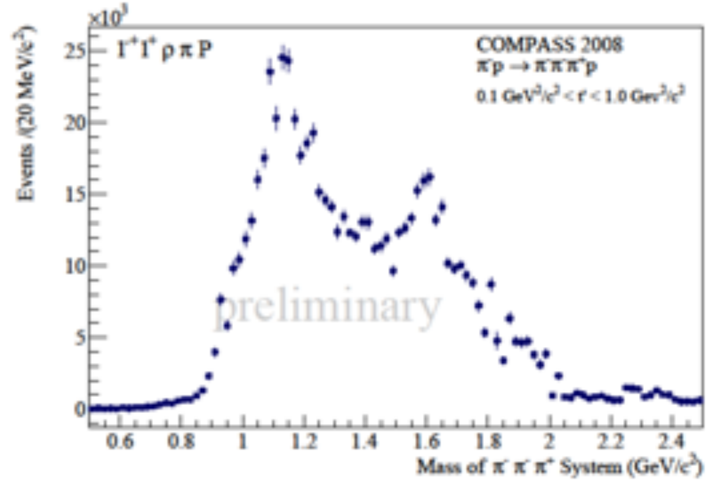


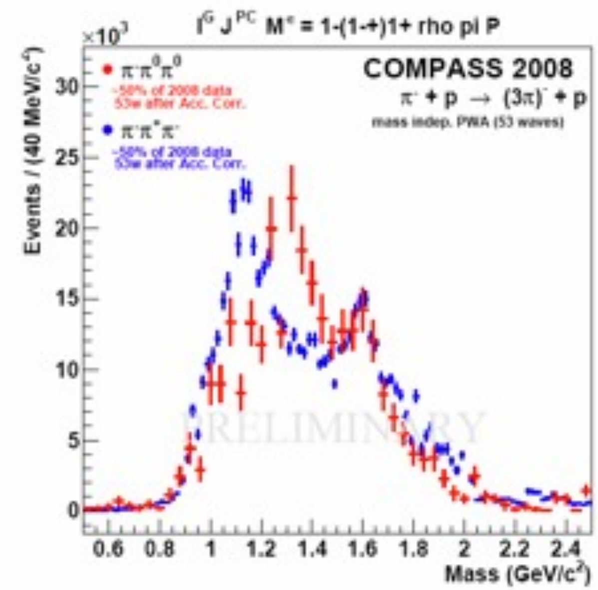



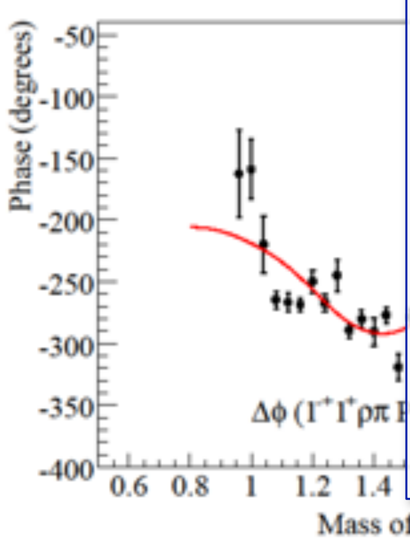
# $J^{PC}=1^{-+}$ – Pb vs H Target

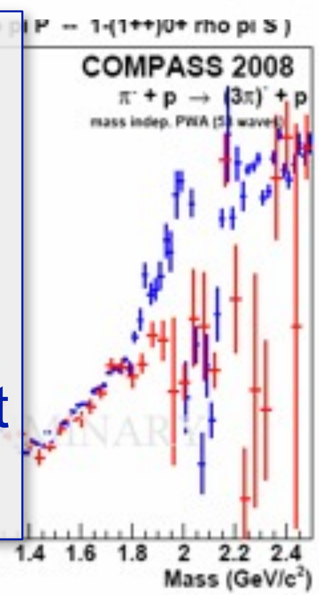
$\pi^- \mathrm{Pb} \rightarrow \pi^- \pi^- \pi^+ \mathrm{Pb}$ | $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ | $\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$



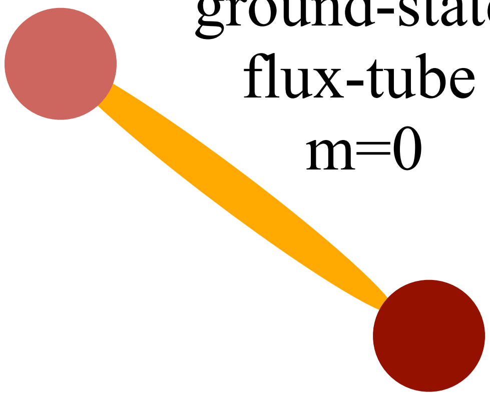

- Peak at 1.67 GeV/$c^2$ for both targets
- Phase motion indicates resonant behavior
- Structure at 1.2 GeV/$c^2$ unstable w.r.t. fit model
- No fit to spin-density matrix yet for H target
- Production of $M$=1 states enhanced for heavy target
- Non-resonant background to be understood

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

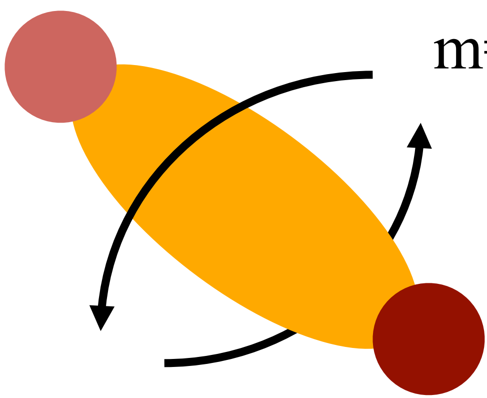
[F. Haas, arXiv:1109.1789 (2011)]

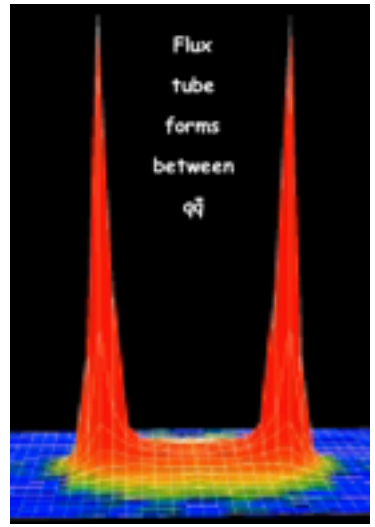
# Gluonic Excitations – Hybrids at JLAB 12 GeV

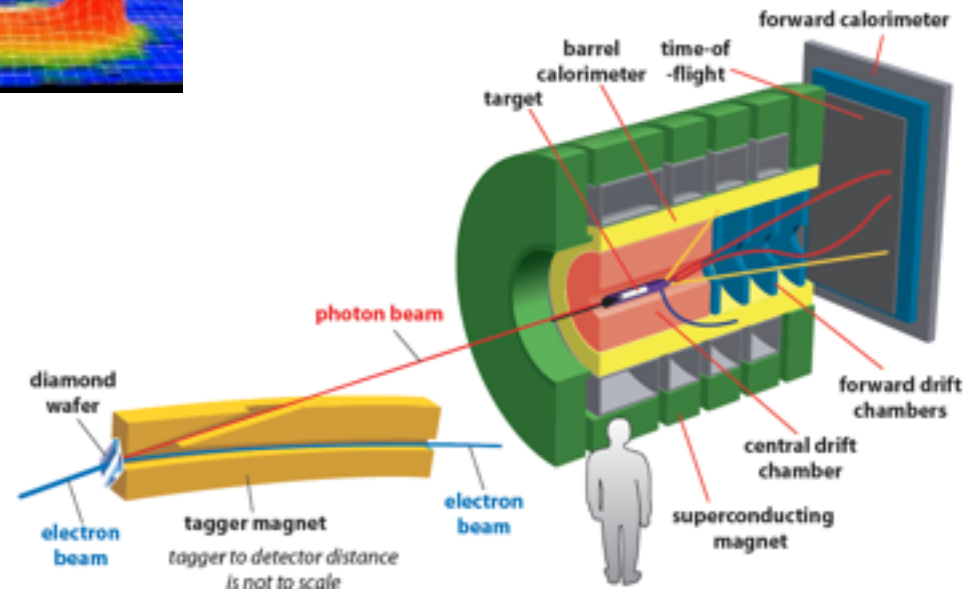
ground-state
flux-tube
m=0



excited flux-tube
m=1






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

... at Hall D

# Hybrids ?

*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.

$\pi_1(1660)$

Mass: $1660 \pm 10^{+0}_{-64}$ MeV/c²

Width: $269 \pm 21^{+42}_{-64}$ MeV/c²

Decay: $(\rho\pi)$

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

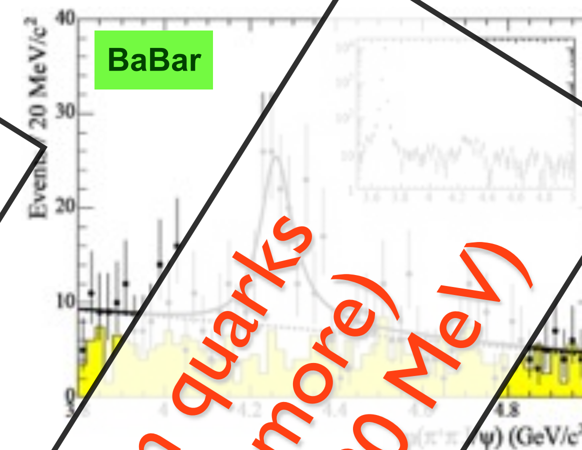
M.G. Alekseev et al.,
PRL 104 (2010) 241803

light quarks:
BROAD (~300 MeV)
(likely unmixed)

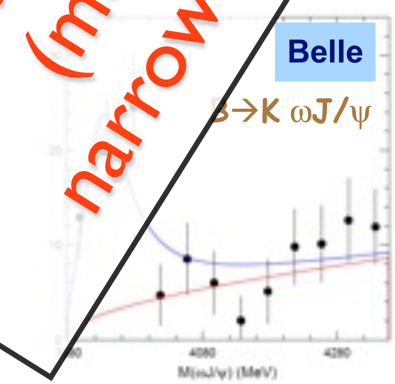
ss hybrids

??????

Y(4260)




Y(3940)

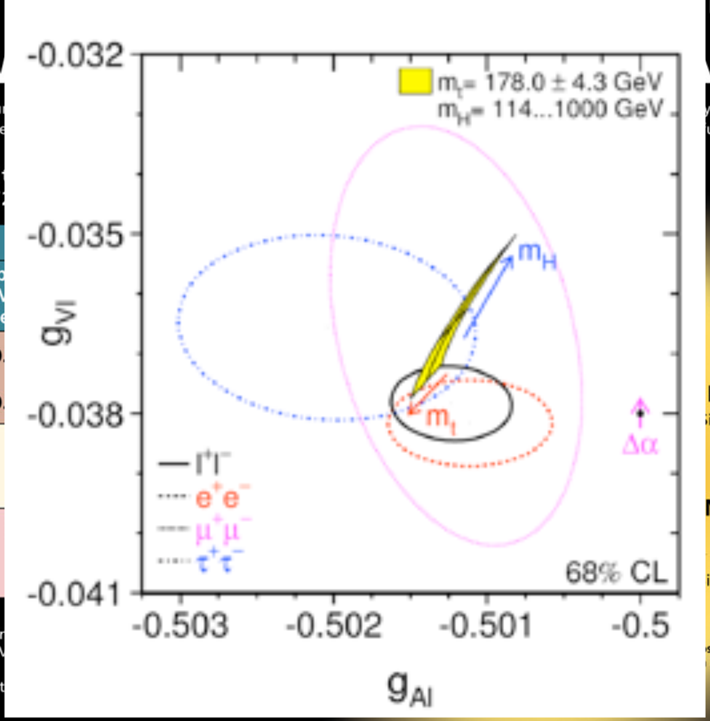


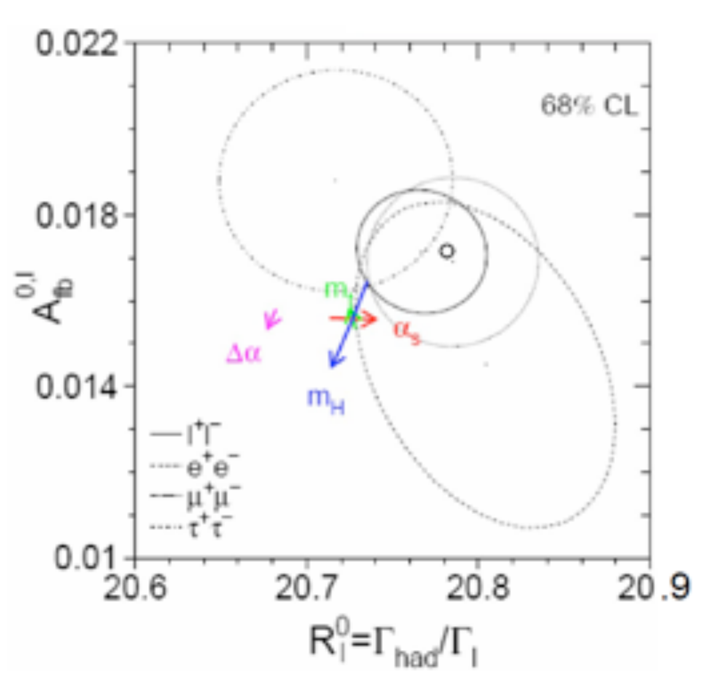

charm quarks
(much more)
narrow (~80 MeV)

JLAB@12 GeV

PANDA

Standard Model of
FUNDAM
ND INTERACTIONS
The Standard Model su
theory of weak and e
of strong interactions (quantum chromodynamics or QCD) and the unified
undamental interactions even though not part of the "Standard Model."
FERMIONS
matter consti
spin = 1/2, 3/
Leptons spin = 1/2
Flavor
Mass GeV/c²
Electric charge
electron neutrino <1×10⁻⁸ 0
e electron 0.000511 −1
muon neutrino <0.0002 0
muon 0.106 −1
tau neutrino <0.02 0
tau 1.7771 −1
Quarks
up
down
charm
strange
t top
b bottom
BOSONS
force carriers
spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name
Mass GeV/c²
Electric charge
photon 0 0
W⁻ 80.4 −1
W⁺ 80.4 +1
Z⁰ 91.187 0
Strong (color) spin = 1
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 electri-
cally-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
Electron
Neutron and Proton
Baryons qqq and Antibaryons q̄q̄q̄
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
p̄ anti-proton ūūd̄ −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
Matter and Antimatter
Figures
Strong
Fundamental
Residual
Color Charge
Hadrons
Mesons
Not applicable to quarks
Mesons qq̄
Mesons are bosonic hadrons.
There are about 140 types of mesons.
Symbol Name Quark content Electric charge Mass GeV/c² Spin
π⁺ pion ud̄ +1 0.140 0
K⁻ kaon sū −1 0.494 0
ρ⁺ rho ud̄ +1 0.770 1
B⁰ B-zero db̄ 0 5.279 0
ηc eta-c cc̄ 0 2.980 0
p p → Z⁰Z⁰ + assorted hadrons
The Particle Adventure
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




Is the Proton radius different if tested with electrons and muons?
g−2 of the muon?

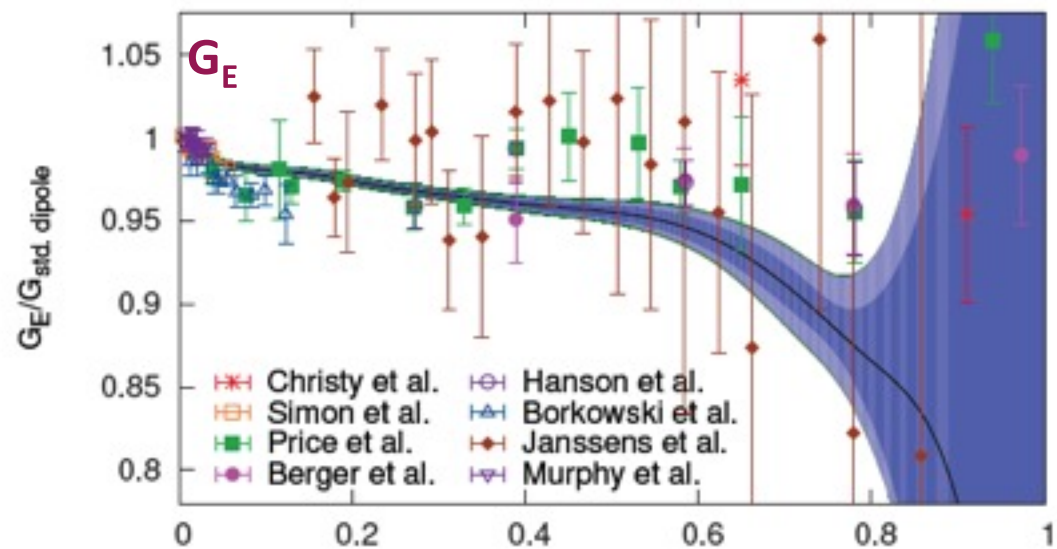
# Highlight A1: Proton Radius Puzzle

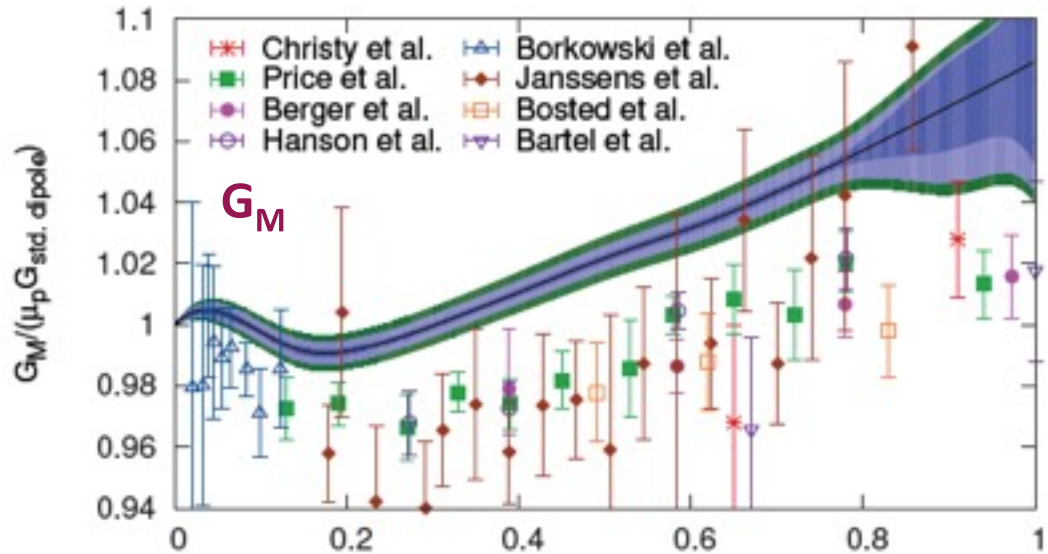
**Form Factor for elastic ep scattering**:

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

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

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



Vol 466 | 8 July 2010 | doi:10.1038/nature09250 nature

LETTERS

# The size of the proton

Randolf Pohl[1], Aldo Antognini[1], François Nez[2], Fernando D. Amaro[3], François Biraben[2], João M. R. Cardoso[3], Daniel S. Covita[3,4], Andreas Dax[5], Satish Dhawan[5], Luis M. P. Fernandes[3], Adolf Giesen[6]†, Thomas Graf[6],

**On the basis of present calculations[11–15] of fine and hyperfine splittings and QED terms, we find $r_p = 0.84184(67)$ fm, which differs by 5.0 standard deviations from the CODATA value[3] of 0.8768(69) fm. Our result implies that either the Rydberg constant has to be shifted by −110 kHz/$c$ (4.9 standard deviations), or the calculations of the QED effects in atomic hydrogen or muonic hydrogen atoms are insufficient.**

pared to ordinary atomic hydrogen causes enhancement of effects related to the finite size of the proton. In particular, the Lamb shift[10] (the energy difference between the $2S_{1/2}$ and $2P_{1/2}$ states) is affected by as much as 2 per cent. Here we use pulsed laser spectroscopy to measure a muonic Lamb shift of 49,881.88(76) GHz. On the basis of present calculations[11–15] of fine and hyperfine splittings and QED terms, we find $r_p = 0.84184(67)$ fm, which differs by 5.0 standard deviations from the CODATA value[3] of 0.8768(69) fm. Our result implies that either the Rydberg constant has to be shifted by −110 kHz/$c$ (4.9 standard deviations), or the calculations of the QED effects in atomic hydrogen or muonic hydrogen atoms are insufficient.

$$\Delta E = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 \text{ meV} \quad (1)$$

where $r_p = \sqrt{\langle r_p^2 \rangle}$ is given in fm. A detailed derivation of equation (1) is given in Supplementary Information.

The first term in equation (1) is dominated by vacuum polarization, which causes the 2S states to be more tightly bound than the 2P states (Fig. 1). The $\mu p$ fine and hyperfine splittings (due to spin–orbit and spin–spin interactions) are an order of magnitude smaller than the Lamb shift (Fig. 1c). The uncertainty of 0.0049 meV in $\Delta\tilde{E}$ is dominated by the proton polarizability term[13] of 0.015(4) meV. The second and third terms in equation (1) are the finite size contributions. They amount to 1.8% of $\Delta\tilde{E}$, two orders of magnitude

Looking forward to a bright and interesting future of hadron physics -
and to many more interesting Hirschegg meetings on this topic.